Open questions in particle physics

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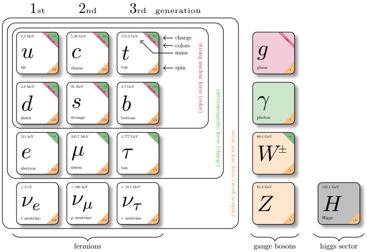
Introduction

Where we are now: the Standard Model

$$\mathcal{L}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + \left(y_{ij}\bar{\psi}^i_L \Phi \psi^j_R + h.c.\right) + |D_\mu \Phi|^2 - V(\Phi)$$

The Standard Model of particle physics



Key aspects

- Based on $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry principle
- Spontaneous breaking of $SU(2)_L \times U(1)_Y$ to $U(1)_{EM}$ via the Higgs mechanism
- Yukawa interactions yield fermion masses and mixing

Where we are now: the Standard Model

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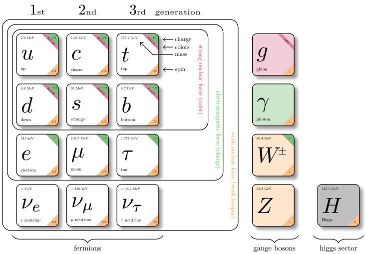


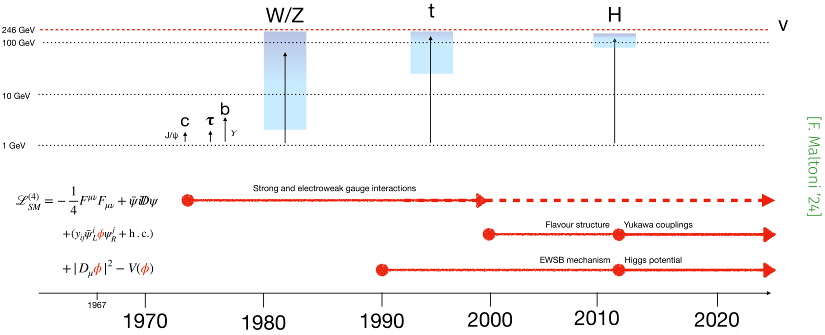
Issues

- no Dark Matter candidate
- unable to explain matter/anti-matter asymmetry of the universe (e.g. EWBG)
- naturalness
- flavor structure unexplained
- strong CP problem

However no element on the theory side to determine the next physics scale

While we wait for a machine able to reach higher-energies, or an input from other sectors, where should we expect deviation from the SM $\rightarrow$ in the Higgs sector

Testing the SM in the past 50 years



Exploring the Standard Model

- In the past 50 years we have explored different sectors of the SM Lagrangian
- With the Higgs discovery in 2012, we have now a direct handle over the EWSB mechanism, and the flavor structure of the Yukawa → particle physics in the 21st century, at the high-energy frontier, will revolve around the study of the Higgs

Why we need physics beyond the standard model

However, at the same time, the SM is unable to explain various observations

Observational signs of New Physics (NP)

- The matter anti-matter asymmetry of the universe
- Dark matter
- Inflation

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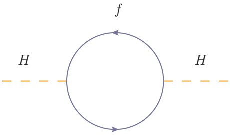

Theoretical arguments in favor of NP

- Naturalness of the Higgs sector
- Gauge coupling unification
- Mass and Flavor hierarchies
- Consistent theory of quantum gravity

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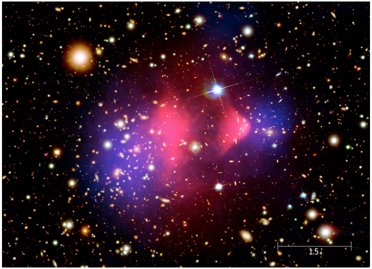
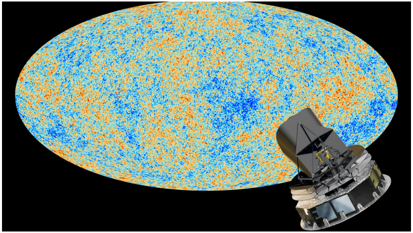


[NASA, Chandra, HST]

The quest for new physics in the 21st century

A wide approach on different fronts: high-energy, low-energy, astro/cosmo etc

[CERN]



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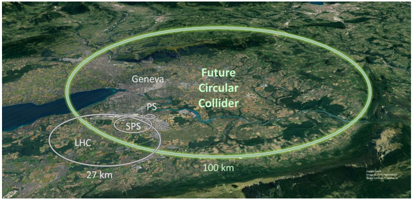

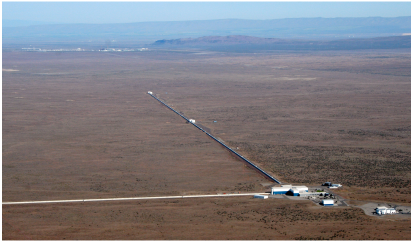

[LIGO]

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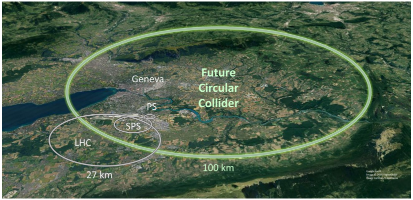

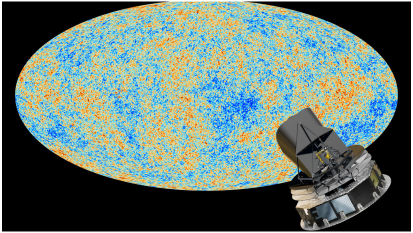

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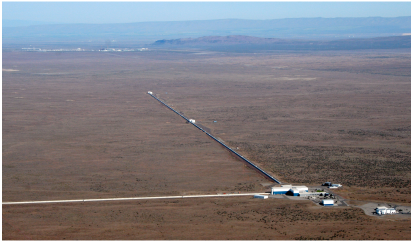


[LIGO]

Scope of the lectures

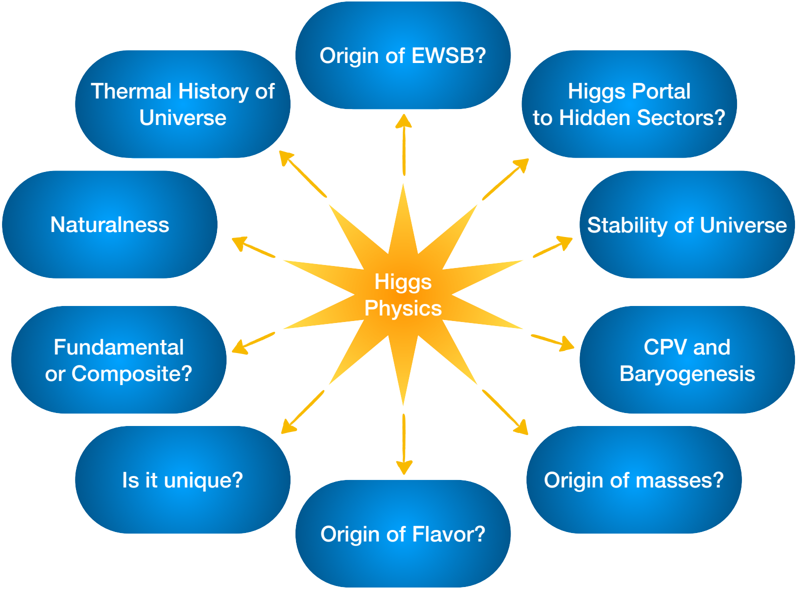
Covering all the possible way in which we can probe new physics will probably take several semesters of university courses. I selected a few topics that are closer to my own research activity

- A focused discussion of Higgs physics at the LHC
- A focused discussion of supersymmetry as a example of a theory motivated model
- A focused discussion of Dark Matter

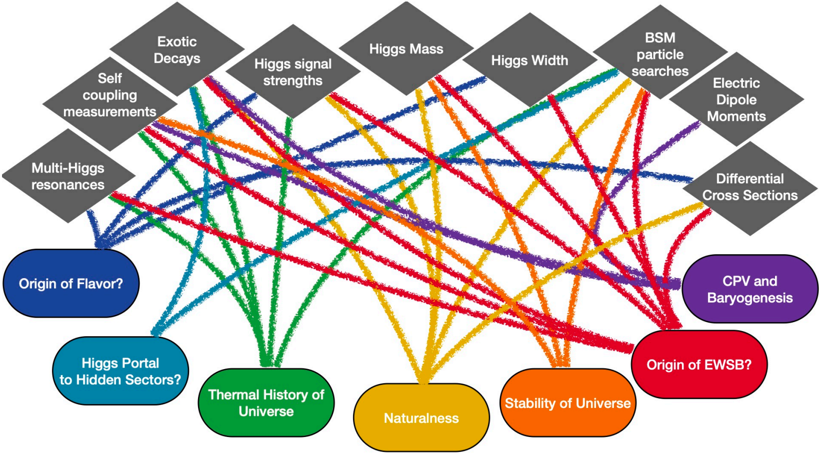
I will also the Higgs physics case to stress important theoretical challenges in the quest for precise predictions.

The Higgs

The Higgs as the focus of the quest for BSM



The Higgs as the focus of the quest for BSM



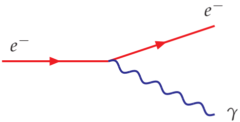
The principle of gauge invariance

Observable	Limit
electron lifetime	$> 4.3 \times 10^{23}$ years
neutron lifetime for the decay $n \to p + neutrals$	$\gtrapprox 10^{19}$ years
proton lifetime	$> 10^{32}$ years
photon mass	$< 6 \times 10^{-22}$ MeV

- Conservation of electric charge experimentally less probed than conservation of baryonic charge
- Nevertheless none doubts electric charge conservation, while we search for baryonic charge violation (i.e. proton decay)
- Why? Because we believe that the QED has a gauge symmetry as the underline structure!

[Pokorski gauge field theories book ’85]

Gauge invariance in QED



$$\mathcal{L}_{\text{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi - ie\,\overline{\psi}\gamma^\mu\psi\,A_\mu$$

where ψ is the fermion (electron) spinor, A_μ is the photon field, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the photon field strength tensor.

$U(1)$ global	$U(1)$ gauge (local)
$\psi \to e^{-i\alpha}\psi$	$\psi \to e^{-i\alpha(x)}\psi$ $A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha(x)$

- We could in principle add a mass term for the photon without violating the *global* $U(1)$ symmetry (such a theory has also been proven to be renormalizabe [Matthews '49, Boulware '70, Salam & Strathdee '80])
- However it seems unphysical that the phase can be redefined freely if all observers in the universe redefine it in the same way $\to$ promote the symmetry from global to local (gauge)

Gauge invariance in QED

The mass term for a photon would have the form

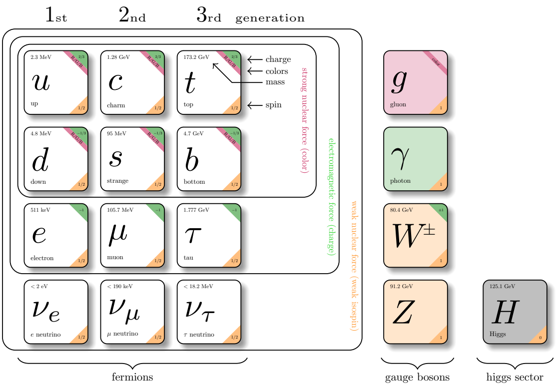
$$\mathcal{L}_{\text{photon mass}} = \frac{1}{2} m_A^2 A_\mu A^\mu$$

We immediately see that this term is not gauge invariant. Indeed we have

$$\frac{1}{2} m_A^2 A_\mu A^\mu \rightarrow \frac{1}{2} m_A^2 \left(A_\mu A^\mu + \frac{2}{e} A^\mu \partial_\mu \alpha + \frac{1}{e^2} \partial_\mu \alpha \partial^\mu \alpha \right)$$

We are left to conclude that the photon should massless in QED as a gauge theory, as it has been found experimentally

The Standard Model of particle physics



- Formulated as a gauge theory based on the groups $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Problem: the mediators of the weak interactions are experimentally found to be massive
- In the case of non-abelian theories, it is not possible to introduce a mass term for the vector bosons explicitly and still have a renormalizable theory, even if we decide not to care about gauging the symmetry

Solution: spontaneous symmetry breaking

- The solution to this conundrum is the so-called Higgs mechanism. The Higgs mechanism breaks spontaneously the gauge symmetry of the theory, allowing for massive vector (gauge) bosons while still starting from a gauge invariant formulation of the Lagrangian
- The simplest implementation consists of a complex scalar field Φ that has a non-zero vacuum expectation value that is constant in space and time

The Lagrangian for this field is

$$\mathcal{L}_\Phi = \mathcal{L}_{\Phi,\mathrm{kinetic}} + \mathcal{L}_{\Phi,\mathrm{potential}}$$

where

$$\begin{aligned}\mathcal{L}_{\Phi,\mathrm{kinetic}} &= (D_\mu\Phi)^*(D^\mu\Phi)\\ -\mathcal{L}_{\Phi,\mathrm{potential}} &= V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2\end{aligned}$$

How can we choose μ and λ?

- λ has to be positive otherwise the potential is unbounded from below
- μ^2 can be either positive or negative, however only the latter choice yields a non-zero vev

How to get a non zero vev

Let's parameterize the complex field Φ in terms of two real scalar fields ϕ and η

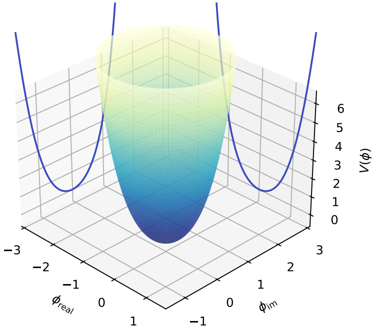
$$\Phi(x) = \frac{1}{\sqrt{2}}\phi(x)e^{i\eta(x)}$$

The scalar potential can be then rewritten as

$$V(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

Imposing the minimization condition

$$\left.\frac{\mathrm{d}V}{\mathrm{d}\phi}\right|_{\phi=\phi_0} = \mu^2\phi_0 + \lambda\phi_0^3 \stackrel{!}{=} 0$$



Only for $\mu^2 < 0$ we have the non-trivial solution with a non-zero vacuum expectation value

$$v := \langle 0|\phi|0\rangle = \phi_0 = \sqrt{\frac{-\mu^2}{\lambda}}$$

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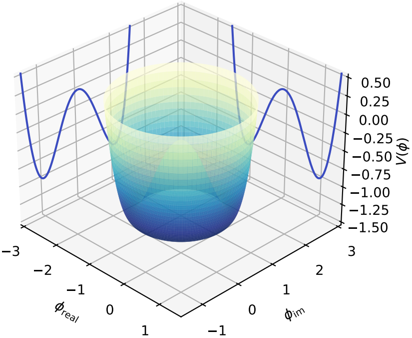

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Massive QED: the Lagrangian in the unitary gauge

Our Lagrangian for a "massive" QED theory therefore is

$$\mathcal{L}_{\text{Massive QED}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}\,(i\gamma^{\mu}D_{\mu} - m)\,\psi + (D_{\mu}\Phi)^{*}(D^{\mu}\Phi) - V(\Phi)$$

with $D_{\mu} = \partial_{\mu} + ieqA_{\mu}$ being the covariant derivative.

We choose the so-called unitary gauge, where the only fields appearing are the physical ones (i.e. ϕ), $\alpha(x) = -\eta(x)/v$.

The scalar field kinetic terms now reads

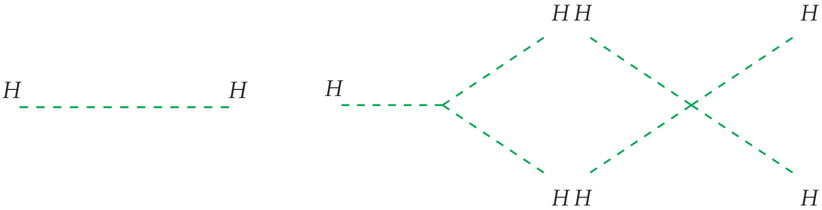
$$(D_{\mu}\Phi)^{*}(D^{\mu}\Phi) \rightarrow \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi + \frac{1}{2}e^{2}q^{2}\phi^{2}A_{\mu}A^{\mu}$$

We expand now the Higgs field around the vev

$$\phi(x) = v + H(x)$$

The remaining degree of freedom, the field $H(x)$ is the so-called Higgs boson

Higgs boson self interactions



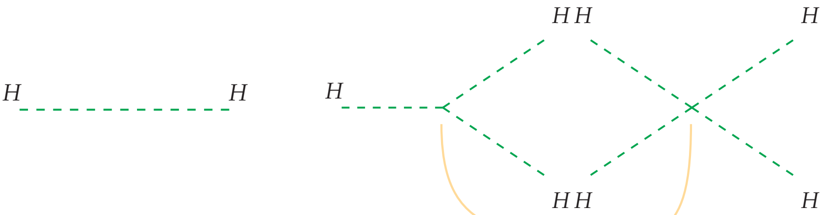
- We can obtain the Higgs boson mass and the self-interactions by replacing the expanded form of the field ϕ in the scalar potential $V(\phi)$

$$-\mathcal{L}_{\text{Higgs}} = -(D^\mu H)(D_\mu H) + \frac{1}{2} m_H^2 H^2 + \frac{k}{3!} H^3 + \frac{\xi}{4} H^4$$

where we have defined

$$m_H^2 = 2\lambda v^2 \qquad k = 3\frac{m_H^2}{v} \qquad \xi = 3\frac{m_H^2}{v^2}$$

Higgs boson self interactions



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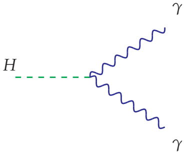
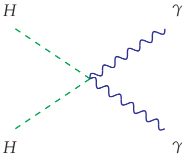
The photon mass and the Higgs-photon interactions



From the Higgs kinetic term, after replacing the covariant derivative with its expression, we obtain

$$\mathcal{L}_{\mathrm{Higgs-photon}} = \frac{1}{2} m_A^2 A_\mu A^\mu + e^2 q^2 v H A_\mu A^\mu + \frac{1}{2} e^2 q^2 H^2 A_\mu A^\mu$$



We have three terms

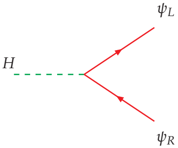
- the first term is the photon mass term ($m_A^2 = e^2 q^2 v^2$)
- the second one is a Higgs-photon-photon vertex
- the third one is a quartic Higgs-Higgs-photon-photon vertex

We can observe a very important feature: the coupling of the photon to the Higgs is proportional to its own mass squared. This is a prediction of the Higgs mechanism that can be used experimentally to test it.

Mass for the chiral fermions

- Suppose now that we want to give mass to a chiral fermion $\psi = (\psi_L, \psi_R)^T$, for which we can not write a mass term explicitly because the left- and right-handed spinors are charged differently under the gauge groups of the theory (as it happens in the SM)
- We can write the following Higgs-fermion Lagrangian term

$$\mathcal{L}_{\text{fermionmass}} = y_\psi \psi_L^\dagger \Phi \psi_R + h.c.$$



where y_ψ is the dimensionless Yukawa coupling. Inserting now the expanded Higgs field $\Phi(x) = v + H(x)$ we find

$$\mathcal{L}_{\text{fermionmass}} = m_\psi \psi_L^\dagger \psi_R + \frac{m_\psi}{v} H \psi_L^\dagger \psi_R + h.c.$$

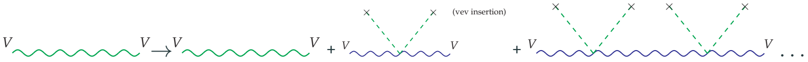
with $m_\psi = y_\psi v$

- We notice again that the coupling of the fermion to the Higgs boson is proportional to its own mass m_ψ

Propagator vev insertion

Another way to see the mass generation is to consider them as insertion to the propagator diagram

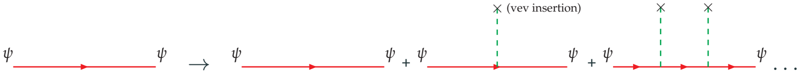
- **Photon mass** – insertion of the Higgs-Higgs-photon-photon vertexes in the photon propagator



$$\frac{1}{q^2} \rightarrow \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2\right]^j = \frac{1}{q^2 - M^2}$$

with $M^2 = g^2 \frac{v^2}{2}$

- **fermion mass** – Yukawa couplings



$$\frac{1}{\not{q}} \rightarrow \frac{1}{\not{q}} + \sum_h \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}}\frac{1}{\not{q}}\right] = \frac{1}{\not{q} - m}$$

with $m_f = g_f \frac{v}{\sqrt{2}}$

The electroweak sector of the Standard Model

The Standard Model of the strong and weak interactions is formulated as a gauge theory of the groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

Focusing on the electroweak sector, the bosonic part of the Lagrangian is given by

$$\mathcal{L}_{bos} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a + |D_\mu\Phi|^2 - V(\Phi)$$
$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

where Φ is a complex scalar $SU(2)_L$ doublet, charged also under hypercharge with $Y = 1/2$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

and

$$D_{mu} = \partial_\mu + ig\frac{\tau^a}{2}W_{\mu a} + ig'\frac{Y}{2}B_\mu$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$
$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - gf^{abc}W_{\mu b}W_{\nu c}$$

The Higgs mechanism in the SM

Assuming that $\mu^2 < 0$, we find the minimum of the Higgs potential at

$$\langle 0|\phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix} \qquad \text{with } v := \sqrt{\frac{-\mu^2}{\lambda}}$$

We rewrite the Higgs doublet as

convention
$1/\sqrt{2}(v+H) \to v \simeq 246$ GeV
$(v + 1/\sqrt{2}H) \to v \simeq 174$ GeV

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1(x) + i\phi_2(x)\\ v + H(x) + i\phi_3(x)\end{pmatrix}$$

Diagonalization of the gauge boson mass matrices show that the three Goldstone bosons (ϕ_i) are absorbed as the longitudinal components of the three massive gauge bosons $W^\pm_\mu, Z_\mu$, while the photon A_mu emerges as massless

$$W^\pm_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \mp iW^2_\mu\right)$$

$$\begin{cases} Z_\mu &= c_W W^3_\mu - s_W B_\mu \\ A_\mu &= s_W W^3_\mu + c_W B_\mu \end{cases}$$

where $\theta_W = \arctan\left(\frac{g'}{g}\right)$ is the weak mixing (Weinberg) angle, and $s_W = \sin\theta_W, c_W = \cos\theta_W$

Higgs-gauge and Higgs-Higgs interactions

The interaction of the Higgs boson with the gauge bosons and the Higgs self-interactions are given by

$$\mathcal{L}_{\rm Higgs-gauge} = \left[M_W^2 W_\mu^+ W^{-,\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right] \left(1 + \frac{H}{v}\right)^2 - \frac{1}{2} M_H^2 H^2 - \frac{k}{3!} H^3 - \frac{\xi}{4!} H^4$$

where

$$M_W = \frac{1}{2} g v \qquad M_Z = \frac{1}{2}\sqrt{g^2 + g'^2} v \qquad M_H = \sqrt{2\lambda} v \qquad k = 3\frac{M_H^2}{V} \qquad \xi = 3\frac{M_H^2}{v^2}$$

- Experimentally, from the measurements of the mass and couplings of the gauge bosons, one find $v \simeq 246$ GeV (note that this value depends on the normalization factors of the Higgs field expansion)
- The masses of the Z and the W are related

$$\frac{M_W}{M_Z} = \frac{g}{\sqrt{g^2 + g'^2}} = c_W$$

Generation of the fermion mass terms

The fermions in the SM are chiral, so we also generate their mass terms via the Higgs mechanism

$$\mathcal{L}_{\mathrm{Higgs-fermion}} = y_b Q_L^\dagger \Phi b_R + y_t Q_L^\dagger \Phi_c t_r + h.c.$$

where $Q_L = (t_L, b_L)^T$ is the left-handed $SU(2)_L$ doublet
In the unitary gauge we can write

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

We can see that we can give mass only to the down-type fermions with this field. However, we have that the field

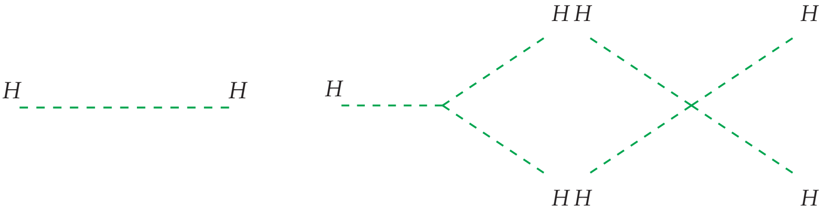
$$\Phi(x)_c = i\sigma^2 \Phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} v + H(x) \\ 0 \end{pmatrix}$$

can be used to generate the mass for the up-type fermions. Expanding explicitly the Lagrangian in terms of the vev we obtain

$$\mathcal{L}_{\mathrm{Higgs-fermion}} = m_b \bar{b} b \left(1 + \frac{H}{v}\right) + m_t \bar{t} t \left(1 + \frac{H}{v}\right)$$

where we have used $\bar{\psi}\psi = \psi_L^\dagger \psi_R + \psi_R^\dagger \psi_L$, $m_b = \frac{y_b v}{\sqrt{2}}$ and $m_t = \frac{y_t v}{\sqrt{2}}$

The Higgs boson self-couplings



We have seen that the self-interactions of the Higgs boson are described by

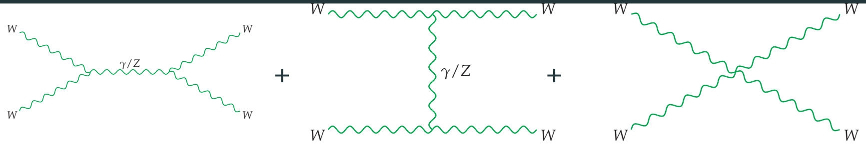
$$\mathcal{L}_{\text{Higgs self int.}} = -\frac{k}{3!}H^3 - \frac{\xi}{4!}H^4 \qquad M_H = \sqrt{2\lambda}v \qquad k = 3\frac{M_H^2}{V} = \qquad \xi = 3\frac{M_H^2}{v^2}$$

which we can rewrite in terms of the original Lagrangian quartic interaction of **Φ**

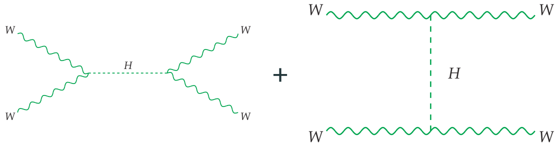
$$\mathcal{L}_{\text{Higgs self int.}} = -\lambda v H^3 - \frac{1}{4}\lambda H^4$$

The measurement of the trilinear and quartic self coupling of the Higgs yield information on the structure of the scalar potential of the Lagrangian *Rightarrow* One of the targets of current and future colliders

Unitarization of the longitudinal vector boson scattering cross section



- The scattering of the longitudinal components of the W boson ($W_L W_L \to W_L W_L$) would grow as $\sim -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$ at large energies *to* unitarity violation

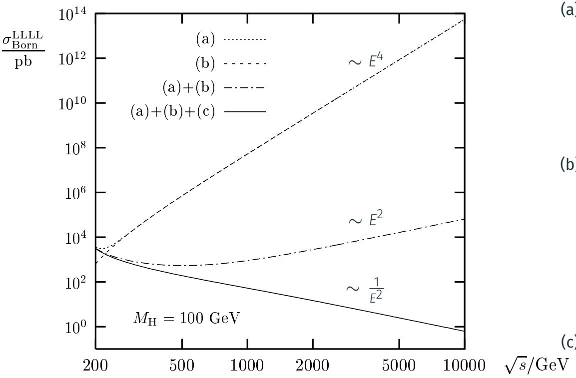


$$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$$

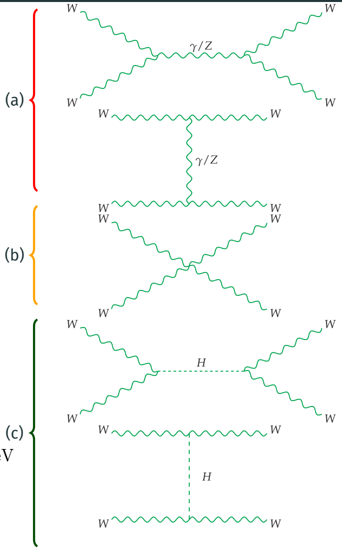
- The sum is $\mathcal{M}_{\rm tot} = \frac{E^2}{M_W^4}\left(g_{WWH}^2 - g^2 M_W^2\right) + \ldots \Rightarrow$ cures the behavior if $g_{WWH} = g M_W$

See [Horjisi book, '94] to see the whole SM constructed in this way

Unitarization of the longitudinal vector boson scattering cross section

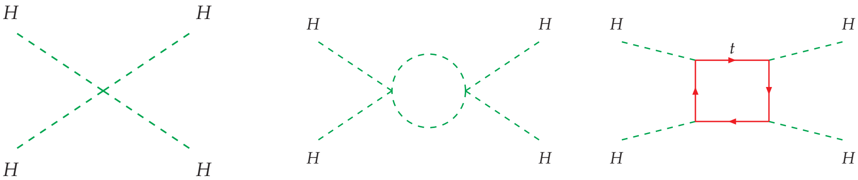


[Denner, Hahn, '97]



Theoretical and indirect bounds on the Higgs

Consistency of the scalar potential

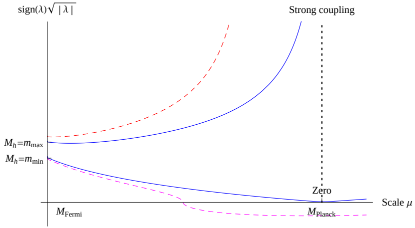


The running of the quartic Higgs self coupling in the SM is described by

$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = \frac{3}{8\pi}\left[\lambda^2 + \lambda g_t - g_t^4 + \frac{1}{16}\left(2g^4 + (g^2 + g_1^2)^2\right)\right] \qquad t = \log\left(\frac{Q^2}{Q_0^2}\right)$$

From the theory viewpoints, we have to satisfy two conditions:

- no Landau pole
- the vacuum should be stable



Consistency of the scalar potential – Landau pole

- **No Laundau pole** – for large $\lambda \sim M_H^2$ we have

$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} \simeq \frac{3}{8\pi^2}\lambda^2$$

whose solution is

$$\lambda(Q^2) = \frac{\lambda(Q_0)}{1 - \frac{3\lambda(Q_0^2)}{8\pi^2}\log\left(\frac{Q^2}{Q_0^2}\right)} \qquad \text{with} \qquad Q_0 \simeq v$$

from which we derive

$$\lambda(\Lambda) < \infty \to M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{Q_0^2}\right)} \qquad \to \text{upper bound on } M_H$$

with Λ being the scale up to which the SM is valid

Consistency of the scalar potential – vacuum stability

- **vacuum stability**, i.e. $\lambda(\Lambda) > 0$ – for small/negative λ

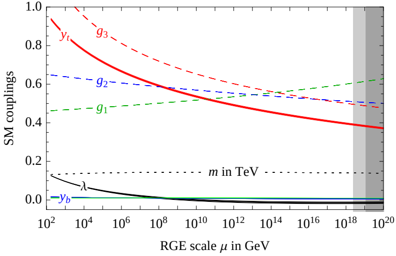
$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} \simeq \frac{3}{8\pi}\left[-g_t^4 + \frac{1}{16}\left(2g^4 + (g^2 + g_1^2)^2\right)\right]$$

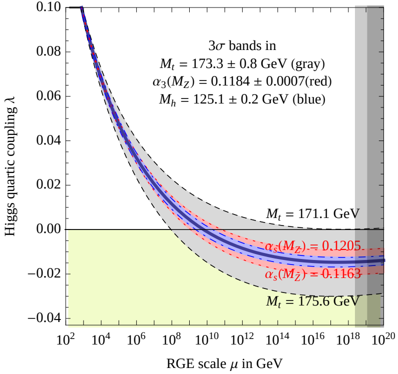
whose solution is

$$\lambda(Q^2) = \lambda(Q_0^2)\frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g^4 + (g^2 + g_1^2)^2\right)\right]\log\left(\frac{Q^2}{Q_0^2}\right)$$

from which we derive

$$\lambda(\Lambda) > 0 \to M_H^2 > \frac{Q_0^2}{4\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g^4 + (g^2 + g_1^2)^2\right)\right]\log\left(\frac{\Lambda^2}{Q_0^2}\right)$$

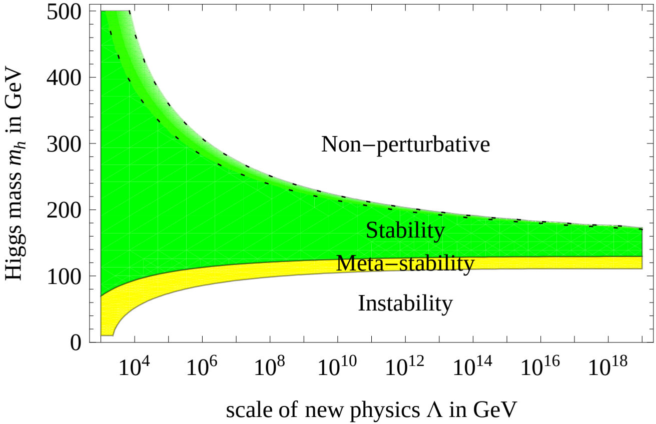




[Buttazzo et al. ’13]

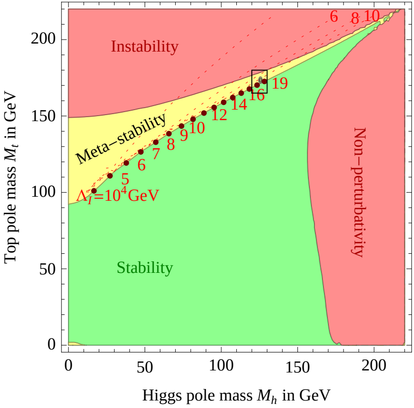
- All couplings are coupled via the RGE system
- The scale at which λ runs to zero strongly depends on the value of the top mass

Combining both limits

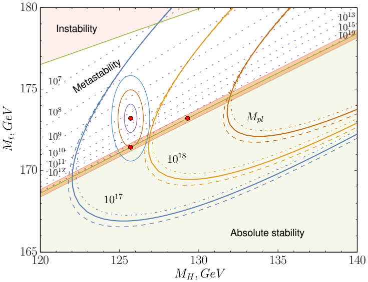


- Important parametric dependence on the value of M_T (dominant term in the RGE of λ)
- Assuming $\Lambda = M_{\mathrm{GUT}} \simeq 10^{16}$ GeV imply $130\ \mathrm{GeV} \lesssim M_H \lesssim 180\ \mathrm{GeV}$

Metastability of the vacuum



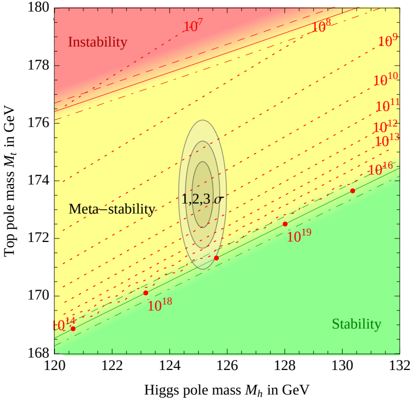
[Buttazzo et al., '13]



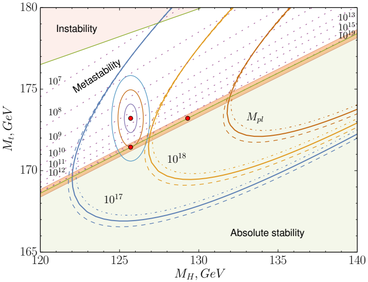
[Bednyakov et al., '15]

- Recent results including the most sophisticated calculations

Metastability of the vacuum



[Buttazzo et al., '13]

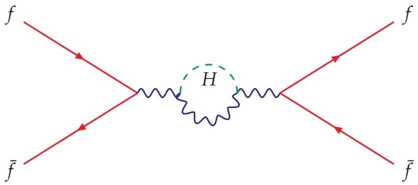


[Bednyakov et al., '15]

- Recent results including the most sophisticated calculations

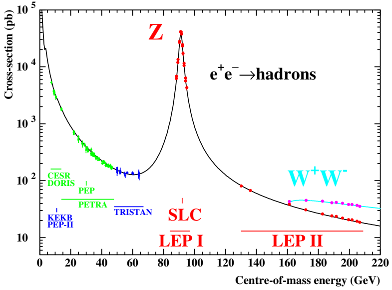
Probing physical states indirectly

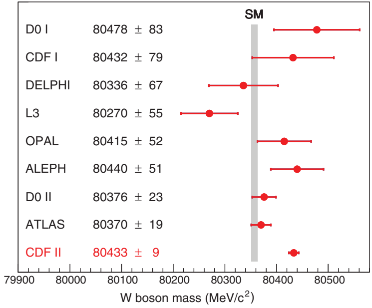
- Idea – if we can not produce the states, we can probe its existence via the sensitivity of a lower-energy observable to the quantum fluctuations it causes (i.e. loop corrections)
- Complementary approach to the direct search of the new states
- In the case of the Higgs, this approach historically played an important role, with the the so-called Electroweak Precision Observables (EWPOs) being the ones having the most capability of probing its existence
- Prerequisite – precisely measured quantities, with comparably small theoretical uncertainties affecting the theory predictions (i.e. higher loop calculations)



Precision observables

- EWPOs: M_W, Z-pole observables ($sin^2\theta^l_{eff}$, A_{fb} etc.) (+anomalous magnetic moment of the leptons (a_e, a_μ))





Others important ones: M_h (after Higgs discovery), b-physics, a_μ, a_e

Computation of the W mass in the SM

M_W calculation

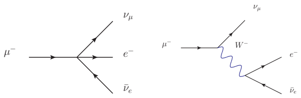
From the matching between the Fermi theory + QED with the MSSM (or the SM or any BSM model)

$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2} (1 + \Delta r)$$

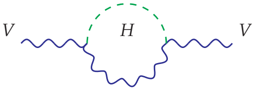
It can be re-arranged to obtain the relationship

$$M_W^2 = M_Z^2 \left(\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\alpha \pi}{\sqrt{2} G_\mu M_Z^2} (1 + \Delta r)} \right)$$

Muon decay



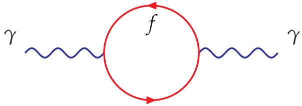
Example Higgs contribution to Δr



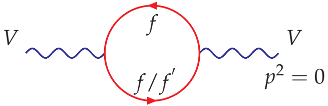
Anatomy of Δr

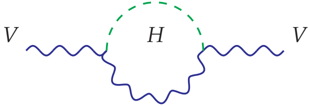
The one loop results for Δr in the SM are available since the ’80s [Sirlin ’80; Marciano, Sirlin ’80] One can write, $\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{remn}}(M_H)$

- $\Delta\alpha \sim \log\left(\frac{M_Z}{m_f}\right) \sim 6\%$
  contribution to the running of α



- $-\frac{c_W^2}{s_W^2}\Delta\rho \sim M_T^2 \sim 3.3\%$
  self-energies of the weak gauge boson at $p^2 = 0$





- $\Delta r_{\text{remn}}(M_H) \sim \log\left(\frac{M_H}{M_W}\right) \sim 1\%$
  the other contributions, including the full Higgs dependence

+ others (box, vertex, self-energies at $p^2 \neq 0$)

The effective weak mixing angle

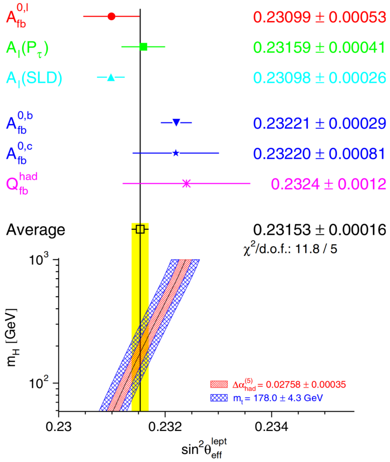
- One of the pseudo-observables measured at the Z-pole by the LEP collider at CERN, SLD at SLAC, and subsequently also at other colliders (Tevatron, LHC)

Defined as

$$\sin^2\theta_{\rm eff} = \frac{1}{4|Q_f|}\left(1 - \mathrm{Re}\frac{g_V^f}{g_A^f}\right)$$

- Higher order contributions shifts the couplings

$$g_V^f \to g_V^f + \Delta g_V^f \qquad g_A^f \to g_A^f + \Delta g_A^f$$



Preference for a light Higgs boson

M_W and the Higgs mass

Higgs contribution to Δr

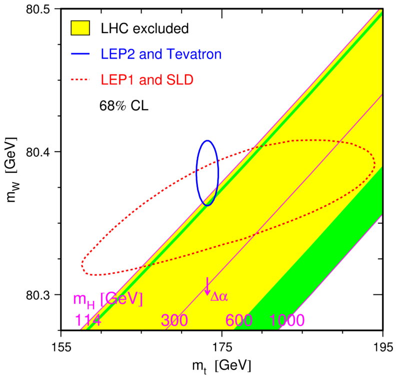
$$\Delta r = -\frac{11}{96}\frac{g_2^2}{\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

More in general for EWPOs

$$\Delta \sim g_2^2\left[\log\left(\frac{M_H}{M_W}\right) + g_2^2\frac{M_H^2}{M_W^2}\right]$$

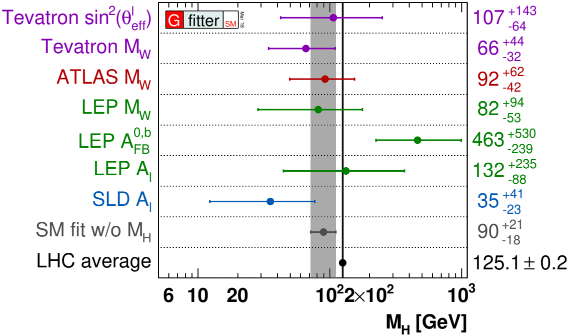
Leading term is only logarithmic dependent on $M_H W$.
The first term with $\sim M_H^2$ is $\mathcal{O}(g_2^4)$

Preference for a light Higgs boson

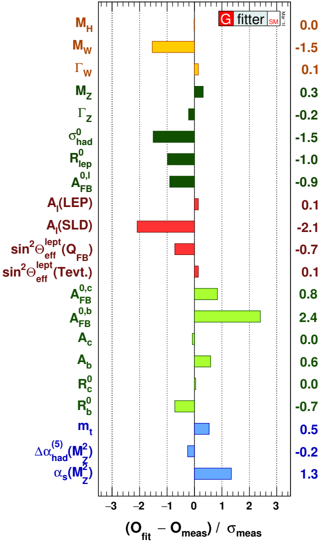


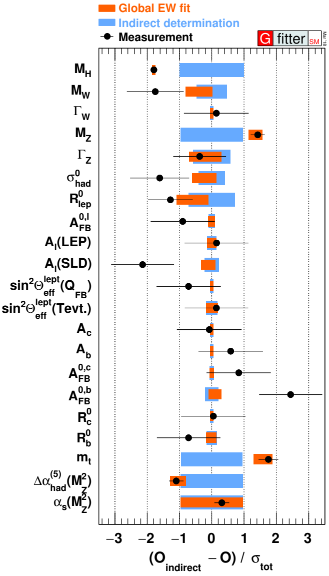
M_H and the other EWPOs

- Heavier Higgs preferred by LEP $A_{\mathrm{FB}}^{0,b}$
- Lighter Higgs preferred by M_W, A_{LR}^{l} (SLD)



Global fit of EWPOs

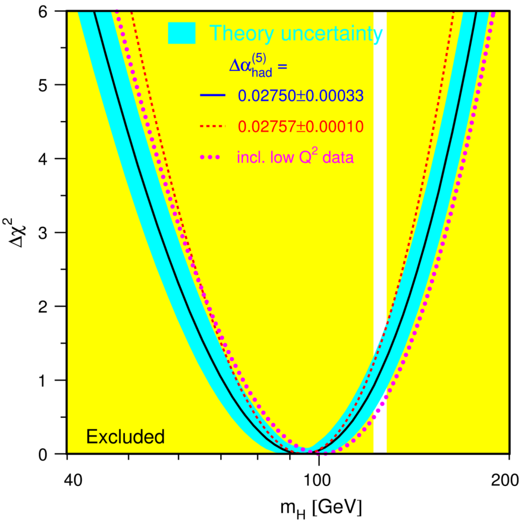




Indirect constraint of M_H from LEP

Global fit to SM data (LEP)

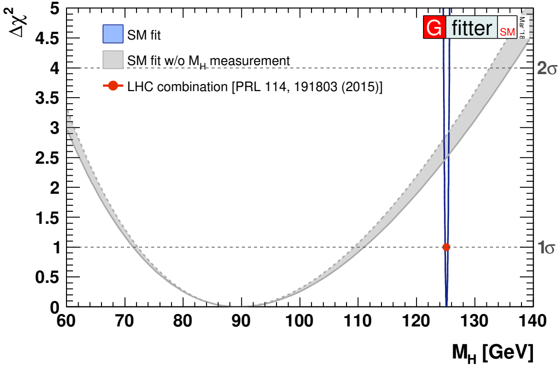
- Best fit value: $M_H = 94^{+29}_{-24}$ GeV
- $M_H < 152$ GeV, 95% CL
- The fit assumes the SM Higgs mechanism



[LEP EWWG Report '12]

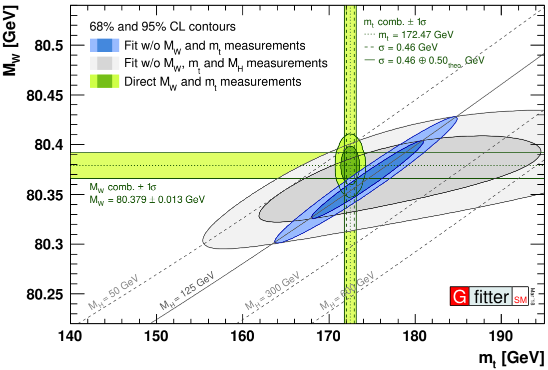
Indirect constraint of M_H vs LHC measurement

- Best fit $M_H = 90^{+21}_{-18}$ GeV
- Slight tension $\simeq 1.8\sigma$
- The fit assumes the SM Higgs mechanism



Indirect constraint of M_H vs LHC measurement

- Compatibility between the measured values of M_W vs M_T vs M_H
- Fitting without direct measurements of M_W and M_T yields an interval compatible with the exp. measurements
- The same is true if we also remove the M_H measurement
- Good statistical consistency of the SM



Uncertainty budget

- Experimental errors

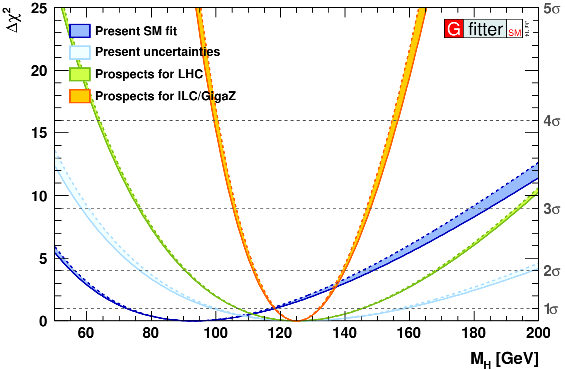
Observable	today	TeV/LHC	Linear Collider	Circular Collider
$\delta \sin^2 \theta_{\text{eff}} \times 10^5$	15	≤ 15	-	1.3
δM_W [MeV]	0.7	≤ 8	2-3	2-3
δM_t [GeV]	0.7	≤ 0.5	0.1	0.1

- Parametric errors from the experimental inputs
- $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$ $\qquad \delta M_Z = 2.1$ MeV

Observable	δM_T [GeV] =	2	1	0.1	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2 \theta_{\text{eff}} \times 10^5$		6	3	0.3	1.8	1.4
δM_W [MeV]		12	6	1	1	2.5

Global SM EW fit: future perspective

- In the prospective results, the central values are tuned to obtain $M_H = 125$ GeV
- LHC scenario: $\delta M_H = 100$ MeV; $\delta M_W = 8$ MeV; 0.5/0.25 GeV exp/theo uncert M_T
- ILC/GigaZ: $\delta M_W = 5$ MeV; 30/100 MeV exp/theo uncert M_T; $\delta \sin^2 \theta_{\text{eff}}^{lept} = 1.3 \times 10^{-5}$; precision on $R_l^0 = 4 \times 10^{-3}$

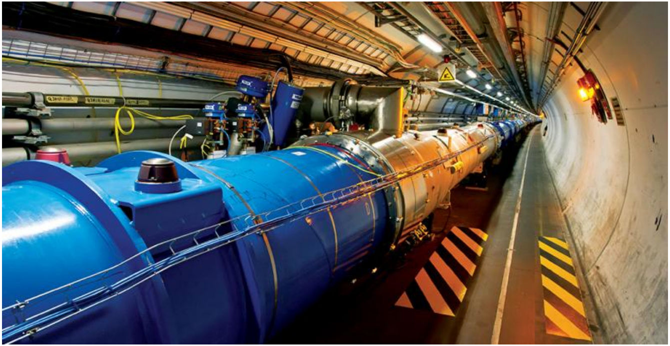


The Higgs boson at the LHC

The Large Hadron Collider (LHC)

- *pp* synchrotron, design energy $\sqrt{s} = 14$ TeV (Run 3 at 13.6 TeV)
- Superconducting `NbTi` magnets cooled down to 1.9 K
- 27 km circumference

- 1.8×10^{11} proton per bunch (2022)
- 2400 bunches per beam (2022)
- Target luminosity (2022): $2 \times 10^{34} \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



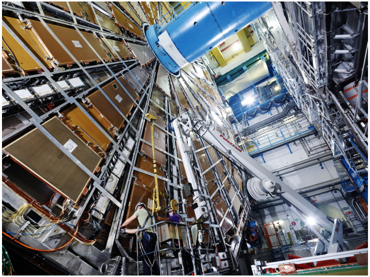
Experiments at the LHC

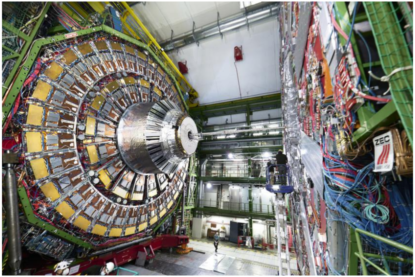
Large experiments

- Two general purpose experiments: ATLAS and CMS
- One experiment focused on b-physics: LHCb
- One experiment focused on HI physics: ALICE

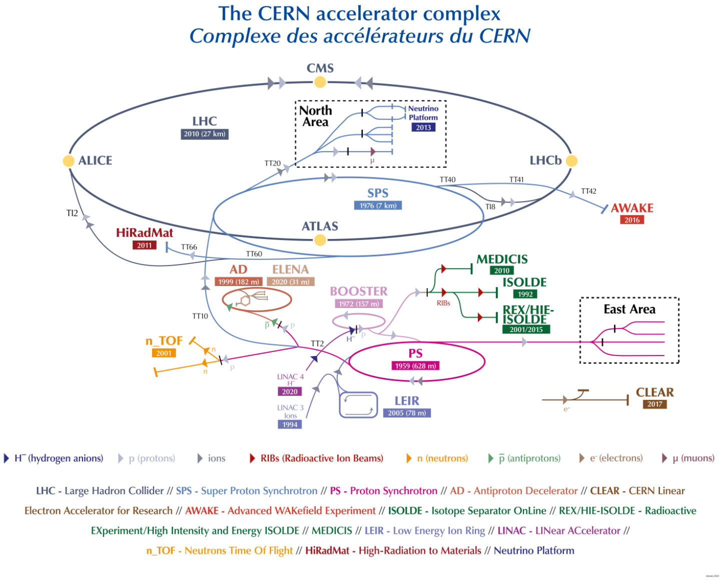
Small experiments

- Forward physics (π^0): LHCf
- total xs, elastic scattering, diffraction: TOTEM
- LLP: Moedal
- Neutrinos, forward BSM: FASER, SND





The CERN accelerator complex

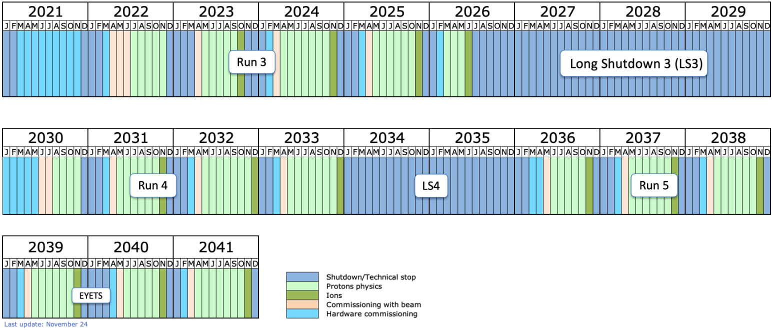


The LHC timeline as of 2022: the past

- 10/09/2008 – machine operational
- 19/09/2008 – accident
- 20/11/2009 – first beams after accident
- 30/03/2010 – first collisions at 7 TeV
- 2010 – $\lesssim 0.05\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV

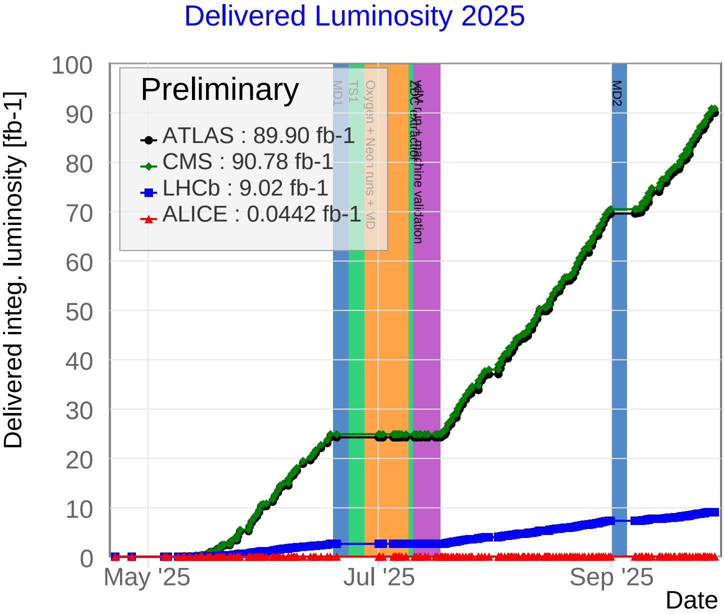
- 2011 – $\simeq 5\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV
- 2012 – $\simeq 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV
- 2013-2014 – maintenance shutdown
- 2015-2018 – $\simeq 40\ \mathrm{fb}^{-1}$/year at $\sqrt{s} = 13$ TeV (Run 2)
- 2019-2021 – maintenance shutdown
- 2022-2024 – $\simeq 195\ \mathrm{fb}^{-1}$ at at $\sqrt{s} = 13.6$ TeV (Run 3, ongoing)

The LHC timeline as of 2025: the future

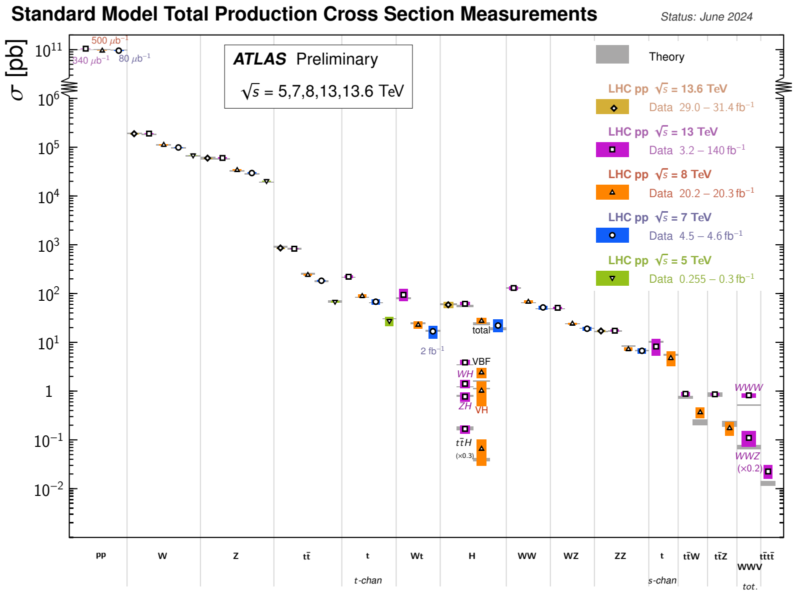


[link]

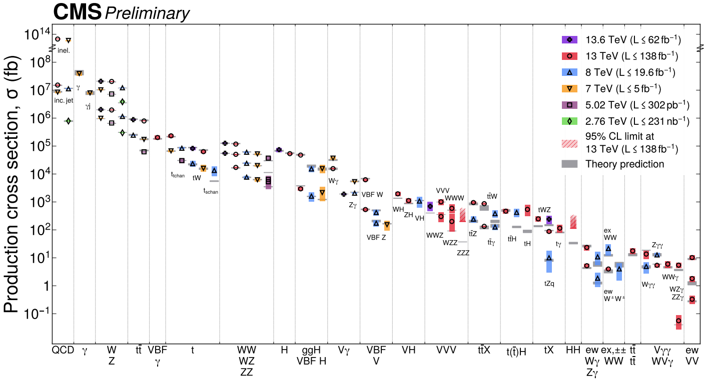
2022 performance plot



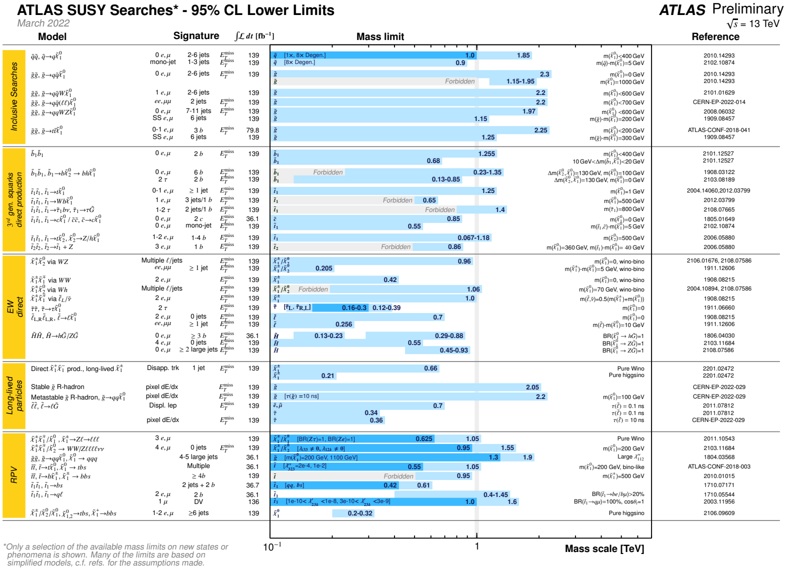
LHC results: SM processes



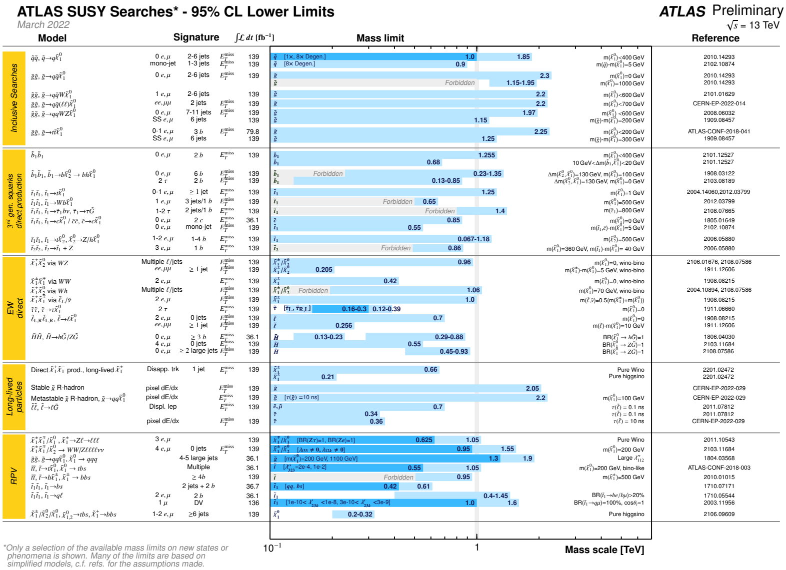
LHC results: SM processes



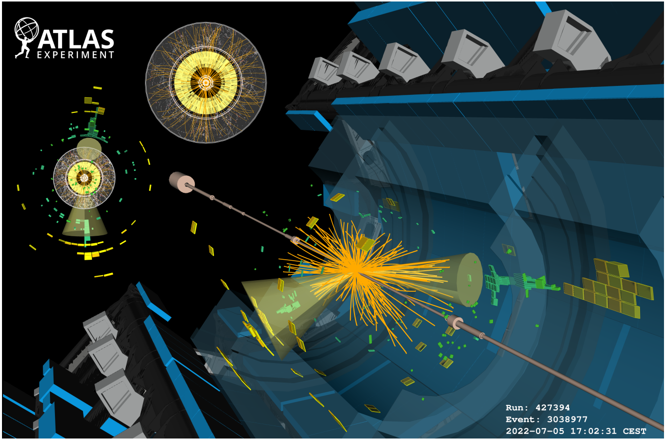
LHC results: BSM searchers



LHC results: BSM searchers



Structure of a collision



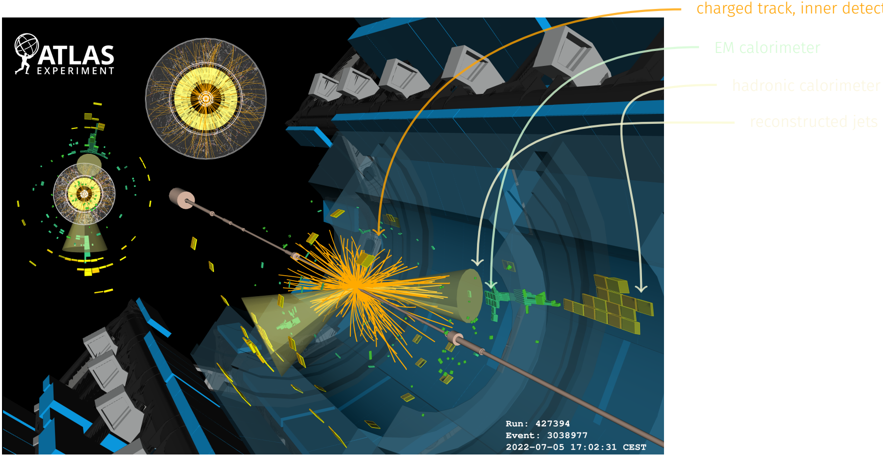
charged track, inner detect

EM calorimeter

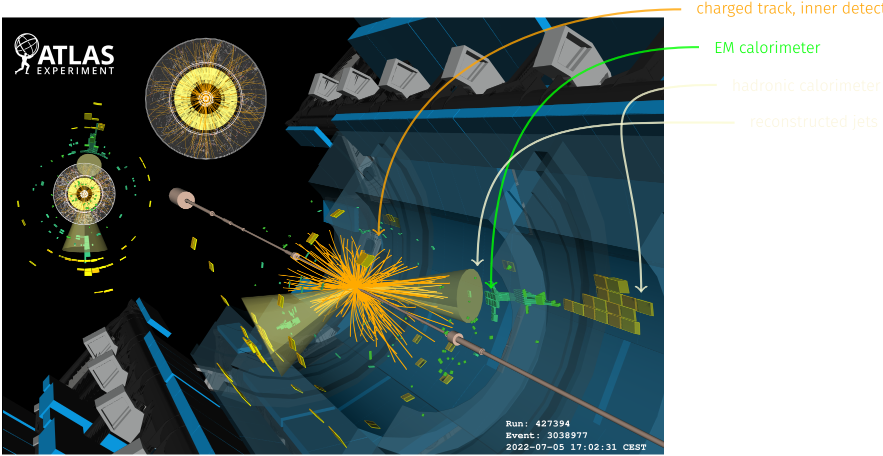
hadronic calorimeter

reconstructed jets

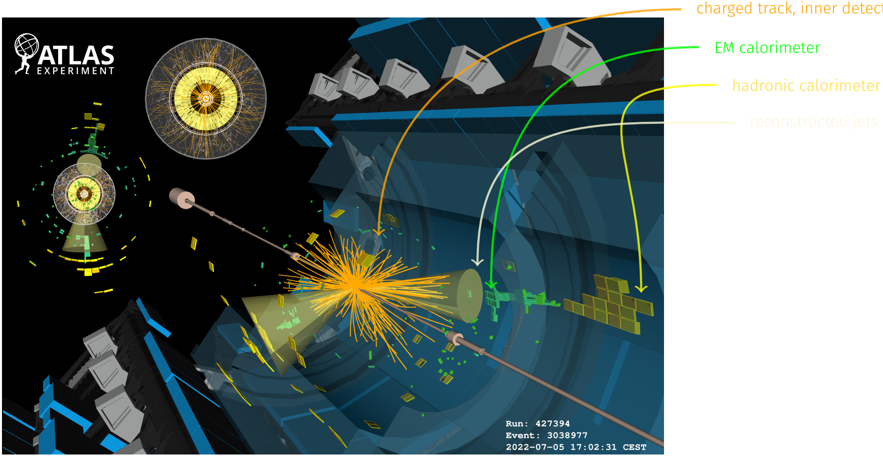
Structure of a collision



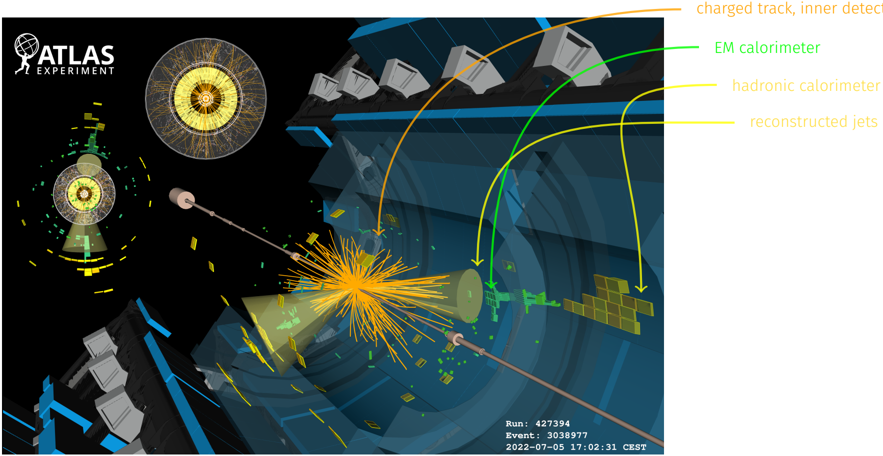
Structure of a collision



Structure of a collision

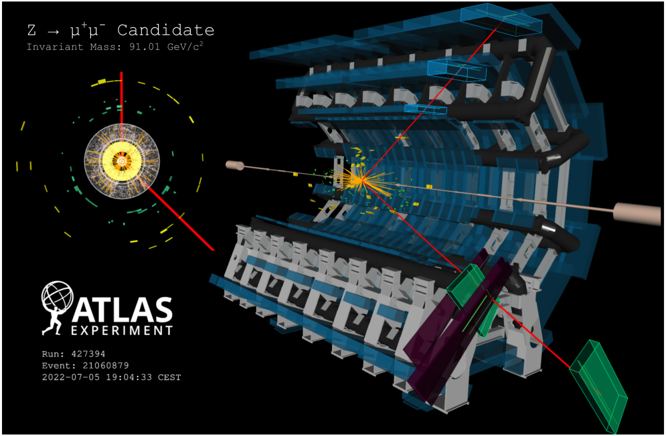


Structure of a collision

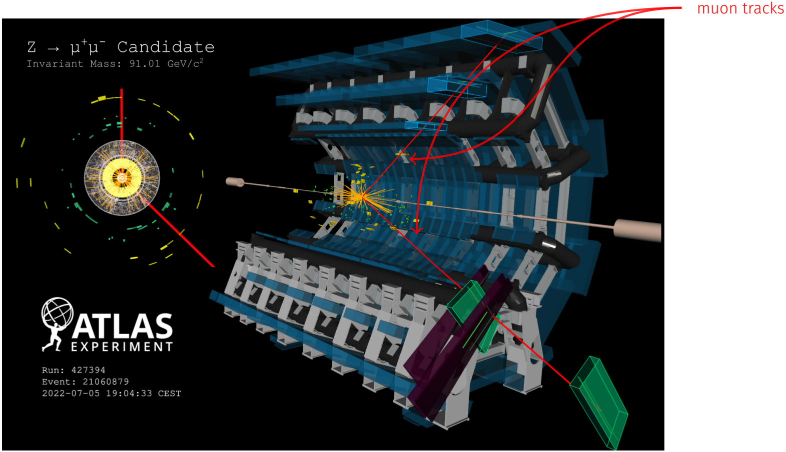


Structure of a collision

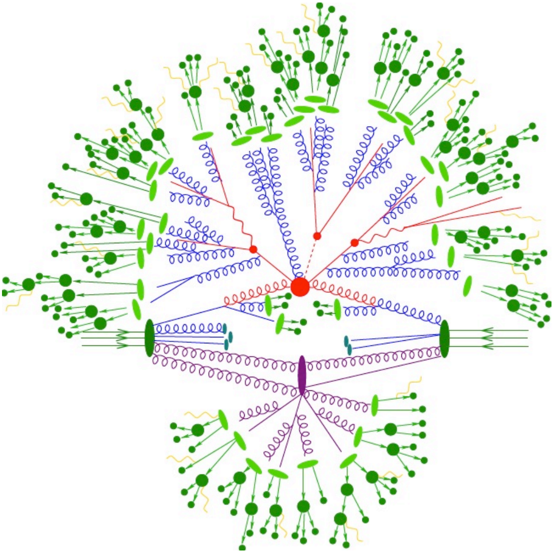
muon tracks



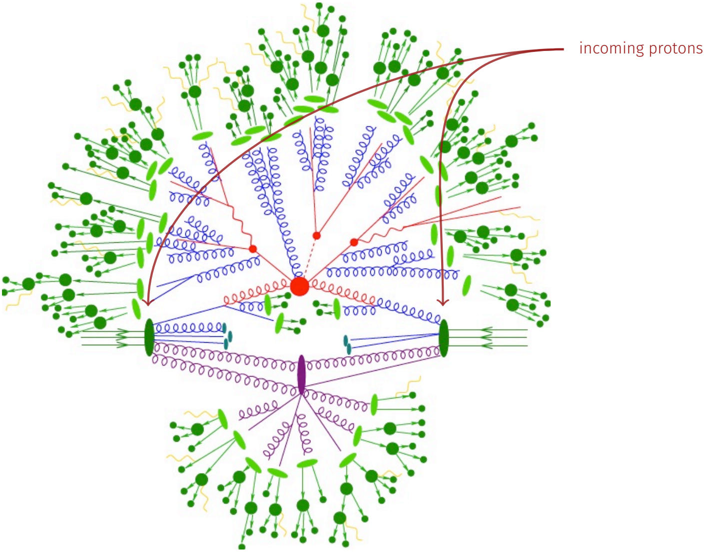
Structure of a collision



Anatomy of a collision



Anatomy of a collision



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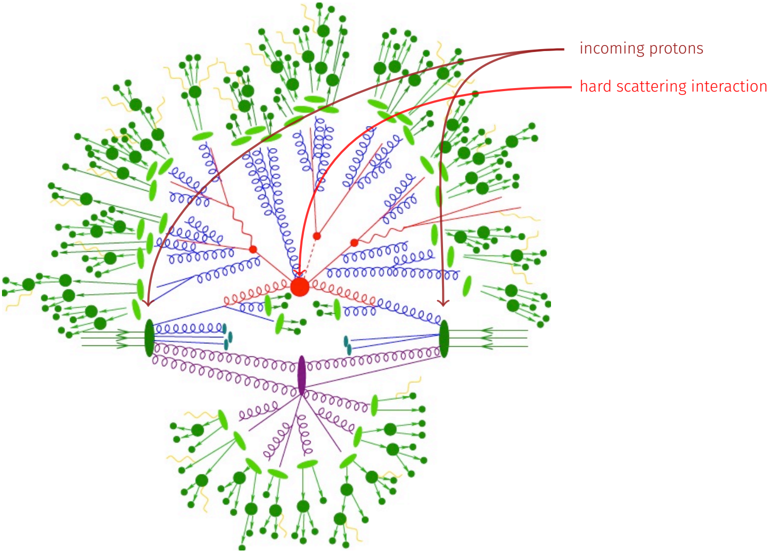
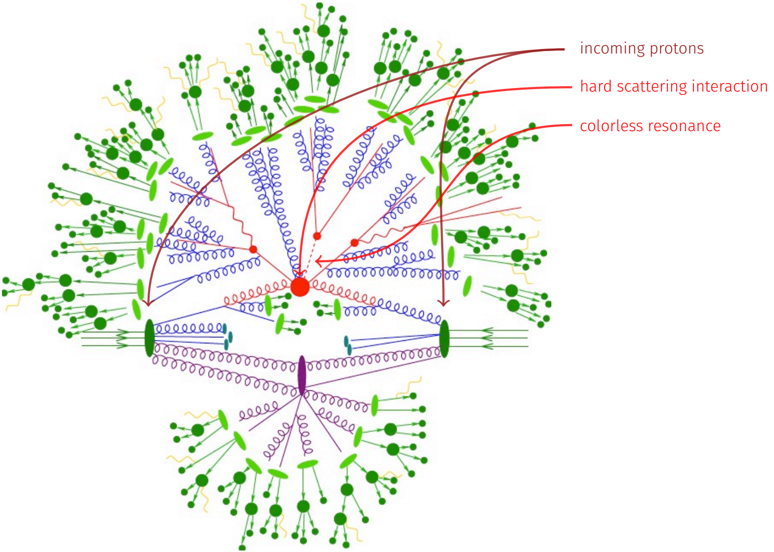


Anatomy of a collision



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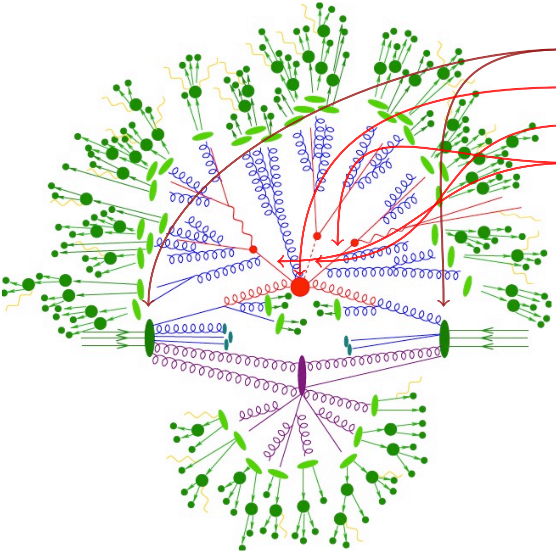
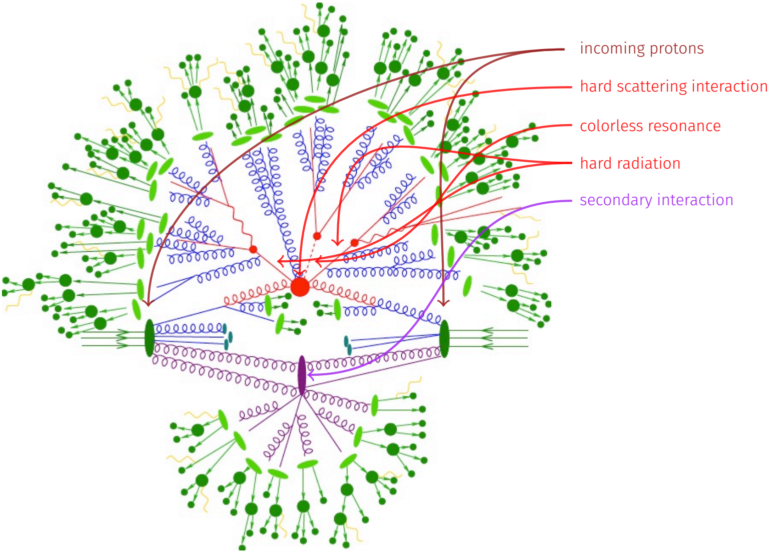
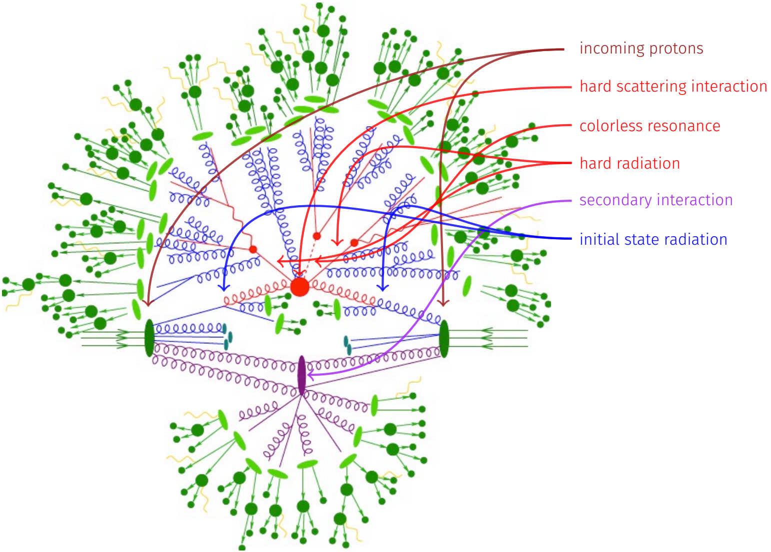


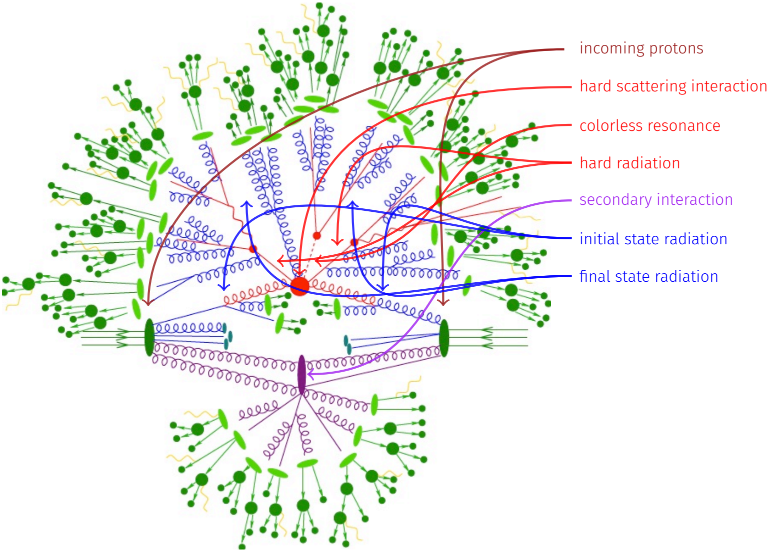
Anatomy of a collision



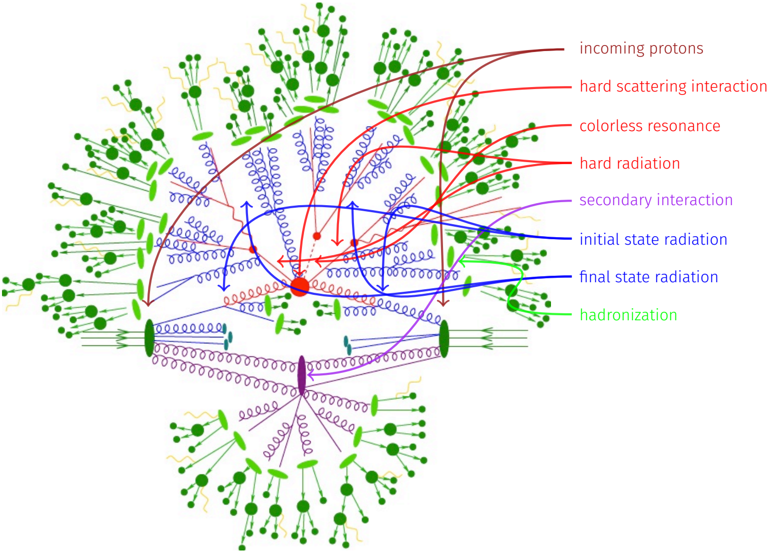
Anatomy of a collision



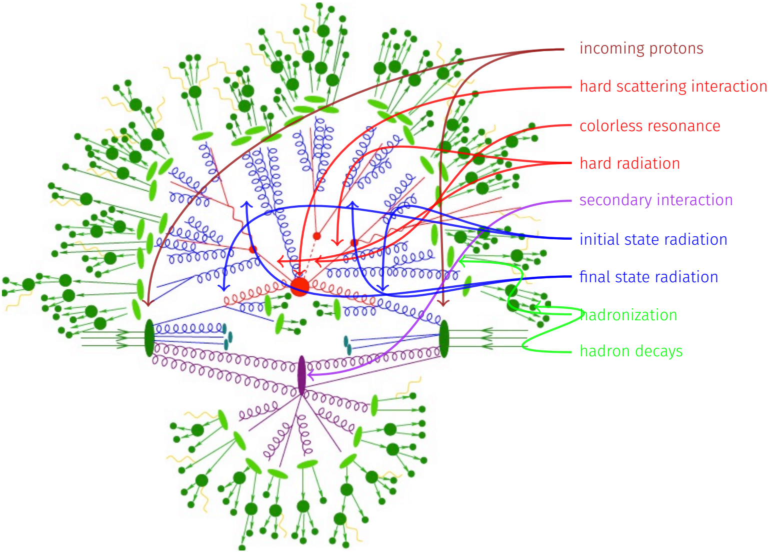
Anatomy of a collision



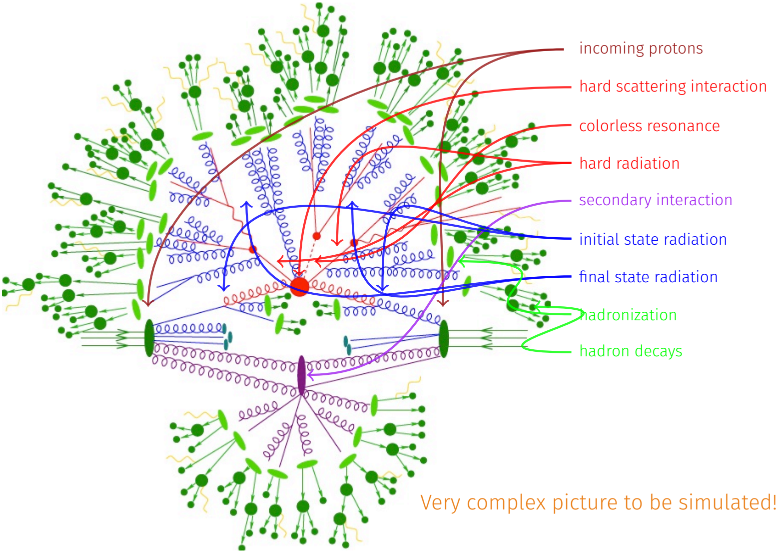
Anatomy of a collision



Anatomy of a collision



Anatomy of a collision



Very complex picture to be simulated!

Physics of the collision

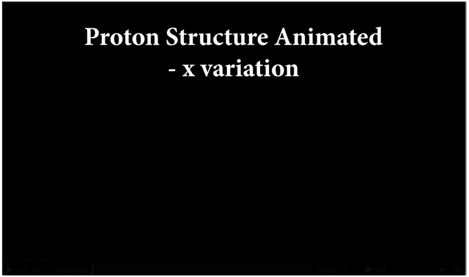
- How to compute cross sections given the complexity of the collisions?
- Fortunately, the time/energy scales of all these processes are all different $\rightarrow$ this suggests the possibility of factorizing the calculation in different elements (that describe physics at different time/scale) that are then combined together

The factorization formula

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \sum_{j,k} \int_{\hat{X}} dx_1 dx_2 f_j(x_1, Q_i) f_j(x_2, Q_i) \frac{d\hat{\sigma}(Q_i, Q_f)}{d\hat{X}} F\left(\hat{X} \to X\,; Q_i, Q_f\right) + \mathcal{O}\left(\left(\frac{\Lambda}{Q_{i,f}}\right)^p\right)$$

- $\frac{\mathrm{d}\sigma}{\mathrm{d}x}$ – differential hadronic scattering cross-section → our observable
- $f_{i,j}(x_{1,2}, Q_i)$ – the so-called Parton Distribution Functions (PDFs) → long range, non-perturbative QCD dynamics of the proton; they are universal
- $\frac{d\hat{\sigma}(Q_i,Q_f)}{\hat{X}}$ – partonic cross section → short range, hard scattering dynamics between the proton constituents (computed in perturbation theory)
- $F\left(\hat{X} \to X\; Q_i, Q_f\right) t$ – a function that represents the transition between the partonic states and the hadronic final states that define the observables if required (e.g. jets or hadrons)
- The formula is valid up to power corrections suppressed by the ratio $\left(\frac{\Lambda}{Q_{i,f}}\right)^p$
- Assumes no-tranverse dynamic of the incoming partons, that is the partons are collinear to the collision/beam axis (“collinear factorization”)

Parton distribution functions



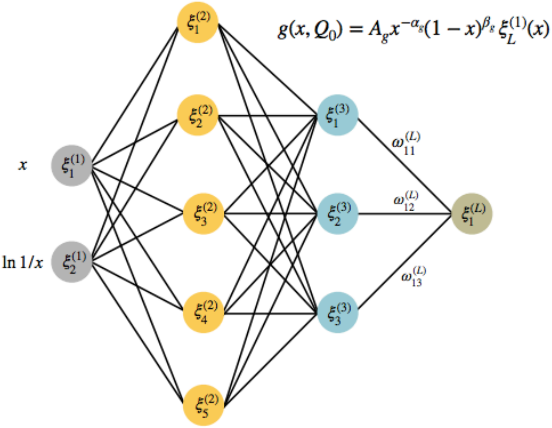
[Arts at MIT '22, youtube]

- They represent the non-perturbative dynamics of the proton $\to$ can not be computed perturbatively
- Efforts ongoing to compute them on the lattice, but still no available datasets
- Solution: fit them experimentally, since they are process independent
- Needs to probe different "x regions" $\to$ many different experiments required
- Every experiments has its own characteristic scale
- Evolution of the PDFs at different scales Q^2 is described by the DGLAP equation

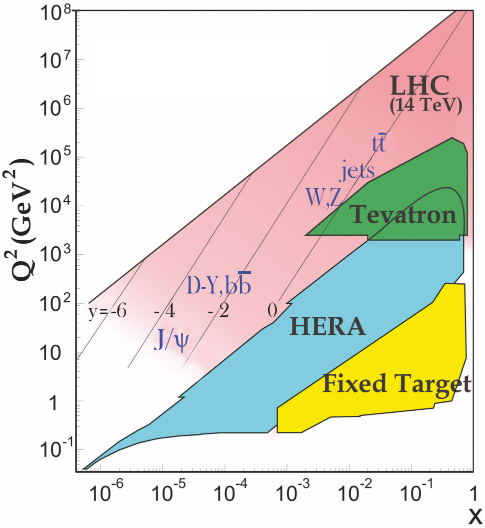
PDF parameterizations

No clear idea of how to parameterize them, different approaches

- Polynomial parameterization inspired by QCD models: MSHT, CT, ABJM, HERAPDF . . .
- Neural networks (theory agnostic): NNPDF

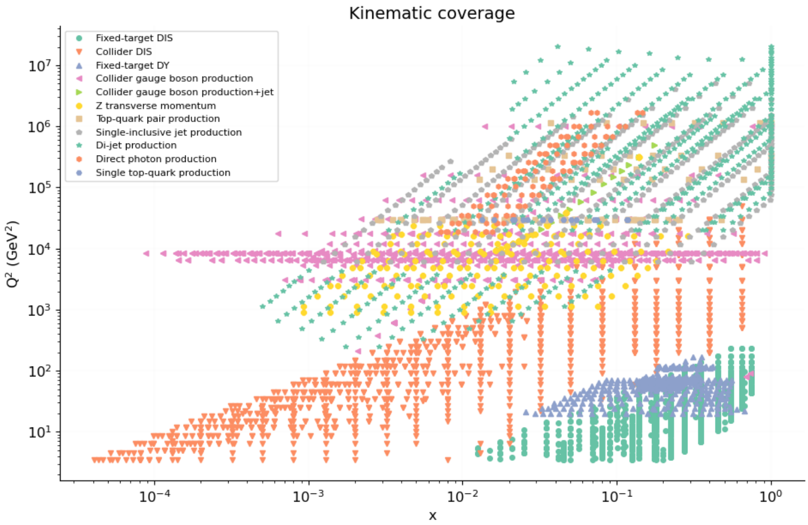


Kinematic coverage



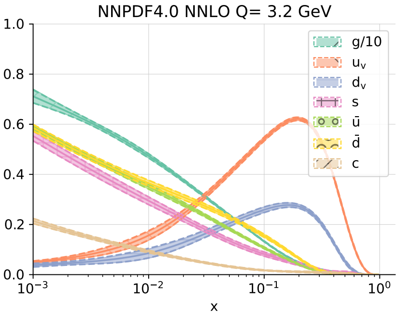
- Different experiments are able to probe different scales (Q^2) and different kinematic regime (x)
- Not only high energy hadron colliders, but also electron-proton collider are especially important
- Fixed target experiments cover low-Q^2 high-x region

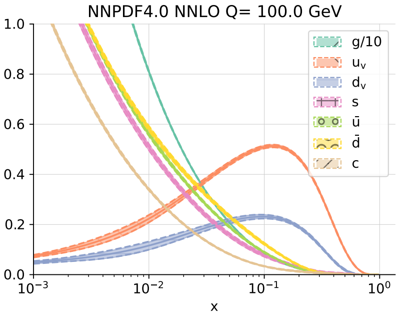
NNPDF kinematic coverage



Example of PDFs of the protons

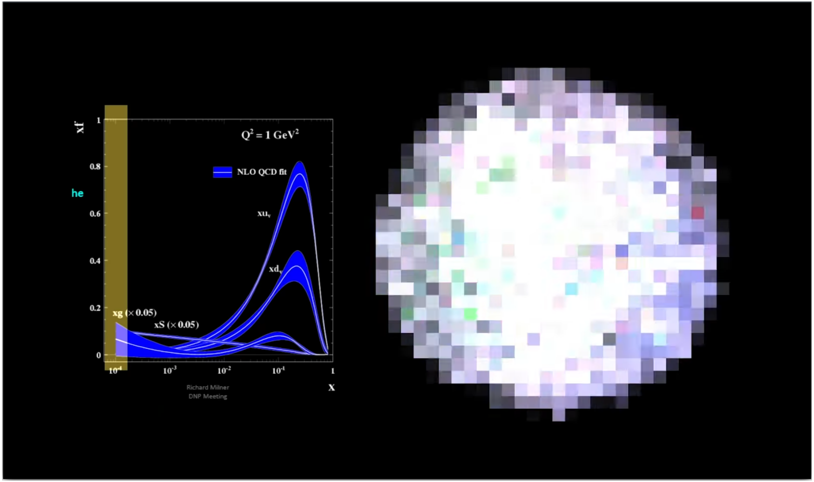
0



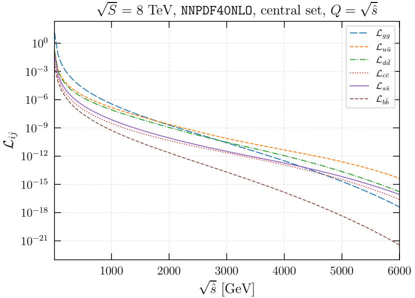


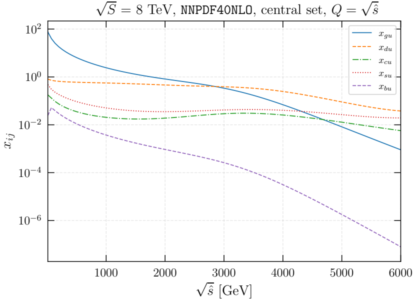
- Different behavior between valence and sea quarks
- Large low-x gluon PDF
- Uncertainty band $\rightarrow$ the data have experimental errors, they cause an error in the fit

The structure of the proton



[Arts at MIT '22, youtube]



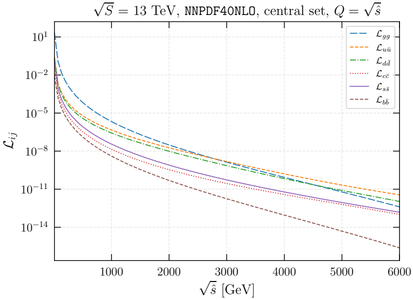


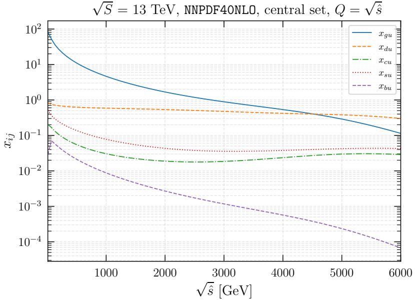
$$\frac{d\mathcal{L}_{ab}}{d\hat{s}} = \frac{1}{S}\frac{1}{1+\delta_{ab}}\int_{\tau}^{1}\frac{dx}{x}f_a(x,\sqrt{\hat{s}})f_b(\frac{\tau}{x},\sqrt{\hat{s}}) + (a \leftrightarrow b) \qquad \tau = \frac{\hat{s}}{S}$$

$$\sigma = \sum_{a,b}\int\left(\frac{d\hat{s}}{\hat{s}}\left(\frac{d\mathcal{L}_{ab}}{d\hat{s}}\right)\hat{s}\hat{\sigma}_{a}b\right)$$

$$x_{ij} = \frac{d\mathcal{L}_{ab}}{d\hat{s}} / \frac{d\mathcal{L}_{uu}}{d\hat{s}}$$

Parton luminosity at the pp colliders





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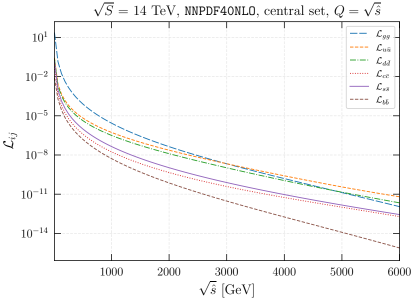

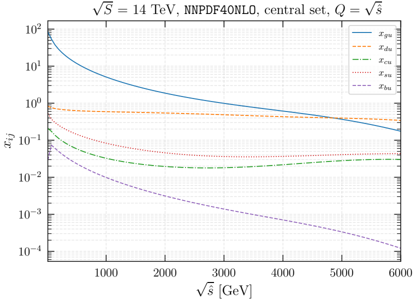

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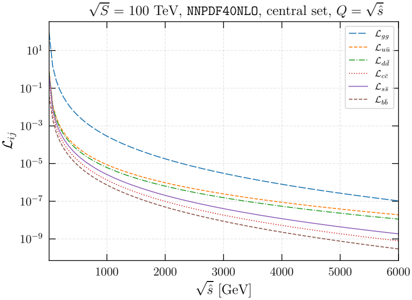

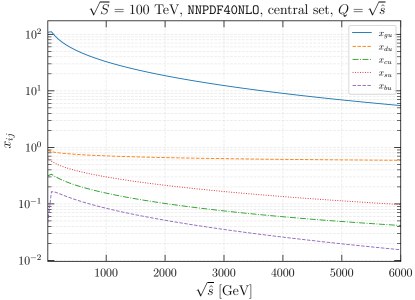

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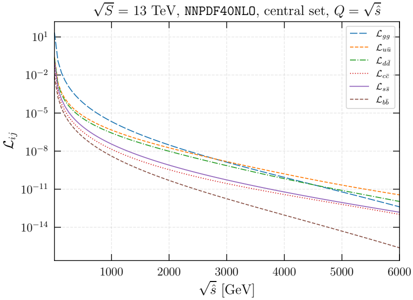

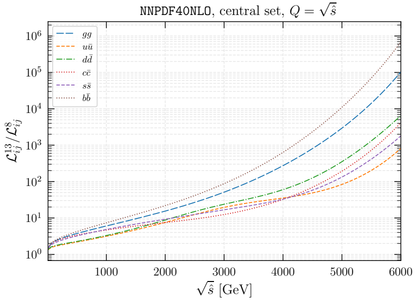

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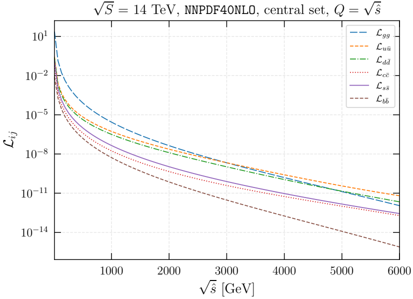

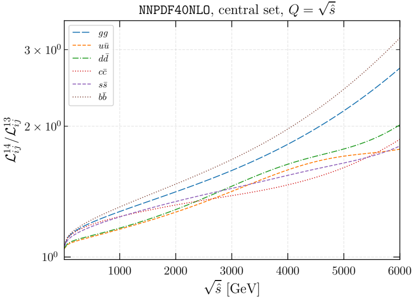

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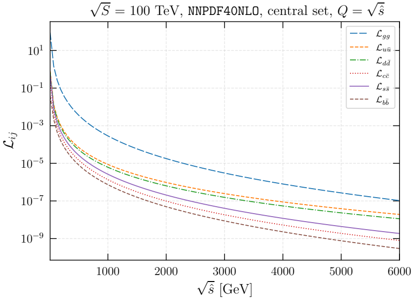
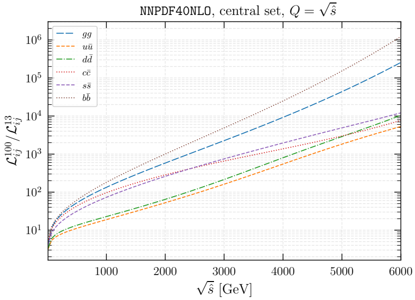
Parton luminosity at the pp colliders





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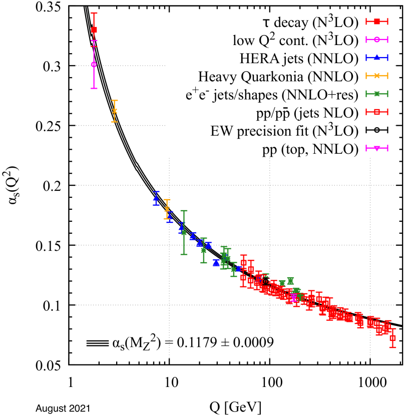
$$x_{ij} = \frac{d\mathcal{L}_{ab}}{d\hat{s}} / \frac{d\mathcal{L}_{uu}}{d\hat{s}}$$

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \ldots)$$

$$b_0 = (11C_A - 4n_f T_R)/(12\pi)$$

$$= (33 - 2n_f)/(12\pi)$$

- QCD is an asymptotically free theory
- The couplings become smaller as the momentum scale grows
- We can do perturbation theory in α_s in high-energy collisions



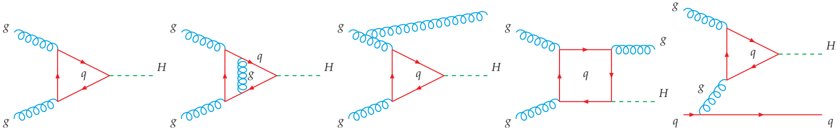
[PDG 22]

Fixed order calculations

The partonic cross section is evaluated as a perturbation theory in the couplings (asymptotic expansion)

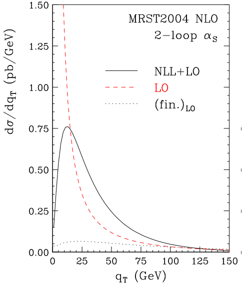
- A process at LO can be purely electroweak (e.g. Drell-Yan) or not (e.g. jet production)
- The QCD corrections are usually the most important ones
- The role of the corrections depend on the observable (e.g. impact of QCD corrections on inclusive observables is different from non-inclusive observables)
- Only the first few orders can be evaluated $\rightarrow$ source of theoretical uncertainty

$$\frac{d\hat{\sigma}}{dX}(Q, \{p_i\}) = \sum_{j,k} \alpha_s^k \alpha^k \frac{d\hat{\sigma}^{(j,k)}}{dx}(Q, \{p_i\})$$

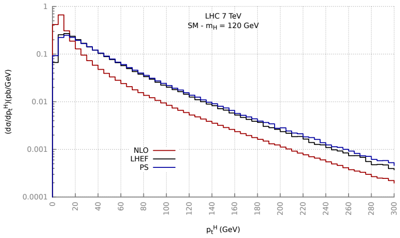


Resummed calculations

- Some observables are characterized by large logarithmic terms that can be accounted at all orders → resummation
- Important to cure unphysical behaviour due to the failure of fixed order perturbation theory
- Can be done both analytically (in some cases) or numerically via a MC



[Bozzi et al., '05]



[EB et al., '12]

Monte Carlo integration

The partonic cross section contains a “phase space integration”

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}X} \sim \int d\Phi_P |\mathcal{M}|^2$$

whose exact form depend on the observable.

- $\Rightarrow$ To compute these observables multi-dimensional integral over phase space needs to performed
- Not always possible to solve them analytically $\Rightarrow$ numerical Monte Carlo integration

$$\int_a^b dx f(x) = (b-a)\langle f \rangle \simeq \frac{1}{N}(b-a)\sum_i f(x_i)$$

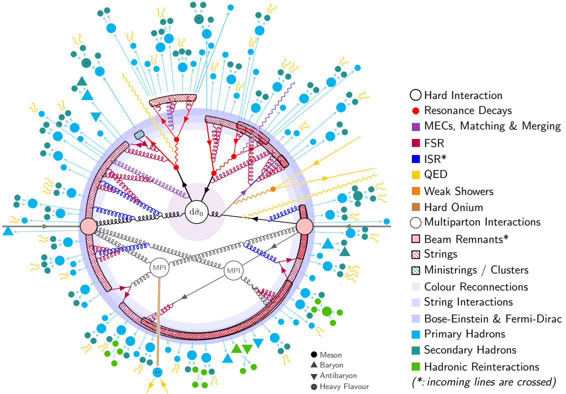
- The error of MC integration goes as $1/\sqrt{N}$, independent from the number of dimensions

Monte Carlo event generators

- For a proper simulation of the collision, we need to generate “unweighted events” (i.e. simulated collisions) one by one
- The events can be fed also to a detector simulation to take into account the presence of the detector
- $\Rightarrow$ “hit or miss” (derived) technique
  1. randomly pick x
  2. calculate f(x)
  3. randomly pick $0 < y < y_{\mathrm{max}}$
  4. if $f(x) > y$ accept, else rejects
- Special fixed-order generators can fed events to shower Monte Carlo (see next slide)
- “Matching scheme” have been developed to avoid double counting (e.g. at NLO `POWHEG`, `MC@NLO`)

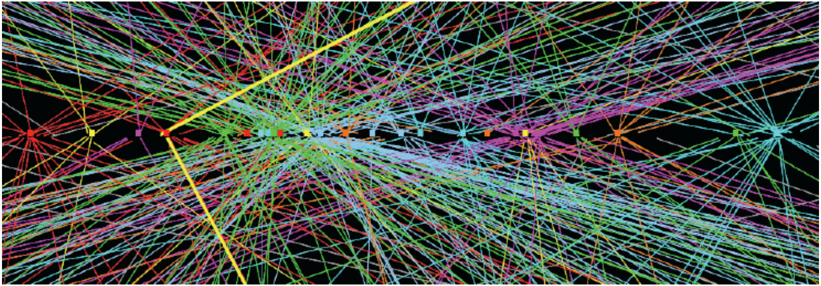
Shower MC and hadronization

- Generation of the shower of QCD radiation (different shower type; ongoing discussion of shower accuracy)
- Implementation an hadronization model (depend on the MC)



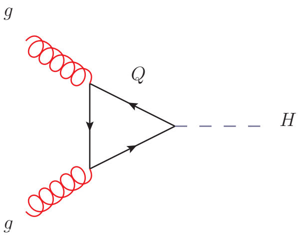
Experimental challenges

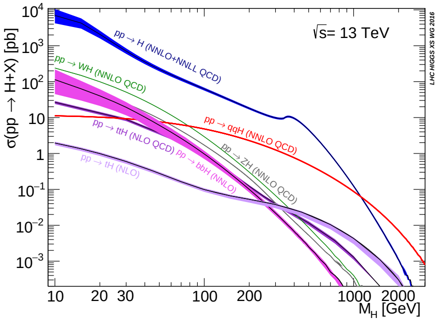
- Huge QCD background $\rightarrow$ devise sophisticated experimental analyses to suppress it and enhance the signal-to-background ratio
- Pile-up: multiple collisions for every bunch crossing
- Very high interaction rate $\rightarrow$ challenge for DAQ



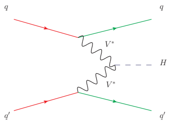
Higgs production channels at the LHC

Gluon fusion

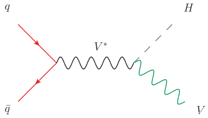




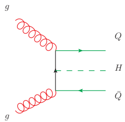
Vector Boson Fusion (VBF)



Higgs Strahlung

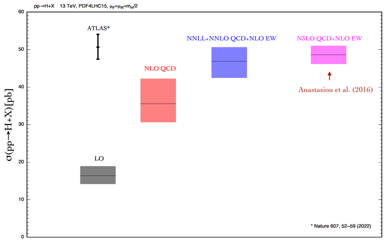


Quark associated production

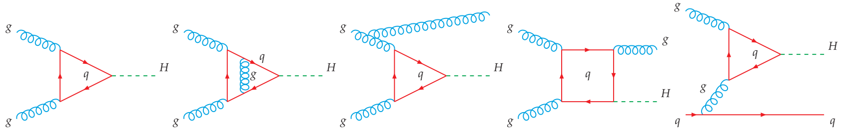


Gluon fusion

- Highest cross section at the LHC
- Loop induced since the Higgs does not couple to gluons
- The stronger the Yukawa, the highest the contribution from the quark
- Can be used to probe the Yukawa couplings (also via p_T^H measurement)
- Very large radiative corrections

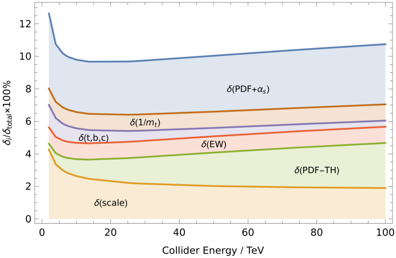


[M. Grazzini, Higgs symposium ’22]

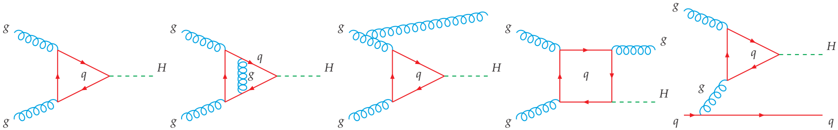


Gluon fusion

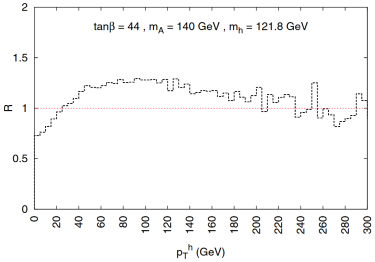
- Highest cross section at the LHC
- Loop induced since the Higgs does not couple to gluons
- The stronger the Yukawa, the highest the contribution from the quark
- Can be used to probe the Yukawa couplings (also via p_T^H measurement)
- Very large radiative corrections



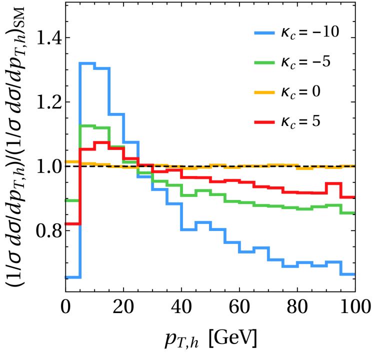
[Dulat '18]



The Higgs p_T



[EB et al.,'12]

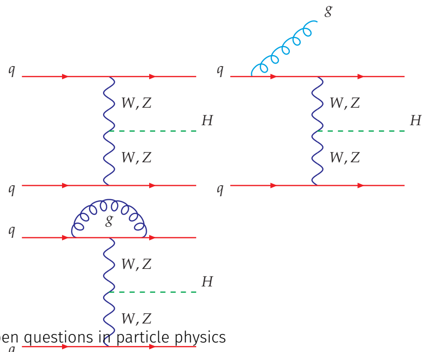


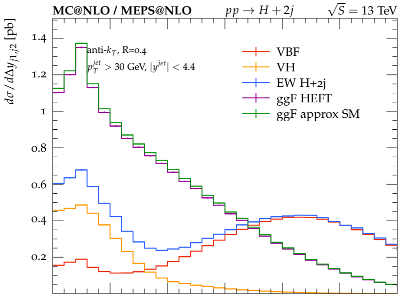
[Bishara et al., '16]

- The emitted parton probe the internal structure of the gluon loop
- Possible to probe the existence of new states, or a modification of the Yukawas

Vector boson fusion

- Second most-important channel
- Vanishes if $v = 0 \Rightarrow$ direct test of EWSB
- Characterized by two forward-backward jets, and low hadronic activity in the central region
- Easier to separate from background than gluon fusion





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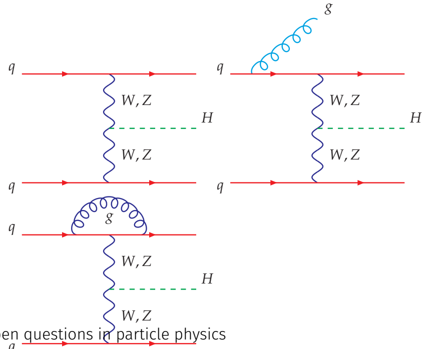
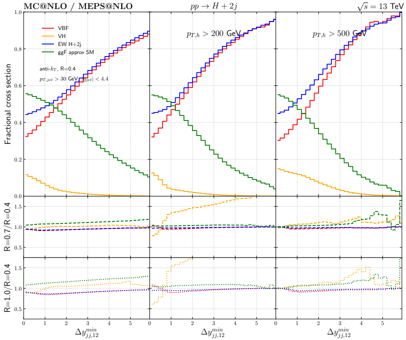
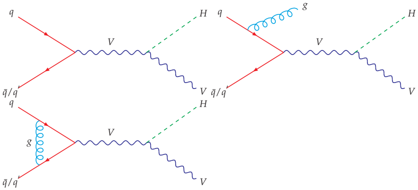
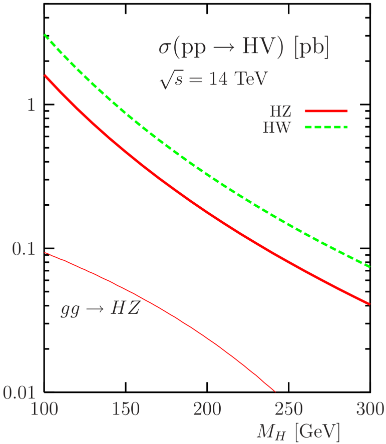




Higgs Strahlung

- Signature of one vector boson and one Higgs
- Vanishes if $v = 0 \Rightarrow$ direct test of EWSB
- Boosted analysis allows to probe the bottom Yukawa coupling, when $H \to b\bar{b}$





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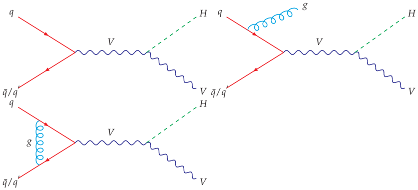
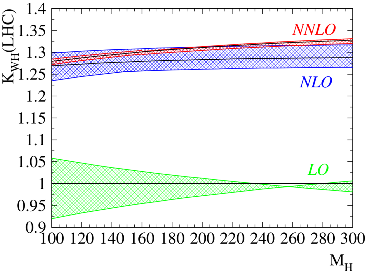
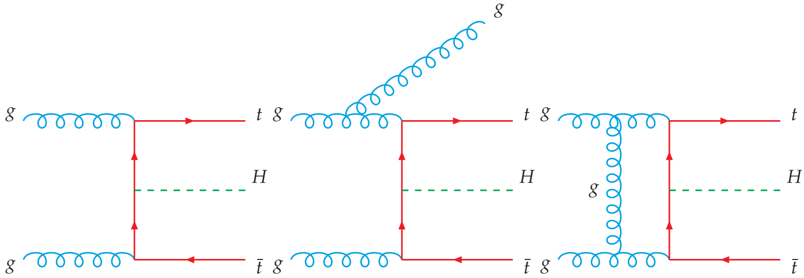




Quark associated production

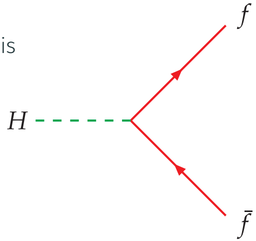
- Probe directly the Yukawas of the quark
- Tag the two heavy quarks
- *ttH* feasibile; *bbH* has been demonstrated to be unfeasibile due to contamination from *ttH* from irreducible background once considering the signal at higher-order



Decay to fermions

- We have that the coupling of the Higgs to fermions is

$$g_{f\bar{f}H} = \left[\sqrt{2}G_F\right] m_f$$



- At tree level, the partial decay width is given by

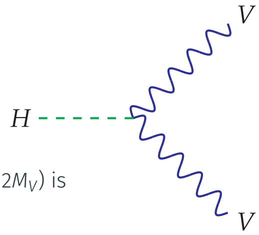
$$\Gamma\left(H \to f\bar{f}\right) = N_c \frac{G_F M_H}{4\sqrt{2}\pi} m_f^2(M_H^2)\left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

- Dominant decay for $M_H = 125$ GeV $\Rightarrow H \to b\bar{b}$

Decay to EW gauge bosons

- We have that the coupling of the Higgs to $V = W, Z$ is

$$g_{VVH} = 2\left[\sqrt{2}G_F\right]^{1/2} M_V^2$$



- The on-shell decay width (that however requires $M_H > 2M_V$) is

$$\Gamma(H \to VV) = \delta_V \frac{G_F M_H^3}{16\sqrt{2}\pi}\left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)$$

with $\delta_{W,Z} = 2, 1$

- In the case of the off-shell decay (which is what happens for $M_H = 125$ GeV) we have

$$\Gamma(H \to VV^*) = \delta_V' \frac{3G_F^2 M_H}{16\pi^3} M_V^4 \times \text{ integral}$$

Decay to $\gamma\gamma$ and gg

- As for the gluon fusion production process, they are loop-induced decay processes

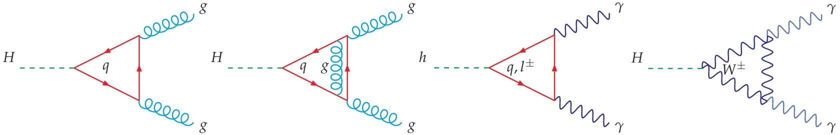
$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2(M_H^2) M_H^3}{36\sqrt{2}\pi^3}\left[1 + \frac{\alpha_s(M_H^2)}{\pi} MC\right]$$

with large higher order corrections (as it happens in gluon fusion) that in the HTL limit are

$$C = \frac{215}{12} - \frac{23}{6}\log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s))$$

- The decay to photon proceeds via a top and a W boson loop

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3}\left|\frac{4}{3}e_t^2 - 7\right|^2$$



The total decay width

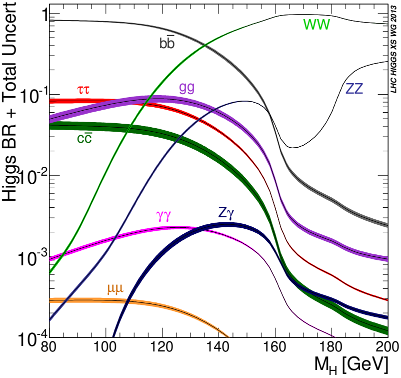
- The total decay width $\Gamma_{H,\text{tot}}$ is given by the sum over all decay widths

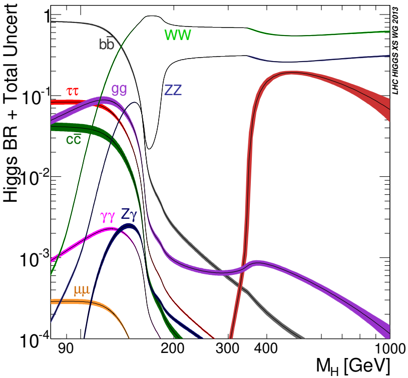
$$
\begin{aligned}
\Gamma_{H,\text{tot}} =& \Gamma\left(H \to t\bar{t}\right) + \Gamma\left(H \to b\bar{b}\right) + \Gamma\left(H \to c\bar{c}\right) + \dots \\
& \Gamma\left(H \to \tau^+\bar{\tau}^-\right) + \Gamma\left(H \to \mu^+\bar{\mu}^-\right) + \dots \\
& \Gamma\left(H \to WW^{(*)}\right) + \Gamma\left(H \to ZZ^{(*)}\right) \\
& \Gamma\left(H \to gg\right) + \Gamma\left(H \to \gamma\gamma\right) + \dots
\end{aligned}
$$

- The branching ratio to a given final state $XX^{'}$ is given by

$$
\mathrm{BR}\left(H \to XX^{'}\right) = \frac{\Gamma\left(H \to XX^{'}\right)}{\Gamma_{H,\text{tot}}}
$$

Overview of the branching ratios





- Low mass range
- High mass range

The Higgs discovery

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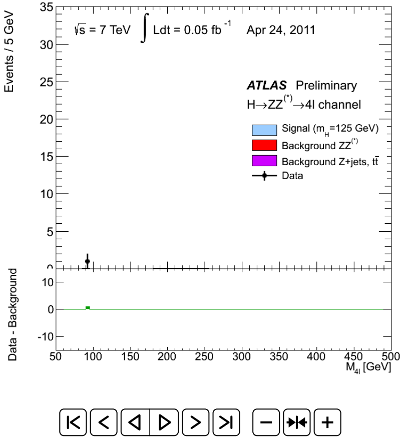

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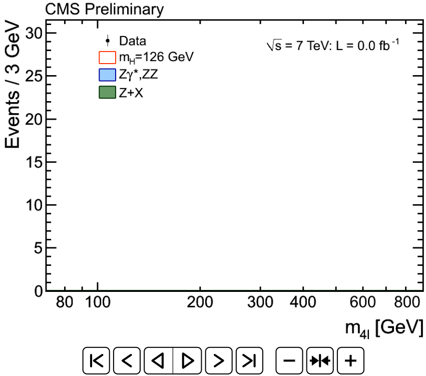

The Higgs discovery

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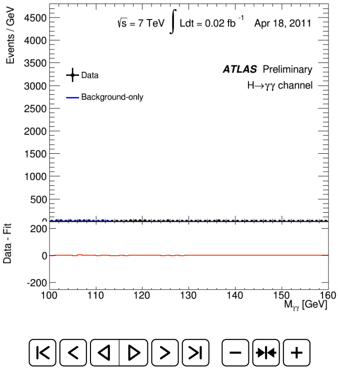

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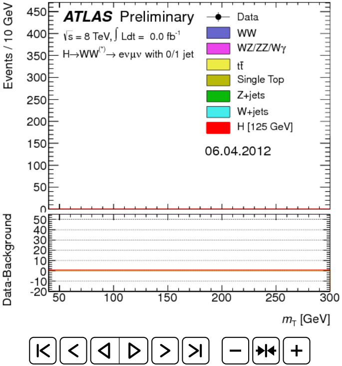


The 4th of July 2012

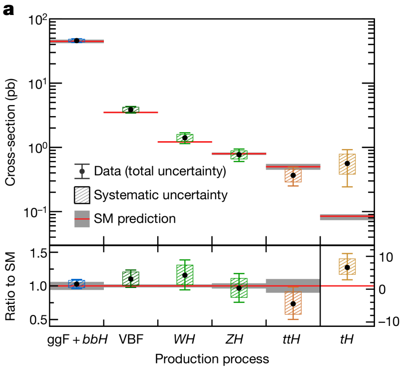
Is it a Higgs or something else?

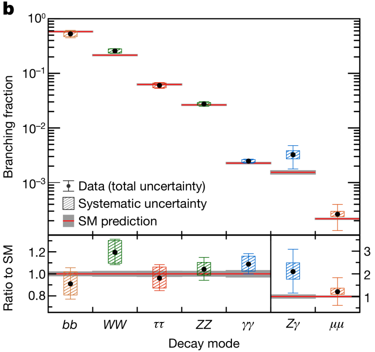
- On the 4th of July 2012, the collaborations of ATLAS and CMS claimed the discovery of a new resonance
- How can we convince ourselves that it is the Higgs boson?
- How can we verify that it is the SM Higgs boson?
- Could it be *a* Higgs boson from a SM extension?

To address these questions we need to characterize the Higgs boson

- Measure its properties (not only inclusive quantities such as $\sigma \times$ BRs but also differential distributions
- Compare with the theoretical predictions in given models
- Search for other Higgs bosons

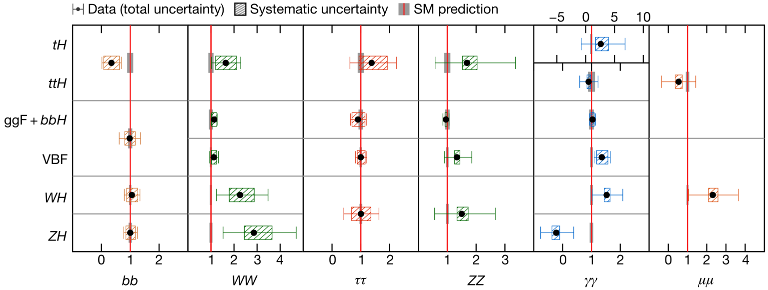
σ and BR_s from ATLAS





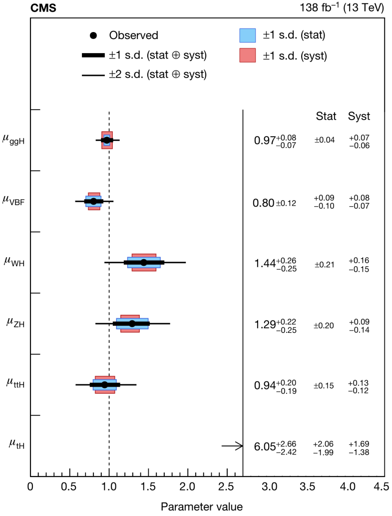
- Production cross sections
- Braching ratios

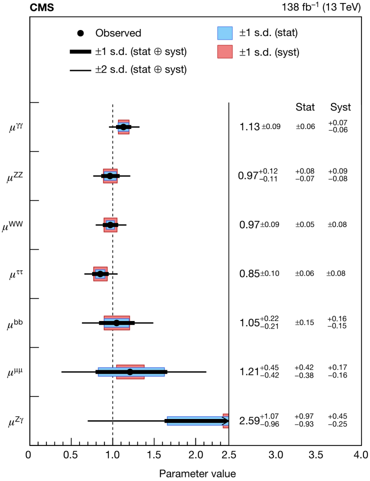
σ and BR_s from ATLAS



- Comparison with SM predictions $\rightarrow$ everything agrees well

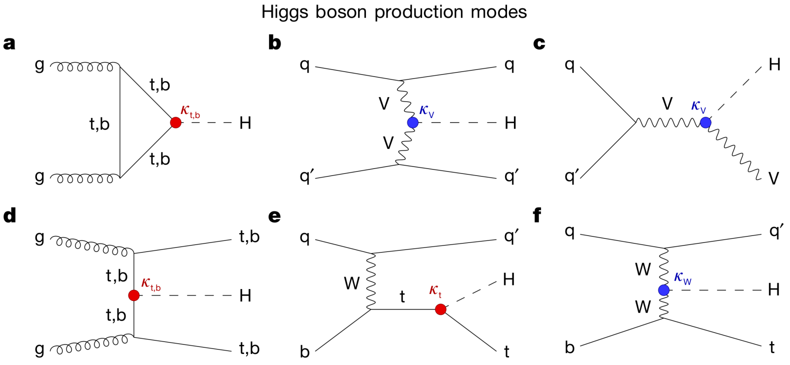
σ and BR_s from CMS





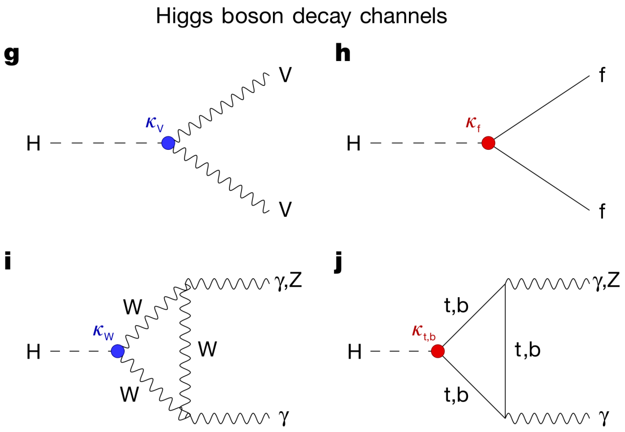
- Similar conclusions to the ones of ATLAS

The k-framework



- Introduce rescaling factor the vertex
- Production diagrams
- Decay diagrams

The k-framework



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- Production diagrams
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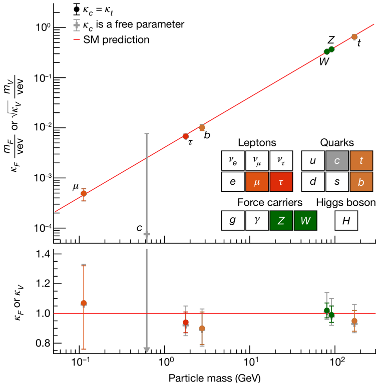
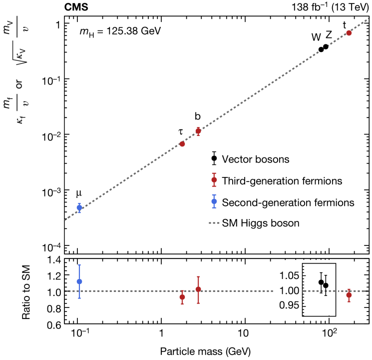
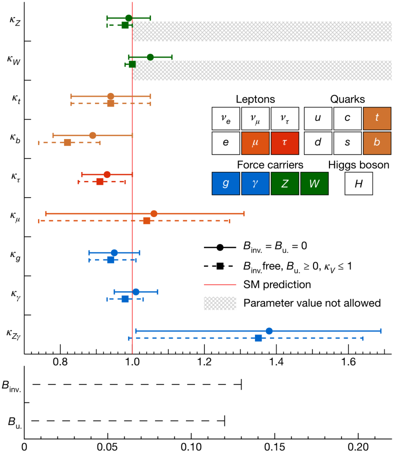
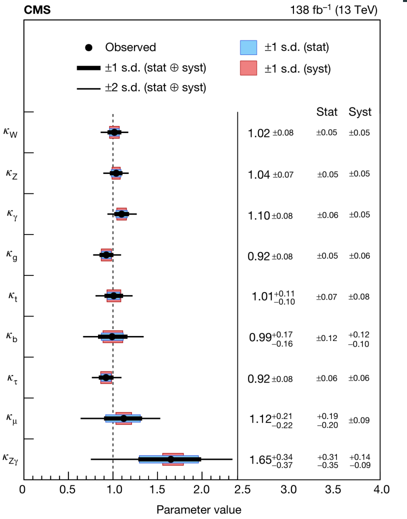




- Confirms the "Higgs nature" of the discovered states

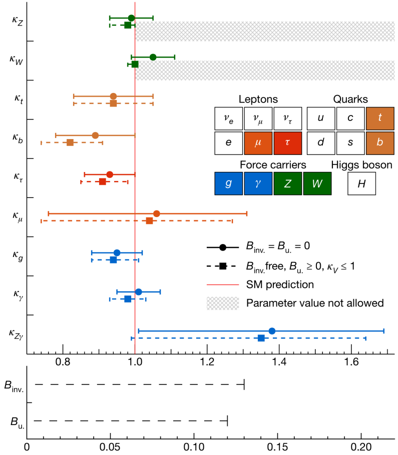
k-framework results

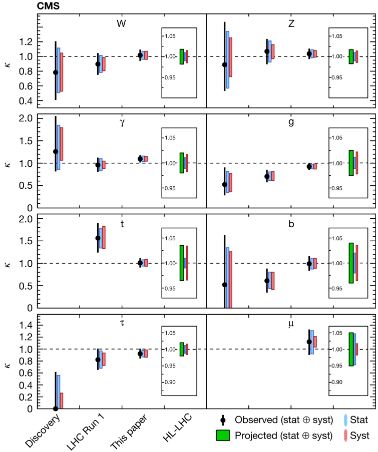




- SM-like nature of the state at 125 GeV

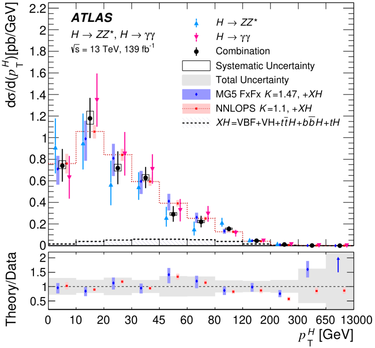
k-framework results

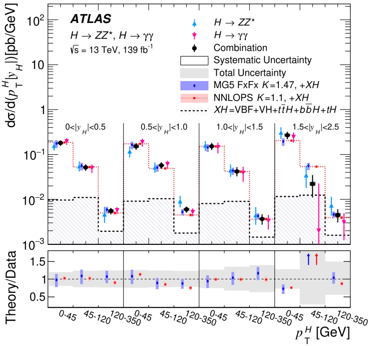




- SM-like nature of the state at 125 GeV

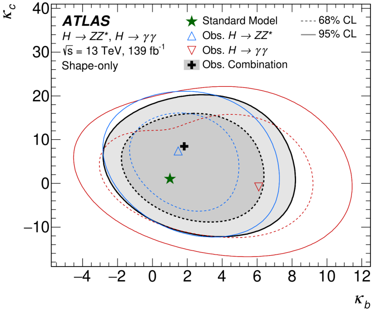
Tranverse momentum of the Higgs

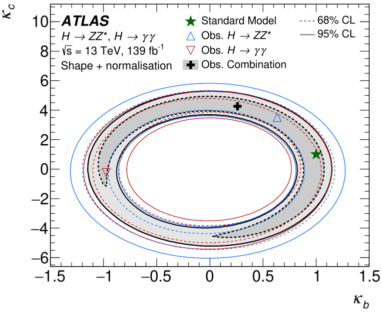




- Good agreement with state of the art predictions
- p_T^H in slices of y_H

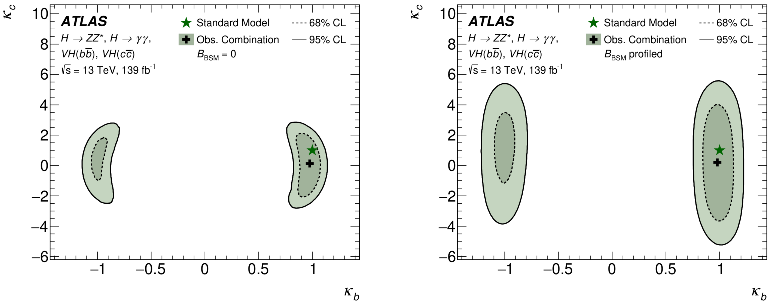
From p_T^H to the Yukawa





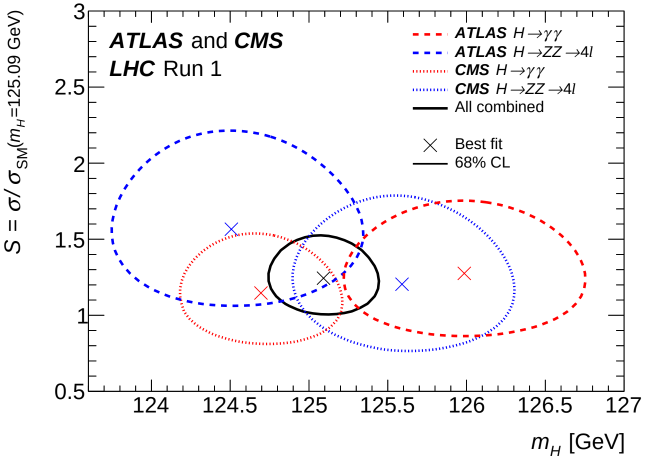
- Probe of the internal dynamics of the loop by the QCD radiation
- Constaints using only p_T^H

From p_T^H to the Yukawa



- Constraints from p_T^H + VBF + VH

The Higgs mass measurement



- Agreement between the two experiments
- Precision measurement → EW Fit / BSM prediction

How to measure the width at the LHC?

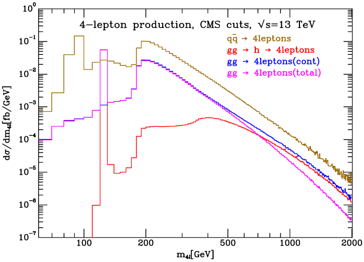
Consdering that:

- it is impossible to perform an energy scan at the LHC (hadron collider)
- the resolution of the detectors is too large for the SM expectation ($\Gamma_J \simeq 4$ MeV) to get any meaningful bound

it seems impossible to test it at the LHC. In the k-framework tests described above, it is assumed to be the SM value, with the proper rescaling coming from the k-factors. However this is not true, assuming the SM we observe that

- on-shell cross-section (narrow width approx.) $\rightarrow \sigma^{on-shell} \sim \frac{g^2_{H\rightarrow gg} g^2_{H\rightarrow ZZ}}{\Gamma_H}$
- off-shell cross-section $\rightarrow \sigma^{off} \sim g^2_{H\rightarrow gg} g^2_{H\rightarrow ZZ}$
- $\Rightarrow \frac{\sigma^{off}}{\sigma^{on-shell}} \sim \Gamma^H$
- $\Rightarrow \left(\frac{\sigma^{off}}{\sigma^{on-shell}}\right)^{exp} / \left(\frac{\sigma^{off}}{\sigma^{on-shell}}\right)^{SM} \sim \left(\Gamma^H\right)^{exp} / \left(\Gamma^H\right)^{SM}$

The reality is more complex because of interference with the background the scaling is $\frac{\sigma^{off}}{\sigma^{on-shell}} \sim a\Gamma^H + b\sqrt{\Gamma^H}$ [Caola & Melnikov, Passarino & Kauer]



[Campbell et al. '12]

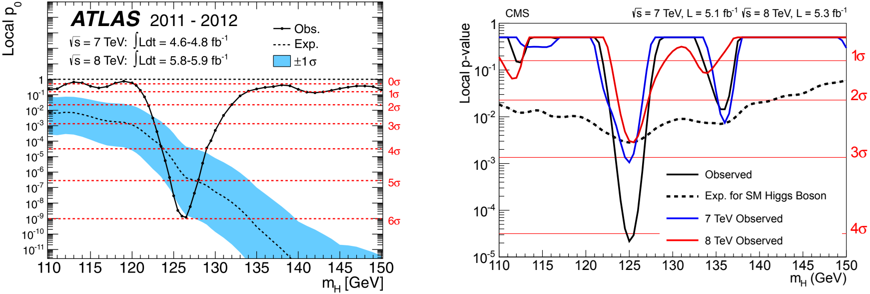
- off-shell rate to ZZ is significant because of the opening up of the decay to two on-shell Z and because the decay to two longitudinally polarized Z bosons is large in that region [Kauer & Passarino]

$$\frac{|\mathcal{A}_{H^* \to Z_L Z_L}|^2}{(s - m_H)^2 + m_h^2 \gamma_h^2} \to const \quad \text{when } s \gg m_H^2$$

- Non trivial interplay with background

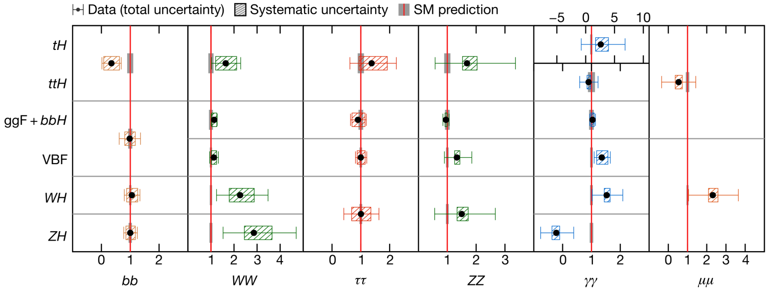
Phenomenological status and outlook

Higgs discovery on the 4th of July 2012



Discovery of a new resonance in July 2012 from both experimental collaborations.

The SM-likeness of the H_{125} state



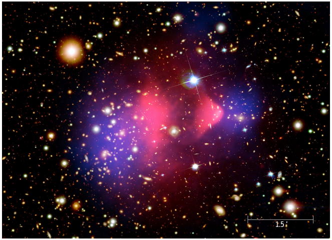
- As we have seen yesterday, the observed state looks a lot like what it would have been predicted by the SM

Limitations of the Standard model

Limitations of the SM

We know that the SM can not be the “ultimate” theory of nature.

- Gravity is not included
- Dark matter is not included
- The Baryon Asymmetry of the Universe is not explained
- Neutrino mass are not included

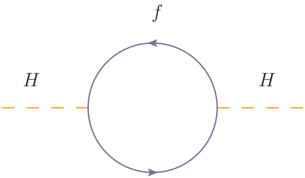


$\hookrightarrow$ Moreover, it can not explain some of the anomalies that we observe (that however are not confirmed)

- the measured value of $(g-2)_\mu$
- the anomalous result of M_W as determined by CDF (one of the Tevatron experiments)

$\hookrightarrow$ Finally, there are also “theory issues” in the SM

- the hierarchy problem
- no unification of the three forces



Is H_{125} the SM Higgs?

Since the SM can not be the “ultimate” description of Nature ...

$\Rightarrow$ the state H_{125} is NOT the SM Higgs

We should then ask ourselves how physics beyond the Standard Model could appear in the Higgs sector. This mainly means two avenues

- study the properties of the discovered state (parity, rates, mass etc.)
- search for extended Higgs sectors, that is, search for other scalar bosons (in principle this could be both lighter or heavier than the state that we have found at the LHC)

Open questions

- **BEH mechanism** – we should verify whether the relations implied by the BEH mechanism, namely the relation between the couplings and the masses of the particles, are realized in Nature
- **properties** – Measure the mass (that however is unpredicted in the SM), the total width, the spin and the $\mathcal{CP}$ properties of H_{125}
- **the scalar potential** – what is the structure of the scalar potential? are the self-couplings of the Higgs as predicted by the BEH mechanism?
- **Higgs nature** – is the state that we observe a single doublet (as in the SM), or part of a more complex Higgs sector? Is it elementary or composite?
- **Higgs portal** – is the Higgs a portal to a hidden sector (i.e. dark matter sector)? Does the Higgs couple to other BSM state (e.g. radion in extra dimensional models?)

All these questions are coupled to each other.

How to extend the SM Higgs sector?

There are an countless ways to extend the Higgs sector. For instance

- Add a singlet to the SM Higgs sector
- Add a doublet to the SM Higgs sector (the so-called two Higgs doublet models)
- Supersymmetry – minimal realization, the MSSM, that we have already mentioned
- MSSM with an additional singlet (NMSSM)
- MSSM with extra singlets
- SM/MSSM with higgs triplets
- Composite Higgs models
- Relaxion models

...

Note however that also models without direct modifications to the Higgs sector, can impact the Higgs sector (i.e. via loop corrections from new states). This happens for instance if we add vector-like fermions (i.e fermions that have a mass term that is not generated by the Higgs) to the SM

Constraints from experimental measurements

Clearly there are constraints that limit our creativity in extending the SM Higgs sector.

- We need a state around 125 GeV which is very in good approximation a CP-even scalar
- New states can not modify too much the Higgs couplings (to respect cross sections measurements)
- If we add other Higgs, the need to be in agreement with the current bounds from direct searches

For instance, there is a sum-rule involving the couplings of the Higgs to vector bosons

$$\sum_i g^2_{h_i VV} = g^2_{H_{SM} VV} \qquad \rightarrow \qquad \text{we know that} \qquad g^2_{H_{125} VV} \sim g^2_{H_S M VV}$$

that is, the structure of “EWSB” for gauge bosons is “rigid”, and all the Higgses participate to that

Which direction to take?

As we have seen, there are countless extensions possible.
We will cover the “simple” extensions of the scalar potentials

- the singlet extension of the SM
- the two Higgs doublet model extension of the SM

These are interesting because they are somehow the minimal way to extend the scalar potential (and only that), still in a consistent way.

However, we are also interested in more complete models that provide solutions also to other issues. We have seen that one very attractive way to extend the SM is supersymmetry. Moreover the minimal supersymmetry extension of the SM provides in a simple way a SM-like Higgs sector, with a *prediction* for the mass compatible with the observed value. It also includes a good dark matter candidate. ⇒ we will take a look at the MSSM and the NMSSM.

Higgs singlet and doublet extensions

The singlet extension of the SM

The Higgs sector is now composed of a doublet and of a singlet, both a acquiring a vev on its own (v and v_S)

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v+\rho+i\eta) \end{pmatrix} \quad , \quad S = \frac{1}{\sqrt{2}}(v_S+\rho_S)$$

The scalar sector of Lagrangian looks like

$$\mathcal{L}_{H\times SM} = (D^\mu\Phi)^\dagger(D_\mu\Phi) + (\partial^\mu S)(\partial_\mu S) - V(\Phi, S)$$

With the potential being

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \left(\Phi^\dagger\Phi, S^2\right)\begin{pmatrix} \lambda_1 & \frac{1}{2}\lambda_3 \\ \frac{1}{2}\lambda_3 & \lambda_2 \end{pmatrix}\begin{pmatrix} \Phi^\dagger\Phi \\ S^2 \end{pmatrix}$$
$$= m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3(\Phi^\dagger\Phi)S^2$$

Field/gauge basis, five parameters: λ_1, λ_2, λ_3, v, v_S

- Potential stability

The potential needs to be bounded from below. This happens if

$$4\lambda_1\lambda_2 - \lambda_3^2 > 0 \qquad \text{and} \qquad \lambda_1\,,\lambda_2 > 0$$

We know take a look at the physical spectrum of the theory. First we move to the unitary gauge

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+\rho) \end{pmatrix} \qquad , \qquad S = \frac{1}{\sqrt{2}}(v_S + \rho_S)$$

The mass term of the Lagrangian is then

$$\begin{aligned} \mathcal{L}_{\rm mass} &= (\rho, \rho_S)\mathcal{M}^2 \begin{pmatrix} \rho \\ \rho_S \end{pmatrix} \\ &= (\rho, \rho_S) \begin{pmatrix} 2\lambda_1 v^2 & \lambda_3 v v_S \\ \lambda_3 v v_S & 2\lambda_2 v_S^2 \end{pmatrix} \begin{pmatrix} \rho \\ \rho_S \end{pmatrix} \end{aligned}$$

The scalar potential

To find the mass eigenstates (i.e. the physical states) we need to diagonalize the mass matrix

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho \\ \rho_S \end{pmatrix}$$

In other terms, the singlet and the doublet state mix with each other to produce two mass eigenstates h and H. The corresponding eigenvalues (i.e. the masses) are

$$M^2_{h,H} = \lambda_1 v^2 + \lambda_2 v_S^2 \mp \sqrt{(\lambda_1 v^2 - \lambda_2 v_S^2)^2 + (\lambda_3 v v_S)^2}$$

Clearly, we need on of the two eigenvalues to be at around 125 GeV, and it to be "mostly" doublet (to satisfy the exp. measurements)

The mixing angle α can be expressed in terms of the potential parameters as

$$\sin 2\alpha = \frac{\lambda_3 v v_S}{\sqrt{(\lambda_1 v^2 - \lambda_2 v_S^2)^2 + (\lambda_3 v v_S)^2}}$$

$$\cos 2\alpha = \frac{\lambda_2 v_S^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 v_S^2)^2 + (\lambda_3 v v_S)^2}}$$

The physical basis is given by: m_h, m_H, α, v, $\tan\beta := v/v_S$, with $v \simeq 246$ GeV (exp. measurement)

The scalar potential

We can re-express the parameters of the field basis in terms of the physical basis

$$\lambda_1 = \frac{1}{2v^2}\left(m_h^2 \cos^2\alpha + m_H^2 \sin^2\alpha\right)$$
$$\lambda_2 = \frac{1}{2v_S^2}\left(m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha\right)$$
$$\lambda_3 = \frac{1}{2vv_S}\left(m_H^2 - m_h^2\right)\sin 2\alpha$$

Note that only the doublet component ρ couples to the SM states

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho \\ \rho_S \end{pmatrix}$$

The states h and H contains part of $\rho \Rightarrow$ all the couplings of the physical states are suppressed w.r.t. to the SM couplings:

$$g_{h-SM-SM} = \cos\alpha\, g_{H_{SM}-SM-SM} \qquad g_{H-SM-SM} = \sin\alpha\, g_{H_{SM}-SM-SM}$$

Higgs phenomenology

Note that we can obtain the SM in two possible limits

- $M_h \sim 125$ GeV, $\alpha \to 0$, $\cos\alpha \to 1$
- $M_H \sim 125$ GeV, $\alpha \to \frac{\pi}{2}$, $\sin\alpha \to 1$

Note that since EWSB is shared inside the two physical states h and H we have the following sum rule satisfied

$$g^2_{hVV} + g^2_{HVV} = (\cos^2\alpha + \sin^2\alpha) g^2_{H_SMVV} \equiv g^2_{H_SMVV}$$

The decay widths of the states are also rescaled with mixing angle factors

$$\begin{aligned} \Gamma(h \to SM) &= \cos^2\alpha\,\Gamma(H_{SM} \to \mathrm{SM}) \qquad \text{with} \quad m_{H_SM} = m_h \\ \Gamma(H \to SM) &= \sin^2\alpha\,\Gamma(H_{SM} \to \mathrm{SM}) \qquad \text{with} \quad m_{H_SM} = m_H \end{aligned}$$

Here and in the following, wherever H_{SM} appears, it is meant to have the same mass as the BSM Higgs state that enter the quantity

Higgs phenomenology

Let's assume now and in the following to be in the case where $M_H > m_h$. A qualitative difference with the SM is that now we have an additional decay channel

$$\Gamma(H \to hh) = \frac{|\mu'|^2}{8\pi m_H}\sqrt{1 - \frac{4m_h^2}{m_H^2}}\text{with} \qquad \mu' = \mu'(m_h, m_H, \alpha, v, \tan\beta)$$

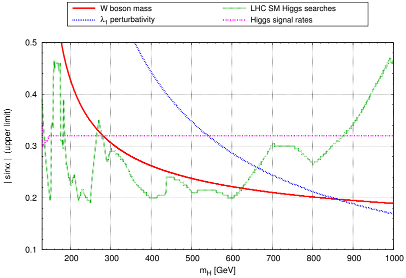
The total decay widths are then

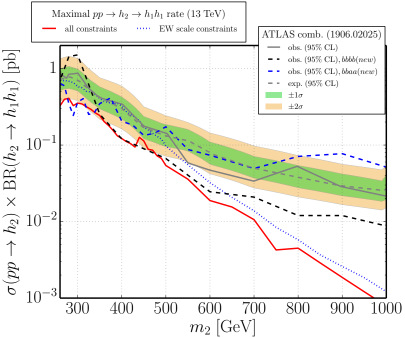
$$\begin{aligned} \Gamma_{h,tot} &= \cos^2\alpha\Gamma_{H_{SM},tot} \\ \Gamma_{H,tot} &= \sin^2\alpha\Gamma_{H_{SM},tot} + \Gamma(H \to hh) \end{aligned}$$

The branching ratios (partial width for the channel over the total width)

$$\begin{aligned} BR(h \to SM) &= \frac{\Gamma(h \to SM)}{\Gamma_{h,tot}} = BR(H_{SM} \to SM) \\ BR(H \to SM) &= \frac{\Gamma(H \to SM)}{\Gamma_{H,tot}} = \sin^2\alpha\frac{BR(H_{SM} \to SM)}{\Gamma_{H,tot}} \\ BR(H \to hh) &= \frac{\Gamma(H \to hh)}{\Gamma_{H,tot}} \end{aligned}$$

Current constraints





- Constraints obtained for $\tan\beta = 0.1$

[Robens '22]

The two Higgs doublet model

We have now two Higgs doublets in the scalar sector of our theory

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \quad , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

The scalar potential is

$$V = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + h.c.) + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2$$
$$+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + h.c.]$$

The physical spectrum is: h, H ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged). The input

parameters, in the physical basis are

$$\cos(\beta - \alpha)\,, \quad \tan\beta\,, \quad v\,, \quad M_h\,, \quad M_H\,, \quad M_A\,, \quad M_{H\pm}\,, \quad m_{12}^2$$

Type of two Higgs doublet models, phenomenology

- We take the assumption that the lightest Higgs h is the state that we observe at 125 GeV
- To avoid Flavor Changing Neutral Currents (which are highly constrained), we impose a $\mathcal{Z}_2$ symmetry

$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2$$

Extension of the $\mathcal{Z}_2$ symmetry to the fermion sector yields for possible 2HDMs types, depending on the way the two fields couple to the fermion fields

Type	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

- Again, we have from the sum rule constraint on the coupling to gauge bosons, that (assuming that h is the SM-like Higgs boson), $\sin(\beta-\alpha) \simeq 1$ and $\cos(\beta-\alpha) \simeq 0$.
- Other constraints (unitarity, perturbativity and EWPOs) push us in the region where $M_A \sim M_H \sim M_{H\pm}$

Higgs boson couplings in the 2HDM

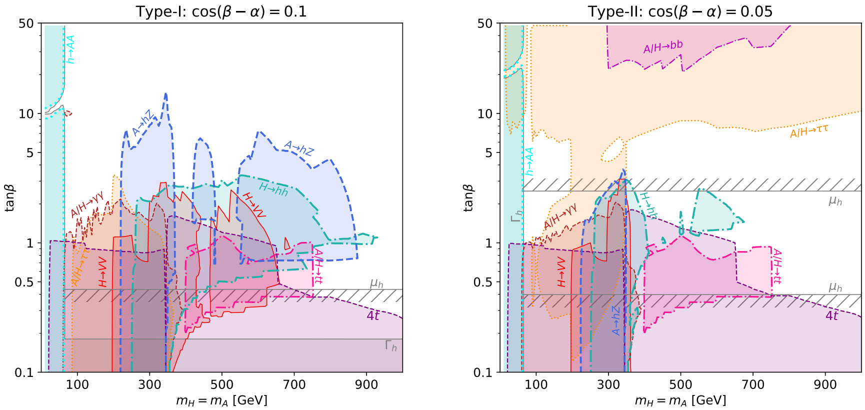
The Lagrangian terms describing the interactions between the two Higgs and the other states is

$$\mathcal{L} = -\sum_{f=u,d,l} \frac{m_f}{v} \left[\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H + i\xi_A^f \bar{f}\gamma_5 f A\right]$$
$$+ \sum_{h_i=h,H,A} \left[g M_W \xi_{h_i}^W W_\mu W^\mu h_i + \frac{1}{2} g M_Z \xi_{h_i}^Z Z_\mu Z^\mu h_i\right]$$

Coupling	type I	type II	type III (Y or flipped)	type IV (X or lepton specific)
ξ_h^u	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^d	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^l	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$
ξ_H^u	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$
ξ_H^d	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$
ξ_H^l	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$
ξ_A^u	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$
ξ_A^d	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
ξ_A^l	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

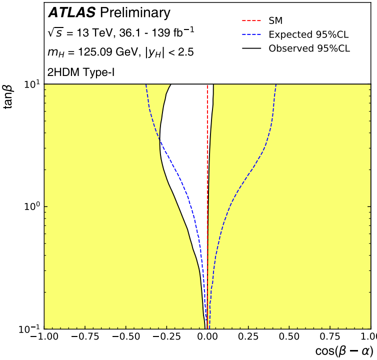
- Remember that we would like $\sin(\beta-\alpha) \simeq 1$ and $\cos(\beta-\alpha) \simeq 0$.

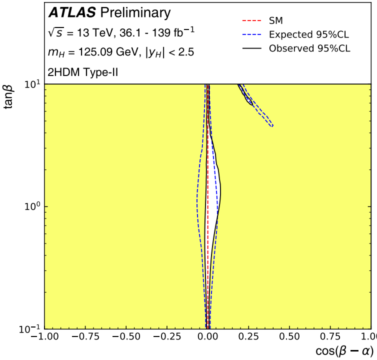
Current constraints from searches



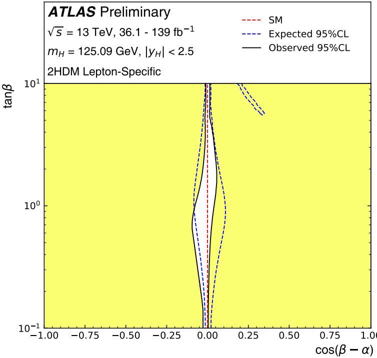
[Kling '20]

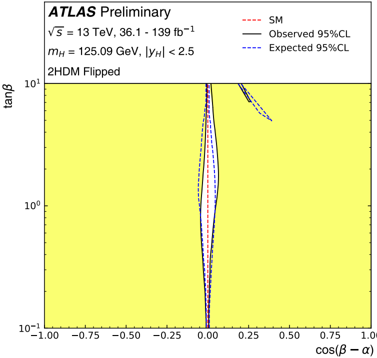
Current constraints from H_{125} characterization





Current constraints from H_{125} characterization





Next Two Higgs Doublet Model (N2HMD)

The field content is the same as the 2HDN, with the addition of a real singlet field

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \quad , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \quad , \quad \Phi_S = v_S + \rho_S$$

The scalar potential is given by

$$\begin{aligned} V = {} & m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + h.c.) + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 \\ & + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

where we have written all the terms allowed by the gauge symmetries and by the discrete symmetries

$$\begin{aligned} Z_2 \text{ symmetry} : \Phi_1 \to \Phi_1\,, \Phi_2 \to -\Phi_2\,, \Phi_S \to \Phi_S \\ Z_2' \text{ symmetry} : \Phi_1 \to \Phi_1\,, \Phi_2 \to \Phi_2\,, \Phi_S \to -\Phi_S \end{aligned}$$

The physical spectrum is: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

N2HDM: couplings to fermions and gauge bosons

Since we have the same Z_2 symmetry as in the 2HDM, and Φ_S does not contribute to EWSB, we have the same Yukawa sector

Type	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

The three neutral Higgs mixes to form the three $\mathcal{CP}$-even states

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}, \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

N2HDM: couplings to fermions and gauge bosons

The couplings to the gauge bosons are the same for all the types (as in the 2HDM)

Higgs	$c_{h_i VV} = c_\beta R_{i1} + s_\beta R_{i2},$
h_1	$c_{\alpha_2} c_{\beta-\alpha_1}$
h_2	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3}$
h_3	$-c_{\alpha_3} c_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta-\alpha_1}$

The couplings to fermions are

Type	u-type	d-type	leptons
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

The input parameters in the “physical” basis are:

$$\alpha_{1,2,3}\,, \qquad \tan\beta\,, \qquad v\,, \qquad v_S\,, \qquad M_{h_{1,2,3}}\,, \qquad M_A\,, M_{H\pm}\,, \qquad m_{12}^2$$

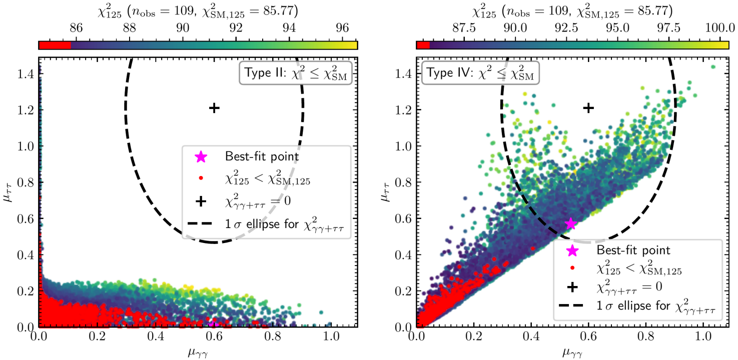


Figure 1: $\mu_{\tau\tau}$ in dependence of $\mu_{\gamma\gamma}$ in the N2HDM type II (left) and type IV (right). The color coding indicates the value of χ^2_{125}. Red points predict $\chi^2_{125} < \chi^2_{\rm SM,125}$. The $1\,\sigma$ confidence-level region with regards to $\chi^2_{\gamma\gamma+\tau\tau}$ is indicated by the dashed black line. The best-fit point is indicated with a magenta star.

$$\mu_{\gamma\gamma}^{95\ \rm GeV,exp} = 0.6 \pm 0.2,\ \mu_{\tau^+\tau^-}^{95\ \rm GeV,exp} = 1.2 \pm 0.5$$

The digamma and ditau excess at 95 GeV

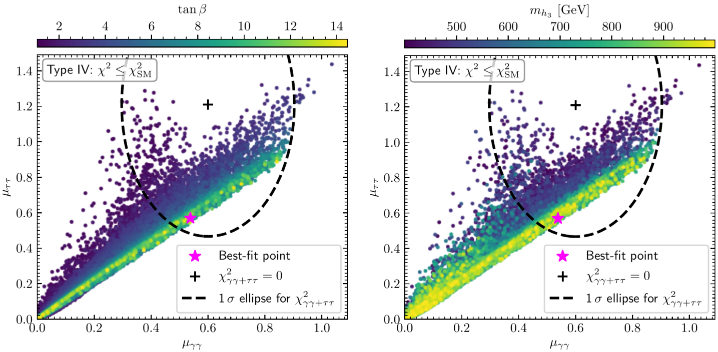


Figure 2: As in Fig. 1, but the color coding indicates the value of $\tan\beta$ (left) and of m_{h_3} (right).

$\mu_{\gamma\gamma}^{95\ \mathrm{GeV,exp}} = 0.6 \pm 0.2$, $\mu_{\tau^+\tau^-}^{95\ \mathrm{GeV,exp}} = 1.2 \pm 0.5$

The Higgs sector of the MSSM

The Higgs sector of the MSSM

Recall that in the SM we have that the Yukawa sector is described by

$$\mathcal{L}_{SM} = m_d \bar{Q} \mathbf{\Phi} d_R + m_u \bar{Q}_L \mathbf{\Phi}_c u_R$$

with

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L , \qquad \mathbf{\Phi}_c = i\sigma_2 \mathbf{\Phi}^* , \qquad \mathbf{\Phi} \to \begin{pmatrix} 0 \\ v \end{pmatrix} , \qquad \mathbf{\Phi}_c \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

However, in SUSY the term $\bar{Q}_L \mathbf{\Phi}^*$ is not allowed!
The superpotential is holomorphic function of chiral superfields, i.e. it should depend only on ϕ_i, and have no dependence on ϕ_i^*.
No soft SUSY-breaking terms allowed for chiral fermions.
$\Rightarrow H_d (\equiv H_1)$ and $H_u (\equiv H_2)$ are needed to give masses to both down- and up-type fermions.
Furthermore, two doublets are also needed for cancellation of anomalies (superpartners of the Higgs scalars are fermions, higgsinos $\to$ anomaly diagrams), and for the cancellation of the quadratic divergences.

The MSSM Higgs sector

We have seen that we need two Higgs doublet (i.e. the Higgs sector is a two Higgs doublet)

$$\Phi_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 + i\chi_1) \\ \phi_1^- \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

However, the scalar potential has the self-interactions dictated by SUSY and it is not as general as in the 2HDM:

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 \left(\epsilon_{ab} H_1^a H_2^b + h.c.\right)$$
$$+ \frac{g'^2 + g^2}{8} \left(H_1 \bar{H}_1 - H_2 \bar{H}_2\right)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

physical states: $h, H, A, H^\pm$ Goldstone bosons: $G^0, G^\pm$. input parameters (to be determined experimentally):

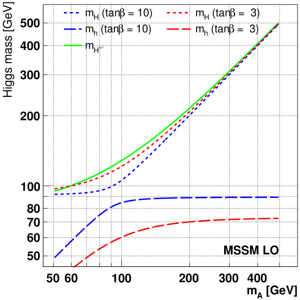
$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Diagonalization of the Higgs mass matrix yields

$$m^2_{H,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

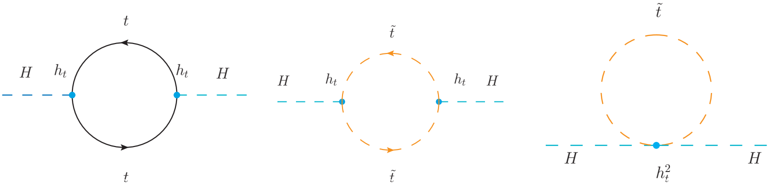
$\Rightarrow m_h \leq M_Z$ at tree level

- The MSSM predicts a light Higgs boson
- The measurement of the Higgs mass is a test of the SUSY structure



Tree level prediction incompatible with the observed value of the mass, $M_h \sim 125$ GeV

Higher order corrections to the Higgs mass



Considering radiative corrections to the self-energies then all MSSM particles contributes.

- $\hat{\Sigma}_{ij}(q^2) = \hat{\Sigma}^1_{ij}(q^2) + \hat{\Sigma}^2_{ij}(q^2) + \ldots$

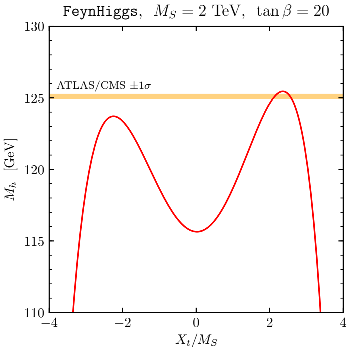
Only stop-top sector for simplicity

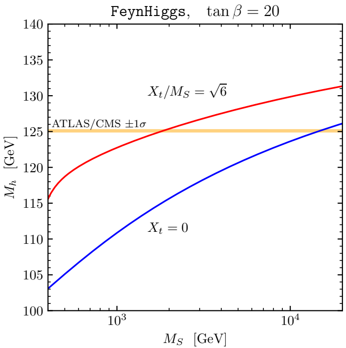
1. At one loop: $\Delta(M_h^{(1)})^2 = m_t^4[L + C^{(1)}]$ with $L = \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$
2. At two loop: $\Delta(M_h^{(2)})^2 = m_t^2\left[m_t^2\alpha_s\left(L^2 + L + C^{(2)}\right) + m_t^4\left(L^2 + L + D^{(2)}\right)\right]$

QCD corrections enter at two loop and can be sizable compared with the experimental precision of the measurement, $\mathcal{O}(1-10)$ GeV.

The Higgs mass in the MSSM

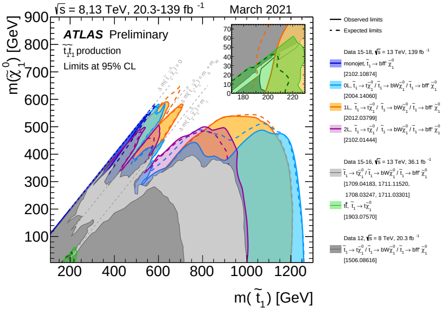
- Loop corrections are sufficient to push the value of the Higgs mass in the range of the measure value
- Leading dependence on the stop mass scale. Strong dependence also on the stop mixing parameter
- However, also all the other parameters of the MSSM enters the calculations via the radiative corrections and may be very important depending on the parameter space point (e.g. bottom/sbottom at large $\tan\beta$)

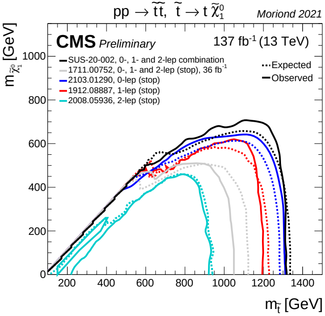




The stop spectrum and the LHC searches

- We have seen that a stop mass scale around 2 TeV is perfectly reasonable to reach 125 GeV
- This mass range is still perfectly allowed by experimental searches
- Purist of fine tuning may find this possibility not very much appealing





- Considering scenarios with $m_{stop} \lesssim 2$ TeV $\rightarrow M_h \leq 135$ GeV

A selection of MSSM scenarios

The following scenarios have been developed in the context of the `LHC Higgs Working Group` to be used as benchmarks for the experimental collaborations.

- They give an idea of the phenomenology of the Higgs sector of the MSSM and of the reach of the LHC.
- They do not include constraints from anything else aside from rough limits from sparticle searches

We have:

- M_h^{125}, a scenario where all the SUSY states are relatively heavy and do not influence the Higgs phenomenology too much (2HDM-like)
- $M_h^{125}(\tilde{\tau})$, $M_h^{125}(\tilde{\chi})$, characterized one by light staus and one by light EWinos
- Two alignment scenarios, one for the heavy and for the light Higgs ($M_h^{125}(alignement)$ and M_H^{125})
- One scenario with $\mathcal{CP}$-*violation*, $M_{h_1}^{125}(CPV)$

We focus on neutral states, but remember that also the charged Higgs is there

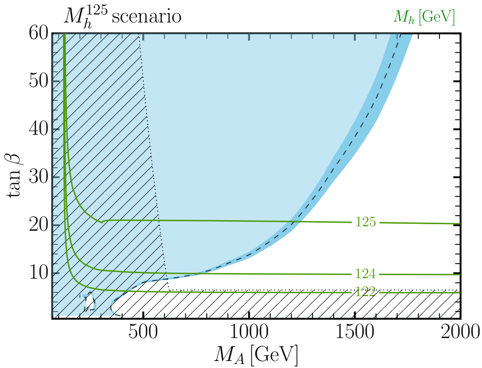
M_h^{125} scenario

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\ \text{TeV}, \quad M_{L_3} = M_{E_3} = 2\ \text{TeV},$$

$$\mu = 1\ \text{TeV}, \quad M_1 = 1\ \text{TeV}, \quad M_2 = 1\ \text{TeV}, \quad M_3 = 2.5\ \text{TeV},$$

$$X_t = 2.8\ \text{TeV}, \quad A_b = A_\tau = A_t\,.$$

- 2HDM-like phenomenology
- LHC reach more important at large **tan** β due to the enhanced coupling to the third-generation fermion (mainly driven by $\tau^+\tau^-$
- Hatched region represents the constraint from the properties of the state h (the one at 125 GeV)



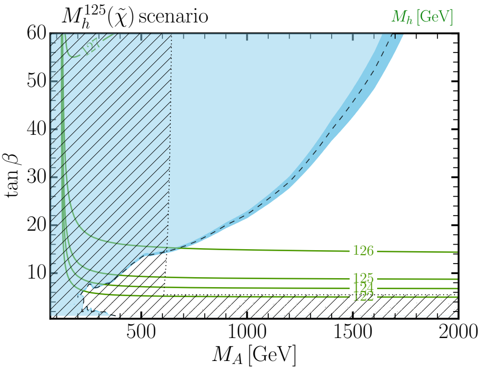
$M_h^{125}(\tilde{\chi})$ scenario

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5 \text{ TeV}, \quad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t\,.$$

- Light electroweakinos $\to$ decay of the heavy Higgs states into SUSY states
- Slightly less strong constraints from the searches due to the point above
- Hatched region represents the constraint from the properties of the state h (the one at 125 GeV) $\to$ note that now it excludes the very large $\tan\beta$ region



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$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t\,.$$

- Light electroweakinos → decay of the heavy Higgs states into SUSY states
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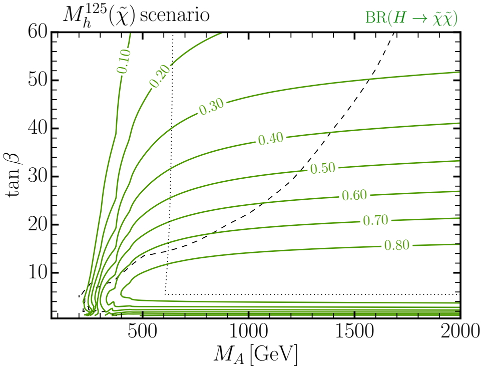

$M_h^{125}(\tilde{\chi})$ scenario

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$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t \,.$$

- Light electroweakinos → decay of the heavy Higgs states into SUSY states
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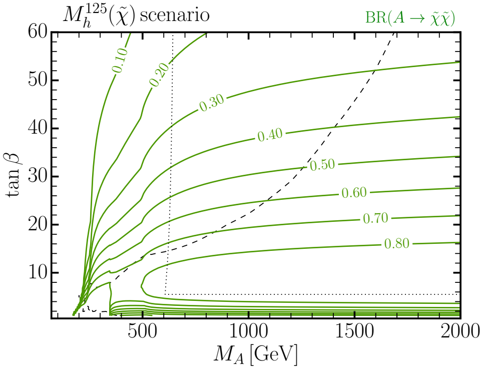

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$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

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- Light electroweakinos → decay of the heavy Higgs states into SUSY states
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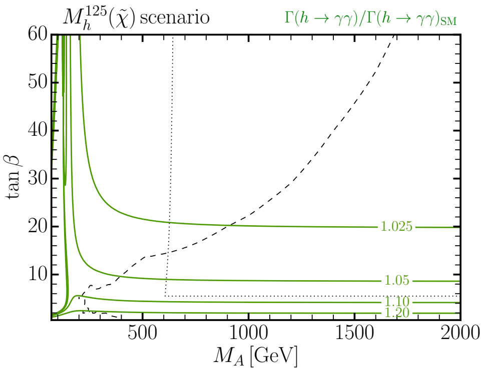
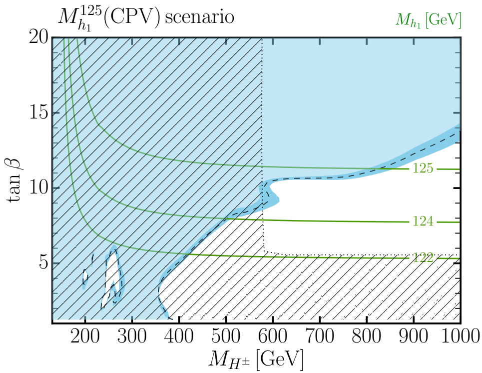


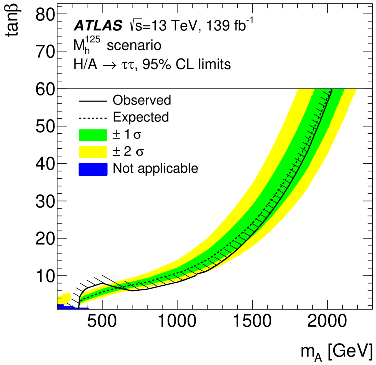
$M_{h_1}^{125}(CPV)$ scenario

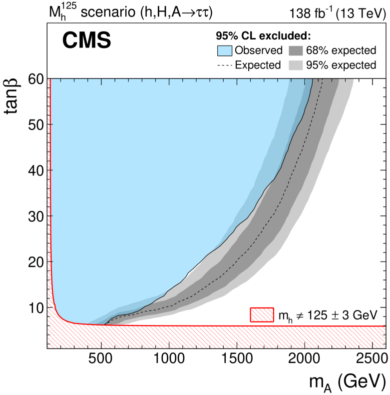
$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$
$$\mu = 1.65 \text{ TeV}, \quad M_1 = M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$
$$|A_t| = \mu \cot\beta + 2.8 \text{ TeV}, \quad \phi_{A_t} = \tfrac{2\pi}{15}, \quad A_b = A_\tau = |A_t| \,.$$

- $\mathcal{CP}$-violating phase $\rightarrow$ affect Higgs sector already at one-loop
- Admixture of the CP-even and CP-odd states $\rightarrow$ h_1, h_2, h_3
- Interference between the states affect the searches $\rightarrow$ “gulf” in the contour

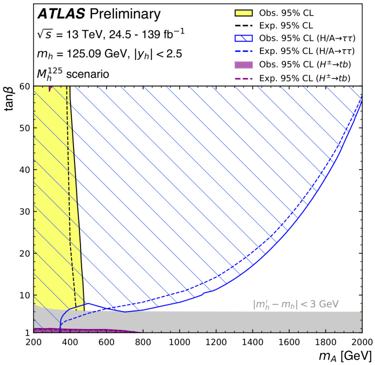


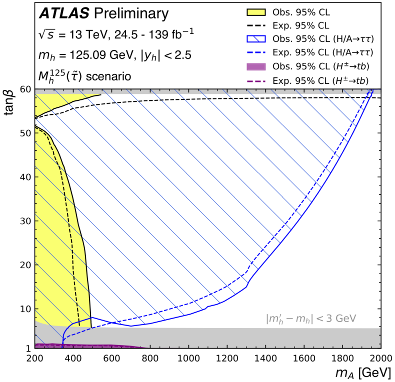
Current constraints from the experiments: searches



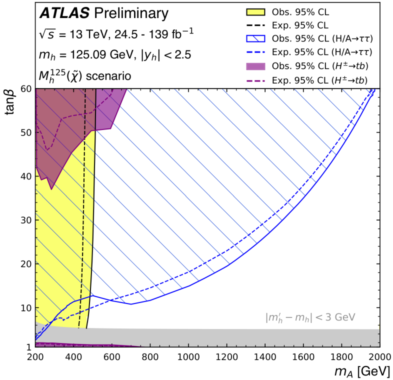


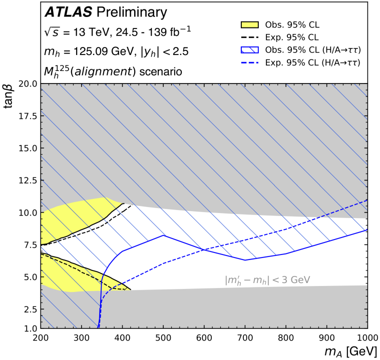
Current constraints from the experiments: H_{125} properties





Current constraints from the experiments: H_{125} properties





The NMSSM Higgs sector

Two Higgs Doublet + singlet:

$$\Phi_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 + i\chi_1) \\ \phi_1^- \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

$$S = v_s + S_R + IS_I$$

The scalar potential has then more terms w.r.t. the MSSM:

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 \left(\epsilon_{ab} H_1^a H_2^b + h.c.\right)$$
$$+ \frac{g'^2 + g^2}{8} \left(H_1 \bar{H}_1 - H_2 \bar{H}_2\right)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$
$$+ \left|\lambda(\epsilon_{ab} H_1^a H_2^b) + kS^2\right|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{k}{3} A_k S^3 + h.c.\right)$$

input parameters (various schemes are possible):

$$\lambda\,, \quad k\,, \quad A_k\,, \quad M_{H\pm}\,, \quad \tan\beta = \frac{v_2}{v_1}\,, \quad \mu_{\mathrm{eff}} = \lambda v_S$$

Physical spectrum

- Scalar spectrum

  - neutral, $\mathcal{CP}$-even $\rightarrow$ h_1, h_2, h_3
  - neutral, $\mathcal{CP}$-odd $\rightarrow$ a_1, a_2
  - charged $\rightarrow$ $H^\pm$
  - Goldstones $\rightarrow$ $G^0, G^\pm$

- Neutralinos

The μ parameters is $\rightarrow \mu_{\text{eff}} = \lambda v_S$

Additional degree of freedom from the singlino $\rightarrow$ one more neutralinos

$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the Higgs bosons of the NMSSM

- Lightest $\mathcal{CP}$-even Higgs

$$m^2_{h,\mathrm{tree,NMSSM}} = m^2_{h,\mathrm{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

- Lightest $\mathcal{CP}$-odd Higgses

MSSM: $M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta) = \mu B (\tan\beta + \cot\beta)$

NMSSM: $M_A^2 = \mu_{\mathrm{eff}} B_{\mathrm{eff}} (\tan\beta + \cot\beta)$ with $B_{\mathrm{eff}} = A_\lambda + k v_S$, $\mu_{\mathrm{eff}} = \lambda v_S$

$\Rightarrow$ one very light pseudoscalar (a_1)

- Lightest Charged Higgses

MSSM: $M_{H\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$

NMSSM: $M_{H\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$

$\Rightarrow M_{h_1}^{\mathrm{MSSM},tree} < M_{h_1}^{\mathrm{NMSSM},tree}$, one light pseudoscalar, $M_{\mathrm{H}\pm}^{\mathrm{MSSM,tree}} \geq M_{\mathrm{H}\pm}^{\mathrm{NMSSM,tree}}$

NMSSM searches, example

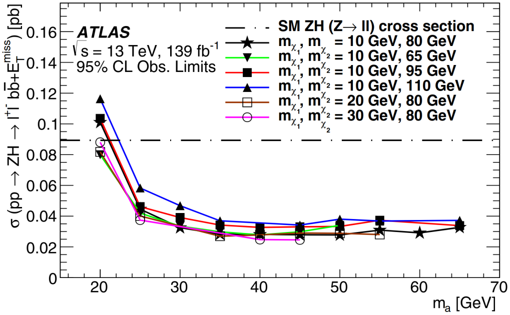
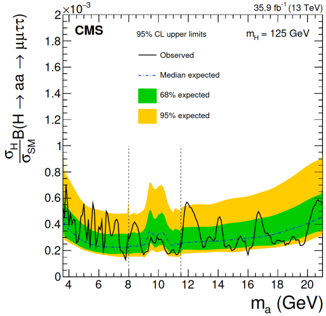


Figure 4: Upper limits at 95% CL on the cross section $pp \to ZH$ times branching ratio for $Z \to \ell^+\ell^-$ (where $\ell = e, \mu$ or τ) and $H \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to a\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ as a function of m_a for several values of $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ for the NMSSM scenario described in the text. All branching ratios in the Higgs boson decay chain after the decay $H \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ are set to 100%. The different ranges in m_a reflect differences in the allowed event kinematics. The lines joining the m_a points come from an assumed linear interpolation of the limits. The SM value for the cross section $\sigma(pp \to ZH) \times BR(Z \to \ell^+\ell^-)$ is shown for reference.

NMSSM searches, example



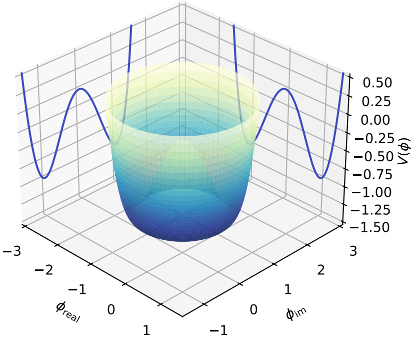
The Higgs mass and the top mass

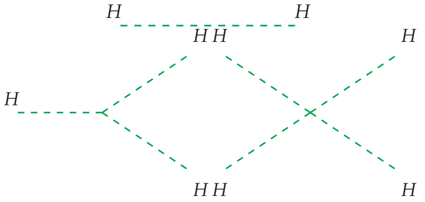
- In nearly any model we have a large coupling of the Higgs to the top quark

$\hookrightarrow$ one-loop corrections $\Delta M_H^2 \sim G_\mu m_t^4$
$\hookrightarrow$ M_H depends strongly on m_t
$\hookrightarrow$ In SUSY $\Delta m_t \simeq \pm 1$ GeV $\Rightarrow \Delta M_h \simeq \pm 1$ GeV
$\Rightarrow$ precision Higgs physics requires $\mathcal{O}(50$ MeV$)$ in $m_t \Rightarrow$ Needs an m_t from a e^+e^- collider

The Higgs potential

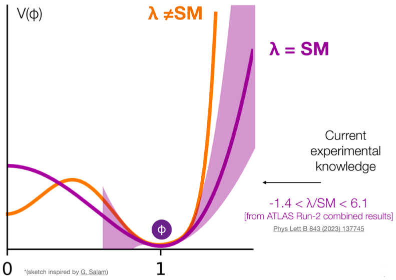
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$





$$m_H^2 = 2\lambda v^2 \tag{1}$$

What we know now



Overview of the Higgs

- We already know two important pieces
- The mass (dictate the shape around the minimum)
- the vacuum expectation value
- We also have limits on the trilinear coupling

The BSM perspective: how large can the trilinear be?

Estimated upper bound on the trilinear deviation

- Assume a UV completion that can be described by SMEFT and generates

$$\mathcal{O}_6 = -\frac{1}{M^2}|H|^6 \,,\; \mathcal{O}_H = \frac{1}{M^2}(\partial_\mu |H|^2)^2 \,,\; \mathcal{O}_R = \frac{1}{M^2}|H|^2|D_\mu H|^2| \,,\; \mathcal{O}_T = \frac{1}{M^2}|H^\dagger D_\mu H|^2|$$

- EFT-based power counting arguments [Durieux et al, 2209.00666], assuming non fine-tuned UV completion (κ IR dimension-4 coupling)
- $c_6 \sim \kappa \;,\; c_{H,R,} \sim \frac{\kappa}{16\pi^2} \;,\; c_{H_8,R_8,T_8} \sim \kappa \qquad (\mathcal{O}_{H_8,R_8,T_8} \equiv |H|^2\mathcal{O}_{H,R,T}/M^2)$

The contributions to the Higgs couplings are of order

$$\delta_{h^3} \sim \kappa \frac{v^4}{M^2 m_h^2} \qquad \delta_{VV} \sim \kappa \frac{v^2}{M^2} \max\left[\frac{1}{16\pi^2}, \frac{v^2}{M^2}\right]$$

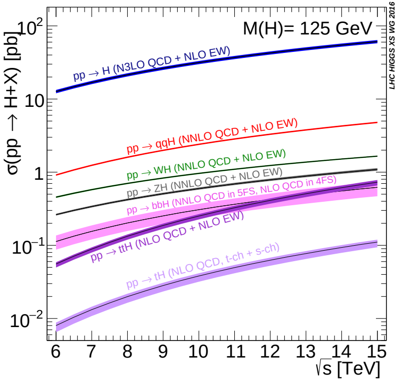
which means that

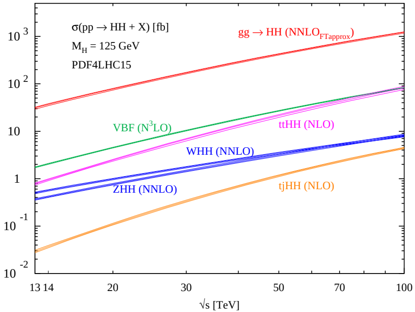
$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)\right]$$

This reaches $(\frac{4\pi v}{m_h})^2 \approx 600$ for $M \gtrsim 4\pi v \approx 3$ TeV
→ The deviation in the self-coupling can be much larger than in the other couplings

Double Higgs production

Single vs double Higgs cross sections





Single vs double higgs gluon fusion

- At 14 TeV single Higgs production in gluon fusion is $\sim$ 55 [pb]
- At 14 TeV double Higgs production in gluon fusion is $\sim$ 0.035 [pb]

Double Higgs production at the LHC

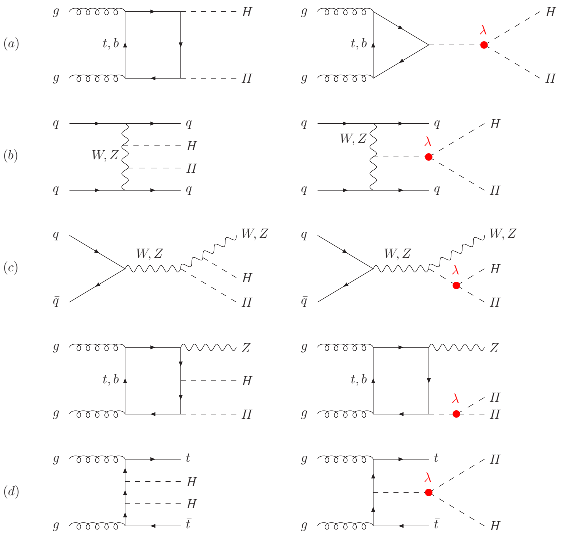
Production processes

(a) Gluon fusion

(b) Vector Boson Fusion (VBF)

(c) Double-Higgs strahlung

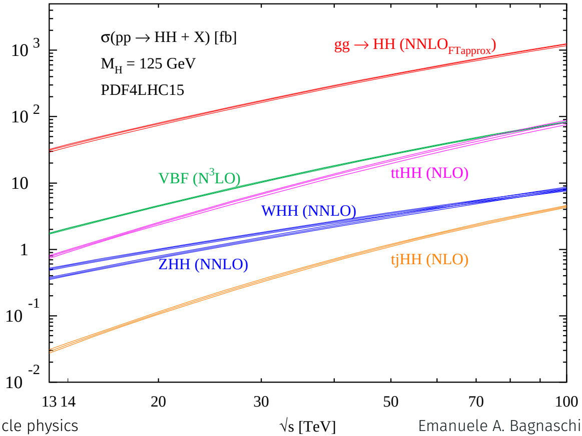
(d) Quark associated production



[Di Micco et al., Rev.Phys. 5 (2020) 100045]

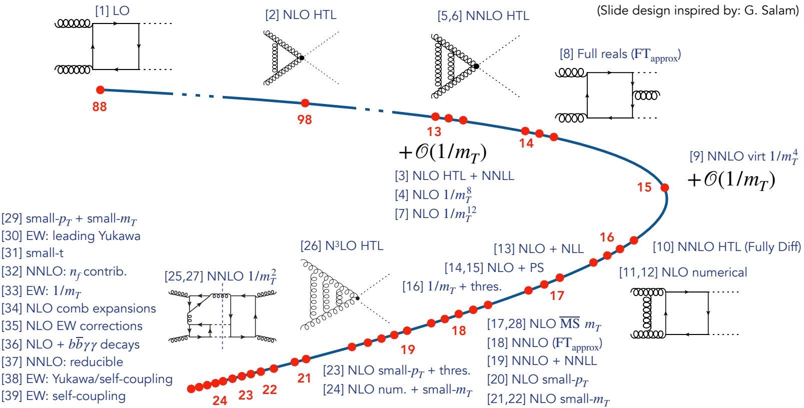
Production channels

- Gluon fusion is the dominant production process
- Other processes are interesting to probe other interactions, i.e. VBF/VHH to the HHVV coupling



[Di Micco et al., Rev.Phys. 5 (2020) 100045]

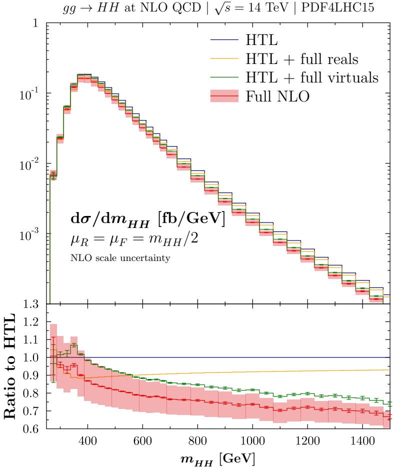
Theoretical status of $gg \to HH$ calculations



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagnaschi, Degrassi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23 [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, SPJ, Kerner, Stone, Vestner [39] Li, Si, Wang, Zhang, Zhao 24

[S. Jones, Higgs Hunting 2024]

Impact of QCD corrections

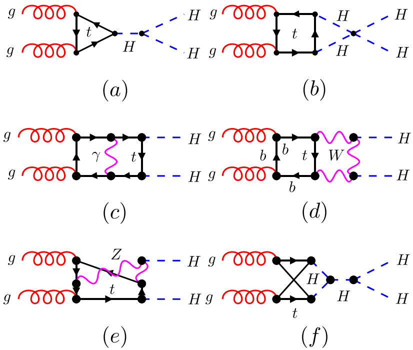


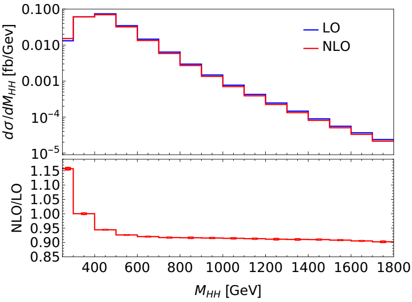
[Baglio et al., 1811.05692]

Complete NLO QCD corrections

- Complete corrections with full mass dependence available only at NLO-QCD
- Extremely difficult to compute the virtual corrections, obtained with semi-numerical methods [Borowska et al, 1604.06447; Baglio et al., 1811.05692]
- Interesting example of precision calculation where complete and approximated results plays an important role

Impact of EW corrections





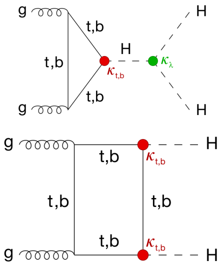
[Bi et al., 2311.16963]

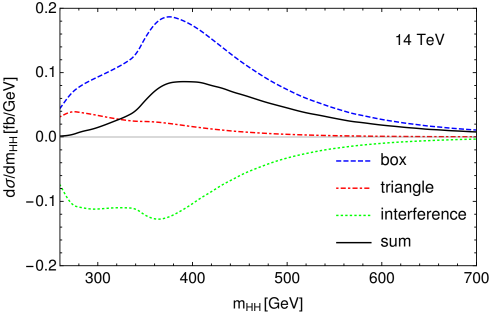
- Impact of about 4% on the total cross section
- Near the HH treshold, +15%; at high-energy −10%
- See also [Mühlleitner at al., 2207.02524] for the Yukawa top induced part

Gluon fusion: interference pattern

Interference pattern

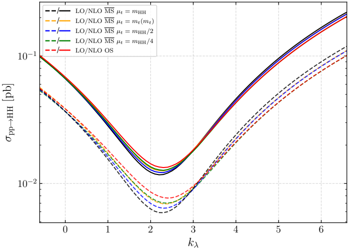
- Non trivial interference pattern between the box and the triangle diagrams
- → the cross section strongly depends on the value of the trilinear coupling (minimum for $\lambda/\lambda_{SM} \sim 2.4$)



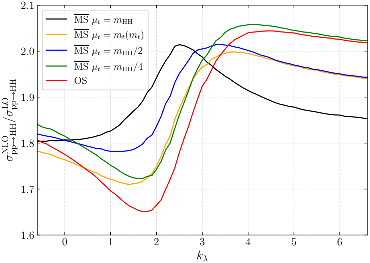


[Di Micco, . . ., EB et al., 1910.00012]

Dependence of total cross section on the value of λ_3



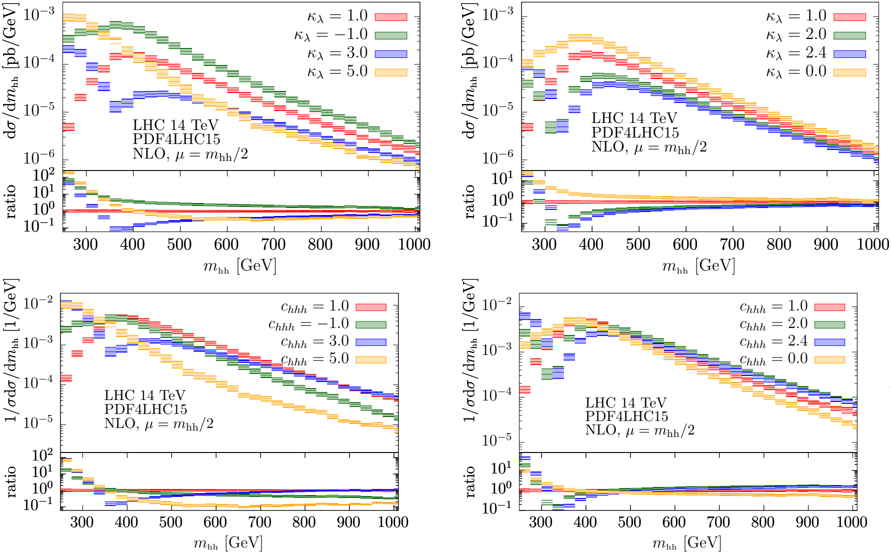
- Total inclusive cross section at LO and NLO for different values of k_λ and different choices of the top mass renormalization scheme



- K-factors for different top mass scheme choices

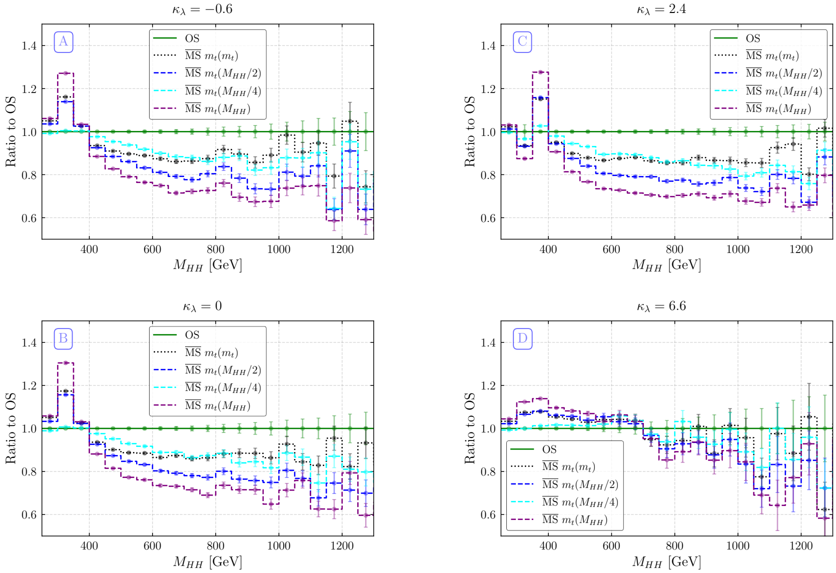
- Minimum of the cross section depends on the top scheme
- As expected, the difference between the schemes is smaller at NLO

m_{HH} distortion due the a non-SM trilinear

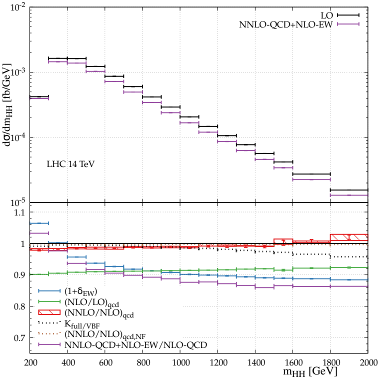


[Heinrich et al., 1903.08137]

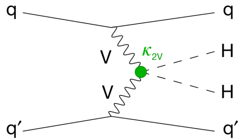
Top scheme dependence with a modified trilinear

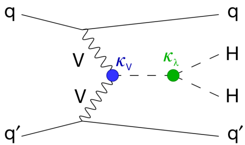


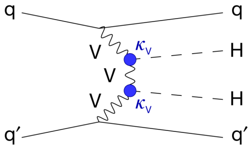
HH in Vector boson fusion



- Allow to probe the $\lambda HHVV$ coupling
- Highest order QCD corrections calculated using structure function approach (i.e. DIS)
- NLO-QCD yields a 10% correction; NNLO+N^{3}LO $\lesssim$ 1%

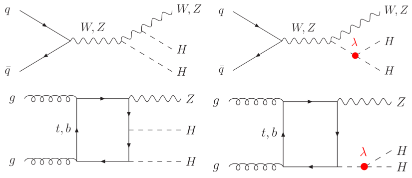




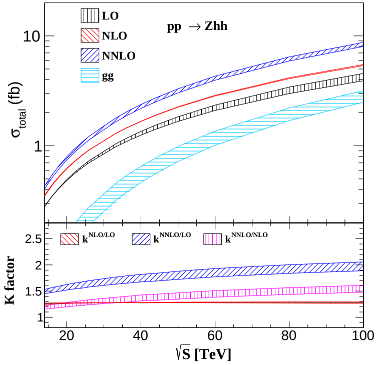


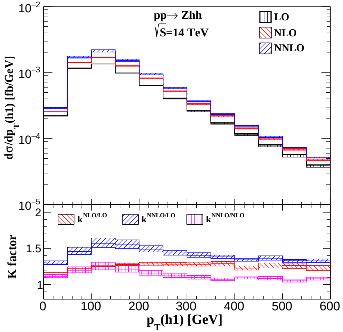
[Dreyer et al., 2005.13341]

Double Higgs-Strahlung



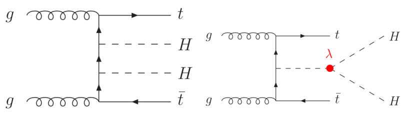
- QCD corrections are DY-like
- NLO+NNLO QCD corrections are around $\sim 30\%$
- At NNLO a new channel appear, $gg \to HHZ \sim 30\%$





[Li et al., 1710.02464]

(Single-top an $t\bar{t}$ associated double Higgs production

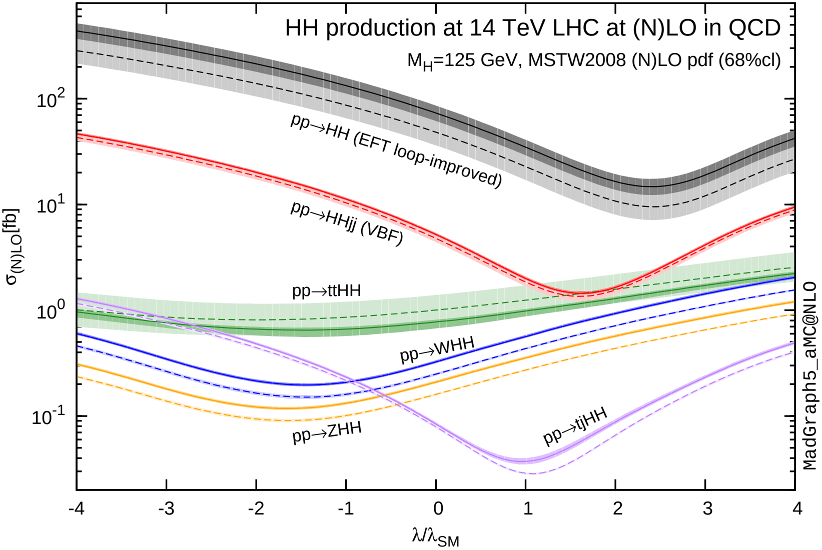


- Computed in using `MG5_aMC@NLO` [Frederix et al., 1401.7340]
- $t\bar{t}$ associated production, QCD corrections -20%
- single top associated production, QCD corrections $+20\%$

	$\sqrt{s} = 8$ TeV (LO) NLO		$\sqrt{s} = 13$ TeV (LO) NLO		$\sqrt{s} = 14$ TeV (LO) NLO	
HH (EFT loop-improv.)	$(5.44^{+38\%}_{-26\%})$	$8.73^{+17+2.9\%}_{-16-3.7\%}$	$(19.1^{+33\%}_{-23\%})$	$29.3^{+15+2.1\%}_{-14-2.5\%}$	$(22.8^{+32\%}_{-23\%})$	$34.8^{+15+2.0\%}_{-14-2.5\%}$
$HHjj$ (VBF)	$(0.436^{+12\%}_{-10\%})$	$0.479^{+1.8+2.8\%}_{-1.8-2.0\%}$	$(1.543^{+9.4\%}_{-8.0\%})$	$1.684^{+1.4+2.6\%}_{-0.9-1.9\%}$	$(1.839^{+8.9\%}_{-7.7\%})$	$2.017^{+1.3+2.5\%}_{-1.0-1.9\%}$
$t\bar{t}HH$	$(0.265^{+41\%}_{-27\%})$	$0.177^{+4.7+3.2\%}_{-19-3.3\%}$	$(1.027^{+37\%}_{-25\%})$	$0.792^{+2.8+2.4\%}_{-10-2.9\%}$	$(1.245^{+36\%}_{-25\%})$	$0.981^{+2.3+2.3\%}_{-9.0-2.8\%}$
W^+HH	$(0.111^{+4.0\%}_{-3.9\%})$	$0.145^{+2.1+2.5\%}_{-1.9-1.9\%}$	$(0.252^{+1.4\%}_{-1.7\%})$	$0.326^{+1.7+2.1\%}_{-1.2-1.6\%}$	$(0.283^{+1.1\%}_{-1.3\%})$	$0.364^{+1.7+2.1\%}_{-1.1-1.6\%}$
W^-HH	$(0.051^{+4.2\%}_{-4.0\%})$	$0.069^{+2.1+2.6\%}_{-1.9-2.2\%}$	$(0.133^{+1.5\%}_{-1.7\%})$	$0.176^{+1.6+2.2\%}_{-1.2-2.0\%}$	$(0.152^{+1.1\%}_{-1.4\%})$	$0.201^{+1.7+2.2\%}_{-1.1-1.8\%}$
ZHH	$(0.098^{+4.2\%}_{-4.0\%})$	$0.130^{+2.1+2.2\%}_{-1.9-1.9\%}$	$(0.240^{+1.4\%}_{-1.7\%})$	$0.315^{+1.7+2.0\%}_{-1.1-1.6\%}$	$(0.273^{+1.1\%}_{-1.3\%})$	$0.356^{+1.7+1.9\%}_{-1.2-1.5\%}$
$tjHH(\cdot 10^{-3})$	$(5.057^{+2.0\%}_{-3.2\%})$	$5.606^{+4.4+3.9\%}_{-2.3-4.2\%}$	$(23.20^{+0.0\%}_{-0.8\%})$	$29.77^{+4.8+2.8\%}_{-2.8-3.2\%}$	$(28.79^{+0.0\%}_{-1.2\%})$	$37.27^{+4.7+2.6\%}_{-2.7-3.0\%}$

Table 1: LO and NLO total cross sections (in fb) for the six largest production channels at the LHC, with $\sqrt{s} = 8, 13, 14$ TeV. The first uncertainty quoted refers to scale variations, while the second (only at the NLO) to PDFs. Uncertainties are in percent. No cuts are applied to final state particles and no branching ratios are included.

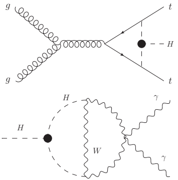
Interference pattern for all the processes

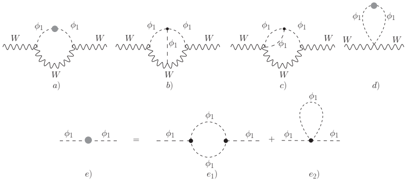


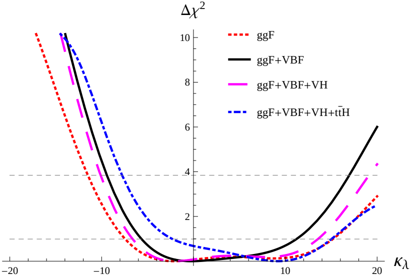
[Frederix et al., 1401.7340]

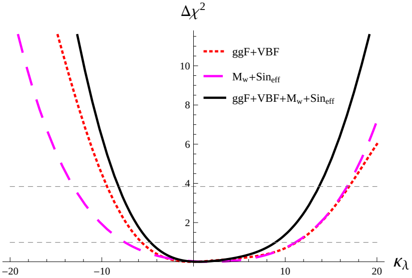
Probing the trilinear coupling indirectly

It is also possible to probe deviation of the trilinear coupling via radiative corrections









- Impact on single Higgs production observables

- Impact on Electroweak precision Observables

Experimental searches: best channels

Best channels

- Tag one higgs in the $b\bar{b}$ channel – largest branching ration, but coarser energy resolution
- Tag the second Higgs in either the $b\bar{b}$ $\tau^+\tau^-$, $\gamma\gamma$ channels

BRs	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

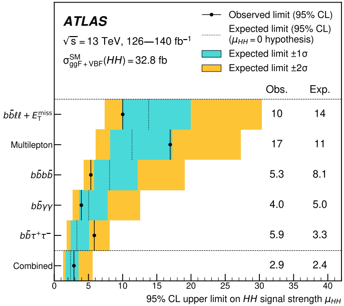
[C. Pandini's talk at "Extended Scalar Sector workshop 2024@CERN"]

Channel complementarity

- $HH \to b\bar{b}b\bar{b}$ – largest BR ($\sim$ 34%), huge QCD multi-jet background
- $HH \to b\bar{b}\tau\tau$ – moderate ($\sim$ 7%), tau-tagging facilitates background rejection
- $HH \to b\bar{b}\gamma\gamma$ – very small BR ($<$ 1%) – clean signature, good resolution

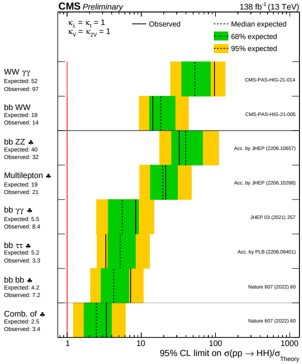
Combinations of HH searches

- Cross section is very small → combine all the channels to maximize the sensitivity
- No observation, only upper limit on the signal strength



[ATLAS, 2406.09971]

$$\mu_{HH}^{\mathrm{ATLAS}} < 2.9\ (2.4)$$

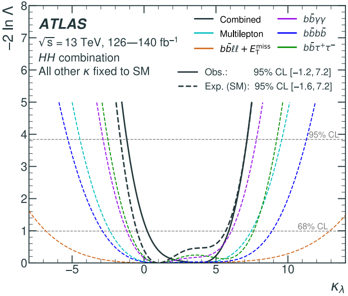


[CMS Summary plot]

$$\mu_{HH}^{\mathrm{CMS}} < 3.4\ (2.5)$$

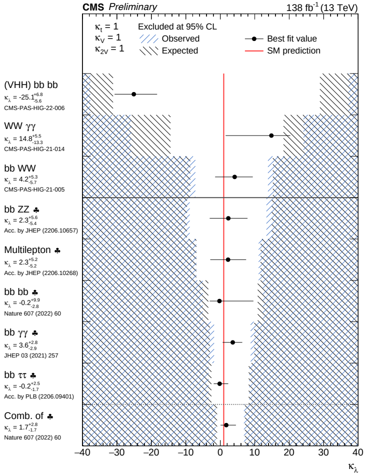
Constraints on the trilinear coupling

- Only from HH measurements



[ATLAS, 2406.09971]

$$k_\lambda^{\mathrm{ATLAS}} \in [-1.2, 7.2]_{\mathrm{obs}}$$

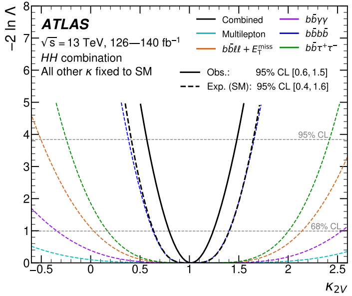


[CMS Summary plot]

$$k_\lambda^{\mathrm{ATLAS}} \in [-1.24, 6.59]_{\mathrm{obs}}$$

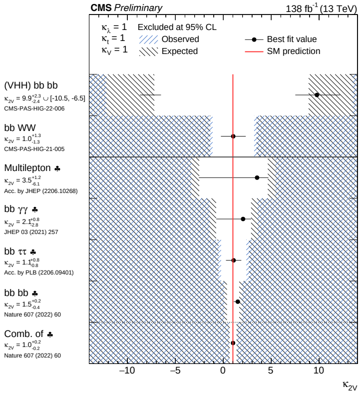
Constraints on the trilinear coupling

- Only from HH measurements. VBF dominant.
- Assuming the SM, $k_{2V} = 0$ is now ecluded at more than 6σ



[ATLAS, 2406.09971]

$$k_\lambda^{\mathrm{ATLAS}} \in [-1.2, 7.2]_{\mathrm{obs}}$$

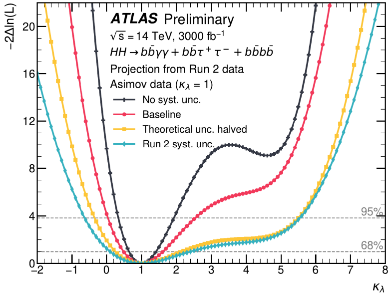


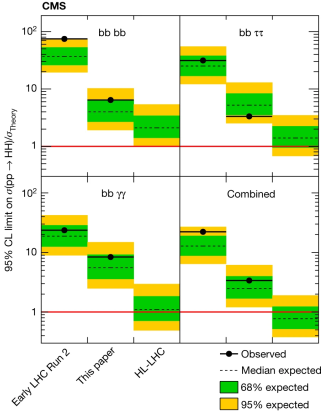
[CMS Summary plot]

$$k_\lambda^{\mathrm{ATLAS}} \in [-1.24, 6.59]_{\mathrm{obs}}$$

The outlook for Run-3 and HL-LHC

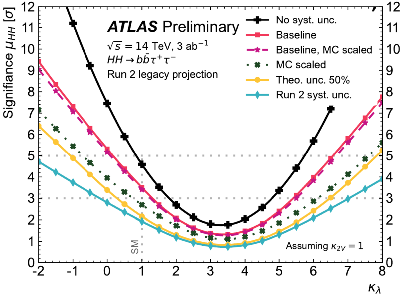
- Double Higgs searches are statistically (sistematics are around 15%-20%limited $\rightarrow$ will fully benefit from the huge dataset of HL-LHC (also complete Run-3)
- Experimental developments: better b-tagging, new triggers etc. $\rightarrow$ the improvement will be better than simply the int. luminosity rescaling



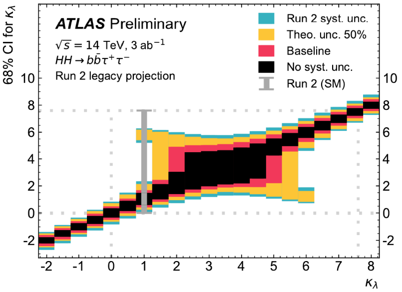


The outlook for Run-3 and HL-LHC

- More recent and advanced study from ATLAS on the $b\bar{b}\tau\tau$ channel
- Depending on the value of k_λ, HH could be observed
- Precision on the measurements will depend on the value of k_λ



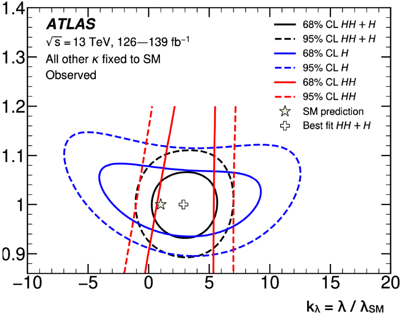
Significance



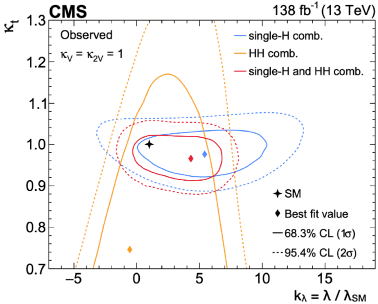
Measurement precision given a value of k_λ

Combined H+HH constraints

- Combination of HH and single Higgs cross sections
- Allows to test simultaneous variation of the trilinear and the top Yukawa

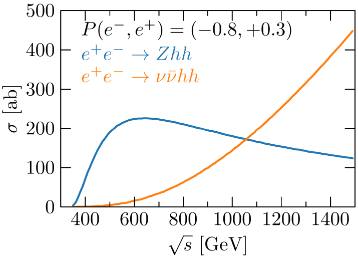


[ATLAS, PLB 843 (2023) 137745]

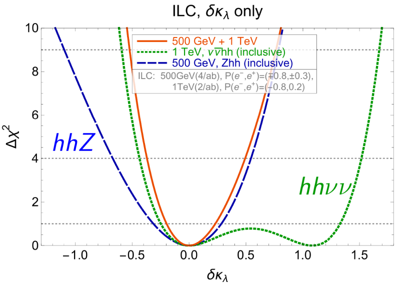


[CMS, 2407.13554]

Probing the trilinear coupling at a high-energy e^+e^- machine

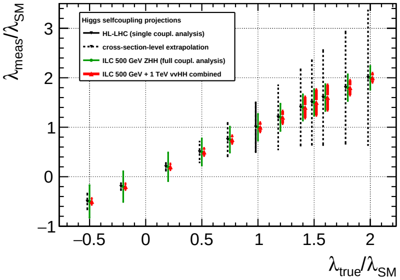


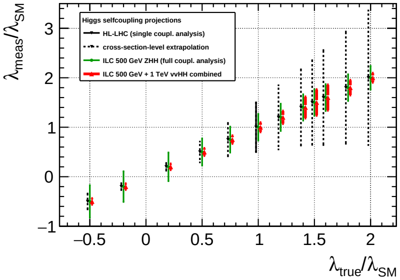
- Associated double Higgs production dominant up to 1*TeV*
- Weak boson fusion larger for higher energies



- Complementarity between 500 GeV and 1 TeV
- 1σ sensitivity at 20% precision

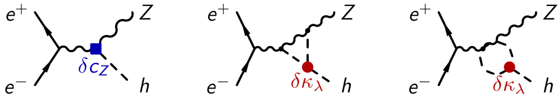
Interference pattern at e^+e^- machines



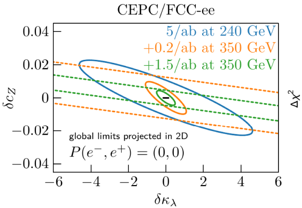


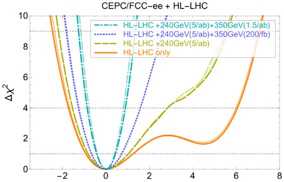
- Complementary interference pattern vs hadron machines
- Back of the envelop estimation

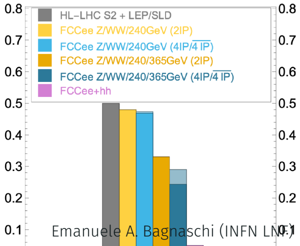
FCC-ee + FCC-hh



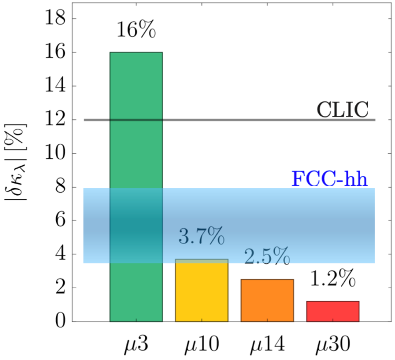
- Below threshold, probe via loop effect
- Two energy measurements necessary to disentangle modification of the trilinear from other couplings



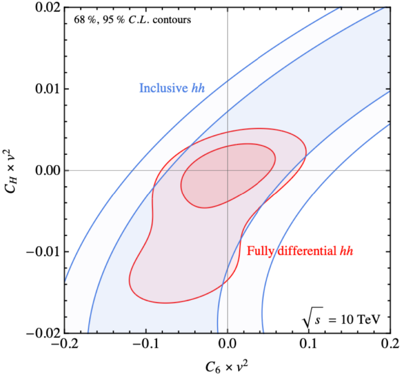




Probing the trilinear coupling at the muon collider

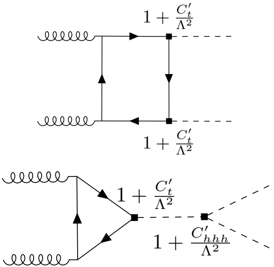


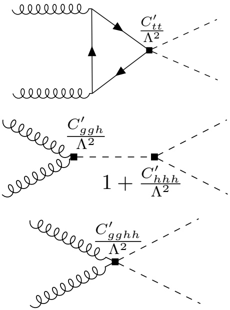
[2203.07256]



[Buttazzo et al., 2012.11555]

- Assume that NP is heavy in respect to the mass scales probed by the measurements
- Describe NP effects via higher-dimensional operators
- $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^6 + \ldots$

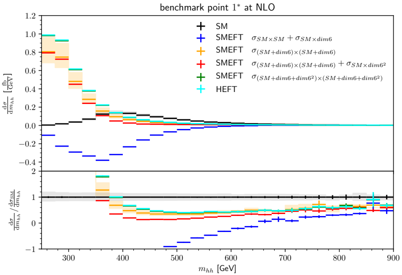


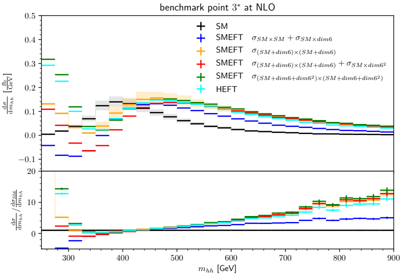


[Heinrich et al., 2204.13045]

SMEFT benchmark points

benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\mathrm{kin}}$	C_H	C_{uH}	C_{HG}	Λ
SM	1	1	0	0	0	0	0	0	0	1 TeV
1*	5.105	1.1	0	0	0	4.95	−6.81	3.28	0	1 TeV
3*	2.21	1.05	$-\frac{1}{3}$	0.5	0.25*	13.5	2.64	12.6	0.0387	1 TeV
6*	−0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV





[Heinrich et al., 2204.13045]

The two Higgs doublet model

We have now two Higgs doublets in the scalar sector of our theory

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \quad , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

The scalar potential is

$$V = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + h.c.) + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2$$
$$+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2 + h.c.]$$

The physical spectrum is: h, H ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged). The input

parameters, in the physical basis are

$$\cos(\beta-\alpha)\,, \quad \tan\beta\,, \quad v\,, \quad M_h\,, \quad M_H\,, \quad M_A\,, \quad M_{H^\pm}\,, \quad m_{12}^2$$

Type of two Higgs doublet models, phenomenology

- We take the assumption that the lightest Higgs h is the state that we observe at 125 GeV
- To avoid Flavor Changing Neutral Currents (which are highly constrained), we impose a $\mathcal{Z}_2$ symmetry

$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2$$

Extension of the $\mathcal{Z}_2$ symmetry to the fermion sector yields for possible 2HDMs types, depending on the way the two fields couple to the fermion fields

Type	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

- Again, we have from the sum rule constraint on the coupling to gauge bosons, that (assuming that h is the SM-like Higgs boson), $\sin(\beta-\alpha) \simeq 1$ and $\cos(\beta-\alpha) \simeq 0$.
- Other constraints (unitarity, perturbativity and EWPOs) push us in the region where $M_A \sim M_H \sim M_{H\pm}$

Higgs boson couplings in the 2HDM

The Lagrangian terms describing the interactions between the two Higgs and the other states is

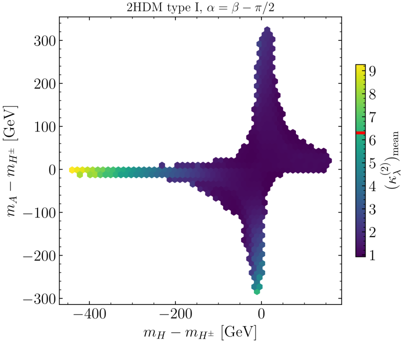
$$\mathcal{L} = -\sum_{f=u,d,l} \frac{m_f}{v}\left[\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H + i\xi_A^f \bar{f}\gamma_5 f A\right] + \sum_{h_i=h,H,A}\left[g M_W \xi_{h_i}^W W_\mu W^\mu h_i + \frac{1}{2} g M_Z \xi_{h_i}^Z Z_\mu Z^\mu h_i\right]$$

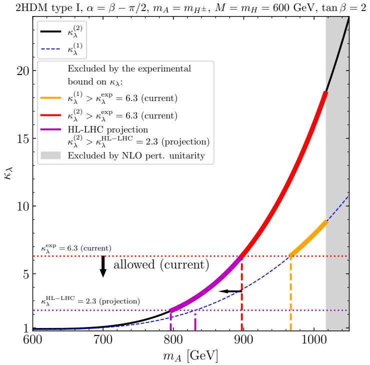
Coupling	type I	type II	type III (Y or flipped)	type IV (X or lepton specific)
ξ_h^u	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^d	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^l	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta$
ξ_H^u	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$
ξ_H^d	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$
ξ_H^l	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$	$c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta$
ξ_A^u	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$
ξ_A^d	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
ξ_A^l	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

- Remember that we would like $\sin(\beta-\alpha) \simeq 1$ and $\cos(\beta-\alpha) \simeq 0$.

An example: 2HDM Type-1

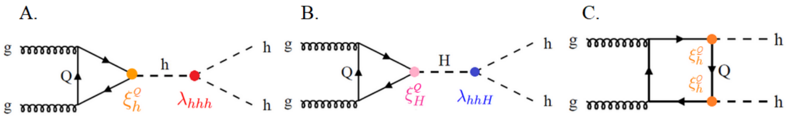
- Parameter space includes regions with very non-SM trilinear coupling
- Higher-order corrections important (diagrams with BSM trilinear couplings)

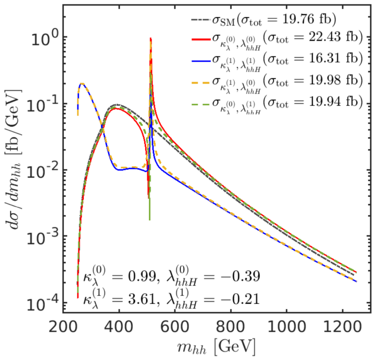


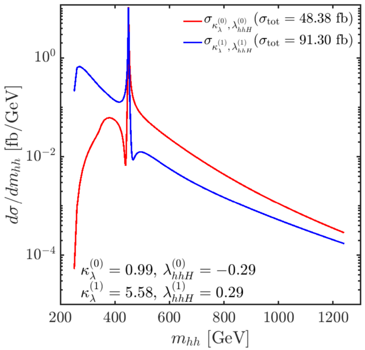


[Bahl et al., 2202.03453]

Interpretation of BSM searches



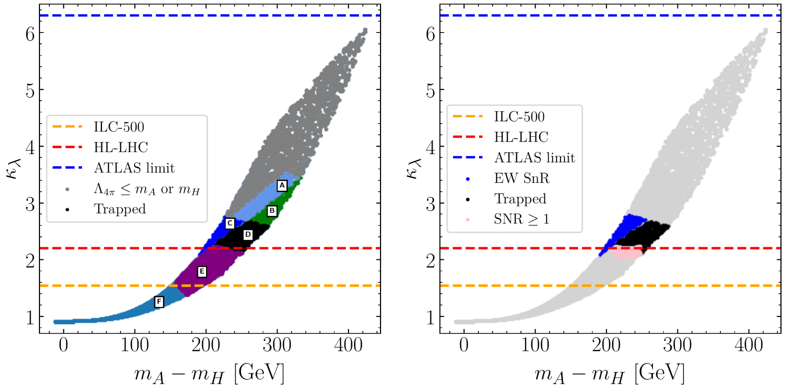




- Change of the non-resonance contribution via loop effects on λ_{hhh}

- BSM corrections to the "BSM trilinear" λ_{hhH} flip the interference pattern

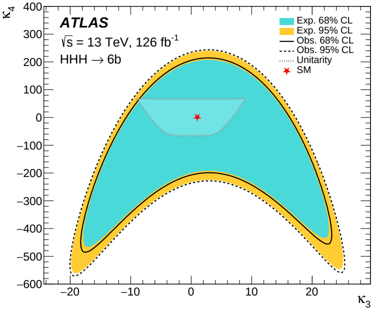
FOEWPT, and GW signal at LISA



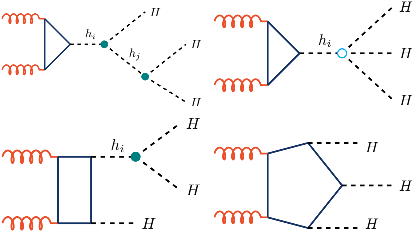
[Biekötter at al., 2208.14466]

Triple Higgs production

Probing the quartic coupling at the LHC

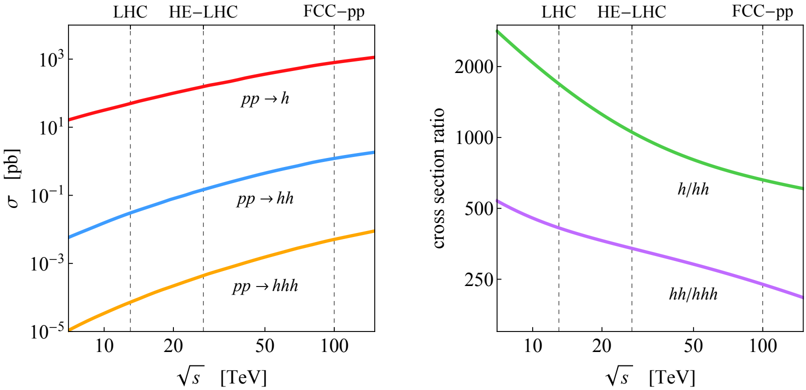


- Very recent first results from ATLAS [ATLAS, 2411.02040]



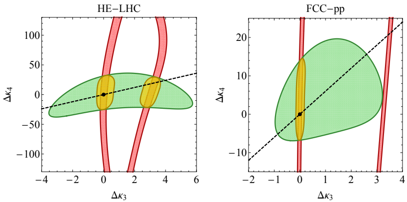
- Very small cross sections → SM hopeless
- Several theory studies have been published
- A working group has been created → a lot of activity

Probing the quartic coupling at FCC-hh

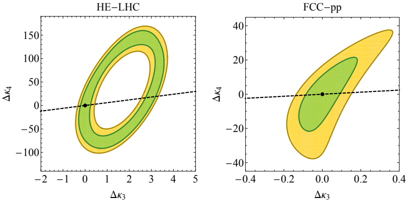


[Bizoń et al, 1810.04665]

Probing the quartic coupling at FCC-hh



Inclusive measurements



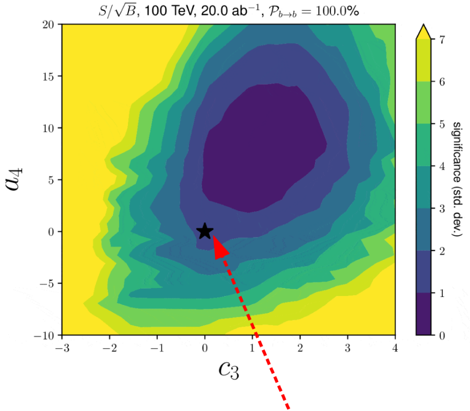
Shape analysis

- Shape analysis solve degeneracy in the couplings

Probing the quartic coupling at FCC-hh

- 6 b-jets, optimized cuts and observable

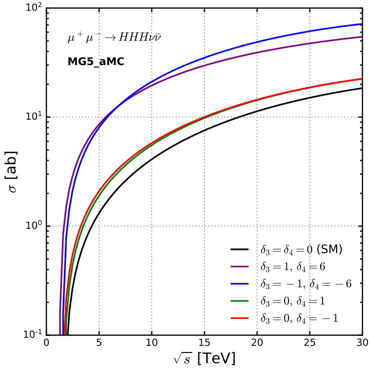
$$V = \frac{1}{2} m_h^2 H^2 + \lambda_{SM}(1 + c_3) v_0 h^3 + \lambda_{SM} \frac{(1 + d_4)}{4} H^4$$

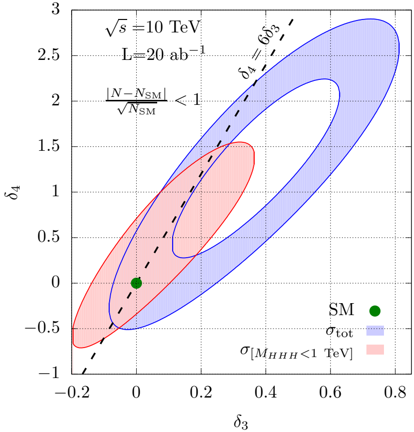


Update of Papaefstathiou, GTX, Zaro: 1909.09166

SM Significance ~ 2.33 σ (New)

Probing the quartic coupling at the muon collider



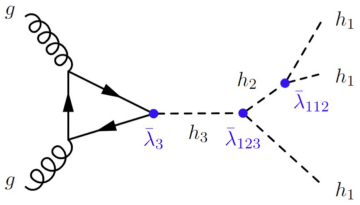


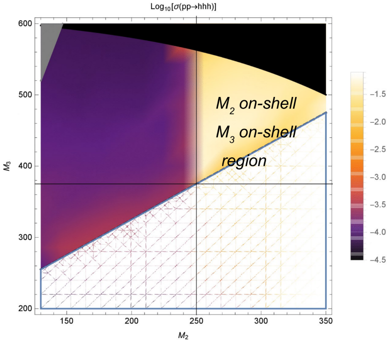
- Preliminary study show very intersting possibilities at a muon collider

BSM perspective: two real singlet Higgs models

- Add two real singlet fields

$$V(\Phi, S, X) = V_{SM}(\Phi) + V(\Phi, S, X)$$
$$V(\Phi, S, X) = \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\phi S} \Phi^\dagger \Phi X^2 + \lambda_{XS} S^2 X^2$$





[G. Tetlalmatzi-Xolocotzi, "Extended scalar sector workshop '24"]

Backup slides

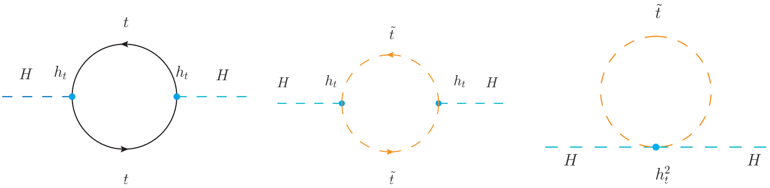
Unnatural scenarios

There is also the possibility of foregoing completely the fine tuning issue by pushing the scalar states to very large masses. Two different philosophies:

- high-scale SUSY: we push all the SUSY states well above the electroweak scale
- split-SUSY: we push only the scalar sfermions to the high scale, and we keep the electroweakinos at the EW scale

In both cases the variations where the heavy doublet is kept (or not) at the EW scale are usually considered. Other variations are possible.

Higher order corrections to the Higgs mass



Considering radiative corrections to the self-energies then all MSSM particles contributes.

- $\hat{\Sigma}_{ij}(q^2) = \hat{\Sigma}^1_{ij}(q^2) + \hat{\Sigma}^2_{ij}(q^2) + \ldots$

Only stop-top sector for simplicity

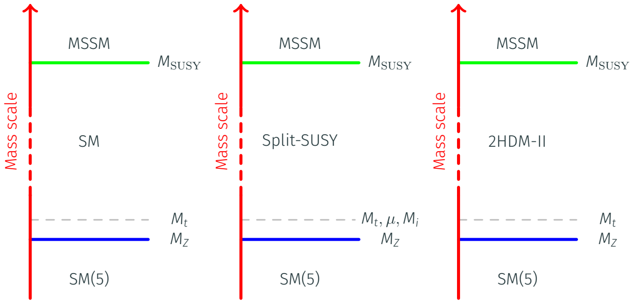
1. At one loop: $\Delta(M_h^{(1)})^2 = m_t^4[L + C^{(1)}]$ with $L = \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$
2. At two loop: $\Delta(M_h^{(2)})^2 = m_t^2\left[m_t^2\alpha_s\left(L^2 + L + C^{(2)}\right) + m_t^4\left(L^2 + L + D^{(2)}\right)\right]$

$\Rightarrow$ the logarithmic terms are now large and problematic at fixed order!

A tower of effective theories

The Higgs mass and the MSSM

- **Motivation**: no evidence of SUSY states at the LHC, what if SUSY is heavy? Use the Higgs mass an handle to probe the spectrum
- **Problem**: mass gap in the physical spectrum makes large logs of the ratio $Q_{\mathrm{EW}}/M_{\mathrm{SUSY}}$ appears in the perturbative expressions
- **Solution**: For a proper computation these logs have to be resummed
- **Method**: tower of matched effective field theories; Use RGE to resum the large logarithms



Depending on the spectrum we have to consider different hierarchies

Matching conditions

At the scale at which we merge the two theories, we have to impose the matching conditions for the couplings of the two theories.

Two ways to do that

- via Feynman diagrammatic calculations of green functions in one and the other theory
- via functional methods (covariant derivate expansion – manly used for dimension-6 operator and SMEFT). In our case we have:

High scale SUSY

$$\tan\beta^{\overline{\text{DR}}}(M_S), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{DR}}}(M_S), \mu^{\overline{\text{DR}}}(M_S), M_i^{\overline{\text{DR}}}(M_S), (m^2_{\tilde{f}})_{ij}^{\overline{\text{DR}}}(M_S)$$

$$\lambda(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right)\cos^2 2\beta + \Delta\lambda^{HSS,1L} + \Delta\lambda^{HSS,2L}$$

Matching conditions

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- via Feynman diagrammatic calculations of green functions in one and the other theory
- via functional methods (covariant derivate expansion – manly used for dimension-6 operator and SMEFT). In our case we have:

split-SUSY

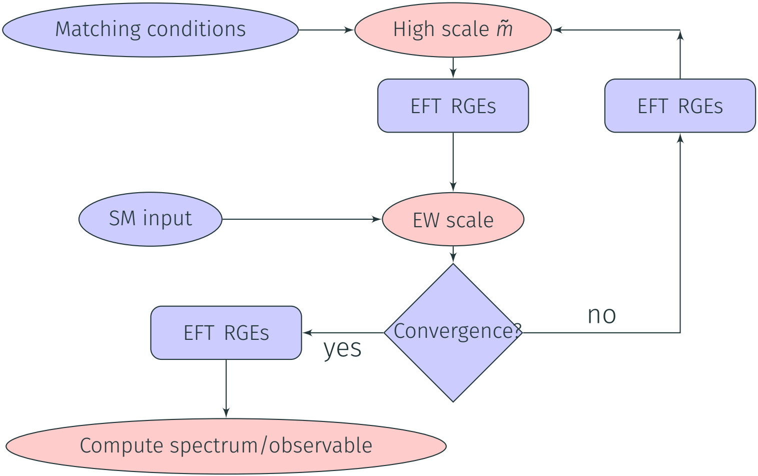
$$\tan\beta^{\overline{\rm DR}}(M_S), A_t^{\overline{\rm DR}}(M_S), m_A^{\overline{\rm DR}}(M_S), (m^2_{\tilde f})_{ij}^{\overline{\rm DR}}(M_S), \mu^{\overline{\rm MS}}(M_Z), M_i^{\overline{\rm MS}}(M_Z)$$

$$\tilde\lambda(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right)\cos^2 2\beta + \Delta\tilde\lambda^{1L} + \Delta\tilde\lambda^{2L}$$

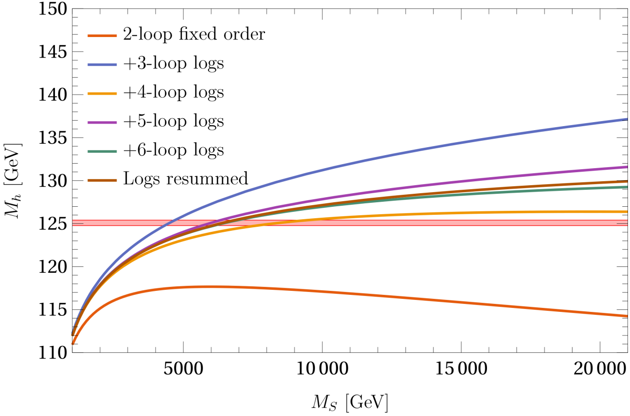
$$\tilde g_{1u}(M_S) = \sqrt{\frac{3}{5}}g_1\sin\beta + \Delta\tilde g_{1u}^{1L}\ , \quad \tilde g_{1d}(M_S) = \sqrt{\frac{3}{5}}g_1\cos\beta + \Delta\tilde g_{1d}^{1L}$$

$$\tilde g_{2u}(M_S) = g_2\sin\beta + \Delta\tilde g_{2u}^{1L}\ , \quad \tilde g_{2d}(M_S) = g_2\cos\beta + \Delta\tilde g_{2d}^{1L}$$

Algorithm implementation



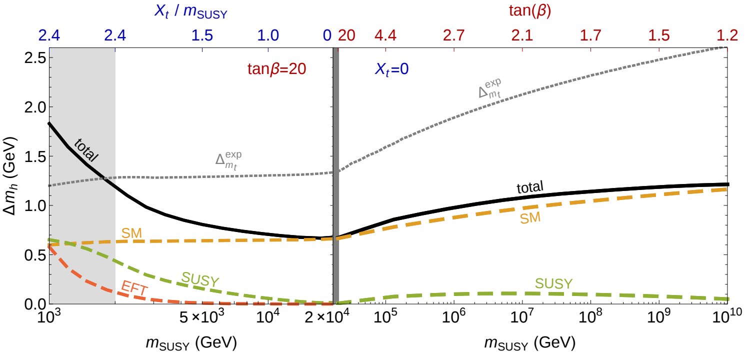
Impact of the large logarithm



[Bahl '17]

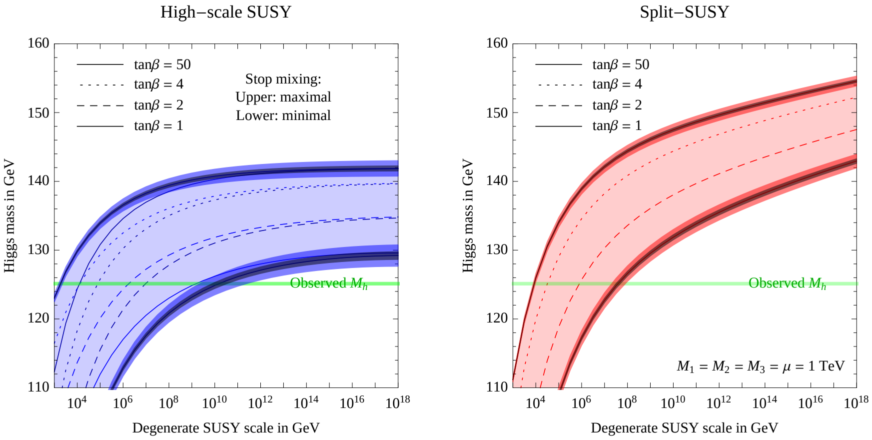
Theory calculation? $\rightarrow$ uncertainties!

- **Low-energy EFT (SM)**: uncertainties in the low-energy EFT such as perturbative uncertianties in the RGE, in the matching relation between the running couplings and the physical inputs, in the relation between M_h and the quartic.
- **EFT uncertainty**: in this matching calculations we are forgetting about terms of order v^2/M_S^2
- **SUSY uncertainty**: perturbative uncertanties in the matching condition

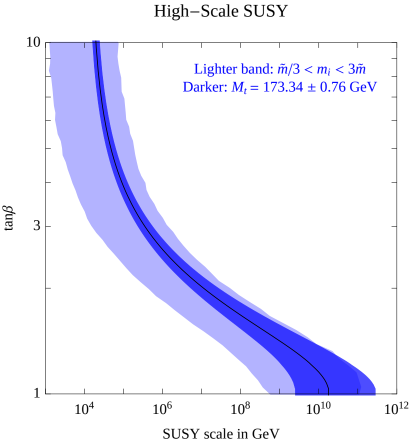


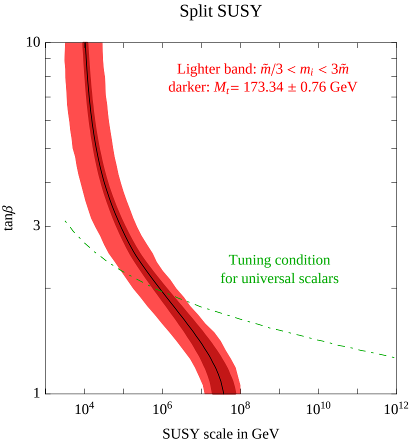
[Pardo Vega & Villadoro '15]

Upper bound on M_h (unnatural scenarios)



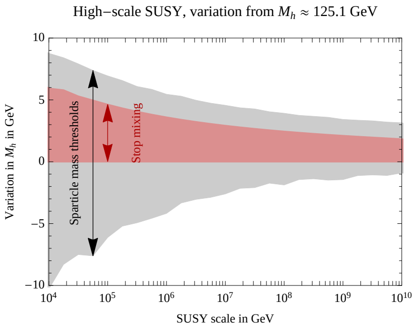
Upper bound on the SUSY mass scale





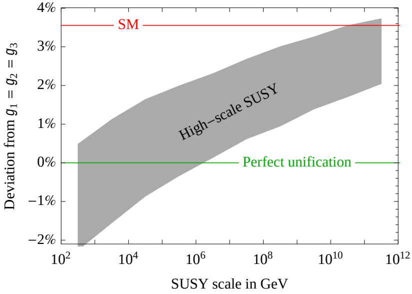
On the degeneracy condition

- The darker (red) region denotes the effect of varying only A_t (respecting vacuum stability)
- Larger (gray) band obtained by random sampling each SUSY particle mass parameter by a factor 3 (1/3)



Unification in High-scale SUSY

- Use on the full one loop threshold corrections to the MSSM couplings $\hat{g}_1, \hat{g}_2, \hat{g}_3, \hat{g}_t$.
- Two-loop MSSM RGEs.
- The gray band is obtained by scanning the SUSY mass parameters by up of a factor 3 (1/3) above (below) $\tilde{m}$.
- $\tan\beta$ in the scan is tuned to reproduce the observed Higgs mass.
- A_t in the range allowed by vacuum stability.



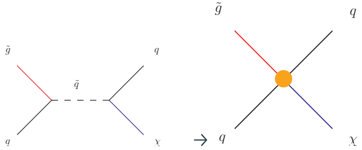
Collider signatures: gluino decay

- Gluino lifetime (decay length) from the determination of $\tilde{m}$ due to the Higgs mass prediction.

$$c\tau_{\tilde{g}} = \left(\frac{2\text{TeV}}{M_{\tilde{g}}}\right)^2 \left(\frac{\tilde{m}}{10^7\text{GeV}}\right)^4 0.4 \text{ m}$$

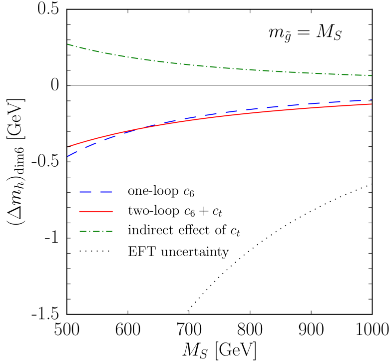
- **tan** $\beta \approx 1 \rightarrow c\tau_{\tilde{g}} \gtrsim 10\text{m}$ (out of detector decay).
- $1 <$ **tan** $\beta < 2 \rightarrow c\tau_{\tilde{g}} \gtrsim 50\mu\text{m}$ (displaced vertex).
- **tan** $\beta > 2 \rightarrow$ prompt decay.

- Need EFT computation to resum large logs. [hep-ph/0506214]



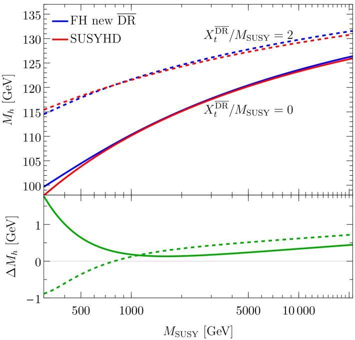
Matched predictions

- For the lowish M_S region, one would like to recover (part of the) v^2/M_S^2 terms, or match with the FO calculation.



EFT matched to SM + (two) dim-6 operators

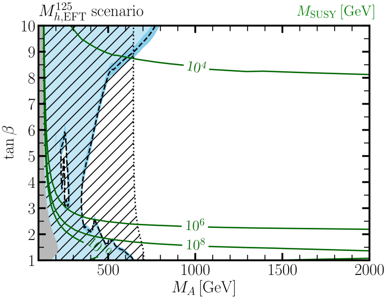
[EB et al., '17]

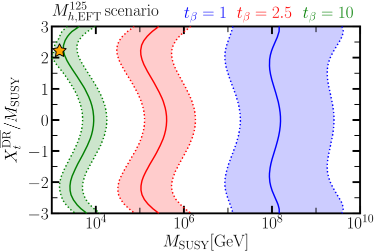


Matched FO+EFT calculation

[FH; Plot from Bahl '17]

2HDM-matched scenario with heavy SUSY

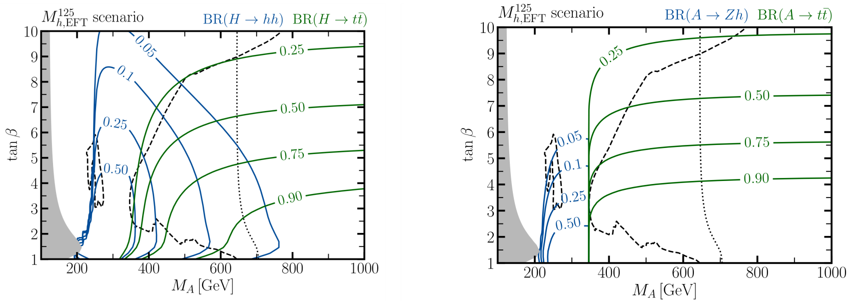




- Extension at low $\tan\beta$ of M_h^{125} by varying M_S

[Bahl et al., '19]

2HDM-matched scenario with heavy SUSY



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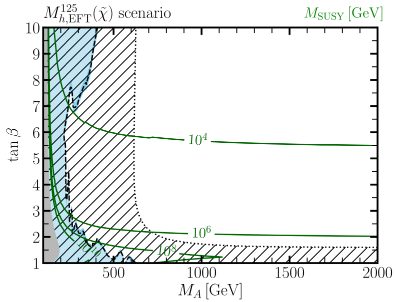
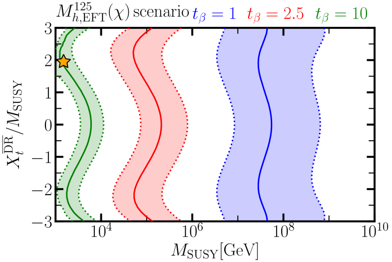
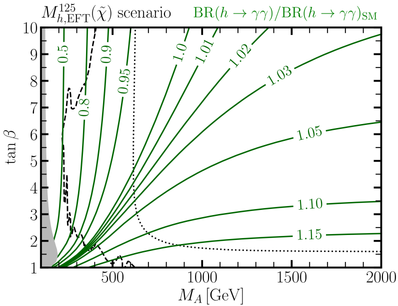


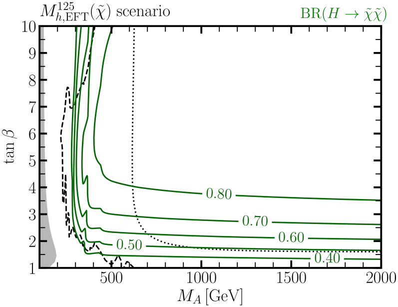


- Extension at low $\tan\beta$ of $M_h^{125}(\tilde{\chi})$ by varying M_S

[Bahl et al., '19]

2HDM-matched scenario with heavy SUSY

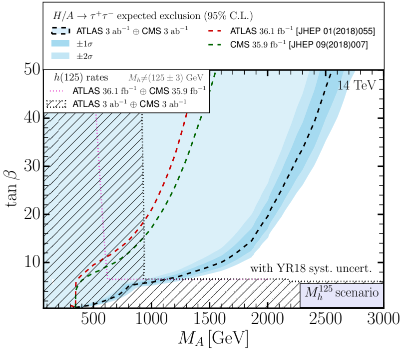


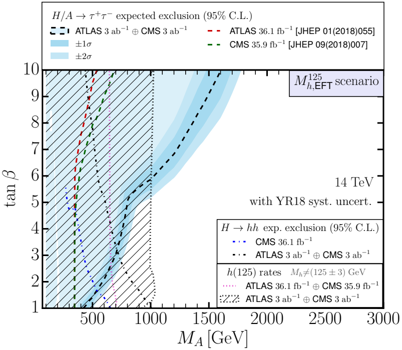


- Extension at low $\tan\beta$ of $M_h^{125}(\tilde{\chi})$ by varying M_S

[Bahl et al., '19]

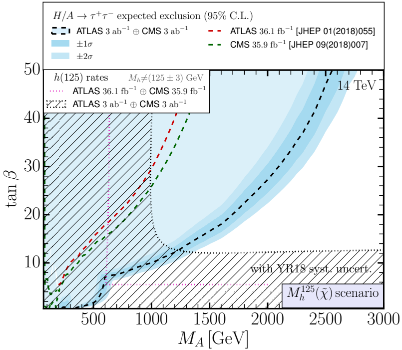
MSSM scenarios: reach at HL-LHC

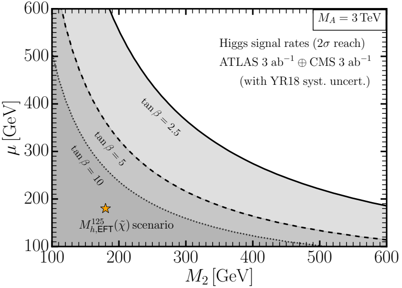




[Bahl et al. '20]

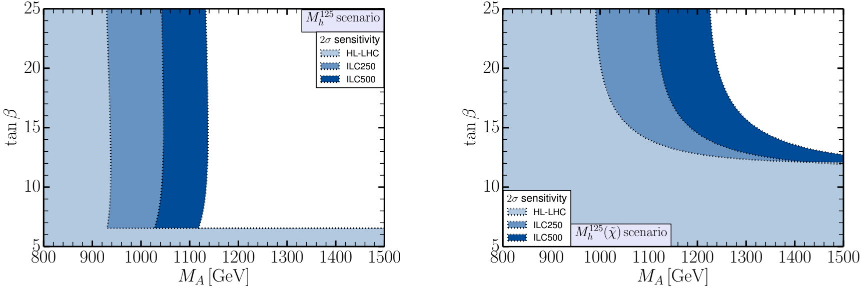
MSSM scenarios: reach at HL-LHC





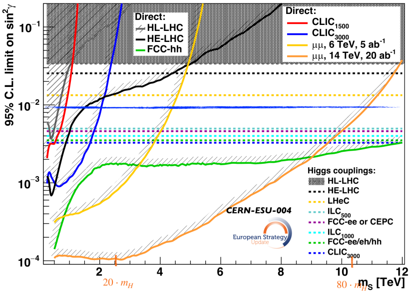
[Bahl et al. '20]

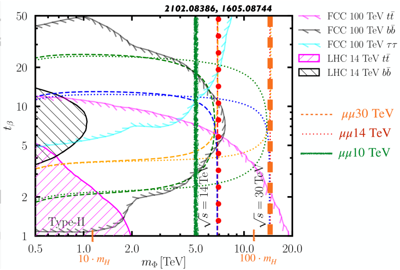
MSSM scenarios: constraints from H_{125}



[Bahl et al. '20]

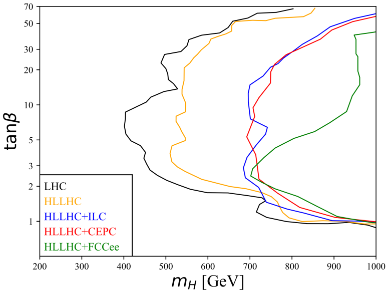
Overview of reach for singlet and doublets

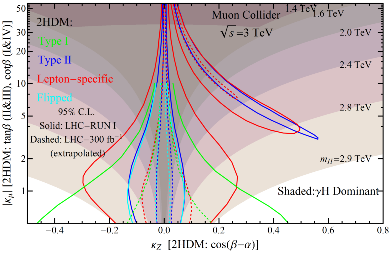




[R. Franceschini at Higgs '22]

More on 2HDMs





[2209.08078]