Characterizing the Higgs potential at the LHC and future colliders

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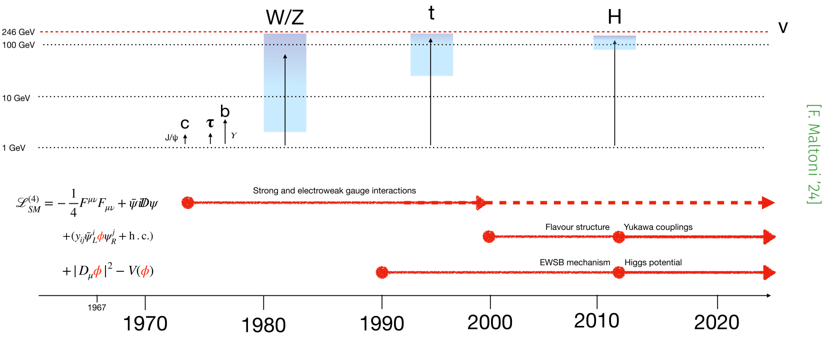
Outline

Overview of the the Higgs at the LHC and future colliders

Elementary particle physics in the past 50 years



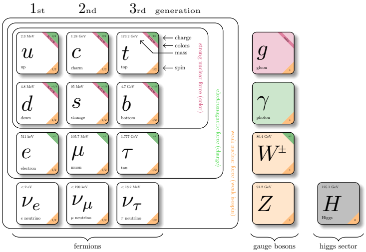
Exploring the Standard Model

- 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

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



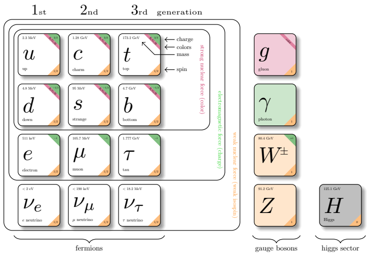
Key aspects

- 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

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

The Standard Model of particle physics



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

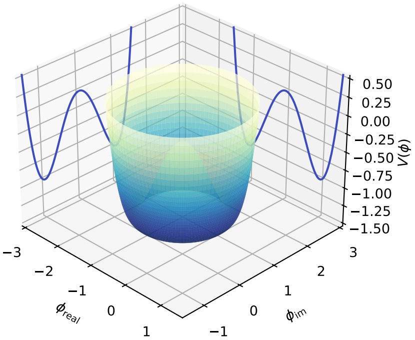
While we wait for a machine able to reach higher-energies, or an input from other sectors, where should we expect deviation from the SM $\rightarrow$ in the Higgs sector

The Higgs sector

After electroweak symmetry breaking ...

$$\mathcal{L}_{\text{Yukawa,Higgs}} = \left(y_{ij}\bar{\psi}_L^i H \psi_R^j + h.c. \right) + |D_\mu H|^2 - V(H)$$

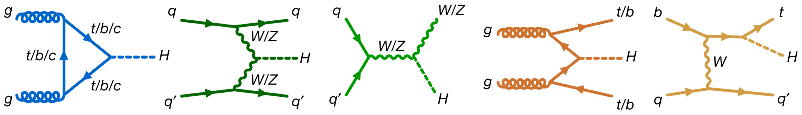
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

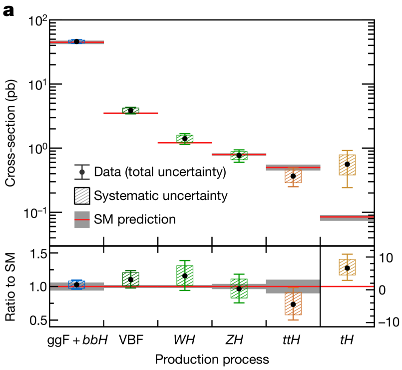


Higgs characterization

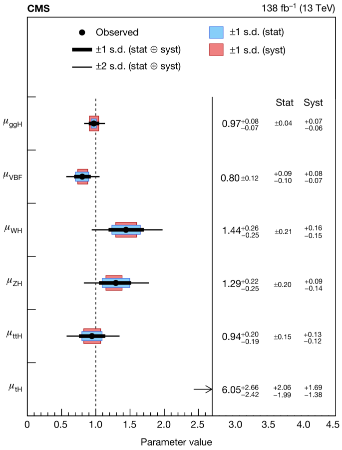
- Characterizing the Higgs means the determination of its couplings via the measurements of production processes/decay channels
- Higgs couplings to gauge bosons (EWSB)
- Higgs couplings to fermions
- Higgs self couplings (the potential)

Where we are with the Higgs: production processes





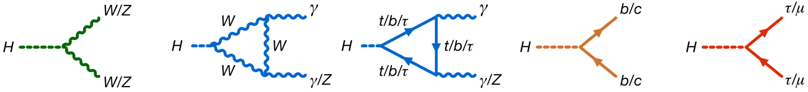
[ATLAS, Nature '22]

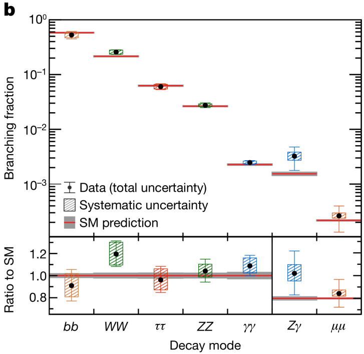


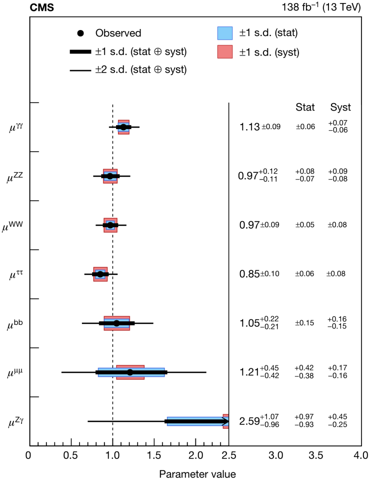
		Stat	Syst
μ_{ggH}	$0.97^{+0.08}_{-0.07}$	± 0.04	$^{+0.07}_{-0.06}$
μ_{VBF}	0.80 ± 0.12	$^{+0.09}_{-0.10}$	$^{+0.08}_{-0.07}$
μ_{WH}	$1.44^{+0.26}_{-0.25}$	± 0.21	$^{+0.16}_{-0.15}$
μ_{ZH}	$1.29^{+0.22}_{-0.25}$	± 0.20	$^{+0.09}_{-0.14}$
μ_{ttH}	$0.94^{+0.20}_{-0.19}$	± 0.15	$^{+0.13}_{-0.12}$
μ_{tH}	$6.05^{+2.66}_{-2.42}$	$^{+2.06}_{-1.99}$	$^{+1.69}_{-1.38}$

[CMS, Nature '22]

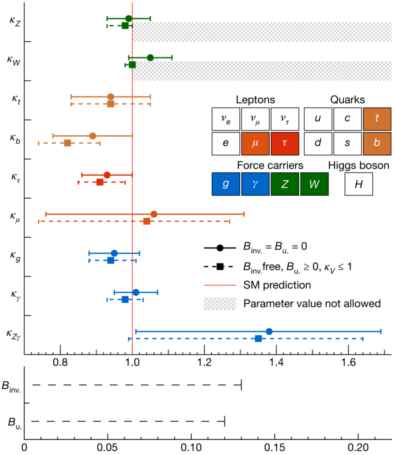
Where we are with the Higgs: decay channels

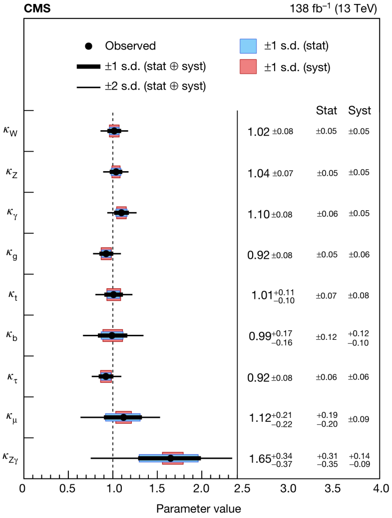






Where we are with the Higgs: couplings





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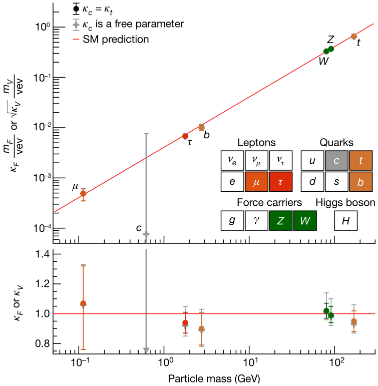
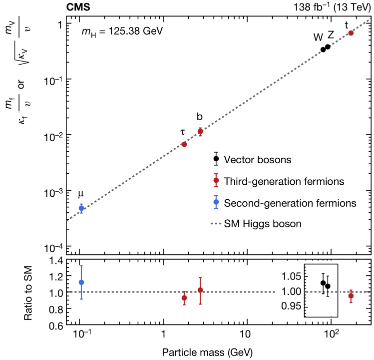
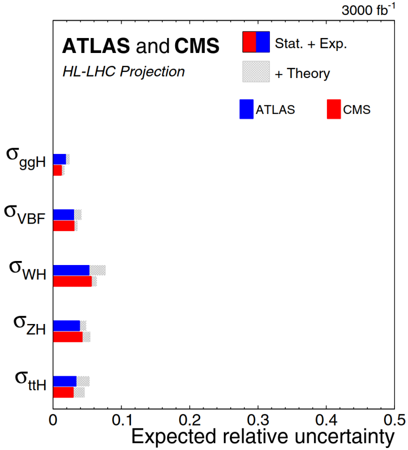
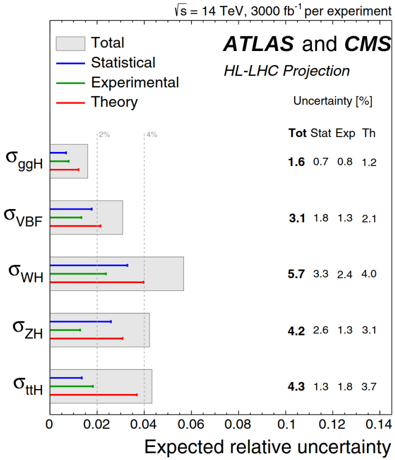


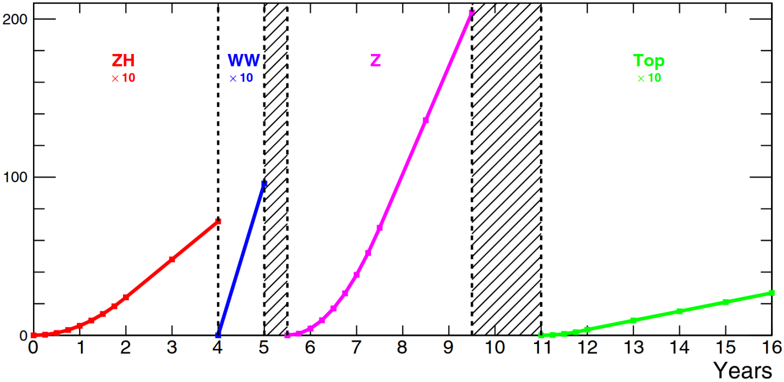


HL-LHC


3000 fb^{-1}
ATLAS and CMS
HL-LHC Projection
Stat. + Exp.
+ Theory
ATLAS
CMS
σ_{ggH}
σ_{VBF}
σ_{WH}
σ_{ZH}
σ_{ttH}
0
0.1
0.2
0.3
0.4
0.5
Expected relative uncertainty


$\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment
Total
Statistical
Experimental
Theory
ATLAS and CMS
HL-LHC Projection
Uncertainty [%]
2%
4%
Tot Stat Exp Th
σ_{ggH} 1.6 0.7 0.8 1.2
σ_{VBF} 3.1 1.8 1.3 2.1
σ_{WH} 5.7 3.3 2.4 4.0
σ_{ZH} 4.2 2.6 1.3 3.1
σ_{ttH} 4.3 1.3 1.8 3.7
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Expected relative uncertainty

Future colliders, FCC-ee



FCC-ee

- Run plan for FCC-ee
- Dedicated run for ZH; recoil mass method, absolute measurement of g_{HZZ} and Γ_H

Future colliders

Table 131 Expected 68%CL relative precision (%) of the κ parameters at HL-LHC and FCC-ee (combined with HL-LHC). The corresponding 95%CL upper limits on the untagged, BR_{unt}, and invisible, BR_{inv}, branching ratios are also given. As denoted with an asterisk (*), for the HL-LHC numbers, a bound on $|\kappa_V| \leq 1$ is applied since no direct access to the Higgs width is possible at hadron colliders. This restriction is lifted in the combination with FCC-ee (or other lepton colliders), since the latter ones provide the necessary access to the Higgs width. Cases in which a particular parameter has been fixed to the SM value due to lack of sensitivity are shown with a dash (–). Results from Ref. [451], updated with the 4-IPs scenario.

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88

- Sub-percent precision for many couplings
- Access light Yukawa couplings
- Will shed light on the BSM nature of these couplings

Sum up

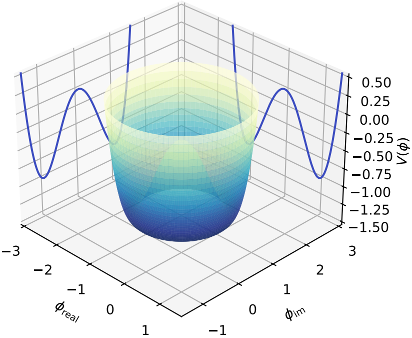
Overview of the Higgs

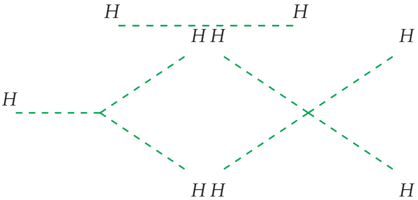
- The Higgs as characterized by the LHC is so far SM-like
- HL-LHC and a future Higgs factory, as envisaged by the European Strategy Process, will probe the compatibility of the couplings to fermions and vector boson up to a new level
- Is that all? No, we should also probe the Higgs self-interactions, i.e. the scalar potential

The Higgs potential

The Higgs potential

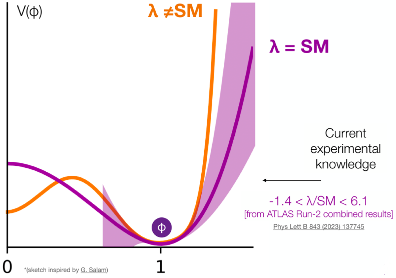
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$





$$m_H^2 = 2\lambda v^2 \quad (1)$$

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

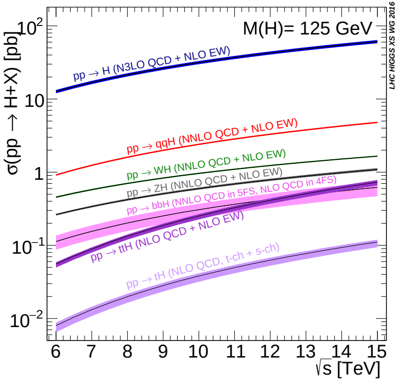
$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)\right]$$

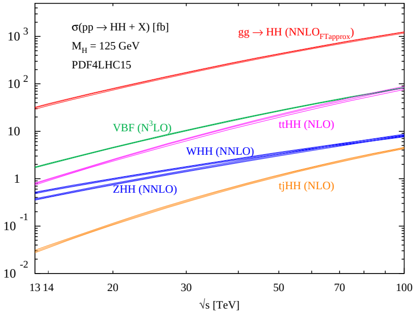
This reaches $(\frac{4\pi v}{m_h})^2 \approx 600$ for $M \gtrsim 4\pi v \approx 3$ TeV

$\rightarrow$ The deviation in the self-coupling can be much larger than in the other couplings

Double Higgs production

Single vs double Higgs cross sections





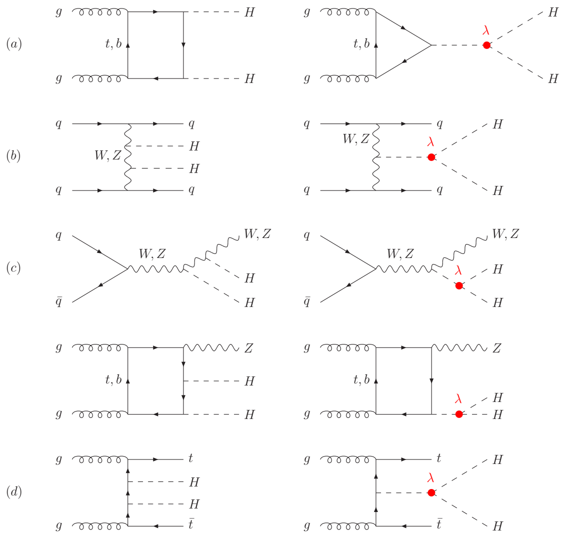
Single vs double higgs gluon fusion

- 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

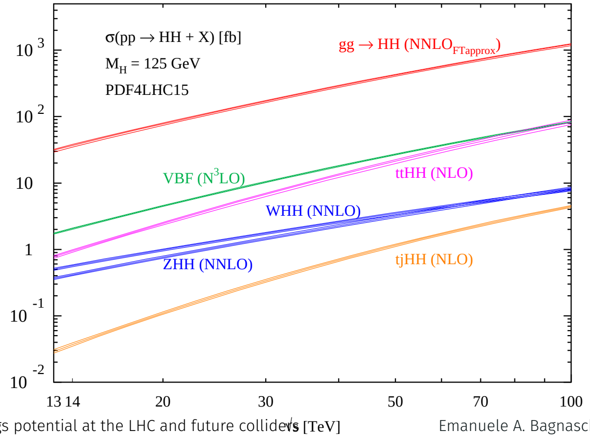
- (a) Gluon fusion
- (b) Vector Boson Fusion (VBF)
- (c) Double-Higgs strahlung
- (d) Quark associated production



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

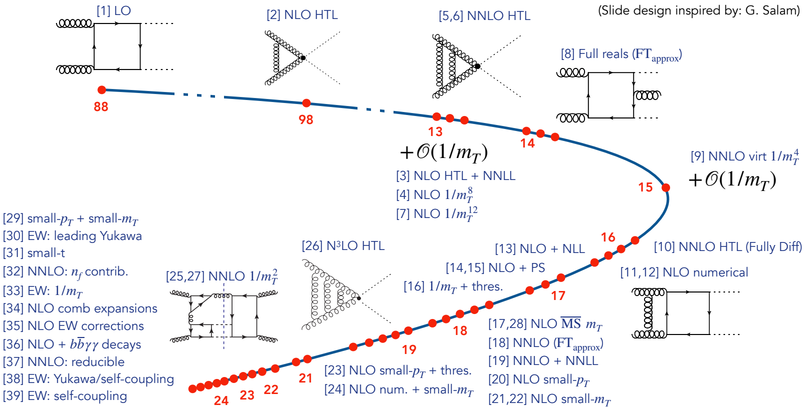
Production channels

- 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]

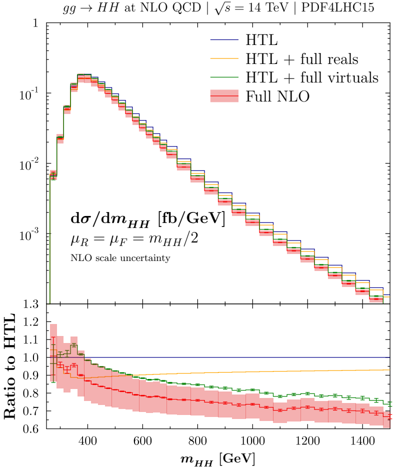
Theoretical status of $gg \to HH$ calculations



[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

The 2-loop amplitudes: transverse momentum expansions

p_T^H expansion

- The $gg \to HH$ amplitude can be written as

$$A^{\mu\nu} = \frac{G_\mu}{\sqrt{2}} \frac{\alpha_S(\mu_R)}{2\pi} \delta_{ab} \, T_F \, \hat{s} \left[A_1^{\mu\nu} \, F_1 + A_2^{\mu\nu} \, F_2 \right]$$

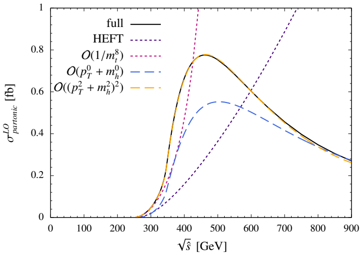
- The transverse momentum can be written in terms of Mandelstam variables

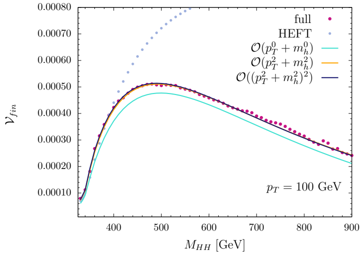
$$(p_T^H)^2 = \frac{\hat{t}\hat{u} - m_h^4}{\hat{s}}$$

- Rewritten as

$$(p_T^H)^2 = \frac{\hat{t}\hat{u} - m_h^4}{\hat{s}}$$

- Expand in $(p_T^H)^2/s' \ll 1$ and $m_h^2/s' \ll 1$ where $s' = \hat{s}/2$
- Very good description up to $\hat{s} < 750$ GeV.

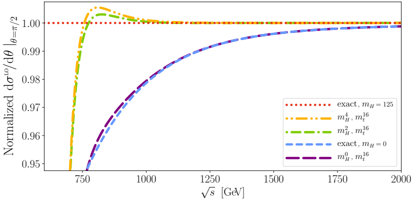




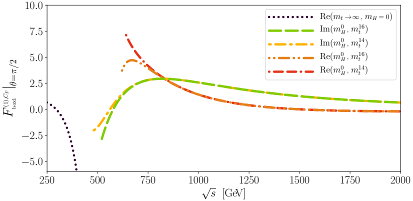
[Bonciani et al., PRL121 (2018), 16200]

The 2-loop amplitudes: high-energy expansion

- High-energy expansion of the two loop form factors
- Valid down to around 700 GeV
- Complementary range with respect to the p_T^H expansion



Cross-check at LO



[Davies et al., JHEP 03 (2018) 048; Davies et al.,JHEP 01 (2019) 176];

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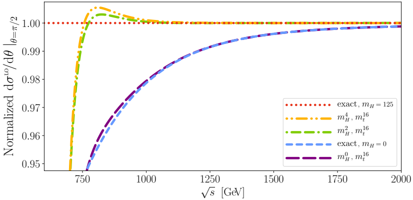

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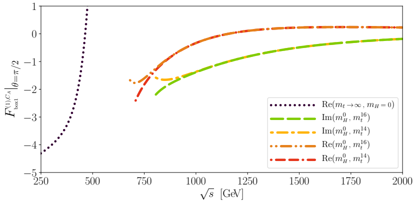


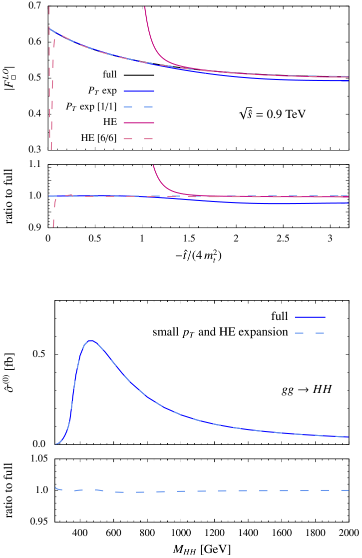
[Davies et al., JHEP 03 (2018) 048; Davies et al.,JHEP 01 (2019) 176];

The 2-loop amplitudes: combining the two expansions

- The two expansions work well in complementary kinematic range
- Build a combined result that therefore reproduces very well the full top mass dependence all across the phase space
- Padé approximant

$$[m/n](x) = \frac{p_0 + p_1 x + \cdots + p_m x^m}{1 + q_1 x + \ldots q_n x^n}$$

- [1/1] for the p_T^H expansion, [6/6] for the HE expansion sufficient to have a good behavior across all the $\sqrt{\hat{s}}$ range



[Bellafronte et al., JHEP 07 (2022) 069]

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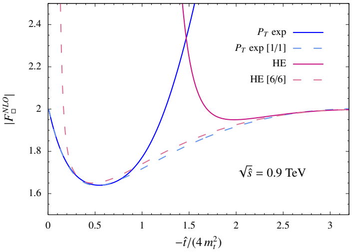
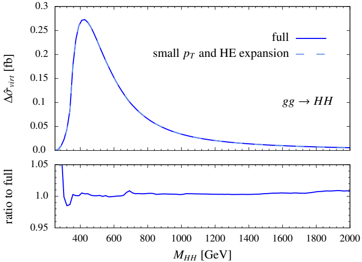


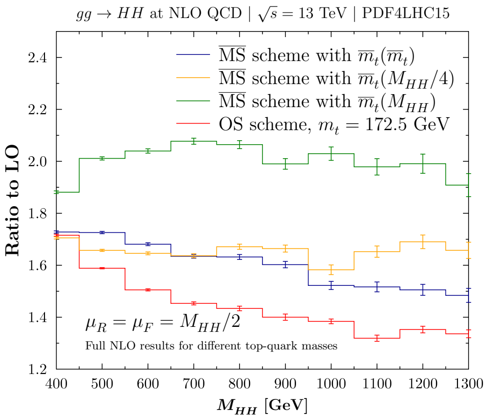


[Bellafronte et al., JHEP 07 (2022) 069]

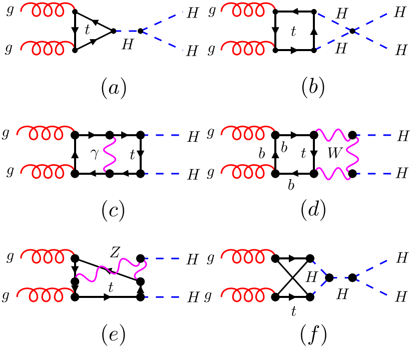
Impact of the choice of the top mass scheme

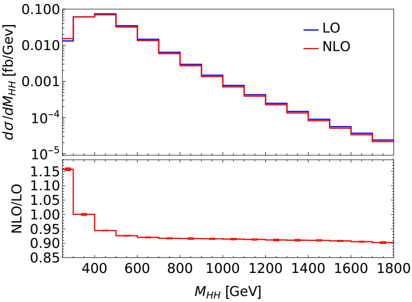
Top scheme uncertainty

- Uncertainty due to the renormalization scheme choice of the top mass
- First shown in [Baglio et al., EPJC79 (2019) 6, 459]
- More in depth studied in [Baglio et al., PRD 103 (2021) 5, 056002]
- Available now in a POWHEG-BOX based MC [Bagnaschi et al., EPJC83 (2023) 11, 1054]



Impact of EW corrections





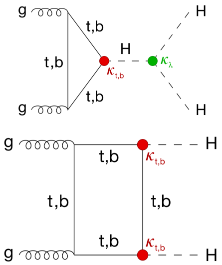
[Bi et al., 2311.16963]

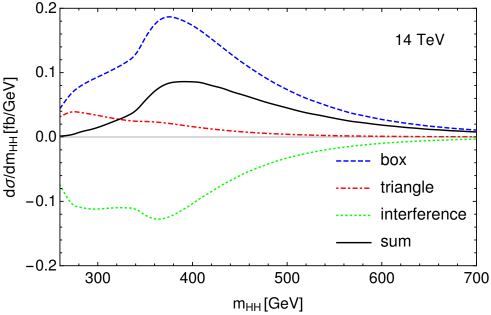
- Impact of about 4% on the total cross section
- Near the HH treshold, +15%; at high-energy −10%
- See also [Mühlleitner at al., 2207.02524] for the Yukawa top induced part

Gluon fusion: interference pattern

Interference pattern

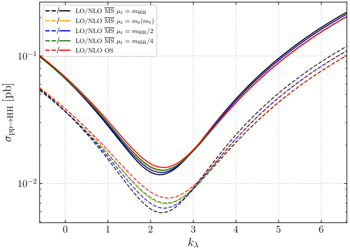
- Non trivial interference pattern between the box and the triangle diagrams
- $\rightarrow$ the cross section strongly depends on the value of the trilinear coupling (minimum for $\lambda/\lambda_{SM} \sim 2.4$)



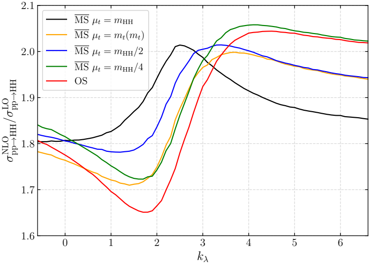


[Di Micco, . . ., EB et al., 1910.00012]

Dependence of total cross section on the value of λ_3



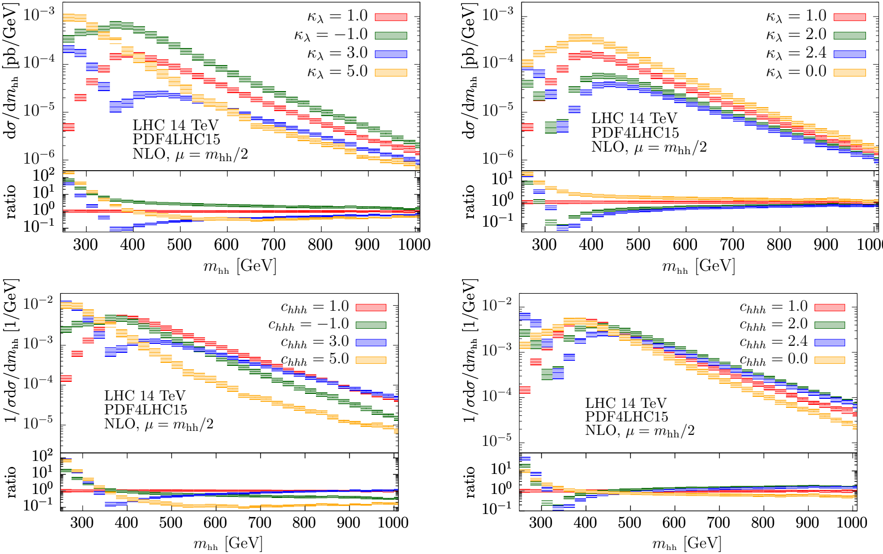
- Total inclusive cross section at LO and NLO for different values of k_λ and different choices of the top mass renormalization scheme



- K-factors for different top mass scheme choices

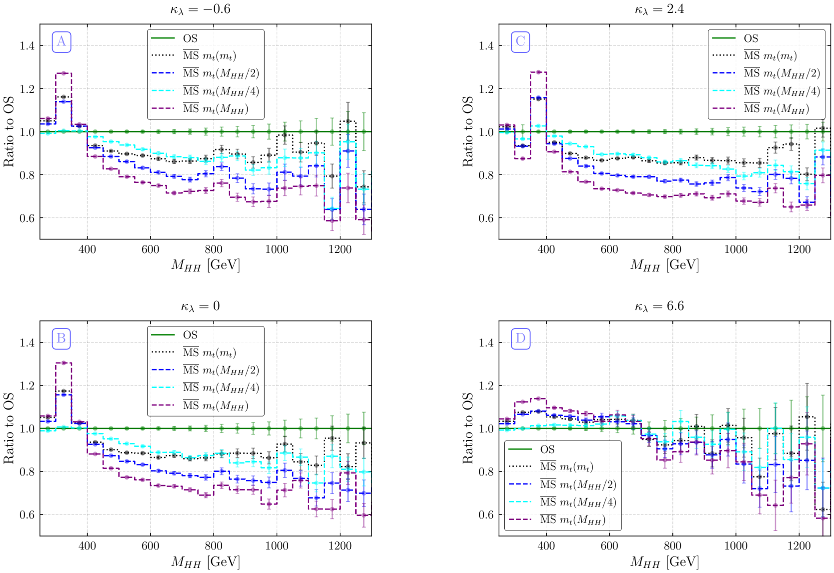
- Minimum of the cross section depends on the top scheme
- As expected, the difference between the schemes is smaller at NLO

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

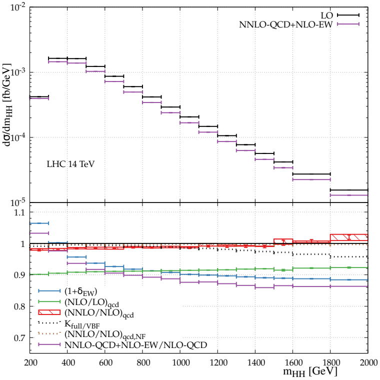


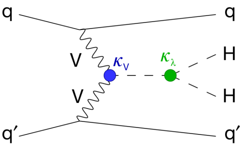
[Heinrich et al., 1903.08137]

Top scheme dependence with a modified trilinear

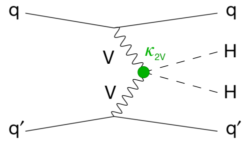


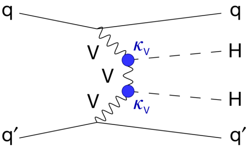
HH in Vector boson fusion





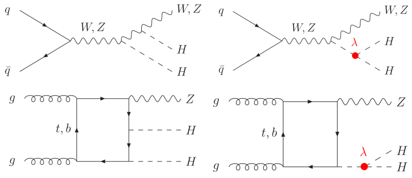
- Allow to probe the $\lambda HHVV$ coupling
- Highest order QCD corrections calculated using structure function approach (i.e. DIS)
- NLO-QCD yields a 10% correction; NNLO+N^{3}LO $\lesssim$ 1%



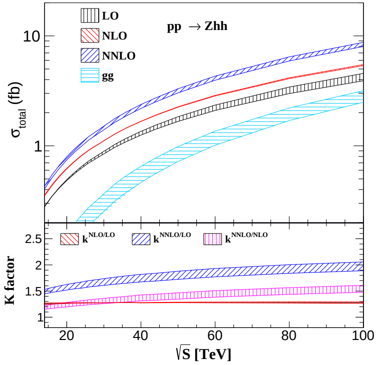


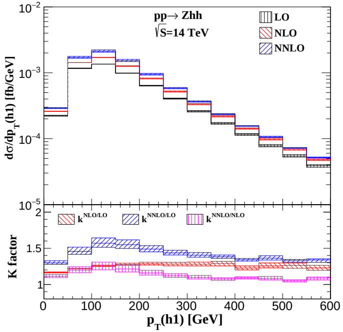
[Dreyer et al., 2005.13341]

Double Higgs-Strahlung



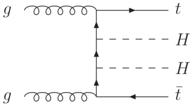
- QCD corrections are DY-like
- NLO+NNLO QCD corrections are around $\sim 30\%$
- At NNLO a new channel appear, $gg \to HHZ \sim 30\%$

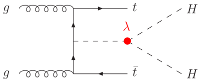




[Li et al., 1710.02464]

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



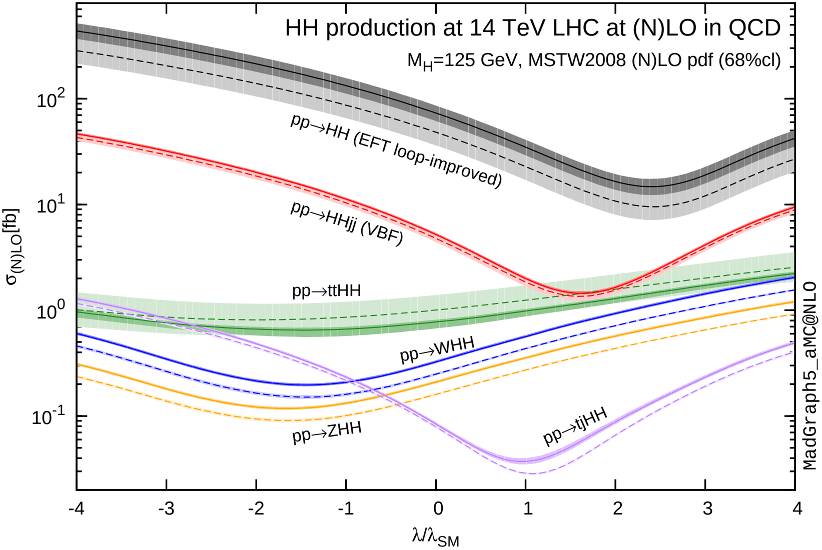


- Computed in using `MG5_aMC@NLO` [Frederix et al., 1401.7340]
- $t\bar{t}$ associated production, QCD corrections -20%
- single top associated production, QCD corrections $+20\%$

	$\sqrt{s} = 8$ 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.

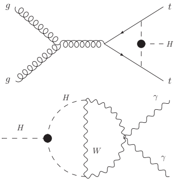
Interference pattern for all the processes

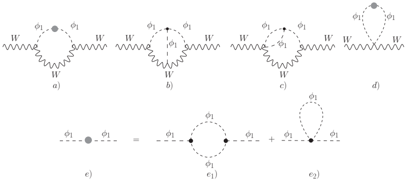


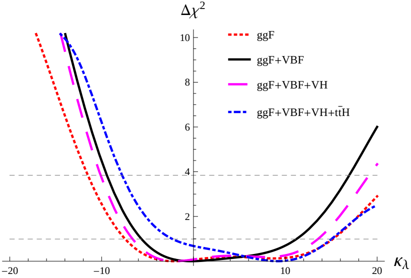
[Frederix et al., 1401.7340]

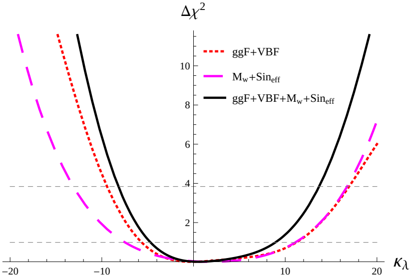
Probing the trilinear coupling indirectly

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%

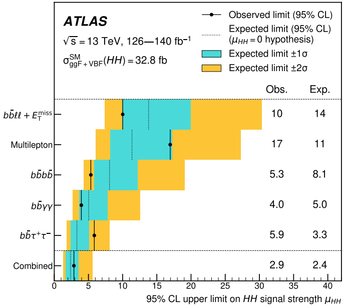
[C. Pandini's talk at "Extended Scalar Sector workshop 2024@CERN"]

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

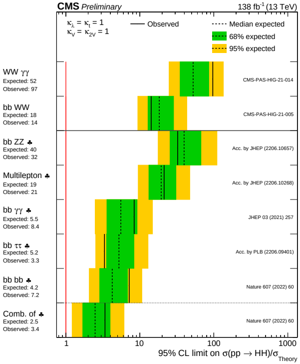
Combinations of HH searches

- 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]

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

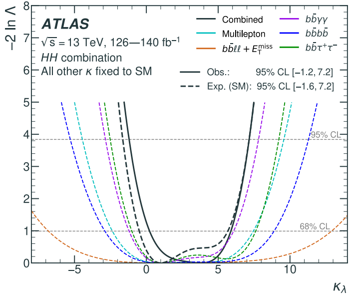


[CMS Summary plot]

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

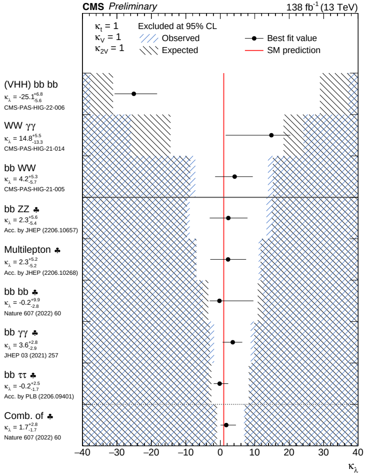
Constraints on the trilinear coupling

- Only from HH measurements



[ATLAS, 2406.09971]

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

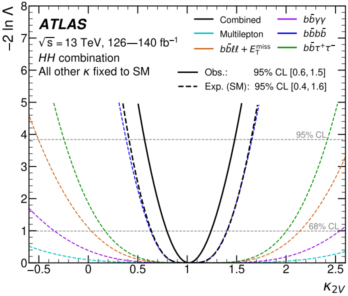


[CMS Summary plot]

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

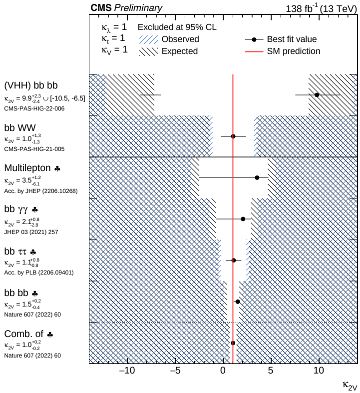
Constraints on the trilinear coupling

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



[ATLAS, 2406.09971]

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

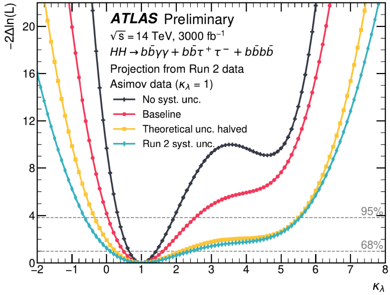


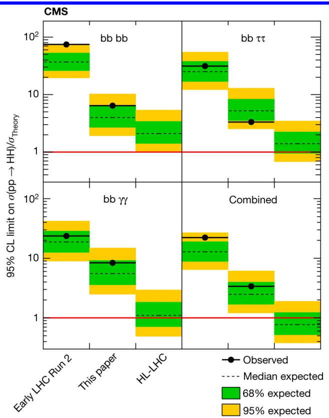
[CMS Summary plot]

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

The outlook for Run-3 and HL-LHC

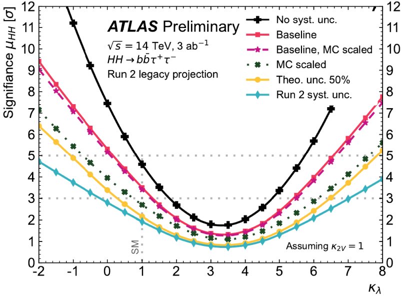
- Double Higgs searches are statistically (sistematics are around 15%-20%limited $\rightarrow$ will fully benefit from the huge dataset of HL-LHC (also complete Run-3)
- Experimental developments: better b-tagging, new triggers etc. $\rightarrow$ the improvement will be better than simply the int. luminosity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



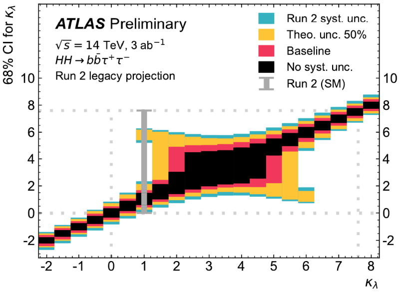


The outlook for Run-3 and HL-LHC

- 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



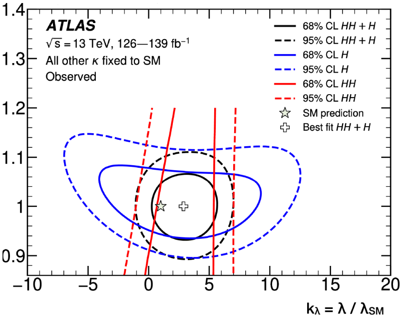
Significance



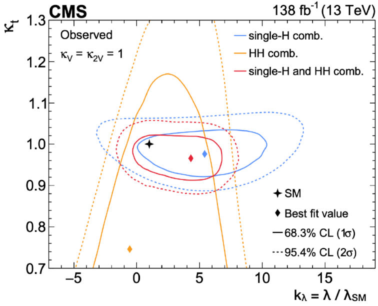
Measurement precision given a value of k_λ

Combined H+HH constraints

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

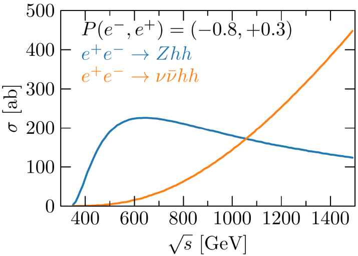


[ATLAS, PLB 843 (2023) 137745]

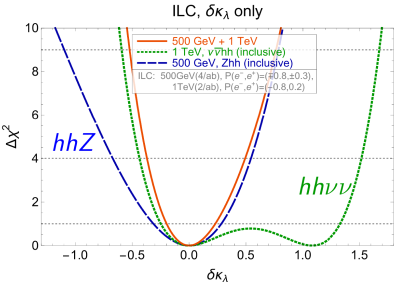


[CMS, 2407.13554]

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

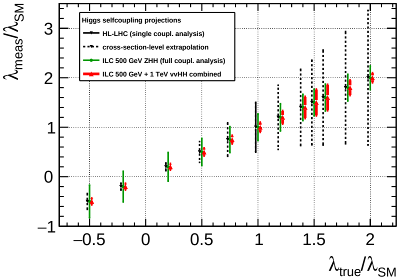


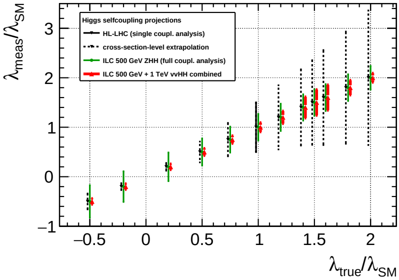
- Associated double Higgs production dominant up to 1*TeV*
- Weak boson fusion larger for higher energies



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

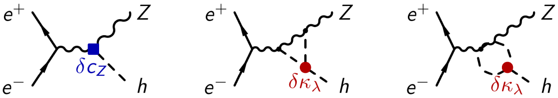
Interference pattern at e^+e^- machines

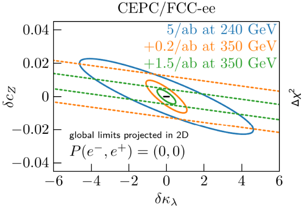




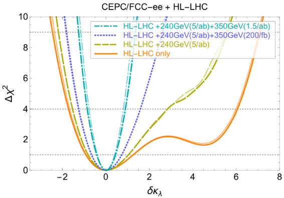
- Complementary interference pattern vs hadron machines
- Back of the envelop estimation

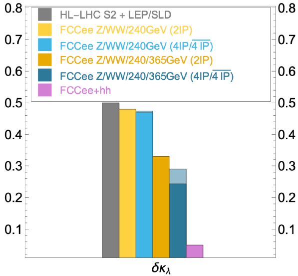
FCC-ee + FCC-hh



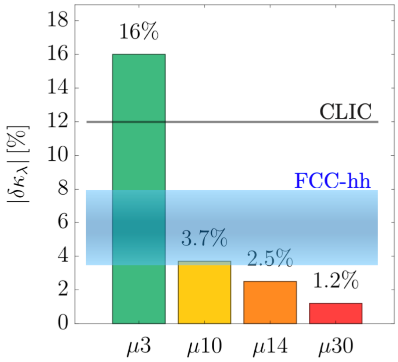


- Below threshold, probe via loop effect
- Two energy measurements necessary to disentangle modification of the trilinear from other couplings

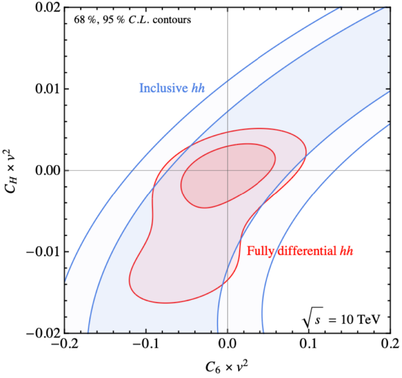




Probing the trilinear coupling at the muon collider

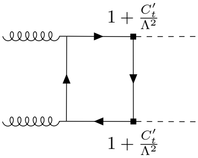


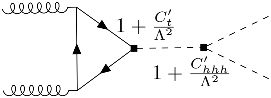
[2203.07256]

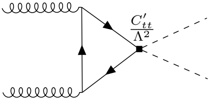


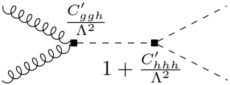
[Buttazzo et al., 2012.11555]

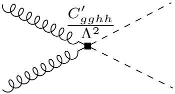
- Assume that NP is heavy in respect to the mass scales probed by the measurements
- Describe NP effects via higher-dimensional operators
- $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^6 + \ldots$







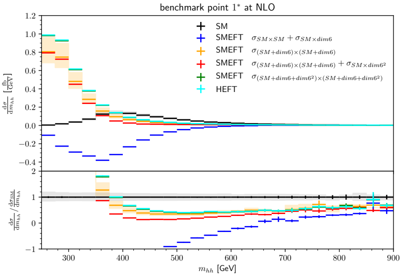


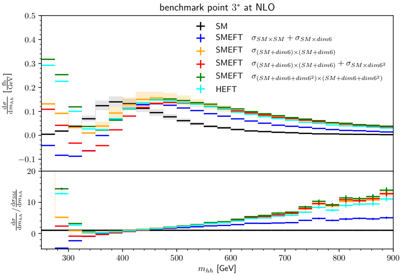


[Heinrich et al., 2204.13045]

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

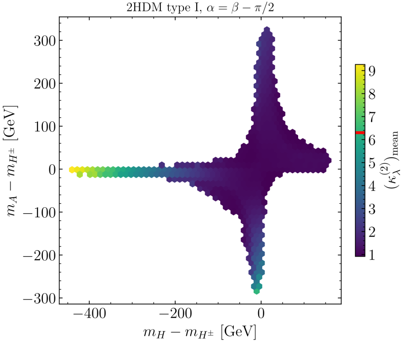
$$\mathcal{L} = -\sum_{f=u,d,l} \frac{m_f}{v} \left[\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H + i \xi_A^f \bar{f} \gamma_5 f A\right]$$
$$+ \sum_{h_i=h,H,A} \left[g M_W \xi_{h_i}^W W_\mu W^\mu h_i + \frac{1}{2} g M_Z \xi_{h_i}^Z Z_\mu Z^\mu h_i\right]$$

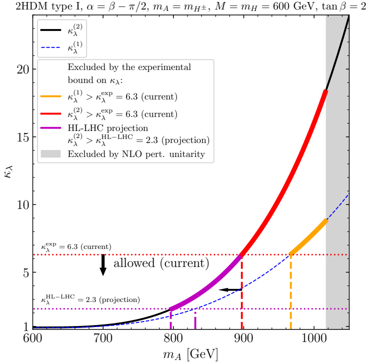
Coupling	type I	type II	type III (Y or flipped)	type IV (X or lepton specific)
ξ_h^u	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$
ξ_h^d	$s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta$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

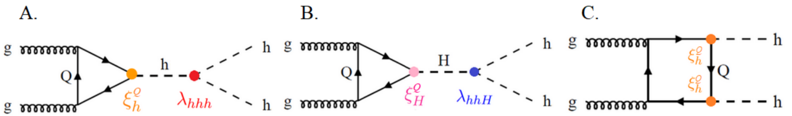
- Parameter space includes regions with very non-SM trilinear coupling
- Higher-order corrections important (diagrams with BSM trilinear couplings)

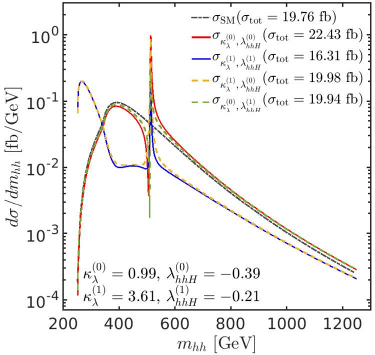


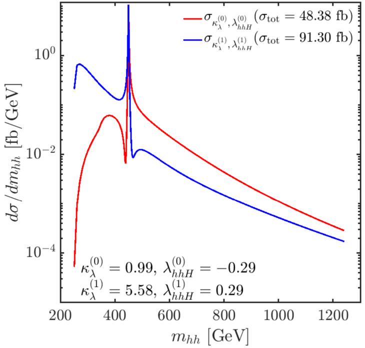


[Bahl et al., 2202.03453]

Interpretation of BSM searches





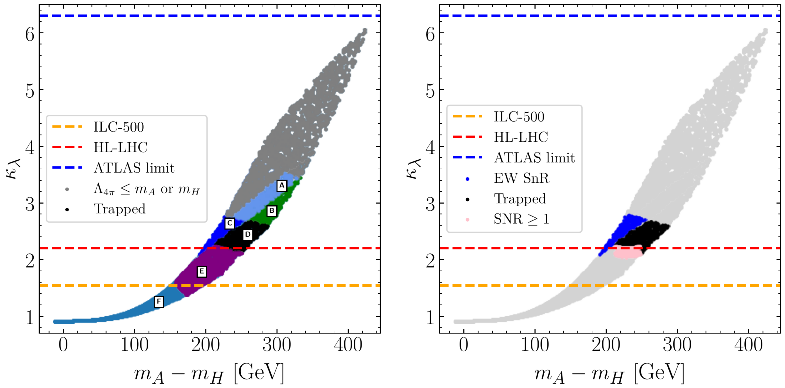


- Change of the non-resonance contribution via loop effects on λ_{hhh}

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

[Heinemeyer et al, 2403.14776]

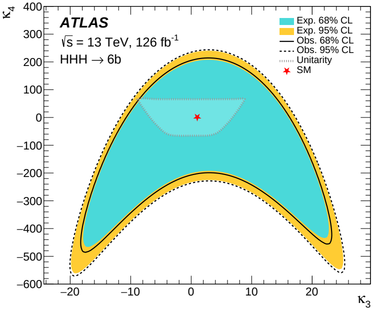
FOEWPT, and GW signal at LISA



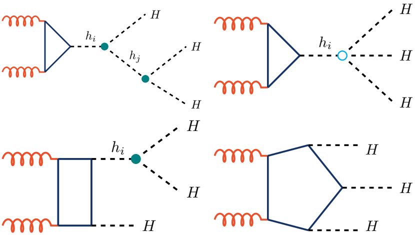
[Biekötter at al., 2208.14466]

Triple Higgs production

Probing the quartic coupling at the LHC

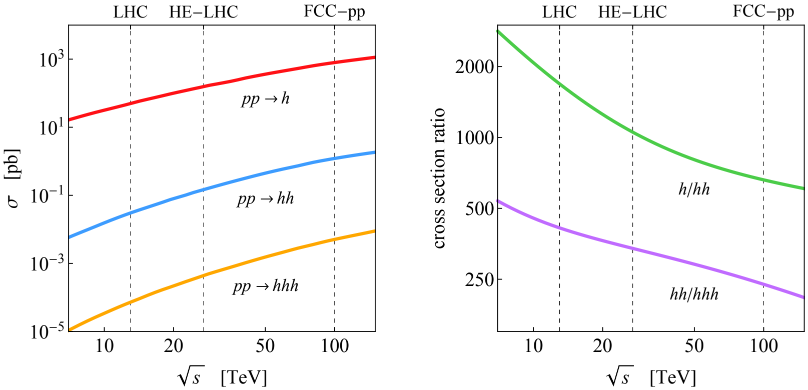


- Very recent first results from ATLAS [ATLAS, 2411.02040]



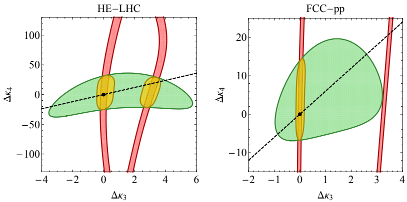
- Very small cross sections → SM hopeless
- Several theory studies have been published
- A working group has been created → a lot of activity

Probing the quartic coupling at FCC-hh

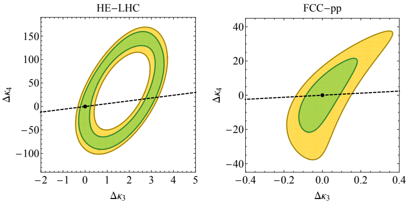


[Bizoń et al, 1810.04665]

Probing the quartic coupling at FCC-hh



Inclusive measurements



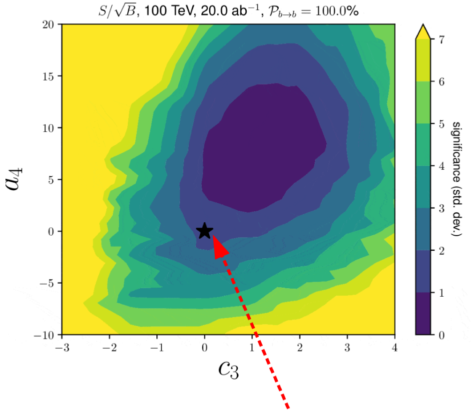
Shape analysis

- Shape analysis solve degeneracy in the couplings

Probing the quartic coupling at FCC-hh

- 6 b-jets, optimized cuts and observable

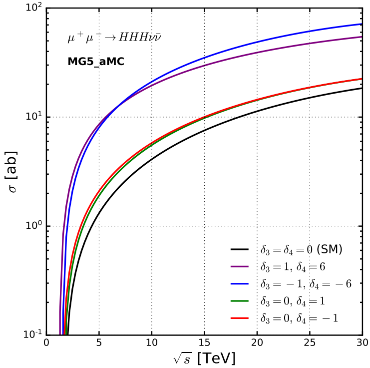
$$V = \frac{1}{2} m_h^2 H^2 + \lambda_{SM}(1 + c_3) v_0 h^3 + \lambda_{SM} \frac{(1 + d_4)}{4} H^4$$

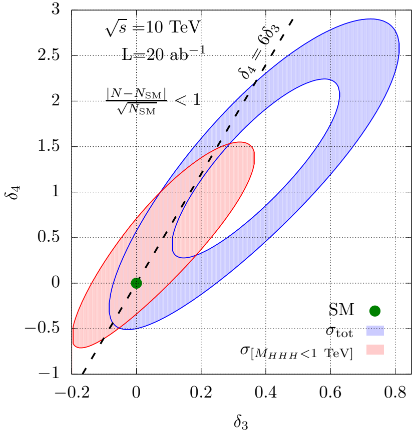


Update of Papaefstathiou, GTX, Zaro: 1909.09166

SM Significance ~ 2.33 σ (New)

Probing the quartic coupling at the muon collider



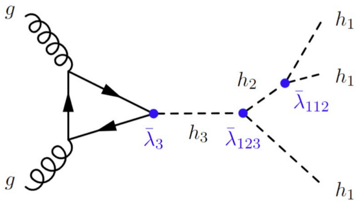


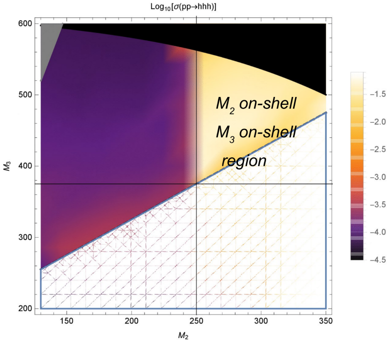
- Preliminary study show very intersting possibilities at a muon collider

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"]

Outlook

Outlook

- The Higgs self-interactions are on the Higgs couplings that remain unprobed
- LHC will be able to probe the trilinear up to a certain level (for SM value)
- The quartic will not be probed at the LHC, also for the FCC-hh it will be diffcult
- Other colliders have better chances
- BSM may yield modifications that boost our chance for discovery