Higgs and Top physics : Theory

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Plan

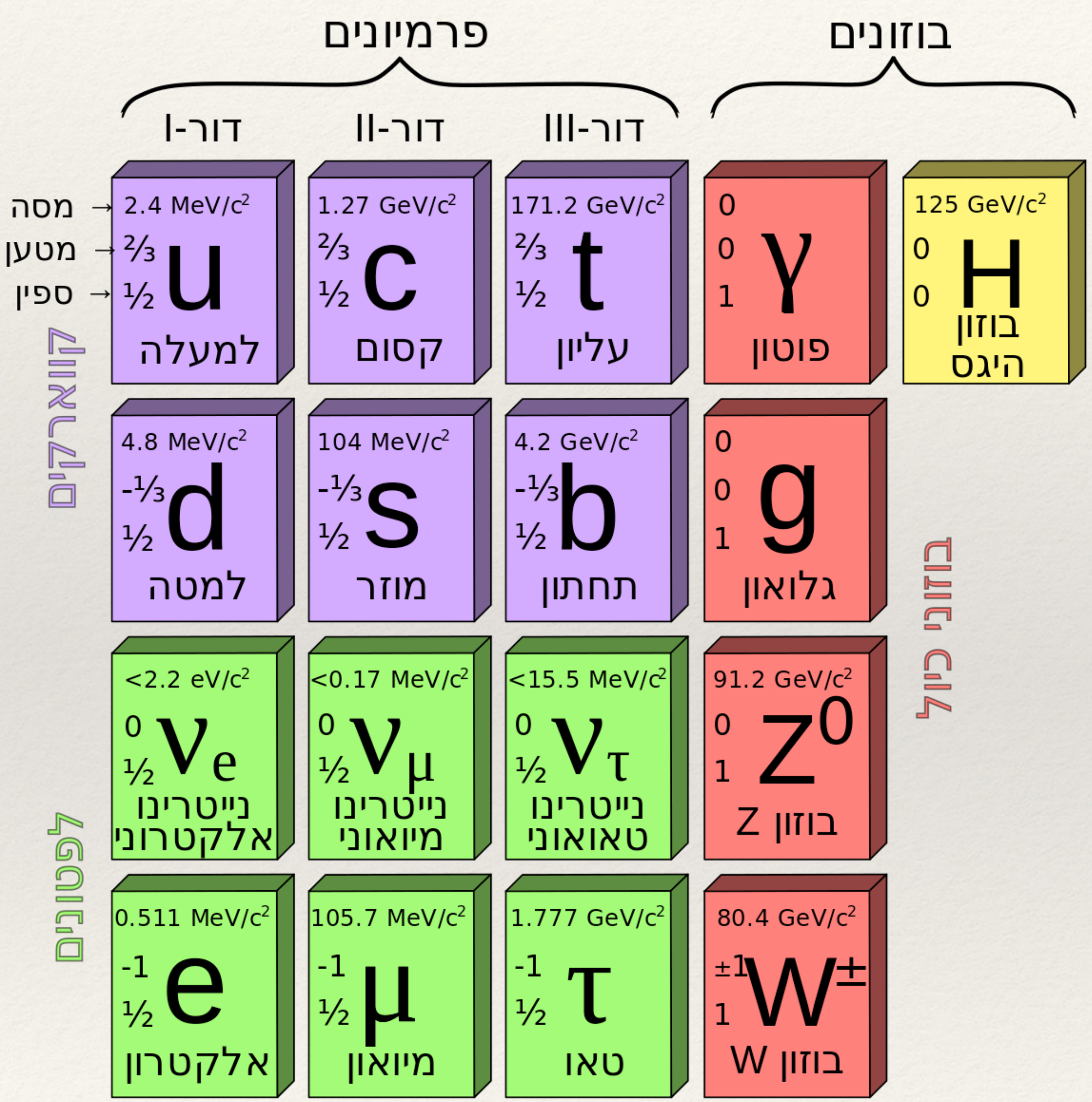
- Lecture I

  - Basics of the SM
  - Higgs decays and production

- Lecture II

  - The Top quark is special
  - New Physics via an EFT

The SM in a nutshell



- SU(3)$_c$ x SU(2)$_L$ x U(1)$_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fundamental representation of the gauge groups.
- The SU(2) x U(1) symmetry is spontaneously broken to EM.
- Yukawa interactions are present that lead to fermion masses and CP violation.
- Neutrino masses can be accommodated in two distinct ways.
- Anomaly free.
- Renormalisable = valid to “arbitrary” high scales.

SU(2)$_L$ x U(1)$_Y$

Experimental evidence, such as charged weak currents couple only with left-handed fermions, the existence of a massless photon and a neutral $Z\ldots$, the electroweak group is chosen to be SU(2)$_L\times$ U(1)$_Y$.

$$\psi_L \equiv \frac{1}{2}(1-\gamma_5)\psi \qquad \psi_R \equiv \frac{1}{2}(1+\gamma_5)\psi \qquad \psi = \psi_L + \psi_R$$

$$L_L \equiv \frac{1}{2}(1-\gamma_5)\begin{pmatrix} \nu_e \\ e \end{pmatrix} = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad e_R \equiv \frac{1}{2}(1+\gamma_5)e$$

- SU(2)$_L$: weak isospin group. Three generators $\Longrightarrow$ three gauge bosons: W^1, W^2 and W^3, with gauge coupling g. The generators for doublets are $T^a = \sigma^a/2$, where σ^a are the 3 Pauli matrices (when acting on the gauge singlet e_R and ν_R, $T^a \equiv 0$).
- U(1)$_Y$: weak hypercharge Y. One gauge boson B with gauge coupling g'.
  One generator (charge) $Y(\psi)$, whose value depends on the corresponding field.

SU(2)$_L$ x U(1)$_Y$

Following the gauging recipe (for one generation of leptons. Quarks work the same way)

$$\mathcal{L}_\psi = i\,\bar{L}_L \not{D}\, L_L + i\,\bar{\nu}_{eR} \not{D}\, \nu_{eR} + i\,\bar{e}_R \not{D}\, e_R$$

where

$$D^\mu = \partial^\mu - igW_i^\mu T^i - ig'\frac{Y(\psi)}{2}B^\mu \qquad T^i = \frac{\sigma^i}{2} \quad \text{or} \quad T^i = 0 \qquad i = 1,2,3$$

$$\mathcal{L}_\psi \equiv \mathcal{L}_{kin} + \mathcal{L}_{CC} + \mathcal{L}_{NC}$$

$$\begin{aligned}
\mathcal{L}_{kin} &= i\,\bar{L}_L \not{\partial}\, L_L + i\,\bar{\nu}_{eR} \not{\partial}\, \nu_{eR} + i\,\bar{e}_R \not{\partial}\, e_R \\
\mathcal{L}_{CC} &= g\,W_\mu^1\,\bar{L}_L\,\gamma^\mu\,\frac{\sigma_1}{2}\,L_L + g\,W_\mu^2\,\bar{L}_L\,\gamma^\mu\,\frac{\sigma_2}{2}\,L_L = \frac{g}{\sqrt{2}}\,W_\mu^+\,\bar{L}_L\,\gamma^\mu\,\sigma^+\,L_L + \frac{g}{\sqrt{2}}\,W_\mu^-\,\bar{L}_L\,\gamma^\mu\,\sigma^-\,L_L \\
&= \frac{g}{\sqrt{2}}\,W_\mu^+\,\bar{\nu}_L\,\gamma^\mu\,e_L + \frac{g}{\sqrt{2}}\,W_\mu^-\,\bar{e}_L\,\gamma^\mu\,\nu_L \\
\mathcal{L}_{NC} &= \frac{g}{2}\,W_\mu^3\,[\bar{\nu}_{eL}\,\gamma^\mu\,\nu_{eL} - \bar{e}_L\,\gamma^\mu\,e_L] + \frac{g'}{2}\,B_\mu\Big[Y(L)\,(\bar{\nu}_{eL}\,\gamma^\mu\,\nu_{eL} + \bar{e}_L\,\gamma^\mu\,e_L) \\
&\quad + Y(\nu_{eR})\,\bar{\nu}_{eR}\,\gamma^\mu\,\nu_{eR} + Y(e_R)\,\bar{e}_R\,\gamma^\mu\,e_R\Big]
\end{aligned}$$

with

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\,(W_\mu^1 \mp iW_\mu^2) \qquad \sigma^\pm = \frac{1}{2}\,(\sigma^1 \pm i\sigma^2)$$

SU(2)$_L$ x U(1)$_Y$

$$\mathcal{L}_{NC} = \frac{g}{2} W_\mu^3 \left[\bar{\nu}_{eL}\,\gamma^\mu\,\nu_{eL} - \bar{e}_L\,\gamma^\mu\,e_L\right] + \frac{g'}{2} B_\mu \Big[Y(L)\,(\bar{\nu}_{eL}\,\gamma^\mu\,\nu_{eL} + \bar{e}_L\,\gamma^\mu\,e_L) + Y(\nu_{eR})\,\bar{\nu}_{eR}\,\gamma^\mu\,\nu_{eR} + Y(e_R)\,\bar{e}_R\,\gamma^\mu\,e_R \Big]$$

Neither W_μ^3 nor B_μ can be interpreted as the photon field A_μ, since they couple to neutral fields.

$$\Psi \equiv \begin{pmatrix} \nu_{eL} \\ e_L \\ \nu_{eR} \\ e_R \end{pmatrix} \qquad \mathcal{T}_3 \equiv \begin{pmatrix} 1/2 & 0 & & \\ 0 & -1/2 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} \qquad \mathcal{Y} \equiv \begin{pmatrix} Y(L) & & & \\ & Y(L) & & \\ & & Y(\nu_{eR}) & \\ & & & Y(e_R) \end{pmatrix}$$

$$\mathcal{L}_{NC} = g\,\bar{\Psi}\,\gamma^\mu\,\mathcal{T}_3\,\Psi\,W_\mu^3 + g'\,\bar{\Psi}\,\gamma^\mu\,\frac{\mathcal{Y}}{2}\,\Psi\,B_\mu$$

$SU(2)_L \times U(1)_Y$

We perform a rotation of an angle θ_W, the Weinberg angle, in the space of the two neutral gauge fields (W^3_μ and B_μ). We use an orthogonal transformation in order to keep the kinetic terms diagonal in the vector fields

$$
\begin{aligned}
B_\mu &= A_\mu \cos\theta_W - Z_\mu \sin\theta_W \\
W^3_\mu &= A_\mu \sin\theta_W + Z_\mu \cos\theta_W
\end{aligned}
$$

so that

$$\mathcal{L}_{NC} = \bar{\Psi}\gamma^\mu \left[g\,\sin\theta_W\,\mathcal{T}_3 + g'\,\cos\theta_W\,\frac{\mathcal{Y}}{2} \right] \Psi\, A_\mu + \bar{\Psi}\gamma^\mu \left[g\,\cos\theta_W\,\mathcal{T}_3 - g'\,\sin\theta_W\,\frac{\mathcal{Y}}{2} \right] \Psi\, Z_\mu$$

We can identify A_μ with the photon field provided

$$e\mathcal{Q} = g\,\sin\theta_W\,\mathcal{T}_3 + g'\,\cos\theta_W\,\frac{\mathcal{Y}}{2} \qquad \mathcal{Q} = \text{electromagnetic charge}$$

The weak hypercharges $\mathcal{Y}$ appear only through the combination $g'\,\mathcal{Y}$. We use this freedom to fix

$$Y(L) = -1$$

$SU(2)_L \times U(1)_Y$

With this choice, the doublet of left-handed leptons gives $\left(e\mathcal{Q} = g\,\sin\theta_W\,\mathcal{T}_3 + g'\,\cos\theta_W\,\frac{\mathcal{Y}}{2}\right)$

$$\begin{aligned} 0 &= \frac{g}{2}\sin\theta_W - \frac{g'}{2}\cos\theta_W \\ -e &= -\frac{g}{2}\sin\theta_W - \frac{g'}{2}\cos\theta_W \end{aligned}$$

so that

$$g\sin\theta_W = g'\cos\theta_W = e$$

and

$$\mathcal{Q} = \mathcal{T}_3 + \frac{\mathcal{Y}}{2} \qquad \text{Gell-Mann–Nishijima formula.}$$

From this formula we have $Y(\nu_{eR}) = 0$ and $Y(e_R) = -2$.

Notice that the right-handed neutrino has zero charge, zero hypercharge and it is in a SU(2) singlet: it does not take part in electroweak interactions.

SU(2)$_L$ x U(1)$_Y$

$$\mathcal{L}_{NC} = \bar{\Psi}\gamma^\mu \left[g\,\sin\theta_W\,\mathcal{T}_3 + g'\,\cos\theta_W\,\frac{\mathcal{Y}}{2}\right]\Psi\,A_\mu + \bar{\Psi}\gamma^\mu\left[g\,\cos\theta_W\,\mathcal{T}_3 - g'\,\sin\theta_W\,\frac{\mathcal{Y}}{2}\right]\Psi\,Z_\mu$$

$$= e\,\bar{\Psi}\gamma^\mu\mathcal{Q}\Psi\,A_\mu + \bar{\Psi}\gamma^\mu\mathcal{Q}_Z\Psi\,Z_\mu$$

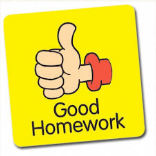
where $\mathcal{Q}_Z$ is a diagonal matrix given by

$$\mathcal{Q}_Z = \frac{e}{\cos\theta_W\sin\theta_W}\left(\mathcal{T}_3 - \mathcal{Q}\sin^2\theta_W\right)$$

We can proceed, in a similar way, with quarks (see more later)

$$Q_L^i = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad \begin{aligned} u_R^i &= u_R, c_R, t_R \\ d_R^i &= d_R, s_R, b_R \end{aligned}$$

SM charge assignments



				$SU(3)$	$SU(2)$	$U(1)_Y$	$Q = T_3 + \frac{Y}{2}$
$Q^i_L =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{3}$	$\frac{2}{3}$, $-\frac{1}{3}$
$u^i_R =$	u_R	c_R	t_R	3	1	$\frac{4}{3}$	$\frac{2}{3}$
$d^i_R =$	d_R	s_R	b_R	3	1	$-\frac{2}{3}$	$-\frac{1}{3}$
$L^i_L =$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	-1	0, -1
$e^i_R =$	e_R	μ_R	τ_R	1	1	-2	-1
$\nu^i_R =$	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	1	1	0	0

Masses

Gauge invariance and renormalizability completely determine the kinetic terms for the gauge bosons

$$\mathcal{L}_{YM} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a$$

$$\begin{aligned} B^{\mu\nu} &= \partial^\mu B^\nu - \partial^\nu B^\mu \\ W^a_{\mu\nu} &= \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\, \epsilon^{abc}\, W_{b,\mu}\, W_{c,\nu} \end{aligned}$$

The gauge symmetry does NOT allow any mass terms for $W^\pm$ and Z.

Mass terms for gauge bosons

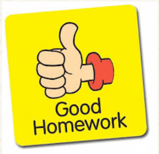
$$\mathcal{L}_{mass} = \frac{1}{2} m_A^2\, A_\mu\, A^\mu$$

are not invariant under a gauge transformation

$$A^\mu \;\to\; U(x) \left(A^\mu + \frac{i}{g}\, \partial^\mu \right) U^{-1}(x)$$

However, the gauge bosons of weak interactions are massive (short range of weak interactions).

Two Subtleties…



Actually, the story is bit more subtle than this...

1. For U(1) the apparent gauge violation of the mass term is irrelevant. The basic reason is that quantization implies a gauge fixing. This is can be easily seen by taking the limit of the $e\to 0$, $\lambda\to 0$, $v\to\infty$, with $\lambda v^2=M^2$ and $ev=m$ fixed, of the Abelian Higgs model, which then becomes a free theory of two massive scalars and one massive vector boson. This vector boson can then be coupled to fermionic matter. This is called the Stuckelberg mechanism. However, for SU(N) this does not work since the selfcoupling of the field $g\to 0$.

Two Subtleties…

Actually, the story is bit more subtle than this…

2. One can still realise the gauge symmetry in a non-linear way, as a gauged non-linear sigma model. In this case one groups the goldstone bosons into a triplet π whose interactions are described by

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}(D^\mu \Sigma)^\dagger D_\mu \Sigma$$

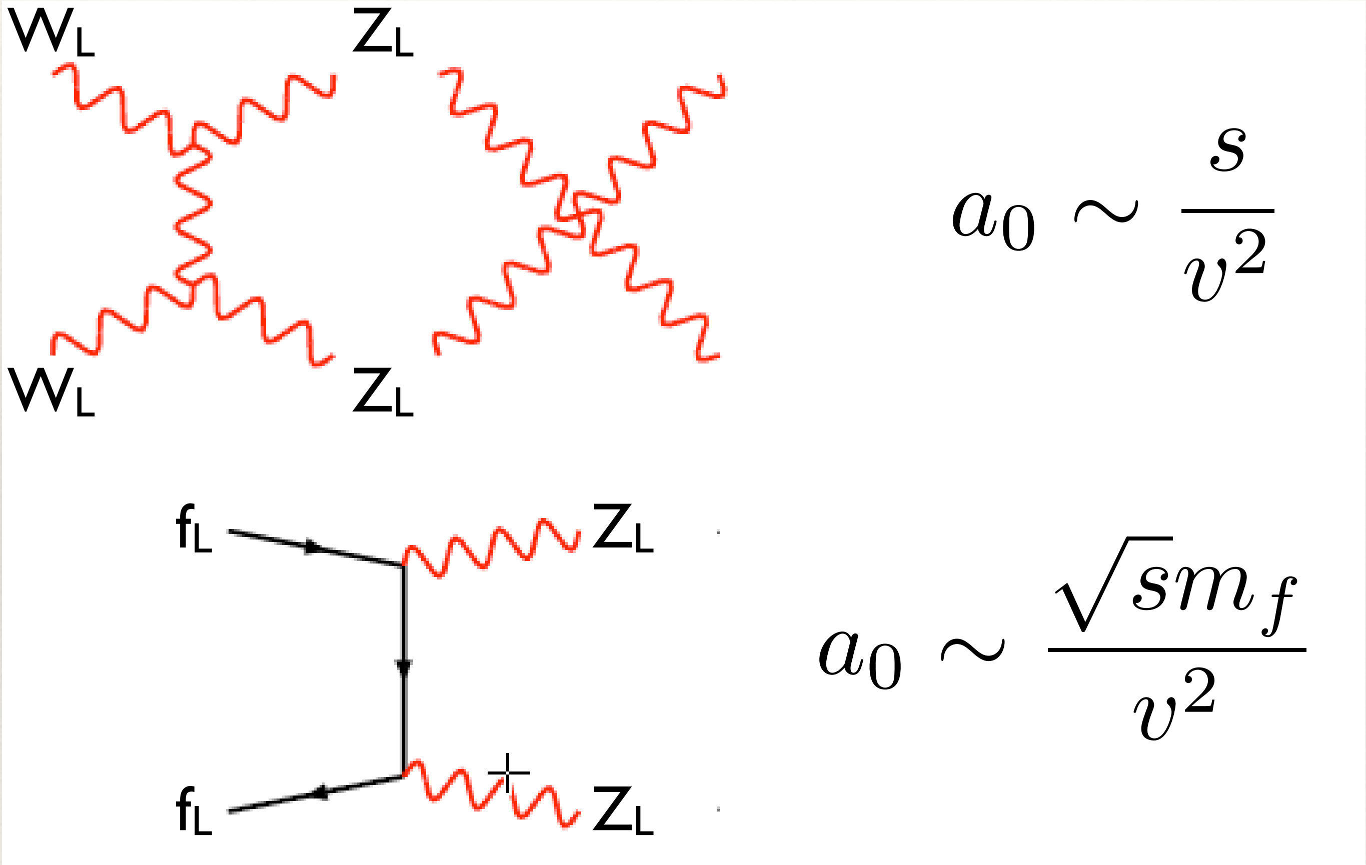
with $D^\mu \Sigma = \partial^\mu \Sigma + i(g/2)\sigma \cdot W^\mu \Sigma - i(g'/2)\Sigma \sigma^3 B^\mu$ and $\Sigma = \exp(i\sigma \cdot \pi / v)$

For the fermions one writes $\mathcal{L} = -m_f \bar{F}_L \Sigma \begin{pmatrix} 0 \\ 1 \end{pmatrix} f_R + \mathrm{H.c.}$

However, this theory is not renormalisable and breaks down at scales Λ of the order $\sqrt{8\pi}v$

The unitarity bound

[Chanowitz, Gallard.1985]
[Appelquist, Chanowitz,1989]



Inelastic tree-level amplitudes for longitudinal W and Z and fermions violate unitarity at a scale:

$$\Lambda_{EWSB} = \sqrt{8\pi} v$$

Our effective description contains information on where it is going to fail.

Only case we know of where unknown physics has to appear below 1 TeV.

Spontaneous Symmetry Breaking

A symmetry is said to be spontaneously broken when the vacuum state is not invariant

$$\exp\left(i\,\delta\theta^{\,a}\,t^a\right)|0\rangle \neq |0\rangle \qquad \Longrightarrow \qquad Q^a|0\rangle \neq 0$$

This condition is equivalent to the existence of some set of fields operators ϕ_k with non-trivial transformation property under that symmetry transformation, and non-vanishing vacuum expectation values

$$\langle 0|\phi_k|0\rangle = v_k \neq 0$$

Proof

If the set of fields ϕ_j transforms non-trivially

$$\phi_j \to \left(e^{i\,\delta\theta^{\,a}\,t^a}\right)_{jk}\phi_k \sim \phi_j + \underbrace{i\,\delta\theta^{\,a}\,t^a_{jk}\,\phi_k}_{\delta\phi_j} = \phi_j + i\,\delta\theta^a\,[Q^a,\phi_j]$$

Taking the expectation value on the vacuum

$$t^a_{jk}\,\langle 0|\phi_k|0\rangle = \langle 0|\,[Q^a,\phi_j]\,|0\rangle \neq 0 \qquad \Longleftrightarrow \qquad Q^a|0\rangle \neq 0$$

BEH mechanism

We give mass to the gauge bosons through the Brout-Englert-Higgs mechanism: generate mass terms from the kinetic energy term of a scalar doublet field Φ that undergoes a broken-symmetry process.

Introduce a complex scalar doublet: four scalar real fields

$$\begin{aligned} \Phi &= \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad Y(\Phi) = 1 \\ \mathcal{L}_{\text{Higgs}} &= (D_\mu \Phi)^\dagger (D^\mu \Phi) - V\left(\Phi^\dagger \Phi\right) \\ D^\mu &= \partial^\mu - igW_i^\mu \frac{\sigma^i}{2} - ig' \frac{Y(\Phi)}{2} B^\mu \\ V\left(\Phi^\dagger \Phi\right) &= -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2, \qquad \mu^2, \lambda > 0 \end{aligned}$$

- The reason why $Y(\Phi) = 1$ is not to break electric-charge conservation.
- Charge assignment for the Higgs doublet through $Q = T_3 + Y/2$. The potential has a minimum in correspondence of

$$|\Phi|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$$

v is called the vacuum expectation value (VEV) of the neutral component of the Higgs doublet.

BEH mechanism

Expanding Φ around the minimum

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left[v + H(x) + i\chi(x)\right] \end{pmatrix} = \frac{1}{\sqrt{2}} \exp\left[\frac{i\sigma_i \theta^i(x)}{v}\right] \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

We can rotate away the fields $\theta^i(x)$ by an $\mathrm{SU}(2)_L$ gauge transformation

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

where $U(x) = \exp\left[-\frac{i\sigma_i \theta^i(x)}{v}\right]$.

This gauge choice is called unitary gauge, and is equivalent to absorbing the Goldstone modes $\theta^i(x)$. Three would-be Goldstone bosons "eaten up" by three vector bosons $(W^\pm, Z)$ that acquire mass. This is why we introduced a complex scalar doublet (four elementary fields).

The vacuum state can be chosen to correspond to the vacuum expectation value

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

BEH mechanism

We can easily verify that the vacuum state breaks the gauge symmetry.

A state $\tilde{\Phi}$ is invariant under a symmetry operation $\exp(igT^a\theta_a)$ if

$$\exp(igT^a\theta_a)\tilde{\Phi} = \tilde{\Phi}$$

This means that a state is invariant if (just expand the exponent)

$$T^a\tilde{\Phi} = 0$$

For the $\mathrm{SU}(2)_L \times$ $\mathrm{U}(1)_Y$ case we have

$$\sigma_1\Phi_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \qquad \text{broken}$$

$$\sigma_2\Phi_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \qquad \text{broken}$$

BEH mechanism

$$\sigma_3 \Phi_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \qquad \text{broken}$$

$$Y \Phi_0 = Y(\Phi) \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = +1 \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \qquad \text{broken}$$

But, if we examine the effect of the electric charge operator $\hat{Q} = Y/2 + T_3$ on the (electrically neutral) vacuum state, we have ($Y(\Phi) = 1$)

$$\hat{Q}\Phi_0 = \frac{1}{2}(\sigma_3 + Y)\,\Phi_0 = \frac{1}{2}\begin{pmatrix} Y(\Phi)+1 & 0 \\ 0 & Y(\Phi)-1 \end{pmatrix}\Phi_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

the electric charge symmetry is unbroken!

The Higgs potential

The scalar potential

$$V\left(\Phi^{\dagger}\Phi\right) = -\mu^2\Phi^{\dagger}\Phi \;+\; \lambda\left(\Phi^{\dagger}\Phi\right)^2$$

expanded around the vacuum state

$$\Phi(x) = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v + H(x) \end{array}\right)$$

becomes

$$V \;=\; \frac{1}{2}\left(2\lambda v^2\right)H^2 \;+\; \lambda v H^3 \;+\; \frac{\lambda}{4}H^4 + \text{const}$$

- the scalar field H gets a mass

$$m_H^2 = 2\lambda v^2 \qquad\qquad v^2 = \mu^2/\lambda$$

- there is a term of cubic and quartic self-coupling.

Note: this means that $\lambda_3 = \lambda_4 = \lambda$ in the SM. To have (independent) deviations of the trilinear or quadrilinear, one needs to deform the potential with a BSM hypothesis.

Vector boson masses

$$
\begin{aligned}
D^\mu \Phi &= \left(\partial^\mu - igW_i^\mu \frac{\sigma^i}{2} - ig' \frac{1}{2} B^\mu\right) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \partial^\mu H \end{pmatrix} - \frac{i}{2\sqrt{2}} \left[g \begin{pmatrix} W_3^\mu & W_1^\mu - iW_2^\mu \\ W_1^\mu + iW_2^\mu & -W_3^\mu \end{pmatrix} + g' B^\mu \right] \begin{pmatrix} 0 \\ v + H \end{pmatrix} \\
&= \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 0 \\ \partial^\mu H \end{pmatrix} - \frac{i}{2}(v+H) \begin{pmatrix} g\left(W_1^\mu - iW_2^\mu\right) \\ -gW_3^\mu + g' B^\mu \end{pmatrix} \right] \\
&= \frac{1}{\sqrt{2}} \left[\begin{pmatrix} 0 \\ \partial^\mu H \end{pmatrix} - \frac{i}{2}\left(1 + \frac{H}{v}\right) \begin{pmatrix} gvW^{\mu+} \\ -v\sqrt{(g^2+g'^2)/2}\, Z^\mu \end{pmatrix} \right]
\end{aligned}
$$

Note: this means that the mass and the Higgs interactions are uniquely linked.

$$
(D^\mu \Phi)^\dagger D_\mu \Phi = \frac{1}{2} \partial^\mu H \partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu+} W_\mu^- + \frac{1}{2} \frac{\left(g^2 + g'^2\right) v^2}{4} Z^\mu Z_\mu \right] \left(1 + \frac{H}{v}\right)^2
$$

Vector boson Higgs couplings

- The W and Z gauge bosons have acquired masses

$$m_W^2 = \frac{g^2 v^2}{4} \qquad m_Z^2 = \frac{\left(g^2 + g'^2\right) v^2}{4} = \frac{m_W^2}{\cos^2 \theta_W}$$

From the measured value of the Fermi constant G_F

$$\frac{G_F}{\sqrt{2}} = \left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{m_W^2} \qquad \Longrightarrow \qquad v = \sqrt{\frac{1}{\sqrt{2} G_F}} \approx 246.22 \text{ GeV}$$

- the photon stays massless

- HWW and HZZ couplings from $2H/v$ term (and $HHWW$ and $HHZZ$ couplings from H^2/v^2 term)

$$\mathcal{L}_{HVV} = \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H + \frac{m_Z^2}{v} Z^\mu Z_\mu H \equiv g m_W W_\mu^+ W^{-\mu} H + \frac{1}{2} \frac{g m_Z}{\cos \theta_W} Z^\mu Z_\mu H$$

Higgs coupling proportional to mass

- tree-level HVV (V = vector boson) coupling requires VEV!
Normal scalar couplings give $\Phi^\dagger \Phi V$ or $\Phi^\dagger \Phi V V$ couplings only.

Fermion masses

A direct mass term is not invariant under $SU(2)_L$ or $U(1)_Y$ gauge transformation

$$m_f\bar{\psi}\psi = m_f\left(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R\right)$$

Generate fermion masses through Yukawa-type interactions terms

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d^{ij}\bar{Q}_L'^{i}\Phi d_R'^{j} - \Gamma_d^{ij*}\bar{d}_R'^{i}\Phi^\dagger Q_L'^{j} \\ &\quad -\Gamma_u^{ij}\bar{Q}_L'^{i}\Phi_c u_R'^{j} + \text{h.c.} \\ &\quad -\Gamma_e^{ij}\bar{L}_L^{i}\Phi e_R^{j} + \text{h.c.}\end{aligned}$$

$$\Phi_c = i\sigma_2\Phi^* = \frac{1}{\sqrt{2}}\begin{pmatrix} v + H(x) \\ 0 \end{pmatrix}$$

where Q', u' and d' are quark fields that are generic linear combination of the mass eigenstates u and d and Γ_u, Γ_d and Γ_e are 3×3 complex matrices in generation space, spanned by the indices i and j.

Fermion masses

In the unitary gauge we have

$$\bar{Q}'^{\,i}_L \, \Phi \, d'^{\,j}_R = \left(\bar{u}'^{\,i}_L \;\; \bar{d}'^{\,i}_L \right) \left(\begin{array}{c} 0 \\ \frac{v+H}{\sqrt{2}} \end{array} \right) d'^{\,j}_R = \frac{v+H}{\sqrt{2}} \, \bar{d}'^{\,i}_L \, d'^{\,j}_R$$

$$\bar{Q}'^{\,i}_L \, \Phi_c \, u'^{\,j}_R = \left(\bar{u}'^{\,i}_L \;\; \bar{d}'^{\,i}_L \right) \left(\begin{array}{c} \frac{v+H}{\sqrt{2}} \\ 0 \end{array} \right) u'^{\,j}_R = \frac{v+H}{\sqrt{2}} \, \bar{u}'^{\,i}_L \, u'^{\,j}_R$$

and we obtain

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}} &= -\Gamma^{ij}_d \frac{v+H}{\sqrt{2}} \, \bar{d}'^{\,i}_L \, d'^{\,j}_R - \Gamma^{ij}_u \frac{v+H}{\sqrt{2}} \, \bar{u}'^{\,i}_L \, u'^{\,j}_R - \Gamma^{ij}_e \frac{v+H}{\sqrt{2}} \, \bar{e}^{i}_L \, e^{j}_R + \text{h.c.} \\ &= -\left[M^{ij}_u \, \bar{u}'^{\,i}_L \, u'^{\,j}_R + M^{ij}_d \, \bar{d}'^{\,i}_L \, d'^{\,j}_R + M^{ij}_e \, \bar{e}^{i}_L \, e^{j}_R + \text{h.c.} \right] \left(1 + \frac{H}{v} \right) \end{aligned}$$

$$M^{ij} = \Gamma^{ij} \frac{v}{\sqrt{2}}$$

Fermion masses

Theorem: For any generic complex squared matrix C, there exist two unitary matrices U, V such that

$$D = U^\dagger \, C \, V$$

is diagonal with real positive entries

We can now diagonalize the matrix M_f $(f = u, d, e)$ with the help of two unitary matrices, U_L^f and U_R^f

$$\left(U_L^f\right)^\dagger M_f \, U_R^f = \text{diagonal with real positive entries}$$

For example:

$$(U_L^u)^\dagger \, M_u \, U_R^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \qquad (U_L^d)^\dagger \, M_d \, U_R^d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

Fermion masses and Higgs couplings

We can make the following change of fermionic fields

$$f'_{Li} = \left(U_L^f\right)_{ij} f_{Lj} \qquad f'_{Ri} = \left(U_R^f\right)_{ij} f_{Rj}$$

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= -\sum_{f',i,j} \bar{f}_L'^{\,i} M_f^{ij} f_R'^{\,j} \left(1 + \frac{H}{v}\right) + \text{h.c.} \\
&= -\sum_{f,i,j} \bar{f}_L^i \left[\left(U_L^f\right)^\dagger M_f U_R^f\right]_{ij} f_R^j \left(1 + \frac{H}{v}\right) + \text{h.c.} \\
&= -\sum_f m_f \left(\bar{f}_L f_R + \bar{f}_R f_L\right) \left(1 + \frac{H}{v}\right)
\end{aligned}$$

Note: this means that the mass and the Yukawa are linked.

- We succeed in producing fermion masses and we got a fermion-antifermion-Higgs coupling proportional to the fermion mass.
- Notice that the fermionic field redefinition preserves the form of the kinetic terms in the Lagrangian ($\bar{\psi} \not{\partial} \psi = \bar{\psi}_R \not{\partial} \psi_R + \bar{\psi}_L \not{\partial} \psi_L$ invariant for left and right field unitary transformation).
- The Higgs Yukawa couplings are flavor diagonal: no flavor changing Higgs interactions.

Mixing

The charged current interaction is given by

$$\frac{e}{\sqrt{2}\sin\theta_W}\bar{u}'^{\,i}_L\, \not{W}^+\, d'^{\,i}_L + \text{h.c.}$$

After the mass diagonalization described previously, this term becomes

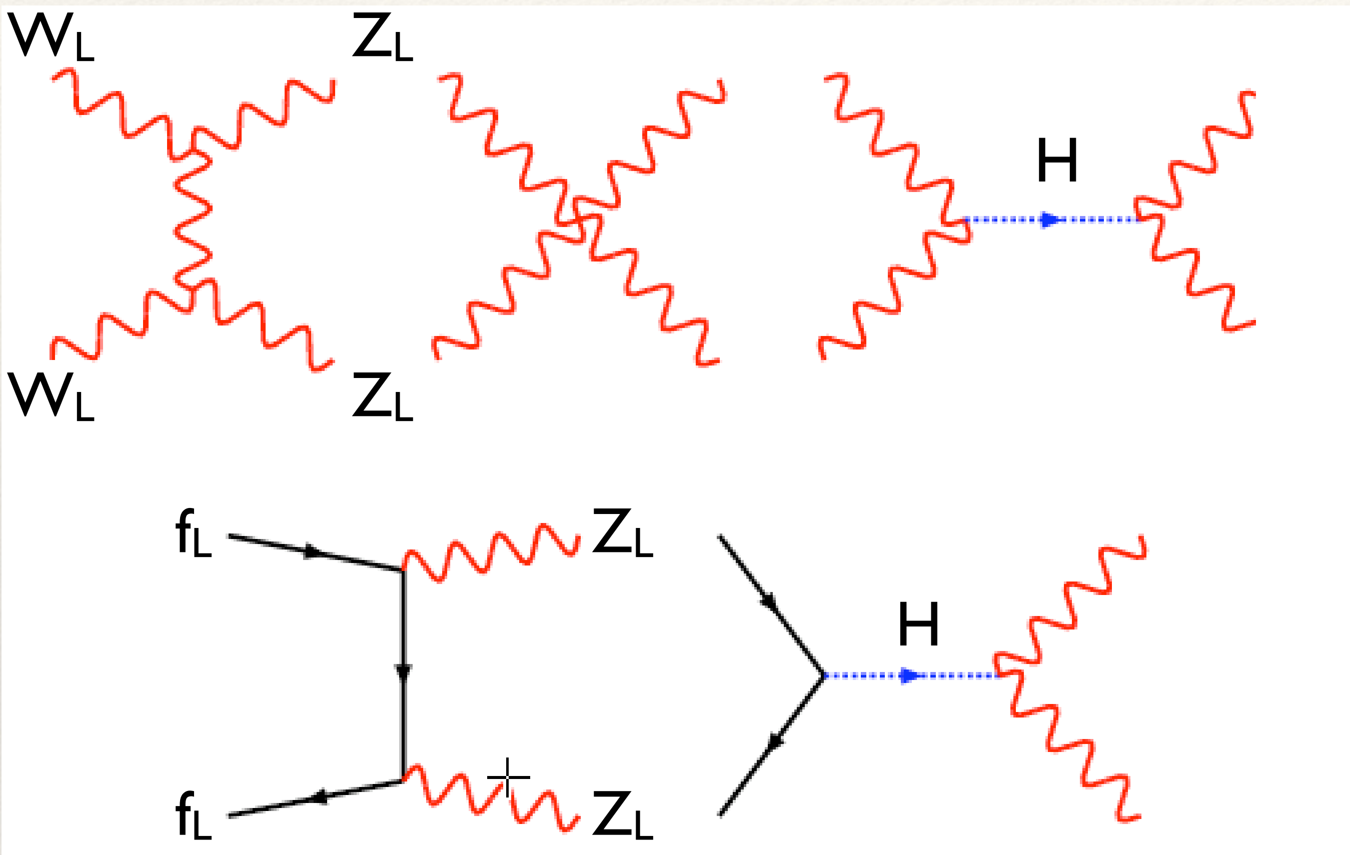
$$\frac{e}{\sqrt{2}\sin\theta_W}\bar{u}^i_L\left[(U^u_L)^\dagger\, U^d_L\right]_{ij}\not{W}^+ d^j_L + \text{h.c.}$$

and we define the Cabibbo-Kobayashi-Maskawa matrix V_{CKM}

$$V_{CKM} = (U^u_L)^\dagger\, U^d_L$$

- V_{CKM} is a complex not diagonal matrix and then it mixes the flavors of the different quarks.
- For N flavour families, V_{CKM} depends on $(N-1)^2$ parameters. $(N-1)(N-2)/2$ of them are complex phases. For $N=3$ there is one complex phase and this implies violation of the **CP** symmetry (first observed in the K^0-$\bar{K}^0$ system in 1964).
- It is a unitary matrix and the values of its entries must be determined from experiments.

The Higgs restores unitarity



$$a_0 \sim \frac{s}{v^2} - \frac{s}{v^2} \sim \frac{m_H^2}{v^2}$$

$$a_0 \sim \frac{\sqrt{s}m_f}{v^2} - \frac{\sqrt{s}m_f}{v^2} \sim \frac{m_f^2}{v^2}$$

SM is a linearly realised gauge theory which valid up to arbitrary high scales (if m_H<<1 TeV).

Vacuum stability

The one-loop renormalization group equation (RGE) for $\lambda(\mu)$ is

$$\frac{d\lambda(\mu)}{d\log\mu^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + \frac{3}{8}g^4 + \frac{3}{16}\left(g^2 + g'^2\right)^2 - 3h_t^4 - 3\lambda g^2 - \frac{3}{2}\lambda\left(g^2 + g'^2\right) + 6\lambda h_t^2\right]$$

where

$$m_t = \frac{h_t v}{\sqrt{2}} \qquad m_H^2 = 2\lambda v^2$$

This equation must be solved together with the one-loop RGEs for the gauge and Yukawa couplings, which, in the Standard Model, are given by

$$\begin{aligned}
\frac{dg(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\left(-\frac{19}{6}g^3\right)\\
\frac{dg'(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\frac{41}{6}g'^3\\
\frac{dg_s(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\left(-7g_s^3\right)\\
\frac{dh_t(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\left[\frac{9}{2}h_t^3 - \left(8g_s^2 + \frac{9}{4}g^2 + \frac{17}{12}g'^2\right)h_t\right]
\end{aligned}$$

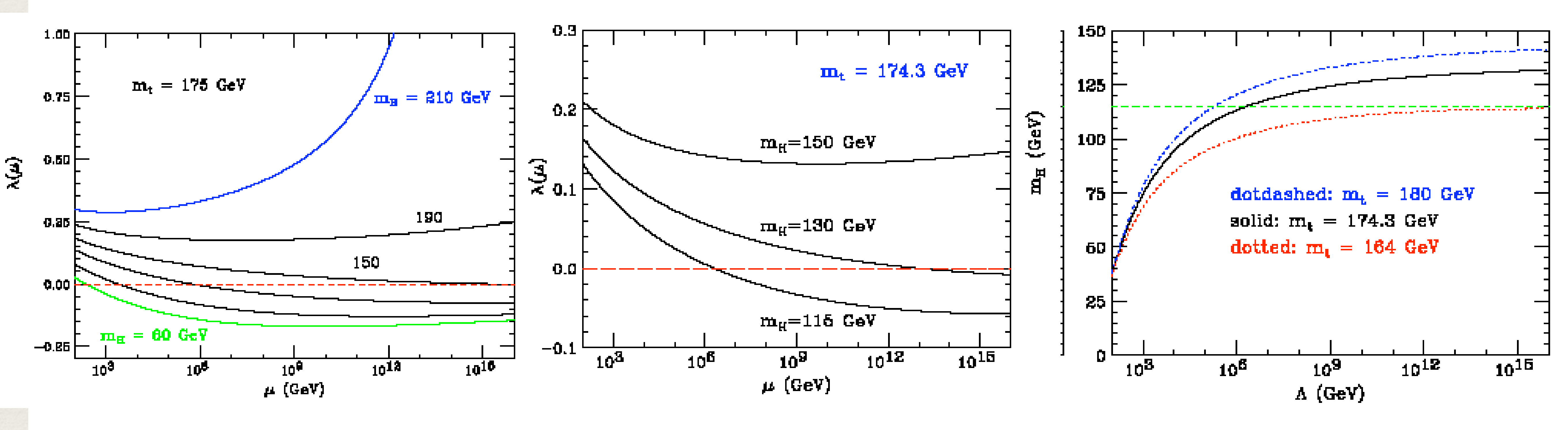
here g_s is the strong interaction coupling constant, and the $\overline{\mathrm{MS}}$ scheme is adopted.

Solving this system of coupled equations with the initial condition

$$\lambda\left(m_H\right) = \frac{m_H^2}{2v^2}$$

Vacuum stability

It can be shown that the requirement that the Higgs potential be bounded from below, even after the inclusion of radiative corrections, is fulfilled if $\lambda(\mu)$ stays positive, at least up to a certain scale $\mu \approx \Lambda$, the maximum energy scale at which the theory can be considered reliable (use effective action).



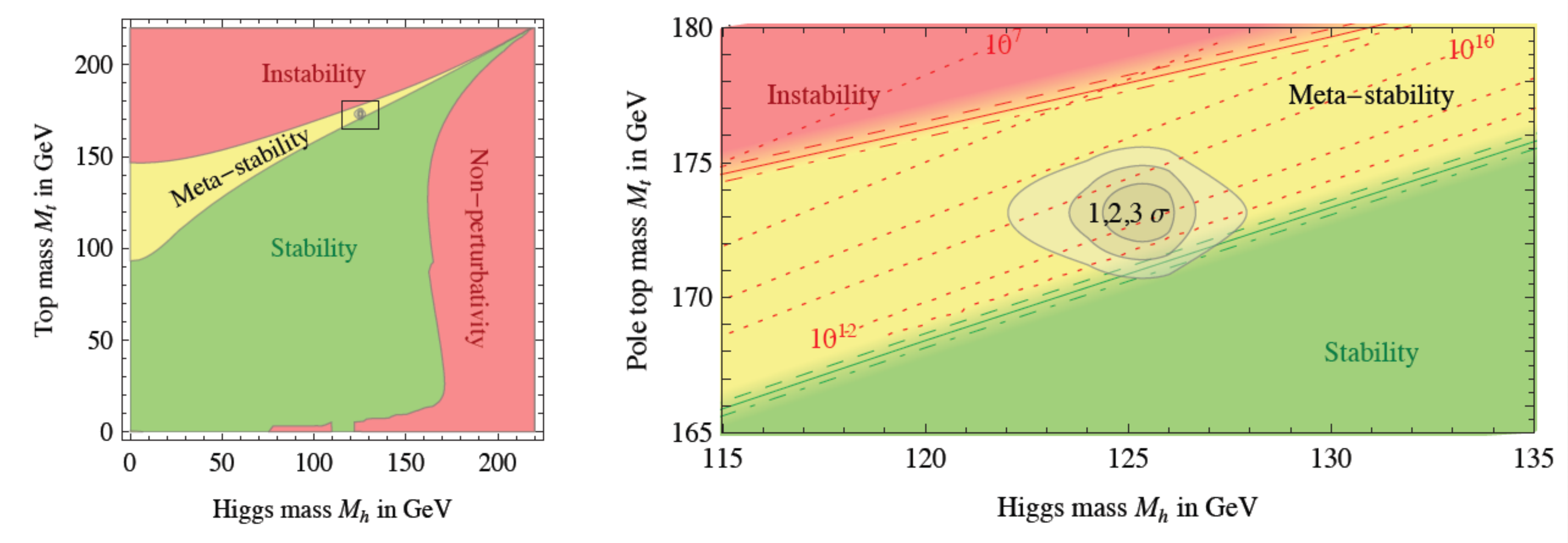
✗ This limit is extremely sensitive to the top-quark mass.

✓ The stability lower bound can be relaxed by allowing metastability

The future of the Universe

The fate of the Universe depends on 1GeV in m_t

[Degrassi, et al. '12]



$$y_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\text{GeV}} - 173.15\right) \ldots \pm 0.00200_{\text{th}}$$

It's the Yukawa that enters in this calculation.

Naturalness

Apart from the considerations made up to now, the SM must be considered as an effective low-energy theory: at very high energy new phenomena take place that are not described by the SM (gravitation is an obvious example) $\Longrightarrow$ other scales have to be considered.

Why the weak scale ($\sim 10^2$ GeV) is much smaller than other relevant scales, such as the Planck mass ($\approx 10^{19}$ GeV) or the unification scale ($\approx 10^{16}$ GeV) (or why the Planck scale is so high with respect to the weak scale $\Longrightarrow$ extra dimensions)?

This is the **hierarchy problem**.

And this problem is especially difficult to solve in the SM because of the un-naturalness of the Higgs boson mass.

As we have seen and as the experimental data suggest, the Higgs boson mass is of the same order of the weak scale. However, it's not naturally small, in the sense that there is no approximate symmetry that prevent it from receiving large radiative corrections.

As a consequence, it naturally tends to become as heavy as the heaviest degree of freedom in the underlying theory (Planck mass, unification scale).

Naturalness : example

Two scalars interacting through the potential

$$V(\varphi, \Phi) = \frac{m^2}{2}\varphi^2 + \frac{M^2}{2}\Phi^2 + \frac{\lambda}{4!}\varphi^4 + \frac{\sigma}{4!}\Phi^4 + \frac{\delta}{4}\varphi^2\Phi^2$$

which is the most general renormalizable potential, if we require the symmetry under $\varphi \to -\varphi$ and $\Phi \to -\Phi$. We assume that $M^2 \gg m^2$. Let's check if this hierarchy is conserved at the quantum level. Compute the one-loop radiative corrections to the pole mass m^2

$$m^2_{\text{pole}} = m^2(\mu^2) + \frac{\lambda m^2}{32\pi^2}\left(\log\frac{m^2}{\mu^2} - 1\right) + \frac{\delta M^2}{32\pi^2}\left(\log\frac{M^2}{\mu^2} - 1\right)$$

where the running mass $m^2(\mu^2)$ obeys the RGE

$$\frac{dm^2(\mu^2)}{d\log\mu^2} = \frac{1}{32\pi^2}\left(\lambda m^2 + \delta M^2\right)$$

Corrections to m^2 proportional to M^2 appear at one loop. One can choose $\mu^2 \approx M^2$ to get rid of them, but they reappear through the running of $m^2(\mu^2)$.

Naturalness : example

The only way to preserve the hierarchy $m^2 \ll M^2$ is carefully choosing the coupling constants

$$\lambda m^2 \approx \delta M^2$$

and this requires fixing the renormalized coupling constants with and unnaturally high accuracy

$$\frac{\lambda}{\delta} \approx \frac{M^2}{m^2}$$

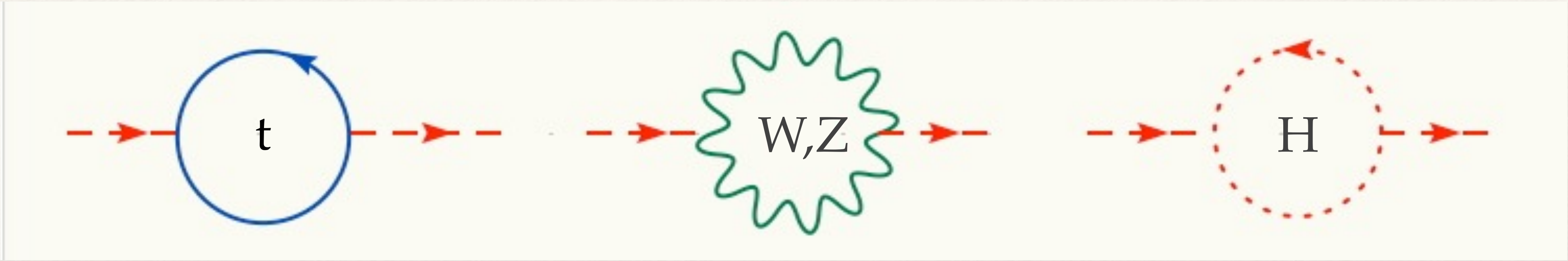
This is what is usually called the fine tuning of the parameters.

The same happens if the theory is spontaneously broken ($m^2 < 0$, $M^2 \gg |m^2| > 0$).

Therefore, without a suitable fine tuning of the parameters, the mass of the scalar Higgs boson naturally becomes as large as the largest energy scale in the theory. This is related to the fact that no extra symmetry is recovered when the scalar masses vanish, in contrast to what happens to fermions, where the chiral symmetry prevents the dependence from powers of higher scales, and gives a typical logarithmic dependence.

Naturalness in the SM

In the SM the radiative corrections to the Higgs mass can be written as



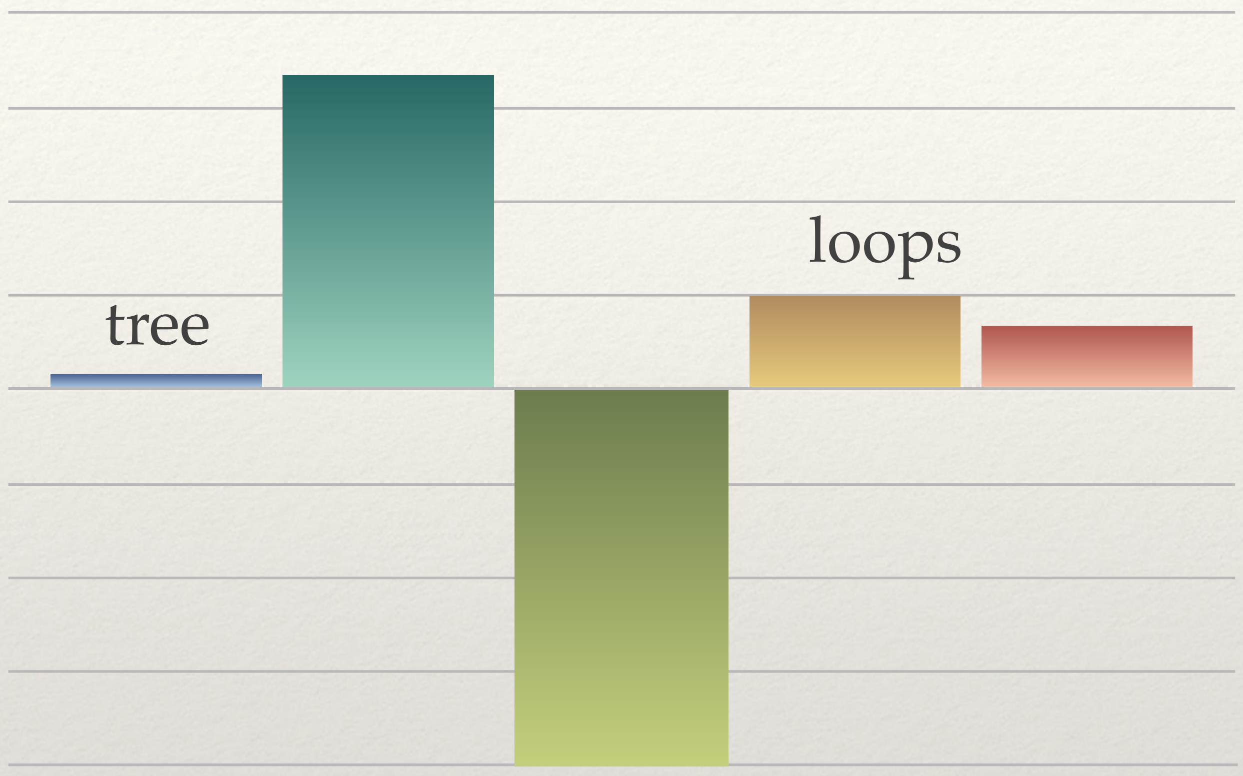
$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, one gets:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Naturalness in the SM

mH² ~ (125 GeV)²



$$(125\,\mathrm{GeV})^2 = m^2_{H0} + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Definition of naturalness: less than 90% cancellation:

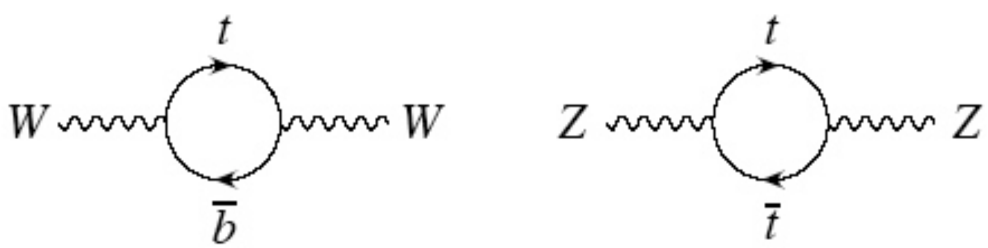
$$\Lambda_t < 3\,\mathrm{TeV}$$

⇒ top partners must be "light"

Loop effects in the SM

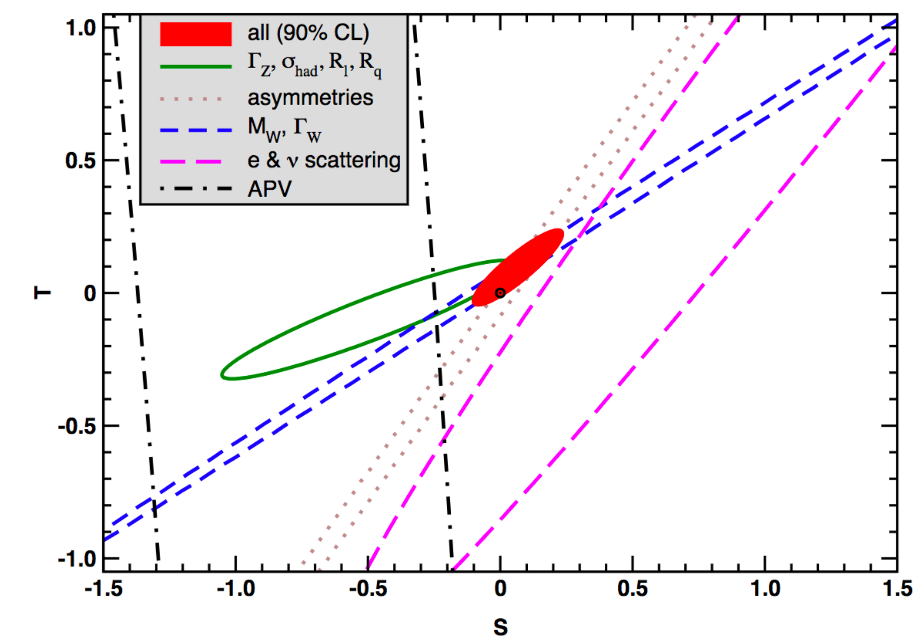
Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level mW=mZ cos θW. At one loop:

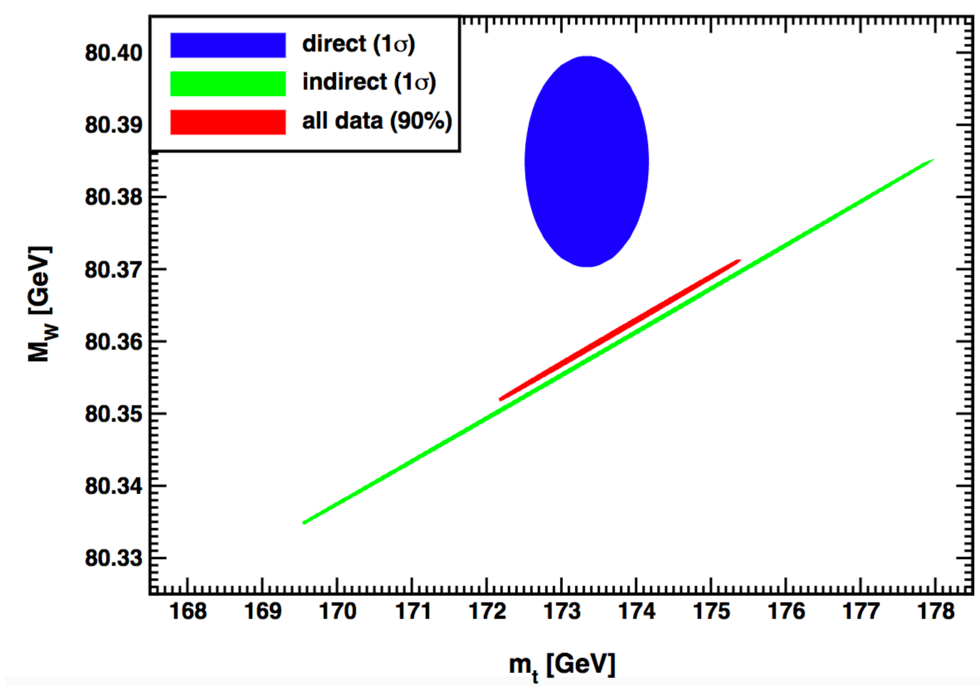
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$





Review questions: SM

1. What are the hypercharge assignments of the fermions in the SM? Can you explain in an elevator ride the anomaly cancellation mechanism in the SM? And its implications?

2. It is often said that a mass term for a gauge boson violates the gauge symmetry. What is the usual argument? Is this really true for an abelian gauge group? Is this true for non-abelian gauge group? Why?

3. Can I write a "SM" for which is SU(2)xU(1) invariant, yet does not contain the Higgs field? If so, how? Is it unitary?

4. If a mass term for the fermions is introduced that does not respect the EW gauge symmetry, at which scale the model will end to be valid?

5. What is the mass of the Goldstones in the SM? What is a shift symmetry? Can you describe the mysterious analogy of the SM EW sector with QCD at low-energy?

7. List the options that exist to give mass to neutrinos in a renormalizable way and by adding higher-dimensional operators.

8. Define as a “SM portal” a combination of SM fields which is a gauge singlet and has dimension less than four. How many of such portals do exist?

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SM Portals

$$(\Phi^\dagger \Phi)$$

dim=2

Scalars and vectors

$$(\bar{L}\Phi_c)$$

dim=5/2

Sterile fermions

$$B^{\mu\nu}$$

dim=2

Dark photons

The Higgs boson

1. The scalar excitation of the Higgs field with respect of the EWSB vacuum.

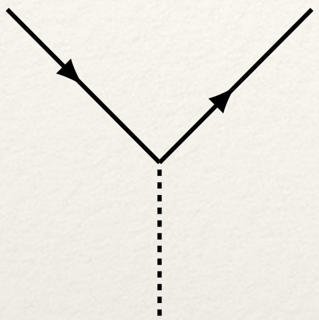
2. $M_H = 125$ GeV

3. Width = 4 MeV

4. Weak couplings to SM particles “proportional" to the mass ⇒ it can radiated by heavy particles

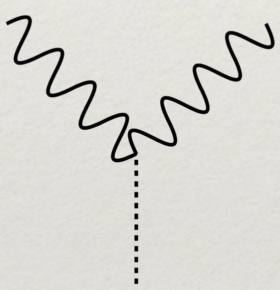
5. QCD and electrically neutral ⇒ interactions with gluons and photons only through loops, it does not radiate.

Higgs couplings



$$i\, m_f / v$$

1. The coupling to fermions is proportional to the mass.

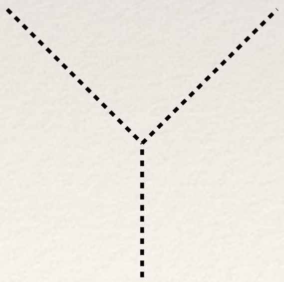


$$i g m_W g_{\mu\nu} = 2 i\, v g_{\mu\nu} \cdot m_W^2 / v^2$$

$$i g \frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2 i v g_{\mu\nu} \cdot m_Z^2 / v^2$$

2. The coupling to bosons is proportional to the mass squared.

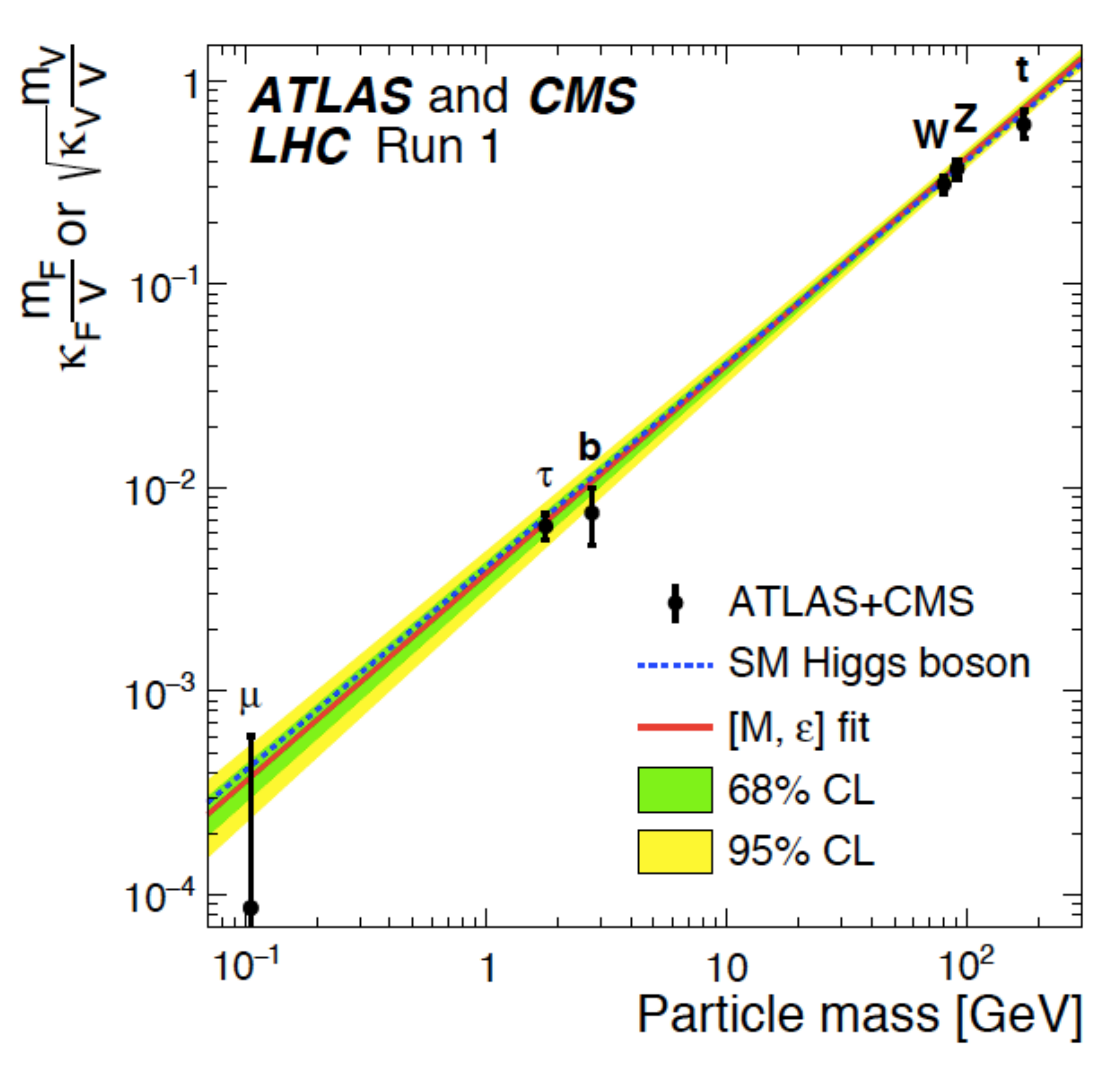
3. Four-point couplings HHVV and HHHH are also predicted from the gauge symmetry and the structure of the Higgs potential.



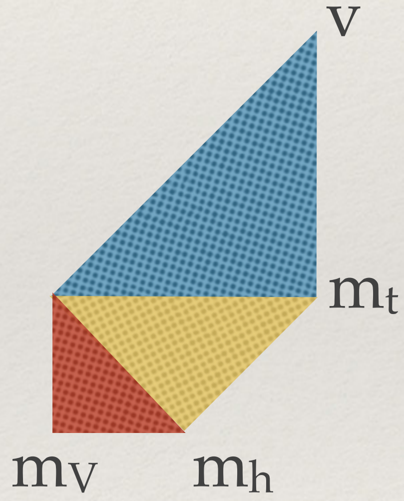
$$-3\, i v \cdot m_h^2 / v^2$$

4. Couplings to photons and gluons are loop (Vs and quarks) induced.

Higgs couplings



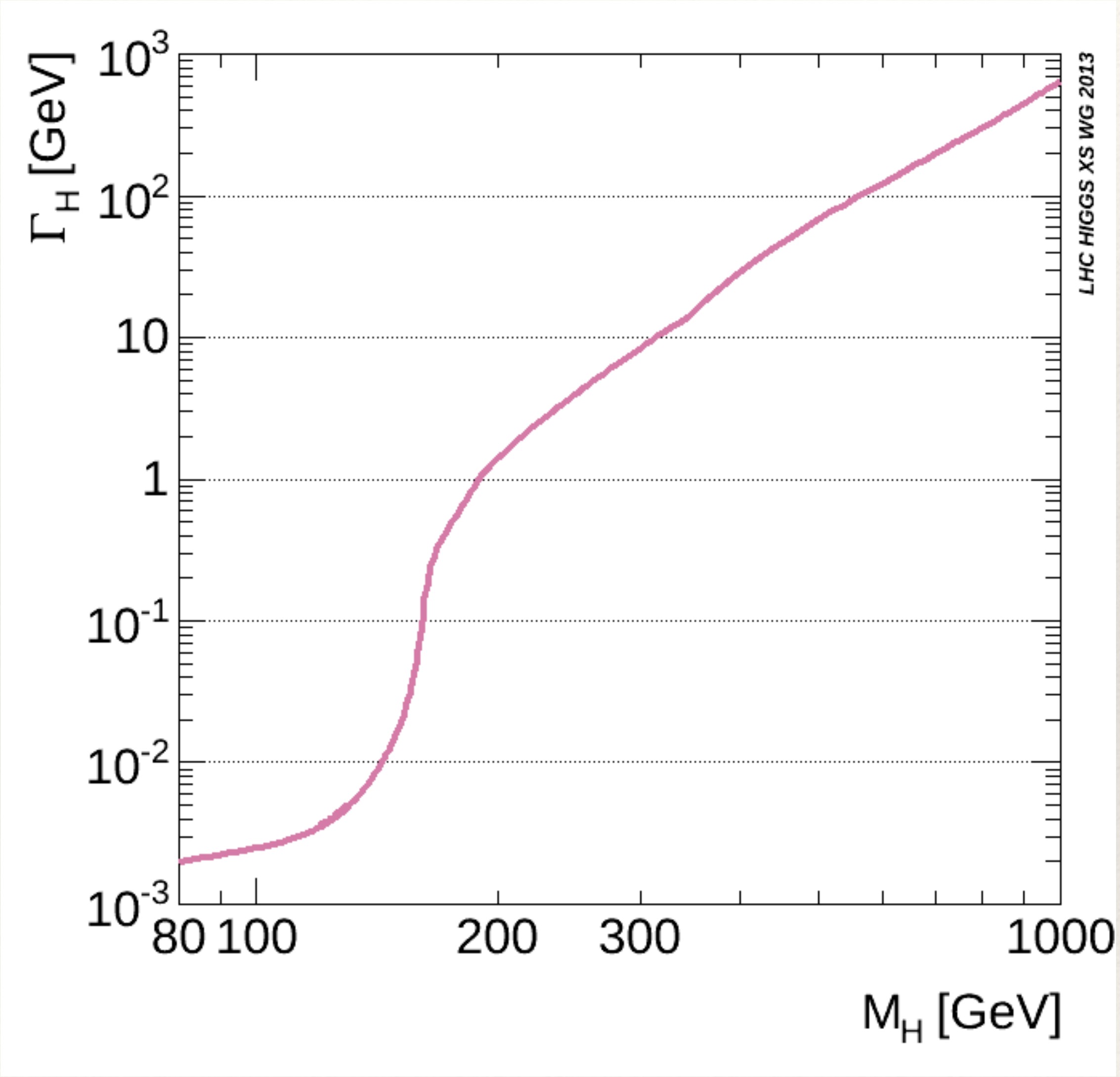
$$\frac{v}{m_t} = \frac{m_t}{m_h} = \frac{m_h}{\bar{m}_V} = \sqrt{2}$$

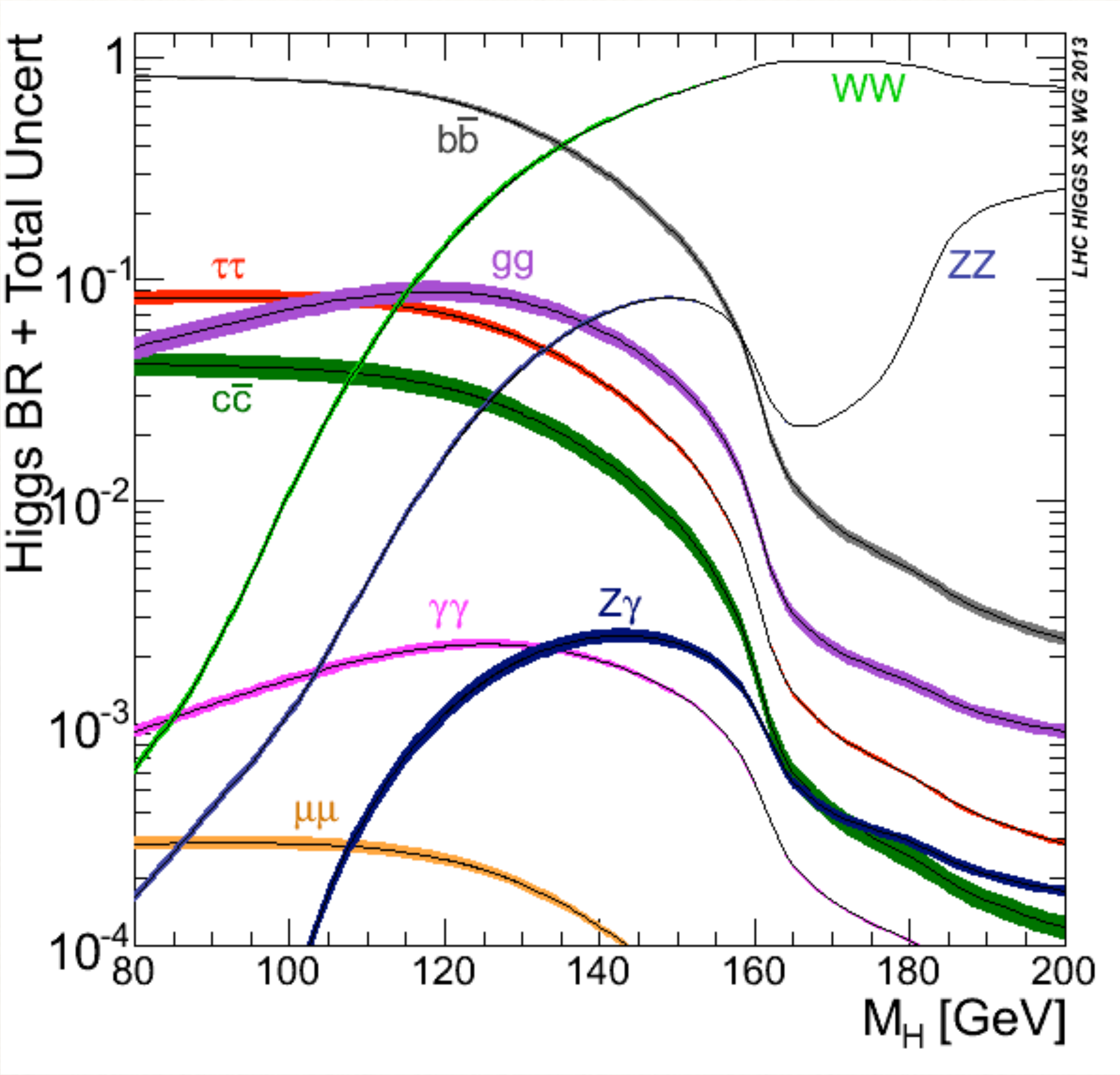


$$r = 2^{\frac{2\theta}{\pi}}$$

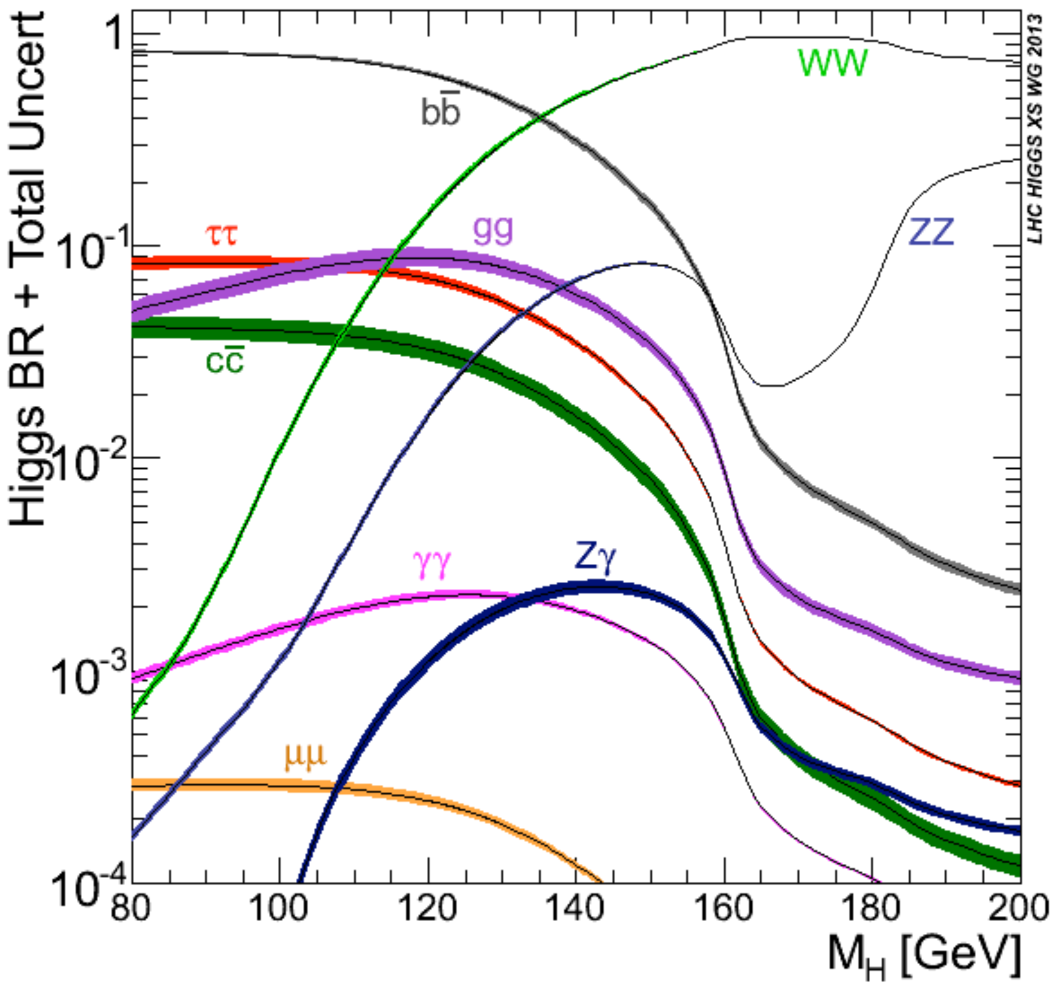
SM logarithmic spiral

Higgs decays





Higgs decays



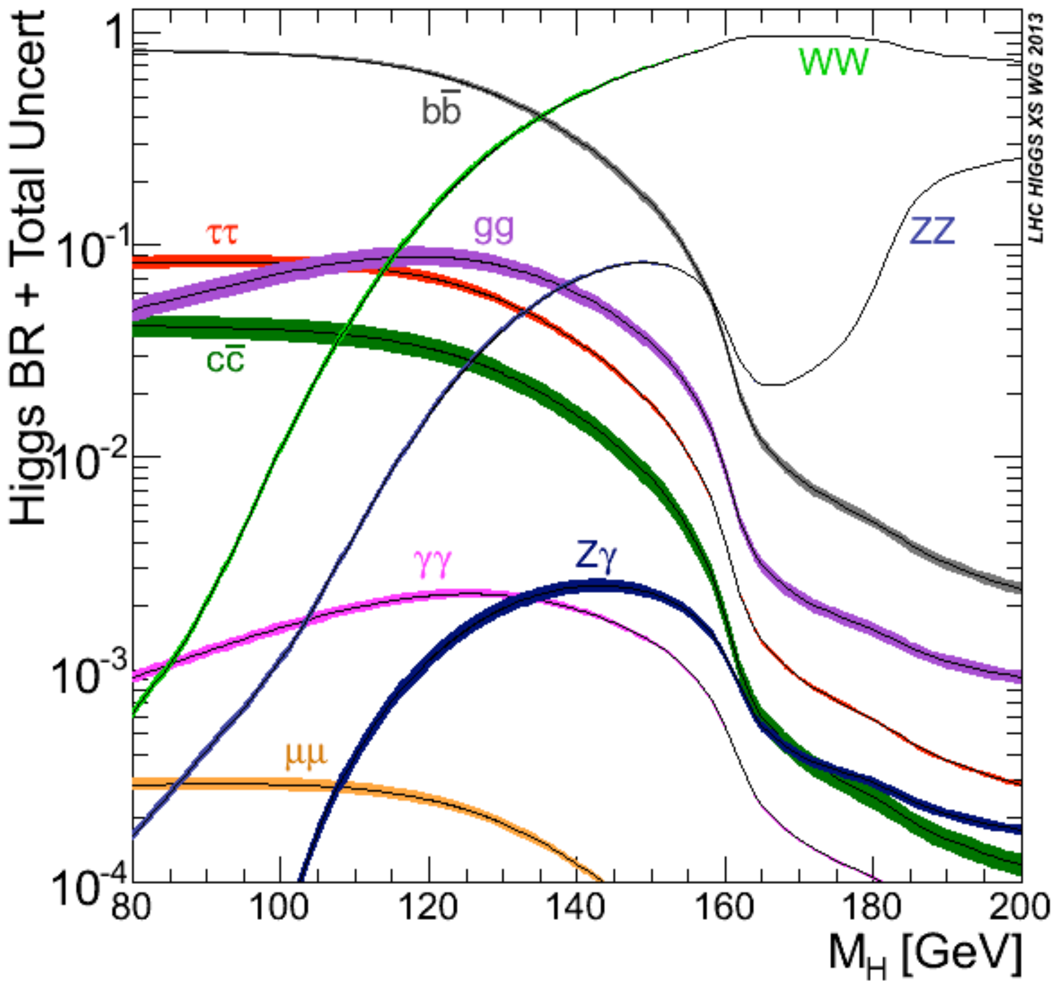
$$\Gamma(h \to f\overline{f}) = \frac{G_F m_f^2 N_{ci}}{4\sqrt{2}\pi} m_h \beta_F^3$$

$$\beta_F \equiv \sqrt{1 - 4m_f^2/m_h^2}$$

$$\Gamma(h \to q\overline{q}) = \frac{3G_F}{4\sqrt{2}\pi} m_q^2(m_h^2) m_h \beta_q^3 \left(1 + 5.67\frac{\alpha_s(m_h^2)}{\pi} + \cdots\right)$$

- H→bb dominating decay mode
- H→tau tau second most important one
- H→c c smaller because of the quark mass running!

Higgs decays

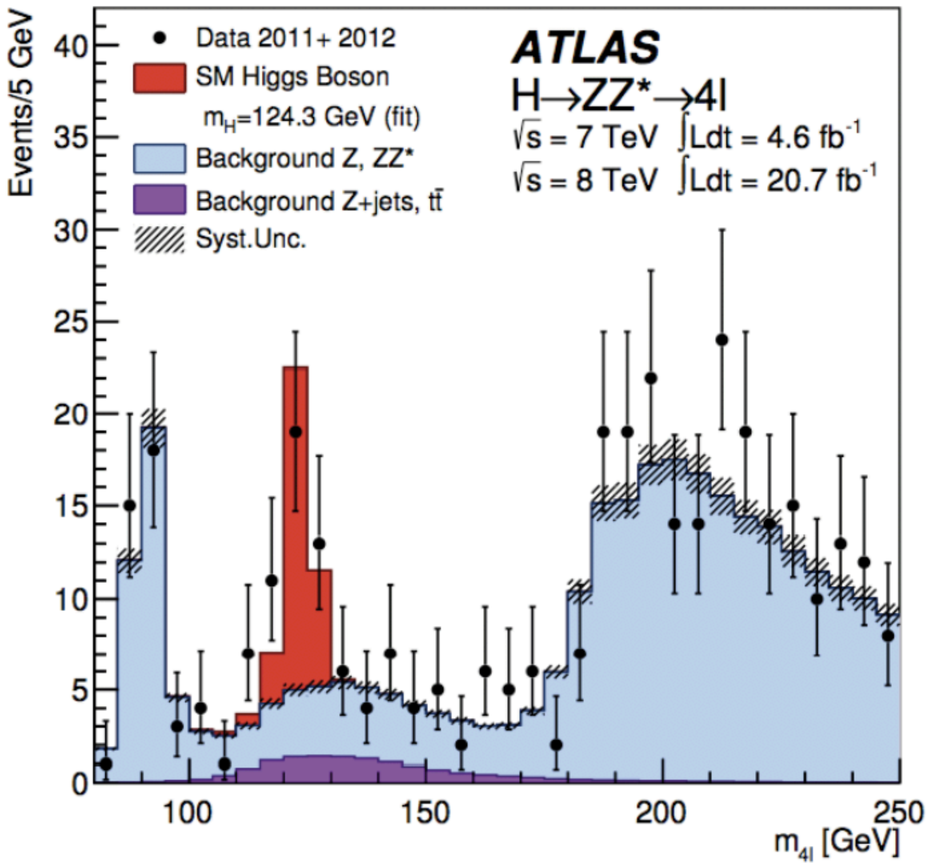


$$\Gamma(h \to WW^*) = \frac{3g^4 m_h}{512\pi^3} F\left(\frac{M_W}{m_h}\right)$$

$$\Gamma(h \to ZZ^*) = \frac{g^4 m_h}{2048 \cos^4_W \pi^3}\left(7 - \frac{40}{3}s_W^2 + \frac{160}{9}s_W^4\right) F\left(\frac{M_Z}{m_h}\right),$$

$$F(x) = -\,|\,1 - x^2\,|\left(\frac{47}{2}x^2 - \frac{13}{2} + \frac{1}{x^2}\right) + 3(1 - 6x^2 + 4x^4)\,|\ln x\,| + \frac{3(1 - 8x^2 + 20x^4)}{\sqrt{4x^2 - 1}} \cos^{-1}\left(\frac{3x^2 - 1}{2x^3}\right)$$

Higgs decays



re

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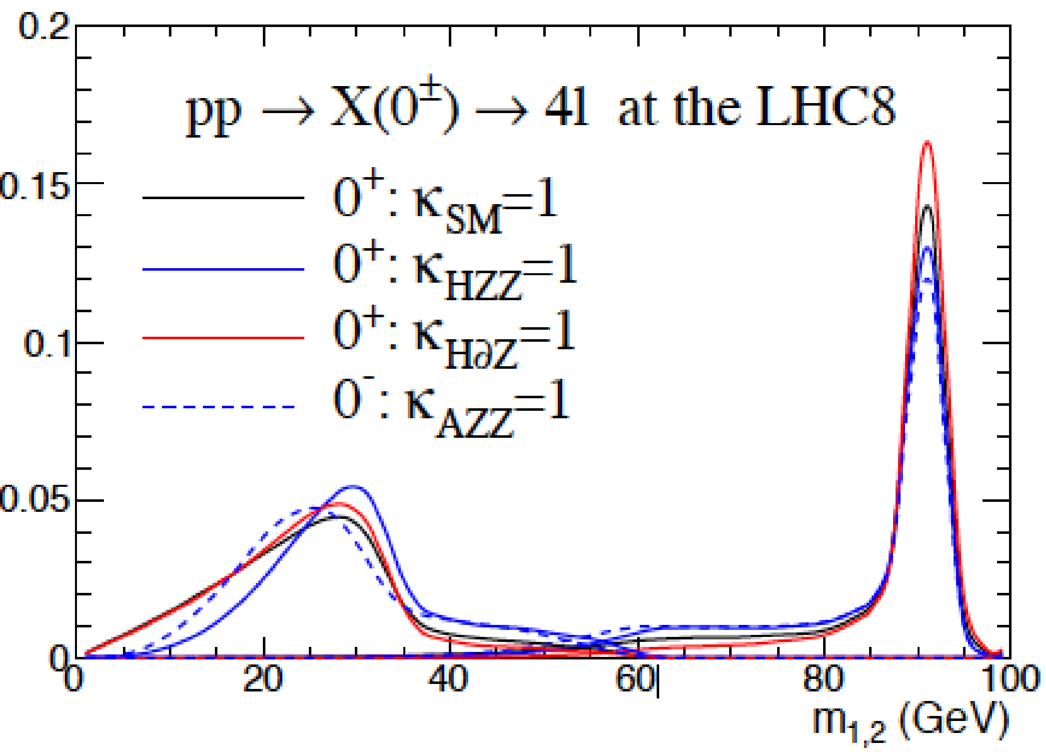
- 4l channel has been the discovery mode

Higgs decays



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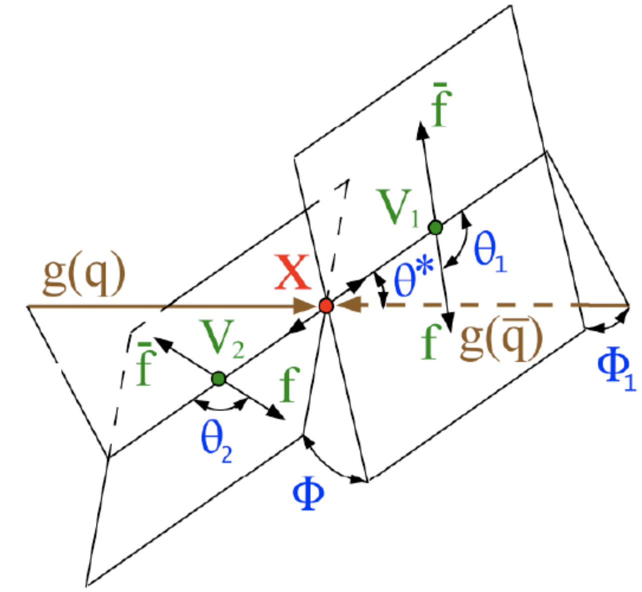
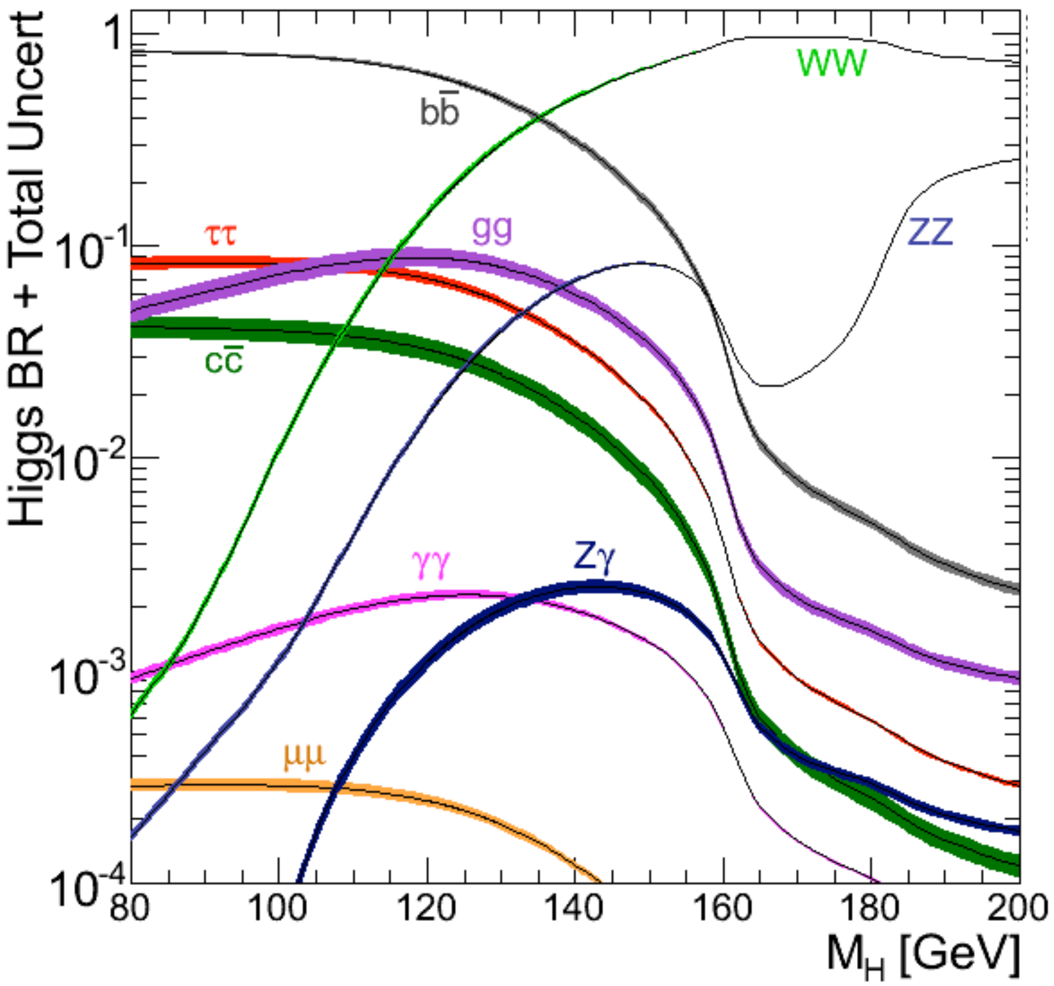
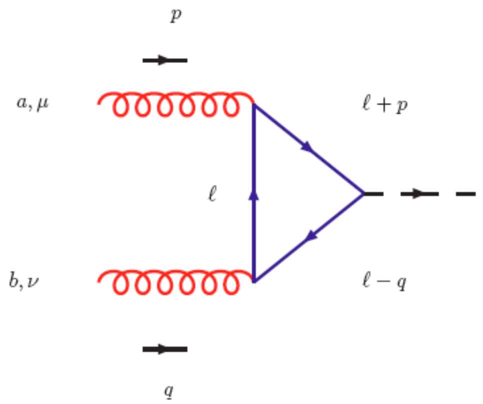
- 4l channel has the possibility of spin and CP analysing the Higgs couplings to VV.



Higgs decays





$$\Gamma(h \to gg) = \frac{G_F \alpha_s^2 m_h^3}{64\sqrt{2}\pi^3} \,|\sum_q F_{1/2}(\tau_q)\,|^2$$

where $\tau_q \equiv 4m_q^2/m_h^2$ and $F_{1/2}(\tau_q)$ is defined to be,

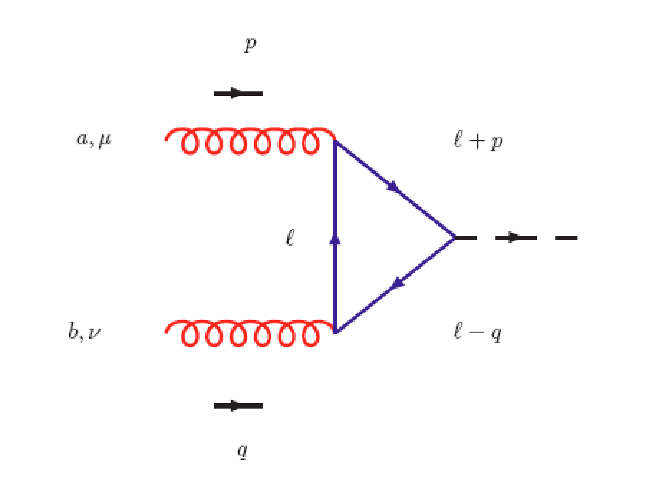
$$F_{1/2}(\tau_q) \equiv -2\tau_q \left[1 + (1-\tau_q) f(\tau_q)\right].$$

$$F_{1/2} \to \frac{2m_q^2}{m_h^2} \log^2\left(\frac{m_q}{m_h}\right)$$ for $m_h >> m_q$

$$F_{1/2} \to -\frac{4}{3}.$$ for $m_q >> m_h$

$H \to gg$ at one loop

In this case, this means that the loop calculation has to give a finite result!



Let's do the calculation!

$$i\mathcal{A} = -(-ig_s)^2 \mathrm{Tr}(t^a t^b) \left(\frac{-im_t}{v}\right) \int \frac{d^d\ell}{(2\pi)^n} \frac{T^{\mu\nu}}{\mathrm{Den}} (i)^3 \epsilon_\mu(p)\epsilon_\nu(q)$$

where

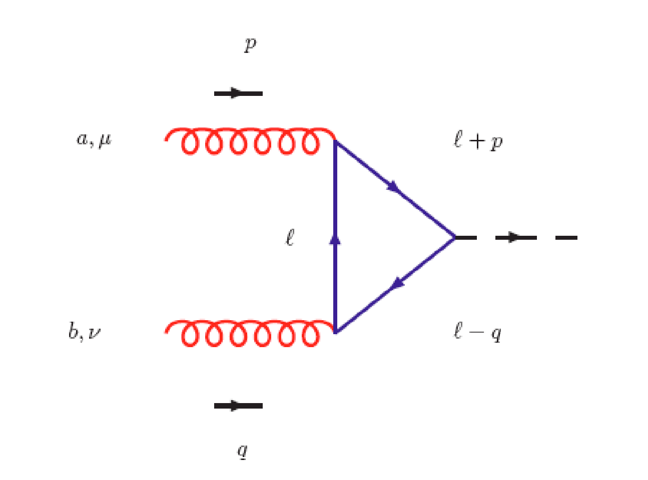
$$\mathrm{Den} = (\ell^2 - m_t^2)[(\ell+p)^2 - m_t^2][(\ell-q)^2 - m_t^2]$$

We combine the denominators into one by using $\frac{1}{ABC} = 2\int_0^1 dx \int_0^{1-x} \frac{dy}{[Ax + By + C(1-x-y)]^3}$

$$\frac{1}{\mathrm{Den}} = 2\int dx\, dy \frac{1}{[\ell^2 - m_t^2 + 2\ell\cdot(px - qy)]^3}.$$

$H \to gg$ at one loop

We shift the momentum:



$$\ell' = \ell + px - qy$$

$$\frac{1}{\text{Den}} \to 2 \int dx \; dy \frac{1}{[\ell'^{\,2} - m_t^2 + M_H^2 xy]^3}.$$

And now the tensor in the numerator:

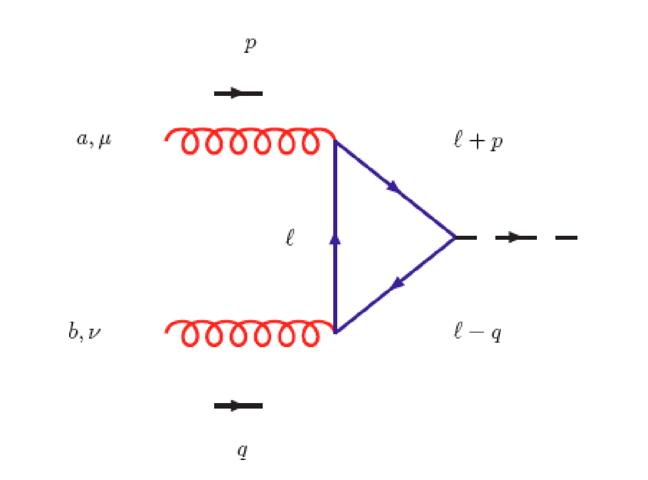
$$T^{\mu\nu} = \text{Tr}\left[(\not\ell + m_t)\gamma^\mu(\not\ell + \not p + m_t)(\not\ell - \not q + m_t)\gamma^\nu)\right]$$

$$= 4m_t\left[g^{\mu\nu}(m_t^2 - \ell^2 - \frac{M_H^2}{2}) + 4\ell^\mu\ell^\nu + p^\nu q^\mu\right]$$

where I used the fact that the external gluons are on-shell. This trace is proportional to mt ! This is due to the spin flip caused by the scalar coupling.

Now we shift the loop momentum also here, we drop terms linear in the loop momentum (they are odd and vanish)

H → gg at one loop



We perform the tensor decomposition using:

$$\int d^d k \frac{k^\mu k^\nu}{(k^2 - C)^m} = \frac{1}{d} g^{\mu\nu} \int d^d k \frac{k^2}{(k^2 - C)^m}$$

So I can write an expression which depends only on scalar loop integrals:

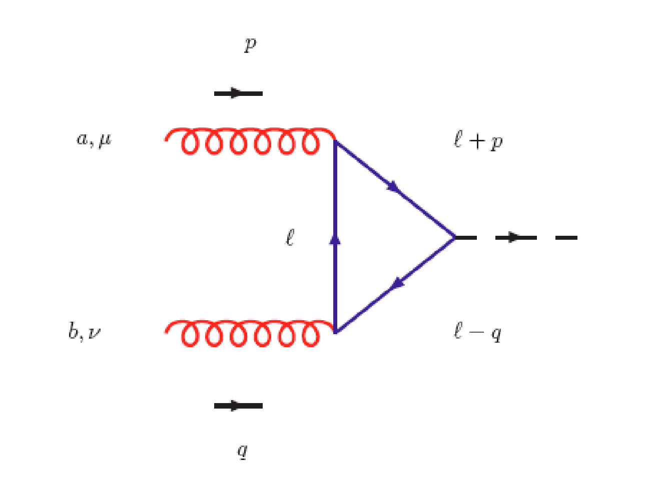
$$i\mathcal{A} = -\frac{2 g_s^2 m_t^2}{v} \delta^{ab} \int \frac{d^d \ell'}{(2\pi)^d} \int dx dy \Big\{ g^{\mu\nu} \Big[m^2 + \ell'^2 \Big(\frac{4-d}{d} \Big) + M_H^2 (xy - \frac{1}{2}) \Big]$$
$$+ p^\nu q^\mu (1 - 4xy) \Big\} \frac{2 dx dy}{(\ell'^2 - m_t^2 + M_H^2 xy)^3} \epsilon_\mu(p) \epsilon_\nu(q).$$

There's a term which apparently diverges....??
Ok, Let's look the scalar integrals up in a table (or calculate them!)

H → gg at one loop

$$\int \frac{d^dk}{(2\pi)^d} \frac{k^2}{(k^2 - C)^3} = \frac{i}{32\pi^2}(4\pi)^\epsilon \frac{\Gamma(1+\epsilon)}{\epsilon}(2-\epsilon)C^{-\epsilon}$$

$$\int \frac{d^dk}{(2\pi)^d} \frac{1}{(k^2 - C)^3} = -\frac{i}{32\pi^2}(4\pi)^\epsilon \Gamma(1+\epsilon)C^{-1-\epsilon}.$$



where d=4-2eps. By substituting we arrive at a very simple final result!!

$$\mathcal{A}(gg \to H) = -\frac{\alpha_S m_t^2}{\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{m_t^2 - m_H^2 xy}\right)\epsilon_\mu(p)\epsilon_\nu(q).$$

Comments:

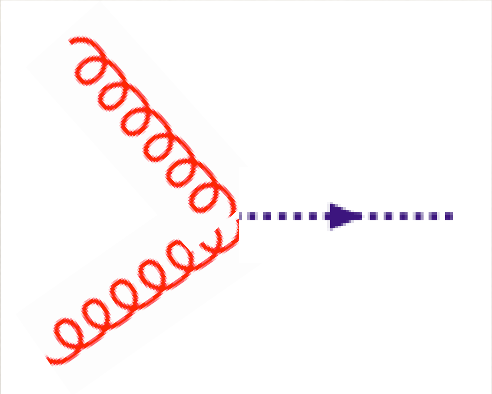
* The final dependence of the result is mt2 : one from the Yukawa coupling, one from the spin flip.
* The tensor structure could have been guessed by gauge invariance.
* The integral depends on mt and mh.

Higgs effective field theory

Let's consider the case where the Higgs is light:

$$\mathcal{A}(gg \to H) = -\frac{\alpha_S m_t^2}{\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{m_t^2 - m_H^2 xy}\right)\epsilon_\mu(p)\epsilon_\nu(q).$$

$$\xrightarrow{m \gg M_H} -\frac{\alpha_S}{3\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\epsilon_\mu(p)\epsilon_\nu(q).$$



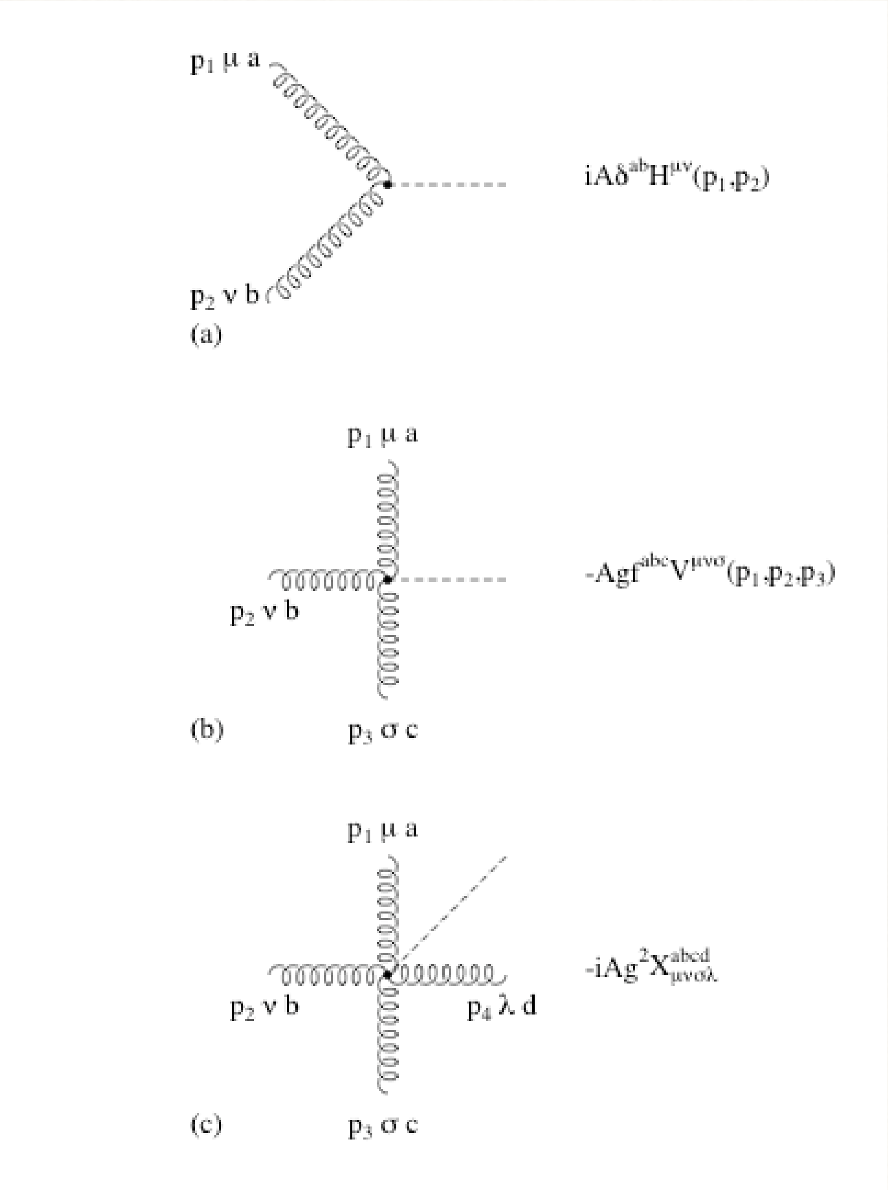
This looks like a local vertex, ggH.

The top quark has disappeared from the low energy theory but it has left something behind (non-decoupling).

Higgs effective field theory

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}\left(1 - \frac{\alpha_S}{3\pi}\frac{H}{v}\right) G^{\mu\nu}G_{\mu\nu}$$

This is an effective non-renormalizable theory (no top) which describes the Higgs couplings to QCD.

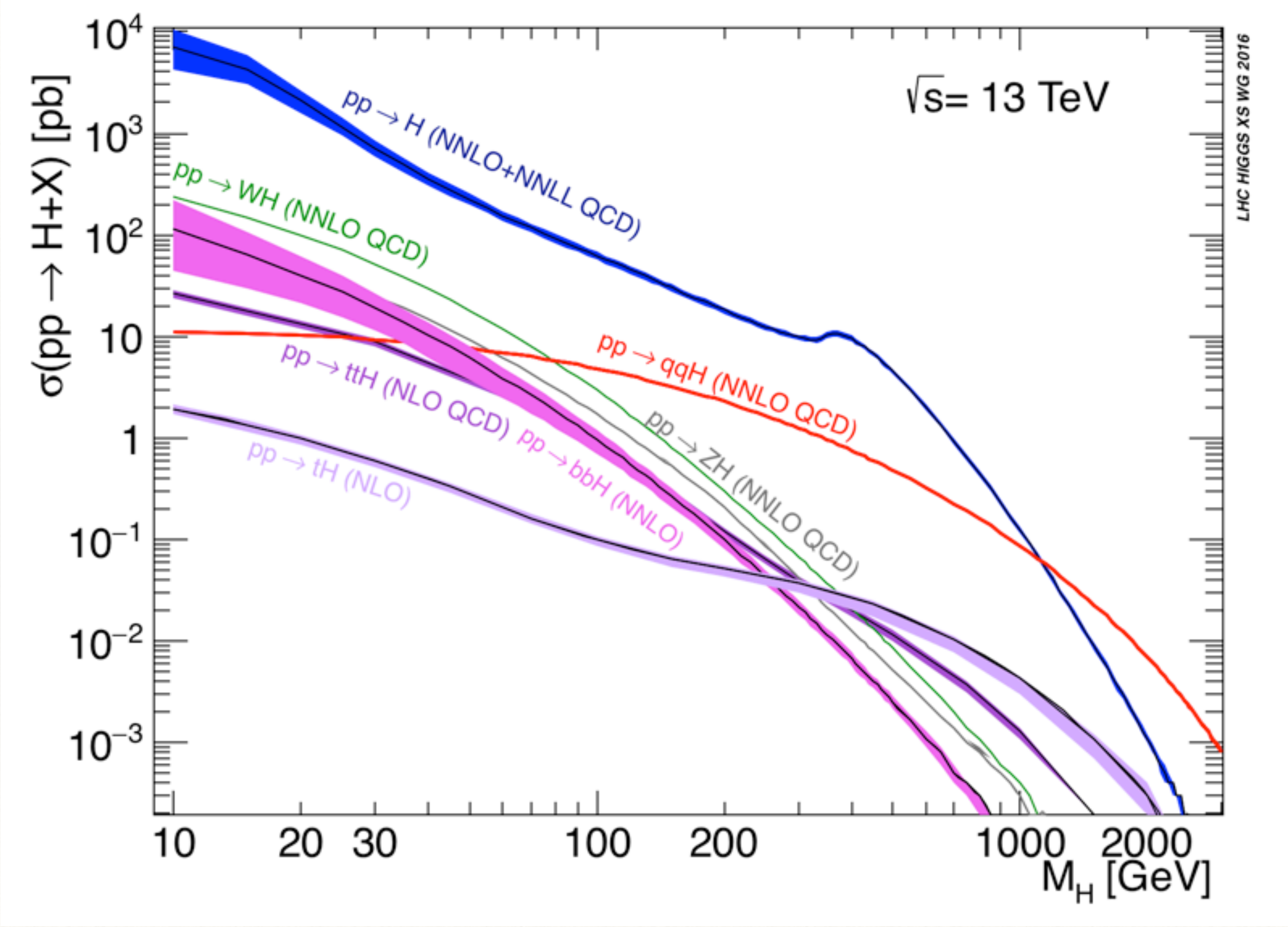


$$H^{\mu\nu}(p_1, p_2) = g^{\mu\nu} p_1 \cdot p_2 - p_1^\nu p_2^\mu .$$

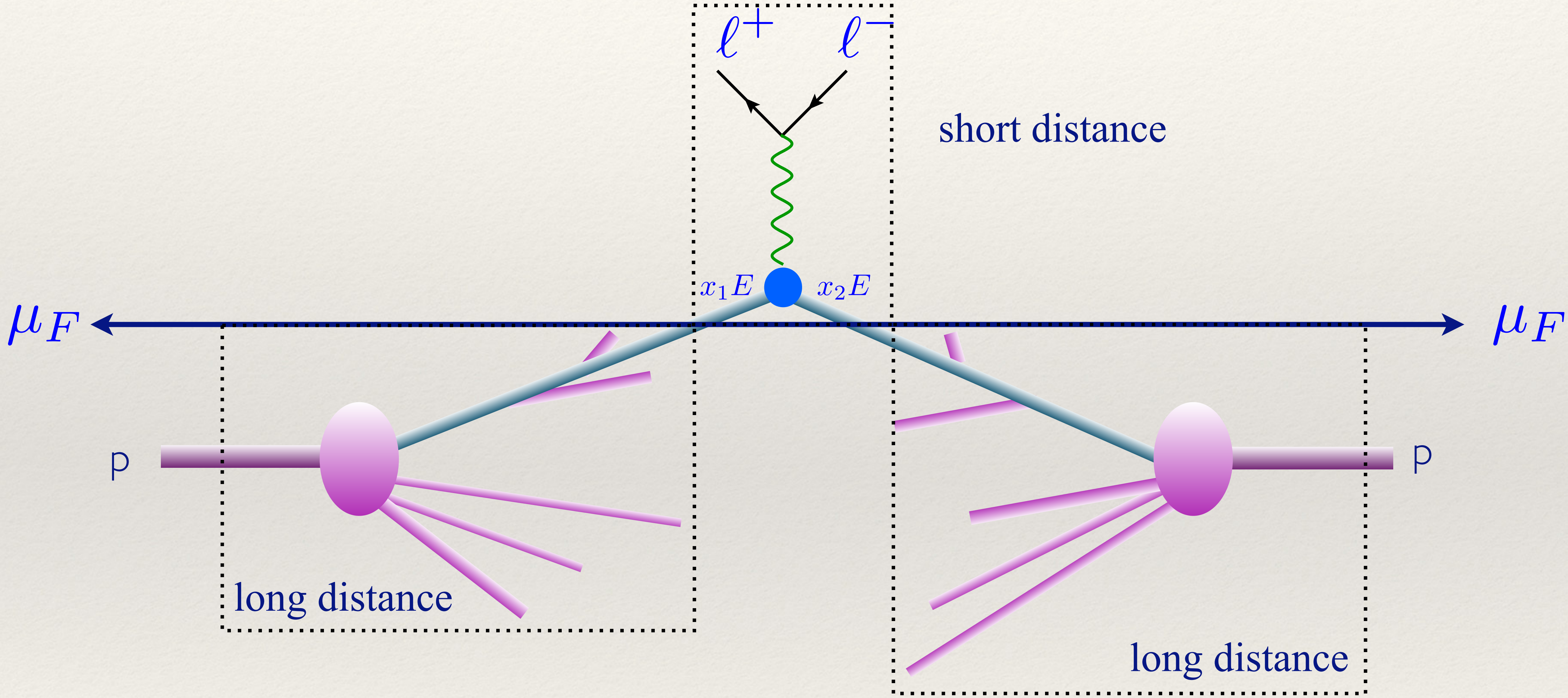
$$V^{\mu\nu\rho}(p_1, p_2, p_3) = (p_1 - p_2)^\rho g^{\mu\nu} + (p_2 - p_3)^\mu g^{\nu\rho} + (p_3 - p_1)^\nu g^{\rho\mu},$$

$$\begin{aligned} X^{\mu\nu\rho\sigma}_{abcd} = & f_{abe} f_{cde}(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}) \\ & + f_{ace} f_{bde}(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\rho}) \\ & + f_{ade} f_{bce}(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma}). \end{aligned}$$

Higgs production



The LHC master formula



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

The LHC master formula

$\hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$ Parton-level cross section

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter

$$\hat{\sigma} = \sigma^{\text{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \dots\right)$$

LO predictions

NLO corrections

NNLO corrections

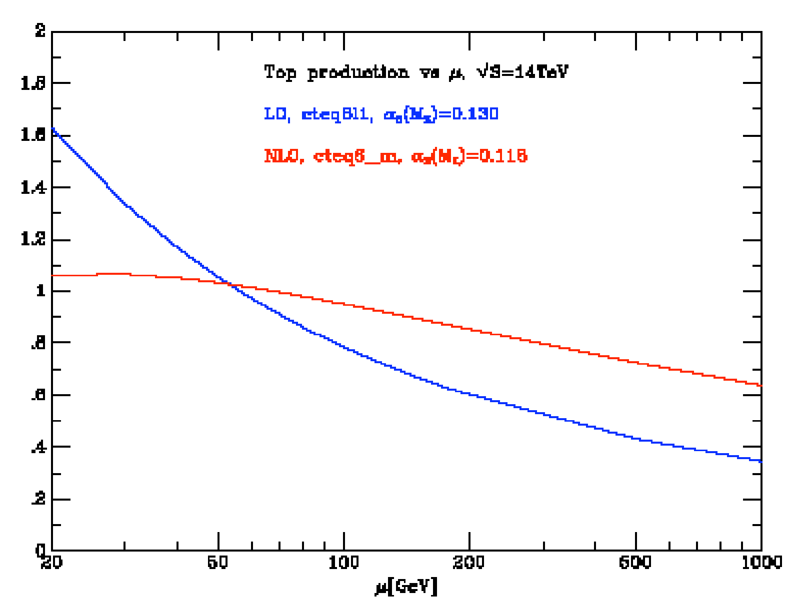
NNNLO corrections

- Including higher corrections improves predictions and reduces theoretical uncertainties: improvement in accuracy and precision.

Perturbative expansion

- Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions

  - the scale of αs is not defined
  - jets partons: jet structure starts to appear only beyond LO
  - Born topology might not be leading at the LHC



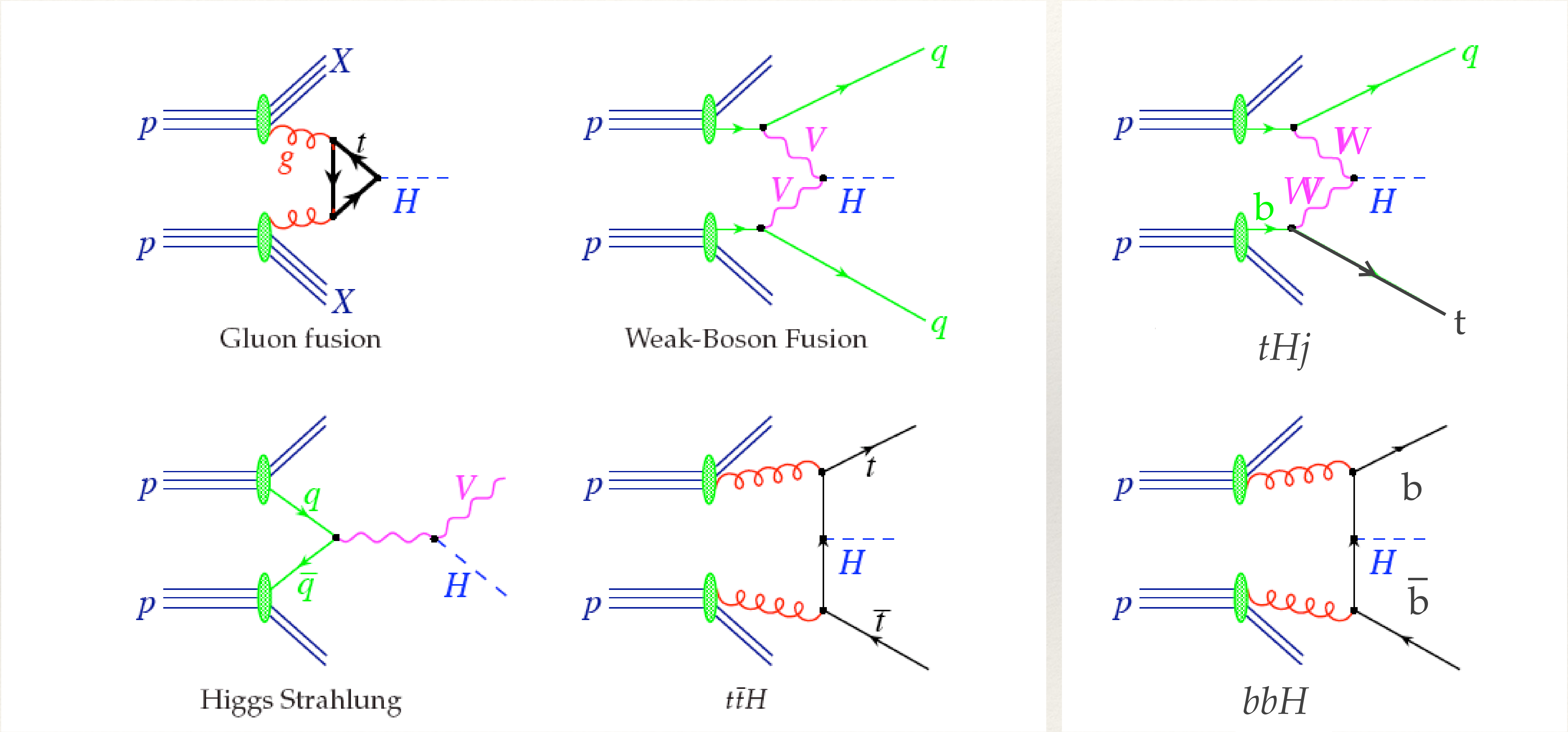
- To obtain reliable predictions at least NLO is needed

- NNLO allows to quantify uncertainties

Furthermore:

- Resummation of the large logarithmic terms at phase space boundaries
- NLO ElectroWeak corrections ($\alpha_s^2 = \alpha_W$)
- Fully exclusive predictions available in terms of event simulation that can be used in experimental analysis

Higgs production channels



Higgs production channels

Observations:

- Each channel has its own theoretical and experimental experts
- The rate of events will always depend on: $\sigma(H+X) \cdot \mathrm{Br}(H \to \mathrm{final\,state})$
- **Gluon fusion:** Loop-induced yet the largest production channel. Theoretically where most of the efforts have gone to achieve precision. Contribution of the loops from the b's around -6%. H+1 jet probes the loop structure. H+2jets background to VBF and sensitive to CP properties of the Higgs interactions.
- **Vector boson fusion**: Large, even though it is an electroweak process, because of the initial state V's. It's the brother of VH and of H to 4 leptons (probing the same couplings in different regions). Very interesting signature with two jets forwards and no QCD radiation in the central region of the detector.
- **VH:** Drell-Yan like. ZH receives also contributions from gg channel through a box. It's the channel through which we detect H to bb.
- **ttH/bbH:** directly sensitive to the to Yukawa couplings. ttH just observed by CMS. Critical to understand the quark sector.
- **tHj :** Unique SM process where the VVH and ttH couplings appear at the same time (like H->gamma gamma) probing the relative sign of the interactions.

pp→Higgs+x at NLO

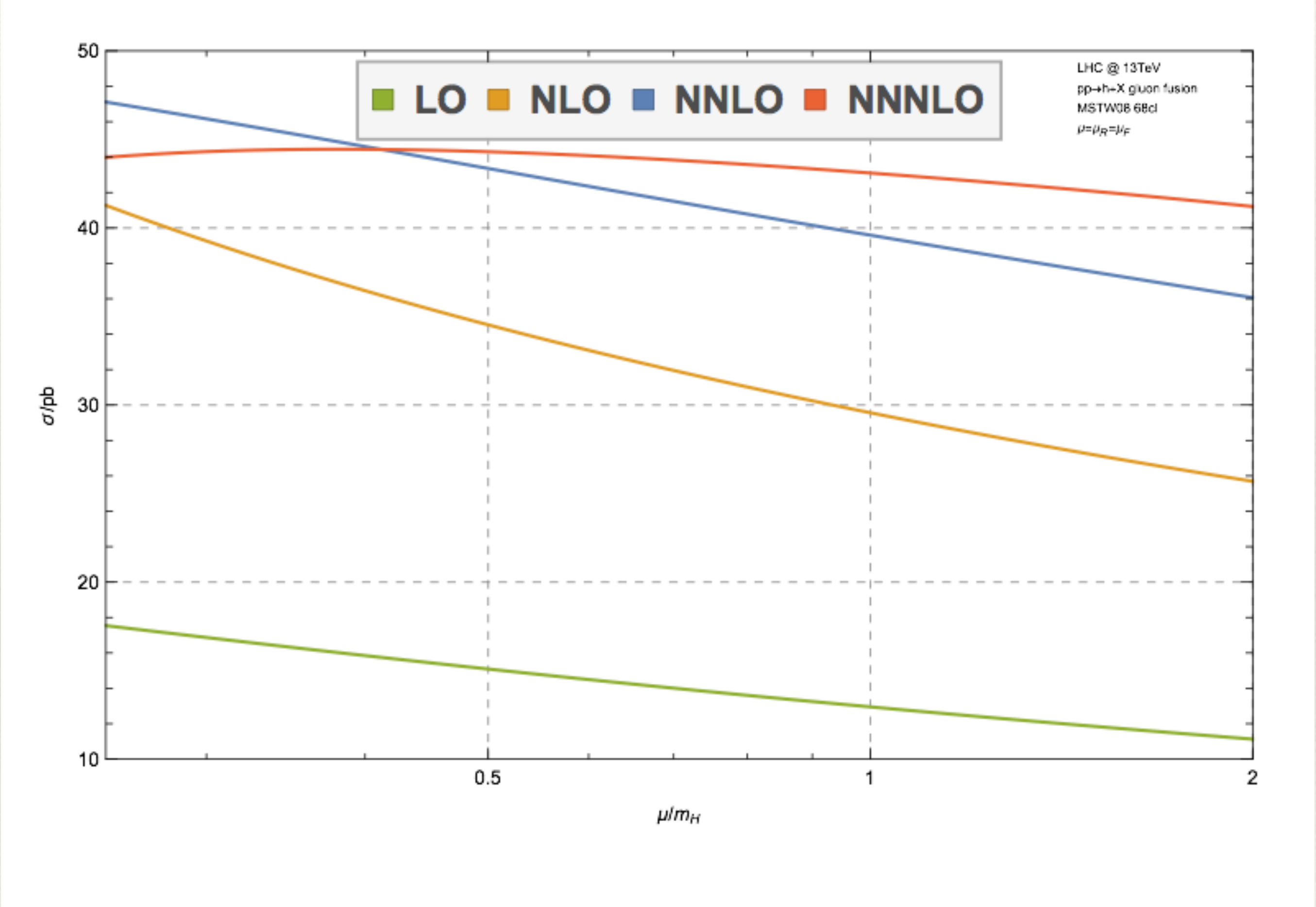
- LO : 1-loop calculation and HEFT
- NLO in the HEFT
  - Virtual corrections and renormalization
  - Real corrections and IS singularities
- Cross sections at the LHC

Write-up can be found HERE

The frontier: N3LO

[C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger (2015)]

Full calculation for the $gg \to H$ completed through the evaluation of 30 terms in the soft-expansion: first ever complete calculation at N3LO in hadronic collisions.



Significant reduction of uncertainties from missing higher orders and PDF+α_s

Scale dep. stabilizes around $\mu=m_H/2$

N3LO effect +2.2% at $\mu=m_H/2$

Corresponding new results for the Higgs cross section including mass effects at NLO and the other known corrections at 13 TeV expected soon.

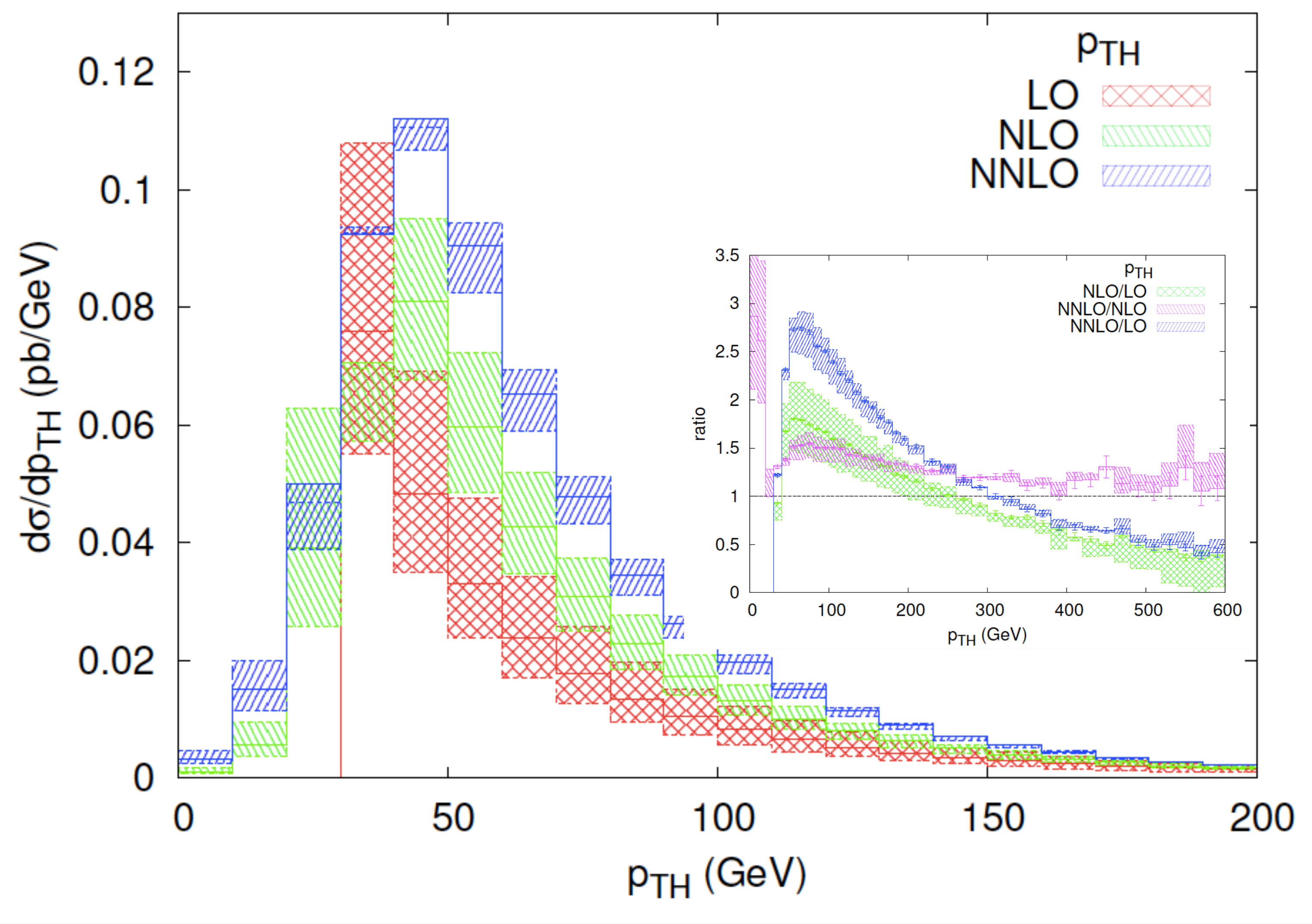
H+jet at NNLO (in the EFT)

NNLO calculation carried out with three independent methods (antenna subtraction, subtraction+sector, N-jettiness)

X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2014)

R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)

R.Boughezal, C.Focke, W.Giele ,X.Liu, F.Petriello (2015)



Quantitative effect smaller than previously anticipated from gg only: at the 20% level ($\mu=m_H$)

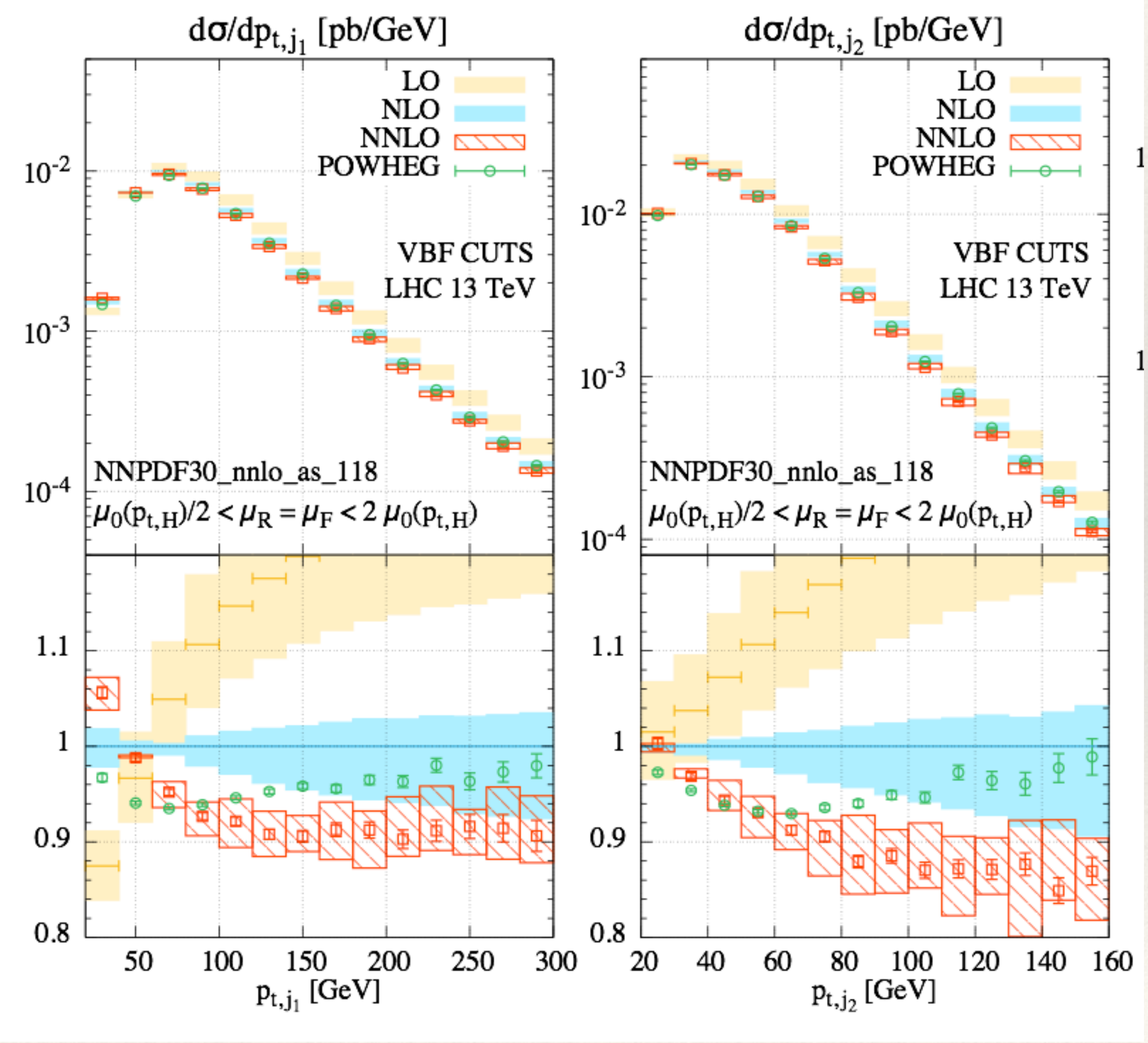
VBF at NNLO

Vector boson fusion (VBF) is an important production channel for the Higgs boson: distinctive signature with little hadronic activity in the central rapidity region.

Fully inclusive NNLO corrections known since quite some time [P.Bolzoni, F.M,S.Moch,M.Zaro (2010)] in the structure function approach: O(1%) effect.

Fully exclusive NNLO computation recently completed (still neglecting color exchanges between quark lines) [M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)]

NNLO corrections make pT spectra softer larger impact when VBF cuts are applied



	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.826\,^{+0.013}_{-0.014}$

Review questions: Higgs

1. Determine the scaling of the partial widths of the Higgs with respect to the Higgs mass and the final state particle mass for fermions and vector bosons.

2. Calculate the width of a pseudo-scalar into two gluons at one-loop or via the EFT.

3. List the most salient features (size, typical signatures, backgrounds, coupling information, status of the predictions) of the each of the main production mechanisms for the Higgs boson at the LHC.

4. Brainstorm on other Higgs subleading production mechanisms at the LHC. Imagine a reason why the could be interesting/useful. Guess-estimate their cross sections first, then check it with an automatic tool MG5aMC.

5. Brainstorm on how new physics could modify the couplings of the Higgs to the SM particles. Make a list of simple modification/additions to the SM and determine how the couplings, production and decay of the Higgs would be modified.

The top quark

- It is the $SU(2)_L$ partner of the bottom.

- $t_L \Rightarrow T_3=+1/2$, t_R singlet.

- Its mass is obtained in the EWSB.

- $Q_t=+2/3$ and is a color triplet.

- $m_t=174$ GeV, $\Gamma_t=1.4$ GeV

- All gauge couplings are fixed.

It is just as all other (up) quarks: what's so special about it?

The top is special

In the SM, it is the ONLY quark

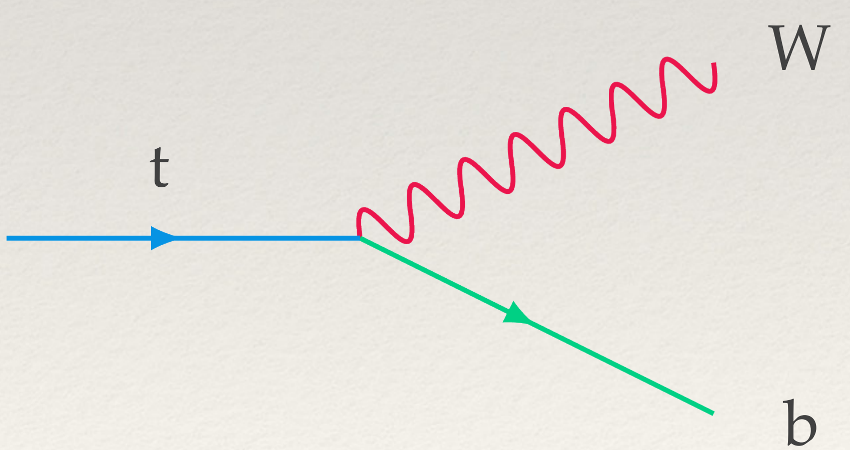
1. with a "natural mass":

$m_{top} = y_t\, v/\sqrt{2} \approx 174$ GeV $\Rightarrow y_t \approx 1$

It "strongly" interacts with the Higgs sector. This also suggests that top might have special role in the mechanism of EWSB and/or fermion mass generation. It also influences the Higgs potential at high energy and it is the main destabiliser for the Higgs.

2. that decays before hadronizing

$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}$ s
$\tau_{top} \approx h/\, \Gamma_{top} = 1/(G_F\, m_t^3\, |V_{tb}|2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}$ s
(with $h = 6.6\ 10^{-25}$ GeV s)



(Compare with $\tau_b \approx (G_F^2\, m_b^5\, |V_{bc}|^2\,)^{-1} \approx 10^{-12}$ s)

Top mass definition

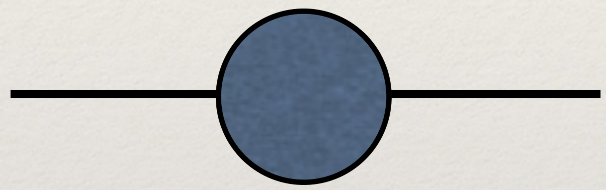
The top mass is so precisely measured (m_t=173.1 ± 1.0 GeV) that we have to worry about its definition.

Leading order:

$$\frac{1}{\not p - m}$$

(pole) mass = m

Higher orders:



$$\frac{1}{\not p - m_R - \Sigma(\not p)}$$

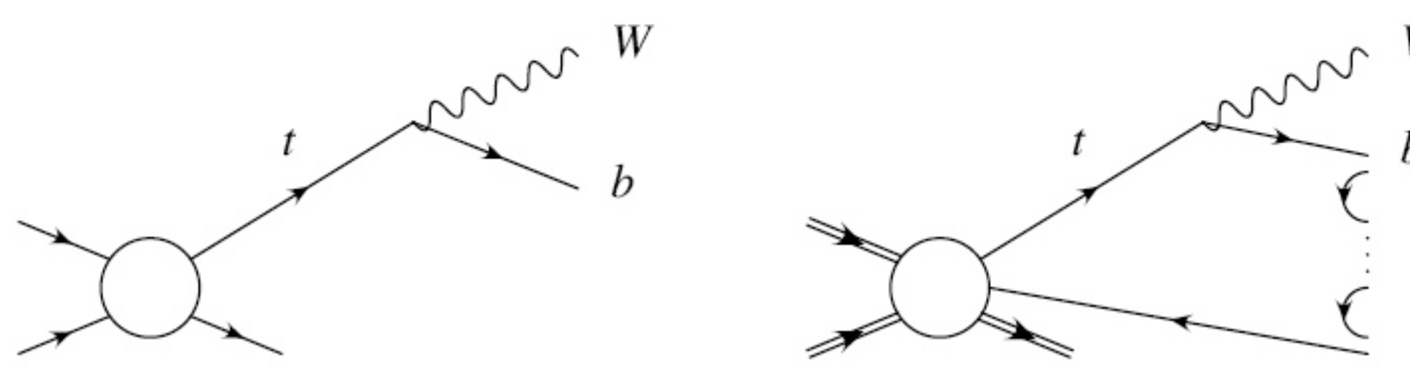
mR = renor. mass

(At least) two possible renormalisation schemes: MSbar and on-shell, leading to to different mass definitions.

The MSbar mass is a fully perturbative object, not sensitive to long-distance dynamics. It can be determined as precisely as the perturbative calculation allows. The mass is thought as any other parameter in the Lagragian. It is the same as the Yukawa coupling.

Mass definition

The pole mass would be more physical (pole = propagation of particle, though a quark doesn't usually really propagate -- hadronisation!) but is affected by long-distance effects: it can never be determined with accuracy better than ΛQCD.

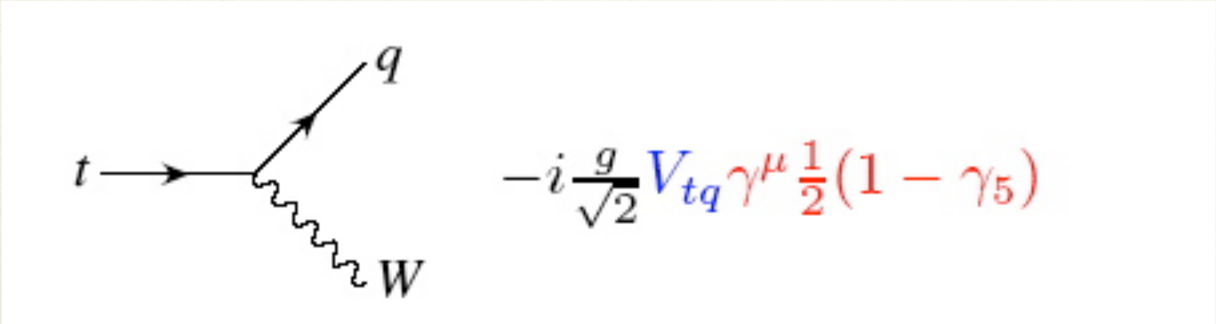


The pole mass is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.

The two masses can be related perturbatively (modulo non-perturbative corrections!!):

$$m_{pole} = \overline{m}(\overline{m}) \left(1 + \frac{4}{3}\frac{\overline{\alpha}_s(\overline{m})}{\pi} + 8.28 \left(\frac{\overline{\alpha}_s(\overline{m})}{\pi}\right)^2 + \cdots\right) + O(\Lambda_{\rm QCD})$$

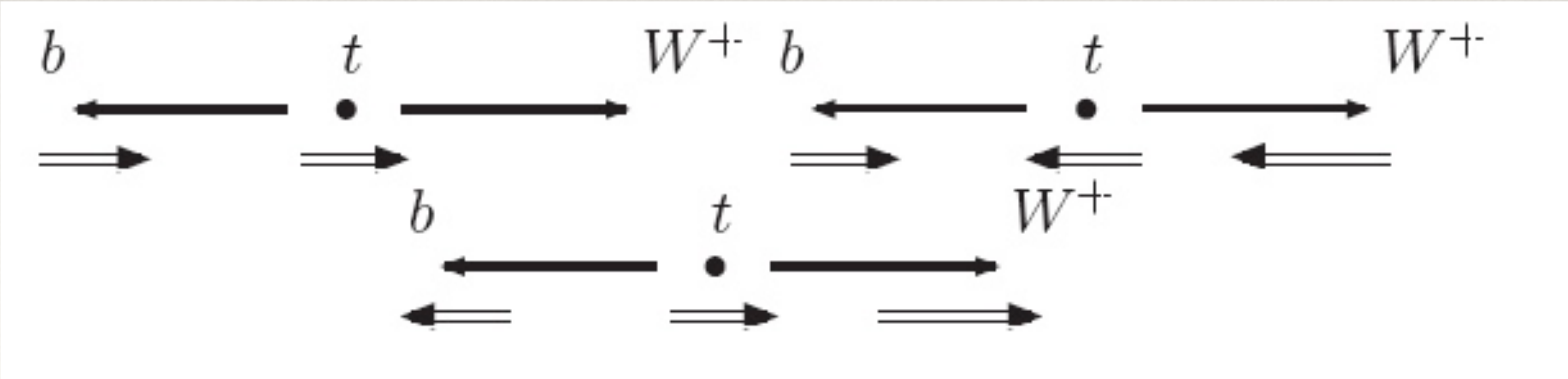
W polarisation



The SM vertex of the top decay implies that it's only the t_L that takes part to the interaction.

This has straightforward consequences on the possible helicity states of the on-shell W produced in the decay.

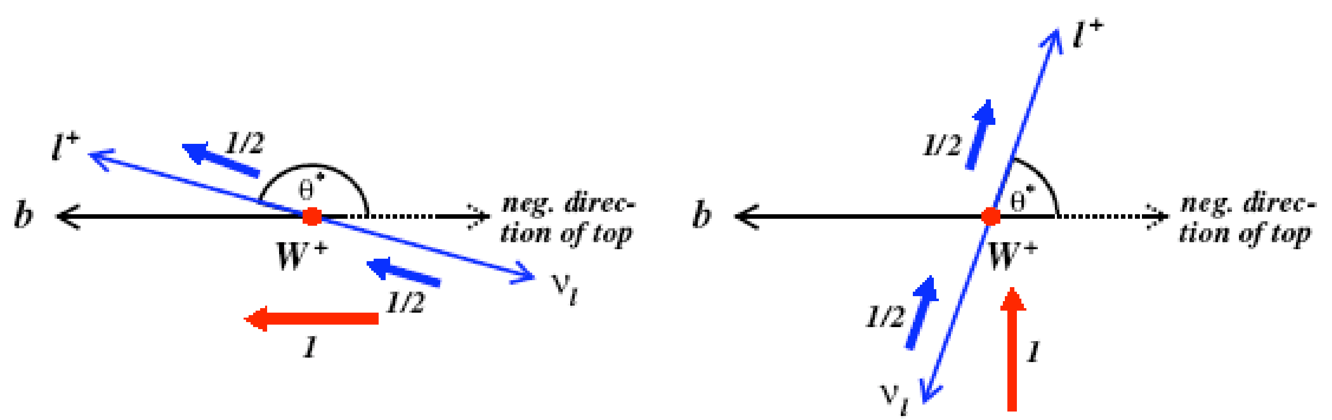
Neglecting mb, this implies that the W can be only either longitudinally polarised or with negative helicity. In general:



How do we measure it?? The W polarisation is inherited by its decay products, which "remember it" in their angular distributions.

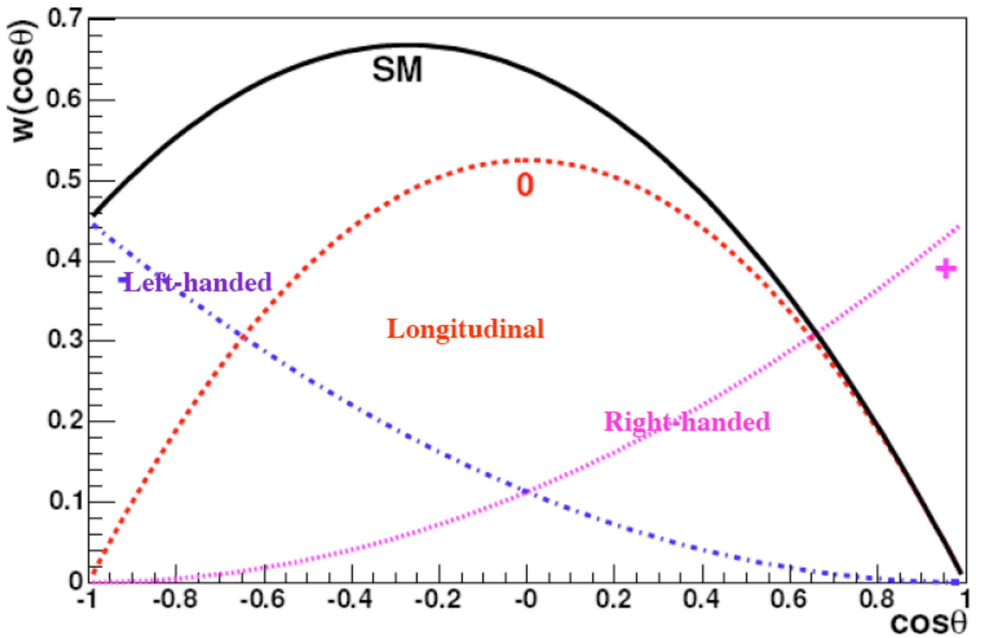
W polarisation

$$\frac{1}{N}\frac{dN(W\to l\nu)}{dcos\theta} = K\left[f_0 \sin^2\theta + f_L(1-\cos\theta)^2 + f_R(1+\cos\theta)^2\right]$$



$$f_0 = \frac{m_t^2}{2m_W^2 + m_t^2} = 70\%$$

Fraction of longitudinal W's (basically the only ones we see in a pp collider!)



- The formula above is already not trivial since it says that W polarisations don't interfere! (This is true only for 1dim distributions!)
- Longitudinal polarisation come from the Higgs doublet (charged component).
- cos(θ), which is defined in a specific frame, can be related to m(lepton,bottom) or pt(lepton) , ergo
- no top momentum reconstruction necessary!
- Rather "easy measurement" .

"No hadronization ⇔ Top spin effects"

We have now very clear that most probably (if Vtb is indeed 1) top decays before hadronising,

$$\tau_{had} \approx h/\Lambda_{QCD} \approx 2{\bullet}10^{-24}\ s\ >\ \tau_{top}^{dec} \approx h/\ \Gamma_{top}\ 5{\bullet}10^{-25}\ s$$

Therefore non-perturbative effects (soft-gluons) don't have the time to change the spin of the top which is then passed from the production to the decay. As a result the spin becomes a typical quantum mechanical quantity and correlation measurements can be performed (see tomorrow).

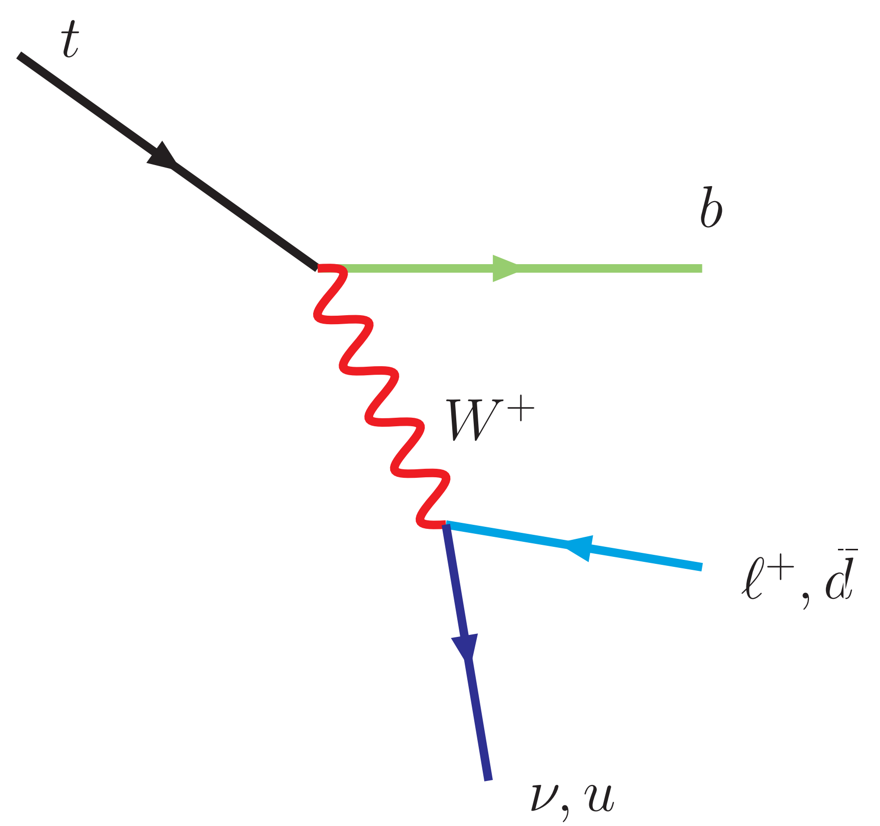
HOWEVER, one can also ask : Is the opposite true? if we see spin correlation effects do we automatically put an upper bound on the width and hadronization? NO! Spin-flips are due to CHROMOMAGNETIC interactions, which are mediated by dimension 5 operators:

$$\mathcal{L}_{\rm mag} = \frac{C_m}{4m_t}\bar{Q}_v G_{\mu\nu}\sigma^{\mu\nu}Q_v \Rightarrow \tau_{\rm flip} \simeq h\left(\frac{\Lambda^2_{QCD}}{m_t}\right)^{-1} >> \tau_{\rm had}$$

If, for instance, Vtb ~ 0.3, then top would start hadronizing into mesons and still conserve its spin!

[Falk and Peskin, 1994]

"No hadronization ⇔ Top spin effects"



	ℓ^+	$\bar{d}$	u	b	$j_<$	**T**	$j_>$
LO:	1	1	-0.32	-0.39	0.51	-0.32	0.2
NLO:	0.999	0.97	-0.31	-0.37	0.47	-0.31	

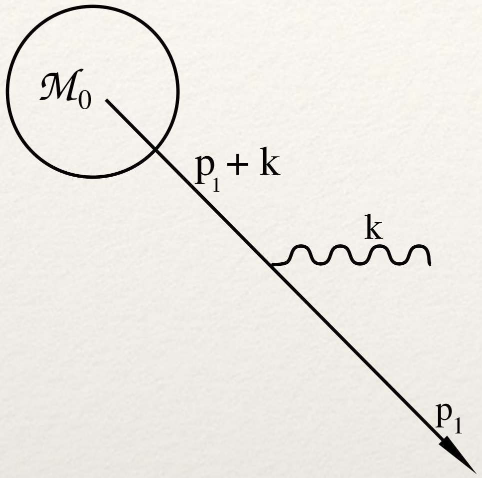
In particular one can easily show that for the top, the lepton+ (or the d), in the top rest frame, tends to be emitted in the same direction of the top spin.

Note that this has nothing to do with W polarisation! In particular one studies spin correlations between the top and anti-top in ttbar production and the spin of the top in single top.

Results depend on the degree of polarisation (p) of the tops themselves and from the choice of the "spin-analyser" k_i.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1 + p\, k_i \cos\theta}{2}$$

Radiation off the top



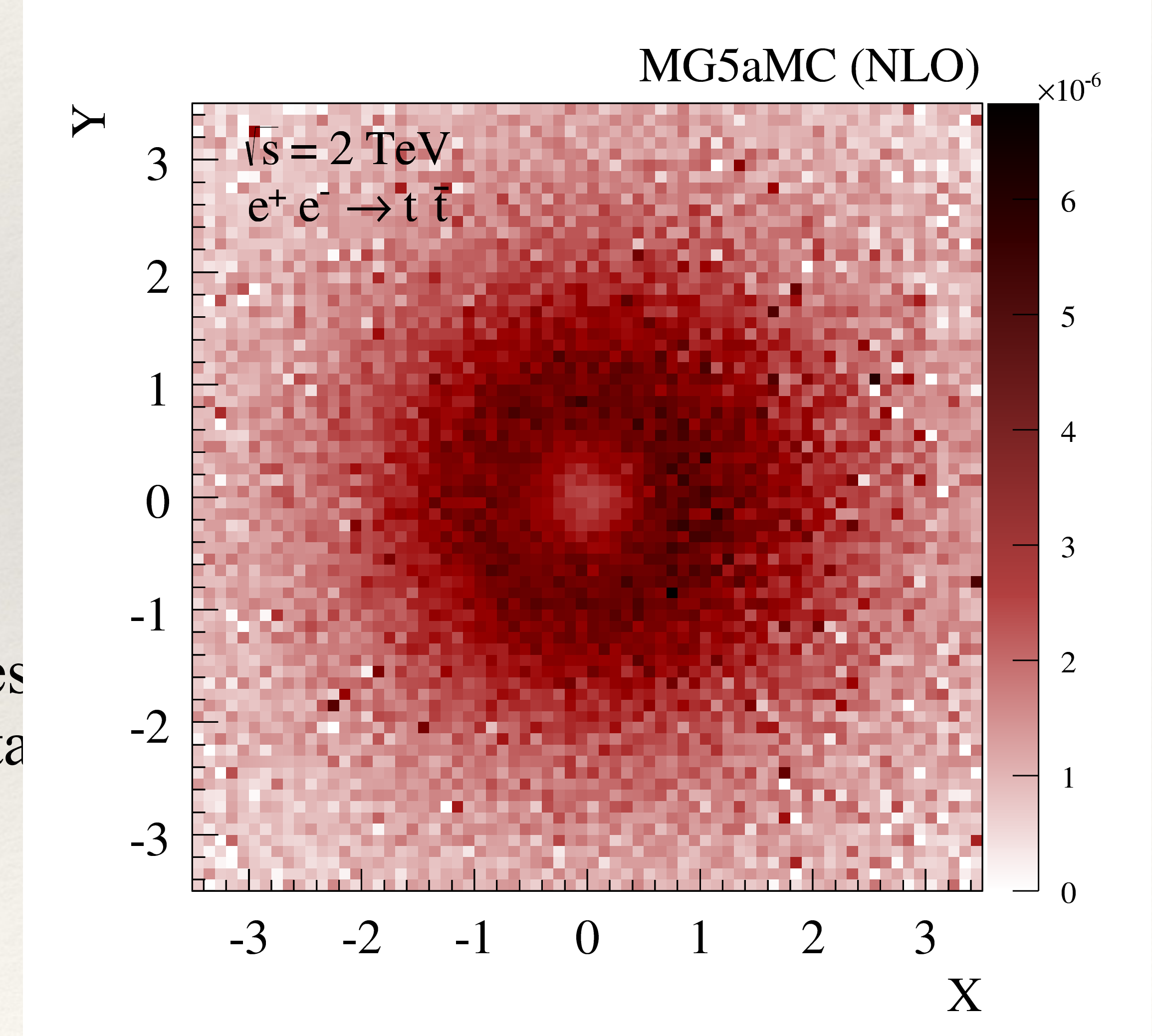
Consider gluon emission off a heavy quark using perturbation theory:

$$D^{\text{real}}(x,k_\perp^2,m^2) = \frac{C_F\alpha_S}{2\pi}\left[\frac{1+x^2}{1-x}\,\frac{1}{k_\perp^2+(1-x)^2m^2} - x(1-x)\,\frac{2m^2}{(k_\perp^2+(1-x)^2m^2)^2}\right]$$

In the massless case (m=0) we have a non-integrable collinear singularity:

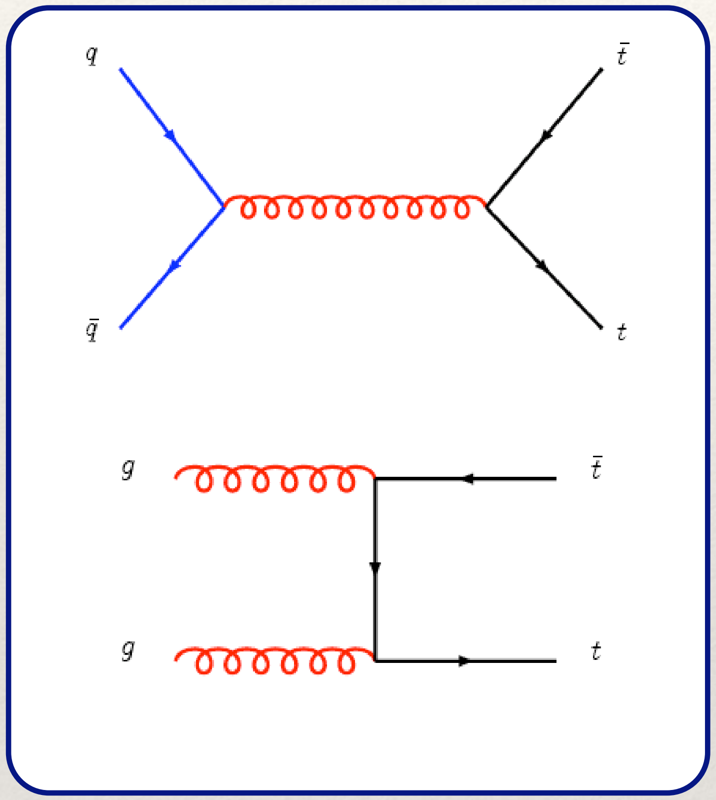
$$\int_0 D(x,k_\perp^2)dk_\perp^2 = \frac{1+x^2}{1-x}\int_0 \frac{dk_\perp^2}{k_\perp^2} = \infty$$

The presence of the heavy quark mass suppresses the collinear radiation at small transverse momenta and allows the integration down to zero.

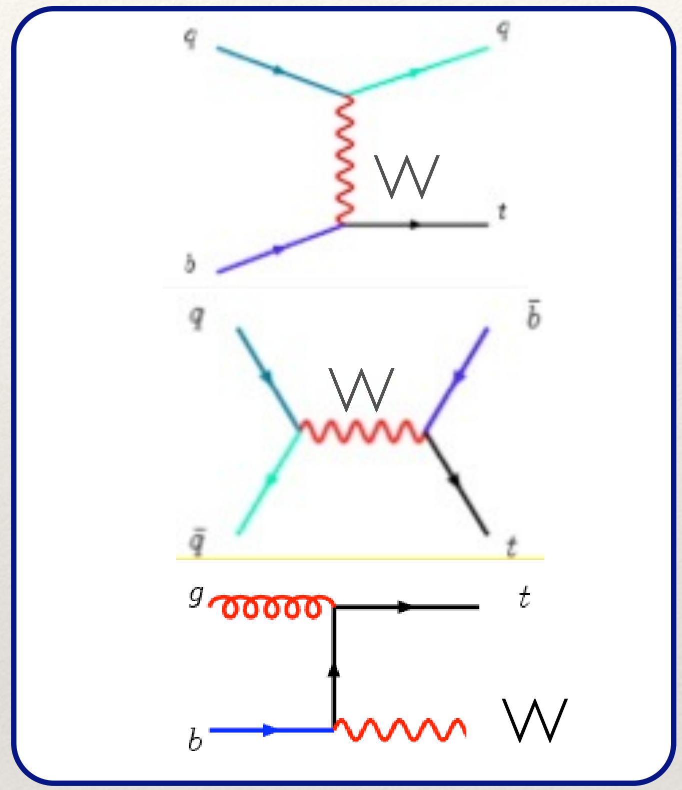


Top production at the LHC

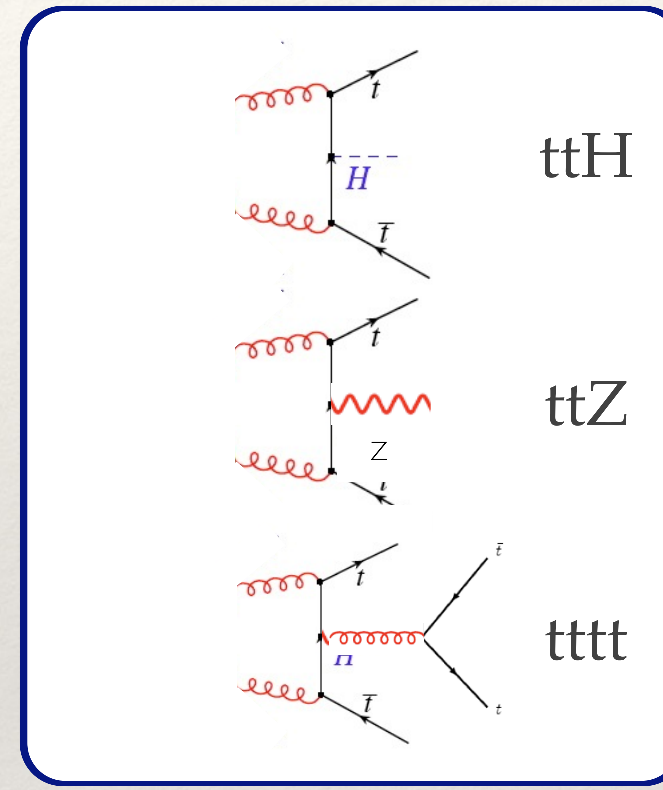
Strong



Weak



Associated



10^6

$250 \cdot 10^3$

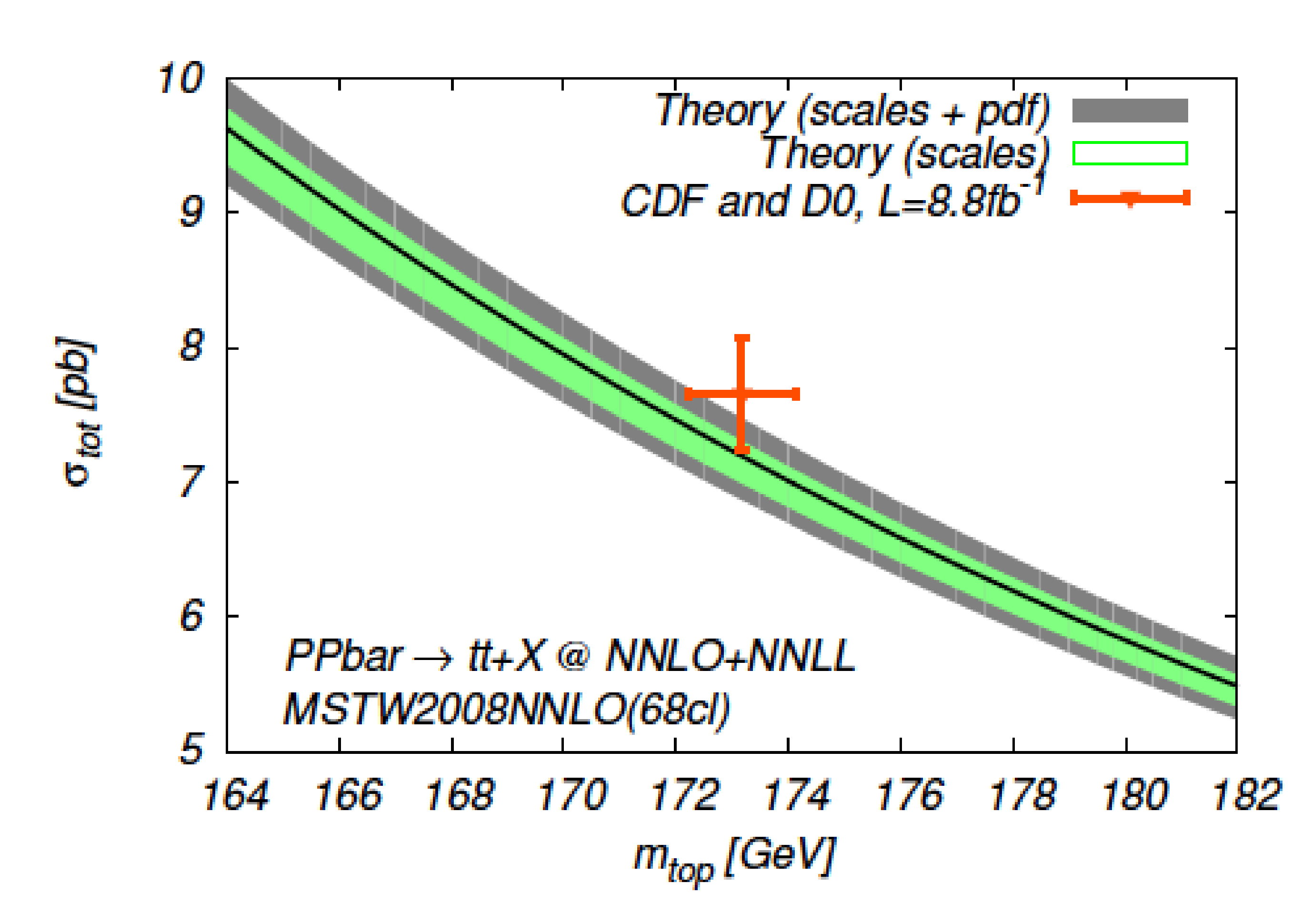
$< (2-3) \cdot 10^3$

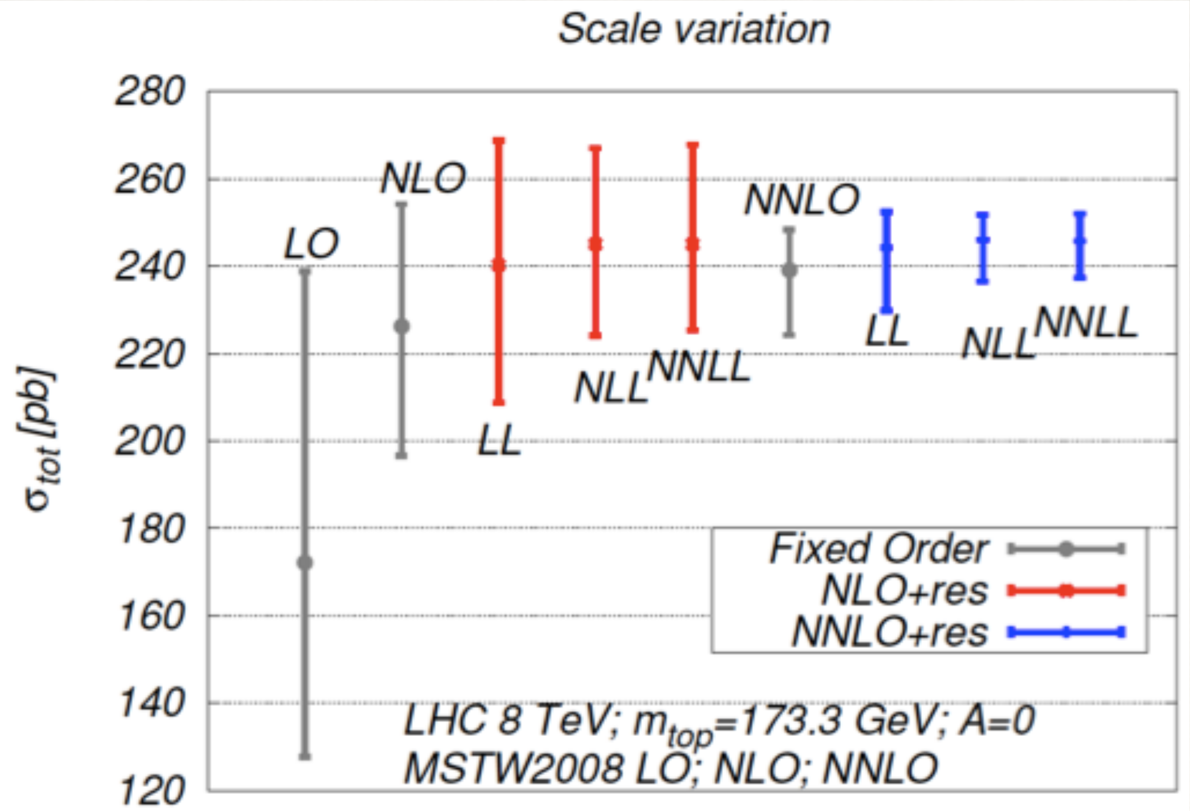
number of events @13TeV 1 fb^{-1}

$t\bar{t}$ cross section

Monumental MILESTONE in perturbative QCD:

[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]





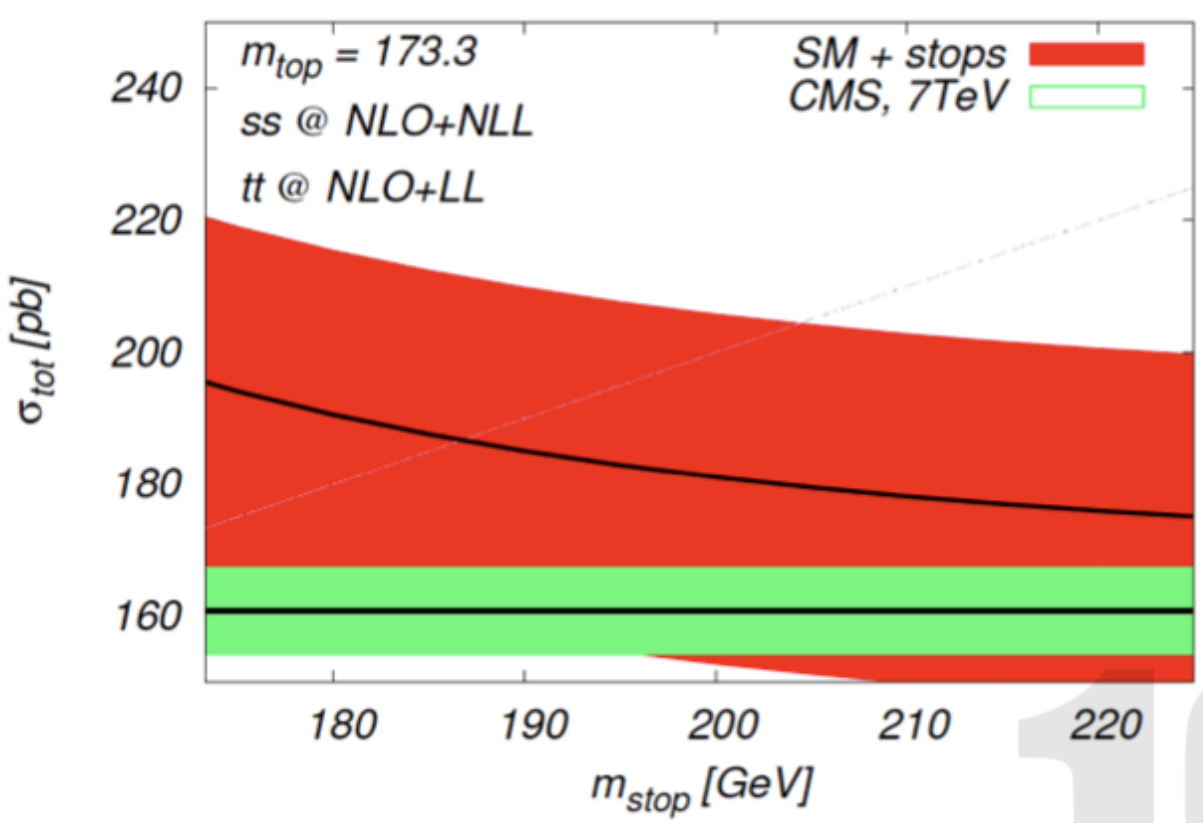
- Two loop hard matching coefficient extracted and included
- Very weak dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ~ 50% scales reduction compared to the NLO+NNLL analysis

$t\bar{t}$ cross section

Having a NNLO prediction opens the door to new possibilities.

Consider the light stop window in a compressed spectrum, that mimicks the normal ttbar production:

[Czakon, Mitov, Papucci, Ruderman, Weiler,2014]



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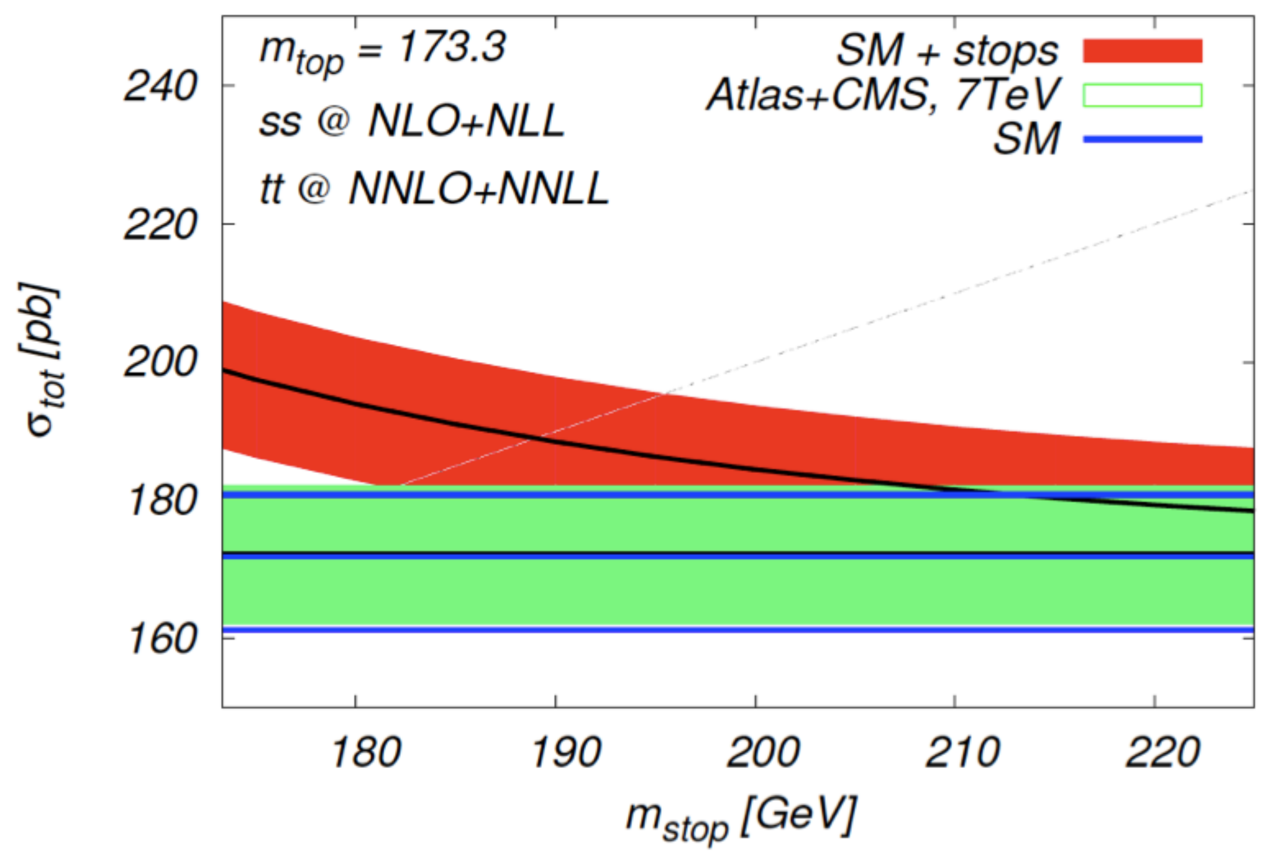
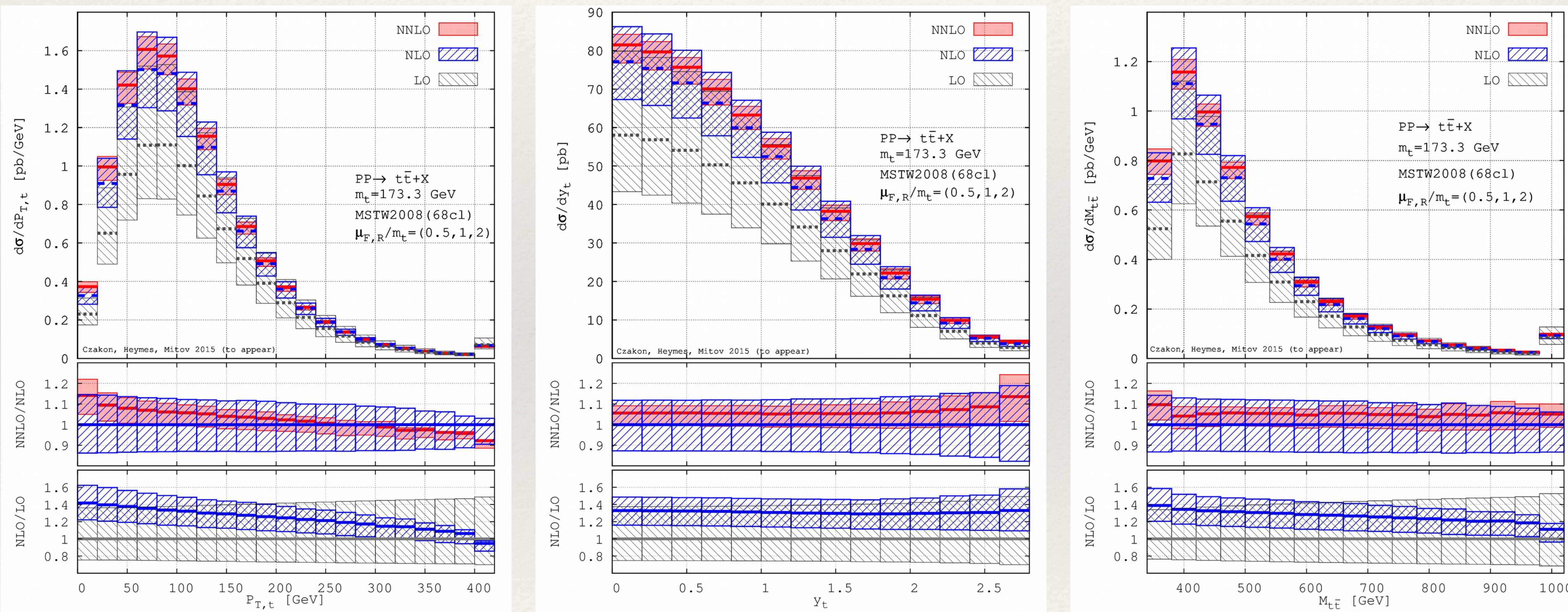


$t\bar{t}$ at NNLO : differential distributions

[Czakon, Fiedler, Heymes, Mitov.; in preperation]

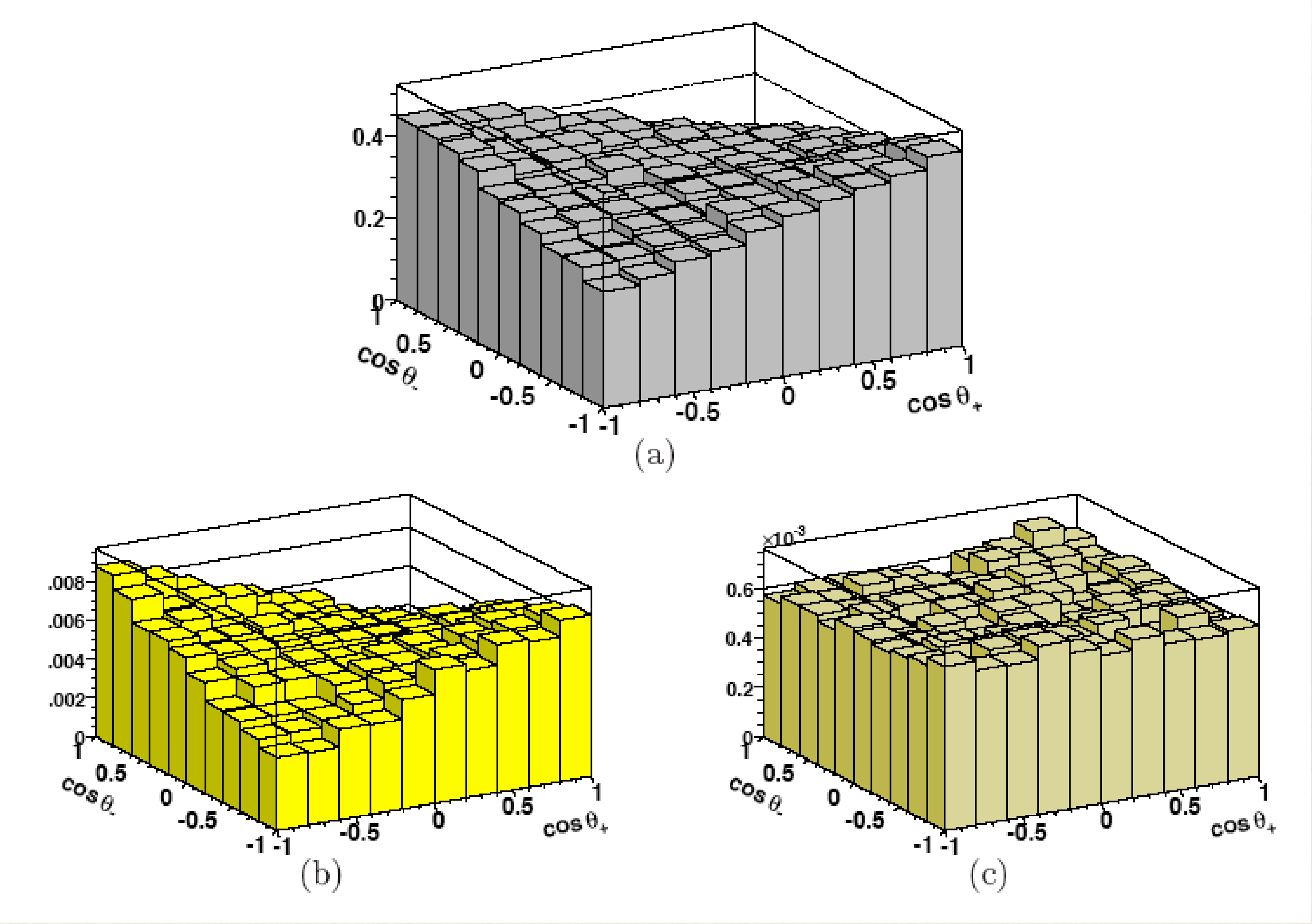


Good perturbative convergence. Improved precision.

Spin correlations

no cuts

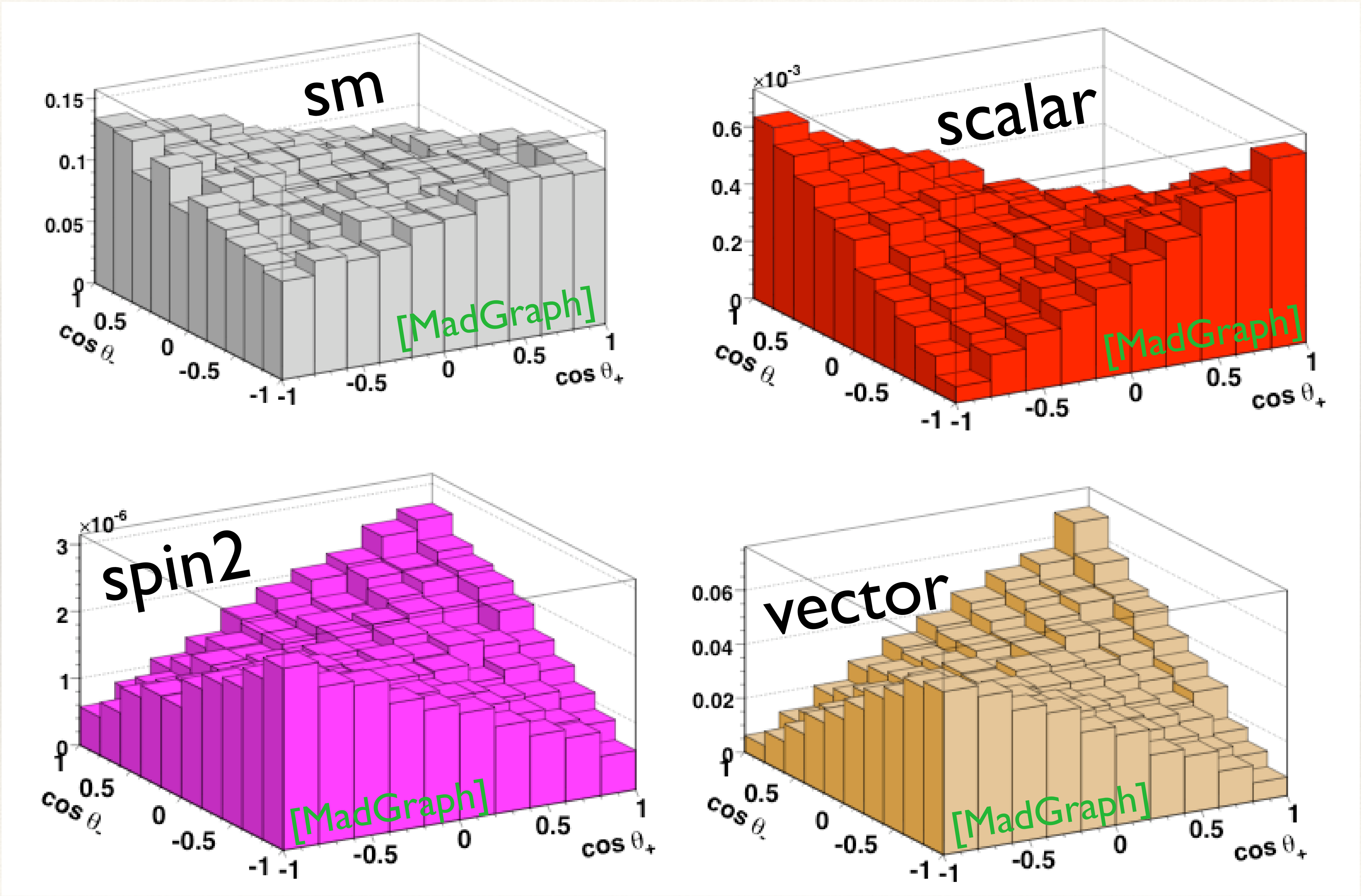
low m(tt)



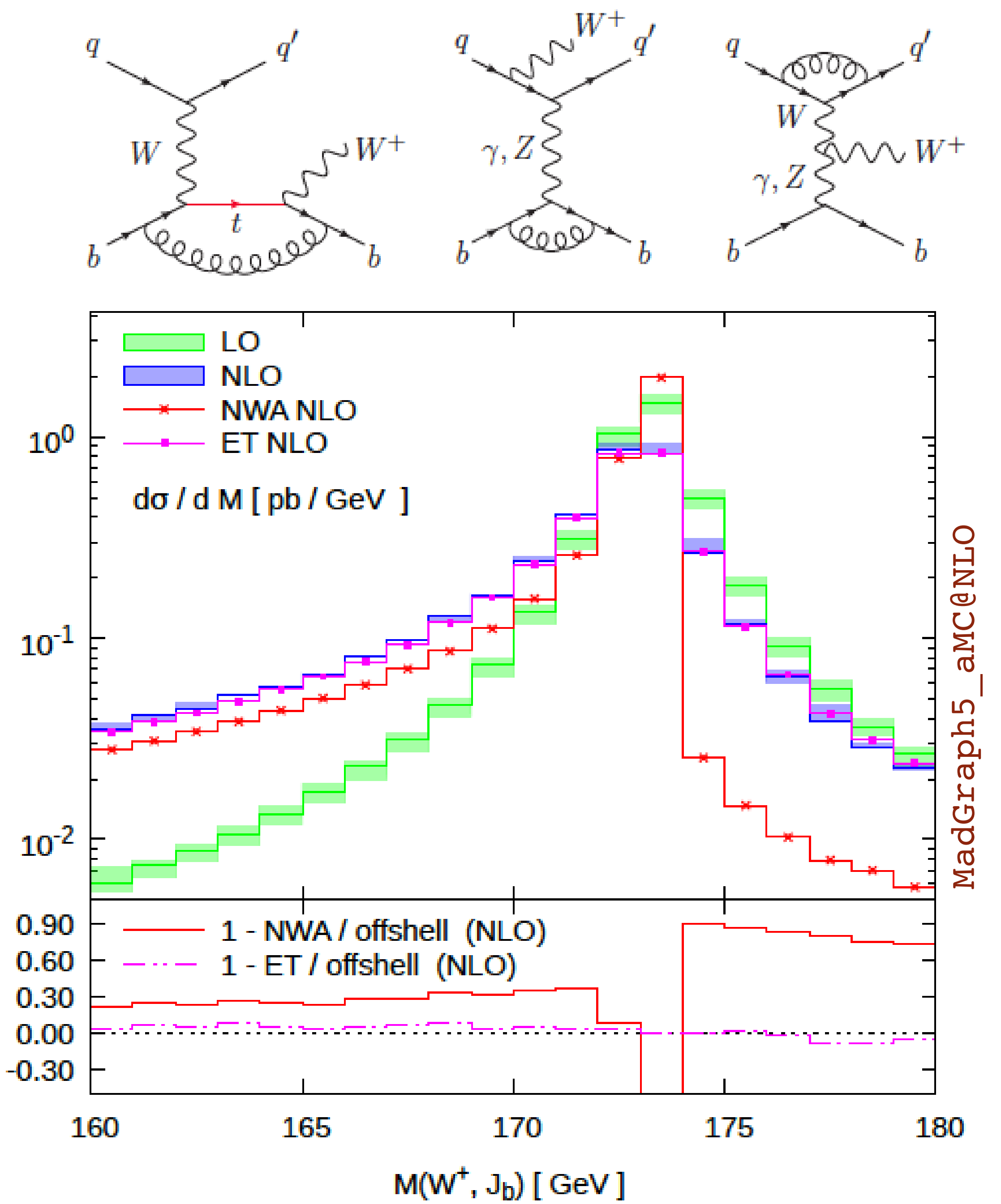
high m(tt)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + \kappa_t \kappa_{\bar{t}} D \cos\theta_- \cos\theta_+\right)$$

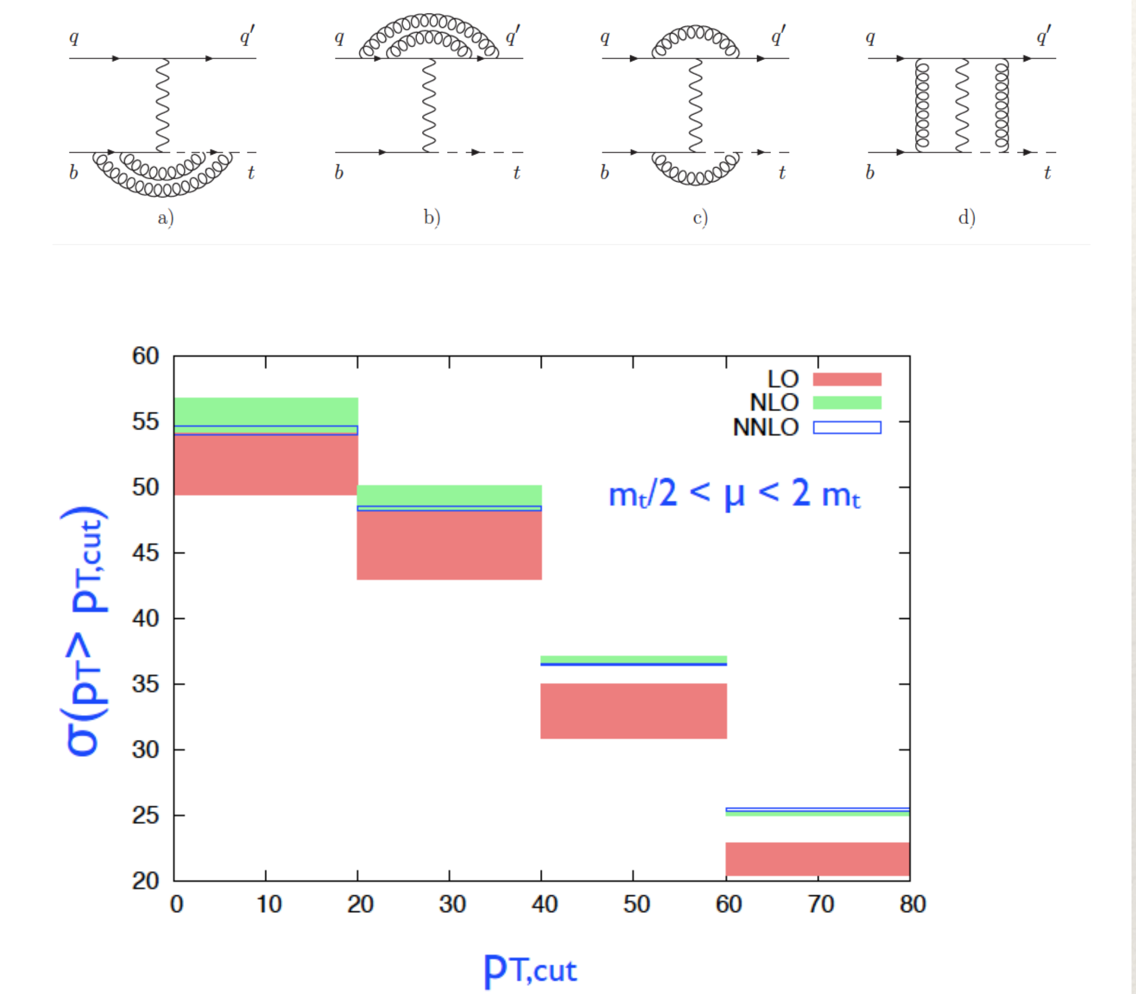
Spin correlations



Single top cross section



[Papanastasiou et al., 2013]



$\sigma_{\rm LO} = 53.8^{+3.0}_{-4.3}$ pb $\quad \sigma_{\rm NLO} = 55.1^{+1.6}_{-0.9}$ pb

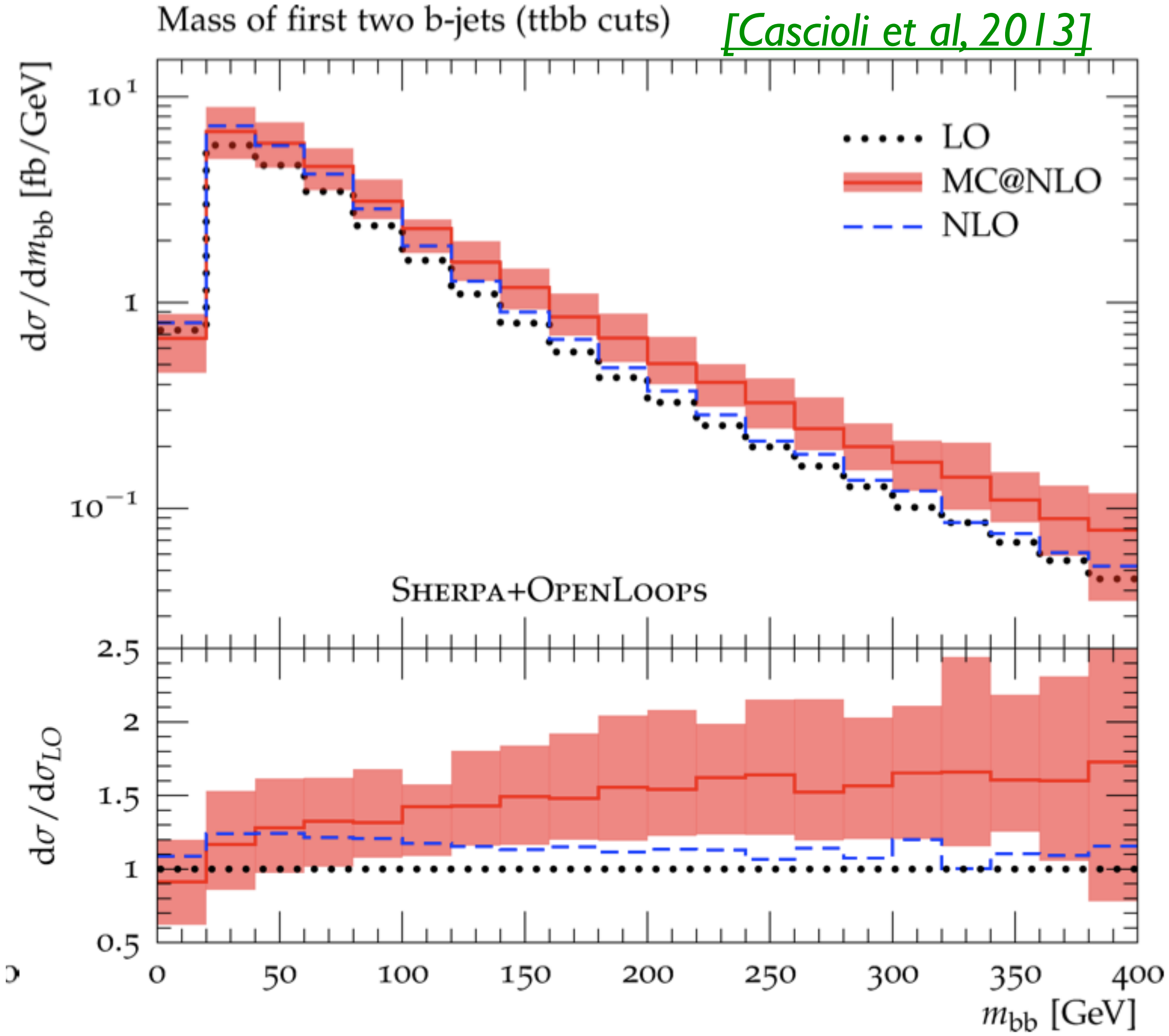
$$\sigma_{\rm NNLO} = 54.2^{+0.5}_{-0.2} \text{ pb}$$

($\mu_R = \mu_F = \{m_t/2, m_t, 2\, m_t\}$)

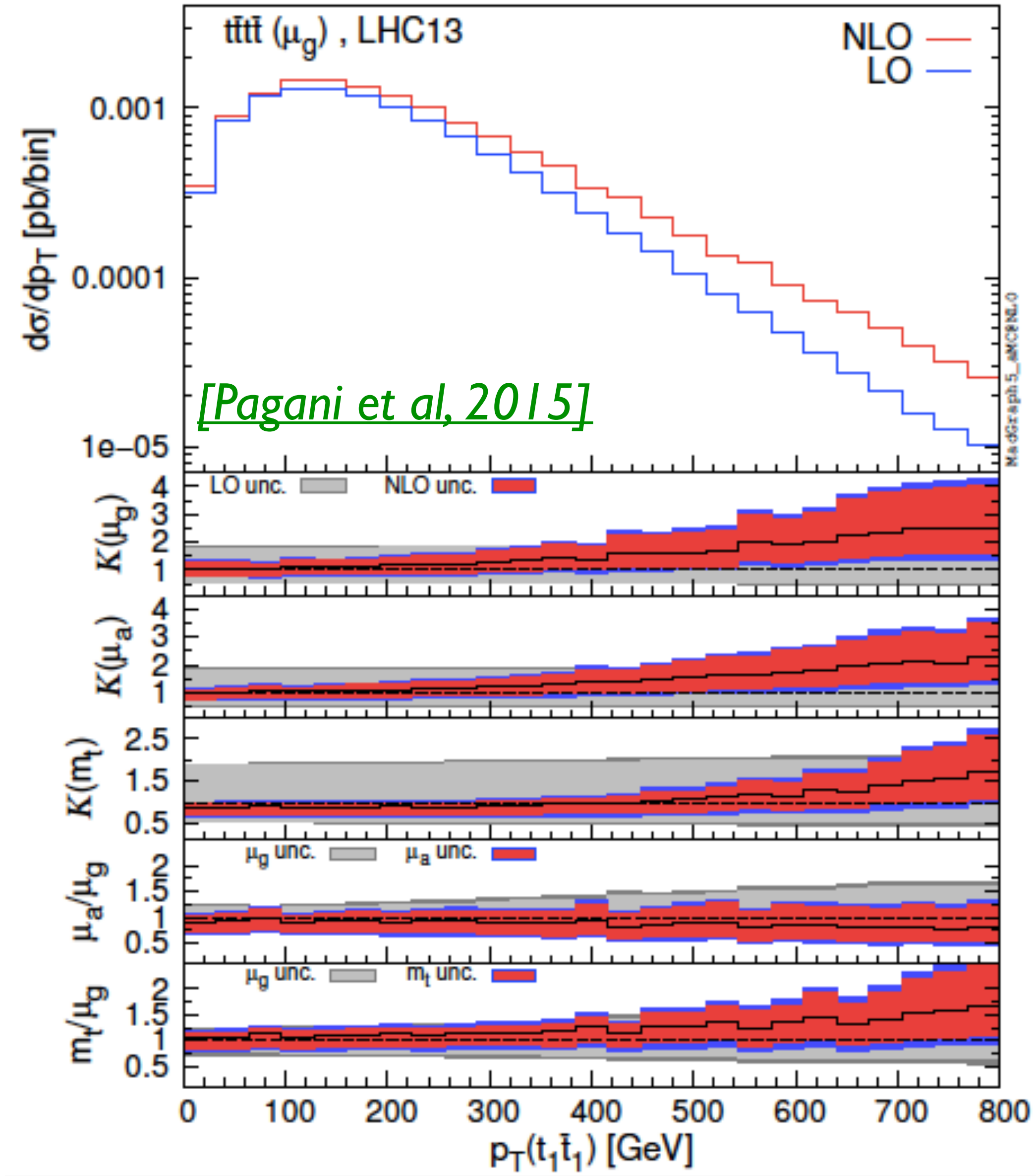
[Caola et al., 2014]

Associated production

$pp \to t\bar{t}b\bar{b}$

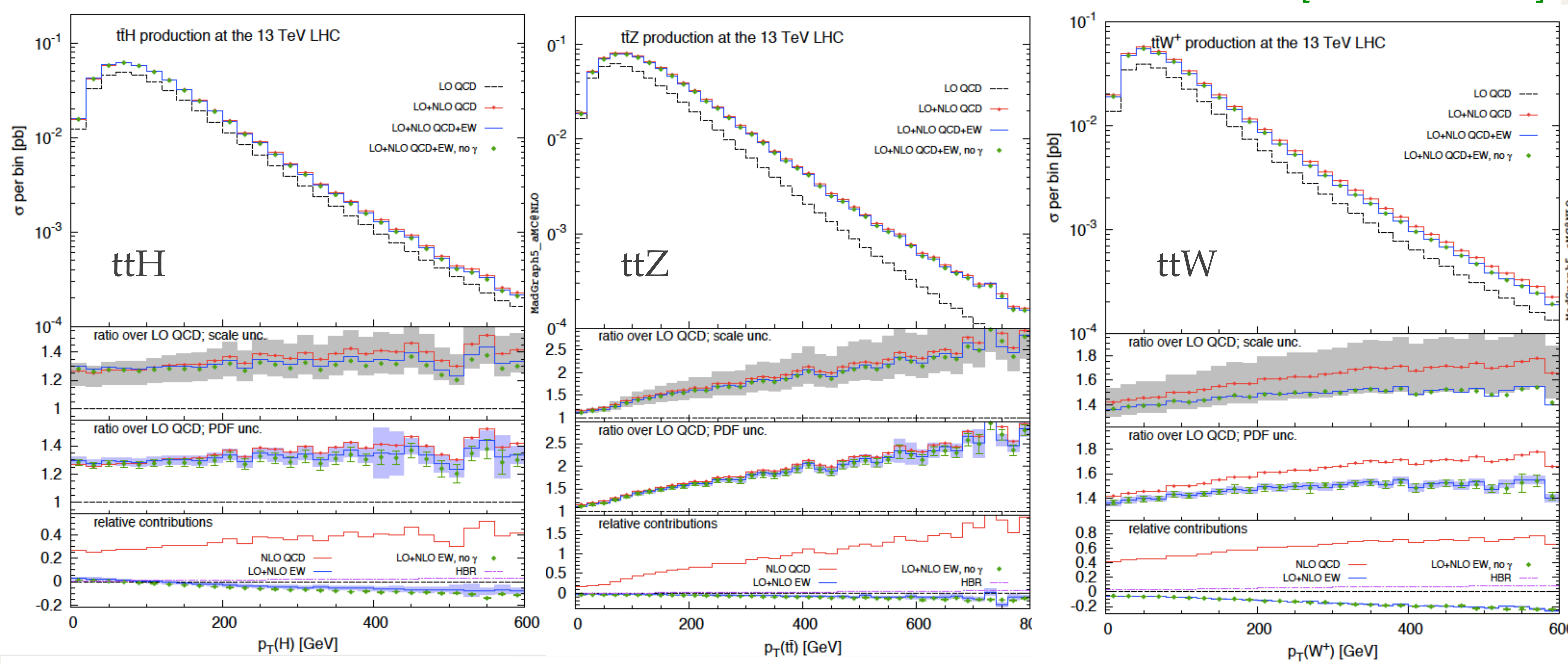


$pp \to t\bar{t}t\bar{t}$



Associated production

[Frixione et al, 2015]



The top is special : summary

1. It is the only quark with a “natural mass” of order v.
2. It is has a “large" weak width and therefore it is only quark that decays before hadronising.
3. Strong interactions cannot scramble its spin state.
4. W polarisation is a good spin analyser for the top spin.
5. Tops do not like to radiate (QCD and QED) very much.
6. It can be produced strongly and weakly with not too different cross sections.
7. It drives Higgs production at the LHC.

Review questions: top quark

1. How does the top width scale with the top mass?

2. Is there an upper bound to the top-quark mass?

3. Imagine the top quark mass were half of its value. What would be the consequences for the SM and the LHC phenomenology?

4. How would you look for a fourth generation? Why nobody talks about its existence lately?

5. Explain the difference between a short-distance mass and the pole mass.

Top & Higgs

- A new force has been discovered, the first elementary Yukawa type ever seen
- Its mediator looks a lot like the SM scalar: H-universality of the couplings
- No sign of……New Physics (from the LHC)!

- We have no bullet-proof theoretical argument to argue for the existence of New Physics between 8 and 13 TeV and even less so to prefer a NP model with respect to another.

New Physics via Top & Higgs

Statement #1

The only viable approach to look for NP at the LHC is to cover the widest range of TH- and/or EXP-motivated searches.

Searches should aim at being sensitive to the highest-possible scales of energy

New Physics via Top & Higgs

STATEMENT #2

THE HIGGS PROVIDES A PRIVILEGED SEARCHING GROUND

- It has just been discovered. Some of its properties are either just been measured or completely unknown.
- A plethora of production and decay modes available.
- First "elementary" scalar ever : carrier of a new Yukawa force, whose effects still need to be measured.
- $(\Phi^\dagger .\Phi)$ dim=2 singlet object $\Longrightarrow$ Higgs portal to a new sector.
- Several motivations to have a reacher scalar sector with more doublets or higher representations $\Longrightarrow$ Higgs= might be the first of many new scalar states.

New Physics via Top & Higgs

STATEMENT #3

THE TOP PROVIDES A PRIVILEGED SEARCHING GROUND

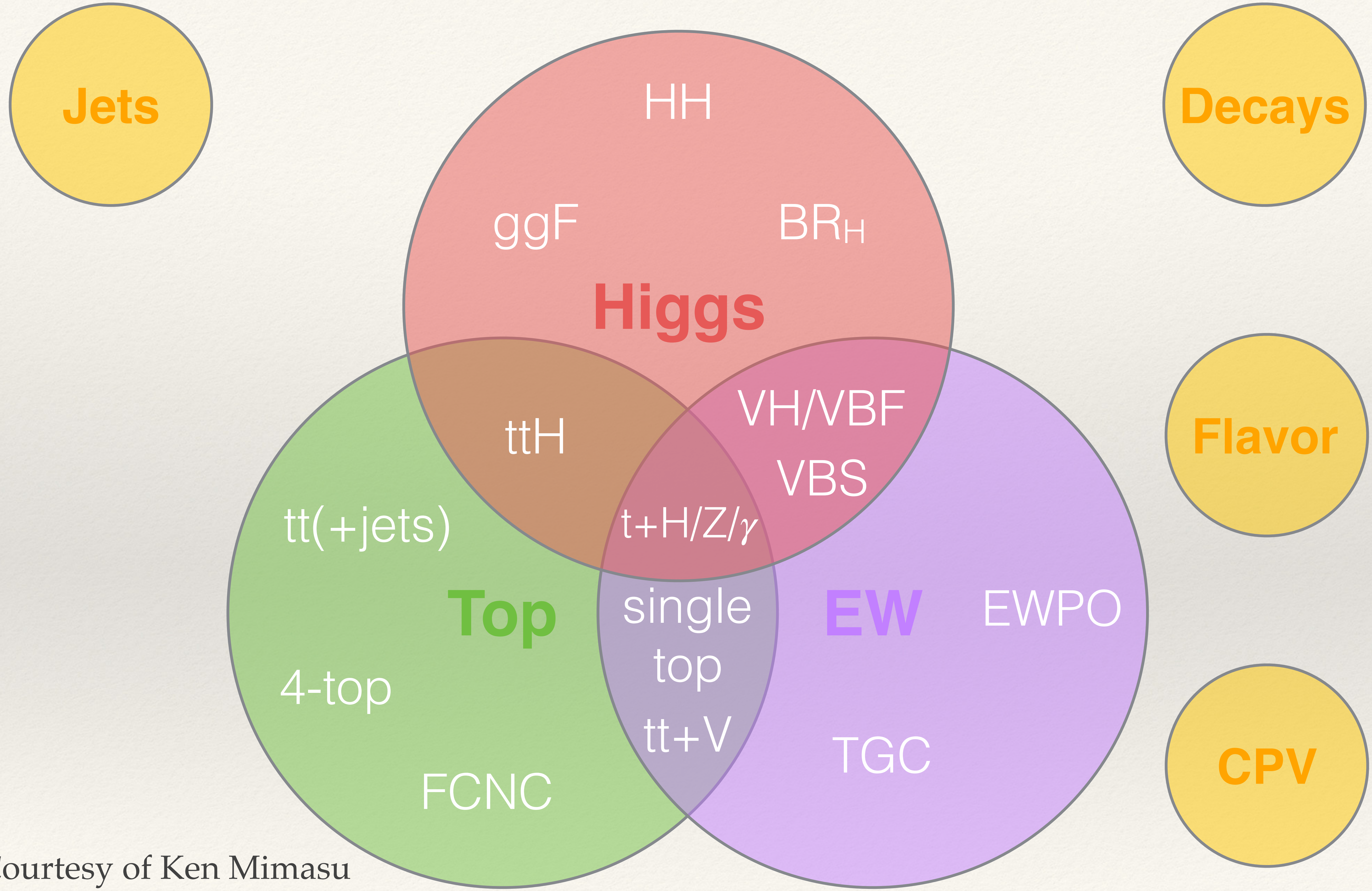
- It interacts "not-so weakly" with the Higgs
- It is the only “naked" quark whose weak interactions are not hidden by QCD
- Its couplings are mildly constrained, t_R is still quite free.
- It has very distinctive signatures at the LHC

Searching for new physics

Model-dependent	⟷	Model-independent
SUSY, 2HDM, ED,…		simplified models, EFT, …
Search for new states	⟷	Search for new interactions
specific models, simplified models		anomalous couplings, EFT…
Exotic signatures	⟷	Standard signatures
precision measurements		rare processes

Search for new interactions

- Such a programme is based on large set of measurements, both in the exploration and in the precision phases:
  - **PHASE I (EXPLORATION):**
    Bound Higgs/top couplings
  - **PHASE II (DETERMINATION):**
    Stress test the SM: Look for deviations wrt dim=4 SM (rescaling factors)
  - **PHASE III (PRECISION):**
    Interpret measurements in terms the dim=6 SM parameters (SMEFT)
- Rare SM processes (induced by small interactions, such as those involving the Higgs with first and second fermion generations or flavour changing neutral interactions) are still in the exploration phase.
- For interactions with vector boson and third generation fermions we are ready to move to phase II.



Courtesy of Ken Mimasu

Phase I (exploration) : examples

COUPLINGS	PROSPECTS FOR DETERMINATION
H self-interactions	Run II / HL-LHC
Second generation Yukawas: ccH, μμH	Run I onwards
Flavor off-diagonal int.s : tqH, ll'H, …	Run II onwards
HZγ	Run II / HL-LHC
Top self-interactions : 4top interactions	?
Top neutral gauge interactions	Run I onwards
Top FCNC's	?
Top CP violation	?

Higgs potential 101

A low-energy parametrisation of the Higgs potential

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \dots$$

In the Standard Model:

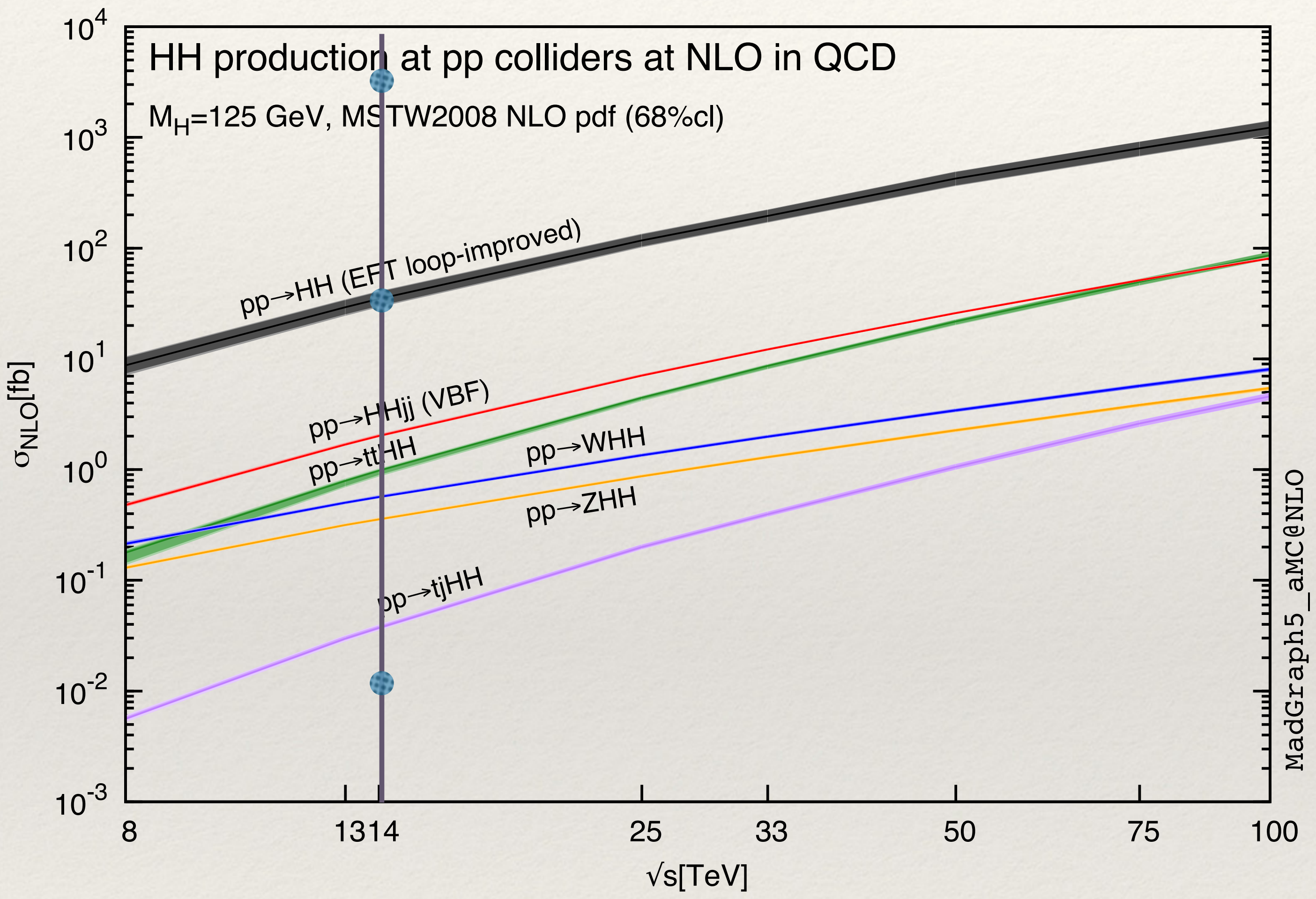
$$V^{\text{SM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\text{SM}} = \lambda \\ \lambda_4^{\text{SM}} = \lambda \end{cases}$$

i.e., fixing v and m_H , uniquely determines both λ_3 and λ_4 .

That means that by measuring λ_3 and λ_4 one can test the SM, yet to interpret deviations, one needs to "deform it", i.e. needs to consider a well-defined BSM extension. Such extensions will necessarily depend on TH assumptions.

Phase I : Higgs self-coupling

[Frederix et al. '14]

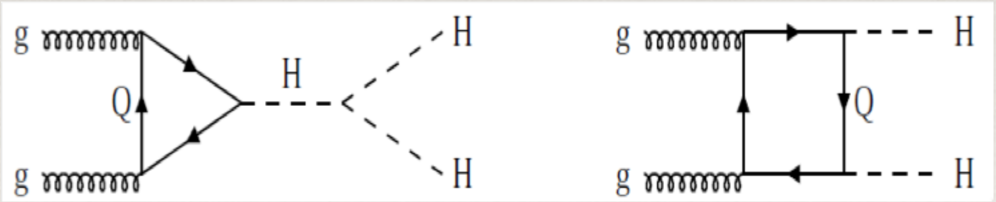


At 14 TeV from gg fusion:

$$\sigma_H = 55 \text{ pb}$$

$$\sigma_{HH} = 44 \text{ fb}$$

$$\sigma_{HHH} = 110 \text{ ab}$$

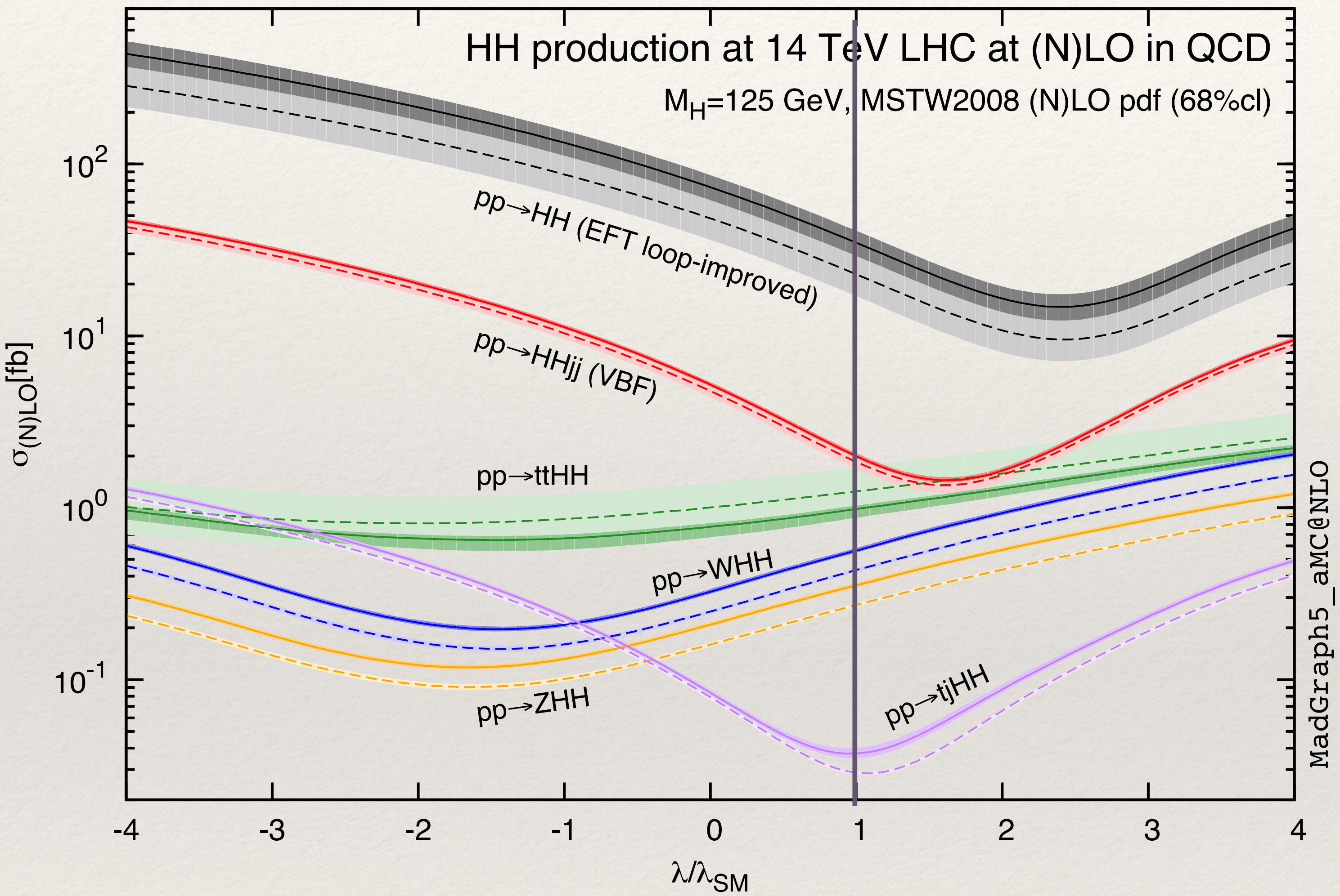


As in single Higgs many channels contribute in principle.

Cross sections for HH(H) increase by a factor of 20(60) at a FCC.

Phase I : Higgs self-coupling

[Frederix et al. '14]



Many channels, but small cross sections.

Current limits are on σ_{SM} (gg→HH) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 19$ (bbγγ) [EPS2017]
ATLAS : $\sigma/\sigma_{SM} < 13$ (bbbb). [Moriond18]

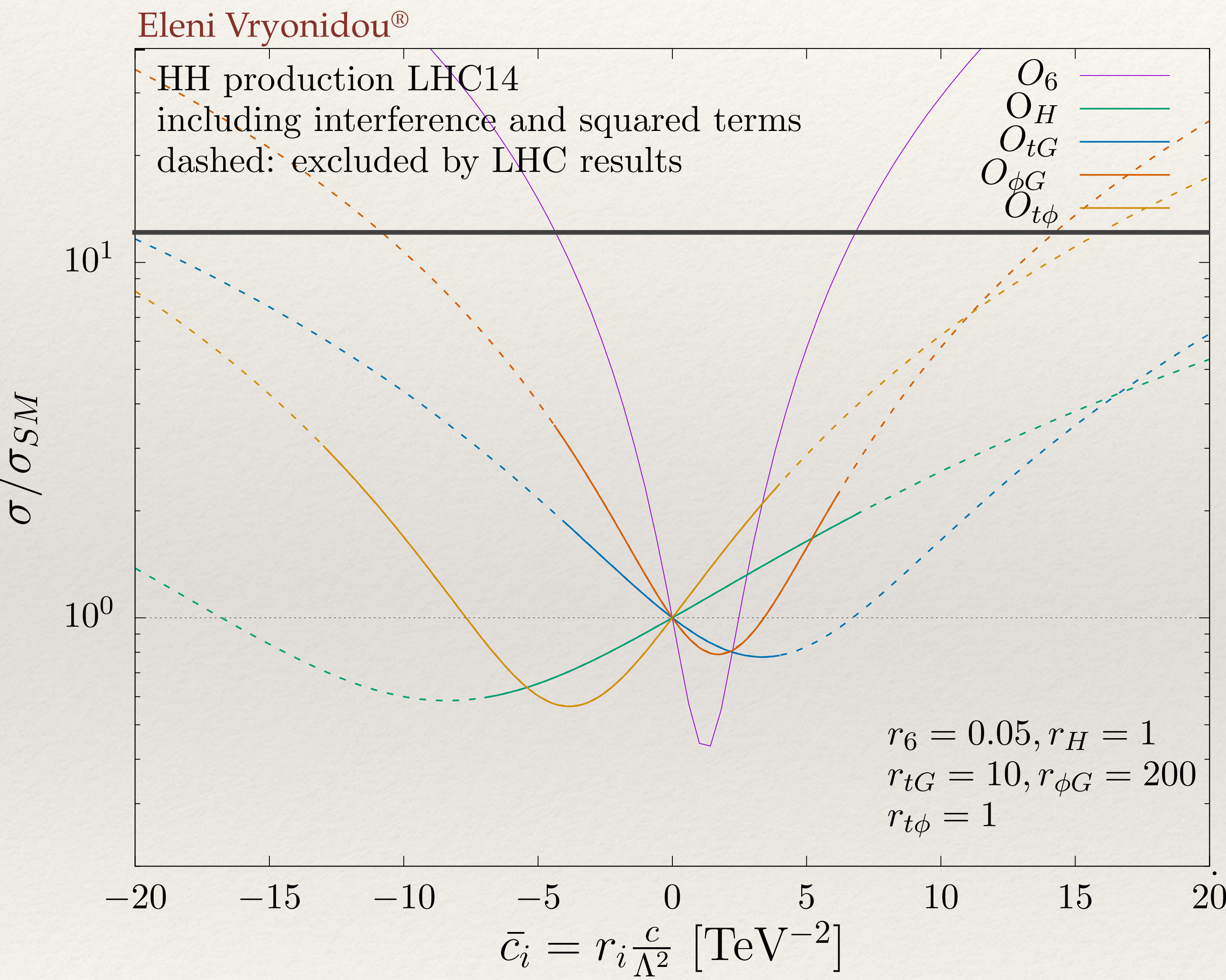
Remarks:

1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of λ_3 which leads to a change in σ as well as of distributions:

$$\sigma = \sigma_{SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

Note: due to shape changes, it is not straightforward to infer a bound on λ_3 from σ(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

Exploration phase: H self-coupling



Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable. The range of c_6 is commensurate to that of $k_{\lambda 3}$.

1. An accurate measurement of the Higgs self-couplings will depend on our ability to bound several (top-related) SMEFT operators: O_{tG},$O_{\varphi G}$,$O_{t\varphi}$.
2. Given the current constraints on σ(HH), the Higgs self-coupling can be constrained “ignoring” the other EFT couplings.

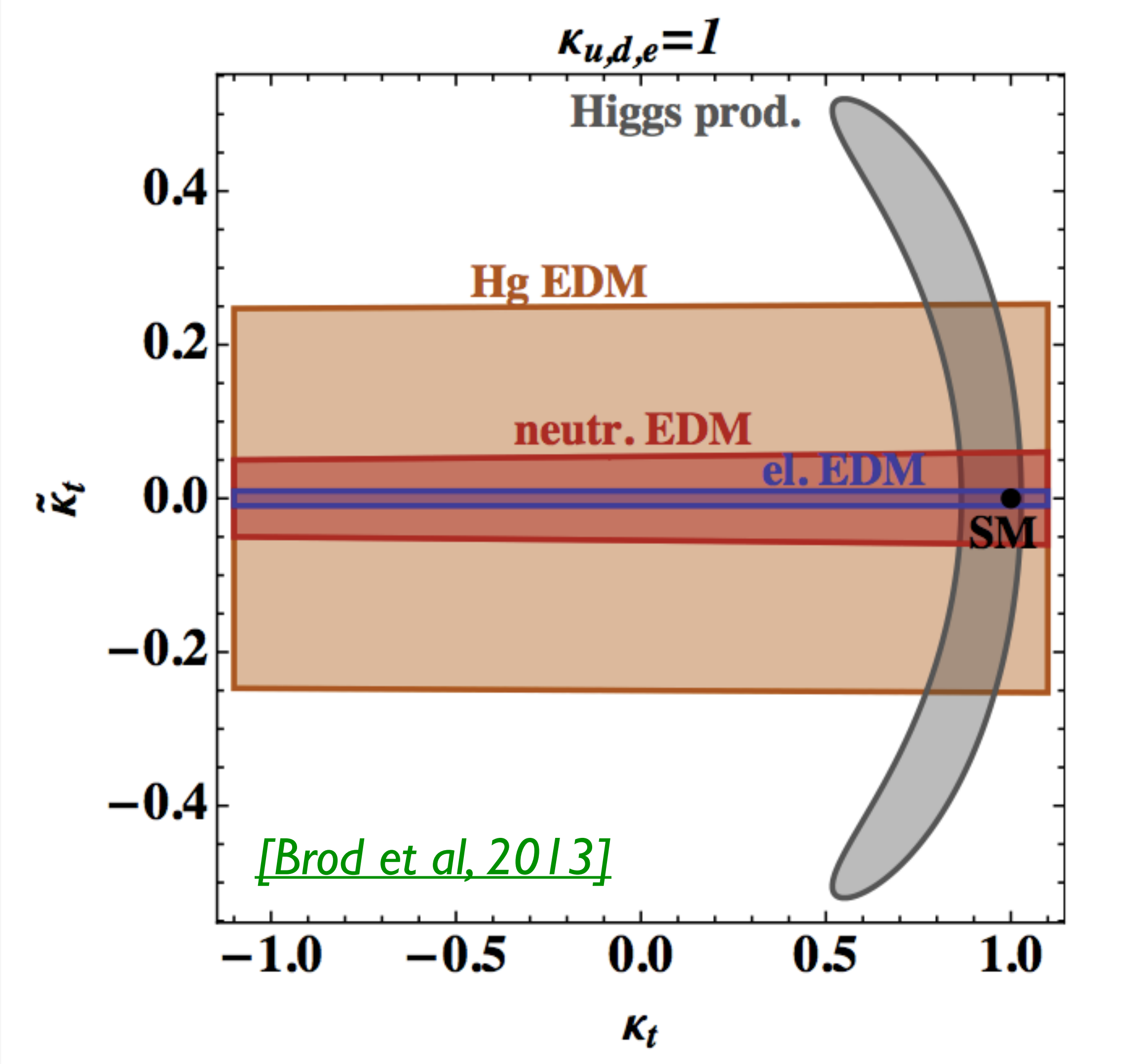
Phase I : CPV in ttH coupling

$$\mathcal{L} = y_t(H\bar{Q}_L)t_R + c_{Hy}H^\dagger H(H\bar{Q}_L)t_R$$
$$= m_t\bar{\psi}_t\psi_t + \bar{\psi}_t(\mathrm{Re}\,c_{Hy} + i\mathrm{Im}\,c_{Hy}\gamma_5)\psi_t h$$

CP violation implies Re AND Im non-zero. Inclusive gg production only constrains [Re(chy)2 + 9/4 Im(chy)2].

Indirect constraints from e-EDM very strong, yet rely on assuming

- SM couplings for the light fermions.
- no other states present in the spectrum



Phase I : CPV in ttH coupling

$$\mathcal{L} = y_t(H\bar{Q}_L)t_R + c_{Hy}H^\dagger H(H\bar{Q}_L)t_R$$
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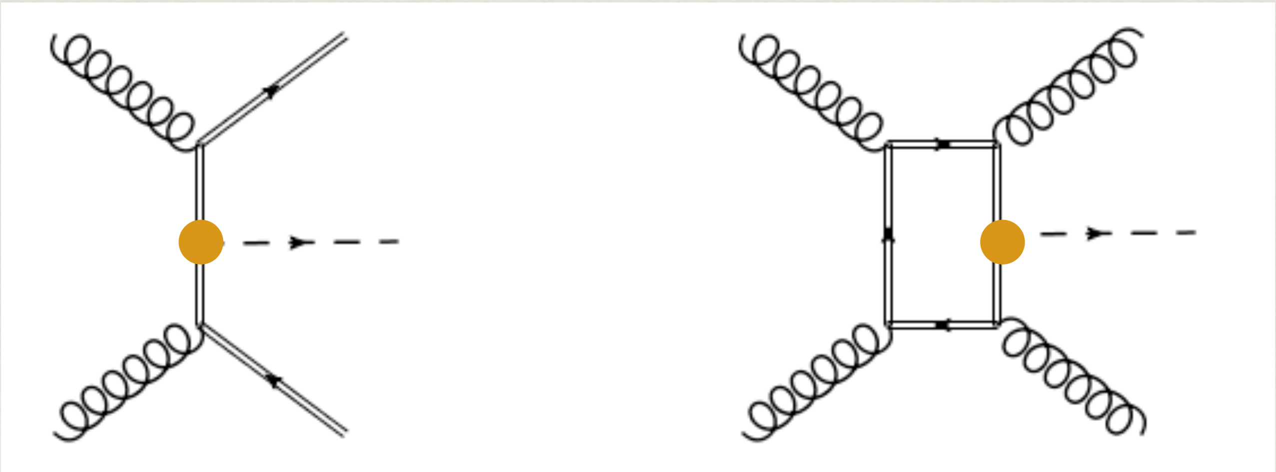
There are ways of directly accessing presence of CP-mixing in top-Higgs interactions at the LHC:

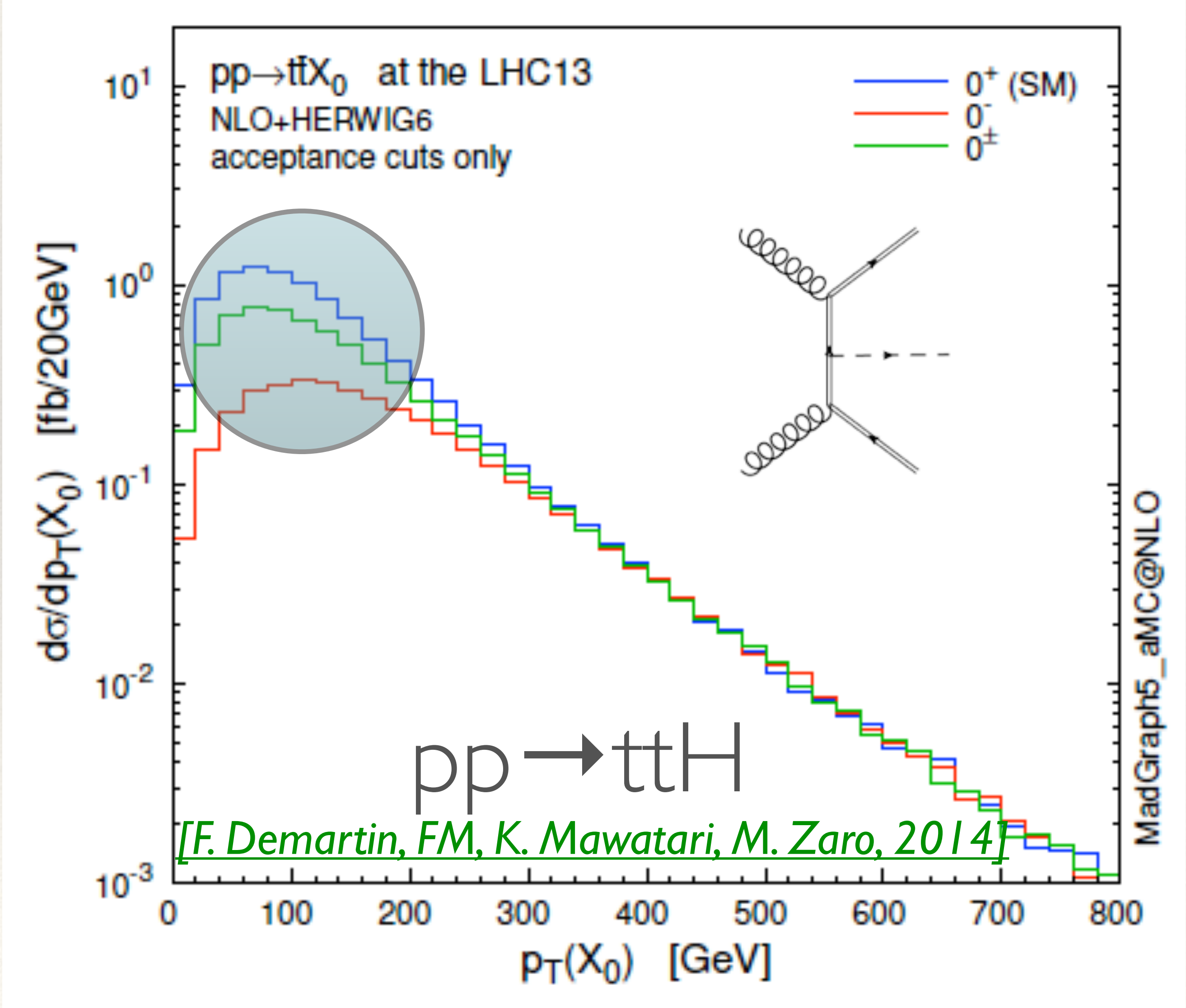


pp→ttH

pp→Hjj

Phase I : CPV in ttH coupling

$$\mathcal{L} = y_t(H\bar{Q}_L)t_R + c_{Hy}H^\dagger H(H\bar{Q}_L)t_R$$
$$= m_t\bar{\psi}_t\psi_t + \bar{\psi}_t(\mathrm{Re}\, c_{Hy} + i\mathrm{Im}\, c_{Hy}\gamma_5)\psi_t h$$



At LO the two contributions add up incoherently. At NLO in QCD CP-even and CP-odd amplitudes interfere.

At threshold large differences appear.

At high Higgs pT shapes and normalization exactly equal (mt effects become subdominant)

⇒ boosted analyses insensitive to CP?

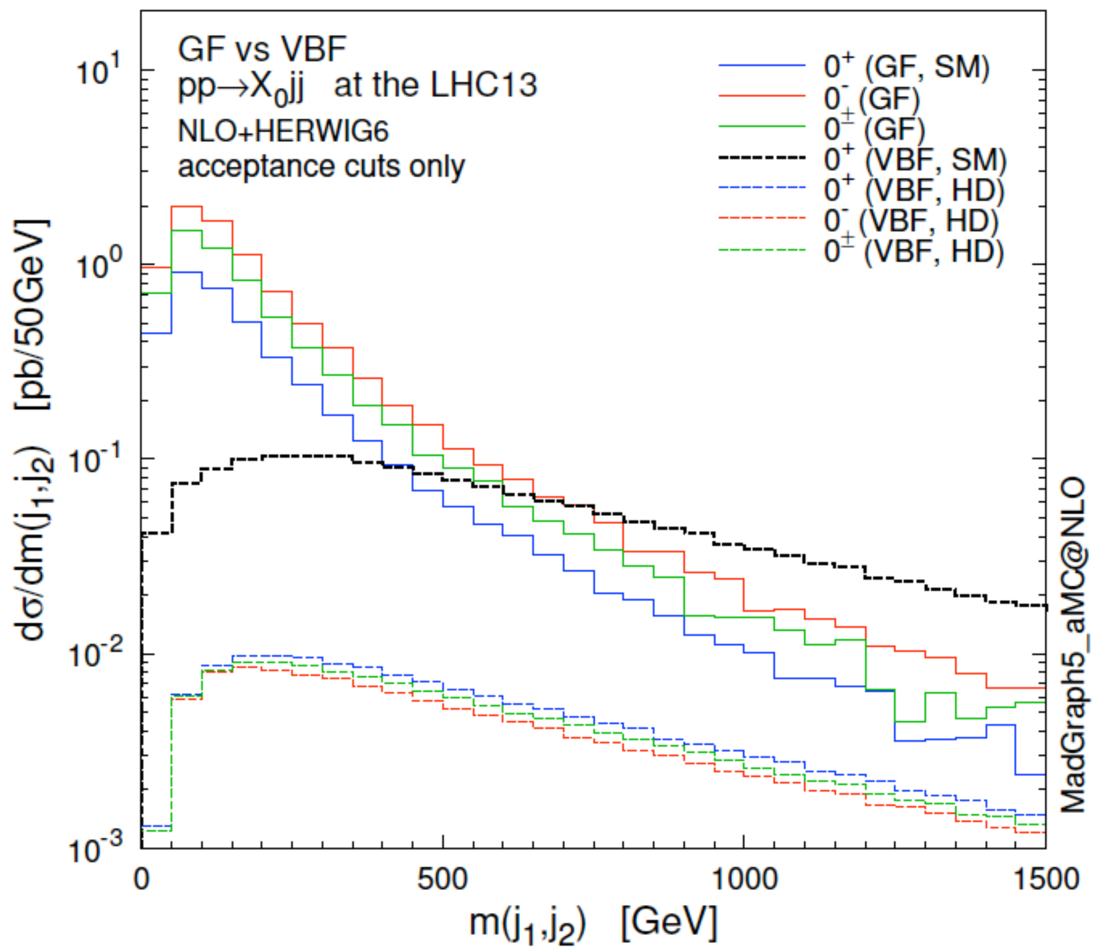
Angular variables between the daughters of the top are sensitive to the CP-mixing.

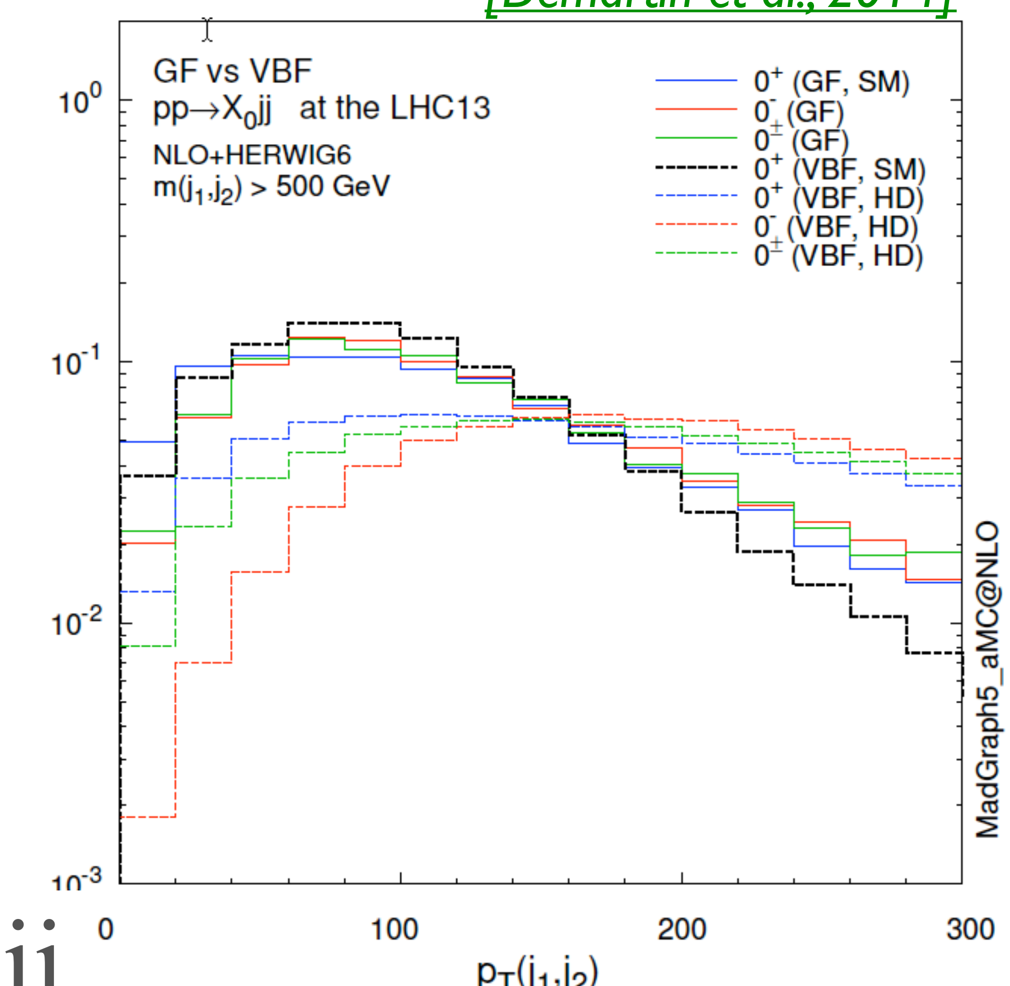
Phase I : CPV in ttH coupling

The CP-mixing in the top coupling induces a CP-mixing at the level of the H-gluon-gluon couplings:

$$\mathcal{L}_0^{\rm loop} = -\frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\right] h$$

[Demartin et al., 2014]





pp⟶Hjj

Phase I : CPV in ttH coupling

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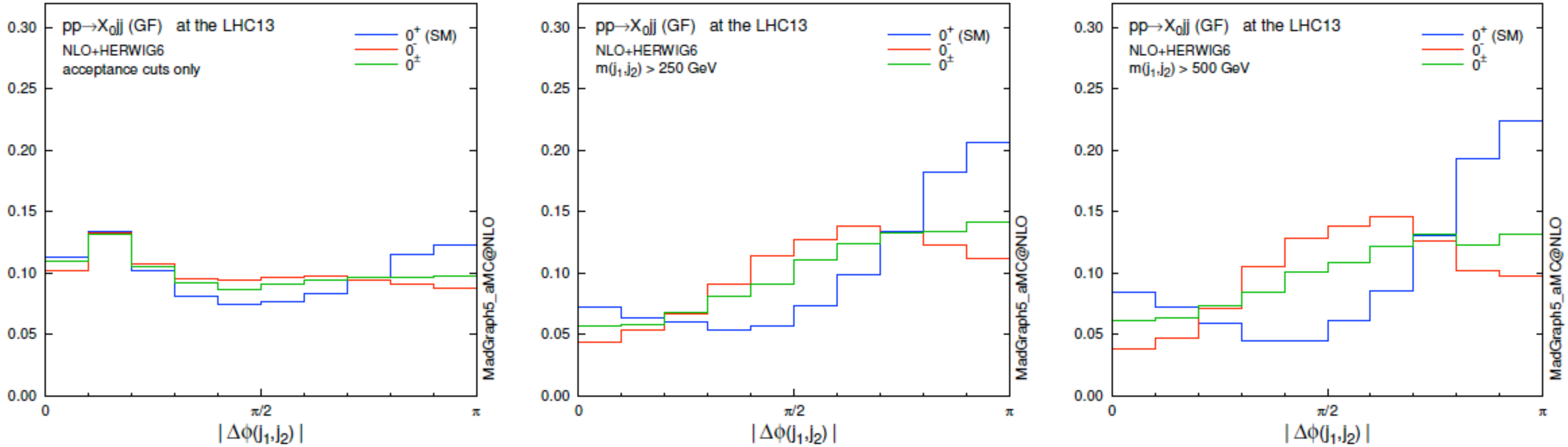
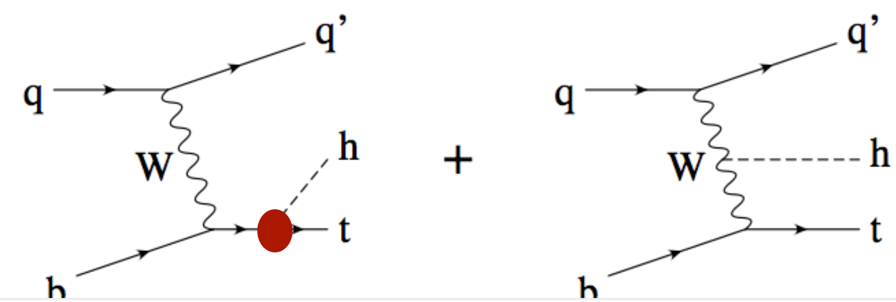
pp→Hjj

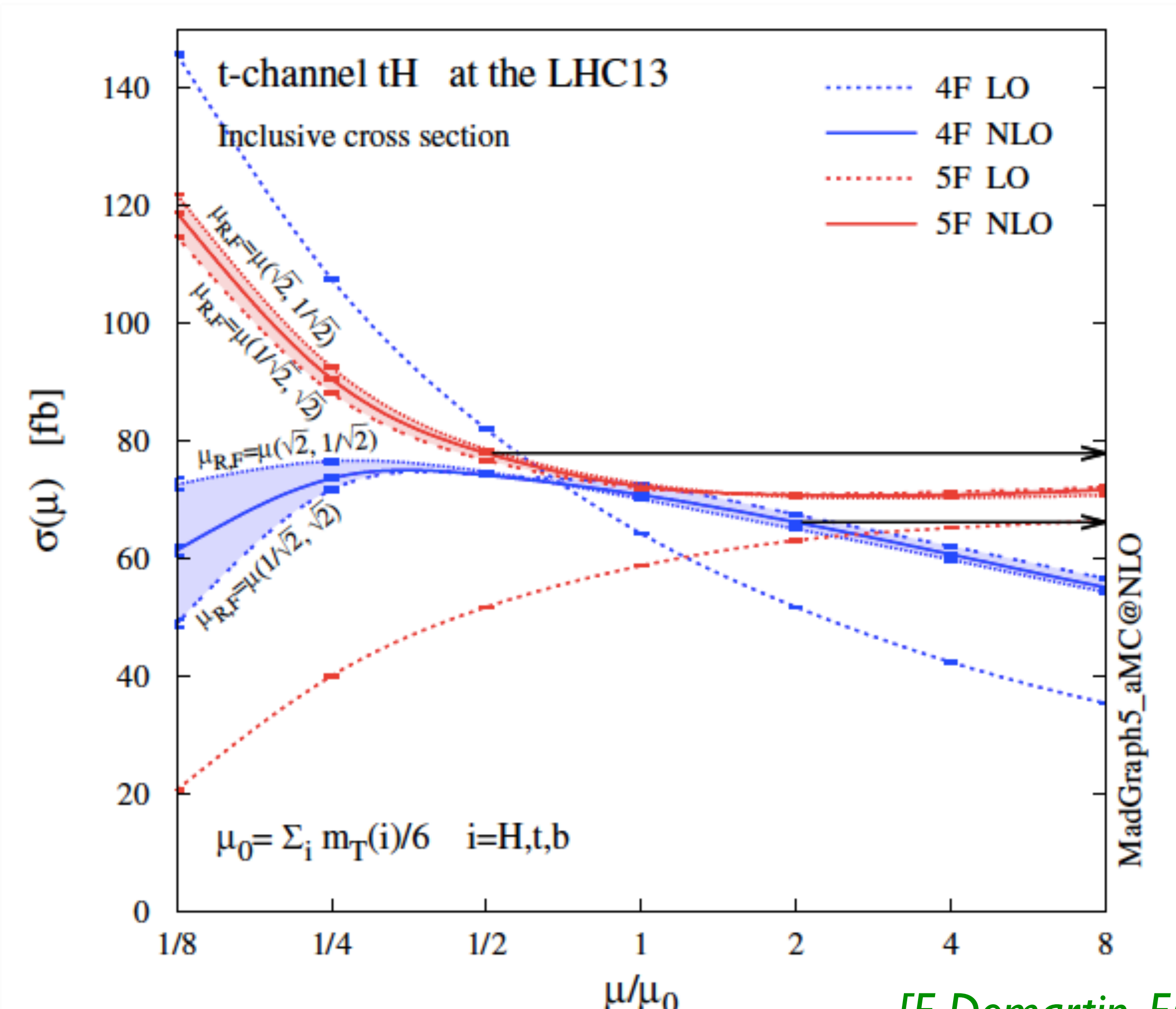


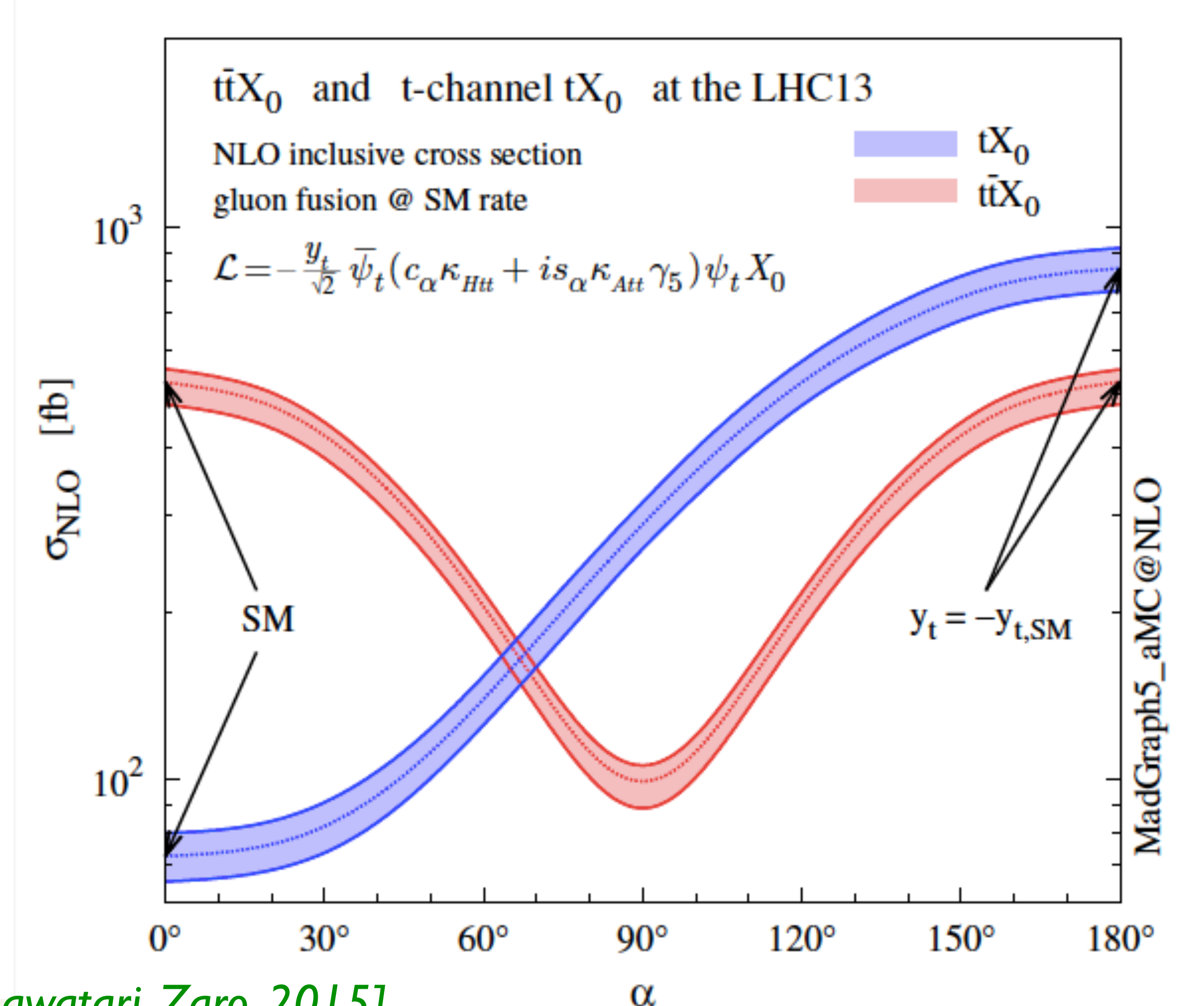
Delta(phi) among the jets is a sensitive variable as mjj increases.

Phase I : CPV in ttH coupling

The relative sign of the yukawa top coupling is fixed by unitarity in the SM. h→ γγ is sensitive to the sign. In production thj can provide further constraints.





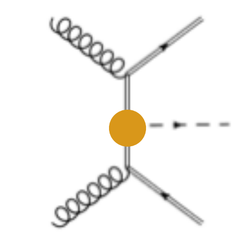


[F. Demartin, FM, K. Mawatari, Zaro, 2015]

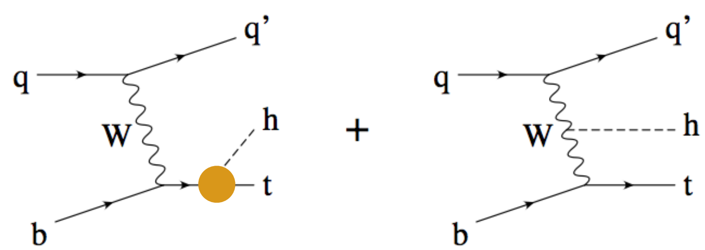
Phase I : CPV in ttH coupling

It is interesting to compare how a phase in the top-higgs coupling would change many of the processes relevant in higgs phenomenology at the LHC:

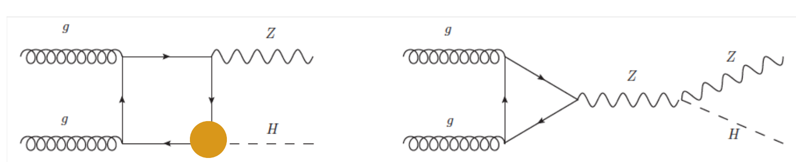
- pp ⟶ ttH



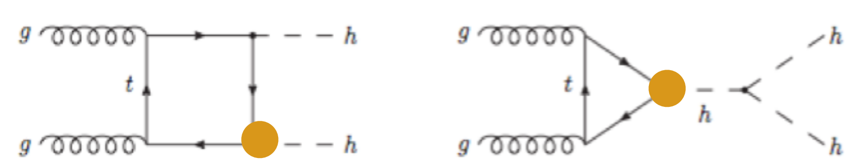
- pp ⟶ tHj



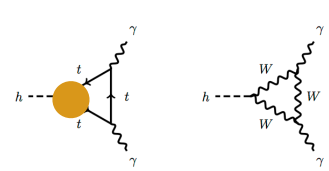
- gg ⟶ ZH

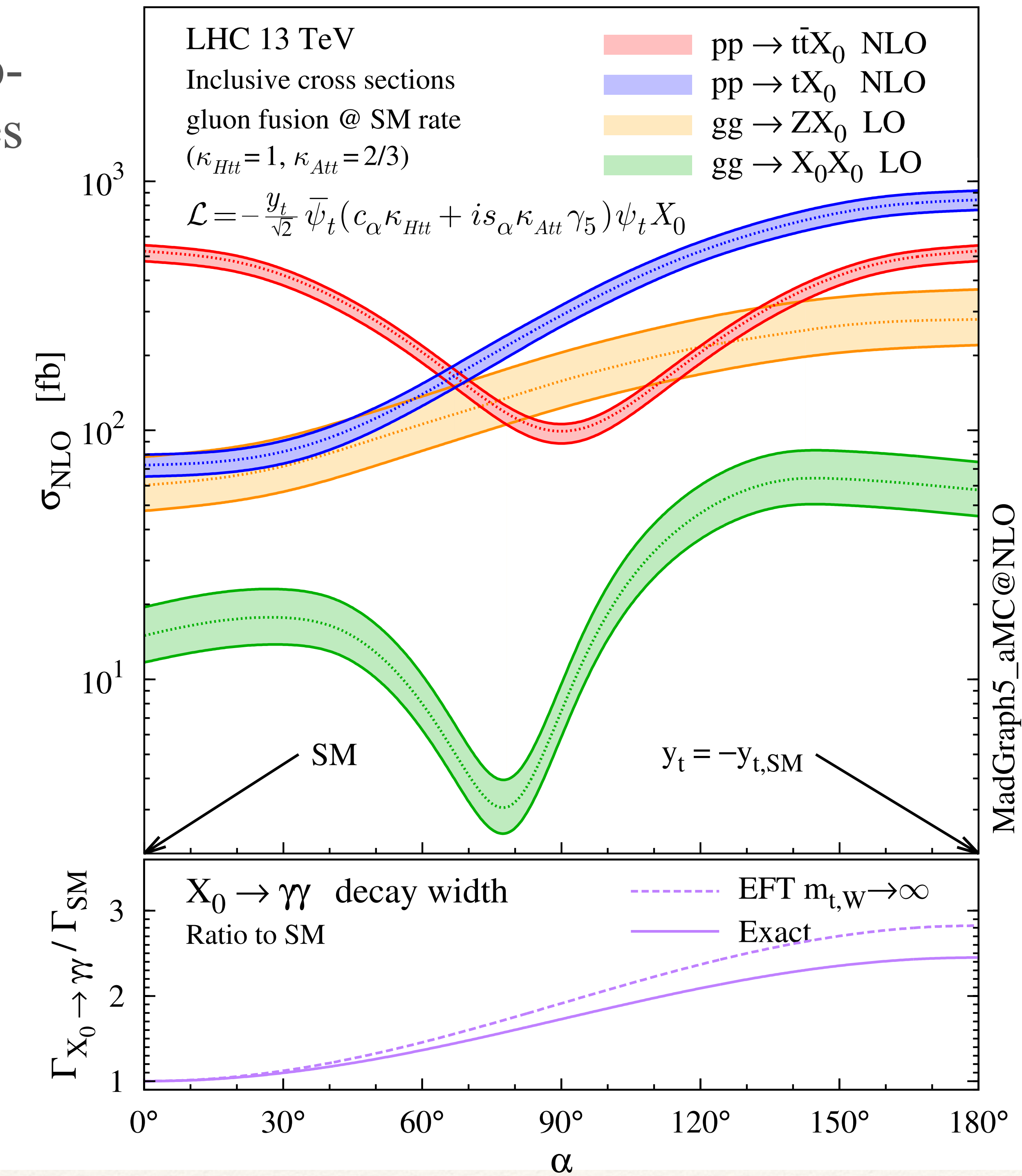


- gg ⟶ HH

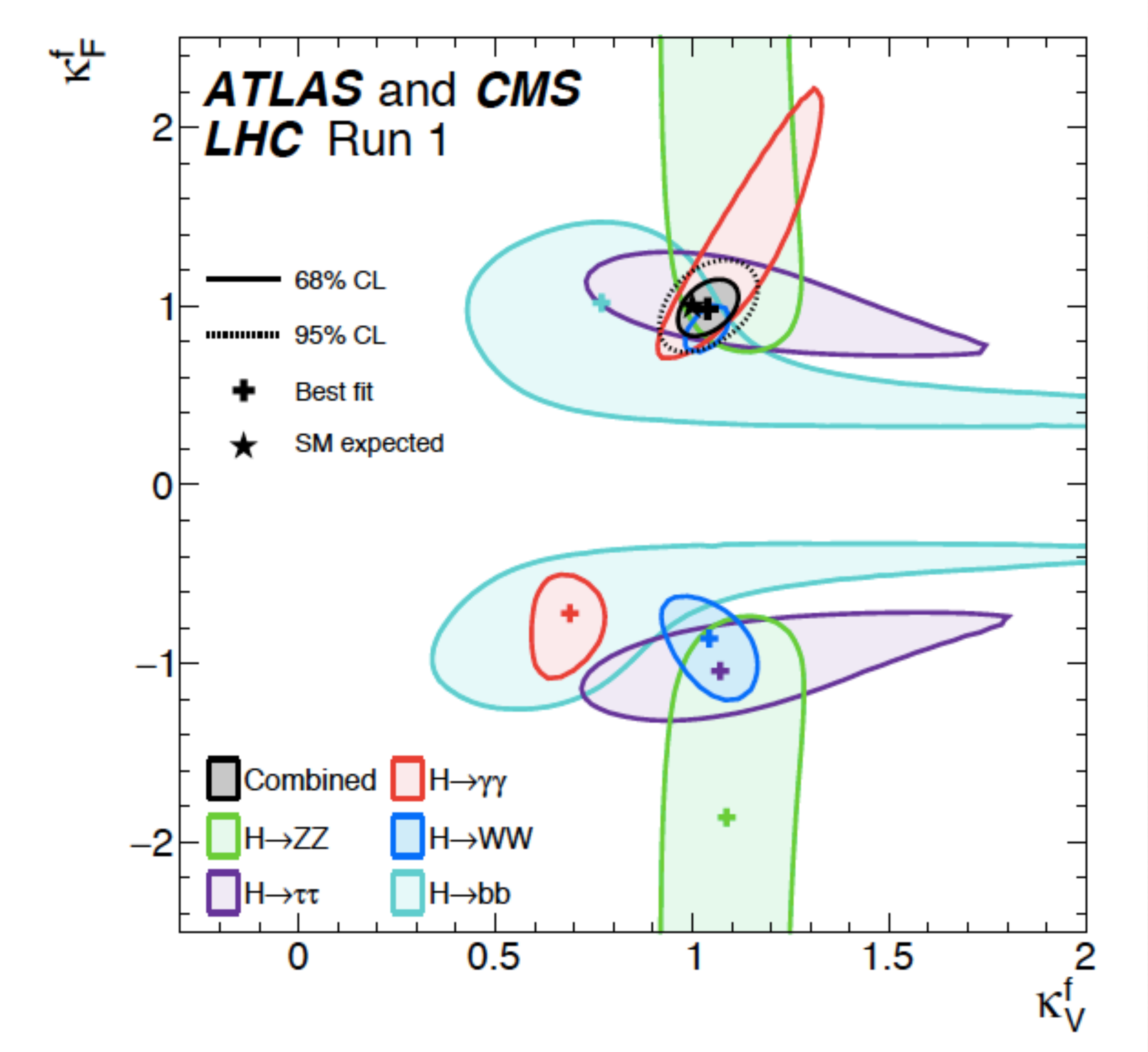


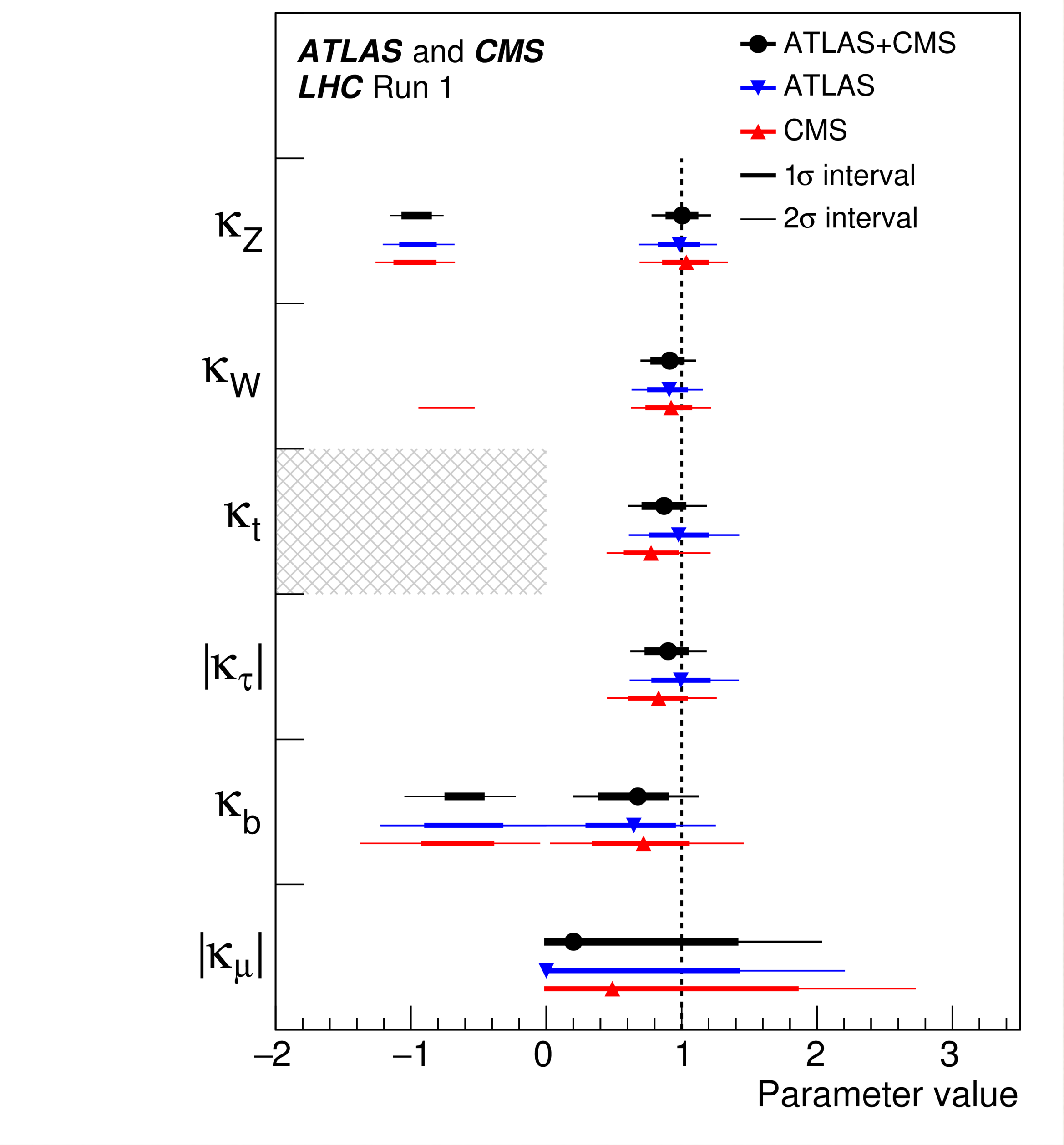
- H ⟶ YY





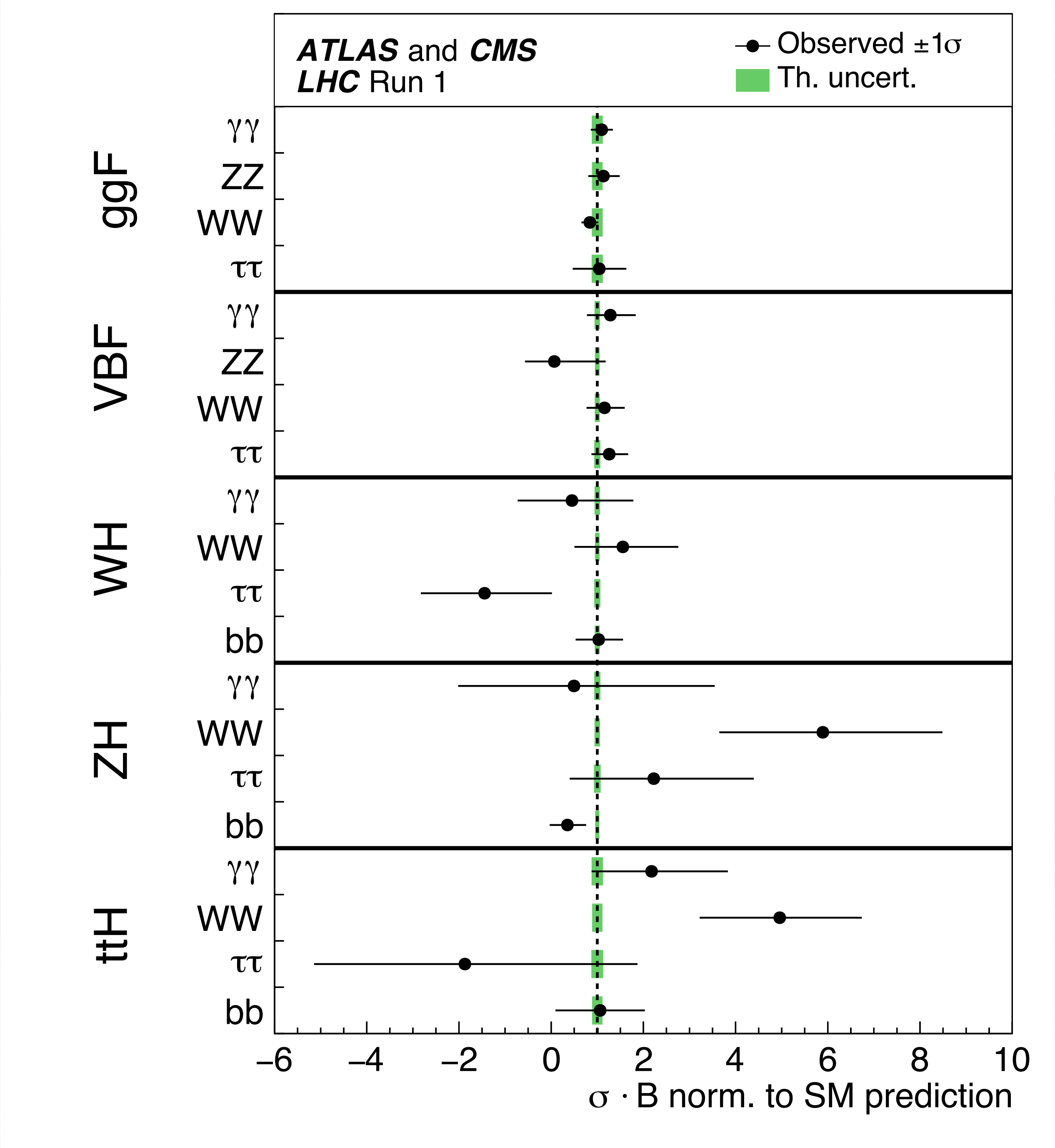
Phase II : CMS/ATLAS Higgs couplings combination





Data points agree with SM hypothesis at the 20-30% level

Phase II : CMS/ATLAS Higgs couplings combination



$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$

$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$

This information can be used by anybody to test BSM scenarios that lead to different patterns of Higgs coupling changes.

Phase III : SMEFT

The matter content of SM has been experimentally verified and evidence for new light states has not yet emerged.

SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions. More in general one can interpret measurements in terms of an EFT:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

the BSM ambitions of the LHC Higgs/Top/SM physics programmes can be recast in as simple as powerful way in terms of one statement:

"BSM goal" of the SM LHC Run II programme:

determination of the couplings of the SM@DIM6

SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

The EFT approach: managing unknown unknowns

- Very powerful model-indepedent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable (LO, NLO,..)
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
- The final reach on the scale of New Physics crucially depends on the THU.

Advanced questions on the SMEFT

- What are the advantages of an EFT vs anomalous couplings approach? What are the disadvantages? Limitations?
- Where does the power of the EFT really lie?
- Unitarity violation in EFTs: Why? How to test for it? How to deal with that in practice? What about form factors?
- In the Higgs case, production or decay in the EFT seem two different worlds. Why? What are the challenges for production and for decays? Is there a genuine or just a technical difference?
- New dim=6 interactions can mediate processes that are extremely suppressed in the SM. How do deal with that?
- The need and the challenges of the global approach.
- There seem to be several EFT bases. Why? Do we care in practice or is a purely TH discussion? Are there operators which are more important than others to start with?
- more…

Status of the SMEFT at NLO: Decays

- H decays:

Channel	SM: QCD, EW	dim=6 : QCD,EW	Comments
H→gg	N3LO,NLO	NLO: $C_{t\phi}$,$C_{\phi G}$ LO:	C_{tG} feasible
H→ff	NNLO, NLO	NLO,NLO	—-
H→γγ	NLO, NLO	one-loop	two-loop?
H→4l	NLO, NLO	LO	NLO EW welcome

  - Part of the NLO effects available in eHDECAY [Contino et al. 14]
  - Event generation for H→4l available from Prophecy4f and Hto4l including dim=6 at LO. [Bredenstein, 07] [Boselli et al. 17]
- Z→ff at NLO: [Hartmann, Shepherd, Trott, 16]
- t decays at NLO: [Zhang, 14]

Status of the SMEFT at NLO: Higgs production

Channel	SM: QCD, EW	dim=6 : QCD	Comments
gg→H	N3LO,NLO	NLO: $C_{t\phi}$,$C_{\phi G}$ C_{tG}	Now complete
gg→Hj	NNLO, LO	NLO: $C_{\phi G}$, LO: $C_{t\phi}$,C_{tG}	NLO hard to complete
ttH	NNLO, NLO	NLO	NLO EW hard
bbH	NNLO, LO	LO	NLO to do
gg→HH (LI)	NLO, LO	LO (apart $C_{\phi G}$)	NLO very hard
gg→HZ (LI)	LO, LO	LO	NLO very hard
tHj	NLO, LO	NLO	Now complete
VBF	N3LO, NLO	(N)NLO	NLO EW welcome
VH	NNLO,NLO	(N)NLO	NLO EW welcome

more SU(3) ↑

more SU(2)xU(1) ↓

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

$$O^{(3)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O^{(1)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

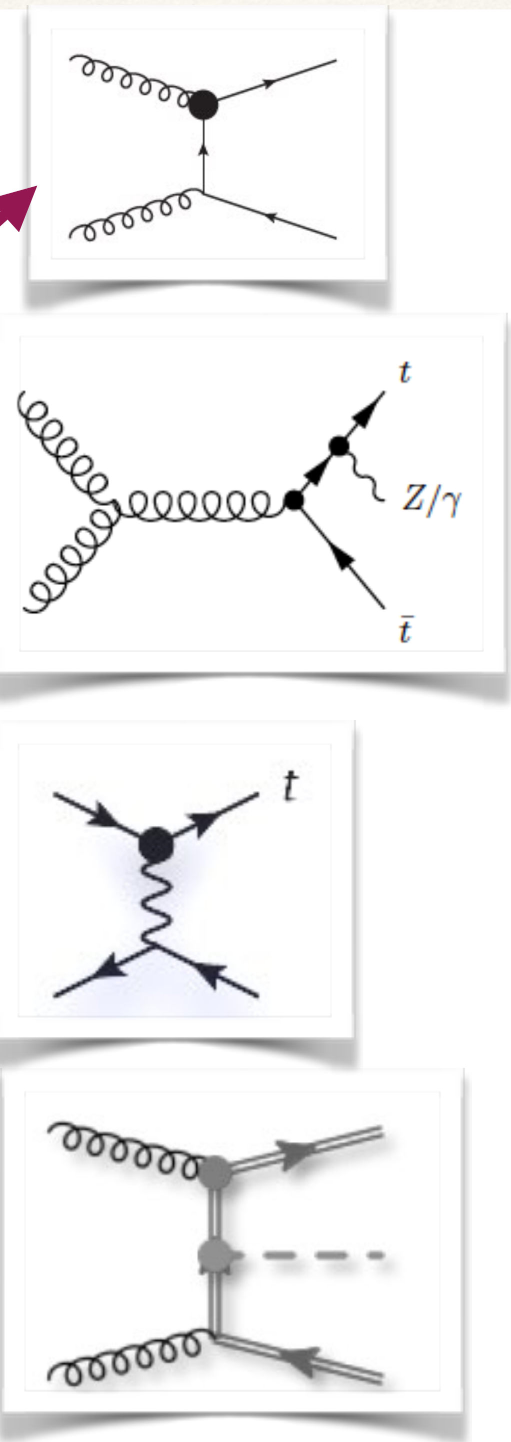
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$



+four-fermion operators

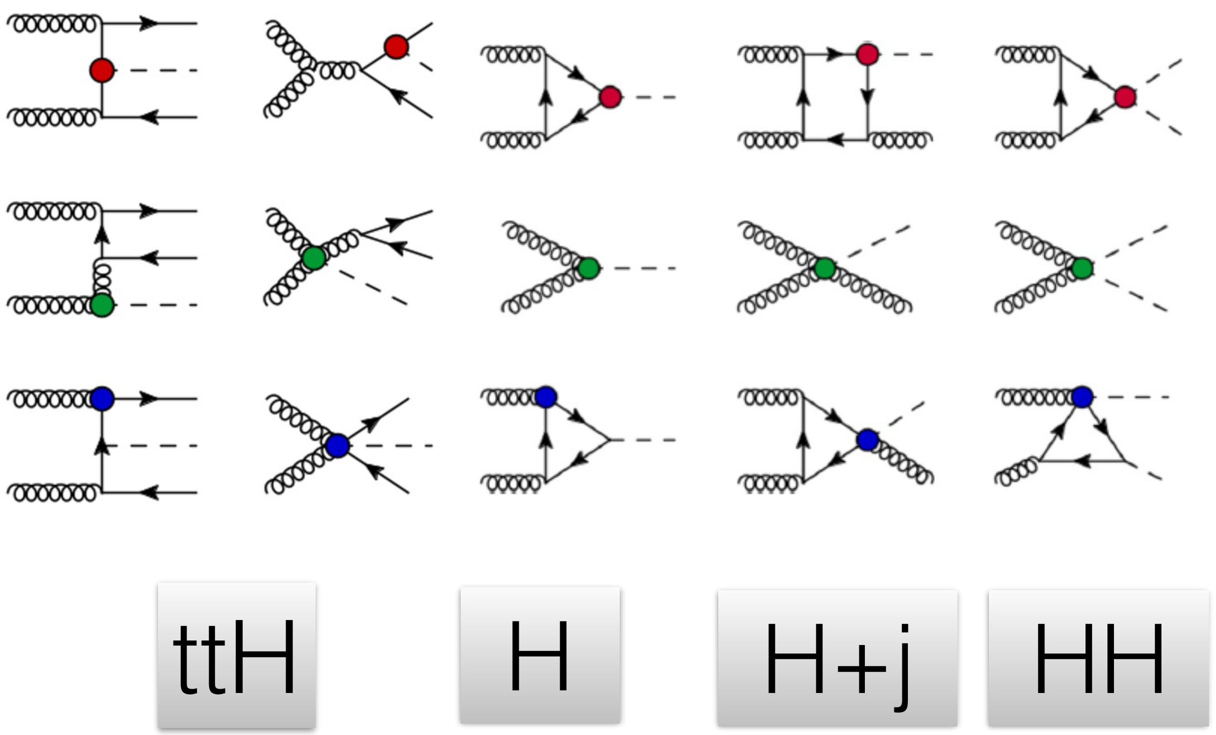
+ operators that do not feature a top, but contribute to the procs…

Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO^2) and

NLO (no	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
○ ✓	$gg \to H$	L						L				N	L
○ ✗	$gg \to Hj$	L						L				L	L
○ ✗	$gg \to HH$	L						L				N	L
○ ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes



$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\,\tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

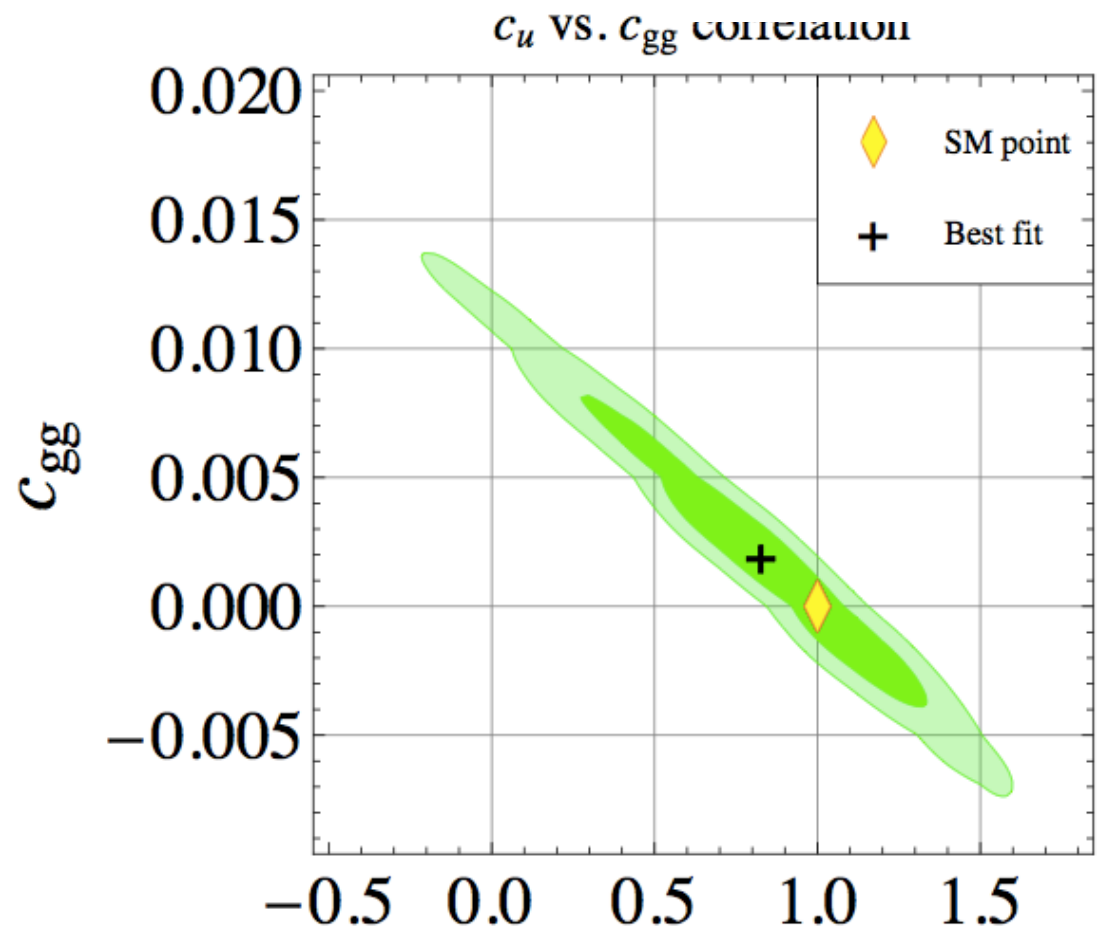
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

Top-Higgs interactions: constraints

From a global fit the coupling of the higgs to the top is poorly determined.

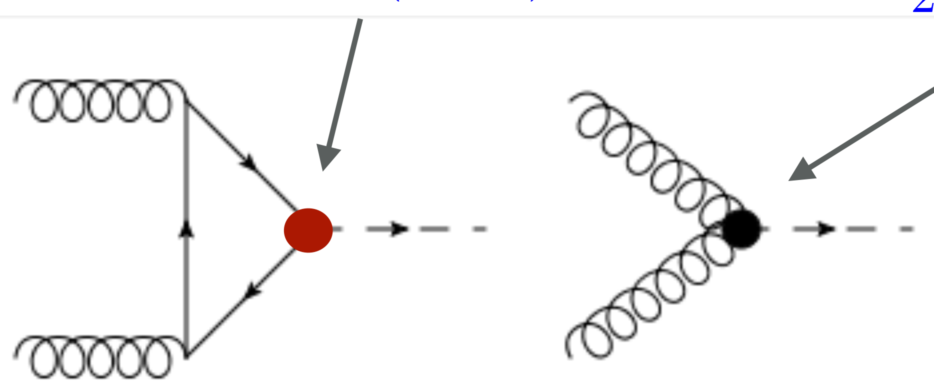
$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq \left|1+\frac{\hat{c}_{gg}}{c_{gg}^{\rm SM}}\right|^2 \qquad \hat{c}_{gg} \simeq c_{gg} + (8.7\delta y_u - (0.3-0.3i)\delta y_d) \times 10^{-3}, \qquad c_{gg}^{\rm SM} \simeq (8.4+0.3i)\times 10^{-3}$$

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$



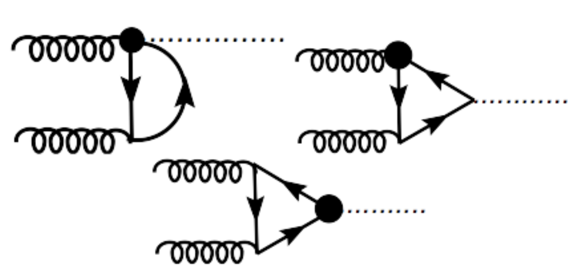
[Belusca-Maite, Falkowski, 2013]

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G_a^{\mu\nu}$$



the loop could still be dominated by np.

THE EFFECT OF THE CM OPERATOR NOT INCLUDED

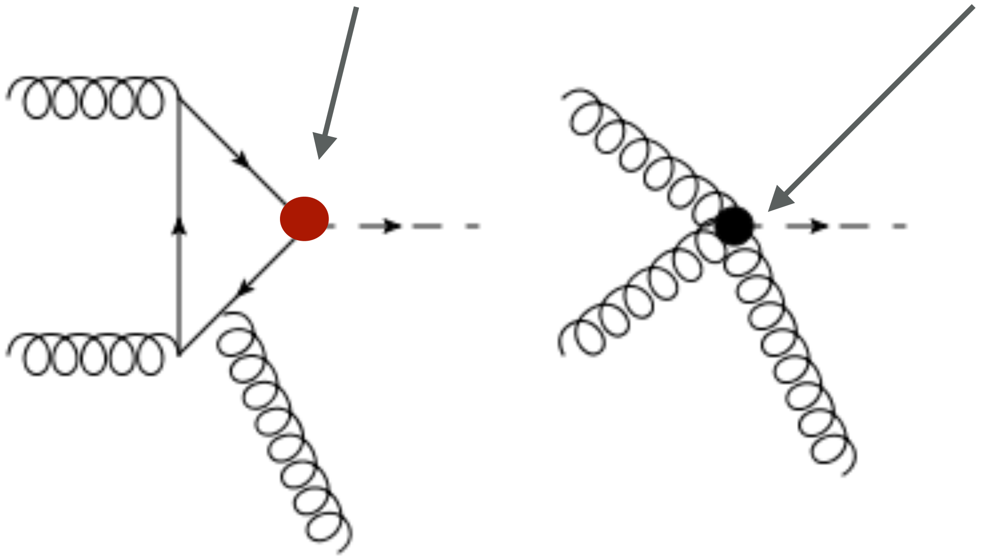


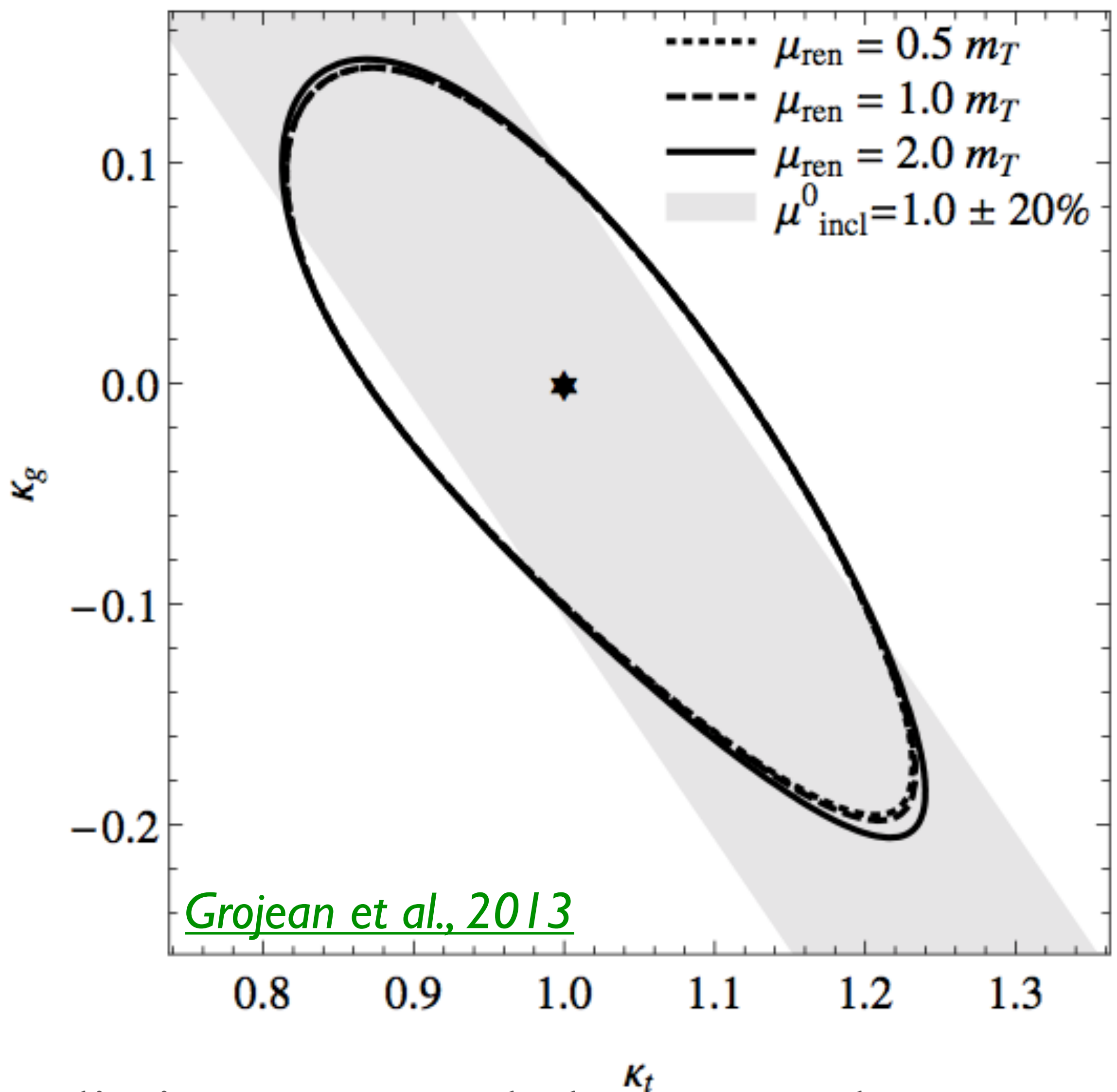
Top-Higgs interactions: high-pt

From a global fit the coupling of the higgs to the top is poorly determined: the loop could still be dominated by np.

[Grojean et al., 2013] [Banfi et al. 2014] [Buschmann, et al. 2014]

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



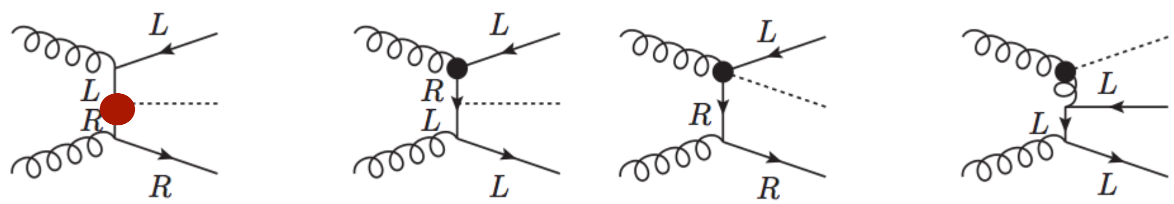


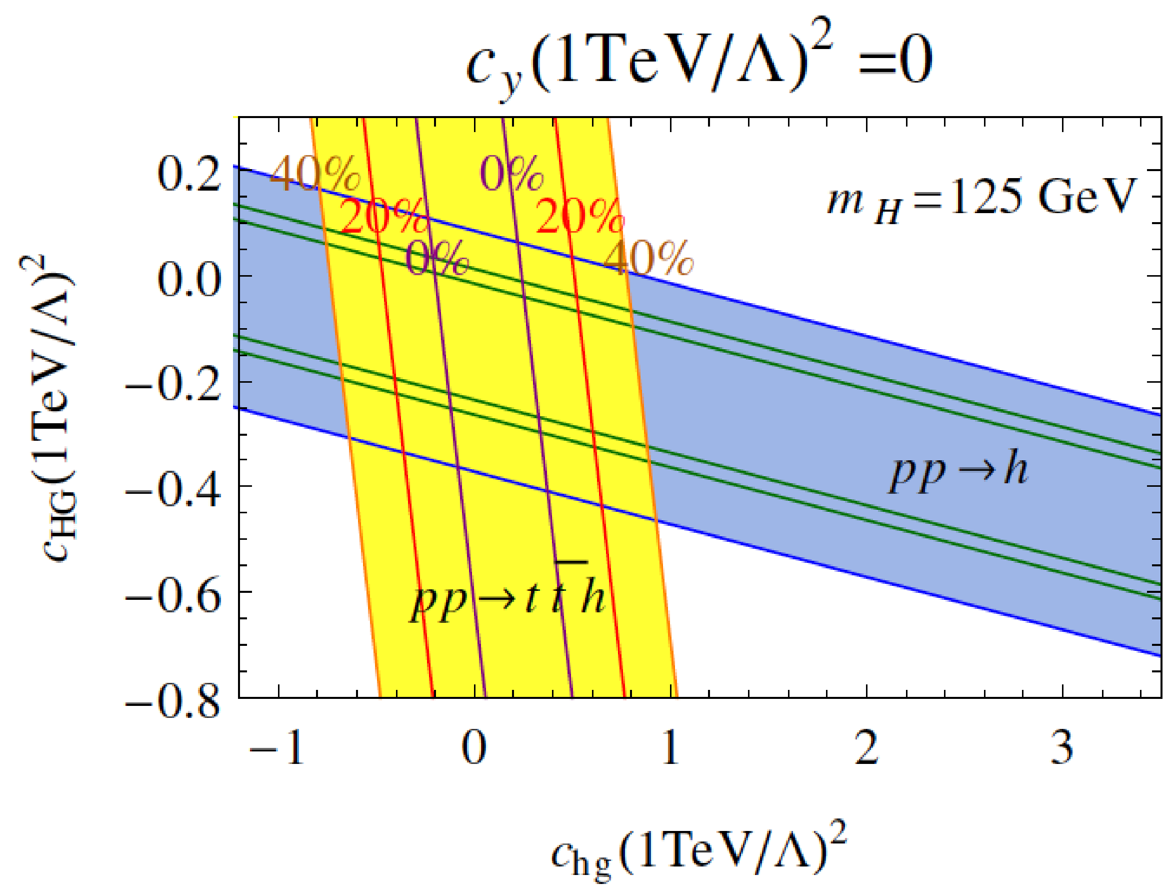
EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision.

Top-Higgs interactions: ttH

$pp \to t\bar{t}h$

[Degrande et al. 2012]





$$
\begin{aligned}
\frac{\sigma(pp \to t\bar{t}h)}{\text{fb}} = {} & 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G \right. \\
& \left. + 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y\right]\left(\frac{\text{TeV}}{\Lambda}\right)^2 \\
& + \left[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232} c_G^2\right. \\
& + 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2 \\
& + 233^{+81}_{-144}\Re c_{hg} c_{HG} - 50^{+16}_{-14}\Re c_{hg} c_y \\
& \left. - 3.2^{+8}_{-8}\Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG}\right]\left(\frac{\text{TeV}}{\Lambda}\right)^4
\end{aligned}
$$

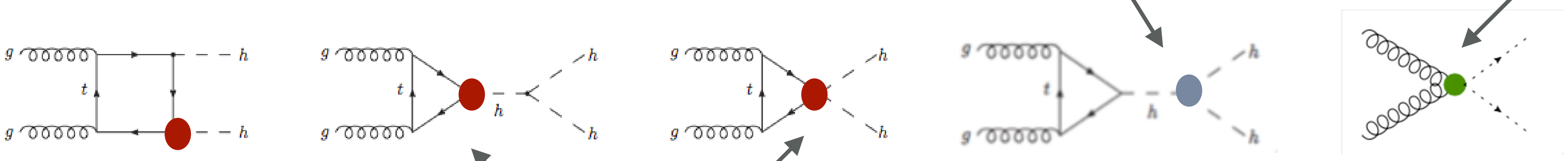
Analysis done at LO! NLO is now within reach

Top-Higgs interactions: HH

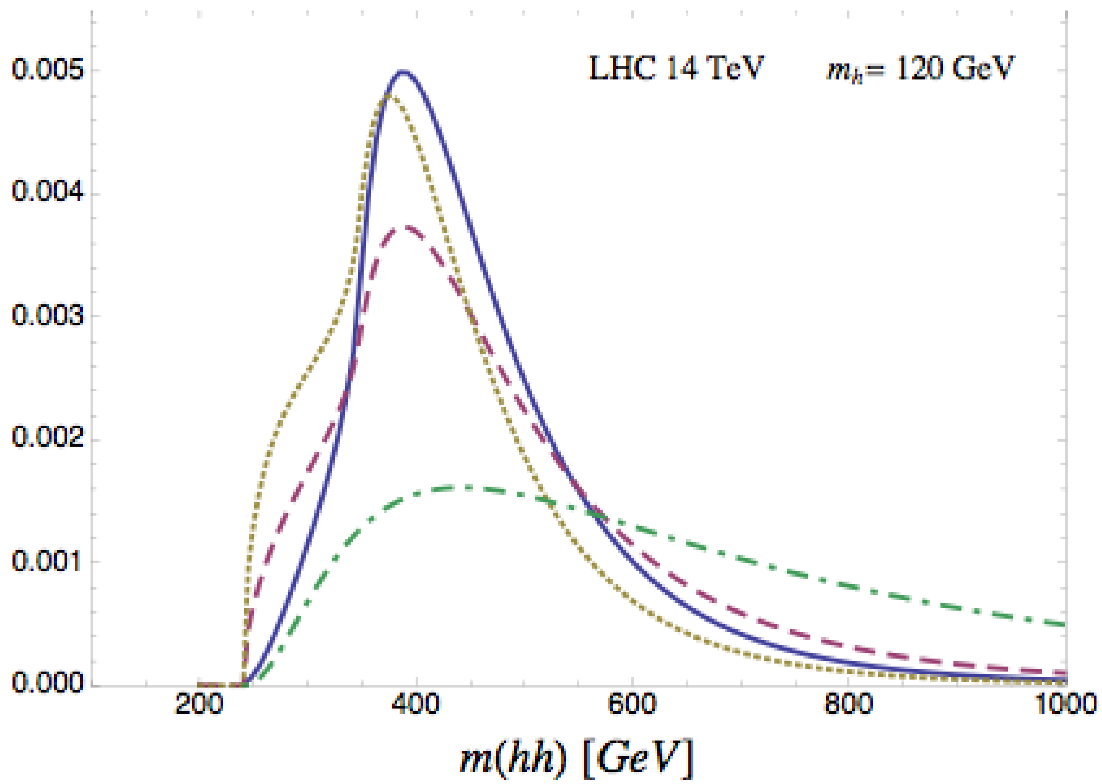
$$pp \to hh$$

$\mathcal{O}_6 = (H^\dagger H)^3$

$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G_a^{\mu\nu}$



$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R$



[Contino et al. 2012]

The strong destructive interference gives extra sensitivity of pp→HH to dim=6 operators.

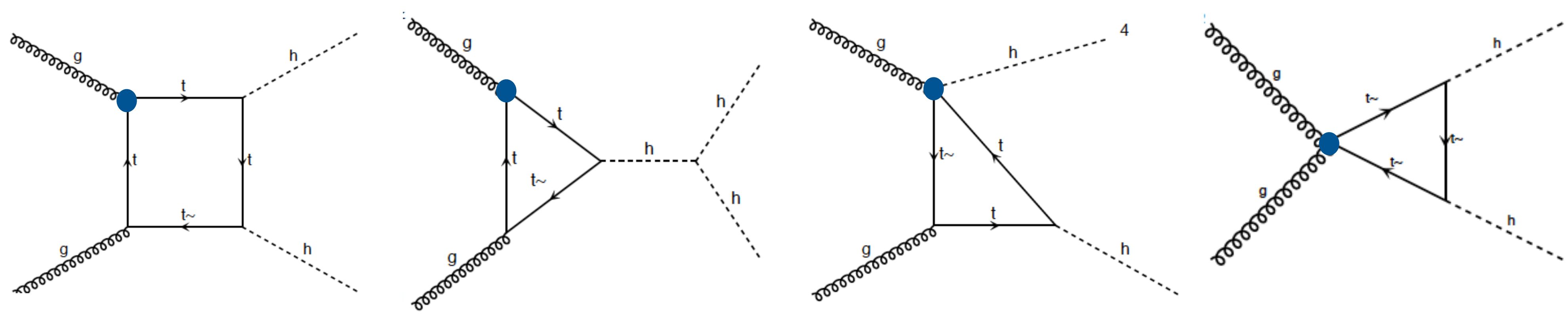
The HHH coupling is modified by two operators of dim=6.

Only a global approach will allow to accurately measure the HHH coupling from HH.

HH production in the SMEFT

Chromomagnetic operator is also contributing [FM, Vryonidou, Zhang, 16]

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$



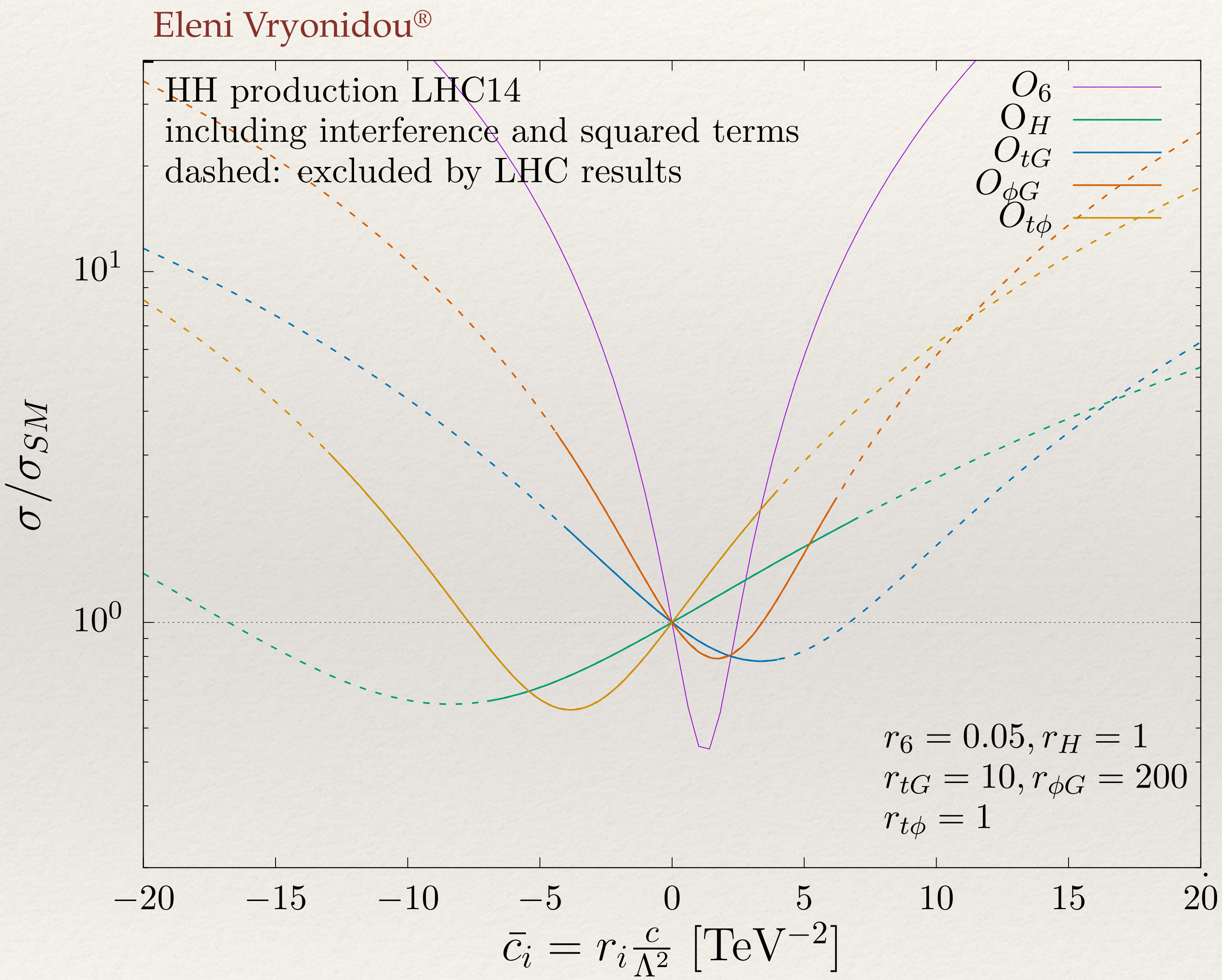
Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

C_{tg}= [-0.42,0.30] [Zhang and Franzosi,15]

show that this operator contribution is important.

Note: now that NLO in the SM is known, one could have c_t,c_H,c_g contributions at NLO.
The c_g is known at NNLO [de Florian, Fabre, Mazzittelli, 17]

HH sensitivity in the SMEFT

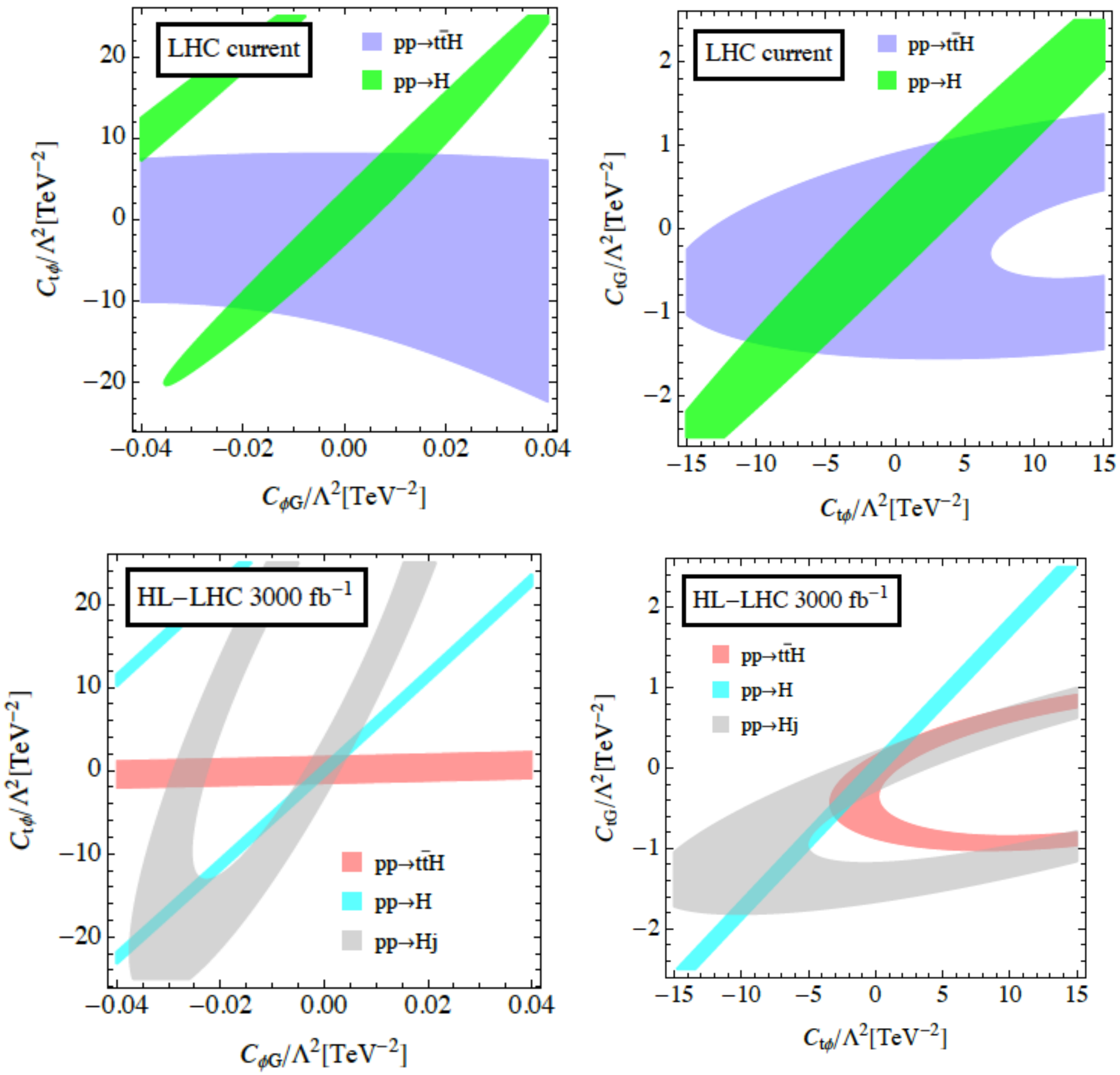


Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable.

1. An accurate measurement of the Higgs self-couplings will depend on our ability to bound several (top-related) SMEFT operators: O_{tG},$O_{\varphi G}$,$O_{t\varphi}$.
2. Given the current constraints on σ(HH), the Higgs self-coupling can be constrained “ignoring” the other EFT couplings.
3. The current “EFT-relevant” range corresponds to values around $-2 \lesssim k_\lambda \lesssim 4$.

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]



Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

14TeV projection

3000 fb-1

Top & Higgs

Thanks a lot for
your attention!

Thanks

- to Carlo Oleari for his original tex slides on the SM which I am still happily using/editing/enjoying after many years.
- to all my collaborators with whom I explore new ideas and features of the SMEFT theories on almost everyday basis: it's really great fun!

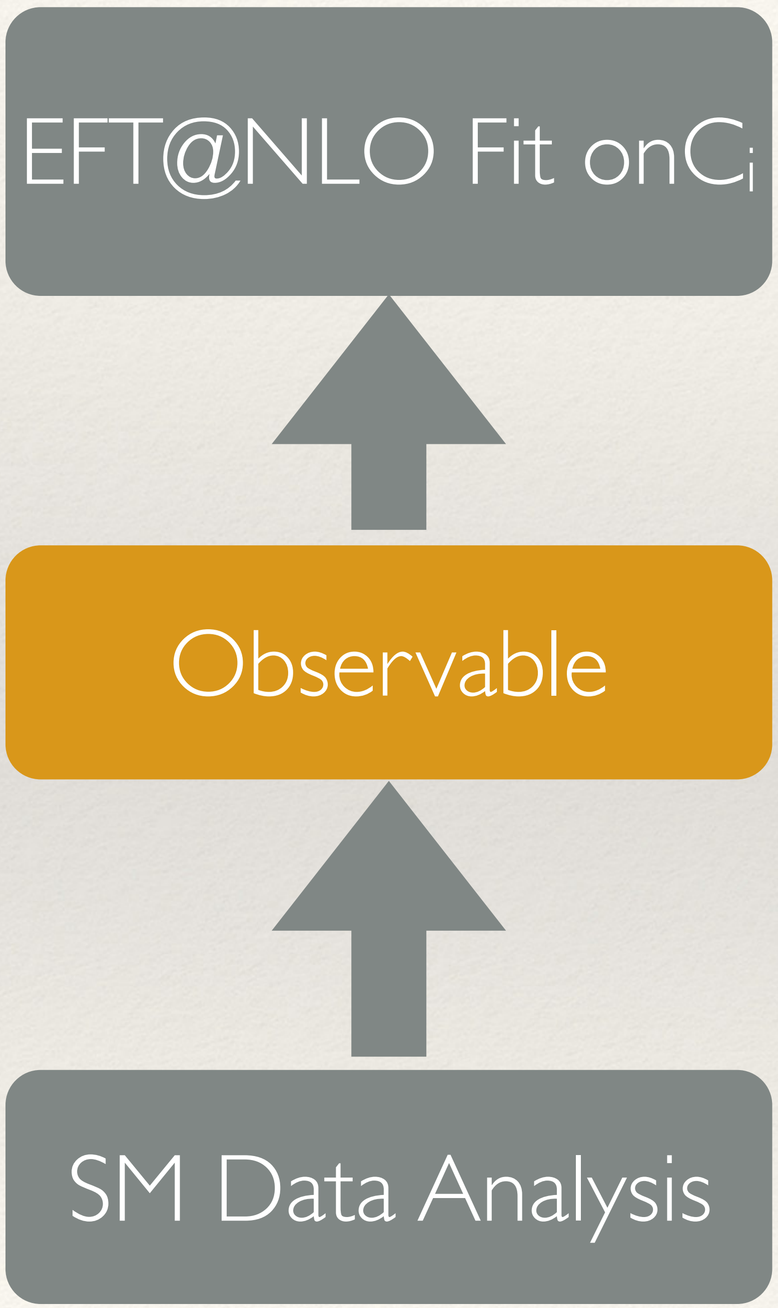
Additional topics

Approaches

OPTION top-down

- This is the ideal way as it would maximise the sensitivity (in analogy to any BSM top-down search) and it does not need providing information back at the particle level.
- However, it assumes several important conditions:
  - The analyses at the experimental level are fully coordinated and can be combined.
  - The theoretical setup is final and the dependence on additional theoretical assumptions is minimal.
- While globally this might not be a realistic option, feasibility studies could start for specific subsets.

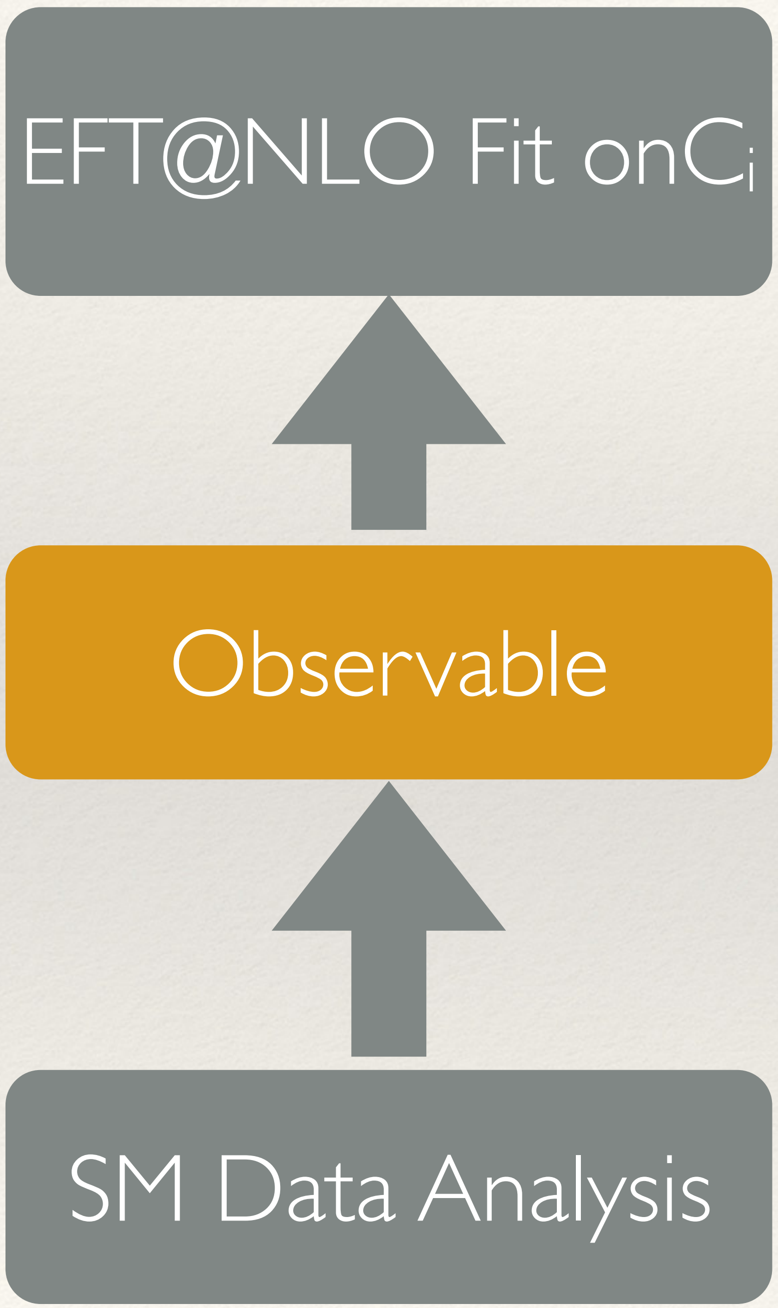
Approaches



OPTION bottom-up

- A (continuously extendable) set of observables is identified and measured.
- Such observables can be of various types, from “total cross section” to differential distributions, typically at the particle level or parton level.
- Ex: total cross sections, (pt, eta) distributions, correlations.
- Results are provided with the minimal systematic uncertainty breakdown so that they can be combined with other measurements.
- One dimensional differential distributions should be provided with the bin-by-bin correlation matrix.

Approaches



OPTION bottom-up

- This approach has the advantage that TH predictions, evaluations of the uncertainties, constraints coming from other studies, can be constantly and continuously included.
- It could be used to prepare a top-down and global approach.
- It might motivate and pave the way to the more sensitive EXP fits.

SMEFT@NLO

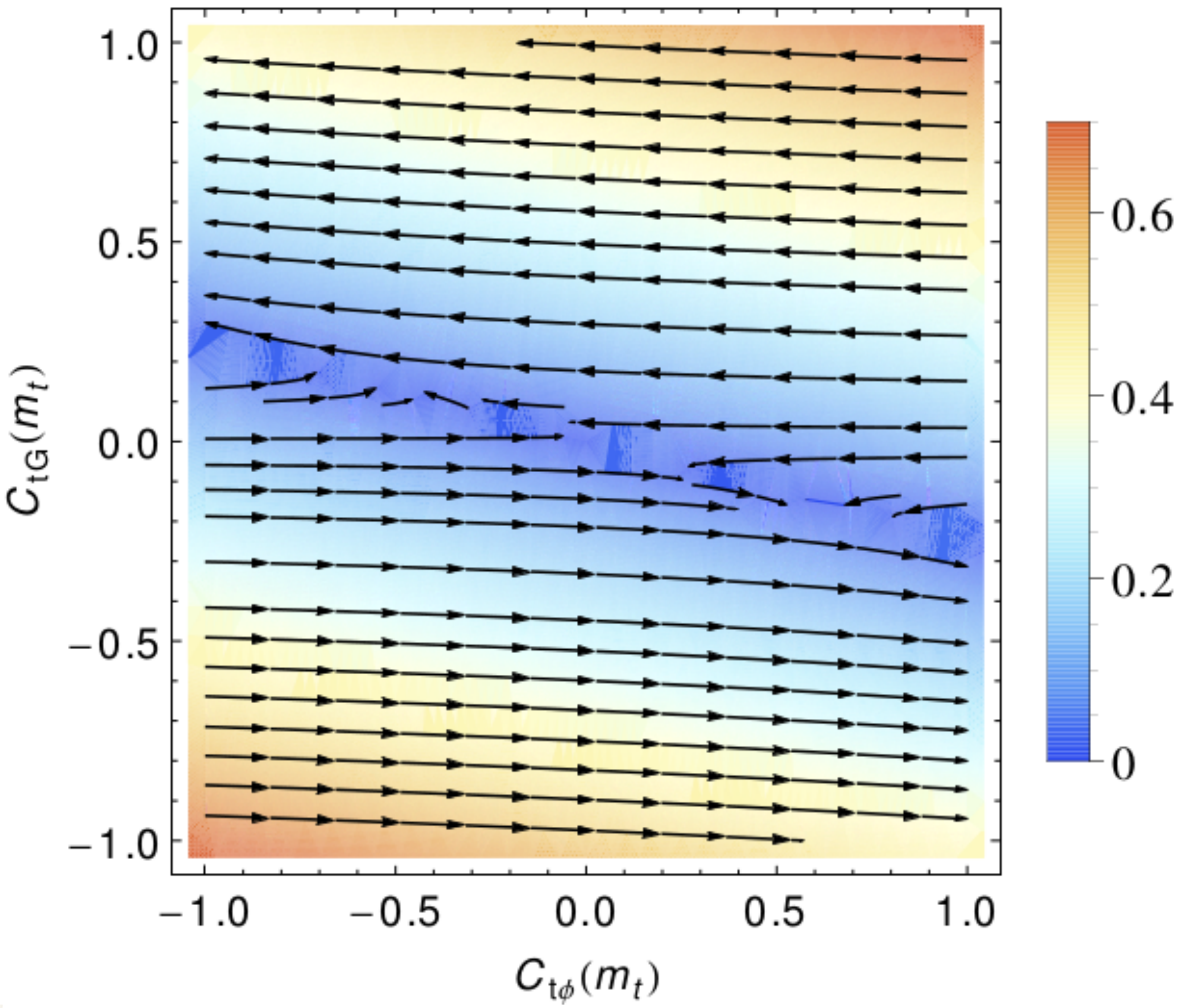
1. Operators run and mix under RGE

Running means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

Mixing means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.

SMEFT@NLO

1. Operators run and mix under RGE



Scale corresponds to the change from mt to 2 TeV.

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q} t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}\,.$$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij} C_j(\mu), \quad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

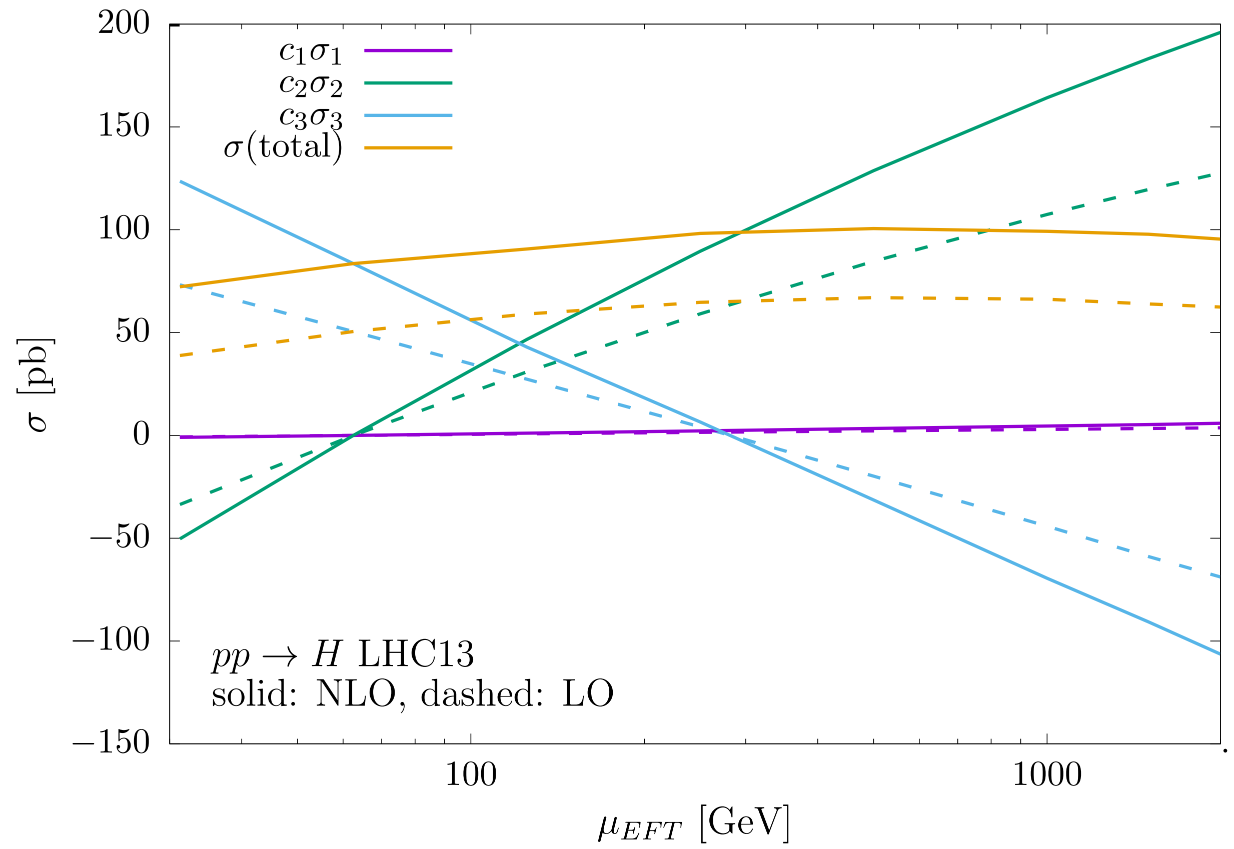
At = 1 TeV: $C_{tG} = 1$, $C_{t\varphi} = 0$;

At = 173 GeV: $C_{tG} = 0.98$, $C_{t\varphi} = 0.45$

SMEFT@NLO

2. EFT scale dependence

[Deutschmann, Duhr, FM, Vryonidou, 17]



$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) (\bar{Q}t)\,\tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij} C_j(\mu),$$

$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.

SMEFT@NLO

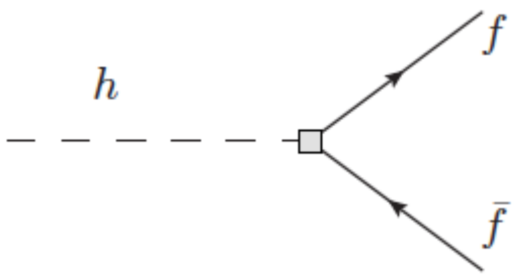
3. Genuine NLO corrections (finite terms) are important

The cancellation of UV divergences from more than 20 dim-6 operators in the full result gives a highly non-trivial check on the calculation. The logarithmic corrections could have been deduced from a Leading Log analysis:

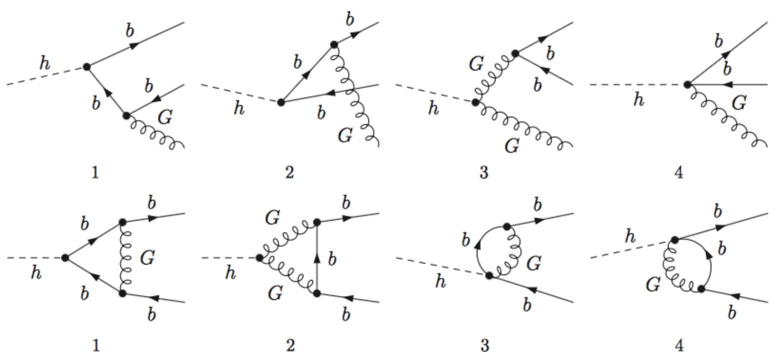
[Gauld, Pecjak, Scott, 15]

[Gauld, Pecjak, Scott, 16]

$$C_i(\mu_t) = C_i(\Lambda_{\rm NP}) + \frac{1}{2}\frac{1}{16\pi^2}\dot{C}_i(\Lambda_{\rm NP}) \ln\left(\frac{\mu_t^2}{\Lambda_{\rm NP}^2}\right)$$



However, calculation of the full NLO calculation illuminates term which would be missed in an RG analysis



$$\overline{\Gamma}^{(6,1)}_{\beta\to 1} = \left(2C_{H,\rm kin} - \frac{\sqrt{2}v_T^3}{\overline{m}_b}C_{bH}\right)\overline{\Gamma}^{(4,1)}_{\beta\to 1} + \frac{\alpha_s C_F}{\pi}\frac{N_c m_h^3 \overline{m}_b}{8\sqrt{2}\pi v_T}C_{bG} + \frac{\alpha_s C_F}{\pi}\frac{N_c m_h \overline{m}_b^2}{8\pi}C_{HG} \times \left(19 - \pi^2 + \ln^2\left[\frac{\overline{m}_b^2}{m_h^2}\right] + 6\ln\left[\frac{\mu^2}{m_h^2}\right]\right)$$

See also Z⟶ff at NLO:

[Hartmann, Shepherd, Trott, 16]

SMEFT@NLO

3. Genuine NLO corrections (finite terms) are important

Let us consider the uncertainties associated to changes of μ_{EFT} .
The result at μ_0 can be expressed as:

$$\sigma(\mu_0) = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0) + \sum_{i,j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0)\,,$$

While the same result at a different scale μ can be expressed as:

$$\begin{aligned}\sigma(\mu) =& \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i(\mu)\sigma_i(\mu) + \sum_{i,j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i(\mu)C_j(\mu)\sigma_{ij}(\mu)\\ =& \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0;\mu) + \sum_{i,j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0;\mu)\end{aligned}$$

with:

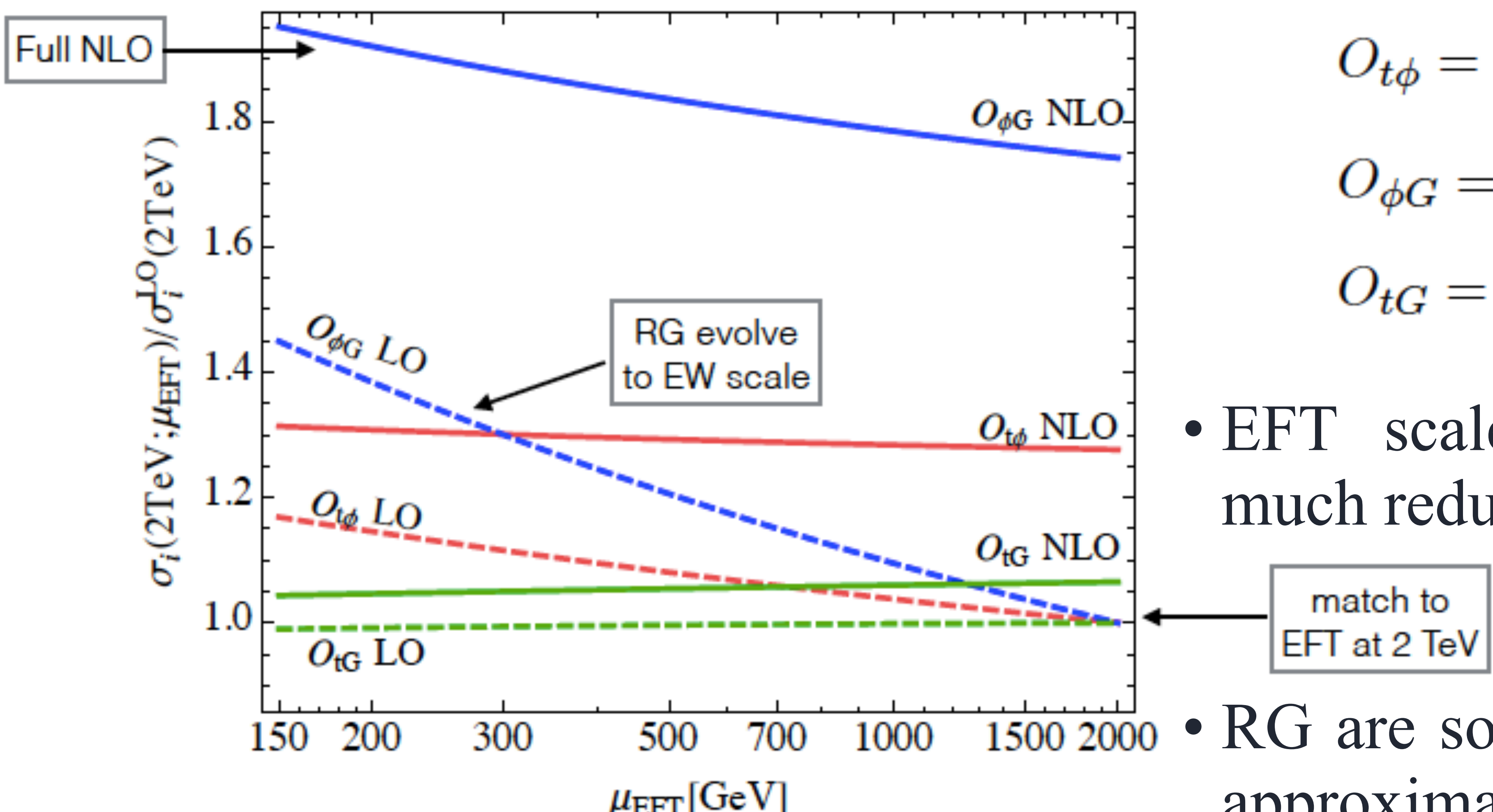
$$C_i(\mu) = \Gamma_{ij}(\mu,\mu_0)C_j(\mu_0)$$
$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu)\,,$$
$$\sigma_{ij}(\mu_0;\mu) = \Gamma_{ki}(\mu,\mu_0)\Gamma_{lj}(\mu,\mu_0)\sigma_{kl}(\mu)\,.$$

$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$
$$\beta_0 = 11 - 2/3n_f\,,$$

SMEFT@NLO

3. Genuine NLO corrections (finite terms) are important

[FM, Vryonidou, Zhang, 16]



- pp → ttH

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q}t\right) \tilde{\phi}\,,$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

- EFT scale uncertainties are very much reduced at NLO.
- RG are sometimes thought to be an approximation for full NLO, but it is often not the case.

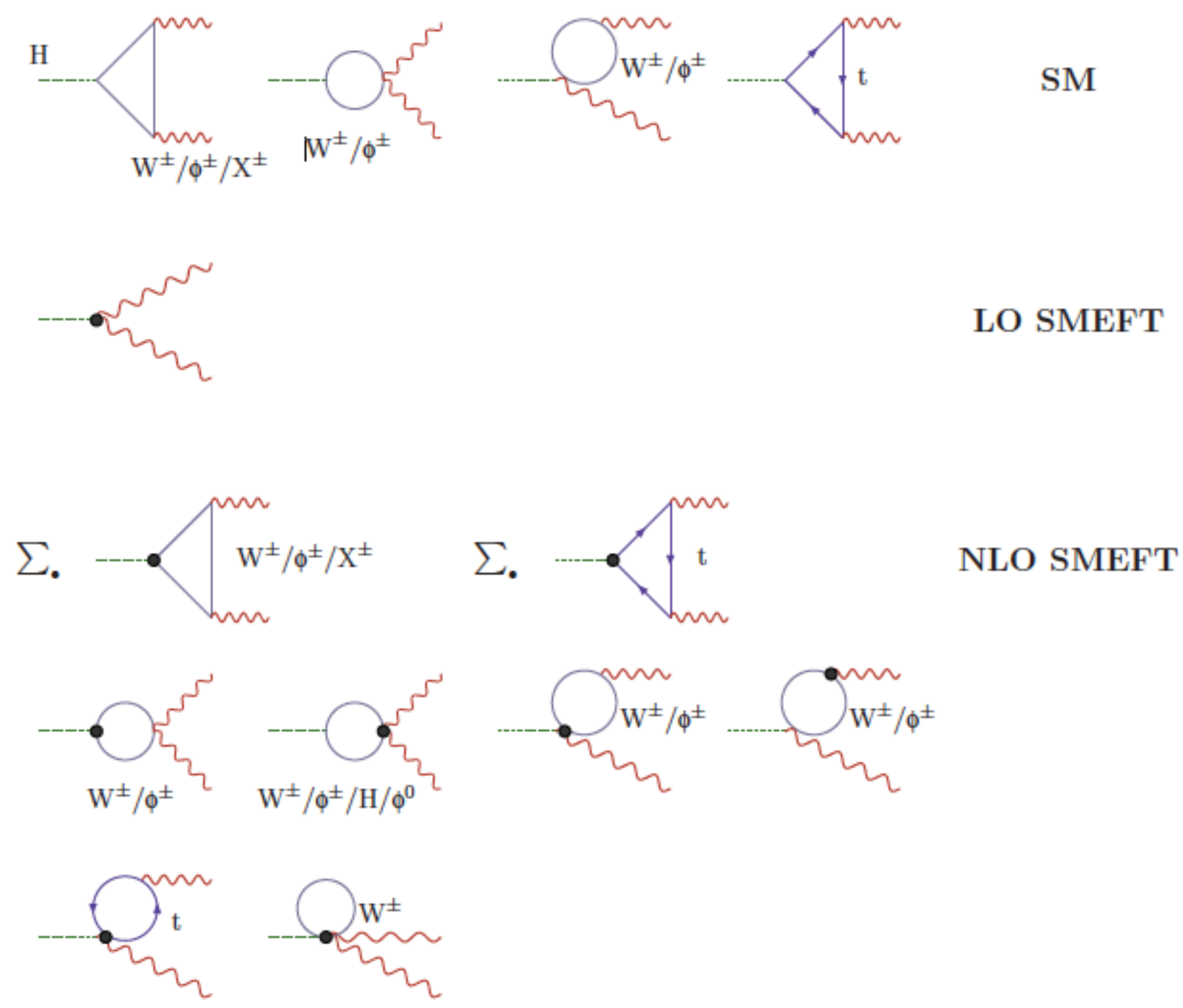
SMEFT@NLO

4. New operators arise

New operators can arise at one-loop or via real corrections.

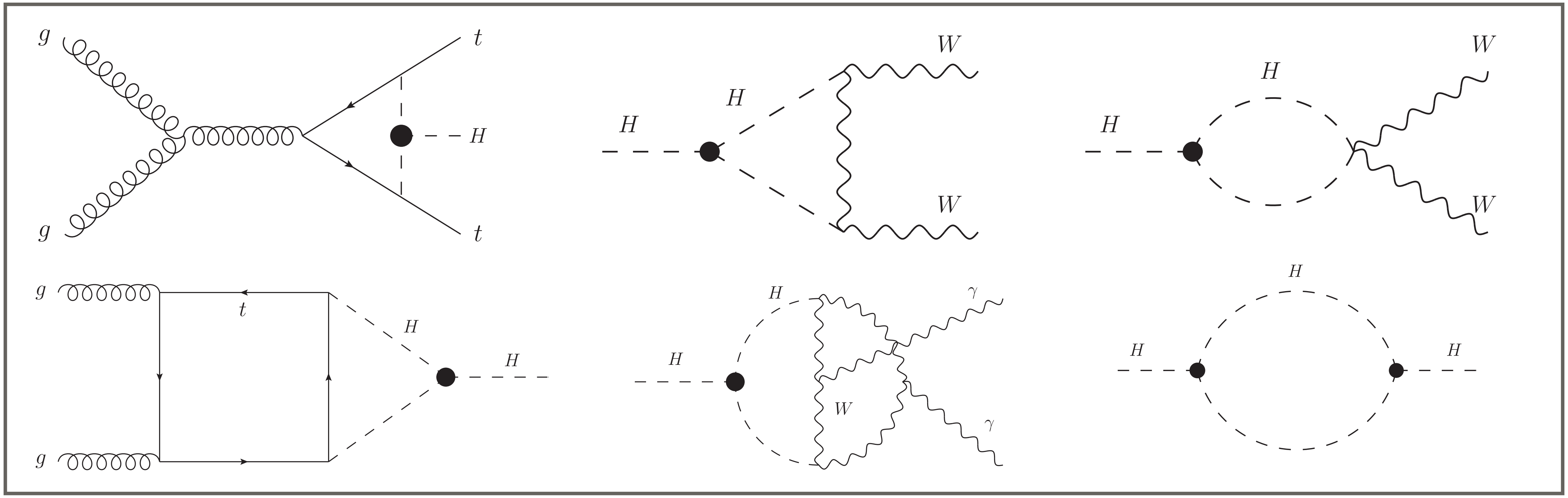
- At variance with the SM, loop-induced processes might not be finite.
- Including the full set of operators at a given order implies that no extra UV divergences appear (closure check).
- Choice of the normalisation of operators matters for LO, NLO nomenclature…

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]



SMEFT@NLO

4. New operators arise ⇒ new sensitiviness. Example: O_6



2) Combine all the information (rates and distributions) coming from the relevant single Higgs channels in a global way.