Higgs EFT : the pheno side

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PLAN

Aneesh → covering theory/formal aspects

André → covering experimental aspects

me

THE NUTS AND THE BOLTS OF THE SM@DIM6 AT THE LHC

- General motivations for searching for new physics through interactions between SM particles
- HEFT: the basic concepts through the simplest possible examples
- The accuracy/precision needs and available tools to make predictions in the SM@dim6
- Higgs production and decay in the SM@dim6 at the LHC

STATUS AT THE DAWN OF LHC13

- 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.

SEARCHING FOR NEW PHYSICS

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

SEARCHING FOR NEW PHYSICS

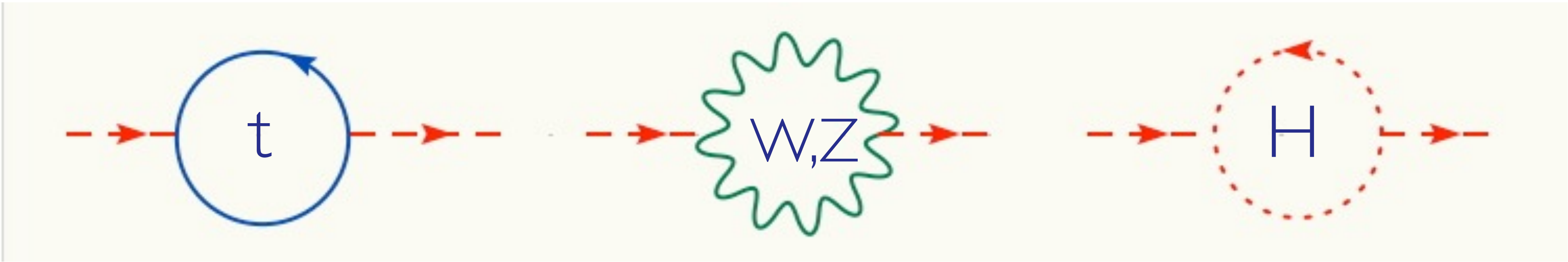
STATEMENT #2

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.

SEARCHING FOR NEW PHYSICS

Quantum corrections affect the stability of the Higgs mass. Consider the SM as an effective field theory valid up to scale Λ:

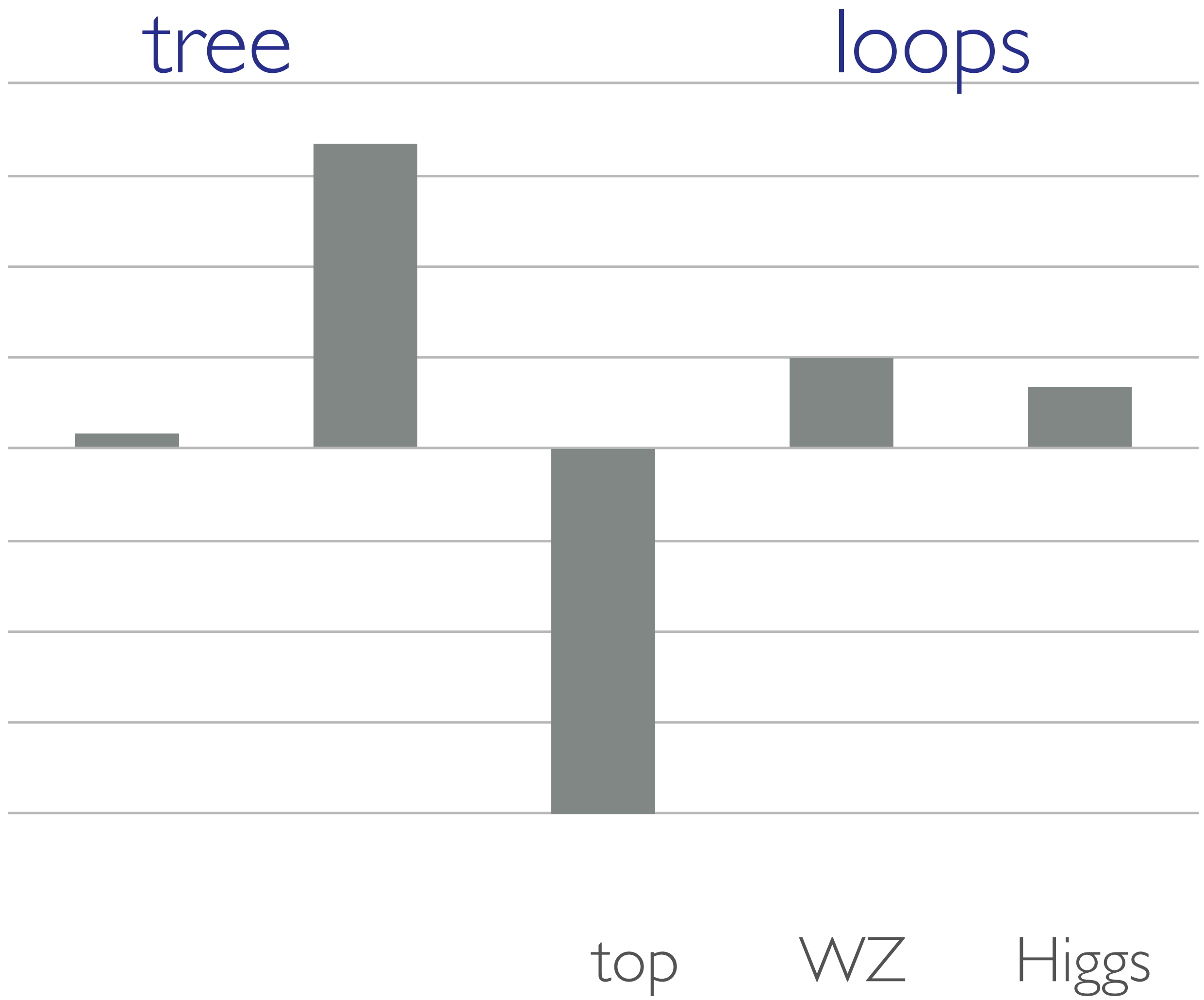


$$m_H^2 = m_{H0}^2 \qquad - \frac{3}{8\pi^2} y_t \Lambda^2 \qquad + \frac{1}{16\pi^2} g^2 \Lambda^2 \qquad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, one gets:

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

SEARCHING FOR NEW PHYSICS



MH^2 ~ (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:

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

Ex1= $\delta m_H^2 = \frac{3y_t^2}{8\pi^2}\tilde{m}_t^2 \ln\frac{\tilde{m}_t^2}{\Lambda^2}$

Ex2= $\delta m_H^2 \approx \frac{\lambda_\Phi}{16\pi^2}M^2 \ln\frac{M^2}{\Lambda^2}$

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 (Frontier):**
    Bound Higgs couplings

  - **PHASE II : DETERMINATION (Dawn):**
    Look for deviations wrt dim=4 SM (rescaling factors)

  - **PHASE III : PRECISION (Legacy):**
    Measure/bound the dim=6 SM parameters (EFT)

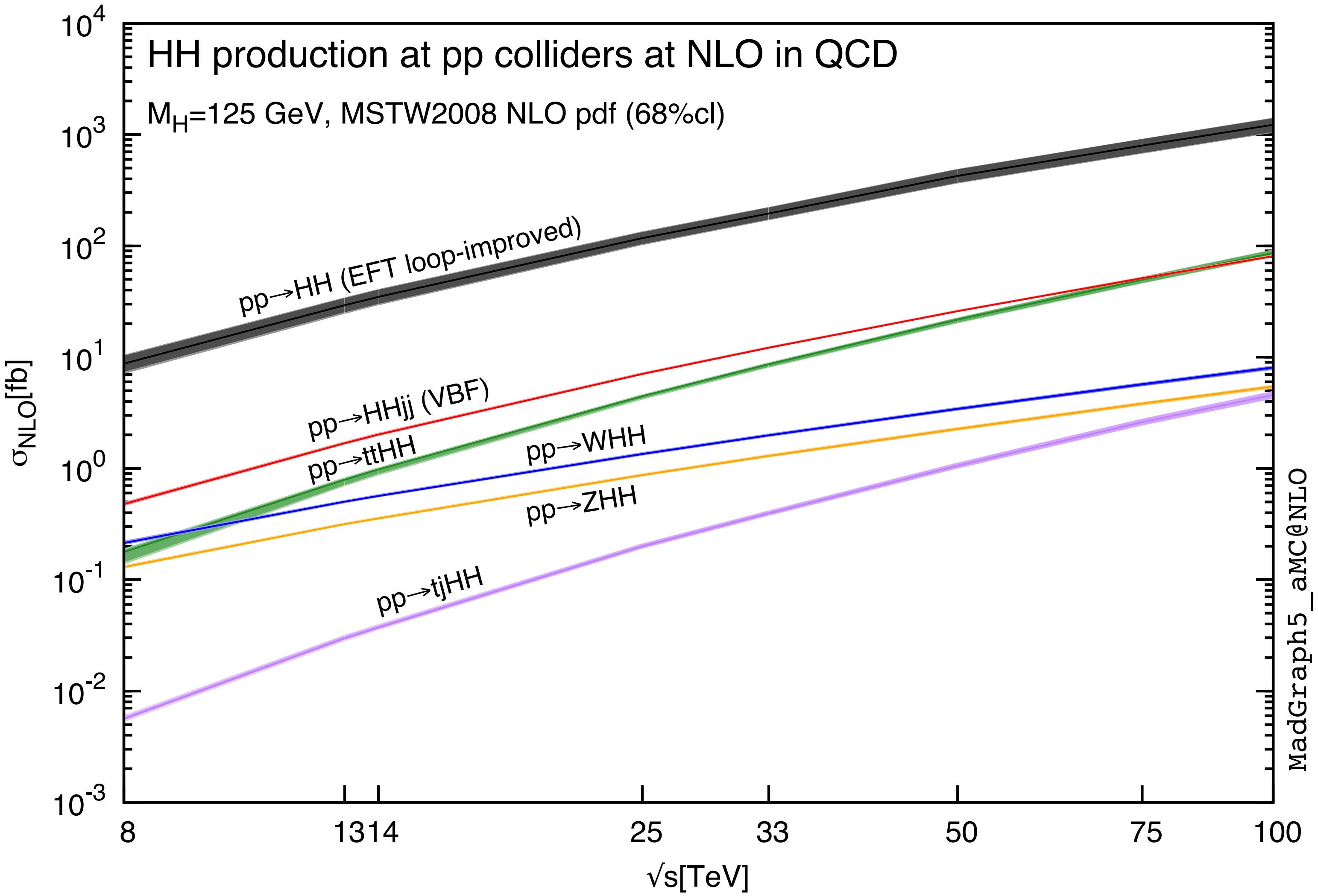
- Rare SM processes (induced by small interactions, such as those involving the Higgs with first and second fermion generations or flavour changing neutral interactions) are still in the exploration phase.

- For interactions with vector boson and third generation fermions we are ready to move to phase II.

PHASE I : EXPLORATION

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

$$\lambda_{HHH} = \lambda_{HHHH} = m_H^2/2v^2$$



Double higgs production is a very rare process.

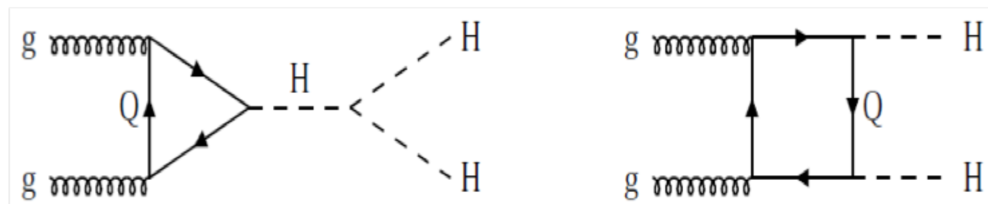
About 1000 times smaller cross section than single Higgs.

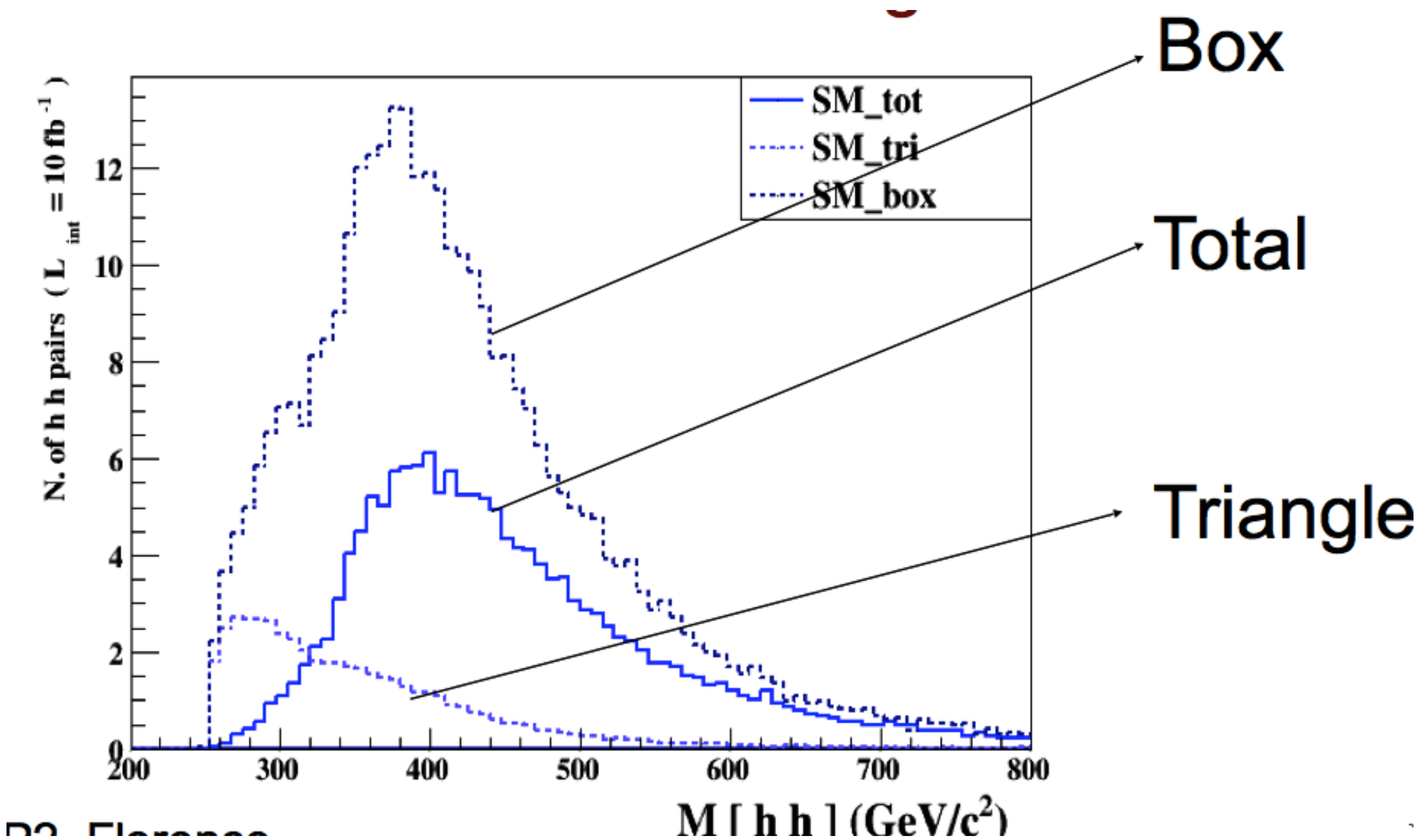
"same" channels as single higgs production available.

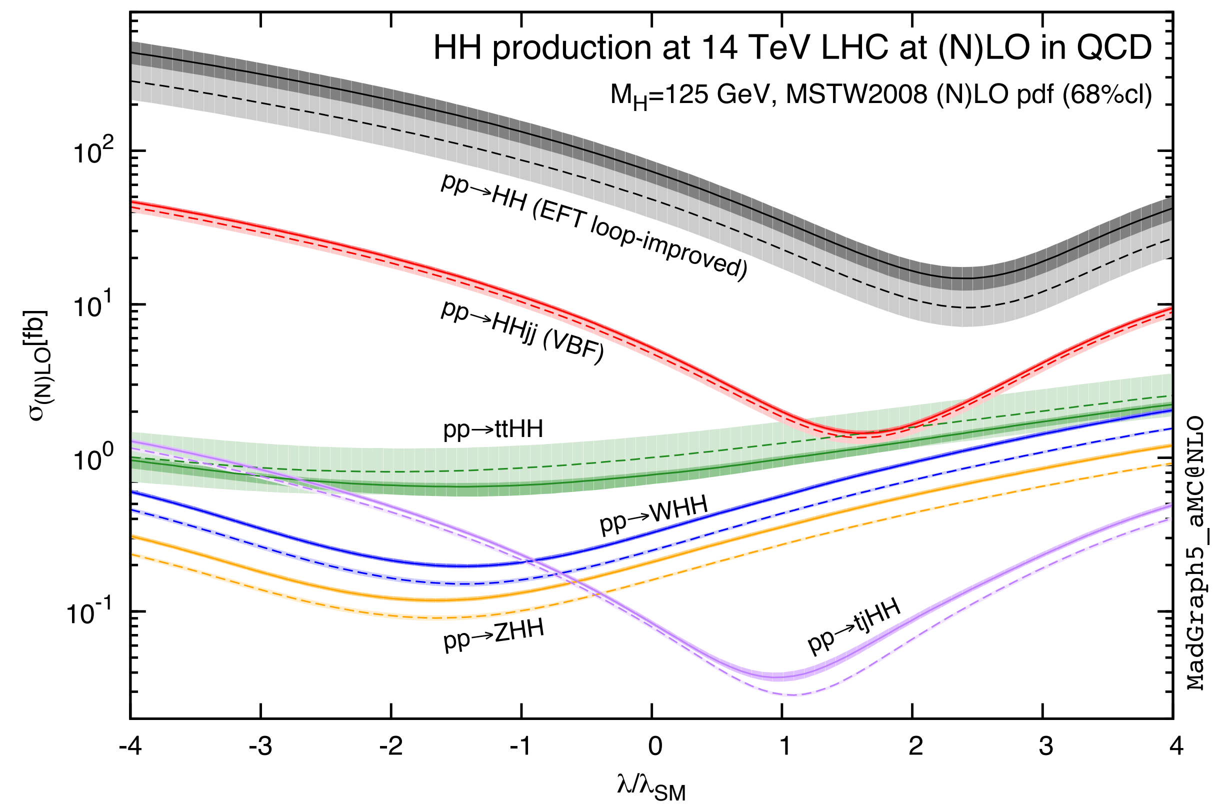
ttHH is the third largest.

(TO ME) THE MOST IMPORTANT MEASUREMENT IN THE HIGGS SECTOR

PHASE I : EXPLORATION







Small cross section due to negative interference

Sensitivity to variations with respect to lambda at NLO in QCD.

PHASE I : EXPLORATION

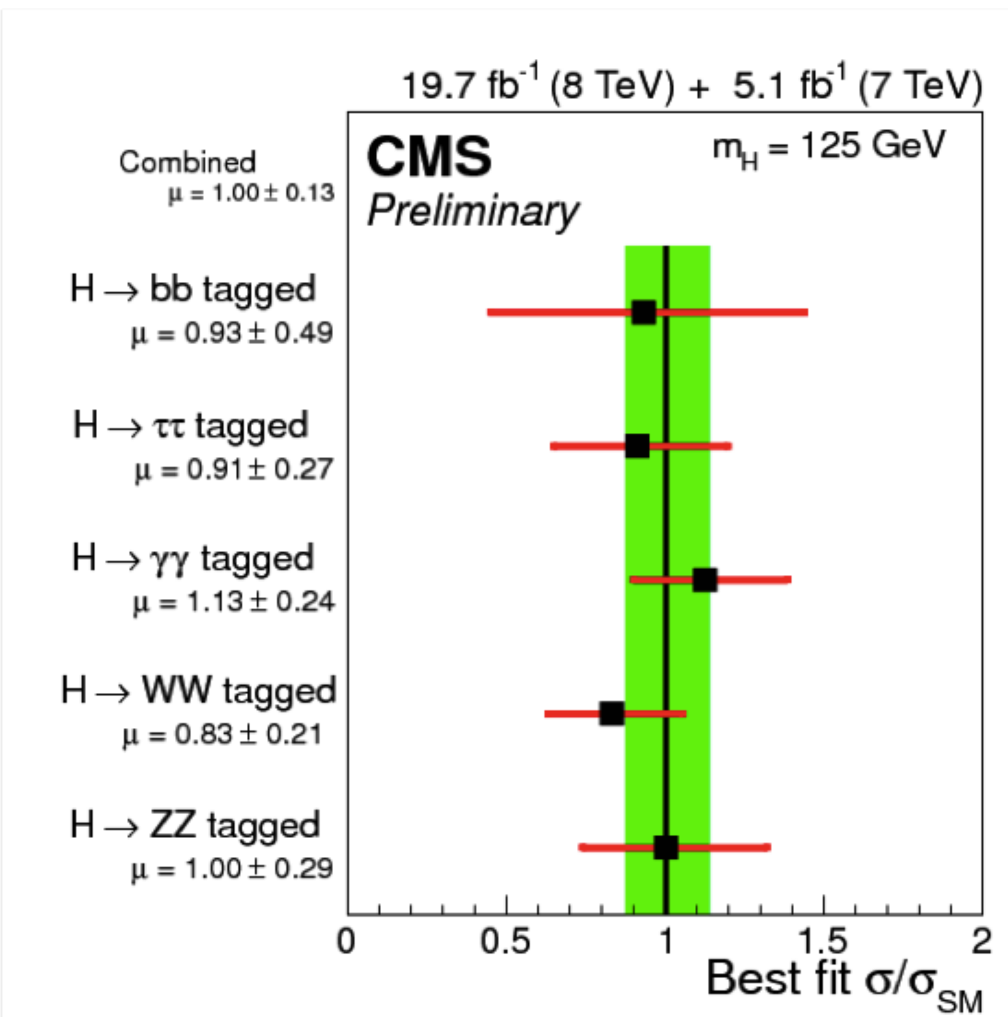
Couplings

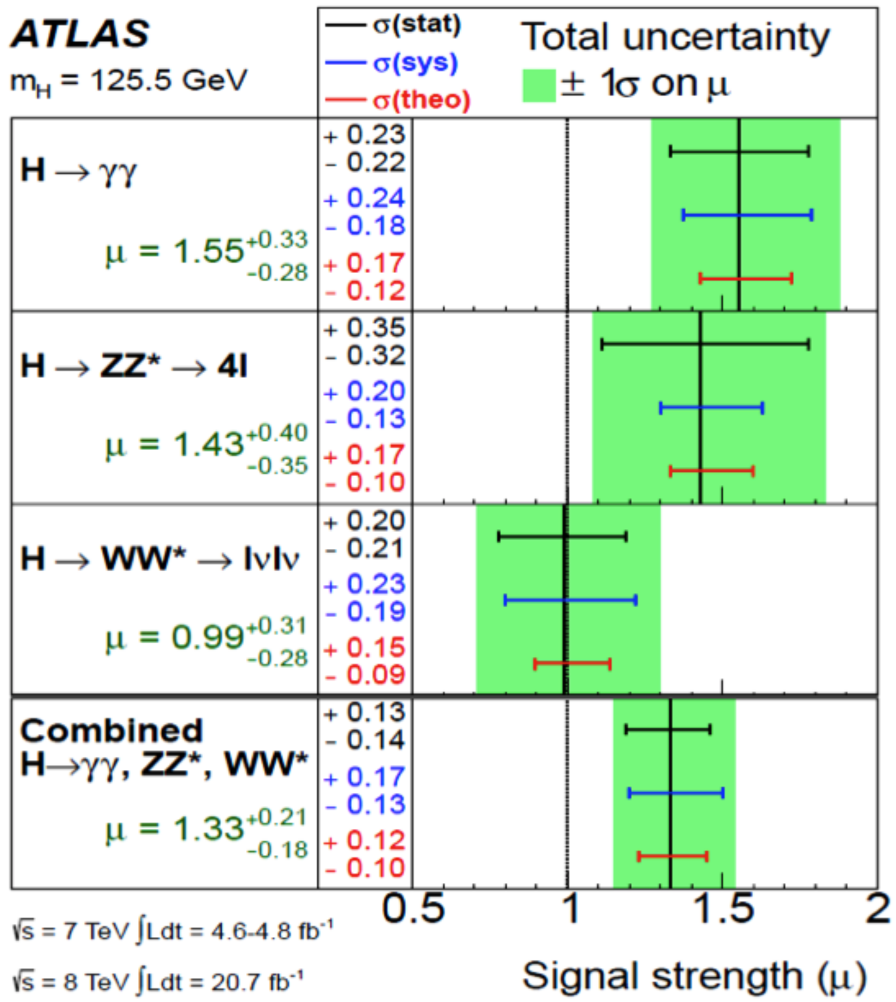
- HHH interactions
- flavor diagonal int.s with I and II generation : ccH, μμH
- Flavor off-diagonal int.s : tqH, ll'H, ...
- HZγ

Prospects

- HL-LHC
- Run II / HL-LHC
- Run I onwards
- Run II onwards

PHASE II : DETERMINATION





the **μ** and kappa's determination is the first necessary step of stress testing the SM. As couplings agree in normalisation to 10-20% one can move on to the next phase.

PHASE III : PRECISION

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:

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

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

PHASE III : PRECISION

- Very powerful approach:
    - It is based on a consistent QFT and therefore is systematically improvable
    - It is the SM, so it can be used globally for many different observables measurable at various experiments.
    - But remember: intrinsically valid max up to scale Λ and no new light state below it.
- Basic strategy:
    - Identify the operators entering a given observable at a given order.
    - Calculate their contributions on top of the most precise SM@dim4 predictions.
    - Find enough observables (cross sections, BR's, distributions,…) to (over)-constrain the operator coefficients.
    - Fit (or in some cases linear fit…)
- Need for accurate and precise predictions for both SM@dim4 and SM@dim6

A FEW QUESTIONS

- 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…

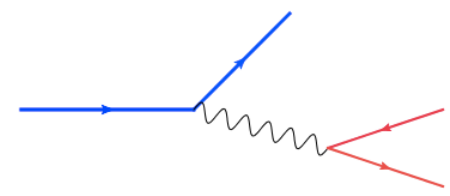
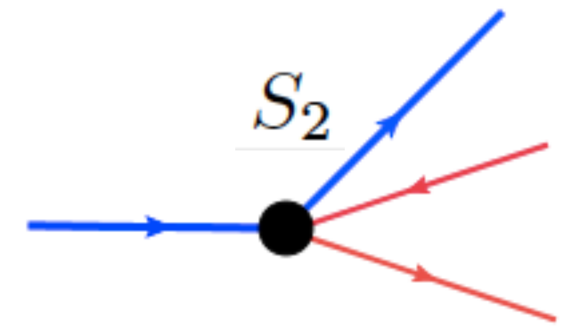
BASIC CONCEPTS VIA SIMPLE EXAMPLES

1. Flavour physics : **running and matching**
2. Majorana neutrinos : **UV completion**, **unitarity violation and new physics scales**
3. SM@dim6 : Bases
4. TGC at the LHC : **EFT vs AC**, unitarity violation, interferences and squares.
5. A simple **UV completion** for the SM@dim6
6. Top FCNC's : **the simple yet complete example**

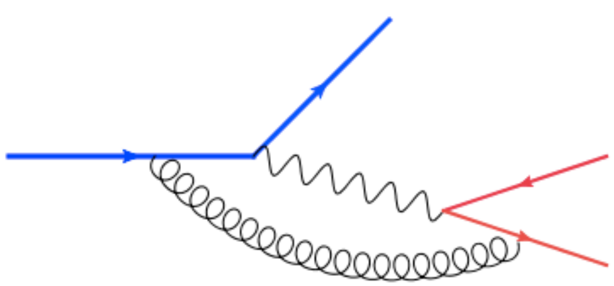
SM AT LOW ENERGIES

Consider the decay of a charm via a weak current:

$$\mathcal{M} = i\frac{G_F}{\sqrt{2}}\frac{M_W^2}{\hat{s}-M_W^2}(\bar{s}_a c_a)_{V-A}(\bar{u}_b d_b)_{V-A}$$
$$= -i\frac{G_F}{\sqrt{2}}(\bar{s}_a c_a)_{V-A}(\bar{u}_b d_b)_{V-A} + \mathcal{O}\left(\frac{\hat{s}}{M_W^2}\right)$$

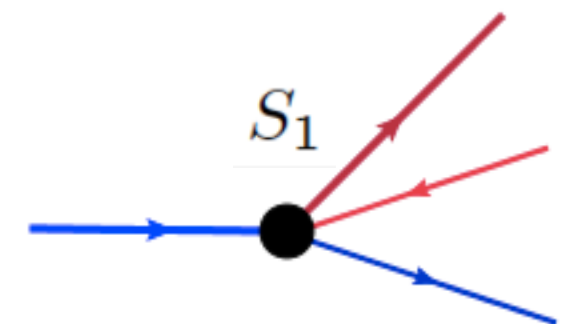

$\Longrightarrow$


At LO there is only one colour configuration. At NLO however, the gluon exchange generates two different colour structures:


$+\ldots$

UV $\Longrightarrow$

$$-3\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2}$$ x



$$S_1 = (\bar{s}_a c_b)_{V-A}(\bar{u}_b d_a)_{V-A}$$
$$S_2 = (\bar{s}_a c_a)_{V-A}(\bar{u}_b d_b)_{V-A}$$

SM AT LOW ENERGIES

There are UV divergences in the EFT that need are reabsorbed by a normalisation of the Ci

which can be obtained by matching to the full theory

$$\frac{\sqrt{2}}{G_F}\langle \hat{O}_1 \rangle = \left(1 + 2C_F \frac{\alpha_s}{4\pi} \log \frac{\mu^2}{\hat{s}}\right) S_1 + \frac{\alpha_s}{4\pi} \log \frac{\mu^2}{\hat{s}} S_1 - 3\frac{\alpha_s}{4\pi} \log \frac{\mu^2}{\hat{s}} S_2$$

$$\frac{\sqrt{2}}{G_F}\langle \hat{O}_2 \rangle = \left(1 + 2C_F \frac{\alpha_s}{4\pi} \log \frac{\mu^2}{\hat{s}}\right) S_2 + \frac{\alpha_s}{4\pi} \log \frac{\mu^2}{\hat{s}} S_2 - 3\frac{\alpha_s}{4\pi} \log \frac{\mu^2}{\hat{s}} S_1$$

$$C_1 = -3\frac{\alpha_s}{4\pi} \log \frac{M_W^2}{\mu^2}$$

$$C_2 = 1 + \frac{\alpha_s}{4\pi} \log \frac{M_W^2}{\mu^2}$$

In our effective Hamiltonian a scale dependence of the Ci compensates that of the matrix elements:

$$\hat{\mathcal{H}}_{\text{eff}} = \sum_i C_i(\mu)\hat{O}_i(\mu)$$

$$\frac{\mathrm{d}C_i}{\mathrm{d}\log\mu} = \gamma_{ij} C_j$$

One can "resum" the large RGE logs by calculating the Ci at low scales wrt mW with RGE equations.

$$C_i(\sqrt{\hat{s}}) \simeq \left(\delta_{ij} + \gamma_{ij}(\sqrt{\hat{s}}) \log \frac{\sqrt{\hat{s}}}{\mu}\right) C_j(\mu)$$

The operators mix under the RGE.

$$\gamma = -\lim_{\varepsilon\to 0} \frac{\mathrm{d}\log Z_C}{\mathrm{d}\log\mu} \qquad \gamma = \frac{1}{16\pi^2}\begin{bmatrix} -2g_s^2 & 6g_s^2 \\ 6g_s^2 & -2g_s^2 \end{bmatrix}$$

SM AT LOW ENERGIES

Many other examples exist of low energy predictions where it is convenient

to out heavy particles of the SM leading to various EFT's :

- Integrating out the h and building an EFT with the SU(2)xU(1) symmetry non-linearly realised

$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}(D^\mu \Sigma)^\dagger D_\mu \Sigma \qquad D^\mu \Sigma = \partial^\mu \Sigma + i(g/2)\sigma \cdot W^\mu \Sigma - i(g'/2)\Sigma \sigma^3 B^\mu$$

$$\mathcal{L} = -m_f \bar{F}_L \Sigma \begin{pmatrix} 0 \\ 1 \end{pmatrix} f_R + \mathrm{H.c.} \qquad \Sigma = \exp(i\sigma \cdot \pi / v)$$

This theory has a upper bound from unitarity of WW scattering $\Lambda_{EWSB} \equiv \sqrt{8\pi} v \approx 1 \ \mathrm{TeV}$

- Integrating out heavy quarks in QCD leads to different number of flavour schemes

MAJORANA NEUTRINOS

- Consider the SM@dim5. There is only one such operator that can be added:

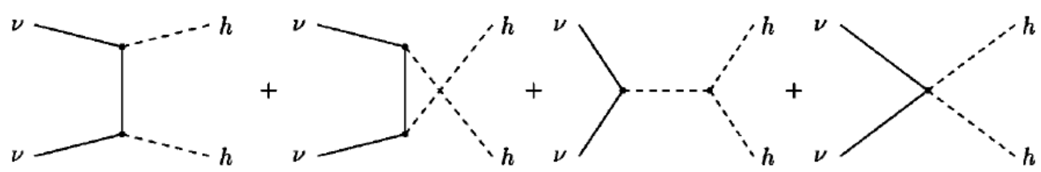
$$\mathcal{L} = \frac{c}{\Lambda}(L^T\epsilon\phi)C(\phi^T\epsilon L) + h.c.$$

$\epsilon \equiv i\sigma_2$

When the Higgs fields acquires a vev this term give rise to a Majorana neutrino mass

$$m_\nu = c\frac{v^2}{\Lambda}$$

If I now calculate the amplitude νν → hh



$$a_0\left(\frac{1}{\sqrt{2}}\nu_\pm\nu_\pm \to \frac{1}{\sqrt{2}}hh\right) \sim \mp\frac{c\sqrt{s}}{16\pi M} \sim \mp\frac{m_\nu\sqrt{s}}{16\pi v^2}$$

$\Longrightarrow$ grows with energy = unitarity violations

$\Longrightarrow$ $\Lambda_{Maj} \equiv \frac{4\pi v^2}{m_\nu}$ $\Longrightarrow$ min mass for the neutrino $\Longrightarrow$ upper bound for Λ

Majorana neutrino mass implies New Physics before 10^{15} GeV

MAJORANA NEUTRINOS

- An UV completion of the dim=5 operator (there are few) is well known: the see-saw model

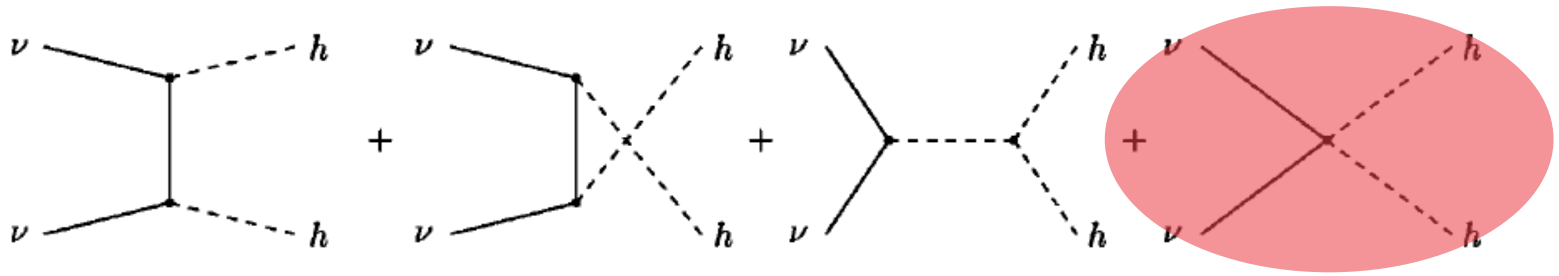
$$\mathcal{L} = -y_D \bar{L} \epsilon \phi^* \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R + \text{H.c.}$$

with a Dirac mass term and a Majorana one (ν_R is a singlet of SU(2)). One can diagonalise the mass matrix and obtains two mass eingenstates

$$\nu \approx \nu_L \qquad m_\nu \approx m_D^2 / M_R$$

$$N \approx \nu_R \qquad M_R$$

and the amplitude $\nu\nu \to hh$ does not grow anymore because the last term is not present. anymore



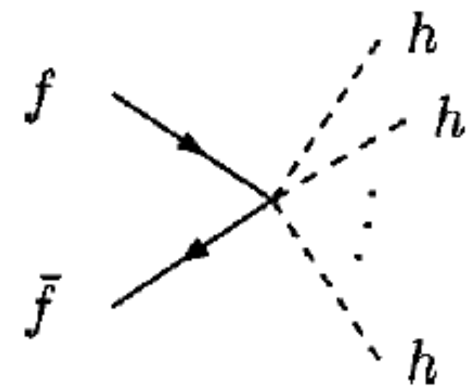
DIRAC FERMIONS IN THE SM

- Is there something similar for Dirac fermions in the SM? The first operator is dim=6

$$\mathcal{L} = -\frac{c}{M^2}\bar{F}_L \phi f_R \phi^\dagger \phi + \mathrm{H.c.}$$

which, once added to the usual Yuakawa leads to a "correction" to the Yukawa/mass relation of the SM:

$$m_f = y_f \frac{v}{\sqrt{2}} + \frac{c}{M^2}\left(\frac{v}{\sqrt{2}}\right)^3$$



It can be then proved that the 2→2 and in fact the 2→3 processes lead to unitarity violation:

$$a_0(f_\pm \bar{f}_\pm \to V_L V_L) \approx \frac{c}{M^2} v \sqrt{s}$$

$$a_0(f_\pm \bar{f}_\pm \to V_L V_L V_L) \approx \frac{c}{M^2} \sqrt{s}$$

$$\Longrightarrow \quad \Lambda^2 \approx \frac{M^2}{c} \approx \frac{v^3}{m_f - y_f v/\sqrt{2}} \quad \Longrightarrow \quad \Lambda \sim \sqrt{\frac{v^3}{m_f}}$$

DIM=6 SM LAGRANGIAN : WARSAW BASIS

[Grazdkowski 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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p\gamma^\mu u_r)$
		Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p\gamma^\mu d_r)$
		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

- 6 gauge dual
- 28 non dual
- 25 fermion operators
- 59+hc operators

EQUATIONS OF MOTIONS

The operator basis is not unique due to the fact that several other operators can be written (non-trivially) in terms of those chosen in the Warsaw basis. For example

$$\mathcal{O}_B = \mathcal{O}_{HB} + \mathcal{O}_{BB} + \mathcal{O}_{WB}\,,$$
$$\mathcal{O}_W = \mathcal{O}_{HW} + \mathcal{O}_{WW} + \mathcal{O}_{WB}\,,$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{WB} = \frac{gg'}{4}(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$$

Or for example:

$$\mathcal{O}_W = g^2 \left[\frac{3}{2}\mathcal{O}_r - \frac{1}{4}\sum_{u,d,e} \mathcal{O}_y - \mathcal{O}_6 + \frac{1}{4}(\mathcal{O}'_{HL} + \mathcal{O}'_{HQ})\right] .$$
$$\mathcal{O}_B = g'^2 \left[-\frac{1}{2}\mathcal{O}_T + \frac{1}{2}\sum_F Y_F \mathcal{O}_{HF}\right] .$$

with $F = \{L_L, e_R, Q_L, u_R, d_R\}$, Y_F the hypercharge, and

$$\mathcal{O}_{HL} \equiv (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L), \quad \mathcal{O}'_{HL} \equiv (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)\,.$$

Other basis (SILH, Pomarol-Riva, ...) can be obtained this way.

DIM=6 SM LAGRANGIAN : HIGGS OPERATORS

Using the above identities one can make the substitution and obtain

$$\{\mathcal{O}_{HL}, \mathcal{O}'_{HL}, \mathcal{O}_{WB}\} \to \{\mathcal{O}_W, \mathcal{O}_B, \mathcal{O}_{HB}\}$$

Higgs Physics Only	
$\mathcal{O}_r = \|H\|^2 \|D^\mu H\|^2$	1
$\mathcal{O}_{BB} = \frac{g'^2}{4} \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	2
$\mathcal{O}_{WW} = \frac{g^2}{4} \|H\|^2 W^a_{\mu\nu} W^{a\mu\nu}$	2
$\mathcal{O}_{GG} = \frac{g_s^2}{4} \|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	2
$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	1
$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	1
$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$	1
$\mathcal{O}_6 = \lambda \|H\|^6$	1

EW and Higgs Physics	
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H \right) D^\nu W^a_{\mu\nu}$	2
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H \right) \partial^\nu B_{\mu\nu}$	2
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	2
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H \right)^2$	1
$\mathcal{O}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	1
$\mathcal{O}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	1
$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$	1
$\mathcal{O}_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$	1
$\mathcal{O}'_{HQ} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	1

$$\mathcal{L}_6 = \sum_{i_1} g_*^2 \frac{c_{i_1}}{\Lambda^2} \mathcal{O}_{i_1} + \sum_{i_2} \frac{c_{i_2}}{\Lambda^2} \mathcal{O}_{i_2} \, ,$$

[Biekotter et al., 1406.7320]

Or by $\mathcal{O}_{WW} \to \mathcal{O}_{HW}$ one obtains the SILH basis

DIM=6 SM LAGRANGIAN : SILH BASIS

$$\mathcal{L}_{\rm SILH} = \frac{\bar c_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{\bar c_T}{2v^2}\left[\Phi^\dagger \overleftrightarrow{D}^\mu\Phi\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] - \frac{\bar c_6\lambda}{v^2}\left[H^\dagger H\right]^3$$
$$- \left[\frac{\bar c_u}{v^2}y_u\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar Q_L u_R + \frac{\bar c_d}{v^2}y_d\Phi^\dagger\Phi\ \Phi\bar Q_L d_R + \frac{\bar c_l}{v^2}y_\ell\ \Phi^\dagger\Phi\ \Phi\bar L_L e_R + {\rm h.c.}\right]$$
$$+ \frac{ig\ \bar c_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar c_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu}$$
$$+ \frac{2ig\ \bar c_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar c_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu}$$
$$+ \frac{\bar g'^2\ c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{\bar g_s^2\ c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}\ ,$$

$$\mathcal{L}_{CP} = \frac{ig\ \tilde c_{HW}}{m_W^2}D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\widetilde W^k_{\mu\nu} + \frac{ig'\ \tilde c_{HB}}{m_W^2}D^\mu\Phi^\dagger D^\nu\Phi\widetilde B_{\mu\nu} + \frac{g'^2\ \tilde c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde B^{\mu\nu}$$
$$+ \frac{g_s^2\ \tilde c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}\widetilde G_a^{\mu\nu} + \frac{g^3\ \tilde c_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho\widetilde W^{\rho\mu k} + \frac{g_s^3\ \tilde c_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho\widetilde G^{\rho\mu c}$$

$$\mathcal{L}_G = \frac{g^3\ \bar c_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho W^{\rho\mu k} + \frac{g_s^3\ \bar c_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho G^{\rho\mu c} + \frac{\bar c_{2W}}{m_W^2}D^\mu W^k_{\mu\nu}D_\rho W_k^{\rho\nu}$$
$$+ \frac{\bar c_{2B}}{m_W^2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} + \frac{\bar c_{2G}}{m_W^2}D^\mu G^a_{\mu\nu}D_\rho G_a^{\rho\nu}\ ,$$

$$\mathcal{L}_{F_1} = \frac{i\bar c_{HQ}}{v^2}\left[\bar Q_L\gamma^\mu Q_L\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] + \frac{4i\bar c'_{HQ}}{v^2}\left[\bar Q_L\gamma^\mu T_{2k}Q_L\right]\left[\Phi^\dagger T_2^k\overleftrightarrow{D}_\mu\Phi\right]$$
$$+ \frac{i\bar c_{Hu}}{v^2}\left[\bar u_R\gamma^\mu u_R\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] + \frac{i\bar c_{Hd}}{v^2}\left[\bar d_R\gamma^\mu d_R\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]$$
$$- \left[\frac{i\bar c_{Hud}}{v^2}\left[\bar u_R\gamma^\mu d_R\right]\left[\Phi\cdot\overleftrightarrow{D}_\mu\Phi\right] + {\rm h.c.}\right]$$
$$+ \frac{i\bar c_{HL}}{v^2}\left[\bar L_L\gamma^\mu L_L\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] + \frac{4i\bar c'_{HL}}{v^2}\left[\bar L_L\gamma^\mu T_{2k}L_L\right]\left[\Phi^\dagger T_2^k\overleftrightarrow{D}_\mu\Phi\right]$$
$$+ \frac{i\bar c_{He}}{v^2}\left[\bar e_R\gamma^\mu e_R\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\ ,$$

$$\mathcal{L}_{F_2} = \Big[- \frac{2g'\ \bar c_{uB}}{m_W^2}y_u\ \Phi^\dagger\cdot\bar Q_L\gamma^{\mu\nu}u_R\ B_{\mu\nu} - \frac{4g\ \bar c_{uW}}{m_W^2}y_u\ \Phi^\dagger\cdot(\bar Q_L T_{2k})\gamma^{\mu\nu}u_R\ W^k_{\mu\nu}$$
$$- \frac{4g_s\ \bar c_{uG}}{m_W^2}y_u\ \Phi^\dagger\cdot\bar Q_L\gamma^{\mu\nu}T_a u_R G^a_{\mu\nu} + \frac{2g'\ \bar c_{dB}}{m_W^2}y_d\ \Phi\bar Q_L\gamma^{\mu\nu}d_R\ B_{\mu\nu}$$
$$+ \frac{4g\ \bar c_{dW}}{m_W^2}y_d\ \Phi(\bar Q_L T_{2k})\gamma^{\mu\nu}d_R\ W^k_{\mu\nu} + \frac{4g_s\ \bar c_{dG}}{m_W^2}y_d\ \Phi\bar Q_L\gamma^{\mu\nu}T_a d_R G^a_{\mu\nu}$$
$$+ \frac{2g'\ \bar c_{eB}}{m_W^2}y_\ell\ \Phi\bar L_L\gamma^{\mu\nu}e_R\ B_{\mu\nu} + \frac{4g\ \bar c_{eW}}{m_W^2}y_\ell\ \Phi(\bar L_L T_{2k})\gamma^{\mu\nu}e_R\ W^k_{\mu\nu} + {\rm h.c.}\Big]$$

[from Contino, Ghezzi, Grojean, Muhlleitner, Spira (JHEP '13)]

BASES

A now an important point:

The bases presented so far are written in terms of field before the EWSB, i.e. respect the global symmetries of the SM as well as SU(2)xU(1).

However, simulations and measurements are made in terms of mass eigenstates (W,Z,H), i.e. in the broken phase of the theory.

$$W^1_\mu = \frac{g_L}{\sqrt{2}}\left(W^+_\mu + W^-_\mu\right), \qquad W^3_\mu = \frac{g_L}{\sqrt{g_L^2+g_Y^2}}\left(g_L Z_\mu + g_Y A_\mu\right),$$

$$W^2_\mu = \frac{i g_L}{\sqrt{2}}\left(W^+_\mu - W^-_\mu\right), \qquad B_\mu = \frac{g_Y}{\sqrt{g_L^2+g_Y^2}}\left(-g_Y Z_\mu + g_L A_\mu\right)$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}G^+ \\ v + h + iG^0 \end{pmatrix}$$

By making the above substitutions (fermions too) one arrives at expressing the new interactions in terms of mass eigenstates.

“MASS” BASIS

BASES

- So for example the single Higgs couplings to vector bosons can be written as:

$$\begin{aligned}\Delta\mathcal{L}_{\rm hvv}^{D=6} = & \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu \\ & + c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\ & + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma}\frac{eg}{2c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz}\frac{g^2}{4c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \\ & + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu} \\ & + \tilde{c}_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{eg}{2c_\theta} Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2}{4c_\theta^2} Z_{\mu\nu}\tilde{Z}_{\mu\nu}\Big]\end{aligned}$$

where the coefficients of the broken phase are **more numerous** yet depend on those of the original parametrisation at dim=6. So they can be expressed through the original dim=6 ones.

BASES

or some of them can be made dependent of a subset of the low-energy ones:

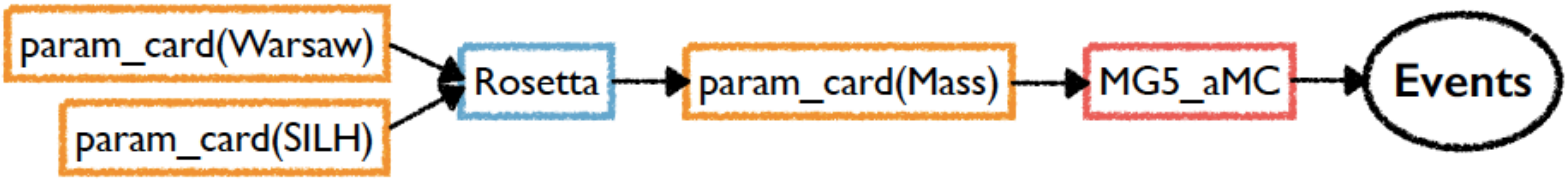
$$\begin{aligned}
\delta c_w &= \delta c_z + 4\delta m, \\
c_{ww} &= c_{zz} + 2s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}, \\
\tilde{c}_{ww} &= \tilde{c}_{zz} + 2s_\theta^2 \tilde{c}_{z\gamma} + s_\theta^4 \tilde{c}_{\gamma\gamma}, \\
c_{w\Box} &= \frac{1}{g^2 - g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2 s_\theta^2 c_{\gamma\gamma} - (g^2 - g'^2) s_\theta^2 c_{z\gamma}\right], \\
c_{\gamma\Box} &= \frac{1}{g^2 - g'^2}\left[2g^2 c_{z\Box} + (g^2 + g'^2) c_{zz} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{z\gamma}\right]
\end{aligned}$$

This is the idea of the **Higgs basis (LHCXSWG)**

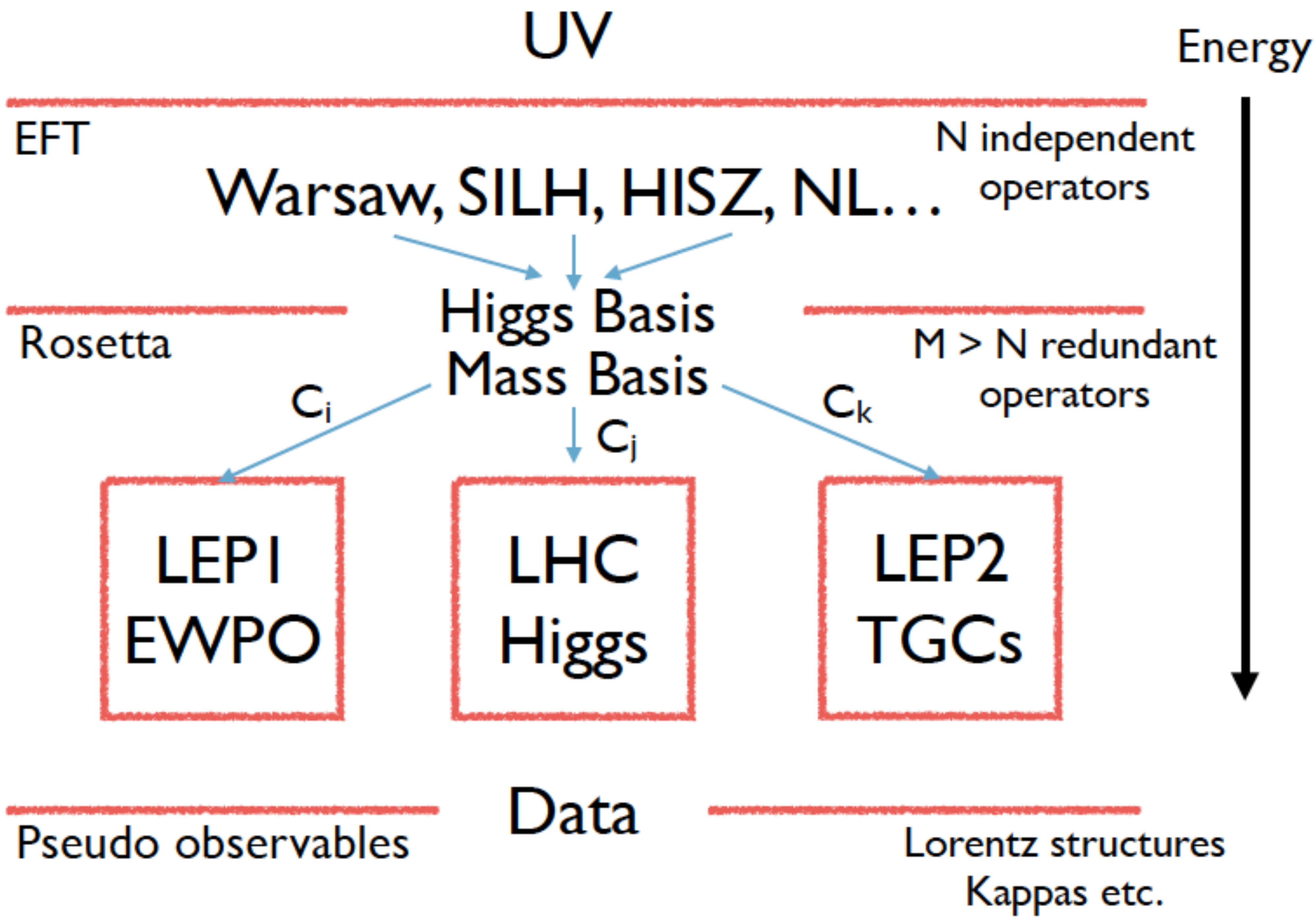
$$\begin{aligned}
\textbf{Independent}: &\quad c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \tilde{c}_{gg},\ \tilde{c}_{\gamma\gamma},\ \tilde{c}_{z\gamma},\ \tilde{c}_{zz}; \\
\textbf{Dependent}: &\quad \delta c_w,\ c_{ww},\ \tilde{c}_{ww},\ c_{w\Box},\ c_{\gamma\Box}.
\end{aligned}$$

BASES : TOOLS

- Full Lagrangians implemented in FeynRules (and UFO)
  - Public (and versioned) models:
    - HC [Artoisenet et al. 1306.6464],
    - HEL (SILH) [Alloul, Fuks, Sanz, 1310.5150]
    - Warsaw [Fuks, Mawatari, Mimasu, Riva, Sanz, to appear]
    - Mass Basis [Fuks, Mawatari, Mimasu, Riva, Sanz, to appear]
  - Extension available to be used for NLO computations in QCD
- Process simulation with tools such as Sherpa, Madgraph5_aMC@NLO and so on.



ROSETTA


UV
Energy
EFT
N independent operators
Warsaw, SILH, HISZ, NL…
Higgs Basis
Mass Basis
Rosetta
M > N redundant operators
Ci
Cj
Ck
LEP1 EWPO
LHC Higgs
LEP2 TGCs
Data
Pseudo observables
Lorentz structures
Kappas etc.

TRIPLE GAUGE COUPLINGS

EFT below EWSB....

[see discussion in Degrande et al, 2012]

$$\begin{aligned}\mathcal{L} = \; & ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho \\ & + ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma \\ & + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\Big)\end{aligned}$$

5 even + 6 odd

EFT above EWSB....

$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho] \\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

$$\begin{aligned}\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^\mu_\rho] \\ \mathcal{O}_{\tilde{W}} &= (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

3 even + 2 odd

The number of free parameters is reduced in an EWSB symmetric L.

TRIPLE GAUGE COUPLINGS

	EFT	AC
Lorentz	✔	✔
$SU(2)_L$	✔	✘
$U(1)_{EM}$	✔	(✔)
Scale suppression	✔	✘
# parameters	5	11
Loop	✔	✘

TRIPLE GAUGE COUPLINGS

THE 5 FREE PARAMETERS OF THE EFT CAN BE DETERMINED FROM THE ANOMALOUS COUPLING MEASUREMENTS:

$$\begin{aligned}
\frac{c_W}{\Lambda^2} &= \frac{2}{M_Z^2}\Delta g_1^Z = \frac{2}{M_Z^2}(\tan^2\theta_W \Delta\kappa_\gamma + \Delta\kappa_Z) \\
\frac{c_B}{\Lambda^2} &= \frac{2}{M_W^2}\Delta\kappa_\gamma - \frac{2}{M_Z^2}\Delta g_1^Z \\
&= \frac{2}{\tan^2\theta_W M_Z^2}\Delta g_1^Z - \frac{2}{\sin^2\theta_W M_Z^2}\Delta\kappa_Z = \frac{2}{M_Z^2}(\Delta\kappa_\gamma - \Delta\kappa_Z) \\
\frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\lambda_\gamma = \frac{2}{3g^2 m_W^2}\lambda_Z \\
\frac{c_{\tilde{W}}}{\Lambda^2} &= \frac{2}{m_W^2}\tilde{\kappa}_\gamma = -\frac{2}{\tan^2\theta_W m_W^2}\tilde{\kappa}_Z \\
\frac{c_{\tilde{W}WW}}{\Lambda^2} &= \frac{2}{3g^2 m_W^2}\tilde{\lambda}_\gamma = \frac{2}{3g^2 m_W^2}\tilde{\lambda}_Z
\end{aligned}$$

CONSISTENCY OF THE DIM=6 APPROACH CAN ALREADY BE TESTED...

TRIPLE GAUGE COUPLINGS

- aTGC + aQGC (Dim6)
  - by default in MG5 (EWdim6)
  - 5 Operators
- nTGC (Dim8)
  - triple for neutral
  - 4 Operators
- aQGC (Dim8)
  - 18 operators
  - to download via FR website

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$

[C. Degrande et al 1205.4231]

$$\mathcal{O}_{BW} = i\,H^\dagger B_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H,$$
$$\mathcal{O}_{WW} = i\,H^\dagger W_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H,$$
$$\mathcal{O}_{BB} = i\,H^\dagger B_{\mu\nu}B^{\mu\rho}\{D_\rho, D^\nu\}H.$$
$$\mathcal{O}_{\widetilde{B}B} = i\,H^\dagger \widetilde{B}_{\mu\nu}B^{\mu\rho}\{D_\rho, D^\nu\}H.$$

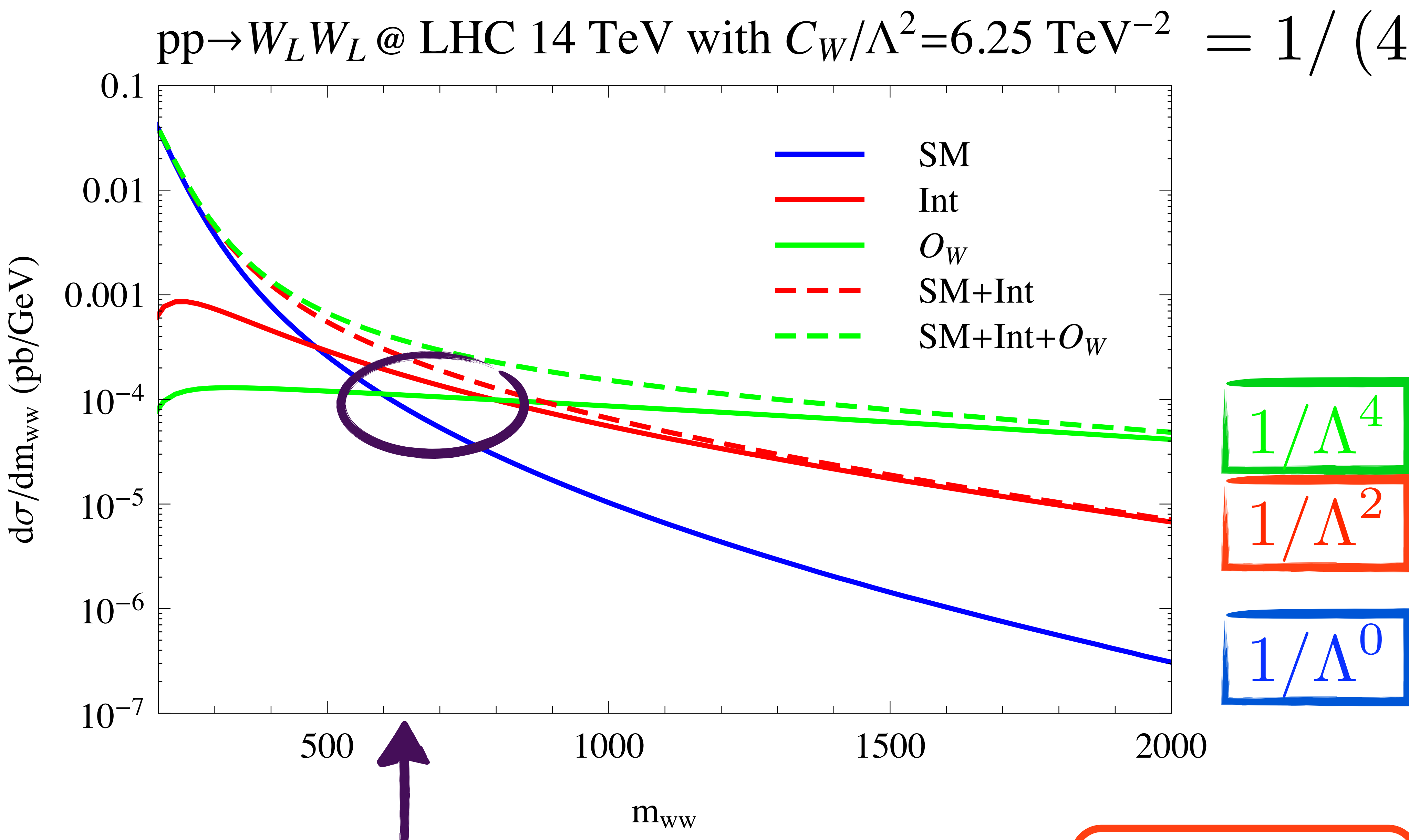
[C. Degrande 1308.6323]

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

[O.J.P. Eboli, M.C. Gonzalez-Garcia, J.K. Mizukoshi hep-ph/0606118]

TRIPLE GAUGE COUPLINGS

$= 1/\left(400\text{GeV}\right)^2$

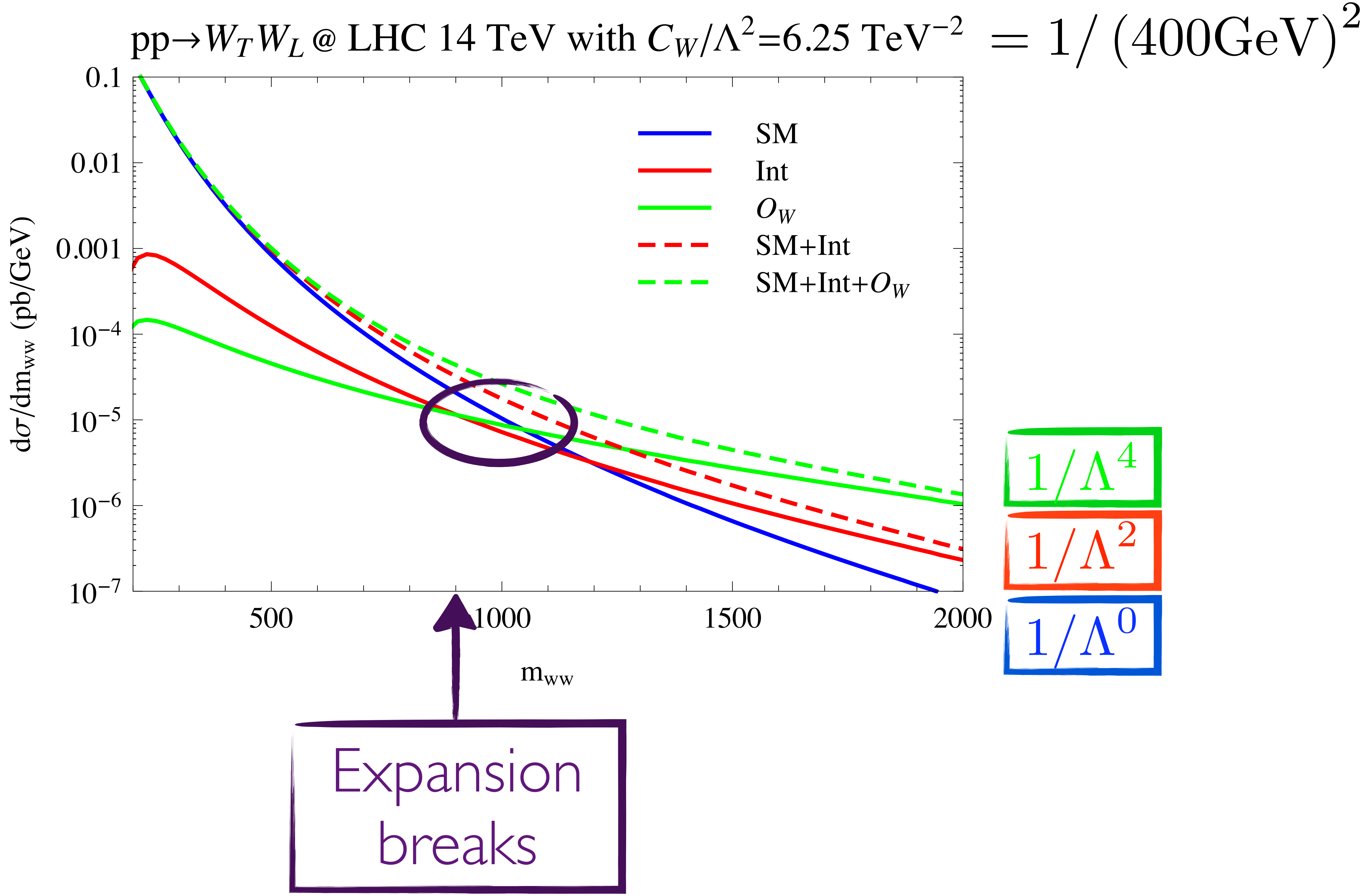


Expansion breaks

$$|M|^2 = |M_{sm}|^2 + 2Re\left(M_{sm}M_{NP}^*\right) + |M_{NP}|^2$$

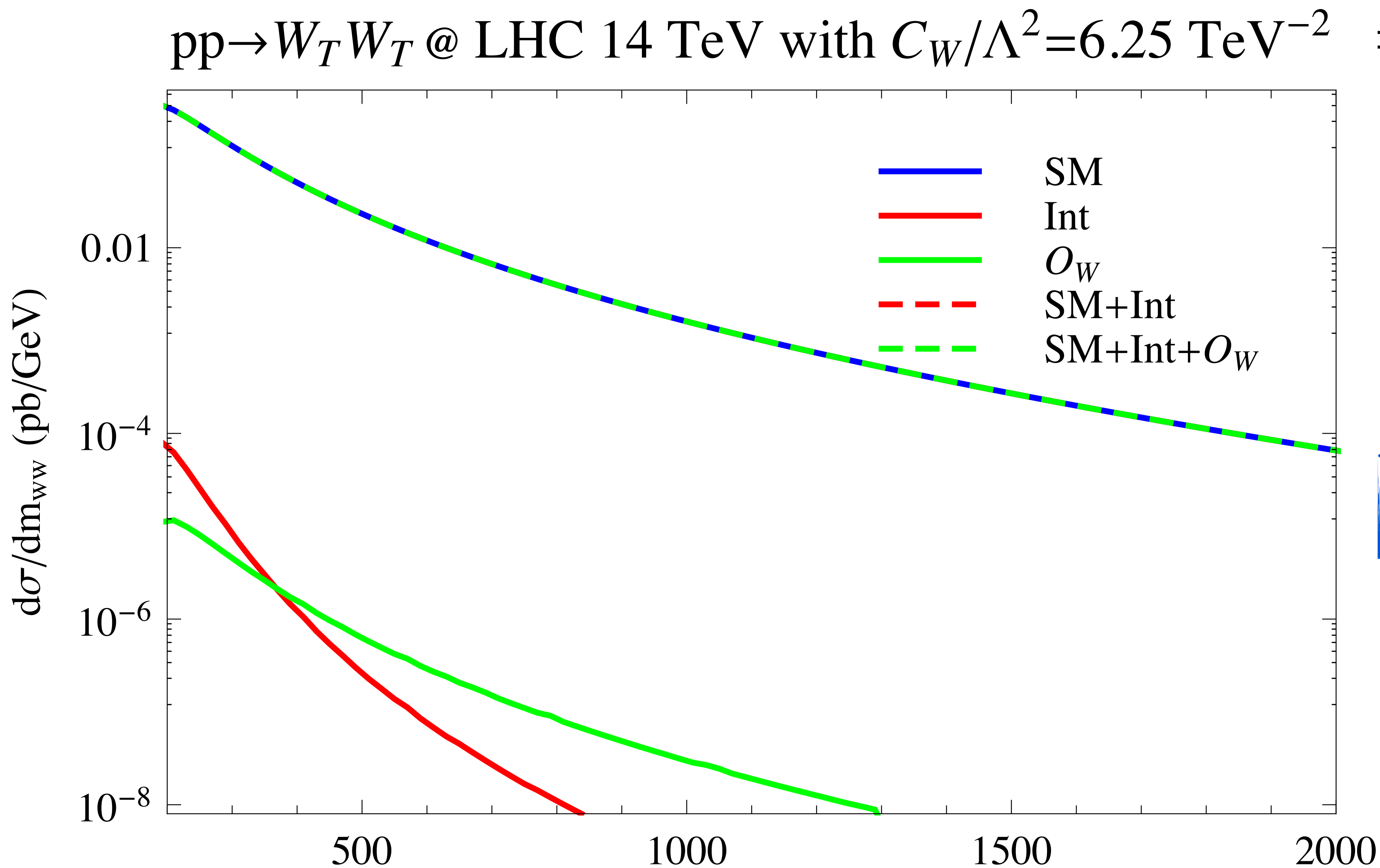
$1/\Lambda^2$ $1/\Lambda^4$

TRIPLE GAUGE COUPLINGS



TRIPLE GAUGE COUPLINGS

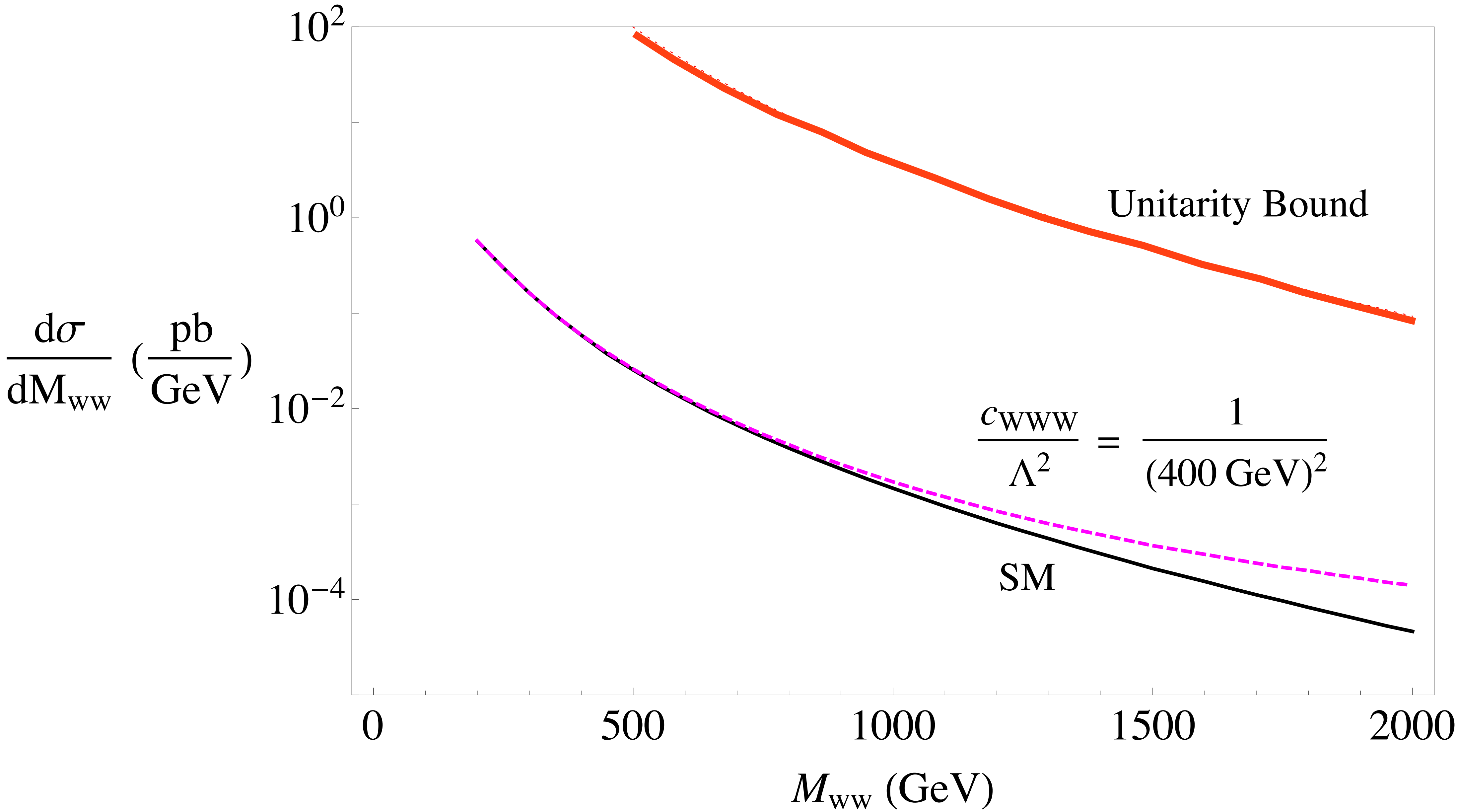
$= 1/(400\text{GeV})^2$



$1/\Lambda^0$

$1/\Lambda^2$ $1/\Lambda^4$

TRIPLE GAUGE COUPLINGS



AC VS EFT

- The Higgs basis is de facto anomalous couplings parametrisation of the interactions between mass eigenstates featuring relations between the coefficients of the different operators.
- However, at variance with an AC, an EFT defined above the EWSB scale, is renormalisable in EW and QCD interactions. The AC is not.
- Another important point is that the use of an EFT is always different from that of the AC, as in the EFT one has to take the interference terms only and use the squares to gauge the stability of the $1/\Lambda$.
- In addition, an AC features many more free parameters and in general, it does not provide either a consistent or a useful interpretation framework. In addition, form factors are needed for AC to be useful in practice.
- For physics: EFT should be used when NP is assumed heavy, explicit models when NP can also be light.

EFT COEFFICIENTS AND UV COMPLETIONS

[Gorbhan, No, Sanz, 2015]

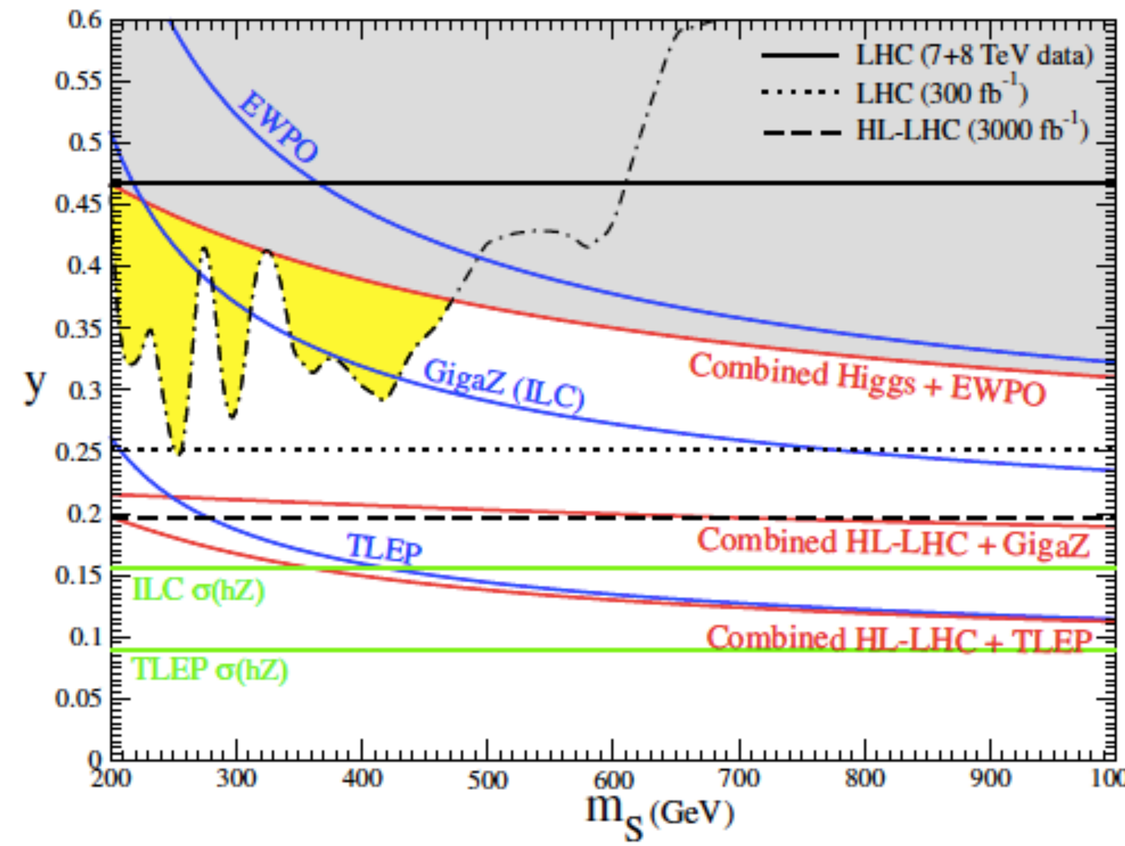
$$V(\Phi, s) = -\mu_{\rm H}^2\,|\Phi|^2 + \lambda\,|\Phi|^4 - \frac{\mu_{\rm S}^2}{2}\,s^2 + \frac{\lambda_{\rm S}}{4}\,s^4 + \frac{\lambda_{\rm m}}{2}\,|\Phi|^2\,s^2$$

$$\begin{aligned}\mathcal{L}_{\rm SILH} = {} & \frac{\bar c_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{\bar c_T}{2v^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] - \frac{\bar c_6\lambda}{v^2}\left[\Phi^\dagger\Phi\right]^3 \\ & + \frac{ig\ \bar c_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar c_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\ & + \frac{2ig\ \bar c_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar c_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\ & + \frac{g'^2\ \bar c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\ & - \left[\frac{\bar c_u\,y_u}{v^2}\Phi^\dagger\Phi\,\bar Q_L\Phi^\dagger u_R + \frac{\bar c_d\,y_d}{v^2}\Phi^\dagger\Phi\,\bar Q_L\Phi\,d_R + \frac{\bar c_l\,y_l}{v^2}\Phi^\dagger\Phi\,\bar L_L\Phi\,l_R\right]\ .\end{aligned}$$

$$\bar c_H = y^2\ \text{(mixing)}$$

$$\bar c_H = \frac{n_s}{96\pi^2}\left(\frac{\lambda_m v}{m_s}\right)^2\ \text{(no mixing)}$$

$$\lambda\,\bar c_6 = 3\ \delta\,\bar c_H\ \text{(only w. explicit symmetry breaking)}$$



EFT COEFFICIENTS AND UV COMPLETIONS

[Gorbhan, No, Sanz, 2015]

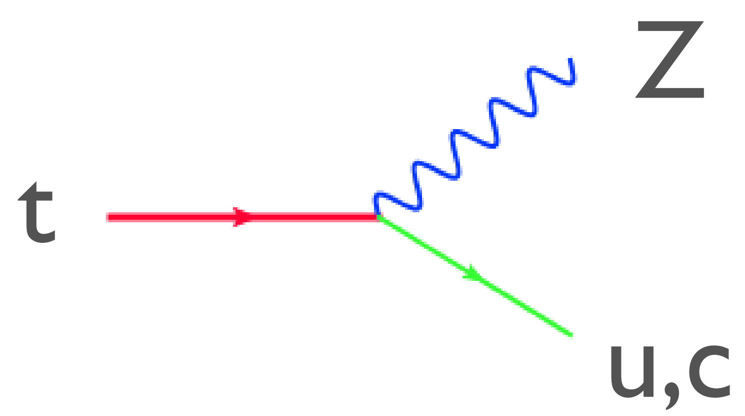
	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_T$	$\bar{c}_W$	$\bar{c}_B$	$\bar{c}_{HW}$	$\bar{c}_{HB}$	$\bar{c}_{3W}$	$\bar{c}_\gamma$	$\bar{c}_g$
Higgs Portal ($\mathcal{G}$)	L	L	X	X	X	X	X	X	X	X
Higgs Portal (Spontaneous $\not{\mathcal{G}}$)	T	L	RG	RG	RG	X	X	X	X	X
Higgs Portal (Explicit $\not{\mathcal{G}}$)	T	T	RG	RG	RG	X	X	X	X	X
2HDM Benchmark A ($c_{\beta-\alpha} = 0$)	L	L	L	L	L	L	L	L	L	X
2HDM Benchmark B ($c_{\beta-\alpha} \neq 0$)	T	T	L	L	L	L	L	L	L	X
Radion/Dilaton	T	T	RG	T	T	T	T	L	T	T

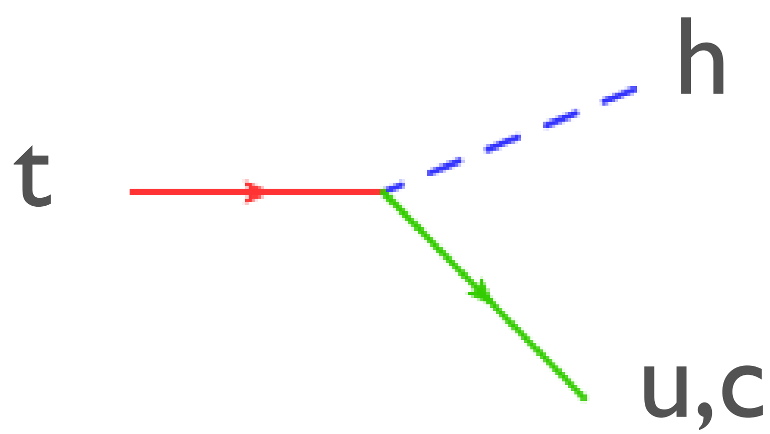
Table 1. Leading order at which the various Wilson coefficients for the $D = 6$ SM effective field theory are generated in each of the scenarios under consideration. In each case, the operator can be generated at Tree-Level (T) or 1-Loop (L). If some operators are generated at Tree-Level, this may lead to the generation of others via operator mixing under 1-loop Renormalization Group evolution (see *e.g.* [27, 28]), which we denote by RG. Operators which are generated at higher order in RG and EFT expansion are denoted with an X.

TOP FCNC'S

The study of FCNC couplings can bring new information:

[Drobnak, 2012 based on CMS and ATLAS results] [Kao et al. 2011 , Kai-Feng et al 2013] [Zhang FM, 2013]





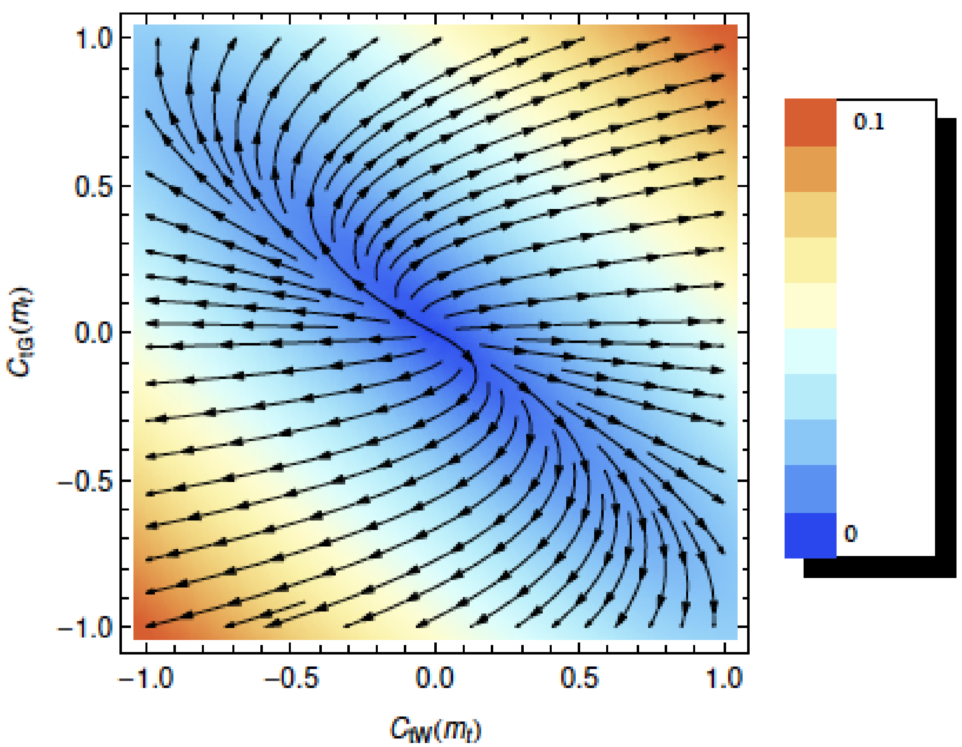
While the exp searches are completely different, one has to remember that the decay rates will depend on several operators that are linked by gauge symmetry. For example:

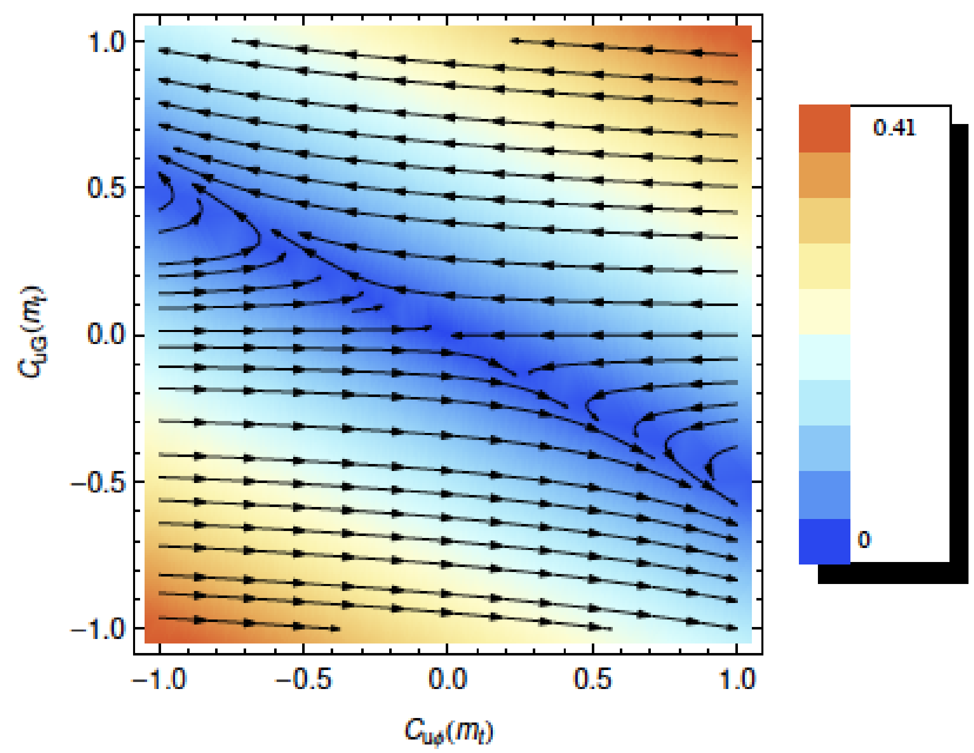
$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I$$
$$O_{uG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G_{\mu\nu}^A$$
$$O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}$$

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

TOP FCNC'S

[Durieux, FM, Zhang 2014]





$$
\begin{aligned}
O_{tG} &= y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\\
O_{tW} &= y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}\\
O_{tB} &= y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}\\
O_{t\varphi} &= -y_t^3(\varphi^\dagger\varphi)(\bar{Q}t)\tilde{\varphi}\ .
\end{aligned}
$$

$$
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0\\ \frac{1}{3} & \frac{1}{3} & 0 & 0\\ \frac{5}{9} & 0 & \frac{1}{3} & 0\\ -4 & 0 & 0 & -1 \end{pmatrix}
$$

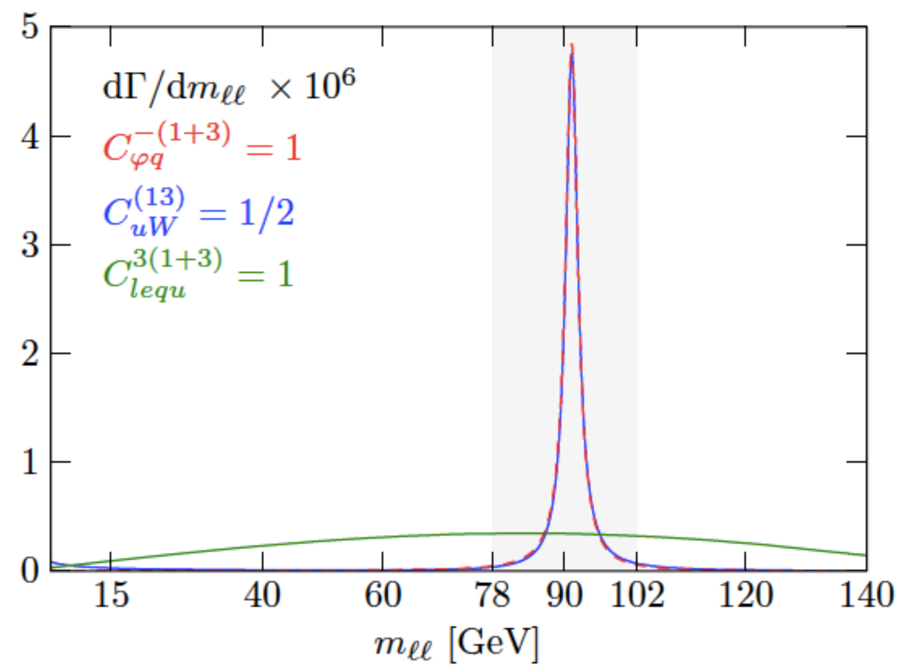
$$
\begin{aligned}
O^{(13)}_{uG} &= y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\\
O^{(13)}_{uW} &= y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}\\
O^{(13)}_{uB} &= y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}\\
O^{(13)}_{u\varphi} &= -y_t^3(\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}\ .
\end{aligned}
$$

$$
\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0\\ \frac{1}{3} & \frac{1}{3} & 0 & 0\\ \frac{5}{9} & 0 & \frac{1}{3} & 0\\ -2 & 0 & 0 & -1 \end{pmatrix}
$$

$$
\begin{cases} C^{(13)}_{uG}(1\ \text{TeV}) = 1,\\ C^{(13)}_{u\varphi}(1\ \text{TeV}) = 0, \end{cases} \longrightarrow \begin{cases} C^{(13)}_{uG}(m_t) = 0.98,\\ C^{(13)}_{u\varphi}(m_t) = 0.23. \end{cases}
$$

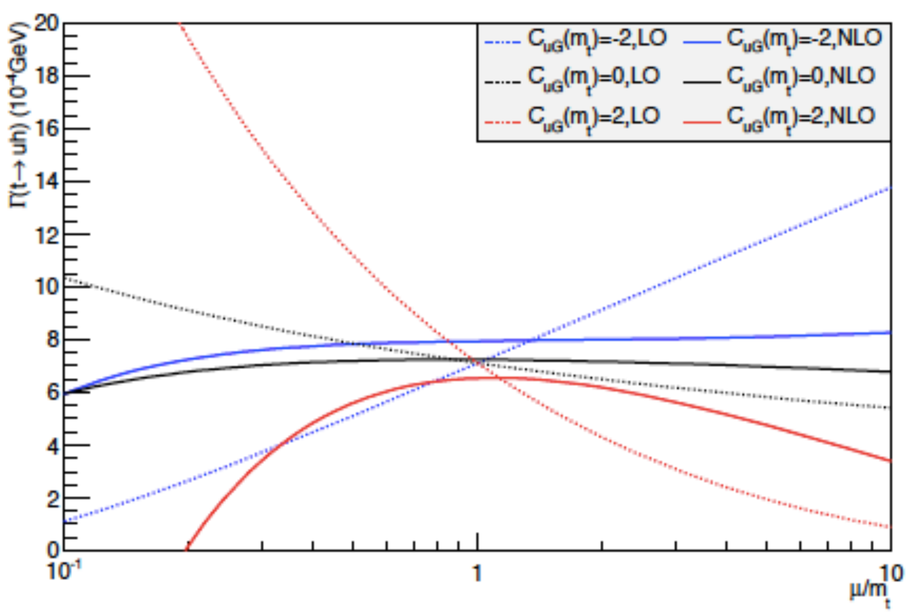
TOP FCNC'S

[Durieux, FM, Zhang 2014]



$$\Gamma^{\text{on-peak}}_{t\to u\, e^+e^-}\ /10^{-5}\ \text{GeV}\ \times (\Lambda/1\ \text{TeV})^4$$
$$= 1.7\, |C_{\varphi q}^{-(1+3)}|^2 + 6.6\, |C_{uW}^{(13)}|^2 + 0.81\, |C_{lequ}^{3(13)}|^2$$

$$\Gamma^{\text{off-peak}}_{t\to u\, e^+e^-}\ /10^{-5}\ \text{GeV}\ \times (\Lambda/1\ \text{TeV})^4$$
$$= 0.2\, |C_{\varphi q}^{-(1+3)}|^2 + 1.0\, |C_{uW}^{(13)}|^2 + 2.7\, |C_{lequ}^{3(13)}|^2$$



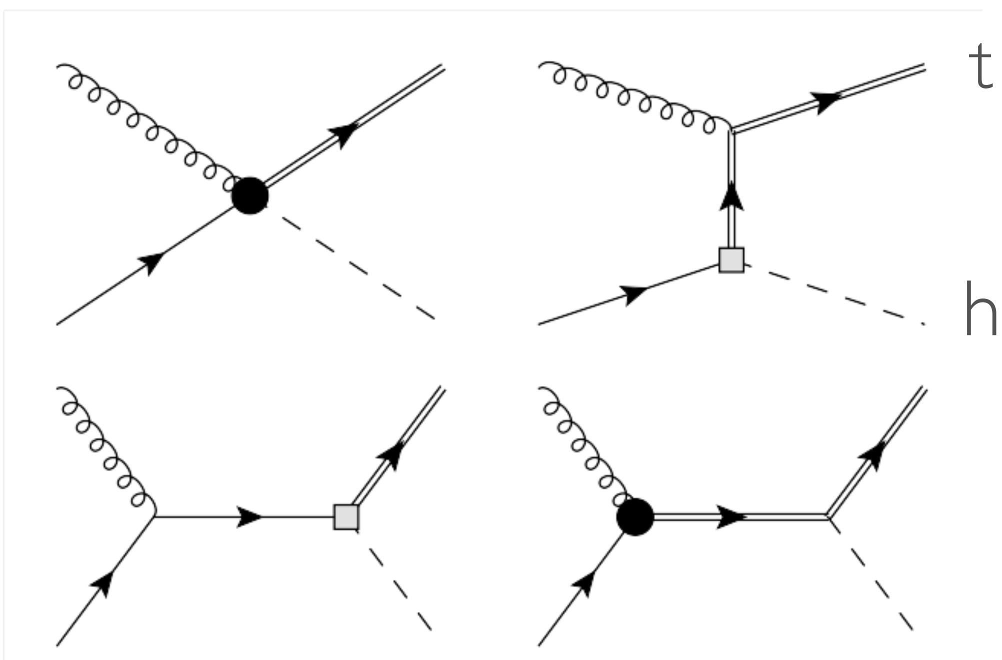
$$\Gamma(t\to u_i h) = \Gamma^{(0)} + \alpha_s \Gamma^{(1)}$$

$$\Gamma^{(0)} = 7.11 |C_{u\varphi}(\mu)|^2\ \times 10^{-4}\,\text{GeV}\,,$$
$$\Gamma^{(1)} = \left\{ \left[1.19 - 9.05 \log\left(\frac{m_t}{\mu}\right)\right] |C_{u\varphi}(\mu)|^2 - \left[3.26 + 18.1 \log\left(\frac{m_t}{\mu}\right)\right] \text{Re}\, C_{uG}(\mu) C^*_{u\varphi} + 9.33\times 10^{-5} |C_{uG}(\mu)|^2 \right\} \times 10^{-4}\,\text{GeV}\,. \quad (48)$$

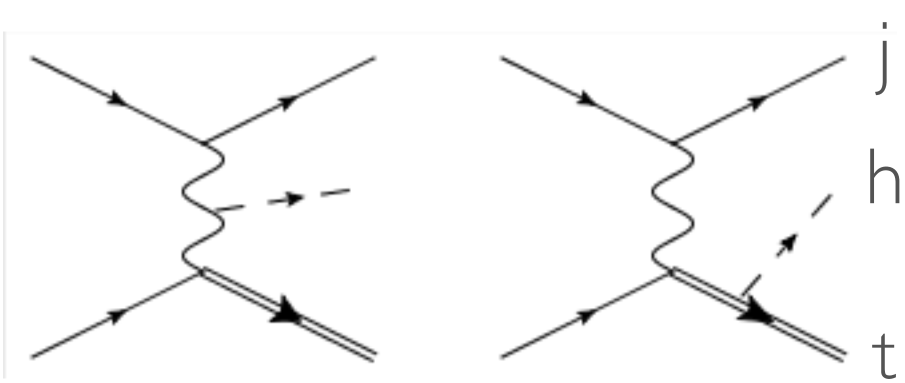
TOP FCNC'S

[Degrande, FM, Wang, Zhang, 2014]

pp → th



pp → thj (SM)



Contributions appear at LO from Otφ and one from OtG..

At NLO in QCD OtG mixes with all the other operators so it has always to be included.

It also means that if a specific (arbitrary) choice of coefficient operators is made at high scales (where one can imagine a full theory to live) many operators become active when evolved to lower scales.

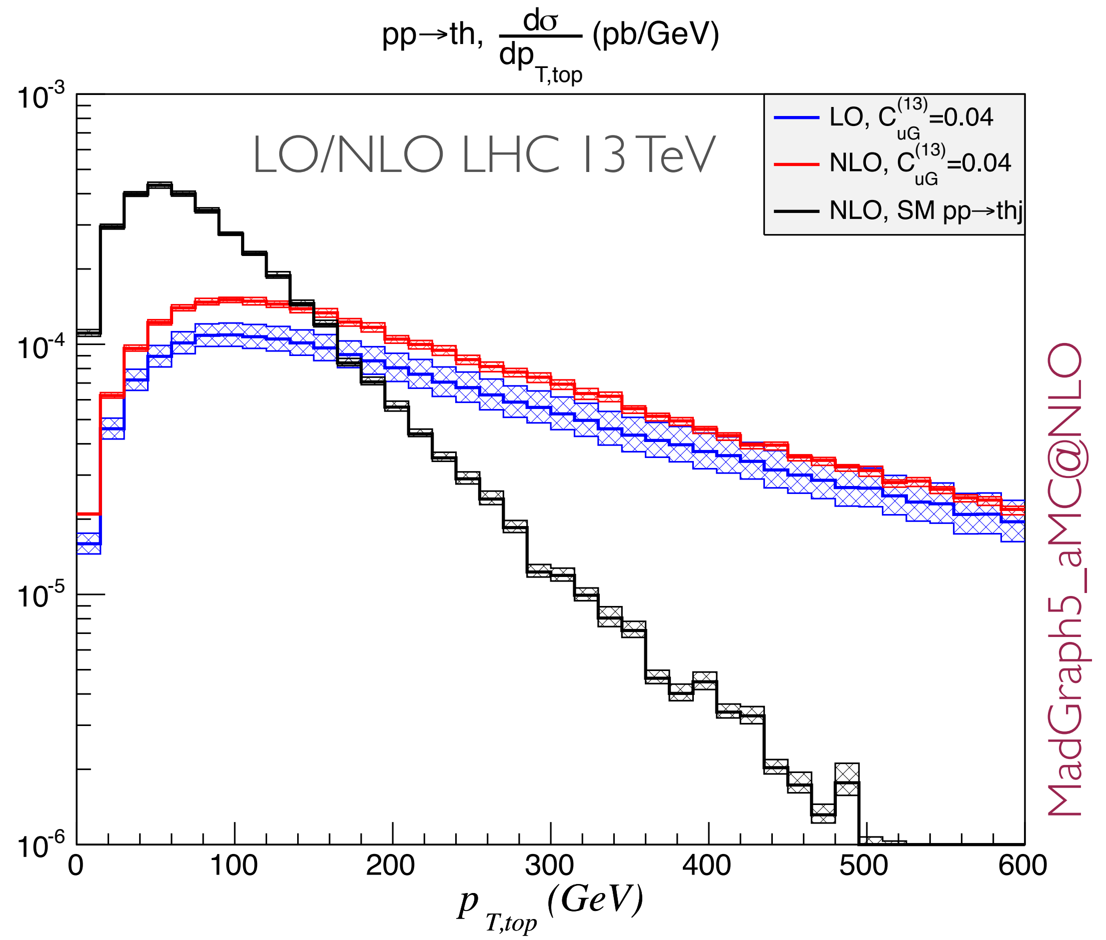
Only a global/fit approach on constraining such operators at the same time can be useful strategy and it has to be at least NLO in QCD.

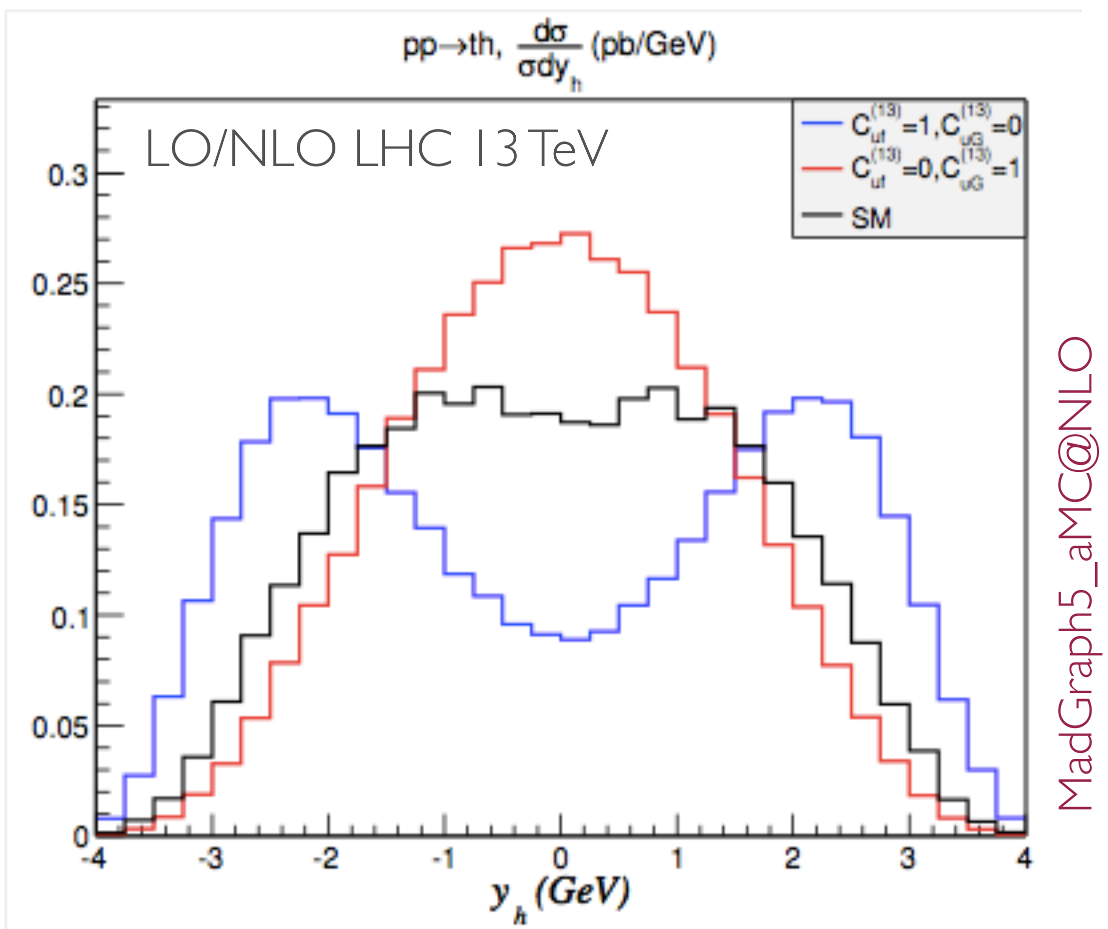
TOP FCNC'S

[Degrande, FM, Wang, Zhang, 2014]

The operators have been implemented in FeynRules, the model was upgraded to NLO automatically and then passed to MG5_aMC.

Results shown here at NLO. the pp →thj interesting process by itself...





Complete implementation of all operators of dim=6 at NLO (including four fermion operators) in QCD is on going.

TOP FCNC'S

[Durieux, FM, Zhang 2014]

$$\mathrm{Br}(t \to j\, e^+e^-) + \mathrm{Br}(t \to j\, \mu^+\mu^-) \lesssim 0.0017\%$$ CMS

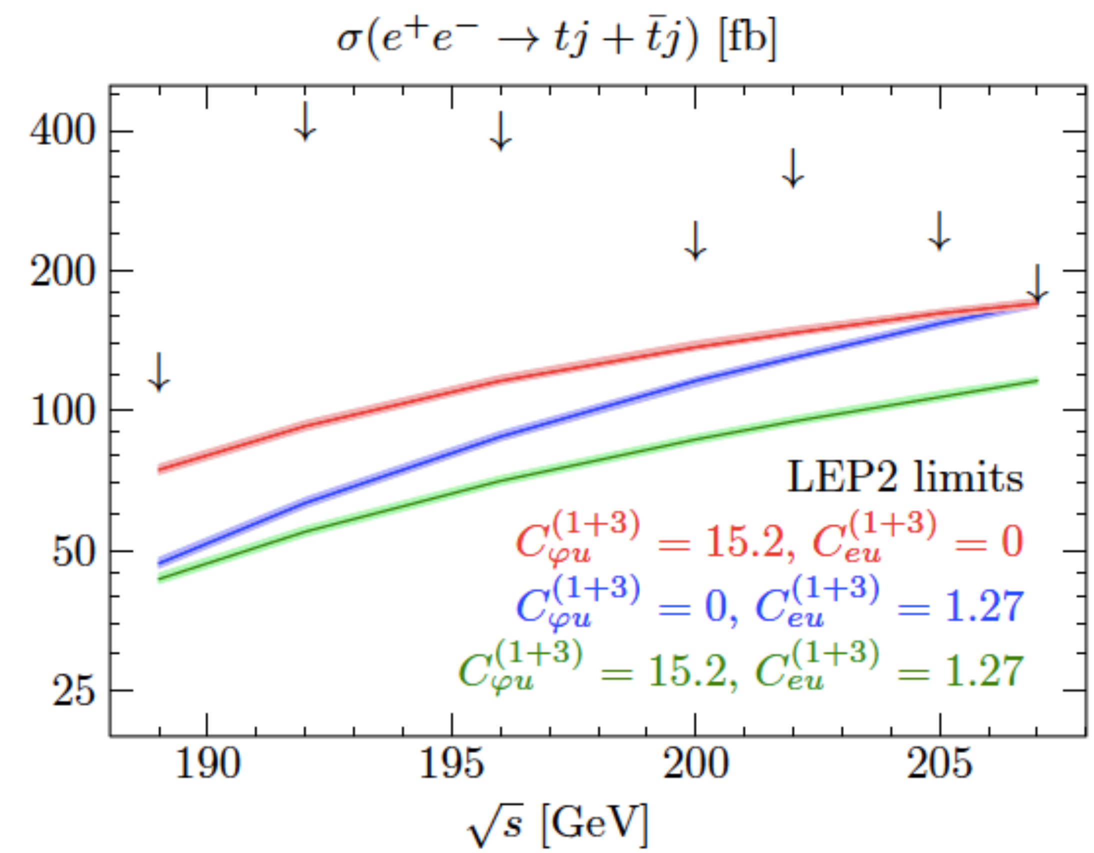
$$\mathrm{Br}(t \to j\gamma) < 3.2\%$$ CDF

$$\mathrm{Br}(t \to j\,\gamma\gamma) < 0.0016\%$$ CMS

$$\sigma(pp \to t) + \sigma(pp \to \bar{t}) < 2.5 \text{ pb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$ ATLAS

$$\sigma(ug \to t\gamma) + \sigma(ug \to \bar{t}\gamma) + 0.778\, [\sigma(cg \to t\gamma) + \sigma(cg \to \bar{t}\gamma)] < 0.0670 \text{ pb} \quad \text{at } \sqrt{s_{pp}} = 8 \text{ TeV}$$ CMS

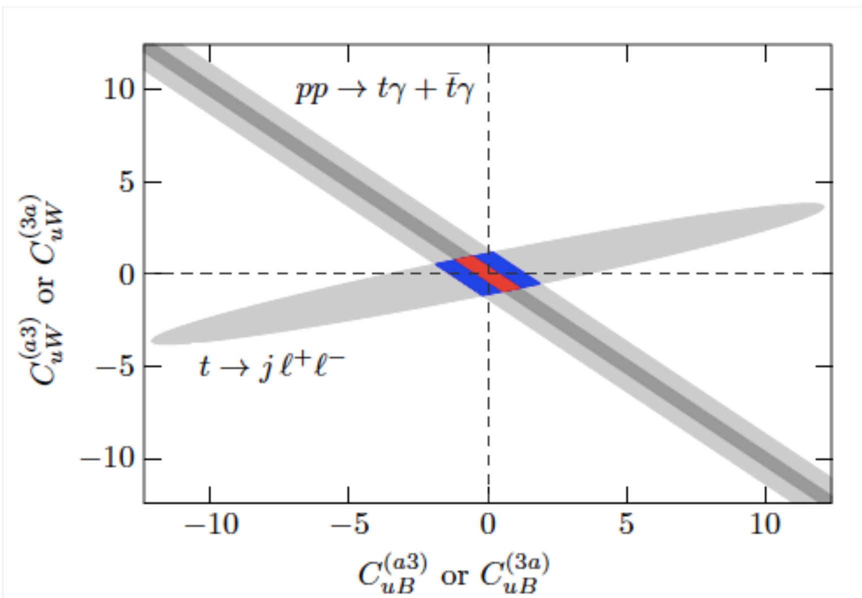
$$\sigma(e^+e^- \to tj + \bar{t}j) < 176 \text{ fb} \quad \text{at } \sqrt{s} = 207 \text{ GeV}$$ LEPII

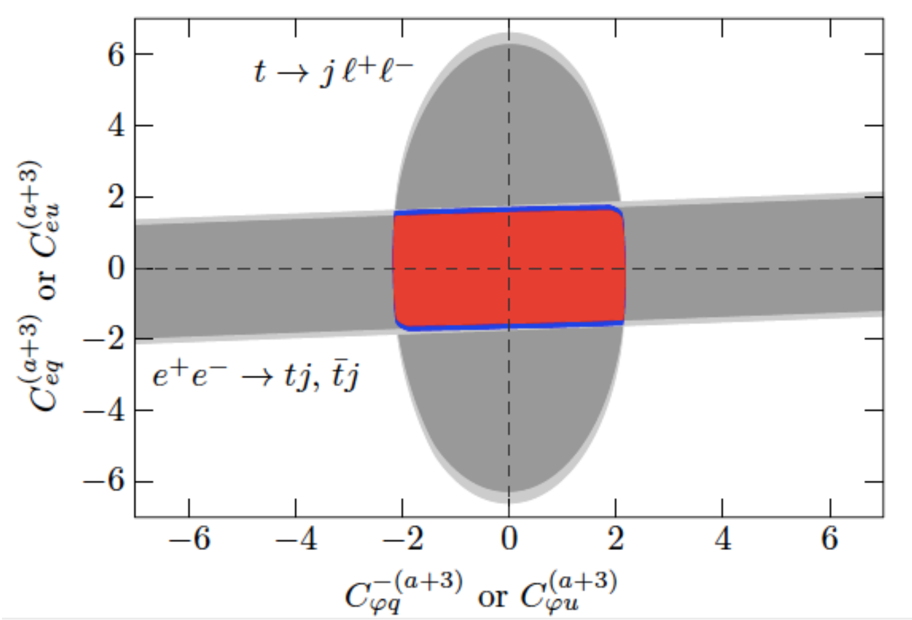


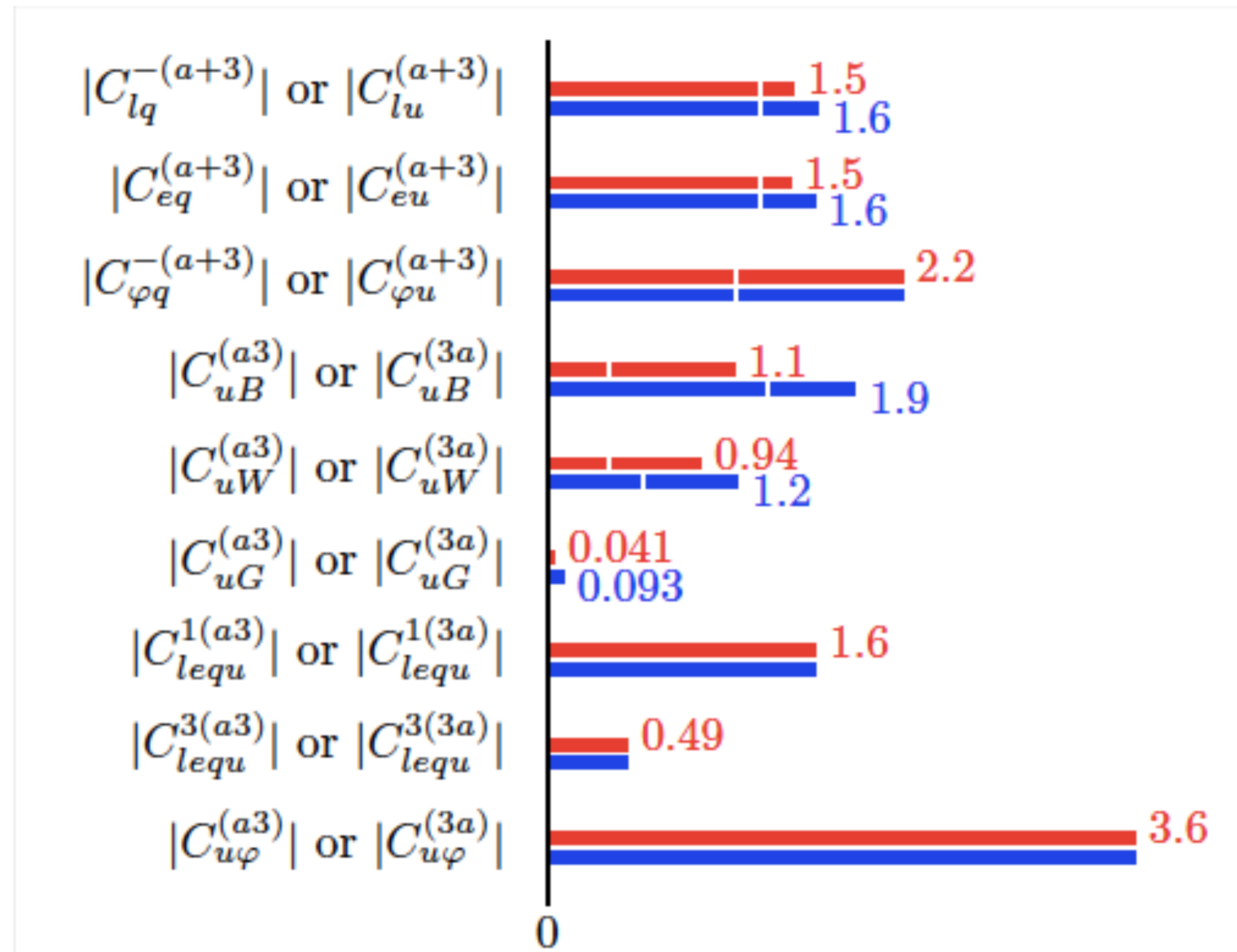
For the sake of illustration and simplicity, we only consider the most constraining observables. This suffices to set significant bounds on all two-quark operators as well as on a subset of the two-quark–two-lepton ones.

TOP FCNC'S

[Durieux, FM, Zhang 2014]

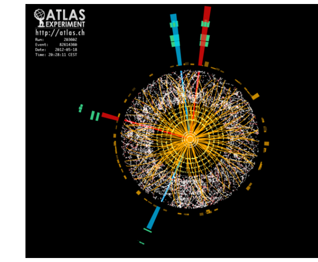




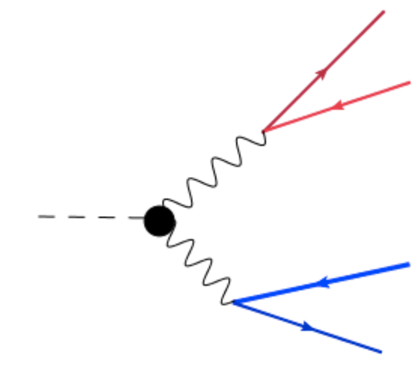


First proof of principle that a complete global fitting strategy in a self-contained sector of the top EFT is possible with the available measurements. The red (blue) are for 1st (2nd) generation. ticks = one on at the time.

HIGGS EFT AT THE LHC



- (Mostly) sensitive to Higgs couplings to bosons
    - $H \to 4$ leptons
    - VBF
    - VH



- (Mostly) sensitive to Higgs couplings to top and bottom quark
    - $H \to bb$
    - ttH
    - $H \to gg$
    - $gg \to H$
- Sensitive to both (and their phase)
    - $H \to \gamma\gamma$, $H \to l^+ l^- \gamma$
    - $gg \to HH$
    - tHj
    - $gg \to HZ$

PHENO

- The basic lagrangian that has been used so far in Higgs phenomenology is

$$\begin{aligned}\Delta\mathcal{L}_{\rm hvv}^{D=6} &= \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu \\ &+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\ &+ c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma}\frac{eg}{2c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz}\frac{g^2}{4c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \\ &+ c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu} \\ &+ \tilde{c}_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{eg}{2c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2}{4c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu}\Big]\end{aligned}$$

$$\mathcal{L}_{\rm hff}^{D=6} = -\frac{h}{v} \sum_{f\in u,d,e} \sum_{ij} \sqrt{m_{f_i} m_{f_j}} [\delta y_f]_{ij} \left[O s\phi_{ij}^f \bar{f}_i f_j - i \sin\phi_{ij}^f \bar{f}_i \gamma_5 f_j \right]$$

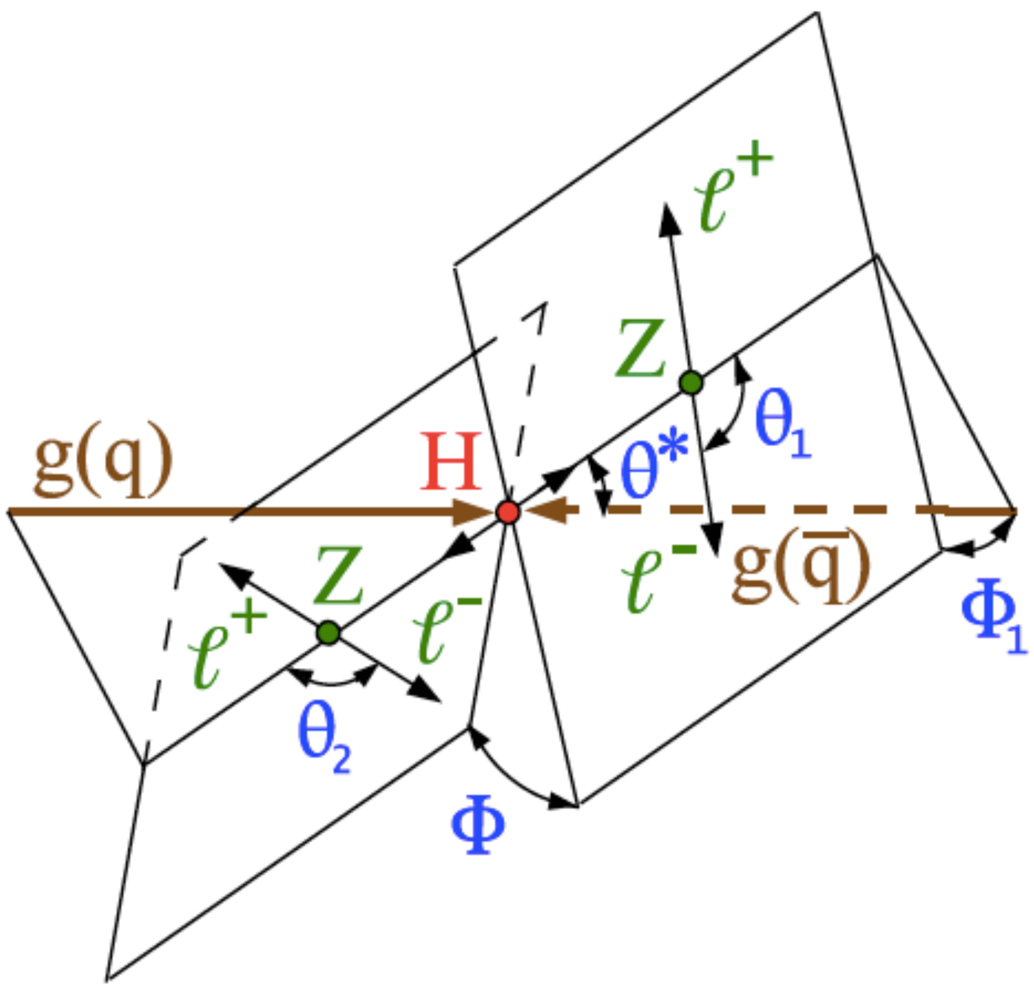
HIGGS DECAY TO 4 LEPTONS

The golden channel: 12 kinematical observables related to production and decay, 5 independent ones in the decay. Small background. Extremely clean state. The most studies final state for the Higgs, with the largest number of papers on new ideas, variables to consider.

This process is extremely well known theoretically (NLO in EW +EM PS) and corresponding tools are public [Prophecy4f and Hto4l].

Major results: The basis for having this channel at NLO in EW in the SM@dim6 have been laid [Ghezzi et al. 2015, see also Hartmann and Trott, 2015].

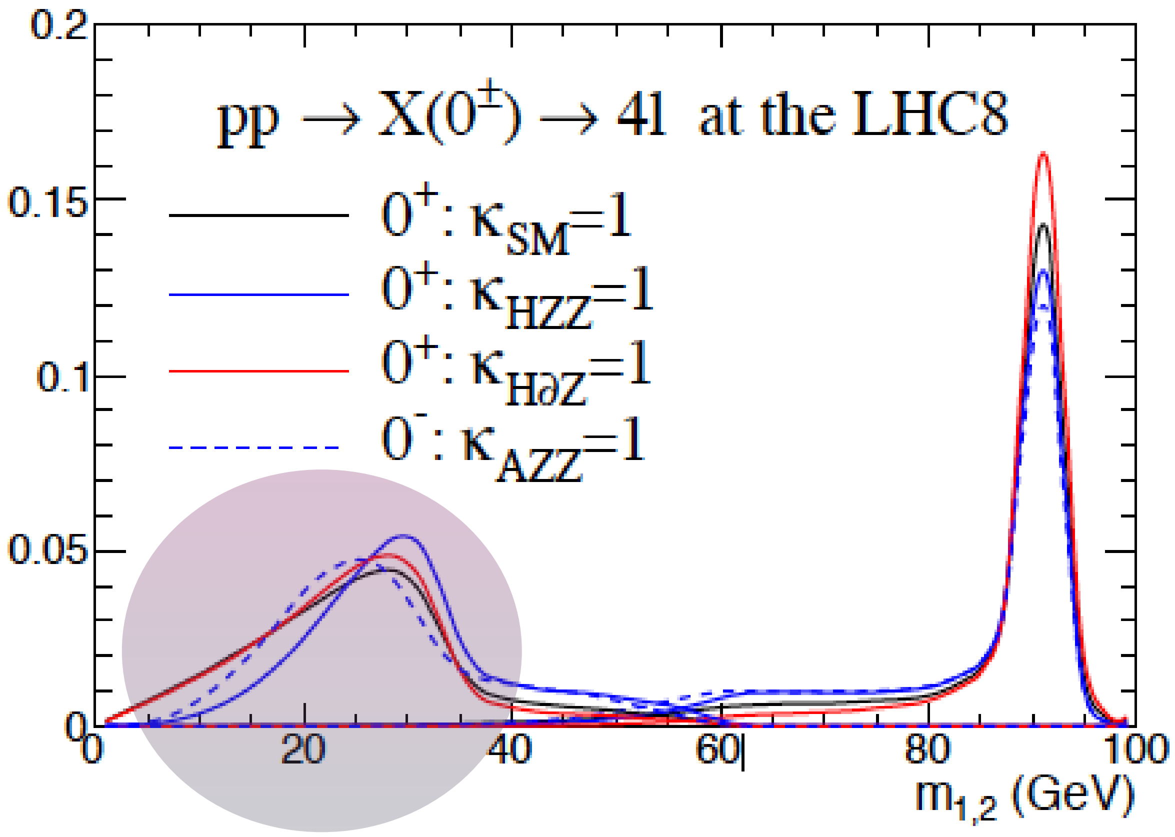
This is the Hydrogen atom of Higgs physics for the theorists and experimentalists alike,



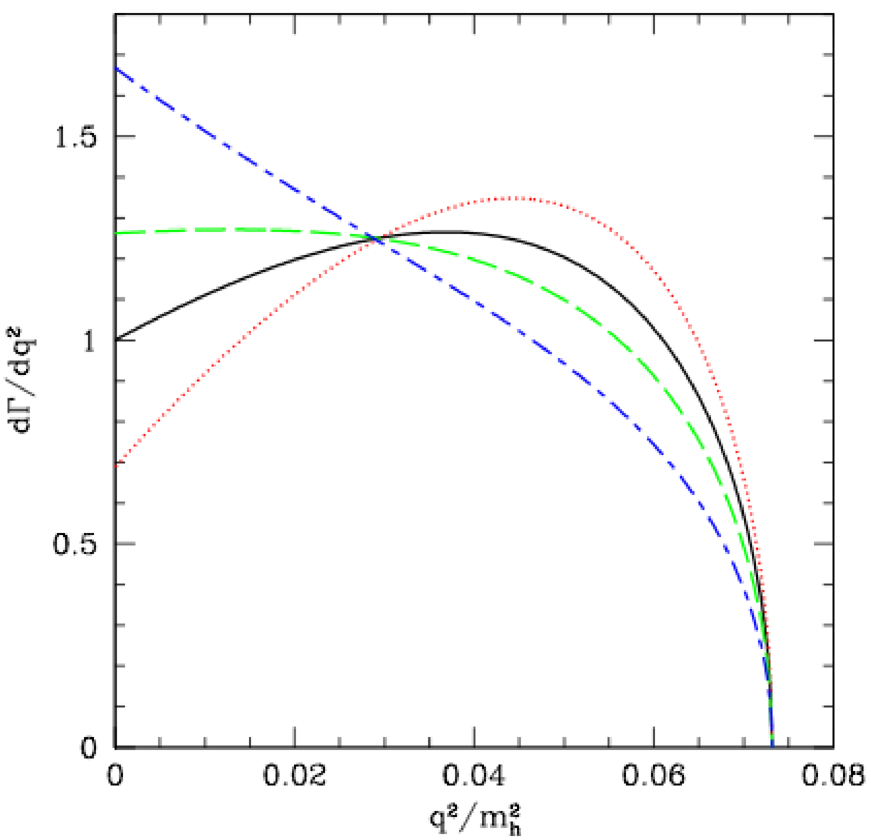
HIGGS DECAY TO 4 LEPTONS

Many observables and correlations can be built.

HC model arXiv:1306.6464 [hep-ph]



Isidori et al. arXiv:1305.0663 [hep-ph]



Effects of the contact interactions could be accessed in the low invariant mass pair and should be part of any parametrization of BSM physics.

HIGGS DECAY TO 4 LEPTONS

- **h → 4f**. The decay process $h \to 2\ell 2\nu$ (where ℓ here stands for charged leptons) proceeds via intermediate W bosons. The relative width is given by

$$\begin{aligned} \frac{\Gamma_{2\ell 2\nu}}{\Gamma^{\rm SM}_{2\ell 2\nu}} &\simeq 1 + 2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to 1 + 2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}. \end{aligned} \quad (4.12)$$

In the SM, the decay process $h \to 4\ell$ proceeds at the tree-level via intermediate Z bosons. In the presence $D = 6$ operators, intermediate photon contributions may also arise at the tree level. If that is the case, the decay width diverges due to the photon pole. Below I quote the relative width $\bar{\Gamma}(h \to 4\ell)$ regulated by imposing the cut $m_{\ell\ell} > 12$ GeV on the invariant mass of same-flavor lepton pairs:

$$\begin{aligned} \frac{\bar{\Gamma}_{4\ell}}{\bar{\Gamma}^{\rm SM}_{4\ell}} &\simeq 1 + 2\delta c_z + \begin{pmatrix} 0.41 \\ 0.39 \end{pmatrix} c_{z\Box} - \begin{pmatrix} 0.15 \\ 0.14 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.07 \\ 0.05 \end{pmatrix} c_{z\gamma} - \begin{pmatrix} 0.02 \\ 0.02 \end{pmatrix} c_{\gamma\Box} + \begin{pmatrix} < 0.01 \\ 0.03 \end{pmatrix} c_{\gamma\gamma} \\ &\to 1 + 2\delta c_z + \begin{pmatrix} 0.35 \\ 0.32 \end{pmatrix} c_{z\Box} - \begin{pmatrix} 0.19 \\ 0.19 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.09 \\ 0.08 \end{pmatrix} c_{z\gamma} + \begin{pmatrix} 0.01 \\ 0.02 \end{pmatrix} c_{\gamma\gamma}. \end{aligned} \quad (4.13)$$

The numbers in the columns correspond to the $2e2\mu$ and $4e/\mu$ final states, respectively. The difference between these two is numerically irrelevant in the total width, but may be important for differential distributions, especially regarding the $c_{\gamma\gamma}$ dependence [91]. The dependence on the $m_{\ell\ell}$ cut is weak; very similar numbers are obtained if $m_{\ell\ell} > 4$ GeV is imposed instead.

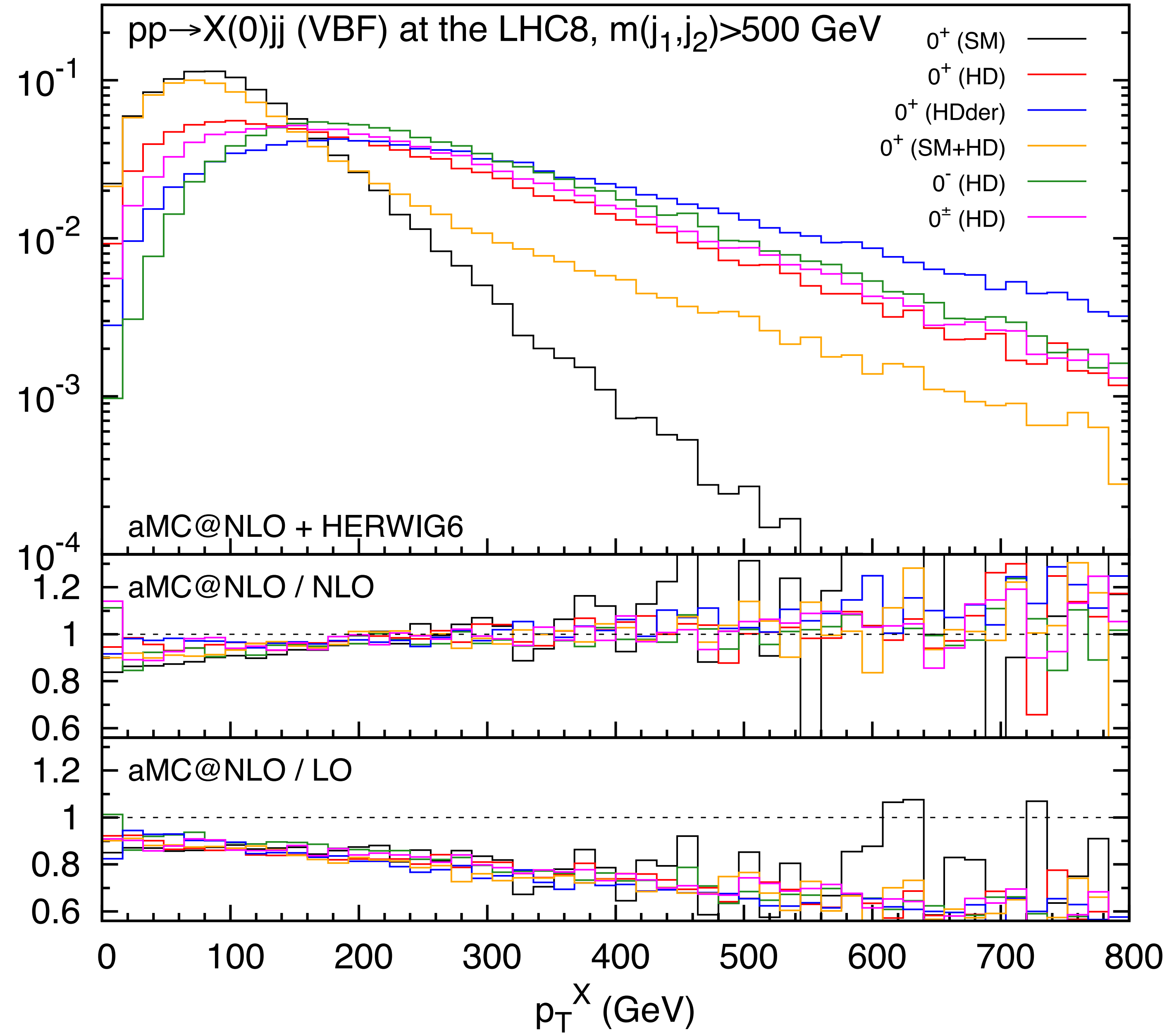
HIGGS PRODUCTION : VBF

pp→Hjj (VBF) at NLO+PS

This process is extremely well known theoretically (NNLO in QCD and NLO in EW) and corresponding tools are public.

Within the SM@dim6 is known at NLO in QCD [HAWK, VBF@NLO, multi-purpose MC's]

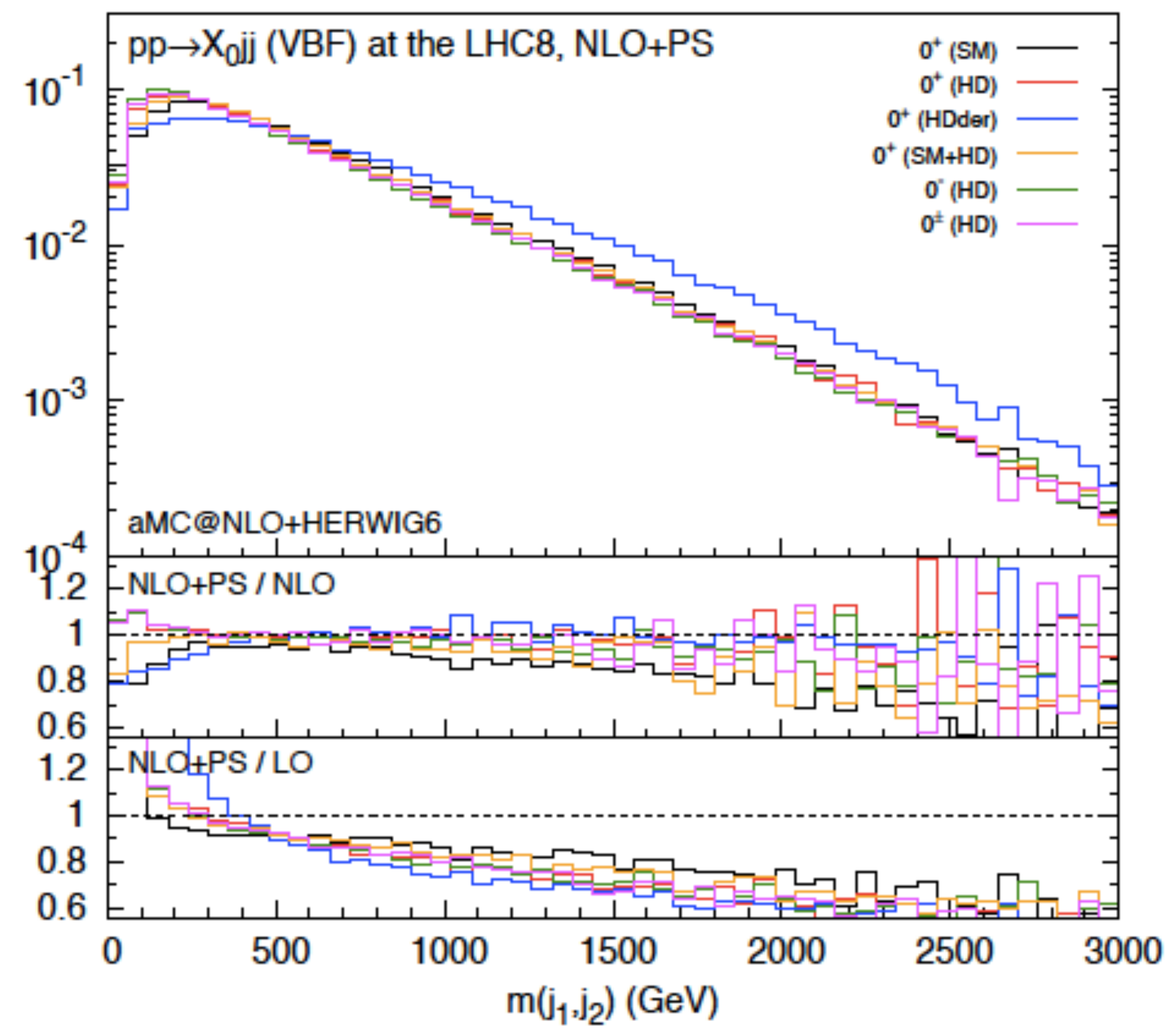
NLO QCD corrections are important for many key observables.

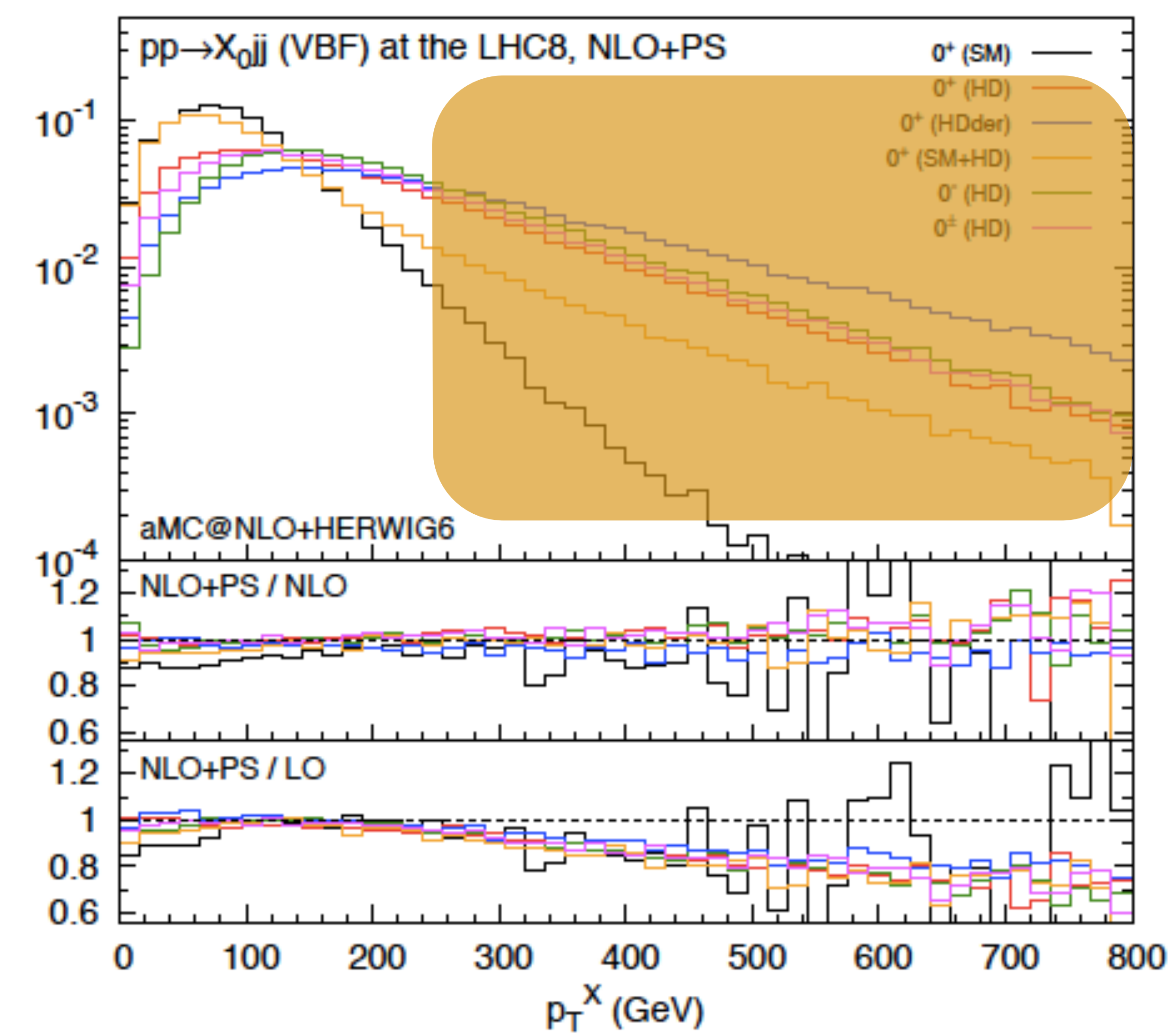


Many studies on VBF in "EFT" have appeared, even very recently [Edezhath 1501.00992, Ellis&Campbell, 1502.02990]

HIGGS PRODUCTION : VBF

pp→Hjj (VBF) at NLO+PS





Shapes of distributions are greatly affected both NLO and NLO+PS.

Substantial degeneracy between several CP-violating scenarios.

HIGGS PRODUCTION : VBF

[Falkowski, 2015]

- Vector boson fusion (VBF), $qq \to hqq$:

$$\begin{aligned}\frac{\sigma_{VBF}}{\sigma_{VBF}^{\mathrm{SM}}} &\simeq 1 + 1.49\delta c_w + 0.51\delta c_z - \begin{pmatrix} 1.08 \\ 1.11 \\ 1.23 \end{pmatrix} c_{w\Box} - 0.10 c_{ww} - \begin{pmatrix} 0.35 \\ 0.35 \\ 0.40 \end{pmatrix} c_{z\Box} \\ &\quad -0.04 c_{zz} - 0.10 c_{\gamma\Box} - 0.02 c_{z\gamma} \\ &\to 1 + 2\delta c_z - 2.25 c_{z\Box} - 0.83 c_{zz} + 0.30 c_{z\gamma} + 0.12 c_{\gamma\gamma}. \qquad (4.6)\end{aligned}$$

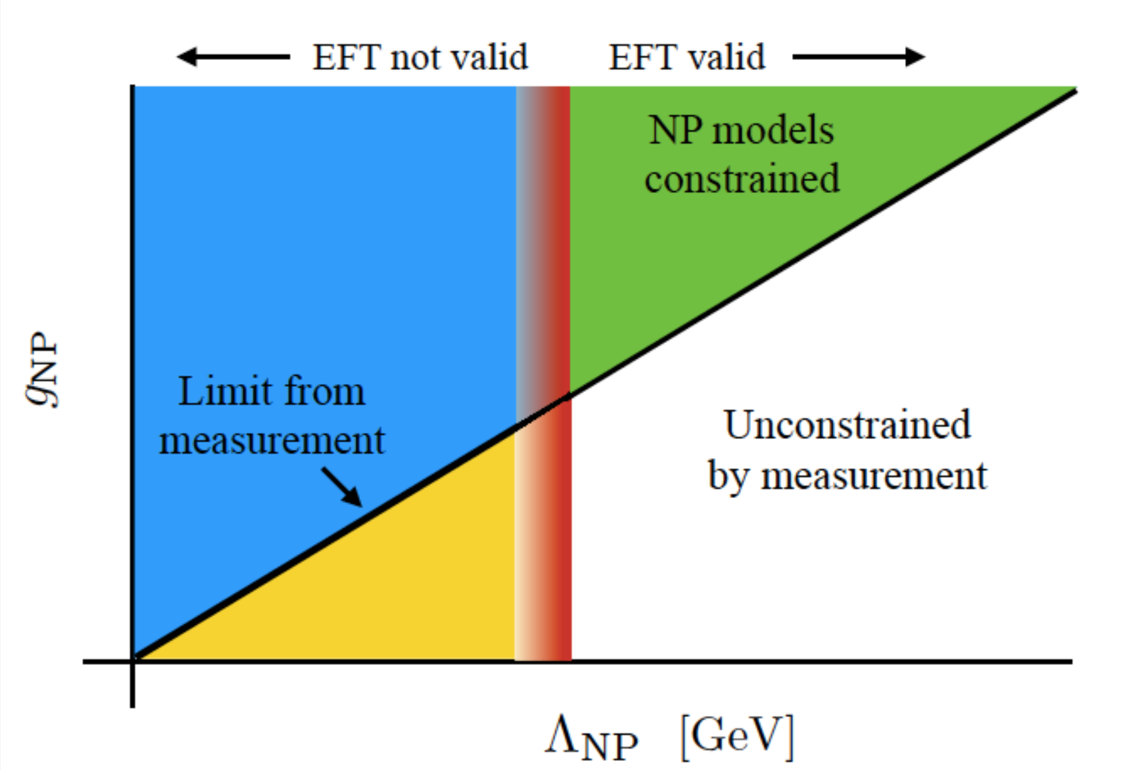
The numbers in the columns multiplying $c_{w\Box}$ and $c_{z\Box}$ refer to the LHC collision energy of $\sqrt{s}$ =7, 8, and 13 TeV; for other parameters the dependence is weaker. The expression after the arrow arises due to replacing the dependent couplings by the independent ones in Eq. (3.2). Each LHC Higgs analysis uses somewhat different cuts to isolate the VBF signal, and the relative cross section slightly depends on these cuts. The result in Eq. (4) has been computed numerically by simulating the parton-level process in MadGraph5 [90] at the tree level with the cuts $p_{T,q} > 20$ GeV, $|\eta_q| < 5$ and $m_{qq} > 250$ GeV. Replacing the last cut by $m_{qq} > 500$ GeV affects the numbers at the level of 5%.

EFT VALIDITY

- The issue of the validity of EFT's is being discussed extensively in the literature both in the case of Higgs and also for DM.

FOR HIGGS:
[BIEKOETTER ET AL. 1406.7320, SEE RIVA'S TALK]
[ENGLERT AND SPANNOWSKY, 1408.5147], ...

FOR DM:
[BUSONI ET AL, 1307.2253,1402.1275, 1405.3102] AND 1005.3797, 1103.0240, 1109.4398, 1203.1662, ...



[ENGLERT AND SPANNOWSKY, 1408.5147]

- Simple, practical, improvable, legacy friendly solutions do exist!

EFT VALIDITY

- Criteria to study the behaviour at HE include:
  - Series behaviour: $1/\Lambda^2$ vs $1/\Lambda^4$ (interference vs amplitude squared)
  - Unitarity
  - size of cross sections VS SM
  - validation/comparison with explicit UV completions
- Simple solutions (practical and legacy-friendly) are available:
  - simulations available for different values of $\Lambda > \sqrt{\hat{s}}$
- Possible improvements:
  - Event-by-event determination of the scale including running of the operators, i.e. QCD (and maybe EW) RGE effects [Englert Spannowsky, arXiv:1104.1798]

HIGGS PRODUCTION : VH

pp→HV at NLO+PS in the SM@dim6

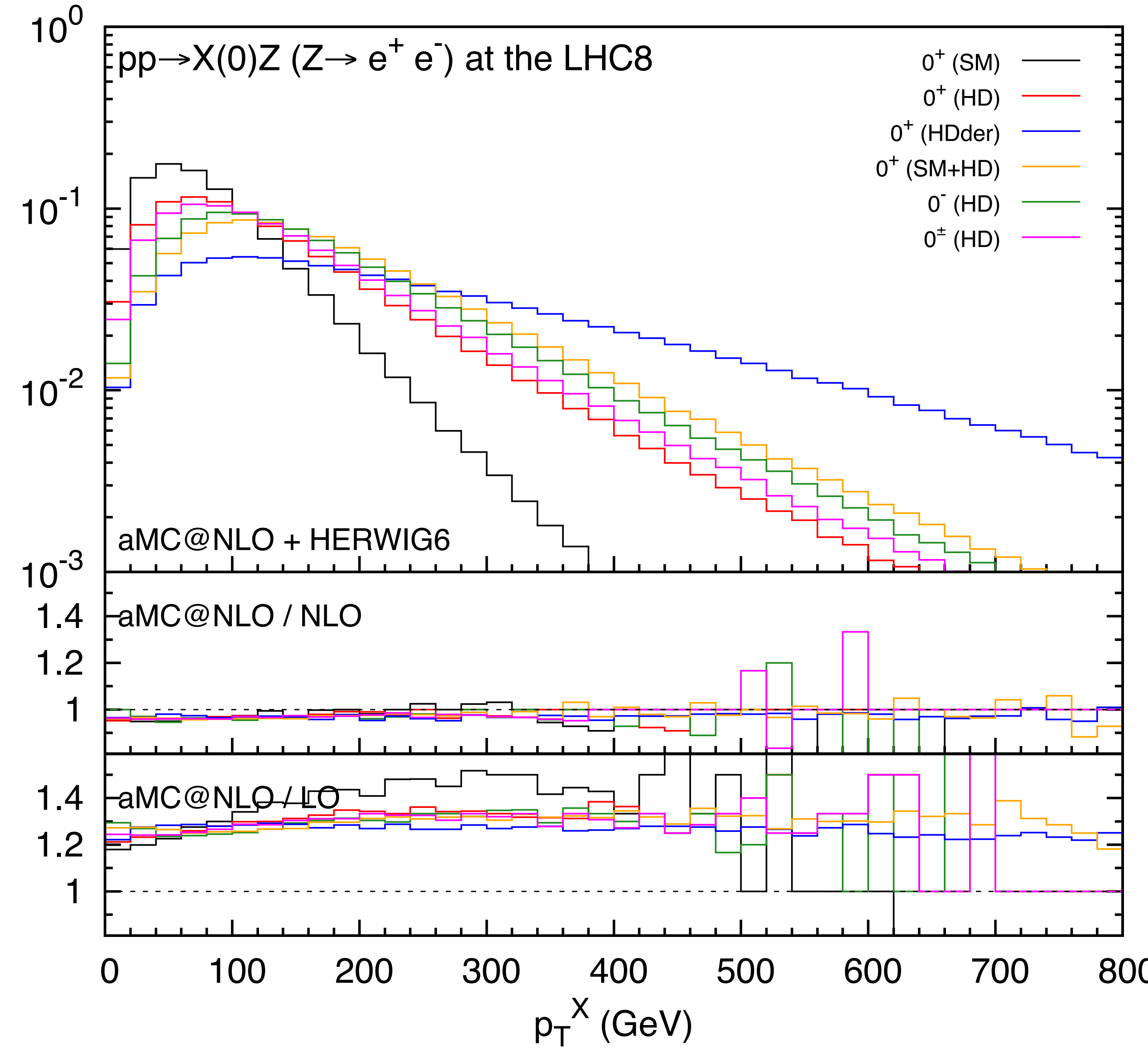
6 HC scenarios considered:

NLO QCD corrections are important in all of them!

$$\frac{\sigma}{\sigma_{SM}} \sim (1 + c_{i_2}\frac{\hat{s}}{\Lambda^2})^2$$

$$\sum_T \int d\cos\theta |\mathcal{M}_T|^2 \rightarrow \frac{4g^4}{3}\frac{m_W^2}{\hat{s}}\left(1 + (c_{WW} + c_W)\frac{\hat{s}}{\Lambda^2}\right)^2,$$

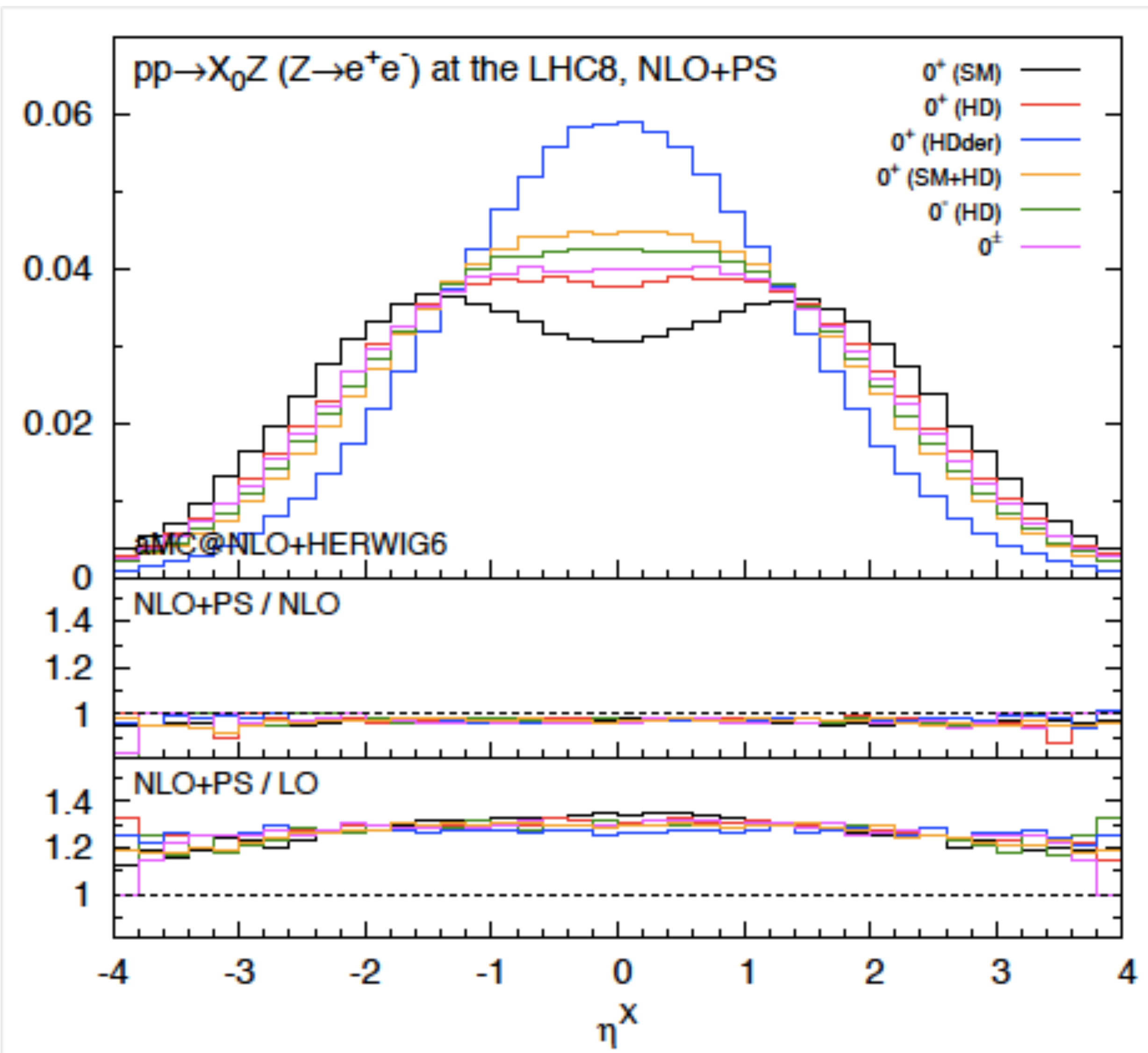
$$\int d\cos\theta |\mathcal{M}_L|^2 \rightarrow \frac{g^4}{6}\left(1 + c_W\frac{\hat{s}}{\Lambda^2} + 4(c_{WW} + c_W)\frac{m_W^2}{\Lambda^2}\right)^2,$$

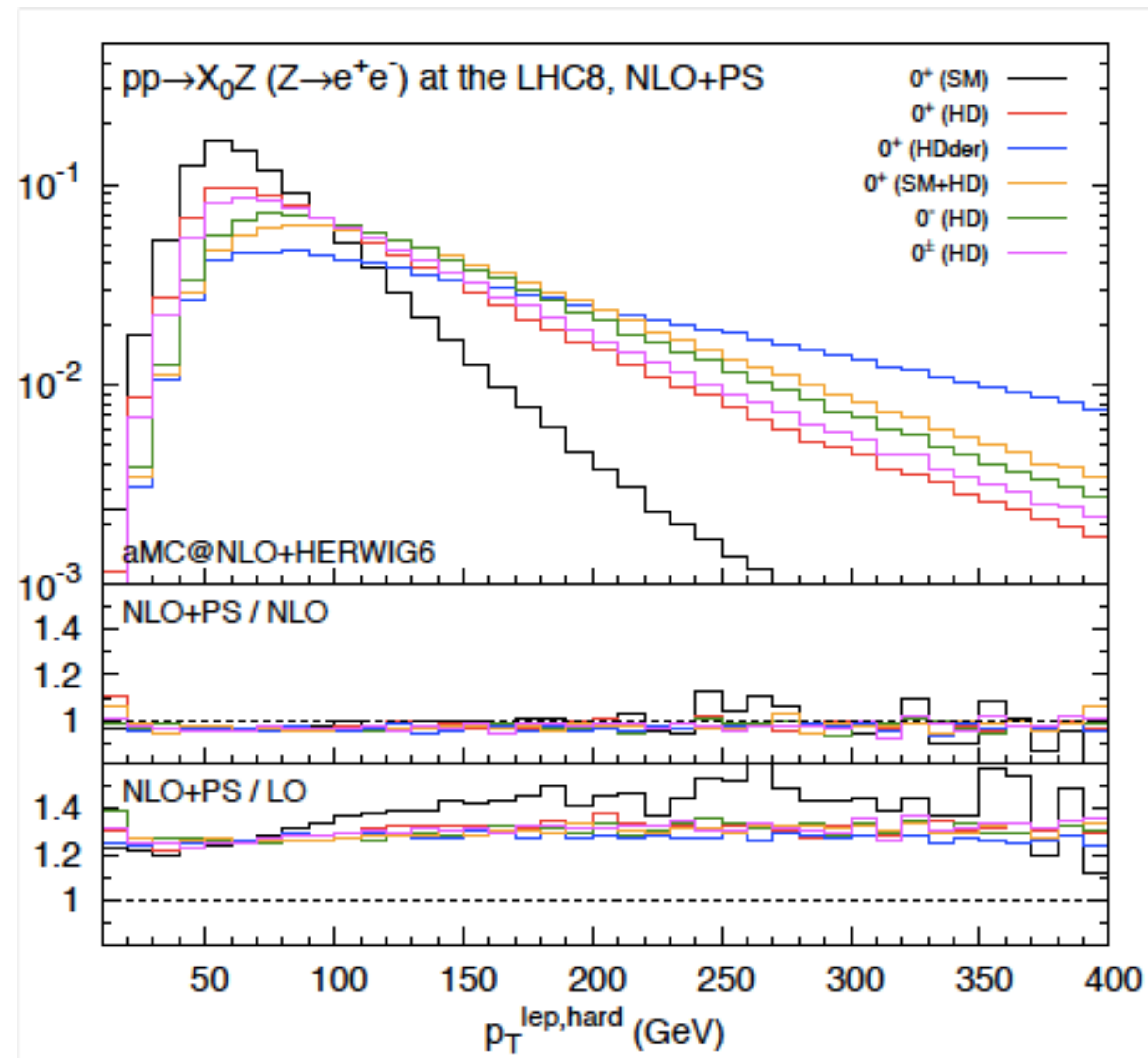


Many studies on HV in "EFT" have appeared, for example [Isidori & Trott 1307.4051, Ellis et al. 1208.6002, 1303.0208, 1404.3667, Biekotter et al. 1406.7320, …..]

HIGGS PRODUCTION : VH

pp➞HV at NLO+PS in the SM@dim6





Plenty of information can be gathered from this process.

HIGGS PRODUCTION : VH

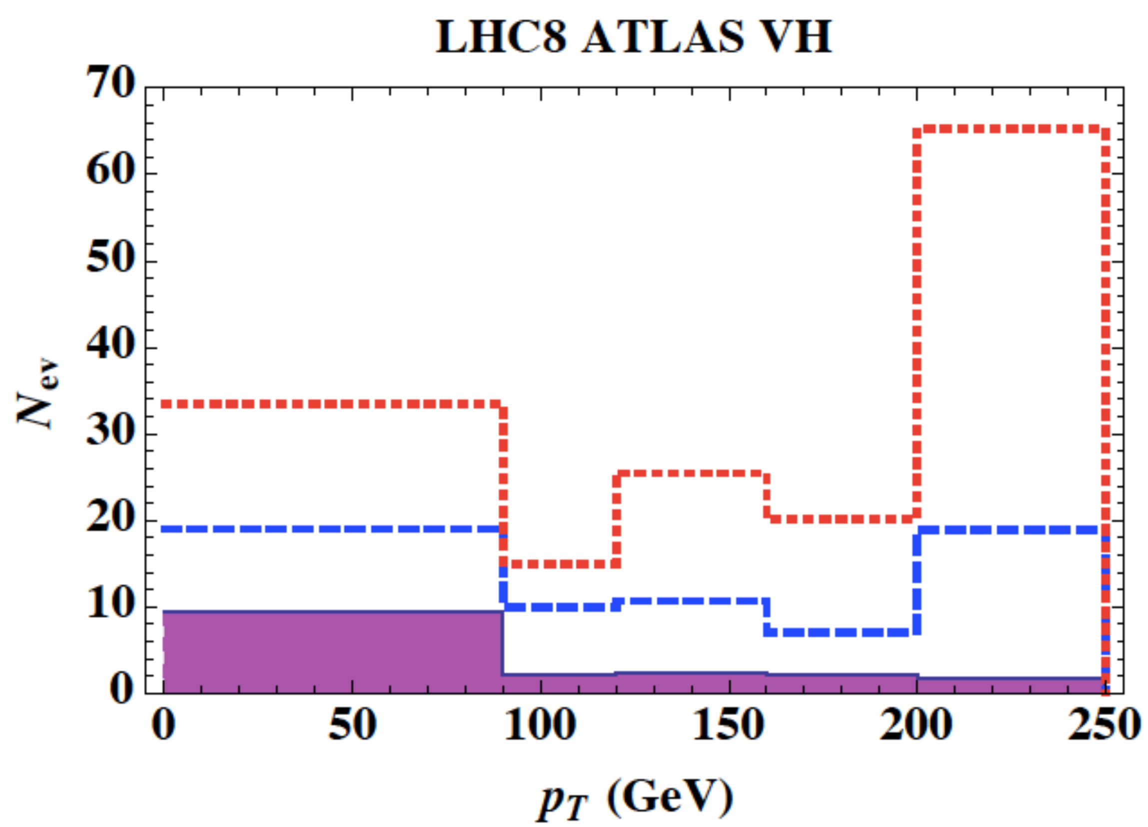
[Falkowski, 2015]

- Vector boson associated production (Vh), $q\bar{q} \to Vh$, where $V = W, Z$,

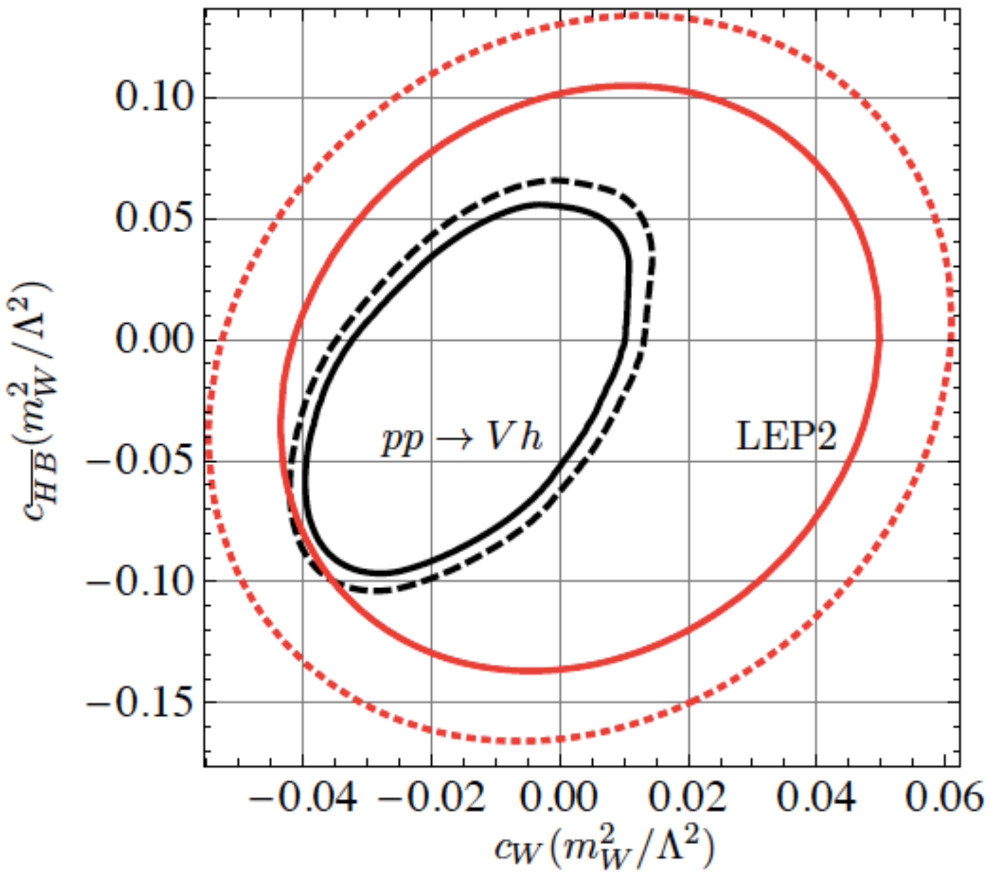
$$\begin{aligned}
\frac{\sigma_{Wh}}{\sigma_{Wh}^{\rm SM}} &\simeq 1 + 2\delta c_w + \begin{pmatrix} 6.39 \\ 6.51 \\ 6.96 \end{pmatrix} c_{w\Box} + \begin{pmatrix} 1.49 \\ 1.49 \\ 1.50 \end{pmatrix} c_{ww} \\
&\to 1 + 2\delta c_z + \begin{pmatrix} 9.26 \\ 9.43 \\ 10.08 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 4.35 \\ 4.41 \\ 4.63 \end{pmatrix} c_{zz} - \begin{pmatrix} 0.81 \\ 0.84 \\ 0.93 \end{pmatrix} c_{z\gamma} - \begin{pmatrix} 0.43 \\ 0.44 \\ 0.48 \end{pmatrix} c_{\gamma\gamma} \\
\frac{\sigma_{Zh}}{\sigma_{Zh}^{\rm SM}} &\simeq 1 + 2\delta c_z + \begin{pmatrix} 5.30 \\ 5.40 \\ 5.72 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 1.79 \\ 1.80 \\ 1.82 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.80 \\ 0.82 \\ 0.87 \end{pmatrix} c_{\gamma\Box} + \begin{pmatrix} 0.22 \\ 0.22 \\ 0.22 \end{pmatrix} c_{z\gamma}, \\
&\to 1 + 2\delta c_z + \begin{pmatrix} 7.61 \\ 7.77 \\ 8.24 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 3.31 \\ 3.35 \\ 3.47 \end{pmatrix} c_{zz} - \begin{pmatrix} 0.58 \\ 0.60 \\ 0.65 \end{pmatrix} c_{z\gamma} + \begin{pmatrix} 0.27 \\ 0.28 \\ 0.30 \end{pmatrix} c_{\gamma\gamma}.
\end{aligned} \tag{4.7}$$

The numbers in the columns refer to the LHC collision energy of $\sqrt{s}$ =7, 8, and 13 TeV.

HIGGS PRODUCTION : VH



[Ellis, Sanz and You, 1404.3667]

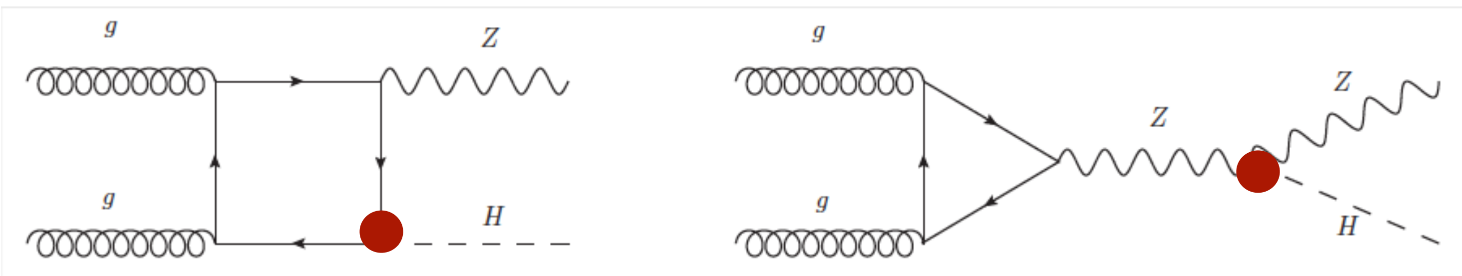


[Biekotter et al., 1406.7320]

HIGGS PRODUCTION : ZH

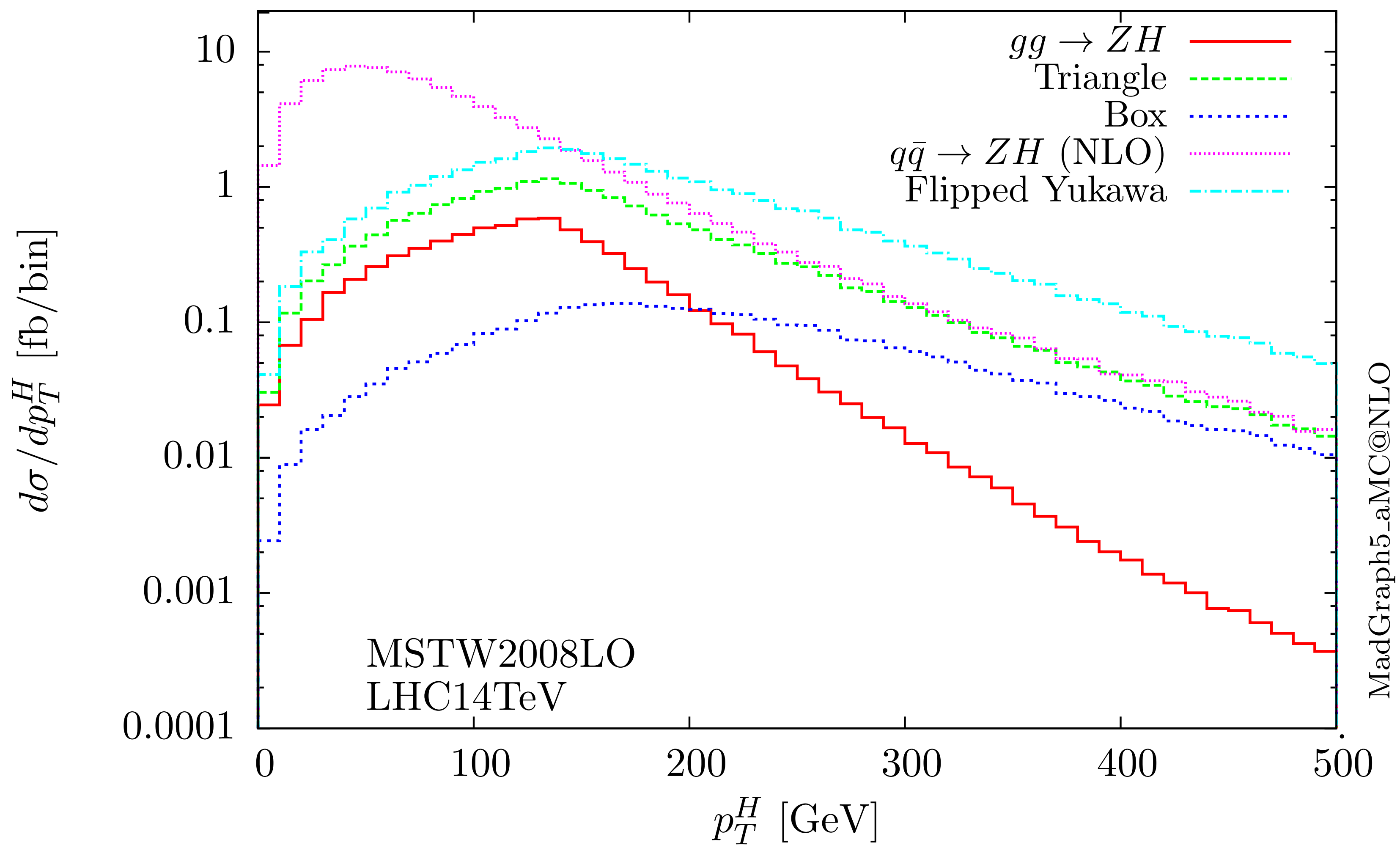
PP→HZ: GG CONTRIBUTION

[Hespel, et al. 1503.01656]



gg→ZH is sensitive to relative phase (and SIGN!) between HVV and ttH coupling (like h→gamma gamma and pp→tHj)!

It contributes in a significant way to the high-pt region of the H: needs to be included in the globa fit and introduces a dependence from the top-Higgs coupling



HIGGS PRODUCTION : GLUON FUSION

Consider, for example, the following top-Higgs interactions:

$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right) \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu},$$

CHROMOMAGNETIC OPERATOR

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

YUKAWA OPERATOR

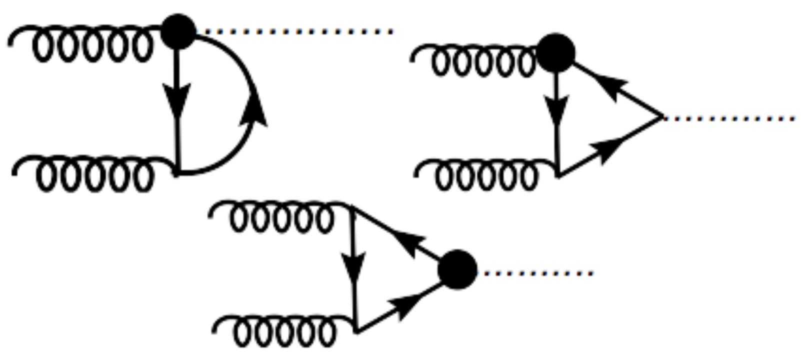
$$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$

HIGGS-GLUON OPERATOR

At NLO in QCD the first two operators mix:

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 \\ -2 & -1 \end{pmatrix}$$

In addition, the third operator receives contributions from the first two at one loop:



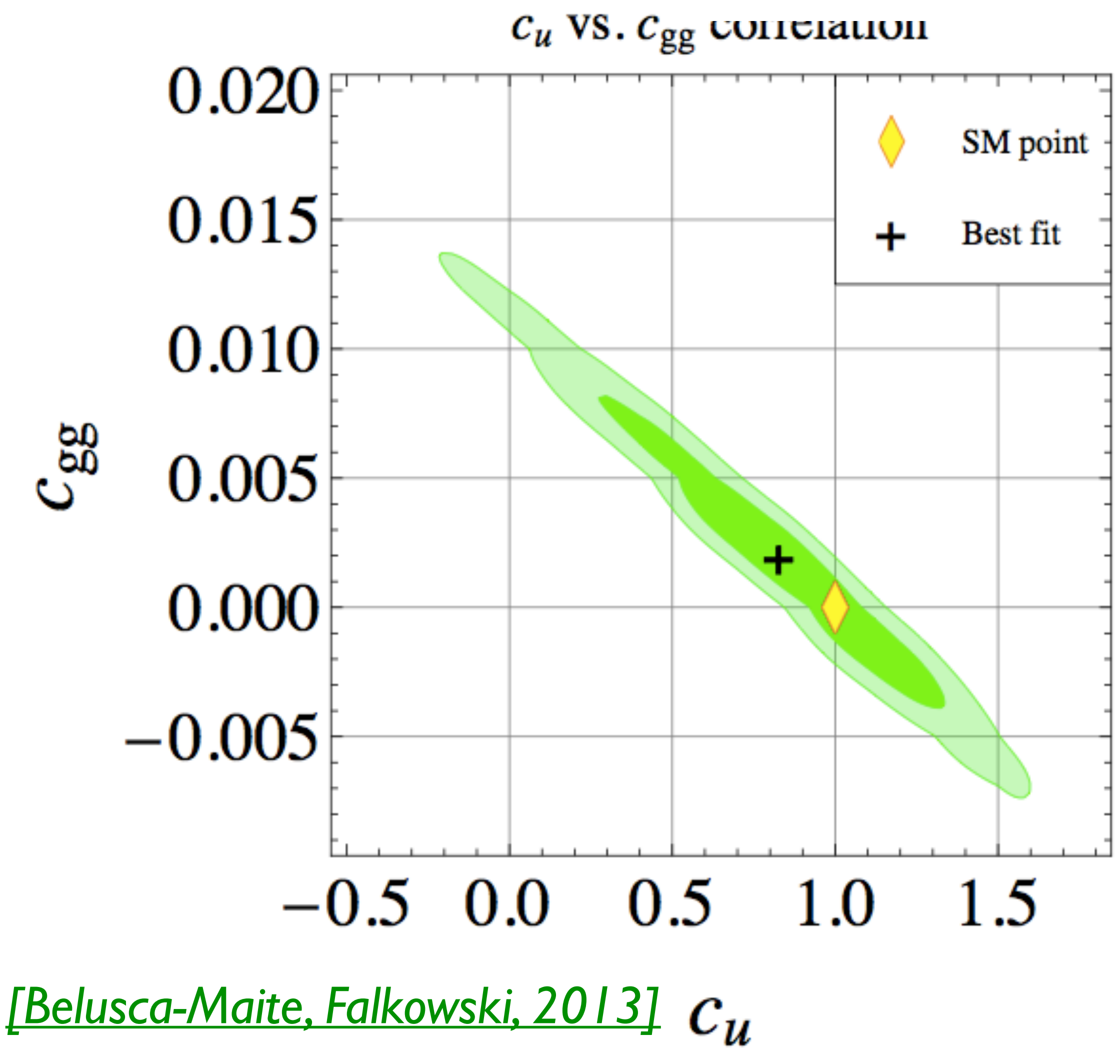
A MEANINGFUL ANALYSIS CAN ONLY BE MADE BY CONSIDERING THEM ALL!

HIGGS PRODUCTION : GLUON FUSION

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

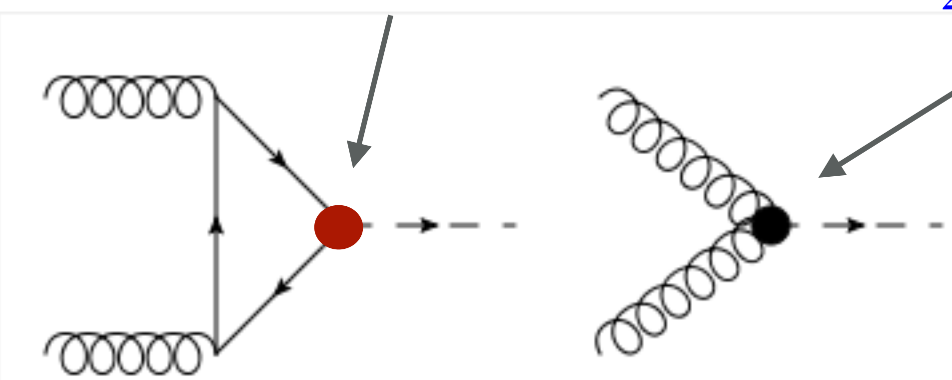
$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq \left|1 + \frac{\hat{c}_{gg}}{c_{gg}^{\rm SM}}\right|^2 \qquad \hat{c}_{gg} \simeq c_{gg} + (8.7\delta y_u - (0.3-0.3i)\delta y_d) \times 10^{-3}, \qquad c_{gg}^{\rm SM} \simeq (8.4+0.3i)\times 10^{-3}$$

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



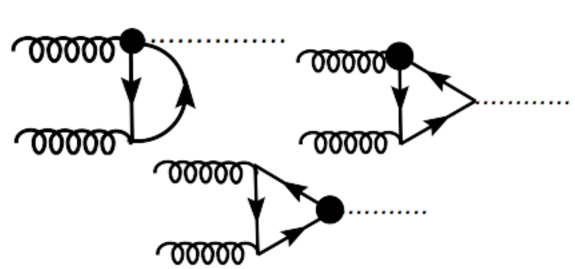
[Belusca-Maite, Falkowski, 2013]

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



the loop could still be dominated by np.

THE EFFECT OF THE CM OPERATOR NOT INCLUDED

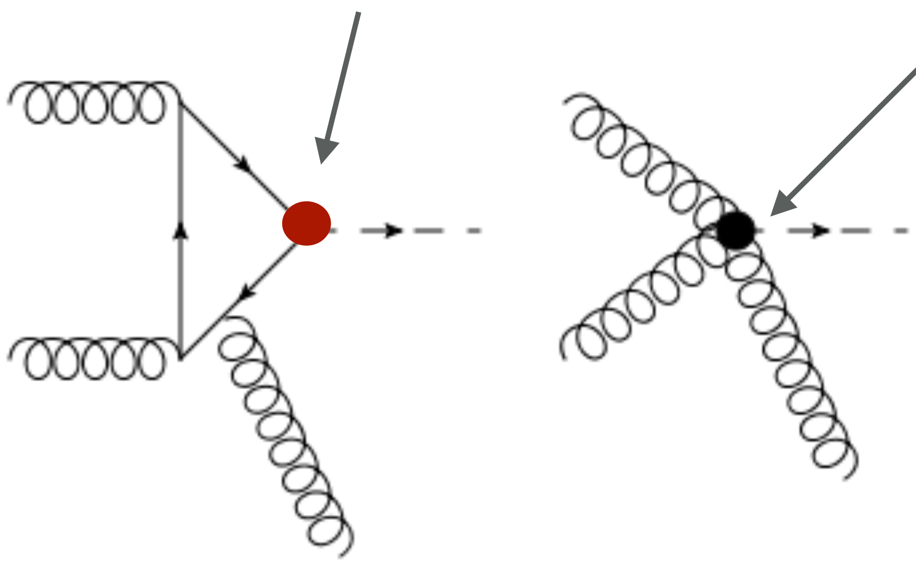


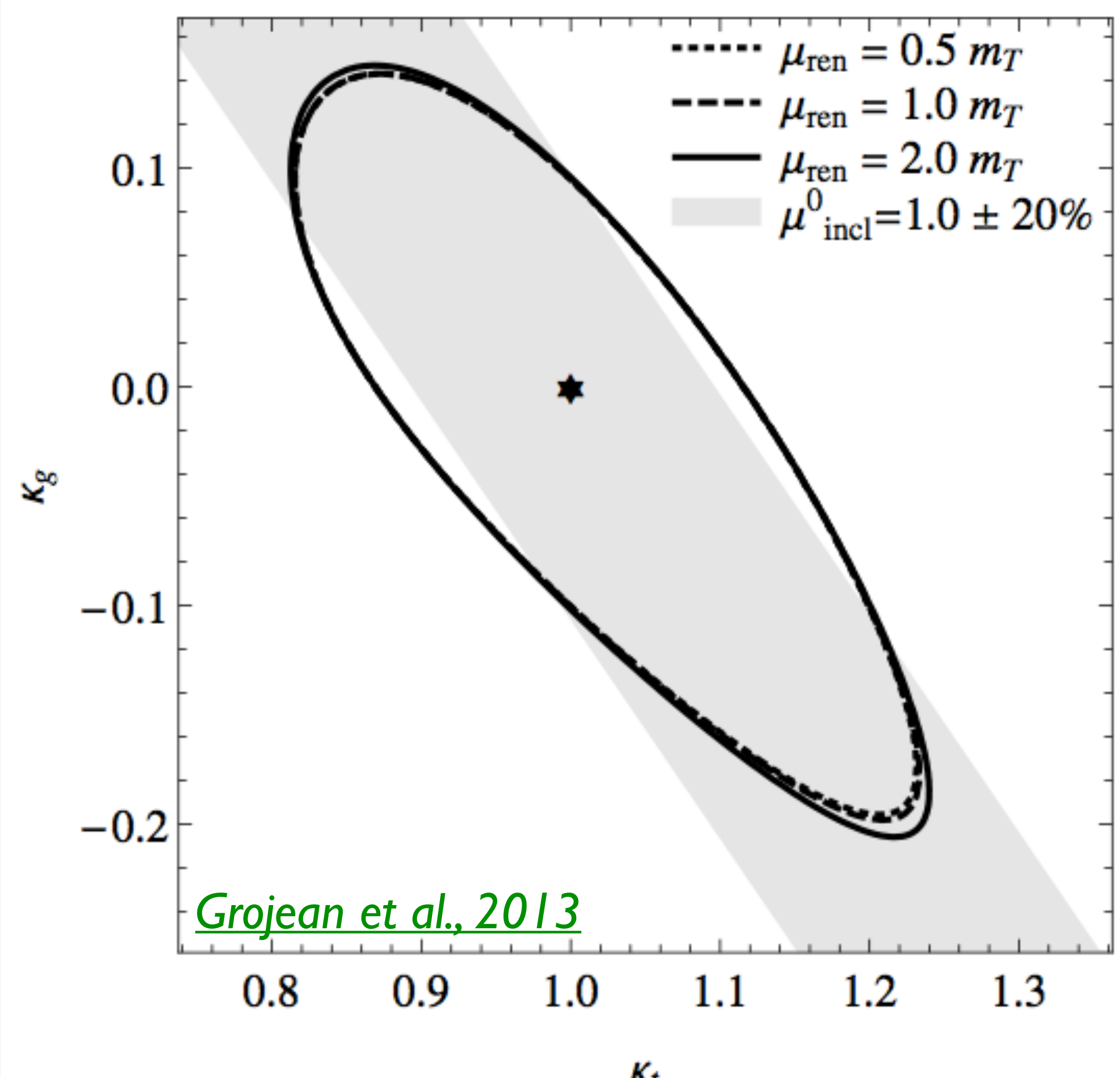
HIGGS PRODUCTION : GLUON FUSION

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]

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



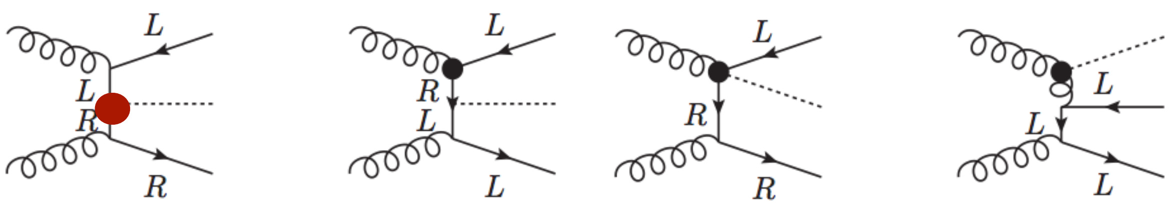


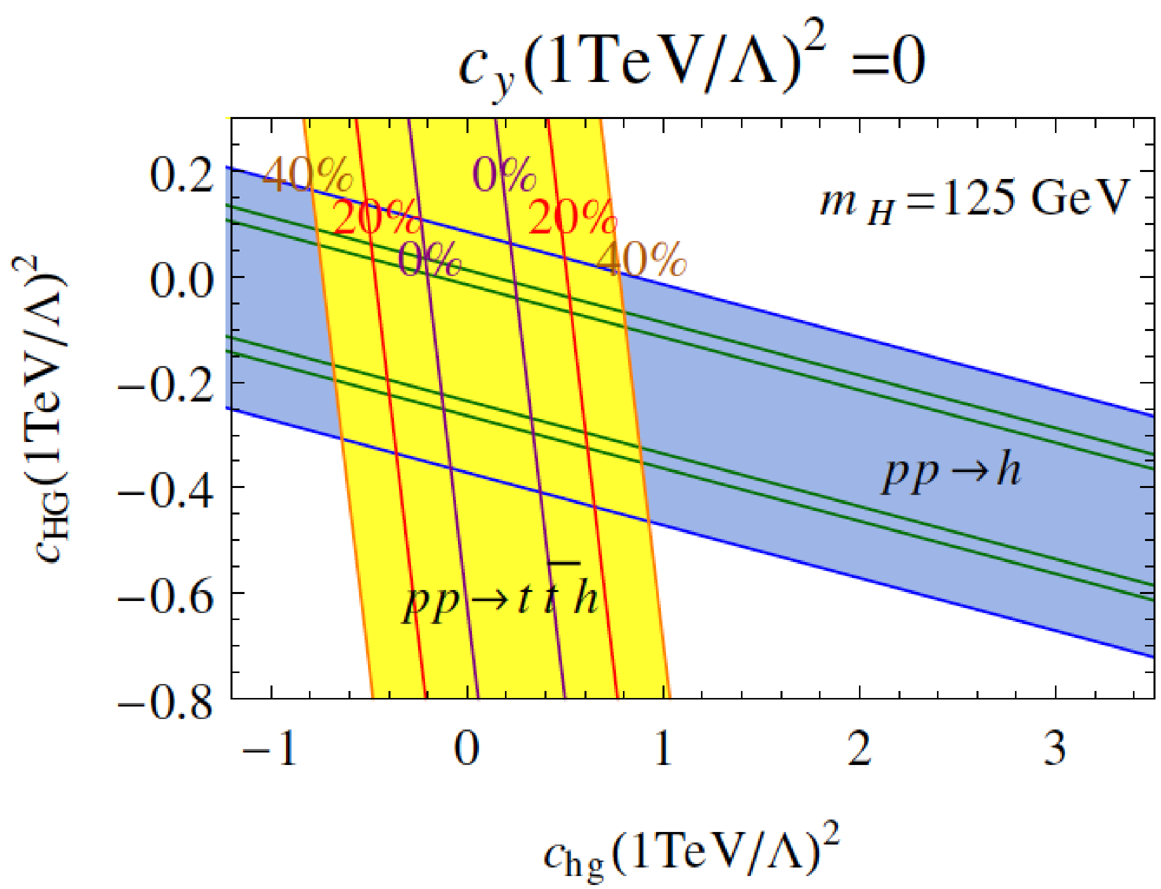
EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy a precision.

HIGGS PRODUCTION : TTH

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

[Degrande et al. 2012]





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

Analysis done at LO! NLO is now within reach

TOP-HIGGS INTERACTIONS

In principle a large number of operators are present. Yet very few operators of dim-6 enter in top and top-higgs physics:

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

CP-even

operator	process
$O_{\phi q}^{(3)} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$	top decay, single top
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I$ (with real coefficient)	top decay, single top
$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{q}\gamma^\mu \tau^I q)$	single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+ \phi) G_{\mu\nu}^A G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

CP-odd

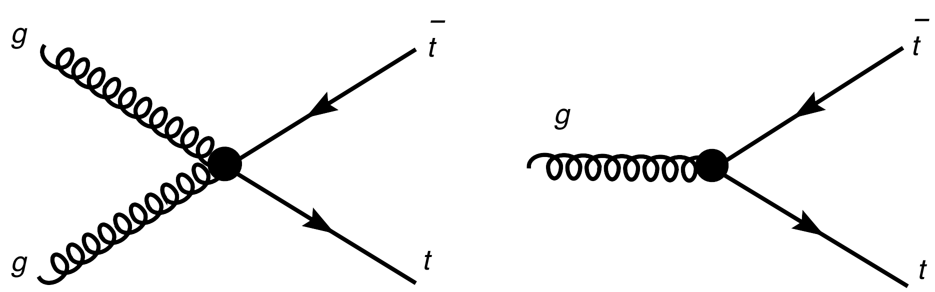
operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = f_{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+ \phi) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$gg \to t\bar{t}$

TOP-HIGGS INTERACTIONS: FIRST STEP

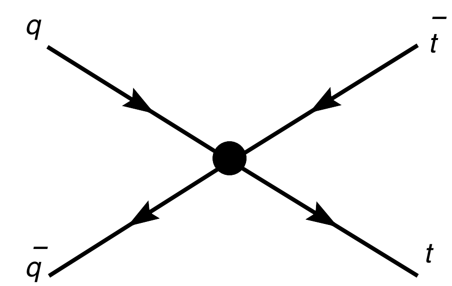
First constrain operators through top-anti-top production. There are only five operators entering:

$$\mathcal{L}_{t\bar{t}} = \mathcal{L}_{t\bar{t}}^{SM} + \frac{1}{\Lambda^2}\left[g_h \mathcal{O}_{hg} + c_R \mathcal{O}_{Rg} + a_R \mathcal{O}_{Ra}^{8} + (R \leftrightarrow L)\right]$$

and in case one is interested only in total rates (and spin independent / FB symmetries) only three parameters are left : gh , cV=cR+cL and aA = aR - aR

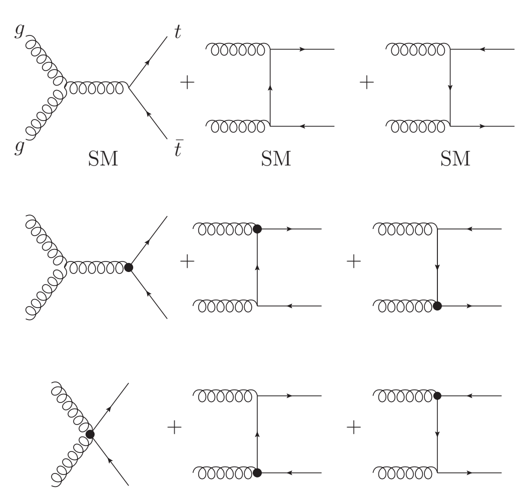


Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^{A}t\, G^{A}_{\mu\nu}$

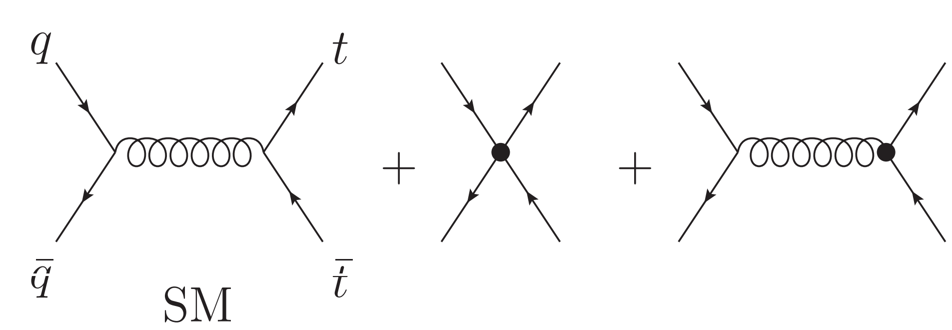


Four-fermion operators

gluon fusion
corrections from c_{hg} only



qq annihilation:
both c_{hg} and 4-fermion operators



TOP-HIGGS INTERACTIONS: FIRST STEP

Non-resonant top philic new physics can be probed using measurements in top pair production at hadron colliders

This model-independent analysis can be performed in terms of 8 operators.

Observables depend on different combinations of only 4 parameters:

$$\sigma(gg \to t\bar{t}), d\sigma(gg \to t\bar{t})/dt \quad \leftrightarrow \quad c_{hg}$$

$$\sigma(q\bar{q} \to t\bar{t}) \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$d\sigma(q\bar{q} \to t\bar{t})/dm_{tt} \quad \leftrightarrow \quad c_{hg}, c_{Vv}$$

$$A_{FB} \quad \leftrightarrow \quad c_{Aa}$$

$$\text{spin correlations} \quad \leftrightarrow \quad c_{hg}, c_{Vv}, c_{Av}$$

TOP-HIGGS COUPLINGS

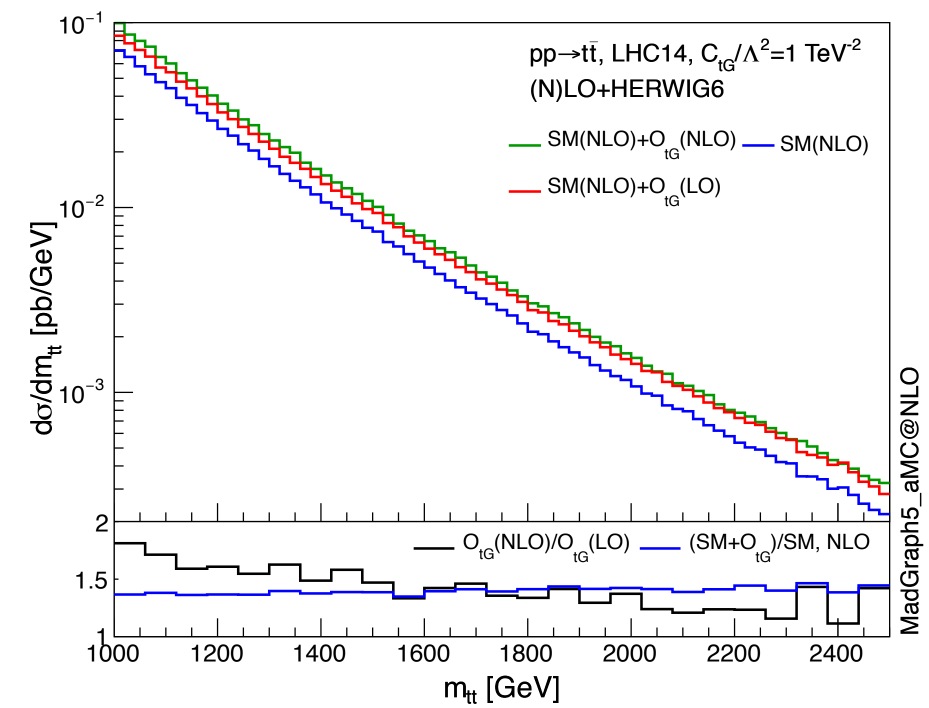
[Franzosi and Zhang, 2015]

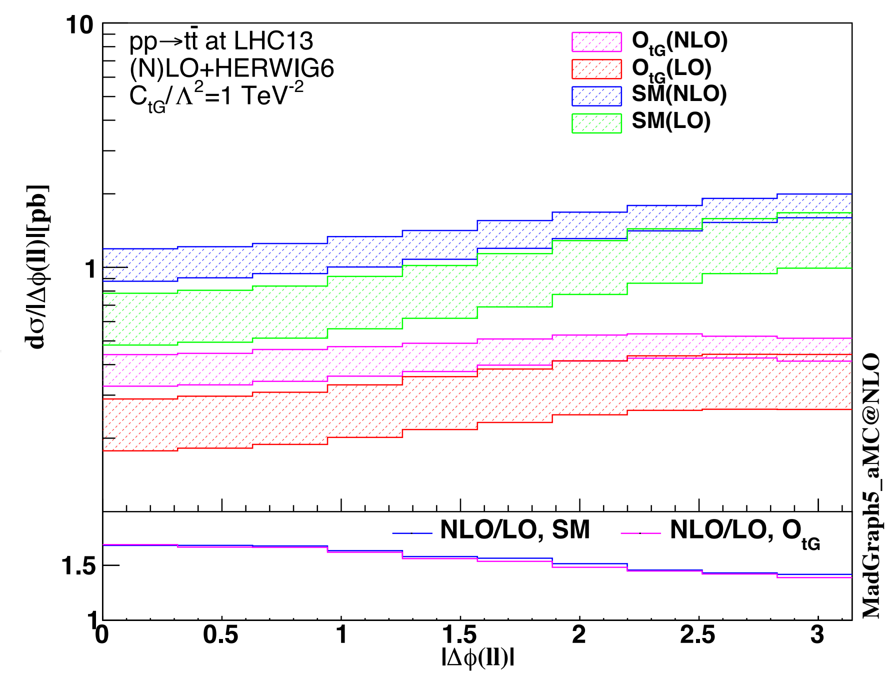
Recent analysis for the chromo-magnetic operator at NLO in QCD:

$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2$$

β_1	LO [pb TeV^2]	NLO [pb TeV^2]	K factor
Tevatron	$1.61^{+0.66}_{-0.43}$ $(+41\%)$ (-27%)	$1.810^{+0.073}_{-0.197}$ $(+4.05\%)$ (-10.88%)	1.12
LHC8	$50.7^{+17.3}_{-12.4}$ $(+34\%)$ (-25%)	$72.62^{+9.26}_{-10.53}$ $(+12.7\%)$ (-14.5%)	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ $(+29.7\%)$ (-22.4%)	$239.5^{+29.0}_{-31.8}$ $(+12.1\%)$ (-13.3%)	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ $(+29.0\%)$ (-22.0%)	$283.0^{+33.6}_{-36.9}$ $(+11.9\%)$ (-13.1%)	1.48

β_2	LO [pb TeV^4]	NLO [pb TeV^4]
Tevatron	0.156	0.158
LHC8	8.94	11.8
LHC13	30.0	43.2
LHC14	35.7	51.6





Limits on ctG from LHC8

	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

TOP-HIGGS COUPLINGS

[Rontsch and Shulze, 2014, 2015]

TTZ AND TTY

$$\mathcal{L}_{t\bar{t}Z} = \mathrm{i}e\bar{u}(p_t)\left[\gamma^\mu\left(C_{1,V}+\gamma_5 C_{1,A}\right)+\frac{\mathrm{i}\sigma_{\mu\nu}q_\nu}{M_Z}\left(C_{2,V}+\mathrm{i}\gamma_5 C_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\,A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d_V^\gamma + i d_A^\gamma\gamma_5\right)t\,A_\mu$$

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

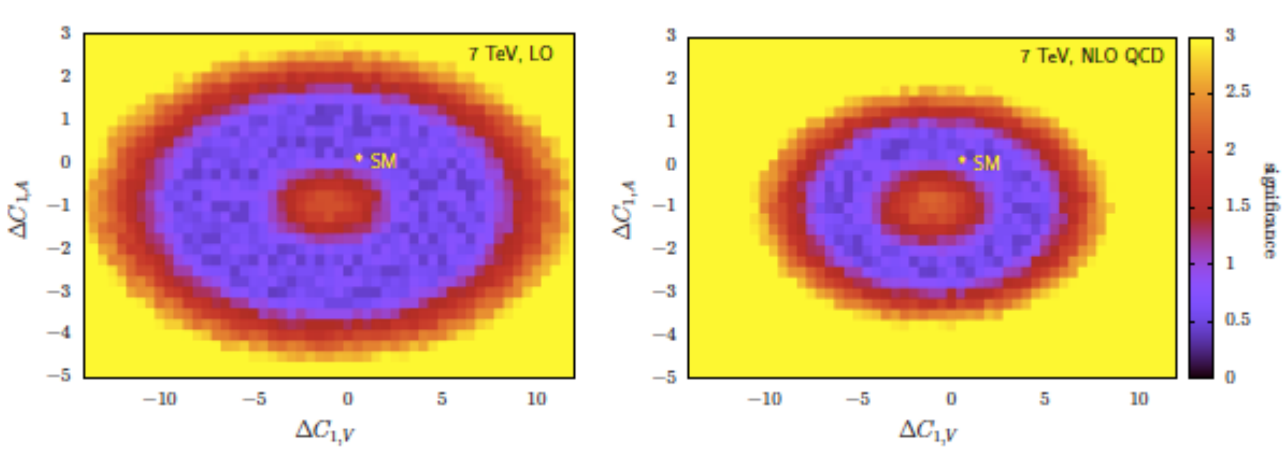
$$O_{\varphi Q}^{(1)} = i y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

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

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

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

- Top couplings not constrained by LEPI Z decays.
- The photon dipole coefficients depend on OtW and tB
- Photon and Z are related above the EWSB.
- Photon couplings enter in the off-shell tt$\ell\ell$



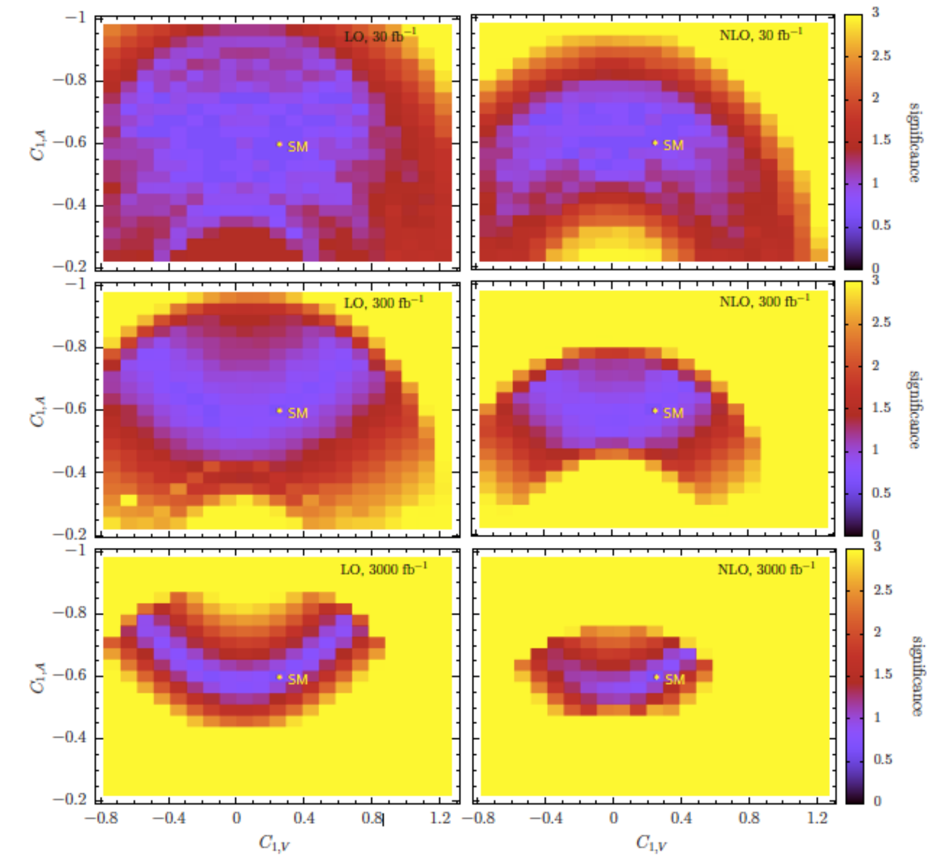
- Constraints from the 7 TeV Run

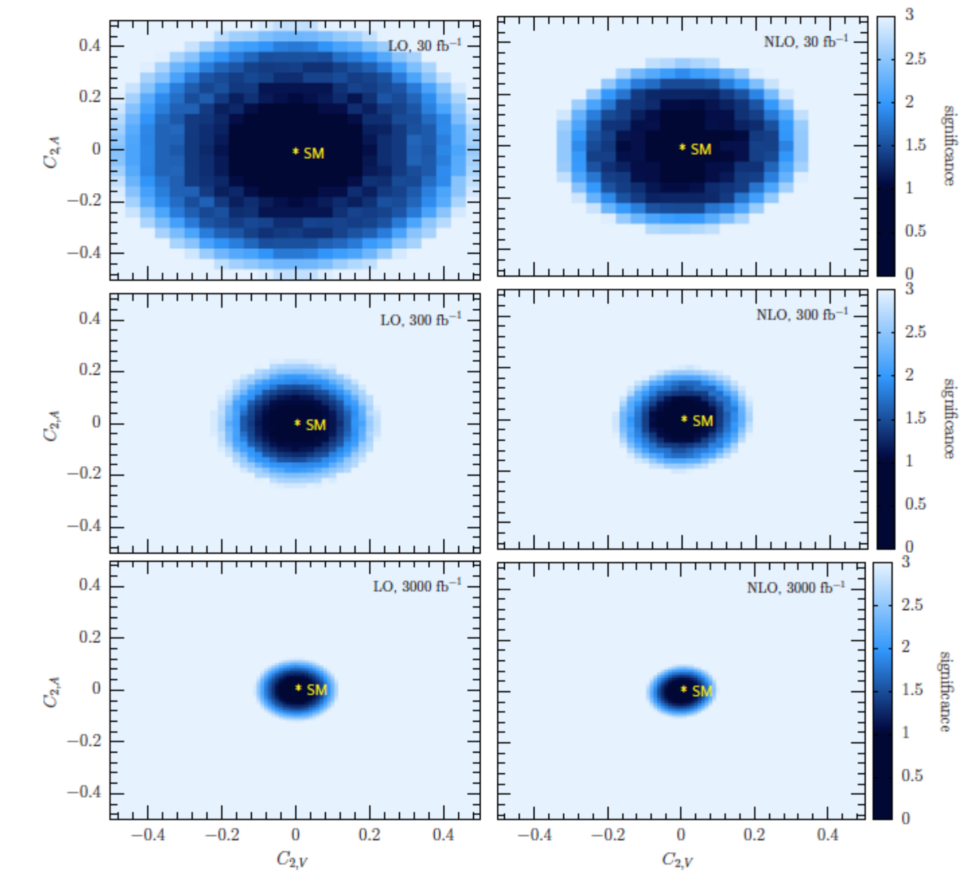
$$-8 \lesssim \Delta C_{1,\mathrm{V}} \lesssim 7 \text{ and } -3 \lesssim \Delta C_{1,\mathrm{A}} \lesssim 1$$

TOP-HIGGS COUPLINGS

TTZ AND TTY

[Rontsch and Shulze, 2014, 2015]





However more work needed:

- In essence still an anomalous coupling approach.
- Global analysis considering ttZ and ttϒ needed.
- Constrains from LEP EW observables [Mebane et al, 2013]
- Also the chromomagnetic operator contributes to ttZ and ttϒ.
- Four-fermion operators enter in the off-shell $tt\ell\ell$

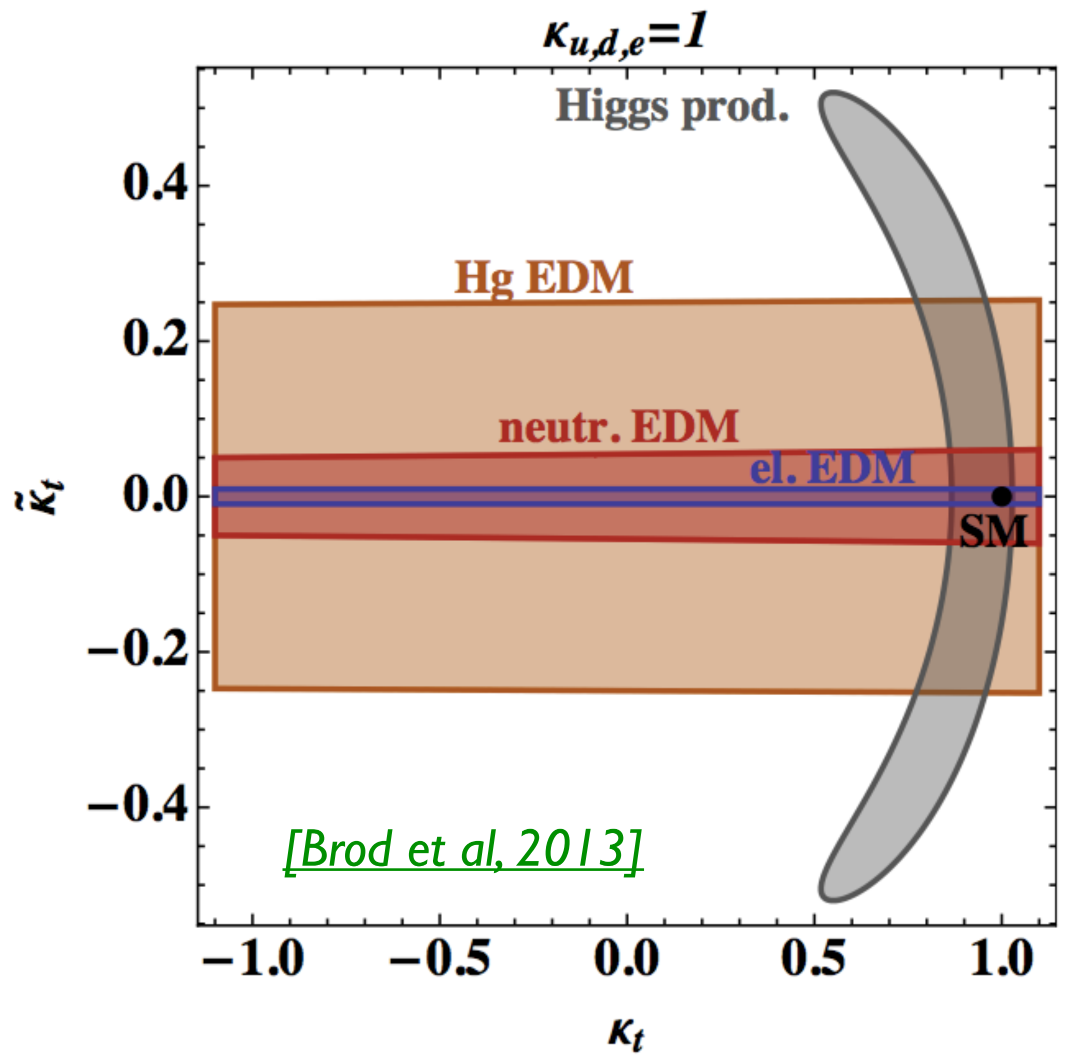
TOP-HIGGS COUPLINGS : CPV

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

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

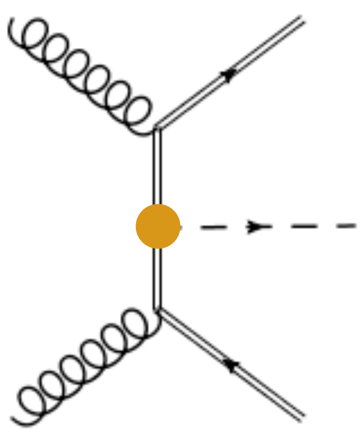
- SM couplings for the light fermions.
- no other states present in the spectrum



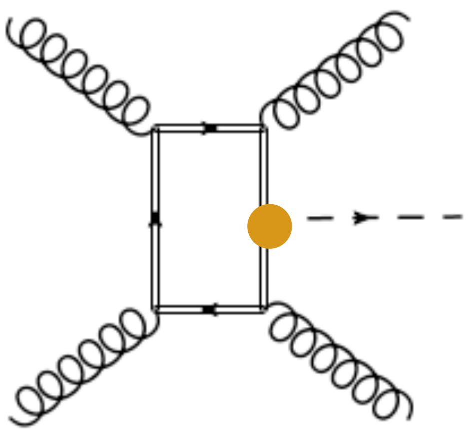
TOP-HIGGS COUPLINGS : CPV

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

There are ways of directly accessing presence of CP-mixing in top-Higgs interactions at the LHC:



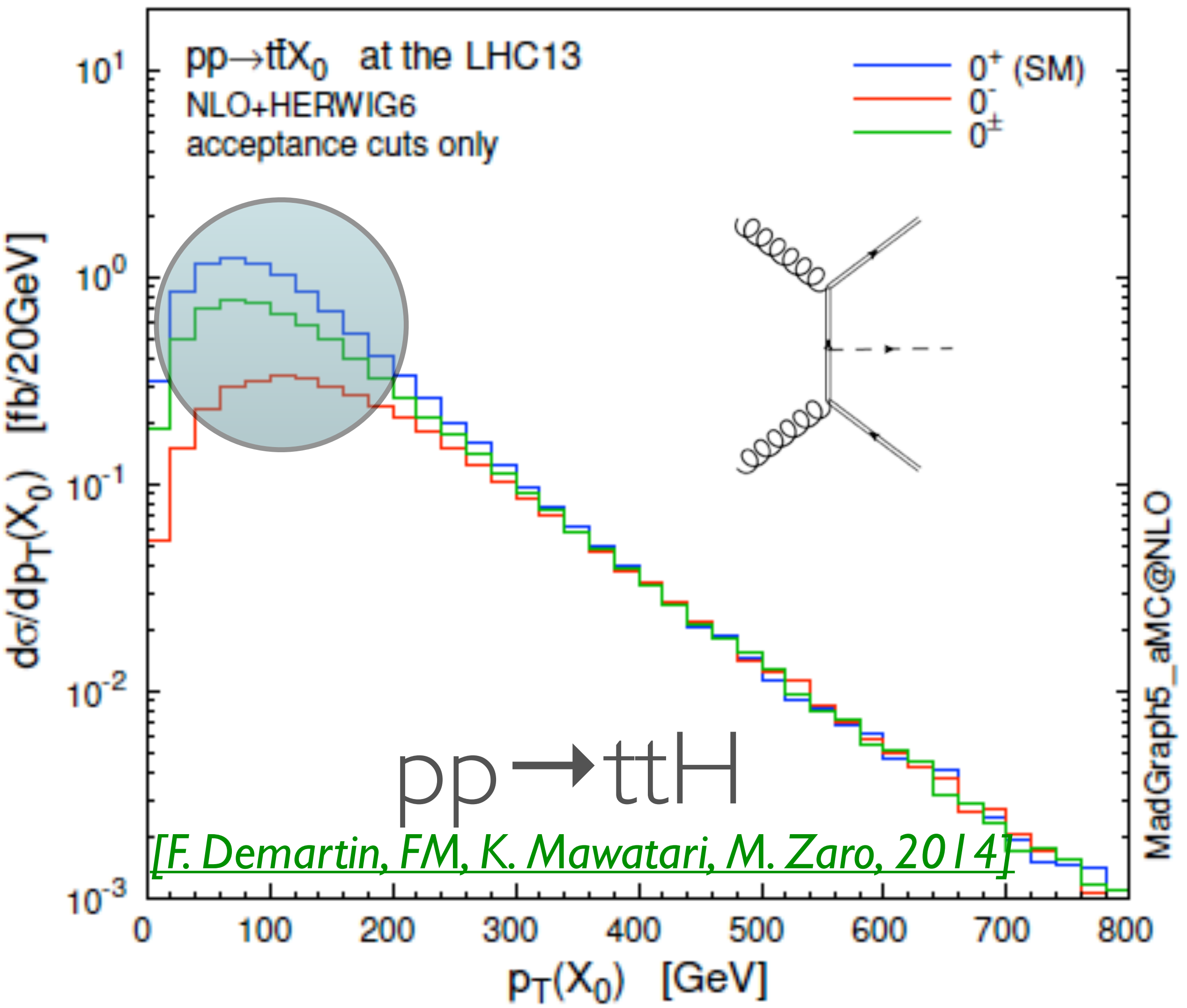
pp→ttH



pp→Hjj

TOP-HIGGS COUPLINGS : CPV

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



[F. Demartin, FM, K. Mawatari, M. Zaro, 2014]

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?

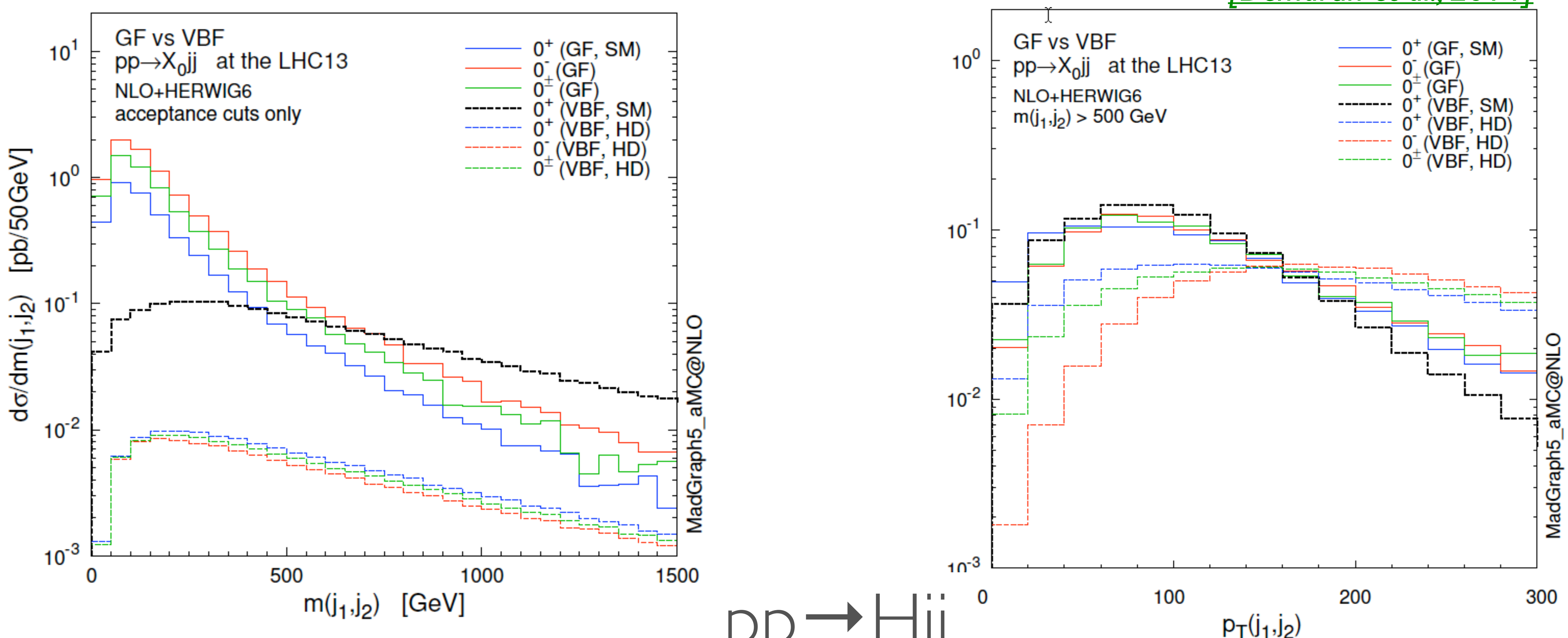
Angular variables between the daughters of the top are sensitive to the CP-mixing.

TOP-HIGGS COUPLINGS : CPV

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

TOP-HIGGS COUPLINGS : CPV

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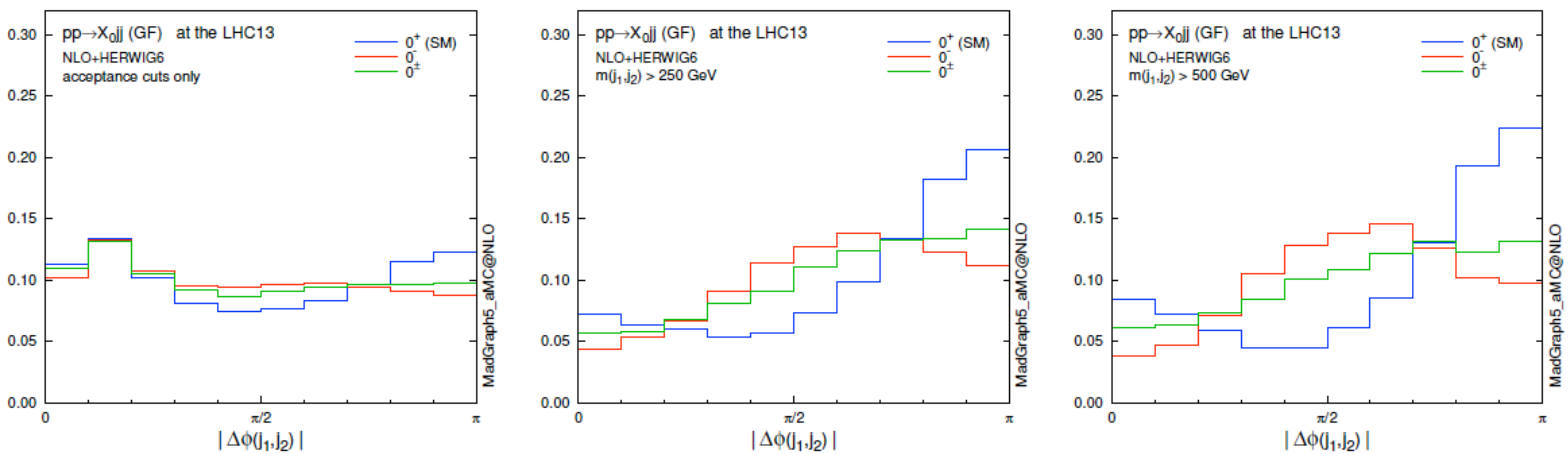
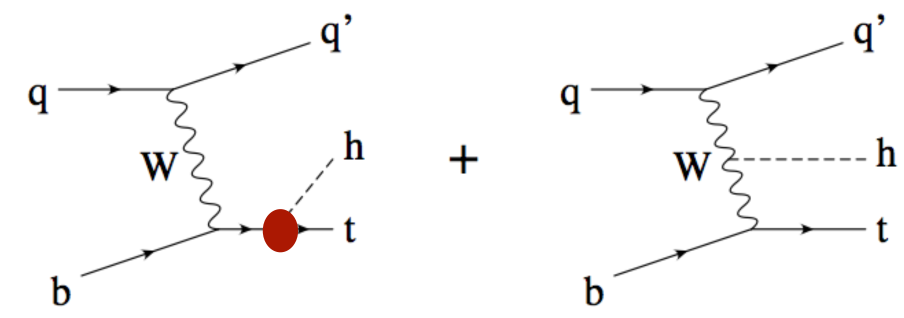
pp→Hjj

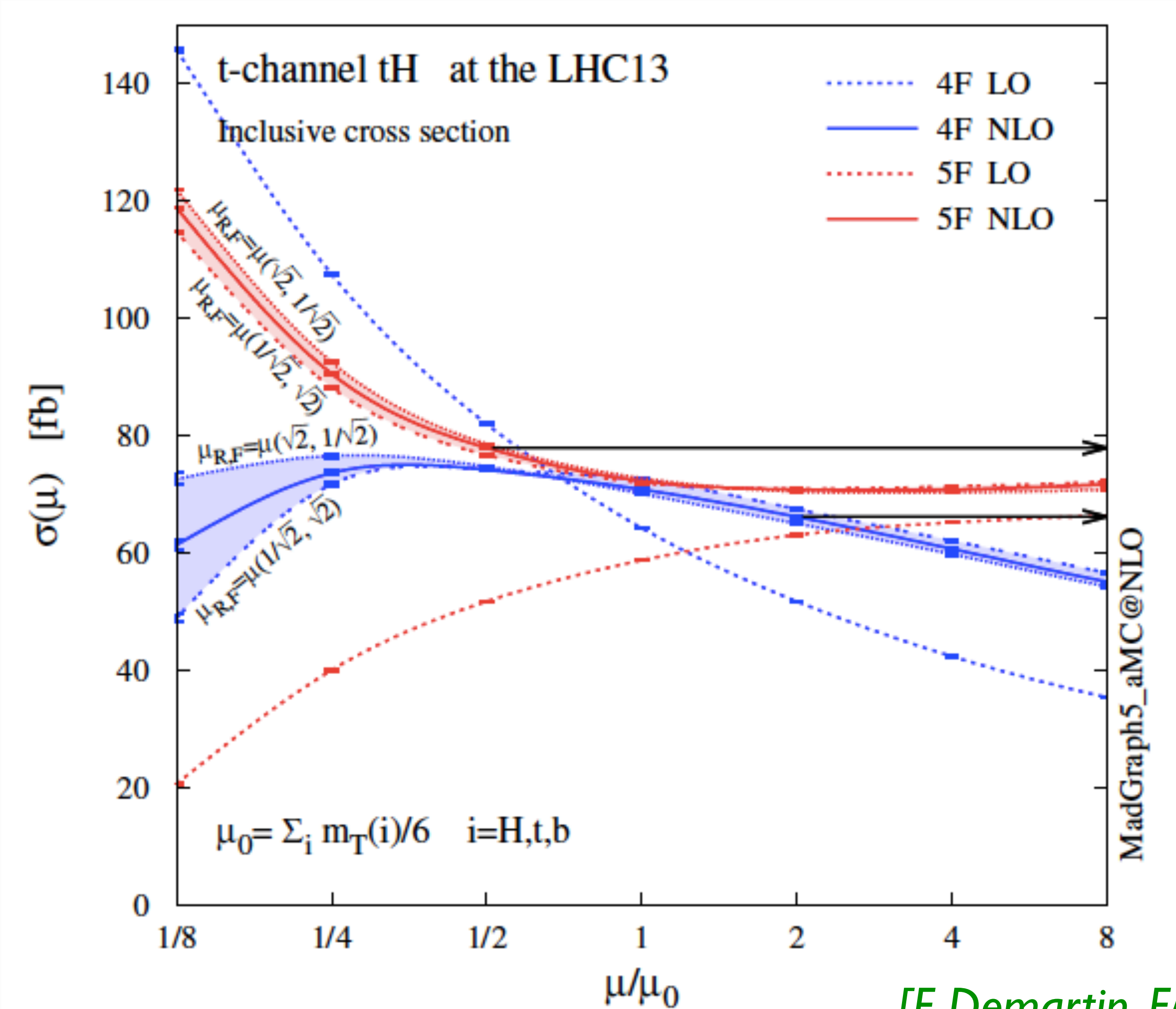


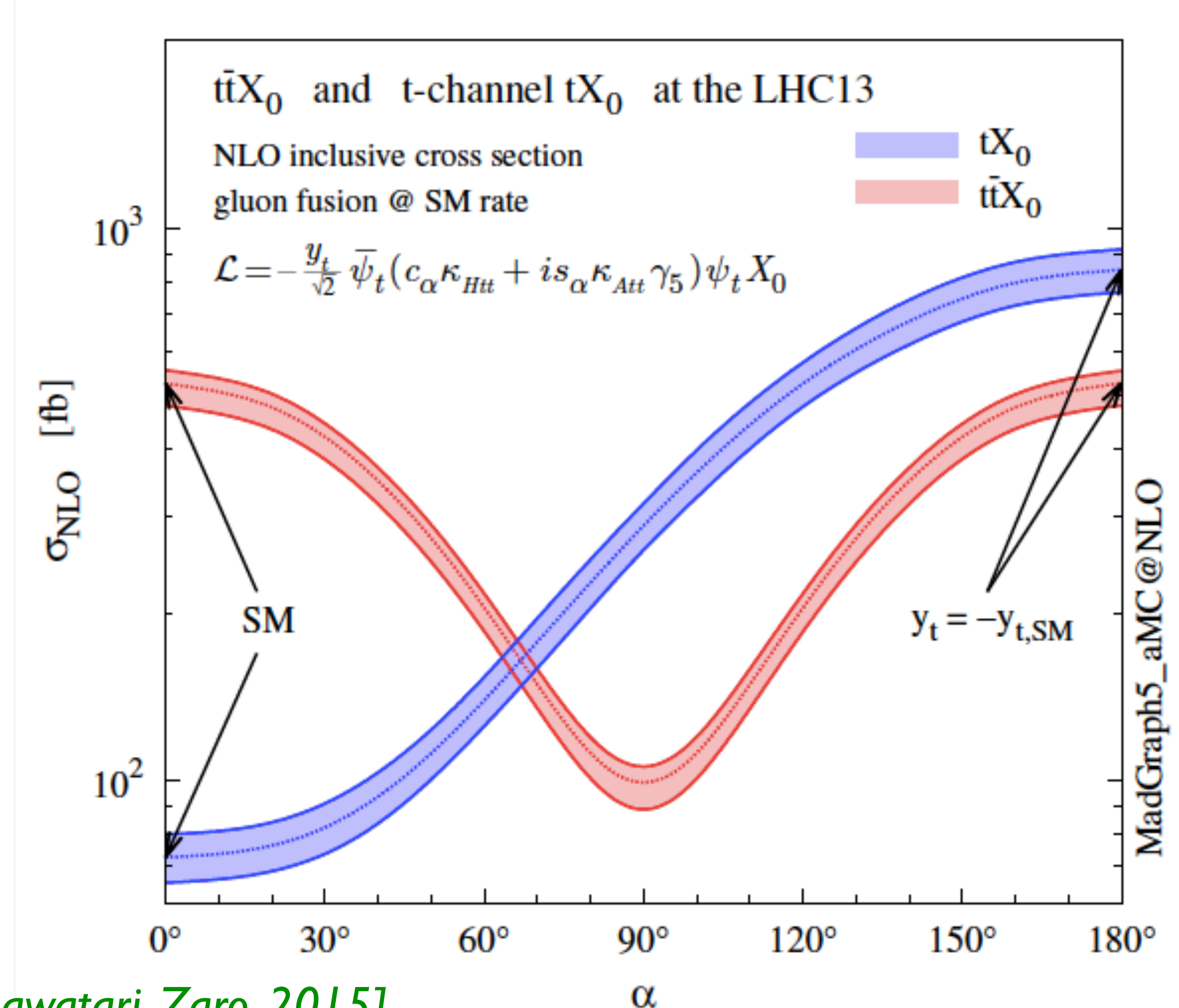
Delta(phi) among the jets is a sensitive variable as mjj increases.

TOP-HIGGS COUPLINGS : CPV

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.





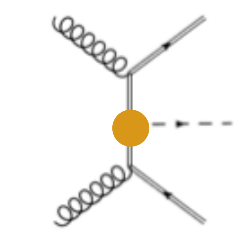


[F. Demartin, FM, K. Mawatari, Zaro, 2015]

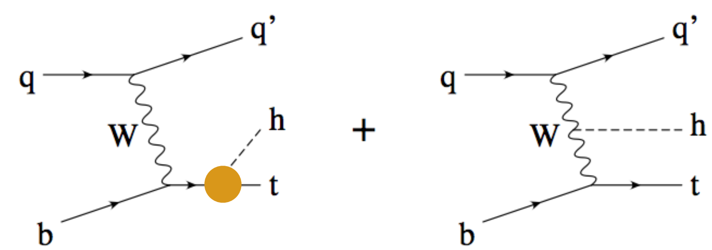
TOP-HIGGS COUPLINGS : CPV

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:

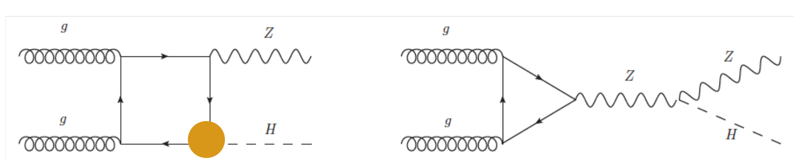
- PP → TTH



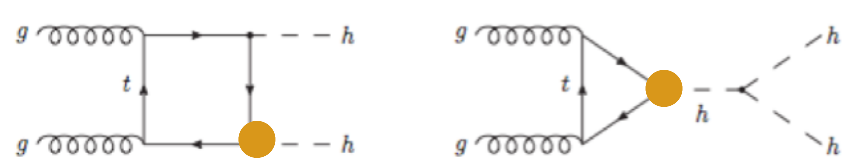
- PP → THJ



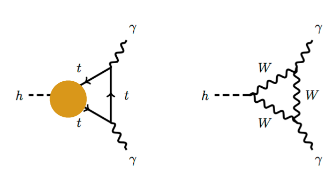
- GG → ZH

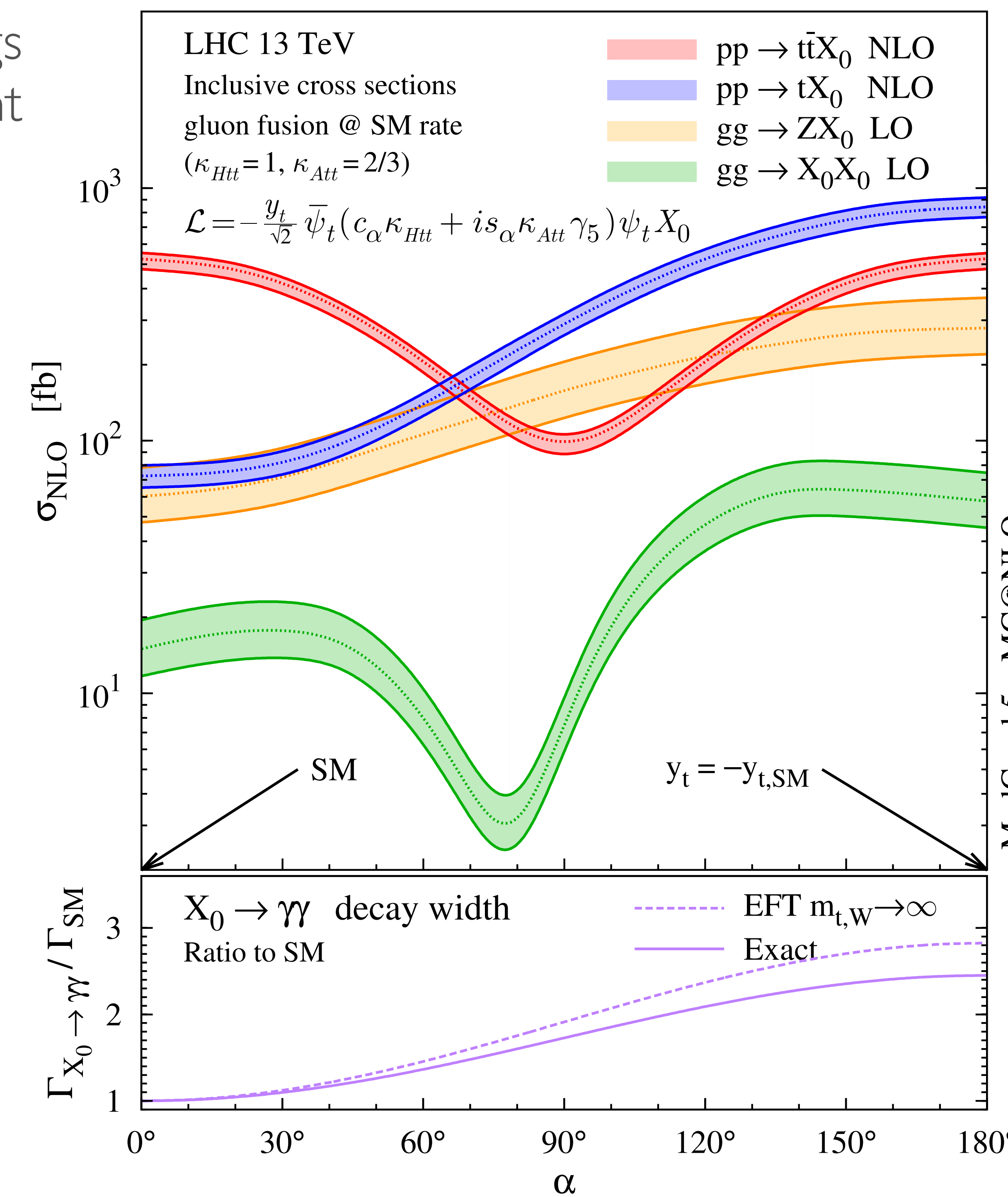


- GG → HH



- H → YY

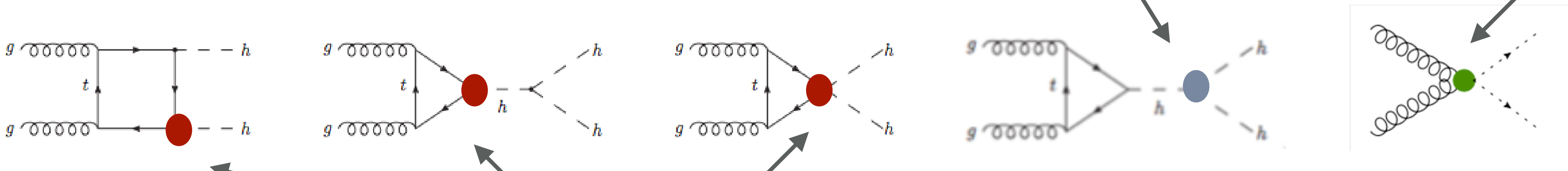




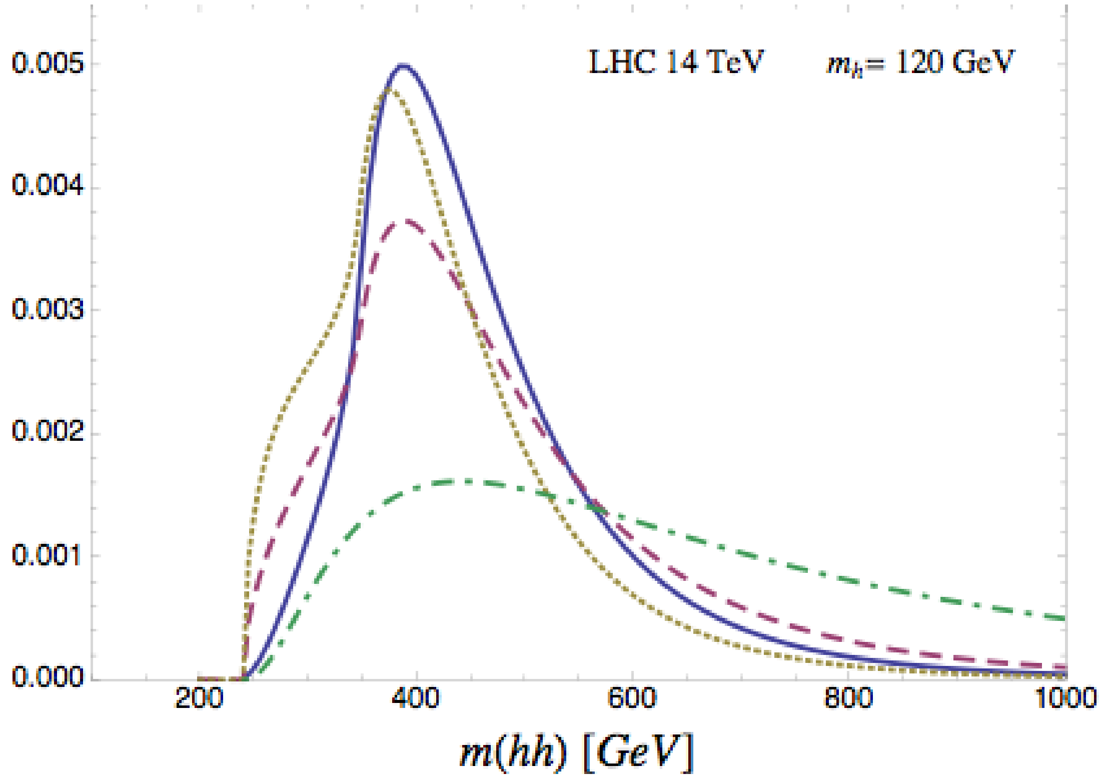
HIGGS PRODUCTION : HH

$$pp \to hh$$

$$\mathcal{O}_6 = (H^\dagger H)^3 \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



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



[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.

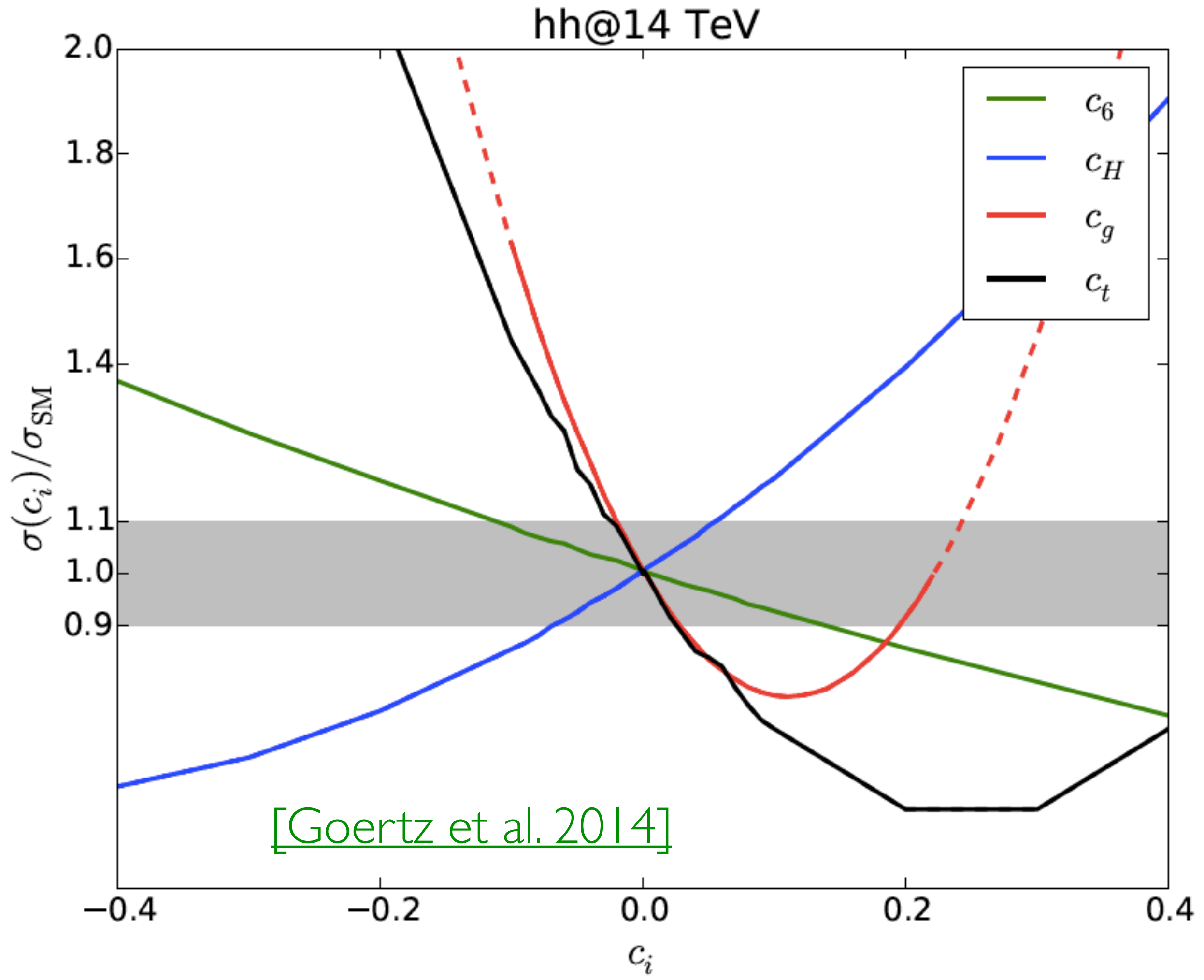
Only a global approach will allow to accurately measure the HHH coupling from HH.

HIGGS PRODUCTION : HH

$$pp \to hh$$

An analysis in the EFT can be performed showing how sensitive to each operator HH is.

Sensitivity at LHC13 is to low and this will need a lot of luminosity…



$$\left.\frac{\mathrm{d}\hat{\sigma}(gg \to hh)}{\mathrm{d}\hat{t}}\right|_{\rm EFT} = \frac{G_F^2 \alpha_s^2}{256(2\pi)^3}\Big\{\Big|C_\triangle F_\triangle(1-2c_H+c_t+c_6)+3F_\triangle(3c_t-c_H)+2c_g C_\triangle + C_\Box F_\Box(1-c_H+2c_t)+2c_g C_\Box\Big|^2+\Big|C_\Box G_\Box\Big|^2\Big\},$$

THE ROAD AHEAD

- The interpretation of most of the SM/Higgs/top measurements analyses can be recast in terms of an EFT. Yet the **IMPLEMENTATION OF A GLOBAL APPROACH/FRAMEWORK IS NEEDED**.
- (Dedicated) differential measurements will also provide necessary information.
- The precision of the theoretical predictions for the dim=4 SM will keep to be improved, by including NNLO in QCD and NLO in EW corrections in a fully exclusive way. Predictions for **EFT AT NLO (IN QCD AND EW)** have started to become **AVAILABLE.**
- Considerable work still to be done and constraining strategies need to be fully worked out/optimised.

NEW JOINT TH/EXP EFFORT!

CONCLUSIONS

- The discovery of a scalar boson has opened a new realm of possibilities for searching new physics and in particular in connection with the Higgs and the top quark
- The most beaten path for searching new physics at the LHC involve top-down (or simplified models) approach to detecting new resonances.
- A complementary and far reaching approach is that of searching for new interactions employing an EFT framework.
- The SM@dimX is a consistent, systematically improvable QFT.
- Precision SM@dim6 measurements, in particular for top quark and the Higgs, can extend the reach of new physics searches at the LHC.

GLOBAL FITS

[Ellis, Sanz, You 1410.7703]

Operator	Coefficient	LEP Constraints Individual	LEP Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W + c_B)$	$(-0.00055, 0.0005)$	$(-0.0033, 0.0018)$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\frac{v^2}{\Lambda^2}c_T$	$(0, 0.001)$	$(-0.0043, 0.0033)$
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$	$\frac{v^2}{\Lambda^2}c_{LL}^{(3)l}$	$(0, 0.001)$	$(-0.0013, 0.00075)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	$\frac{v^2}{\Lambda^2}c_R^e$	$(-0.0015, 0.0005)$	$(-0.0018, 0.00025)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\frac{v^2}{\Lambda^2}c_R^u$	$(-0.0035, 0.005)$	$(-0.011, 0.011)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\frac{v^2}{\Lambda^2}c_R^d$	$(-0.0075, 0.0035)$	$(-0.042, 0.0044)$
$\mathcal{O}_L^{(3)q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^{(3)q}$	$(-0.0005, 0.001)$	$(-0.0044, 0.0044)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$	$\frac{v^2}{\Lambda^2}c_L^q$	$(-0.0015, 0.003)$	$(-0.0019, 0.0069)$

Table 1: *List of operators and coefficients in our basis entering in EWPTs at LEP, together with 95% CL bounds when individual coefficients are switched on one at a time, and marginalized in a simultaneous fit. For the first four coefficients we report the constraints from the leptonic observables, while the remaining coefficients also include the*

GLOBAL FITS

[Ellis, Sanz, You 1410.7703]

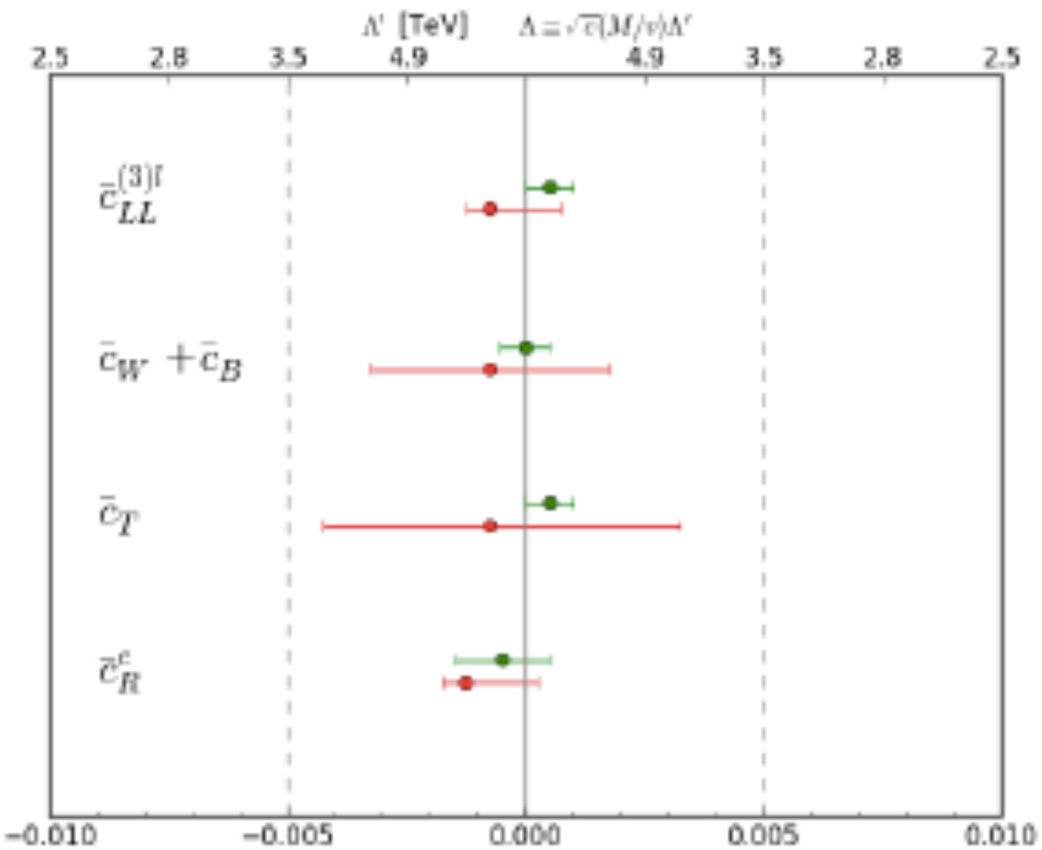


Figure 2: *The 95% CL ranges found in analyses of the leptonic observables (left panel) and including also the hadronic observables (right panel). In each case, the upper (green) bars denote single-coefficient fits, and the lower (red) bars denote multi-coefficient fits. The upper-axis should be read* $\times \frac{m_W}{v} \sim 1/3$ *for* $\bar{c}_W + \bar{c}_B$.

GLOBAL FITS

[Ellis, Sanz, You 1410.7703]

Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$	$\frac{m_W^2}{\Lambda^2} c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2 \|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_g$	$(0, 3.0) \times 10^{-5}$	$(-3.2, 1.1) \times 10^{-4}$
$\mathcal{O}_\gamma = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_\gamma$	$(-4.0, 2.3) \times 10^{-4}$	$(-11, 2.2) \times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \|H\|^2)^2$	$\frac{v^2}{\Lambda^2} c_H$	$(-,-)$	$(-,-)$
$\mathcal{O}_f = y_f \|H\|^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2} c_f$	$(-,-)$	$(-,-)$

Table 2: *List of operators in our basis entering in LHC Higgs (including D0 associated production) and TGC physics, together with 95% CL bounds when individual coefficients are switched on one at a time, and marginalized in a simultaneous fit.*

GLOBAL FITS

[Ellis, Sanz, You 1410.7703]

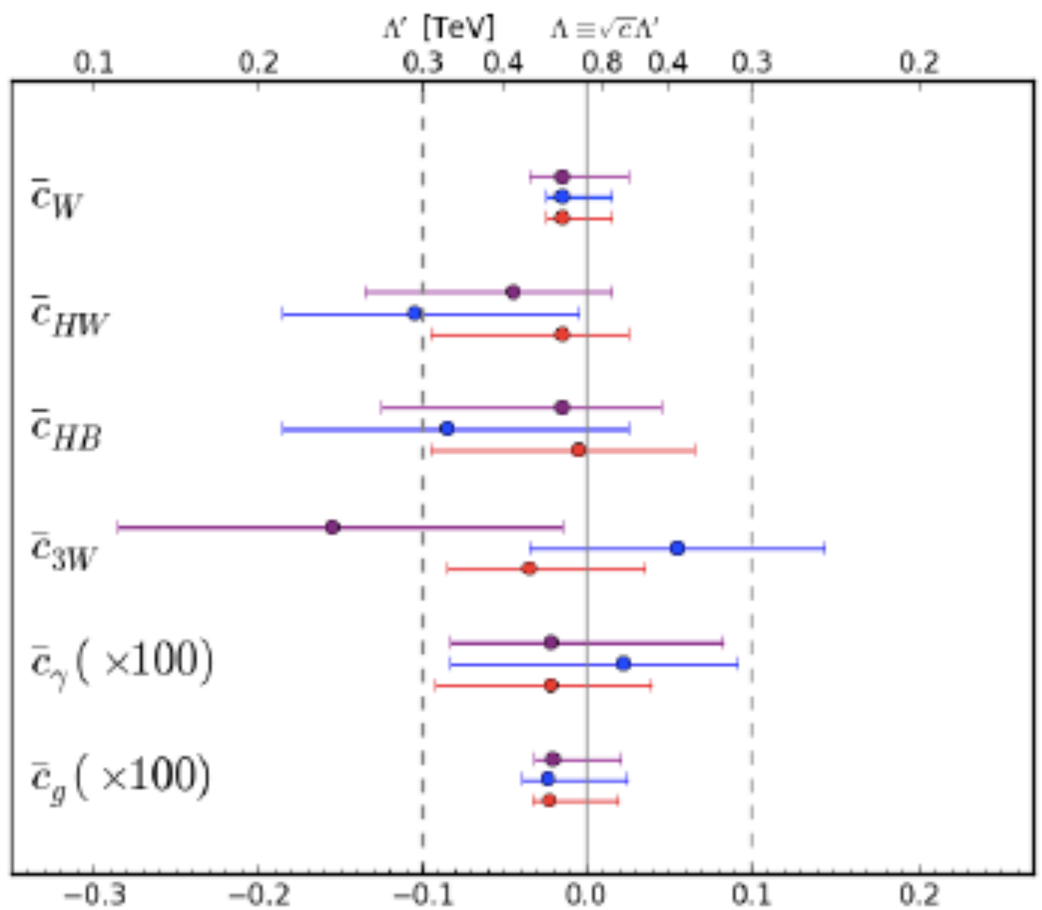


Figure 6: *The marginalised 95% CL ranges for the dimension-6 operator coefficients obtained by combining the LHC signal-strength data with the ATLAS 8-TeV TGC data (purple bars), the CMS 7- and 8-TeV TGC measurements (blue bars), and their combination (red bars). Note that $\bar{c}_{\gamma,g}$ are shown ×100, so for these coefficients the upper axis should therefore be read ×10.*

GLOBAL FITS

[Ellis, Sanz, You 1410.7703]

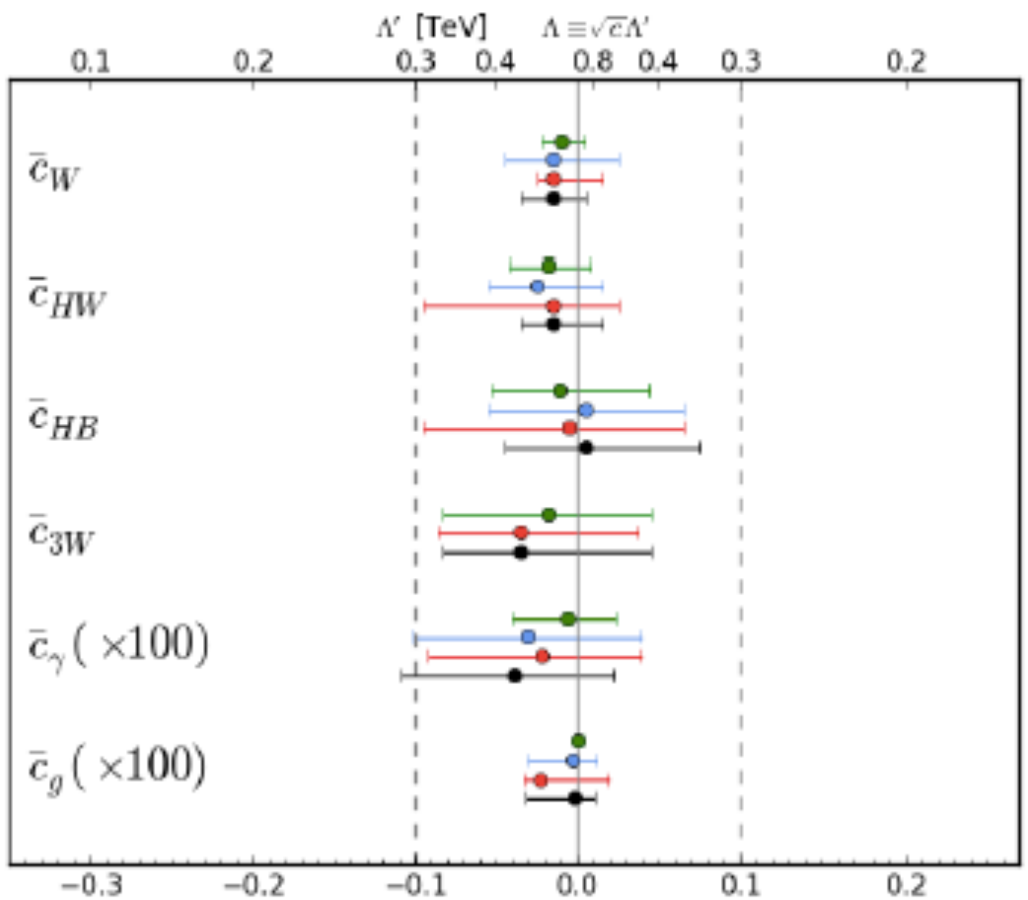


Figure 8: *The 95% CL constraints obtained for single-coefficient fits (green bars), and the marginalised 95% ranges for the LHC signal-strength data combined with the kinematic distributions for associated $H + V$ production measured by ATLAS and D0 (blue bars), combined with the LHC TGC data (red lines), and the global combination with both the associated production and TGC data (black bars). Note that $\bar{c}_{\gamma,g}$ are shown $\times 100$, so for these coefficients the upper axis should therefore be read $\times 10$.*