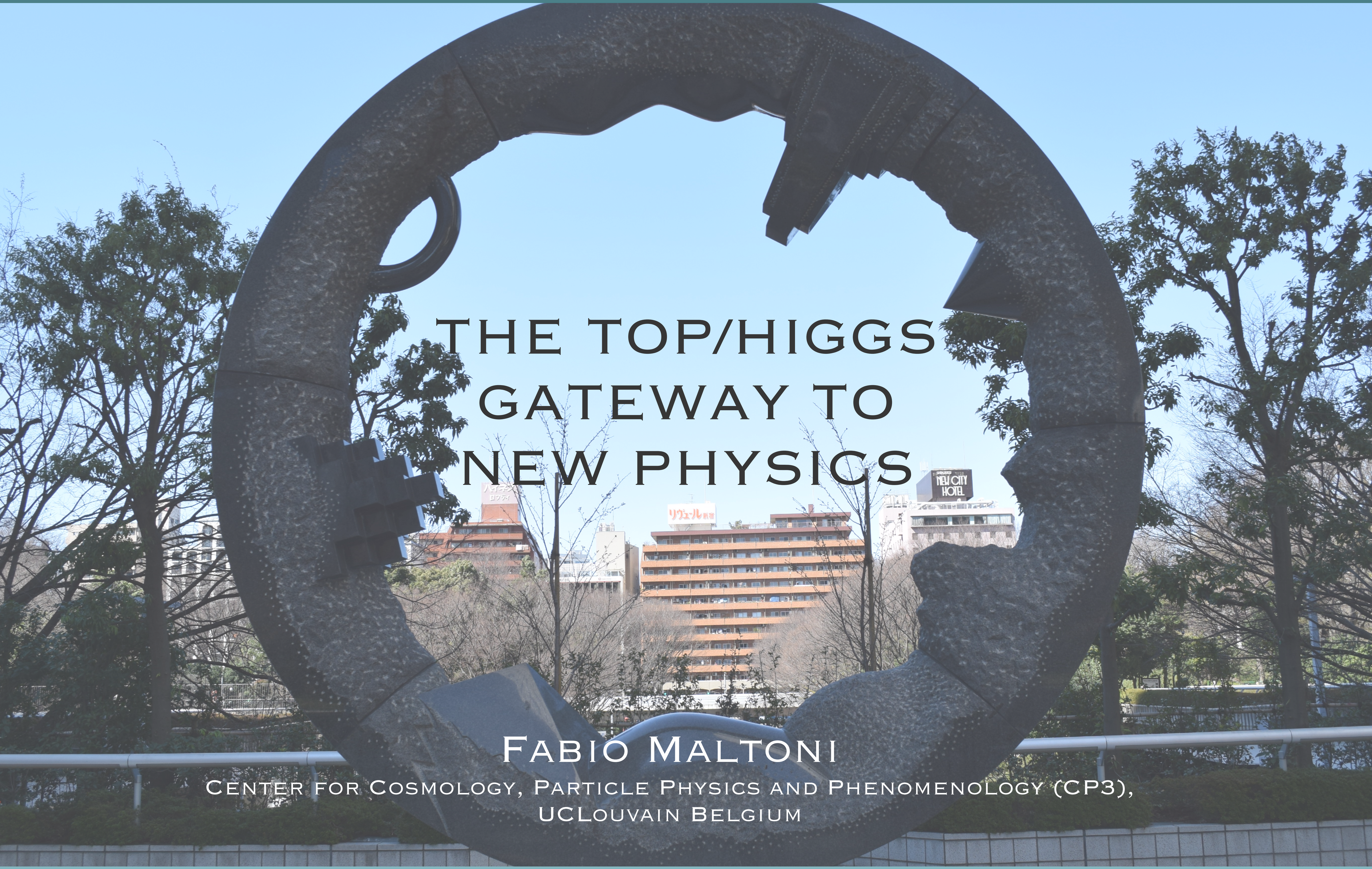

THE TOP/HIGGS GATEWAY TO NEW PHYSICS

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Post LHC8, ante 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.

What (if any) is the best strategy?

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vis-à-vis the Higgs, the top is a special quark
(or equivalently it is the only normal one)

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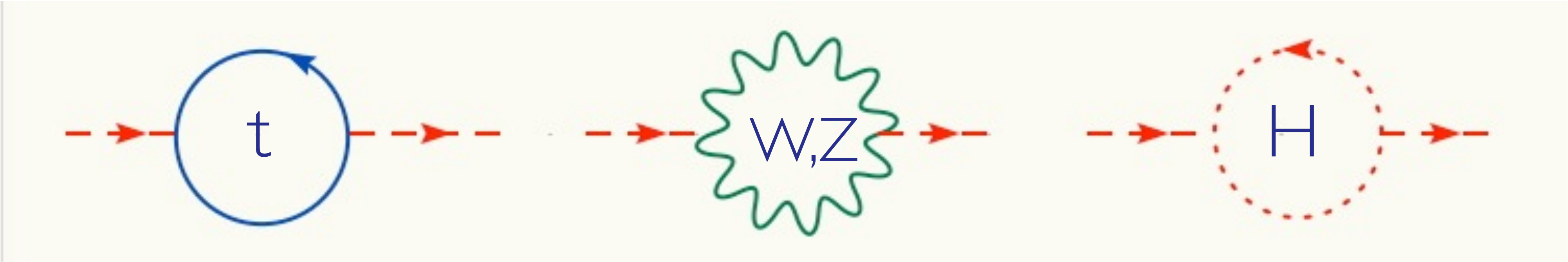
Statement #4

Fine tuning

Fine tuning

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



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

Putting numbers, one gets:

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

Fine tuning

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:

$\Lambda_t < 3\,\mathrm{TeV} \Rightarrow$ new top/Higgs related physics must be "light"

WHAT (IF ANY) IS THE BEST STRATEGY?

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:
  - **exploration:** bound Higgs couplings
  - **precision phase I (dawn):**
    look for deviations wrt dim=4 SM (rescaling factors)
  - **precision phase II (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.

THE EFT APPROACH

THE MATTER CONTENT OF SM HAS BEEN EXPERIMENTALLY VERIFIED AND EVIDENCE FOR LIGHT STATES IS NOT PRESENT.

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 A SIMPLE AND POWERFUL WAY IN TERMS OF ONE STATEMENT:

"BSM GOAL" OF THE SM LHC PROGRAMME:

DETERMINATION OF THE COUPLINGS OF THE SM $\mathcal{L}$ UP TO DIM=6

THE EFT APPROACH : DIM=6 SM LAGRANGIAN

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
[illegible]	[illegible]	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_{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_{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

- Very powerful approach.
- Note, however, that it only makes sense if a **global constraining strategy** is used to extract information from the data:
  - assume all couplings might not be zero at the EW scale.
  - Identify the operators entering each observable.
  - find enough observables (cross sections, BR's, distributions,...) to constrain all operators.
  - solve the (linear) system.
  - Need for predictions at least NLO in QCD.

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
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$ (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
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$ (with real coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_G = f_{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$gg \to t\bar{t}$
$O_{\phi G} = \frac{1}{2}(\phi^+\phi)G^A_{\mu\nu}G^{A\mu\nu}$	$gg \to t\bar{t}$
7 four-quark operators	$q\bar{q} \to t\bar{t}$

CP-odd

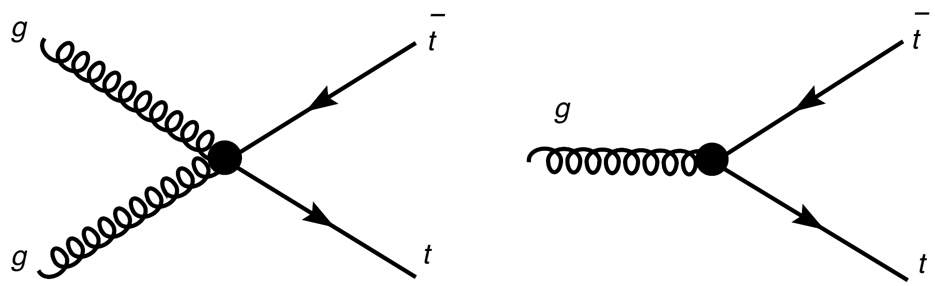
operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = f_{ABC}\tilde{G}^{A\nu}_\mu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

TOP-HIGGS INTERACTIONS: FIRST STEP

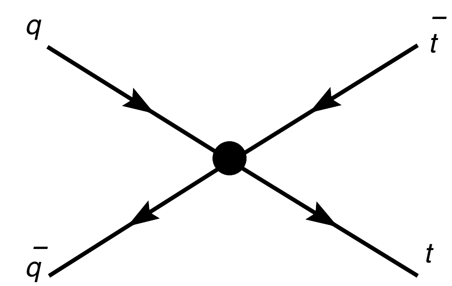
First constrain operators through top-anti-top production. There are only five operators entering:

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

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

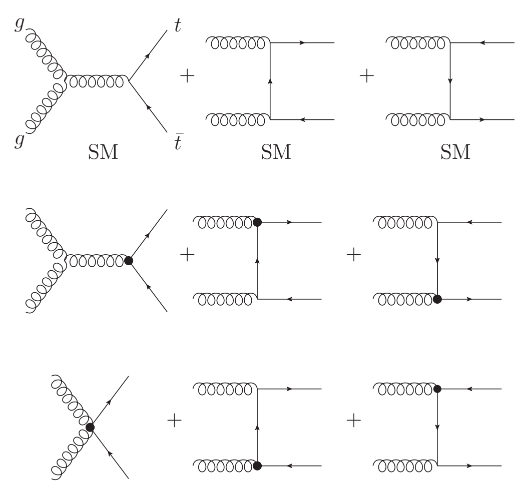


Chromomagnetic operator $\mathcal{O}_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^A t\, G^A_{\mu\nu}$

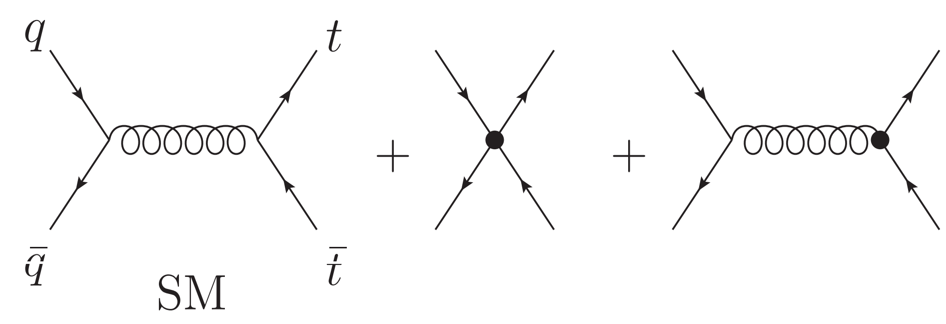


Four-fermion operators

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 INTERACTIONS

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

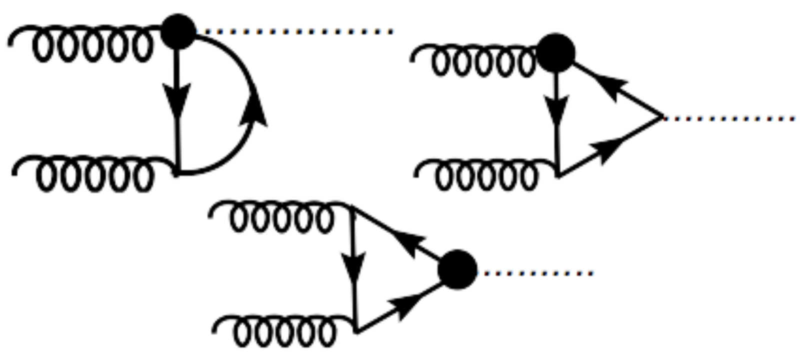
$$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R$$ YUKAWA OPERATOR

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



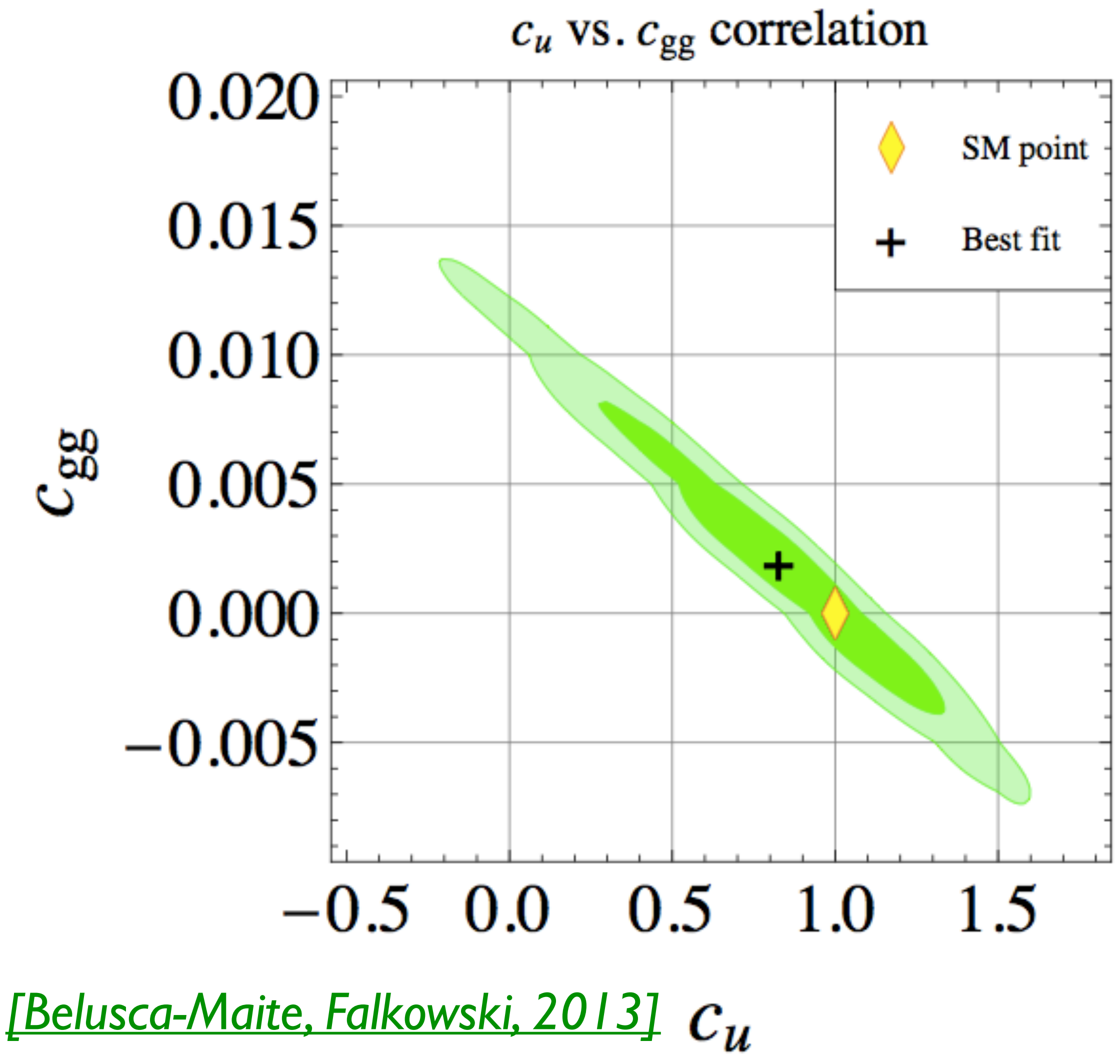
A meaningful analysis can only be made by considering them all!

TOP-HIGGS INTERACTIONS: CONSTRAINTS

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

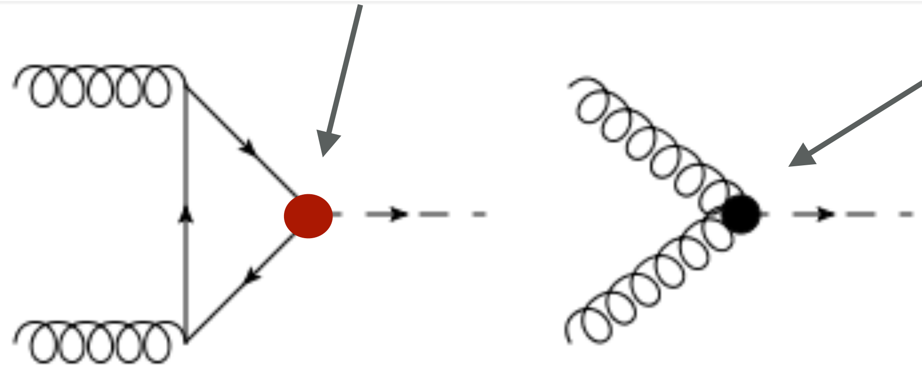
$$c_V = 1.04 \pm 0.03, \quad c_t = 1.1^{+0.9}_{-3.0} \quad c_b = 1.06^{+0.30}_{-0.23}, \quad c_\tau = 1.04 \pm 0.22$$

$$c_{gg} = -0.002 \pm 0.036, \quad c_{\gamma\gamma} = 0.0011^{+0.0019}_{-0.0028}, \quad c_{Z\gamma} = 0.000^{+0.019}_{-0.035}\,.$$



[Belusca-Maite, Falkowski, 2013]

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



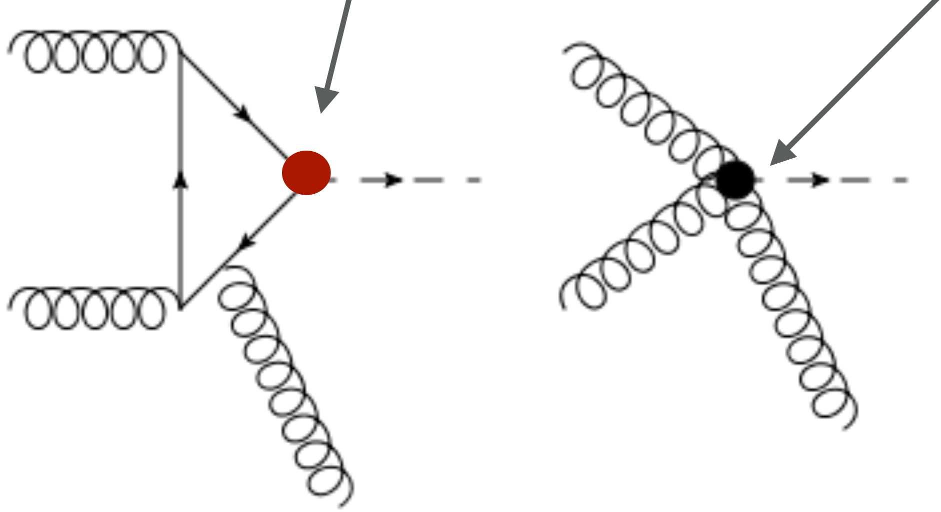
The loop could still be dominated by NP.

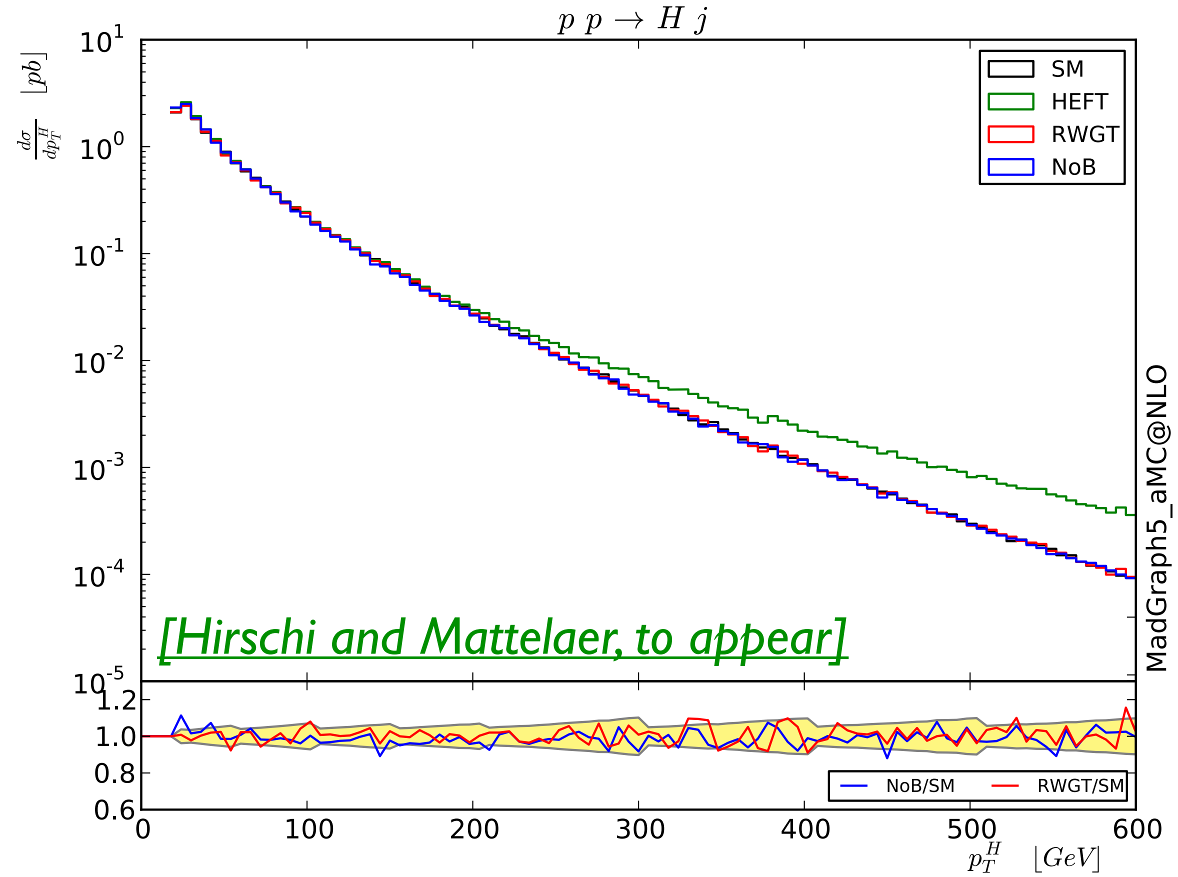
TOP-HIGGS INTERACTIONS: HIGH-PT

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]

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

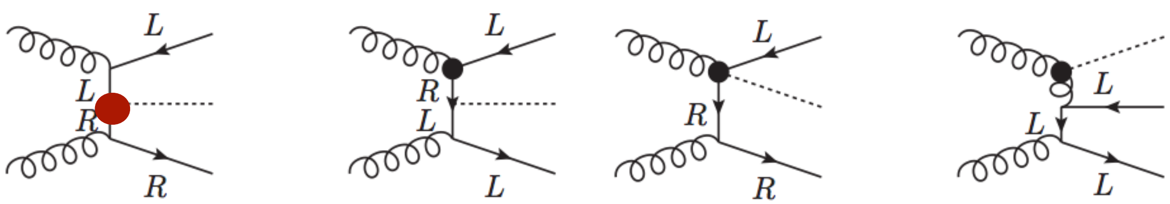


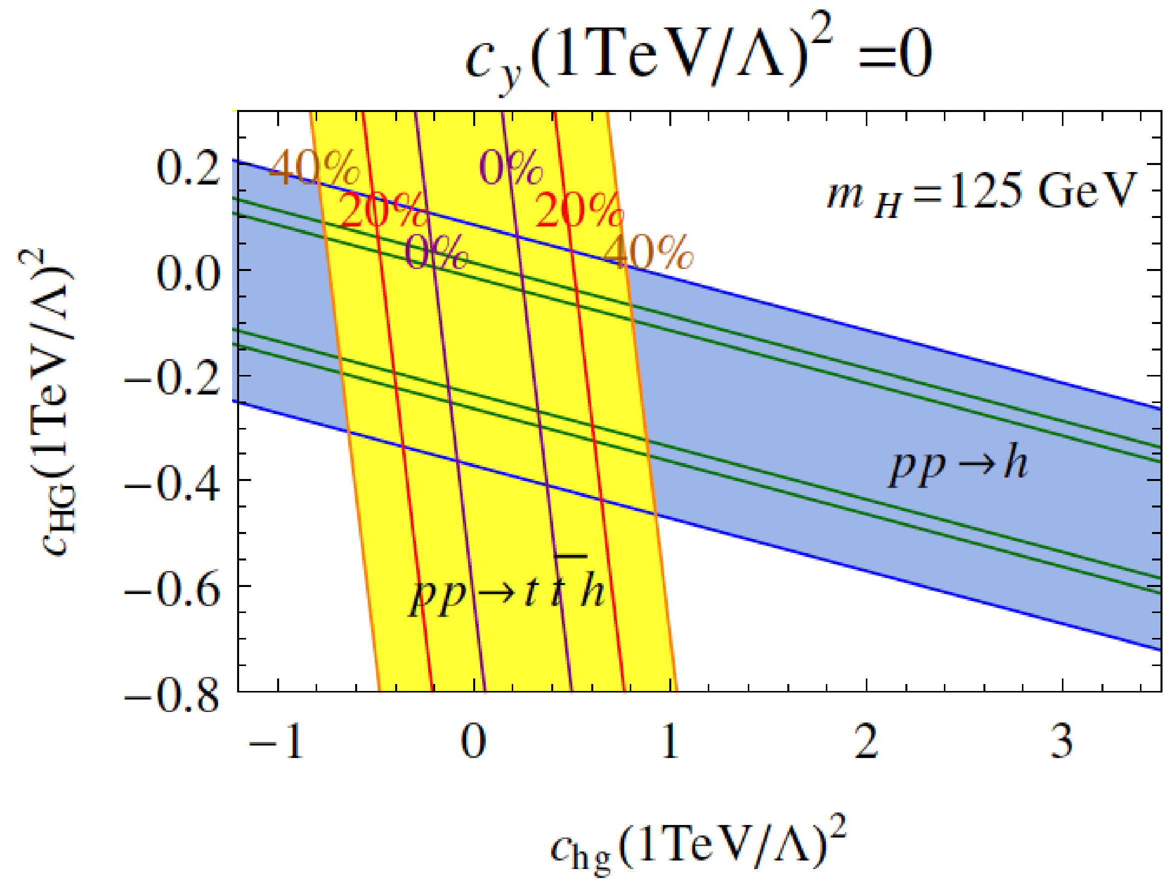


EFT AT NLO PREDICTIONS AVAILABLE, YET SM NLO PREDICTIONS ARE NEEDED CONTROL ACCURACY AND PRECISION.

TOP-HIGGS INTERACTIONS: TTH

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





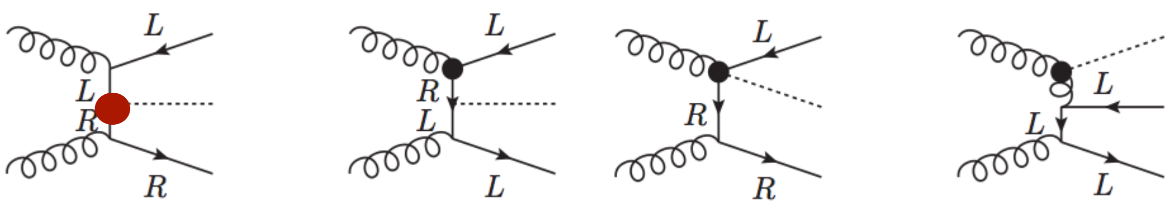
[Degrande et al. 2012]

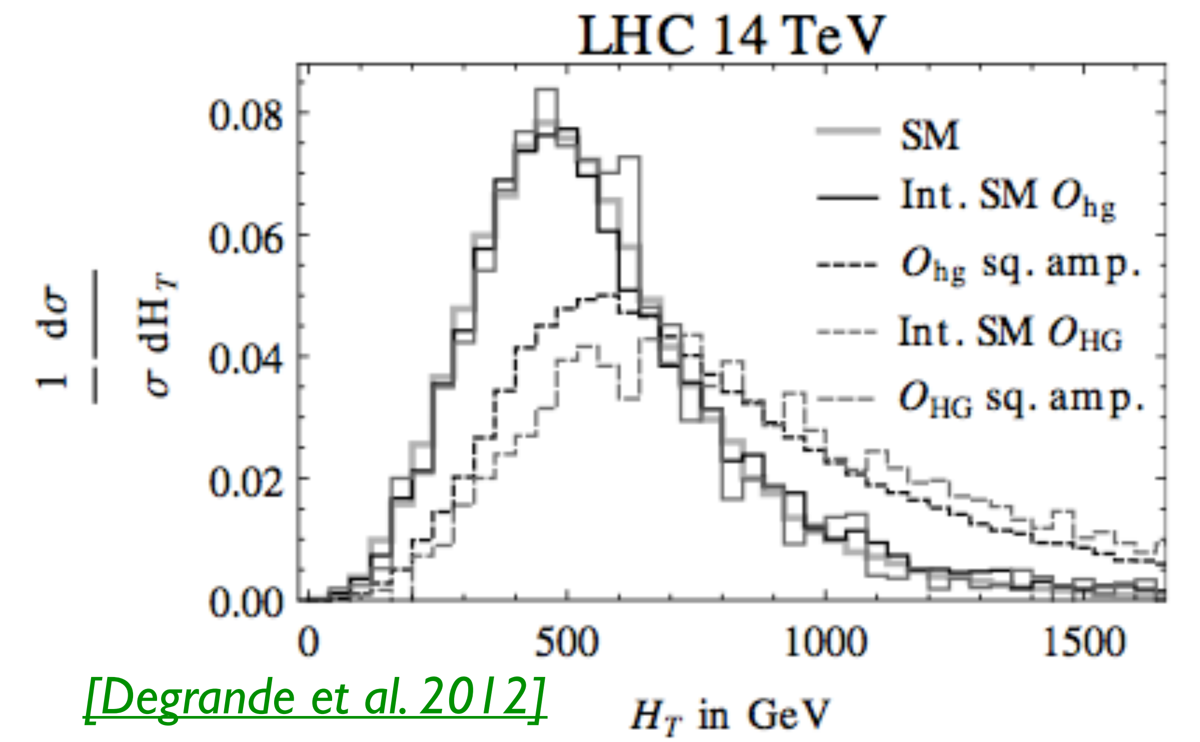
$$
\begin{aligned}
\frac{\sigma(pp \to t\bar{t}h)}{\text{fb}} = \; & 611^{+92}_{-110} + \Big[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G \\
& + 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y\Big]\left(\frac{\text{TeV}}{\Lambda}\right)^2 \\
& + \Big[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232}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

ANALYSIS DONE AT **LO! NLO** IS QUICKLY BECOMING AVAILABLE

TOP-HIGGS INTERACTIONS: TTH

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





[Degrande et al. 2012]

DIFFERENT OPERATORS INTERFERE IN A GIVEN PROCESS. THIS TOGETHER WITH THE FACT THAT THE WILSON COEFFICIENTS RUN AND OPERATORS MIX, IMPLIES THAT THE IT MAKES NO SENSE TO CONSTRAIN OPERATORS ONE AT THE TIME. GLOBAL STRATEGY IS NEEDED:

OBS1(S,T,U) = C1 F11(S,T,U) + C3 F31(S,T,U) + ...

OBS2(S,T,U) = C1 F12(S,T,U) + C2 F22(S,T,U) + ...

OBS3(S,T,U) = C1 F13(S,T,U) + C4 F43(S,T,U) + ...

NOT YET DONE AT THE LHC! ROOM FOR IMPROVEMENTS AND NEW IDEAS...

TOP-HIGGS INTERACTIONS: BOUNDING THE CHROMOMAGNETIC OPERATOR

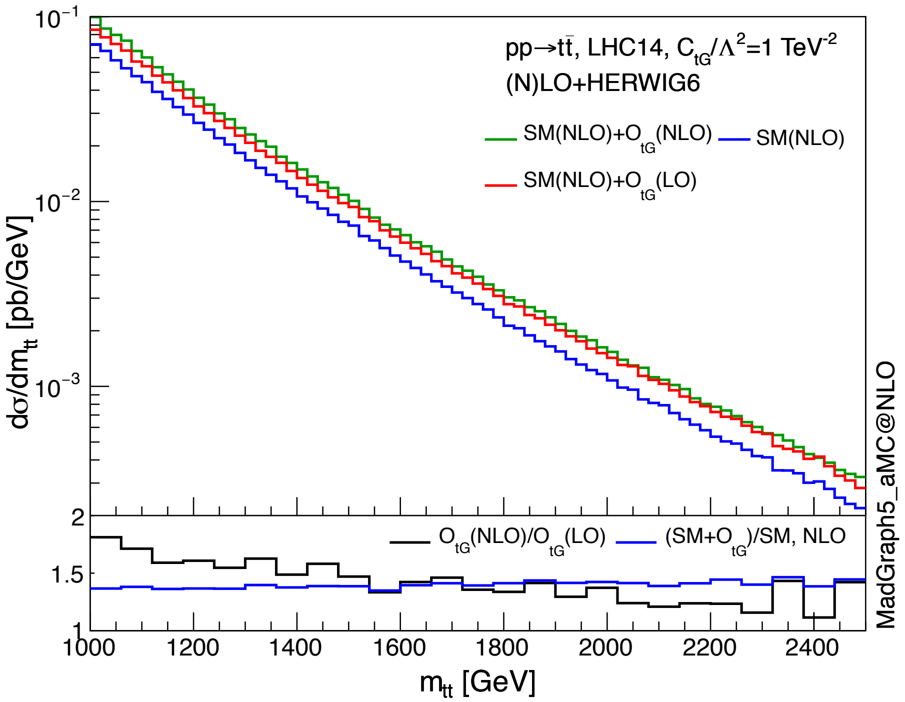
Recent analysis at NLO in QCD

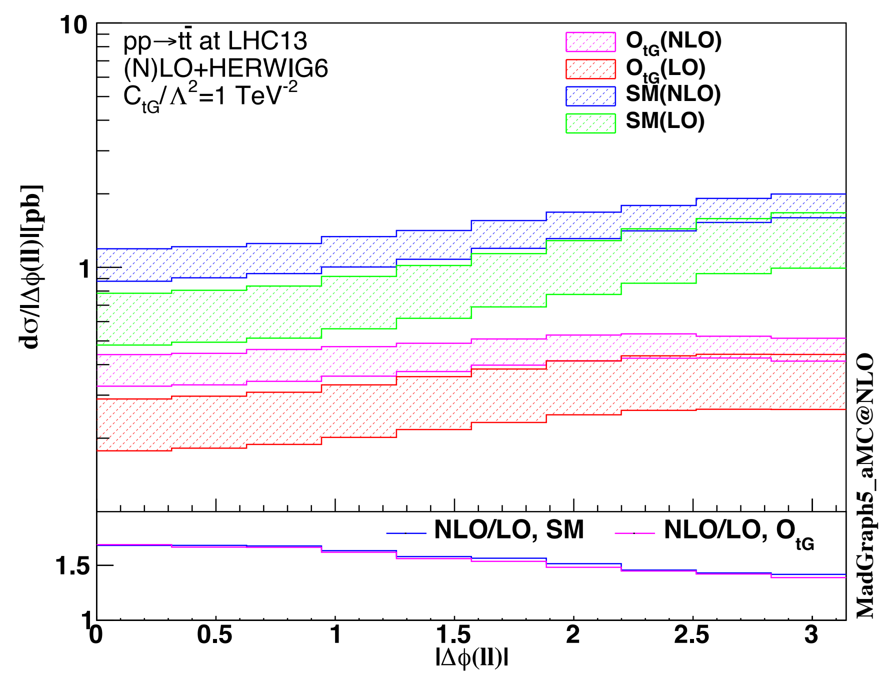
[Cen and Franzosi, 2015]

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

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]

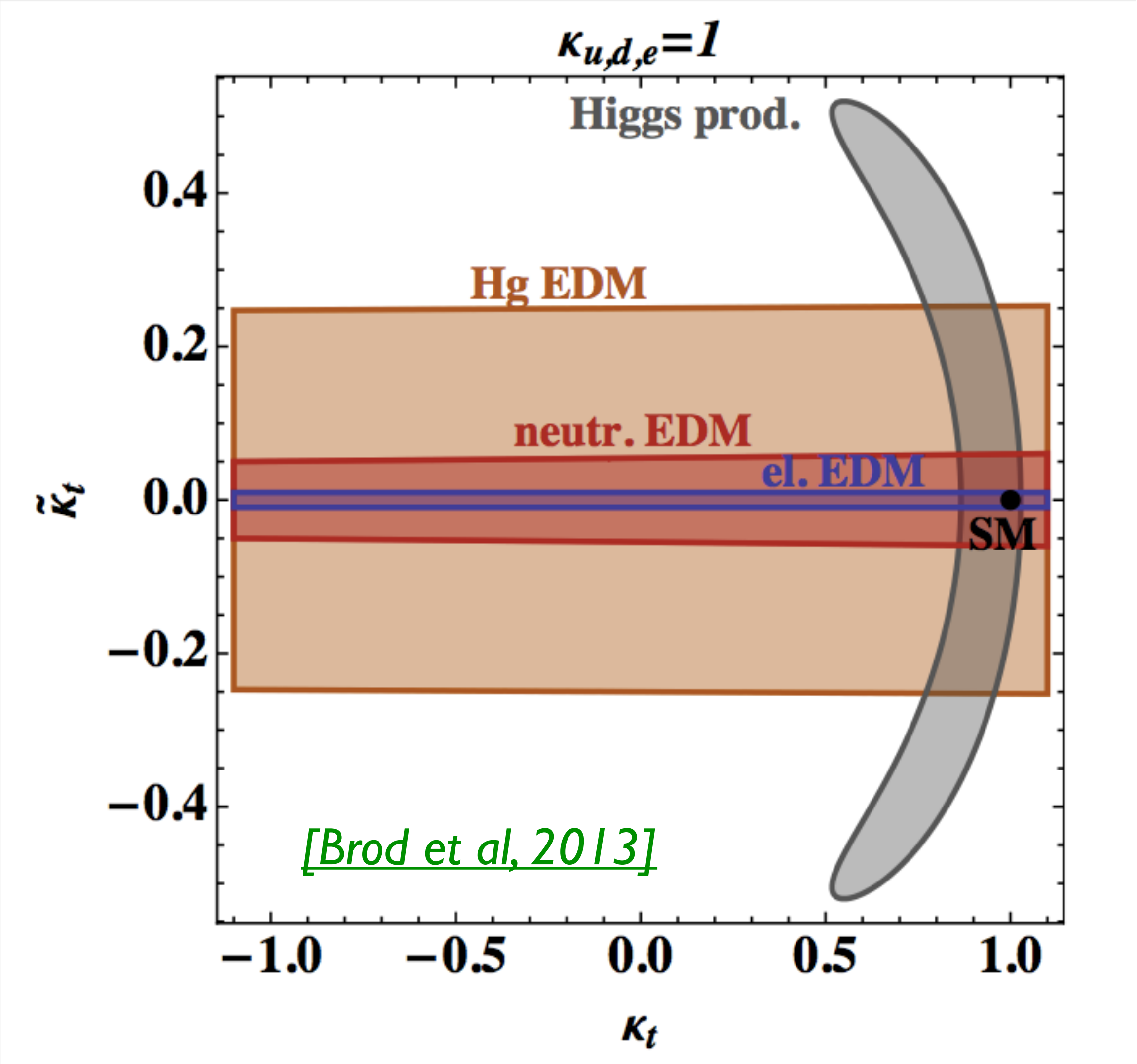
TOP-HIGGS INTERACTIONS: CP VIOLATION

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

CP violation implies Re AND Im non-zero. Inclusive gg production only constrains [$\mathrm{Re}(c_{HY})^2 + 9/4\ \mathrm{Im}(c_{HY})^2$].

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

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



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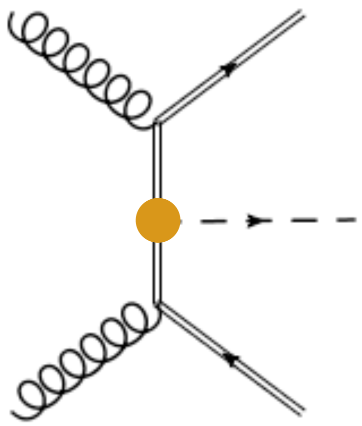
There are ways of directly accessing presence of CP-mixing in top-Higgs interactions at the LHC:



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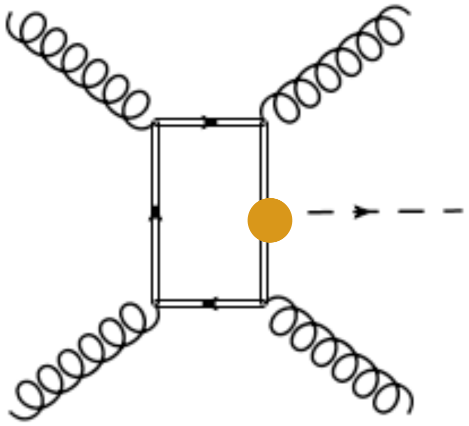

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TOP-HIGGS INTERACTIONS: CP VIOLATION

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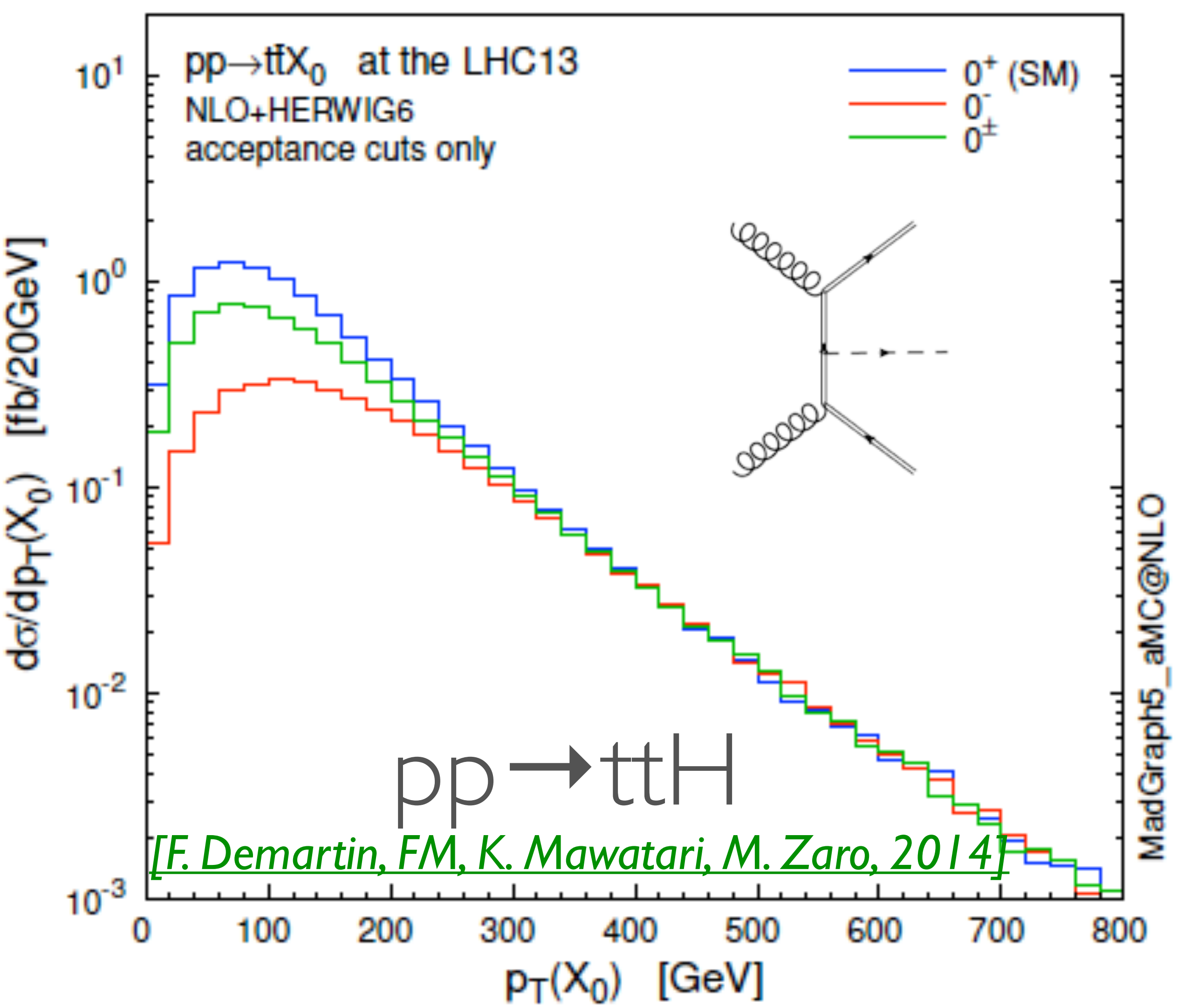

At LO the two contributions add up incoherently. At NLO in QCD CP-even and CP-odd amplitudes interfere.

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 INTERACTIONS: CP VIOLATION

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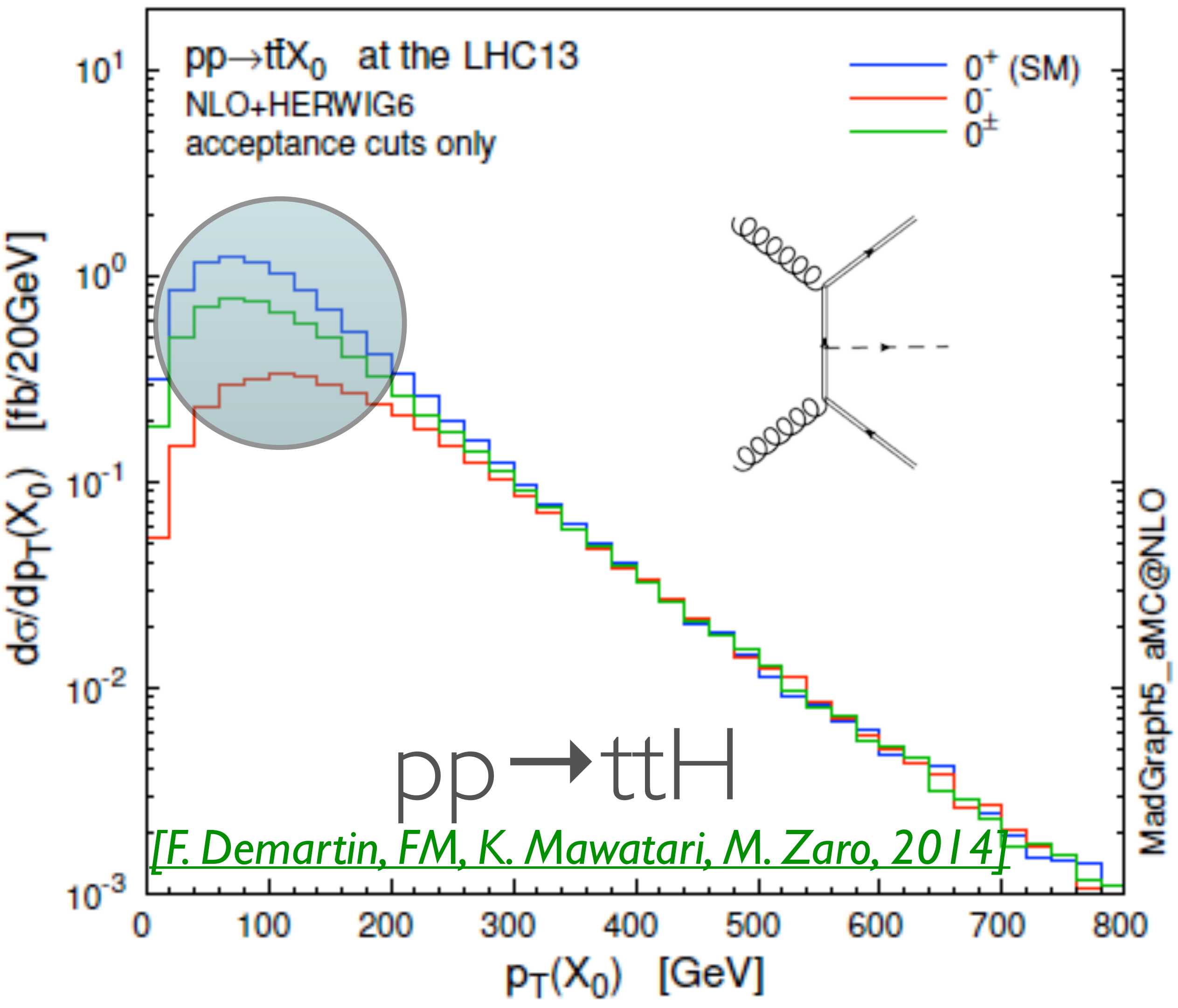

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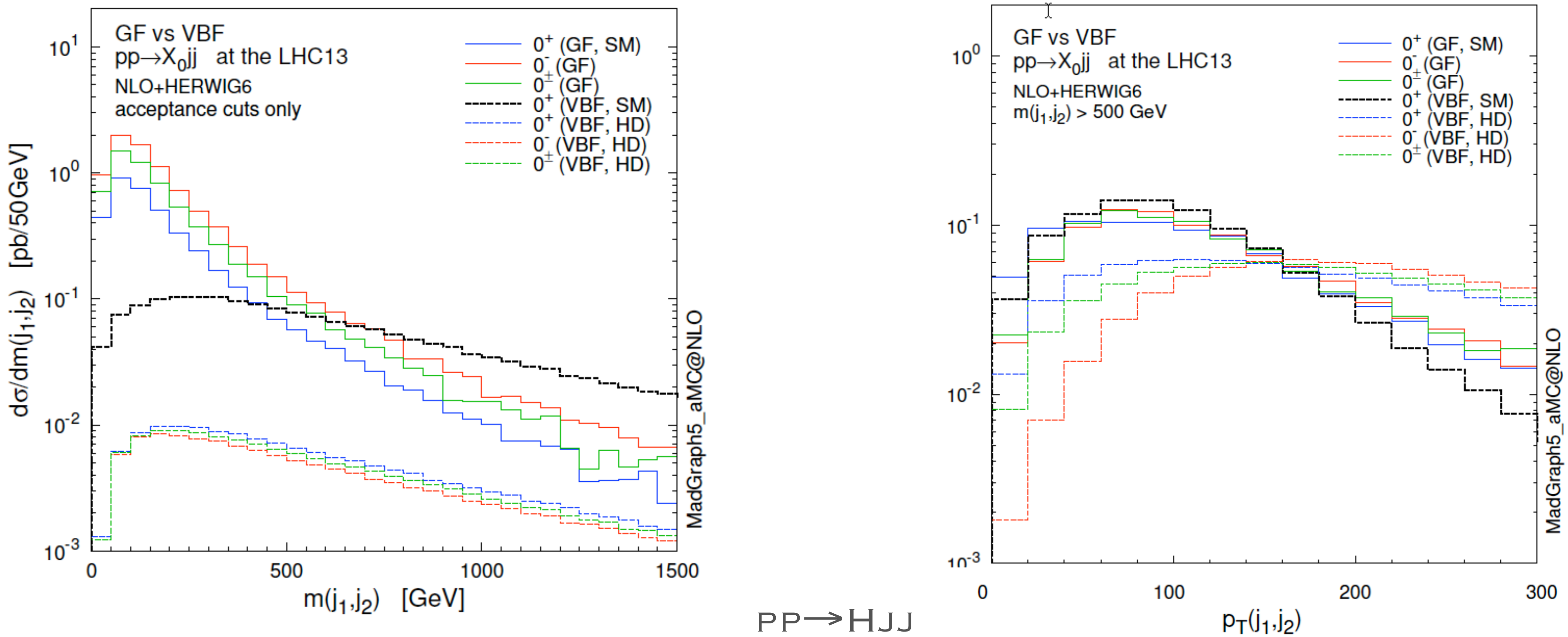
top-higgs interactions: CP violation

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

$$\mathcal{L} = \frac{1}{4}\{c_\alpha \kappa_H g_H G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_A g_A G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\}h$$

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



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TOP-HIGGS INTERACTIONS: CP VIOLATION

THE CP-MIXING IN THE TOP COUPLING INDUCES A CP-MIXING AT THE LEVEL OF THE H-GLUON-GLUON COUPLINGS:

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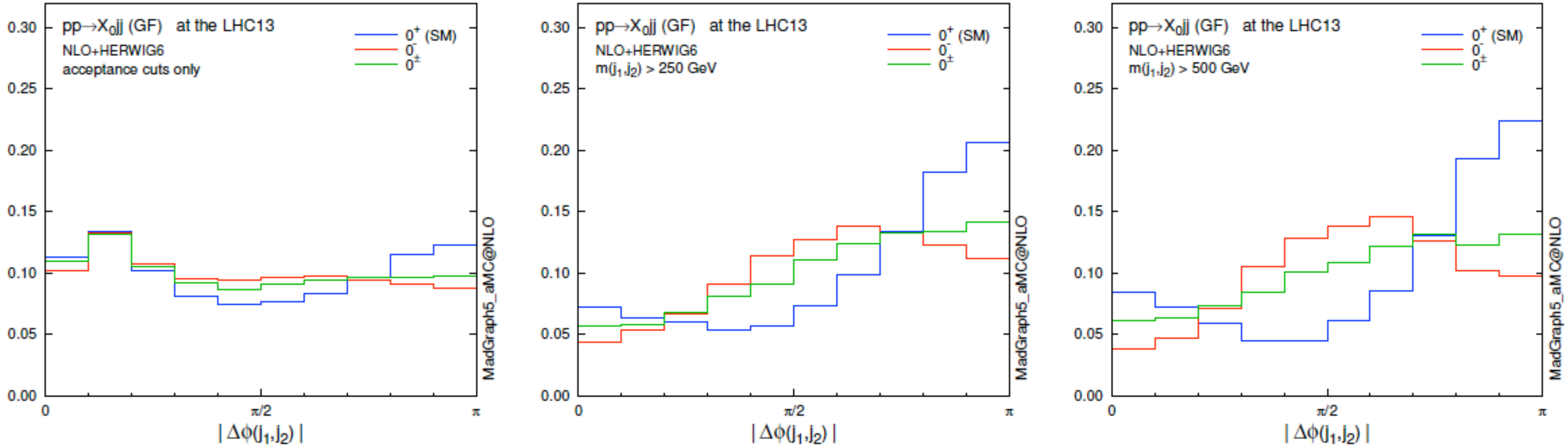
PP→HJJ

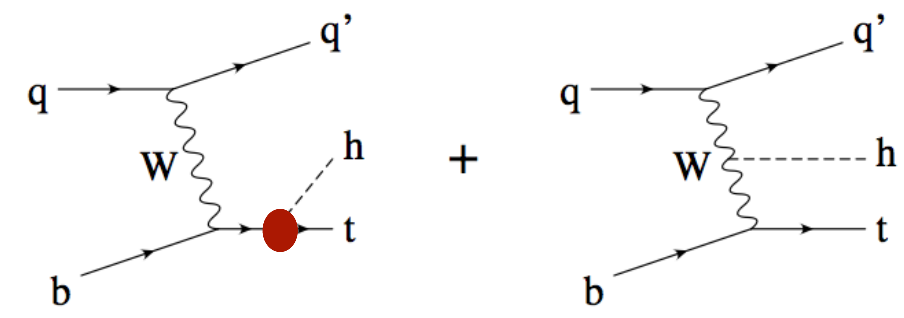
[F. Demartin, FM, K. Mawatari, Zaro, 2014]

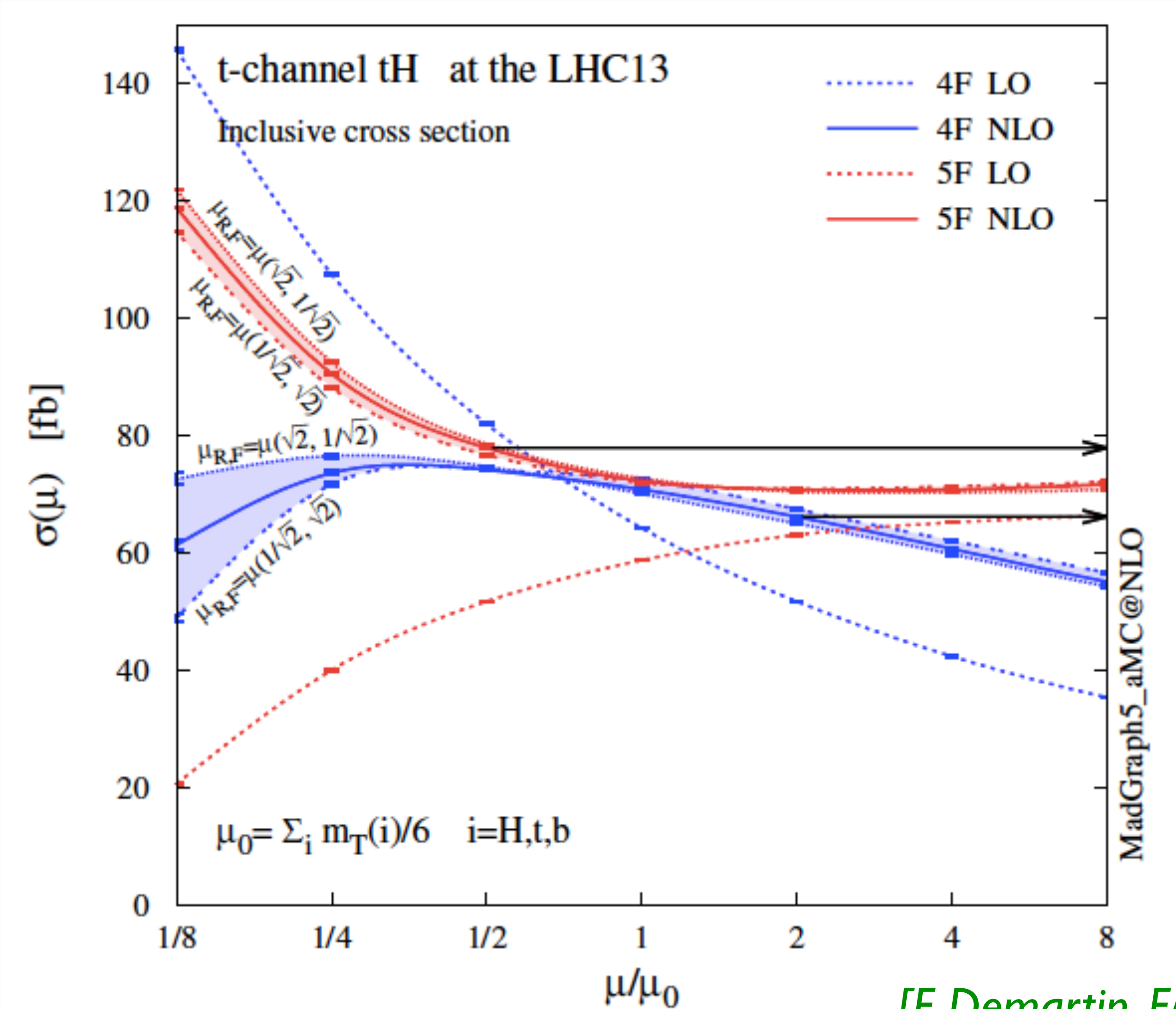


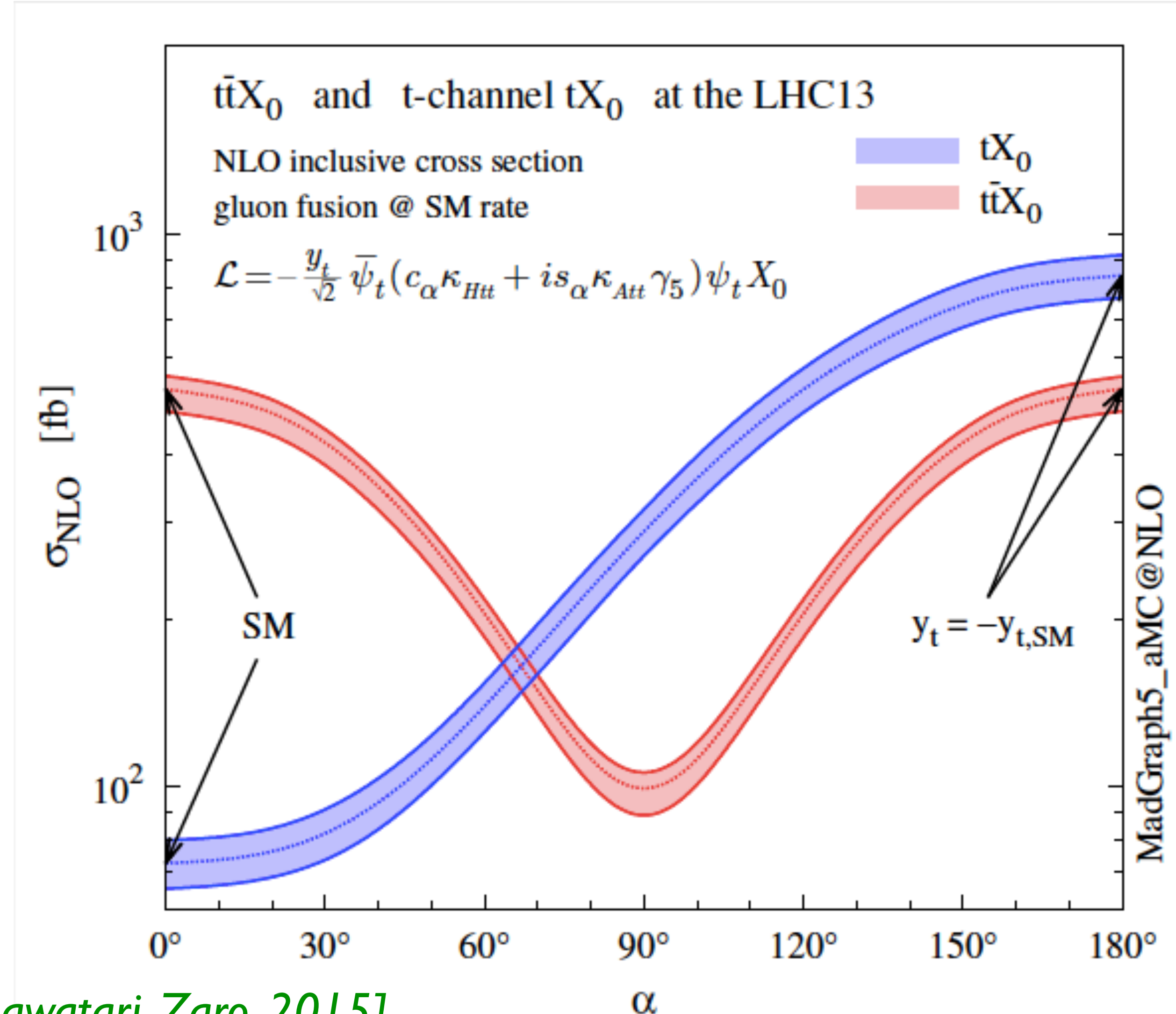
DELTA(PHI) AMONG THE JETS IS A SENSITIVE VARIABLE AS MJJ INCREASES.

TOP-HIGGS INTERACTIONS: CP VIOLATION

THE RELATIVE SIGN OF THE YUKAWA TOP COUPLING IS FIXED BY UNITARITY IN THE SM. $H \to \gamma\gamma$ IS SENSITIVE TO THE SIGN. IN PRODUCTION THJ CAN PROVIDE FURTHER CONSTRAINTS.







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

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 valuable 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** have started to become **available through the MadGraph5_aMC@NLO platform.**

- Proof of principle available of a global approach at NLO in QCD for FCNC top quark. [G. Durieux , FM, C. Zhang, 2014]

- Considerable work still to be done and constraining strategies need to be fully worked out/optimised.

NEW JOINT TH/EXP EFFORT!

Conclusions

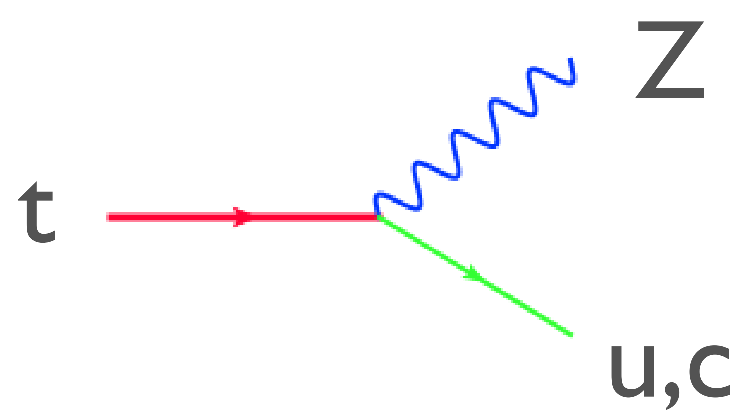
- The discovery of a scalar boson has opened a new realm of possibilities for searching new physics.
- The most beaten path for searching new physics at the LHC involve top-down (or simplified models) approach to detecting new resonances.
- **A complementary and far reaching approach is that of searching for new interactions employing an EFT framework.**
- Precision dim=6 SM measurements, in particular for higgs and top quark, can extend the reach of new physics searches at the LHC.

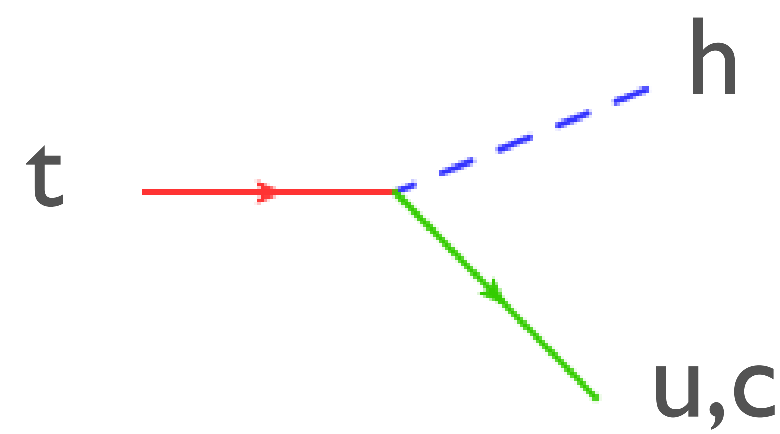
Global approach to top-higgs FCNC

[Durieux, FM, Zhang 2014]

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]





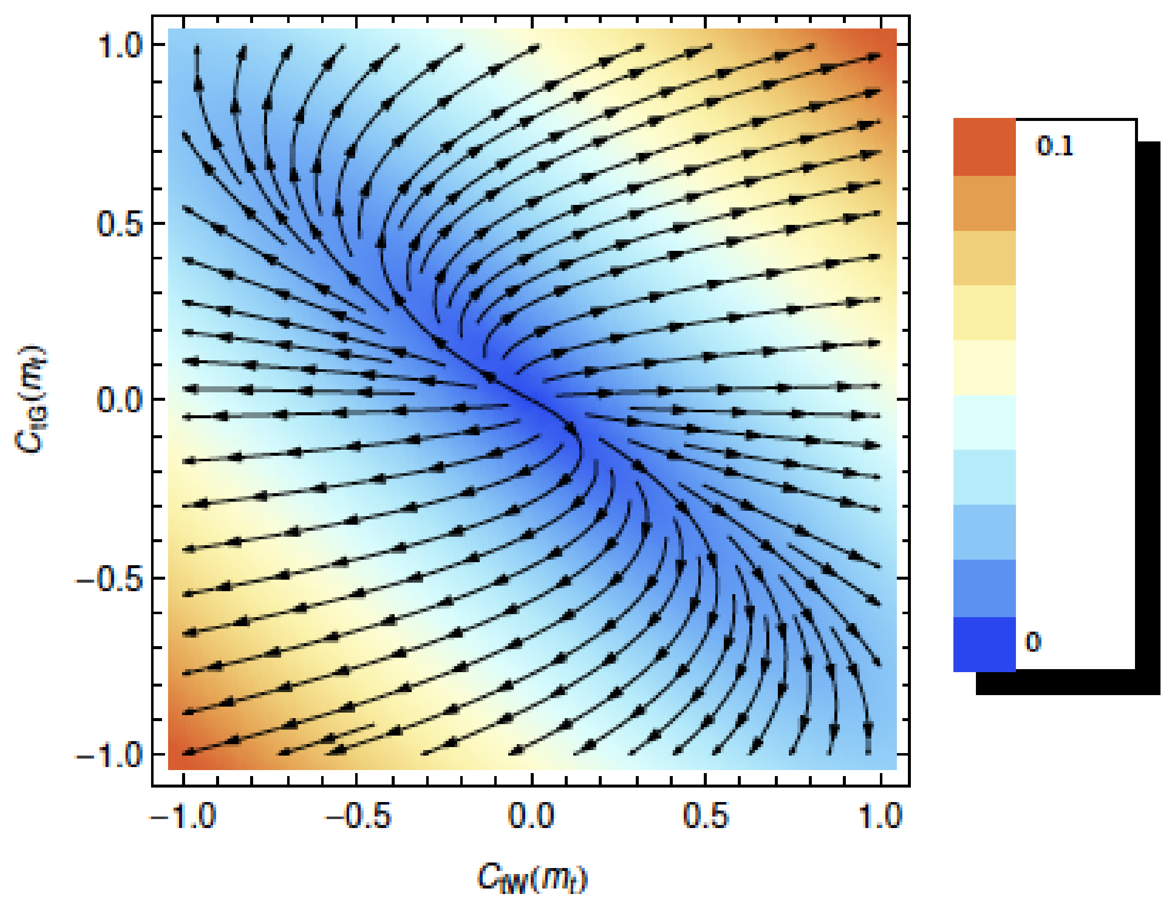
While the exp searches are completely different, one has to remember that the decay rates will depend on several operators that are linked by gauge symmetry. For example:

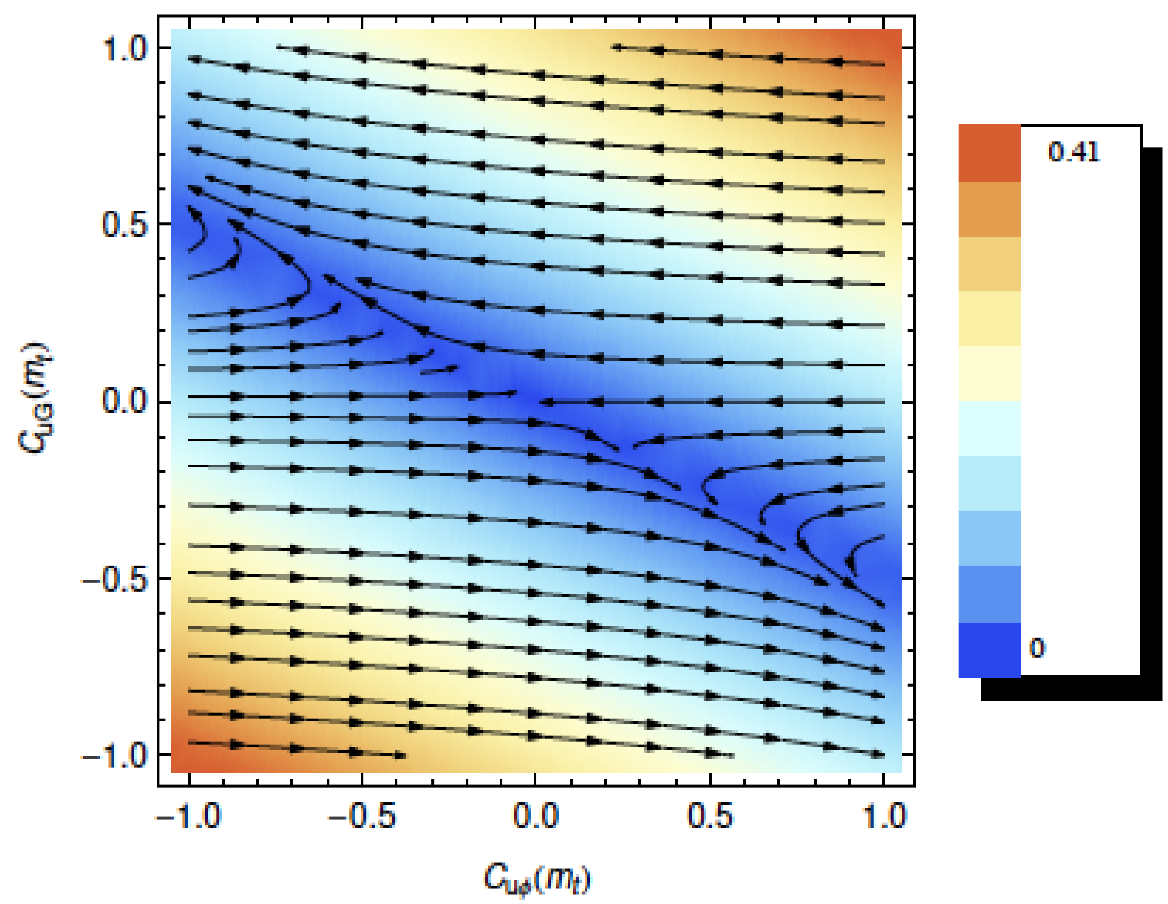
$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$
$$O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{uG}^{(13)} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
$$O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger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

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

Global approach to top-higgs FCNC

[Durieux, FM, Zhang 2014]





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

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

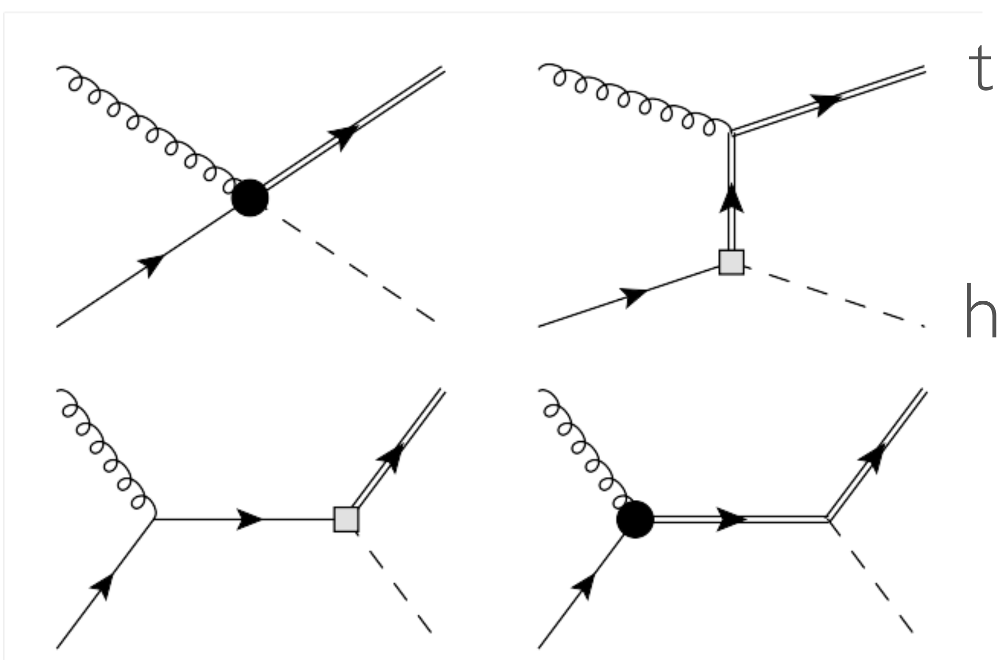
$$O^{(13)}_{uG} = y_t g_s (\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O^{(13)}_{uW} = y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O^{(13)}_{uB} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O^{(13)}_{u\varphi} = -y_t^3 (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}\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

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

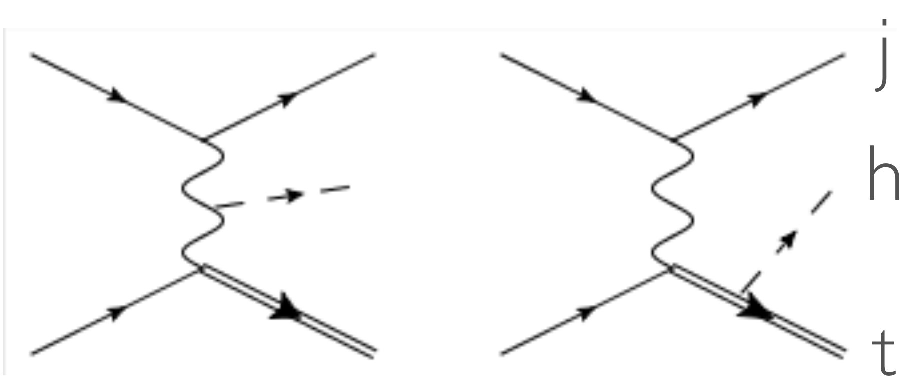
Global approach to top-higgs FCNC

[Durieux, FM, Zhang 2014]

pp →th



pp →thj (SM)



Contributions appear at LO from $O_{t\phi}$ and one from O_{tG}..

At NLO in QCD O_{tG} 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.

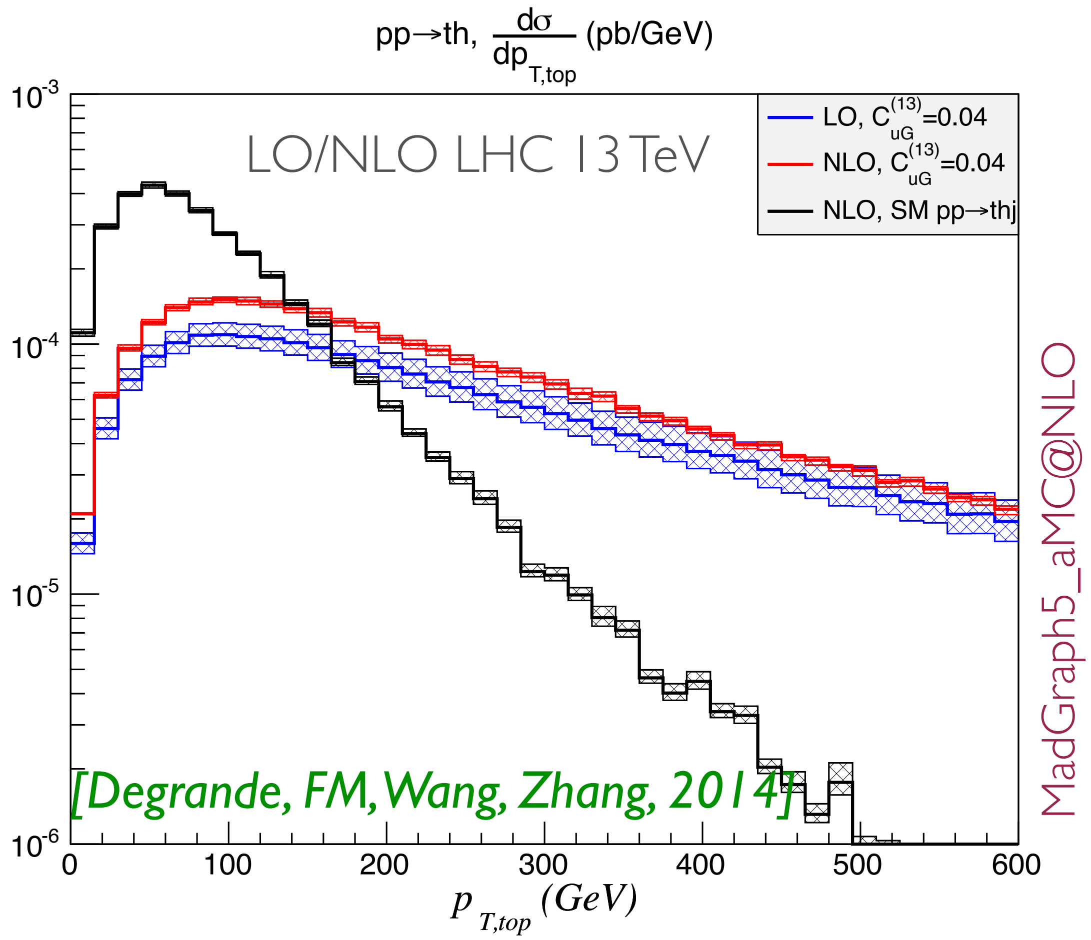
Only a global/fit approach on constraining such operators at the same time can be useful strategy and it has to be at least NLO in QCD.

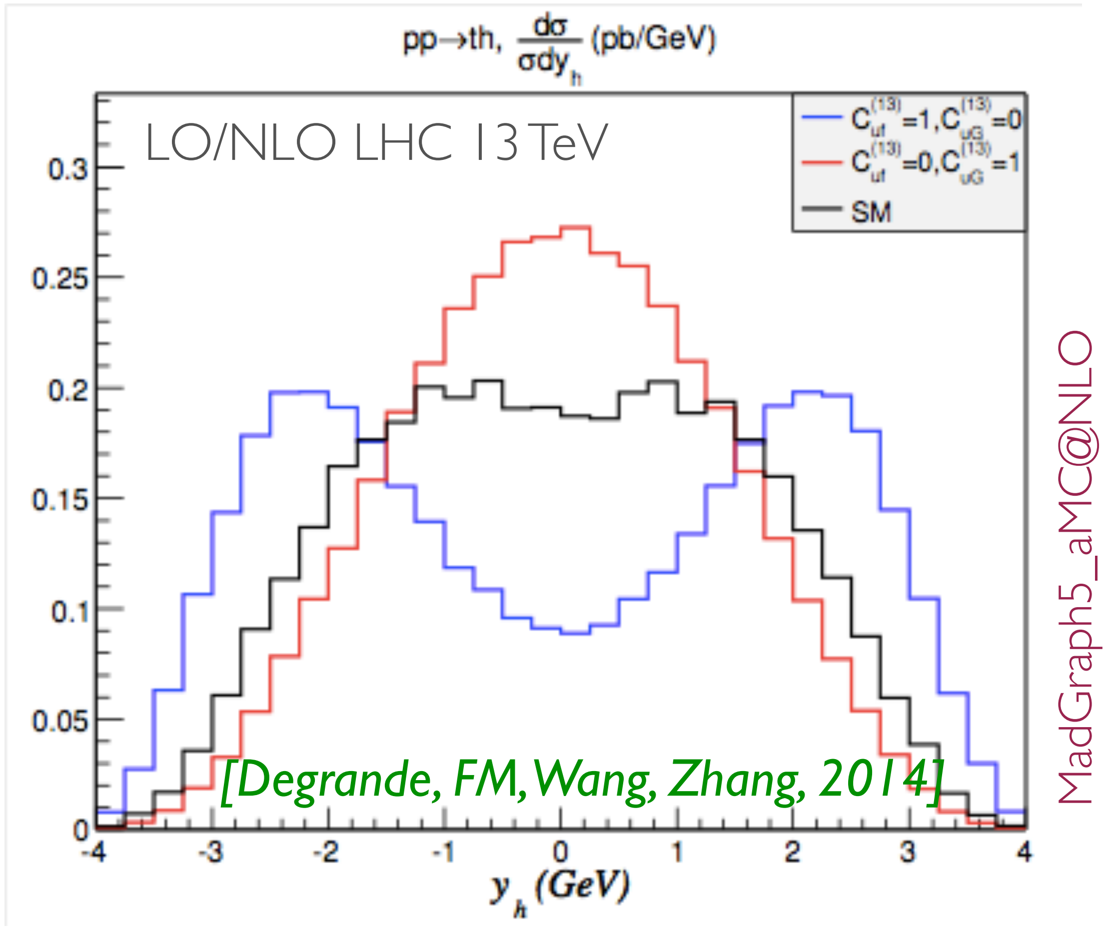
Global approach to top-higgs FCNC

[Durieux, FM, 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...

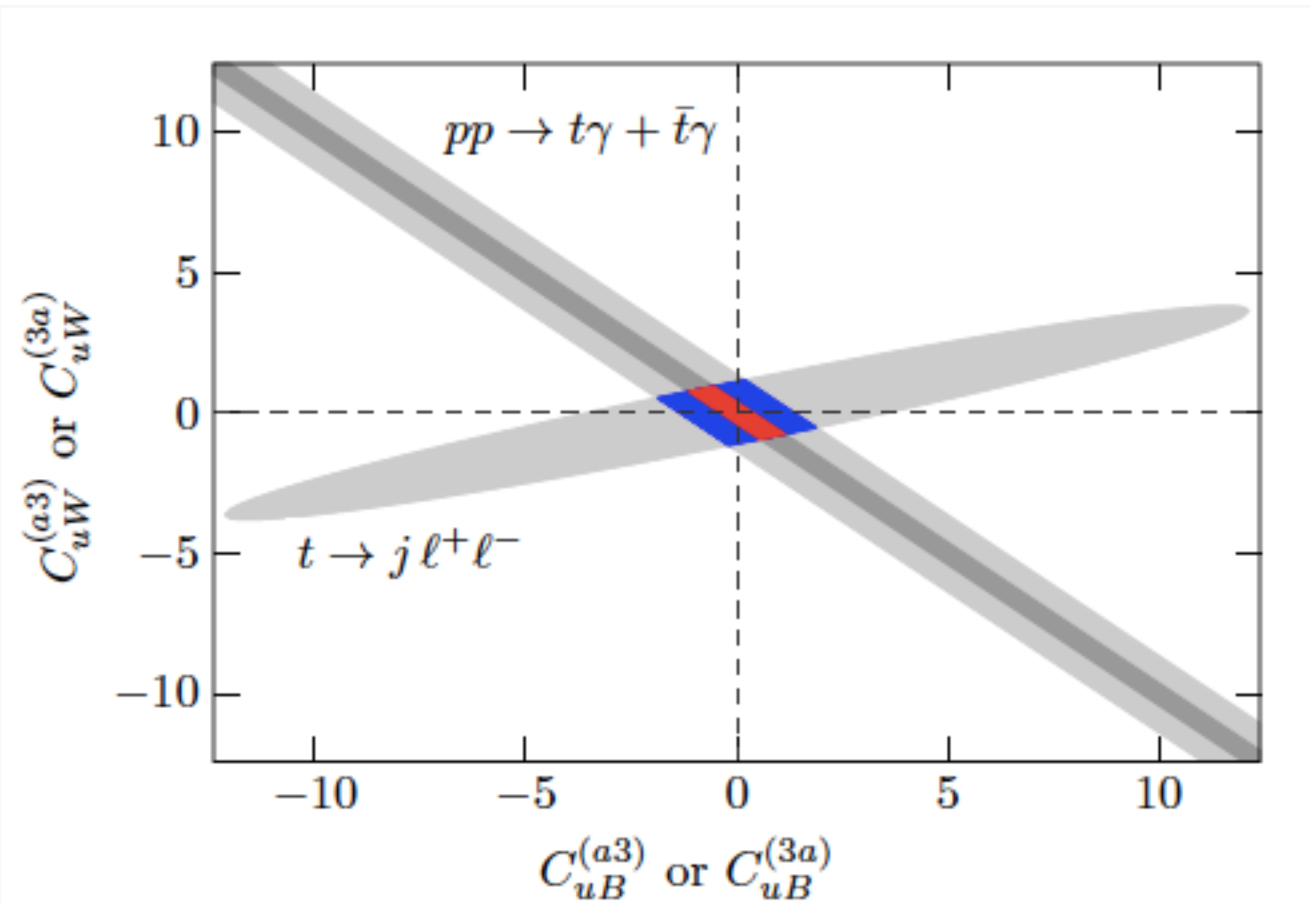


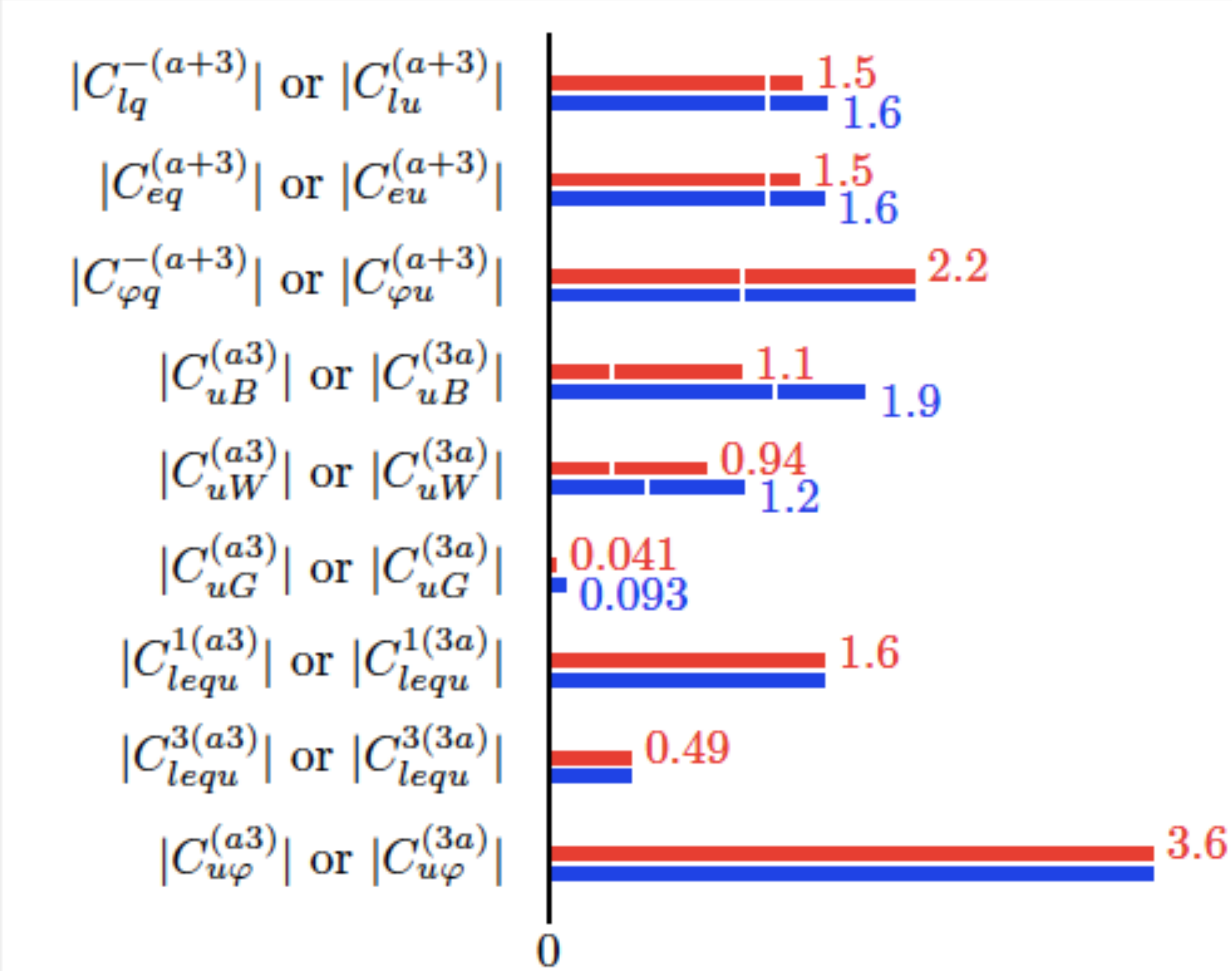


Complete implementation of all operators of dim=6 at NLO (including four fermion operators) in QCD is on going.

Global approach to top-higgs FCNC

[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 already with the available measurements.

Towards a global fit at NLO

[Cen Zhang]

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ and $O_{\varphi G} = g_s^2 \left(\varphi^\dagger \varphi\right) G_{\mu\nu}^A G^{A\mu\nu}$ are included because they mix with other top-quark operators and play a role in NLO calculations.