NLO predictions for SM effective field theory in the top-quark sector

Cen Zhang

BROOKHAVEN NATIONAL LABORATORY

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- Goal: search for **new interactions** of the top at the LHC.

- Approach: the standard model **effective field theory** (SM EFT)

- Tool: recently developed NLO automatic Monte Carlo event generator based on **MadGraph5_aMC@NLO**.

Outline

- Background
- Developments on MC for top EFT
- Outlook

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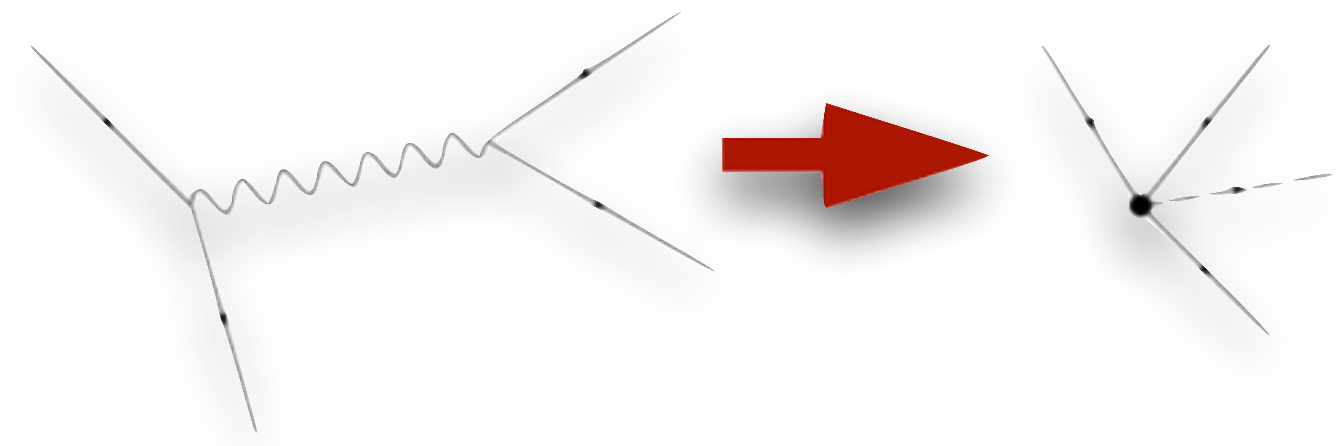
- Look for new interactions (of the SM particles).
    - Extends the reach of LHC to higher scales.
    - …but how do we do this? (without messing things up…)
        - ➡ The EFT

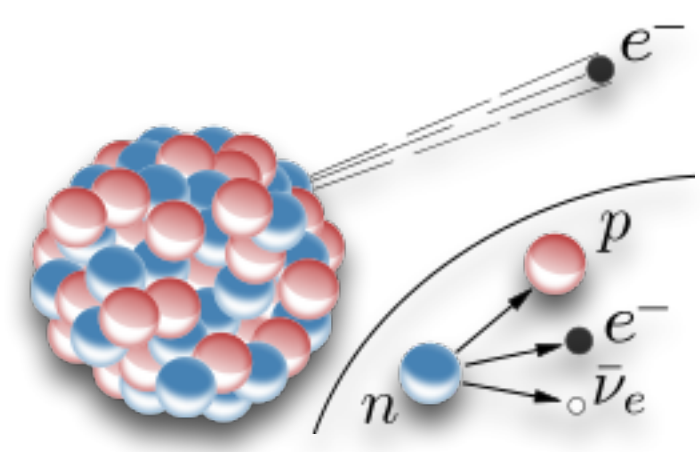
A historical precedent



$$\mathcal{L}_{G_F} = -\frac{4G_F}{\sqrt{2}} \left(\bar{\nu}_\mu \gamma^\mu P_L \mu\right)\left(\bar{e}\, \gamma_\mu P_L \nu_e\right)$$

Fermi's theory, as an effective theory of the weak interactions.

- Measurements at low scales could reveal information at high scales.
- A systematically improvable framework.
    - Muon lifetime has been measured with ~10^{-6} uncertainties. TH predicts at the same level, with 2-loop QED corrections.



Effective Field Theory of the SM

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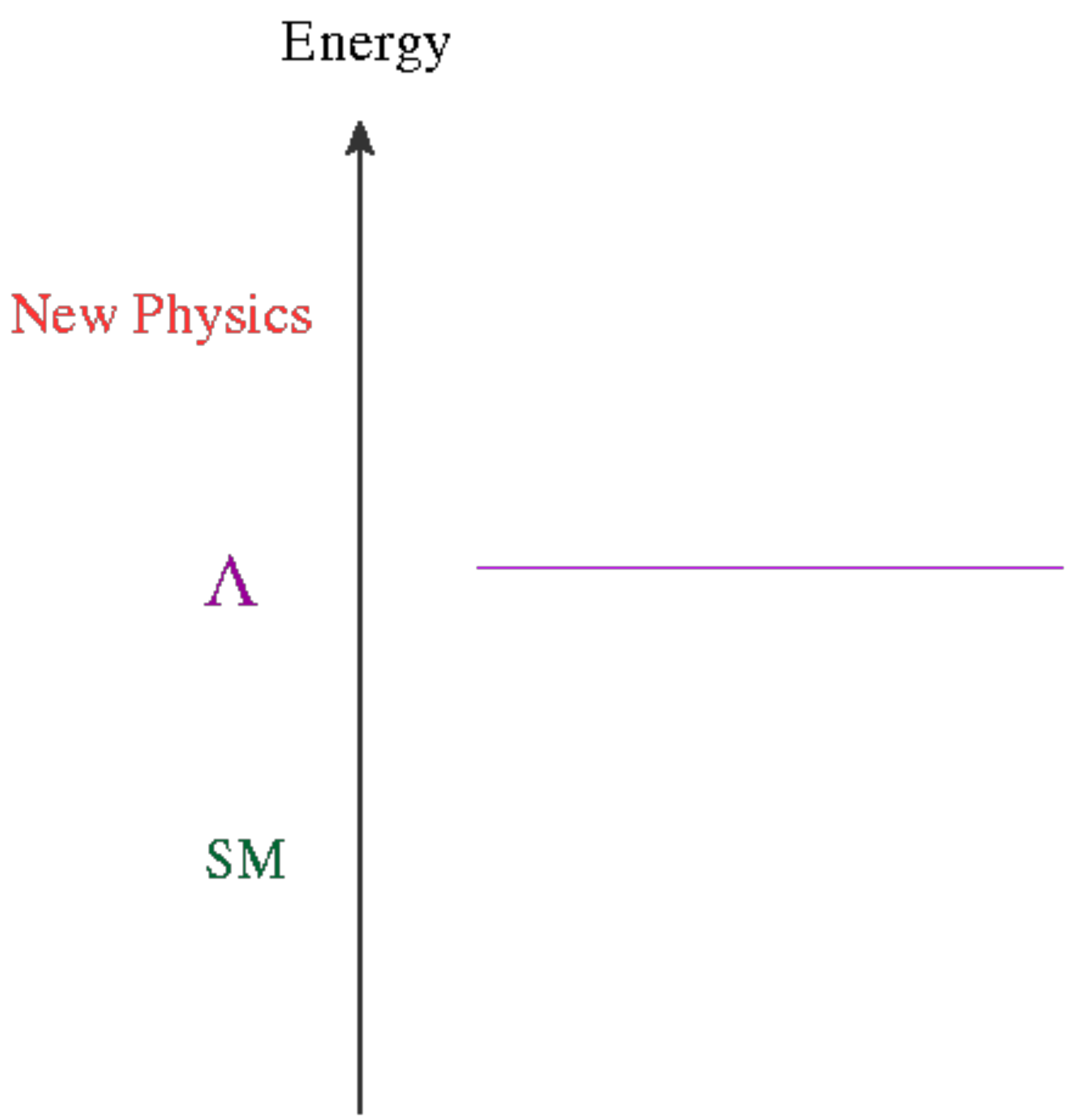

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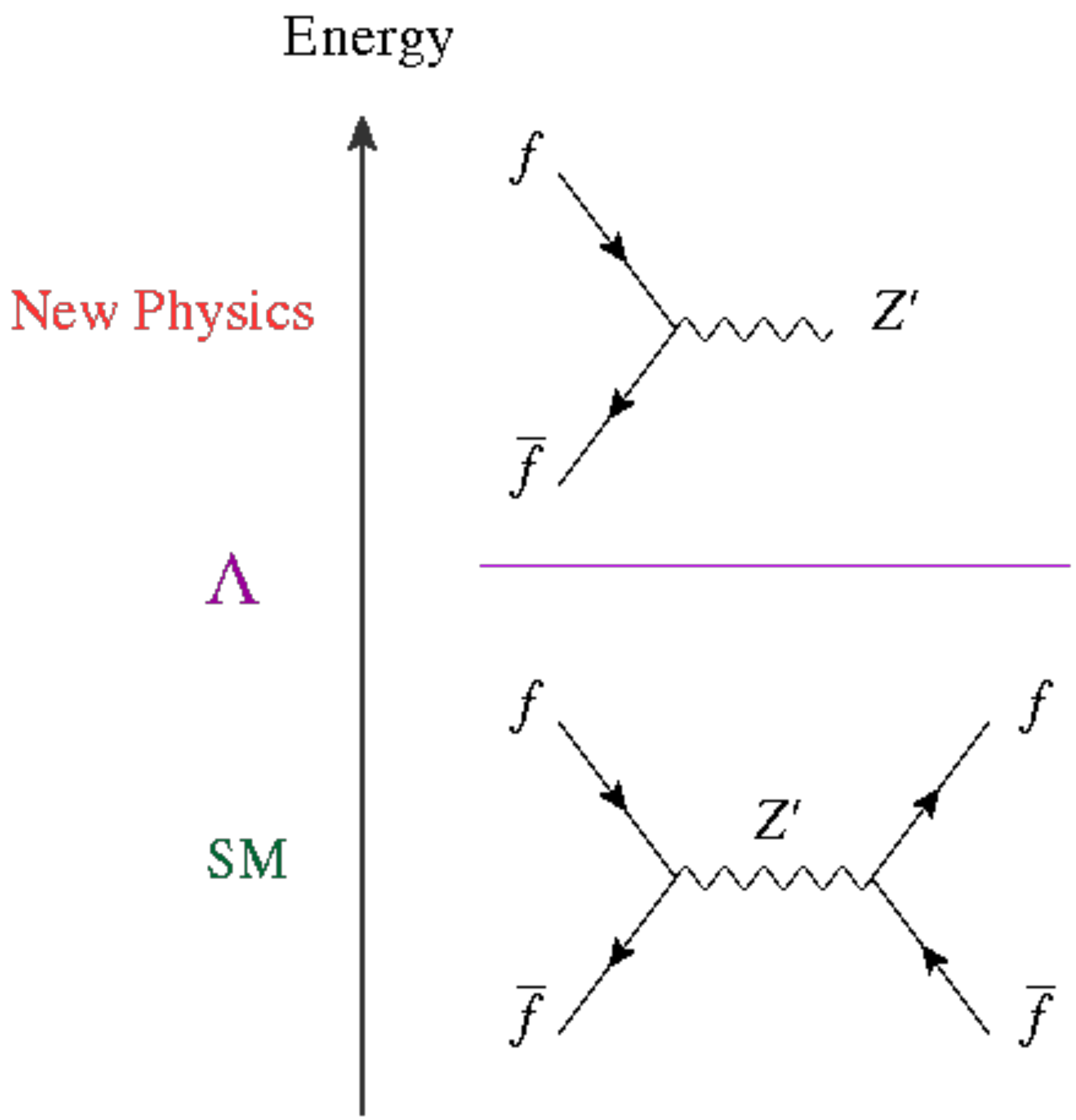

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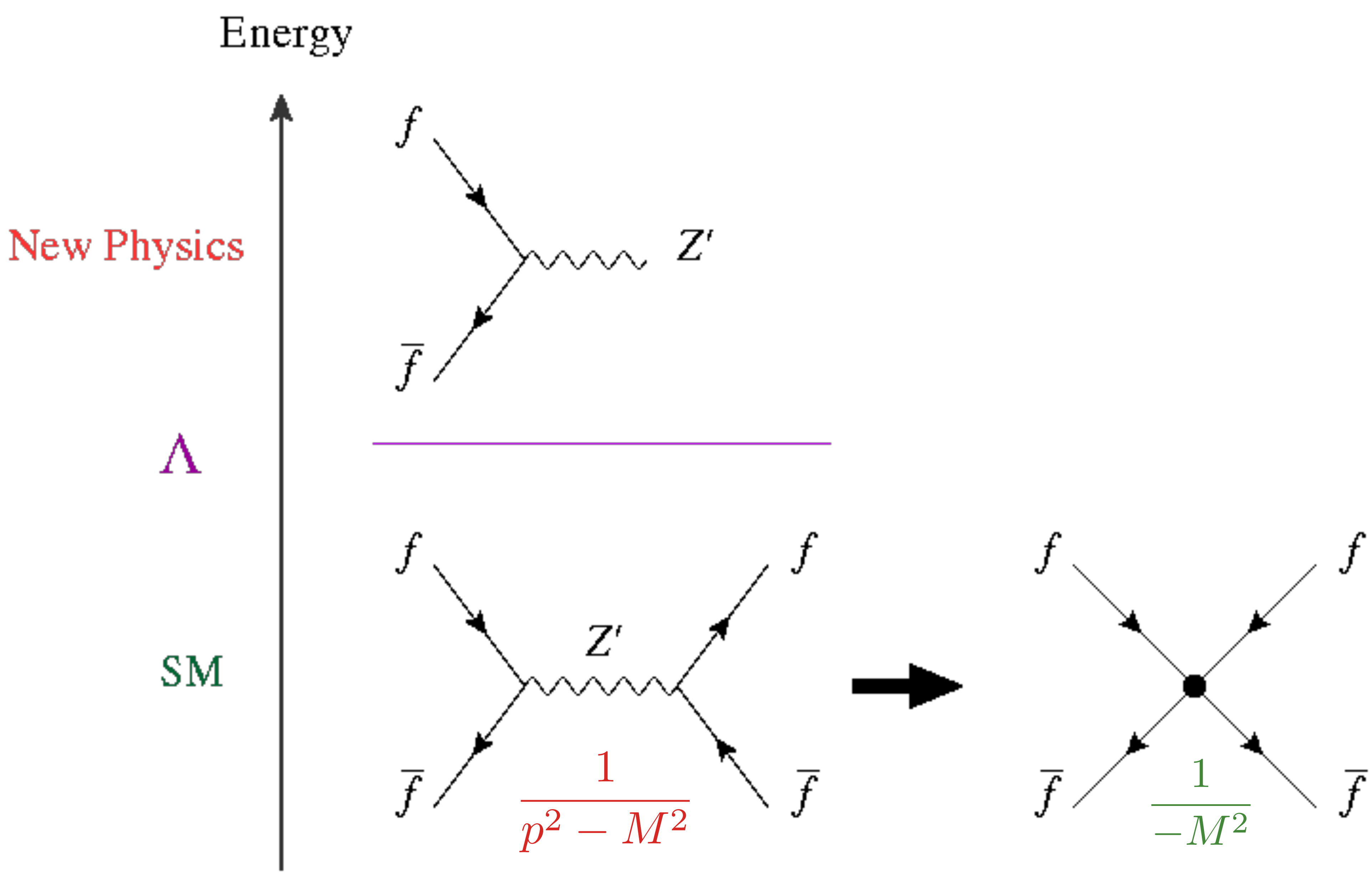
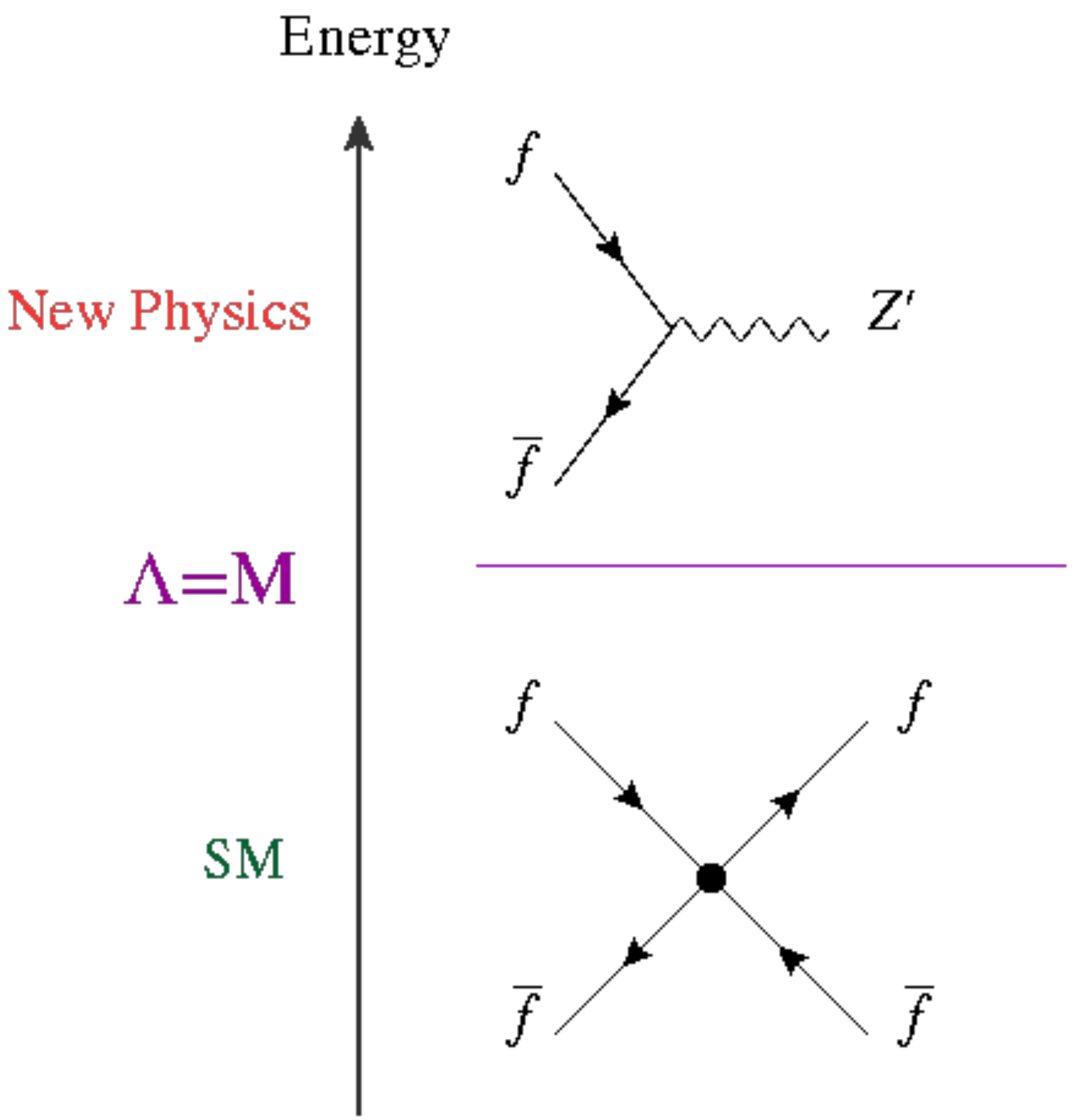


$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

Effective Field Theory of the SM



$$\mathcal{L}_{NP}(\varphi, Z')$$

$$\mathcal{L}_{SM}(\varphi) + \mathcal{L}_{Dim6}(\varphi) + \cdots$$

where $\mathcal{L}_{Dim6}(\varphi) = \dfrac{C}{\Lambda^2}(\bar{f}\gamma^{\mu} f)(\bar{f}\gamma_{\mu} f)$

Effective Field Theory of the SM

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4}) \qquad \Lambda = \text{NP scale}$$

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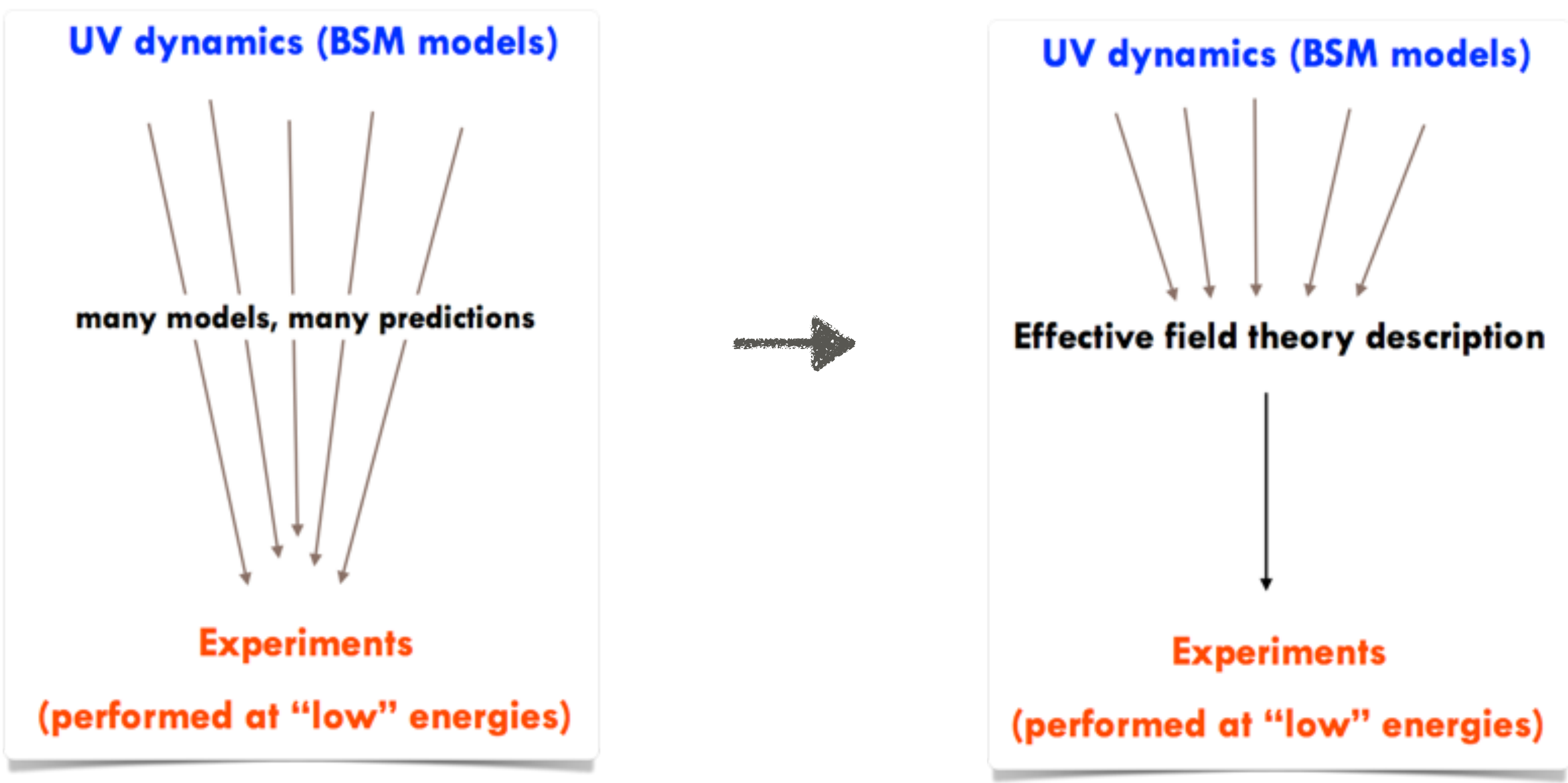
- Valid only if Λ > energy of measurements

+ connects BSM models with EXP observable

Data ⇄ Model-independent EFT ⇄ BSM models


UV dynamics (BSM models)
many models, many predictions
Experiments
(performed at "low" energies)
UV dynamics (BSM models)
Effective field theory description
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BSM goal at the LHC:

determination of SM EFT up to Dim=6

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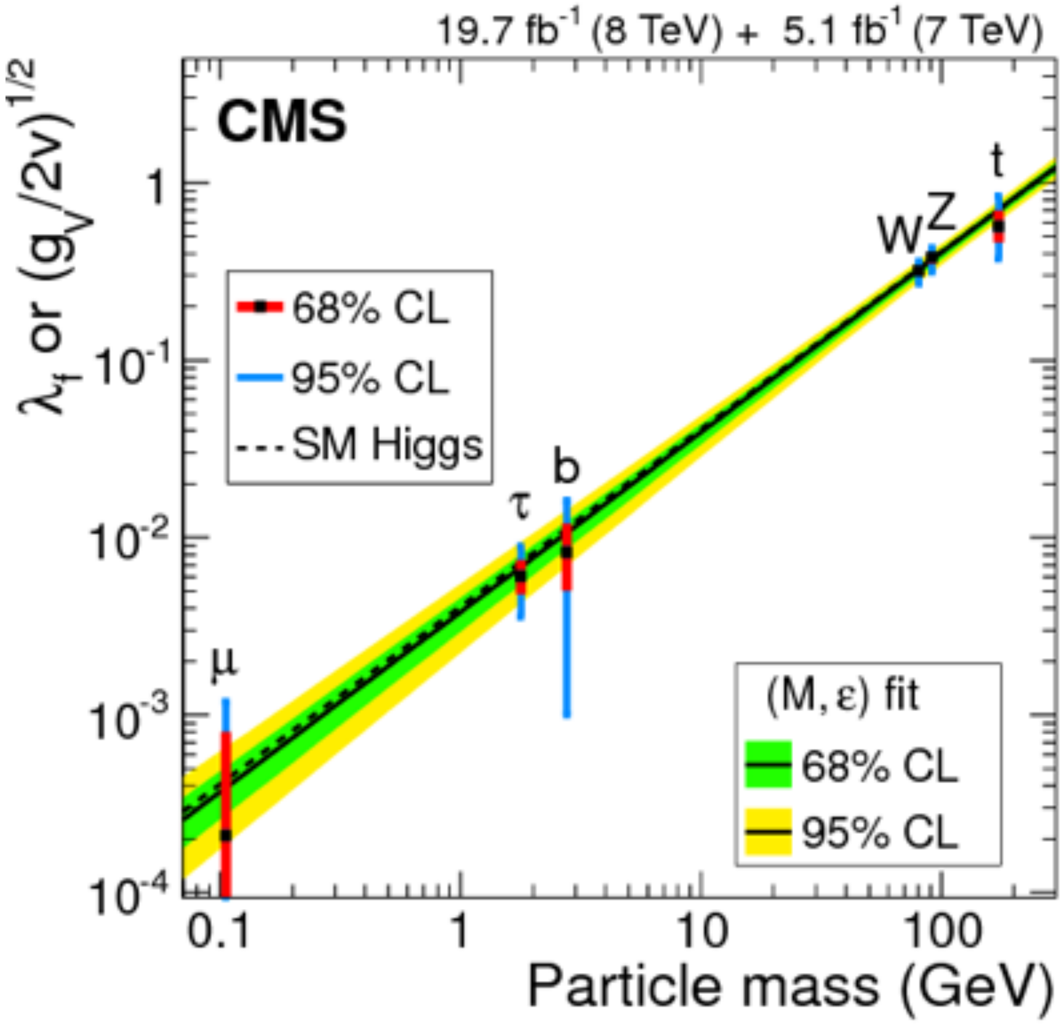
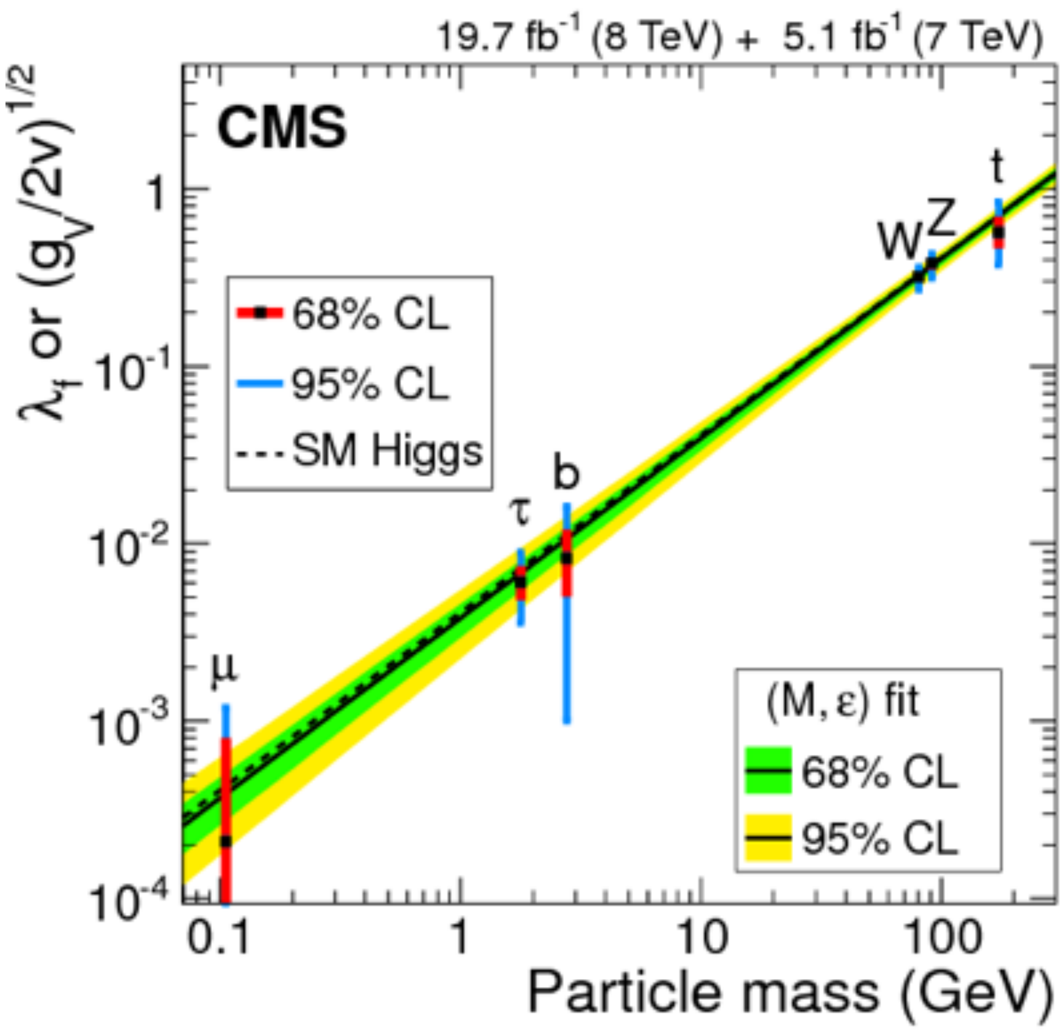
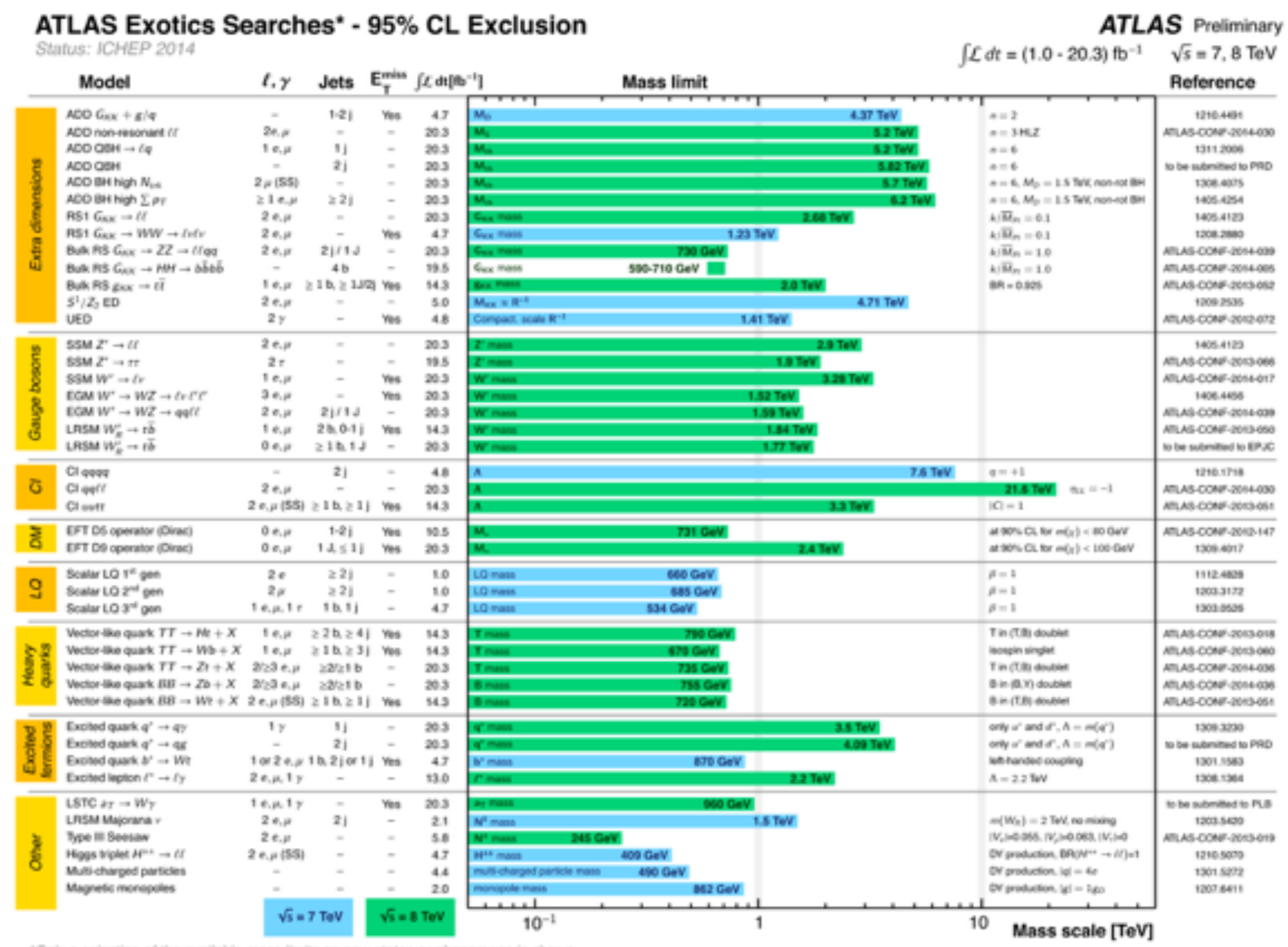


- The SM EFT becomes popular in the past few years, because
  - All known elementary particles are like SM particles (and hence SM)
  - All unknown particles seem to be heavy (and hence EFT)





[W. Buchuller, D.Wyler 1986] [B. Grzadkowski et al, 2010] [L. Lehman, A. Marin, 2015]

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Including:

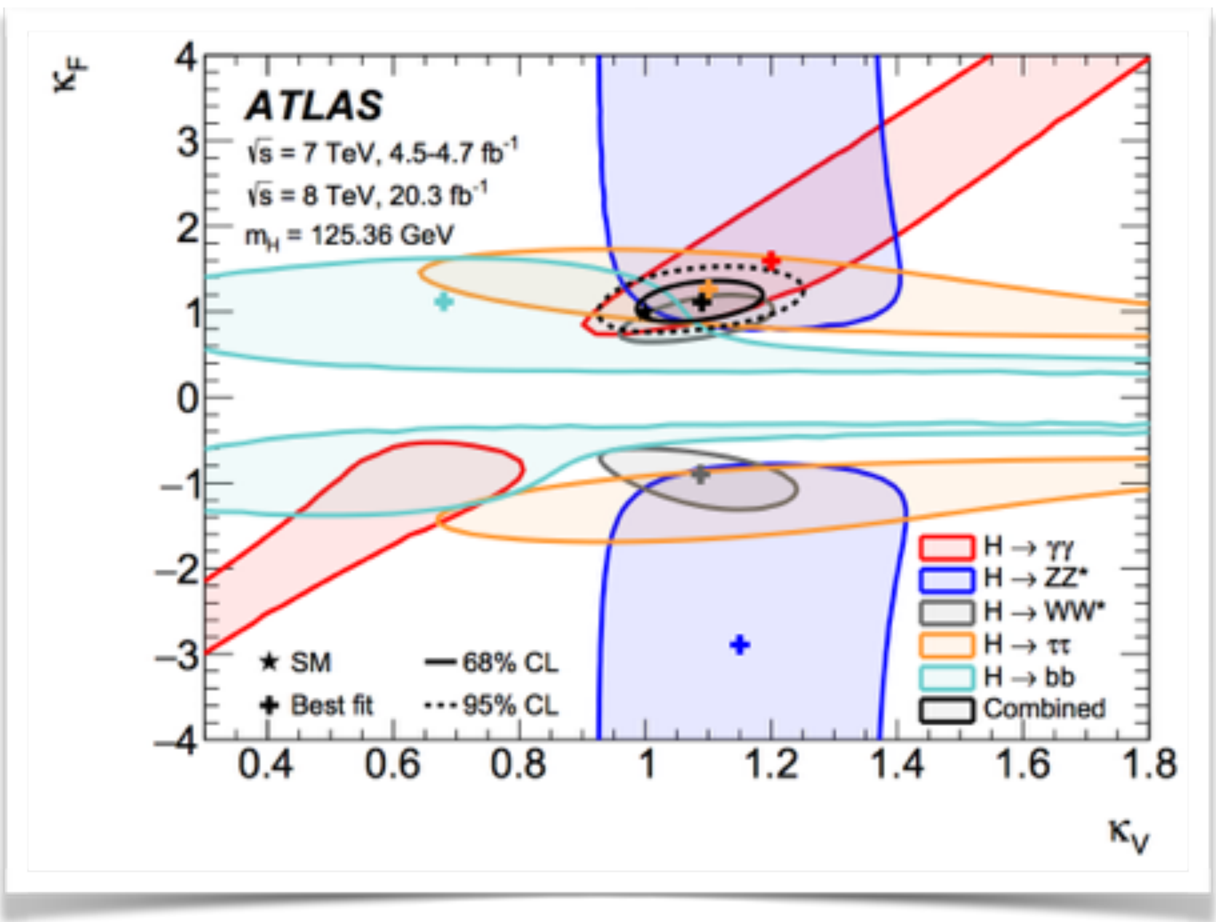
- TGC
- Higgs self interaction
- Yukawa
- Higgs-Gauge boson
- Dipole
- W/Z-Fermion current
- 4-fermion

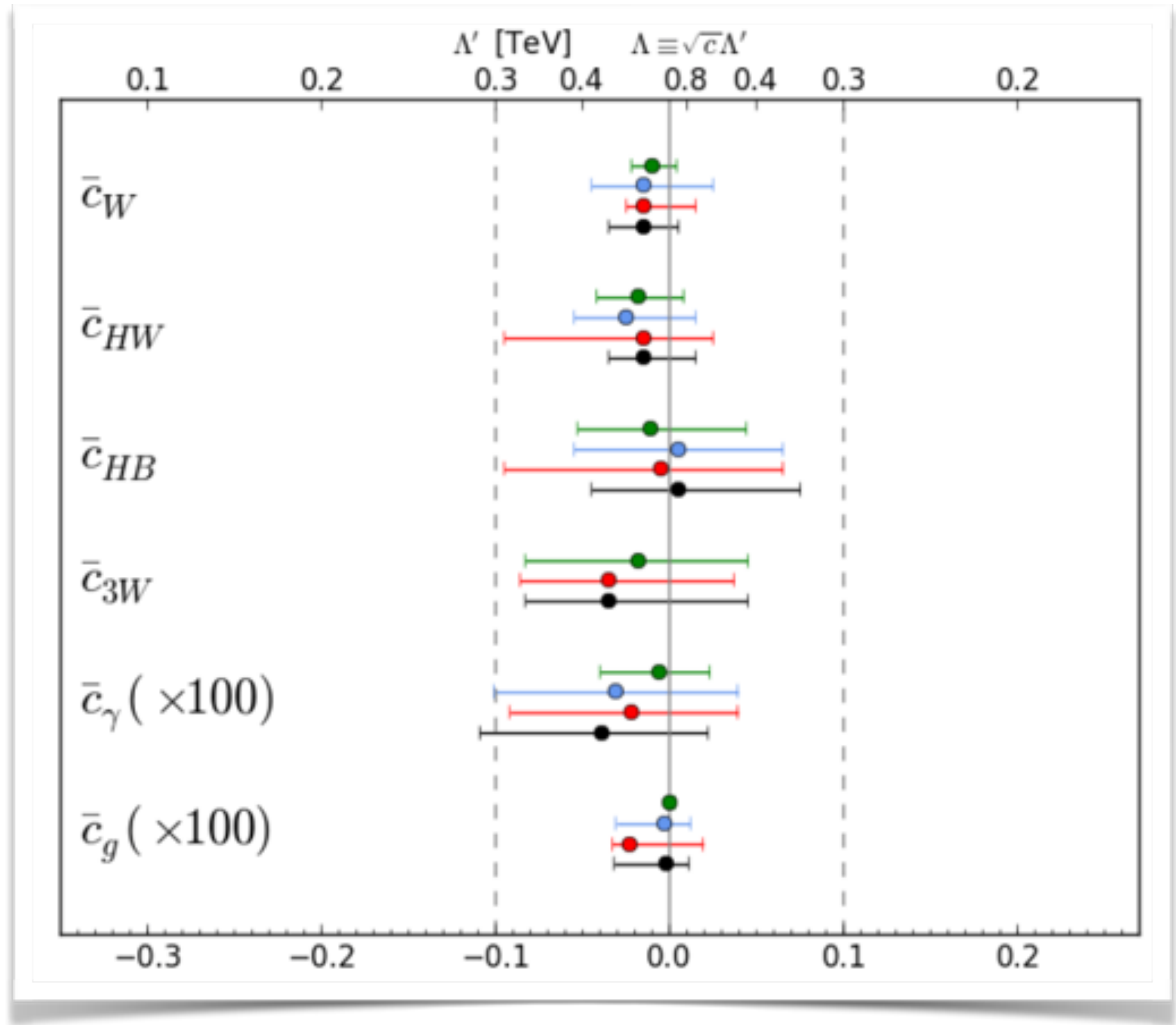
- Dim6: 59 operators,
  76 d.o.f, 2499 with N_g=3
- Dim8: 535 operators (N_g=1)

Example #1: Kappa -> HEFT

Higgs data combined with TGC
(Higgs, TGC, combination)

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



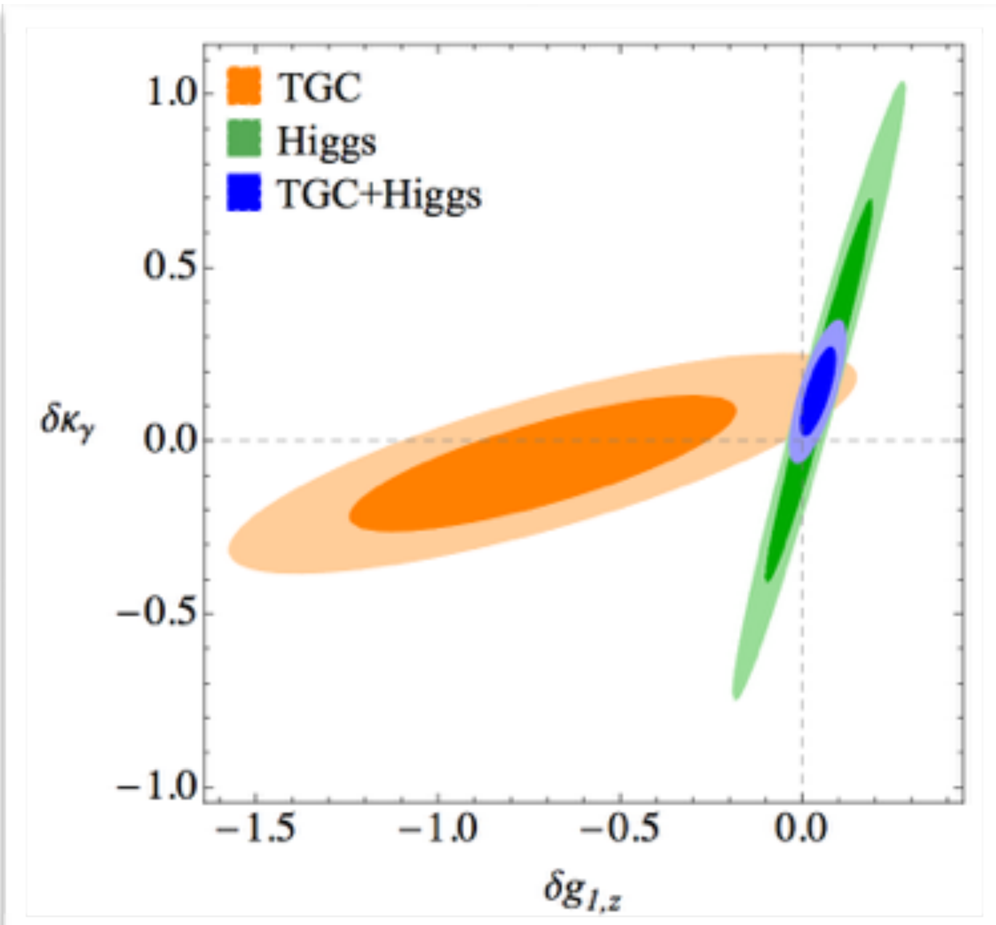


[J. Ellis et al. 2014]

See also [A. Falkowski, F. Riva 2014] [A. Pomarol, F. Riva 2013] [T. Corbett et al. 2015] [T. Corbett et al. 2013] [H. Belusca-Maito 2014] and many others…

Example #2: Use Higgs to fit TGC

[A. Falkowski et al. 2015]



Higgs is the new tool
to precision EW physics

"Accidental flat direction"

$$\delta g_{1,Z} = -0.83 \pm 0.34,\ \delta\kappa_\gamma = 0.14 \pm 0.05,\ \lambda_Z = 0.86 \pm 0.38,$$

$$\rho = \begin{pmatrix} 1 & -0.71 & -0.997 \\ \cdot & 1 & 0.69 \\ \cdot & \cdot & 1 \end{pmatrix}$$

[1411.0669 Falkowski and Riva]

To lift the degeneracy,

- Add Higgs data
- Use polarized beam
- Go to higher energy

Example #3: Top couplings

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- The **old** way: Anomalous couplings (AC), vertex functions…

$$\Gamma_\mu^{ttV}(k^2,\, q,\, \bar{q}) = ie\left\{\gamma_\mu\,\left(\widetilde{F}_{1V}^V(k^2) + \gamma_5 \widetilde{F}_{1A}^V(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\,\left(\widetilde{F}_{2V}^V(k^2) + \gamma_5 \widetilde{F}_{2A}^V(k^2)\right)\right\}.$$

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- The **modern** way: SM EFT

$$\Delta\mathcal{L} = \sum_i \frac{C_i}{\Lambda^2}O_i + h.c.$$

with

$$\begin{aligned} O_{tW} &= y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I \\ O_{tB} &= y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \\ O_{tG} &= y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A\,, \end{aligned}$$

and more

[arXiv: 0704.2809 Cao, Wudka, Yuan]
[arXiv: 0811.3842 Aguilar-Saavedra]
[arXiv:1008.3869 CZ and Willenbrock]

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	Gauge invariance
AC	×
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AC	×	×	×
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AC	×	×	×	×
EFT	✓	✓	✓	✓

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

and more

[arXiv: 0704.2809 Cao, Wudka, Yuan]
[arXiv: 0811.3842 Aguilar-Saavedra]
[arXiv:1008.3869 **CZ** and Willenbrock]

	Gauge invariance	Higher-order corrections	Complete description	Non-redundancy	Applied to off-shell top
AC	×	×	×	×	×
EFT	✓	✓	✓	✓	✓

Example #3: Top couplings

- The **old** way: Anomalous couplings (AC), vertex functions…

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^V(k^2) + \gamma_5\widetilde{F}_{1A}^V(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^V(k^2) + \gamma_5\widetilde{F}_{2A}^V(k^2)\right)\right\}.$$

- The **modern** way: SM EFT

$$\Delta\mathcal{L} = \sum_i \frac{C_i}{\Lambda^2} O_i + h.c.$$

with

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Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t)$, $M_{t\bar{t}}$, $\lvert y_{t\bar{t}}\rvert$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t)$, $M_{t\bar{t}}$, y_t, $y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t)$, $M_{t\bar{t}}$, y_t, $y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}$, $p_T(t)$, $\lvert y_t\rvert$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}$, $Z\gamma$, WW	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1405.0421
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CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				*W*-boson helicity fractions:			
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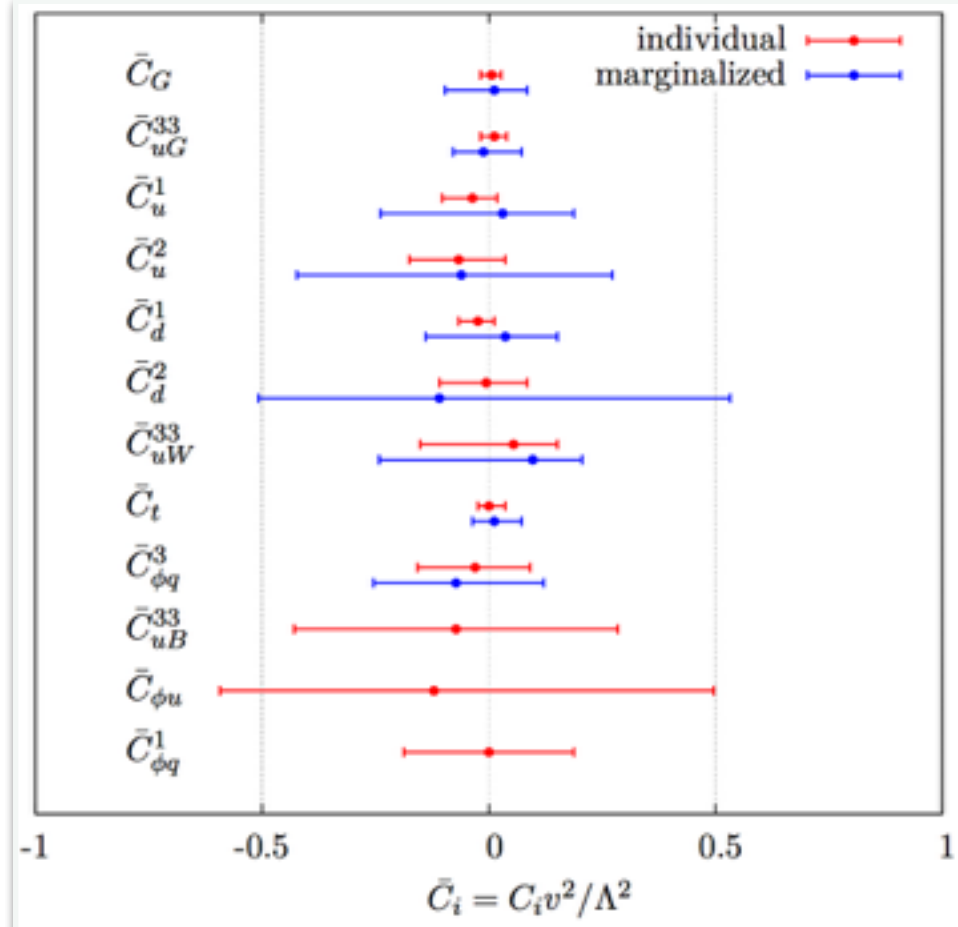
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				



[1512.03360 A. Buckley et al.]

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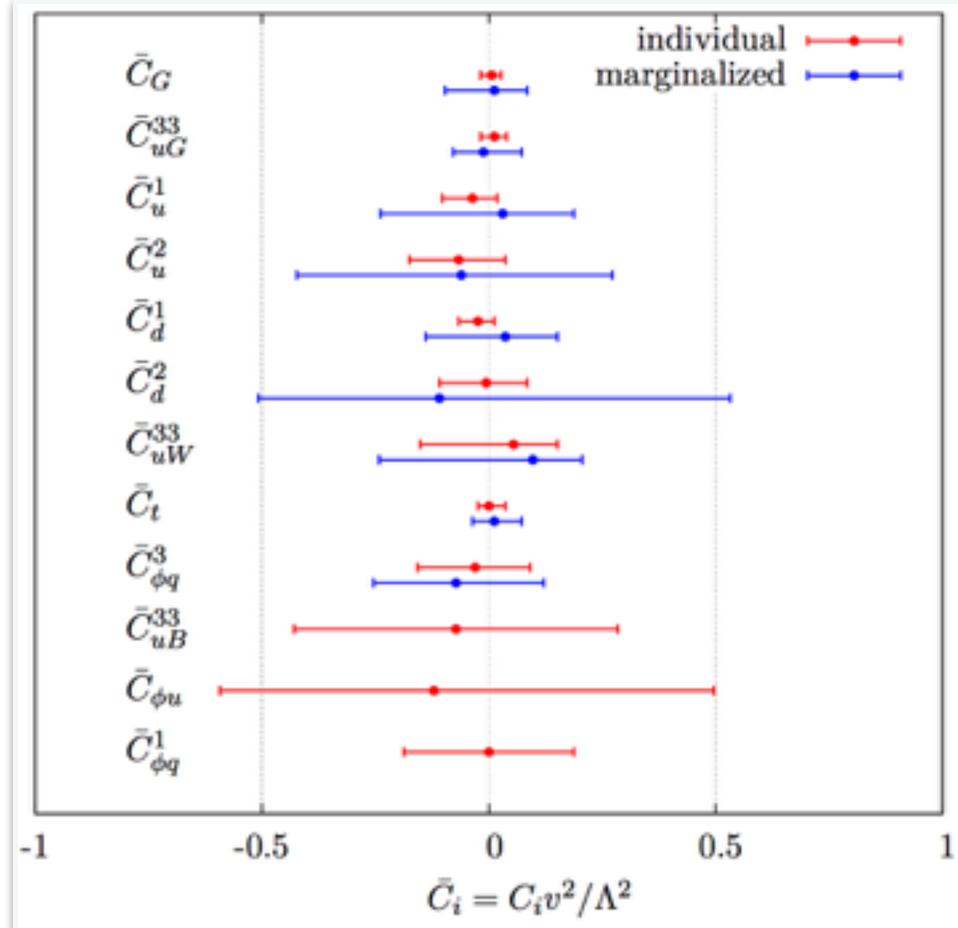

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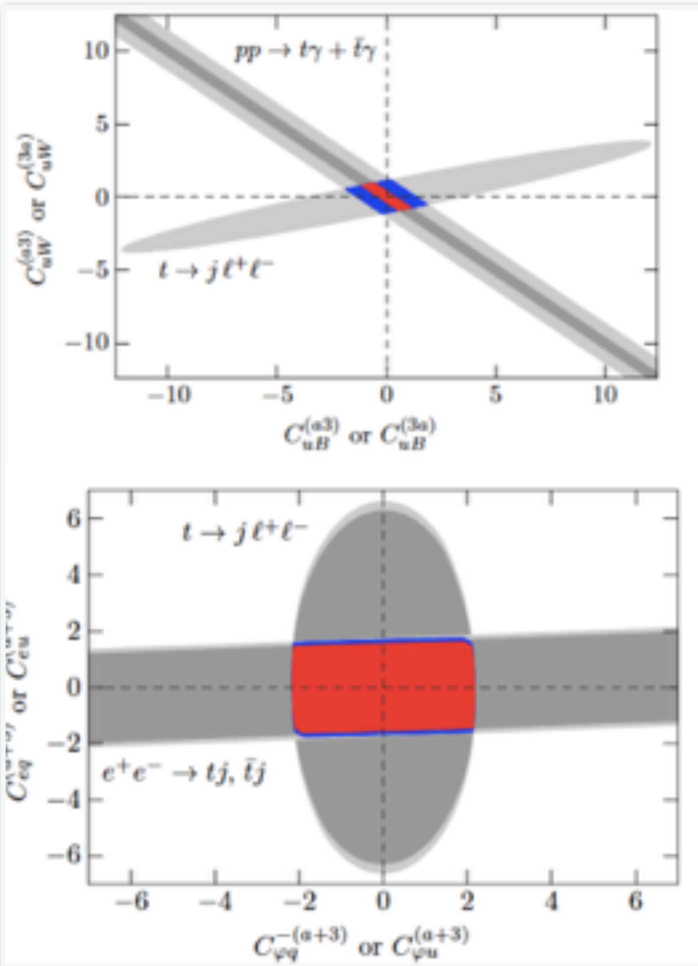

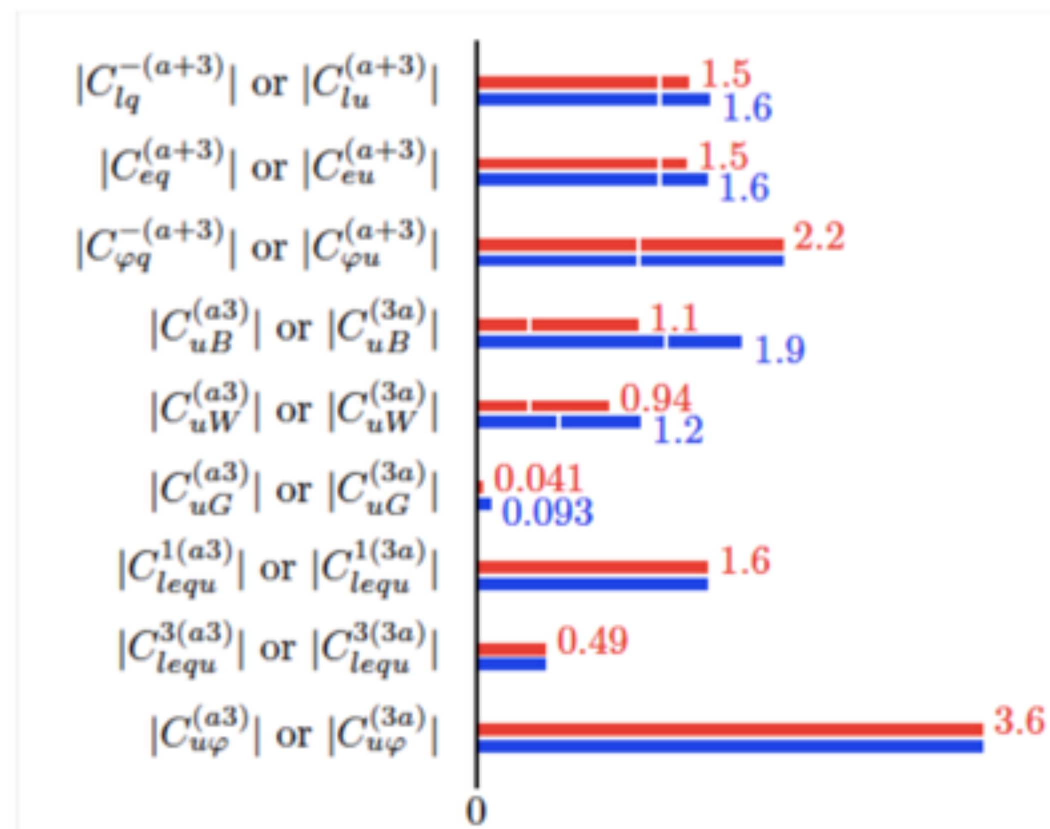

[1412.7166 Durieux, Maltoni, **CZ**]

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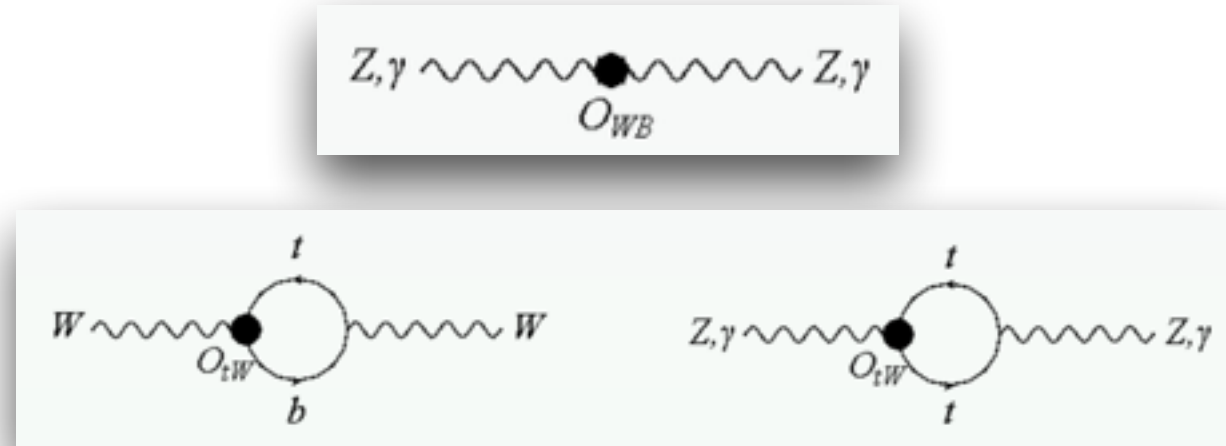
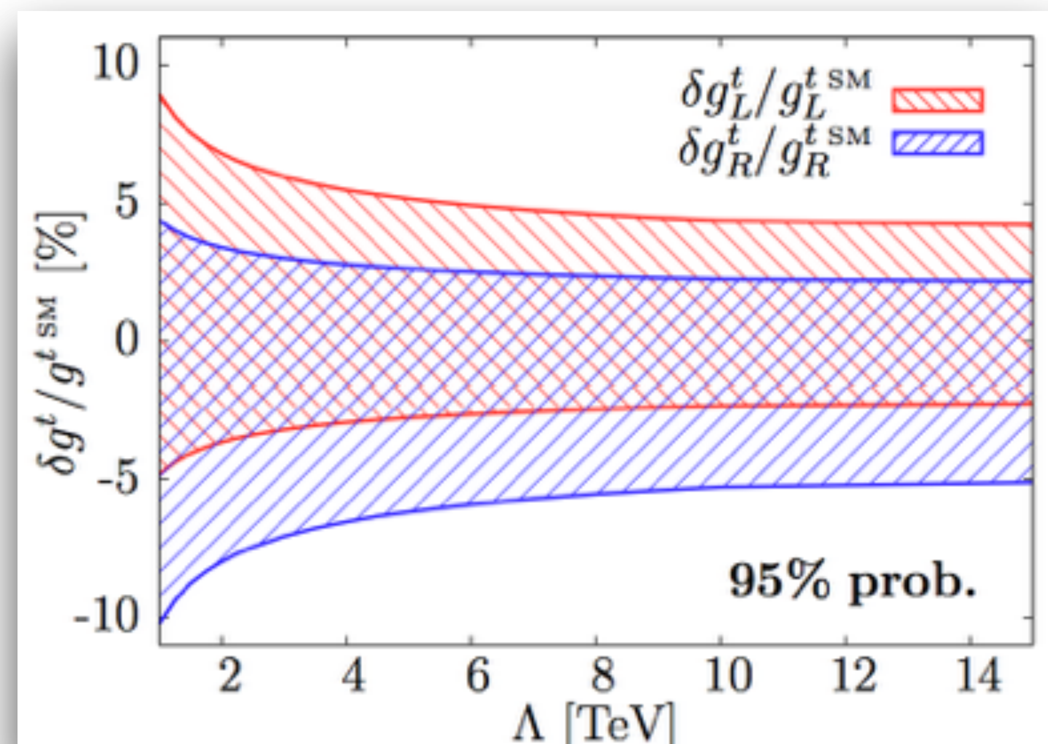
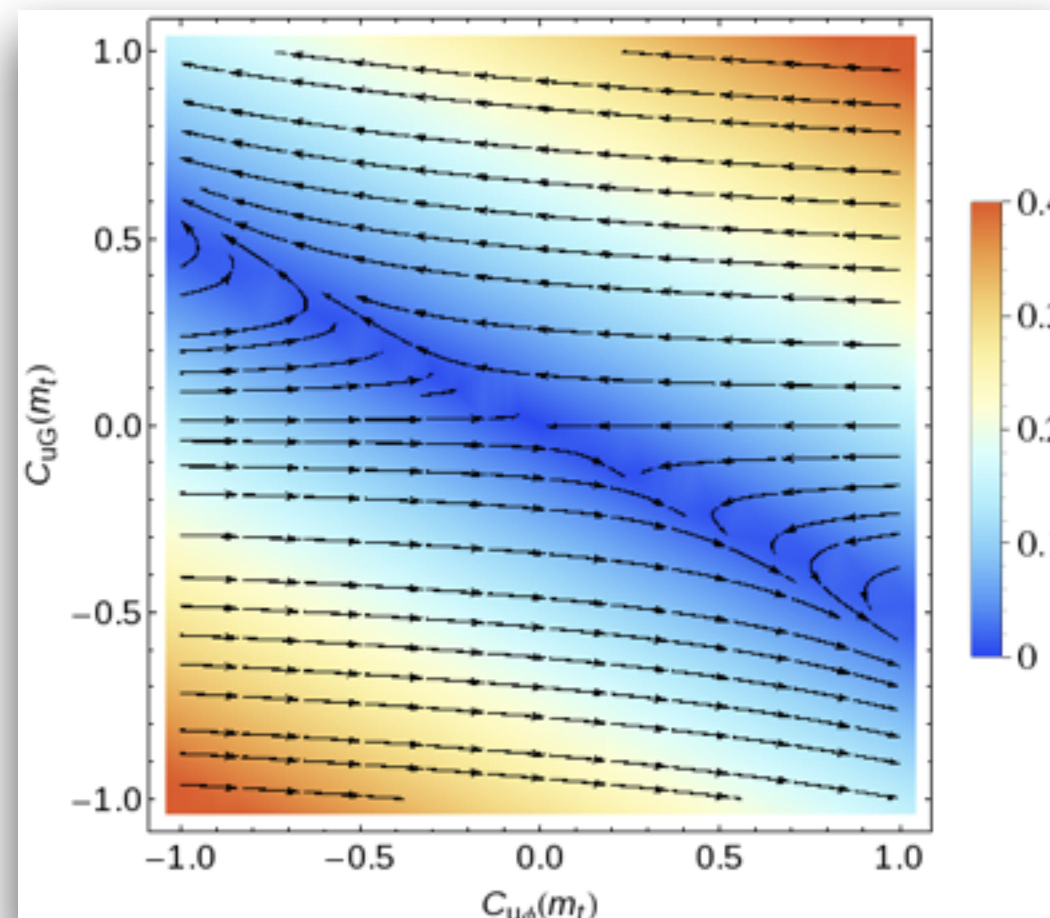
[1201.6670 **CZ**, Greiner, Willenbrock]



Coefficients	Electroweak data
$\left(C_{\phi q}^{(3)} + C_{\phi q}^{(1)}\right)/\Lambda^2$	0.016 ± 0.021
$\left(C_{\phi q}^{(3)} - C_{\phi q}^{(1)}\right)/\Lambda^2$	2.0 ± 2.7
$C_{\phi t}/\Lambda^2$	1.8 ± 1.9
$C_{\phi b}/\Lambda^2$	-0.16 ± 0.10
$C_{\phi\phi}/\Lambda^2$	
C_{tW}/Λ^2	-0.4 ± 1.2
C_{bW}/Λ^2	11 ± 13
C_{tB}/Λ^2	4.8 ± 5.3
C_{bB}/Λ^2	8 ± 19



[1507.00757 de Blas, Chala, Santiago]



[1404.1264 **CZ**]

[1312.2014 Alonso et al.]

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  - NLO predictions and MC tools.
  - …

[1601.06163, **CZ**]
[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou ,**CZ**]
[1503.08841 D.B. Franzosi, **CZ**]
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[D. Y. Shao et al. 2011] [J. Gao et al. 2009] [J. J. Liu et al. 2005]

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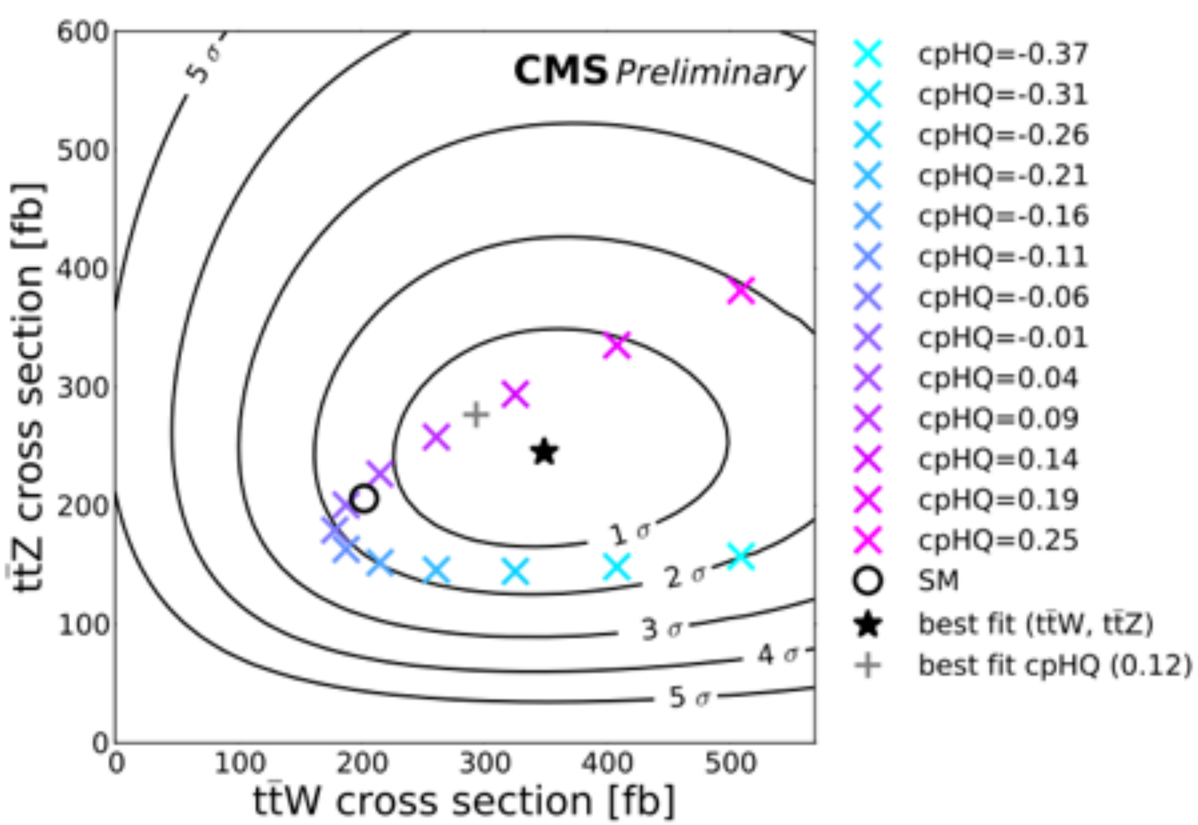
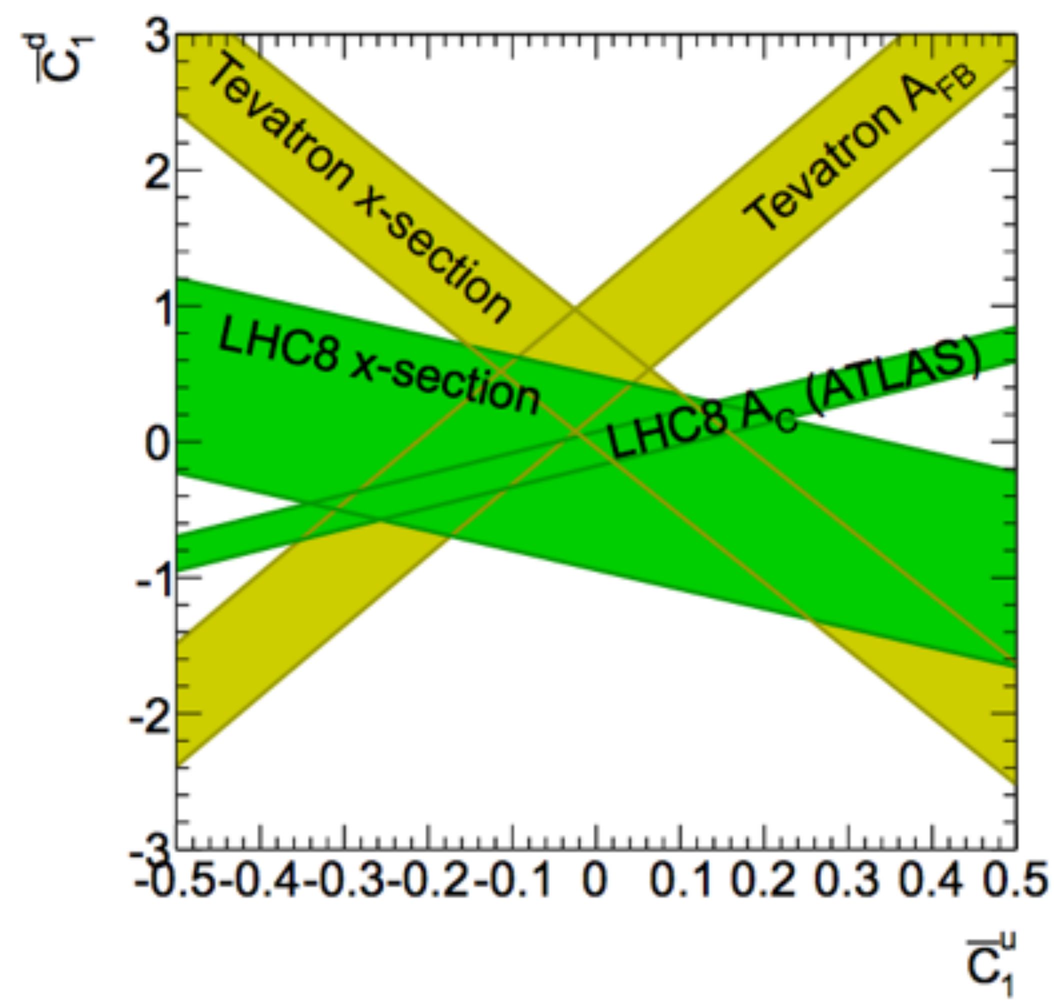
- Experiment side, also accepted by the community.

CMS PAS TOP-14-021

ttZ+ttW



[1512.07542 Perello Rosello, Vos]



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➡ These kind of reasonings eventually lead to a new and lively field: **SM EFT @ NLO**

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MC: bridging theory with experiments

Theory

Experiment

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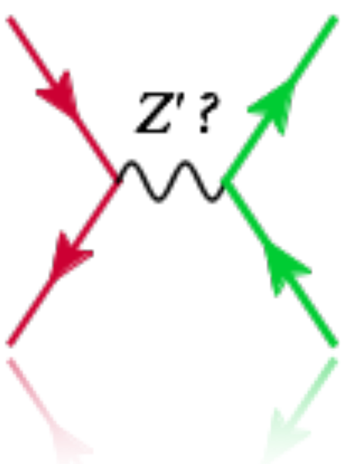

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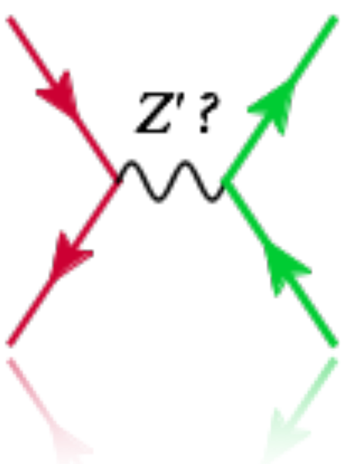
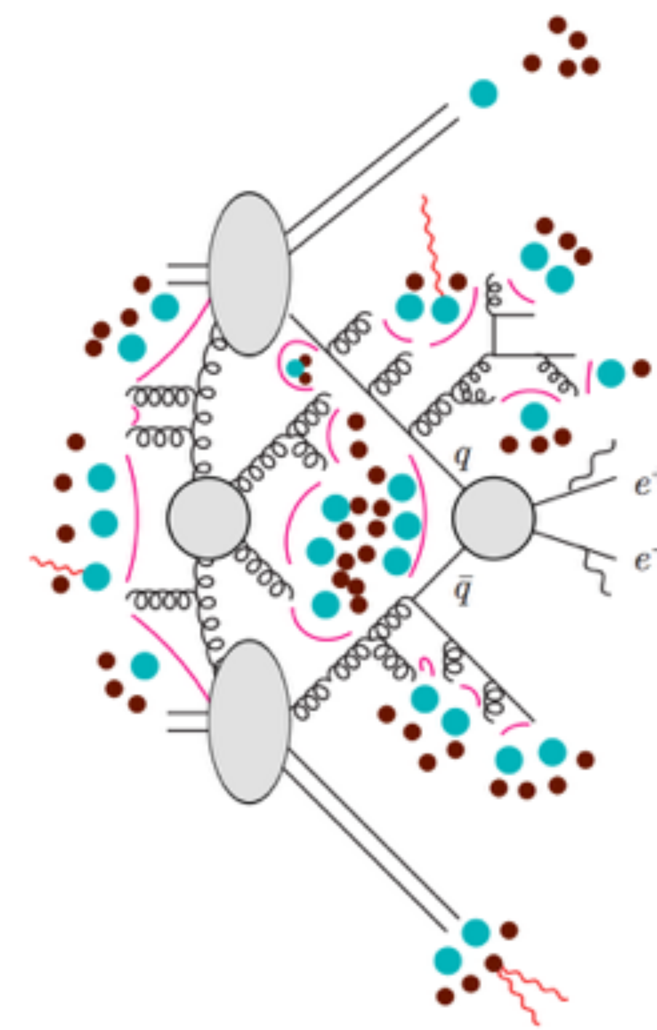


Experimentalists face:



Experiment

Search for NP signal at LHC

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peak

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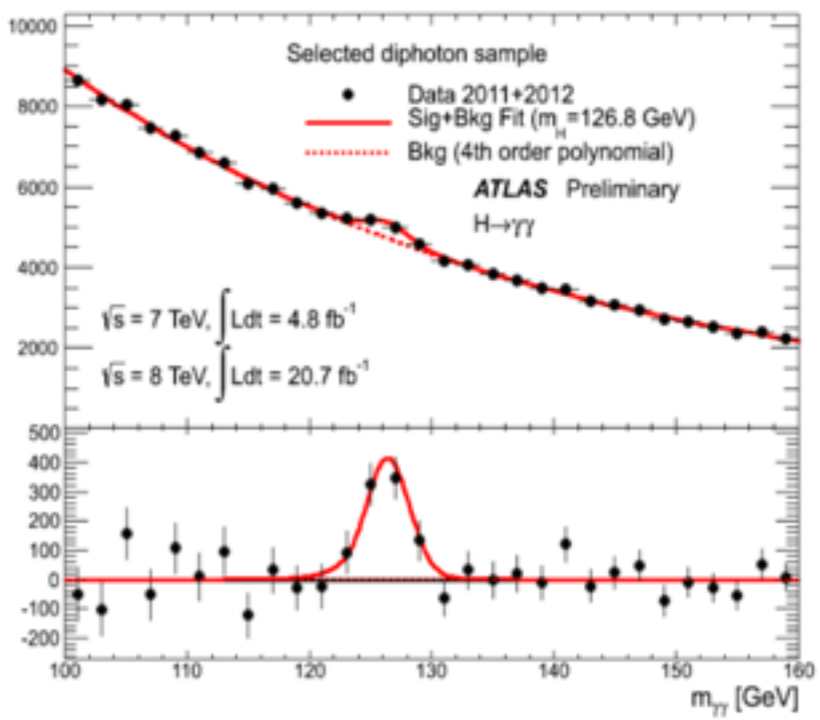

Background measured from data. TH needed only for **parameter extraction**.

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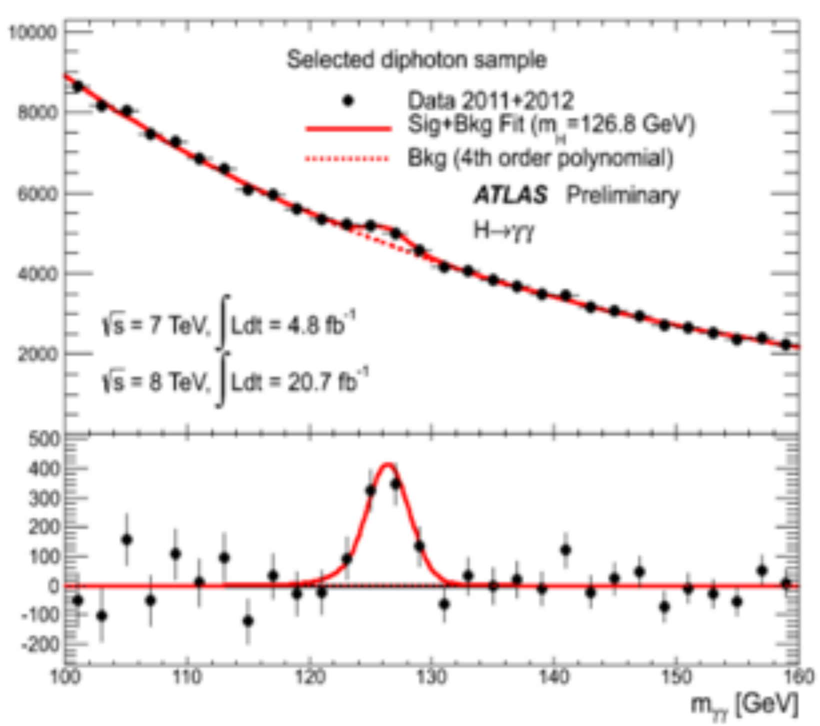

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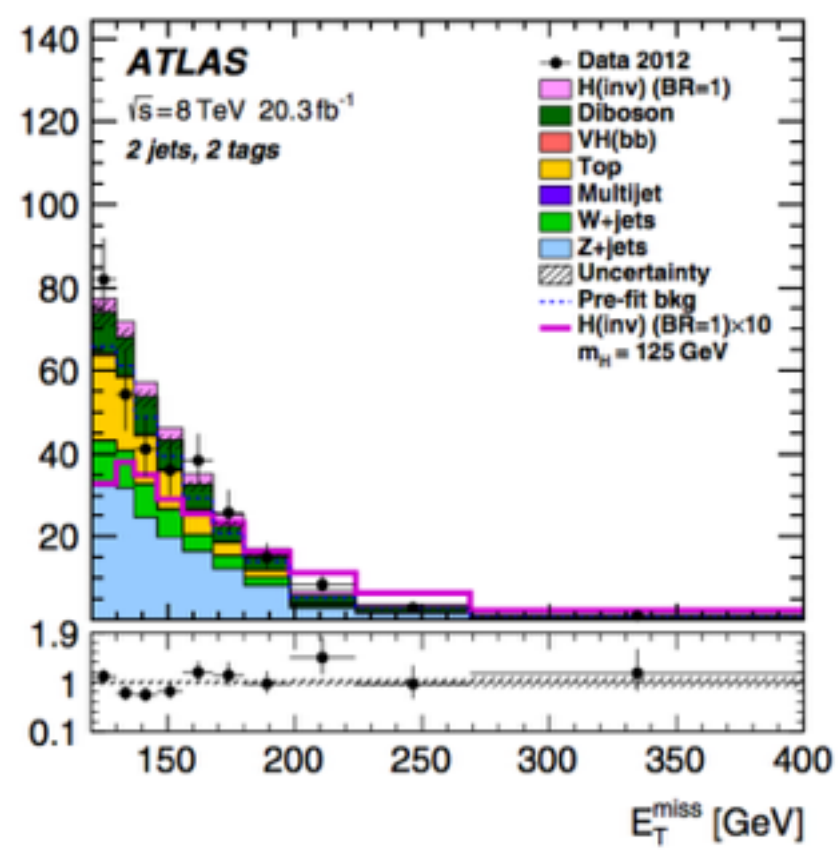
shape

$$pp \to VH(\to inv.)$$



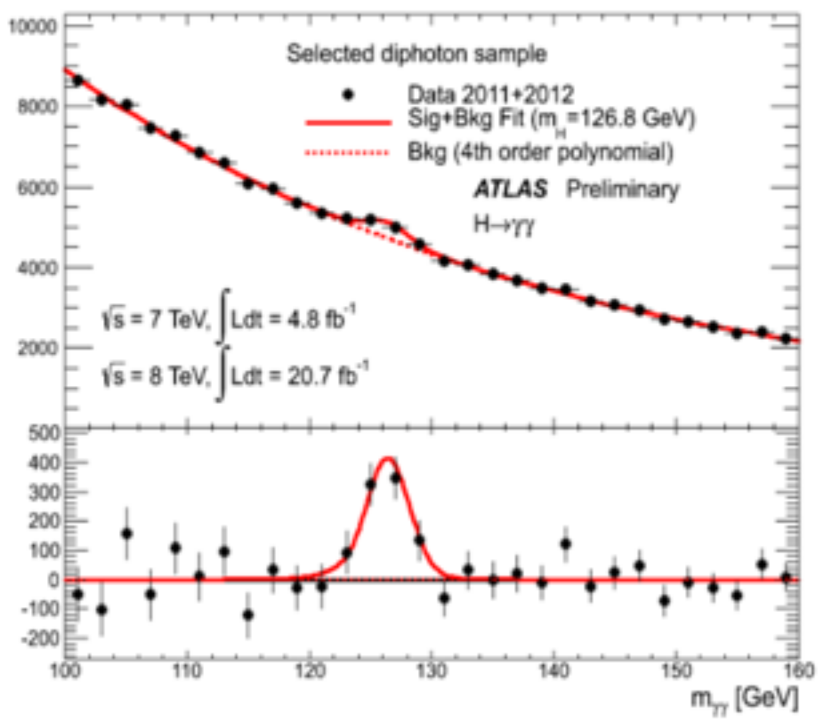
Background shapes are needed. Flexible MC turned and validated with data.

Search for NP signal at LHC

Accurate and experimental friendly MC predictions range from being <u>very useful to strictly needed</u>.

peak

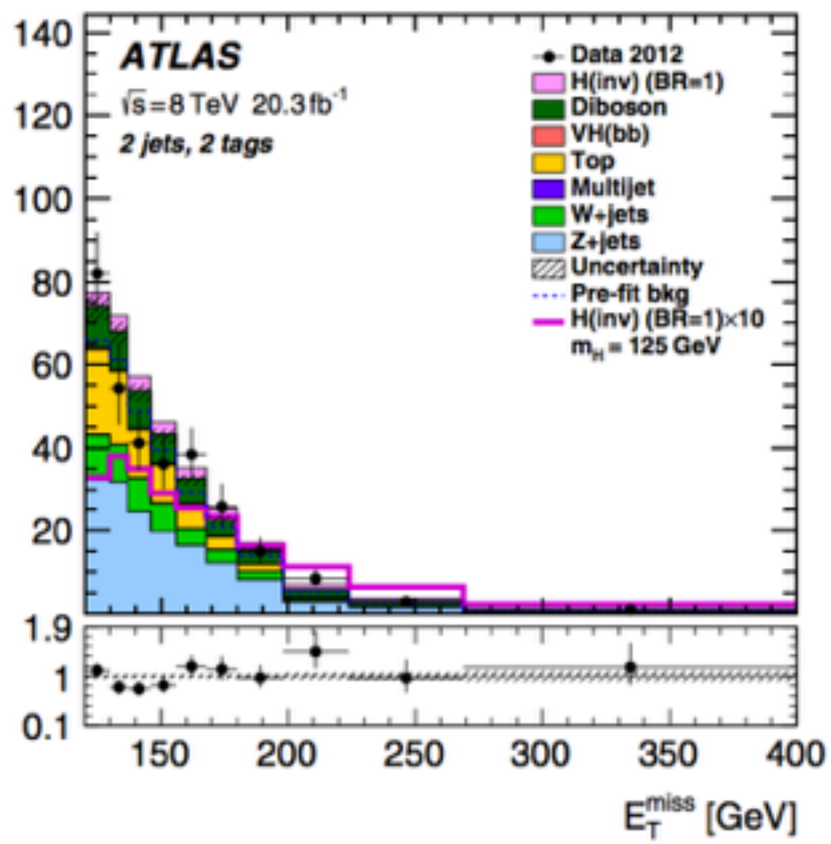
$$pp \to H \to \gamma\gamma$$



Background measured from data. TH needed only for **parameter extraction**.

shape

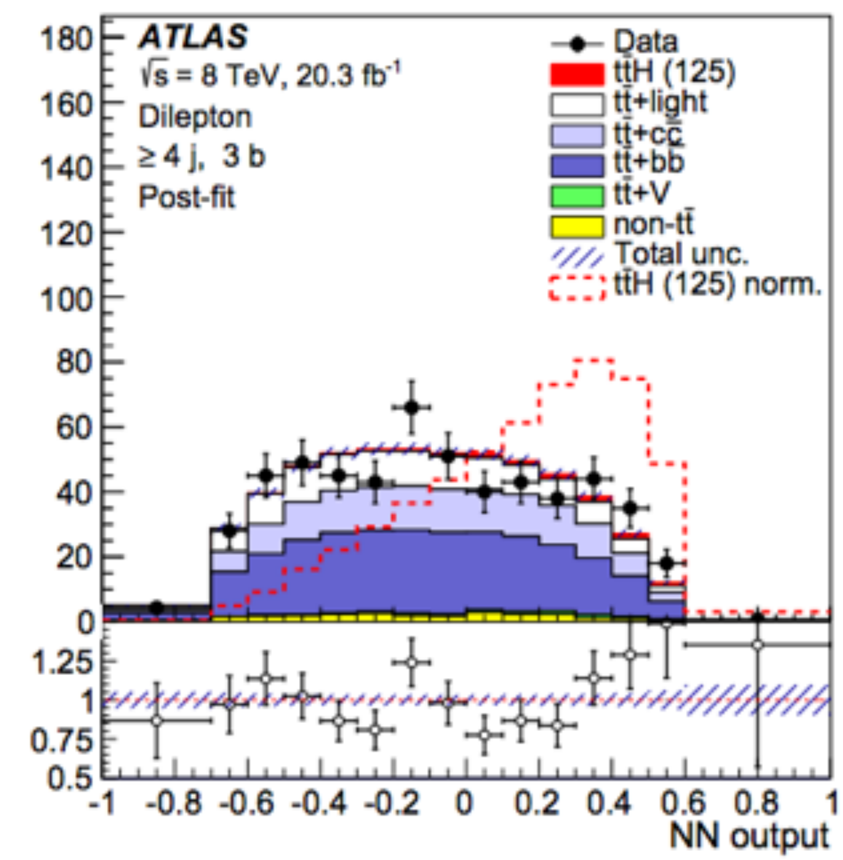
$$pp \to VH(\to inv.)$$



Background shapes are needed. Flexible MC turned and validated with data.

discriminant

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



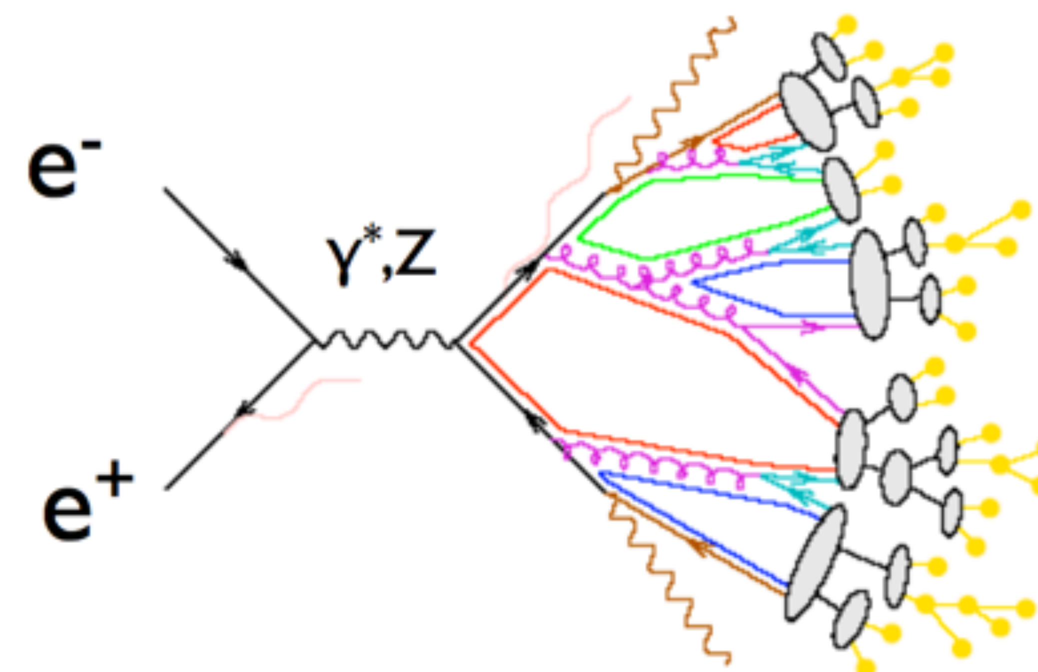
MC for both **background** and **signal** are needed. MVA relies on all features of events.

Search for NP signal at LHC

- Optimism: New Physics could be hiding somewhere. We need to be more smart to dig it out.
- Advanced EXP techniques: SM measurements and exclusions are particularly sensitive to the accuracy of the MC simulations.
- BSM flexibility: We need MC that are able to predict the pheno of the unexpected.
- Mass distribution: MC's in the hands of every TH/EXP might turn out to be the best overall strategy for discovering the unexpected.

Making predictions at the LHC

- Inclusive (ME)
- Parton level
  FeynCalc, FormCalc,
  MadGraph, Whizard, CompHEP,…
- Fully exclusive (PSEG)
  Shower & Had.: Pythia, Herwig, Sherpa
  Merging: CKKW, MLM
  Matching: MC@NLO, POWHEG,…
- Fully exclusive and automated
  MadGraph5_aMC@NLO (Whizard, Sherpa)



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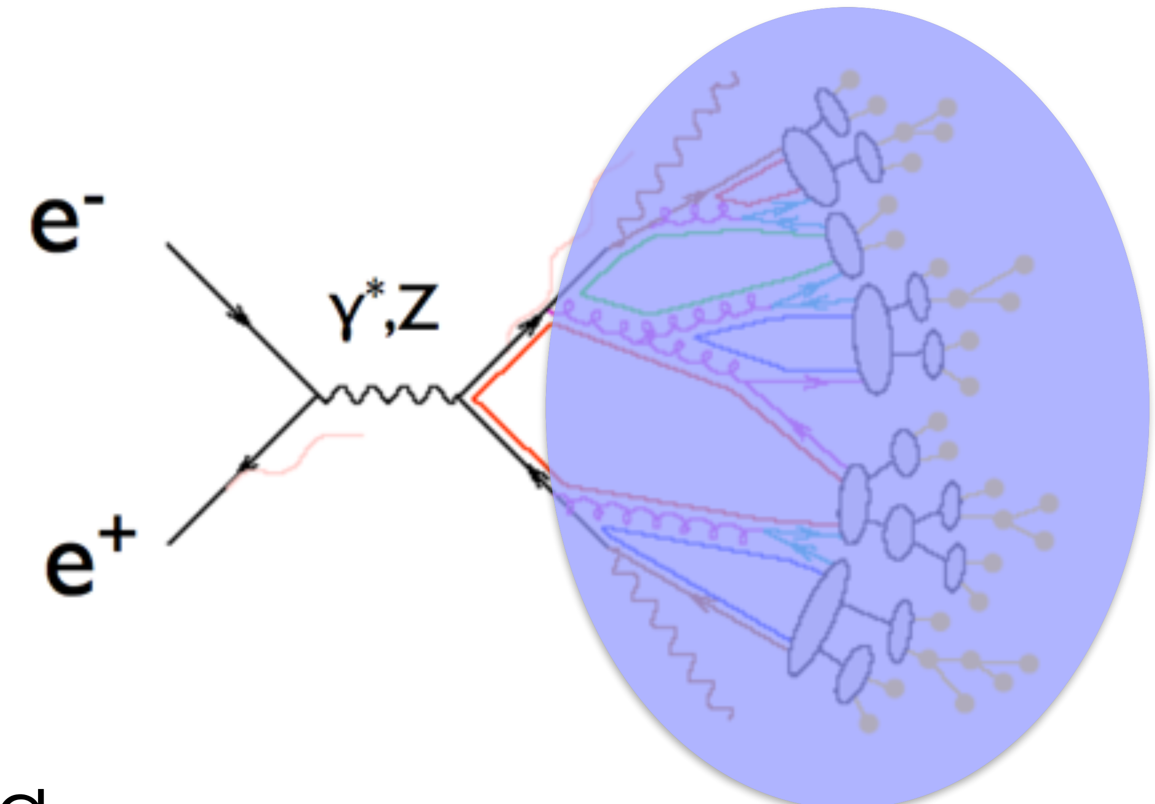

Making predictions at the LHC

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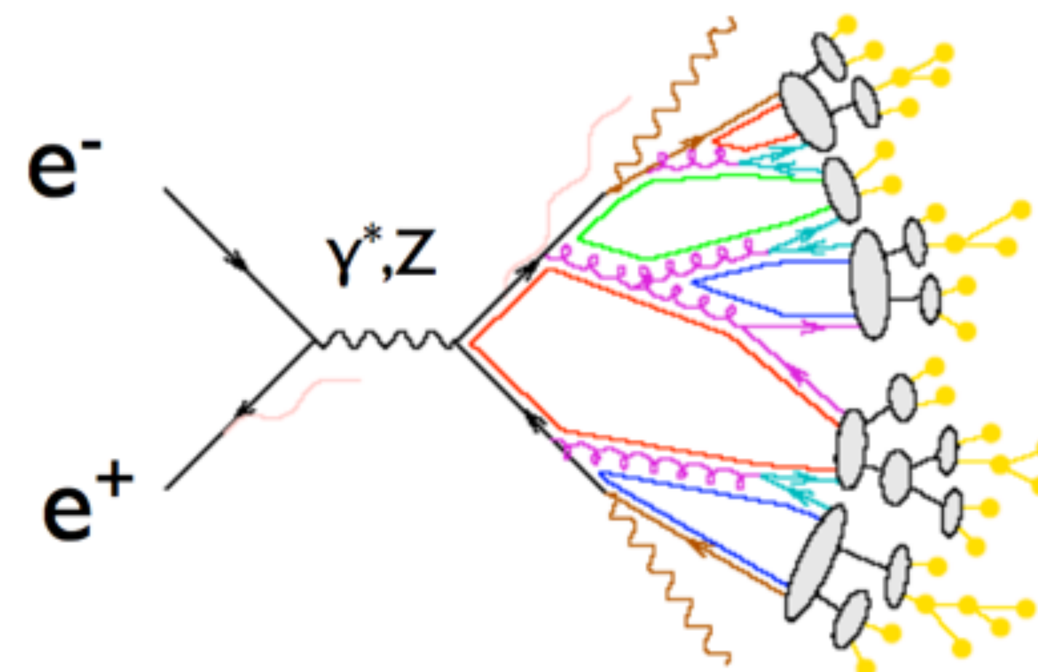
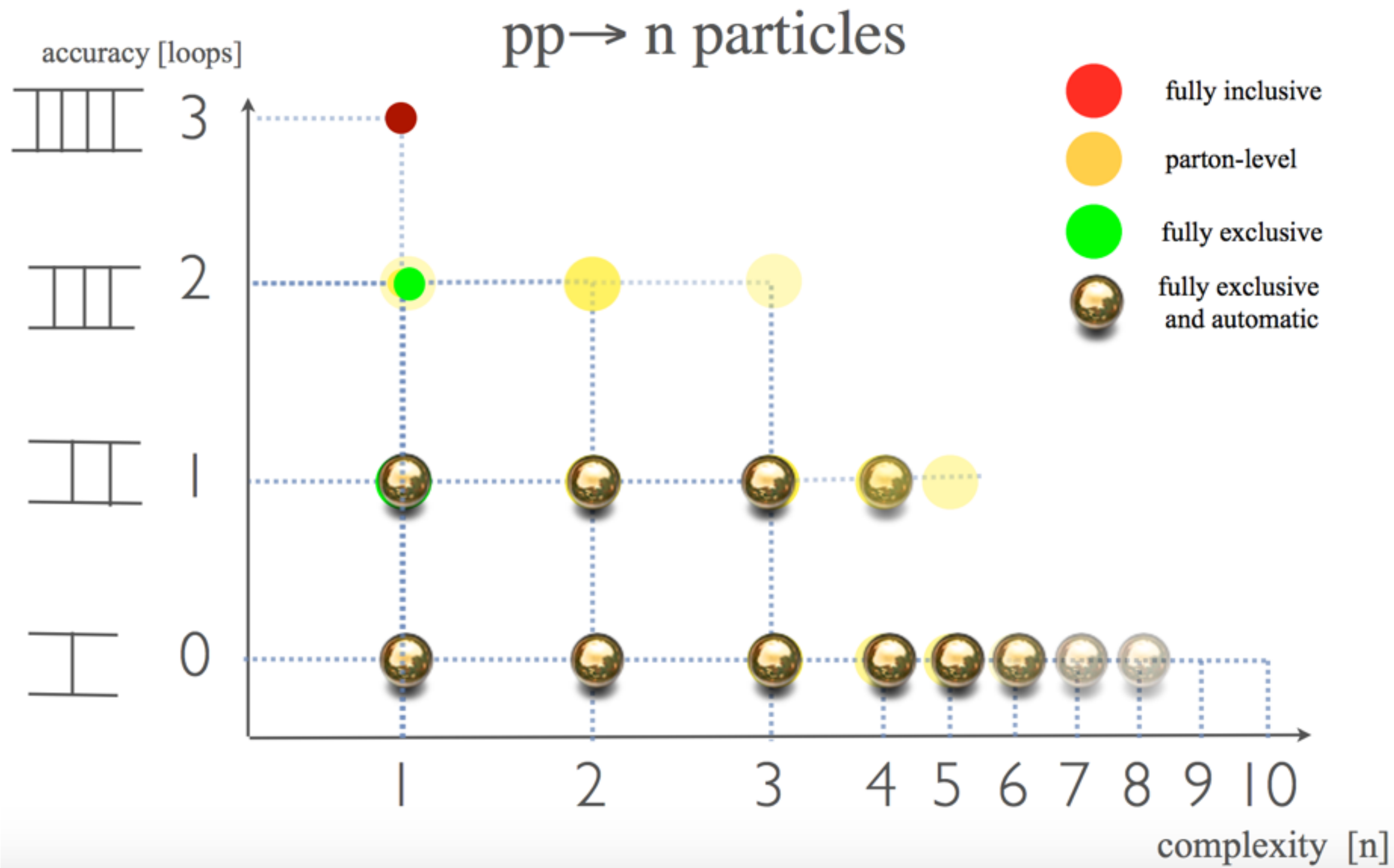


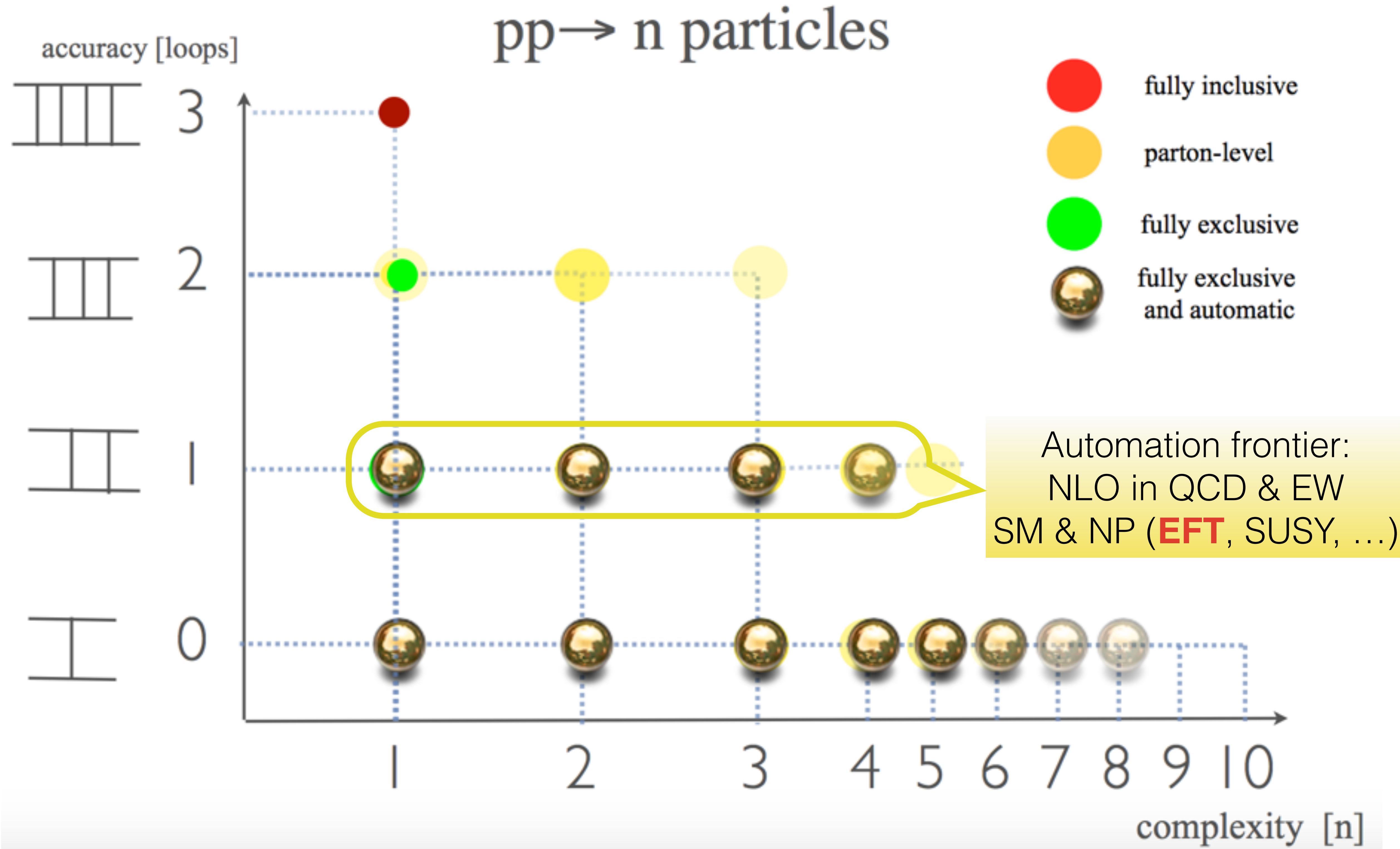
Why automatic?

- **Academic completion**: meaning that computation up to a certain accuracy is completely solved.
  - MCFM: O(50) processes, over ~15 years. Implemented one by one by hand.
  - MadGraph: Once upgraded to NLO, ALL SM processes become available.
- **Efficiency**: For top, already ~20 processes, ~50 operators.
- **Mass distribution**: easy access for the entire community. Both TH/EXP can benefit from the most advanced TH results, without having to know technical detail.

Making predictions at the LHC



Making predictions at the LHC



Outline

- Background
- Developments on MC for top EFT
- Outlook

Status of NLO automation

- Fully automated in the SM (2014)
    - In principle arbitrary process.
    - fNLO or matched to PSEG

[J. Alwall et al. 2014]

Status of NLO automation

- Fully automated in the SM (2014)
  - In principle arbitrary process.
  - fNLO or matched to PSEG
- On-going efforts in New Physics
  - SUSY (C. Degrande, B. Fuks, V. Hirschi, J. Proudom, H.-S. Shao)
  - Dark matter (A. Martini, B.Fuks, K. Mawatari, J. Wang, **CZ, ...**)
  - EFT (C. Degrande, I. Tsinikos, E. Vryonidou, CZ)
  - …

[J. Alwall et al. 2014]

Top EFT fully exclusive and automated

	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

We aim to provide: (in particular for experimentalists)

- An automated tool for testing **top-couplings & FCNC**, with **QCD NLO + PSMC**.
- Which in principle takes care of all top-quark processes and operators.

	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- Decays and FCNC direct t production is available analytically.
[1404.1264 **CZ**], [1305.7386 F. Maltoni, **CZ**], [1004.0898 J. J. Zhang et al.]

	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- Decays and FCNC direct t production is available analytically.
  [1404.1264 **CZ**], [1305.7386 F. Maltoni, **CZ**], [1004.0898 J. J. Zhang et al.]
- FCNC associated productions have been implemented.
  [1412.5594 Degrande, Maltoni, Wang, **CZ**] http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

ttg | ttZ/γ, tbW | ttH | qqtt | ggH

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

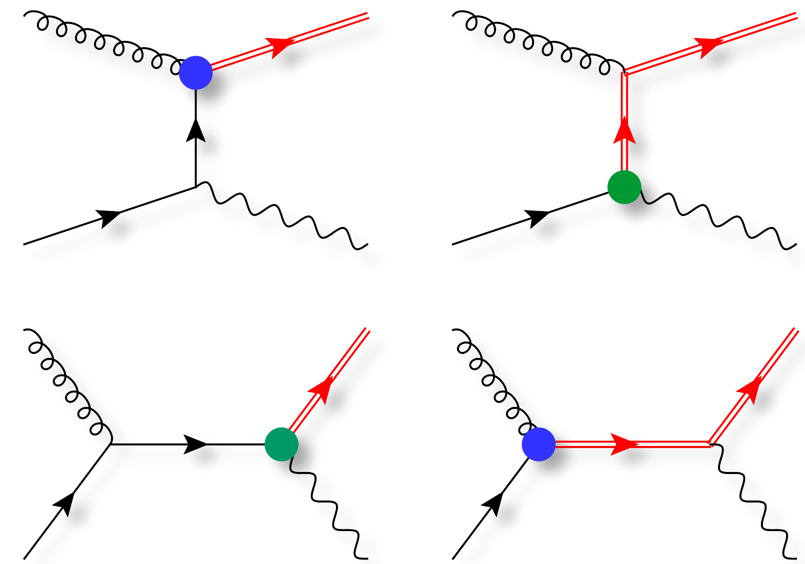
c.f. [Y. Wang et al. 2012][B. H. Li et al. 2011]
[Y. Zhang et al. 2011] [J. Gao et al. 2011]

tqZ/γ | tqg | tqH | lltq

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

Top-FCNC operators



available at

http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

Description of the model & reference

The top effective theory model contains the dimension-six operators affecting top flavor changing processes. The UFO model can be used for computation at the NLO in QCD.

Phys.Rev. D91 (2015) 034024: C. Degrande, F. Maltoni, J. Wang, C. Zhang, *Automatic computations at next-to-leading order in QCD for top-quark flavor-changing neutral processes*

Phys.Rev. D91 (2015) 074017: G. Durieux, F. Maltoni, C. Zhang, *Global approach to top-quark flavor-changing interactions*

Model files

The UFO (TopFCNC.tar.gz) and the FeynRules model (TopEFTFCNC.fr) are available

Will be used by ATLAS single top and top properties sub-group

$$O_{\varphi q}^{(3,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}_i \gamma^\mu \tau^I Q)$$
$$O_{\varphi q}^{(1,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i \gamma^\mu Q)$$
$$O_{\varphi u}^{(i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_i \gamma^\mu t)$$
$$O_{uB}^{(i3)} = g_Y(\bar{q}_i \sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}, \quad O_{uW}^{(i3)} = g_W(\bar{q}_i \sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{uG}^{(i3)} = g_s(\bar{q}_i \sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}, \quad O_{u\varphi}^{(i3)} = (\varphi^\dagger \varphi)(\bar{q}_i t)\tilde{\varphi}\,,$$

Fully automated pp>tH @ NLO+PS

Fully automated
pp>tH @ NLO+PS

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

$$O_{\varphi q}^{(1,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i\gamma^\mu Q)$$

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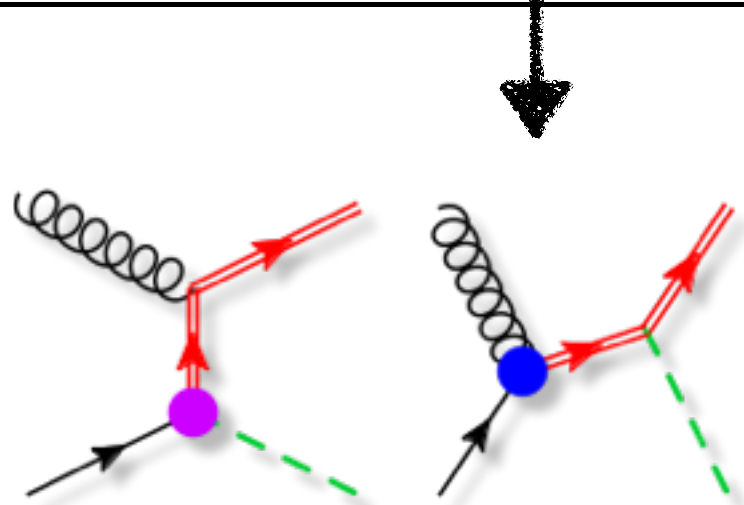

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$$O_{uB}^{(i3)} = g_Y(\bar{q}_i \sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}, \quad O_{uW}^{(i3)} = g_W(\bar{q}_i \sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

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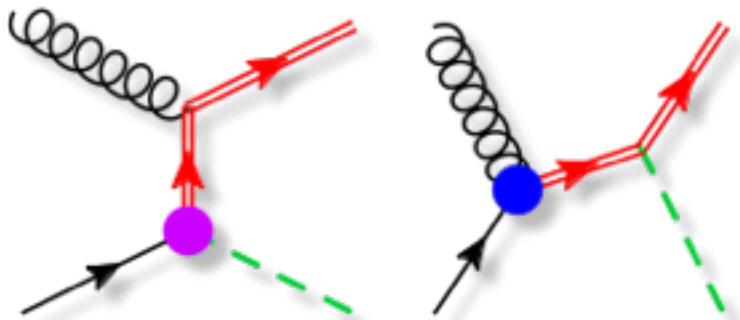
Fully automated pp>tH @ NLO+PS



```
>import model TopFCNC
>generate p p > t h [QCD]
>output some_DIR
>launch
```

$$O_{\varphi q}^{(3,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}_i \gamma^\mu \tau^I Q)$$
$$O_{\varphi q}^{(1,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i \gamma^\mu Q)$$
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$$O_{uG}^{(i3)} = g_s(\bar{q}_i \sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}, \quad O_{u\varphi}^{(i3)} = (\varphi^\dagger\varphi)(\bar{q}_i t)\tilde{\varphi},$$

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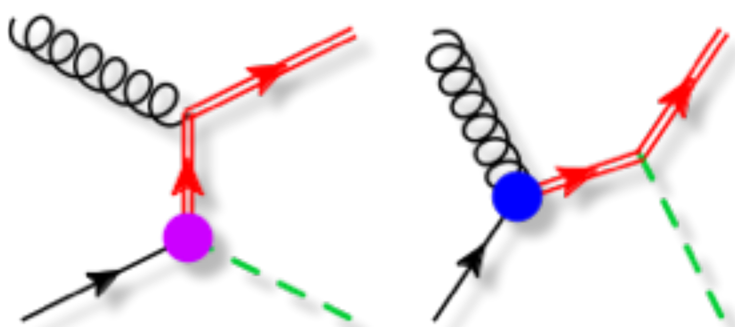

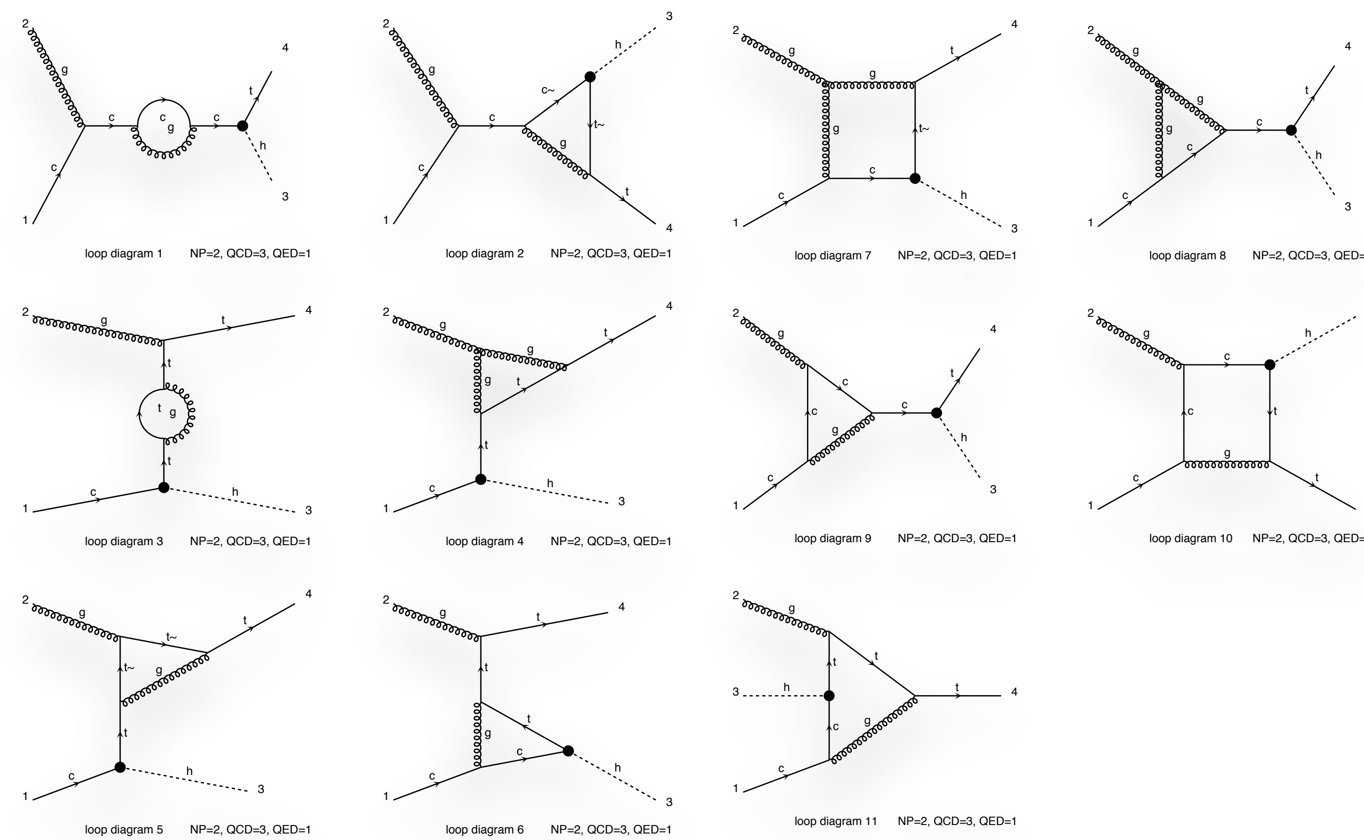


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$$O_{\varphi q}^{(1,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i \gamma^\mu Q)$$
$$O_{\varphi u}^{(i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_i \gamma^\mu t)$$
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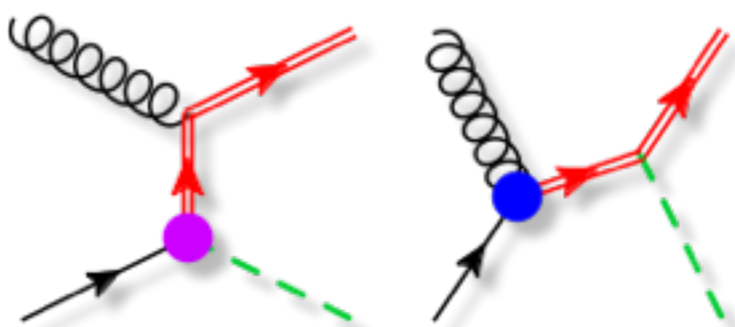
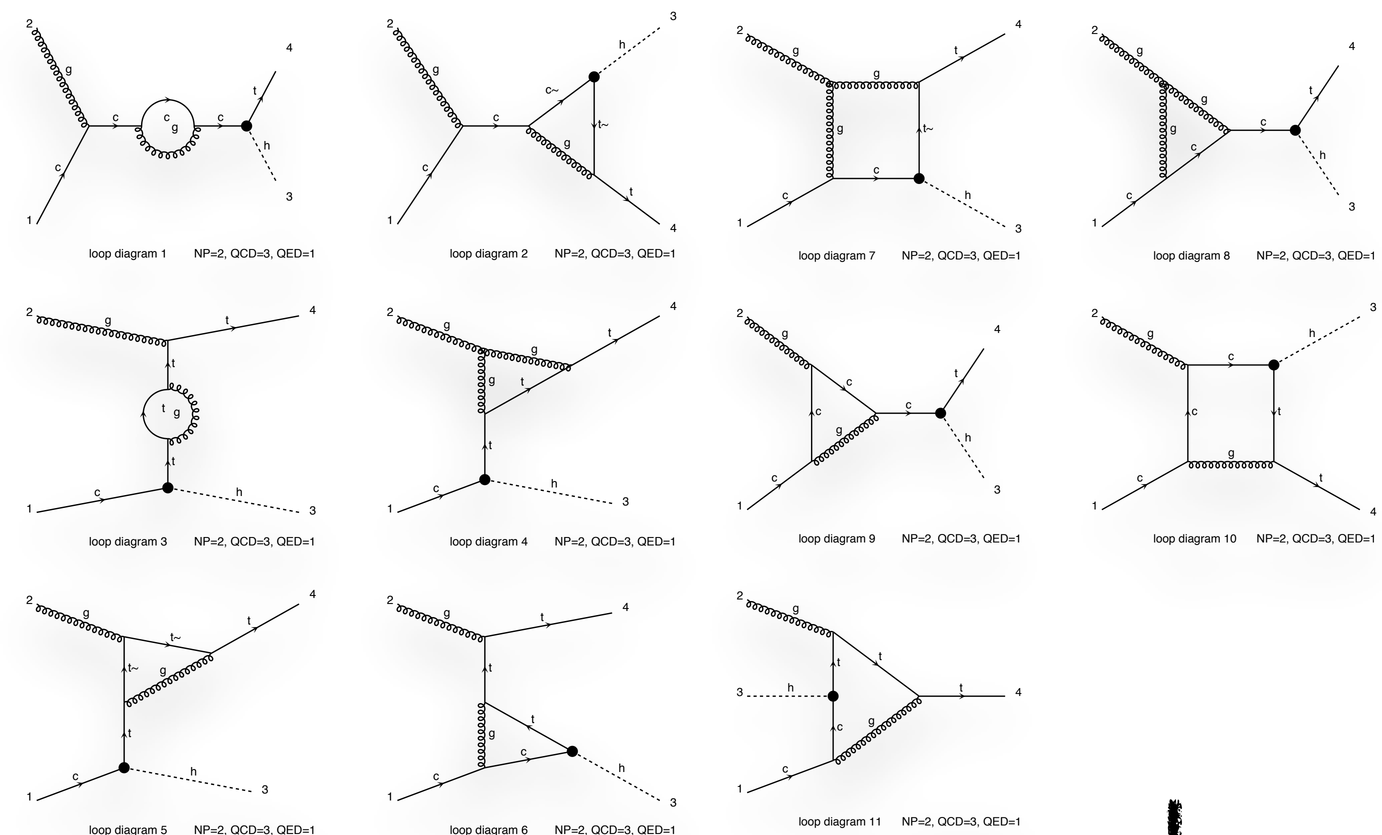
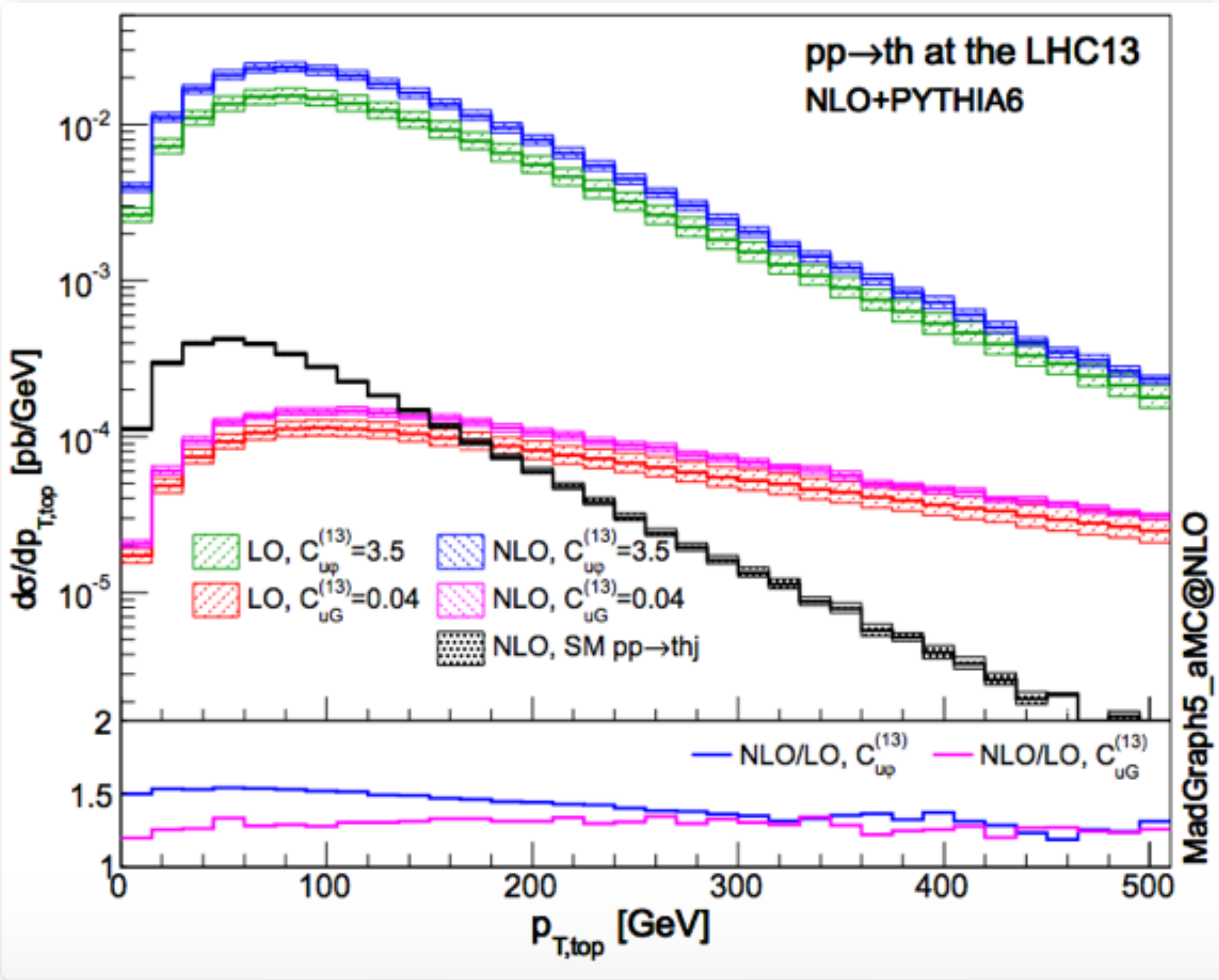
Fully automated pp>tH @ NLO+PS



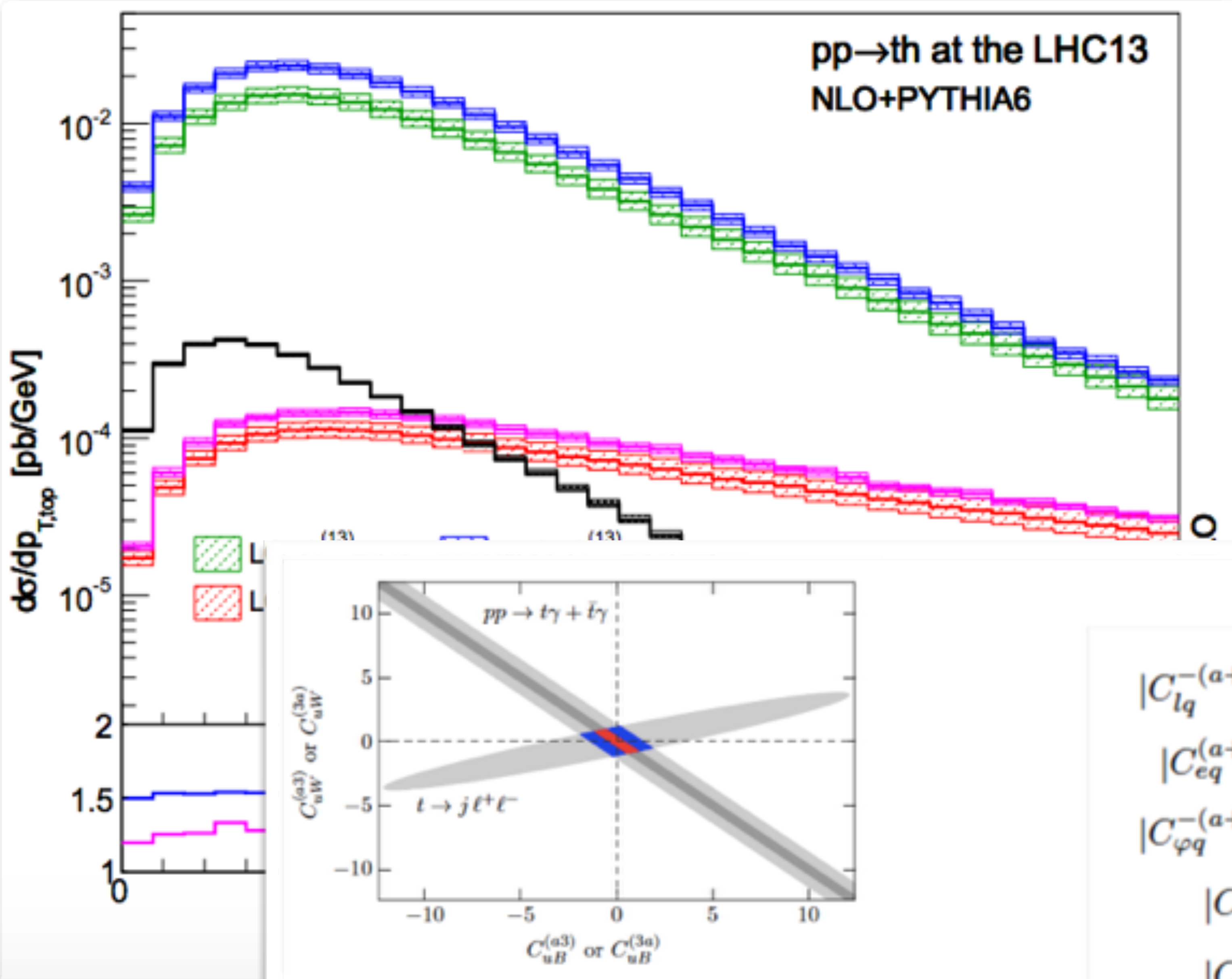


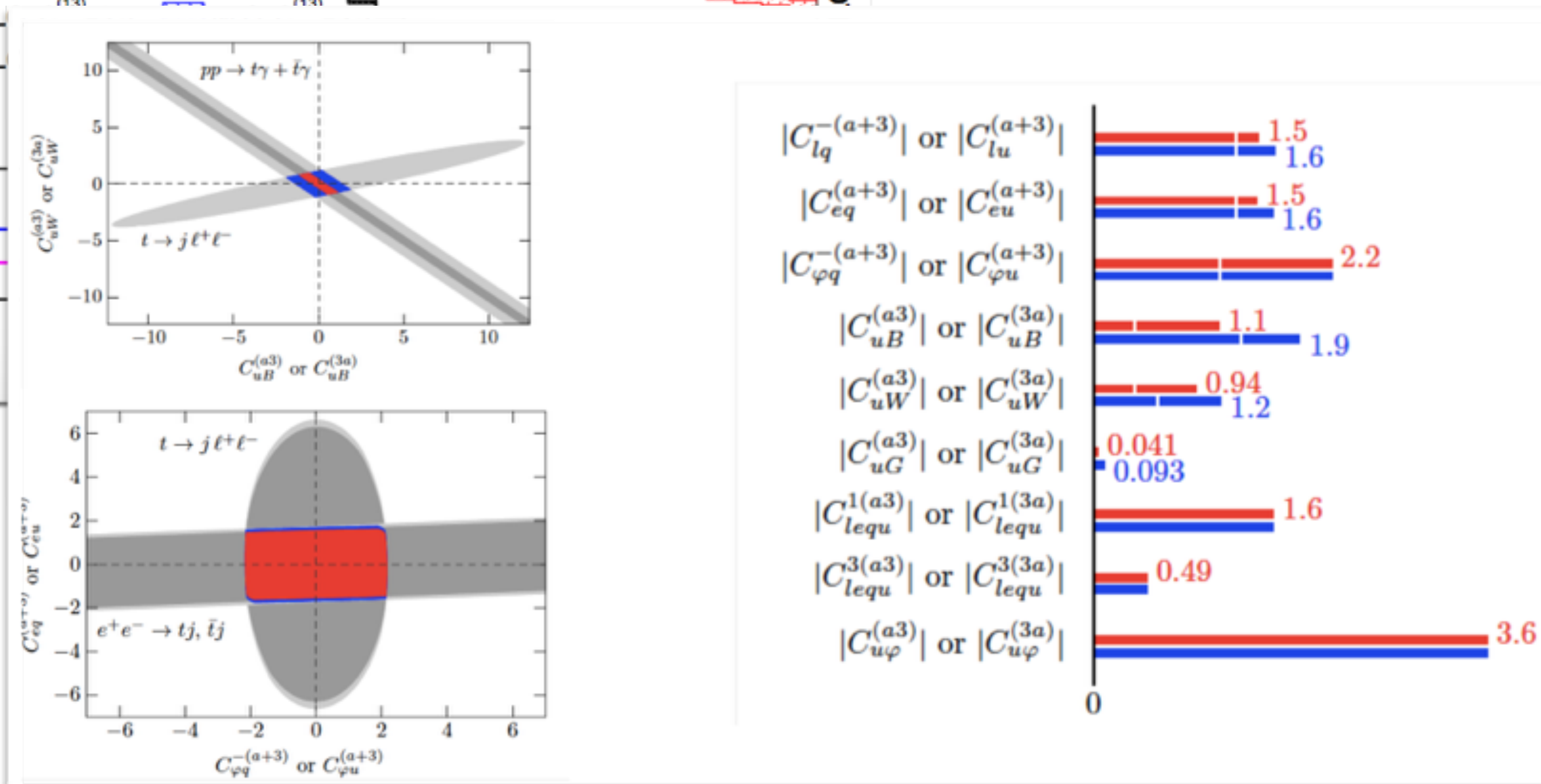

```
>import model TopFCNC
>generate p p > t h [QCD]
>output some_DIR
>launch
```

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{u\varphi}^{(13)} = 3.5$	2603	+13.0% -11.0%	3858	+7.4% -6.7%
$C_{uG}^{(13)} = 0.04$	40.1	+16.5% -13.2%	50.7	+4.0% -5.2%
$C_{u\varphi}^{(23)} = 3.5$	171	+9.7% -8.7%	310	+7.3% -6.3%
$C_{uG}^{(23)} = 0.09$	9.53	+11.0% -9.7%	16.6	+5.5% -5.1%


pp→th at the LHC13
NLO+PYTHIA6
LO, C(13)uφ=3.5
NLO, C(13)uφ=3.5
LO, C(13)uG=0.04
NLO, C(13)uG=0.04
NLO, SM pp→thj
dσ/dpT,top [pb/GeV]
10-2
10-3
10-4
10-5
2
1.5
1
NLO/LO, C(13)uφ
NLO/LO, C(13)uG
0
100
200
300
400
500
pT,top [GeV]
MadGraph5_aMC@NLO

[1412.7166 Durieux, Maltoni, **CZ**]





- Decays and FCNC direct t production is available analytically.
  [1404.1264 **CZ**], [1305.7386 F. Maltoni, **CZ**], [1004.0898 J. J. Zhang et al.]
- FCNC associated productions have been implemented.
  [1412.5594 Degrande, Maltoni, Wang, **CZ**] http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

	ttg	ttZ/γ, tbW					ttH	qqtt	ggH
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

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Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O^{(3)}_{\phi q}$	$O^{(1)}_{\phi q}$	$O^{(1)}_{\phi u}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- First automation in flavor-conserving case: ttbar with chromo-dipole
  [1503.08841 D.B. Franzosi, **CZ**]

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$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

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	tqZ/γ					tqg	tqH	lltq
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$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- First automation in flavor-conserving case: ttbar with chromo-dipole
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- Complete top-EW operators [1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, **CZ**], [1601.06163, **CZ**]

Top-EW operators

O_{tG}, O_{tW}, O_{tB} mixing

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

- $tt\gamma/ttg$, EM/color dipole

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

- tbW
  - V/A

$$O^{(3)}_{\varphi Q} = i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{Q}\tau^I \gamma^\mu Q) \qquad O_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

  - Weak dipole

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

- ttZ
  - V/A

$$O^{(1)}_{\varphi Q} = i(\varphi^\dagger D_\mu \varphi)(\bar{Q}\gamma^\mu Q) \qquad O_{\varphi u} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu t)$$

  - Weak dipole O_{tW}

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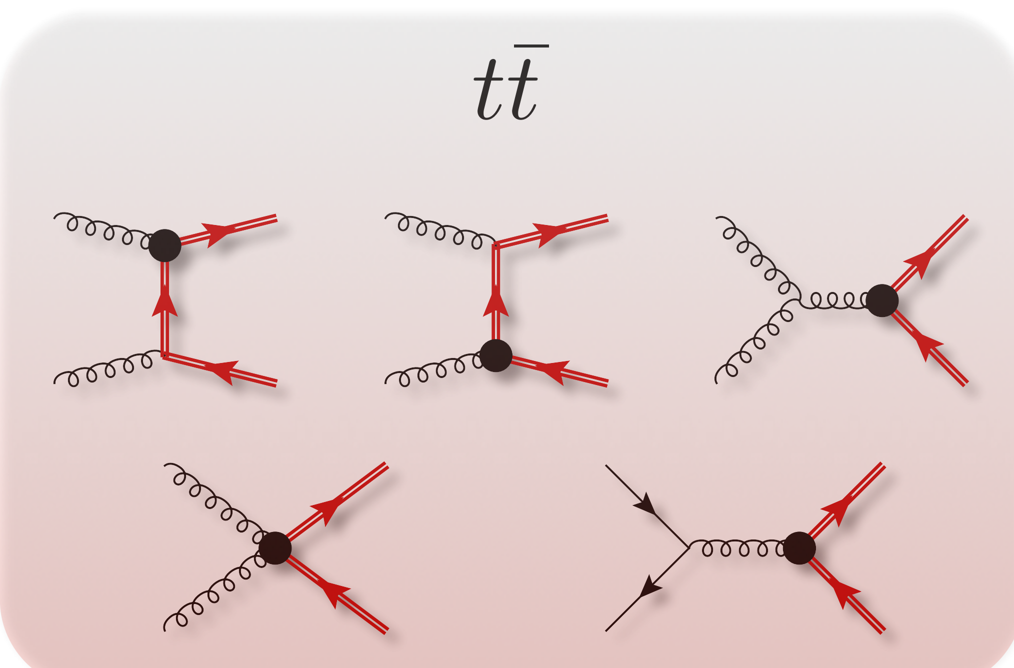

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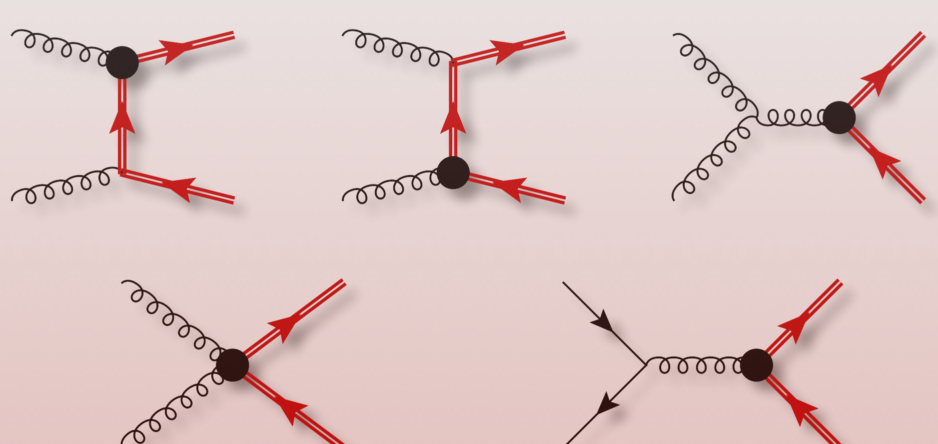
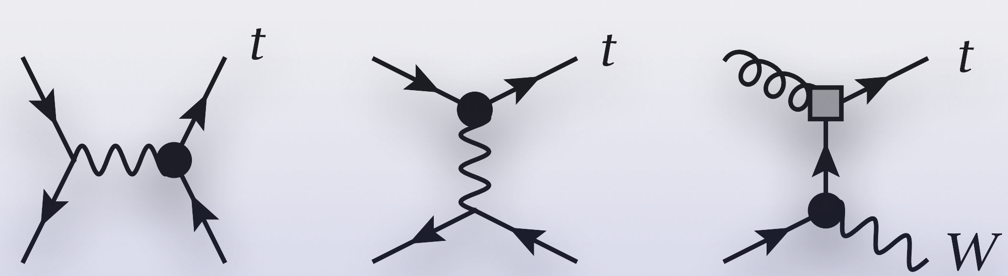
$t\bar{t}$



single top



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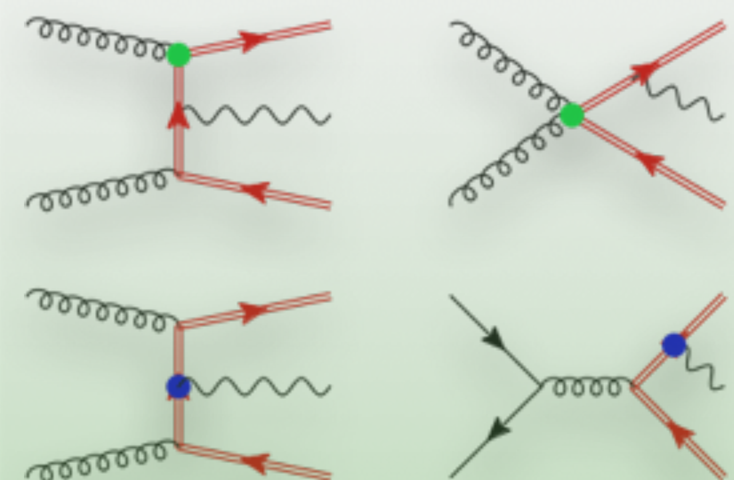
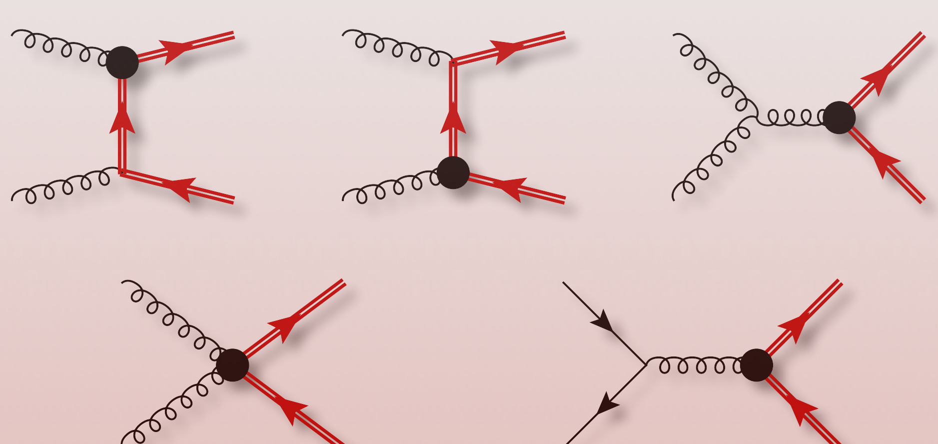
$t\bar{t}\gamma/t\bar{t}Z$



cf. [1404.1005, 1501.0593 Rontsch and Schulze]

$t\bar{t}$



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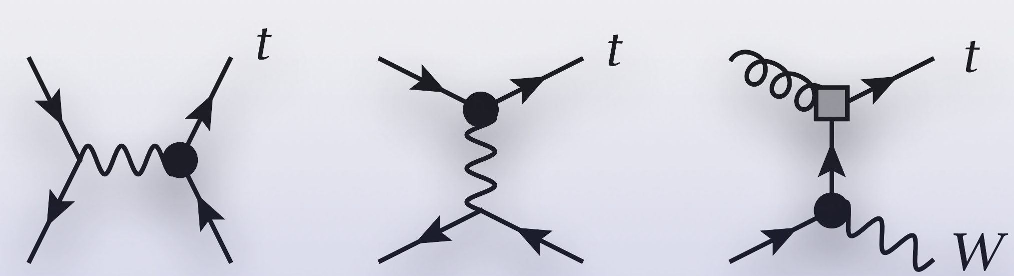

- Operator fit with NLO xsecs: improved limits

Current limit from top-pair
cross section measurements:
[-1.10, 0.41] (LO) -> [-0.50, 0.25] (NLO)

[1503.08841 D.B. Franzosi, CZ]

- Operator fit with NLO xsecs: improved limits
- Corrections on distributions can be more important

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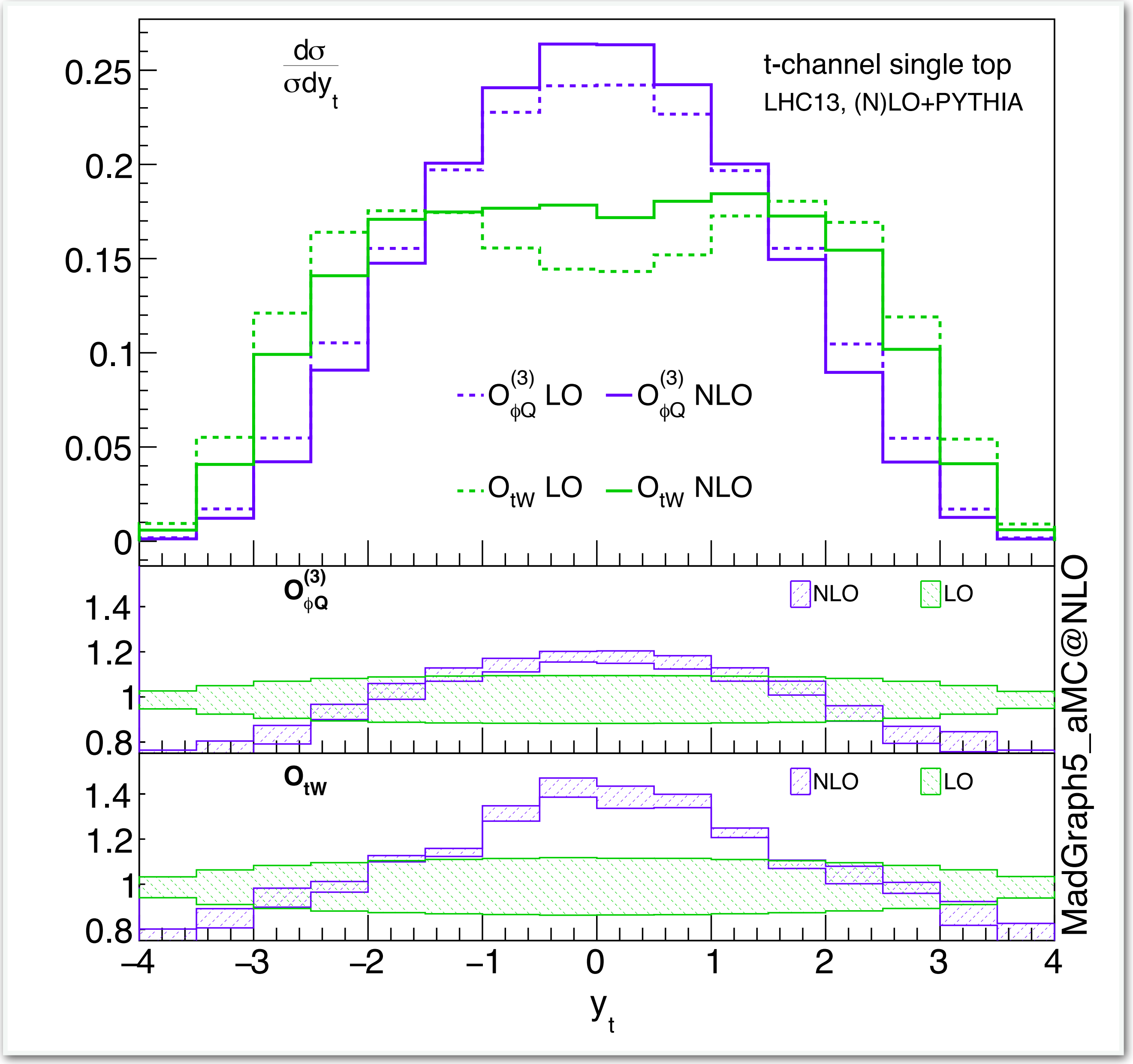

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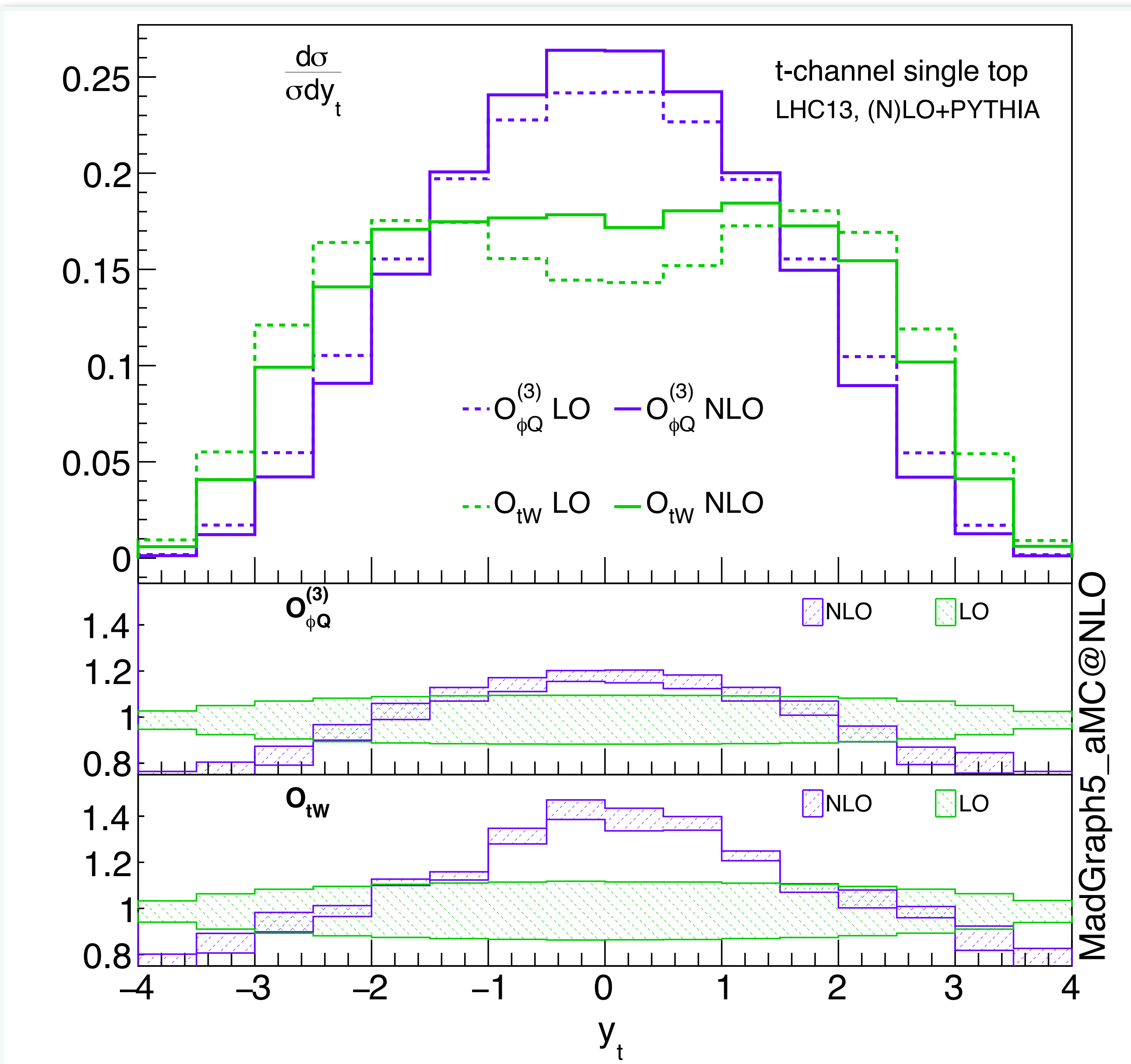

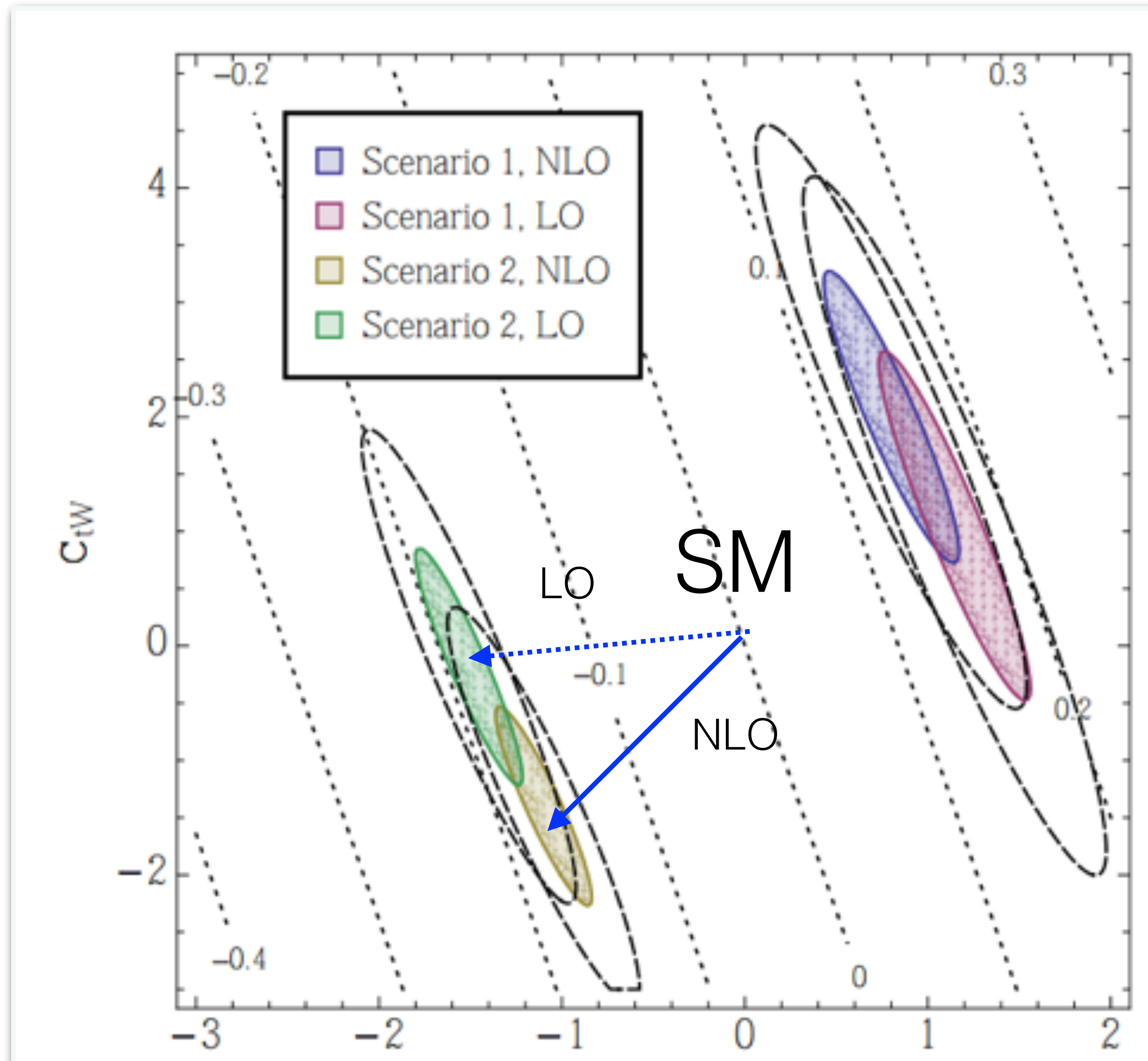

[1601.06163, **CZ**]

Automation Example
ttZ production

```
MG5_aMC>import model TEFT
MG5_aMC>generate p p > t t~ z EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

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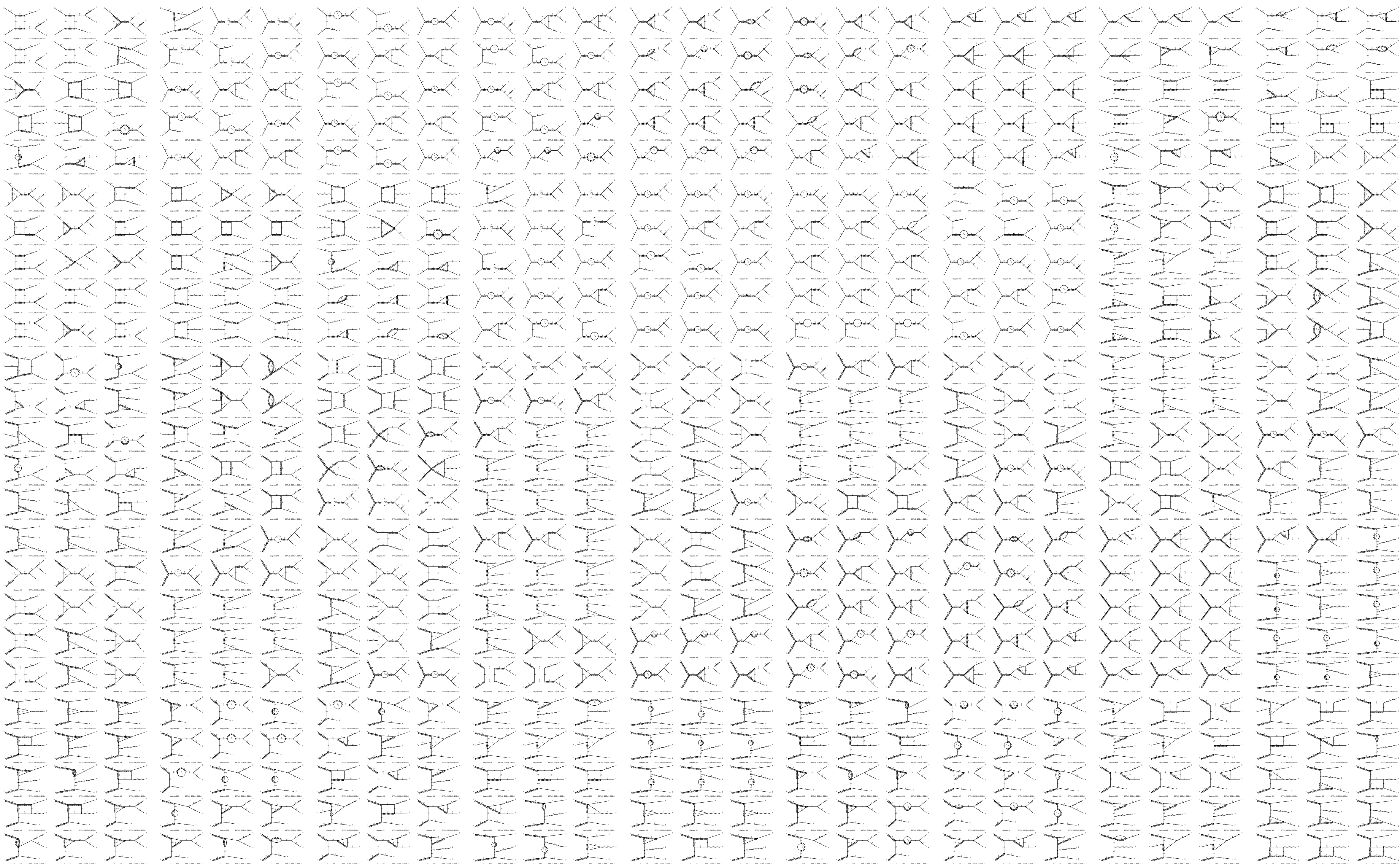
ttZ loops



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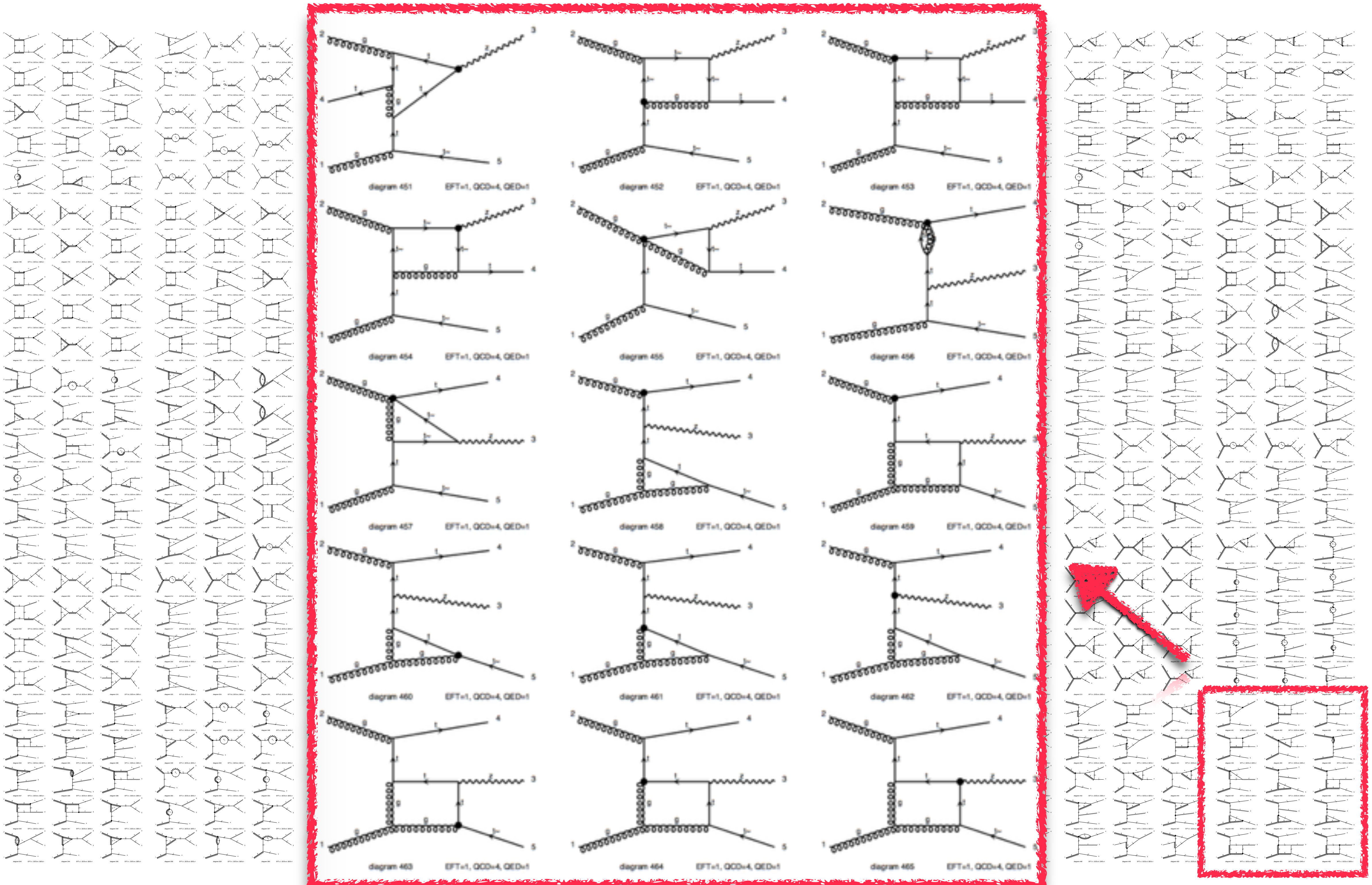

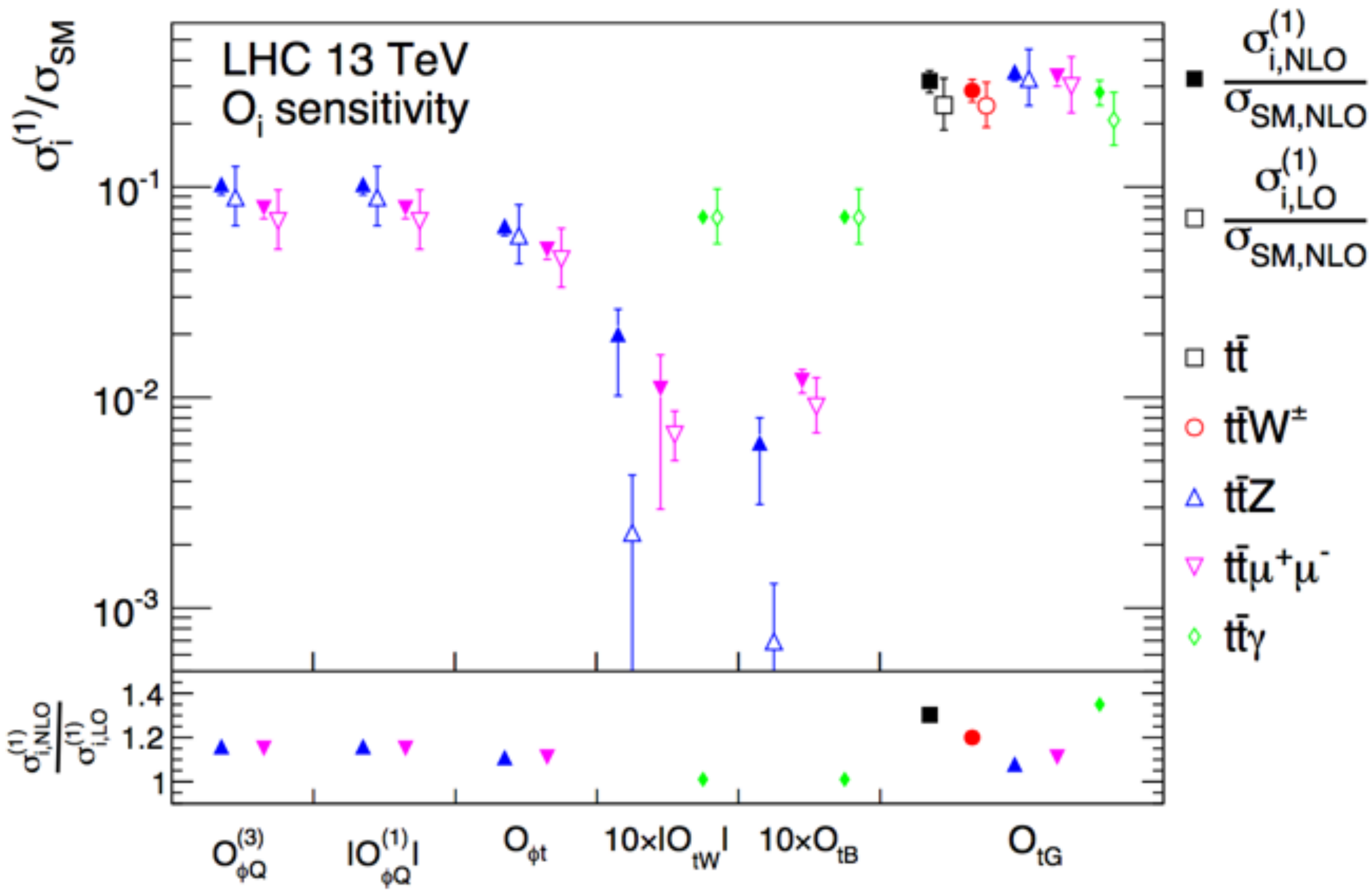

More to look:

- Single t+V+j
- Resonant top with complex mass scheme, i.e. WbWb, Wbj, etc.

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$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

	tqZ/γ					tqg	tqH	lltq
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

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ttg | ttZ/γ, tbW | ttH | qqtt | ggH

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

Coupling measurements

tqZ/γ | tqg | tqH | lltq

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

- First automation in flavor-conserving case: ttbar with chromo-dipole
  [1503.08841 D.B. Franzosi, **CZ**]
- Complete top-EW operators [1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, **CZ**], [1601.06163, **CZ**]
- ttH and tHj: ongoing
- Four fermion operators are planned

Outline

- Background
- Developments on MC for top EFT
- Outlook

- A frequently asked question for MCer:
  - Automation is good. Computer takes care of everything. But what are you gonna do next?

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Dream

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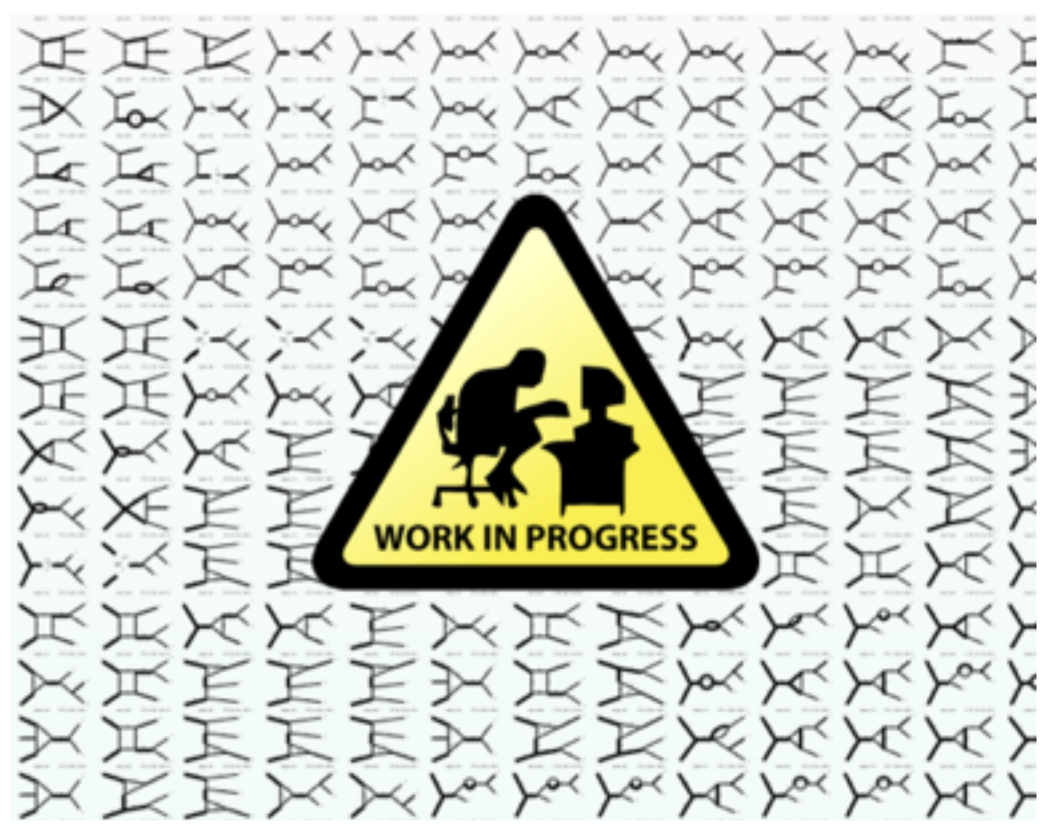
  - Automation is good. Computer takes care of everything. But what are you gonna do next?
  - Rest?
  - No that's only a WISH!

Dream



Reality

- Complete SM EFT at NLO
- Global fitting for top
- Towards electroweak corrections
- …

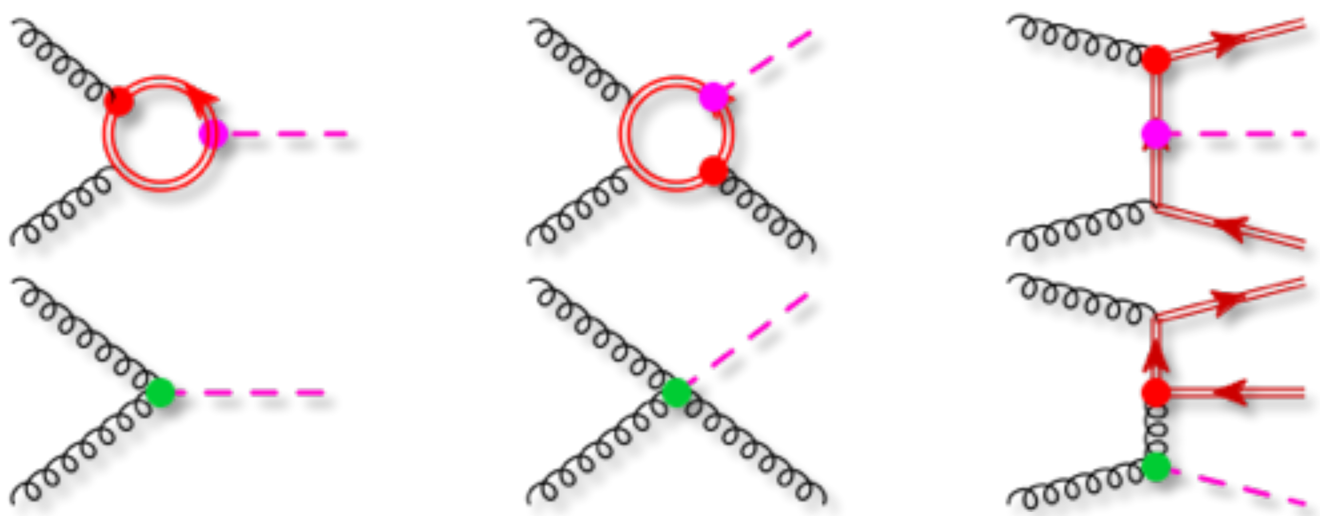
On-going implementation for ttH, ggH, gtt

chromo-dipole $O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G_{\mu\nu}$

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

gluon-Higgs $O_{\phi G} = y_t^2 (\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$

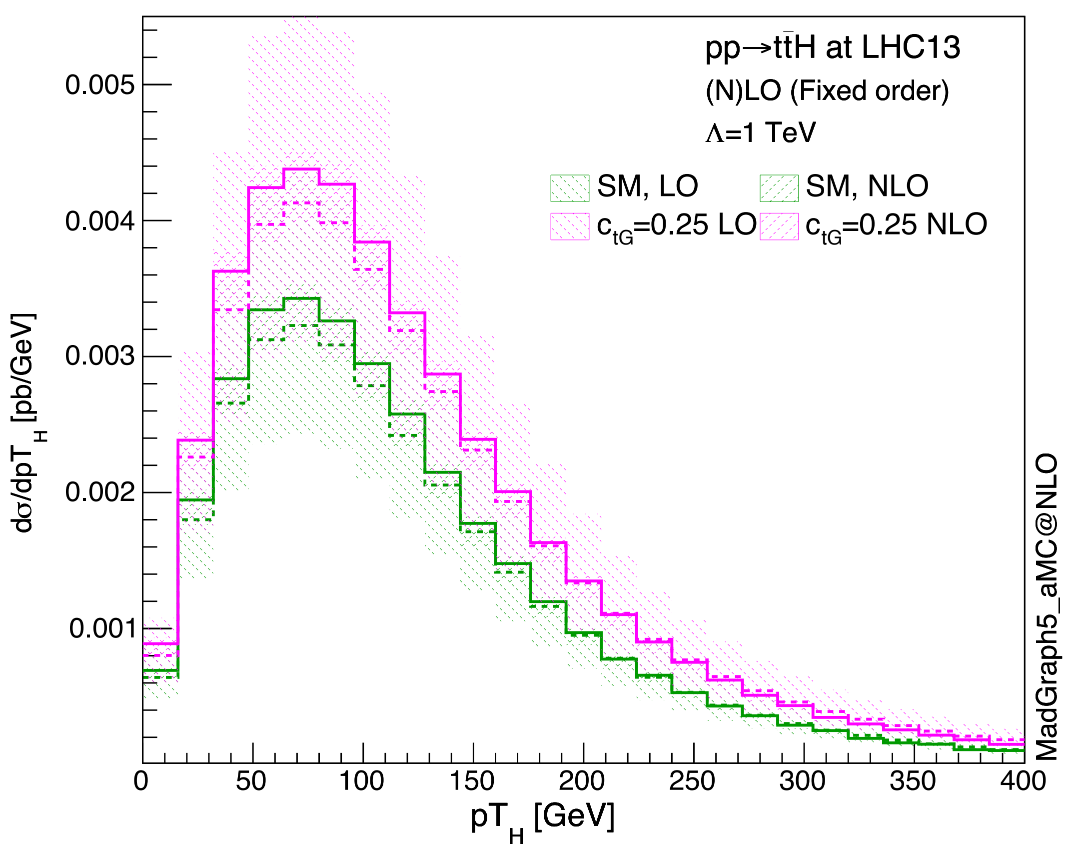
$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$



(very preliminary) pp>ttH at LHC 13 TeV

	O_{tG}	$O_{t\phi}$	$O_{\phi G}$
LO	513^{+188}_{-132}	-60^{+15}_{-22}	690^{+256}_{-178}
NLO	523^{+11}_{-46}	-65^{+7}_{-3}	936^{+131}_{-139}

[in fb]

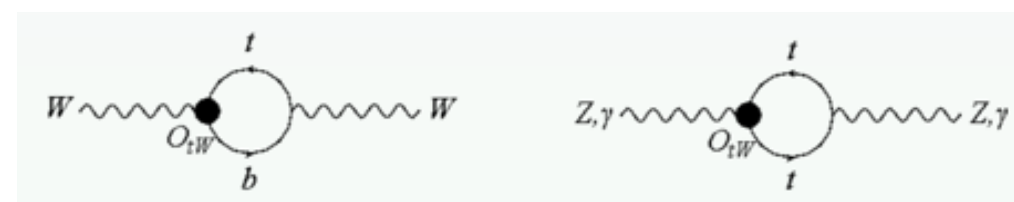


Global analysis for top couplings

- Global fitting at the LHC exits, based on LO predictions

[1512.03360 A. Buckley et al.]

- But we'll do better with NLO+PS
- and also adding
    - PEWM (improvement expected at future linear collider)
    - Flavor, Higgs, other indirect data

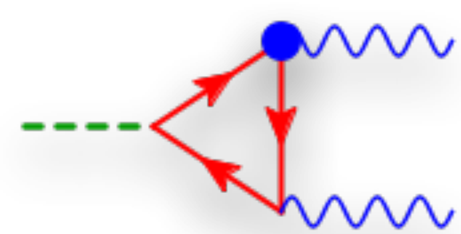


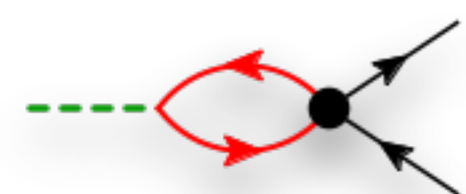
[1201.6670 **CZ**, Greiner, Willenbrock]

- Will be in collaboration with
    - Louvain team, who has NLO
    - Heidelberg SFitter team, who has the fitter

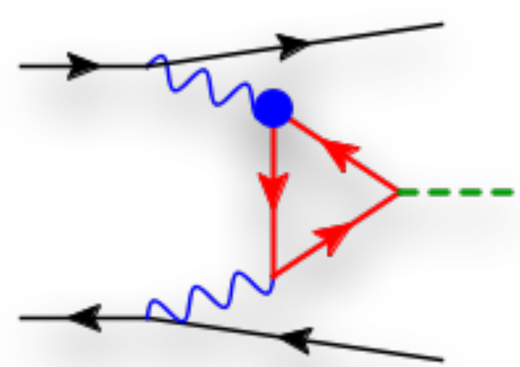
EW corrections in EFT

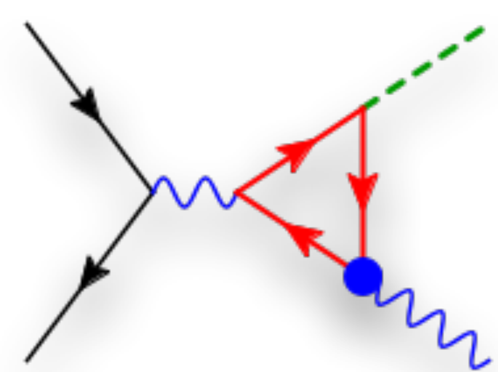
- SM EFT @ NLO in EW is becoming available for Higgs decay
    - diphoton [1505.02646, 1507.03568, Hartmann and Trott]
    - $Z\gamma$, ZZ*, WW* [1505.03706, M. Ghezzi et al.]
    - bb, tau tau [1512.02508, R. Gauld et al.]
- But is likely to be limited to decays.
- EW automation with MG5 is now becoming available, chances to compete:
    - Decay





    - and also production
    - Even PEWM+TGC+…





- With the MG5_aMC team.

Summary

- Search for New Interactions at LHC relies on
  - SM EFT, model-independence framework
  - MC tools, automated and NLO matched
- We've (almost) solved NLO automation and matching for SM EFT for the top, and provided experimentalists with MC tools
- Lots of things are planned for the future.

Thank you!