Introduction to EFT
and application to top-quark physics

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SM@LHC

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Outline

- Introduction
- Top EFT
- Electroweak
- Summary

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Two strategies to BSM

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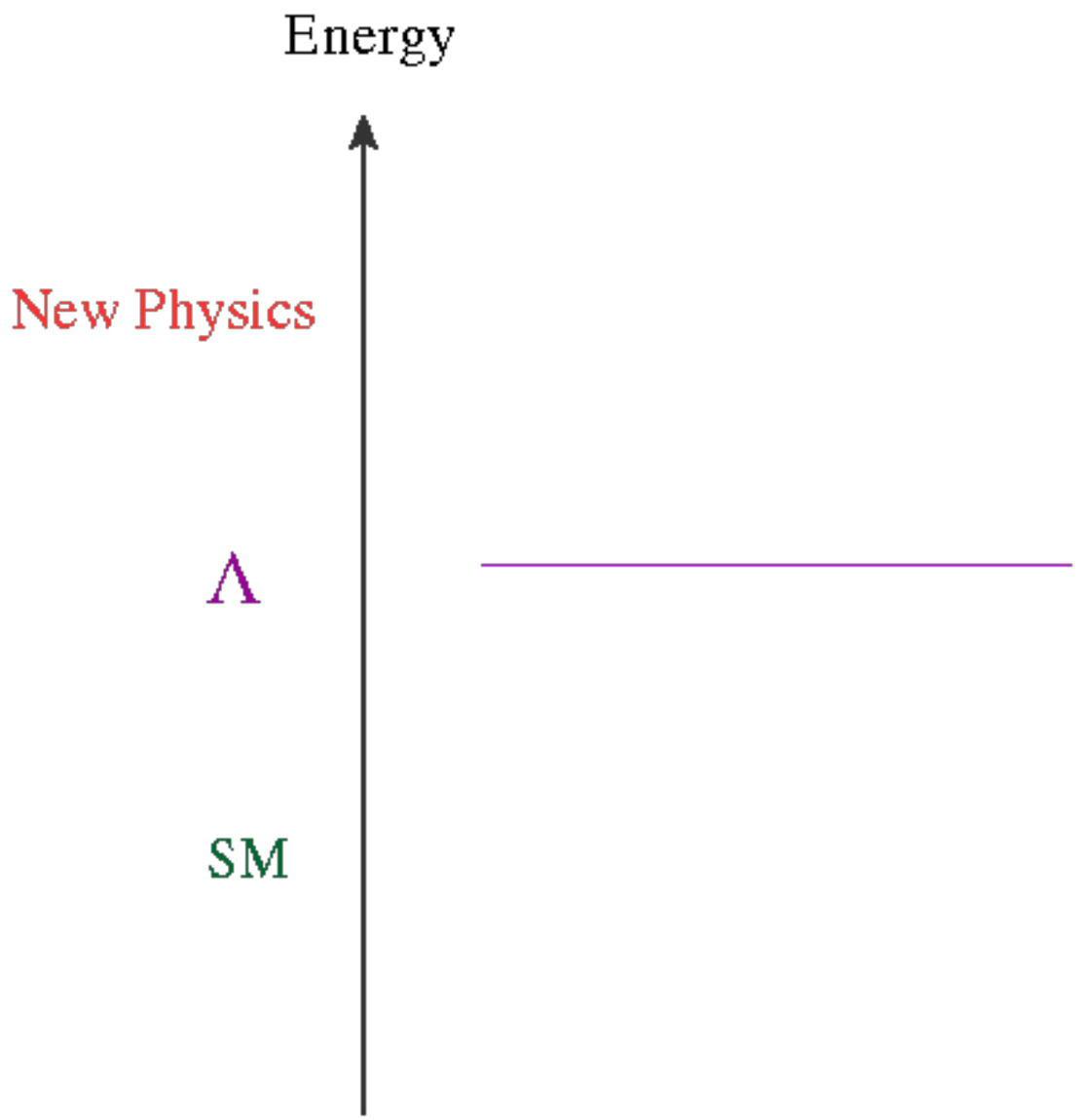
    ➡ SM EFT


Energy
New Physics
Λ
SM

Energy

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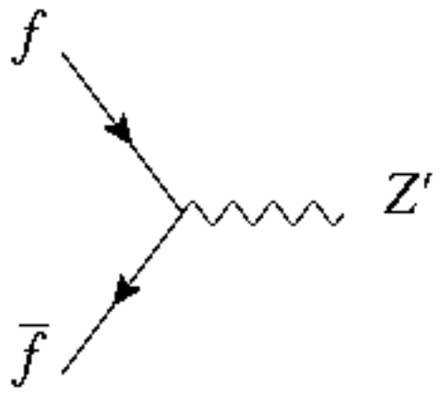
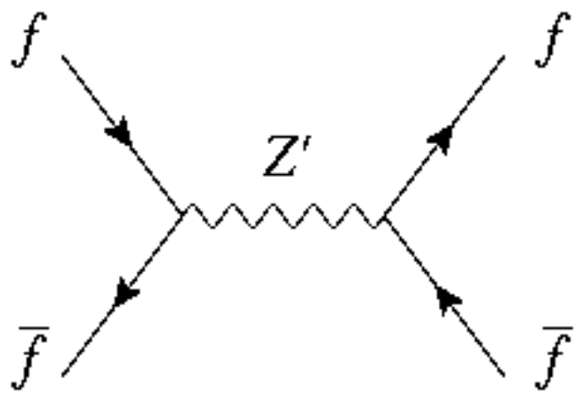
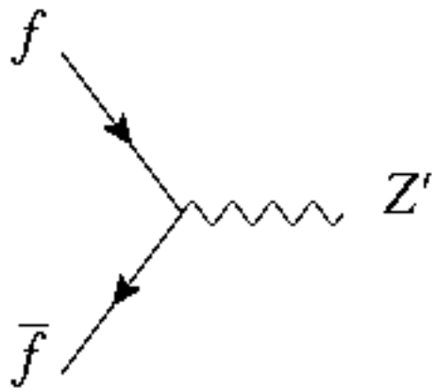




Energy

New Physics



Λ

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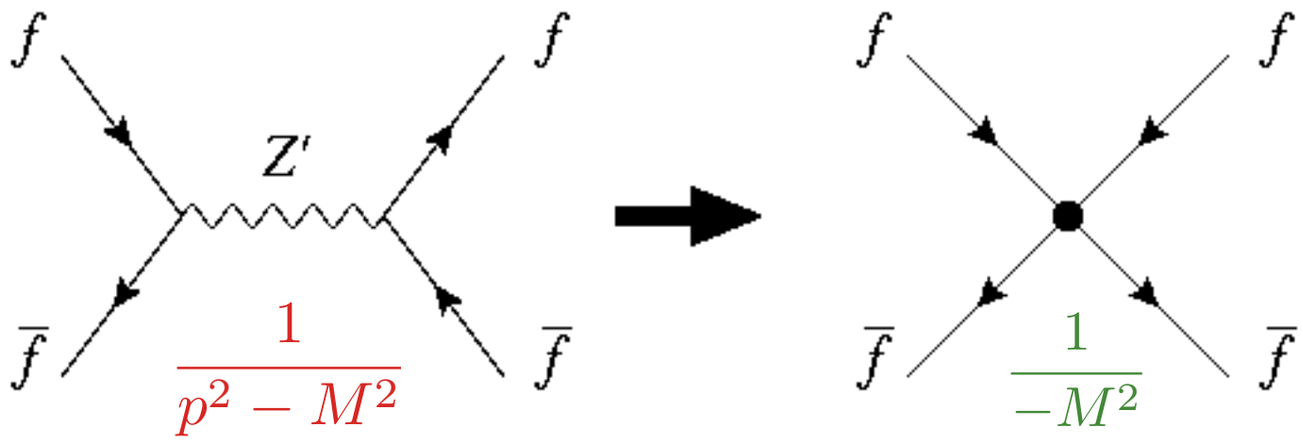
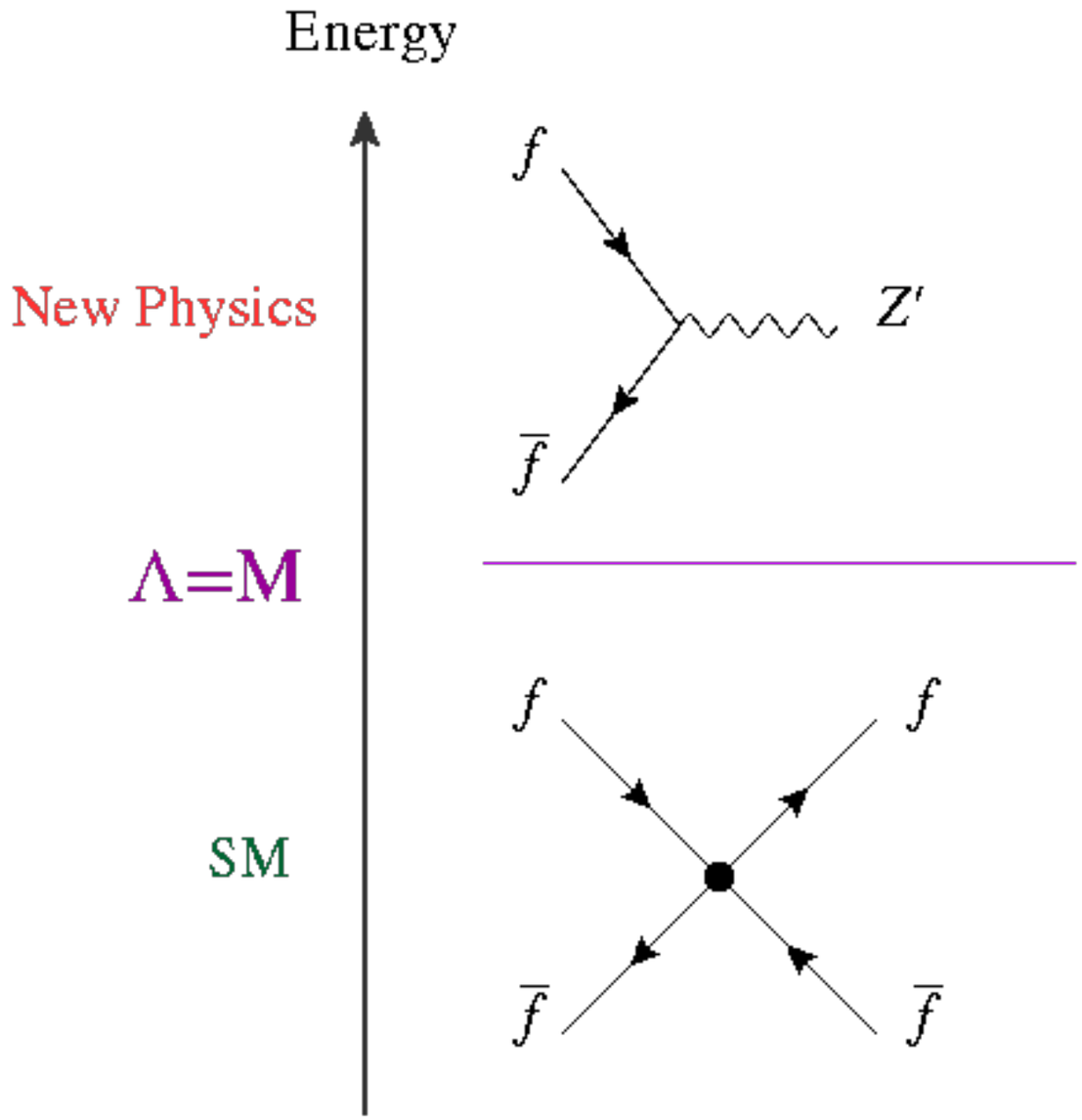


$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$



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

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

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

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

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}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

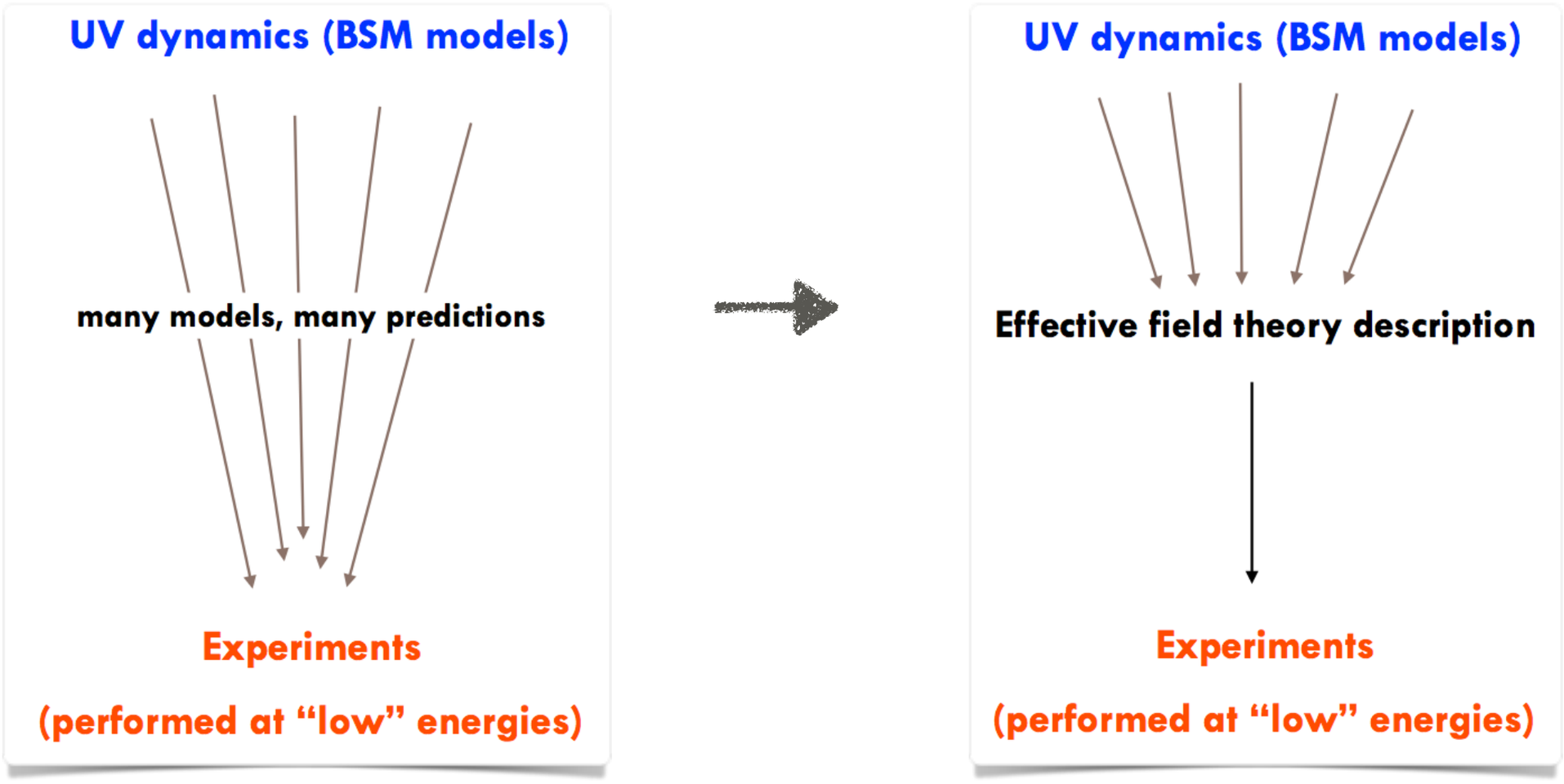
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

Including:

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

- Dim 6: 3045 operators
- Dim 8: 44807
- Dim 10: 2092441
- …
- Dim 15: everyone gets an operator

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



[R. Contino]

BSM goal at the LHC:
determination of SM EFT up to Dim=6

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Top quark is unique in many ways:

- Heaviest, of course… but also:
- It's a bare quark, decaying before hadronization.

  $\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}$ s

  $\tau_{flip} \approx h\, m_t / \Lambda_{QCD}^2 >> \tau_{had}$

  $\tau_{top} \approx h/\Gamma_{top} = 1/(G_F m_t^3 |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}$ s

- Top Yukawa is the largest SM coupling.

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

  and hence largest Higgs mass correction.

- They are many: 6 million from Run-I, ~2 orders of magnitude to go.

Top couplings

Top couplings

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

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

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- The **modern** way: SM EFT

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

with

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

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	×
EFT	✓

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

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

TH progresses in ~1 year

- Global fit.

  [1512.03360 A. Buckley et al.]
  [1506.08845 A. Buckley et al.]
  [1412.7166 Durieux, Maltoni, CZ]
  [1507.00757 J. de Blas et al.]
  [1406.4570 S. Jung et al.]

- Loops, running & mixing.

  [1601.06163, CZ] [1503.08841 D.B. Franzosi, CZ]
  [1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]
  [1412.5594 Degrande, Maltoni, Wang, CZ]

- NLO predictions and MC tools.

  [1501.05939 & 1404.1005, R. Rontsch and M. Schulze]

- More general for SMEFT

  - Operator counting

    [L. Lehman, A. Marin, 2015]
    [B. Henning et al., 2015]

  - Universal one-loop & NLO matching

    [1512.03003 A. Drozd et al.] [1604.02445 S. Ellis et al.]
    [1602.00126 F. Aguila et al.] [1412.1837,1604.01019 B. Henning et al.]

  - v-improved matching

    [1510.03443 J. Brehmer et al.]

  - EFT for universal (oblique) theories

    [1510.08462,1512.03056 J. Wells and Z. Zhang]

  - Basis translator

    [1508.05895 A. Falkowski et al.]

  - …

Global approach

- As a model-independent interface between TH and EXP, EFT makes sense only if **global constraining strategy** is used to extract information.

  - Always assume all coefficients can be nonzero.

    - Mostly like all coefficients can get some contribution as the EFT runs down from high scale.

- Once we go beyond tree level (which we should), an EFT without a complete operator basis is, most likely, unrenormalizable.

Example: top-Higgs interactions

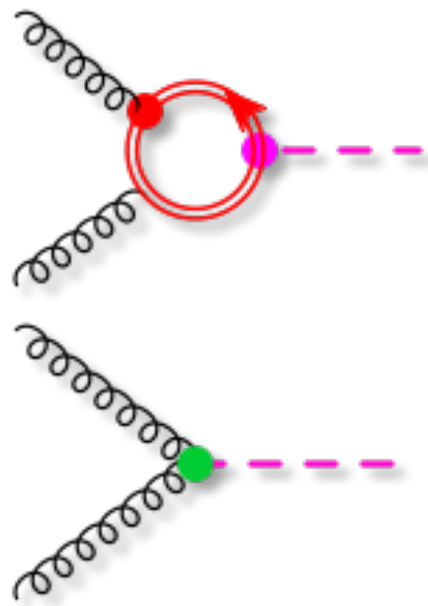
chromo-dipole $O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G_{\mu\nu}$

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

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

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

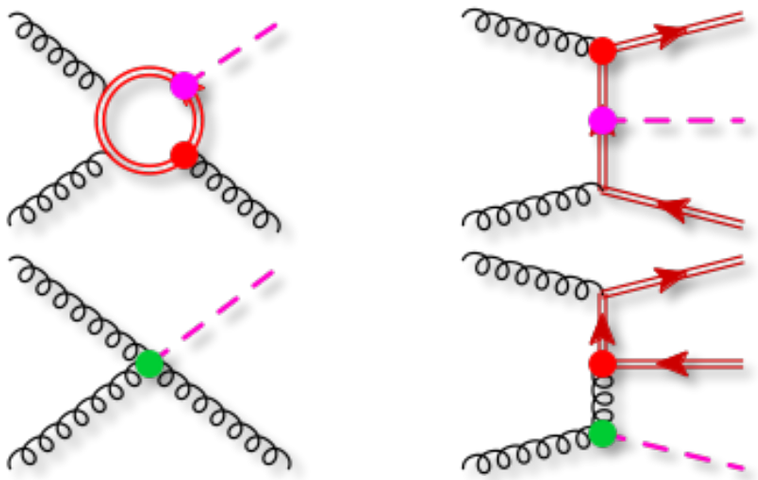
- gg>H accurately determined, but:
  - Cannot resolve 3 operators -> more rooms for each coef., if **marginalized**.
  - Operator mixing: at NLO should not talk about each operator individually. **EFT with only O_{tG} is not renormalizable**



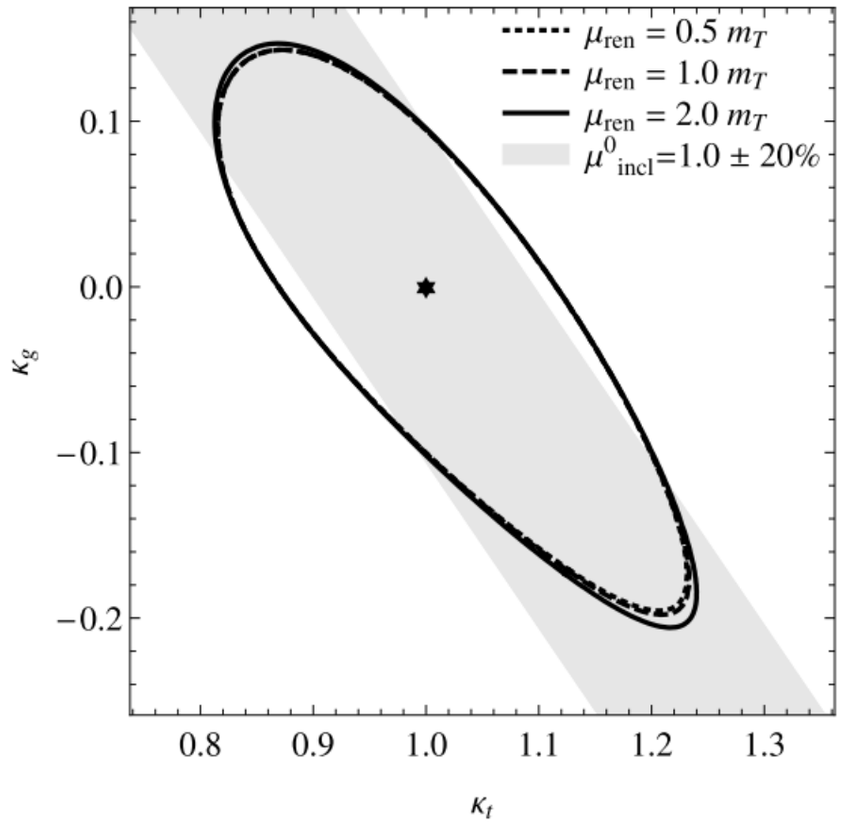
- A global analysis should:
  - Consider all 3 operators simultaneously,
  - Use more observables to set bounds.

Example: top-Higgs interactions

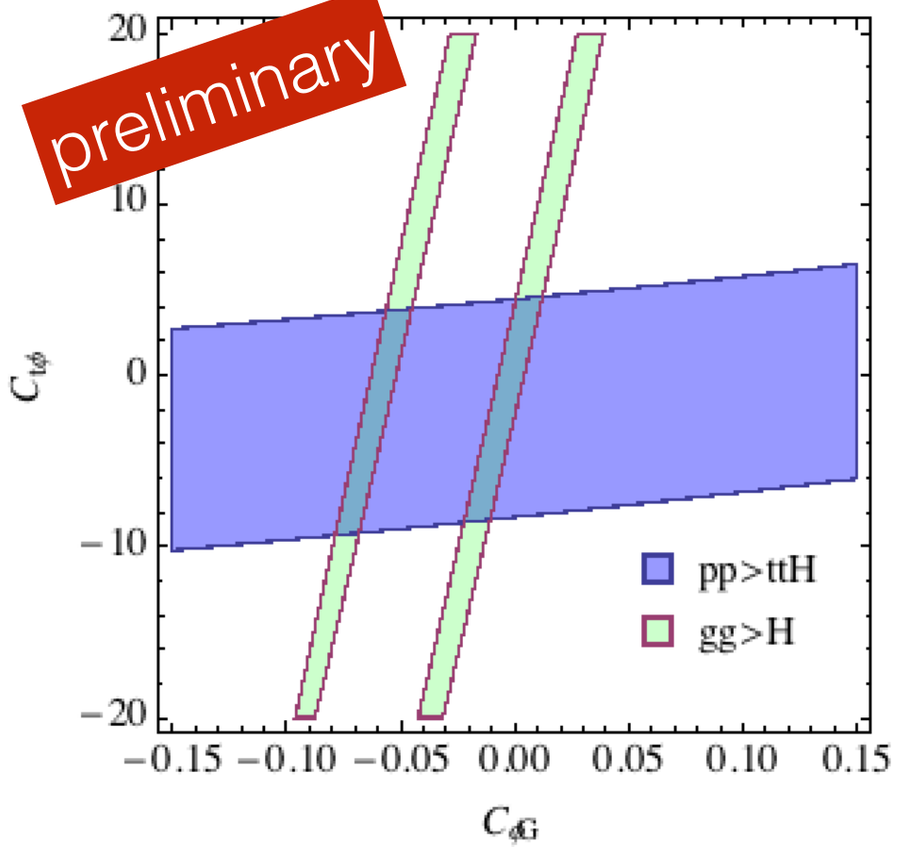
- H+j, use boosted jet to resolve
- ttbar+H, directly probe ttH (but chromo/ggH will also enter)
- ttbar gives so far the best (direct) limit on chromo op. O_{tG}, but the situation might change in future.



[1312.3317 C. Grojean et al.]



[in prep., F. Maltoni, E. Vryonidou, CZ]



- $tt\gamma/ttg$, 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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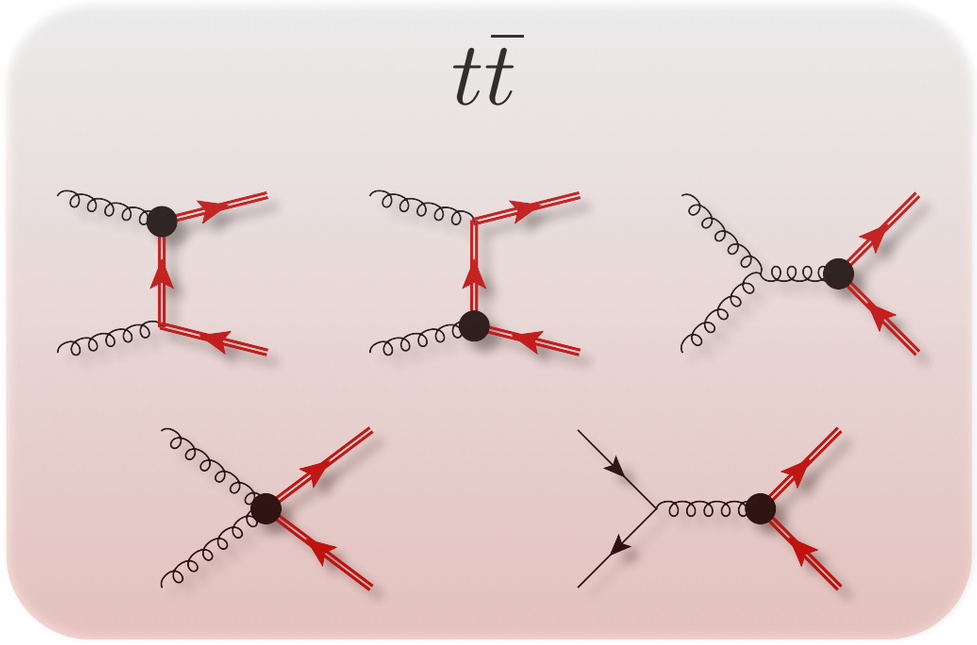

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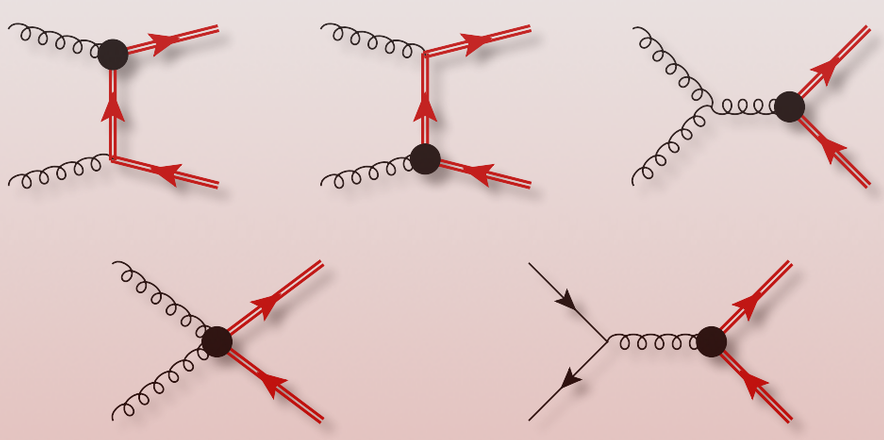
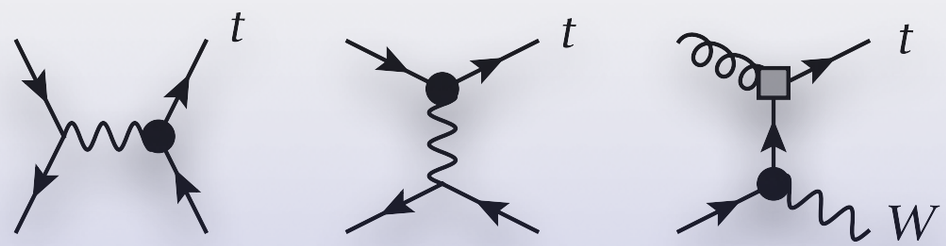
  - Weak dipole O_{tW}

$t\bar{t}$



single top + decay



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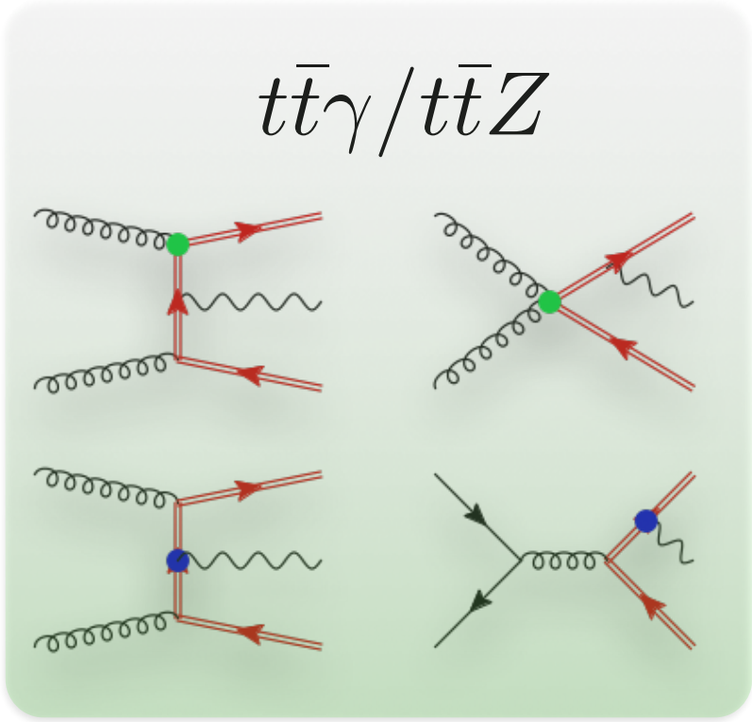

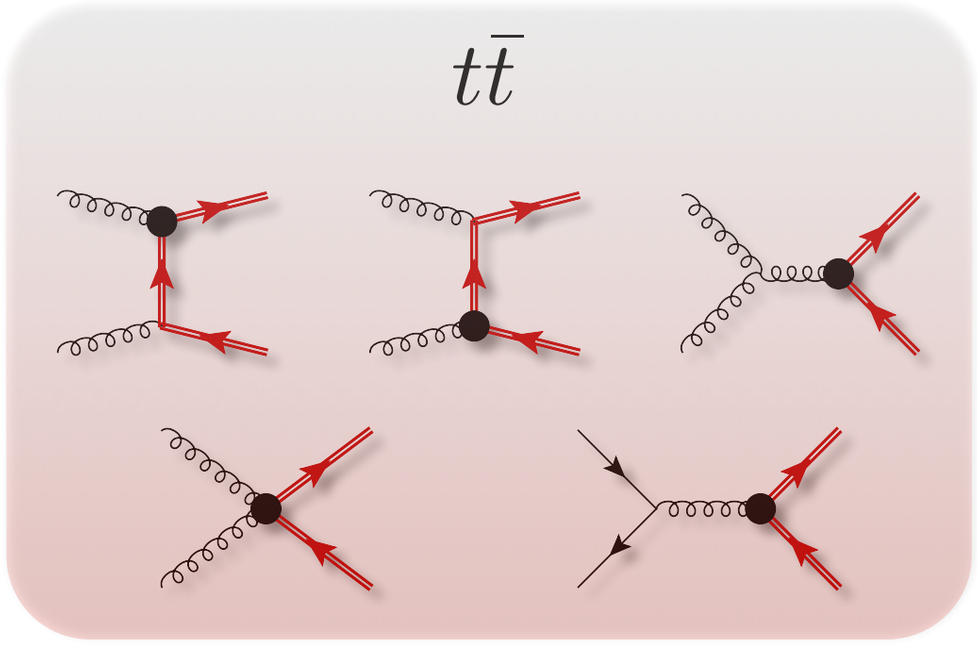

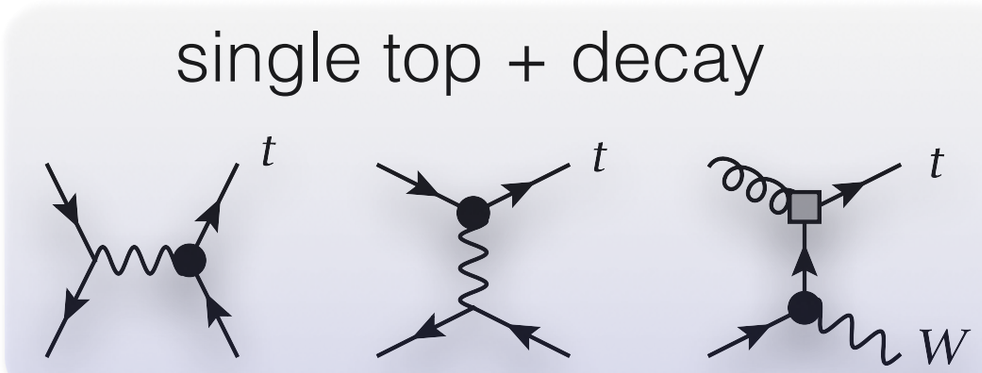

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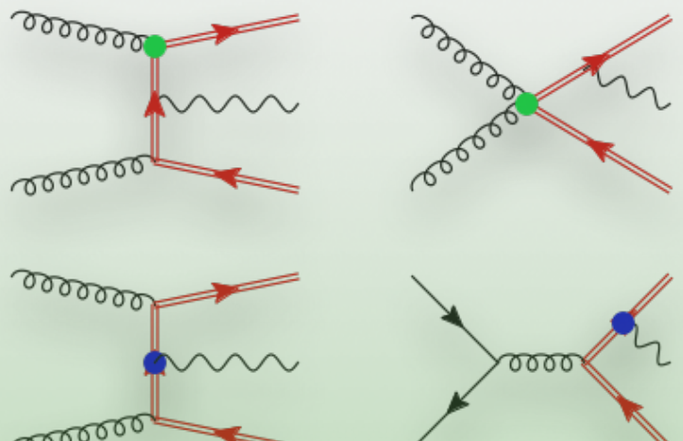
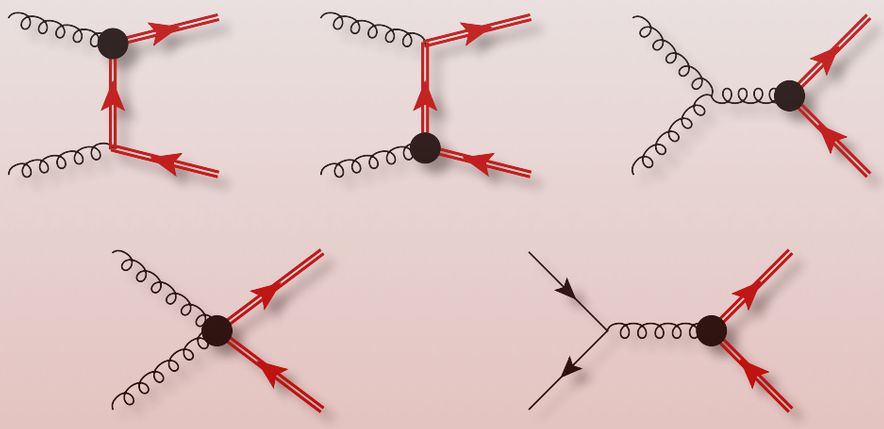
$t\bar{t}\gamma/t\bar{t}Z$



$t\bar{t}$



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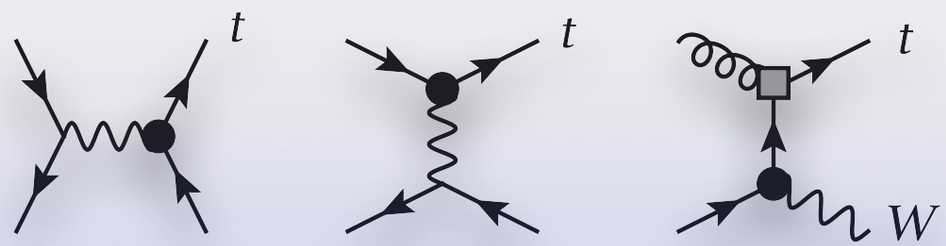

But keep in mind that several operators can enter more than one classes

Towards a global fit at LHC

Global fit for flavor-conserving sector

[1512.03360 A. Buckley et al.]

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
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
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:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
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				

- EFT based, LHC+Tevatron, total rates and differential information (for the first time). (ttbar: a total of 195 measurements, 174 from differential observables)
- SM at (N)NLO + LO EFT (FeynRules + MadGraph)

Towards a global fit at LHC

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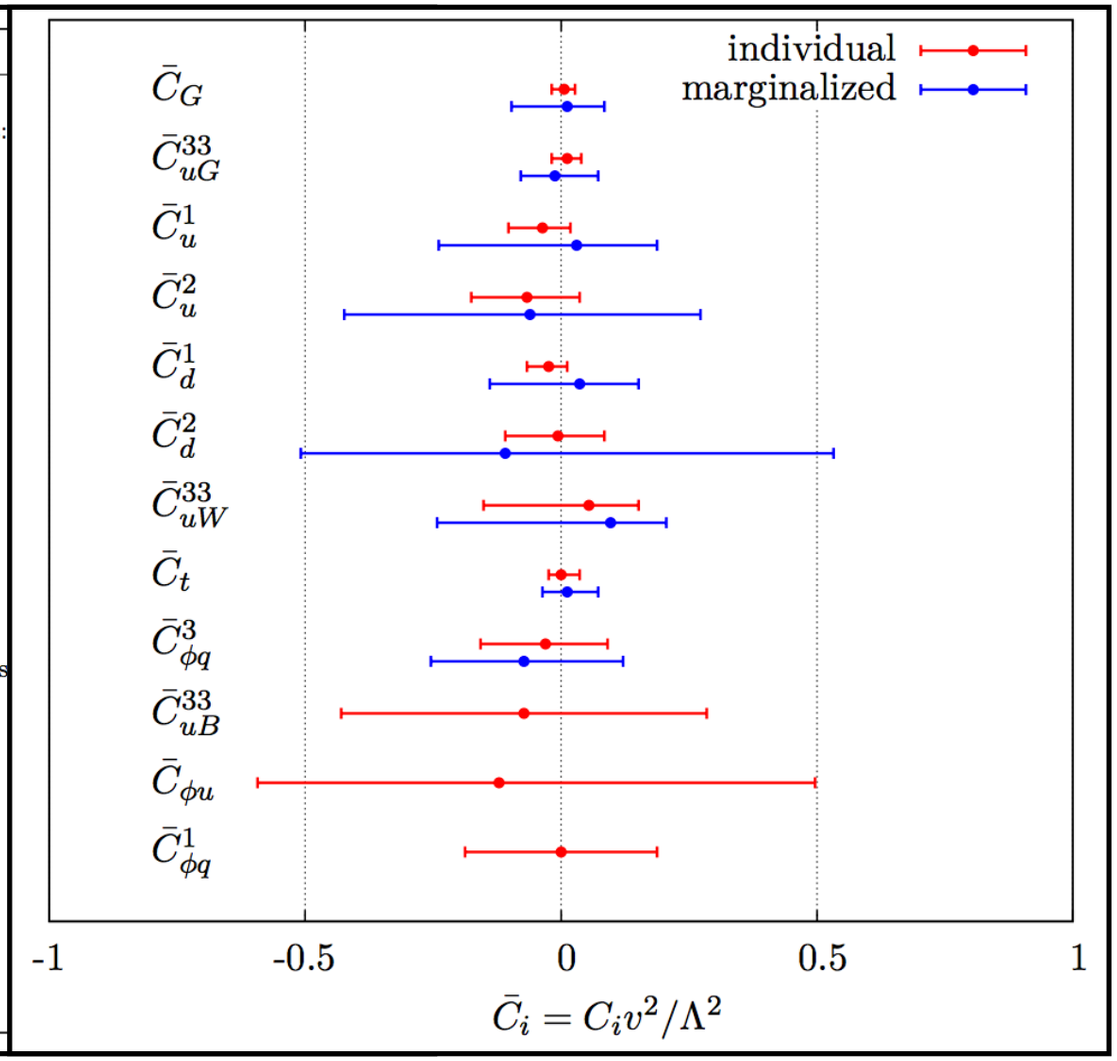
Dataset	$\sqrt{s}$ (TeV)
Differential cross-sections:	
ATLAS	7
CDF	1.96
CMS	7
CMS	8
DØ	1.96
Charge asymmetries:	
ATLAS	7
CMS	7
CDF	1.96
DØ	1.96
Top widths:	
DØ	1.96
CDF	1.96
W-boson helicity fractions	
ATLAS	7
CDF	1.96
CMS	7
DØ	1.96
Run II data	
CMS	13



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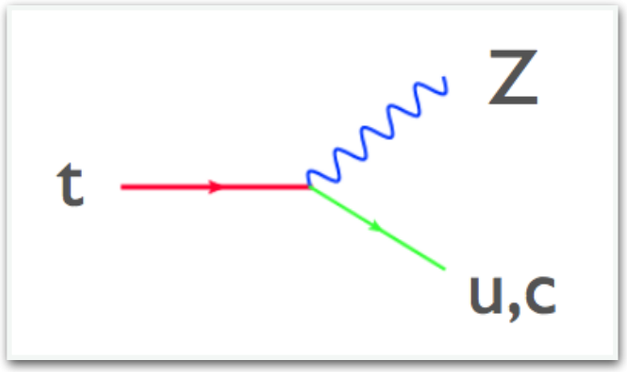
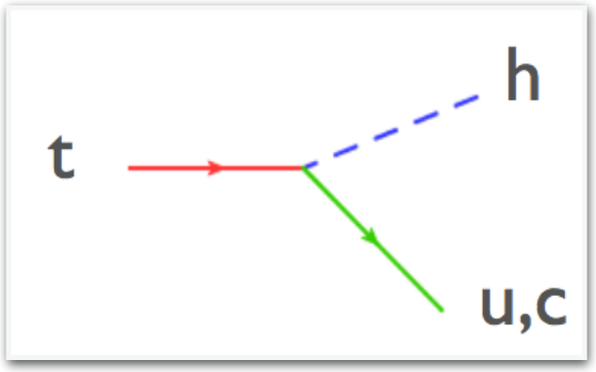
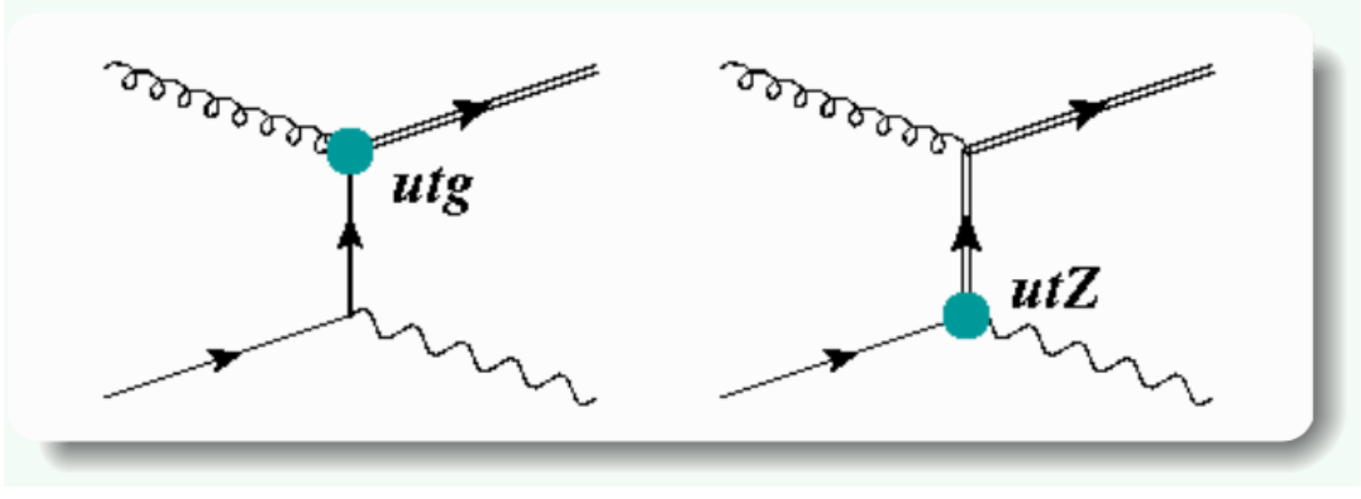
Towards a global fit at LHC

What about FCNC?







Towards a global fit at NLO

FCNC: NLO proof of principle [1412.7166 Durieux, Maltoni, CZ]

- Identify operators (including those coming in at NLO only)
- Understand the mixing

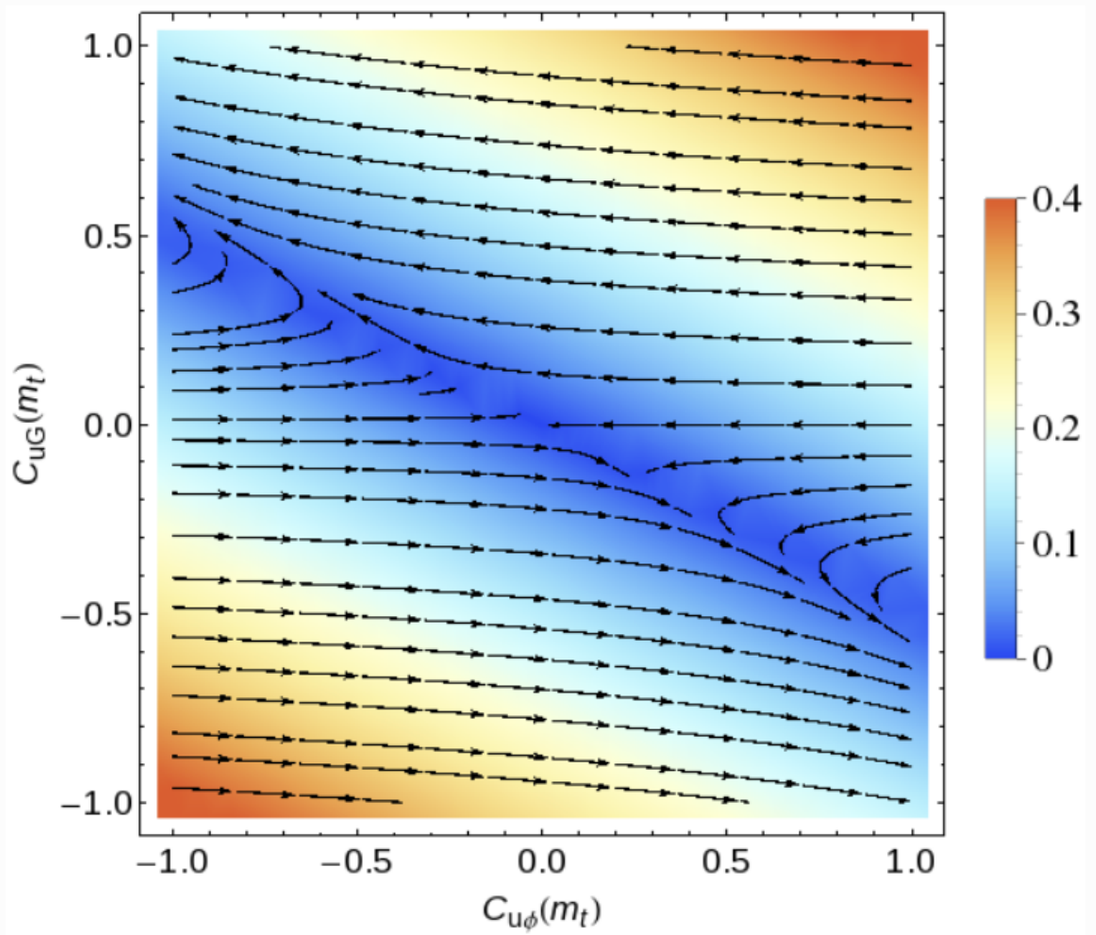
Operators

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

Anomalous dimension

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

Mixing between color-dipole and Yukawa



Towards a global fit at NLO

FCNC: NLO proof of principle [1412.7166 Durieux, Maltoni, CZ]

- Identify operators (including those coming in at NLO only)
- Understand the mixing
- NLO event generation

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

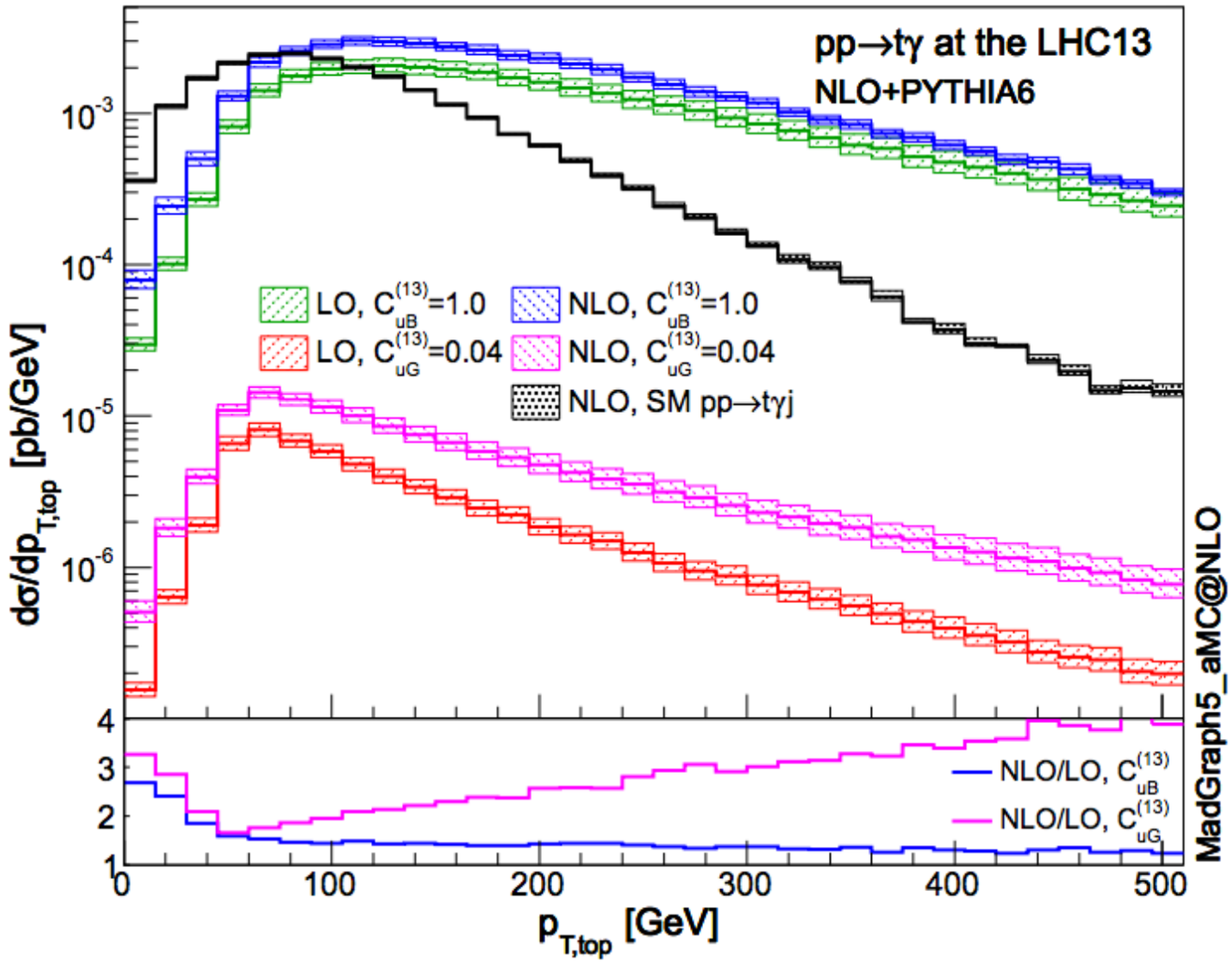
Towards a global fit at NLO

FCNC: NLO proof of principle [1412.7166 Durieux, Maltoni, CZ]

- Identify operators (including those coming in at NLO only)
- Understand the mixing
- NLO event generation

fNLO / NLO+PS within a few lines in MG5_aMC [1405.0301 J. Alwall et al.]

```
your_shell> ./bin/mg5
MG5_aMC> import model Top_FCNC
MG5_aMC> generate p p > t h [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch
```



Towards a global fit at NLO

FCNC: NLO proof of principle [1412.7166 Durieux, Maltoni, CZ]

- Identify operators (including those coming in at NLO only)
- Understand the mixing
- NLO event generation
- Fit to measurements

At LO:

$$\Gamma_{t\to jZ} = \frac{\alpha m_t (1-x^2)^2}{8\Lambda^4 s_W^2 c_W^2}$$
$$\sum_{a=1,2} \Big\{ \Big| \frac{1}{2x} C_{\varphi q}^{-(a+3)} - 2x\left(s_W^2 C_{uB}^{(a3)} - c_W^2 C_{uW}^{(a3)}\right)\Big|^2$$
$$+ \Big| \frac{1}{2x} C_{\varphi u}^{(a+3)} - 2x\left(s_W^2 C_{uB}^{(3a)*} - c_W^2 C_{uW}^{(3a)*}\right)\Big|^2$$
$$+2\Big| \frac{1}{2} C_{\varphi q}^{-(a+3)} + 2\left(s_W^2 C_{uB}^{(a3)} - c_W^2 C_{uW}^{(a3)}\right)\Big|^2$$
$$+2\Big| \frac{1}{2} C_{\varphi u}^{(a+3)} + 2\left(s_W^2 C_{uB}^{(3a)*} - c_W^2 C_{uW}^{(3a)*}\right)\Big|^2 \Big\},$$

At NLO, $O_{uG}^{(a3,3a)}$ come in:

$$\sum_{a=1,2} \Big\{ \big|0.40\, C_{\varphi q}^{-(a+3)} + 0.25\, C_{uB}^{(a3)} - 0.88\, C_{uW}^{(a3)} + 0.036\, C_{uG}^{(a3)}\big|^2$$
$$+ \big|0.40\, C_{\varphi u}^{(a+3)} + 0.25\, C_{uB}^{(3a)} - 0.88\, C_{uW}^{(3a)} - 0.021\, C_{uG}^{(3a)}\big|^2$$
$$+0.048\, \big|0.92\, C_{\varphi q}^{-(a+3)} - 0.11\, C_{uB}^{(a3)} + 0.39\, C_{uW}^{(a3)} + 0.030\, C_{uG}^{(a3)}\big|^2$$
$$+0.048\, \big|0.92\, C_{\varphi u}^{(a+3)} - 0.11\, C_{uB}^{(3a)} + 0.39\, C_{uW}^{(3a)} - 0.027\, C_{uG}^{(3a)}\big|^2 \Big\}$$
$$< 0.23 \left(\frac{\Lambda}{1\ \text{TeV}}\right)^4.$$

Towards a global fit at NLO

FCNC: NLO proof of principle [1412.7166 Durieux, Maltoni, CZ]

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

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

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

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

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

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

Same analysis, i.e. NLO global fit, still needs to be done for the flavor-conserving sector

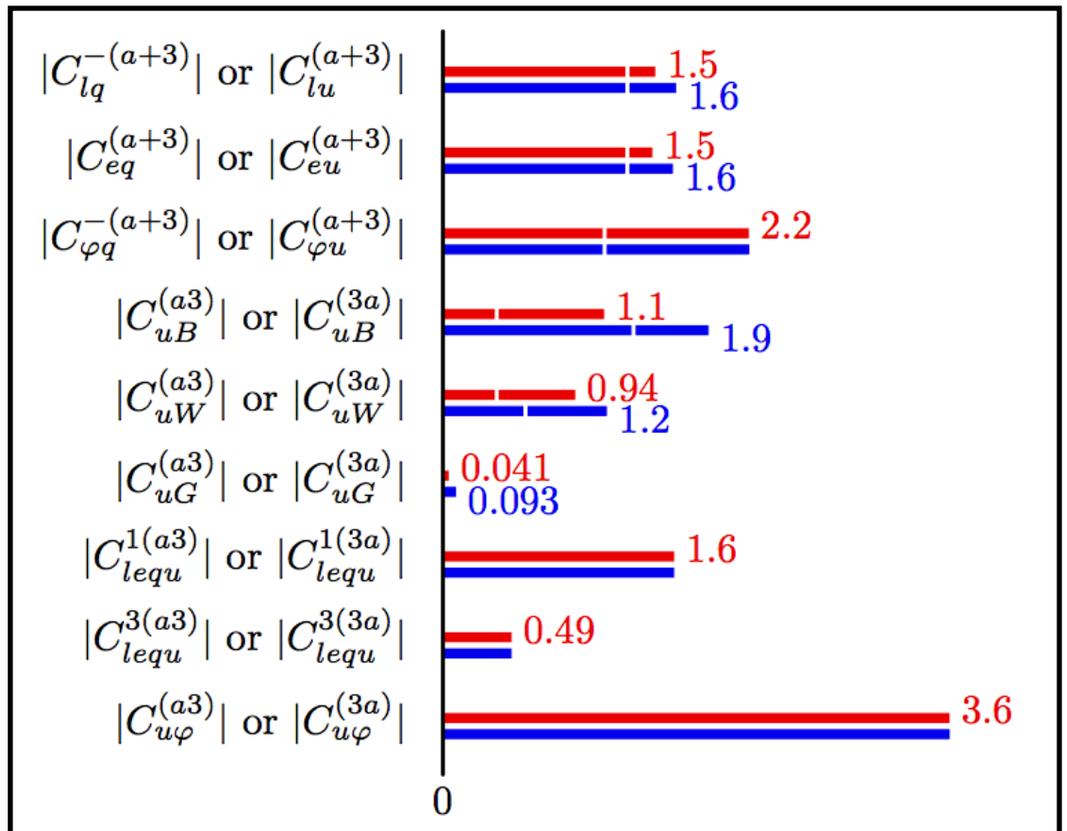


FIG. 12: The 95% CL limits on the moduli of operator coefficients for $\Lambda = 1\,\text{TeV}$, as deriving from current bounds on $t \to j\,\ell^+\ell^-$, $t \to j\gamma\gamma$, $pp \to t+\bar{t}$, $pp \to t\gamma+\bar{t}\gamma$ and $e^+e^- \to tj+\bar{t}j$. Two-quark–two-lepton operators containing an electron pair are shown, for the one containing a muon pair we refer to the figures in Section V B and Section V C. The red allowed regions apply for $a = 1$ and the blue ones for $a = 2$. A white mark indicates the bound that would have been obtained by fixing all coefficients to zero but the one constrained, instead of performing a global analysis.

Towards a global fit at NLO

- SMEFT at NLO is an active field, for both HEFT and top-EFT.

- One might think that NLO log terms should dominate over the finite correction, so NLO RG corrections/improvements are enough. This may be true for HEFT in several cases, but is certainly not the case for top-EFT.

- Top operators involve colored fields, so it's important to study QCD NLO. <u>QCD corrections giving O(1) effects</u> are common at the LHC.

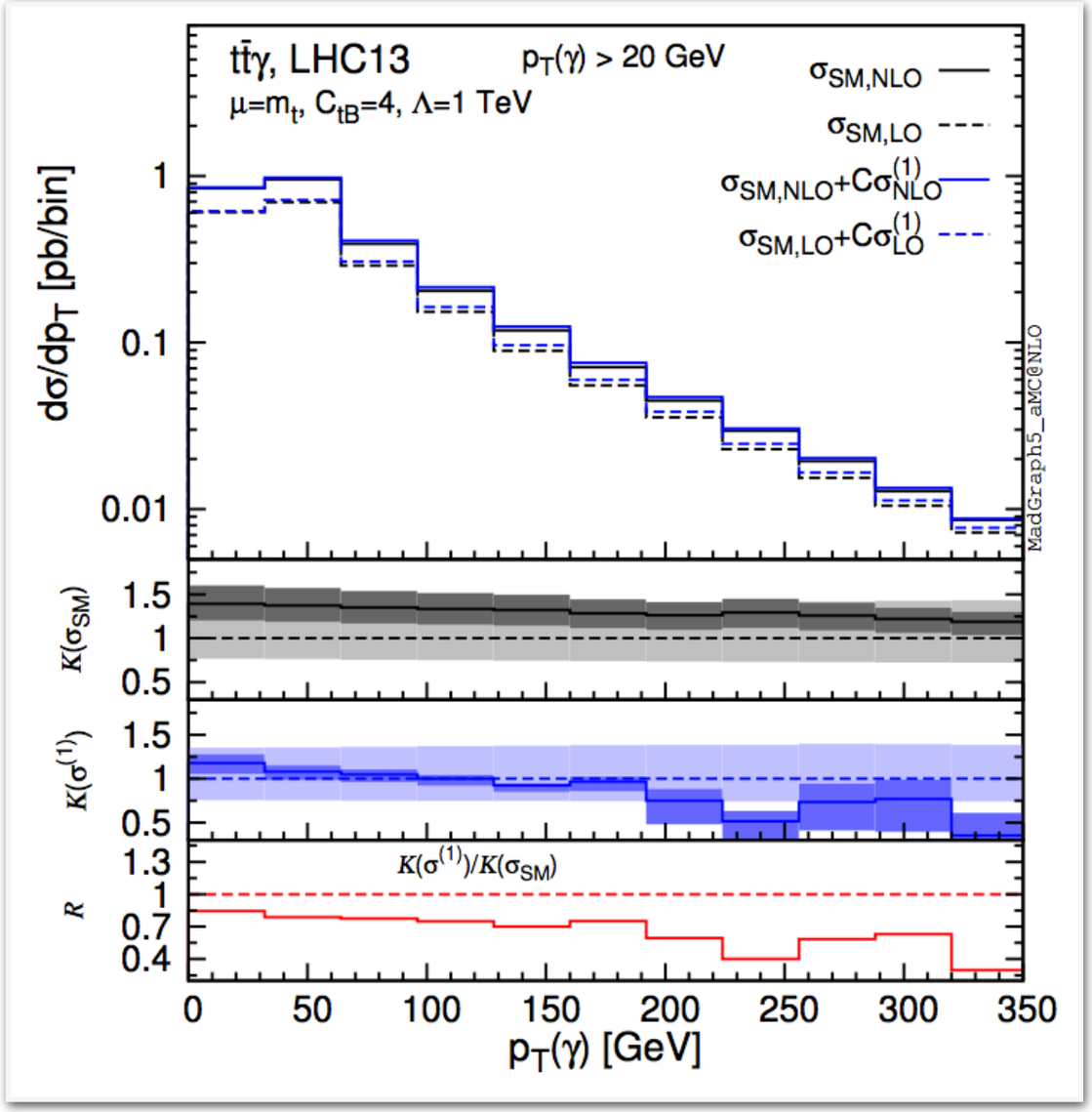
  - This is at <u>differential level</u>.

  - **Operator fit using differential information can be very sensitive to QCD correction.** [1601.06163, CZ]

  ➡ Important to have accurate prediction for shapes.

pp>tt**γ**

[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]



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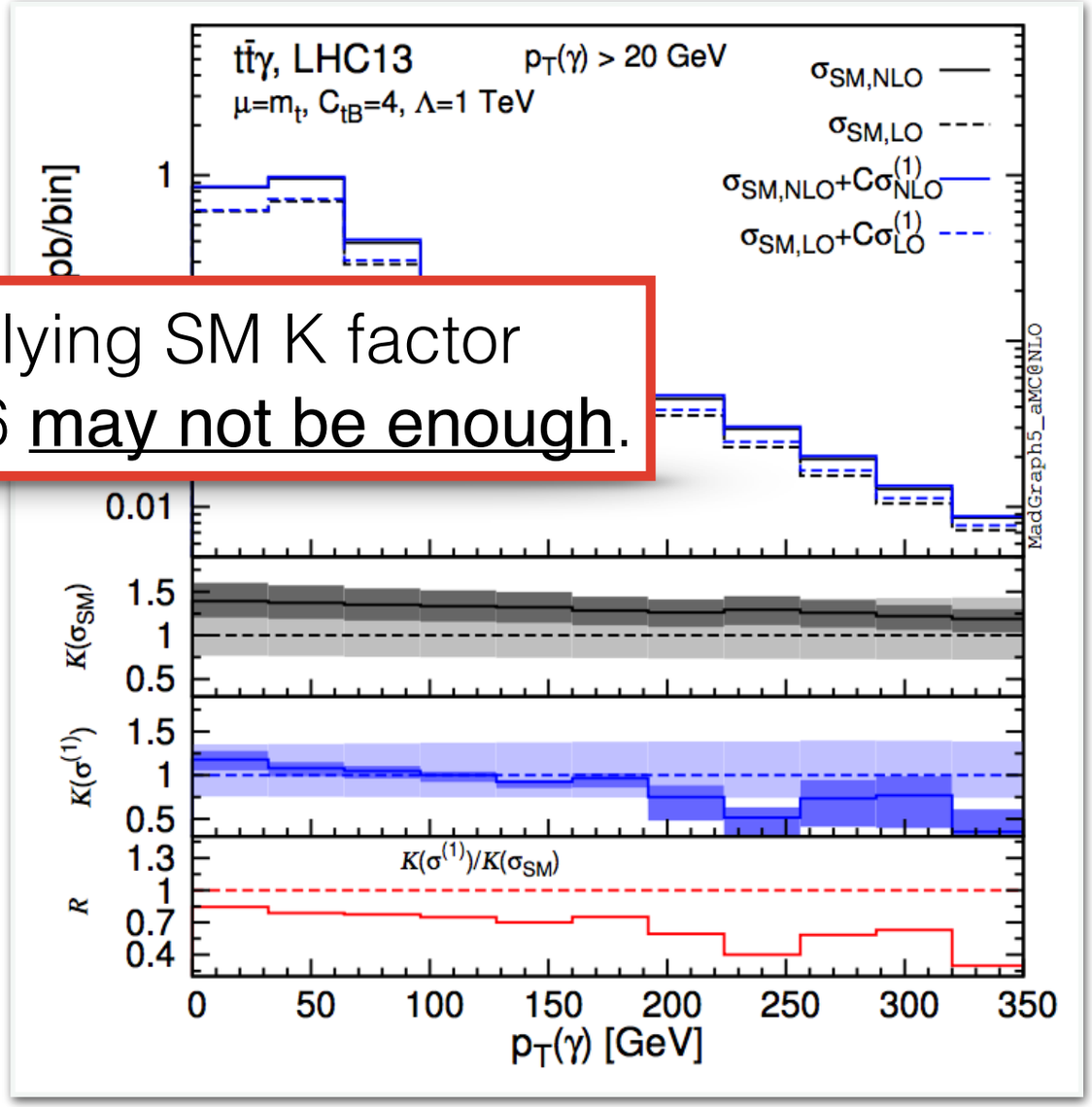
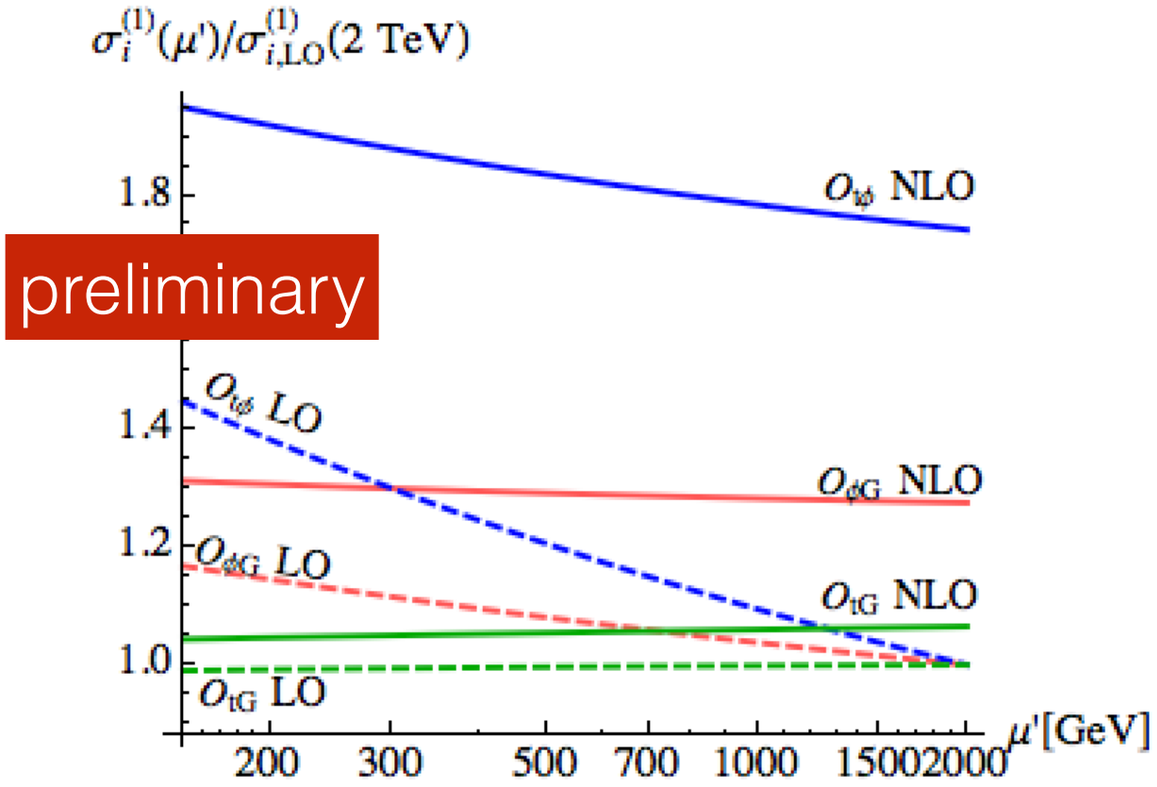


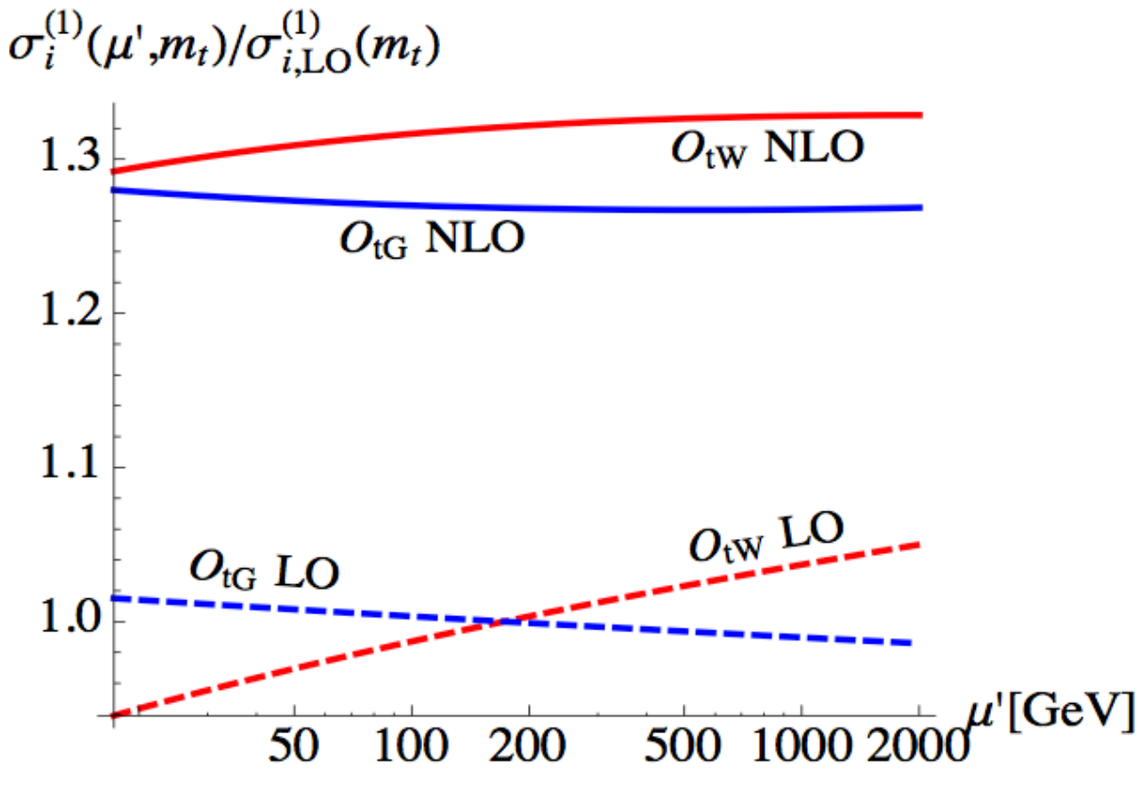
Applying SM K factor to dim-6 <u>may not be enough</u>.

NLO vs RG

- When talking about NLO EFT, how much of full NLO actually comes from RG corrections?
  - Sometimes RG correction can even have the opposite sign…



pp>ttH



pp>tW

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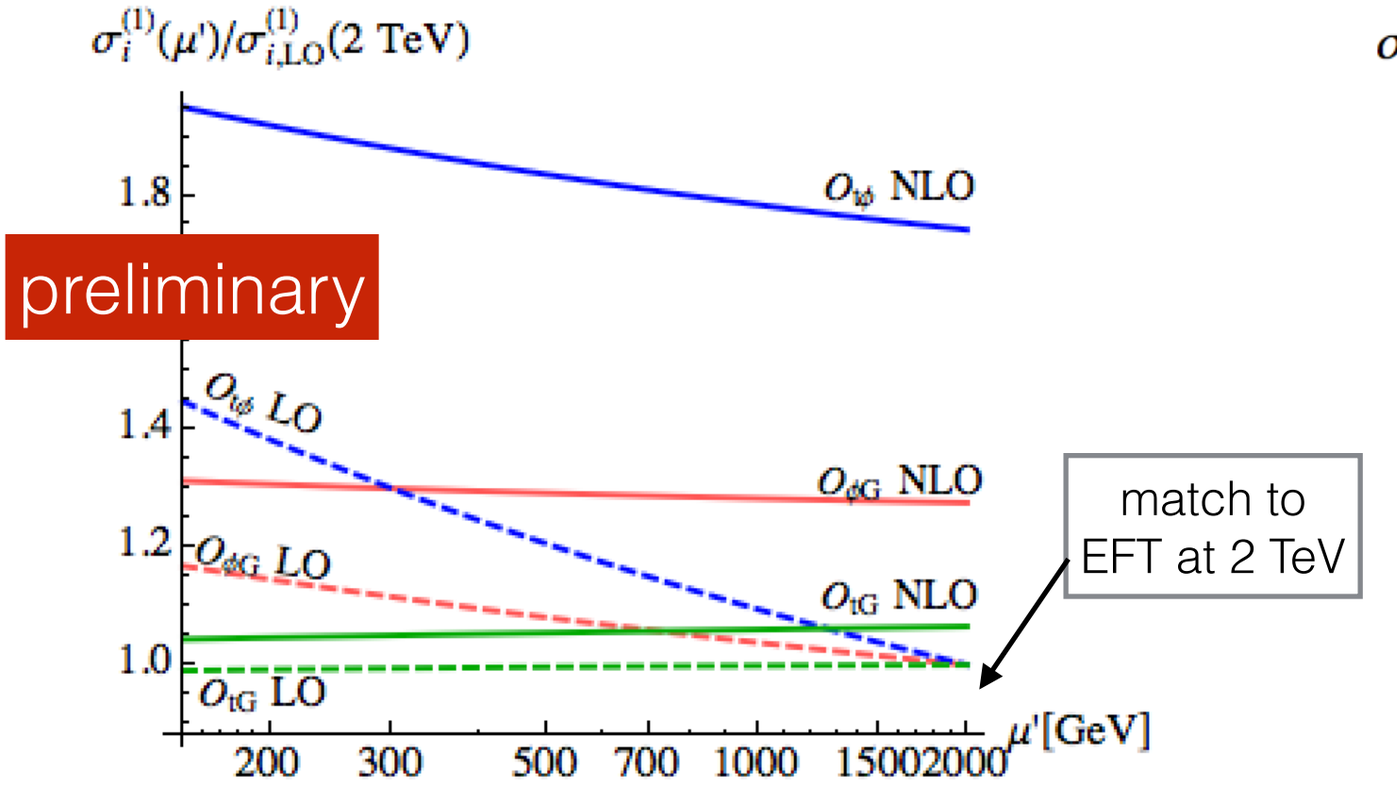
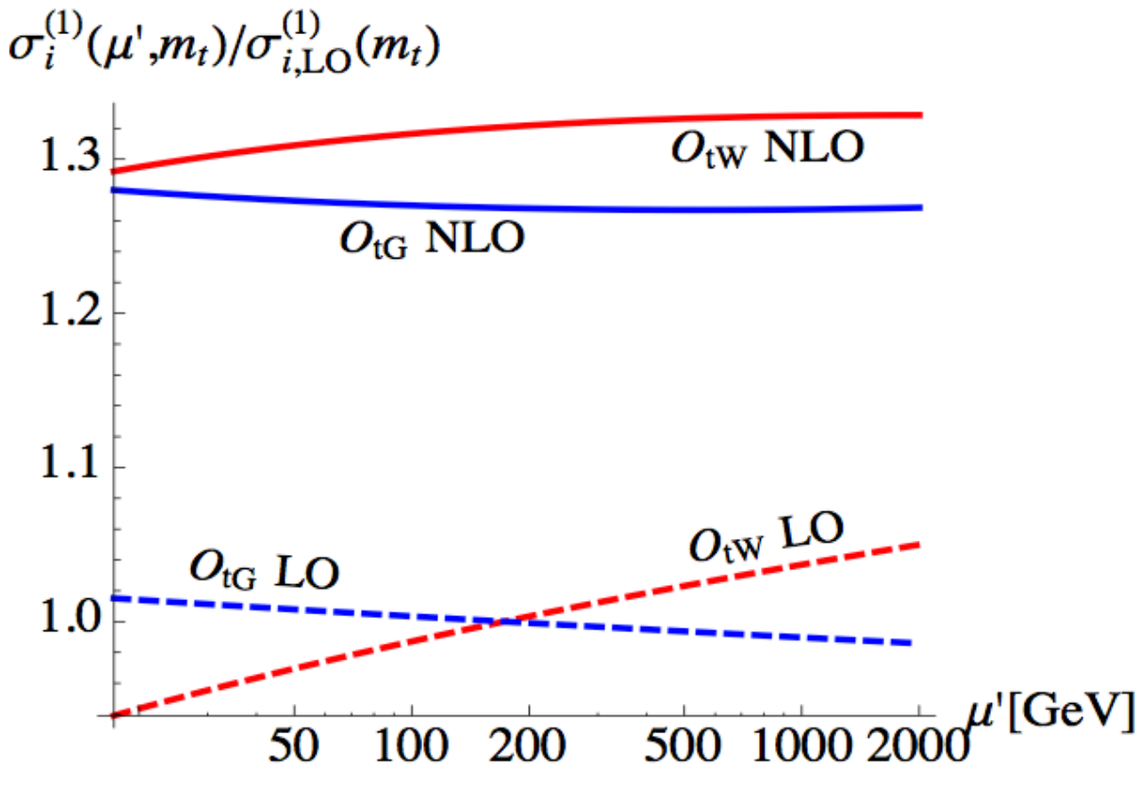


pp>ttH



pp>tW

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

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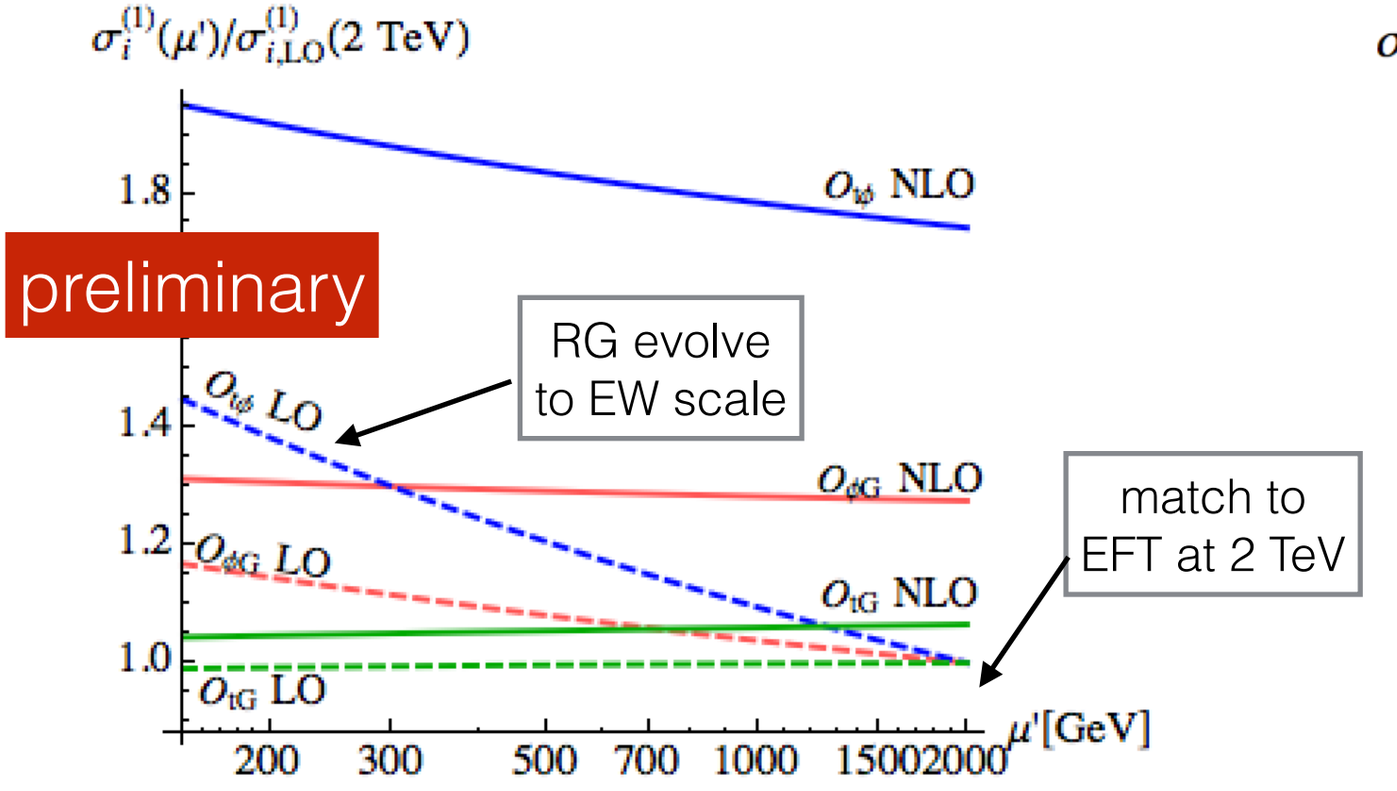
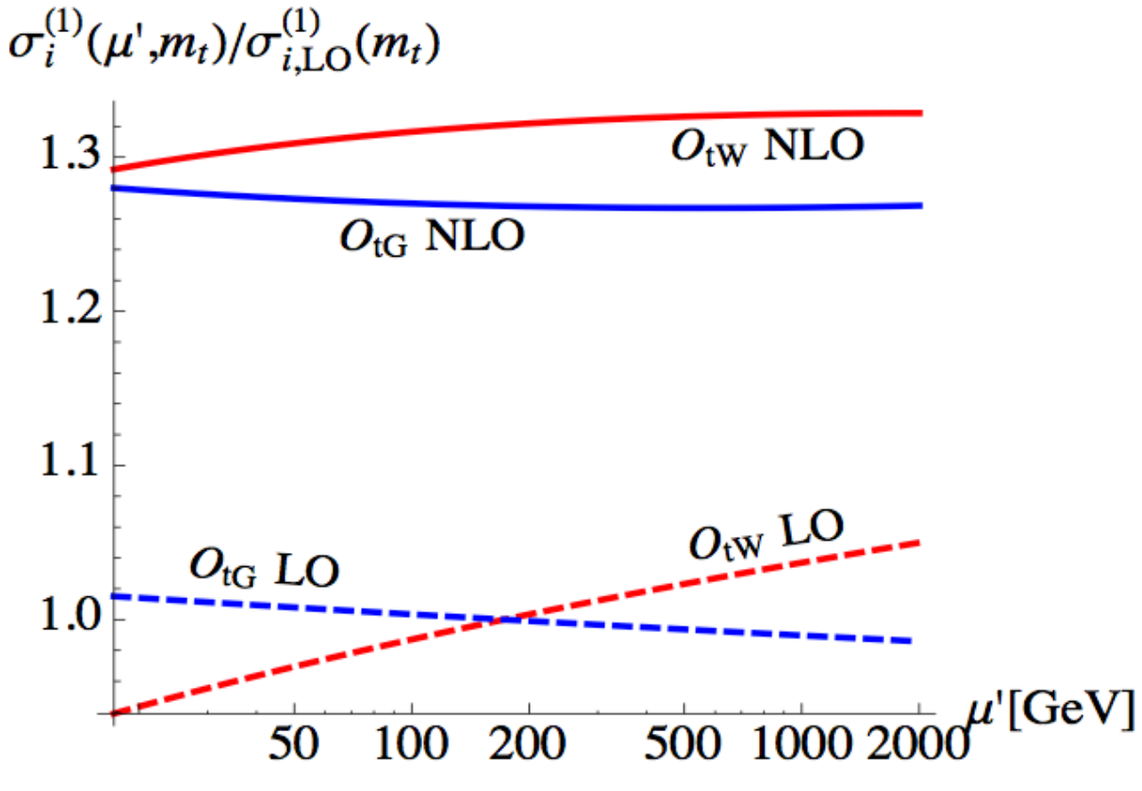


pp>ttH



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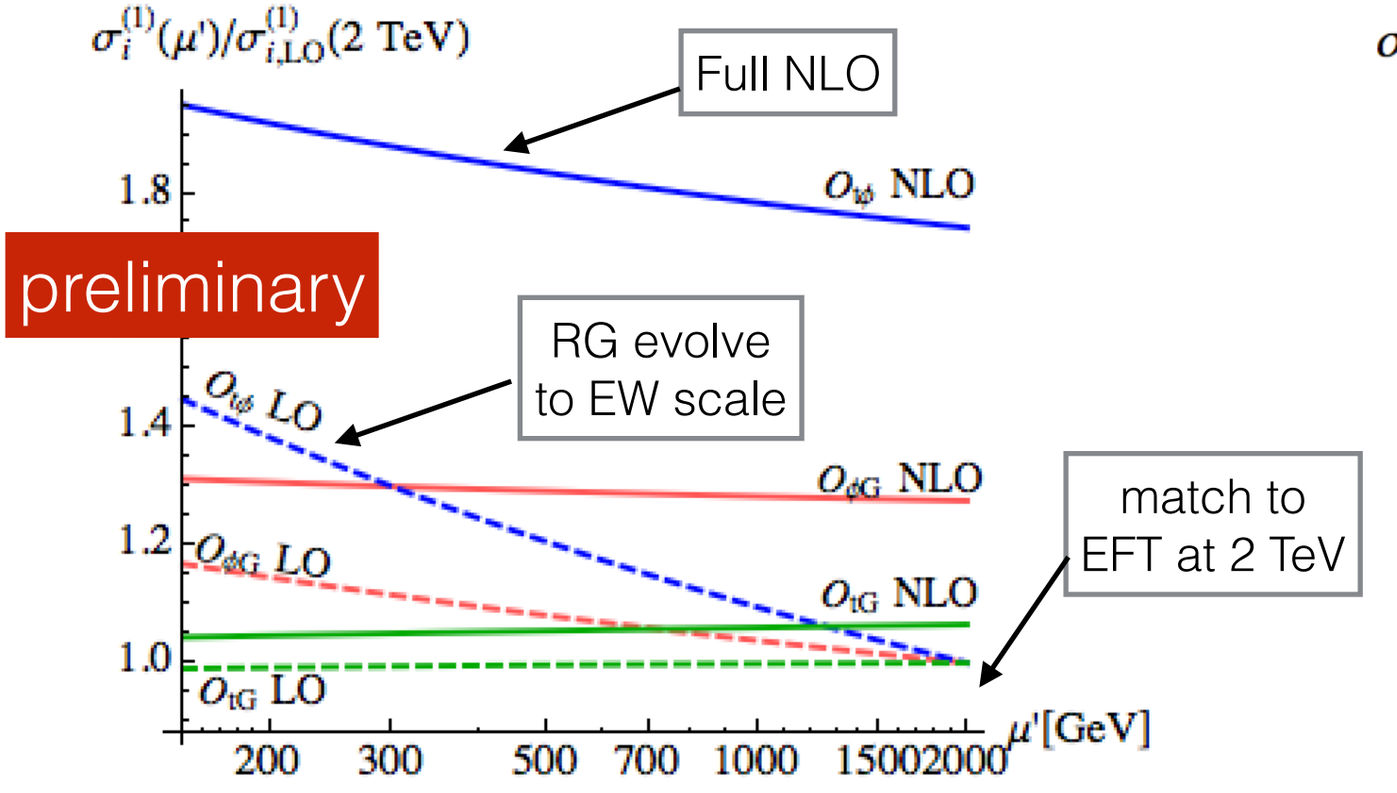
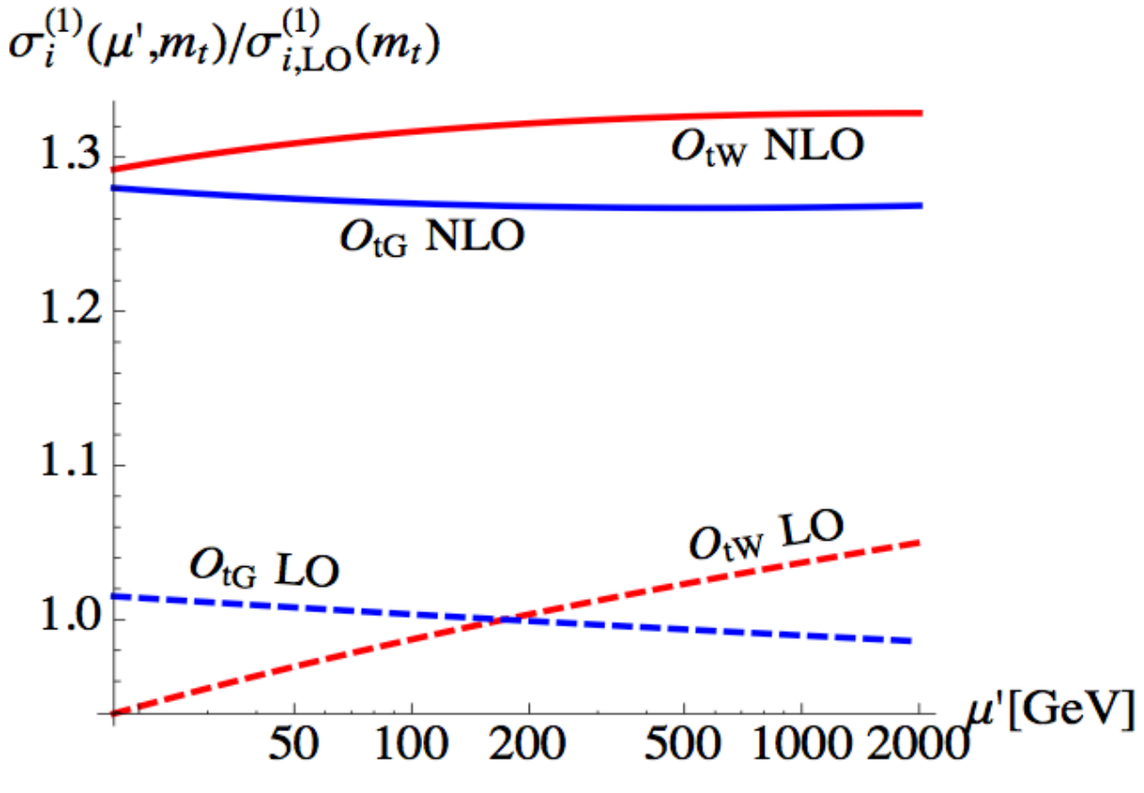


pp>ttH



pp>tW

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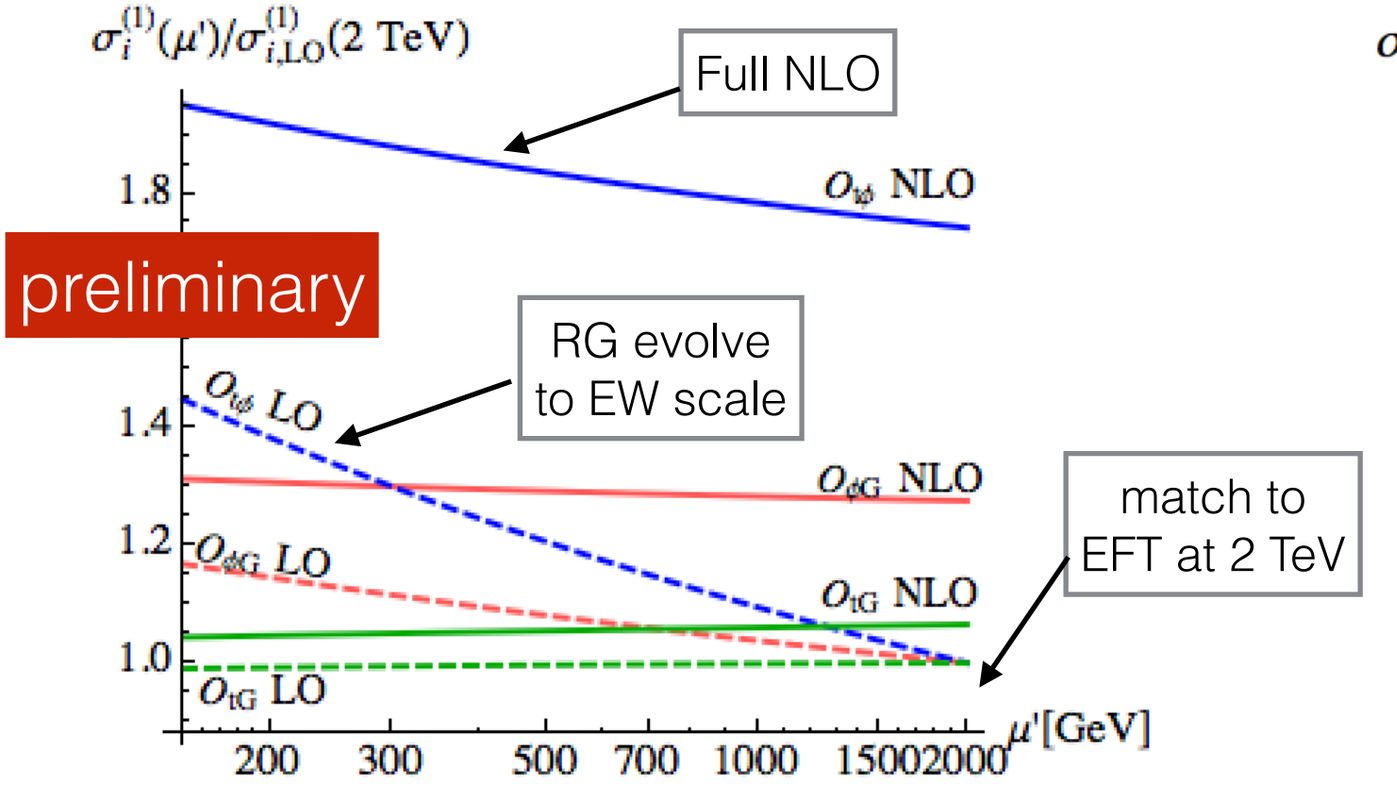
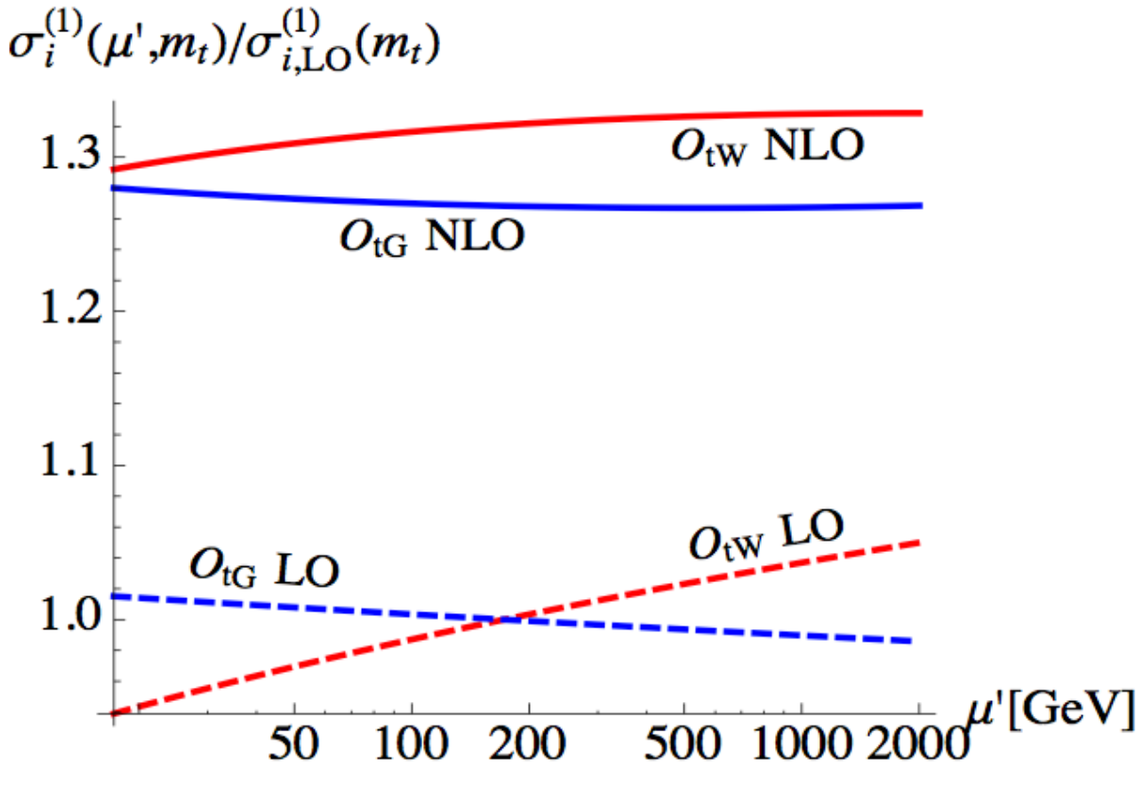


pp>ttH



pp>tW

RG corrections should be used with care

- Rescale with SM K factor is not good;
- RG as an approximation is not good;

➡ But we can always regenerate.

NLO status

ttg | ttZ/γ, tbW | ttH | qqtt | ggH

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

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}	$O_{u\phi}$	$O_{4\mathrm{f}}$
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

FCNC searches

We aim to provide: (in particular for experimentalists)

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

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

cf
[1501.05939 & 1404.1005, R. Rontsch and M. Schulze]

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}
$t \to ql^+l^-$	✓	✓	✓	✓	✓	✓		✓
$t \to q\gamma$				✓	✓	✓		
$t \to qH$						✓	✓	
$pp \to t$						✓		
$pp \to tl^+l^-$	✓	✓	✓	✓	✓	✓		(✓)
$pp \to t\gamma$				✓	✓	✓		
$pp \to tH$						✓	✓	

Coupling measurements

- ttbar with chromo
  [1503.08841 D.B. Franzosi, CZ]
- Complete top-EW operators, single t and ttV
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ttg ttZ/γ, tbW ttH qqtt ggH

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$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓								
$pp \to t\bar{t}\gamma$	✓	✓							
$pp \to t\gamma j$	✓	✓							
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
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$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$gg \to H, Hj, HZ$	✓			✓	✓	✓	✓		✓

cf
[1501.05939 & 1404.1005, R. Rontsch and M. Schulze]

NLO EFT for top is becoming available and will be complete in the near future

γ tqg tqH lltq

	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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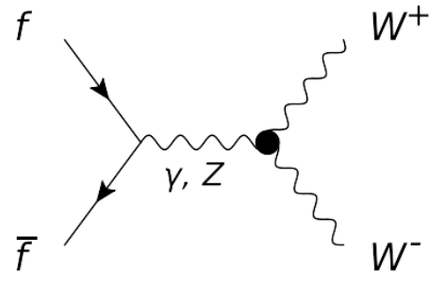
FCNC searches

Outline

- Introduction
- Top EFT
- Electroweak
- Summary

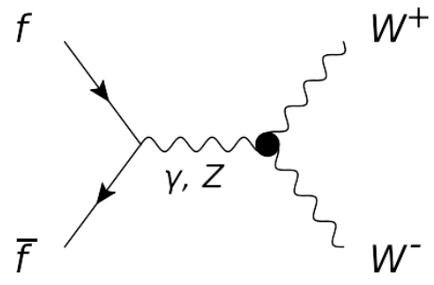
SMEFT for EW/Higgs



$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right)$$

- 5 anomalous coupling $g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$

SMEFT for EW/Higgs



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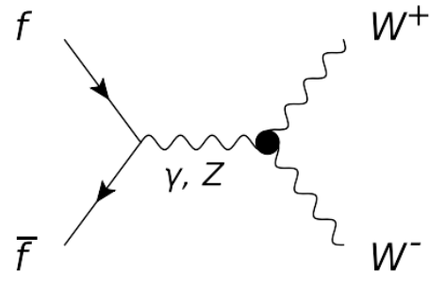
- 5 anomalous coupling $g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$
- EFT up to dim-6: 3 independent $\lambda_\gamma = \lambda_Z \quad \Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$

SMEFT for EW/Higgs



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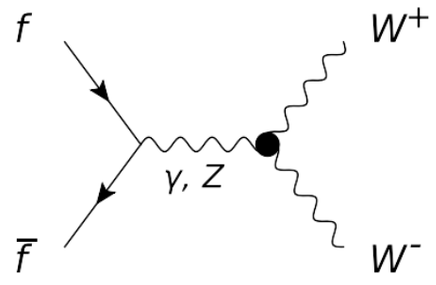
- EFT up to dim-6: 3 independent $\lambda_\gamma = \lambda_Z \quad \Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$
- Operators in HISZ basis

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

$$\begin{aligned}
g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}
\end{aligned}$$

SMEFT for EW/Higgs



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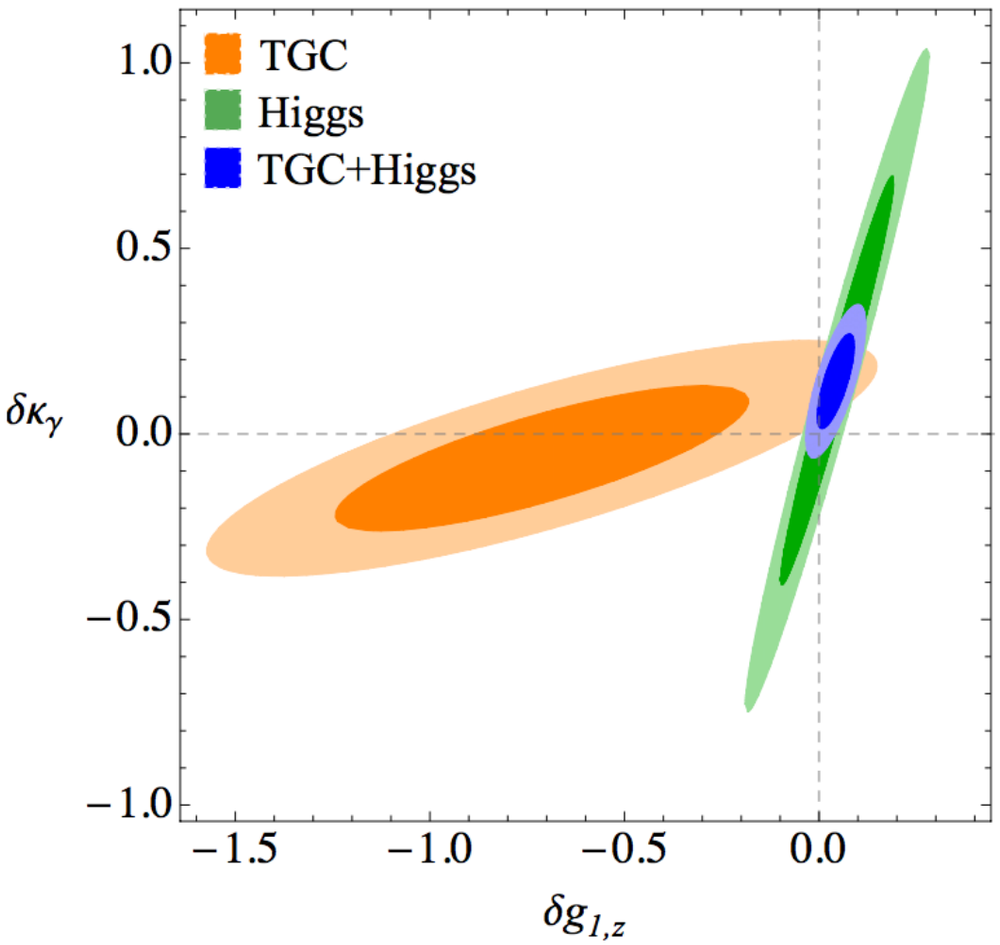
\end{aligned}$$

$$\begin{aligned}
g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}
\end{aligned}$$

- Are two approaches equivalent..?



"Accidental flat direction"

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

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

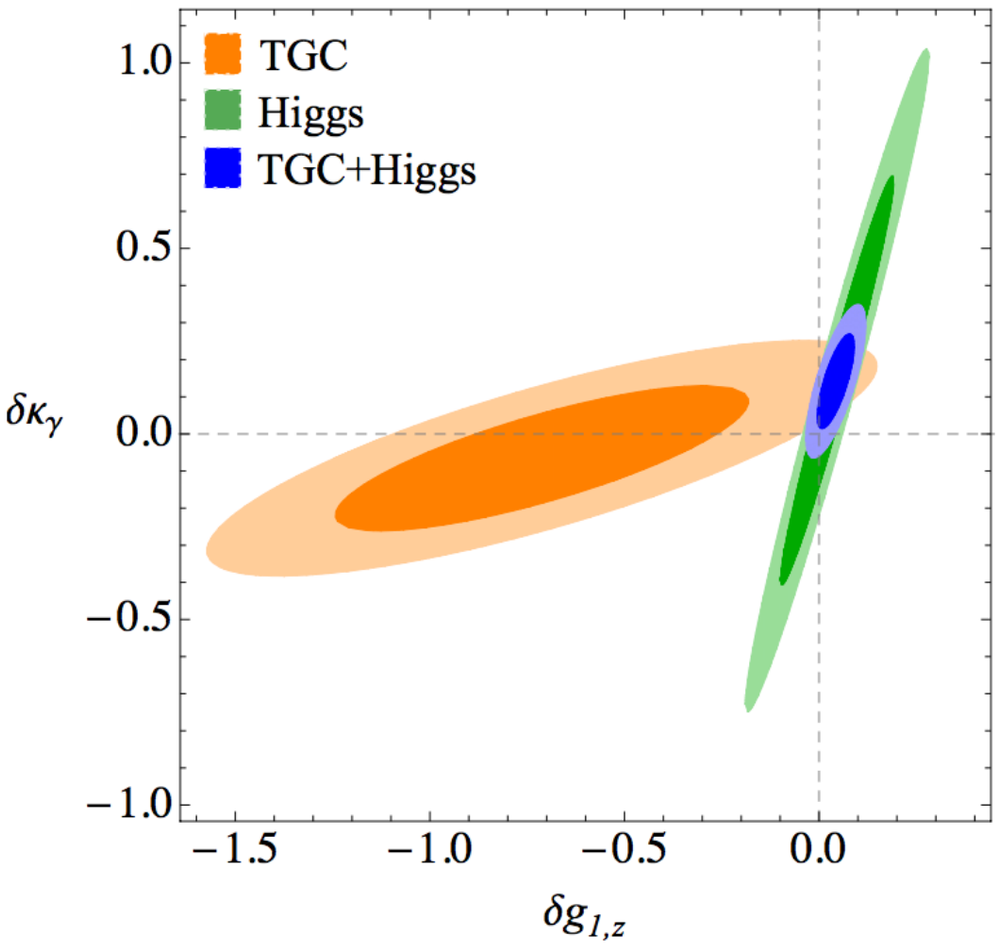
[1508.00581 Falkowski et al.]

[1304.1151 Corbett et al.]

To lift the degeneracy,

- Add Higgs data: EFT makes a connection between Higgs and TGC sectors

  or:
- Use polarized beam
- Go to higher energy
- …



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- …

EFT allows for connecting TGC with Higgs

- Dim-6/8 with both QGC and TGC are best constrained by TGC;
- We need operators with QGC but no TGC;
- They start to appear at Dim-8

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \qquad \mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \qquad \mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \qquad \mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \qquad \mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \qquad \mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \qquad \mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \qquad \mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \qquad \mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

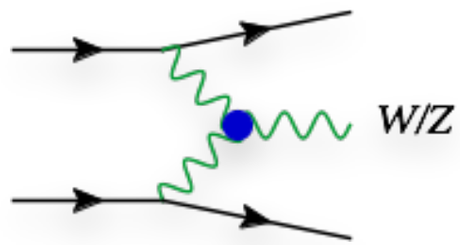
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \qquad \mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right] \qquad \mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

[hep-ph/0606118 J. P. Eboli et al.]

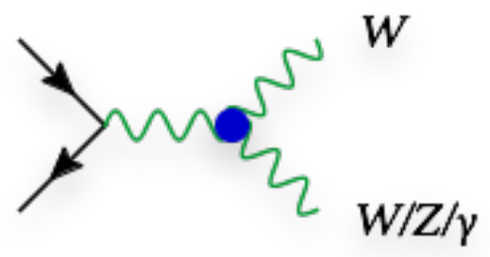
TGC measurements at LHC

- VBF
  - Zjj [1401.7610 ATLAS] [1410.3153 CMS]
  - Wjj [CMS-PAS-SMP-13-012]



aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

- Di-boson
  - WW [1507.03268 CMS] [1603.01702 ATLAS]
  - WZ [1603.02151 ATLAS]
  - more at 7 TeV…



Λ_{co}	Coupling	Expected	Observed
2 TeV	Δg_1^Z	[−0.023 ; 0.055]	[−0.029 ; 0.050]
	$\Delta\kappa^Z$	[−0.22 ; 0.36]	[−0.23 ; 0.46]
	λ^Z	[−0.026 ; 0.026]	[−0.028 ; 0.028]

EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]

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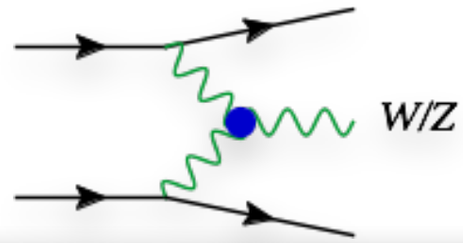
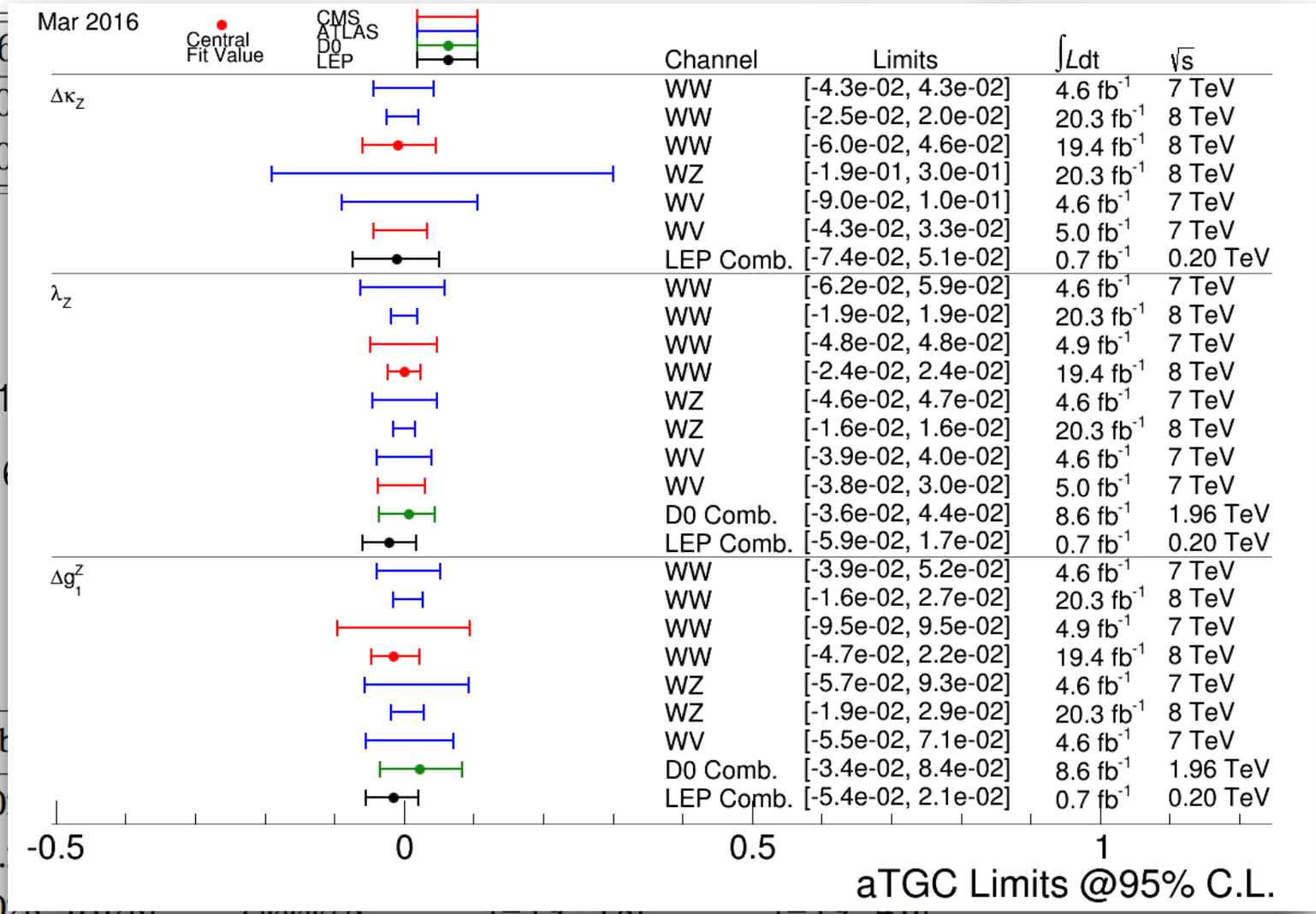


aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0$
λ_Z	$[-0.22, 0.19]$	$[-0$



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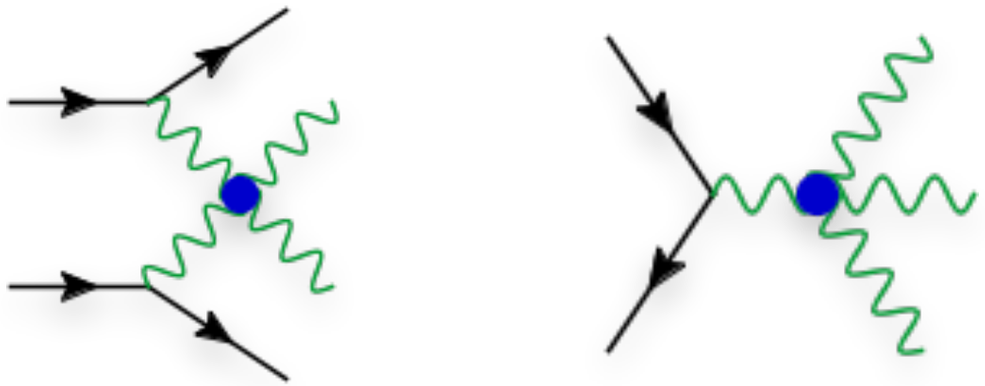
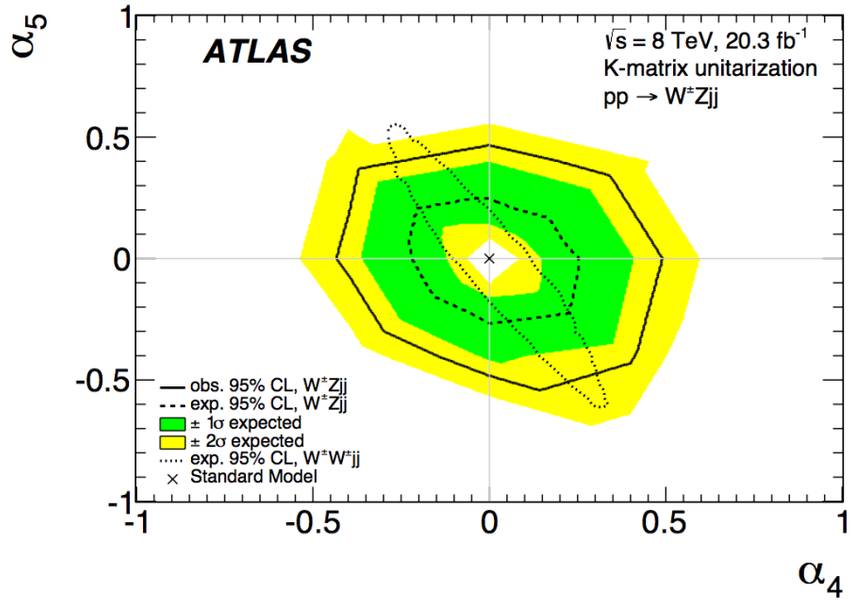
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

QGC measurements at LHC





- VBS:
  - Wγ, Zγ [CMS-PAS-SMP-14-018, CMS-PAS-SMP-14-011]
  - same sign WW [1410.6315 CMS] [1405.6241 ATLAS]
  - WZ [1603.02151 ATLAS]

- Tri-boson production
  - W$\gamma\gamma$, Z$\gamma\gamma$ [CMS-PAS-SMP-15-008] [1503.03243 ATLAS]
  - WWγ, WZγ [1404.4619 CMS]

Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

WW$\gamma\gamma$ QGC from W$\gamma\gamma$ production (CMS)

(Biased) comments from an EFTheorist

- Λ_{CO} does not have a clear TH meaning and is difficult to use. <u>Always give EFT interpretation</u>.

- If you worry about EFT validity: give results for different energy cutoff, so that theorists can <u>assess errors due to truncating</u> higher-dim operators. $c_i^{(6)} < \delta_i^{\rm exp}(M_{\rm cut})$ [1604.06444 R. Contino et al.]

- Limits on operators, assuming one or two operators at a time, are not very useful. Would be better if <u>global fit</u> can be provided.

- Use NLO for SM EFT.

TGC/QGC tools

- Dim-6 TGC
  - UFO model: EWdim6 https://feynrules.irmp.ucl.ac.be/wiki/EWdim6

    [arXiv:1205.4231, Degrande, Greiner, Kilian, Mattelaer, Mebane, Stelzer, Willenbrock, CZ]

CP-even

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

CP-odd

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

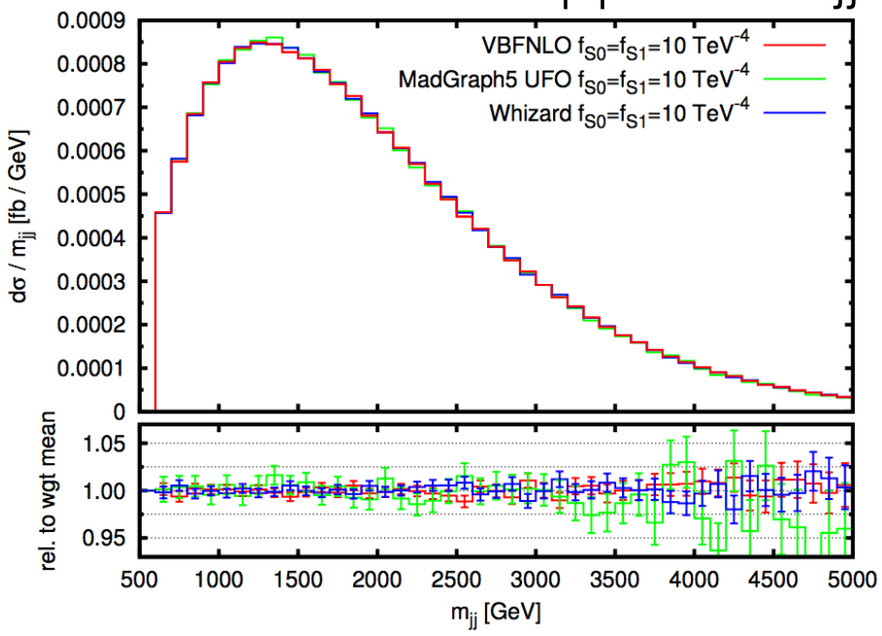
  - VBFNLO [1404.3940 J.Baglio]
  - Complete dim-6 EFT implementation with Whizard [0708.4233 W. Kilian]

- Dim-8 QGC: UFO, VBFNLO, Whizard

  https://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X			X	X	X	X

pp>W+W+jj



[1309.7890, C. Degrande et al.]

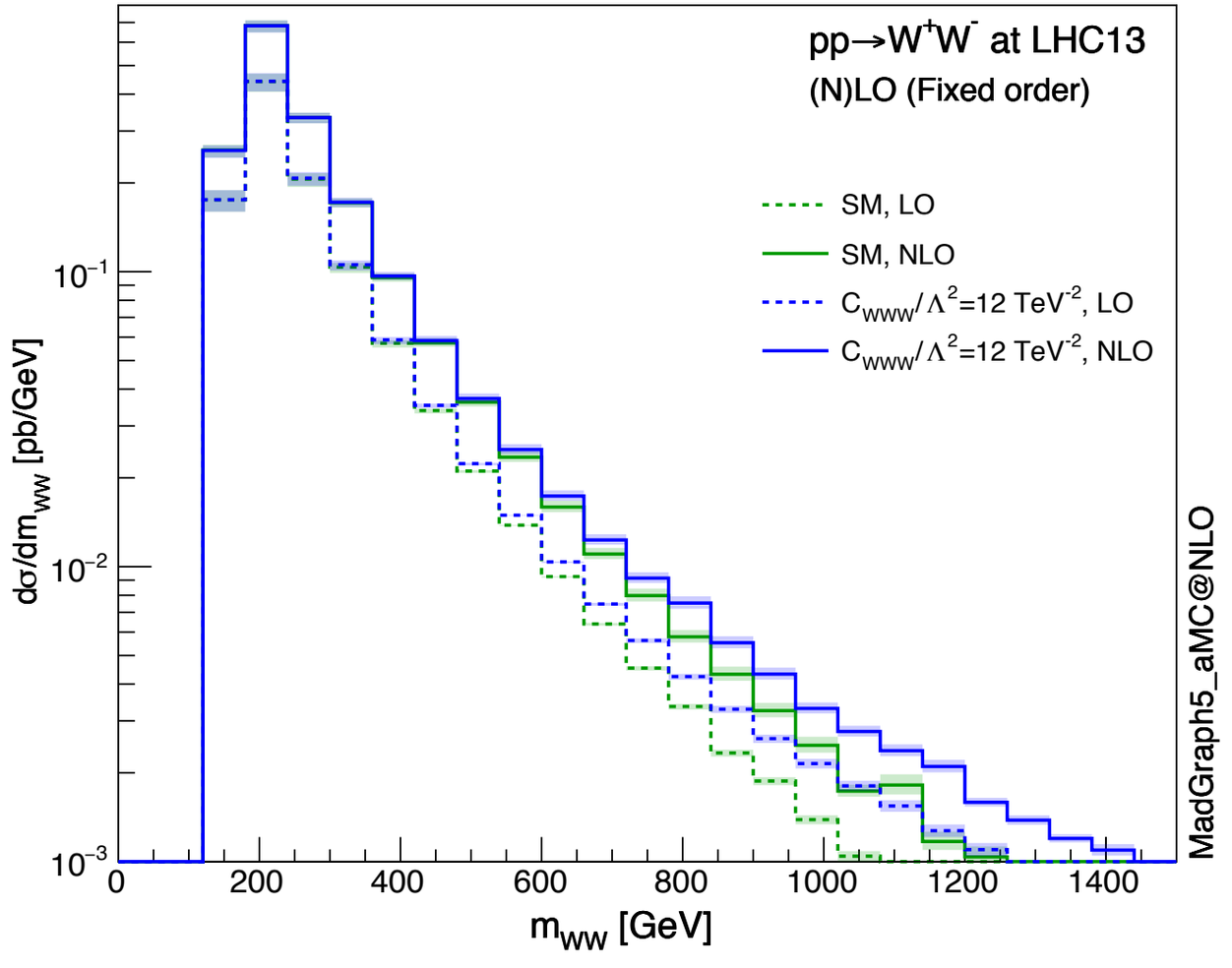
TGC/QGC tools

TGC & QGC operators are decouple from QCD corrections. NLO EFT in general available

- VBFNLO, including VBF, VBS, di-boson/tri-boson, …

- MC@NLO, WZ and WW production.[hep-ph/0204244 S. Frixione and B.R. Webber]

- General purpose implementation available based on public tools:
  - ➡ FeynRules [1310.1921 A. Alloul et al.]
  - ➡ NLOCT [1406.3030 C. Degrande et al.]
  - ➡ UFO [1108.2040 C. Degrande et al.]
  - ➡ generator (MG5_aMC/Sherpa/…)



Outline

- Introduction
- Top EFT
- Electroweak
- Summary

Summary

- **SM@DIM6 EFT** can be used to interpret most of the SM Higgs/Top/EW/… measurements.

- **TH prediction**: SM will continue to be improved (by including NNLO in QCD etc.), and in the meantime, **EFT @ NLO in QCD is becoming available**, in an automatic way, and can be **directly used in EXP analysis**.

- **Global fit** for top operators including shapes for LHC has appeared. **Proof of principle for NLO fit** also exists. On the EW side many multi-boson channels are analyzed with EFT and limits on TGC/QGC operators are placed.

- More works still need to be done concerning the best fitting/searching strategy.

Basis

Certain (linear combinations of) operators may be equivalent, due to EOM, integration by parts, Fierz identity, etc.

- Warsaw basis: always use EOM to eliminate “D”; complete RG available

[1312.2014 R. Alonso et al.]

- EGGM basis *[J. Elias-Miro et al. 2013]*

$$
\begin{aligned}
(H^\dagger \tau^a \overleftrightarrow{D}^\mu H)(\bar{L}_1 \gamma_\mu \tau^a L_1) &\to O_W = ig(H^\dagger \tau^a \overleftrightarrow{D}^\mu H)(D^\nu W^a_{\mu\nu}),\\
(H^\dagger \overleftrightarrow{D}^\mu H)(\bar{e}\gamma_\mu e) &\to O_B = ig' Y_H (H^\dagger \overleftrightarrow{D}^\mu H)(\partial^\nu B_{\mu\nu}),\\
(\bar{u}\gamma^\mu t^A_s u)(\bar{d}\gamma_\mu t^A_s d) &\to O_{2G} = -\frac{1}{2}(D^\mu G^a_{\mu\nu})^2,\\
(\bar{L}_1\gamma^\mu \tau^a L_1)(\bar{L}_1\gamma_\mu \tau^a L_1) &\to O_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2,\\
(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e) &\to O_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2.
\end{aligned}
$$

EOM

&

$$
\begin{aligned}
O_W &= O_{HW} + \frac{1}{4}(O_{WW} + O_{WB}),\\
O_B &= O_{HB} + \frac{1}{4}(O_{BB} + O_{WB}).
\end{aligned}
$$

- SILH basis *[G. F. Giudice et al., 2007]*

$$
\begin{aligned}
O_{WW} &= g^2 (H^\dagger H) W^a_{\mu\nu} W^{a\mu\nu}\\
O_{WB} &= 2gg' (H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu}
\end{aligned}
$$

$$
\begin{aligned}
O_{HW} &\equiv 2ig(D^\mu H)^\dagger \tau^a (D^\nu H) W^a_{\mu\nu}\\
O_{HB} &\equiv ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu},
\end{aligned}
$$

[A. Falkowski and F. Riva 2014]

[C. Grojean et al. 2006]

- HISZ basis *[K. Hagiwara et al. 1993]*

$$
\begin{aligned}
O_W &= ig(H^\dagger \tau^a \overleftrightarrow{D}^\mu H)(D^\nu W^a_{\mu\nu})\\
O_B &= ig' Y_H (H^\dagger \overleftrightarrow{D}^\mu H)(\partial^\nu B_{\mu\nu})
\end{aligned}
$$

Convenient for PEWM, TGC, and Higgs

- 2 flat directions in PEWM become more transparent
- 3 TGC couplings directly related to 3 operators

- Rosetta [1508.05895 A. Falkowski et al.]

EW sector probed by PEWM+TGC+Higgs: 8+3+8

assuming flavor symmetry

1. PEWM (10^{-3})

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$
(+) $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D_\mu} H\right)^2$
$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D_\mu} H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D_\mu} H)(\bar{Q}_L \gamma^\mu Q_L)$

Mainly from Z-pole: only 8 d.o.f
(10 would appear in BW/Warsaw)

[A. Falkowski and F. Riva 2014]

2. TGC (10^{-2})

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$
(-) $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$

W-pair production: $g_1^Z,\ \kappa_\gamma,\ \lambda_Z$

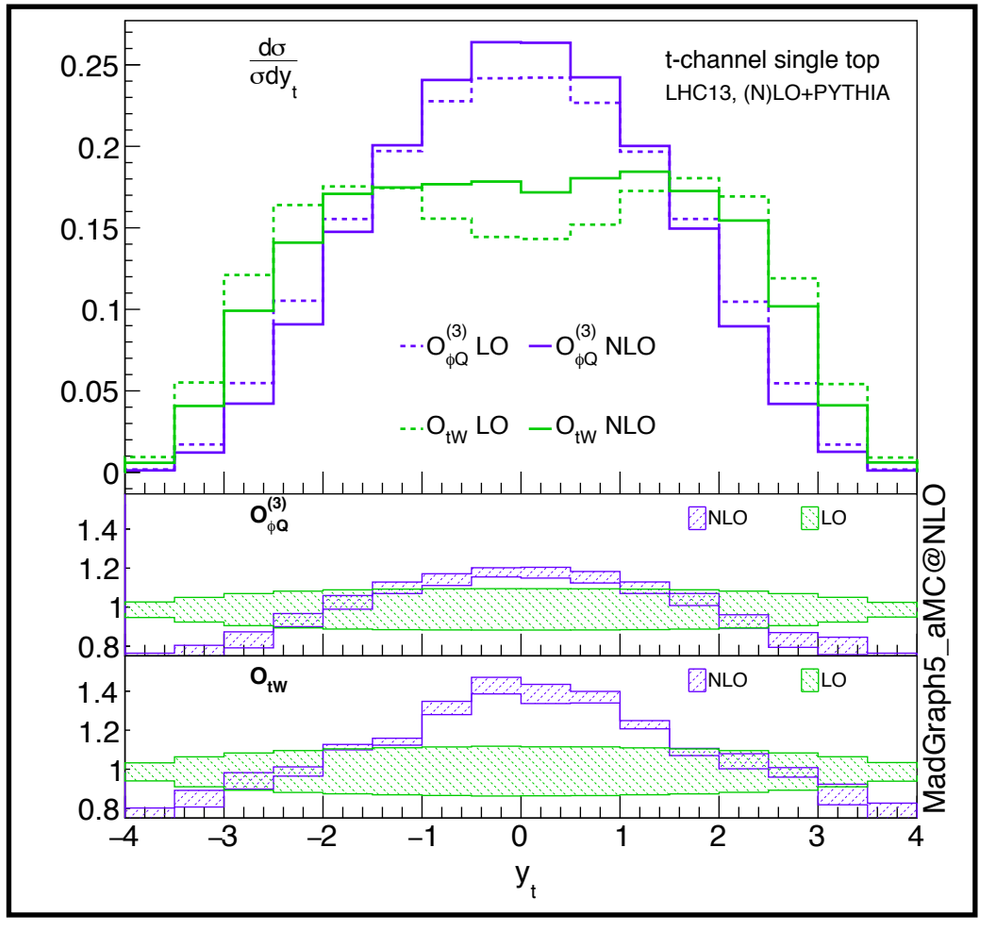
- In principle, WW also test 4 more parameters, from the PEWM class.
- They decouple because at LEP, they are measured with ~O(10) better accuracy.
- However this may change in future.

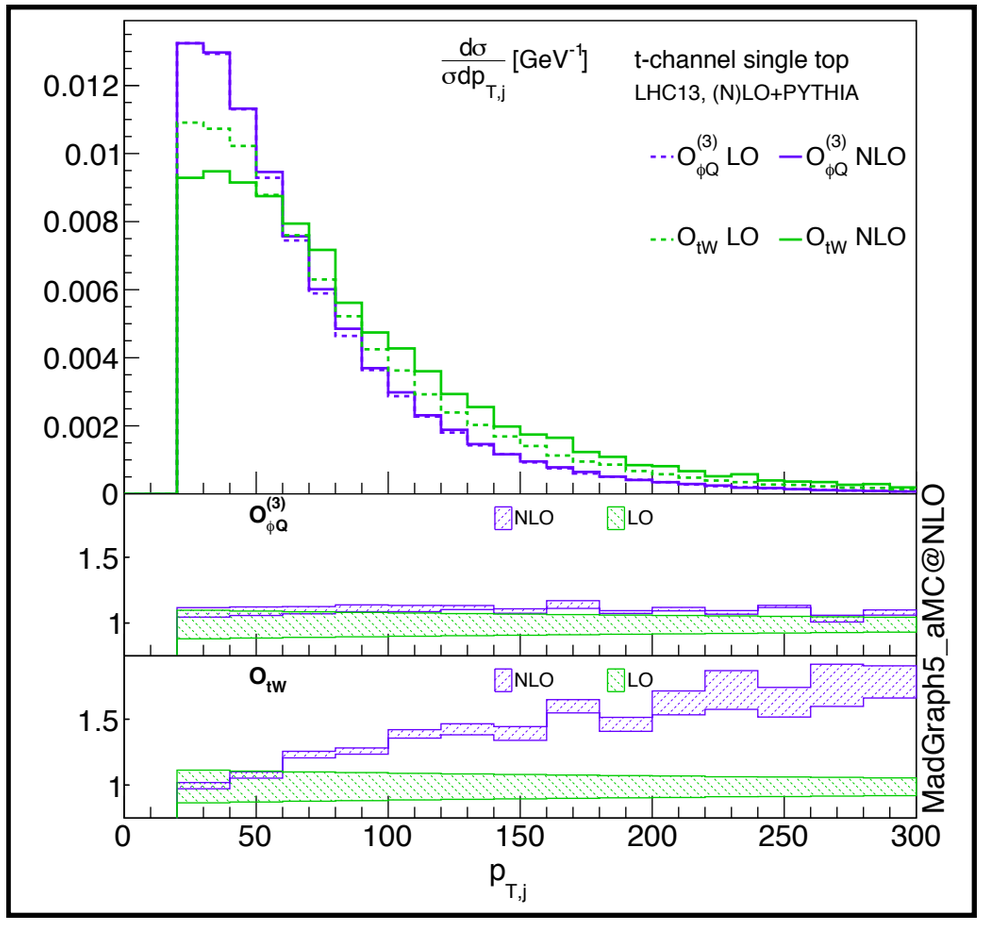
3. New from Higgs

$\mathcal{O}_H = [\partial_\mu (H^\dagger H)]^2$
$\mathcal{O}_{BB} = \frac{g'^2}{4}\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{WW} = \frac{g^2}{4}\lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$
$\mathcal{O}_{GG} = \frac{g_s^2}{4}\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$
$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$
$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$

Towards a global fit at NLO

- In addition, there are non-trivial effects if “discriminant” observables are used in global fits
  - Shapes of O_1 and O_2 differs
  - QCD corrections <u>shift both curves in one direction</u>
  - Leads to bias in a fit that uses shape info





t-ch. single top [1601.06163, CZ]

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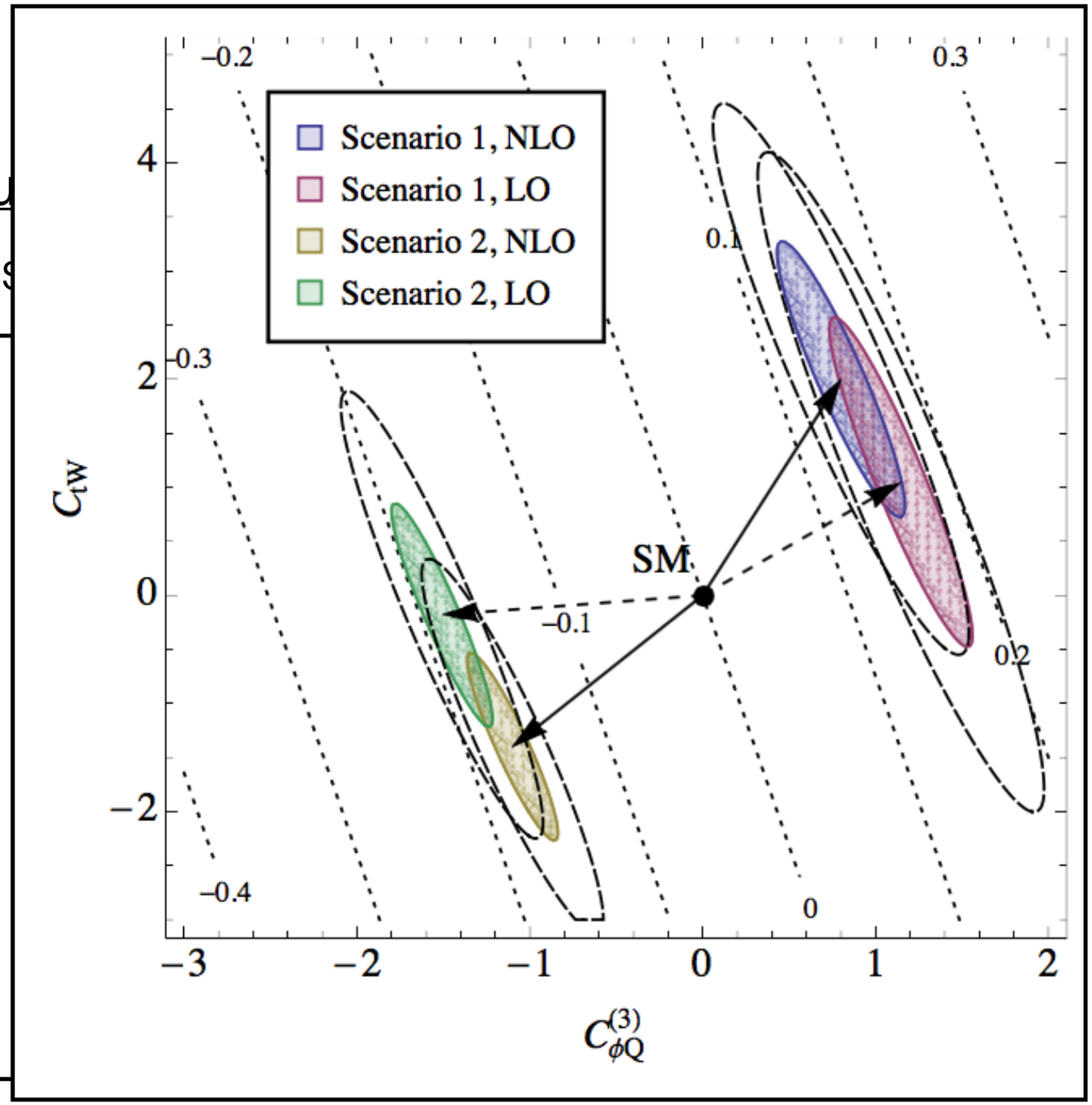

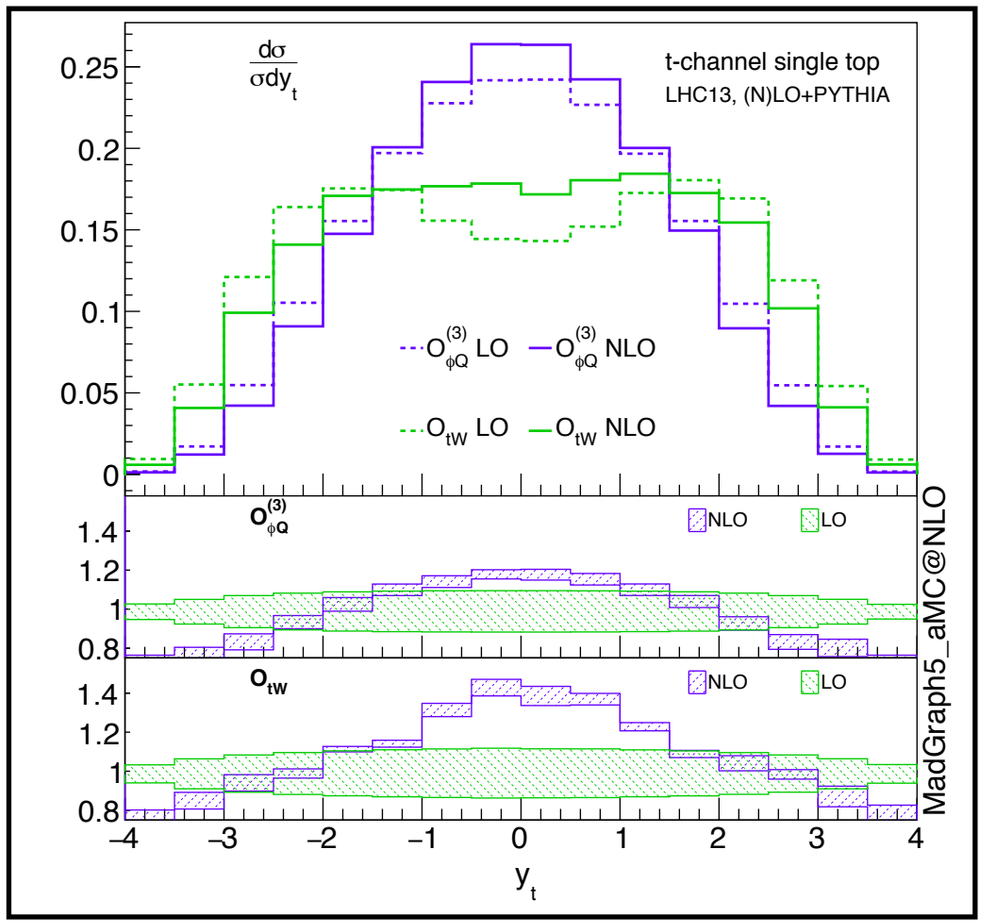

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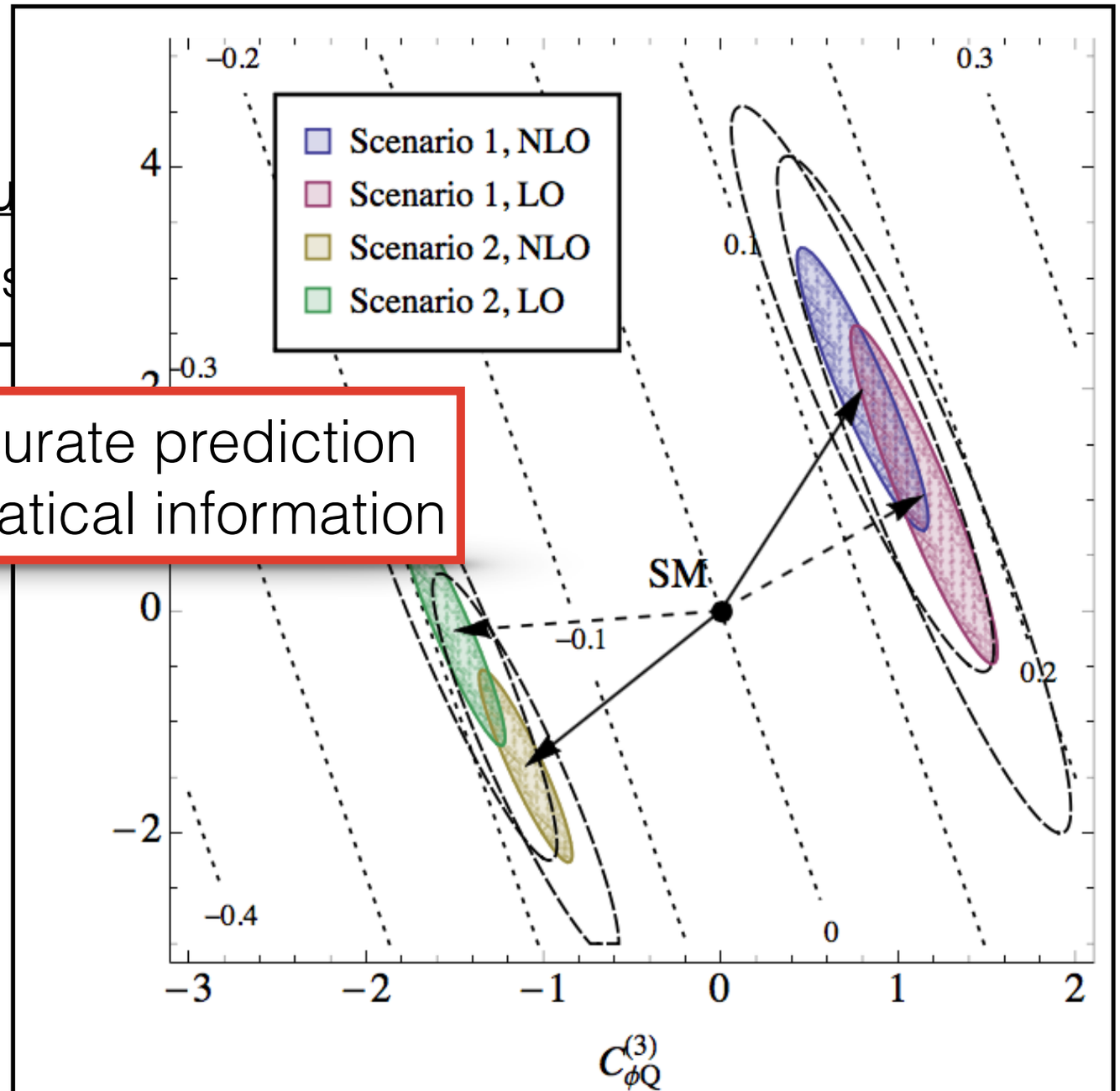
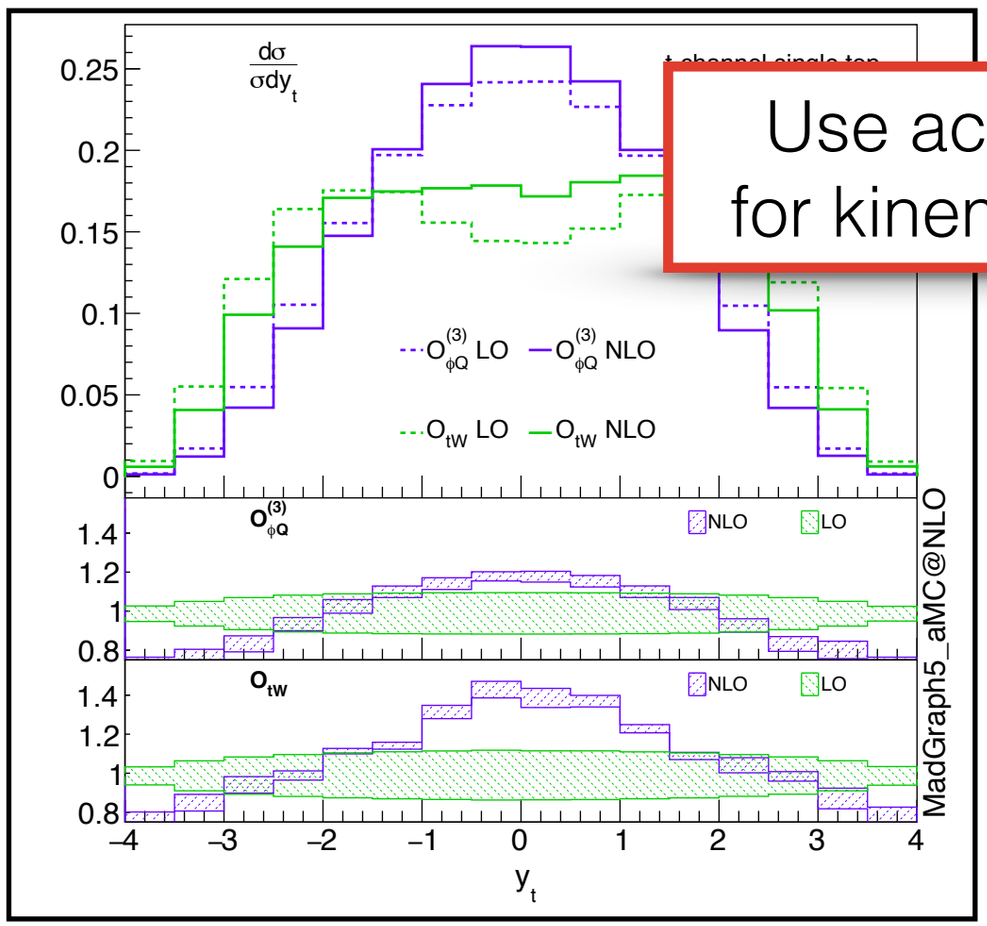


Use accurate prediction for kinematical information



t-ch. single top [1601.06163, CZ]

Top-down search based on EFT

- In addition, there are non-trivial effects on the “discriminant” observables
  - Important for top-down search strategy: designing optimized search based on all information we know from an EFT

preliminary

SM $t\bar{t}$ fixed, float one operator at a time:

Operator	Uncertainty on $c_i\Lambda^{-2}$ (TeV^{-2})		
	Yields only	$\Delta\phi(l^+, l^-)$	Variable D_i
$\mathcal{O}_{tG}$	0.0057	0.0057	0.0057
$\mathcal{O}_{G}$	0.072	0.071	0.049
$\mathcal{O}_{\phi G}$	0.19	0.18	0.17
$\mathcal{O}_{qq}^{(8,1)}$	0.32	0.31	0.24
$\mathcal{O}_{qq}^{(8,3)}$	2.23	2.06	1.29
$\mathcal{O}_{ut}^{(8)}$	0.55	0.46	0.36
$\mathcal{O}_{dt}^{(8)}$	0.73	0.63	0.50

Already substantial improvements using MEM-based discriminants

[V. Lemaitre, S. Brochet, S. Wertz]

- The SM EFT becomes popular in the past few years, because
  - Need HEFT for analyzing Higgs couplings (talk in the afternoon)

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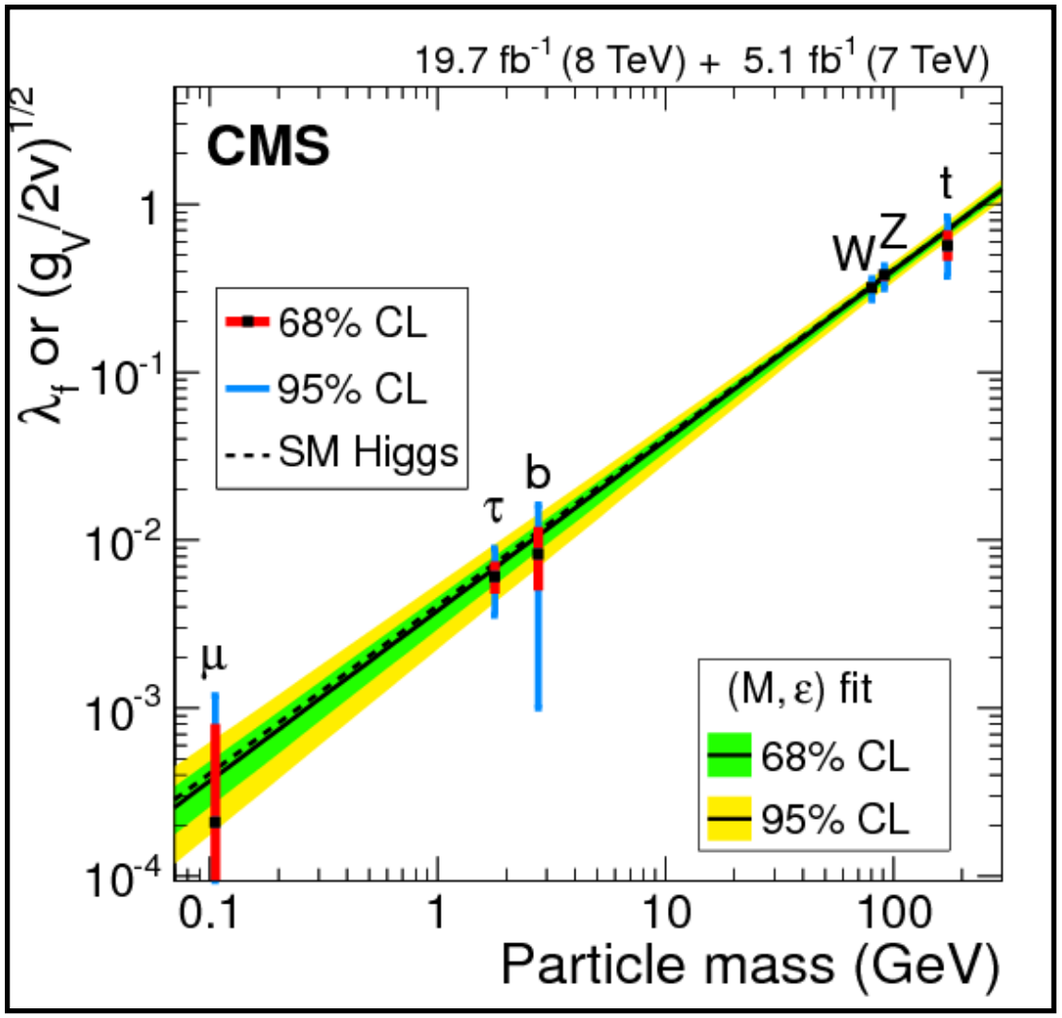
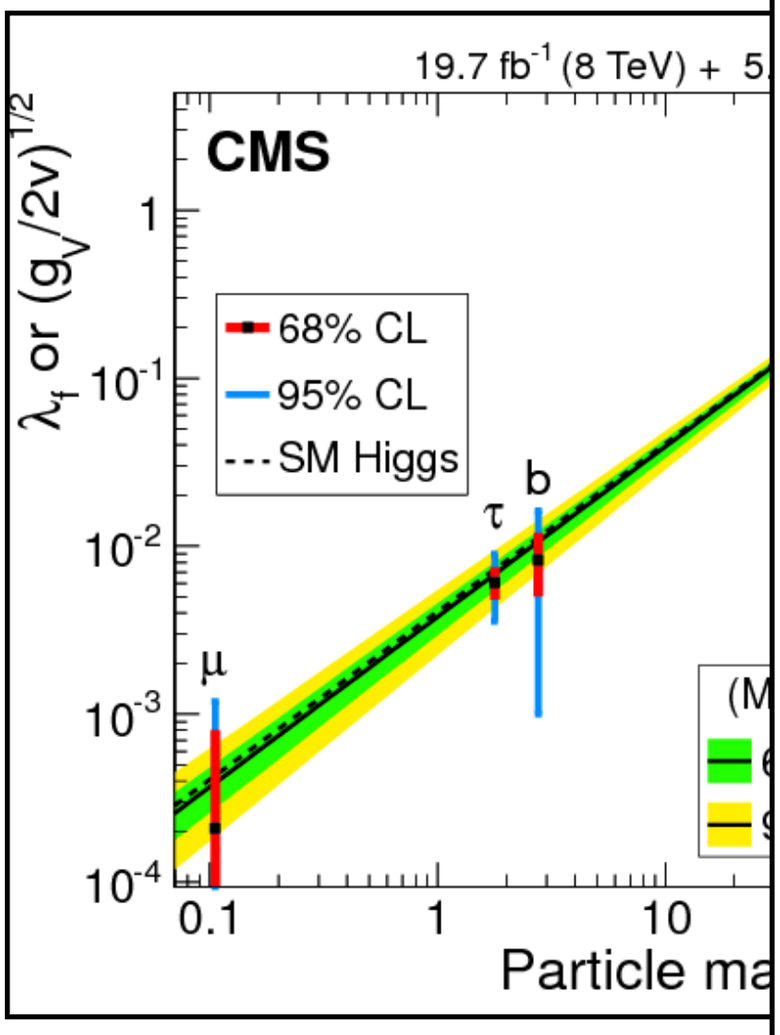
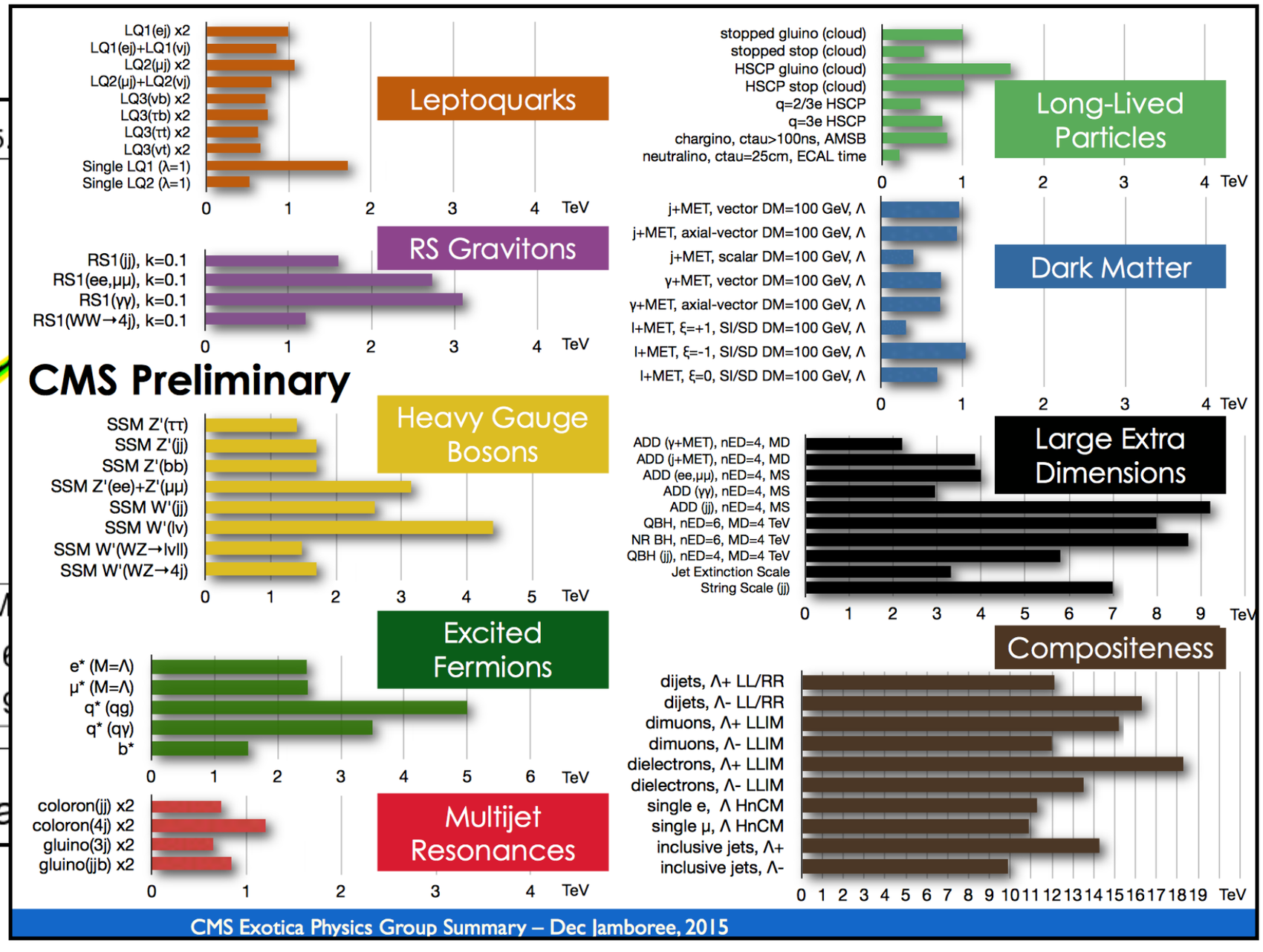


- The SM EFT becomes popular in the past few years, because
  - Need HEFT for analyzing Higgs couplings (talk in the afternoon)
  - All known elementary particles are like SM particles (and hence “SM”)
  - The unknown particles seem to be heavy (and hence “EFT”)





Automation Example
ttZ production

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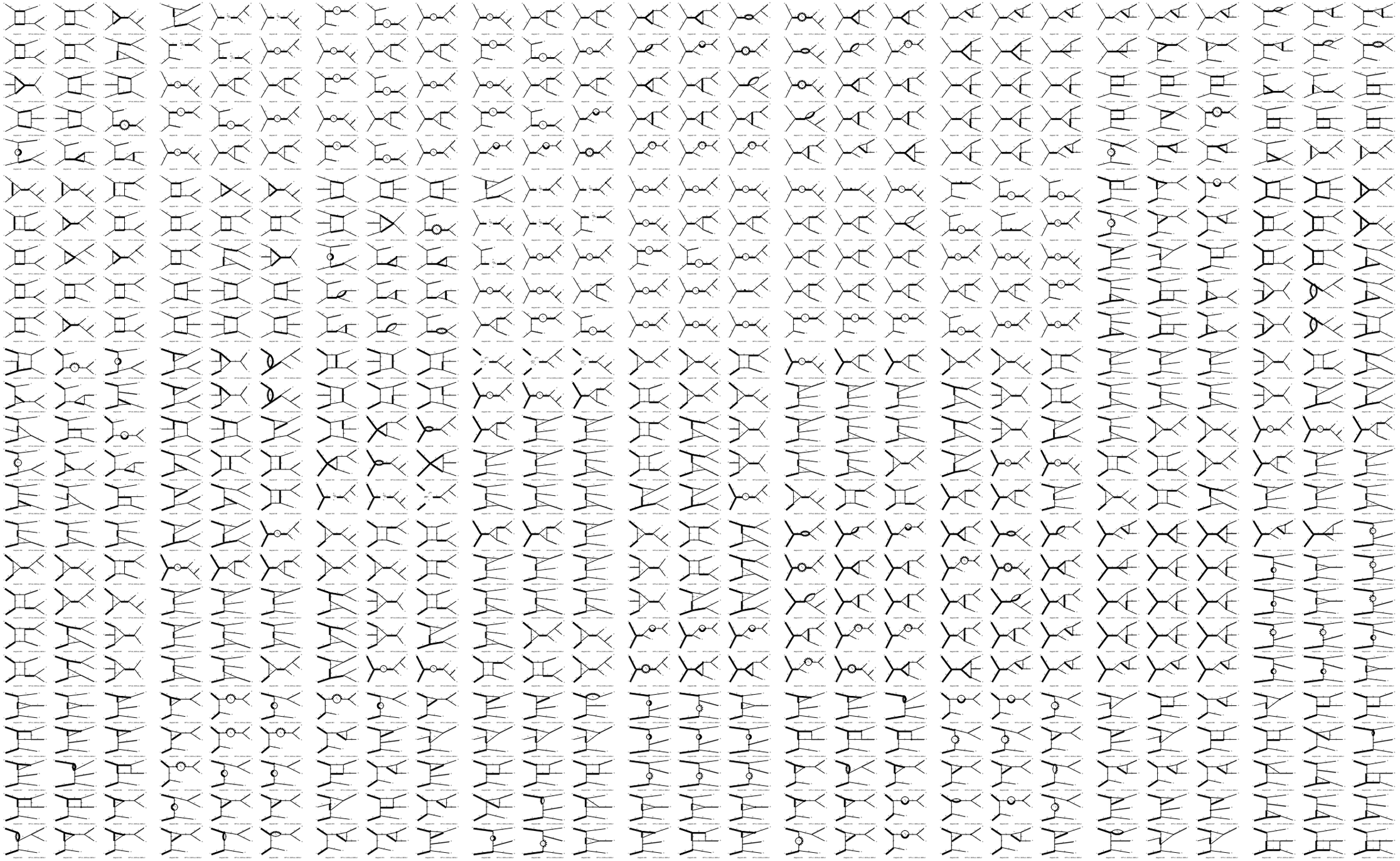

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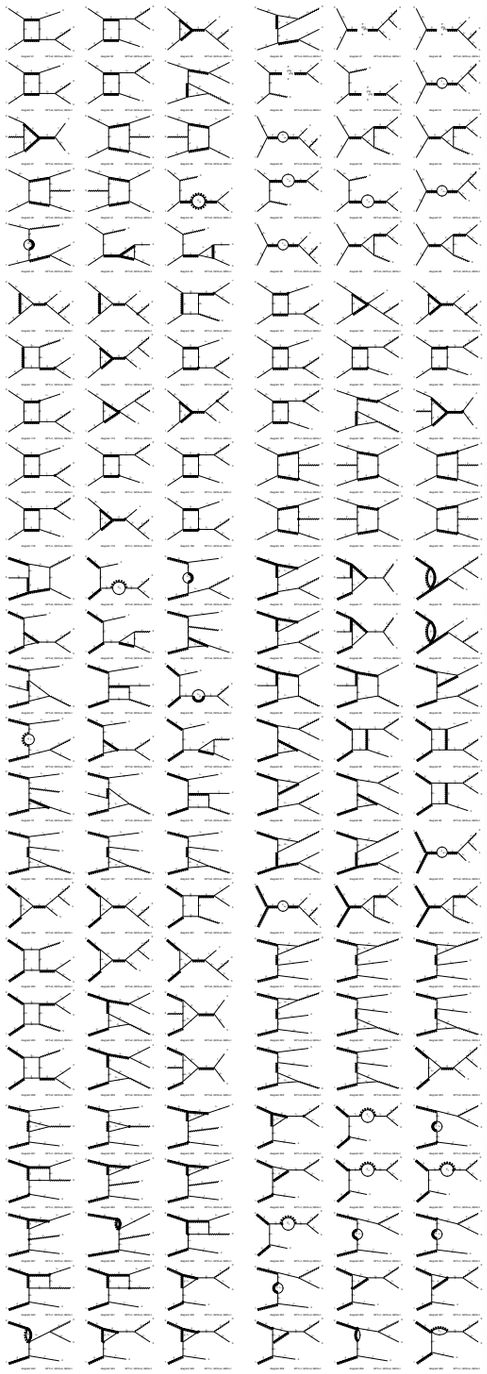
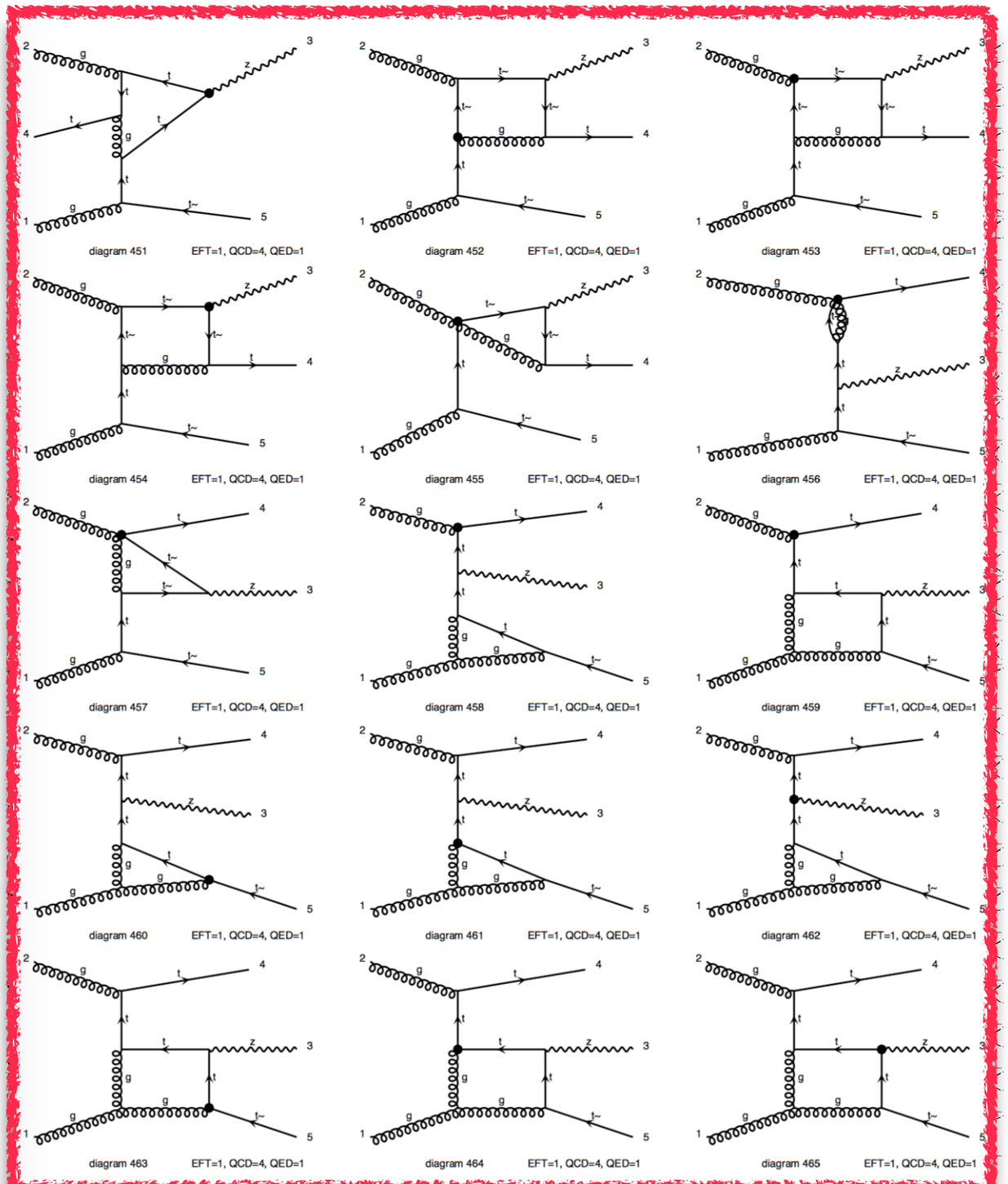
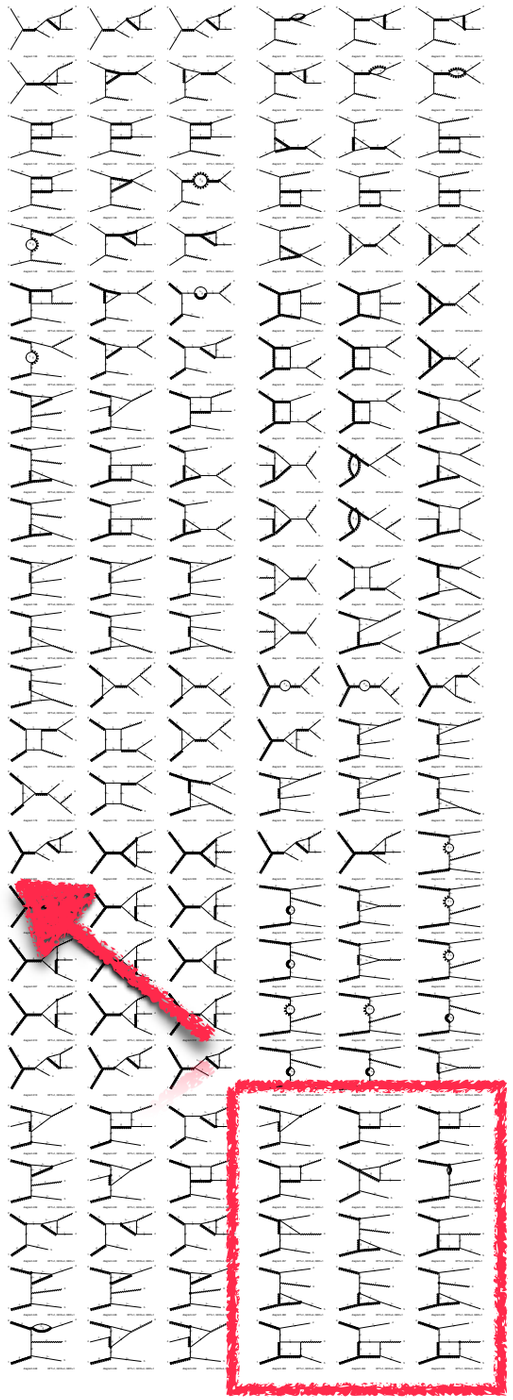
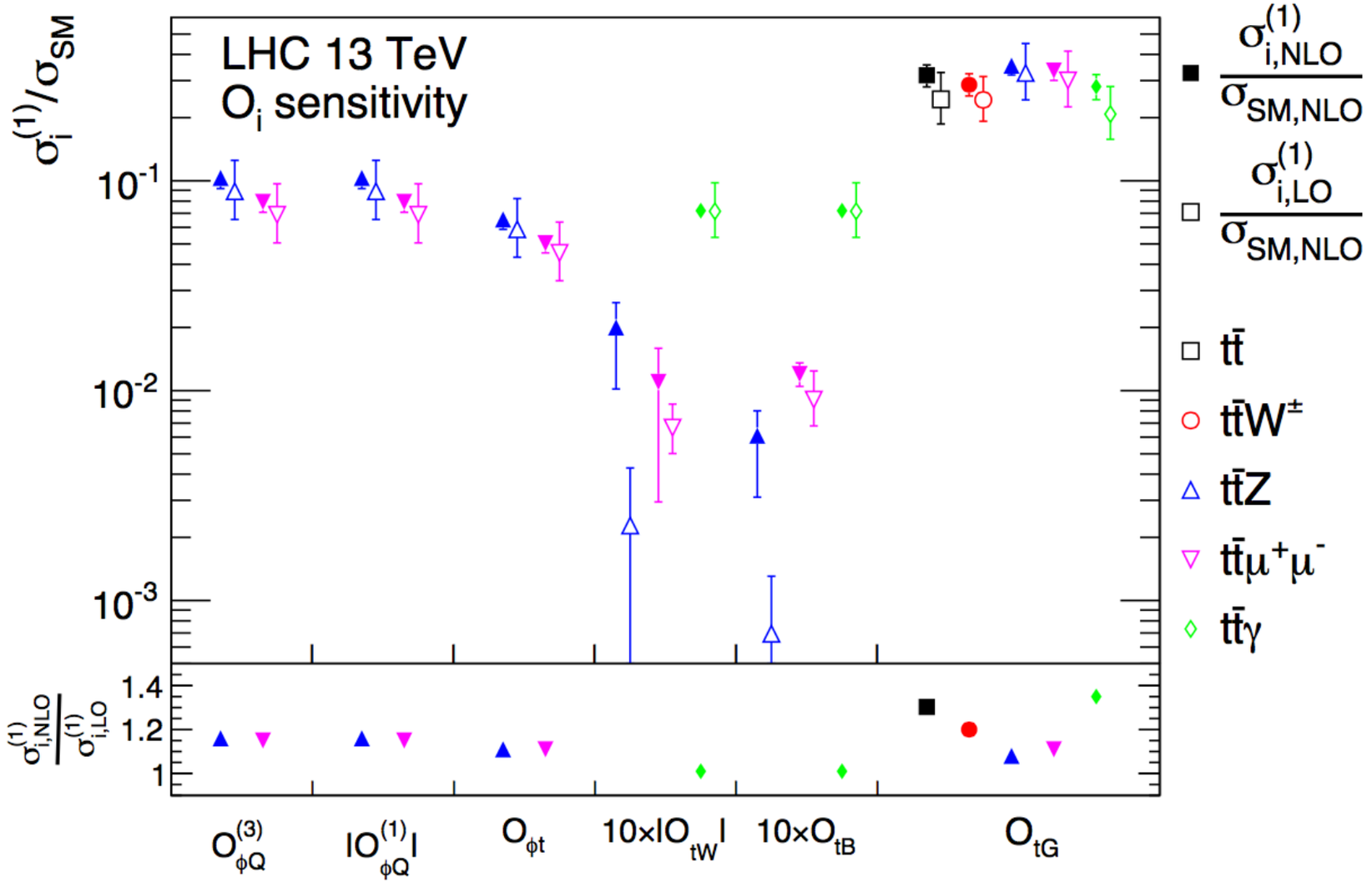
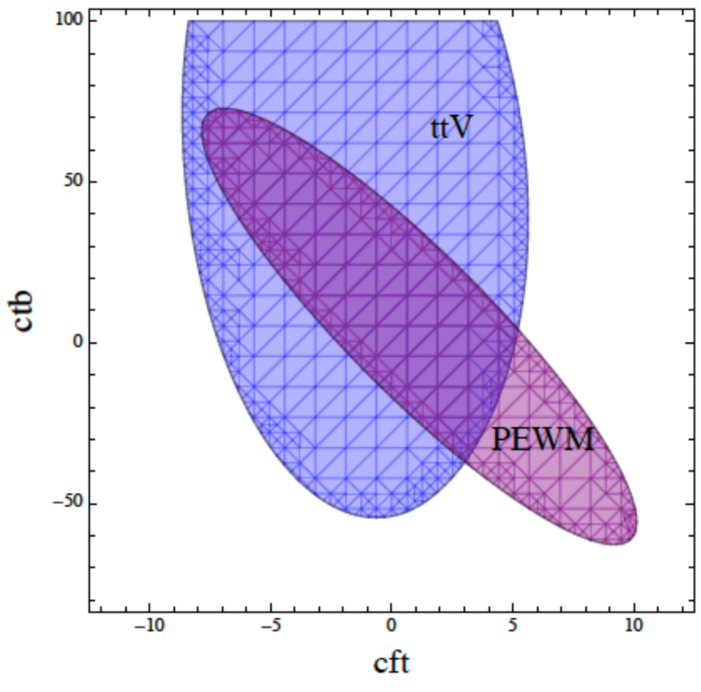








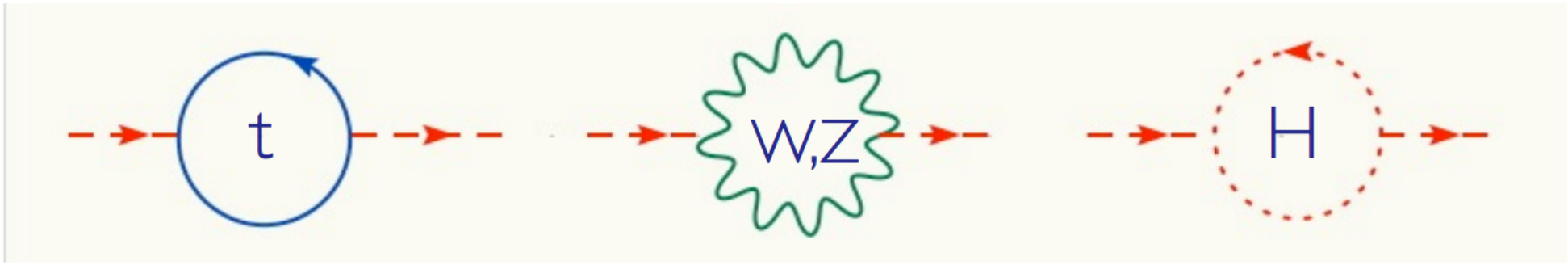


More to look with the model:

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

"Hierarchy problem"

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



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

Numbers

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

"Hierarchy problem"

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

$m_H^2 \sim (125\ \mathrm{GeV})^2$

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

Searching for new interactions of the top-quark

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

- $tt\gamma/ttg$, 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

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

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

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- ttH

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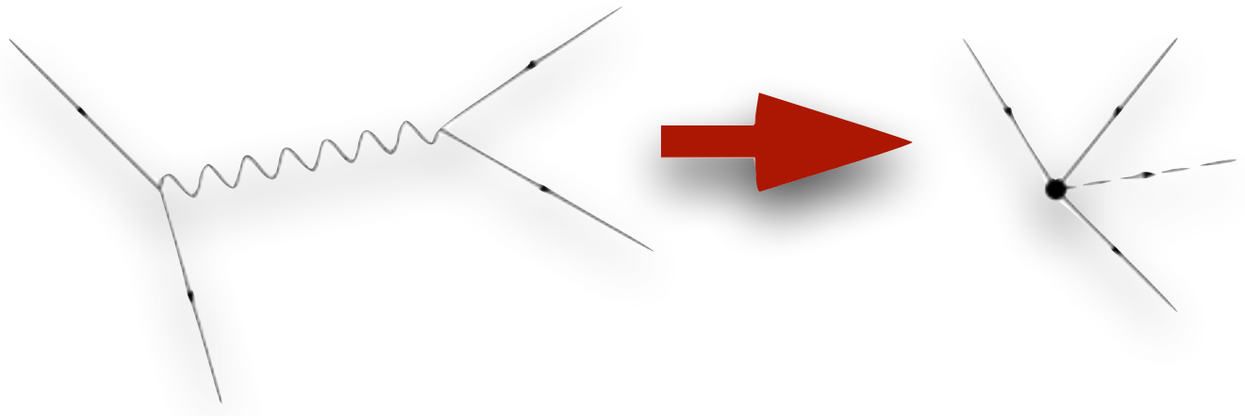
Also four-fermions, e.g.

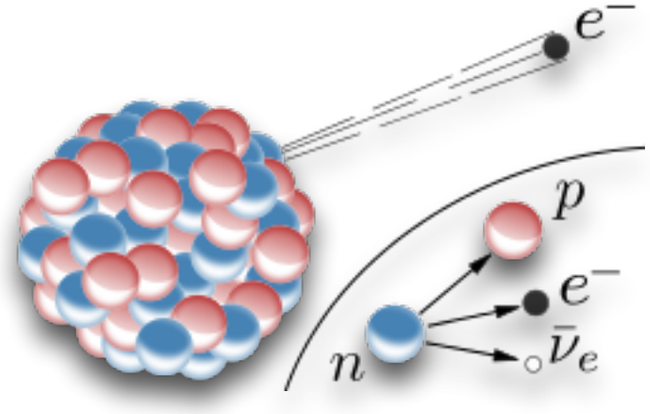
$$\begin{aligned} O^{(1)}_{lQ} &= (\bar{l}\gamma^\mu l)\,(\bar{Q}\gamma_\mu Q) \\ O_{eQ} &= (\bar{e}\gamma^\mu e)\,(\bar{Q}\gamma_\mu Q) \\ O_{lt} &= (\bar{l}\gamma^\mu l)\,(\bar{t}\gamma_\mu t) \\ O_{et} &= (\bar{e}\gamma^\mu e)\,(\bar{t}\gamma_\mu t) \end{aligned}$$

and FCNC, etc.

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.