Theoretical aspects of TOP properties

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Top quark is unique in many ways:

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

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

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

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

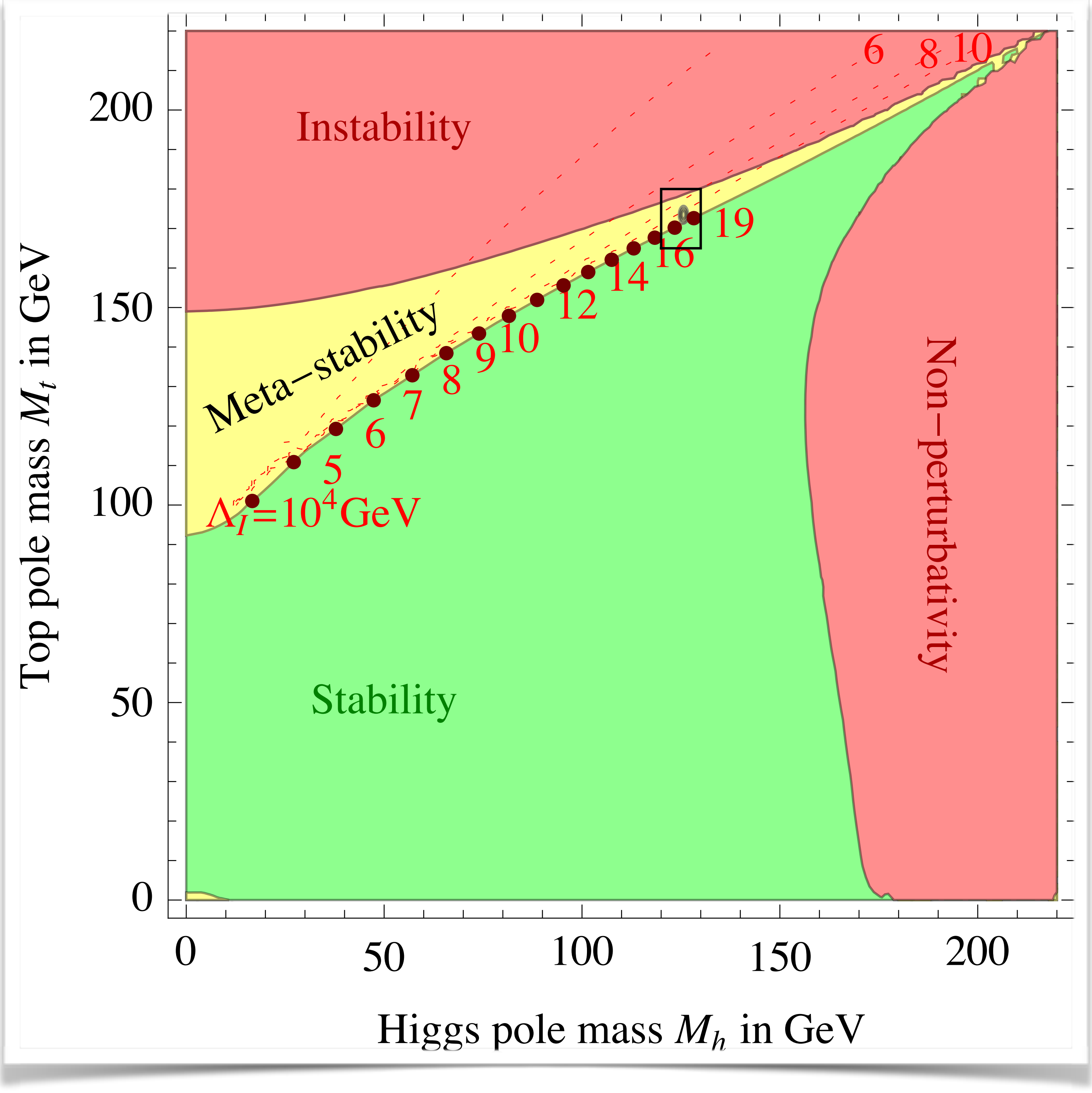
- Top Yukawa is the largest SM coupling.

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

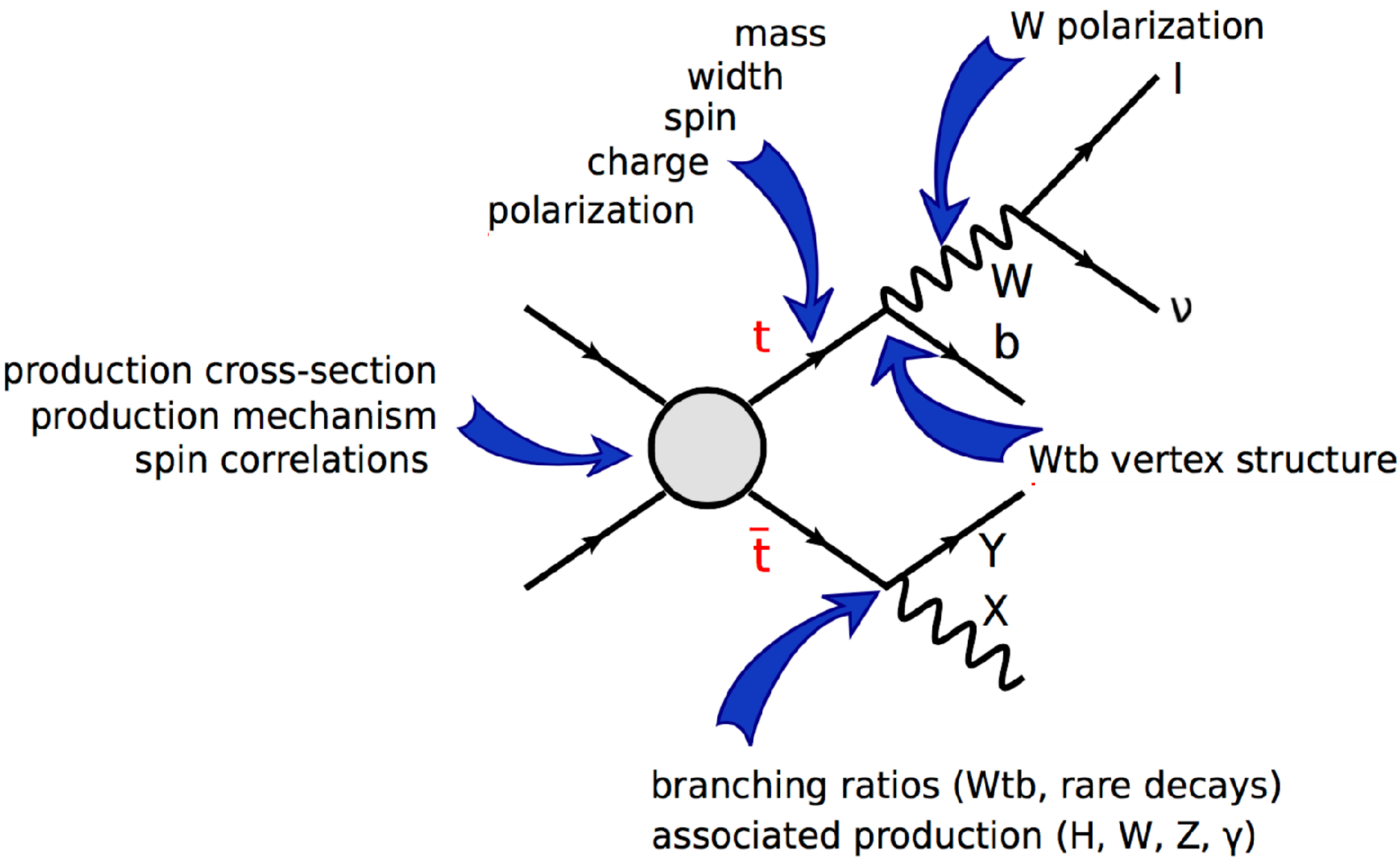
  and hence largest Higgs mass correction.

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

…and it determines the fate of our universe



Outline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production cross-section
production mechanism
spin correlations
Wtb vertex structure
t̄
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branching ratios (Wtb, rare decays)
associated production (H, W, Z, γ)

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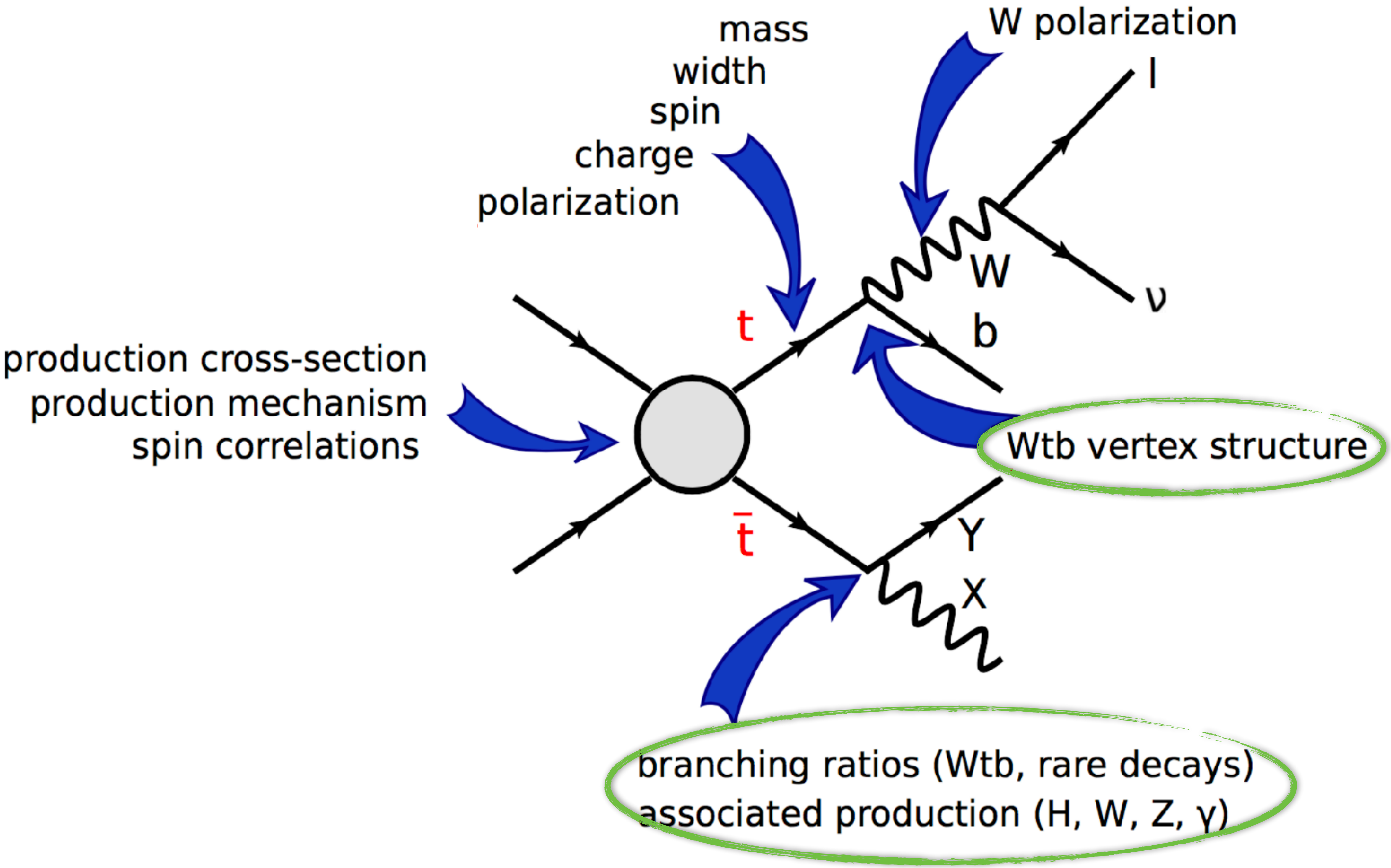
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This talk

- Top-quark couplings, SM and anomalous.
- FCNC decay & production.
- Extracting/interpreting top couplings with SMEFT

Other interesting TH topics

- Top pair NNLO QCD + NLO EW, D. Pagani
- Resonance-aware matching, J. Lindert
- Single top + decay NNLO, J. Gao
- MC mass calibration, M. Preisser

The TH framework

for extracting/interpreting top-quark couplings

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

The matter content of SM has been experimentally verified and evidence for light states is not present

- look for deviations from the dim=4 SM Lagrangian predictions.

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

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

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
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		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
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$(\bar LR)(\bar RL)$ 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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Valid up to scale Λ.
- Extends the reach of NP search beyond LHC energy.
- Global approach: all measurements, top, Higgs, EW, B,… are accessing the same operators and can be combined.

See talks by David Marzocca and Martin Gonzalez Alonso

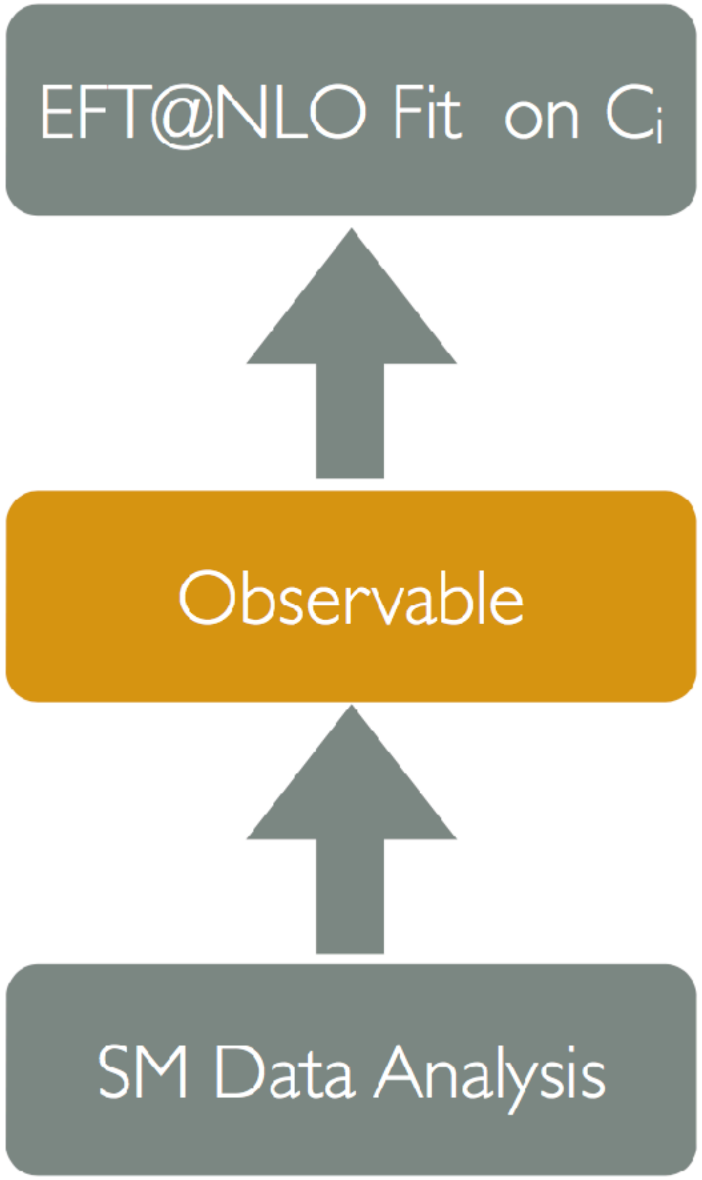
The global EFT fit

SMEFT makes sense only if a global strategy is used for extracting information from experiments.

- Assume all operator coefficients/couplings might not be zero at the scale of measurements.
- In practice, may not easy for EXP analyses.

In practice theorists often take bottom-up approaches

- Fit to <u>observables</u> (xsec, distributions, polarizations,…) provided by SM measurements, typically unfolded.
- EXP uncertainties often treated in an approximated way.



First example:
Global fit for (flavor conserving) couplings
at Tevatron+LHC 7/8

[Buckley, Englert, Ferrando, Miller, Moore, Russell, White, 16]

Operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
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[Cao, Wudka, Yuan, 07] [Aguilar-Saavedra, 08] [CZ, Willenbrock, 10]

Measurements

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	$p_T(t)$, $M_{t\bar{t}}$, $\|y_{t\bar{t}}\|$	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	$M_{t\bar{t}}$, $p_T(t)$, $\|y_t\|$	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				

Production

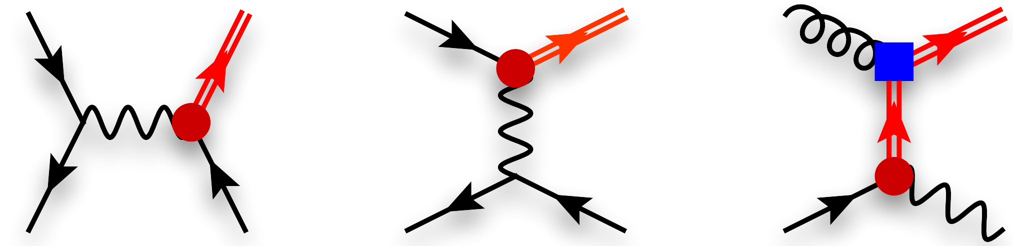
Charged current

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

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

$$O_{\varphi\varphi} = i y_t^2 \left(\varphi^\dagger D_\mu \tilde{\varphi}\right) (\bar{b}\gamma^\mu t)$$

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



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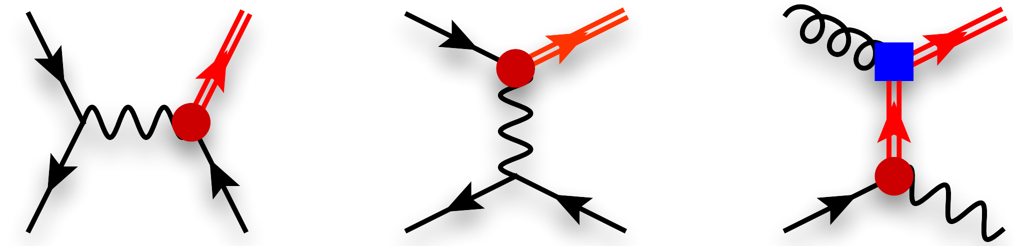
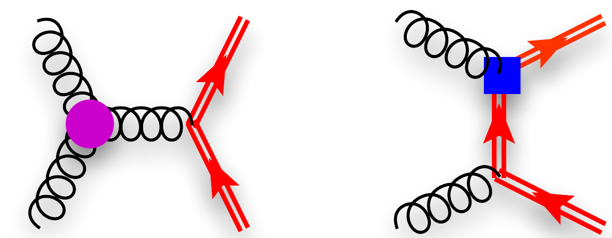


Strong

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

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$



Production

Charged current

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

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

$$O_{\varphi\varphi} = i y_t^2\left(\varphi^\dagger D_\mu\tilde{\varphi}\right)(\bar{b}\gamma^\mu t)$$

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

Strong

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

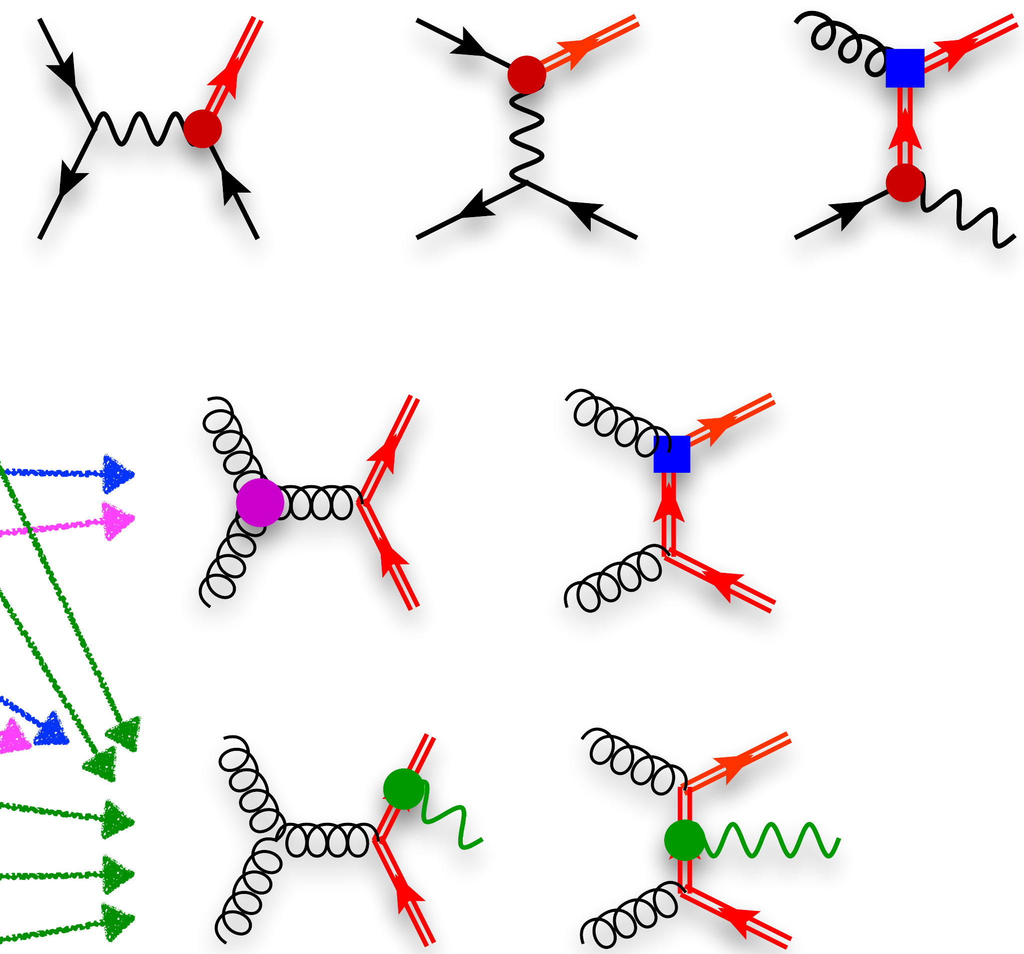
$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

Neutral current

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

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

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



Production

Charged current

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

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

$$O_{\varphi\varphi} = i y_t^2 \left(\varphi^\dagger D_\mu \tilde{\varphi}\right)\left(\bar{b}\gamma^\mu t\right)$$

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

Strong

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

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

Neutral current

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

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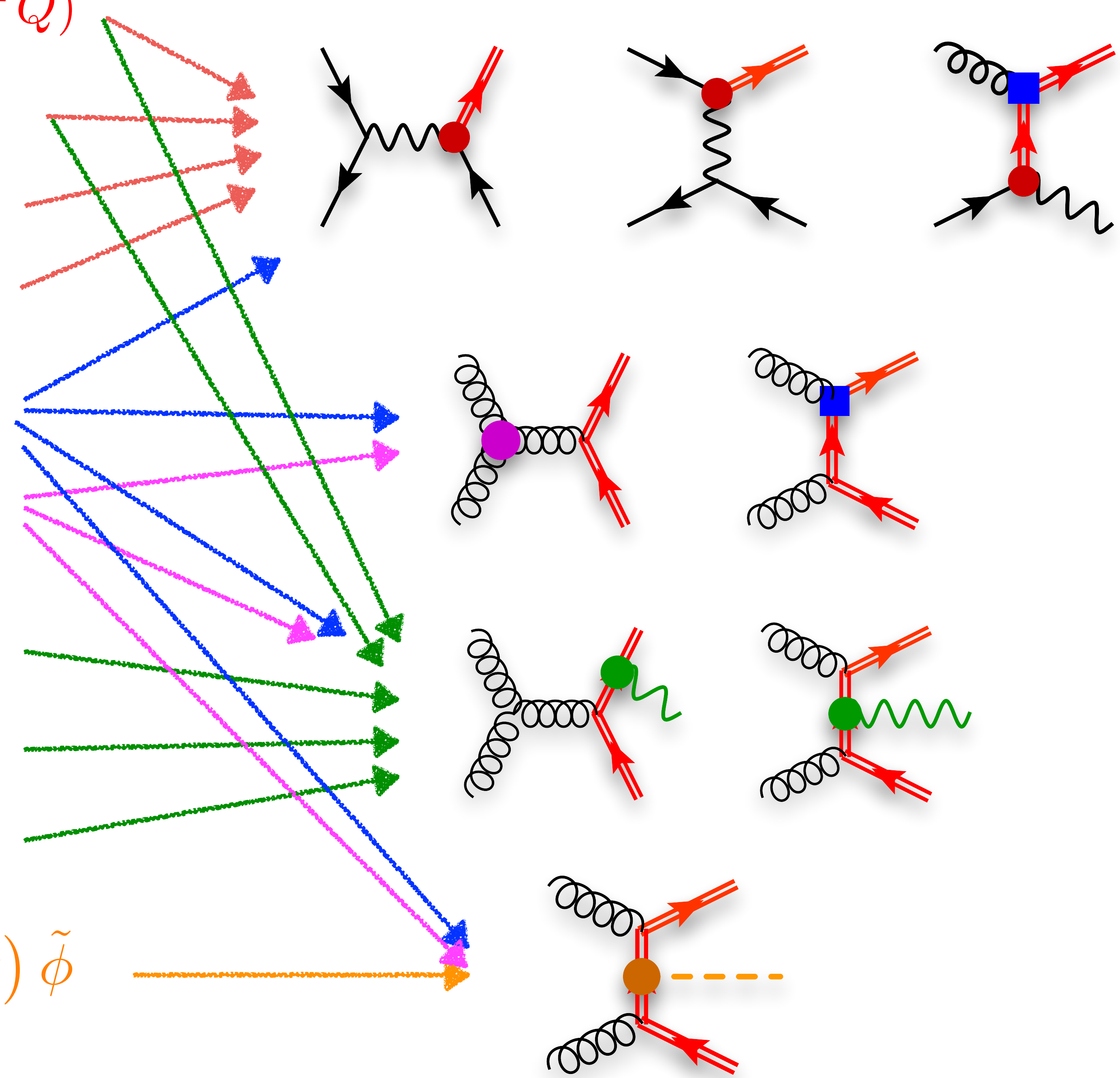
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$

Yukawa

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi - v^2/2\right)\left(\bar{Q}t\right)\tilde{\phi}$$



Non-negligible effects from O_{tG} to ttH: [Maltoni, Vryonidou, **CZ**, 16]

see also constraining O_G from multi-jets: [Krauss, Kuttimalai, Plehn, 16]

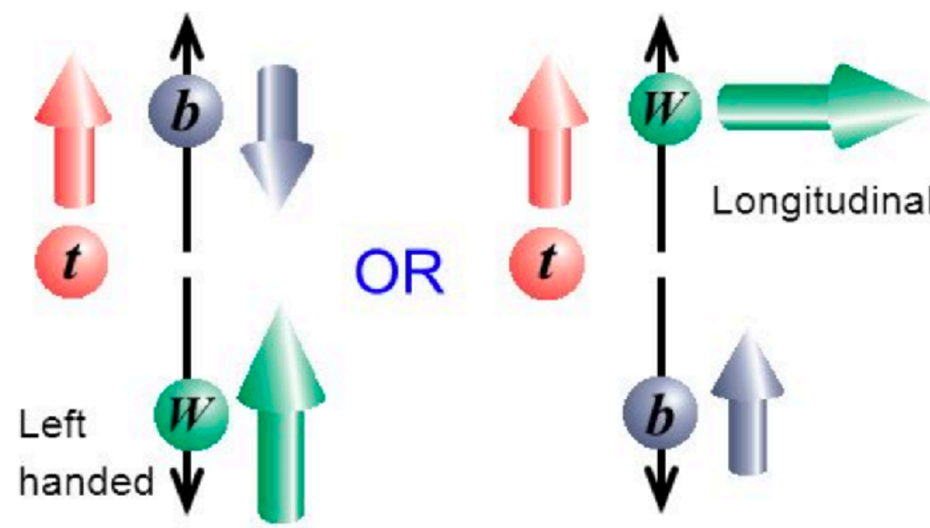
Decay & distribution

- W-helicity fraction: sensitive to O_{tW}

$$F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}C_{tW}v^2}{\Lambda^2}\frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

$$F_L = \frac{2m_W^2}{m_t^2 + 2m_W^2} + \frac{4\sqrt{2}C_{tW}v^2}{\Lambda^2}\frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2}$$

$$F_R = 0$$

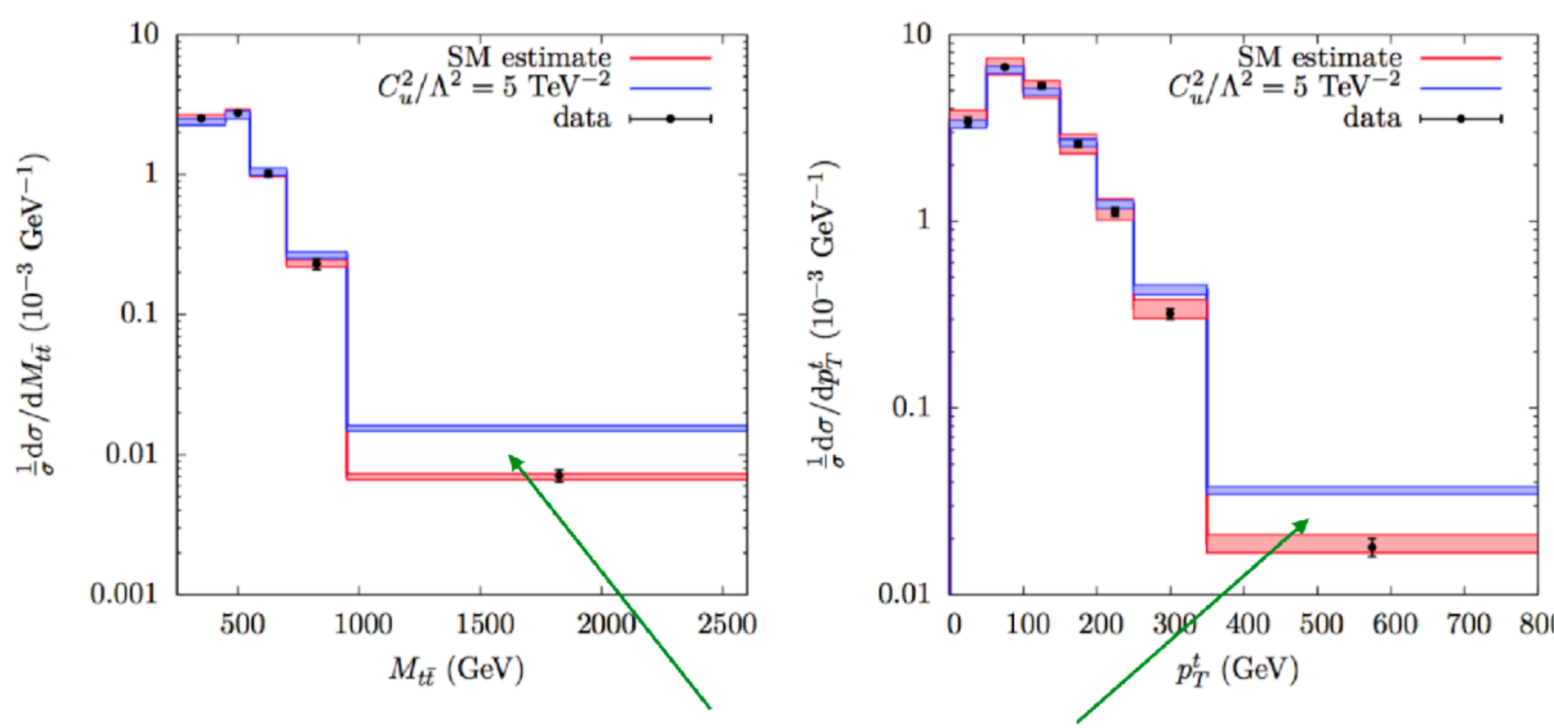


See talk by Prolay Kumar Mal

Operators differ in shapes, e.g.

- Energy dependence: E^2/Λ^2 => high sensitivity at tail
- Angular dependence: Lorentz structure
- Asymmetries (A_{FB}, A_C): lifting four-fermion degeneracies.

[Rosello, Vos, 16]



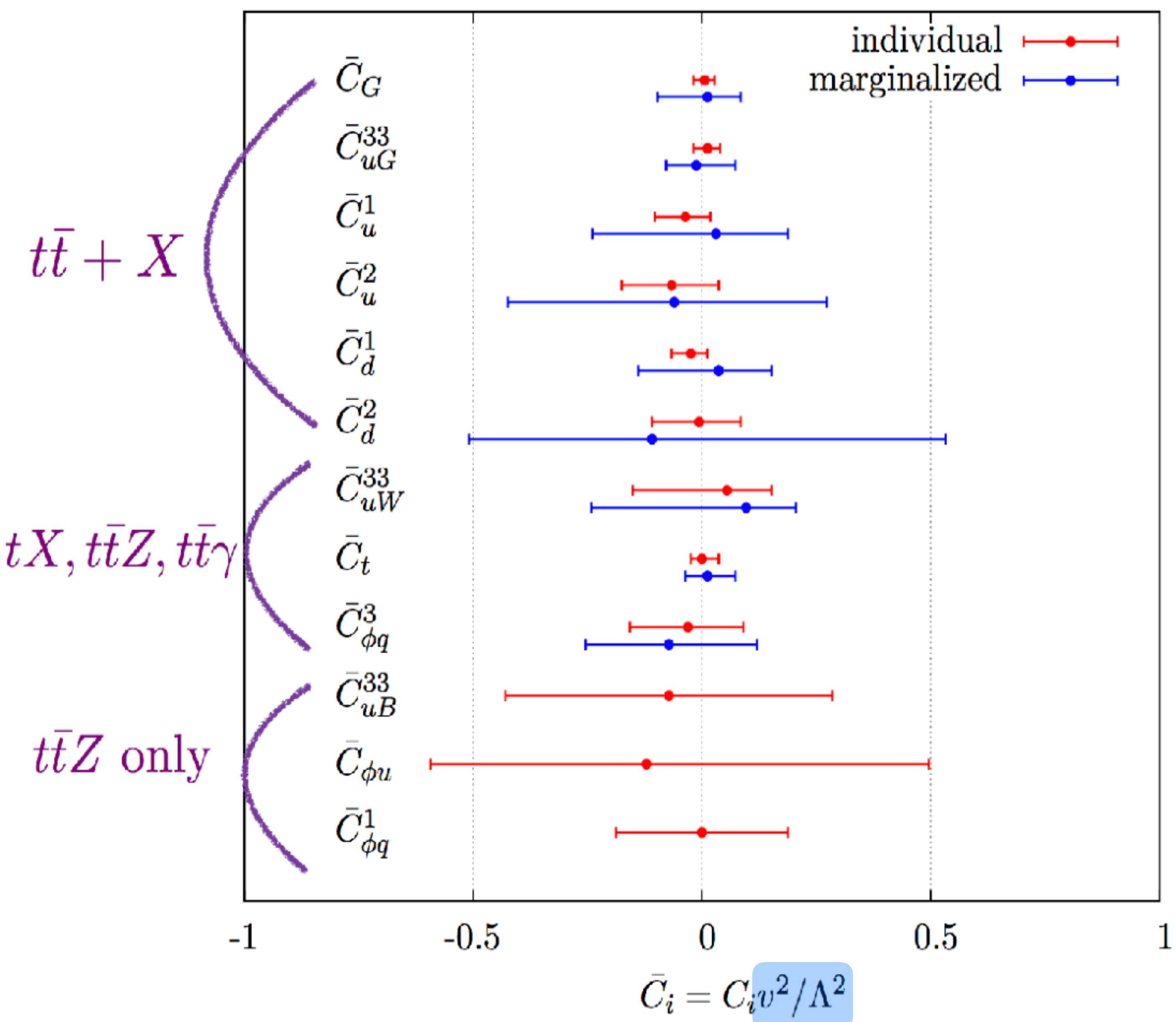
Most sensitivity in the tails

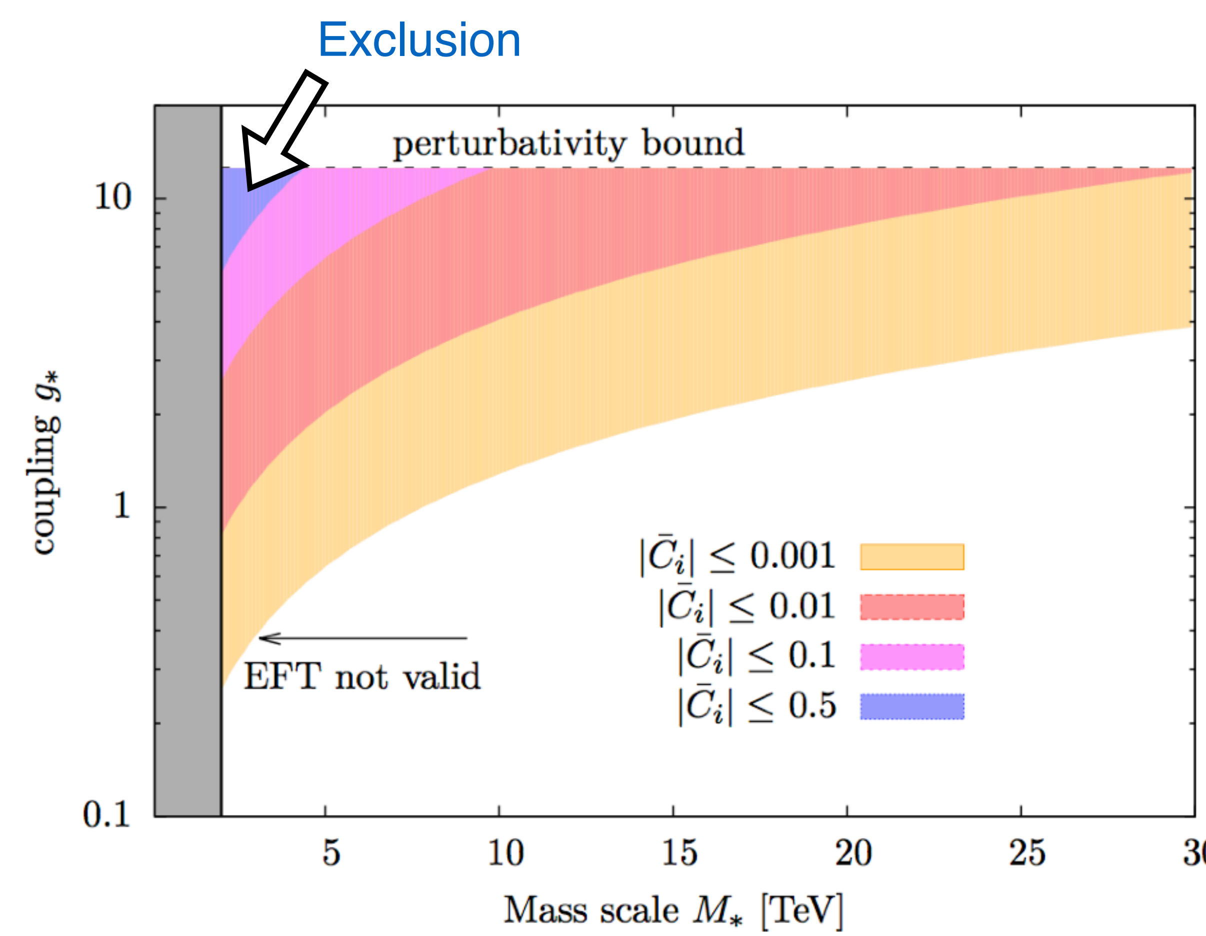
Extracting global bounds

[Buckley, Englert, Ferrando, Miller, Moore, Russell, White, 16]

$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

$$\frac{C_i}{\Lambda^2} = \frac{g_*^2}{M_*^2}$$





Tevatron + LHC Run I summary:

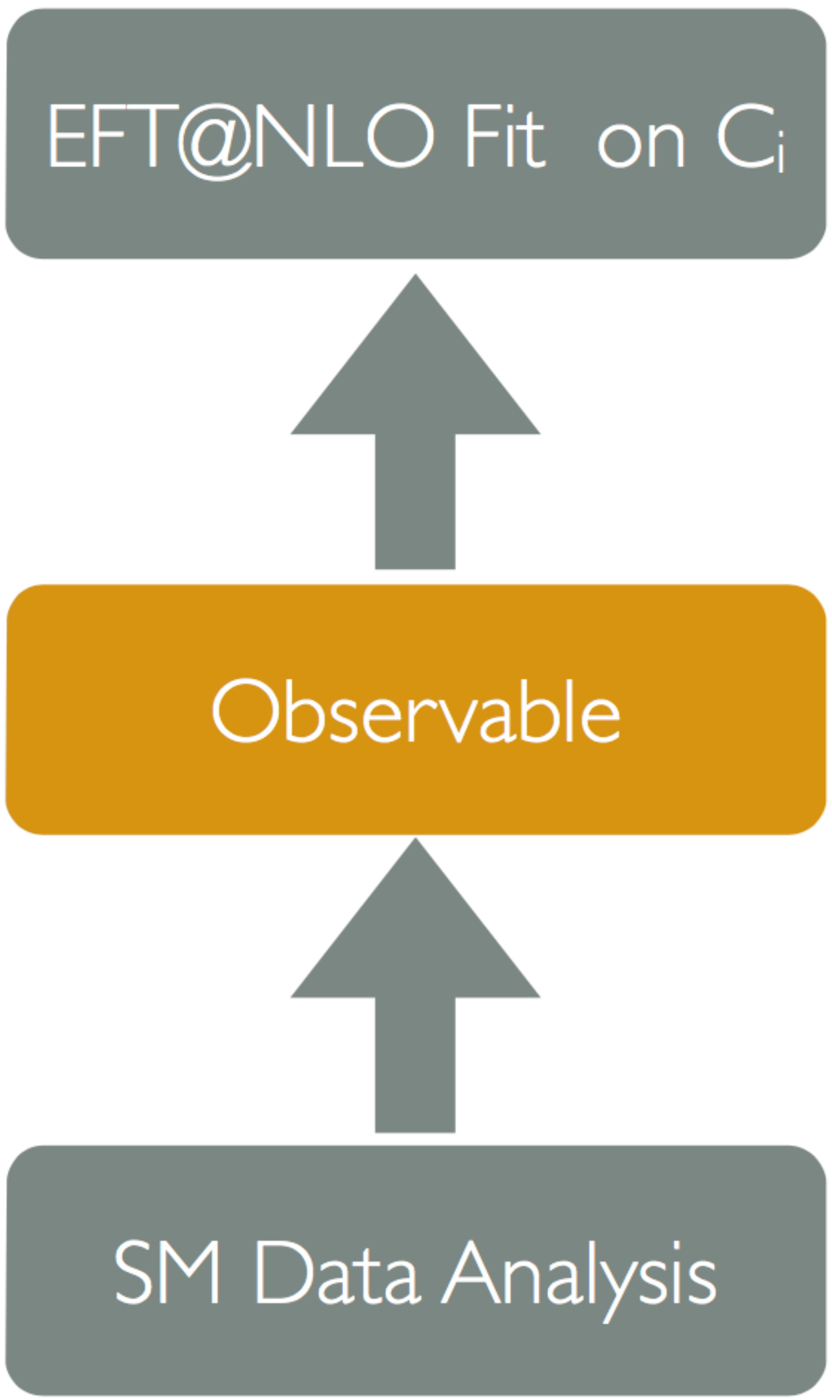
- No significant deviation
- Still early stage in LHC program
- Many measurements dominated by statistics
- Improvements expected for HL

Are we (theorists) done?

Towards a global EFT "search"

- The ideal approach goes in a top-down way:
  - No SM assumption. No unfolding.
  - Use all information of events (MVA analyses) => maximize sensitivity.
- However, it assumes several conditions:
  - EXP analyses are fully coordinated and can be combined.
  - TH setup is final (basis, calculation, tools…), dependence on additional TH assumptions is minimal.
- Still early, but should start to prepare.

Towards a global EFT “search”



- This can be done by using the bottom-up approach.
- Fit with (continuously extendable) set of observables.
- Results should be provided with the minimal systematic uncertainty breakdown.
- The advantage is that TH progresses, such as improved predictions, evaluation of uncertainties, combination of more channels/ observables, can be constantly and continuously added. (see examples)

Progresses in the past ~5 years

- Operator running/mixing — [Alonso, Jenkins, Manohar, Trott, 13] [Jung, Ko, Yoon, Yu, 14] [Elias-Miro, Grojean, Gupta, Marzocca, 13]
- Extension to dim-7/8 — [Lehman, Martin, 15] [Henning, Lu, Melia, Murayama, 15a] [Liao, Ma, 16] [Henning, Lu, Melia, Murayama, 15b]
- Re-parametrization invariance — [Passarino, 16] [Brivio, Trott, 17]
- One-loop matching with functional approach — [Henning, Lu, Murayama, 14] [Henning, Lu, Murayama, 16] [Drozd, Ellis, Quevillon, You, 15] [Ellis, Quevillon, You, Zhang, 16] [Zhang, 16]
- HEFT tools

Handbook of LHC Higgs Cross Sections: 4

NLO top EFT

In EFT, predictions can be systematically improved.

$$\mathcal{O}(1)+\mathcal{O}(\alpha_s)+\mathcal{O}(1/\Lambda^2)+\mathcal{O}(\alpha_s/\Lambda^2)+\cdots$$

Top EFT with full set of dim-6 operators is being pushed to NLO in QCD, by means of **automated and matched MC tools**

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

FCNC [Degrande, Maltoni, Wang, **CZ**, 15]

[G. Durieux, F. Maltoni, **CZ**, 14]

tt [D. B. Franzosi, **CZ**, 15]

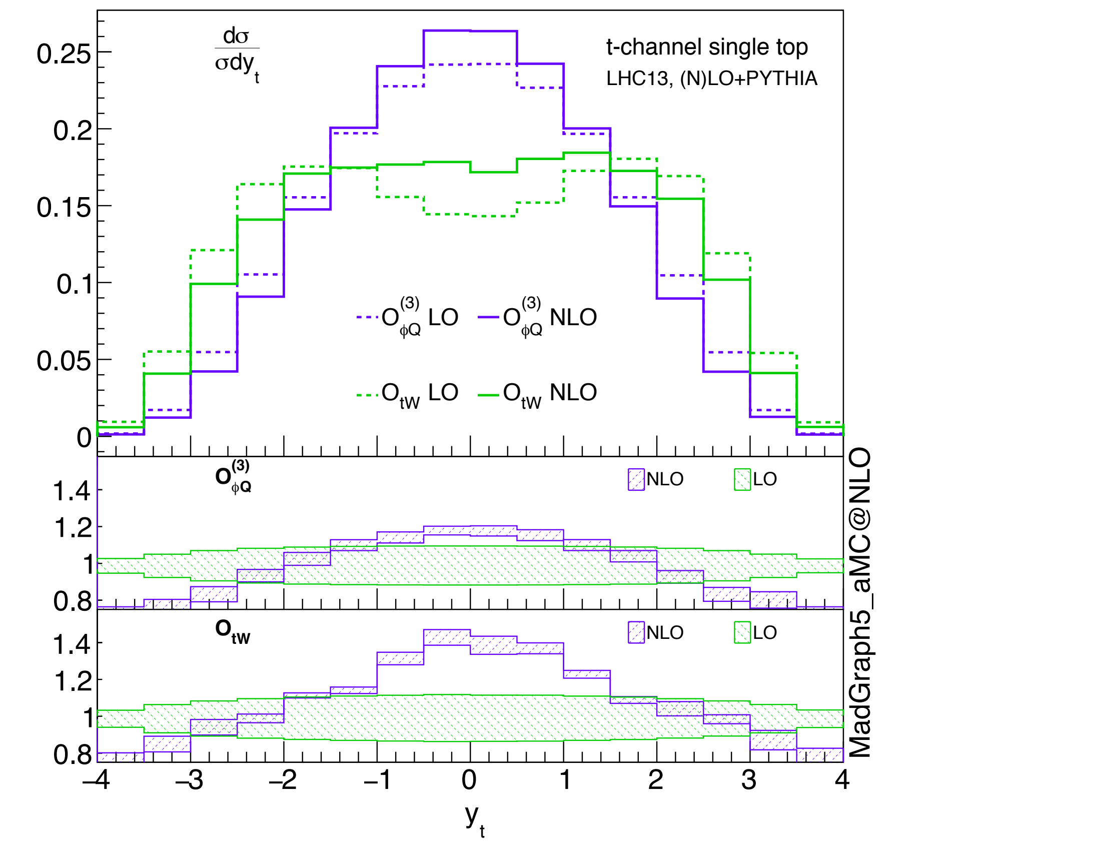
single t [**CZ**, 16]

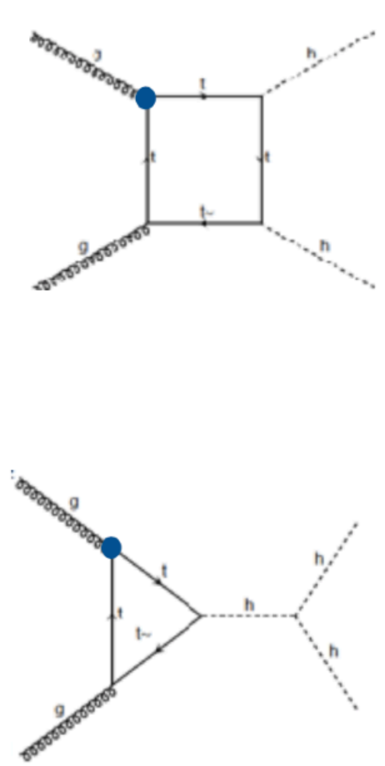
tt+H [Maltoni, Vryonidou, **CZ**, 16]

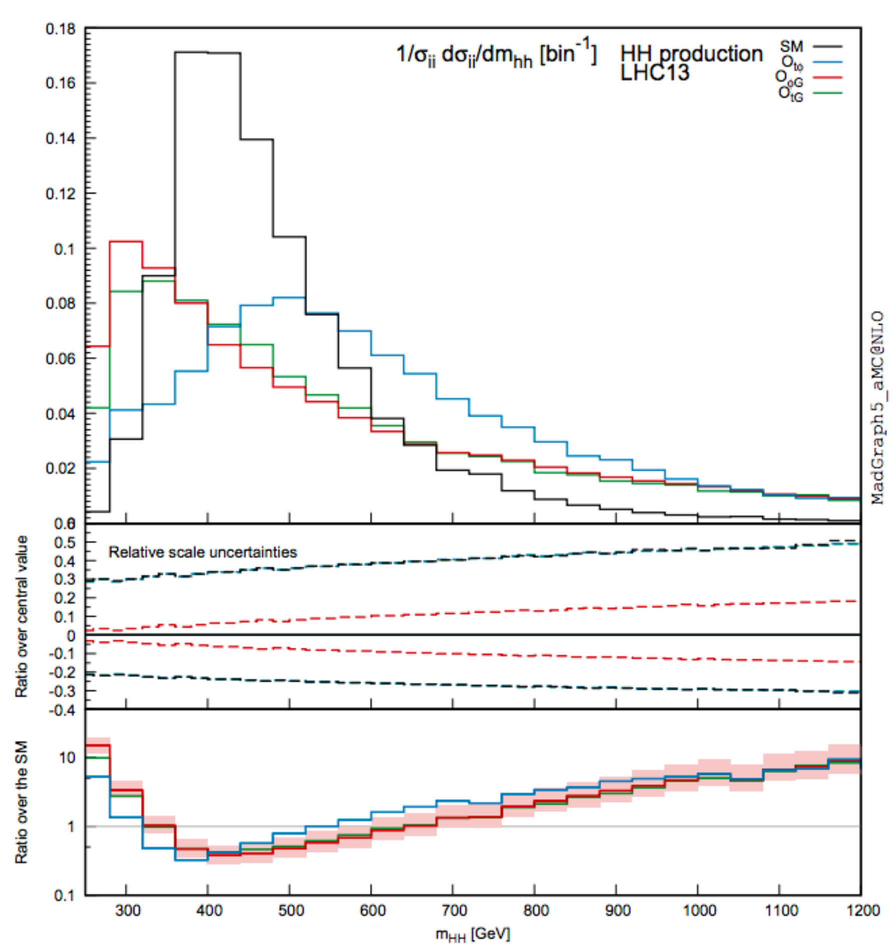
tt+Z/γ [Bylund, Maltoni, Tsinikos, Vryonidou, **CZ**, 16]

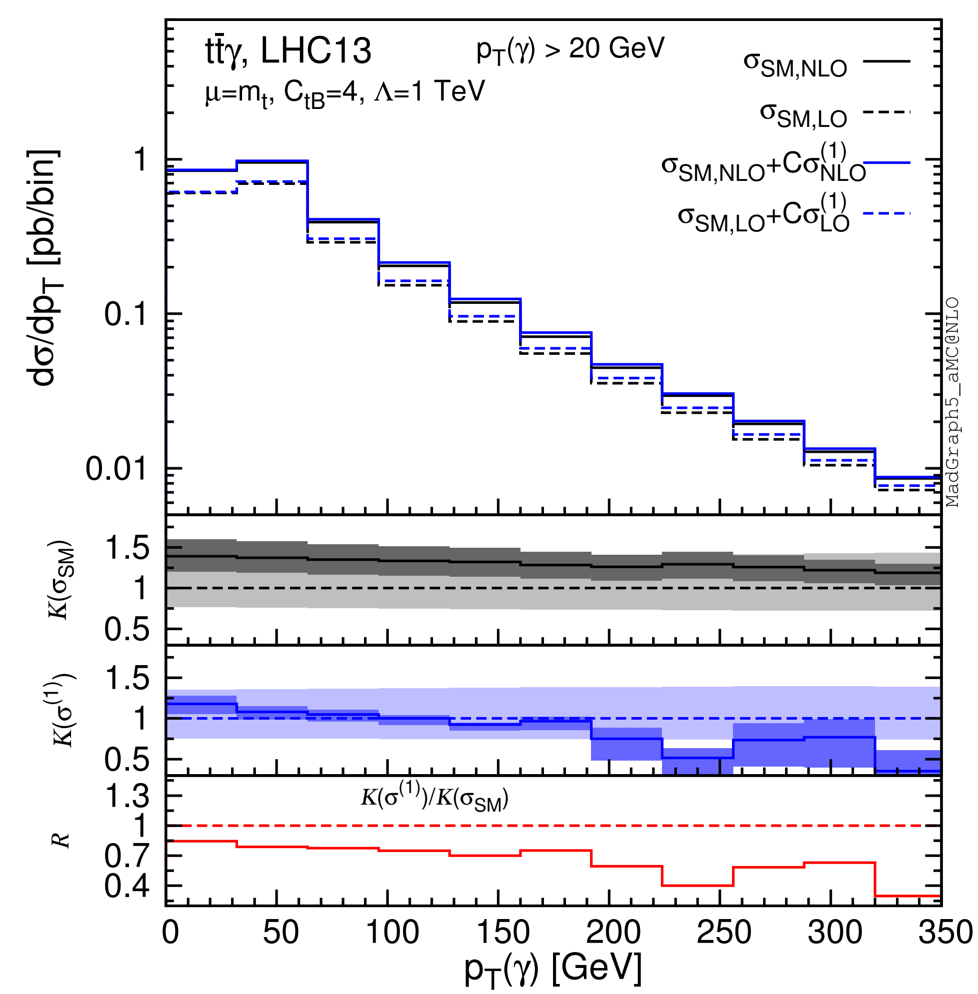
Some NLO/loop-induced results

- Corrections on distributions can be important for discriminator observables.
- Differential K-factors not flat, and different than in SM → regenerate
- Loop-induced processes automated in the same framework.









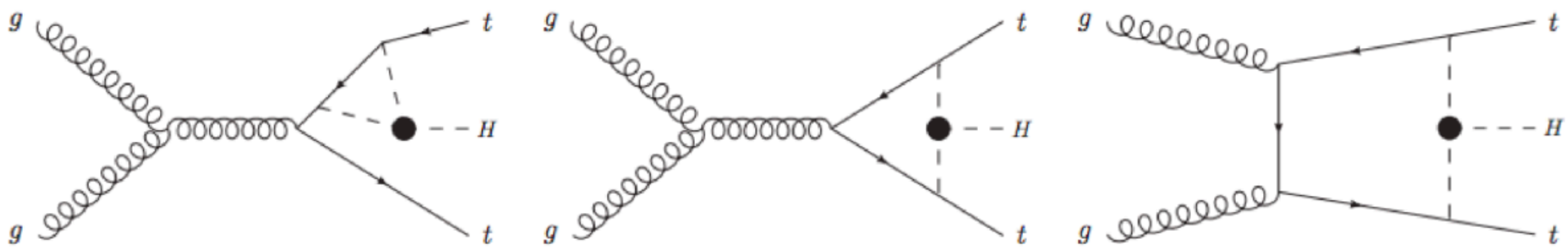
NLO motivation

- Same for SM (Dim=4)
  - Accuracy: corrections relevant for total rate and shapes
  - Precision: control uncertainties from scale/PDF

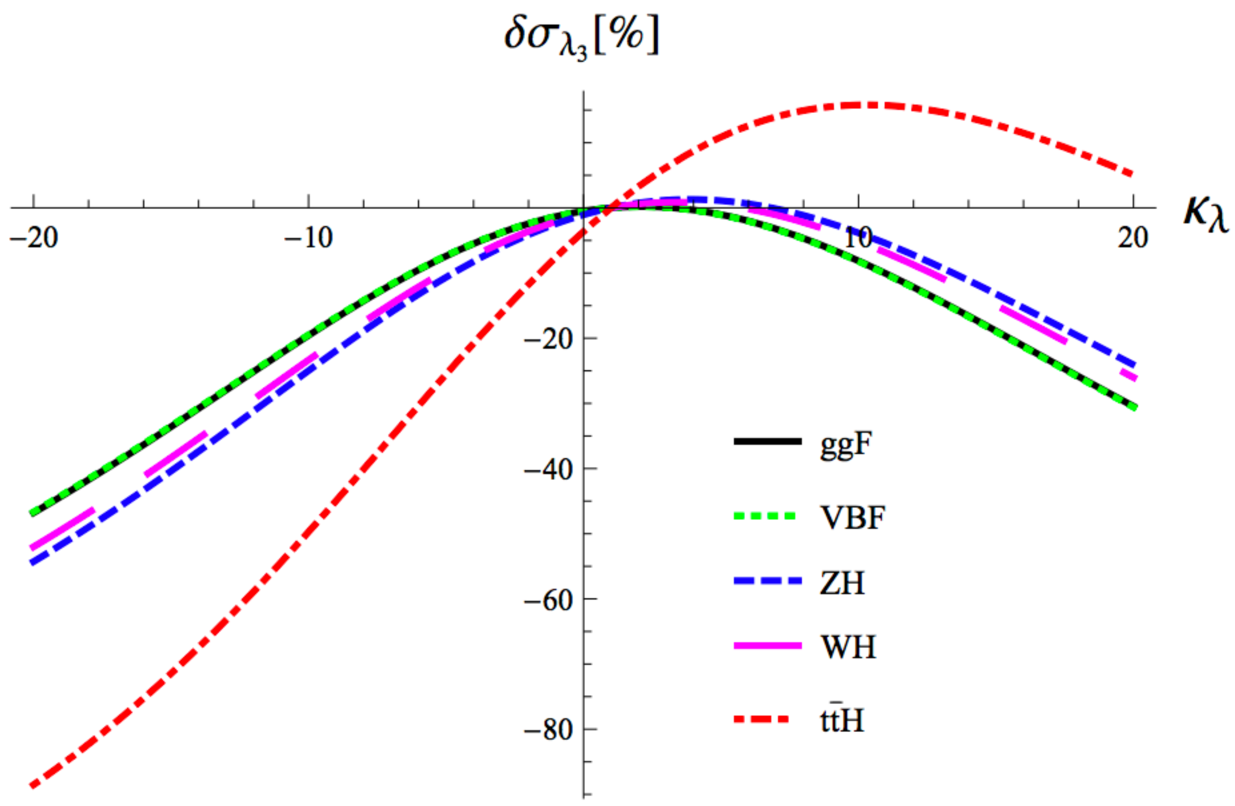
- Specific issues for EFT (Dim>=6), i.e. when NLO is the first order where non-trivial EFT structure manifests
  - Operator mixing (and RG induced constraints, see [Degrande et al. 12] [Elias-Miro et al. 13] [Jung et al. 14] [Blas, Chala, Santiago, 15] [Cirigliano, Dekens, de Vries, Mereghetti, 16]…)
  - EFT scale uncertainty (see [Maltoni, Vryonidou, CZ, 16])
  - New operators arise!

Probing Higgs self coupling via single Higgs

[Degrassi, Giardino, Maltoni, Pagani, 16]



The trilinear coupling appears in Single Higgs processes at NLO



- $t\bar{t}H$ receives sizeable positive corrections.
- The other σ receive very small positive corrections.
- The corrections have a parabolic shape around the SM.

See also [Gorbahn, Haisch, 16] [Degrassi, Fedele, Giardino, 17]

An NLO fit example:
Global fit for the top FCNC sector

[G. Durieux, F. Maltoni, **CZ**, 14]

Operators

Two-quark operators: **10 $\times$ 2$_{(u,c)}$ complex coefficients**

Scalar: $O_{u\varphi} \equiv -y_t^3 \quad \bar{q}u\,\tilde{\varphi} \quad (\varphi^\dagger\varphi - v^2/2),$

Vector: $[O^+_{\varphi q} + O^-_{\varphi q}]/2 \equiv y_t^2/2 \quad \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi,$

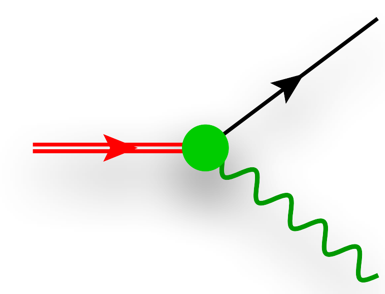
$[O^+_{\varphi q} - O^-_{\varphi q}]/2 \equiv y_t^2/2 \quad \bar{q}\gamma^\mu\tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi,$

$O_{\varphi u} \equiv y_t^2/2 \quad \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi,$

Tensor: $O_{uB} \equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu}u\,\tilde{\varphi} \quad B_{\mu\nu},$

$O_{uW} \equiv y_t g_W \quad \bar{q}\sigma^{\mu\nu}\tau^I u\,\tilde{\varphi} \quad W^I_{\mu\nu},$

$O_{uG} \equiv y_t g_s \quad \bar{q}\sigma^{\mu\nu}T^A u\,\tilde{\varphi} \quad G^A_{\mu\nu}.$



Two-quark–two-lepton operators: **8 $\times$ 2$_{(u,c)}$ $\times$ 3^2 complex coefficients**

Scalar: $O^1_{lequ} \equiv \bar{l}e \;\; \varepsilon \;\; \bar{q}u,$

Vector: $[O^+_{lq} + O^-_{lq}]/2 \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q,$

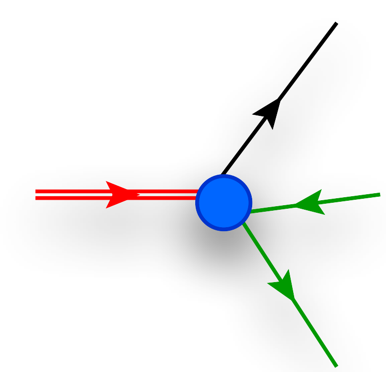
$[O^+_{lq} - O^-_{lq}]/2 \equiv \bar{l}\gamma_\mu\tau^I l \quad \bar{q}\gamma^\mu\tau^I q,$

$O_{lu} \equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u,$

$O_{eq} \equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q,$

$O_{eu} \equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u,$

Tensor: $O^3_{lequ} \equiv \bar{l}\sigma_{\mu\nu}e \;\; \varepsilon \;\; \bar{q}\sigma^{\mu\nu}u.$



Four-quark operators: ...

$\overleftrightarrow{D}^{(I)}_\mu \equiv (\tau^I)\overrightarrow{D}_\mu - \overleftarrow{D}_\mu(\tau^I)$

EFT predictions

e.g. $$\Gamma^{m_{\ell\ell}\in[78,102]\ \mathrm{GeV}}_{t\to j\,\ell^+\ell^-} = 10^{-5}\ \mathrm{GeV} \times \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 \times$$

$$\mathrm{Re}\begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34}i & \underset{-}{+0.014} - \underset{-}{0.013}i \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18}i & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09}i & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3}\,i & \underset{-}{-0.007} + \underset{-}{0.017}i \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095}i & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095}i & \underset{-}{+0.27} + \underset{-}{0.2}i \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029}i & \underset{-}{+0.16} + \underset{-}{0.14}i \\ & & & & \underset{-9\%}{+6.6} & \underset{-}{-0.53} - \underset{-}{0.47}i \\ & & & & & \underset{-}{+0.002} \end{pmatrix} \begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}$$

$$+\mathrm{Re}\begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2}\,i & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1}\,i & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34}i & \underset{-}{-0.002} + \underset{-}{0.013}i \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18}i & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09}i & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3}\,i & \underset{-}{+0.0067} - \underset{-}{0.006}i \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095}i & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095}i & \underset{-}{-0.17} - \underset{-}{0.09}i \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029}i & \underset{-}{-0.098} - \underset{-}{0.068}i \\ & & & & \underset{-9\%}{+6.6} & \underset{-}{+0.31} + \underset{-}{0.21}i \\ & & & & & \underset{-}{+0.00066} \end{pmatrix} \begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}$$

$$+\underset{0\%}{0.02}\left(|C_{lequ}^{1(13)}|^2 + |C_{lequ}^{1(31)}|^2\right) + \underset{-9\%}{0.81}\left(|C_{lequ}^{3(13)}|^2 + |C_{lequ}^{3(31)}|^2\right)$$

Higher orders can be consistently included. In practice, top FCNC @ NLO in QCD is available in the form of UFO models, and can be directly used by NLO event generator e.g. MG5_aMC@NLO

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

[Degrande, Maltoni, Wang, **CZ**, 15]

```
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
```

See also:

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

EFT predictions

e.g. $\Gamma^{m_{\ell\ell}\in[78,102]\ \mathrm{GeV}}_{t\to j\,\ell^+\ell^-} = 10^{-5}\ \mathrm{GeV} \times \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 \times$

$$\mathrm{Re}\begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2\,i} & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1\,i} & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34i} & \underset{-}{+0.014} - \underset{-}{0.013i} \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18i} & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09i} & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3\,i} & \underset{-}{-0.007} + \underset{-}{0.017i} \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095i} & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095i} & \underset{-}{+0.27} + \underset{-}{0.2i} \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029i} & \underset{-}{+0.16} + \underset{-}{0.14i} \\ & & & & \underset{-9\%}{+6.6} & \underset{-}{-0.53} - \underset{-}{0.47i} \\ & & & & & \underset{-}{+0.002} \end{pmatrix} \begin{pmatrix} C_{lq}^{-(a+3)} \\ C_{eq}^{(a+3)} \\ C_{\varphi q}^{-(a+3)} \\ C_{uB}^{(a3)} \\ C_{uW}^{(a3)} \\ C_{uG}^{(a3)} \end{pmatrix}$$

$$+\mathrm{Re}\begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}^{\dagger} \begin{pmatrix} \underset{-9\%}{+0.069} & 0 & \underset{+6\%}{-0.02} - \underset{-9\%}{0.2\,i} & \underset{-5\%}{-0.053} - \underset{-8\%}{0.1\,i} & \underset{-16\%}{-0.052} + \underset{-8\%}{0.34i} & \underset{-}{-0.002} + \underset{-}{0.013i} \\ & \underset{-9\%}{+0.069} & \underset{+6\%}{+0.017} + \underset{-9\%}{0.18i} & \underset{-10\%}{-0.053} + \underset{-8\%}{0.09i} & \underset{+0\%}{-0.054} - \underset{-8\%}{0.3\,i} & \underset{-}{+0.0067} - \underset{-}{0.006i} \\ & & \underset{-9\%}{+1.7} & \underset{-8\%}{+1.7} - \underset{-8\%}{0.0095i} & \underset{-8\%}{-5.7} - \underset{-8\%}{0.0095i} & \underset{-}{-0.17} - \underset{-}{0.09i} \\ & & & \underset{-9\%}{+0.64} & \underset{-9\%}{-3.9} - \underset{-9\%}{0.029i} & \underset{-}{-0.098} - \underset{-}{0.068i} \\ & & & & \underset{-9\%}{+6.6} & \underset{-}{+0.31} + \underset{-}{0.21i} \\ & & & & & \underset{-}{+0.00066} \end{pmatrix} \begin{pmatrix} C_{lu}^{(a+3)} \\ C_{eu}^{(a+3)} \\ C_{\varphi u}^{(a+3)} \\ C_{uB}^{(3a)*} \\ C_{uW}^{(3a)*} \\ C_{uG}^{(3a)*} \end{pmatrix}$$

$$\underset{0\%}{+0.02}\left(|C_{lequ}^{1(13)}|^2 + |C_{lequ}^{1(31)}|^2\right) + \underset{-9\%}{0.81}\left(|C_{lequ}^{3(13)}|^2 + |C_{lequ}^{3(31)}|^2\right)$$

Higher orders can be consistently included. In practice, top FCNC @ NLO in QCD is available in the form of UFO models, and can be directly used by NLO event generator e.g. MG5_aMC@NLO

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

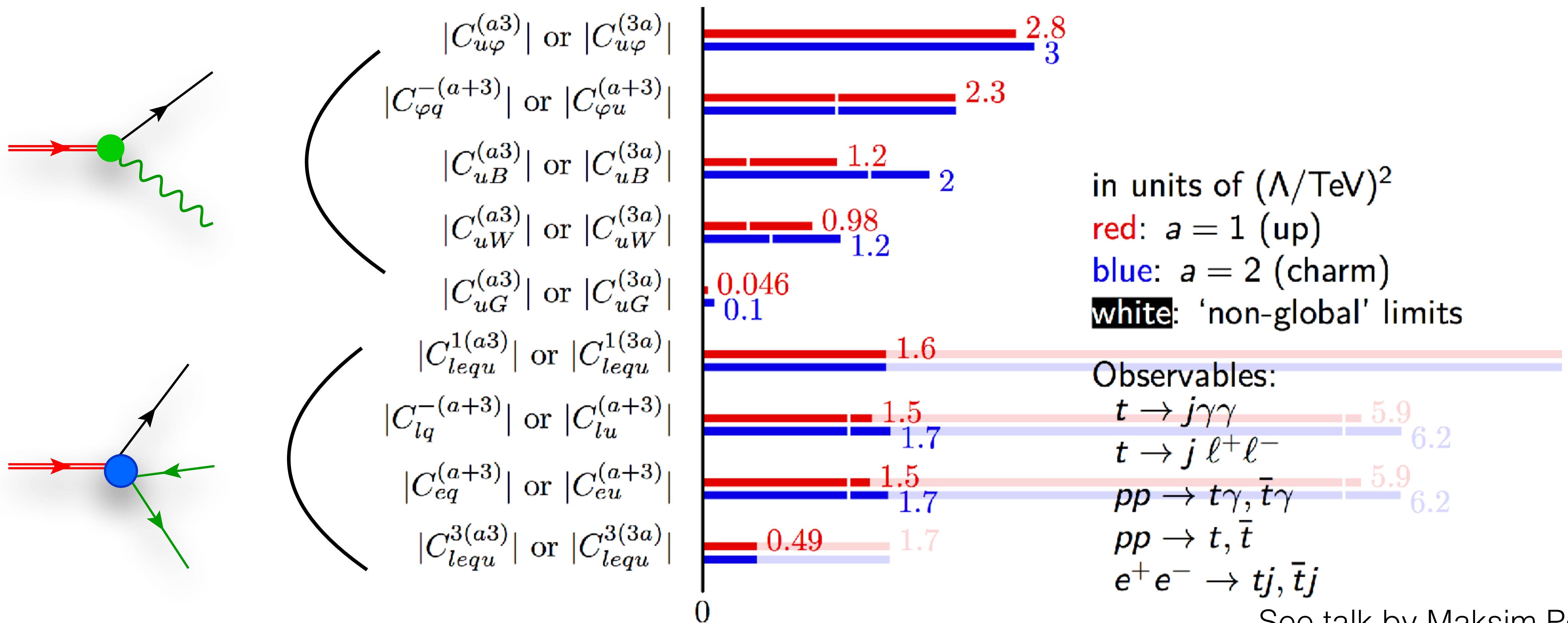
[Degrande, Maltoni, Wang, **CZ**, 15]

```
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
```

See also:

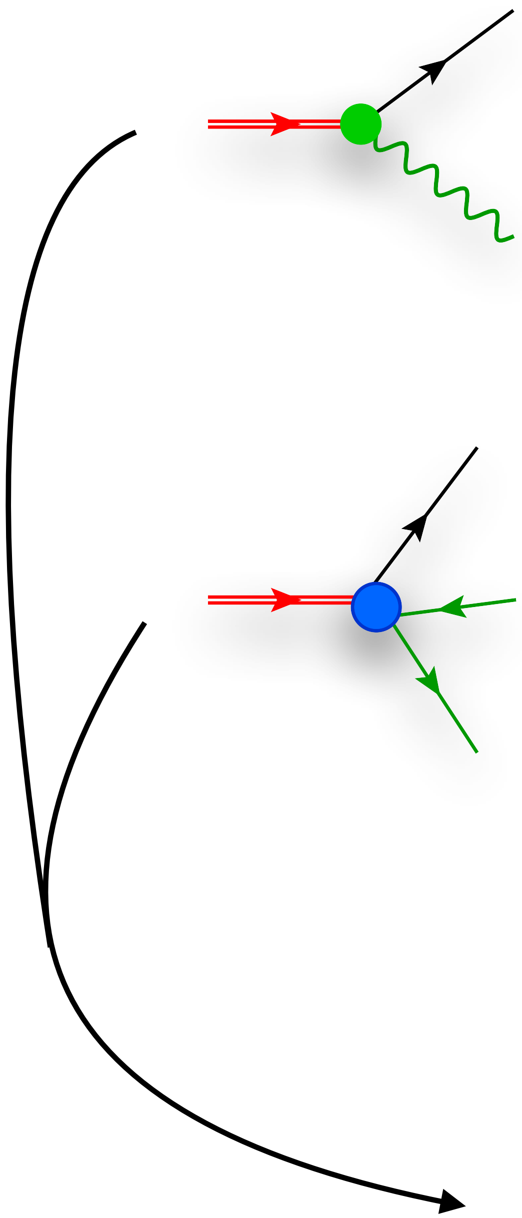
[Y. Wang et al. 2012][B. H. Li et al. 2011]
[Y. Zhang et al. 2011][J. Gao et al. 2011]

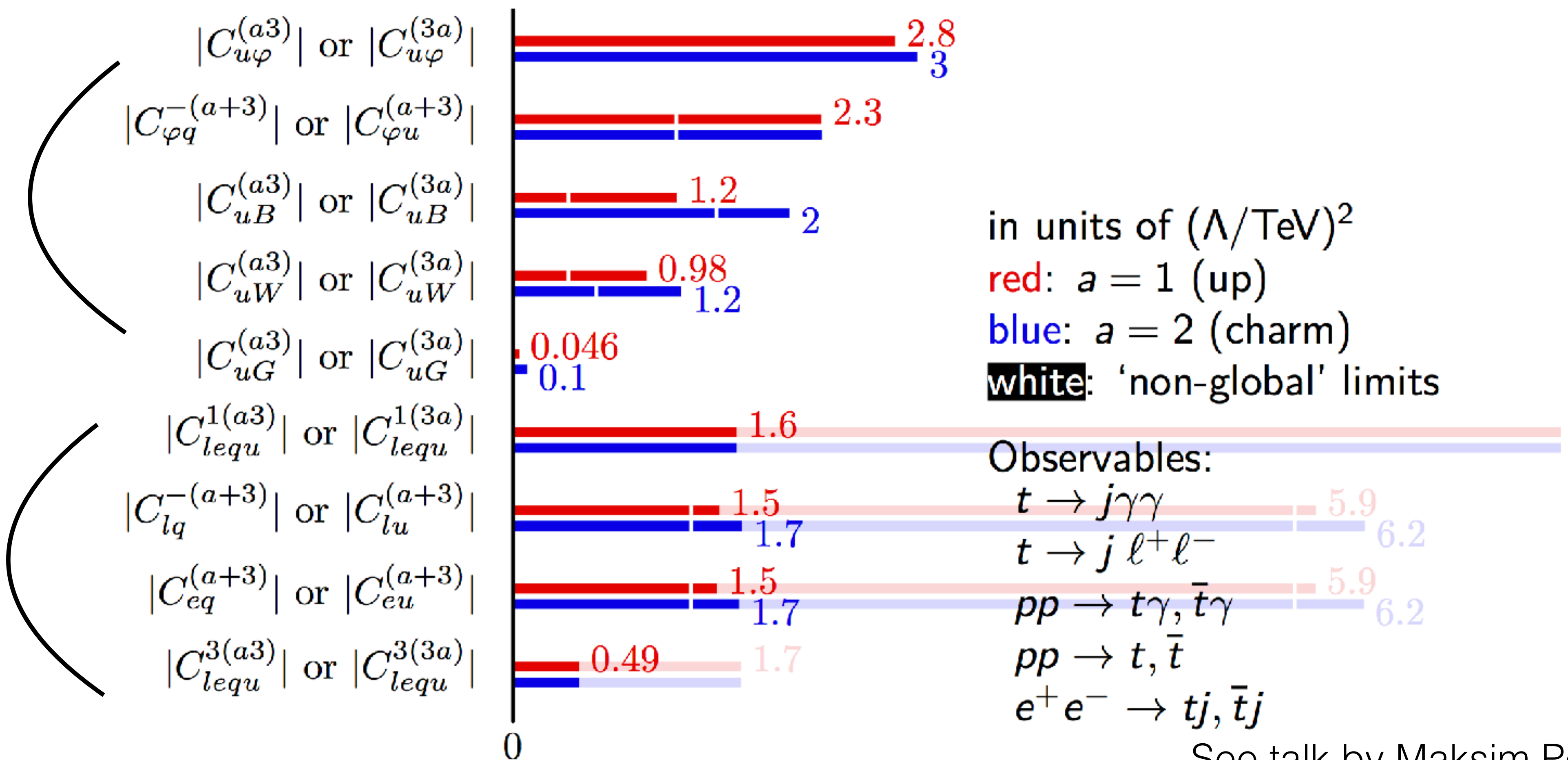
Global limits



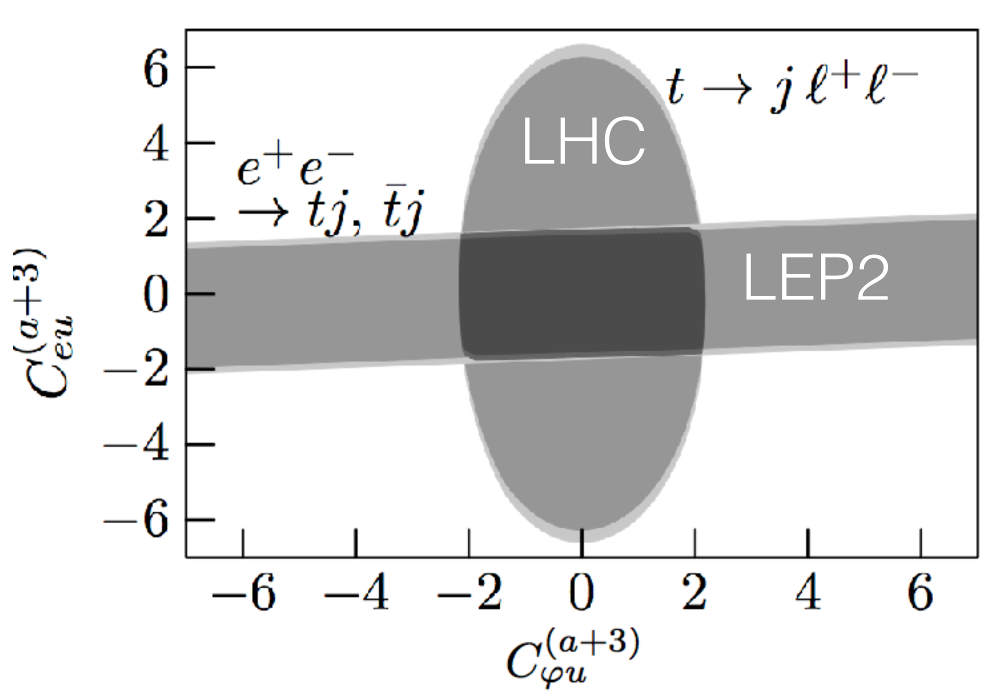
See talk by Maksim Perfilov

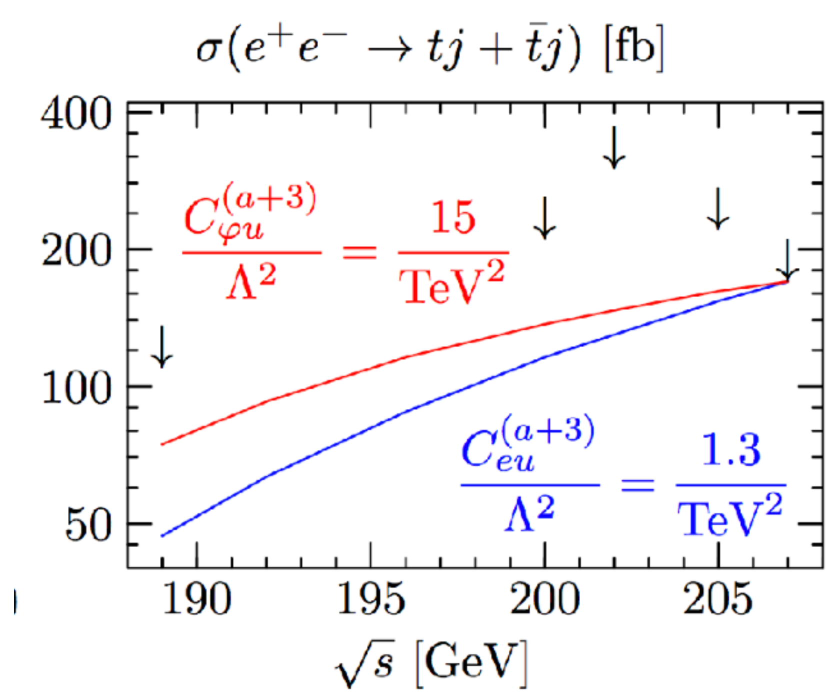
Global limits





See talk by Maksim Perfilov





More NLO

SMEFT@NLO:

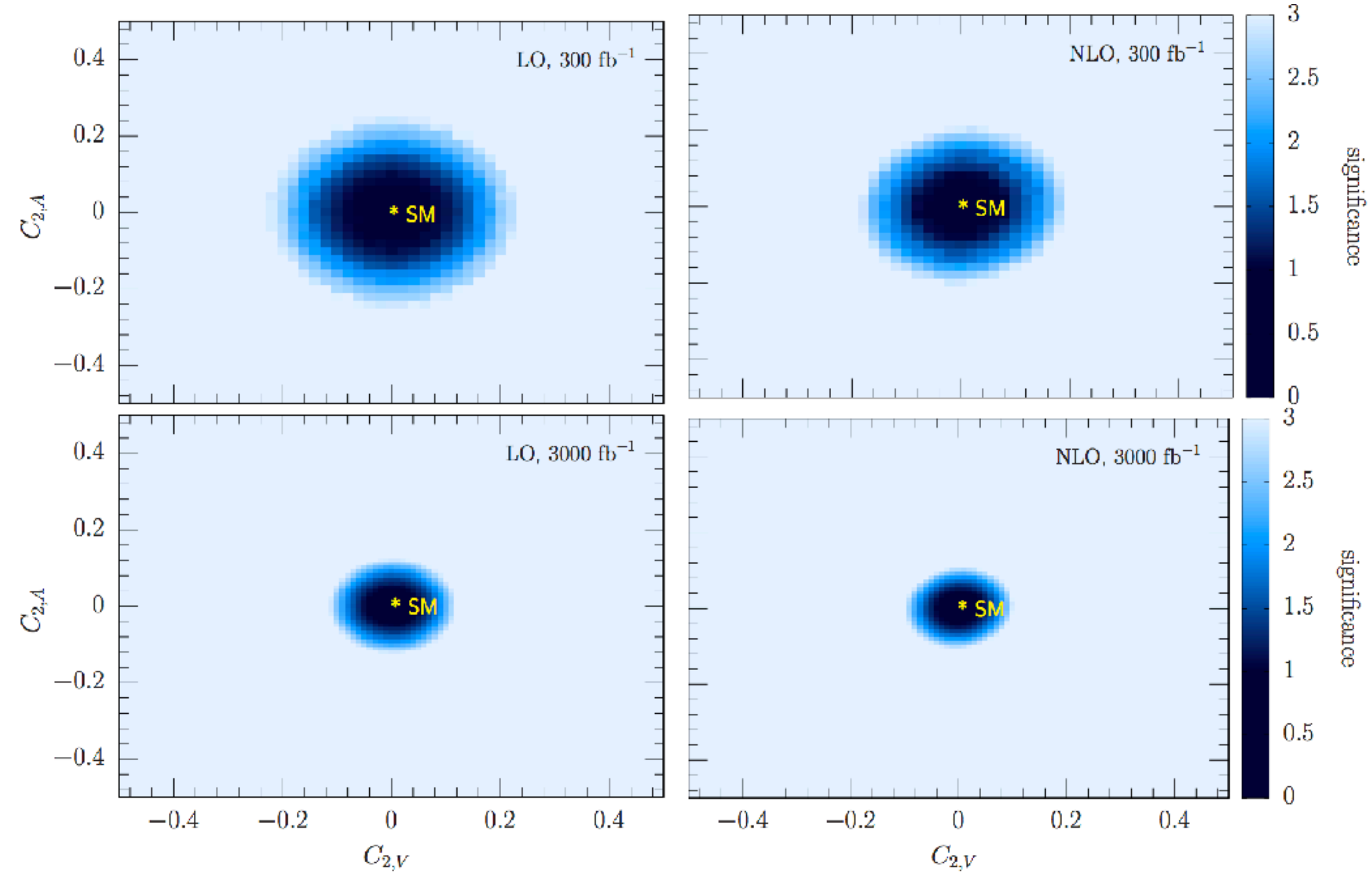
- **H decay**: [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a] [Hartmann, Trott, 15] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b] [Gauld, Pecjak, Scott, 15] [Gauld, Pecjak, Scott, 16]
- **Z decay**: [Hartmann, Shepherd, Trott, 16]
- **top decay**: [CZ, 14] [CZ, Maltoni, 13]
- **Higgs EW production**: [Degrande, Fuks, Mawatari, Mimasu, Sanz, 16]
- **tt+Z/γ**: [Rontsch, Schulze, 14] [Rontsch, Schulze, 15]

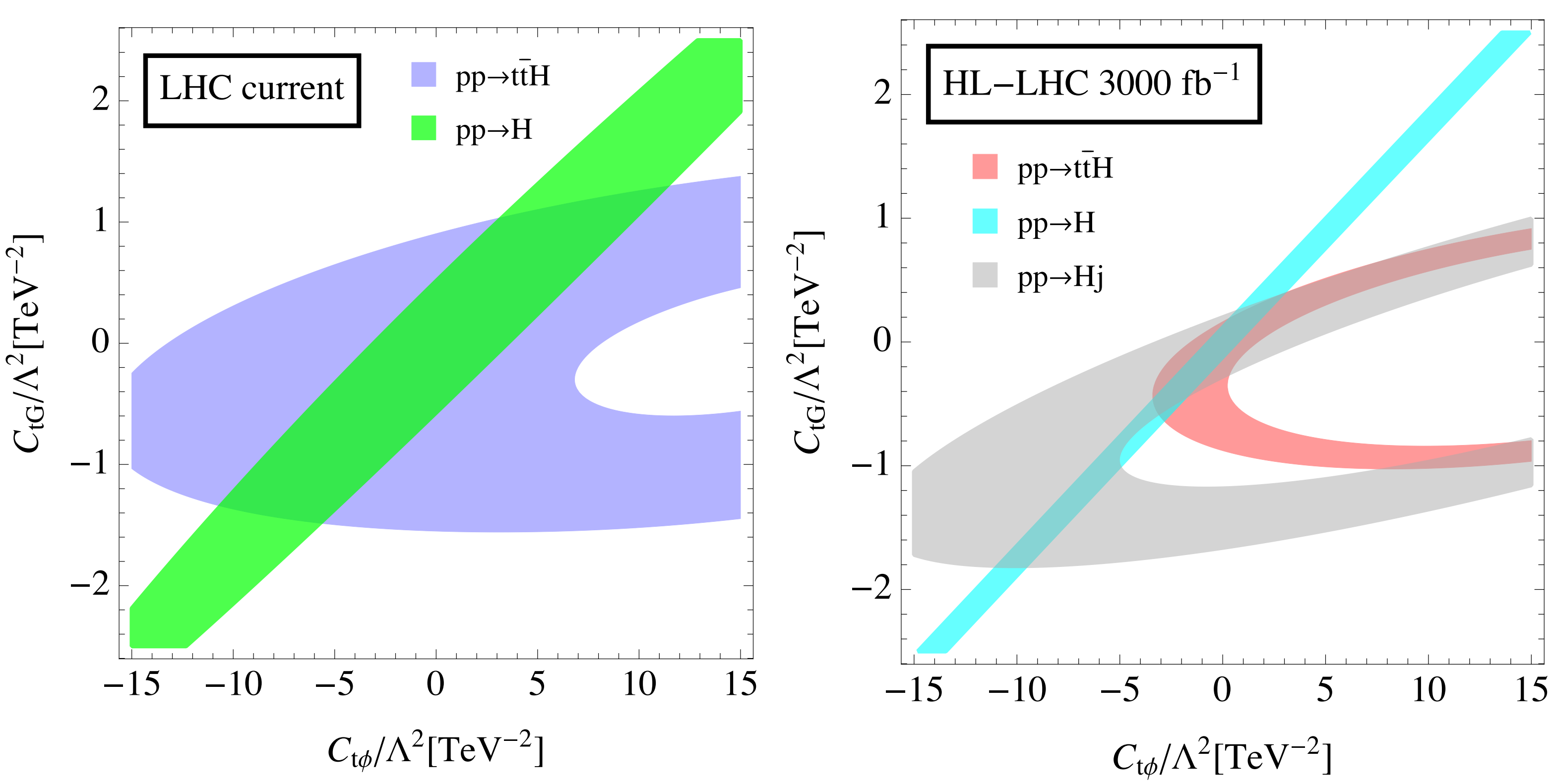
and many more

Sub-sets of operators, where NLO predictions are complete, can be continuously studied and added to the program.

[Rontsch, Schulze, 15]

- First prediction for pp→ttZ/γ→ttll including off-shell Z/photon, at NLO in QCD.
- Projected constraints derived from $\Delta\phi_{ll}$.
- CP-even/odd ttZ couplings included.





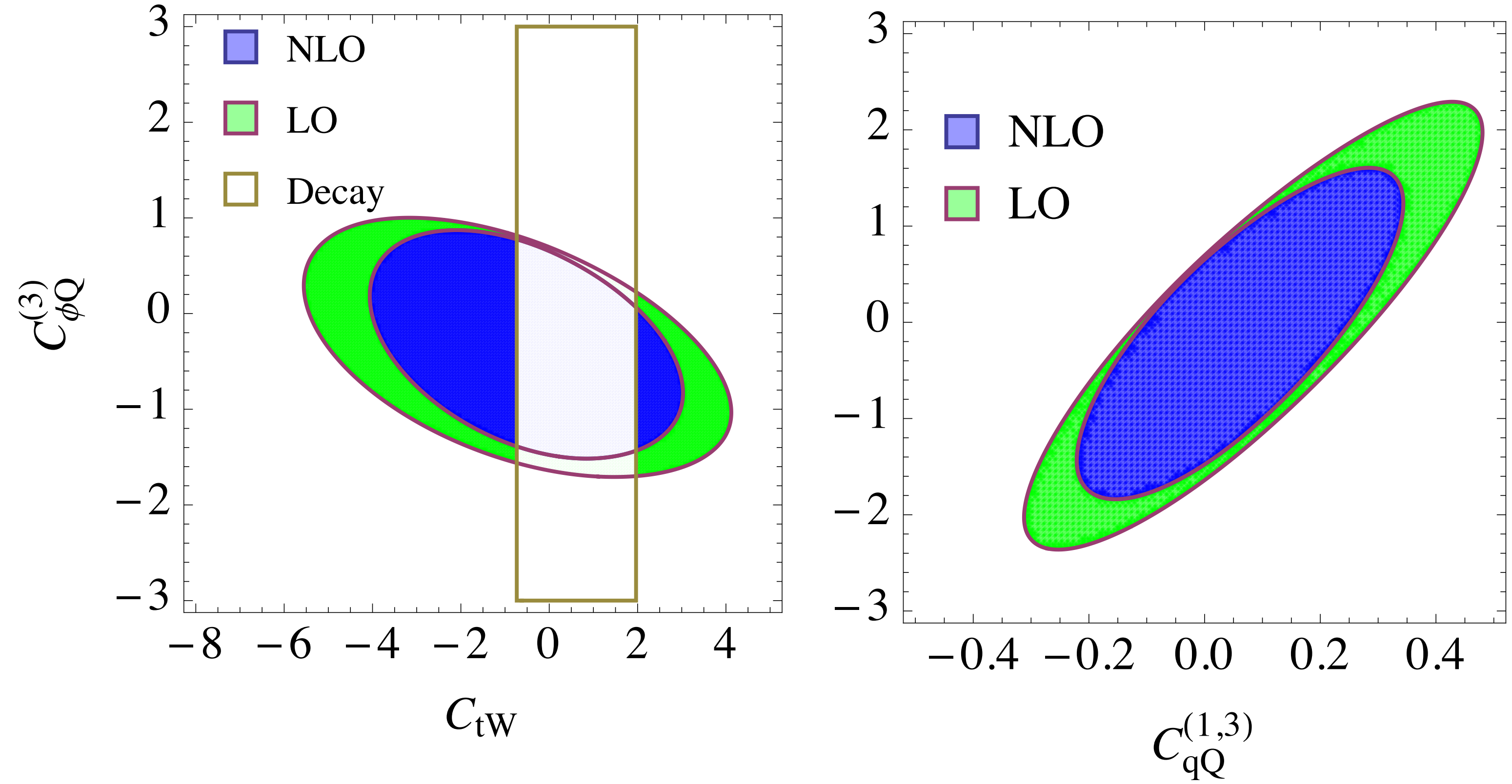
[Maltoni, Vryonidou, **CZ**, 16]

- Top-Higgs operators, fitted from ttH, single Higgs, and possibly H+j in the future.

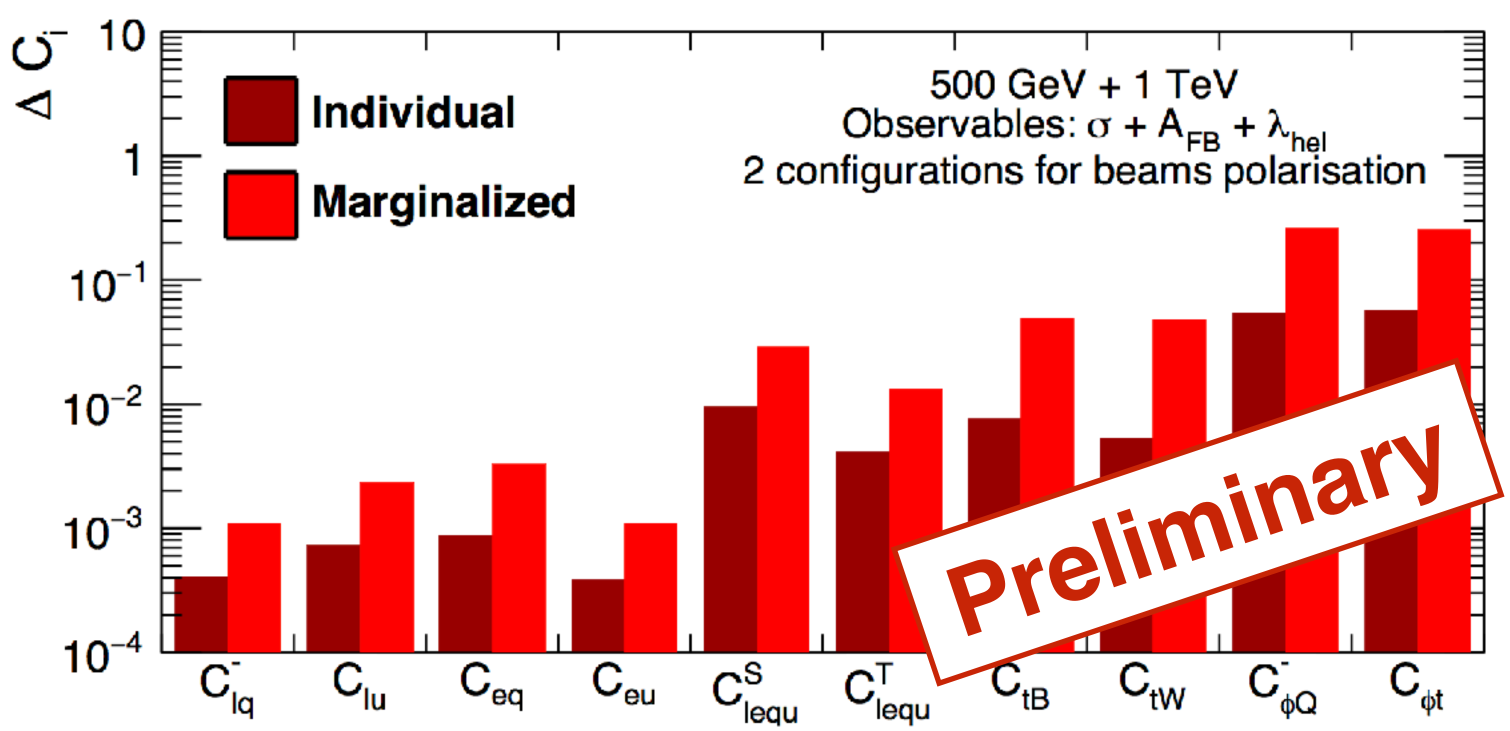
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G_{\mu\nu}$$
$$O_{t\phi} = y_t^3(\phi^\dagger\phi)\bar{Q}t\tilde{\phi}$$
$$O_{\phi G} = y_t^2(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

[CZ, 16]

- Fit based on single top (cross section only) + W helicities.
- Wtb operators and four-fermion operators implemented at NLO in QCD.
- NLO improvement is significant.

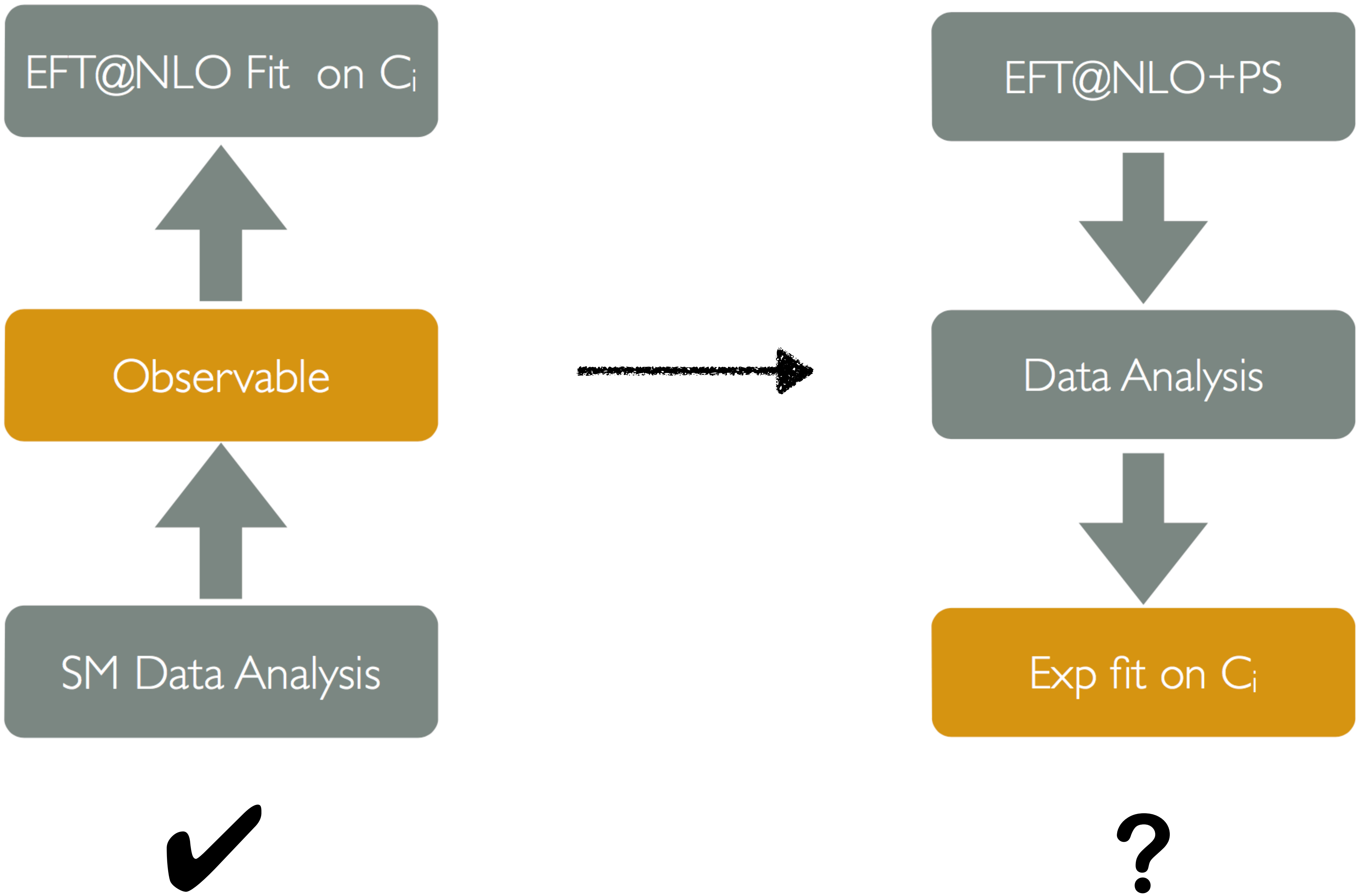


[Durieux, Perelló, Vos, **CZ**]



- Projections at future lepton colliders are being investigated.
- Full NLO prediction for ee→WbWb available, i.e. top pair (tt) and single t (tWb).
- Cross section, FB asymmetry, and Helicity angle, at 2 beam energies and 2 polarizations are used. More to come.

Towards a top-down global fit



Towards a top-down global fit

[Lemaître, Brochet, Wertz]

- ttbar analyzed with 7 operators in a top-down way.
- MEM based on full kinematic information.
- Sensitivity improved w.r.t rates and distributions.

Preliminary

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

13 TeV, 100 fb^{-1}

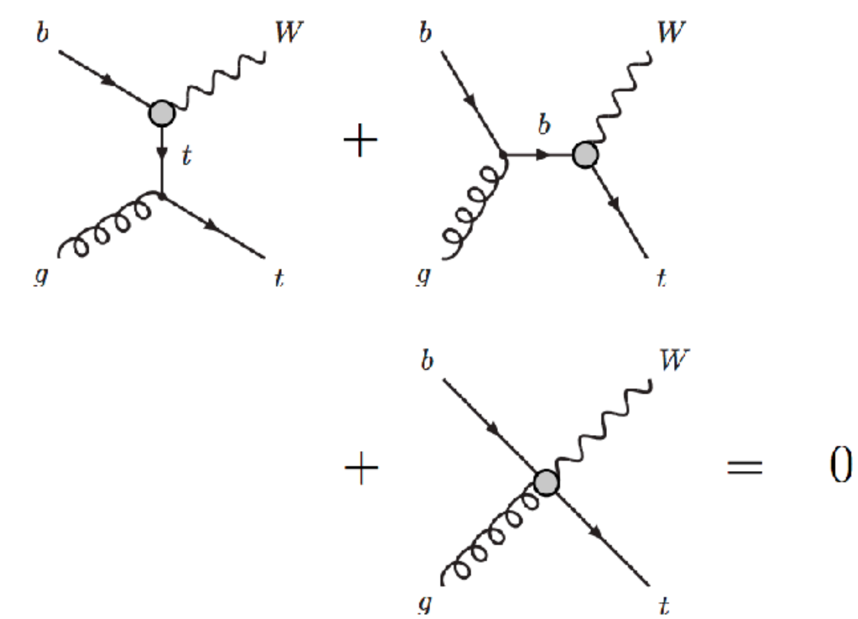
Summary

- “Top couplings” are interpreted and extracted within the SMEFT framework. Global bottom-up approach has been followed by theorists. First results based on Run-I data are ready.
- In the meantime, the TH framework continues to evolve, with improved predictions and non-trivial higher-order effects. Tools are being developed. These progresses are constantly and continuously being added to the fitting program.
- For the future, both top-down and bottom-up approaches are possible. More joint TH/EXP discussions are still needed concerning the best fitting/searching strategy.

Backups

Wtb

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$



Off-shell couplings

$$-\frac{g}{\sqrt{2}M_W}\bar{b}\,[i\sigma^{\mu\nu}k_{\nu}(f_{1L}P_L + f_{1R}P_R) - (m_b f_{1L} - m_t f_{1R})\gamma^{\mu}P_L - (-m_t f_{1L} + m_b f_{1R})\gamma^{\mu}P_R - q^{\mu}(f_{1L}P_L + f_{1R}P_R)]\,t\,W_{\mu}^{-} + \text{H.c.}\,,$$

$$-\frac{g}{\sqrt{2}M_W}\bar{b}\,[k^{\mu}(f_{2L}P_L + f_{2R}P_R) - i\sigma^{\mu\nu}q_{\nu}(f_{2L}P_L + f_{2R}P_R) - (m_b f_{2L} + m_t f_{2R})\gamma^{\mu}P_L - (m_t f_{2L} + m_b f_{2R})\gamma^{\mu}P_R]\,t\,W_{\mu}^{-} + \text{H.c.}\,,$$

[J.A. Aguilar-Saavedra]

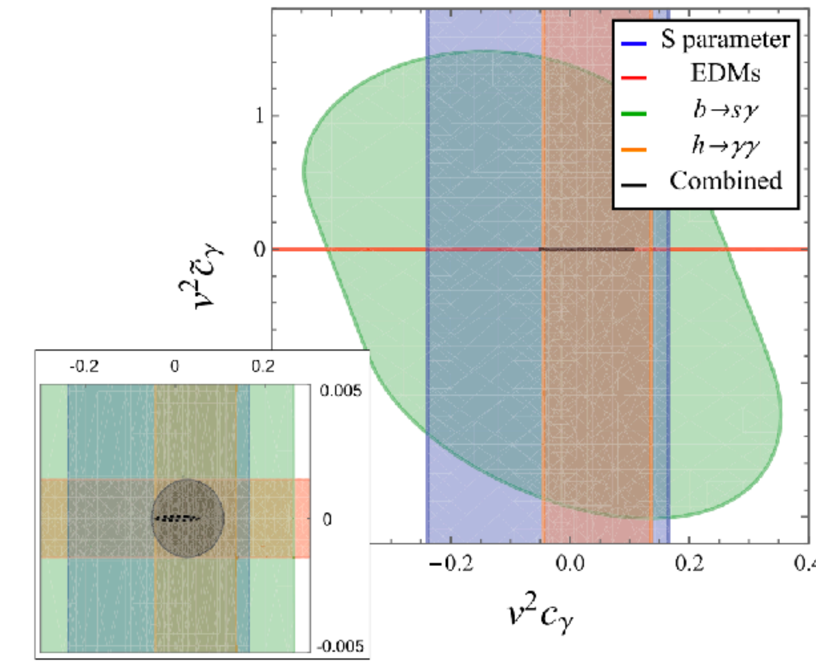
- **Anomalous Coupling**: no SM symmetry => 4 more “off-shell” coupling constants.
- **Gauge-invariant operators**: gauge symmetry leads to contact interactions cancelling the “off-shell” contribution => back to 4 d.o.f
- The widely-used $V_{L,R}/g_{L,R}$ parametrization is **good only when they are understood as being derived from a the EFT framework.**

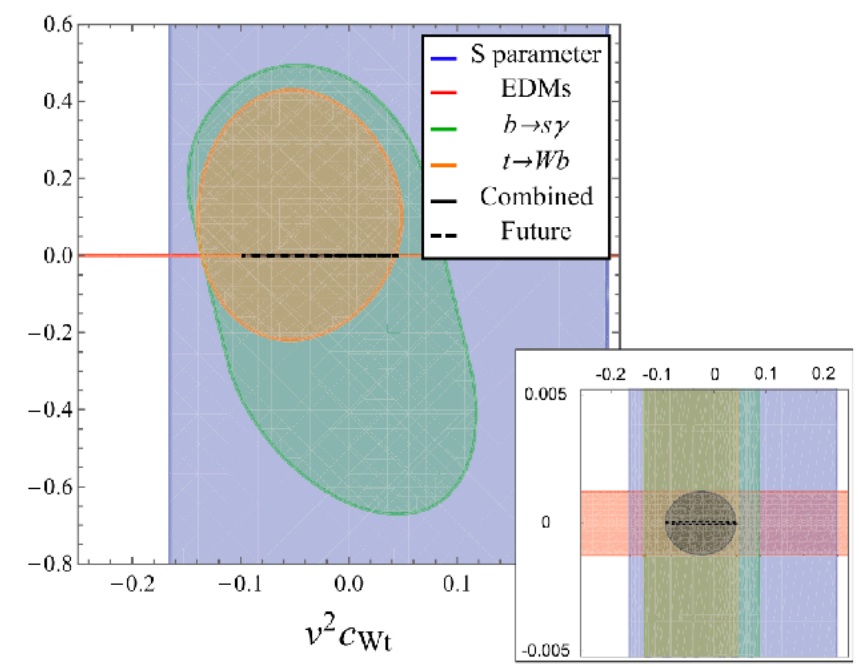
RG-induced constraints

[Cirigliano, Dekens, de Vries, Mereghetti, 16]

	Obs.	c_γ	c_g	c_{Wt}	c_{Wb}	c_Y
Direct	t	✗	✗	✓	✗	✗
	$t\bar{t}$	✗	✓	✗	✗	✗
	$t\bar{t}h$	✗	✓	✗	✗	✓
	$F_0,\ F_L,\ \delta^-$	✗	✗	✓	✗	✗
Indirect	$gg \leftrightarrow h$	✗	$\gamma^{(1,2)}_{t\to\varphi\varphi XX}$	✗	✗	**Threshold** (25)
	$h \to \gamma\gamma$	$\gamma^{(2,1),\,(4,1)}_{t\to\varphi\varphi XX}$	✗	✗	✗	**Threshold** (25)
S	S	$\gamma^{(4,1)}_{t\to\varphi\varphi XX}$	✗	$\gamma^{(4,3)}_{t\to\varphi\varphi XX}$	✗	✗
$b \to s\gamma$	BR, A_{CP}	$\gamma^{(1,1)}_{t\to(bs)}$	✗	$\gamma^{(1,3)}_{t\to(bs)}$	$\gamma^{(1,4)}_{t\to(bs)}$	✗

TABLE VI. An overview of the dominant contributions of the real parts of the anomalous top-Higgs couplings to high- and low-energy observables. ✓ indicates a direct (tree-level) contribution, × a negligible contribution, $\gamma_{t\to X}$ a contribution induced by the RG flow, and "Threshold" a threshold contribution with the numbers indicating the corresponding equations.





For RG induced constraints see also [Degrande et al. 12] [Elias-Miro et al. 13] [Jung et al. 14] [Blas, Chala, Santiago, 15], …

EFT scale uncertainty

UV Model → EFT: $C_i(\Lambda)$

e.g. 1 TeV:

$C_{tG} = 1, \; C_t\phi = 0$

[Alonso, Jenkins, Manohar, Trott, 13]

[Elias-Miro, Grojean, Gupta, Marzocca, 13]

[Jung, Ko, Yoon, Yu, 14]

$$\mu \frac{d}{d\mu} C_i^{(6)} = \gamma_{ij} C_j^{(6)}$$

$$\mu \frac{d}{d\mu} C^{(4)} \propto C^{(4)} + \frac{m_H^2}{\Lambda^2} C^{(6)}$$

m_t = 173 GeV:

$C_{tG} = 0.98, \; C_t\phi = 0.45$

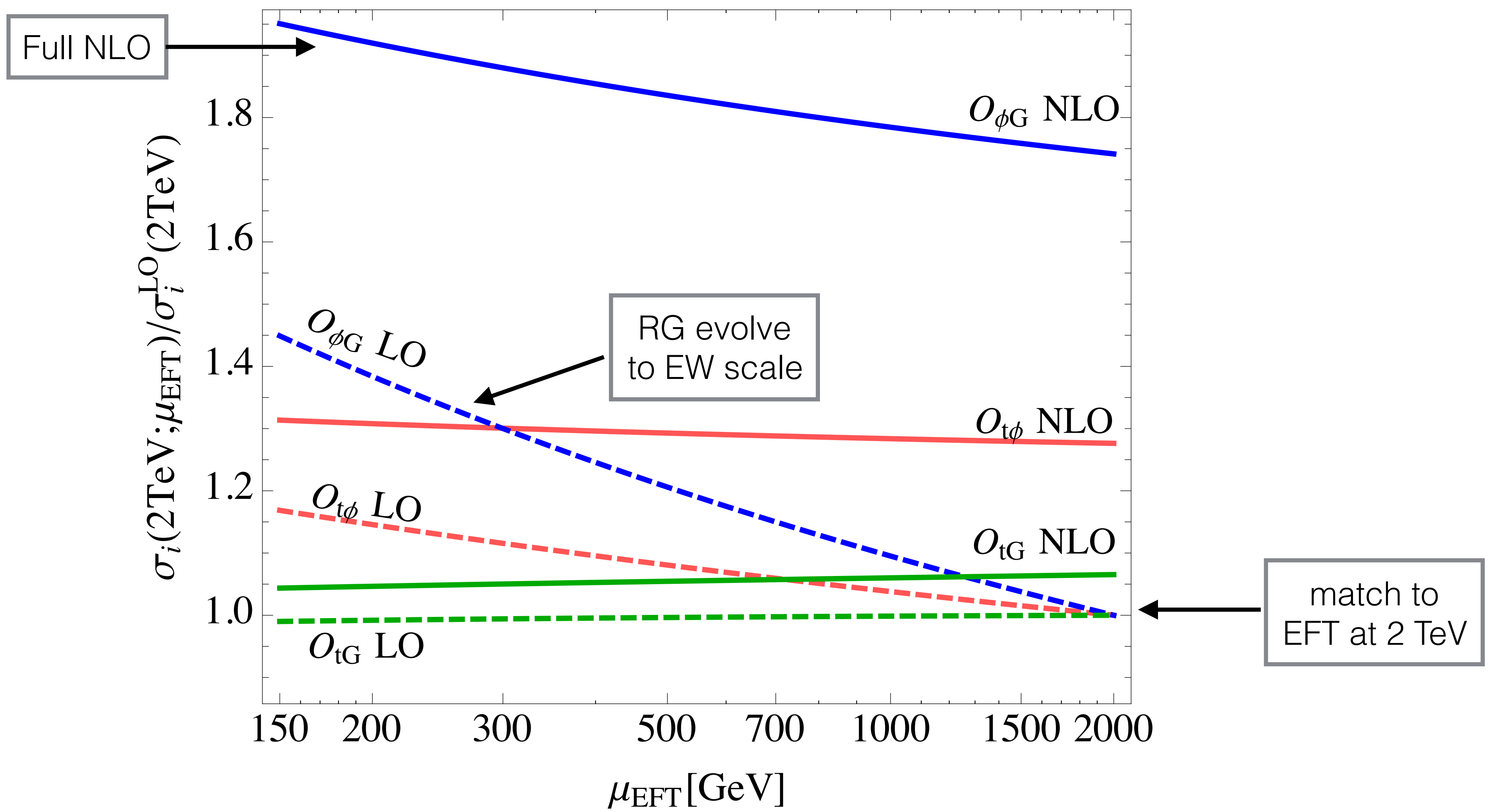
EFT: $C_i(m_H)$ → Observables

↓

At which scale shall we stop running? → New uncertainty

EFT scale uncertainty

[Maltoni, Vryonidou, **CZ**, 16]



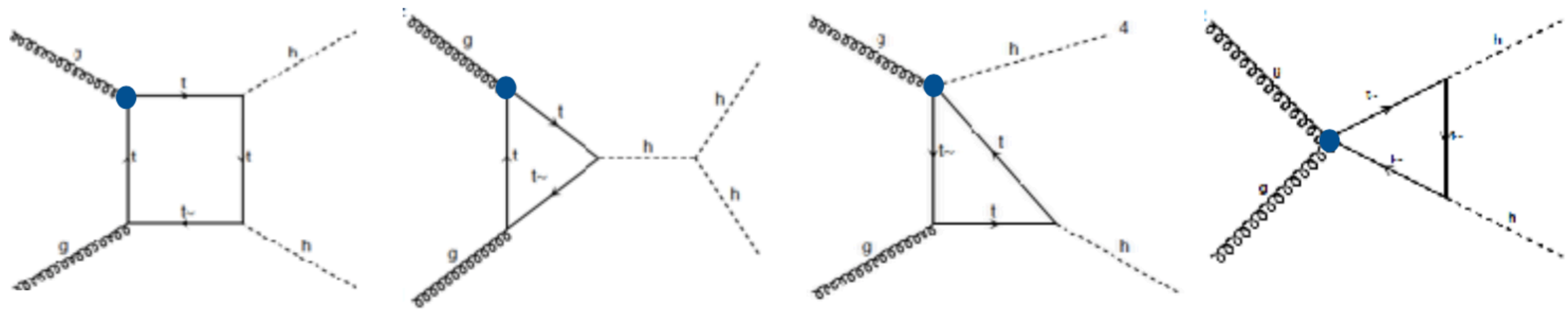
- EFT scale uncertainties are very much reduced at NLO.
- RG is sometimes thought to be an approximation for full NLO, but it's often not the case.

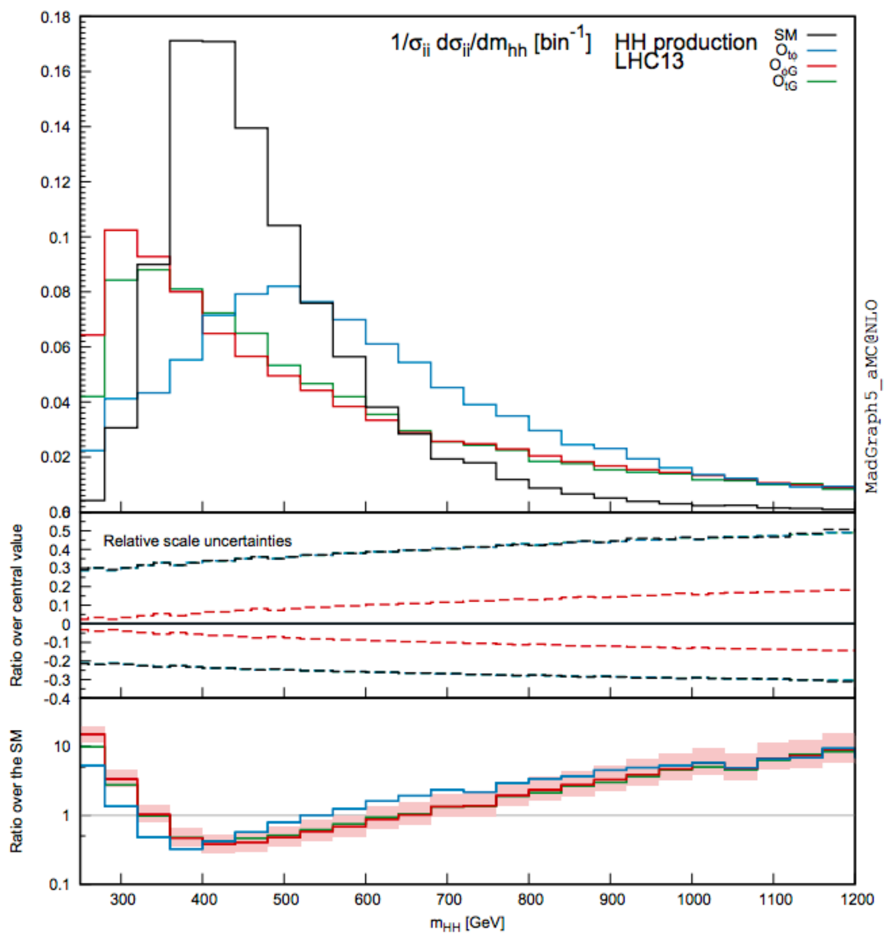
chromo-dipole $O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G_{\mu\nu}$

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

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

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



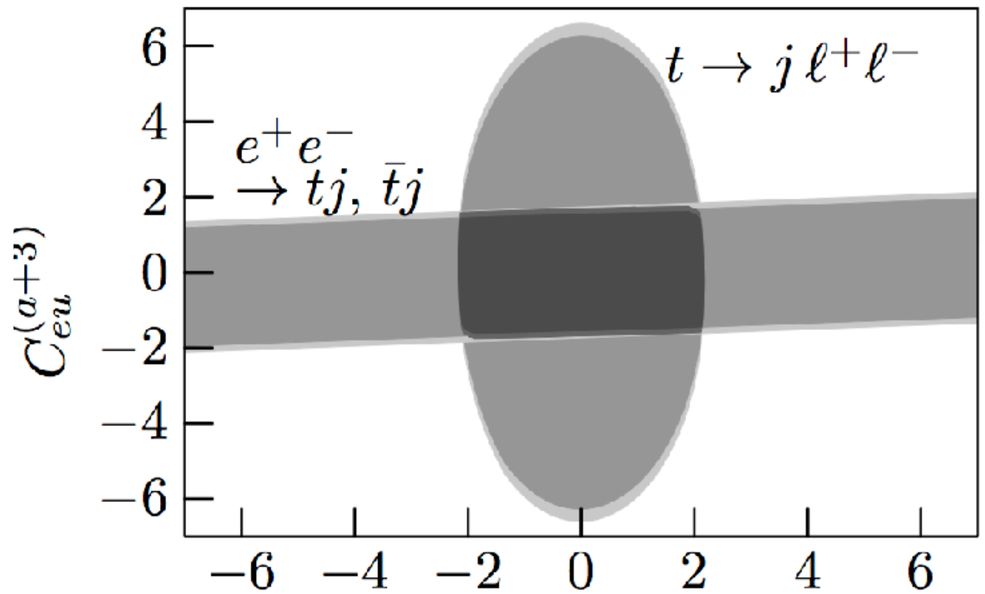


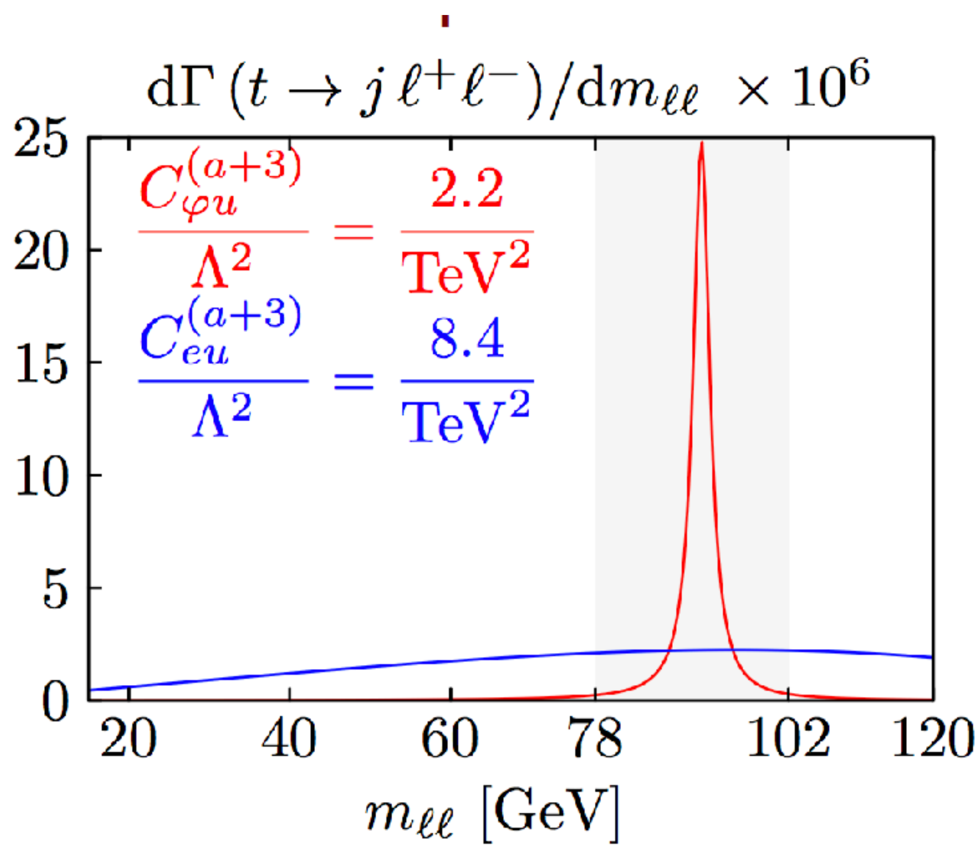
13 TeV	σ LO	σ/σ_{SM} LO
σ_{SM}	$0.0256^{+0.00904+0.000}_{-0.00625-0.000}$	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.00580^{+0.00209+0.000297}_{-0.00144-0.000259}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-1.208^{+0.231+0.0948}_{-0.291-0.113}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-0.0347^{+0.00804+0.0041}_{-0.0113-0.0013}$	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.000748^{+0.000290+0.000079}_{-0.000194-0.000065}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$73.02^{+7.54+14.1}_{-6.48-10.9}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$0.0496^{+0.0198+0.00505}_{-0.01305-0.0126}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-0.303^{+0.0506+0.0362}_{-0.0641-0.0453}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.00870^{+0.00213+0.00163}_{-0.00309-0.00120}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$3.77^{+0.914+0.554}_{-0.681-0.802}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$

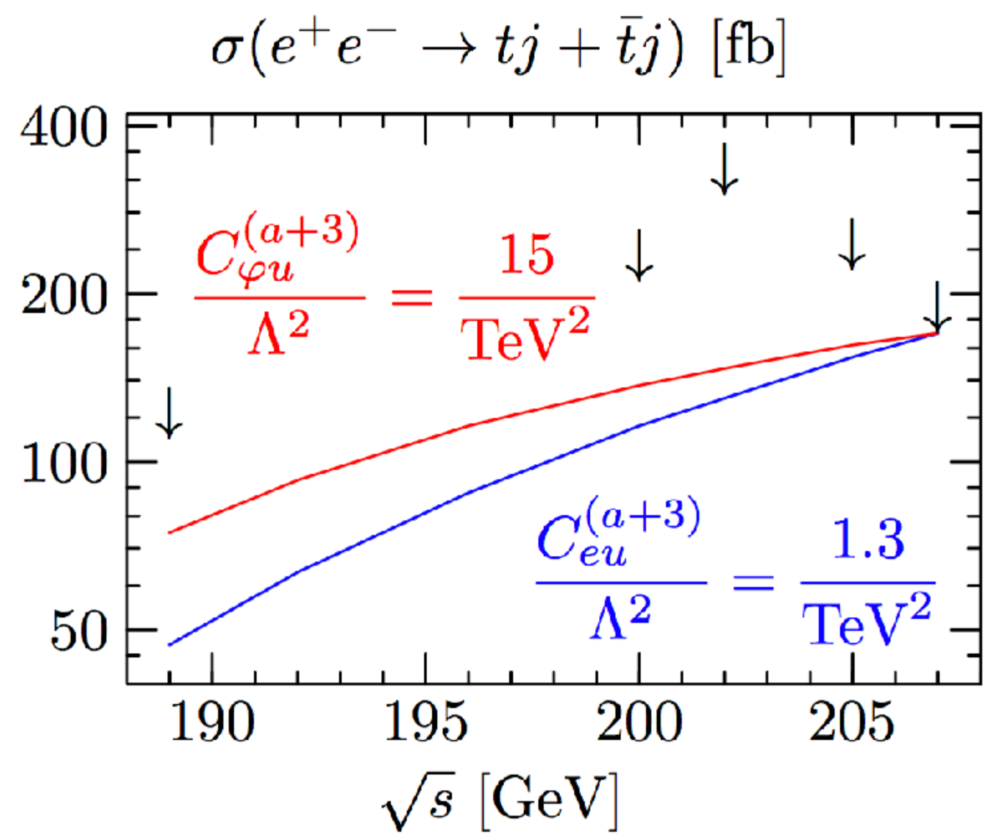
(Loop-induced) HH: top coupling can have large impact on the extraction of Higgs self coupling

FCNC

- Consider two kinds of flavor-changing couplings: tcZ and tcll
- LHC more sensitive to the former (2-body decay)
- LEP2 more sensitive to the latter (ee>tt cross section goes up quickly with energy)
- LEP bounds are still complementary to LHC





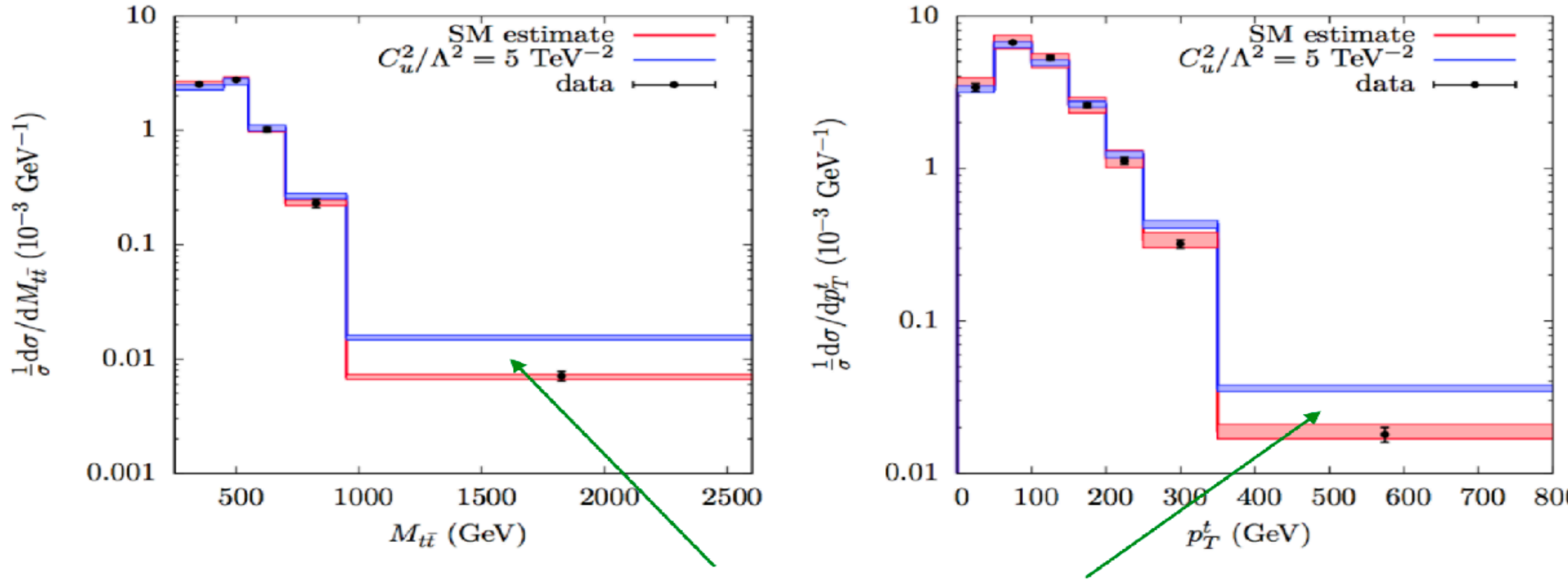


FCNC

Gauthier Durieux®			tqg, T	$tqgh$ T	$tq\gamma$ T	tqZ V,T	$tq\ell\ell$ S,V,T	$tqqq$ S,V,T	tqh S
The broken-phase effective Lagrangian:			✓	✗	✓	✓,✓	✗	✗	✓
production	• $e^+e^- \to t\ j$	OPAL, DELPHI, ALEPH, L3			✓	✓,✗	✗ ✓		
	$e^-p \to e^-t$	**H1**, ZEUS			✓	✗	✗		
	• $p\overset{(-)}{p} \to t$	CDF, **ATLAS**	✓						
	$p\overset{(-)}{p} \to t\ j$	D0, **CMS**	✓		✗	✗		✗	
	• $p\ p \to t\ \gamma$	CMS	✗		✓				
	$p\ p \to t\ \ell^+\ell^-$	CMS	✗		✗	✗,✓	✗		
	$p\ p \to t\ \gamma\gamma$	—	✗	✗	✗				✗
decay	$t \to j\gamma$	**CDF**, D0, ATLAS, CMS			✓				
	• $t \to j\ell^+\ell^-$	CDF, D0, ATLAS, **CMS**			✗	✓,✗	✗		
	• $t \to j\gamma\gamma$	**CMS**, ATLAS			✗				✓

- EXP analysis often assume one particular type of coupling/operator.
- In particular 4-fermion operators have long been overlooked.
- Theorists could often “recast” to have a global EFT interpretation, if fiducial cross sections are provided, but statistical combination is difficult.

Distributions



Most sensitivity in the tails

Operators differ in shapes, e.g.

- Energy dependence: 4-fermion operators leads to E^2/Λ^2 dependence => high sensitivity at tail
- Angular dependence: forward scattering suppressed by Lorentz structure of O_{tW}
- Asymmetries (A_{FB}, A_C): lift four-fermion degeneracies.

[Rosello, Vos, 16]

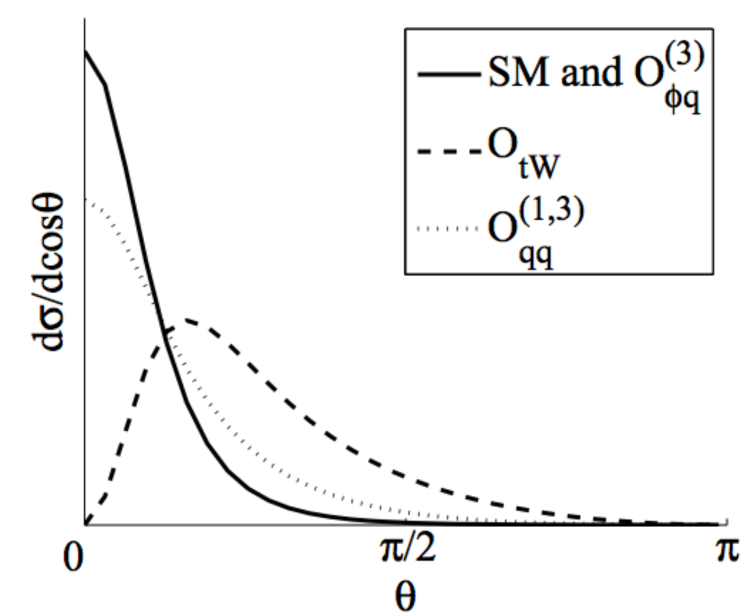


Figure 9: The t-channel ($d\bar{b} \to \bar{u}t$) differential cross section at $\sqrt{s} = 2m_t$.

[CZ, Willenbrock, 10]