Top quark effective field theory in the LHC era

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tifr

TopFitter collaboration

Based on 1506.08845
1512.03360
1607.04304

CKM workshop, Mumbai, November 2016

Outline

- Why (top) EFT?
- The Standard Model EFT
- A global fit of top quark EFT to data
- Prospects for improvement over Run II
- Summary

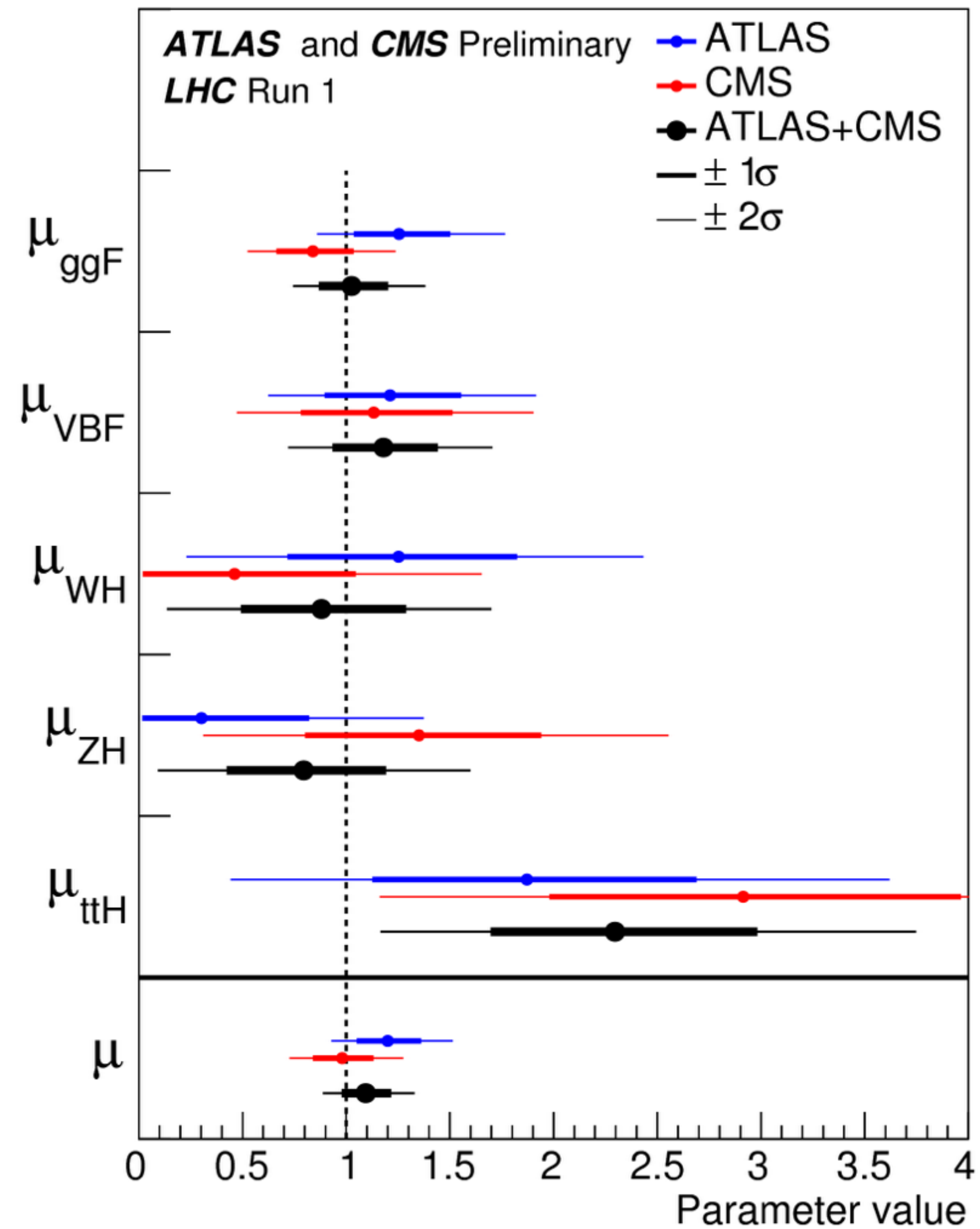
The Standard Model in 2016

- All measurements more or less consistent with SM (~10%)
- Dedicated searches for new physics continually finding null results for NP
- Many concrete models, but large degeneracy in experimental signatures

  e.g. "tails of distributions"

- If there is heavy new physics, looks like it decouples

Where do we go from here?



The Standard Model EFT

- Resurgence of model-independent frameworks to go beyond SM

(κ framework, anomalous couplings, form factors…)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i O_i}{\Lambda^2} \quad (+\ldots)$$

Why bother with Effective Field Theory?

- completely general
- can be matched to UV completions
- radiative corrections calculable
- allows contact interactions
- allows power counting
- keeps gauge invariance manifest
- differential distributions
- …

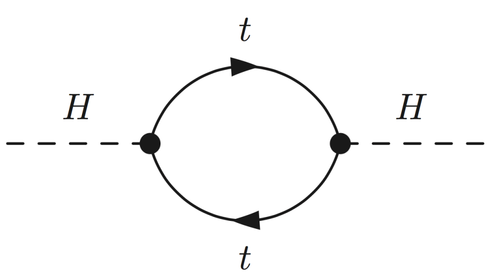
EFT: Which Lagrangian best describes the currently available data?

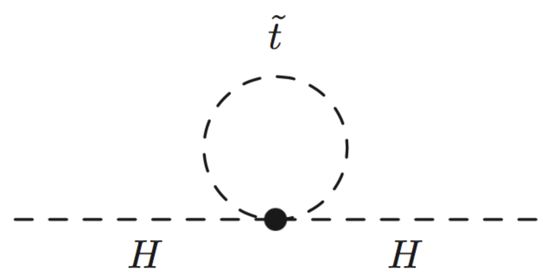
Why top EFT?

DIRECTLY:

Top plays a special role in most scenarios of electroweak symmetry breaking:

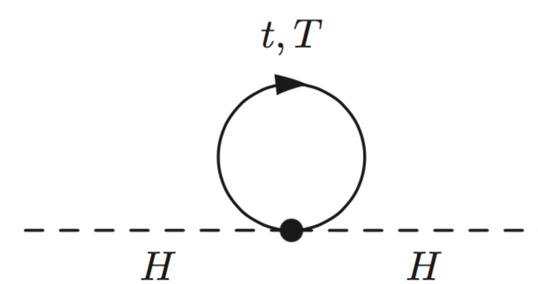
- SUSY: Top partners cancel UV divergences in m_h (if light enough)



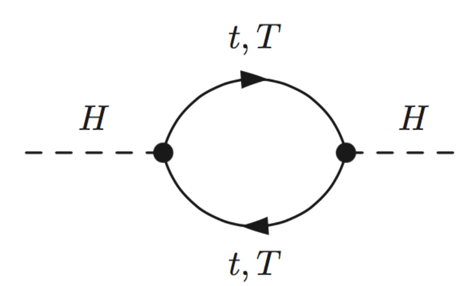


$$\delta m_H^2 = -\frac{|\lambda_F|^2}{8\pi^2}[\Lambda_{UV}^2 + ...]$$

$$\delta m_H^2 = 2 \times \frac{|\lambda_S|^2}{16\pi^2}[\Lambda_{UV}^2 + ...]$$

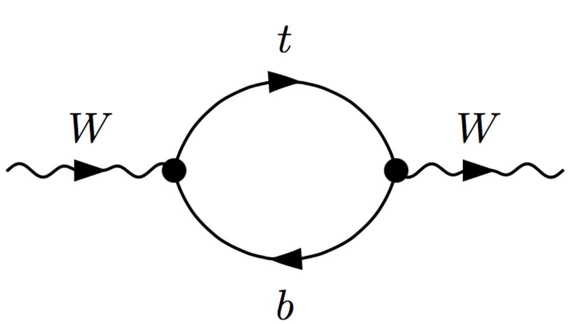


- Little Higgs and friends: Spin-1/2 top partners with large T-t mixing



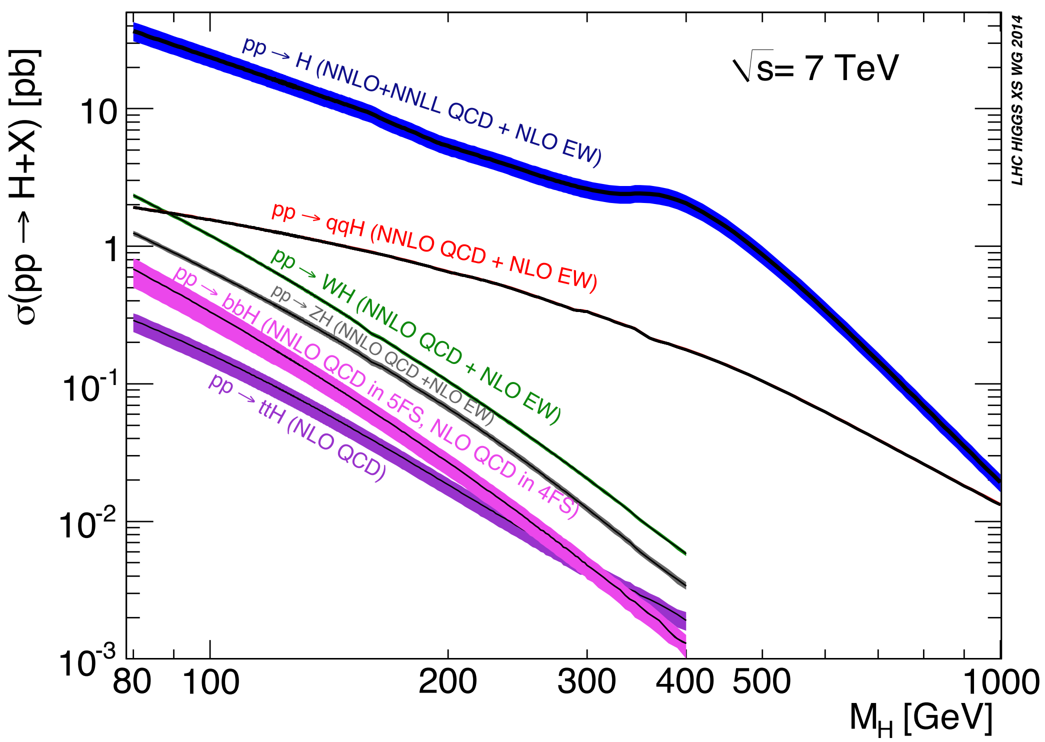
INDIRECTLY:

Large effects in electroweak measurements: ripe for deviations



All lead to modified top couplings

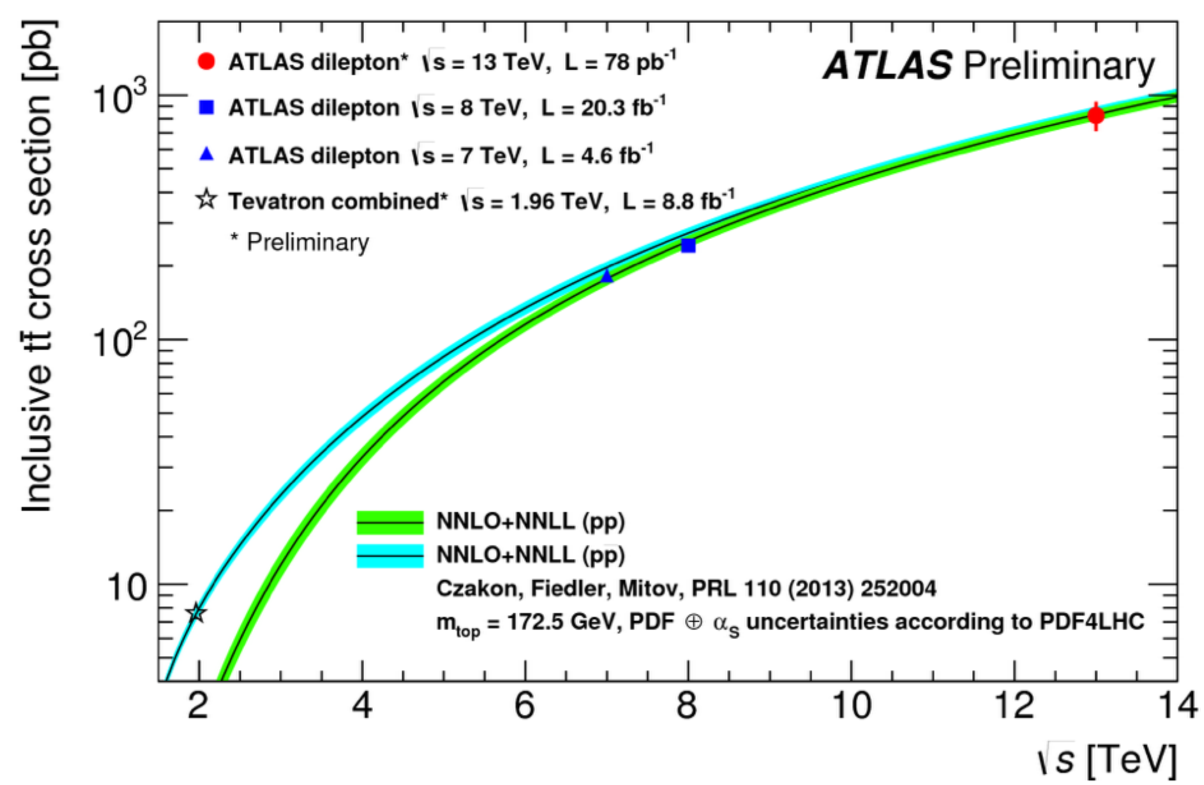
Why top EFT?



LHC run 1:
4.57 fb^{-1} @ 7 TeV
20.3 fb^{-1} @ 8 TeV

550,000 Higgs produced (before BRs!)

>8 million top quarks produced!



Dimension six operators

Choice of basis

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}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q^{(1)}_{lq}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q^{(3)}_{lq}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q^{(8)}_{qd}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		*B*-violating	
Q_{ledq}	$(\bar l^j_p e_r)(\bar d_s q^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$Q^{(1)}_{quqd}$	$(\bar q^j_p u_r)\varepsilon_{jk}(\bar q^k_s d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$Q^{(8)}_{quqd}$	$(\bar q^j_p T^A u_r)\varepsilon_{jk}(\bar q^k_s T^A d_t)$	$Q^{(1)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(1)}_{lequ}$	$(\bar l^j_p e_r)\varepsilon_{jk}(\bar q^k_s u_t)$	$Q^{(3)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(3)}_{lequ}$	$(\bar l^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q^k_s \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$

Grzadkowski et al, 1008:4884

see also:
Guidice et al. [hep-ph/0703164]
Contino et al. 1303.3876
Gupta, Pomarol & Riva 1405.0181

Relevant operators

$$O^1_{qq} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$$

$$O^3_{qq} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$$

$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$$

$$O^8_{qu} = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$$

$$O^8_{qd} = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$$

$$O^8_{ud} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$$

$$O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi} W^I_{\mu\nu}$$

$$O_{uG} = (\bar{q}\sigma^{\mu\nu}\lambda^A u)\tilde{\phi} G^A_{\mu\nu}$$

$$O_G = f_{ABC} G^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda$$

$$O_{\tilde{G}} = f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda$$

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

$$O^3_{\phi q} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$$

$$O^1_{\phi q} = i(\phi^\dagger D_\mu \phi)(\bar{q}\gamma^\mu q)$$

$$O_{uB} = (\bar{q}\sigma^{\mu\nu} u)\tilde{\phi} B_{\mu\nu}$$

$$O_{\phi u} = (\phi^\dagger i D_\mu \phi)(\bar{u}\gamma^\mu u)$$

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

A handful of operators

And many measurements…

GLOBAL FIT

List of papers submitted to refereed journals

Full Title	Journal	Links	Status	Groups
NEW Measurement of the correlations between the polar angles of leptons from top quark decays in the helicity basis at $\sqrt{s}=7$ TeV using the ATLAS detector	Phys. Rev. D (RC)	Figures	Submitted: 2015/10/26	TOPQ
Measurement of the production cross-section of a single top quark in association with a W boson at 8 TeV with the ATLAS experiment	JHEP	Inspire, arXiv, Figures	Submitted: 2015/10/13	TOPQ
Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $√s$ = 8 TeV proton--proton collisions using the ATLAS detector	PRD	Inspire, arXiv, Figures	Submitted: 2015/10/13	TOPQ
Search for anomalous couplings in the Wtb vertex from the measurement of double differential angular decay rates of single top quarks produced in the t-channel with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/10/13	TOPQ
Search for the production of single vector-like and excited quarks in the Wt final state in pp collisions at $√s = 8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/10/09	EXOT / TOPQ
Search for flavour-changing neutral current top quark decays $t\to Hq$ in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/09/20	TOPQ / HIGG
Measurement of the $t\bar{t}W$ and $t\bar{t}Z$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Submitted: 2015/09/17	TOPQ
Measurement of the charge asymmetry in top-quark pair production in the lepton-plus-jets final state in pp collision data at $√s=8$ TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Submitted: 2015/09/08	TOPQ
Search for single top-quark production via flavour changing neutral currents at 8 TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Submitted: 2015/09/01	TOPQ
Measurements of fiducial cross-sections for $t\bar{t}$ production with one or two additional b-jets in pp collisions at $\sqrt{s}$=8 TeV using the ATLAS detector	EPJC	Inspire, arXiv, Figures	Submitted: 2015/08/27	TOPQ
Search for flavour-changing neutral current top-quark decays to qZ in pp collision data collected with the ATLAS detector at $√s=8$ TeV	EPJC	Inspire, arXiv, Figures	Submitted: 2015/08/24	TOPQ
PUBLISHED Determination of the top-quark pole mass using $t t̄$ +1-jet events collected with the ATLAS experiment in 7 TeV pp collisions	JHEP	Inspire, arXiv, Figures	JHEP 10 (2015) 121 (Submitted: 2015/07/07)	TOPQ
PUBLISHED Measurement of colour flow with the jet pull angle in $t\bar{t}$ events using the ATLAS detector at $\sqrt{s}=8$ TeV	PLB	Inspire, arXiv, Figures	Physics Letters B (2015) 475-493 (Submitted: 2015/06/18)	TOPQ
PUBLISHED Measurement of the top quark branching ratios into channels with leptons and quarks with the ATLAS detector	PRD	Inspire, arXiv, Figures	Phys. Rev. D 92, 072005 (2015) (Submitted: 2015/06/16)	TOPQ
PUBLISHED A search for $t\bar{t}$ resonances using lepton-plus-jets events in proton--proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP08 (2015) 148 (Submitted: 2015/05/26)	TOPQ / EXOT
PUBLISHED Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 08 (2015) 105 (Submitted: 2015/05/16)	EXOT / TOPQ
Analysis of events with b-jets and a pair of leptons of the same charge in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	Accepted (Submitted: 2015/04/17)	EXOT / TOPQ
PUBLISHED Measurement of the top pair production cross-section in 8 TeV proton--proton collisions using kinematic information in the lepton+jets final state with ATLAS	PRD	Inspire, arXiv, Figures	Phys. Rev. D 91, 112013 (2015) (Submitted: 2015/04/16)	TOPQ
PUBLISHED Measurement of the top quark mass in the $t\bar t \to {\rm lepton+jets}$ and $t\bar t \to {\rm dilepton}$ channels using $\sqrt{s}=7$ TeV ATLAS data	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:330 (Submitted: 2015/03/18)	TOPQ
PUBLISHED Search for vector-like B quarks in events with one isolated lepton, missing transverse momentum and jets at $\sqrt{s}=$ 8TeV with the ATLAS detector	PRD	Inspire, arXiv, Figures	Phys. Rev. D 91, 112011 (2015) (Submitted: 2015/03/18)	EXOT / TOPQ
PUBLISHED Differential top--antitop cross-section measurements as a function of observables constructed from final-state particles using pp collisions at $\sqrt{s}=7$ TeV in the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 06 (2015) 100 (Submitted: 2015/02/20)	TOPQ
PUBLISHED Observation of top-quark pair production in association with a photon and measurement of the $t\bar{t}\gamma$ production cross section in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector	PRD	Inspire, arXiv, Figures	Phys. Rev. D 91, 072007 (2015) (Submitted: 2015/02/02)	TOPQ
PUBLISHED Measurement of the ttbar and lepton charge asymmetry in dilepton events in √s=7 TeV data with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 05 (2015) 061 (Submitted: 2015/01/29)	TOPQ
PUBLISHED Measurement of spin correlation in top-antitop quark events and search for stop quark pair production in proton-proton collisions at √s = 8 TeV using the ATLAS detector	PRL	Inspire, arXiv, Figures	Phys. Rev. Lett. 114, 142001 (2015) (Submitted: 2014/12/15)	TOPQ / SUSY
PUBLISHED Search for invisible particles produced in association with single-top-quarks in proton-proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:79 (Submitted: 2014/10/20)	TOPQ / EXOT
PUBLISHED Search for $W' \to t\bar{b}$ in the lepton plus jets final state in proton-proton collisions at a centre-of-mass energy of $\sqrt{s}$ = 8 TeV with the ATLAS detector	PLB	Inspire, arXiv, Figures	Physics Letters B 743 (2015) 235-255 (Submitted: 2014/10/15)	TOPQ / EXOT
PUBLISHED Search for s-channel single top-quark production in proton-proton collisions at $\sqrt{s}$=8 TeV with the ATLAS detector	PLB	Inspire, arXiv, Figures	Phys.Lett. B740 (2015) 118 (Submitted: 2014/10/02)	TOPQ
PUBLISHED Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector	JHEP	Inspire, arXiv, Figures	JHEP 11 (2014) 104 (Submitted: 2014/09/19)	EXOT / TOPQ
PUBLISHED Measurement of the top-quark mass in the fully hadronic decay channel from ATLAS data at sqrt(s) = 7 TeV	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:158 (Submitted: 2014/09/02)	TOPQ
PUBLISHED Search for W' →tb →qq'bb decays in pp collisions at √s=8 TeV with the ATLAS detector	EPJC	Inspire, arXiv, Figures	Eur. Phys. J. C (2015) 75:165 (Submitted: 2014/08/05)	EXOT / TOPQ

The TopFitter method

- Sample a set of points in the N-dimensional parameter space of $\{C_i\}$

- Construct *parameterising* function $f_b(\{C_i\})$ which models change in MC w.r.t Wilson coefficient

$$\sigma \sim \sigma_{\mathrm{SM}} + C_i \sigma_{D6} + C_i^2 \sigma_{D6^2} \longrightarrow f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i \leq j} \gamma_{i,j}^b C_i C_j + \ldots$$

- Construct goodness-of-fit between $f_b(\{C_i\})$ and data

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

- Minimise it

GOAL: Global fit of all relevant operators in top quark production & decay to available data from Tevatron & LHC

Datasets

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				

Top pair production

At dimension-six

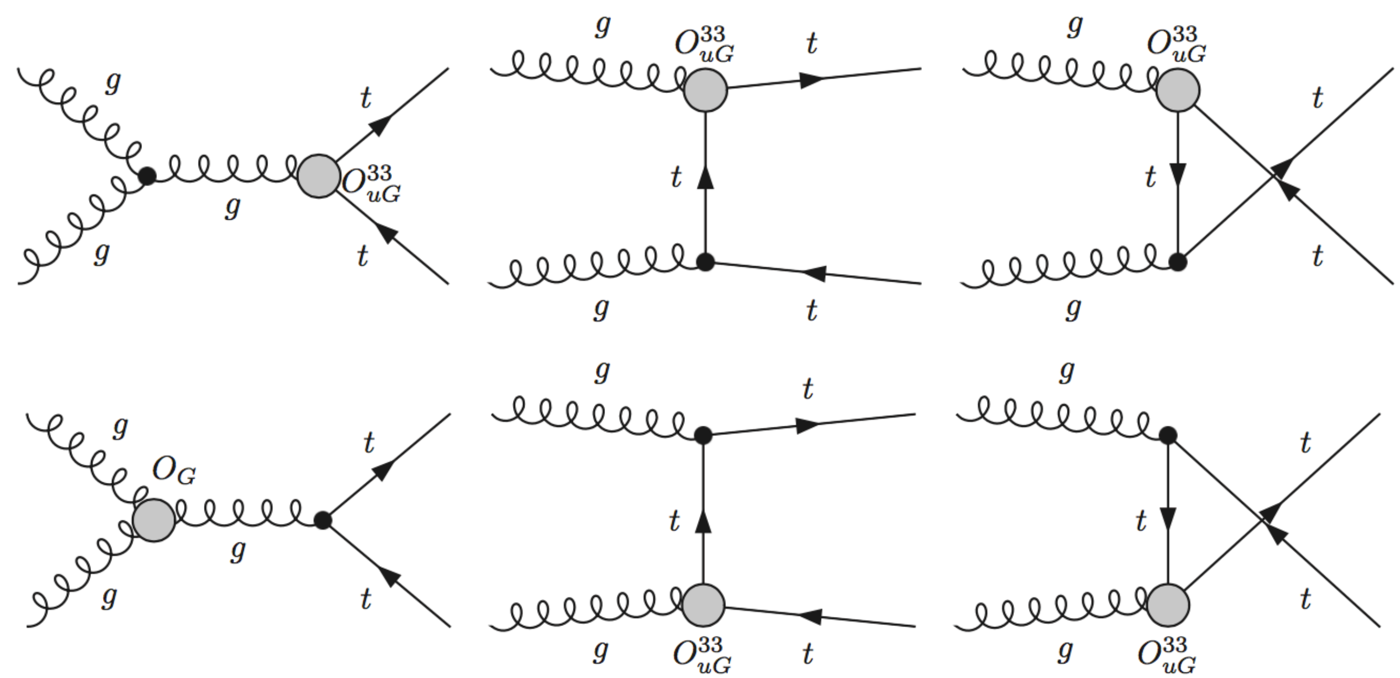
$$|\mathcal{M}_{\rm tot}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\Re\left\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{D6}\right\} + |\mathcal{M}_{D6}|^2$$

gg channel dominates @ LHC

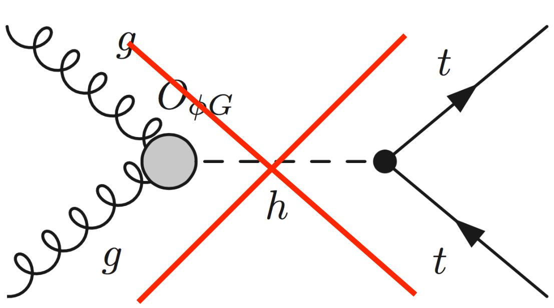
$$O_{uG} = (\bar{q}\sigma^{\mu\nu}\lambda^A u)\tilde{\phi}G^A_{\mu\nu}$$

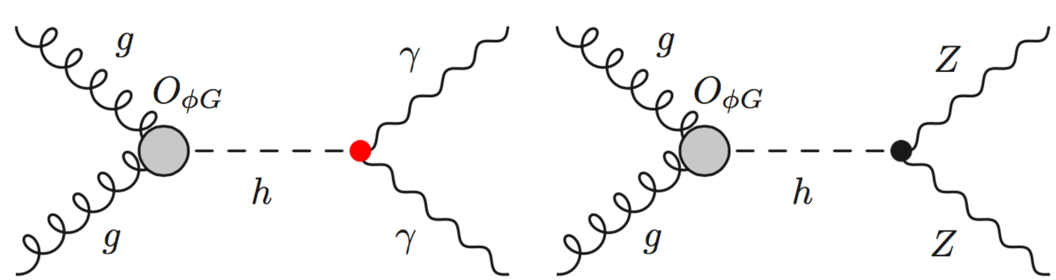
$$O_G = f_{ABC}G^{A\nu}_{\mu}G^{B\lambda}_{\nu}G^{C\mu}_{\lambda}$$

$$O_{\phi G} = \frac{1}{2}(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$$ ⁇



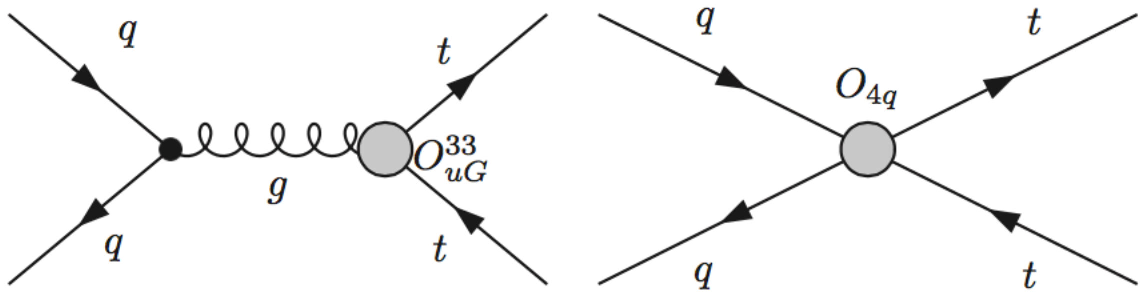
No constraint here, but can probe in Higgs physics





Corbett et al.1505.05516

Top pair production



Kamenik, Shu & Zupan, 1107.5257

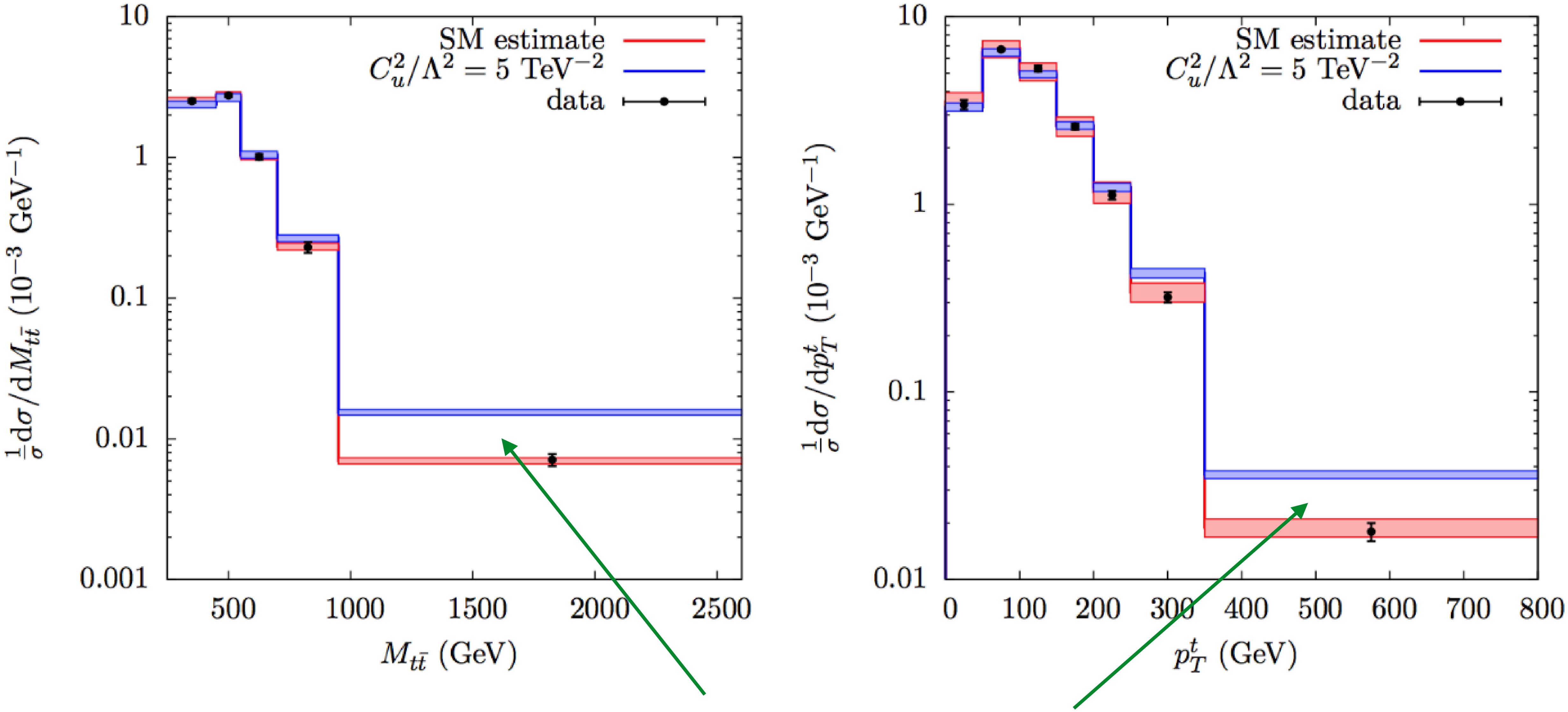
Zhang and Willenbrock, 1008.3869

Degrande, Gerard, Grojean, Maltoni & Servant, 1010.6304

$$
\begin{aligned}
O_{qq}^{1} &= (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)\\
O_{qq}^{3} &= (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)\\
O_{uu} &= (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)\\
O_{qu}^{8} &= (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)\\
O_{qd}^{8} &= (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)\\
O_{ud}^{8} &= (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)
\end{aligned}
$$

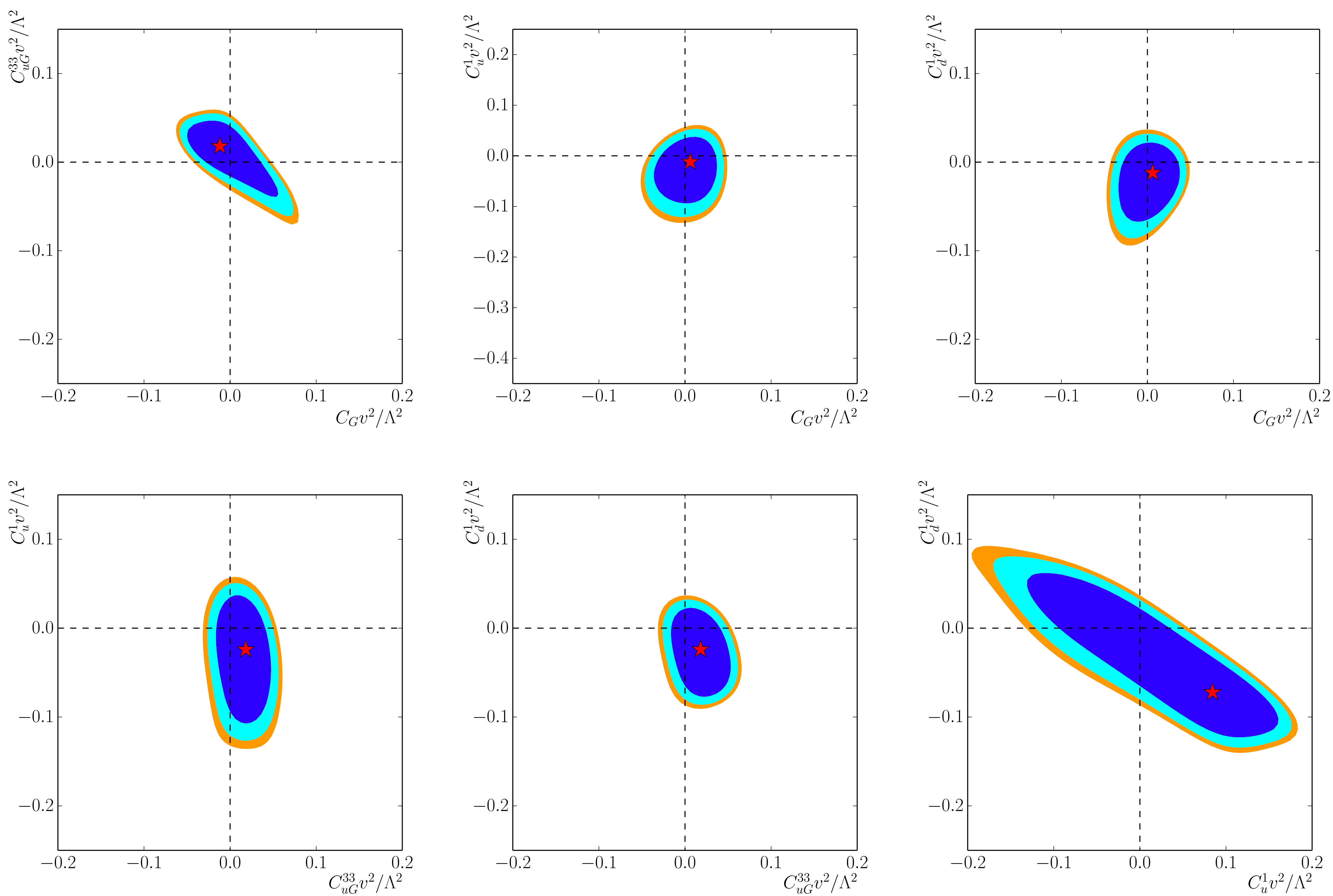
$$
\begin{aligned}
O_u^1 &= 3(2O_{qq}^{(1)1331} + O_{uu}^{1331}) - (O_{qq}^{(1)1133} + O_{qq}^{(3)1133} + O_{uu}^{1133})\\
O_u^2 &= -(O_{qu}^{(8)1133} + O_{qu}^{(8)3311})\\
O_d^1 &= 3(O_{qq}^{(3)1331} - O_{qq}^{(1)1331}) + (O_{qq}^{(3)1133} - O_{qq}^{(1)1133}) + 6O_{ud}^{(8)3311}\\
O_d^2 &= -(O_{qu}^{(8)1133} + O_{qd}^{(8)3311}),
\end{aligned}
$$

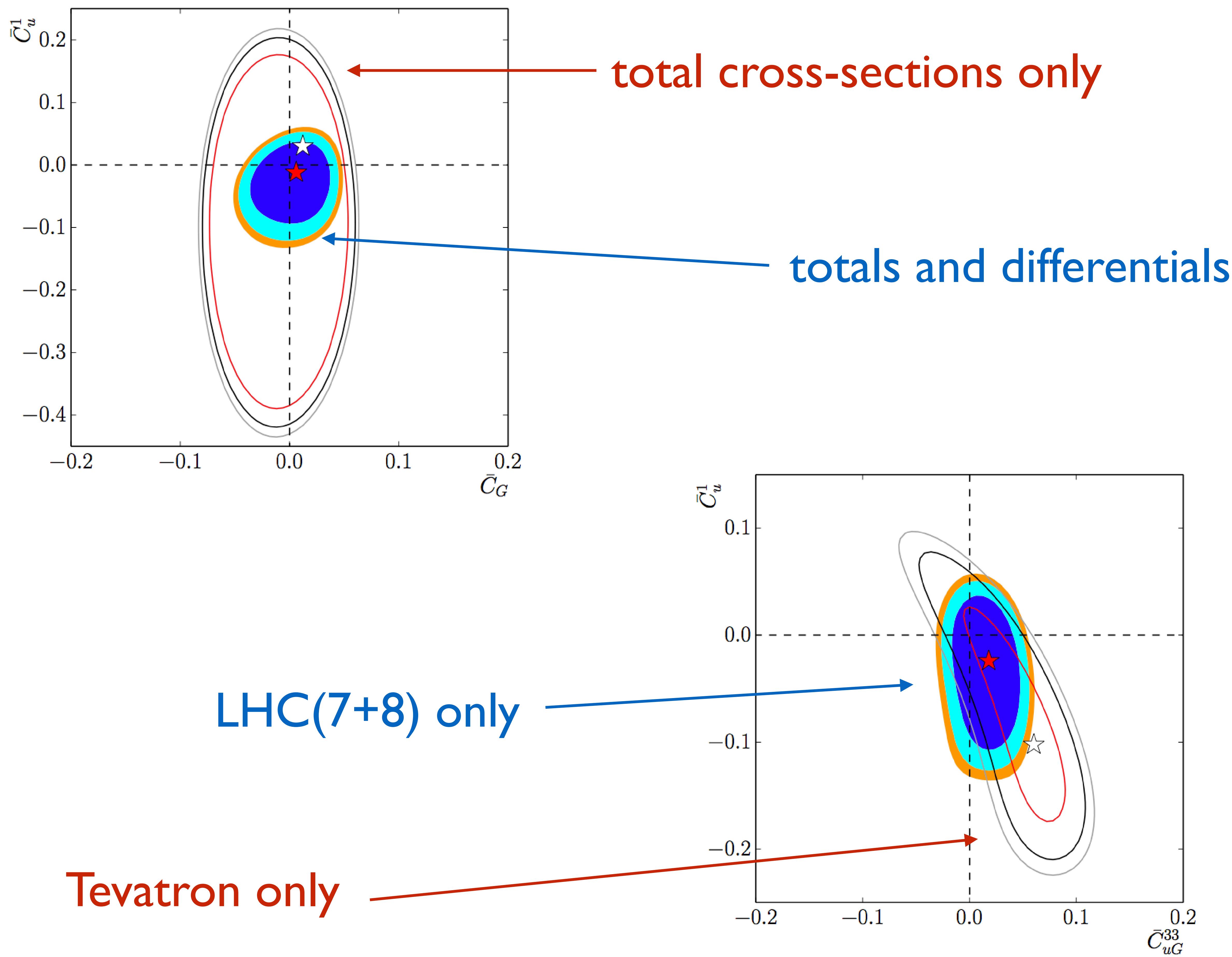
SUMMARY: 6 constrainable operators in top pair production



Most sensitivity in the tails

Selected Correlations

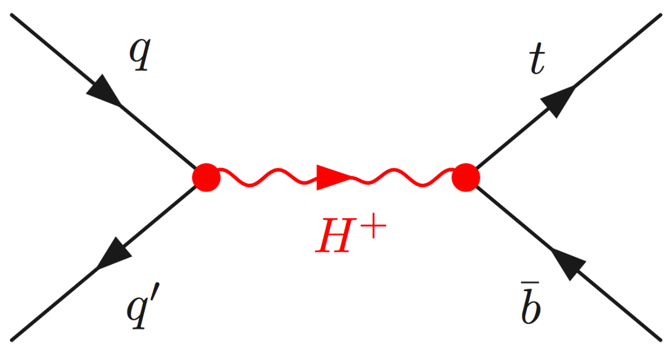


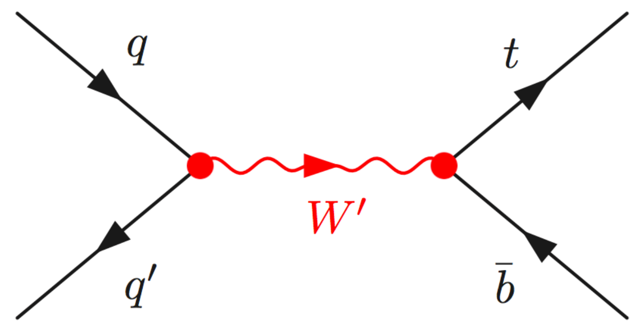

total cross-sections only
totals and differentials
LHC(7+8) only
Tevatron only
$\bar{C}_u^1$
$\bar{C}_G$
$\bar{C}_{uG}^{33}$

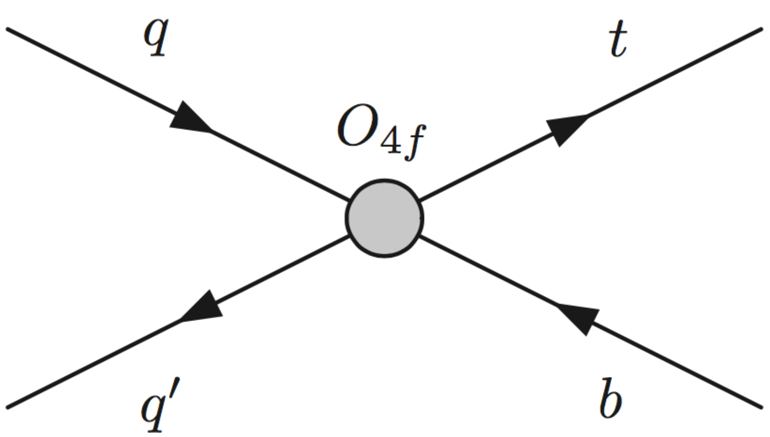
Single-top production

Single top in simple BSM models:

in low-energy limit:







$$O^3_{qq} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$$

$$\mathcal{M}_{D6} \sim C_i v^2/\Lambda^2$$

$$O^1_{qq} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$$

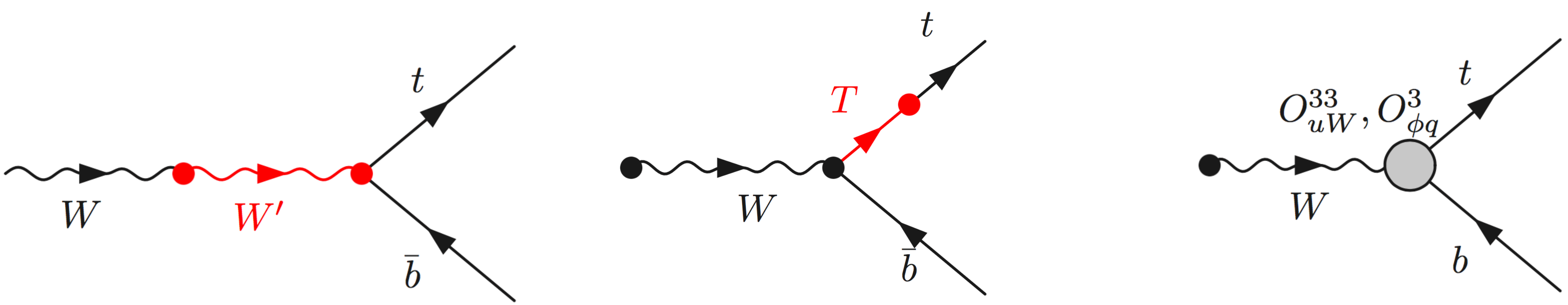
$$O^1_{qu} = (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$$

$$\mathcal{M}_{D6} \sim C_i m_t m_b/\Lambda^2$$

Single-top production

Single top in simple BSM models:

in low-energy limit:



Relation to anomalous couplings:

$$O^{33}_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi}W^I_{\mu\nu}$$

$$O^{3}_{\phi q} = i(\phi^\dagger \tau^I \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$$

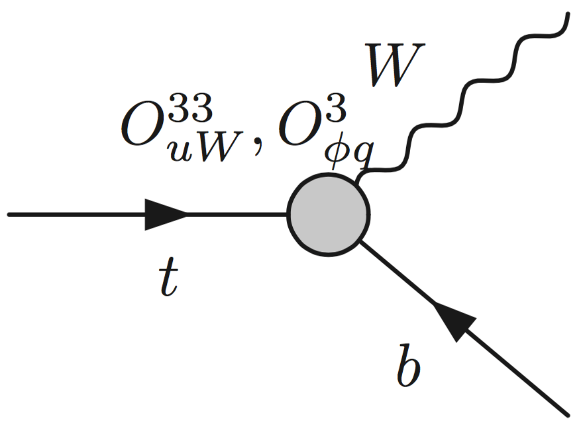
$$\mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW^-_\mu + \frac{g}{\sqrt{2}}\bar{b}i\sigma^{\mu\nu}(g_L P_L + g_R P_R)tW^-_\mu + h.c.$$

Cao, Wudka & Yuan 0704.2809

Aguiliar-Saavedra 0803.3810

SUMMARY: 3 constrainable operators in single top production

Decay observables



$$F_0 = \frac{m_t^2}{m_t^2 + 2M_W^2} - \frac{4\sqrt{2}C_{uW}^{33}v^2}{\Lambda^2 V_{tb}} \frac{m_t M_W (m_t^2 - M_W^2)}{(m_t^2 + 2M_W^2)^2}$$

$$F_L = \frac{2M_W^2}{m_t^2 + 2M_W^2} + \frac{4\sqrt{2}C_{uW}^{33}v^2}{\Lambda^2 V_{tb}} \frac{m_t M_W (m_t^2 - M_W^2)}{(m_t^2 + 2M_W^2)^2}$$

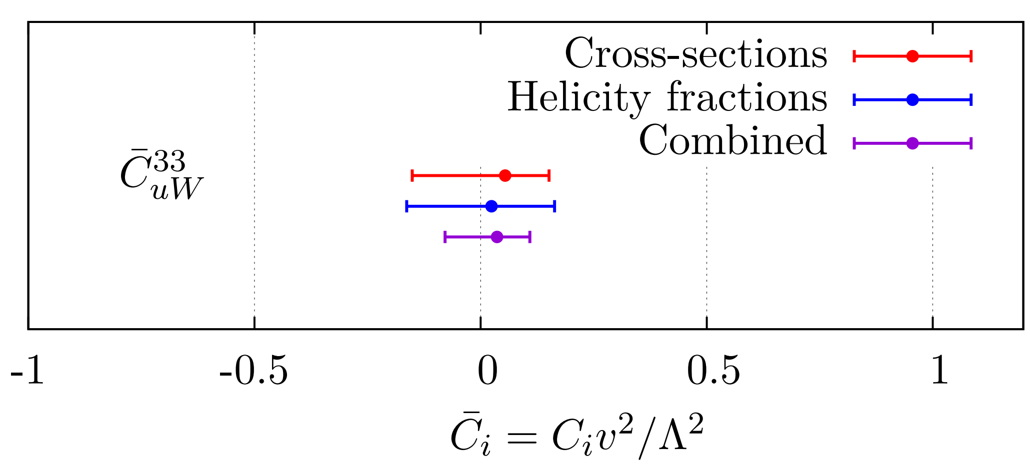
$$F_R \simeq 0$$

In SM $F_0 \approx 0.66, F_L \approx 0.33, F_R \approx 0$

Stable against higher-order corrections

Do angular observables give better bounds than cross-sections?

Czarnecki, Korner and Piclum 1005.2635

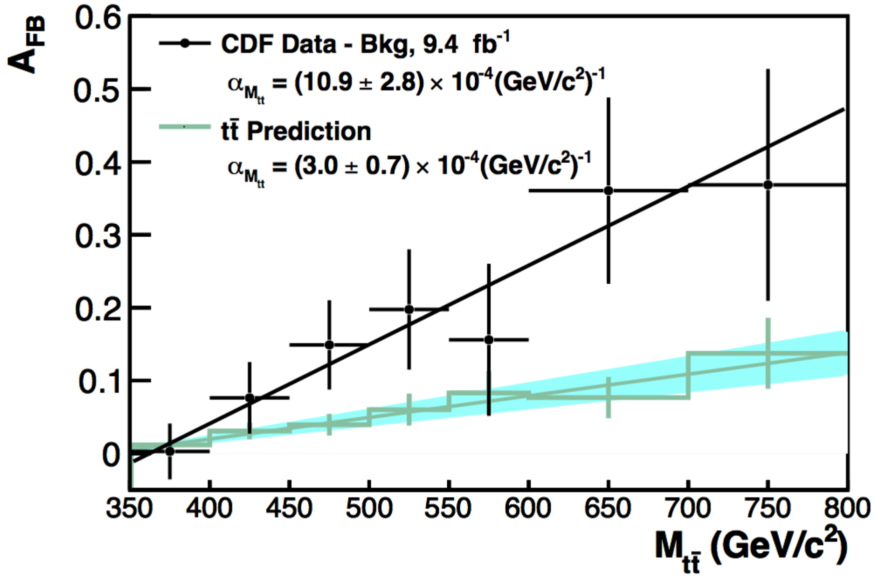


Completely different measurements …

…but similar precision

Benefits of a global analysis

Charge asymmetries

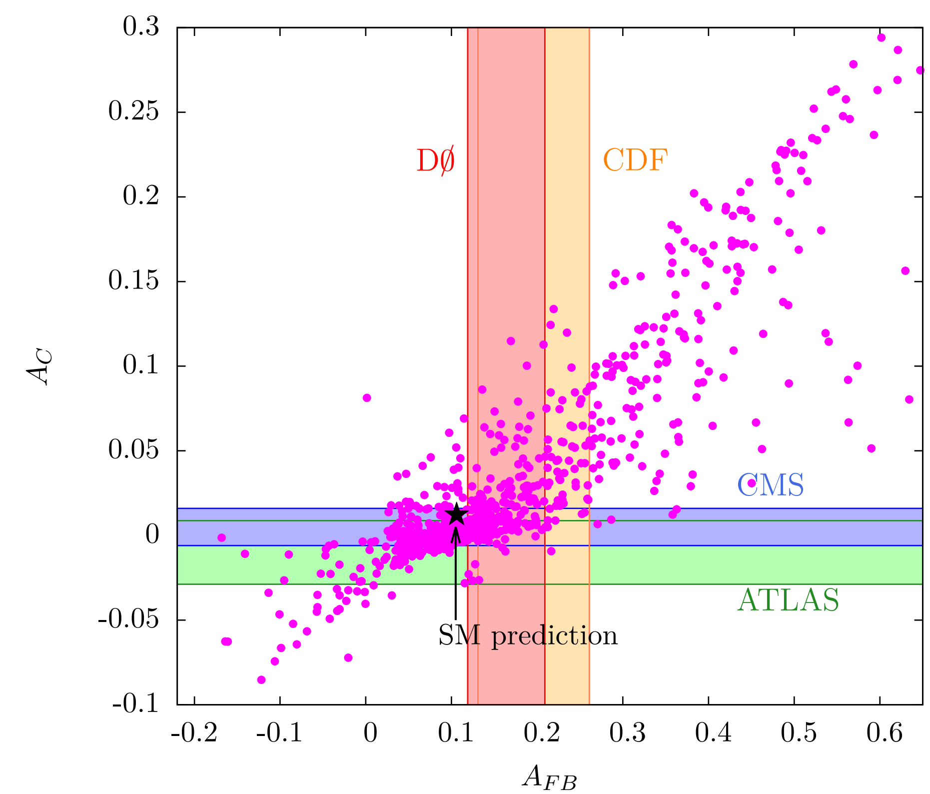


$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

A_{FB} (more or less) explained by large NNLO QCD

Czakon, Fiedler & Mitov, 1411.3007

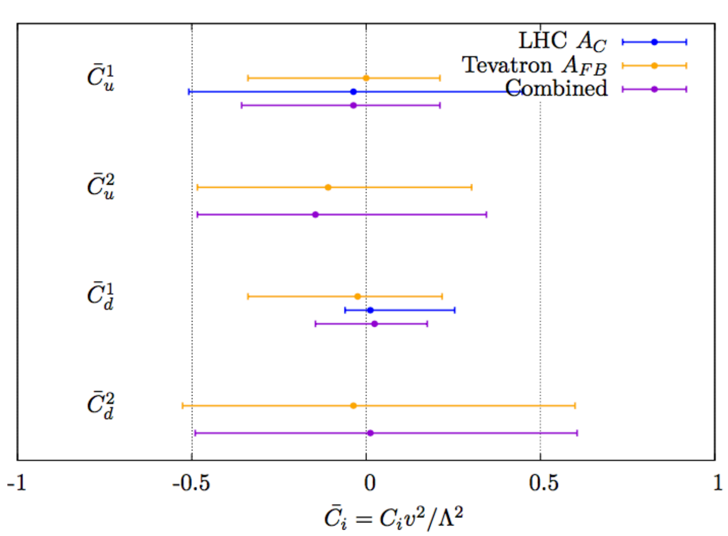
Is there any room for $\{C_i\}$?

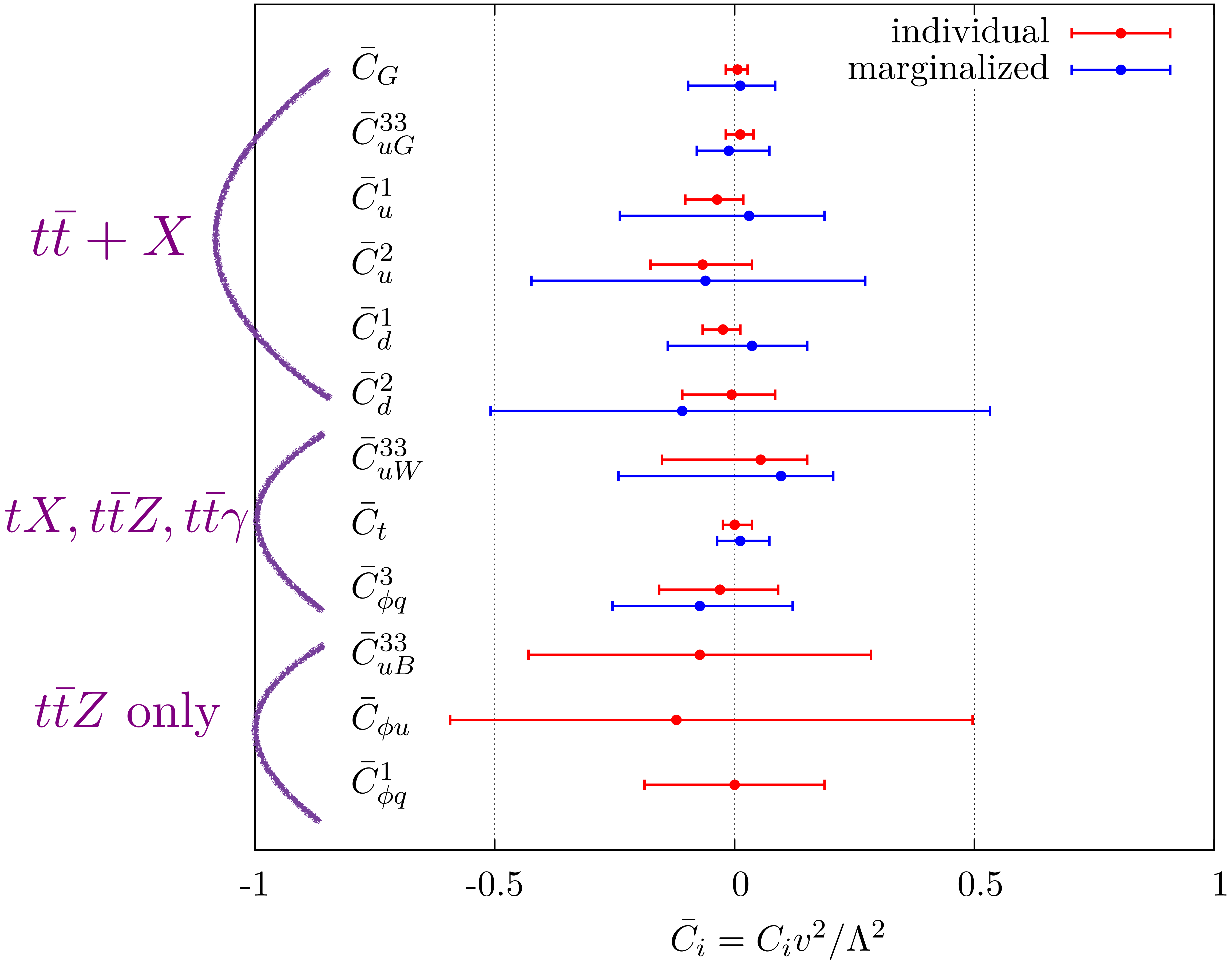


In EFT language: $$A_{FB} \sim (C_u^1 + C_d^1 - C_u^2 - C_d^2) \times \Lambda^{-2}$$

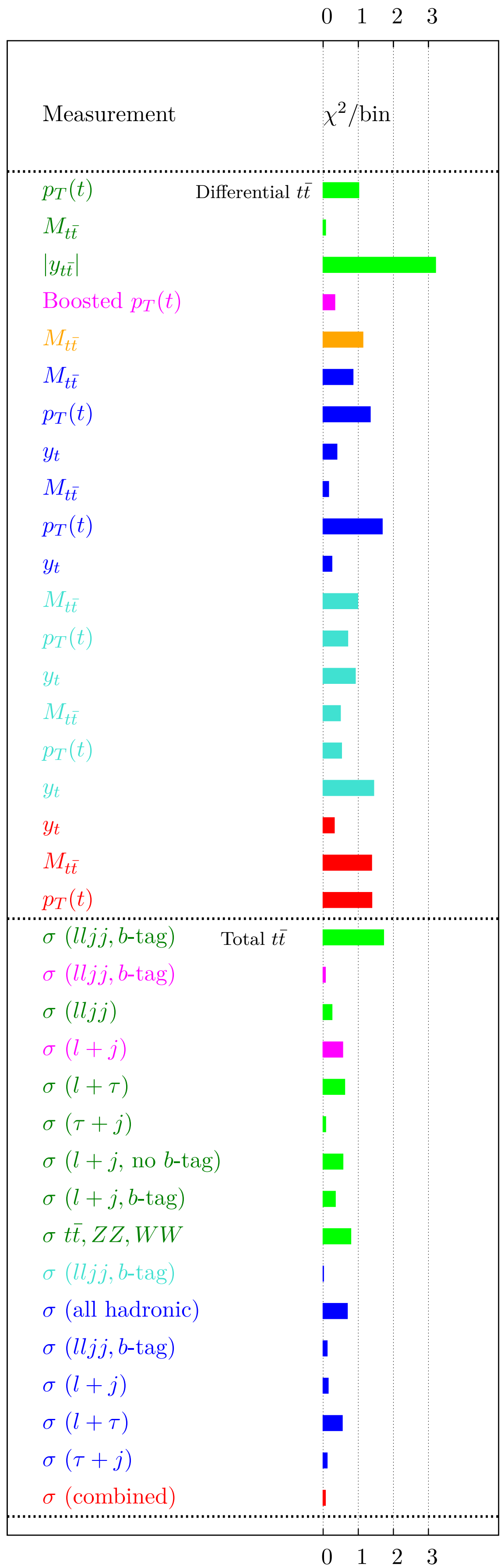
Zhang and Willenbrock 1008.3869

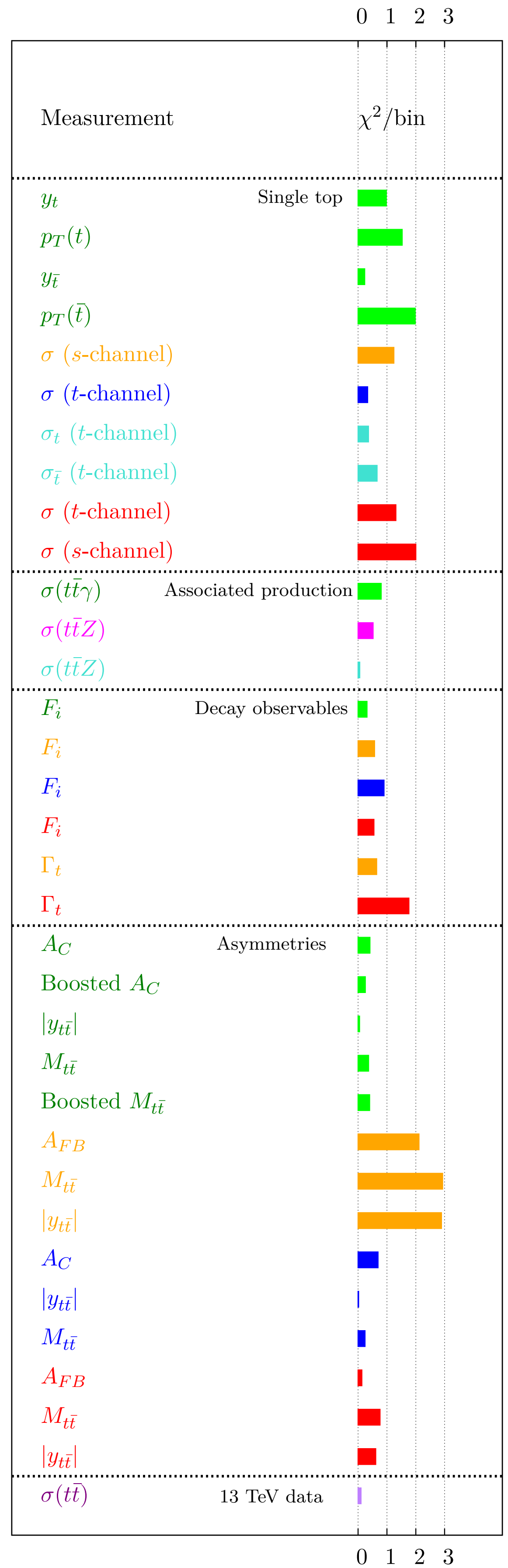
correlated with $$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$





individual
marginalized
$\bar{C}_G$
$\bar{C}_{uG}^{33}$
$\bar{C}_u^1$
$\bar{C}_u^2$
$\bar{C}_d^1$
$\bar{C}_d^2$
$\bar{C}_{uW}^{33}$
$\bar{C}_t$
$\bar{C}_{\phi q}^3$
$\bar{C}_{uB}^{33}$
$\bar{C}_{\phi u}$
$\bar{C}_{\phi q}^1$
$t\bar{t} + X$
$tX, t\bar{t}Z, t\bar{t}\gamma$
$t\bar{t}Z$ only
-1
-0.5
0
0.5
1
$\bar{C}_i = C_i v^2/\Lambda^2$





Run I SUMMARY

SM a good fit everywhere?

No significant deviations at this stage

BUT

Early days in the LHC programme

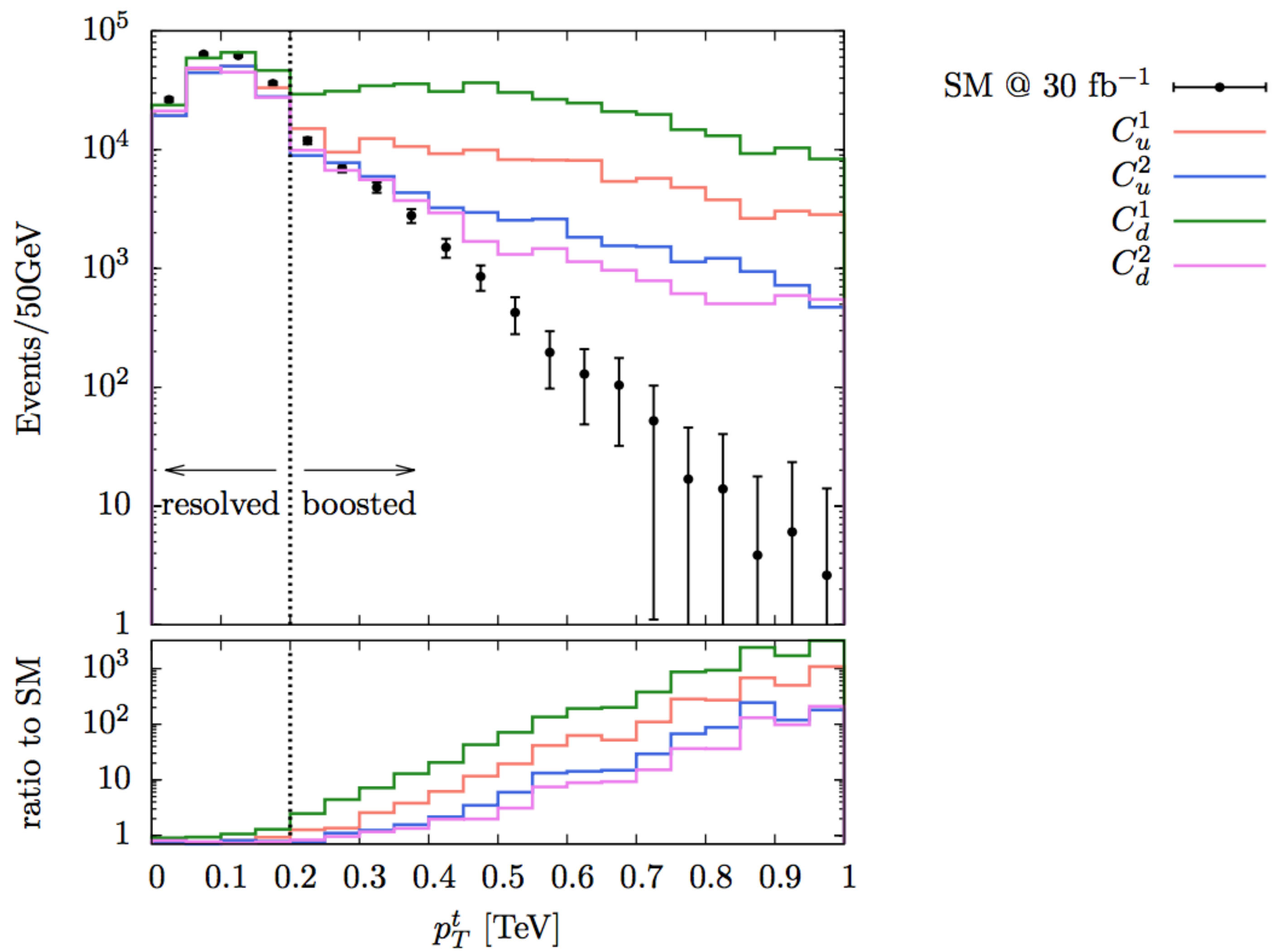
Many measurements statistics dominated

Many more measurements to come!

The future

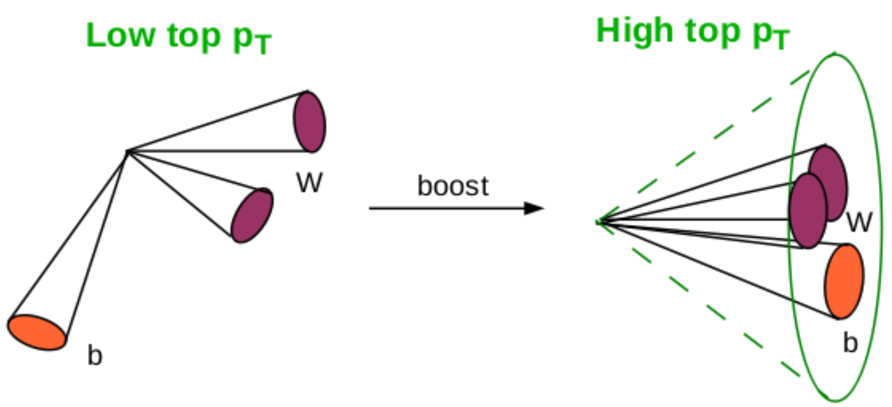
Based on 1607.04304

Limits generally poor: how can we improve?

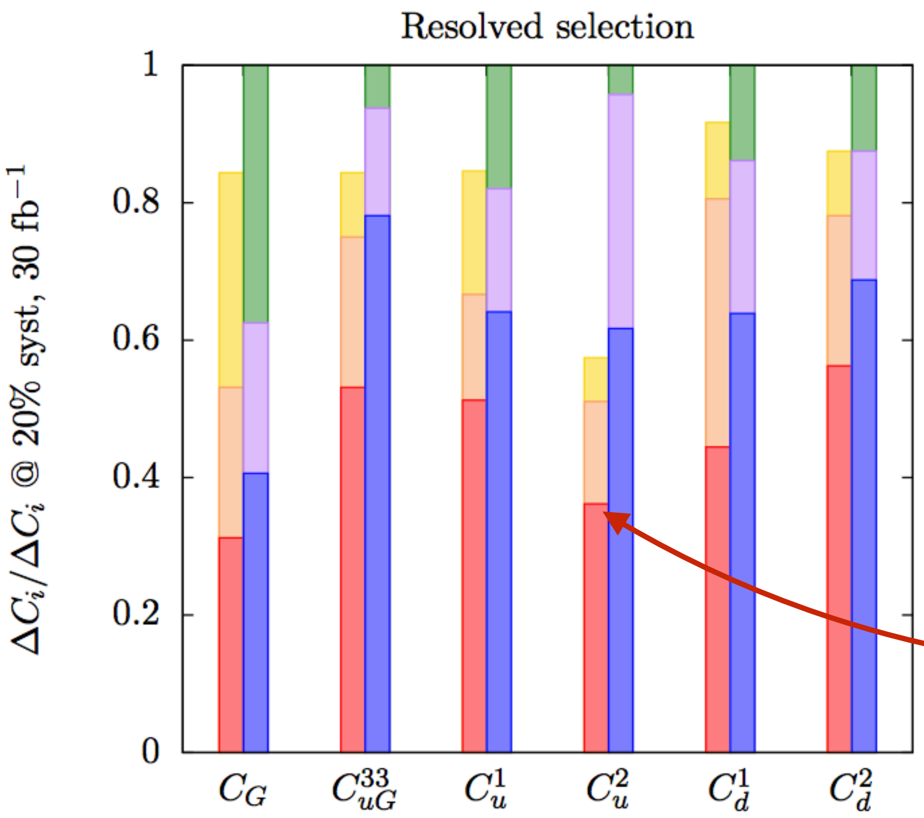


Most sensitivity to tails

Target this region of phase-space!



The future



30 fb^{-1}

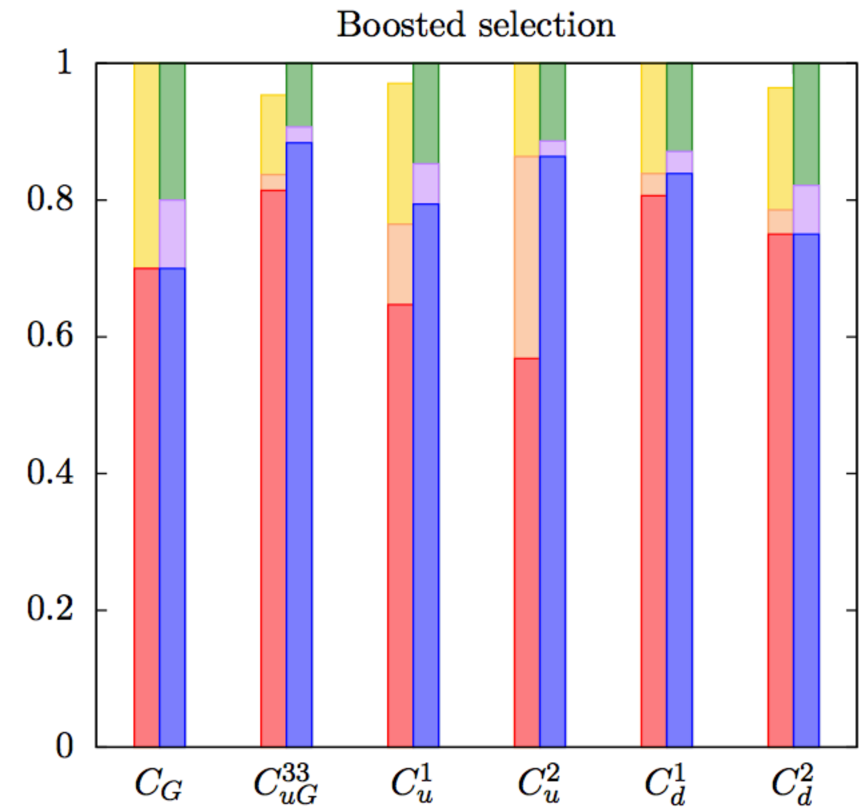
300 fb^{-1}

3000 fb^{-1}

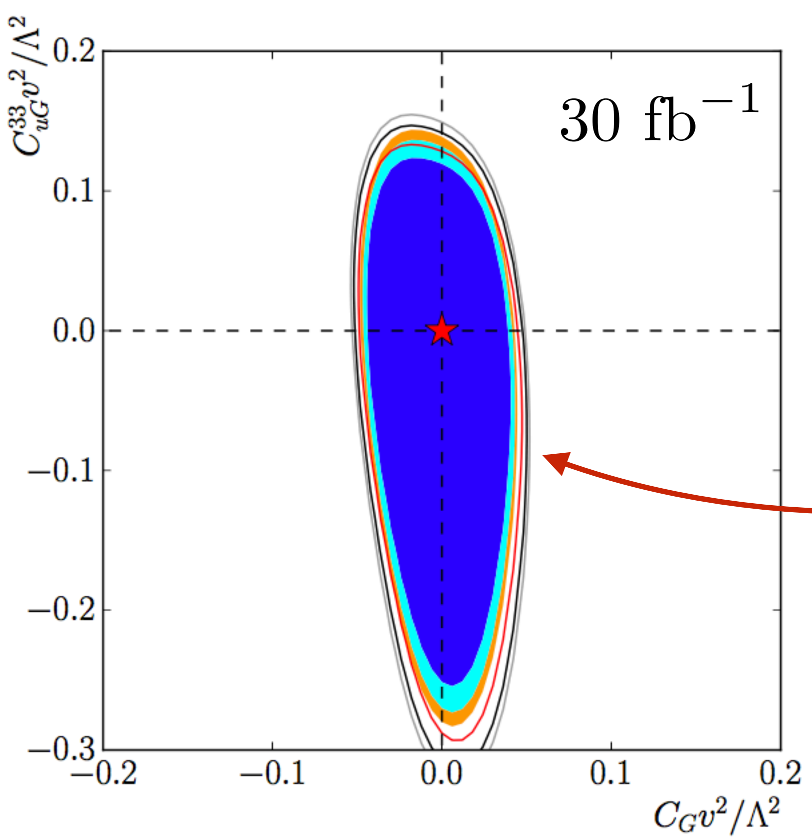
Limits from low-energy phase space get better and better

Up to 70% improvement possible!

Boosted constraints saturated by systematics



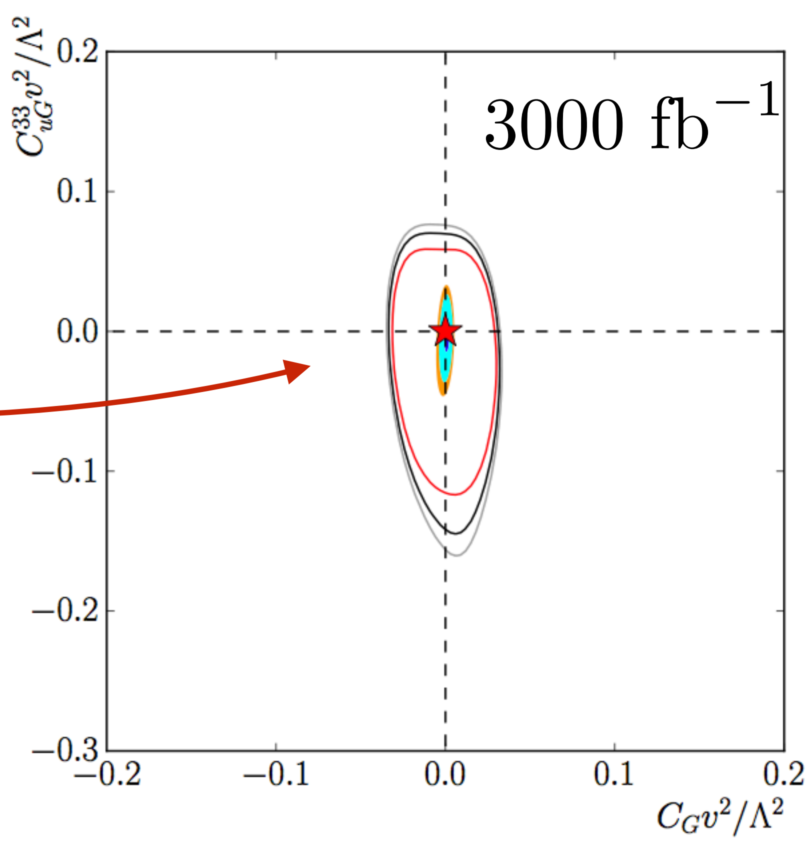
The future



Lines: NLO theory uncertainties

Contours: NO theory uncertainties

Little gain in improving theory description currently



But it will eventually come to dominate

The bigger picture

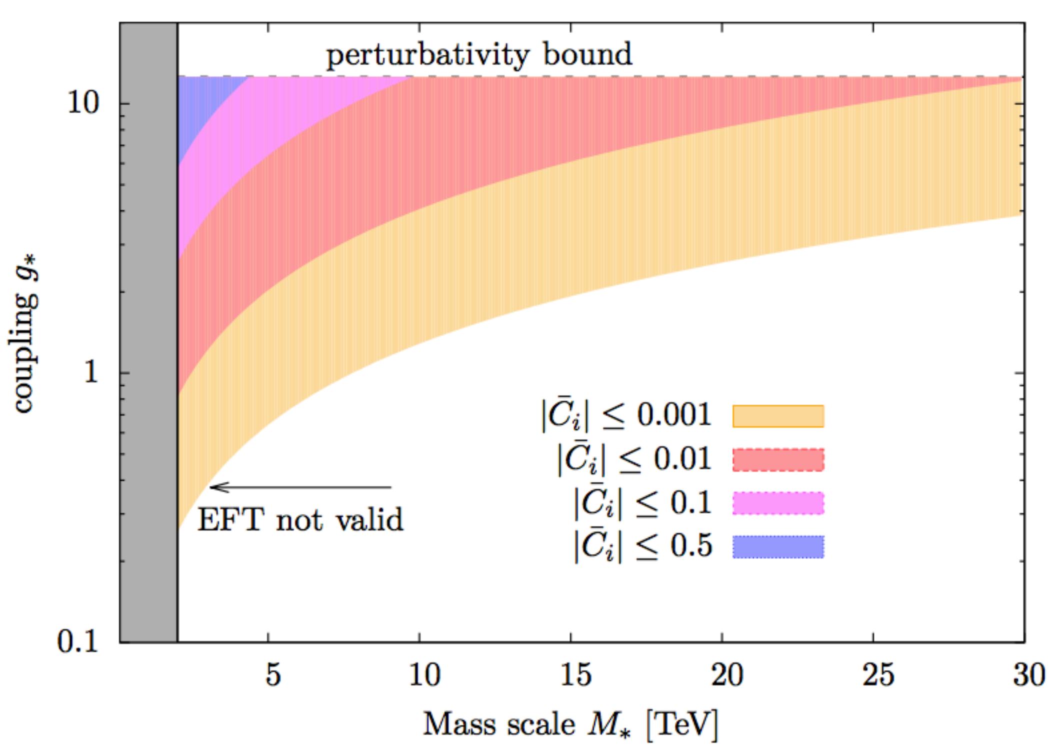
What do these projections actually mean for new physics?

Simplest case:

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

Current constraints not very helpful

Early days for the LHC



Summary

- Top quark physics in a renaissance period
- Vast amounts of data already available for global fit
- No convincing deviations from SM predictions

BUT

- Current constraints relatively weak
- Improvements can be made, with work on both sides
- LHC is a long-term project, nowhere near full potential

The Professor method

Buckley et al. 0907.2973

Brief detour: MC tuning

- Every MC event generator comes with many free parameters that must be tuned in order to describe the data

Different approaches:

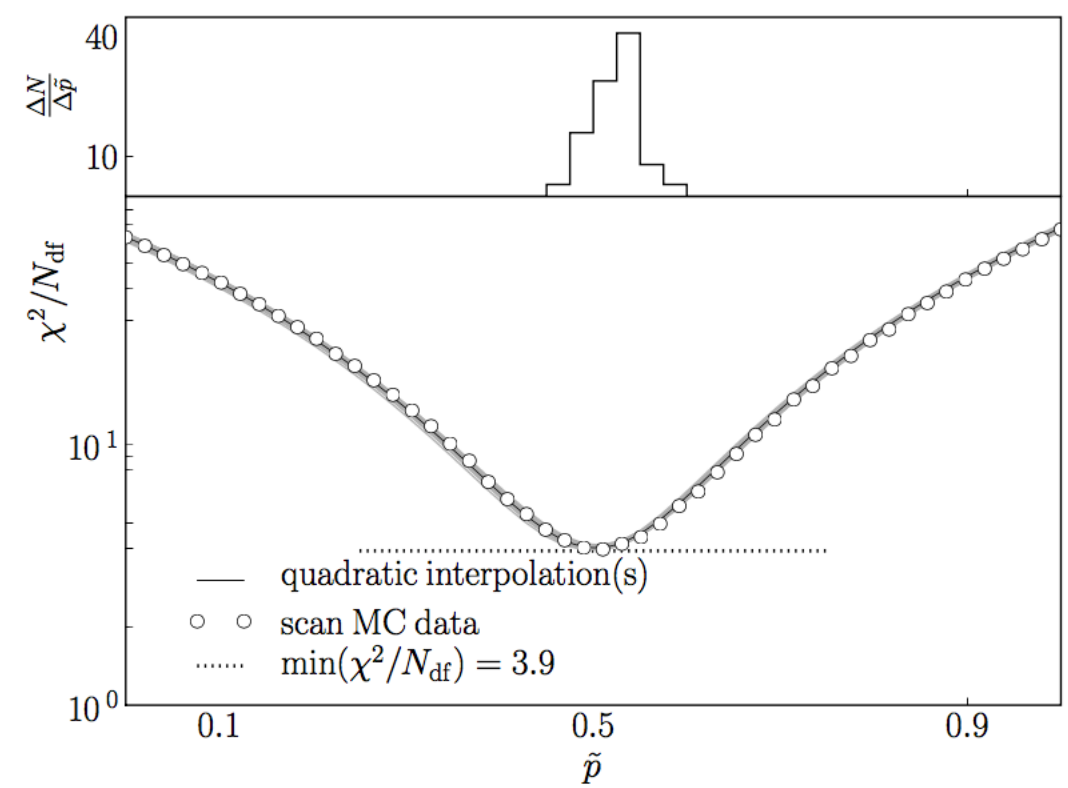
Tune by hand (!?)

Brute force computation (N^D)

Parameterisation-based tuning:

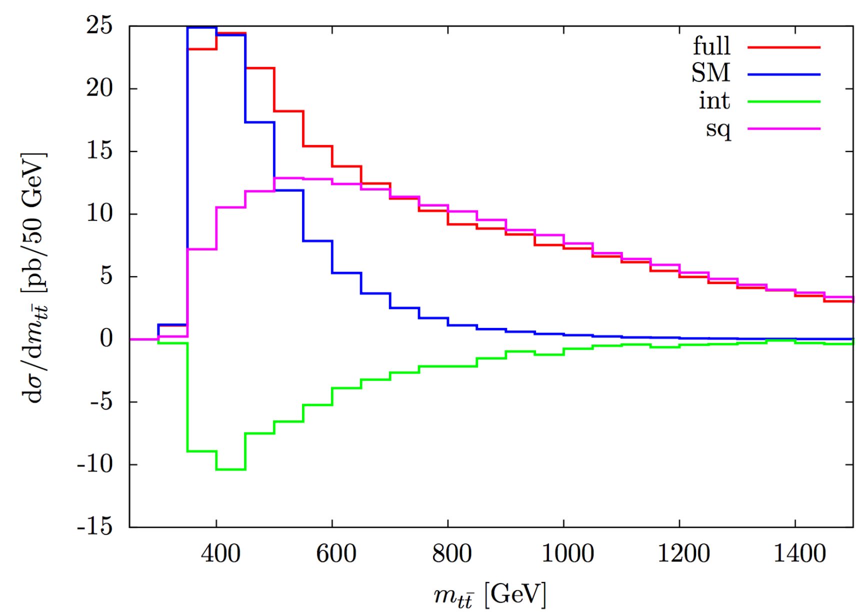
Parameterise MC response

Fit to data ⟶ Optimal ‘tune’



Assessing the validity of the EFT

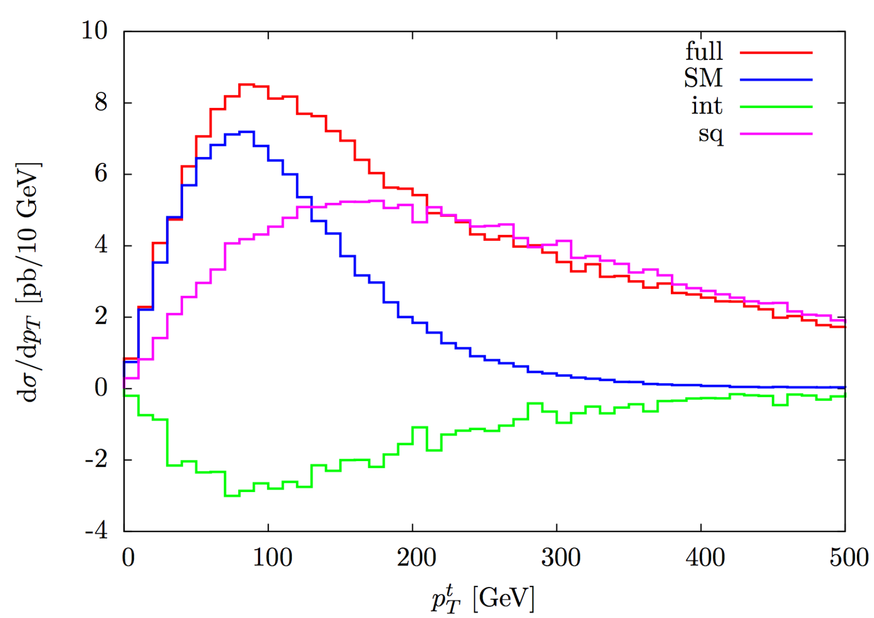
$$|\mathcal{M}_{\rm full}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\Re\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm D6} + |\mathcal{M}_{\rm D6}|^2$$



$$\mathcal{O}(\frac{1}{\Lambda^2}) \qquad \mathcal{O}(\frac{1}{\Lambda^4})$$

But so is $2\Re\mathcal{M}^*_{\rm D8}\mathcal{M}_{\rm SM}$

Subtract it off??



Ensures controlled expansion

BUT

Unphysical effects in distributions

Ultimately a model dependent question

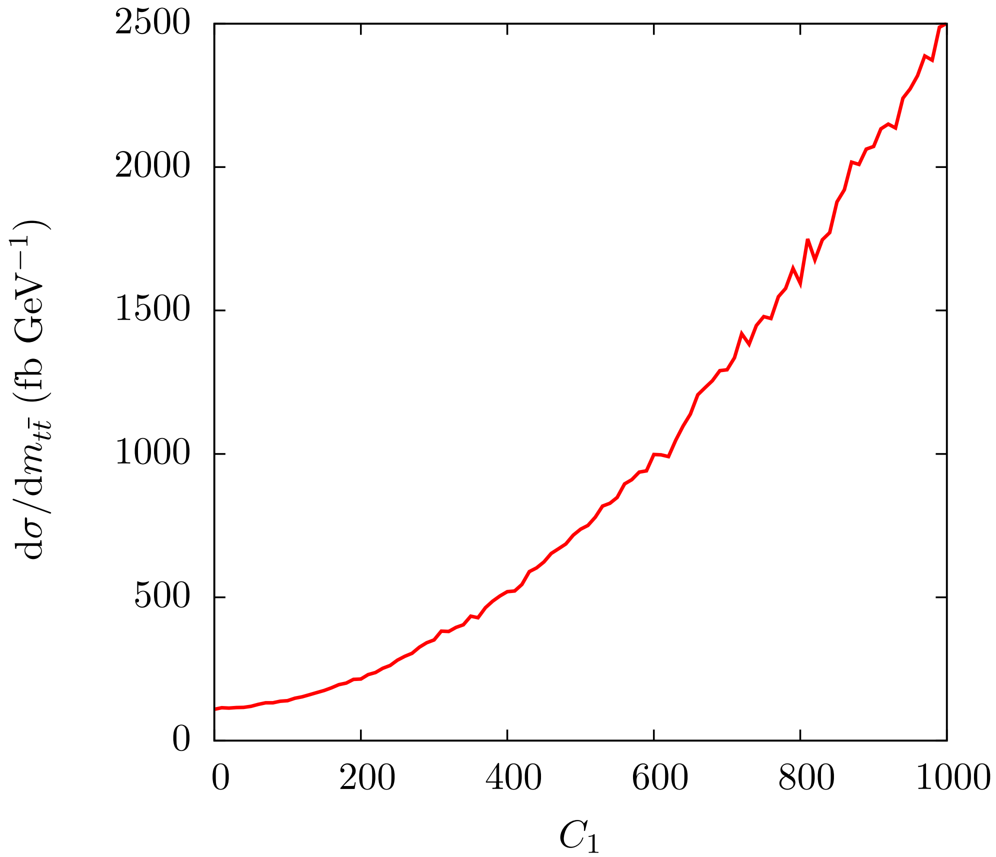
see also Biekotter, Brehmer, Plehn 1602.05202

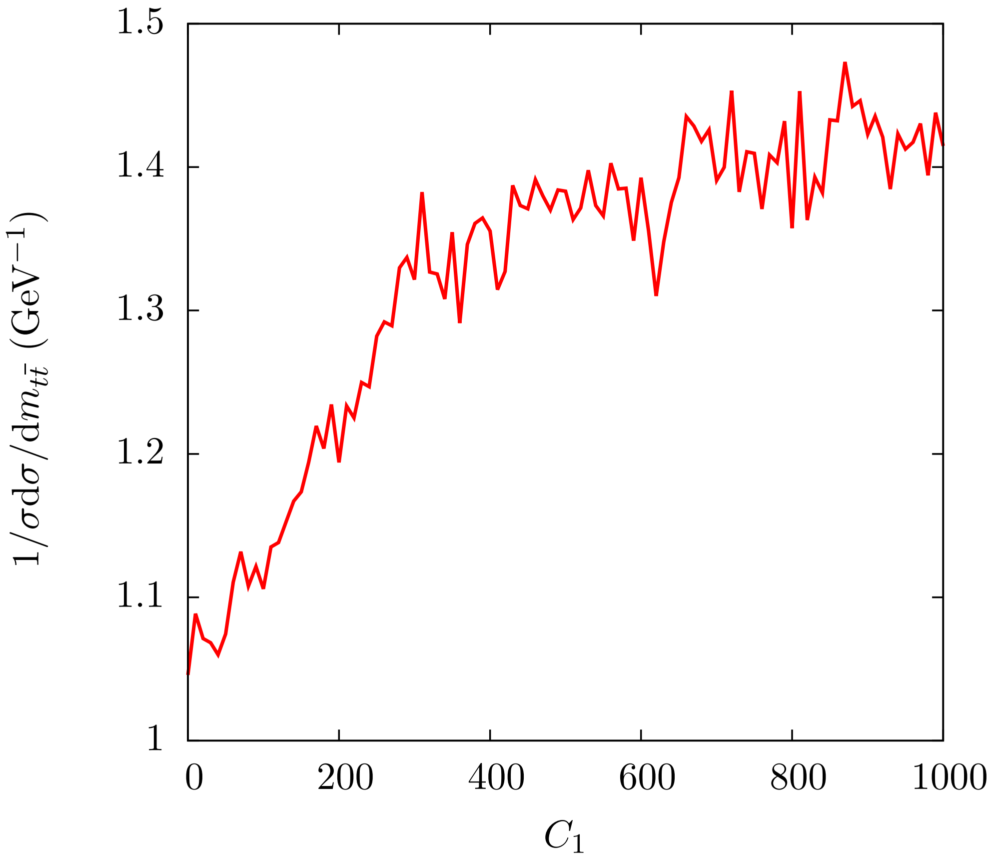
Brehmer et al. 1510.03443

Contino et al. 1604.06444

Backup: Interpolation order

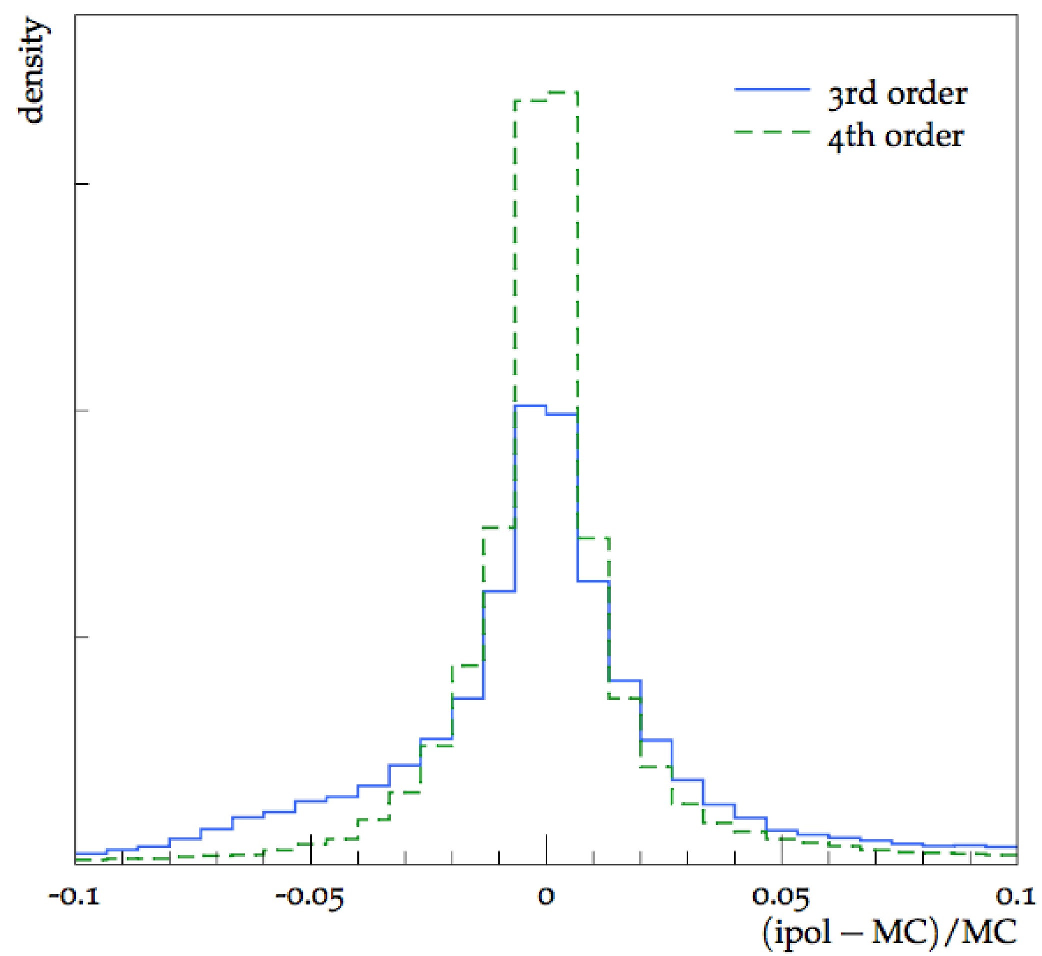
$$\frac{1}{\sigma(C_i)}\frac{d\sigma(C_i)}{dX} \sim \frac{1}{f + gC_i + hC_i^2} \times (f' + g'C_i + h'C_i^2)$$

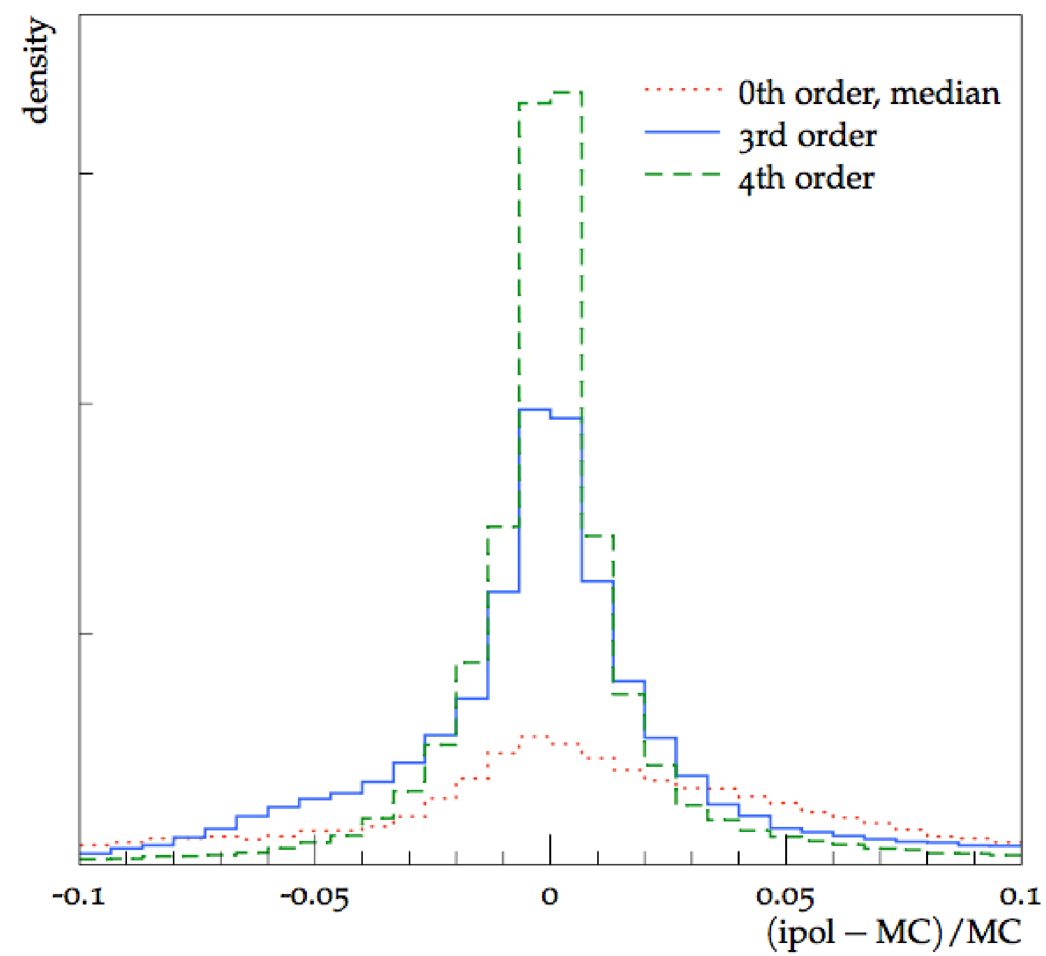




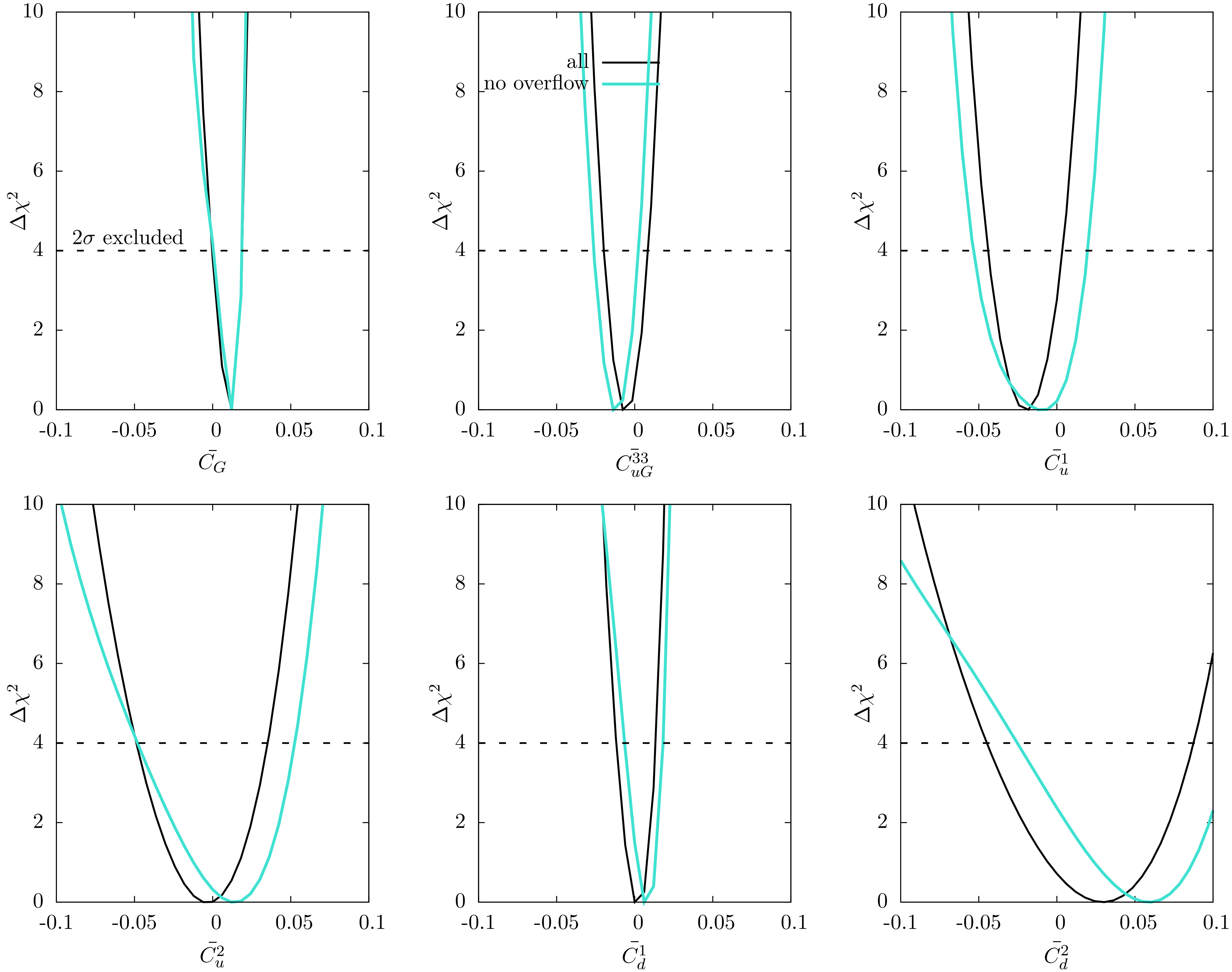
Normalised distributions: Complicated behaviour

Backup: Interpolation error





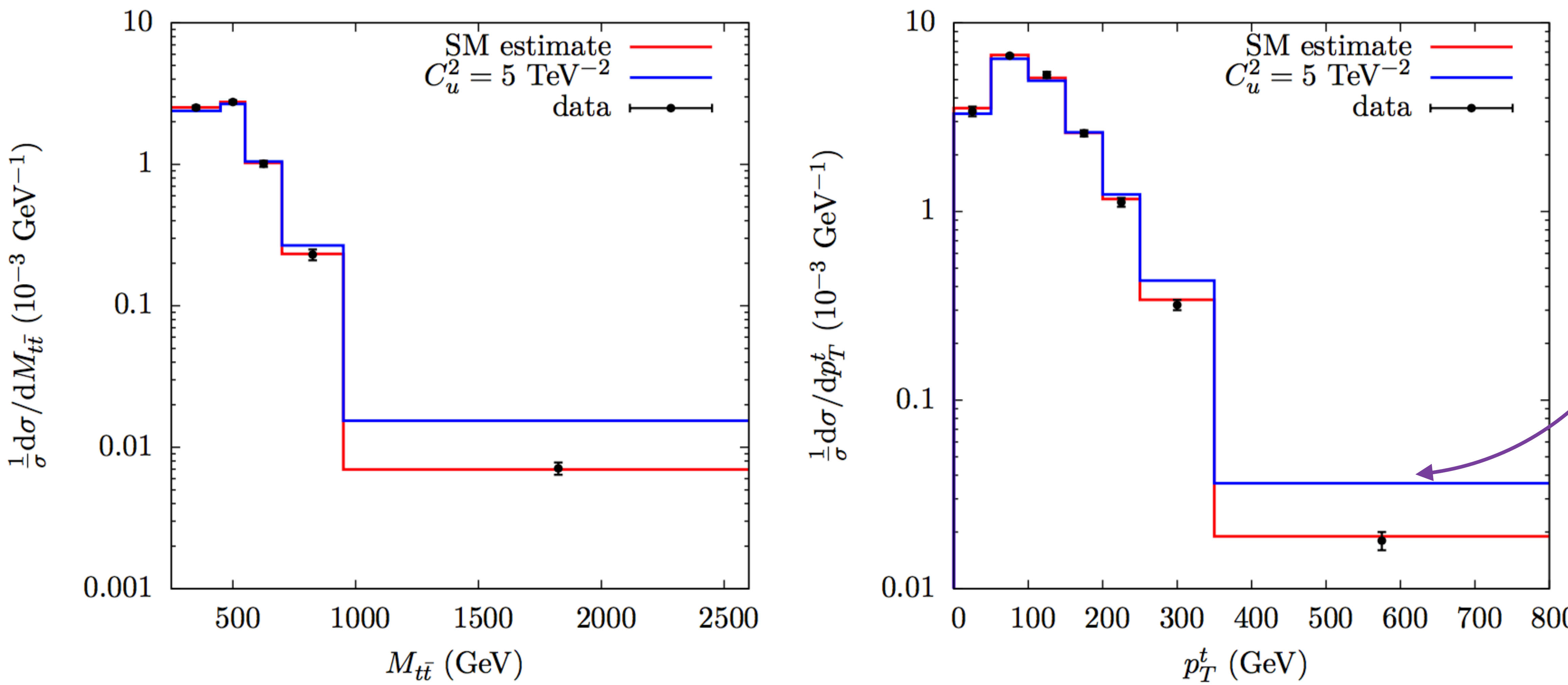
Assessing the validity of the EFT



Assessing the validity of the EFT

$$\frac{g_*^2 v^2}{\Lambda^2} < 1 \quad \text{and} \quad \frac{E^2}{\Lambda^2} < 1$$ ← Overflow bins can be a problem…

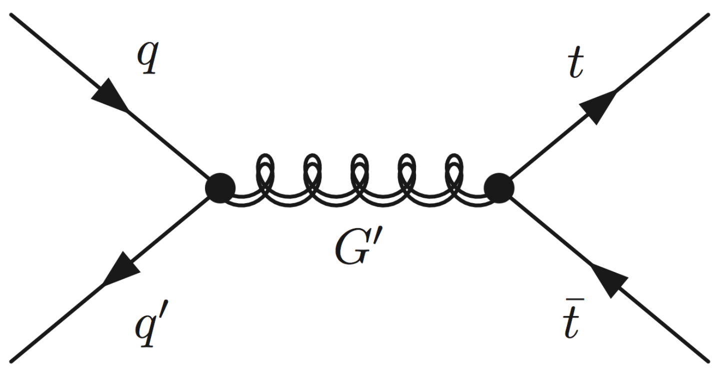
No control over scales



Assessing the validity of the EFT

Compare to a few "models"

Axigluon



Constraints on c_i map to limits on $M_{G'}$

$$M_{G'} > 1.4 \text{ TeV}$$

Case of W' in single top is analogous: similar bound

Masses probed by measurements in fit-> not valid constraints*

Tevatron vs. LHC