Global fit of top quark EFT to data

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arXiv:1506.08845

Higgs Effective Field Theories workshop, Chicago, November 2015

The Standard Model EFT

Why bother with Effective Field Theory?

- All measurements more or less consistent with SM
- Resurgence of model-independent frameworks to go beyond SM

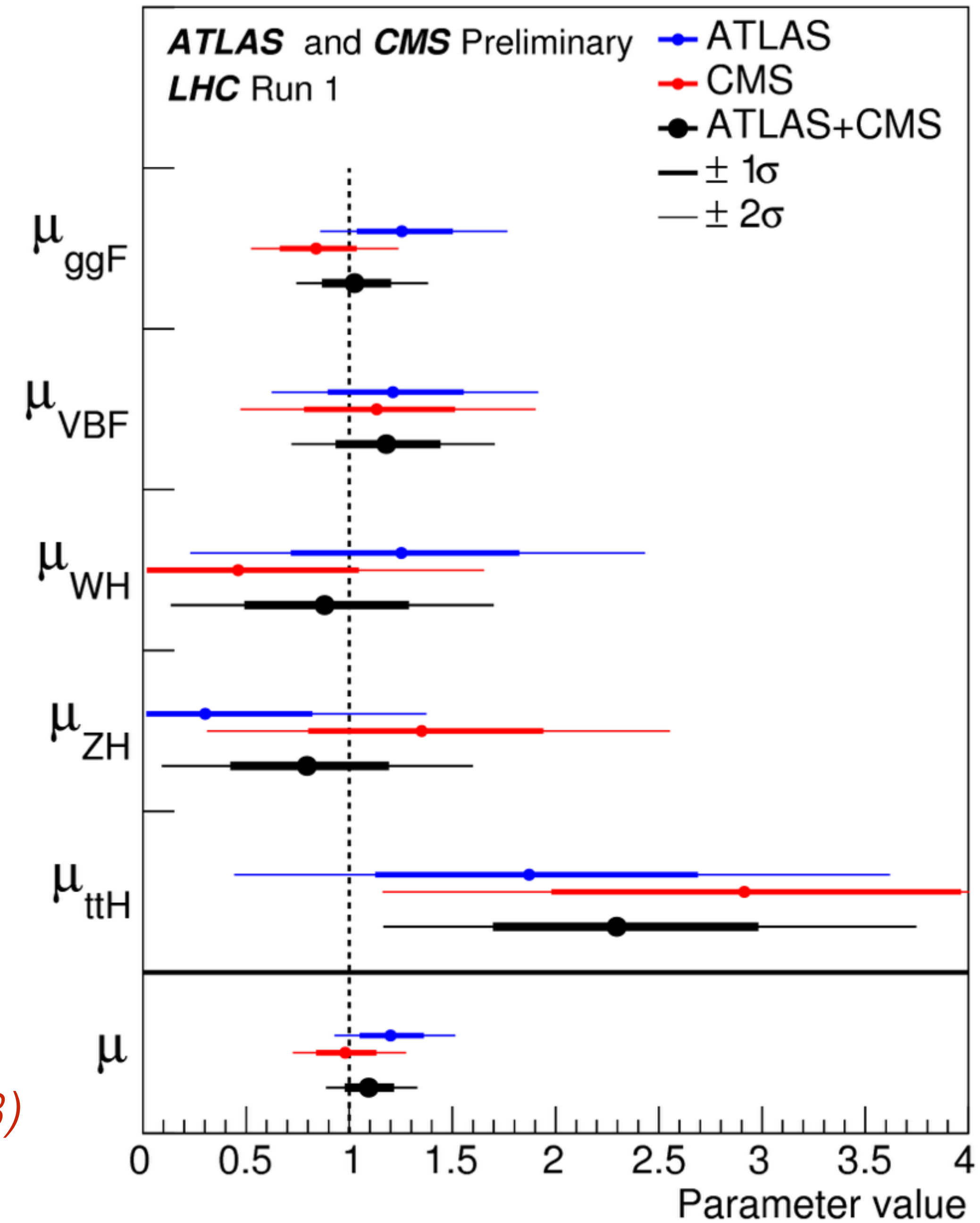
(κ framework, anomalous couplings, form factors…)

- Merits of EFT: completely general, can be matched to UV completions, radiative corrections calculable etc.
- If there is new physics, looks like it decouples

$$\mathcal{O}^{d_i}(E) = \mathcal{O}^{d_i}(\Lambda)(E/\Lambda)^{d_i-4}$$

Wilson, Rev. Mod. Phys. 55, 583 (1983)

Appelquist & Carazzone, Phys. Rev. D11, 28565 (1973)



Any decoupled new physics (at high scale) = A higher-dimensional operator (at low scale)

The Standard Model EFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i(G^a_\mu, W^I_\mu, B_\mu, \Phi, q_L, u_R, d_R, l_L, e_R) + \mathcal{O}(\Lambda^{-4})$$

see e.g.

Gripaios & Sutherland, 1309.7822

Hayreter & Valencia, 1304.6976

Henning, Lu & Murayama, 1412.1837

Alonso, Jenkins, Manohar & Trott 1312.2014

Buchalla, Cata & Krause 1312.5624

Chiang & Huo 1505.06334

Gupta, Pomarol & Riva 1405.0181

Aguilar, Bouzas, Larios, 1509.06431

Ellis, Sanz & You 1410.7703

Lehman 1410.4193

Corbett, Eboli, Goncalves, Gonzalez-Fraile, Plehn & Rauch 1505.05516

Englert & Spannowsky 1408.5147

Pierce, Thaler & Wang hep-ph/0609049

Djouadi 1208.3436

Efrati, Falkowski & Soreq 1503.07872

Wells & Zhang 1406.6070

de Blas, Chala & Santiago 1507.00757

Berthier & Trott 1508.05060

Degrande 1308.6323

Alonso, Gavela, Merlo, Rigolin & Yepes 1202.3305

Dawson, Lewis & Zeng 1409.6299

Delgado, Dobado, Herrero, Sanz-Cillero 1404.2866

Elias-Miró, Espinosa, Masso & Pomarol 1302.5661

Low, Lykken & Shaughnessy 1207.1093

Greiner, Willenbrock & Zhang 1104.3102

Contino, Ghezzi, Grojean, Muhlleitner & Spira 1303.3876

Grojean, Salvioni, Schlaffer & Weiler, 1312.3317

Azatov, Contino, Panico & Son 1502.00539

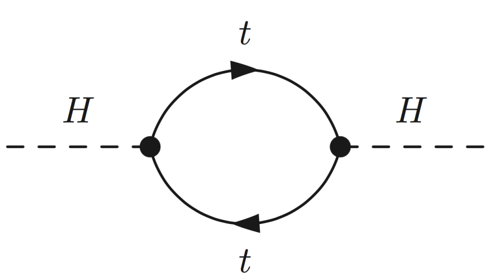
Gavela, Kanshin, Machado & Saa 1409.1571

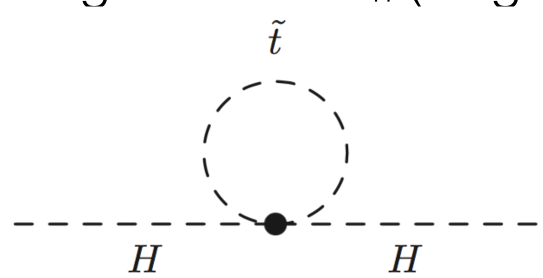
Why top EFT?

DIRECTLY:

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

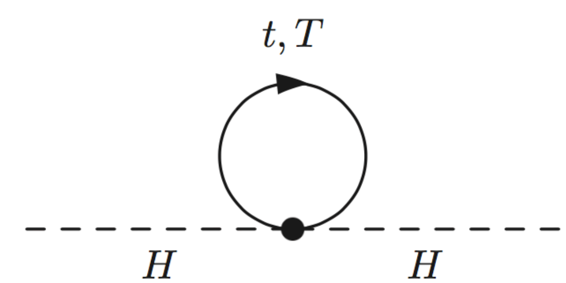
- SUSY: Top partners cancel UV divergences in m_h (if light enough)



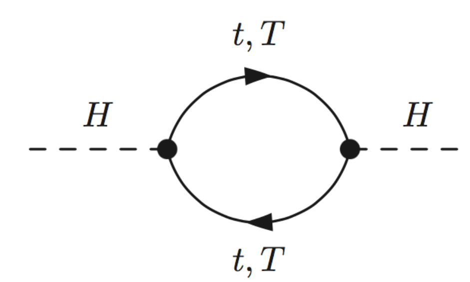


$$\delta m_H^2 = -\frac{|\lambda_F|^2}{8\pi^2}[\Lambda_{UV}^2 + ...]$$

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

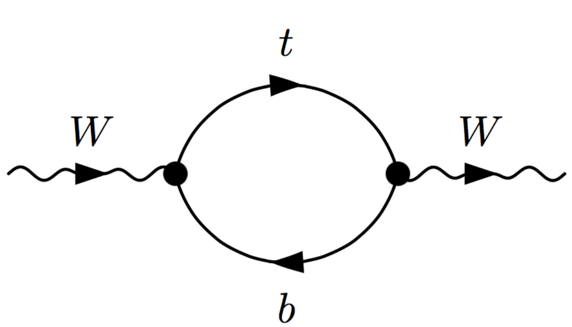


- Little Higgs and friends: Spin-1/2 top partners with large T-t mixing

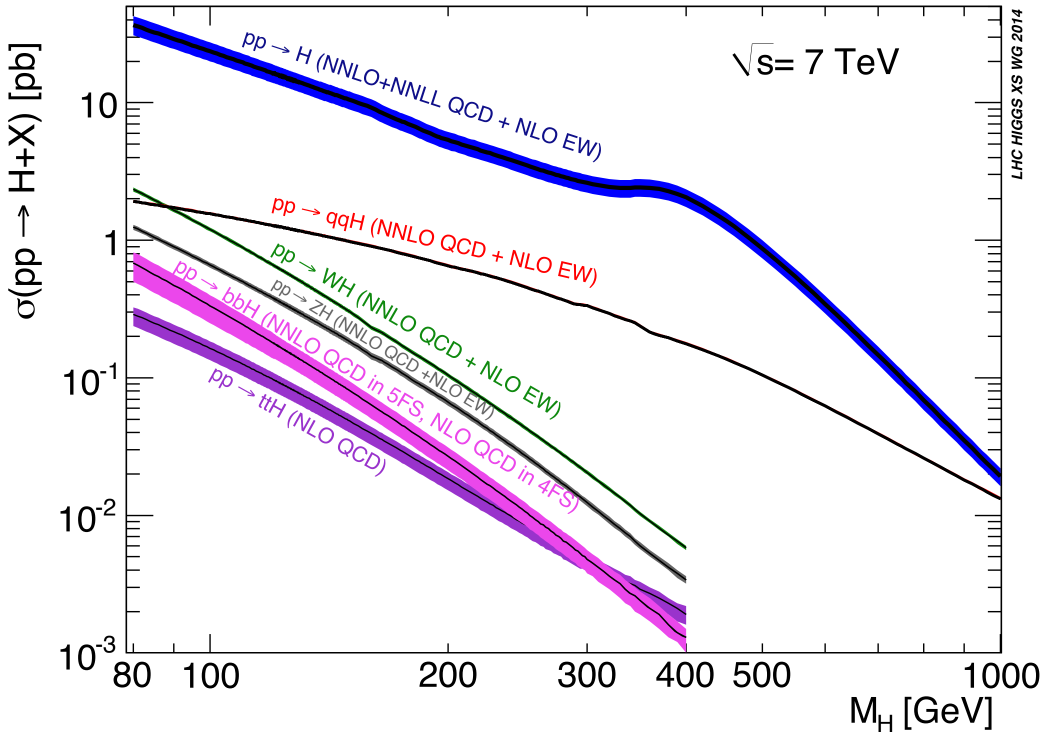


INDIRECTLY:

Large effects in electroweak measurements: ripe for deviations

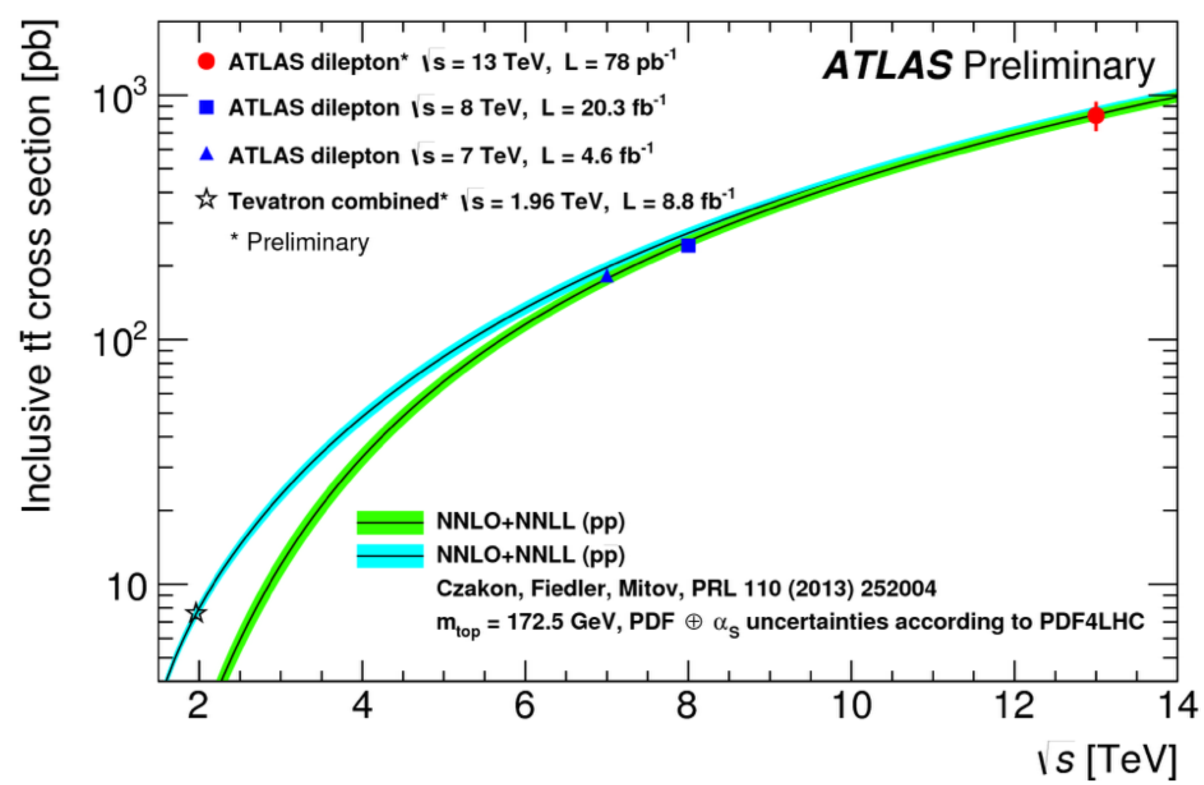


Why top EFT?



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!

EFT: Which Lagrangian best describes the currently available data?

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

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

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

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

$$O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi} W_{\mu\nu}^I$$
$$O_{uG} = (\bar{q}\sigma^{\mu\nu}\lambda^A u)\tilde{\phi} G_{\mu\nu}^A$$
$$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$$
$$O_{\tilde{G}} = f_{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$$
$$O_{\phi G} = (\phi^\dagger \phi) G_{\mu\nu}^A G^{A\mu\nu}$$

$$O_{\phi q}^{3} = i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$$
$$O_{\phi q}^{1} = i(\phi^\dagger D_\mu \phi)(\bar{q}\gamma^\mu q)$$
$$O_{uB} = (\bar{q}\sigma^{\mu\nu} u)\tilde{\phi} B_{\mu\nu}$$
$$O_{\phi u} = (\phi^\dagger i D_\mu \phi)(\bar{u}\gamma^\mu u)$$
$$O_{\phi \tilde{G}} = (\phi^\dagger \phi) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$$

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

Datasets

Dataset	$\sqrt{s}$ (TeV)	Measurements	Ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	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	1.96		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				

~200 independent* measurements: Need a fast, reliable fitting framework!

→ **PROFESSOR**

The PROFESSOR method

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 (!?)

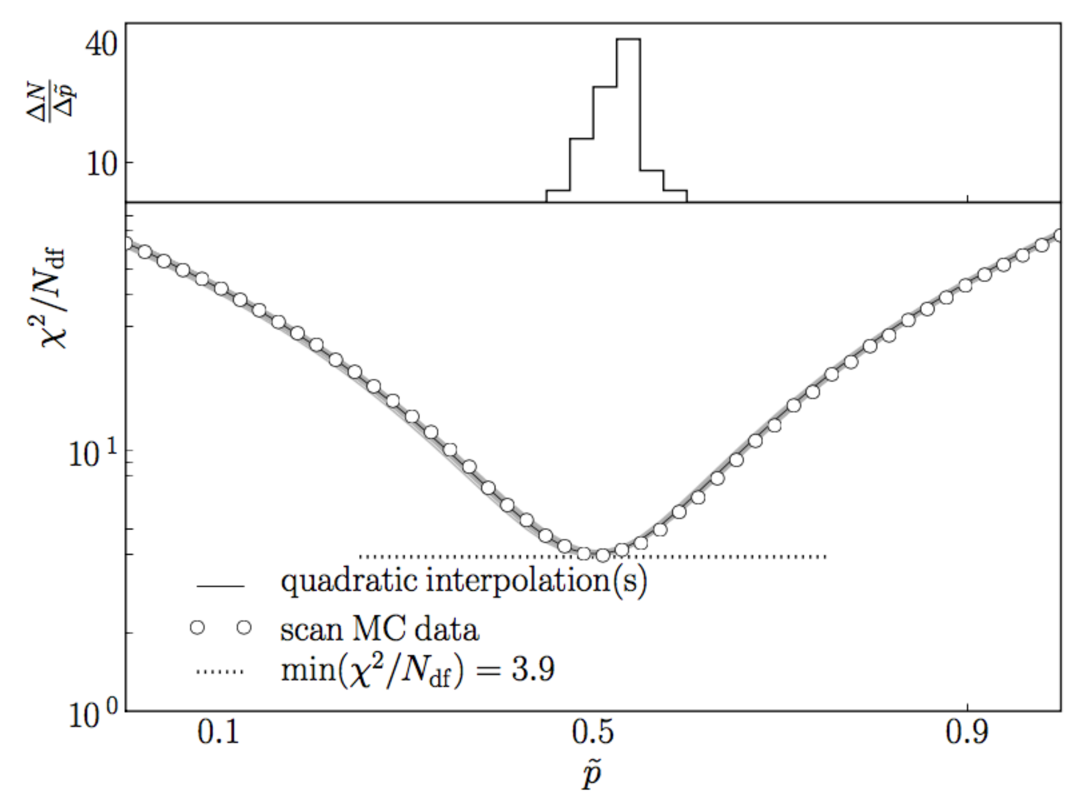
Brute force computation (N^D)

Parameterisation-based tuning:

Buckley et al. 0907.2973

Parameterise MC response

Fit to data ⟶ Optimal ‘tune’



The PROFESSOR 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

$$|\mathcal{M}_{\text{tot}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\Re\left\{\mathcal{M}_{\text{SM}}\mathcal{M}^*_{D6}\right\} + |\mathcal{M}_{D6}|^2 \longrightarrow f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i\leq j} \gamma_{ij}^b C_i C_j$$

should be small!

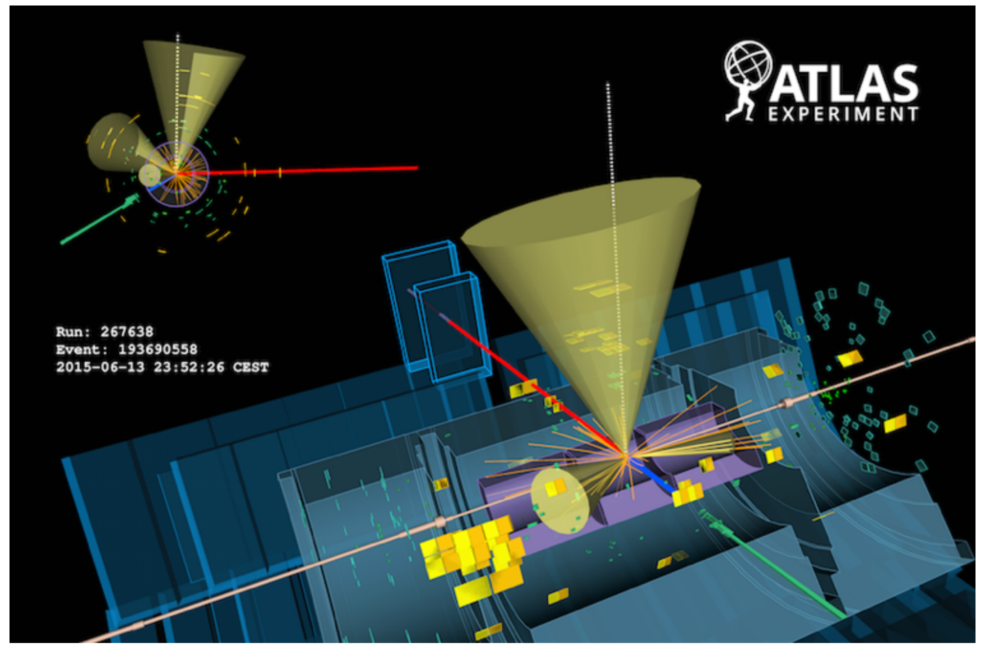
- Construct goodness-of-fit between $f_b(\{C_i\})$ and data

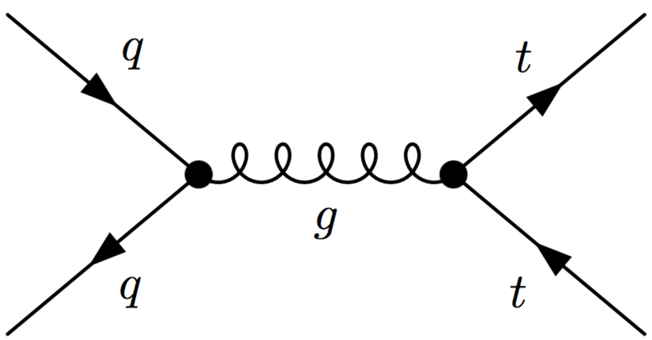
$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

- Minimise it!

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

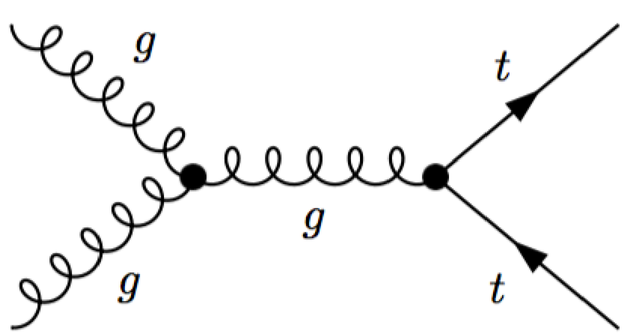
Top pair production

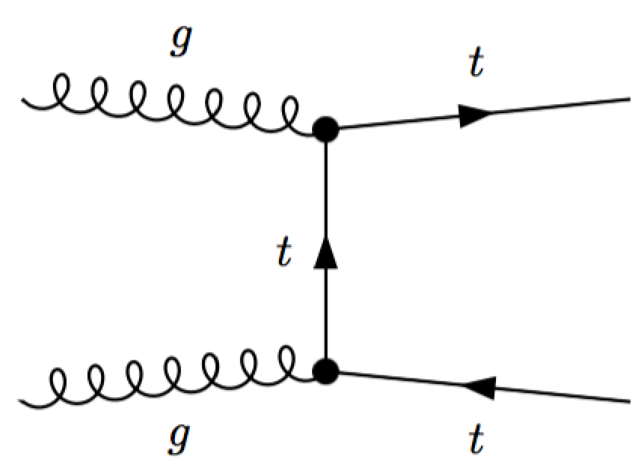


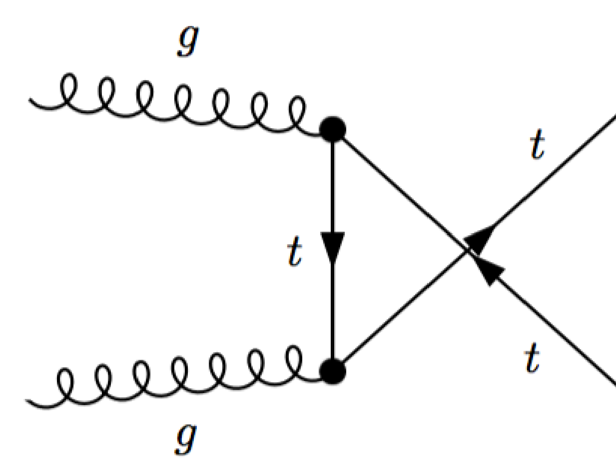


85% of Tevatron cross-section

~ 90% of LHC cross-section







Top pair production

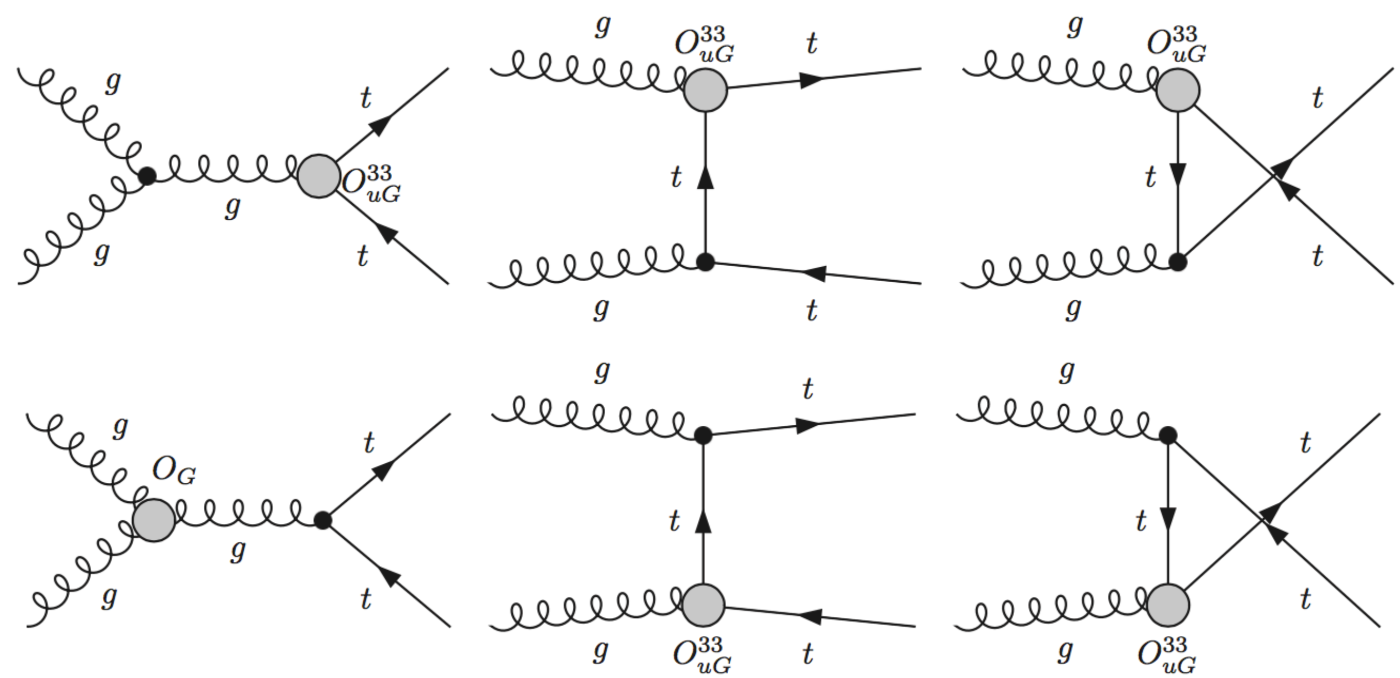
At dimension-six

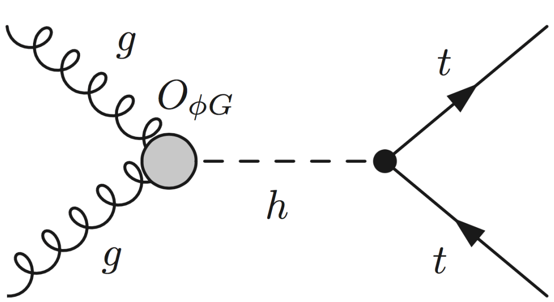
$$|\mathcal{M}_{\rm tot}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\Re\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{D6}\} + |\mathcal{M}_{D6}|^2$$

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

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

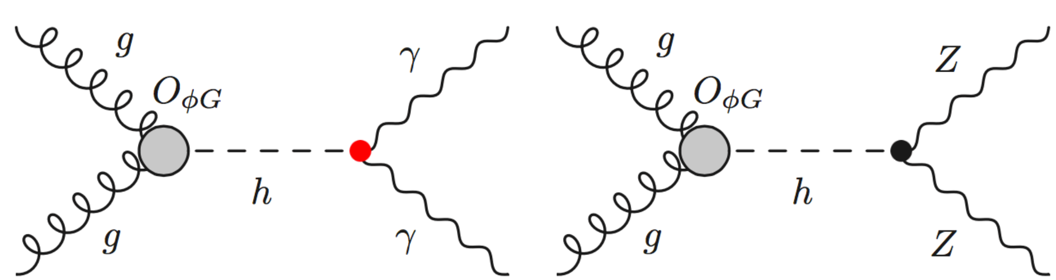
$$O_{\phi G} = \frac{1}{2}(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$$??



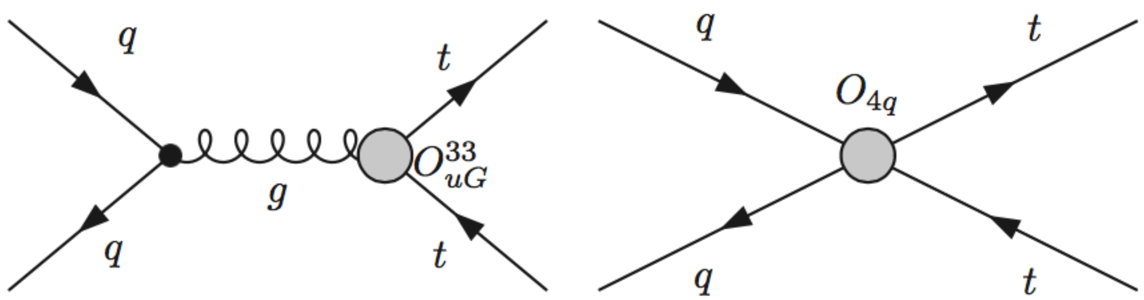


No constraint here, but can probe in Higgs physics

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

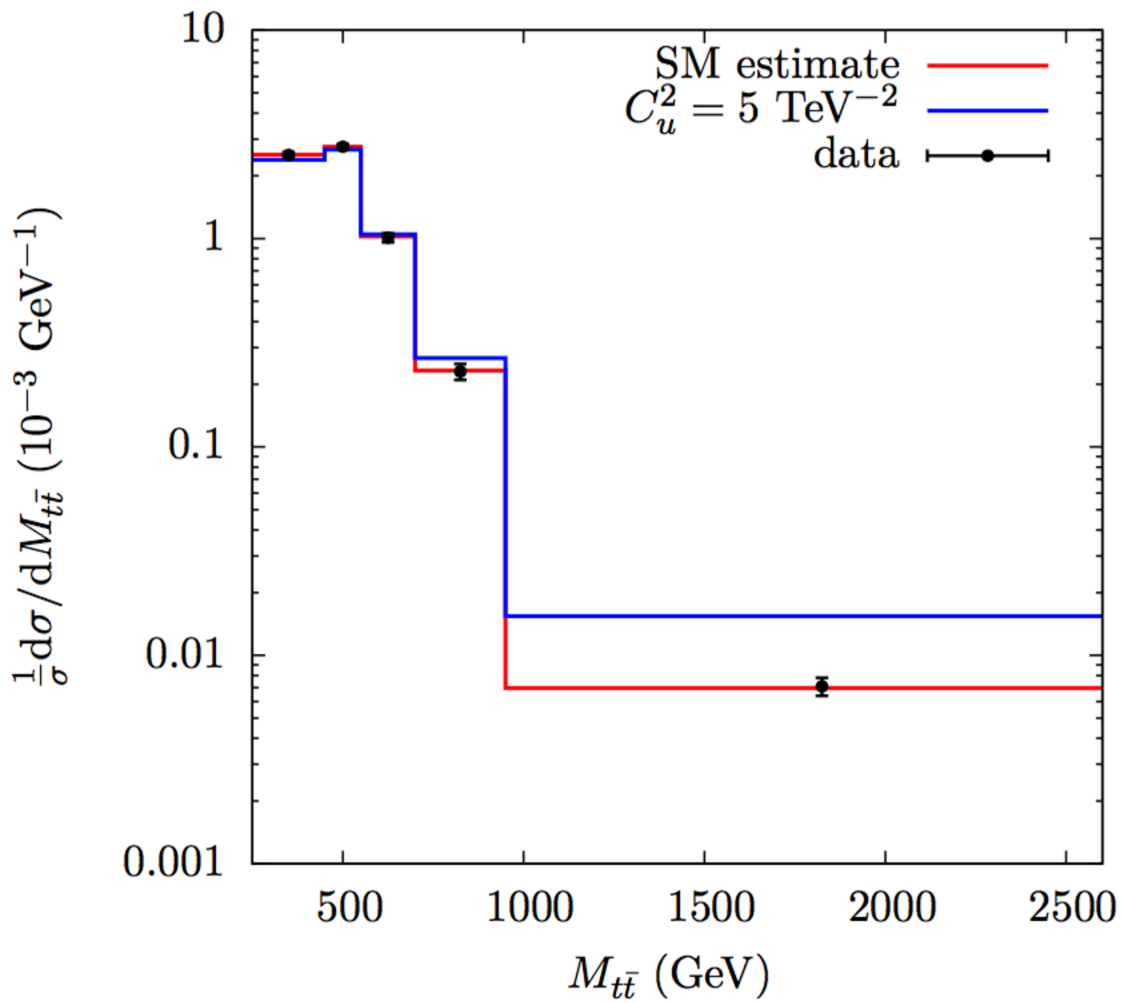
$$
\begin{aligned}
O^1_{qq} &= (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)\\
O^3_{qq} &= (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)\\
O_{uu} &= (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)\\
O^8_{qu} &= (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)\\
O^8_{qd} &= (\bar{q}\gamma_\mu T^A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

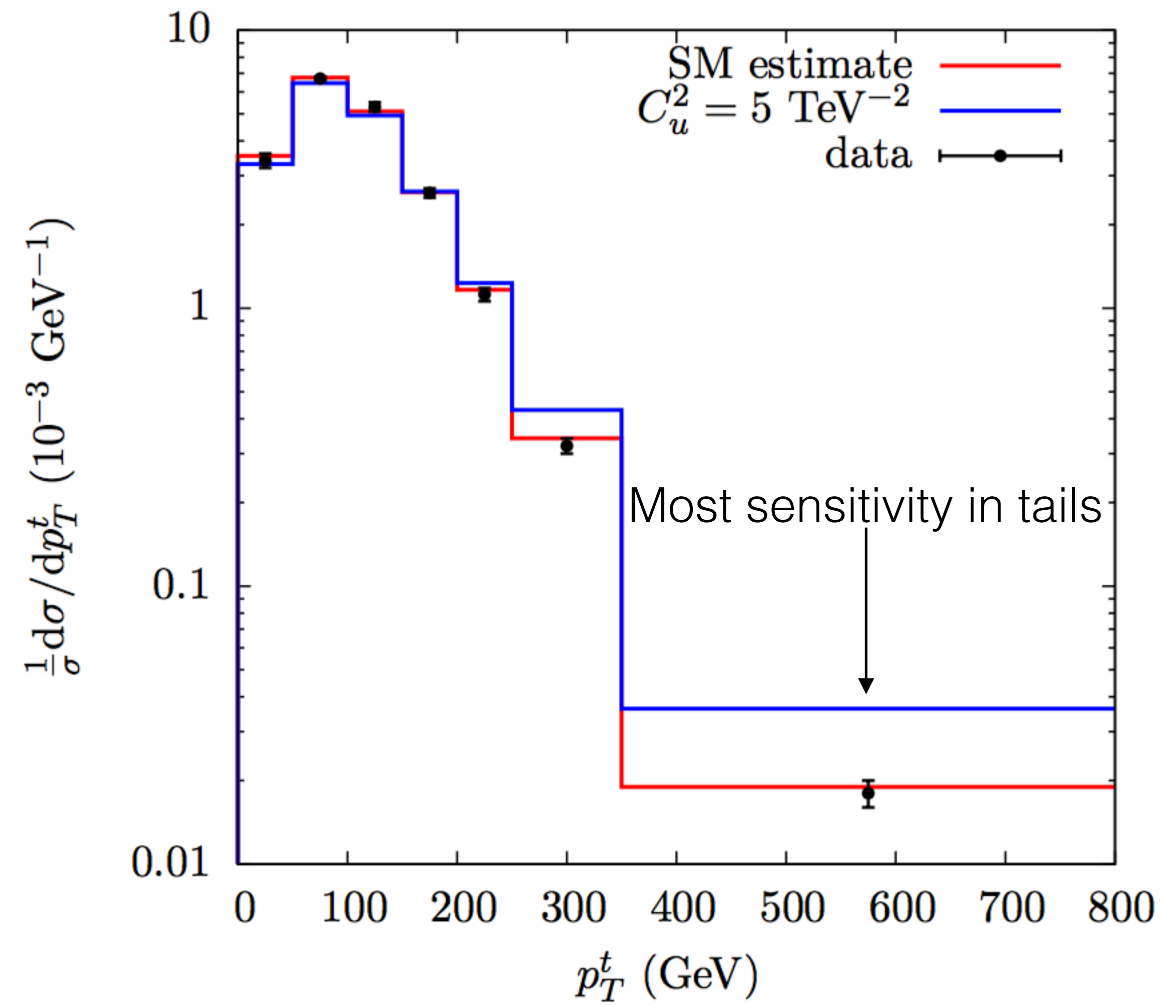
$\longrightarrow$

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

SUMMARY: 6 constrainable operators in top pair production

Top pair production



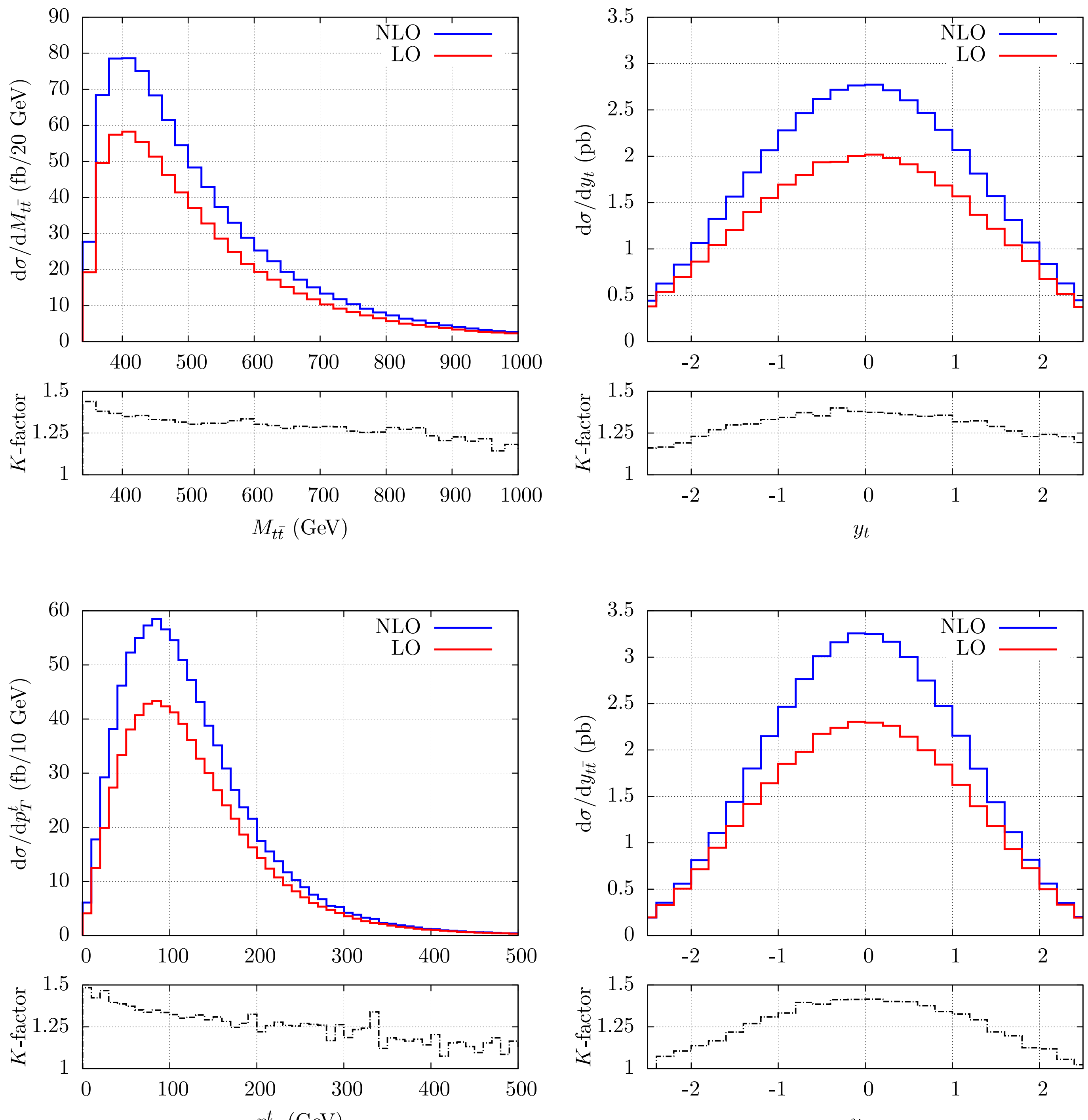


Small effect on shapes

NLO corrections

Known to be large (~1.6) for top pair production

Nason, Dawson & Ellis Nucl.Phys. B303 (1988) 607



Re-weight SM piece to NLO estimate to model higher-order effects

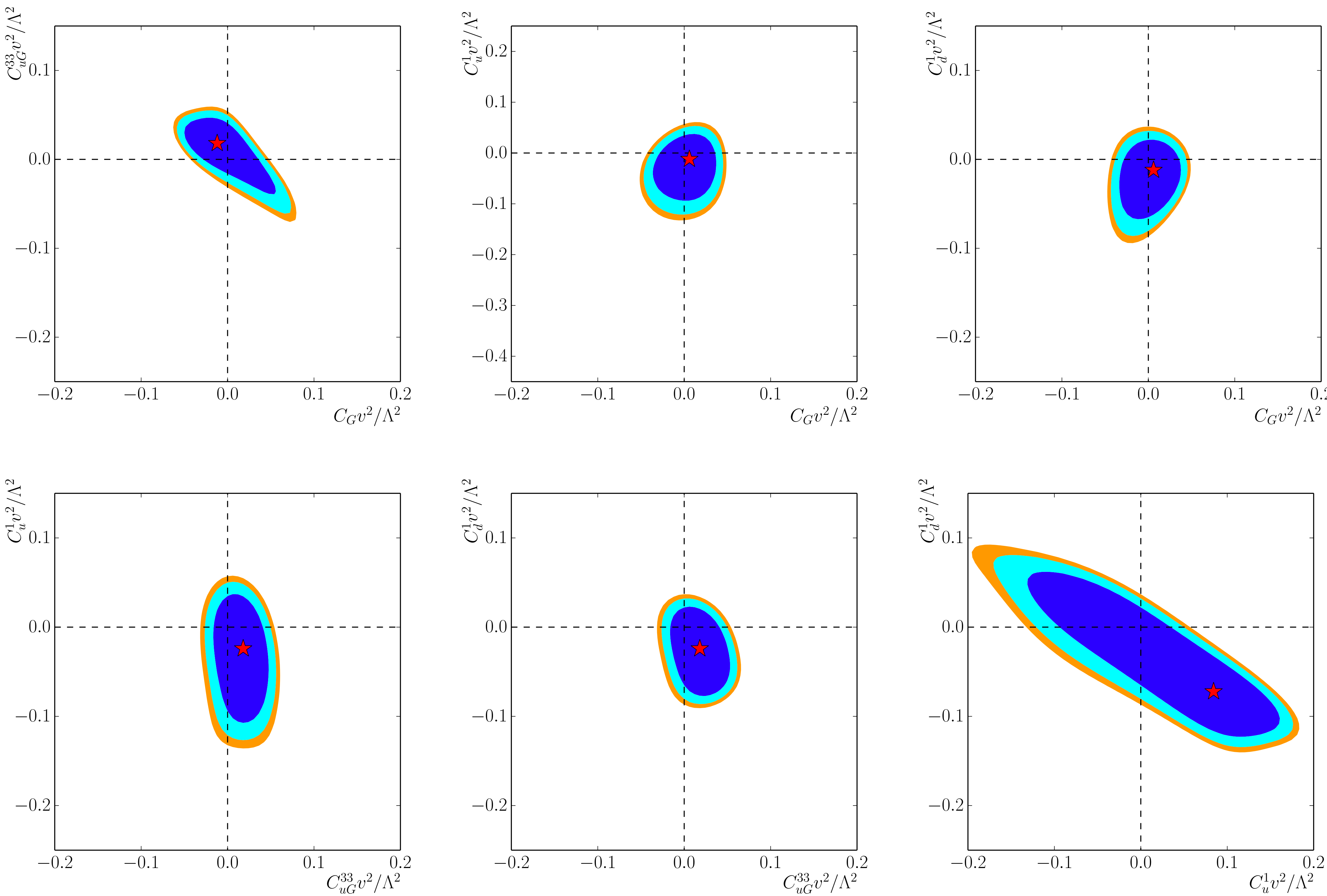
Scale + PDF uncertainties added linearly (maximally correlated)

Butterworth et al. arXiv:1101.0538

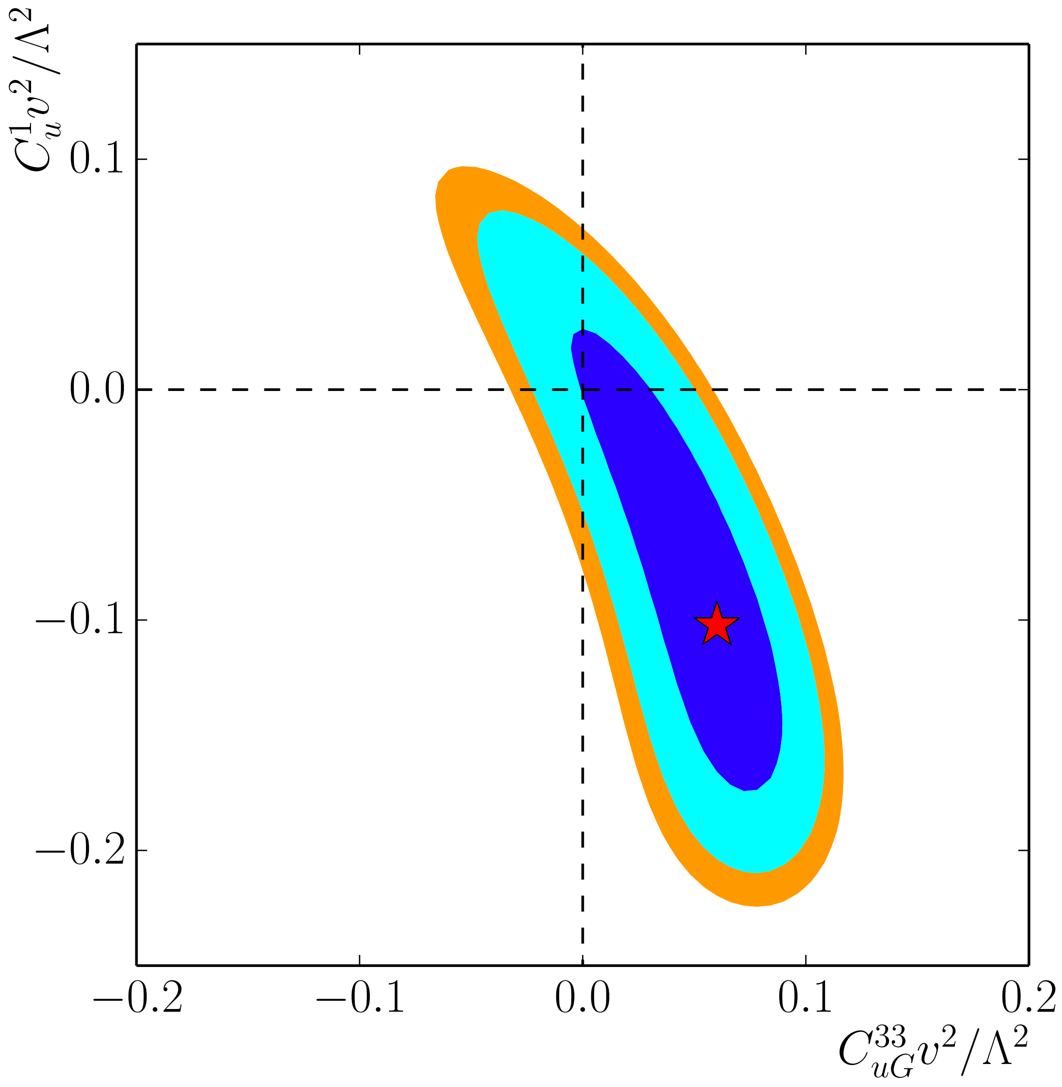
NNLO available for total cross-sections

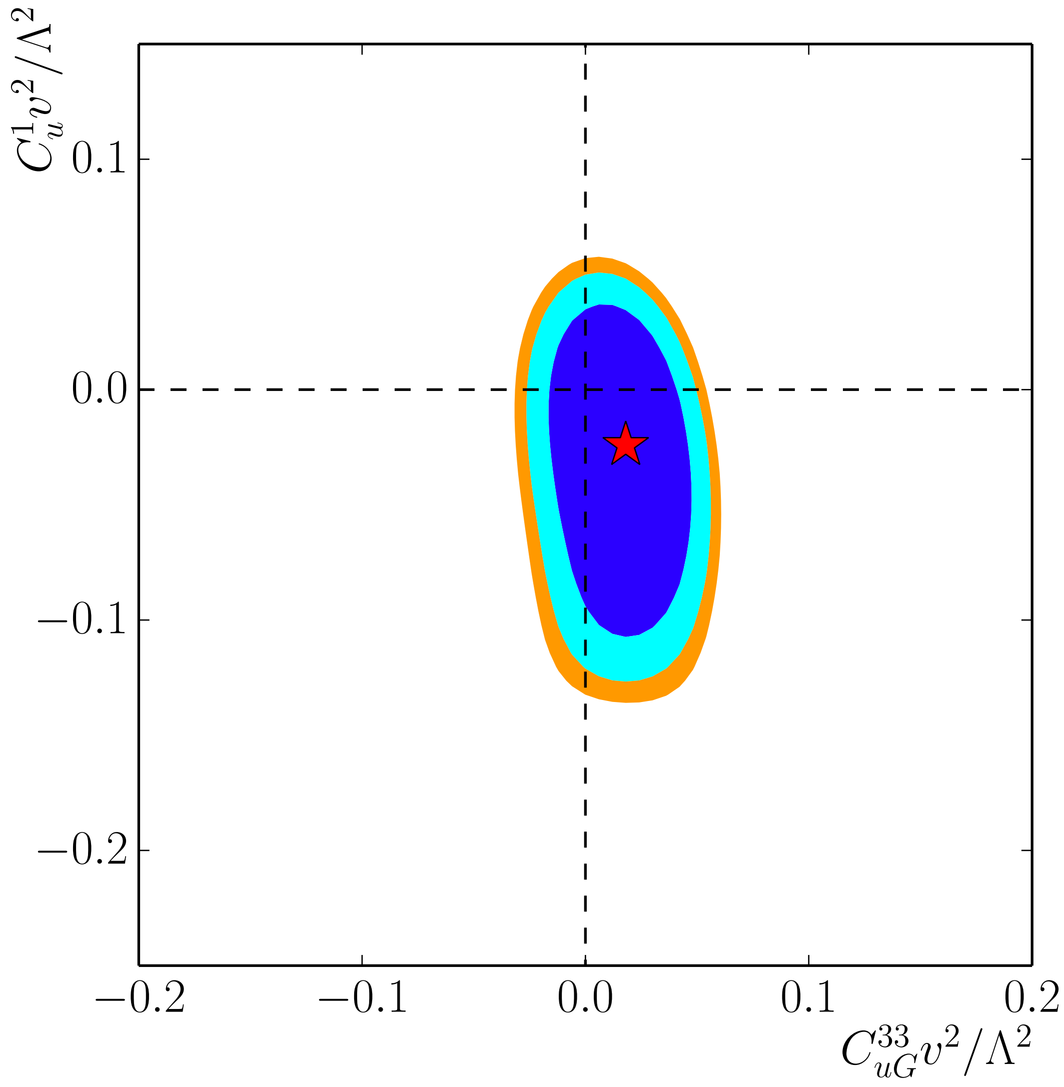
(and differential on the way)

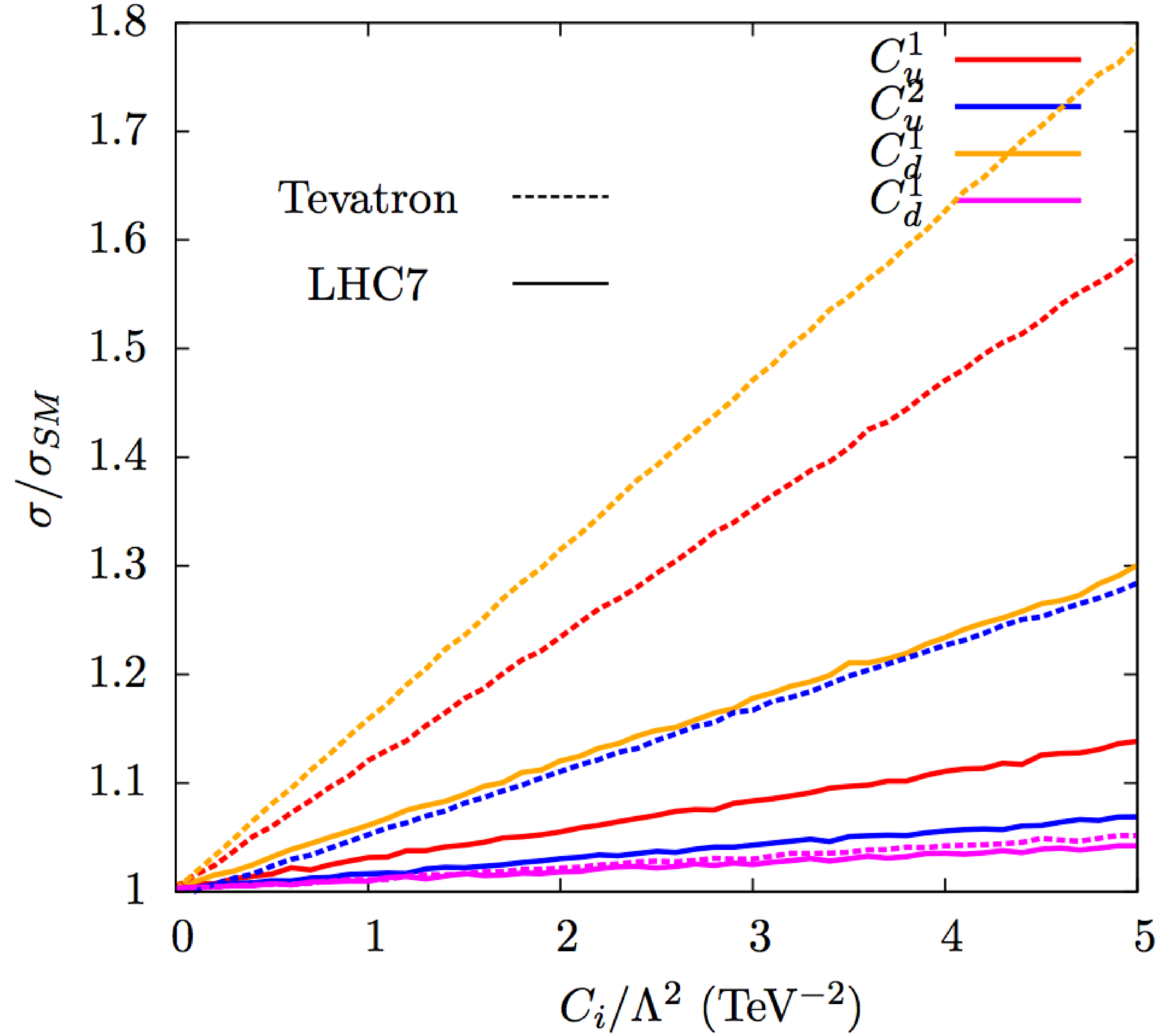
Selected correlations



Tevatron-LHC complementarity

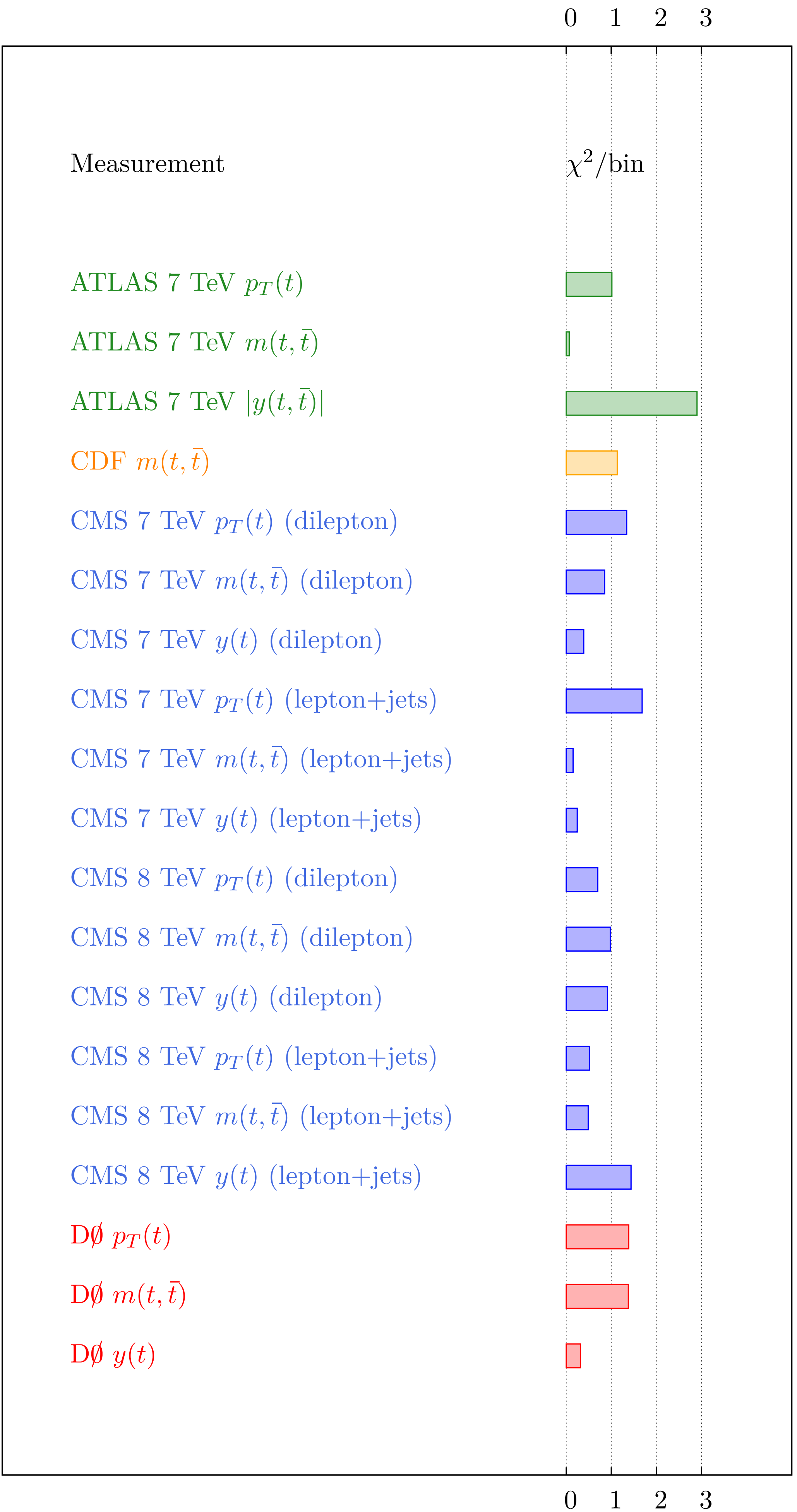






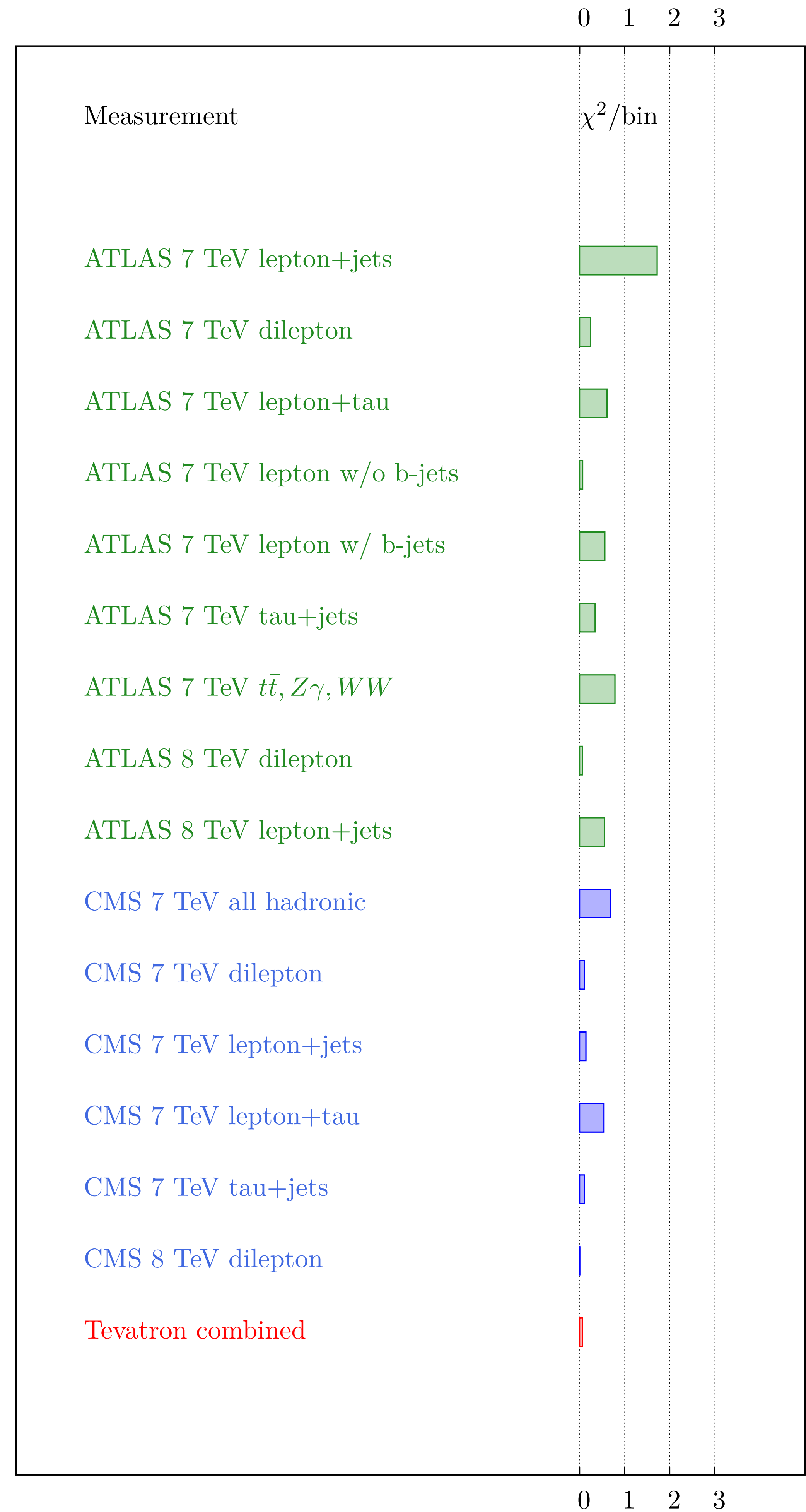
Statistics appears to be winning over sensitivity

Global χ^2



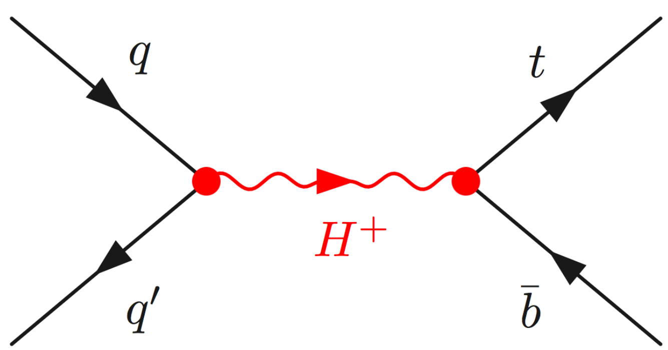
Differential distributions

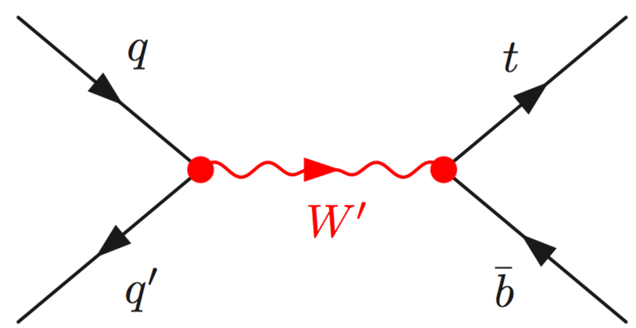
Total rates



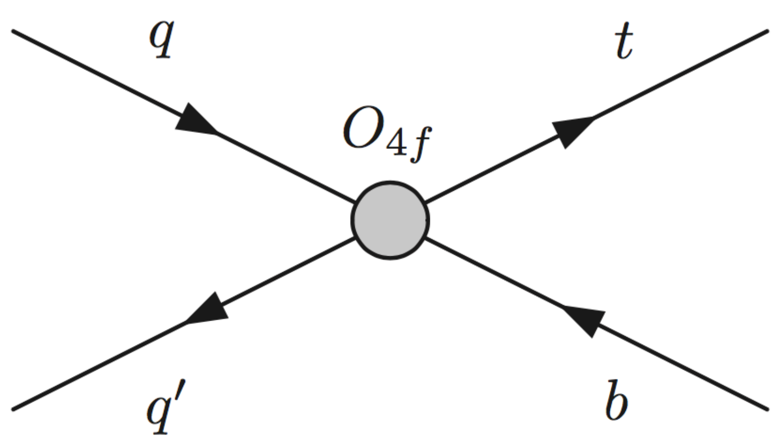
Single-top production

Single top in simple BSM models:





in low-energy limit:



$$O_{qq}^{3} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q) \qquad \mathcal{M}_{D6} \sim C_i v^2/\Lambda^2$$

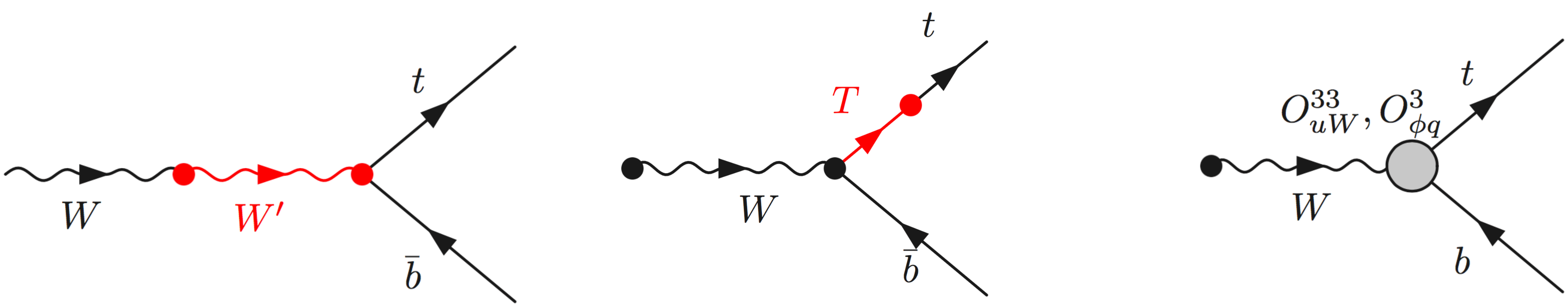
$$O_{qq}^{1} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$$

$$O_{qu}^{1} = (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u) \qquad \mathcal{M}_{D6} \sim C_i m_t m_b/\Lambda^2$$

Single-top production

Single top in simple BSM models:

in low-energy limit:



Relation to anomalous couplings:

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

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

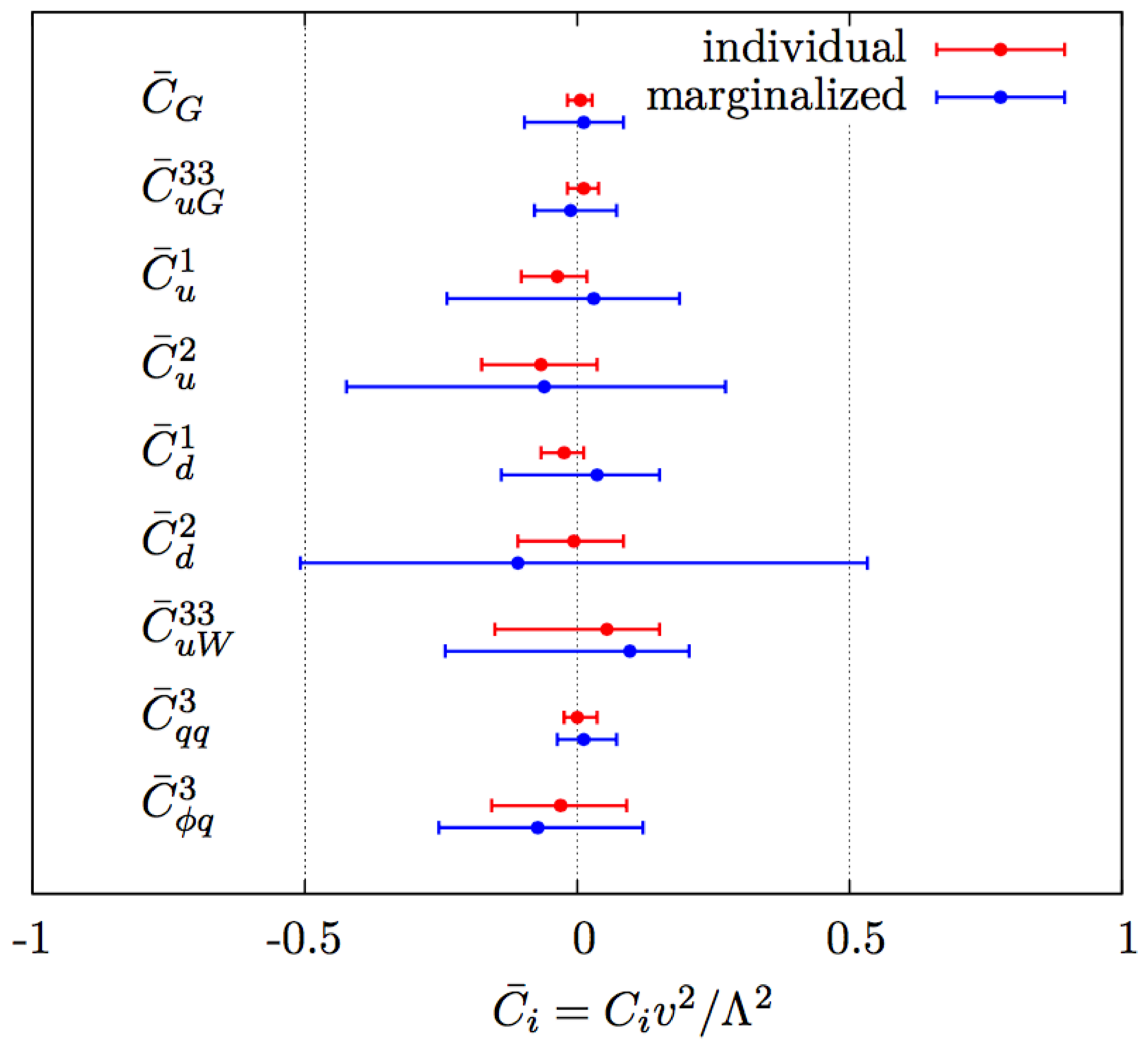
$$\mathcal{L}_{Wtb} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu + \frac{g}{\sqrt{2}}\bar{b} i\sigma^{\mu\nu}(g_L P_L + g_R P_R) t W^-_\mu + h.c.$$

Cao, Wudka & Yuan 0704.2809

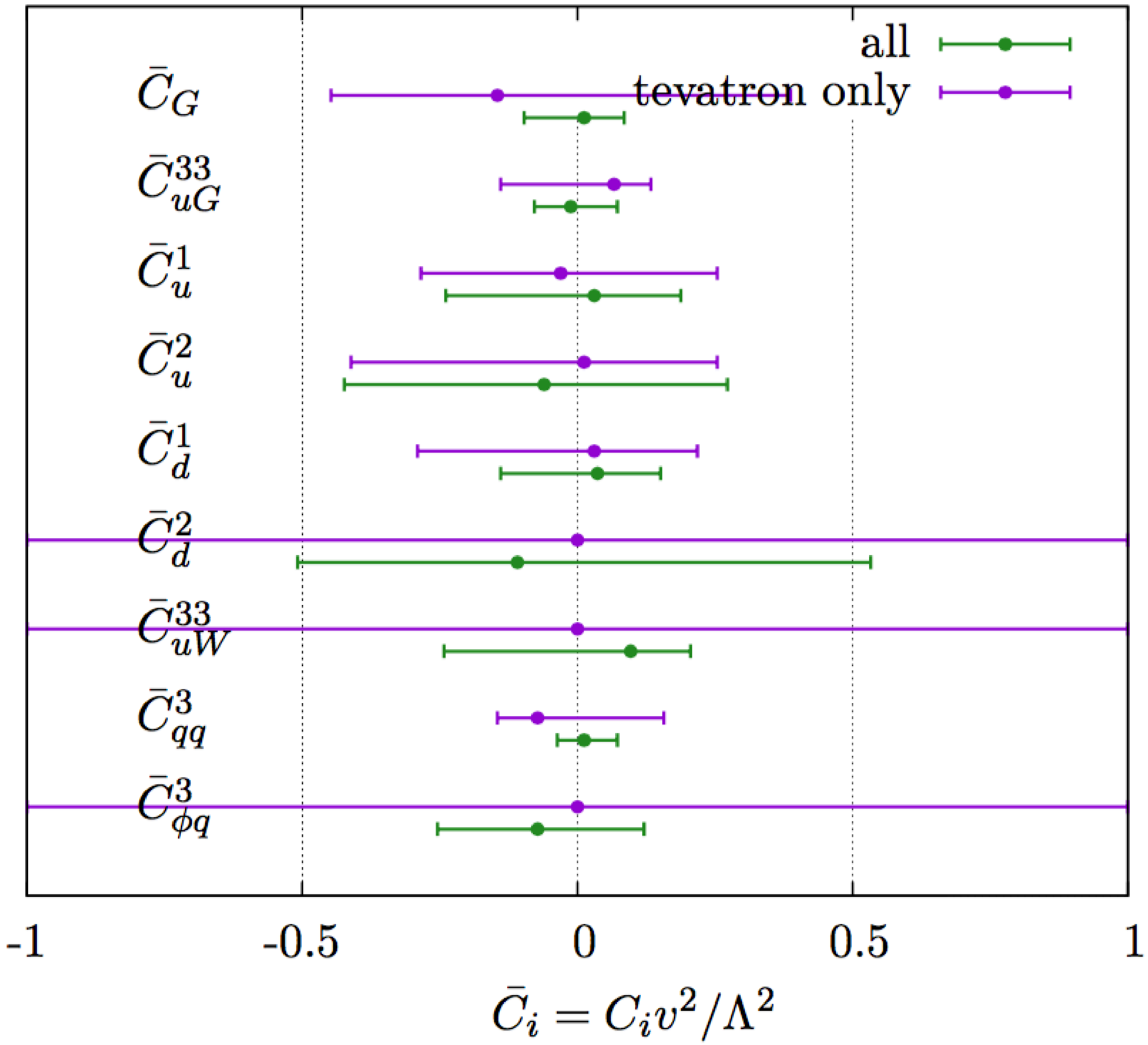
Aguiliar-Saavedra 0803.3810

SUMMARY: 3 constrainable operators in single top production

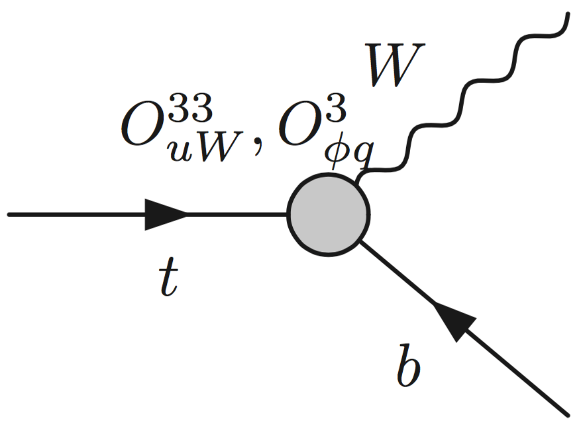
Bottom-line constraints



Tevatron vs. LHC



Decay observables



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

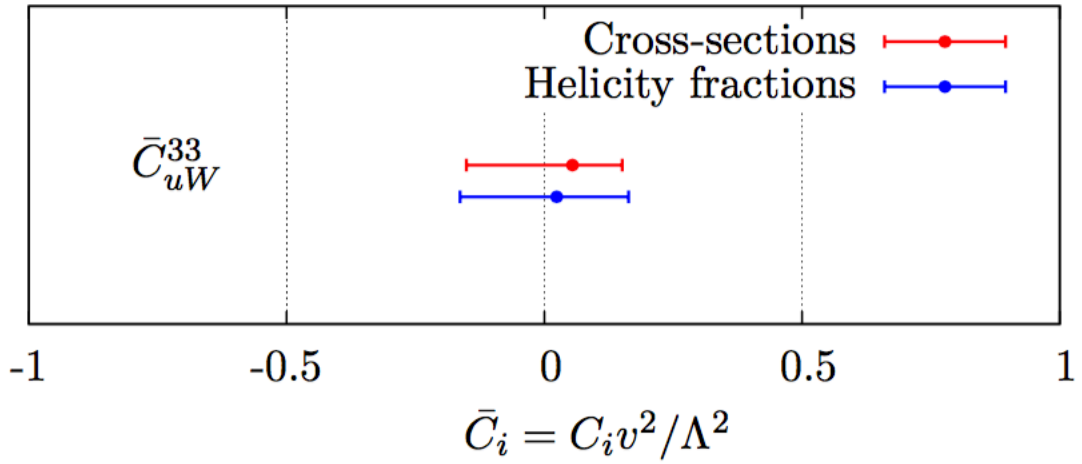
$$F_L = \frac{2M_W^2}{m_t^2 + 2M_W^2} + \frac{4\sqrt{2}C_{uW}^{33}v^2}{\Lambda^2 V_{tb}} \frac{m_t M_W (m_t^2 - M_W^2)}{(m_t^2 + 2M_W^2)^2}$$

$$F_R \simeq 0$$

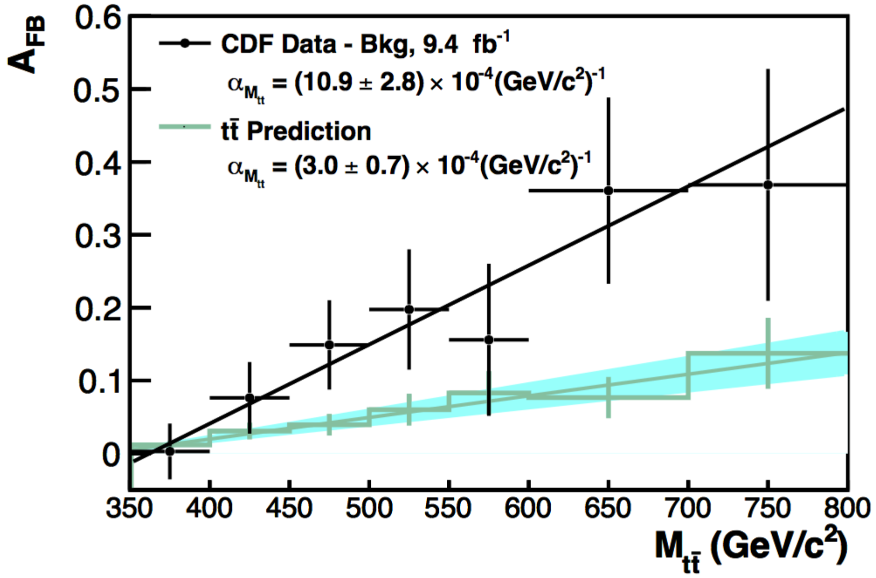
In SM: F_0 ≈ 0.66 , F_L ≈ 0.33, F_R ≈ 0

Stable against higher-order corrections

Do angular observables give better bounds than total cross-sections?



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 $\{C_i\}$?

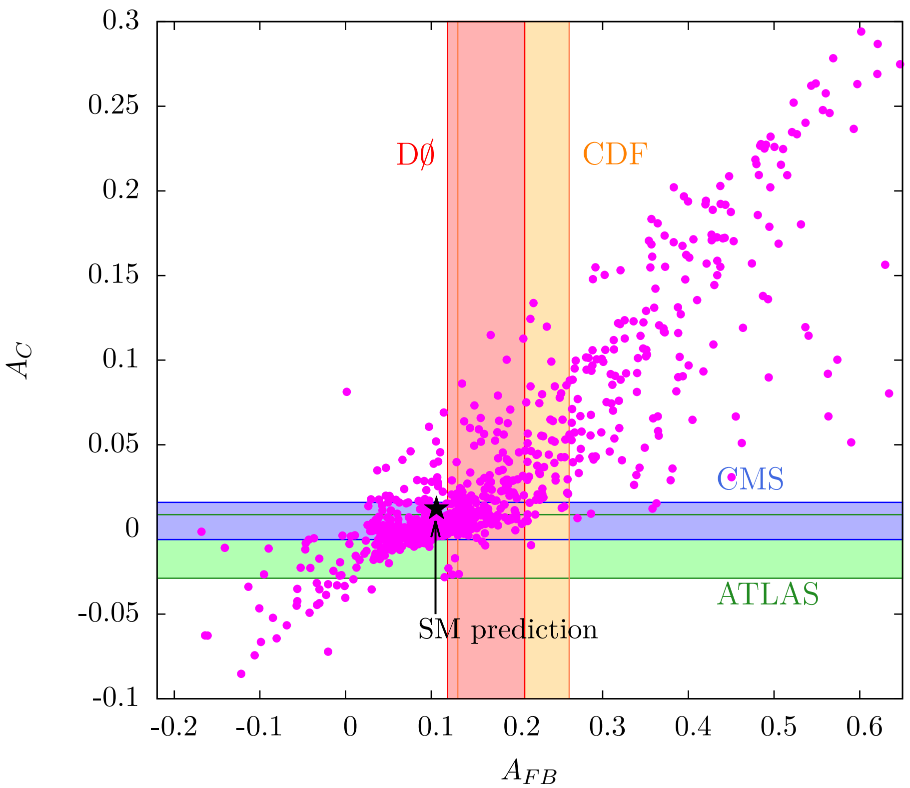
Hewett, Shelton, Spannowsky, Tait, Takeuchi 1103.4618

In EFT language: $A_{FB} \sim (C^1_u - C^2_u) \times \Lambda^{-2}$

Zhang and Willenbrock 1008.3869

correlated with

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



Summary and outlook

Global fit of dimension-six operators to top quark production and decay data

Fitting methods borrowed from Monte Carlo tuning techniques

Run 1 data: Few surprises, all results in agreement with SM, all $\{C_i\} = 0$ within 95% confidence intervals

Not shown here: Higher-order processes (ttZ, ttγ), and decay observables (but similar conclusions apply)

Reasons to be cheerful:

NNLO distributions in top pair production soon to be available, reduction in scale uncertainties

Plenty of room for surprises at run 2.

All non-resonant new physics is a higher-dimensional operator!