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TopFitter: Fitting top quark Wilson Coefficients to Run II data

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Outline

- Why use an Effective Field Theory?
- A reminder of TopFitter for Run I
- TopFitter Run I results
- New features for Run II
- A first test example for Run II
- Conclusions and Summary

Searching for New Physics

Direct Searches	Effective Field Theory
Choose a specific model of new physics (e.g. supersymmetry, technicolor)	Expand the SM with higher dimensional operators
Search for specific deviations	Place limits on their coefficients
Only works if we are in the energy reach of new physics	Scale of new physics should be well above that of the experiment
Provides strong exclusions	Provides weaker exclusions
Not at all general	Very general

Methods are very complementary

Standard Model Effective Field Theory

The effect of new physics can be included into our Lagrangian by adding higher dimensional operators.

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_i C_i^{(n)} \mathcal{O}_i^{(n)}$$

$$= \frac{1}{\Lambda} C_1^{(5)} \mathcal{O}_1^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \ldots$$

Dimension 5 operator is not of interest to Top physics.

Scale of new physics

Dimension 6 operators.

The Wilson coefficients Ci are parameters set by the form of the new physics. Our aim is to constrain these.

The operators are constructed out of only SM fields, maintaining gauge invariance.

Dimension 6 operators for top physics

We use the "Warsaw basis" of operators [Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)].

This is 59 independent operators to augment the SM, with some flavour assumptions.

Only 16 of these are relevant for top quarks.

$$
\begin{aligned}
O_{qq}^{(1)} &= (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) & O_{uW} &= (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\varphi}W_{\mu\nu}^I & O_{\varphi q}^{(3)} &= i(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\gamma^\mu\tau^I q) \\
O_{qq}^{(3)} &= (\bar{q}\gamma_\mu\tau^I q)(\bar{q}\gamma^\mu\tau^I q) & O_{uG} &= (\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G_{\mu\nu}^A & O_{\varphi q}^{(1)} &= i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q) \\
O_{uu} &= (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u) & O_G &= f_{ABC}G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu} & O_{uB} &= (\bar{q}\sigma^{\mu\nu}u)\tilde{\varphi}B_{\mu\nu} \\
O_{qu}^{(8)} &= (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u) & O_{\tilde{G}} &= f_{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu} & O_{\varphi u} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u) \\
O_{qd}^{(8)} &= (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d) & O_{\varphi G} &= (\varphi^\dagger\varphi)G_{\mu\nu}^A G^{A\mu\nu} & O_{\varphi\tilde{G}} &= (\varphi^\dagger\varphi)\tilde{G}_{\mu\nu}^A G^{A\mu\nu} \\
O_{ud}^{(8)} &= (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)\,.
\end{aligned}
$$

This is not a unique choice [see e.g. Zhang, Willenbrock (2011)] and some observables are be better suited to combinations of these operators.

LHC Run 1 and Tevatron data sets

We use results from ATLAS and CMS 7 and 8 TeV data, as well as the Tevatron.

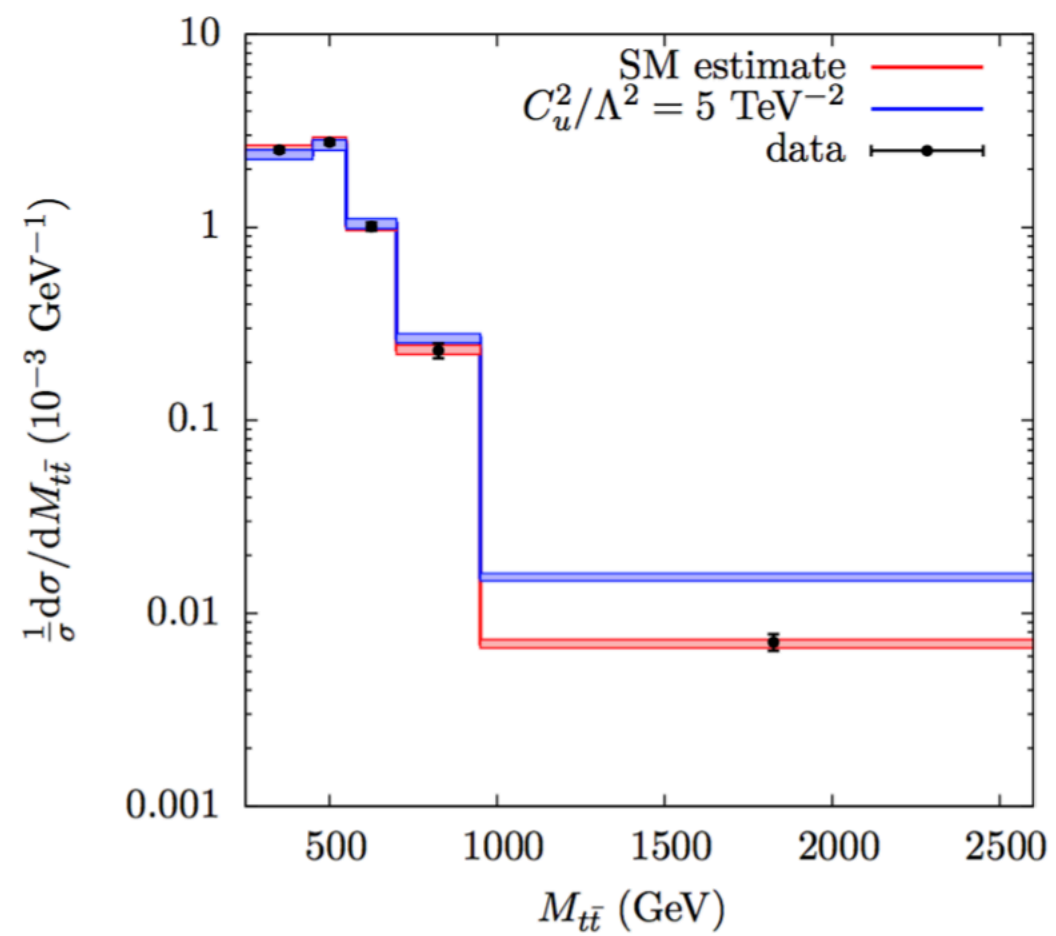
This includes 227 different measurements. Most are top-pair (195) but we also include single top and associated production. (We didn't include Wt associated production.)

Most of these are differential observables.

We include both systematic and statistical uncertainties, adding them in quadrature.

We include correlations between measurements were available, though these are not available for many.

All of these measurements are **parton-level** (including only direct decay products of the top).



Data from ATLAS arXiv:1407.0371

LHC Run 1 and Tevatron data sets

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_{C} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_{C} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				W-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				

Methodology

We implemented the SMEFT Lagrangian in FeynRules [Christensen and C. Duhr (2008)].

We regularly sample the space of Wilson Coefficients $\mathbf{C} = \{C_i\}$ and calculate all Parton-level observables at LO using Madgraph 5 [Alwall et al (2014)].

Include NLO K-factors (bin-by-bin for differential distributions) using MCFM [Campbell, Ellis (2010)].

Include partial NNLO for top-pair [Czakon, Fiedler, and Mitov (2015)].

Include theoretical uncertainties from factorisation/renormalisation scale and PDF uncertainties.

Some of the 16 operators are not constrained by data or only constrained in particular combinations.

Not including Wt associated production, the space factorises into 6 operators constrained by top-pair, and 3 constrained by single-top and decays.

Methodology

We calculate $|\mathcal{M}_{\mathrm{SM}} + \mathcal{M}_{\mathrm{D6}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{D6}} + |\mathcal{M}_{\mathrm{D6}}|^2$

for $\mathbf{C} = \{C_i\}$ and fit observables to $f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i \leq j} \gamma_{i,j}^b C_i C_j + \ldots$.

using a χ^2 fit:

Experimental values

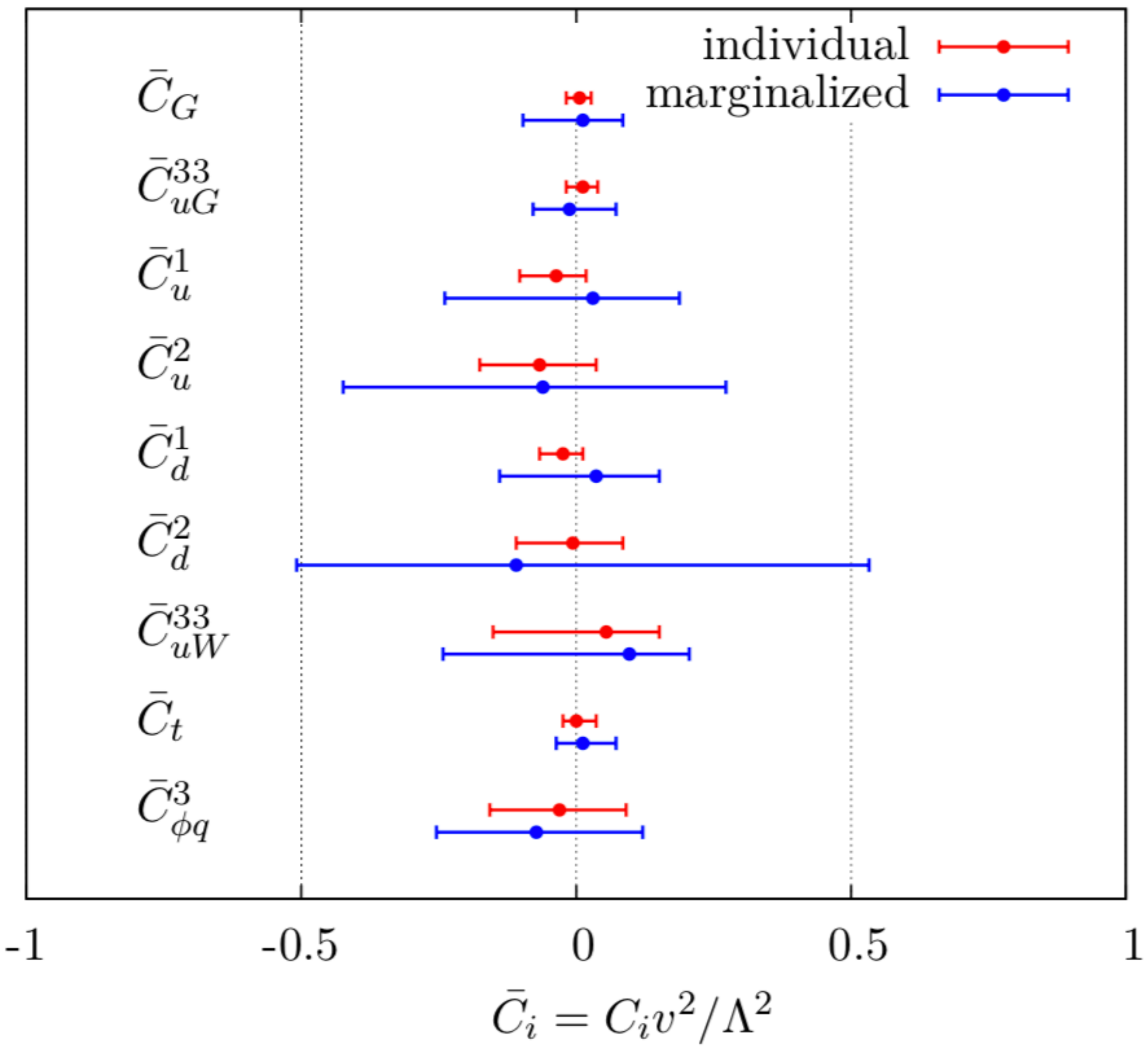
$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}^{-1}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

$$\sigma_i = \sqrt{\sigma_{\mathrm{th},i}^2 + \sigma_{\mathrm{exp},i}^2}$$

The interpolation between discrete Wilson coefficient choices, and the fitting is done with PROFESSOR [Buckley et al (2010)].

Run I Results

95% confidence



The first 6 are constrained by top-pair.

The remaining 3 are single-top.

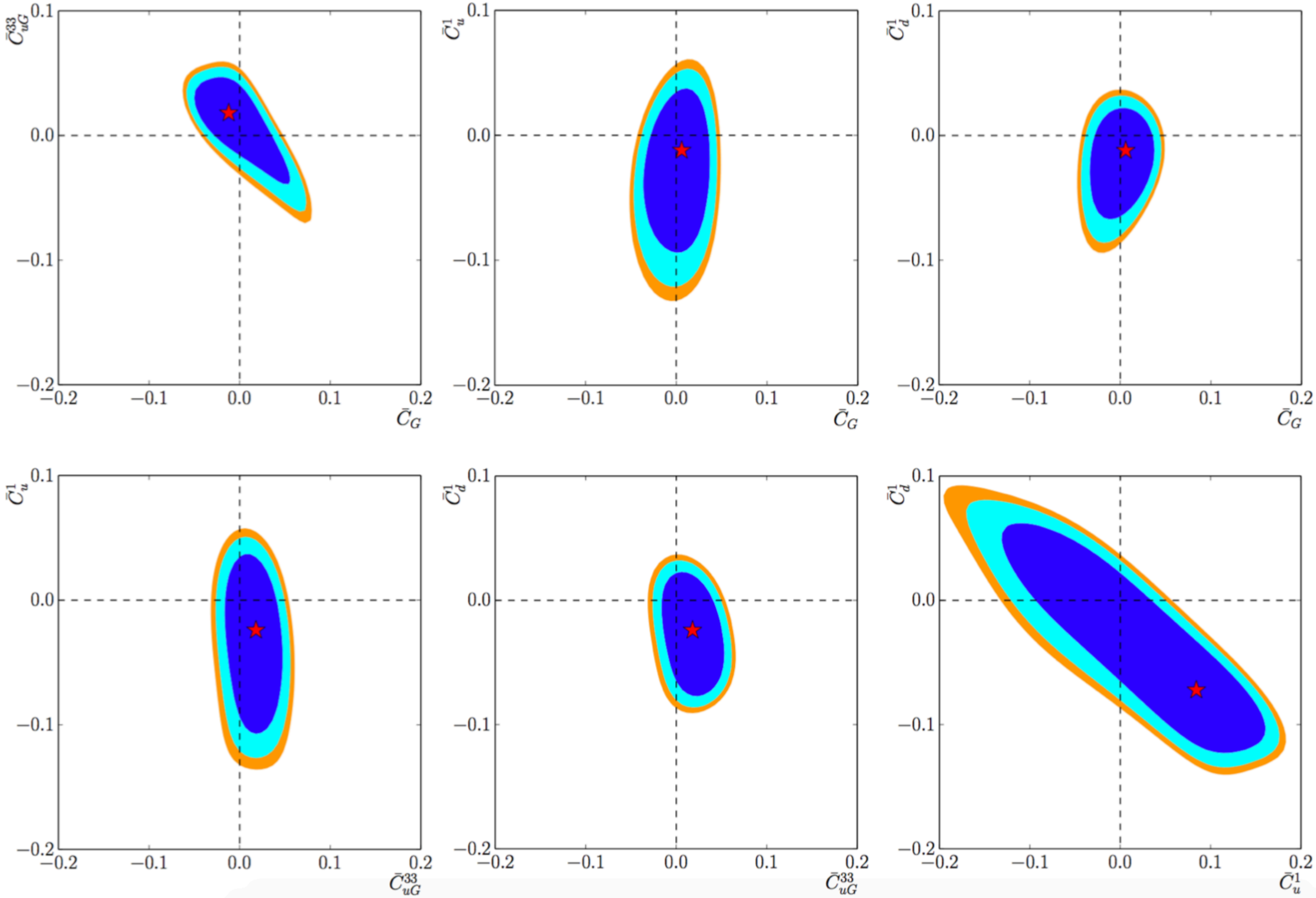
Some are combinations of the operators we saw earlier.

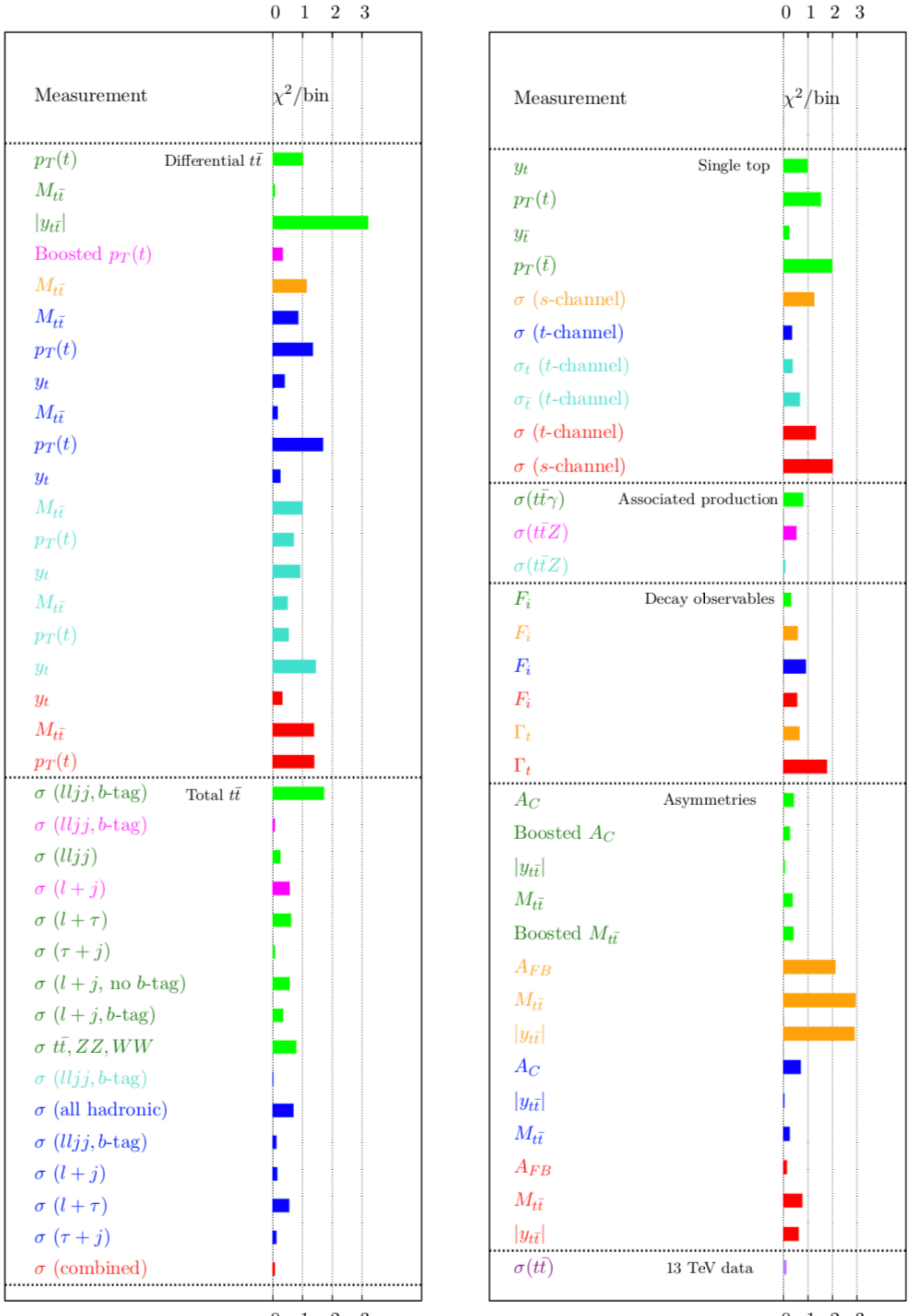
$$
\begin{aligned}
C_u^1 &= C_{qq}^{(1)1331} + C_{uu}^{1331} + C_{qq}^{(3)1331} \\
C_u^2 &= C_{qu}^{(8)1133} + C_{qu}^{(8)3311} \\
C_d^1 &= C_{qq}^{(3)1331} + \tfrac{1}{4} C_{ud}^{(8)3311} \\
C_d^2 &= C_{qu}^{(8)1133} + C_{qd}^{(8)3311} \,.
\end{aligned}
$$

$$C_t = C_{qq}^{(3)1133} + \tfrac{1}{6}\left(C_{qq}^{(1)1331} - C_{qq}^{(3)1331}\right)$$

Notice that there is a big difference between **individual** constraints, with all other Wilson coefficients set to zero, and **marginalised** constraints, where all the Wilson coefficients are allowed to deviate from zero at once.

Run I Results





Quality of fit

Examined the quality of fit by calculating χ^2 per bin between data and the global best fit point.

No significant tension observed.

Highest χ^2 arises from top-pair rapidity distribution.

Also note associated production, decay observables and charge asymmetries, which were also studied but I won't talk about here.

Improving to Particle Level

In extending the TopFitter analysis to Run II we would like to improve on our analysis.

In particular, we want a **Particle Level** analysis instead of our previous **Parton Level** analysis to better reflect experimental analyses.

$\Rightarrow$ Shower with Pythia 8 [Sjöstrand et al (2015)]

However, this is too computationally intensive to do using our method described earlier.

Instead we have **linearised** (only possible with new version of MadGraph):

Calculate $|\mathcal{M}_{\mathrm{SM}}|^2$ separately and then calculate interference $\mathcal{M}^*_{\mathrm{SM}}\,\mathcal{M}_{\mathcal{O}_i}$ for each operator $\mathcal{O}_i$.

This is much more efficient as we no longer need a grid of points in Wilson space.

Once these samples are generated, we can use them for any set of Wilson coefficients.

$$|\mathcal{M}|^2 \sim |\mathcal{M}_{\rm SM}|^2 + 2C_i \sum_i {\rm Re}\mathcal{M}^*_{\rm SM}\mathcal{M}_{\mathcal{O}_i}$$

This is now exactly linear in each Wilson coefficient. The generation of theory test points is much faster and the fit much easier.

However, now we have no $|\mathcal{M}_{\mathcal{O}_i}|^2$ terms. Although this is formally OK (truncating the expansion at order $1/\Lambda^2$, it could be problematic:

- If the interference $\mathcal{M}^*_{\rm SM}\,\mathcal{M}_{\mathcal{O}_i}$ is small or even zero (e.g. due to colour or helicity) then $|\mathcal{M}_{\mathcal{O}_i}|^2$ could provide the leading contribution of new physics.

- $|\mathcal{M}_{\mathcal{O}_i}|^2$ may also be leading in some regions of phase space.

- If the interference is large and negative we could, in principle, find negative cross sections!

One could overcome this by also generating samples for each $|\mathcal{M}_{\mathcal{O}_i}|^2$ though this **hasn't** been done for the following analysis.

Monte Carlo Samples for Run II trial

SM sample: Generate 13 TeV NLO Parton-level events using MadGraph5_aMC@NLO and shower with Pythia 8.

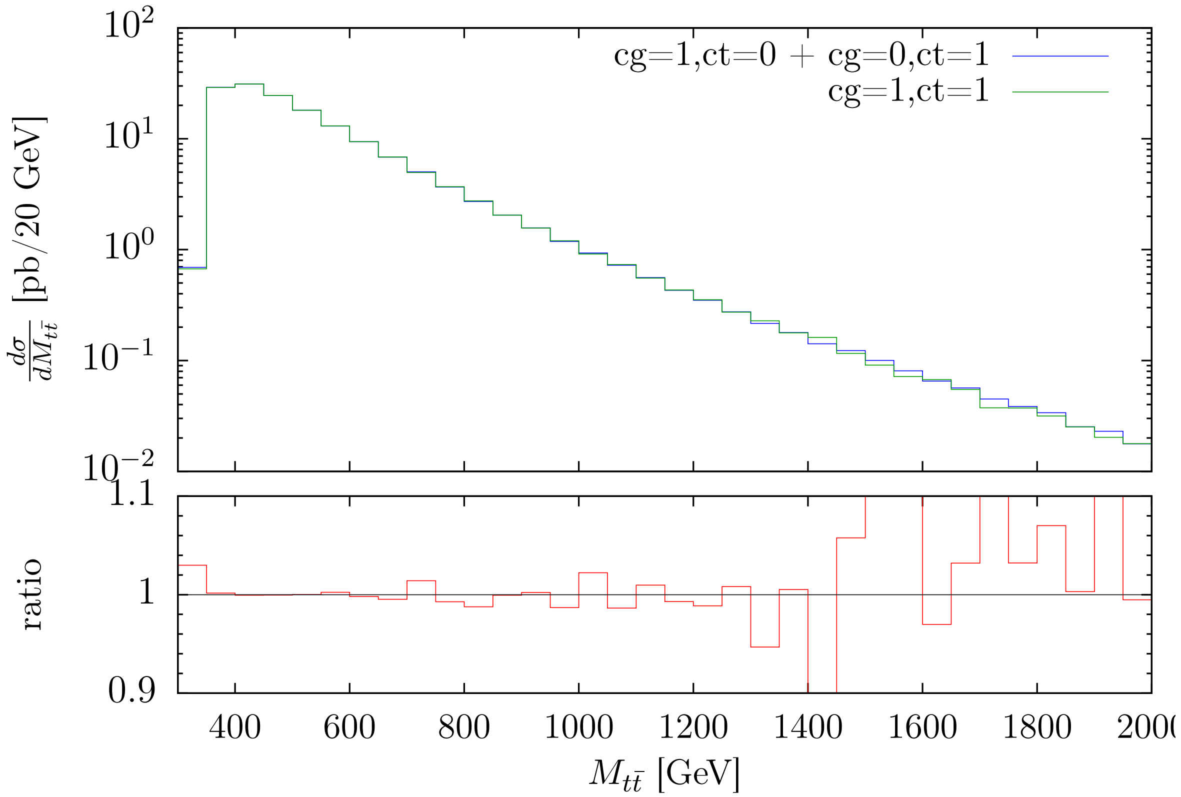
Use NNPDF with NLO QCD + LO QED.

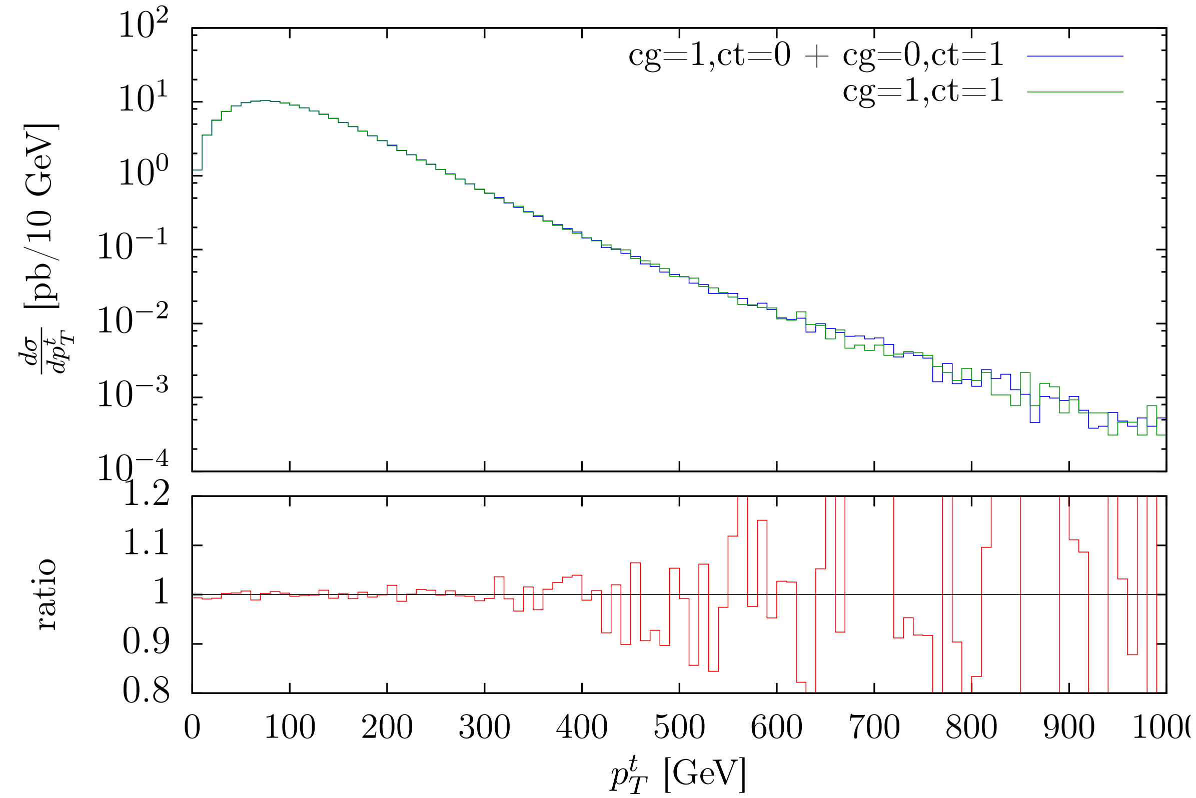
Decay $t\bar{t}$ using MadSpin [Artoisenet, Frederix, Mattelaer and Rietkerk (2013)]

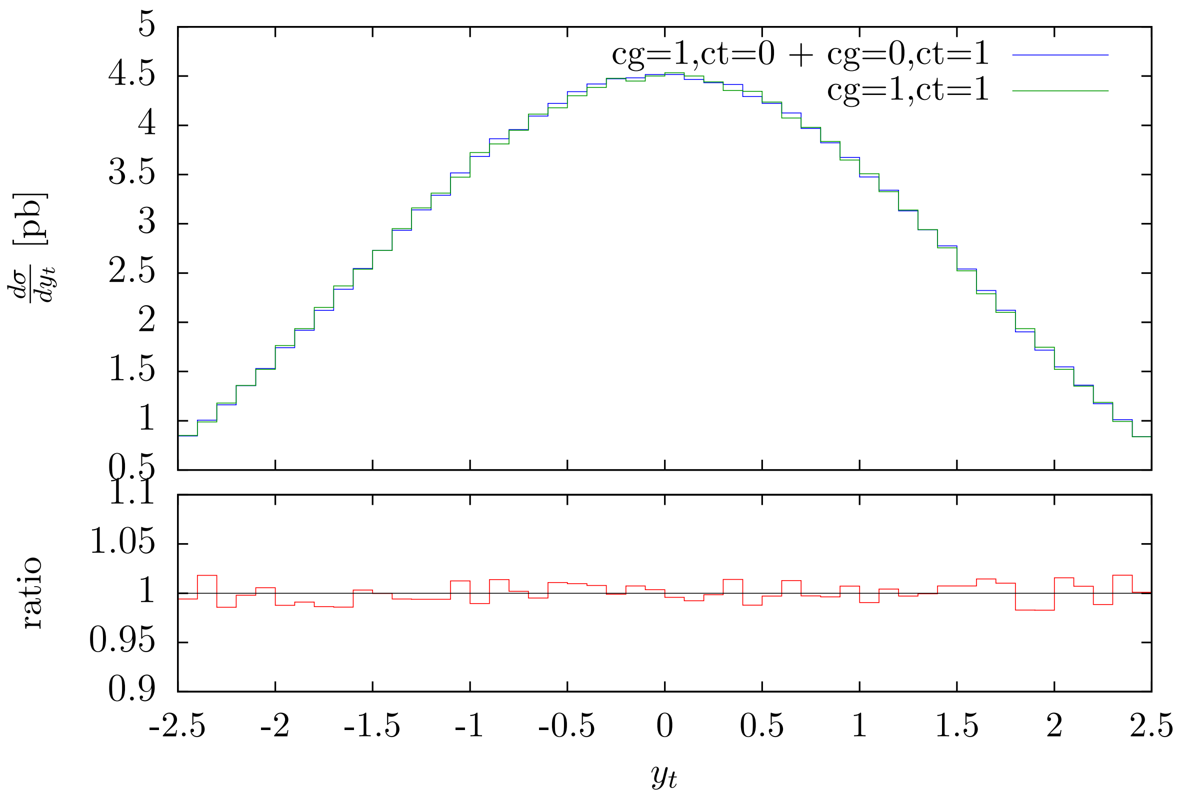
Generate $t\bar{t}$ and $t\bar{t}$ + jet and merge and match with the parton shower using the FxFx [Frederix and Frixione (2012)]

Include jet matching scale in uncertainties as well as factorisation scale and renormalisation scale.

Linearisation Test (parton level)



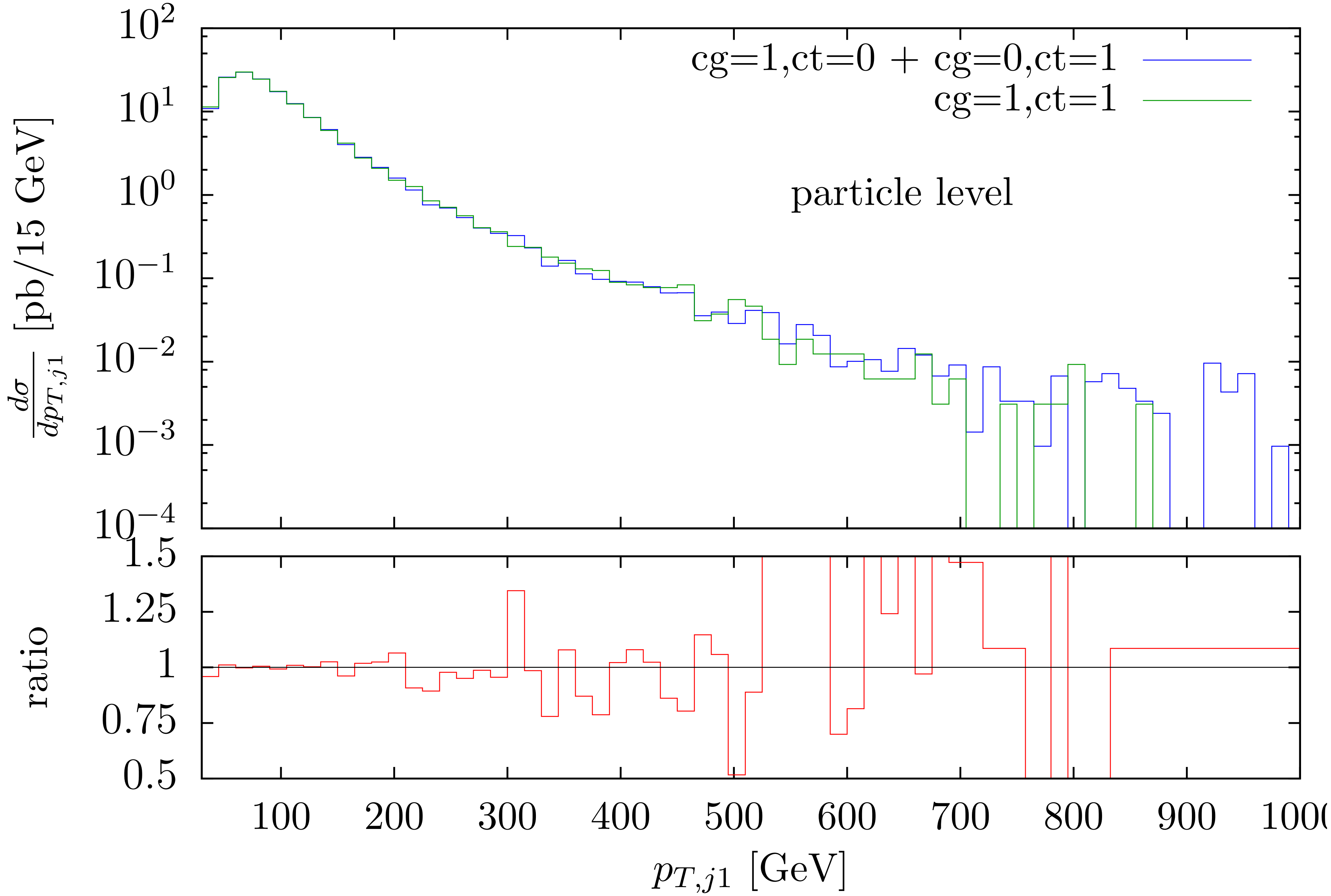




As expected, adding operators one at a time is identical (within uncertainties) to adding both at once.

These are parton level distributions but…

Linearisation Test (particle level)



…this also works at the particle level.

Monte Carlo Samples for Run II trial

SM-EFT interference sample: Generated as previous slide **except…**

EFT only generated at Leading Order

Decays handled by Pythia 8 since new functionality of MadGraph 5 to include only interference terms doesn't allow us to specify decay chains.

Used the SMEFT implementation by [Brivio, Jiang and Trott (2017)]

Note that for both SM and EFT contributions, decays of the top quarks and in Pythia are **all SM decays**. We have not included the effects of the higher dimensional operators here!

Run II ATLAS data trial

For a preliminary test of our set-up we choose to examine just one ATLAS analysis, arxiv.org:1801.02052.

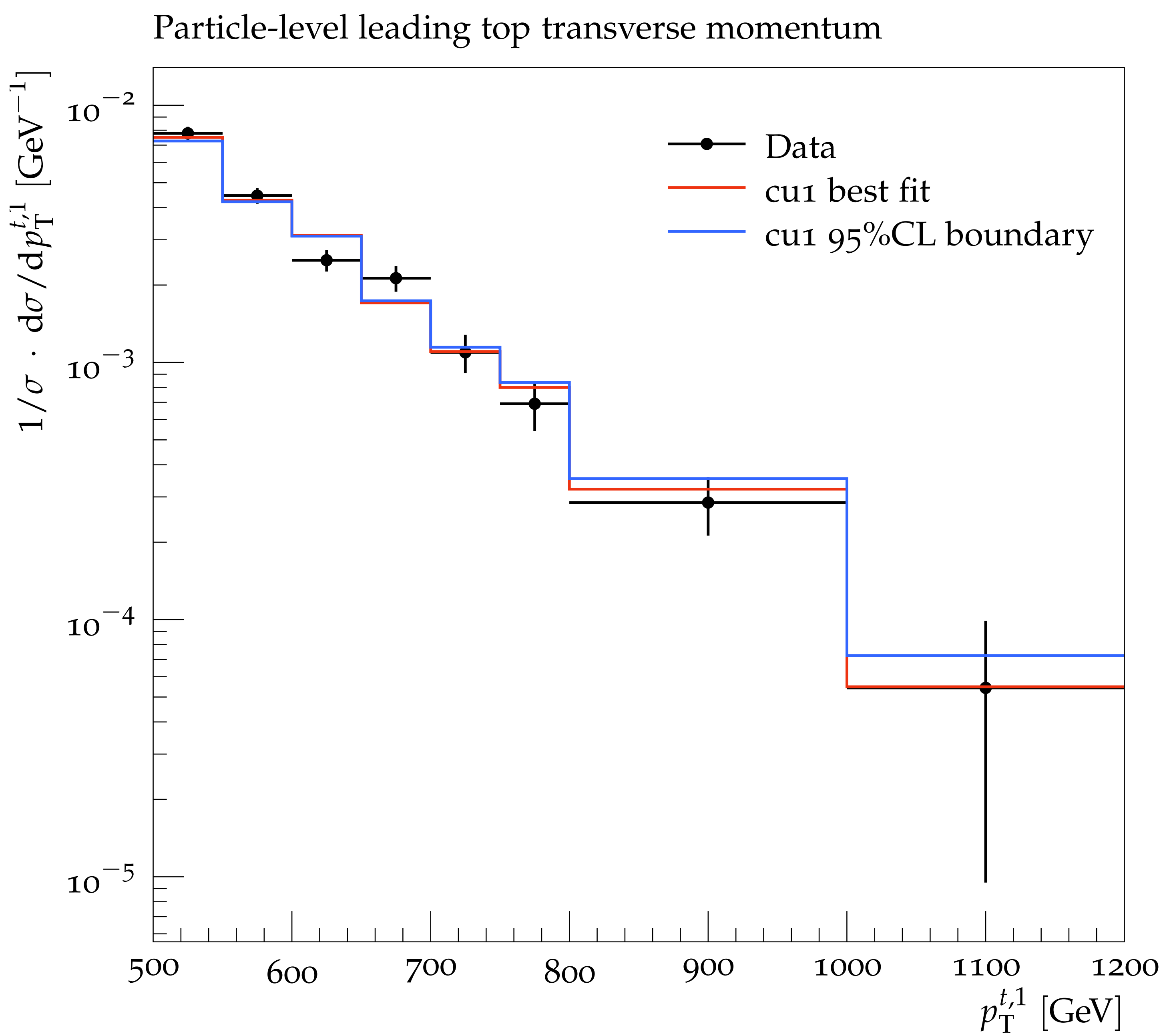
This contains 13 differential observables in top-pair production at 13 TeV.

Why did we choose this?

- Fully available on HEPData.
- Has a RIVET analysis available.
- Has full correlations between observables as well as between bins.

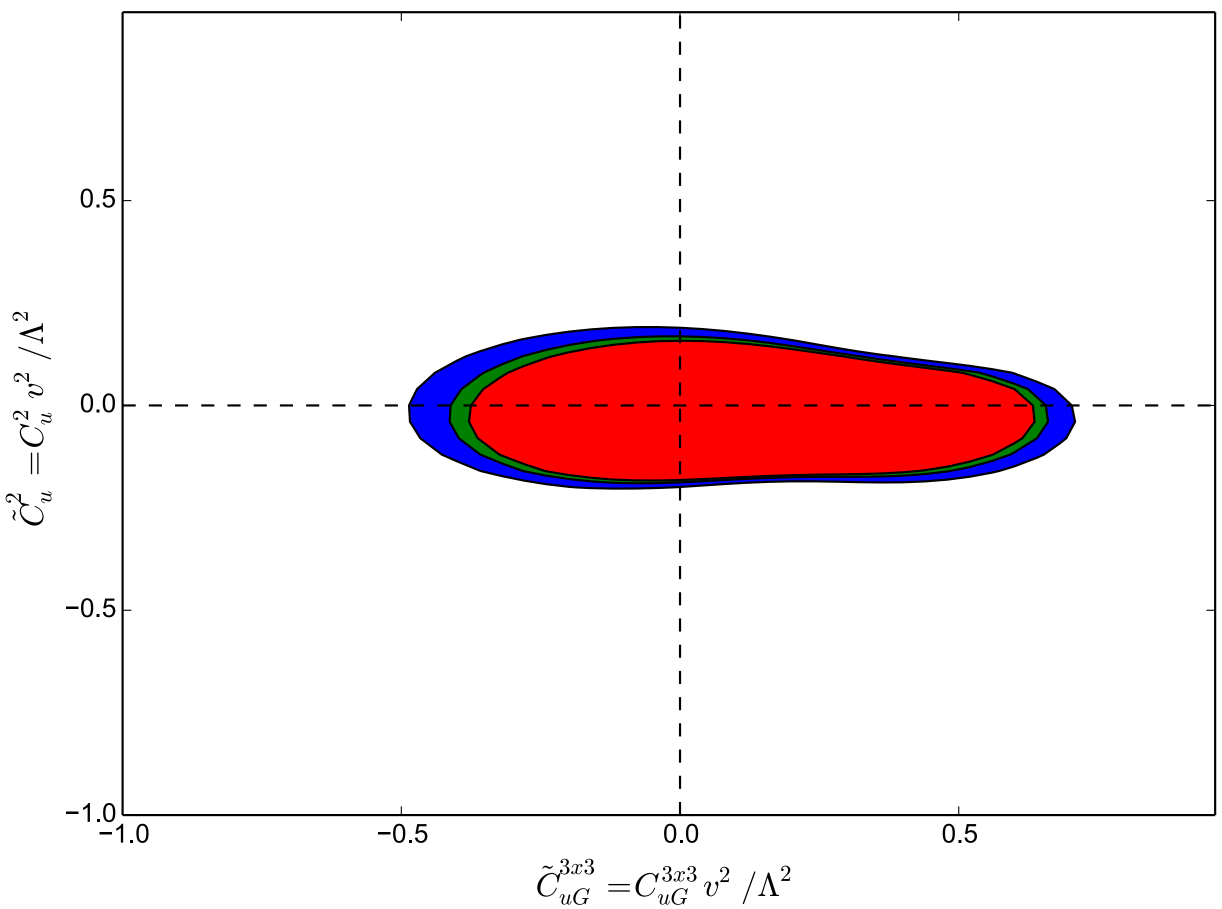
These observables constrain the Wilson coefficients C_G, C_{uG}^{33}, C_u^1, C_u^2, C_d^1, C_d^2

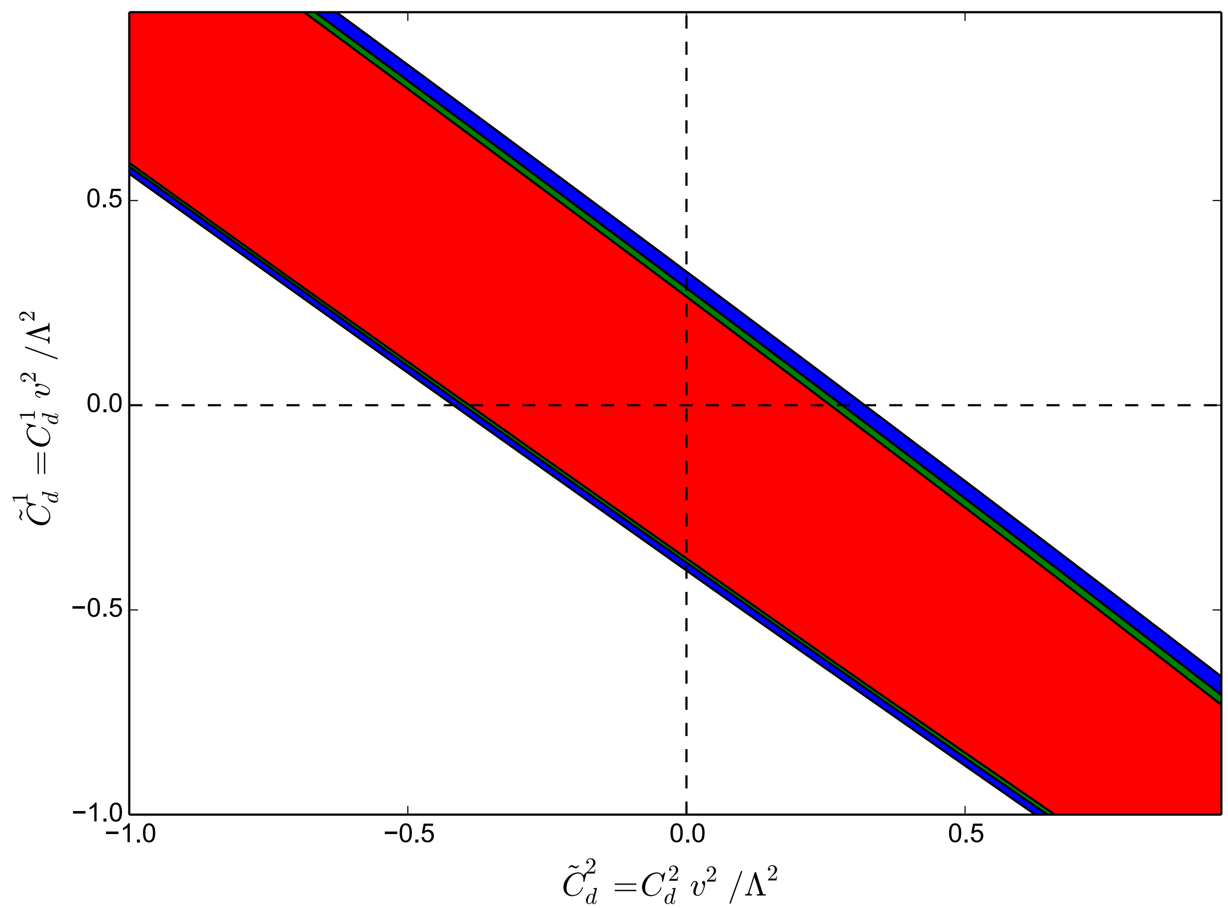
An example deviation from a single operator



Contours in Wilson Space

Preliminary!

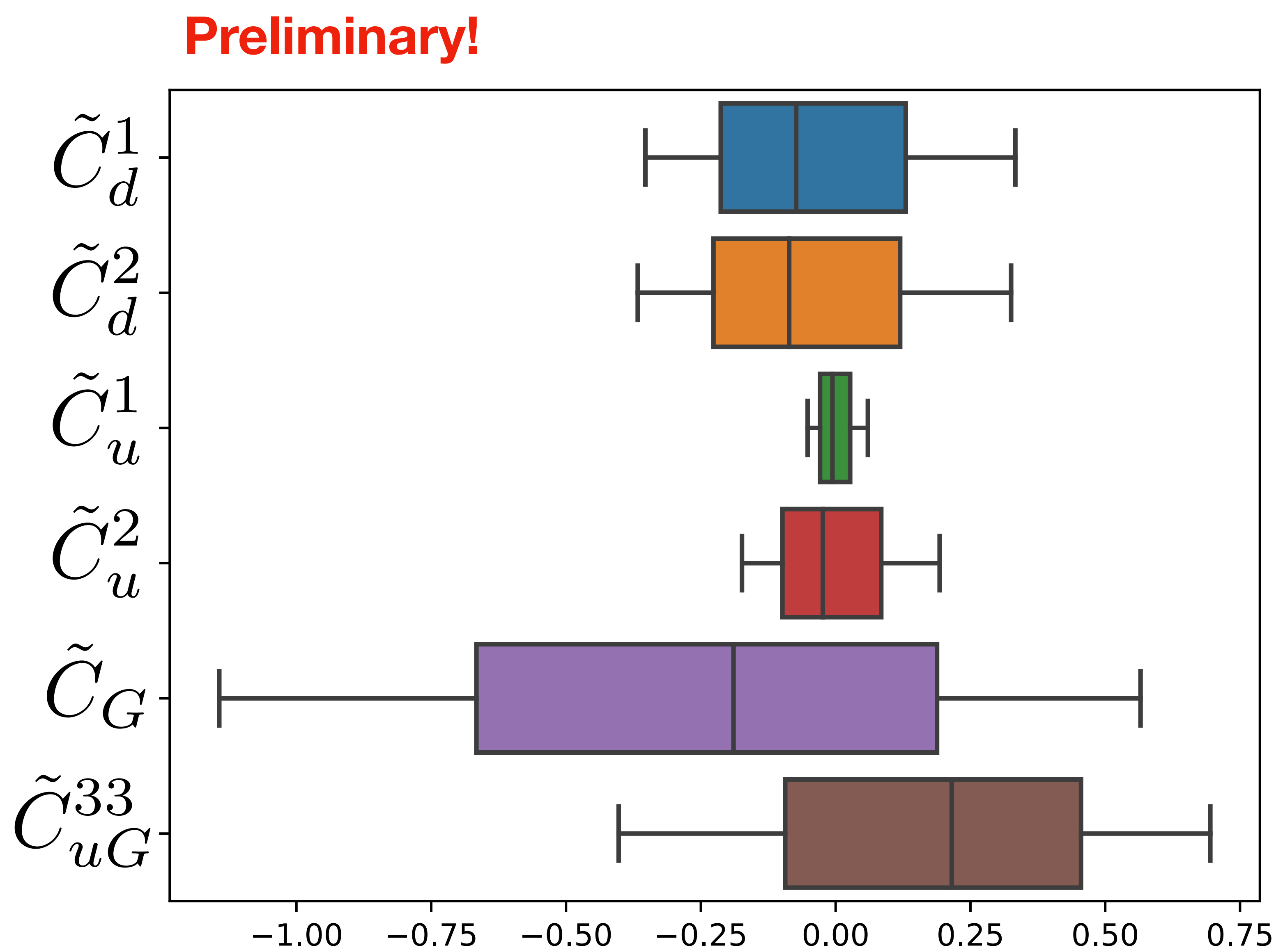




Notice that constraints on individual operators can be quite tight but marginalised constraints can be much bigger.

We are not quite ready to show you the marginalised constraints yet!

Constraints on individual operators



These have **not** been marginalised.
Also, correlations between observables are not yet included.

Conclusions and Summary

- Effective Field Theory can be used to search for new physics in a model independent way. It is complementary with direct searches, being sensitive to physics above the LHC energy scale.

- **TopFitter** is a fit of top quark effective operator Wilson coefficients to LHC (and Tevatron) data.

- We have previously presented our fit to Run I data to constrain the Wilson coefficients and are now moving onto Run II.

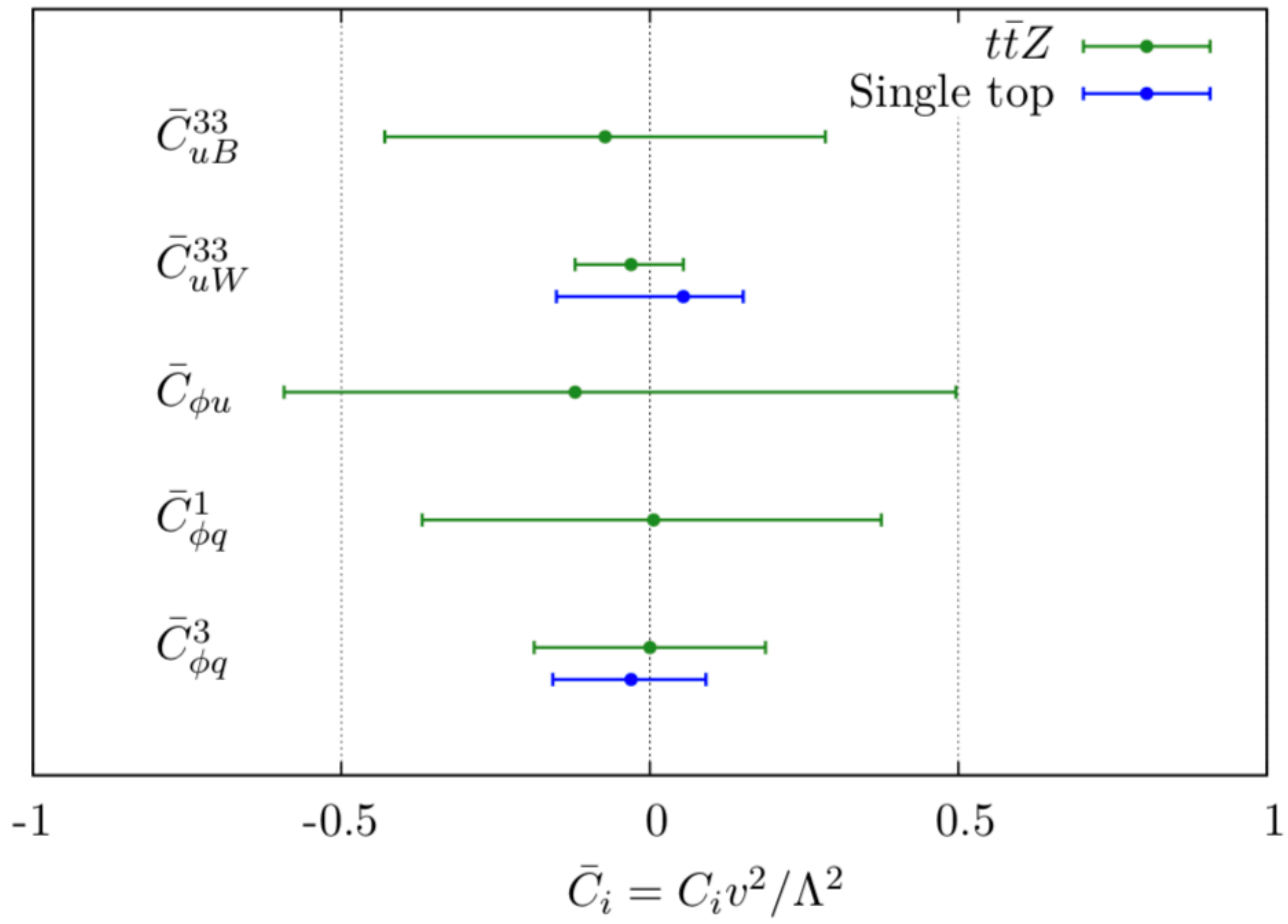
- Particle Level data presents a new challenge due to computing time. We have adopted a system of **linearisation** in the Wilson coefficients to overcome this.

- To make theorists' lives easier, I urge experiments to share their analyses on HEPData, make their Rivet analyses public and provide full correlation matrices.

- No sign of any deviation from the SM yet!

Additional Slides

Results from associated production



Much smaller cross-sections, so give weak constrains, but provides constraints on operators not previously accessible.

Results from top decays

Top decays $t \to Wb$ can also give us constraints on higher dimension operators.

Ratios of helicity fractions (of W) give information on a single Wilson coefficient.

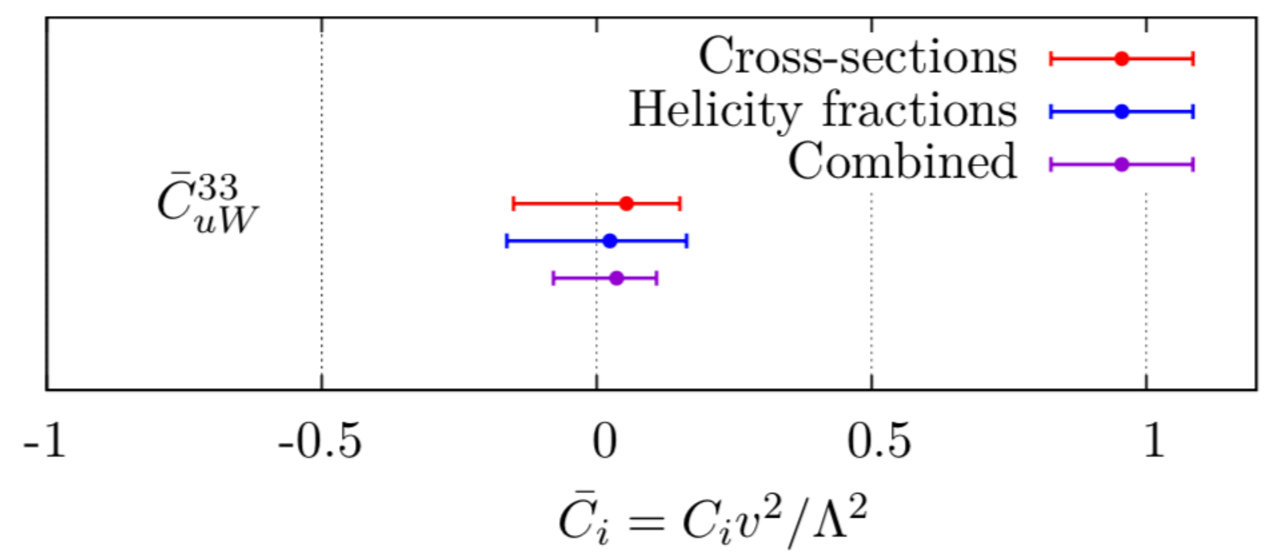
$$F_0 = \frac{(1-y^2)^2 - x^2(1+y^2)}{(1-y^2)^2 + x^2(1-2x^2+y^2)}$$

$$F_L = \frac{x^2(1-x^2+y^2) + \sqrt{\lambda}}{(1-y^2)^2 + x^2(1-2x^2+y^2)}$$

$$F_R = \frac{x^2(1-x^2+y^2) - \sqrt{\lambda}}{(1-y^2)^2 + x^2(1-2x^2+y^2)}$$

$$x = M_W/m_t$$

$$y = m_b/m_t$$



The result is comparable to that from single top.

Charge Asymmetry

At the Tevatron, one may measure the forward-backwards asymmetry, which can be altered from the SM prediction by additional four fermion operators:

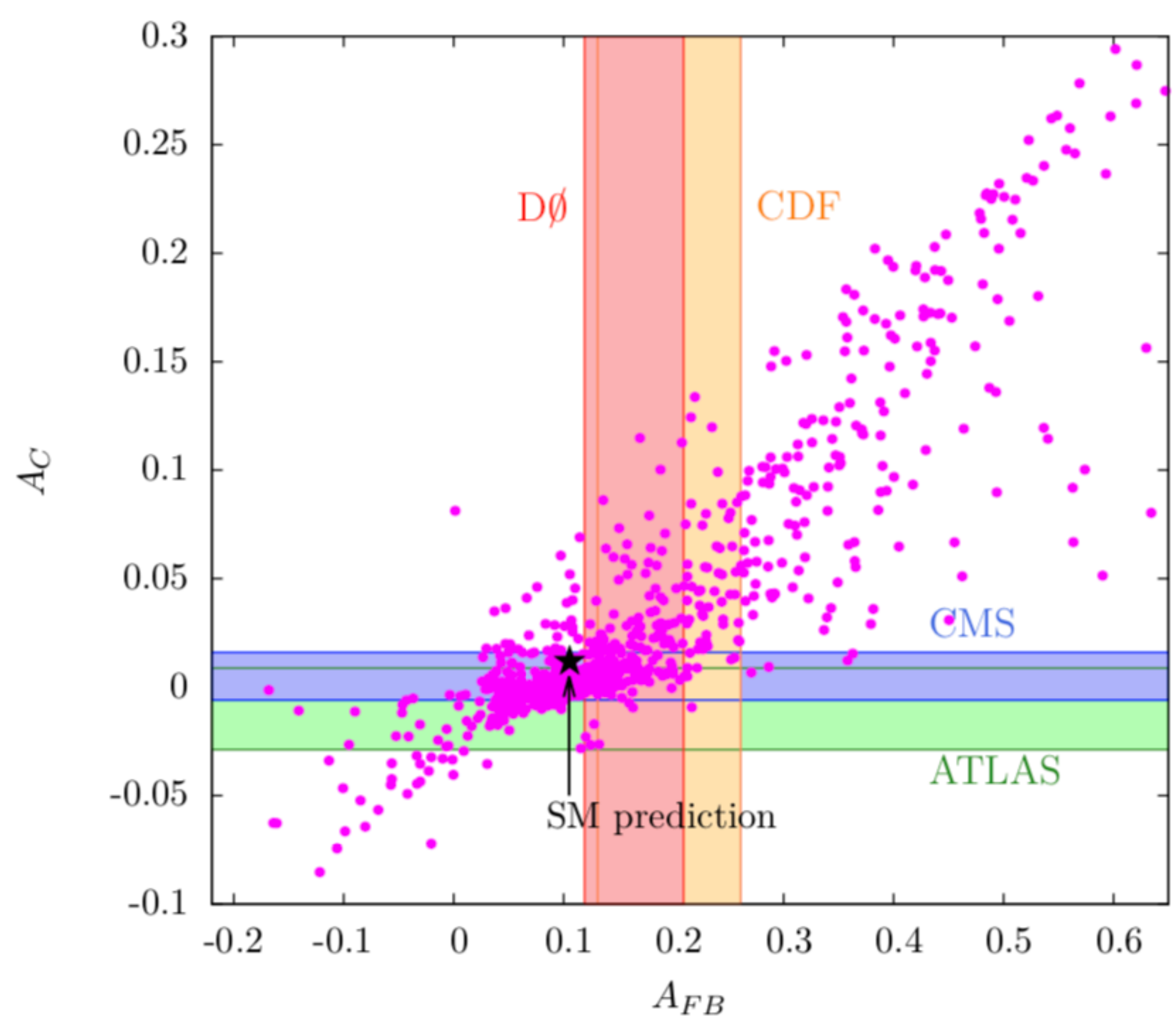
$$A_{\text{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad = (C_u^1 - C_u^2 + C_d^1 - C_d^2)\frac{3\hat{s}\beta}{4g_s^2\Lambda^2(3-\beta^2)}$$

$$(\Delta y = y_t - y_{\bar{t}})$$

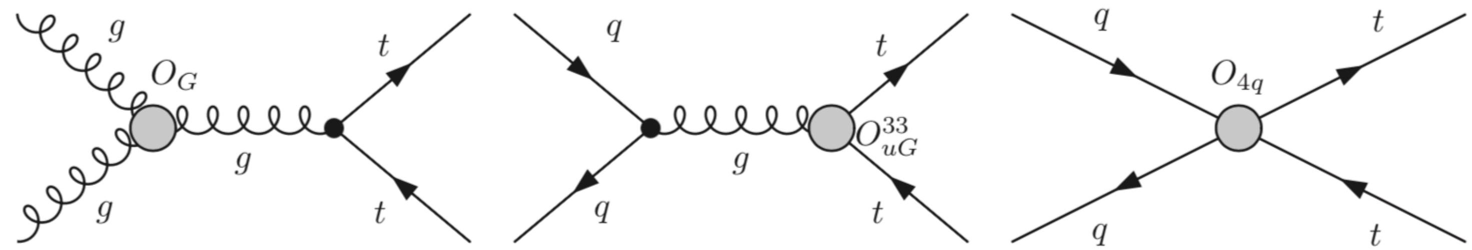
A related measurement at the LHC is the charge asymmetry:

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

NLO corrections are included
[Bernreuther and Si (2012)]



Top pair production



$$\mathcal{L}_{D6} \supset \frac{C_{uG}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G^A_{\mu\nu} + \frac{C_G}{\Lambda^2} f_{ABC} G^{A\nu}_{\mu} G^{B\lambda}_{\nu} G^{C\mu}_{\lambda} + \frac{C_{\varphi G}}{\Lambda^2}(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu}$$
$$+ \frac{C^{(1)}_{qq}}{\Lambda^2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) + \frac{C^{(3)}_{qq}}{\Lambda^2}(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q) + \frac{C_{uu}}{\Lambda^2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$$
$$+ \frac{C^{(8)}_{qu}}{\Lambda^2}(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u) + \frac{C^{(8)}_{qd}}{\Lambda^2}(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d) + \frac{C^{(8)}_{ud}}{\Lambda^2}(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$$

Single Top

$$\mathcal{L}_{D6} \supset \frac{C_{uW}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}\tau^I u)\,\tilde{\varphi}\,W^I_{\mu\nu} + \frac{C^{(3)}_{\varphi q}}{\Lambda^2} i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\gamma^\mu\tau^I q)$$
$$+ \frac{C_{\varphi ud}}{\Lambda^2}(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu d) + \frac{C_{dW}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}\tau^I d)\,\tilde{\varphi}\,W^I_{\mu\nu}$$
$$+ \frac{C^{(3)}_{qq}}{\Lambda^2}(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q) + \frac{C^{(1)}_{qq}}{\Lambda^2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) + \frac{C^{(1)}_{qu}}{\Lambda^2}(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$$

Associated production

$$\mathcal{L}_{D6} \supset \frac{C_{uW}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu}\tau^I u)\,\tilde{\varphi}\,W^I_{\mu\nu} + \frac{C_{uB}}{\Lambda^2}(\bar{q}\sigma^{\mu\nu} u)\,\tilde{\varphi}\,B_{\mu\nu} + \frac{C^{(3)}_{\varphi q}}{\Lambda^2} i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\gamma^\mu\tau^I q)$$
$$+ \frac{C^{(1)}_{\varphi q}}{\Lambda^2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q) + \frac{C_{\varphi u}}{\Lambda^2}(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)\,.$$