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TopFitter: elucidating new physics in the top sector

NExT Workshop

Overview

- Introduction to effective field theory.
- The TopFitter approach.
- Results.
- Outlook.

Motivation

- The SM has been highly successful...
- ...despite us having good reasons to doubt its validity (e.g. hierarchy problem, dark matter, naturalness).
- Plethora of BSM models that are not ruled out by precision tests.
- How, then, should we look for new physics?

Two paths to new physics

- Two main ways to search:
  - (i) **Choose a specific model** (e.g. SUSY, technicolor, composite Higgs), and confront with data. Many assumptions, although can choose "generic" scenarios.
  - (ii) **Effective theory**: write down possible corrections to SM on general grounds. Can be completely model-independent!
- The second approach is only valid if the energy scale of new physics is above that probed in data.
- Absence of clear new physics at LHC is a reasonable, but not necessarily sufficient, motivation.

Effective field theory

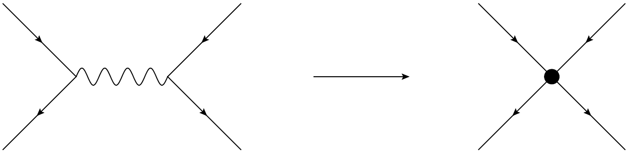
- Basic idea: can parametrise generic corrections to the SM using higher dimensional operators:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n)}$$

- Λ is the energy scale at which new physics first appears.
- Each operator $\mathcal{O}_i^{(n)}$ is of mass dimension n, and contains SM fields only. Gauge invariance manifest.
- $\{c_i^{(n)}\}$ are undetermined coefficients, that would be fixed by a particular new physics model.

EFT - clarifying example

- Imagine there is a new vector boson with mass M_V:



- The Feynman diagram on the left is $\propto g_V^2 (s - m_V^2)^{-1}$, where g_V is the coupling of V to the quarks.
- If V is very heavy, one may approximate

$$\frac{g_V^2}{s - M_V^2} \to -\frac{g_V^2}{M_V^2} \equiv \frac{c_i}{\Lambda^2},$$

with $c_i \propto g_V^2$, and Λ the new particle mass.

EFT - clarifying example

- The result for large M_V looks like an effective Feynman rule.
- Comes from an operator in the Lagrangian involving four (anti-)quark fields - indeed dimension six.
- Corrections to the propagator approximation involve more powers of $1/M_V^2$, so are further suppressed.
- Other effective operators are possible from different types of new physics particle at high energy.

Dimension six operators

- There is only a single independent dimension 5 operator, which generates neutrino masses and mixings.
- Dimension six operators originally classified by Buchmuller, Wyler; Burgess, Schnitzer; Leung, Love, Rao.
- Not all of these are independent - equations of motion can be used to reduce the set to 59 (Grzadkowski, Iskrzynski, Misiak, Rosiek). Usually referred to as the "Warsaw basis".
- The choice of operator basis is not unique. Some choices may be optimised for different applications (e.g. Higgs, top).
- Another choice commonly used in top physics is due to Zhang, Willenbrock.

Top physics in the Warsaw basis

- Potentially 16 operators affecting the top sector:

$$O^1_{qq} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) \qquad O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi}W^I_{\mu\nu} \qquad O^3_{\phi q} = i(\phi^\dagger\tau^I D_\mu\phi)(\bar{q}\gamma^\mu\tau^I q)$$

$$O^3_{qq} = (\bar{q}\gamma_\mu\tau^I q)(\bar{q}\gamma^\mu\tau^I q) \qquad O_{uG} = (\bar{q}\sigma^{\mu\nu}\lambda^A u)\tilde{\phi}G^A_{\mu\nu} \qquad O^1_{\phi q} = i(\phi^\dagger D_\mu\phi)(\bar{q}\gamma^\mu q)$$

$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u) \qquad O_G = f_{ABC}G^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda \qquad O_{uB} = (\bar{q}\sigma^{\mu\nu}u)\tilde{\phi}B_{\mu\nu}$$

$$O^8_{qu} = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u) \qquad O_{\tilde{G}} = f_{ABC}\tilde{G}^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda \qquad O_{\phi u} = (\phi^\dagger iD_\mu\phi)(\bar{u}\gamma^\mu u)$$

$$O^8_{qd} = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d) \qquad O_{\phi G} = (\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu} \qquad O_{\phi\tilde{G}} = (\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$$

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

- Each of these gives new effective Feynman rules, that can be included in top quark production / decay.
- Leads to a general, model-independent programme for constraining new physics in the top sector.

Global fits of EFT

- Assuming the new physics scale Λ is sufficiently high, we can constrain new physics in the top sector as follows:
  1. Pick a set of observables $\mathcal{O}$ involving tops (e.g. total cross-sections, p_T and invariant mass distributions, spin correlation measurements).
  2. Generate theory predictions $f(\mathbf{C})$ depending on EFT operator coefficients $\mathbf{C}$.
  3. For each choice of $\mathbf{C}$, define

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

     where ρ_{ij} is the correlation matrix, and

     $$\sigma_i = \sqrt{\sigma^2_{\mathrm{th},i} + \sigma^2_{\mathrm{exp},i}}.$$

  4. Minimise the χ^2, construct confidence contours etc.

Global fits of EFT

- Different datasets constrain different operators.
- For full model independence, need to include all operators in the top sector.
- Also need as many datasets as possible (top pair, single top, production and decay observables).
- This poses considerable technical challenges.

Challenges for Global Fits

- Theory predictions for observables should ideally include higher order QCD corrections, parton shower effects etc.
- It is not feasible to run Monte Carlo generators for all observables at each step in the χ^2 minimisation.
- Especially true given that the number of observables can be large (over 200 individual bins).
- Can make progress using techniques borrowed from Monte Carlo tuning (Buckley et. al.).

Analytic parametrisation

- A given observable (e.g. bin of a distribution) can be approximated by a fitting function:

$$f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i \le j} \gamma_{i,j}^b C_i C_j + \dots .$$

- Can sample $N \gg \dim\{c_i\}$ points in the parameter space, and fit coefficients β_i etc. using fast matrix inversion techniques.
- Resulting *interpolating function* can be used for very fast theory calculations, as input in the global fit.
- Technique well tested in the Professor MC tuning framework.
- Here it should do even better, as the polynomial dependence is exact for some observables at parton level.

TopFitter

- The TopFitter collaboration has produced a proof of principle global fit of top quark EFT (Buckley, Englert, Ferrando, Miller, Moore, Russell, White).
- Theory is LO parton level, supplemented by (bin-by-bin) K factors to estimate NLO QCD effects.
- Operators neglected if completely unconstrained by data, or if interference with SM is heavily suppressed - 12 remain.
- For full details, see arXiv:1506.08845 and arXiv:1512.03360.
- Related work (in top sector) by Perelló Roselló, Vos; Bylund, Maltoni, Tsinikos, Vryonidou, Zhang.

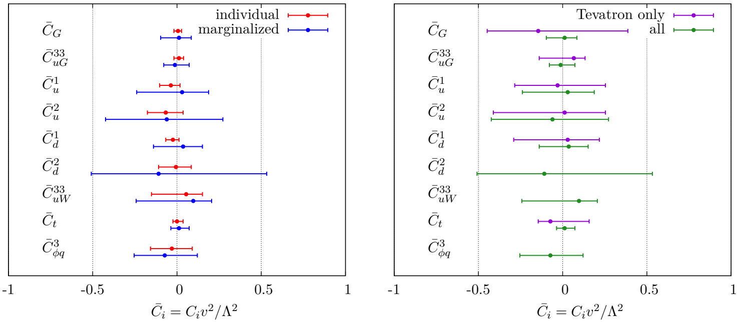
Datasets

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	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	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				

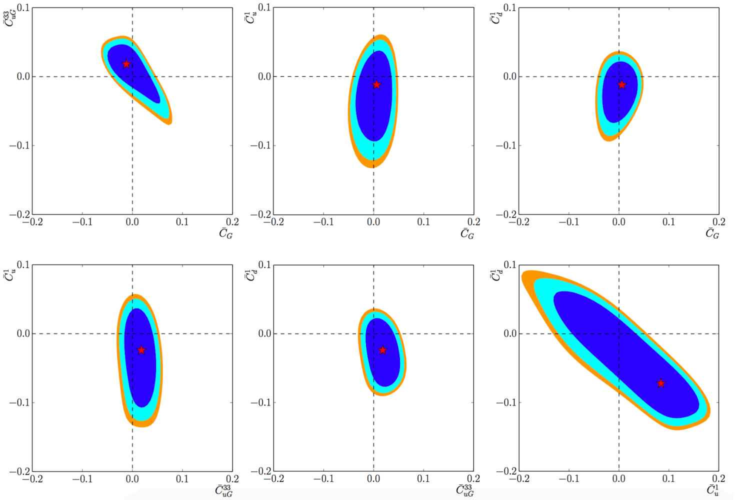
Datasets

- Mix of top pair, single top, and associated production.
- 227 individual measurements in total.
- Neglecting associated production, can decompose operators into orthogonal sets of 6 and 3, constrained by top pair and single top / decay observables respectively.
- Associated ($t\bar{t}V$) production currently does not change this picture much, due to large experimental uncertainties.
- Can constrain operator coefficients in two ways:
  - (i) By setting all other coefficients to zero;
  - (ii) By marginalising over all other operators.
- Results presented for both choices.

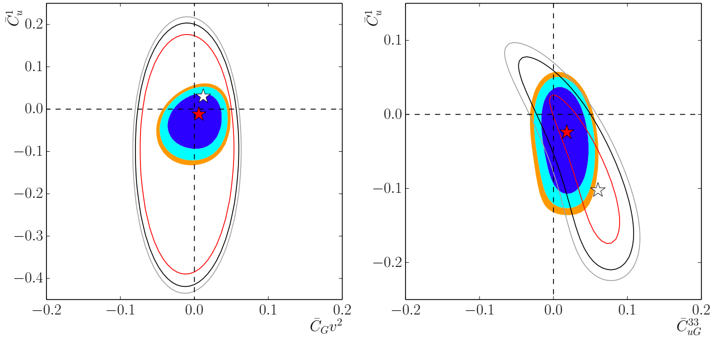
Results



- Upper 6 constrained by top pair, lower 3 by single top.
- Top pair more constraining, as expected.
- Can clearly see the importance of LHC data.
- Can also look at correlations between operators...

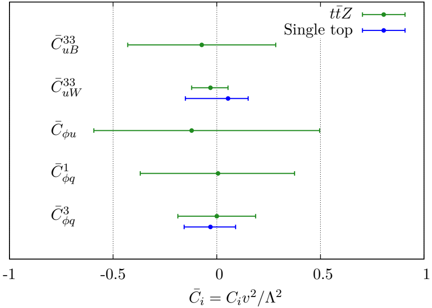


- Red star is best fit point.
- All results so far consistent with SM.



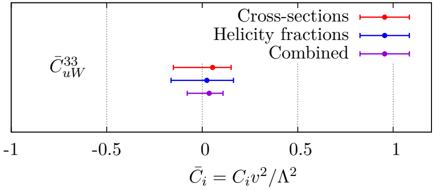
- Left plot: constraints with / without differential cross-section data.
- Right plot: constraints with / without LHC data.

Associated Production



- Have studied impact of $t\bar{t}V$ ($V = \gamma, Z$) measurements.
- Much weaker constraints than top pair where relevant (not shown).
- In some cases, $t\bar{t}V$ constraints better than single top.
- As more data becomes available, a full global fit will be necessary.

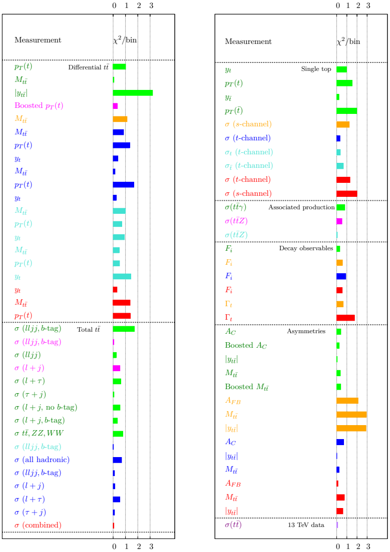
W boson helicity fractions



- There is a single operator constrained by both helicity measurements in top pair, and single top production.
- Constraints comparable from both sources.

- Not all helicity measurements can be included due to assumptions in experimental analysis.

Goodness of fit

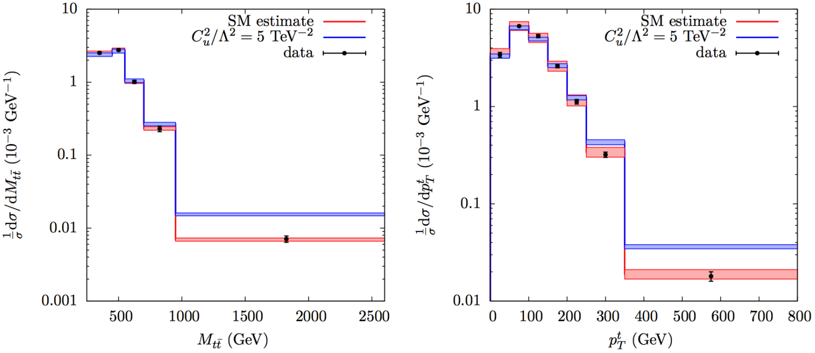


- Can examine goodness of fit (χ^2 per d.o.f.) for each dataset.
- No significant tensions observed at this stage.
- Will be interesting as more (precise) data is added.

What next?

- More statistics will be very useful, particularly for $t\bar{t}V$ and single top.
- Spin correlation measurements are crucial for pinning down the difference between CP even / odd operators.
- Some discussion would be useful about what is best to measure for polarisation-based observables.
- Jet substructure studies at 13 TeV would be very interesting, as they isolate the kinematic regime where EFT deviations are enhanced.

EFT and boosted kinematics



- Tails of distributions sensitive to EFT effects, even if total rates are not.

Conclusions

- Exciting time for top quark physics!
- Absence of clear new physics means its energy scale could exceed that of the data.
- Can then use EFT to probe new physics in a model-independent way.
- Have shown that global fits of EFT in the top sector are possible.
- Ongoing dialogue useful for enhancing usefulness of data and theory.