New Developments in TopFitter

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in collaboration with

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(Re)interpreting the results of new physics searches at the LHC

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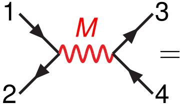
Outline

1. Introduction: Fitting EFT to Experimental Data
2. TopFitter Results for LHC Run I & Tevatron
3. New Features for LHC Run II
4. Preliminary Results
5. Summary

EFT as a Tool for the Search for New Physics

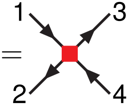
- Searches at the LHC did not find any New Physics so far
- Hint: New Physics at higher energy scale well separated from electro-weak scale $\rightarrow$ new heavy particles
- These heavy states are not directly producible at low energies but generate effective interactions suppressed by their mass M

schematically:



$$= (\overline{\psi}_1 \Gamma_\mu \psi_2) \frac{1}{p^2 - M^2} (\overline{\psi}_3 \Gamma^\mu \psi_4)$$

$$\xrightarrow{M \gg p} \frac{1}{M^2} (\overline{\psi}_1 \Gamma_\mu \psi_2)(\overline{\psi}_3 \Gamma^\mu \psi_4) =$$



New Physics mass scale

effective operator/interaction of (mass) dimension six

- many different kind of Lorentz and Gauge invariant dim.6 operators possible
- more terms in the $1/M^2$ expansion possible $\rightarrow$ dim.8, dim.10, ... (Standard Model Effective Field Theory — SMEFT)

Standard Model Effective Field Theory

$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}} &= \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{4-n}} \sum_i C_i^{(n)} \mathcal{O}_i^{(n)} \\
&= \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_i C_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \ldots
\end{aligned}
$$

Λ: scale of New Physics, $C_i^{(n)}$: Wilson coefficients, $\mathcal{O}_i^{(n)}$: dim.-n operators

The SMEFT allows us to parametrize high-scale New Physics in terms of Wilson coefficients.

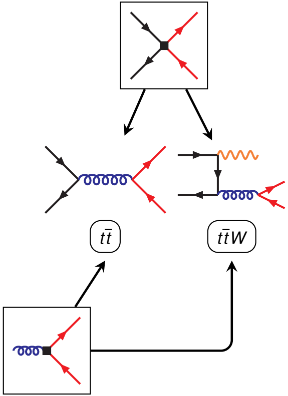
This is a very general approach to New Physics and facilitates constraining a large class of high-scale BSM models.

Top Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \cancel{\frac{1}{\Lambda}\sum_i C_i^{(5)}} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \cdots$$

- Operators of mass dimension 5 are not relevant for top physics
- There are 59 independent dim 6 operators in the SMEFT
  - counting all possible flavour configurations using 3 fermion generations: 2499
  - addional 4 B-violating operators possible (flavour not counted)
  - we use Warsaw basis [Grzadkowski et al., 2010]
- dim 6 operators relevant for top quark physics (not counting flavour):
  - 20 operators contain the top quark and other quarks and/or gauge bosons
  - 4 additional 4-fermion operators containing top quarks and leptons
- operators that do not contain the top quark also contribute to top quark physics but can often be constrained using other processes and are not considered for now (of course ultimate goal is a fully global fit)

Global approach to fitting top EFT parameters



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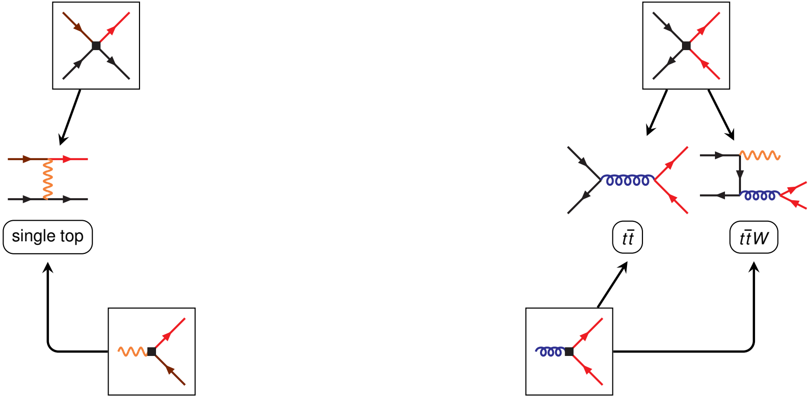

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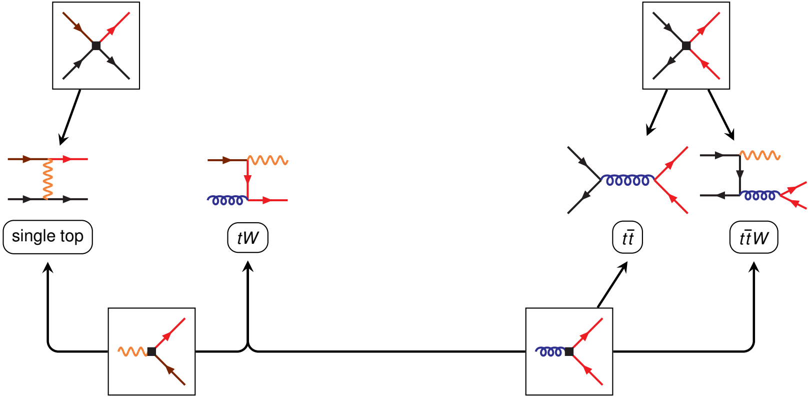

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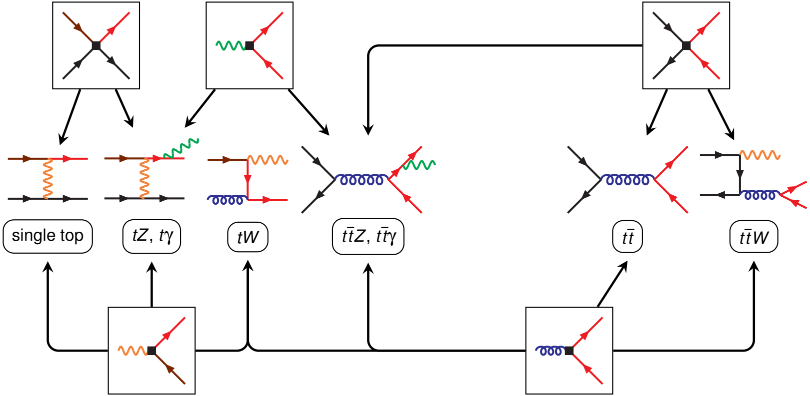

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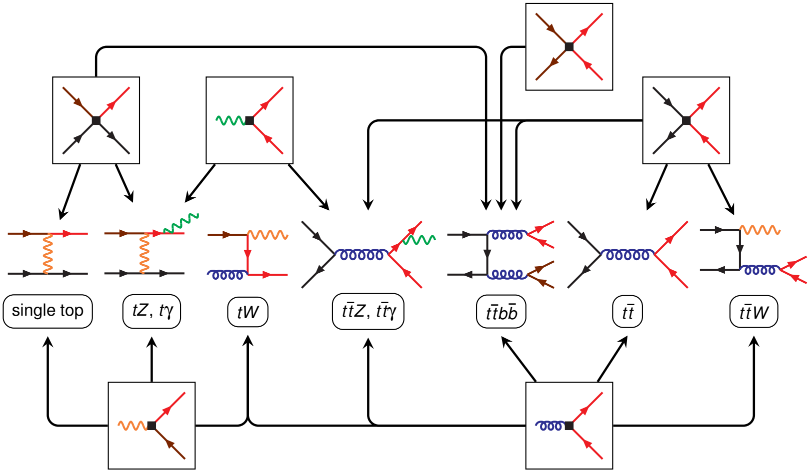

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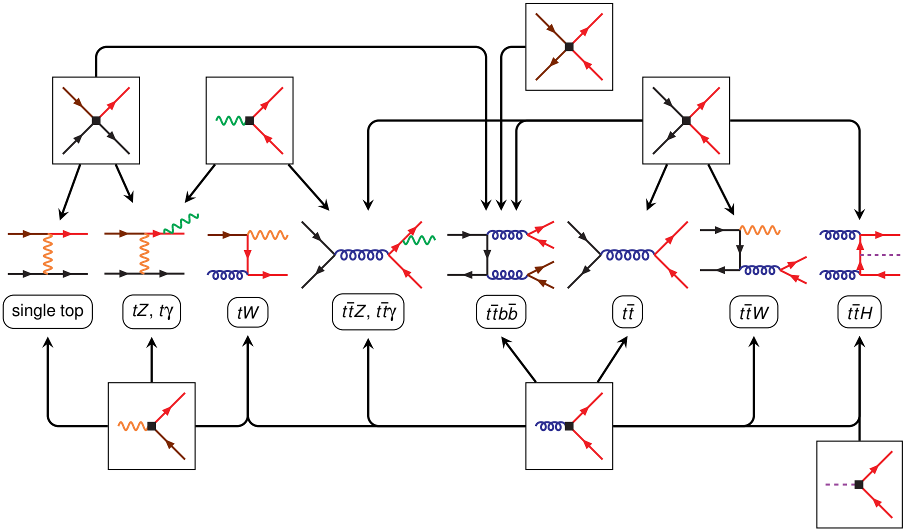

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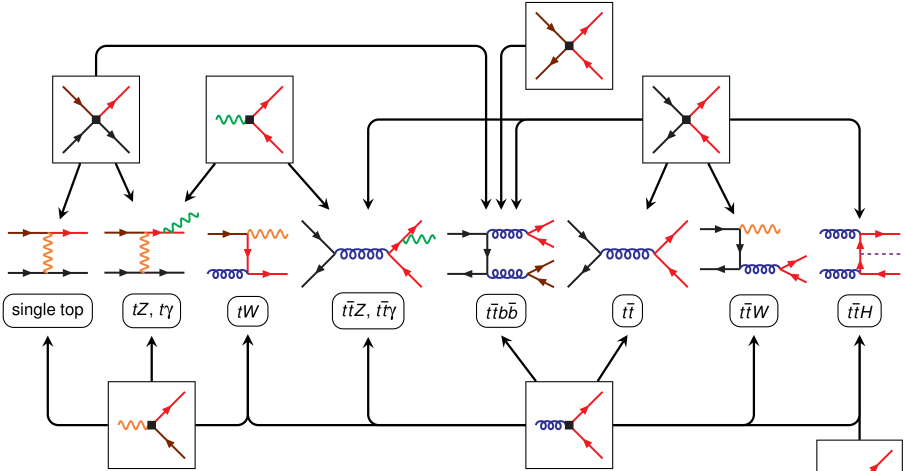
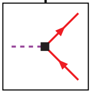


- several different operators can contribute to one vertex, e.g. with different particle helicities
- some processes are only sensitive to compinations of operators, e.g. single-top:
  $C_t = C_{qq}^{(3)1133} + \frac{2}{6}\left(C_{qq}^{(1)1331} - C_{qq}^{(3)1331}\right)$

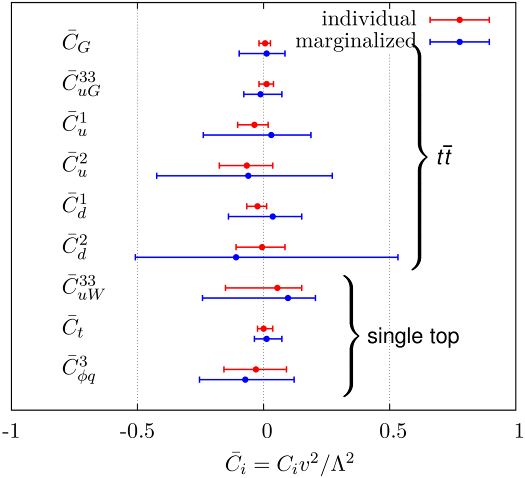


including more processes:

- sensitivity to more kinds of operators
- lift unconstrained directions in Wilson coefficient space
- improve bounds

TopFitter Results for LHC Run I and Tevatron

[1512.03360, Buckley et. al]



95% confidence

- individual constraints stronger than marginalized ones
- fit consistent with the SM

$$C^1_u = C^{(1)1331}_{qq} + C^{1331}_{uu} + C^{(3)1331}_{qq}$$
$$C^2_u = C^{(8)1133}_{qu} + C^{(8)3311}_{qu}$$
$$C^1_d = C^{(3)1133}_{qq} + \tfrac{1}{4} C^{(8)3311}_{ud}$$
$$C^2_d = C^{(8)1133}_{qu} + C^{(8)3311}_{qd}$$
$$C_t = C^{(3)1133}_{qq} + \tfrac{1}{6}\left(C^{(1)1331}_{qq} - C^{(3)1331}_{qq}\right)$$

Improvements for Run II

An increasing number of experimental results are given in terms of fiducial measurements at the particle level instead of or in addition to parton level results.

Aim

perform fit including particle level results

However, this is too costly if the Wilson coefficient parameter space has to be sampled pointwise especially if a larger number of different dim.-6 operators is involved.

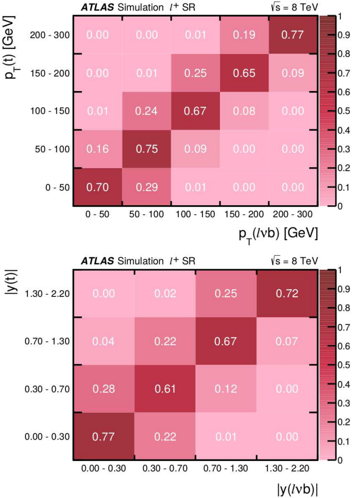
Improvement needed

speed up calculation by efficient use of matrix element

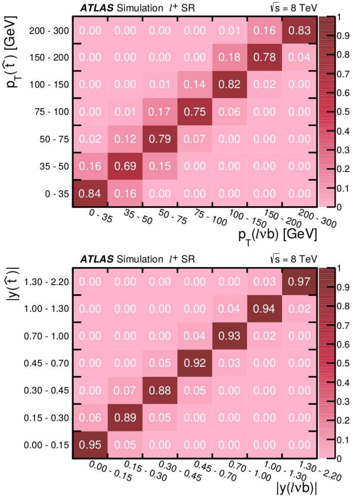
Motivation for using particle level results

Migration

Parton Level



Particle Level



Particle / Parton Level Bins

Reconstruction Level Bins

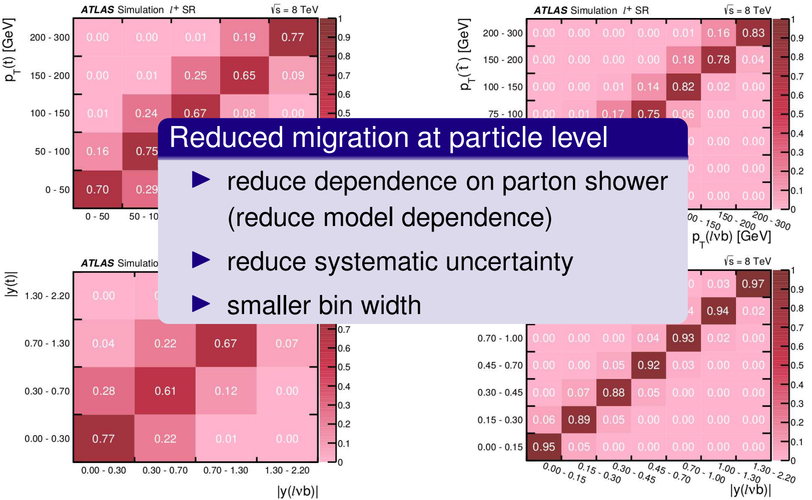
[ATLAS single top *t*-channel @ 13 TeV, 1702.02859]

Motivation for using particle level results

Migration

Parton Level | Particle Level

Particle / Parton Level Bins



Reduced migration at particle level

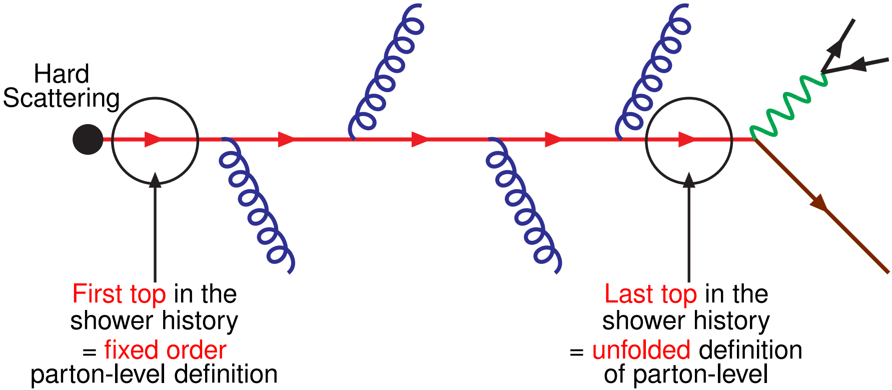
- reduce dependence on parton shower (reduce model dependence)
- reduce systematic uncertainty
- smaller bin width

Reconstruction Level Bins

[ATLAS single top *t*-channel @ 13 TeV, 1702.02859]

Motivation for using particle level results

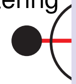
Mismatch between results unfolded to parton level and fixed order calculations



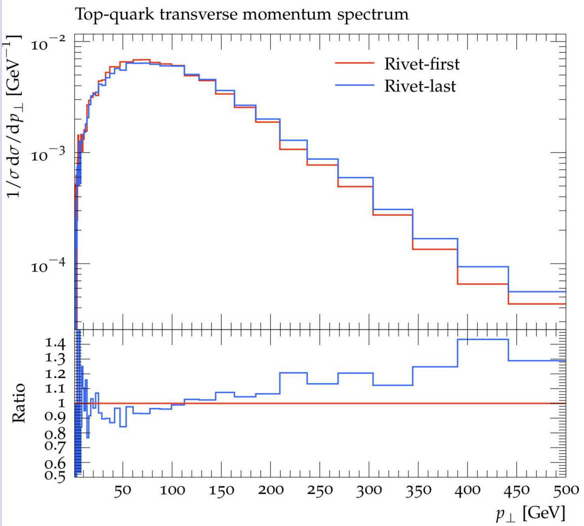
Motivation for using particle level results

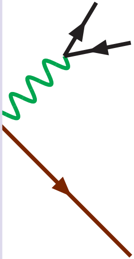
Mismatch … er calculations

Hard Scattering



First vs. last top Rivet analysis of $t\bar{t}$ events



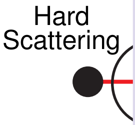


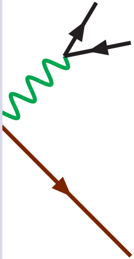
First t… showe… = fix… parton-le…

…e …y …tion …el

Motivation for using particle level results

Mismatch ... er calculations





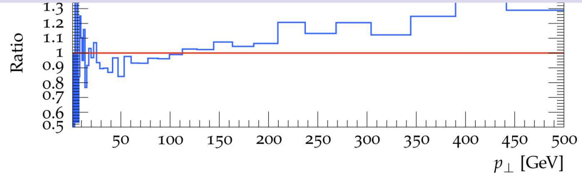
First t... show... = fixe... parton-le... e y tion l

discrepancy between first and last top in p_T tails

This could pose a problem for EFT fit where we expect an excess in the p_T tails from EFT contributions.

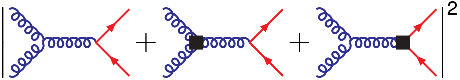
$\Rightarrow$ include parton shower in EFT predictions even if experimental results are presented at parton level

It would be favourable if the exp. collaborations would provide Rivet analyses also for the parton level case. Sometimes this is already done, e.g. 1801.02052 (ATLAS).



EFT: splitting up the matrix element

$$|\mathcal{M}|^2 =$$



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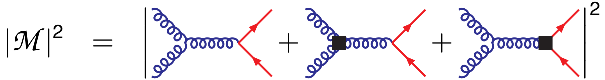
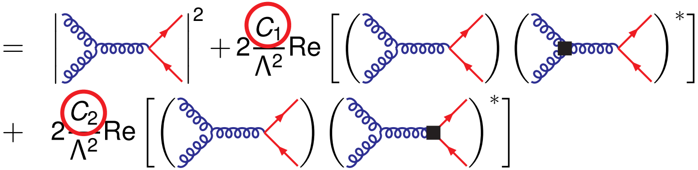


linear contribution



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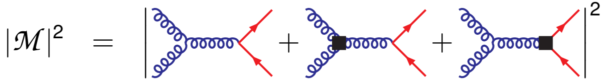
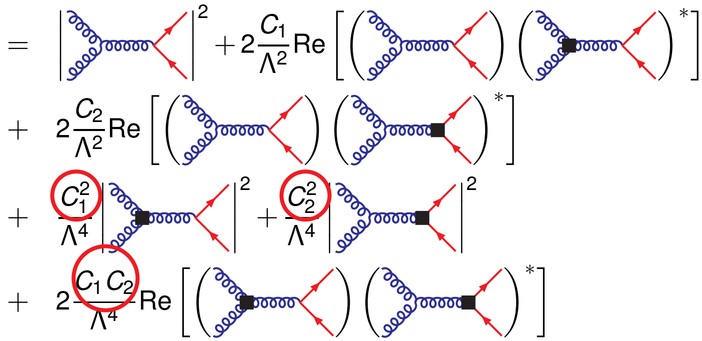


quadratic / bilinear contribution



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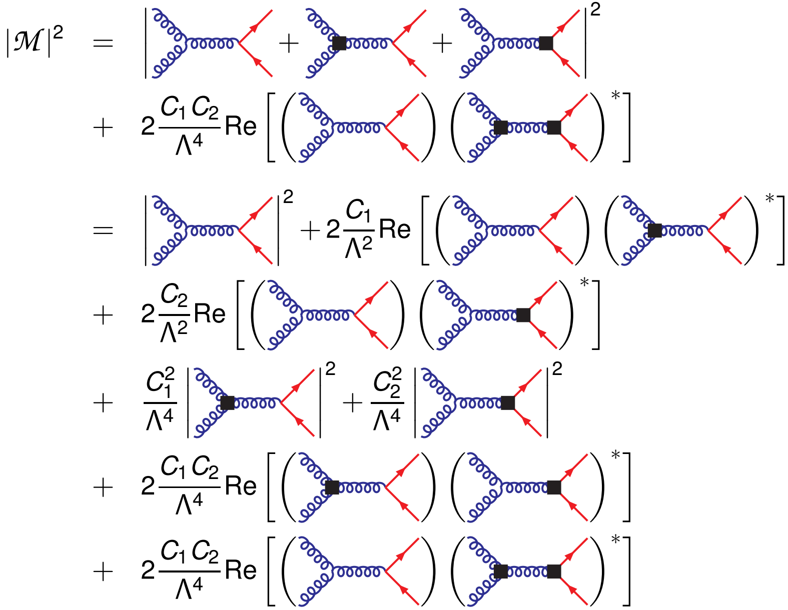

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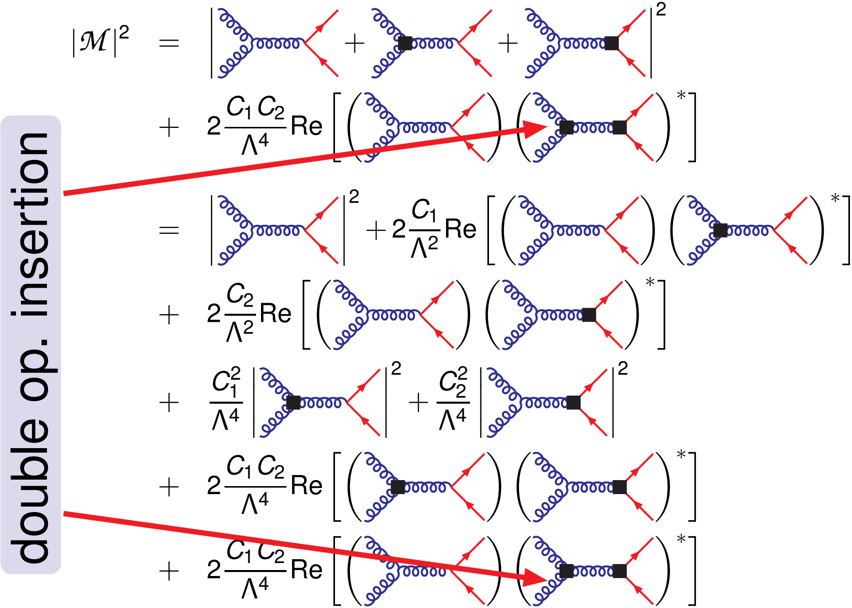

EFT: splitting up the matrix element

We neglect contributions to $\frac{1}{\Lambda^4}$ from dimension 8 operators.
This is valid for Wilson coefficients in the perturbative regime (linear contributions dominate over quadratic contributions).

This does not hold for cases in which dim. 8 operators are the leading EFT contribution

$$
\begin{aligned}
\left|\mathcal{M}\right|^2 &= \left|\mathcal{M}_{\mathrm{SM}}\right|^2 + 2\frac{C_1^{(6)}}{\Lambda^2}\mathrm{Re}\left[\mathcal{M}_{\mathrm{SM}}\left(\mathcal{M}_1^{(6)}\right)^*\right] + 2\frac{C_2^{(6)}}{\Lambda^2}\mathrm{Re}\left[\mathcal{M}_{\mathrm{SM}}\left(\mathcal{M}_2^{(6)}\right)^*\right] \\
&+ 2\frac{C_1^{(6)}C_2^{(6)}}{\Lambda^4}\mathrm{Re}\left[\mathcal{M}_1^{(6)}\left(\mathcal{M}_2^{(6)}\right)^*\right] + \frac{(C_1^{(6)})^2}{\Lambda^4}\left|\mathcal{M}_1^{(6)}\right|^2 + \frac{(C_2^{(6)})^2}{\Lambda^4}\left|\mathcal{M}_2^{(6)}\right|^2 \\
&+ 2\frac{C_1^{(6)}C_2^{(6)}}{\Lambda^4}\mathrm{Re}\left[\mathcal{M}_{\mathrm{SM}}\left(\mathcal{M}_{12}^{(6)}\right)^*\right] + 2\sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathrm{Re}\left[\mathcal{M}_{\mathrm{SM}}\left(\mathcal{M}_i^{(8)}\right)^*\right]
\end{aligned}
$$

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\end{aligned}$$

(differential) cross section can be split up in the same way:

$$\begin{aligned}
\sigma &= \sigma_{\mathrm{SM}} + \frac{C_1^{(6)}}{\Lambda^2}\sigma_{\mathrm{SM}-1} + \frac{C_2^{(6)}}{\Lambda^2}\sigma_{\mathrm{SM}-2} \\
&+ \frac{C_1^{(6)}C_2^{(6)}}{\Lambda^4}\sigma_{12} + \frac{(C_1^{(6)})^2}{\Lambda^4}\sigma_1 + \frac{(C_2^{(6)})^2}{\Lambda^4}\sigma_2 + \frac{C_1^{(6)}C_2^{(6)}}{\Lambda^4}\sigma_{\mathrm{SM}-12}
\end{aligned}$$

EFT: splitting up the matrix element

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This does not hold for cases in which dim. 8 operators are the leading EFT contribution

$$\left|\mathcal{M}\right|^2$$

Instead of scanning over $O(10^5) - O(10^6)$ parameter points one needs to sample only over n linear contributions, $n(n+1)/2$ squared and double insertion contributions (n = number of operators).

Example: for 10 operators, calculate 65 samples.

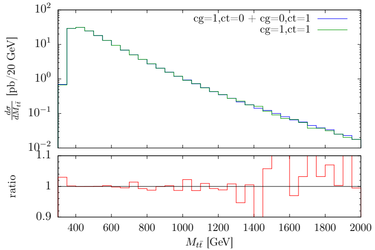
(differential) cross section can be split up in the same way:

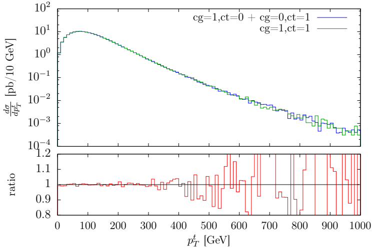
$$\sigma = \sigma_{SM} + \frac{C_1^{(6)}}{\Lambda^2}\sigma_{SM-1} + \frac{C_2^{(6)}}{\Lambda^2}\sigma_{SM-2}$$
$$+ \frac{C_1^{(6)}C_2^{(6)}}{\Lambda^4}\sigma_{12} + \frac{(C_1^{(6)})^2}{\Lambda^4}\sigma_1 + \frac{(C_2^{(6)})^2}{\Lambda^4}\sigma_2 + \frac{C_1^{(6)}C_2^{(6)}}{\Lambda^4}\sigma_{SM-12}$$

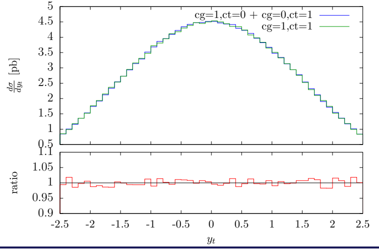
Numerical test of linear combination (parton level)

Example: $t\bar{t}$ production

$$\frac{d\sigma}{dX}(C_G = 1, C_{tG} = 1) = \frac{d\sigma}{dX}(C_G = 1, C_{tG} = 0) + \frac{d\sigma}{dX}(C_G = 0, C_{tG} = 1); \quad X = m_{t\bar{t}}, y_t\, p_T^t$$





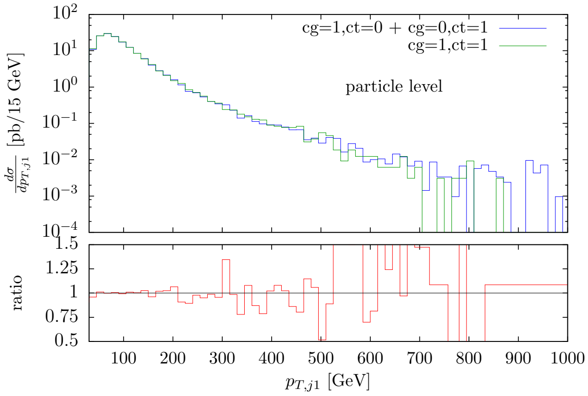


This example tests the linear behaviour of the $\mathcal{O}(1/\Lambda^2)$ contribution of the dim. 6 operators. We have also tested the quadratic terms.

Numerical test of linearisation (particle level)

Example:

Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8\text{TeV}$ [Eur.Phys.J. C75 (2015) 542]



using Rivet analysis: CMS_2015_I1370682 [CMS-PAS-TOP-15-011]

Linear combination also works at the particle level!

more extensive tests at the particle level using more complicated observables (e.g. gap function) and incl. dim.-6 $\mathcal{O}(1/\Lambda^4)$ contributions are investigated

TopFitter Setup

SMEFTsim [Brivio et al. 2017]

UFO model file
[Christensen et. al 2008]
[Degrande et al. 2011]

MadGraph
[Alwall et al. 2014]

$|\mathcal{M}_{\mathrm{SM}}|^2$ NLO SM | LO EFT $2\mathrm{Re}[\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{D6}}] + |\mathcal{M}_{\mathrm{D6}}|^2$

$n + \frac{n(n+1)}{2} \ll N$ samples

n: number of operators
N: usual number of param. space samples $\sim \mathcal{O}(10^5) - \mathcal{O}(10^6)$

parton shower: Pythia 8
[Sjöstrand et al. 2015]

particle level analysis: Rivet
[Buckley et al. 2010]

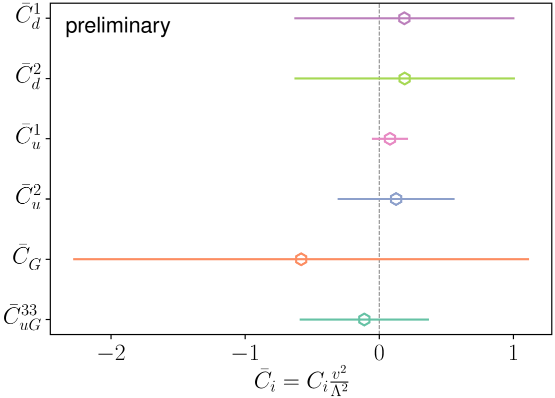
rescale observables

$2\mathrm{Re}[\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{D6}}] \sim C_i$

$|\mathcal{M}_{\mathrm{D6}}|^2 \sim C_i C_j$

$\chi^2(\mathbf{C}) = \sum_{ij}(f_i(\mathbf{C}) - E_i)V^{-1}_{ij}(f_j(\mathbf{C}) - E_j)$ χ^2 ← Exp. Data

Results for Particle-Level Trial Fit



- uses only fiducial differential cross sections from one ATLAS analysis: [Phys.Rev. D98 (2018) no.1, 012003]
- non-marginalized constraints

- theoretical uncertainties: renorm. and fact. scale, jet matching scale, no PDF uncertainty
- theo. and exp. uncertainty added in quadrature
- only linear (interference, $\mathcal{O}(1/\Lambda^2)$) contribution for dim.-6 operators taken into account $\rightarrow$ C_G constraints much worse than in previous fit

Single-Top Fit: Experimental Data

Analysis	fiducial	parton-level	differential	total
t-channel				
1702.08309 (ATLAS)		x	x	
1702.02859 (ATLAS)	x	x	x	x
1610.00678 (CMS)		x		x
1609.03920 (ATLAS)		x		x
1511.02138 (CMS)		x	x	
1503.05027 (TEV)		x		x
1406.7844 (ATLAS)		x	x	x
1403.7366 (CMS)		x		x
1209.4533 (CMS)		x		x
s-channel				
1511.05980 (ATLAS)		x		x
1402.5126 (TEV)		x		x
tZ-channel				
1712.02825 (CMS)		x		x
1710.03659 (ATLAS)		x		x
tγ-channel				
1808.02913 (CMS)	x			x

available data except *Wt*-channel

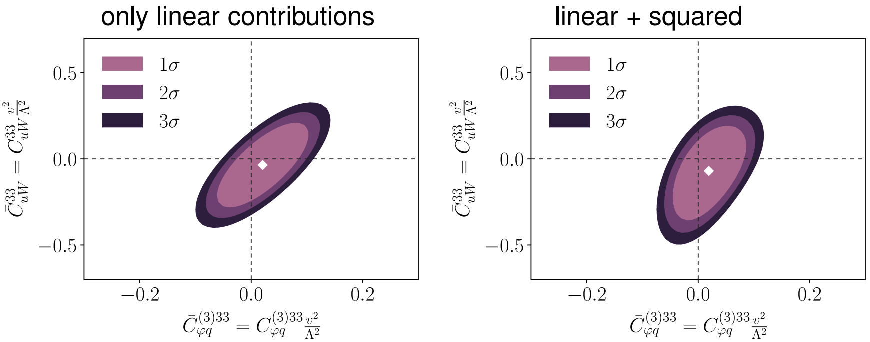
blue: used in this fit (only *s* and *t* channel, only tot. and diff. cross sections)
$\rightarrow$ only parton level

Single-Top Fit: Results

preliminary

linear vs. squared dim.-6 contributions

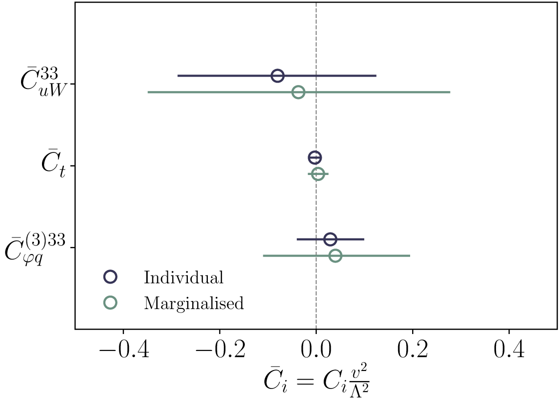
$C_{\varphi q}^{(3)33}$ vs. C_{uW}^{33}



Single-Top Fit: Results

preliminary

comparison of marginalized vs. individual bounds



- 95% CL

Summary

- Effective Field Theory can be used to search for new physics in a general model independent way. It is complementary with direct searches, being sensitive to physics above the LHC energy scale.
- TopFitter is a fit of Wilson coefficients of effective operators relevant for top physics to LHC and Tevatron data
- Fit to experimental parton-level results at the Tevatron and LHC Run I are available
- NEW: Fit data at the particle-level
- overcome computational limitations by using matrix elements efficiently and scan parameter space by linear combination instead of random sampling
- proof of principle: first preliminary fit results for $t\bar{t}$
- fit of single top relevant Wilson coefficients to t-channel and s-channel data including study of the influence of dim-6 terms of order $O(1/\Lambda^4)$
- work in progress.....

Thank you for your attention!