Improving top EFT constraints using $t\bar{t}$ polarisation and spin-correlation observables

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Top 2017

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2. Spin-sensitive observables
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Motivations

The large top mass $m_t \sim 173$ GeV $\leftrightarrow y_t \sim 1$ in the SM $\iff$ **t** ♡ **H**

- Quantum fluctuations of t-quark are chief troublemaker creating the hierarchy problem.
- Naturalness $\implies$ BSM correct this to stablize the electroweak scale $\implies$ should expect NP not far away from t-physics!
- $m_t > m_W + m_b \implies \Gamma_t \gg \Lambda_{\mathrm{QCD}}$. Decay rate $>$ hadronisation timescale, so spin information preserved in decay products.
- Measuring angular distributions gives additional information on production/decay mechanism, sensitive to $\mathcal{P}, \mathcal{CP} \ldots$

Question:

What are the prospects for constraining sources of NP, in angular distributions sensitive to t-polarisation and spin-correlations?

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Non-resonant BSM with the SMEFT

The future divides into two possibilities:

- $\sqrt{s}_{\text{LHC}} \geq \Lambda_{\text{NP}}$: resonances kinematically accessible, can measure properties, answer questions. The 'good ending'.
- $\sqrt{s}_{\text{LHC}} < \Lambda_{\text{NP}}$: states decoupled, can observe only inconclusive off-shell effects. The 'bad ending'.

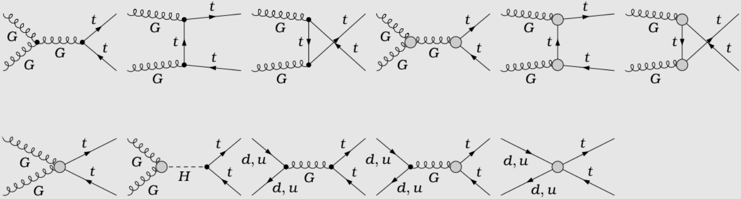
In the latter case, can construct general gauge-invariant $\mathcal{L}_{\text{SMEFT}}$ from operators at each order in $1/\Lambda_{\text{NP}}$, constrain unknown C_i:

$$\mathcal{L}_{\text{SMEFT}} \equiv \mathcal{L}^{(4)}_{\text{SM}}(\{\Phi_{\text{SM}}\}) + \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}(\{\Phi_{\text{SM}}\}) + \ldots$$

Powerful, but. . .

- 2499 free C_i without flavour restrictions (59 for $n_f = 1$). . .
- Validity delicate issue, dep. on BSM matching, strength of limits. . .
- Beyond LO hard (mixing, redundancy, n_{diags}, evanescent ops. . .)

The SMEFT playbook



In a process of interest - e.g. $t\bar{t}$ production - typically:

- A subset of operators $\mathcal{O}_i$ will contribute vertices $\propto {}^{C_i}/_{\Lambda^2}$
- Leading effects (*usually*) linear, from interference :
  $$d\sigma_{\text{D6}} \propto \frac{C_i}{\Lambda^2} \int d\Pi \; \Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{D6}}) + \mathcal{O}(\Lambda^{-4}) \quad = \quad \frac{q^2}{\Lambda^2} C_i \times (\ldots)$$
- Can calculate observables to $\mathcal{O}(\Lambda^{-2})$, fit C_i to data, identify sensitive observables/regions, interpret by matching to BSM. . .

An example: new physics in $t\bar{t}$ production

Coefficient C_i	Operator $\mathcal{O}_i$
C_G	$f_{ABC}G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$
C_{uG}^{33}	$(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G_{\mu\nu}^A$
$C_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$
$C_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$
C_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$
$C_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$
$C_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$
$C_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$

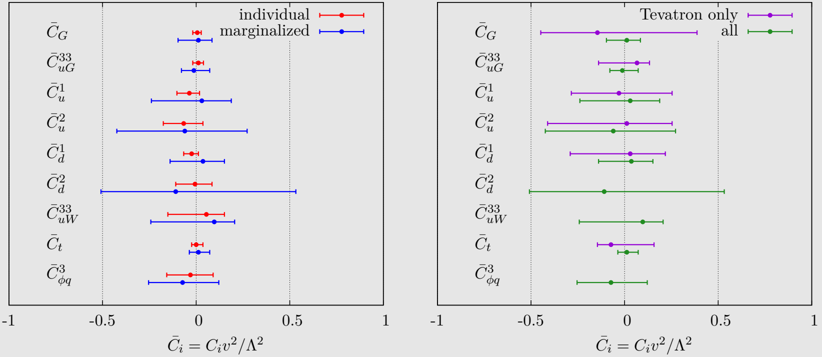
Table: $\mathcal{O}_i$ $(pp \to t\bar{t})$: viable UV models

EFT can constrain multiple BSM models simultaneously:

- Heavy coloured fermions, technihadrons. . .
- Composite top scenarios
- W' & Z's
- Heavy (axi)gluons. . .
- To compare hypotheses, allow all $\mathcal{O}_i$ simultaneously $\Longrightarrow$ **global fit**

TopFitter: global χ^2 fit, unfolded LHC+TeVatron measurements of $t\bar{t}$ and single top $\leftrightarrow$ MG5_aMC@NLO+UFO, NLO SM + LO EFT **(1512.03360)**

TopFitter v1.0 at a glance - Global 95% C.I.



Nothing surprising: all consistent with SM within 95% CI, but limits consistent and hierarchy intuitively understandable. Fit dominated by differential measurements, $t\bar{t}$ > single top, LHC $>$ TeVatron, $gg > q\bar{q}\ldots$

Lessons from TopFitter

Limits 'weak': $m_{t\bar{t}} = \mathcal{O}(1\text{TeV})$ range resolved in differential datasets

$\Longrightarrow$ **weakly coupled UV unconstrained**! How to do better?

- Add new measurements (e.g. $t\bar{t} + X$ differential) $\Leftrightarrow$ consolidate existing bounds + become sensitive to new $\mathcal{O}_i$ ...
- Fit to particle level data $\Leftrightarrow$ reduce SM bias, $\mathcal{O}_i$ in decays...
- Calculate NLO corrections to EFT $\Leftrightarrow$ reduce theory uncertainties, open up sensitivity to $\mathcal{O}_i$ in loops...
- Study exotic channels $\Leftrightarrow$ find enhanced sensitivity to classes of operator (e.g. $t\bar{t}t\bar{t}$ production - Cen's talk)...
- Include distributions of decay products $\Leftrightarrow$ sensitive to $\mathcal{P}, \mathcal{CP}$-odd $\mathcal{O}_i$, break C_i degeneracies, derive complementary bounds...
- Collect $\mathcal{L}_{\text{int}}$, reduce ϵ_{syst} $\Leftrightarrow$ tighten all existing limits...

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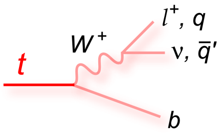
Beyond parton-level distributions in $t\bar{t}$ production

- QCD conserves $\mathcal{P}$ $\implies$ chiral ψ^4 operators aren't resolved in cross section distributions: only four linear combinations of six C_i.
- Can recover information in observables sensitive to spins of $t\bar{t}$ $\implies$ break degeneracies in fit
- The left-handed weak interaction constrains $t \to bW \to b\bar{\psi}\psi$ decay $\implies$ spin aligned with l/d direction in t-rest frame

i	b	W^+	l^+	$\bar{d}/\bar{s}$	u/c
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

Table: Analysing power $\alpha_i \propto \hat{s} \cdot \hat{p}_i$ of i



Inferring $t\bar{t}$ spins from decay modes

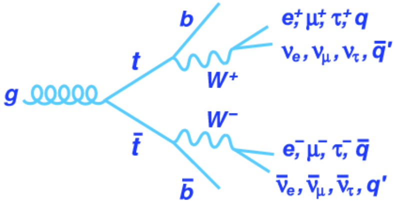


Figure: $t\bar{t}$ decay modes

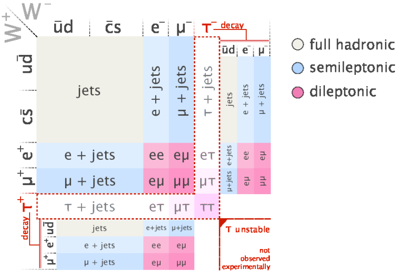


Figure: Credit: Nazar Bartosik

Use $l^{\pm}$ or light jet three-momentum as proxy to top spin. 2 options:

- Semileptonic: $BR \sim 30\%$, but $\alpha_i^{\text{jet}} \sim 50\%\, \alpha_i^d$
- Dileptonic: $BR \sim 5\%$, max α_i. $2 \times \nu \implies$ reconstruction harder

The $t\bar{t}$ spin-density matrix

$\mathcal{M}^{*\,\alpha'\beta'}_{xy\to t\bar{t}}\,\mathcal{M}^{\alpha\beta}_{xy\to t\bar{t}}$ with $t,\bar{t}$ spin indices explicit $\equiv$ $t\bar{t}$ **spin density matrix**

$$R^{t\bar{t}} \propto \left[A^I\,\mathbb{1}\otimes\mathbb{1} + \tilde{B}_i^+\,\sigma^i\otimes\mathbb{1} + \tilde{B}_i^-\,\mathbb{1}\otimes\sigma^i + \tilde{C}_{ij}\,\sigma^i\otimes\sigma^j\right]$$

NP $\Leftrightarrow$ $\mathbf{C_i}$ **contribute to functions** $\mathbf{A}, \mathbf{B_i}, \mathbf{C_{i\,j}}$ appropriately

This information is propagated through the W-decay to the distributions:

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_+\mathrm{d}\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}_1'\cdot\hat{\ell}_+ + \mathbf{B}_2'\cdot\hat{\ell}_- - \hat{\ell}_+\cdot C'\cdot\hat{\ell}_-\right)$$

$\mathrm{d}\Omega_\pm = \mathrm{d}\cos\theta_\pm \mathrm{d}\phi_\pm \equiv$ angular phase space measures for ℓ^+, ℓ'^-.

Lepton angular distributions probe $\mathcal{P}$-odd sources of polarisation, $\mathcal{P}/\mathcal{CP}$-even and odd spin correlations in the production mechanism

NP in angular distributions

Fix (an arbitrary) set of axes along which to quantize the $t\bar{t}$ spins. Each contribution then isolated in the 1D distributions:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\pm} = \frac{1}{2}\left(1 + B_{1,2}\,\cos\theta_\pm\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\xi_{ab}} = \frac{1}{2}\left(1 - C\xi\right)\,\ln\left(\frac{1}{|\xi_{ab}|}\right)\,, \xi_{ab} = \cos\theta_+\cos\theta_-$$

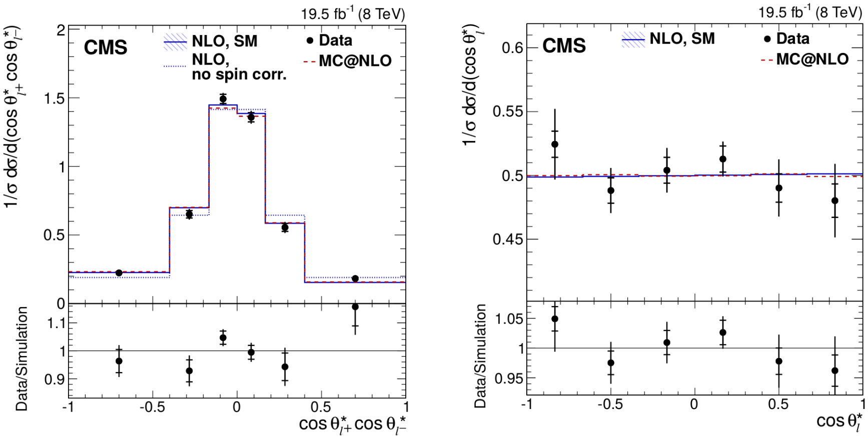
Can make a choice of axes to simplify dependence on NP in production mechanism. **(Bernreuther et al 1508.05271)** proposed:

$$\hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}})\,, \quad \hat{\mathbf{k}} \equiv \hat{t}_{\text{ZMF}}\,, \quad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,, y_p = \hat{\mathbf{p}}_p.\hat{\mathbf{k}}$$

with $\cos\theta^\pm$ measured with respect to the axes $\hat{\mathbf{a}}$, $\hat{\mathbf{b}} = \hat{\mathbf{r}}, \hat{\mathbf{k}}, \hat{\mathbf{n}}$.

Each B, C contains dependence on $t\bar{t}$ kinematics $\propto$ operator coefficients. c.f. in QCD, spin-correlations along $\hat{\mathbf{k}}$ degrade for high $m_{t\bar{t}}$.

CMS $\cos\theta_l^{\pm}$ for $t\bar{t}$ spin corr. + t-polarisation (1601.01107)



Unfolded measurements of $\cos\theta^{\pm}$ distributions, probing spin correlations $C(k,k)$ (left) and polarisation coefficients $B(k)$ (right)

Operators ↔ observables

Correlation	$\mathcal{CP}$-properties	sensitive to
$B_1(r) + B_2(r)$	$\mathcal{P}$-odd, $\mathcal{CP}$-even	$\hat{c}_{VA}$, $\hat{c}_3$
$B_1(k) + B_2(k)$	$\mathcal{P}$-odd, $\mathcal{CP}$-even	$\hat{c}_{VA}$, $\hat{c}_3$
$C(n, n)$	$\mathcal{P}$-, $\mathcal{CP}$-even	$\hat{c}_{VV}$, $\hat{c}_1$, $\hat{\mu}_t$
$C(r, r)$	$\mathcal{P}$-, $\mathcal{CP}$-even	$\hat{c}_{VV}$, $\hat{c}_1$, $\hat{\mu}_t$
$C(k, k)$	$\mathcal{P}$-, $\mathcal{CP}$-even	$\hat{c}_{VV}$, $\hat{c}_1$, $\hat{\mu}_t$
$C(r, k) + C(k, r)$	$\mathcal{P}$-, $\mathcal{CP}$-even	$\hat{c}_{VV}$, $\hat{c}_1$, $\hat{\mu}_t$

Subset of correlation coefficients in **(Bernreuther et al 1508.05271)**. Angular distributions w.r.t. axes $(r, k, n \ldots)$ probe different $\mathcal{O}_i$.

- Each distribution is sensitive to subset of $t\bar{t}$ dimension-six operators.
- Here we'll pick one each for the polarisation angle and spin-correlation distributions.

ATLAS $\Delta\phi_{\hat{\ell}_+\hat{\ell}_-}$, + $\cos\theta_k$

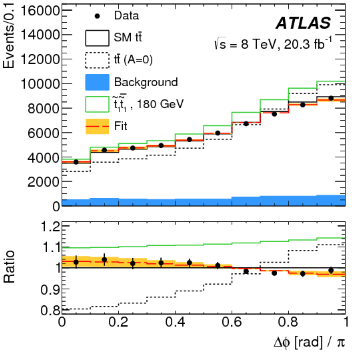


Figure: **(1412.4742)**

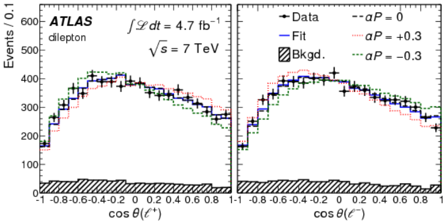


Figure: **(1307.6511)**

Reconstructed distributions from ATLAS. $\cos\theta_k^{\pm}$ sensitive to $\frac{1}{3}\Sigma_i \mathbf{C_{ii}}$ (left), $\mathbf{B}_k$ (right)

Sensitivity of observables

	NLO+EW	$\propto \hat{\mu}_t$
$C(r,\ r)$	$0.071^{+0.008}_{-0.006}$	$2.475^{+0.020}_{-0.019}$
$C(k,\ k)$	$0.331^{+0.002}_{-0.002}$	$0.917^{+0.006}_{-0.006}$
--	--	$\propto \hat{c}_{VA}$
$B_{1/2}(r)$	$(3.2^{+2.3}_{-1.7}) \cdot 10^{-3}$	$0.210^{+0.009}_{-0.009}$
$B_{1/2}(k)$	$(8.0^{+3.4}_{-2.4}) \cdot 10^{-3}$	$1.607^{+0.051}_{-0.052}$

Table: Numerical sensitivity of obs $\propto C_i$ (parton-level). Errors: $\mu = m_t/2 \leftrightarrow 2m_t$

(Bernreuther et al 1508.05271, 1003.3926)

$$\mathcal{O}_{\text{CMDM}} = -\frac{g_s}{2m_t}\hat{\mu}_t \bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu}$$

$$\mathcal{O}_{VA} = \frac{g_s^2}{2m_t^2}\hat{c}_{VA}(\bar{q}\gamma^\mu T^a q)(\bar{t}\gamma_\mu\gamma_5 T^a t)$$

- C generated by LO QCD, B negligible at NLO(+EW).
- How are these changed by parton shower, acceptance cuts, reconstruction. . . ?
- Oft-studied CMDM overlaps with global fit: compare sensitivity
- Double differential: resolve $m_{t\bar{t}}$ dependence, enhance NP. Gains?

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Overview

We aim to quantify discriminating power in particle-level, reconstructed spin angle distributions both inclusively and differentially in $m_{t\bar{t}}$. So:

- Dimension-six $t\bar{t}$ operators implemented as FeynRules $\to$ UFO model
- Parton-level events for LOEFT in MadGraph5_ aMC@NLO
- Generate hadron-level pseudodata samples with improved kinematics via UMEPS jet merging in Pythia8
- Particle-level analysis, reconstruction in Rivet framework
- Map pseudodata to Run II $\mathcal{L}_{\text{int}}$ scenarios, impose toy ϵ_{syst}
- Construct binned log-likelihood for 1D/2D YODA histograms, form frequentist confidence intervals for excluding C_i assuming SM

Analysis Summary

Leptons	$p_T > 25$ GeV
	$\|\eta\| < 4.2$
Missing energy	$E_T^{\text{miss}} > 60$ GeV
Jets	anti-k_T $R = 0.4$
	$p_T > 30$ GeV , $\|\eta\| < 2$
	b-tag w/ 70% efficiency
	1% fake rate w/ FastJet
Reconstruction	Pair b jets, $l^{\pm}$ using MT2
	ν solutions w/ MAOS
Require	$\geq$ 2 jets w/ $\geq$ 2 b-tags
	$\geq 1 \times l^{+}, l^{-}$

Table: Event selection criteria in Rivet analysis

- Need two ν four momenta from one missing E_T vector. Eight solutions for $p_{\nu}, p_{\bar{\nu}}$
- We use M_{T2}-assisted on-shell reconstruction method (**(Cho et al. 0810.4853)**) to guess transverse components of p_t, assuming on-shell production
- Performance $m_{t\bar{t}}$ dependent

Simulated observables

Plot the distributions for θ_i measured w.r.t. $\hat{n}, \hat{r}, \hat{k}$

$$\frac{d\sigma}{d\cos\theta_\pm}, \quad \frac{d^2\sigma}{d\cos\theta_\pm dm_{t\bar{t}}} \qquad \frac{d\sigma}{d\xi_{ab}}, \quad \frac{d^2\sigma}{d\xi_{ab} dm_{t\bar{t}}}$$

using MC pseudodata, for SM and two choices of $\hat{\mu}_t, \hat{c_{VA}}$ within current 95% bounds (if constrained). Isolate EFT contribution in each bin as:

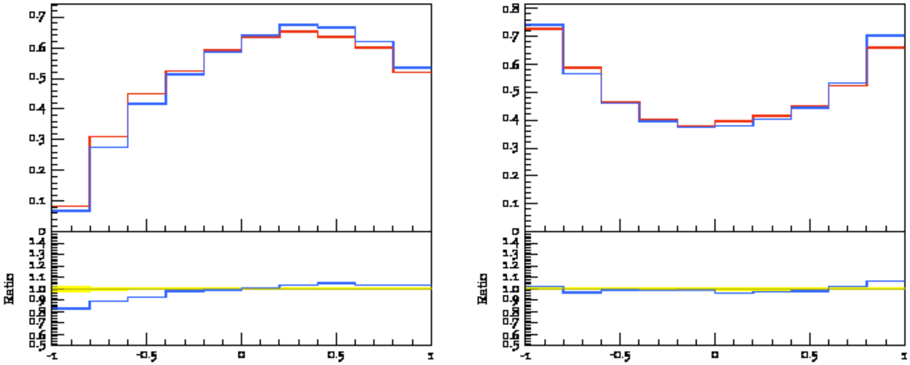
$$\left(\frac{d\sigma}{d\mathcal{O}_i}\right)_{\text{SMEFT}} - \left(\frac{d\sigma}{d\mathcal{O}_i}\right)_{\text{SM}} \propto \mu\hat{c}\left(\frac{d\sigma}{d\mathcal{O}_i}\right)_{\text{int}} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Can scale dimension-six contribution by attaching an arbitrary μ to extrapolate to different $\hat{c}$ values (provided don't get too large).

Fix $\mathcal{L}_{\text{int}}$, assign bins poisson likelihoods with SM count as background:

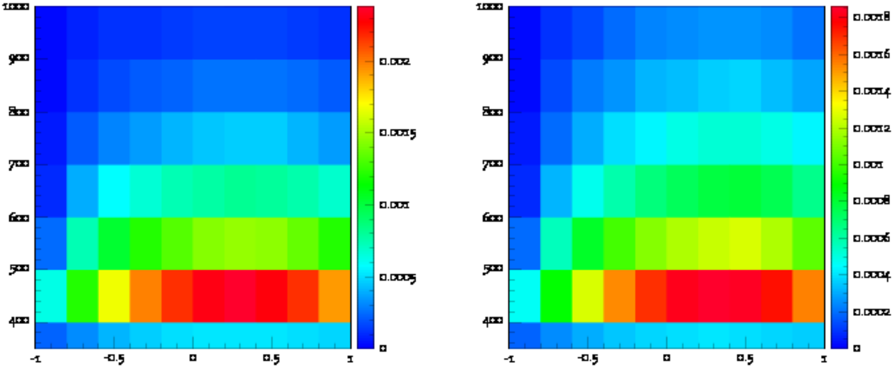
$$\mathcal{L}_0 = \frac{e^{-B}B^n}{n!} \qquad \mathcal{L}_1 = \frac{e^{-(\mu S+B)}(\mu S+B)^n}{n!} \qquad \mathcal{L}_{\text{tot}} = \prod_{i=1}^{n_{\text{bins}}} \mathcal{L}_i$$

$\cos\theta_{\pm}$ polarisation distributions - $c_{\hat{VA}}$ vs SM



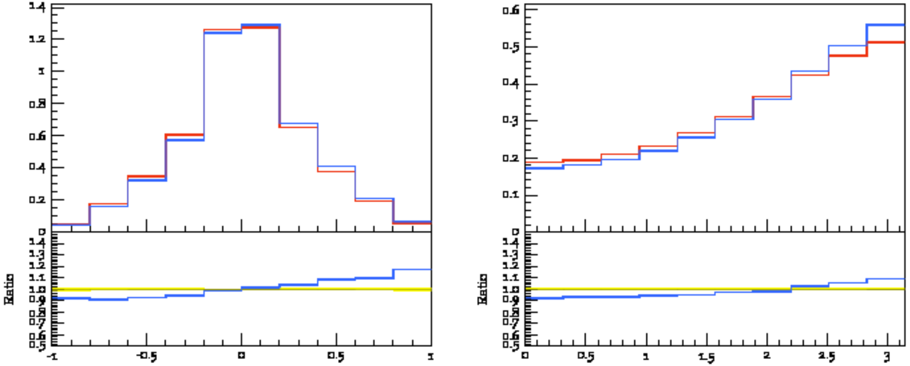
Left (Right): Reconstructed $\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta^{+}_{k(r)})}$ distributions for the SM and $c_{\hat{VA}} = 0.25$ sensitive to $\mathbf{B_k}$ $(\mathbf{B_r})$.

2D $\cos\theta_{\pm}$ polarisation distributions - $\hat{c_{VA}}$ vs SM



Left (Right): Reconstructed $\frac{1}{\sigma}\frac{d^2\sigma}{dm_{t\bar{t}}d(\cos\theta^{+}_{k(r)})}$ distributions for the SM ($\hat{c_{VA}} = 0.25$) sensitive to $\mathbf{B_k}$ $(\mathbf{B_r})$.

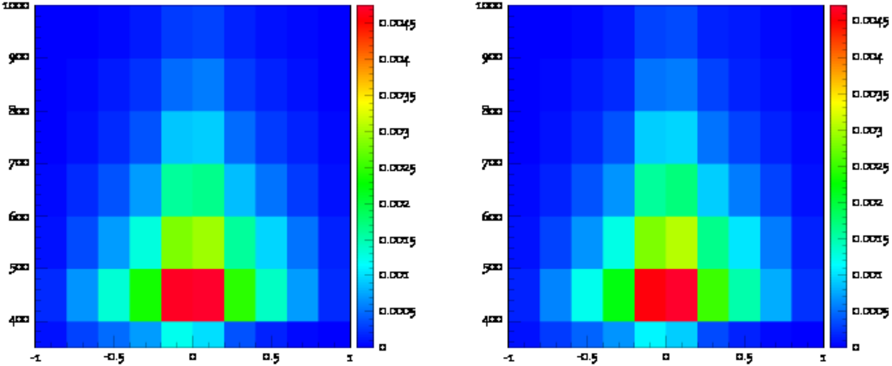
$\cos\theta_+ \cos\theta_-$ spin correlation distributions - $\hat{\mu}_t$ vs. SM



Left (Right): $\frac{d\sigma}{d(\cos\theta_n^+ \cos\theta_n^-)}$ $\left(\frac{d\sigma}{d(\Delta\phi_{l^+l^-}}\right)$ for the SM, $\hat{\mu}_t = 0.05$.

Sensitive to $\mathbf{C_{nn}}$ $\left(\frac{1}{3}\Sigma_i \mathbf{C_{ii}}\right)$.

2D $\cos\theta^+ \cos\theta^-$ spin-correlation distributions - $\hat{\mu}_t$ vs SM



Left (Right): Reconstructed $\frac{1}{\sigma}\frac{d^2\sigma}{dm_{t\bar{t}}d(\cos\theta_n^+ \cos\theta_n^-)}$ distributions for the SM ($\hat{\mu}_t = 0.05$) sensitive to $\mathbf{C_{nn}}$.

Limit-setting

- We use log-likelihood ratio $q = -2\log(\frac{\mathcal{L}_1}{\mathcal{L}_0})$ as test statistic
- Systematic uncertainties simulated as flat $\%$ gaussian uncertainty on the background imposed on all bins
- Theory uncertainties not represented here (yet) ($\sim$ negligible in (1D) measurements). Flat NNLO k-factor **(Czakon et al 2013)**.
- Build up LLR p.d.f.s under $f_{0/1}(q)$ for SM and SM+D6 respectively
- Can form confidence intervals $CL_{(s+)b} = \int_{LLR_{obs}}^{\infty} f_{(1)0}(q)dq$ assuming observe SM expectation
- Exclude μ at 95$\%$ confidence level $\iff$ $CL_s = \frac{CL_{s+b}}{CL_b} < 0.05$

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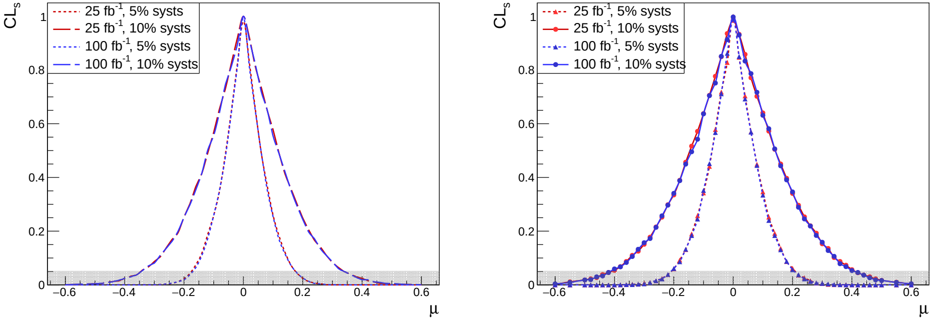
1D exclusion limits - $\hat{\mu}_t = 0.05$



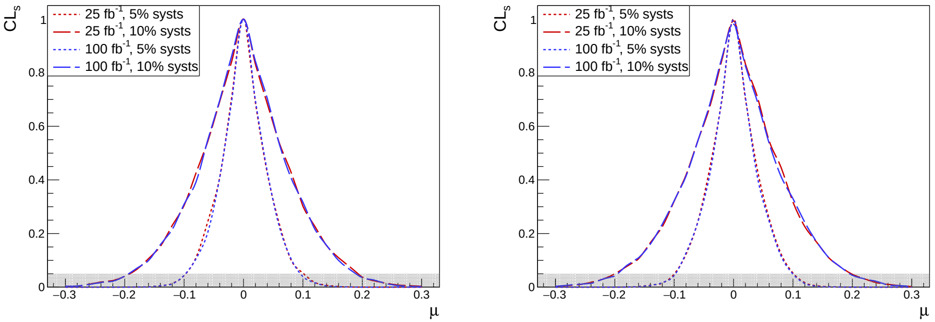
Left (Right): CLs vs μ for $\frac{d\sigma}{d(\xi_{rr})}$, $\left(\frac{d\sigma}{d(\xi_{kk})}\right)$

$|\hat{\mu}_t^{10\%}| \lesssim 0.018, |\hat{\mu}_t^{5\%}| \lesssim 0.009$ $\quad$ $|\hat{\mu}_t^{10\%}| \lesssim 0.02, |\hat{\mu}_t^{5\%}| \lesssim 0.01$

$-0.053 < \hat{\mu}_t < 0.042$ CMS, 8TeV **(1601.01107)**

$-0.068 < \hat{\mu}_t < 0.029$ TopFitter w/ 8TeV p_T spectra, ATLAS+CMS

1D exclusion limits $\hat{c}_{VA} = 0.25$

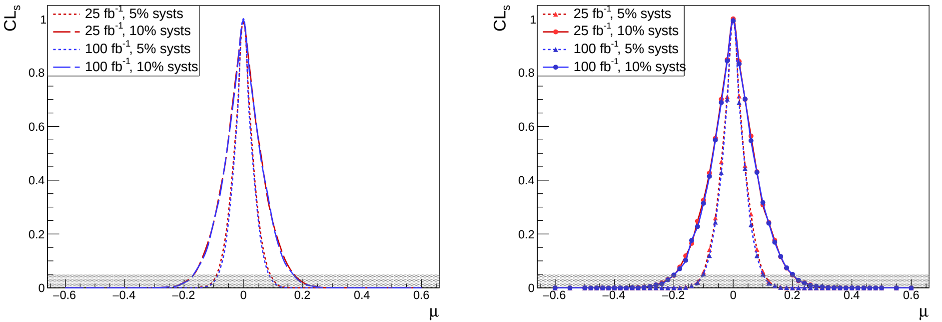


Left (Right): CLs vs μ for $\frac{d\sigma}{d(\cos\theta_r^+)}$, $\left(\frac{d\sigma}{d(\cos\theta_k^+)}\right)$.

$|\hat{c}_{VA}^{10\%}| \lesssim 0.08, |\hat{c}_{VA}^{5\%}| \lesssim 0.043$ $\quad$ $|\hat{c}_{VA}^{10\%}| \lesssim 0.048, |\hat{c}_{VA}^{5\%}| \lesssim 0.025$

(c.f. Typical TopFitter ψ^4 limits $\lesssim 0.1$)

2D exclusion limits - $\hat{\mu}_t = 0.05$



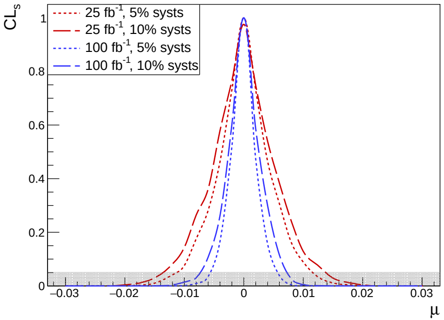
Left (Right): CLs vs μ for $\frac{d^2\sigma}{dm_{tt}d(\xi_{rr})}$, $\left(\frac{d^2\sigma}{dm_{tt}d(\xi_{kk})}\right)$

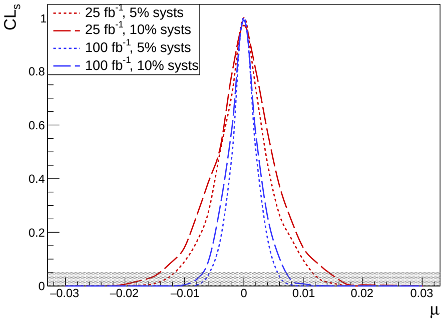
$|\hat{\mu}_t^{10\%}| \lesssim 0.008, |\hat{\mu}_t^{5\%}| \lesssim 0.004$ $\quad$ $|\hat{\mu}_t^{10\%}| \lesssim 0.01, |\hat{\mu}_t^{5\%}| \lesssim 0.005$

$-0.053 < \hat{\mu}_t < 0.042$ CMS, 8TeV **(1601.01107)**

$-0.068 < \hat{\mu}_t < 0.029$ TopFitter w/ 8TeV p_T spectra, ATLAS+CMS

2D exclusion limits $\hat{c}_{VA} = 0.25$





Left (Right): CLs vs μ for $\frac{d^2\sigma}{dm_{tt}d(\cos\theta_r^+)}, \left(\frac{d^2\sigma}{dm_{tt}d(\cos\theta_k^+)}\right)$.

$|\hat{c}_{VA}^{10\%,\,25}| \lesssim 0.0035, |\hat{c}_{VA}^{5\%\ 25}| \lesssim 0.0028$

$|\hat{c}_{VA}^{10\%,\,100}| \lesssim 0.0019, |\hat{c}_{VA}^{5\%\ 100}| \lesssim 0.0015$

$|\hat{c}_{VA}^{10\%,\,25}| \lesssim 0.0035, |\hat{c}_{VA}^{5\%,\,25}| \lesssim 0.003$

$|\hat{c}_{VA}^{10\%,\,100}| \lesssim 0.0018, |\hat{c}_{VA}^{5\%,\,100}| \lesssim 0.0015$

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Outlook

Several directions for improvement:

- Test remaining operators, convert basis, compare with TopFitter v1.0
- Include spin-correlated decays with MadSpin for NLO SM $\longrightarrow$ differential SM NLO k-factors
- NLO matched+merged parton shower, state-of-the-art kinematics
- Evaluate theory uncertainties with explicit scale variation, quantify results on 2D distributions
- Expand likelihoods to asymmetries and normalized distributions
- Investigate quadratic EFT behaviour, treat EFT uncertainties
- Compare with lepton + jets. . .

Summary and Conclusions

- $t\bar{t}$ spin-sensitive observables offer a unique opportunity to break degeneracies in global fit and probe discrete symmetry violating NP
- We studied the expected sensitivity from $t\bar{t}$ polarisation and spin correlation observables to EFT coefficients
- For two representative dimension-six operators, preliminary results suggest existing 13TeV data should better constrain their coefficients than existing 8TeV p_T spectrum measurements
- 2D double-differential $m_{t\bar{t}}$ observables naively have the potential to improve bounds by a factor of ~ 2, warranting further study and treatment of theory uncertainties

Contents

1. Constraining Top EFT
2. Spin-sensitive observables
3. Analysis
4. Preliminary results
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TopFitter v1.0 - Overview

Idea: perform a simultaneous fit of the $(\mathcal{CP}-\text{even})$ operators affecting (single + pair) top production and decay observables. In a nutshell:

- Use FeynRules/MadGraph5_aMC@NLO/MadAnalysis toolchain, sample observables at fixed points in $\{C_i\}$ space
- Approximate linear dep. of observables on C_i $\implies$ use polynomial interpolation method (Professor) to fill parameter space
- Perform a χ^2 fit using this and publicly available LHC and TeVatron (differential and rate) measurements

Goals: Search for non-resonant NP signals, identify and understand sensitivity to operators, compare limits with resonance searches, establish feasibility of 9+ dimensional fit. . .

Backup: TopFitter Setup (I)

- MadGraph+UFO observables supplemented by approximate NLO QCD corrections, modelled by differential SM-only $k-$factors generated with MCFM and verified with aMC_@NLO
- Theory uncertainties estimated by independently varying $\mu_{\text{central}}/2 < \mu_{\mathrm{R,F}} < 2\mu_{\text{central}}$, $\mu_{\text{central}} = m_t$.
- PDF uncertainties were estimated by generating events using the NLO NNPDF23, MSTW2008, and CT10 PDF sets, according to the PDF4LHC prescription.
- For top pair total inclusive cross-sections we used global K-factors from NNLO QCD with soft gluons resummed to NNLL accuracy

Central value taken as estimate and the **width of the envelope** (including scale variations) as the total theoretical uncertainty.

Backup: TopFitter Setup (II)

- Total of 195 measurements, predominantly Run I LHC $t\bar{t}$, single top (differential) cross sections, but also $A_{\rm FB}$, $A_{\rm C}$, $\Gamma_{\rm top}$ and $W-$helicity fractions and $\sigma_{t\bar{t}V}$
- Measurements included quoted in terms of parton-level unfolded quantities (far more abundant, computationally less expensive)
- Experimental uncertainties (stat, syst, lumi) included as quoted, correlations between bins from unfolding included wherever quoted (otherwise assumed to be uncorrelated)
- Interpolated $f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i\leq j} \gamma_{i,j}^b C_i C_j + \ldots$ introduces parametrisation error $\lesssim 5\%$ from explicit MC
- Confidence intervals constructed from minimizing $\chi^2/\text{d.o.f.}$ allowing all C_i to vary (marginalized), or each to vary individually

TopFitter v1.0 - Datasets

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production			
Total cross-sections:			
ATLAS	7	lepton+jets	1406.5375
ATLAS	7	dilepton	1202.4892
ATLAS	7	lepton+tau	1205.3067
ATLAS	7	lepton w/o b jets	1201.1889
ATLAS	7	lepton w/ b jets	1406.5375
ATLAS	7	tau+jets	1211.7205
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573
ATLAS	8	dilepton	1202.4892
CMS	7	all hadronic	1302.0508
CMS	7	dilepton	1208.2761
CMS	7	lepton+jets	1212.6682
CMS	7	lepton+tau	1203.6810
CMS	7	tau+jets	1301.5755
CMS	8	dilepton	1312.7582
CDF + DØ	1.96	Combined world average	1309.7570
Single top production			
ATLAS	7	t-channel (differential)	1406.7844
CDF	1.96	s-channel (total)	1402.0484
CMS	7	t-channel (total)	1406.7844
CMS	8	t-channel (total)	1406.7844
DØ	1.96	s-channel (total)	0907.4259
DØ	1.96	t-channel (total)	1105.2788
Associated production			
ATLAS	7	$t\bar{t}\gamma$	1502.00586
ATLAS	8	$t\bar{t}Z$	1509.05276
CMS	8	$t\bar{t}Z$	1406.7830

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Differential cross-sections:			
ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
CDF	1.96	$M_{t\bar{t}}$	0903.2850
CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
Charge asymmetries:			
ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
Top widths:			
DØ	1.96	Γ_{top}	1308.4050
CDF	1.96	Γ_{top}	1201.4156
W-boson helicity fractions:			
ATLAS	7		1205.2484
CDF	1.96		1211.4523
CMS	7		1308.3879
DØ	1.96		1011.6549
Run II data			
CMS	13	$t\bar{t}$ (dilepton)	1510.05302

Consequences of EFT Validity

- Strength of constraints $\Longleftrightarrow$ range of EFT validity
- Match $\frac{C_i}{\Lambda^2} = \frac{g_*^2}{M_*^2}$
- Impose $M_* > \kappa\Lambda > m_{t\bar{t}}^{\mathrm{max}}$
- Weak constraint $\Longrightarrow$ larger g_*, higher-order corrections to BSM important
- Truncation at e.g. $\mathcal{O}(\Lambda^{-2})$ less reliable

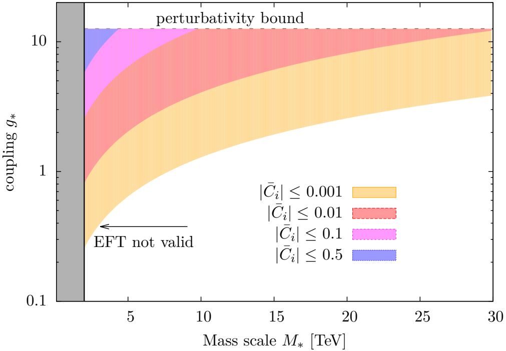
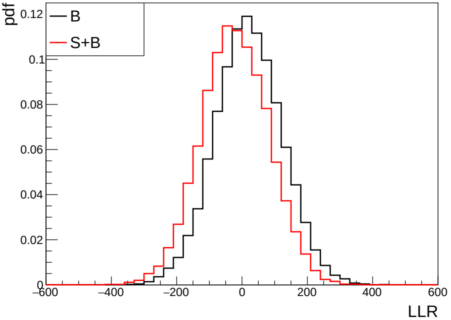
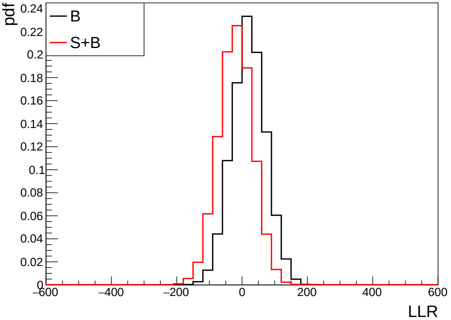


Figure: Areas in the $g_* - M_*$ plane. Coloured areas constrained in perturbative models subject to condition $C/\Lambda^2 = g_*^2/M_*^2$. Shaded grey area: mass scales $M_* < m_{t\bar{t}}^{\mathrm{max}}$

1D vs 2D LLRs: $\hat{\mu}_t$, 5%syst, $100 fb^{-1}$





Left (Right): 1D (2D) LLR distributions for ξ_{kk} distribution in **SM** and **D6 EFT**.
Smaller overlap between the distributions signifies 2D observables discriminate signal from background.