Top EFT prospects with differential spin observables

Liam Moore\textsuperscript{1}, based on 171X.XXXX \textit{(to appear)}
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Motivations

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

- $t$-quark chief troublemaker creating hierarchy problem. Naturalness: if NP stabilizes EW scale, should expect that BSM is $t$-philic

- $m_t > m_W + m_b \implies \Gamma_t \gg \Lambda_{QCD}$. Decay rate $> \text{hadronisation timescale}$, so spin information preserved in decay products.

- Measuring angular distributions gives additional information on production/decay mechanism, sensitive to $\mathcal{P}, \mathcal{CP}$ . . .

- (HL-)LHC: $\sim 3 \times 10^9 t \bar{t}$ pairs at $4 \text{ab}^{-1}$. Both precision and a wide array of differential measurements possible.

**Question:**

What are the prospects for constraining sources of NP, in differential distributions sensitive to $t$-polarisation and spin-correlations?
Non-resonant BSM with the SMEFT

The future divides into two possibilities:

- $\sqrt{s_{\text{LHC}}} \geq \Lambda_{\text{NP}}$: resonances accessible, measure properties
- $\sqrt{s_{\text{LHC}}} < \Lambda_{\text{NP}}$: states decoupled, observe only off-shell effects

Latter case: construct general gauge-invariant $L_{\text{SMEFT}}$ from operators at each order in $1/\Lambda_{\text{NP}}$, constrain NP in contact interactions $\propto C_i/\Lambda^2$:

$$L_{\text{SMEFT}} \equiv L_{\text{SM}}^{(4)}(\{\Phi_{\text{SM}}\}) + \frac{C_i}{\Lambda^{d-4}} O_i^{(d)}(\{\Phi_{\text{SM}}\}) + \ldots$$
An example: new physics in $t\bar{t}$ production

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<th>Coefficient $C_i$</th>
<th>Operator $O_i$</th>
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Table: $O_i (pp \rightarrow t\bar{t})$: viable UV models

EFT can constrain multiple BSM models simultaneously:

- Heavy coloured fermions, technihadrons.
- Compositeness, stops, 2HDM.
- $W'$ & $Z'$s
- Heavy (axi)gluons.
- Allow all $O_i$ simultaneously

$\implies$ Global fit $\text{(1512.03360)}$

TopFitter: use parton-level top measurements to extract marginalised constraints on $C_i$ in (primarily) $t\bar{t}$ + single-$t$ production.
TopFitter v1.0 at a glance - Global 95% C.I.

- Limits ‘weak’: weakly coupled
  UV unconstrained!

- Partonic distributions \(\Rightarrow\) see
  only 4 l.c. of 6 \(\psi^4\) operators

- One route to improvement:
  include distributions of decay
  products \(\Rightarrow\) probe \(t\bar{t}\) spins

- Sensitive to \(P, CP\)-odd \(O_i\),
  break \(\psi^4\) degeneracies, derive
  complementary bounds. . .

- Requires comparing
  distributions at the particle level

\[ \bar{C}_i = C_i v^2 / \Lambda^2 \]
Inferring $t\bar{t}$ spins from decay modes

**Left-handed decay** $\implies$ spin aligned with $l/d$ direction in $t$-rest frame.

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

- **Semileptonic**: $BR \sim 30\%$, but $\alpha_i^{jet} \sim 50\%$, $\alpha_i^d \equiv \hat{s} \cdot \hat{p}_d \simeq 1$

- **Dileptonic**: $BR \sim 5\%$, $\alpha_i \simeq 1$, $2 \times \nu \implies$ reconstruction harder

**Figure**: Credit: Nazar Bartosik
The $t\bar{t}$ spin-density matrix

$$M_{xy \rightarrow t\bar{t}}^* \alpha' \beta', M_{xy \rightarrow t\bar{t}}^{\alpha \beta}$$ with $t, \bar{t}$ spin indices explicit $\equiv t\bar{t}$ spin density matrix

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

NP $\Leftrightarrow C_i$ contribute to functions $A, B_i, C_{ij}$ appropriately

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

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

Choosing basis for spin axes $\Leftrightarrow$ isolate $O$'s in particular angular distributions. (Bernreuther et al 1508.05271) proposed $i, j = \{\uparrow, \hat{k}, \mathbf{n}\}$.

$6+9 \cos \theta^\pm_i$ distributions probe sources of polarisation+spin correlations

Each $B, C$ has dependence on kinematics $\propto$ operator coefficients
Unfolded 8 TeV measurements of \( \cos \theta_k^\pm \) distributions, probing spin correlations \( C(k, k) \) (left) and polarisation coefficients \( B(k) \) (right)
**ATLAS: $\cos \theta^{\pm}_{r/k}$ (1612.07004)**

8 TeV particle-level reconstructed distributions for $\cos \theta^{\pm}_{r/k}$ sensitive to spin correlations $C(r, k)$ (left), and polarisation coefficients $B(r)$ (right).
Studying the sensitivity of spin observables

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<td>$C(r, r)$</td>
<td>$0.071^{+0.008}_{-0.006}$</td>
<td>$2.475^{+0.020}_{-0.019}$</td>
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<td>$C(k, k)$</td>
<td>$0.331^{+0.002}_{-0.002}$</td>
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<td></td>
<td>$\propto \hat{c}_{VA}$</td>
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<tr>
<td>$B_{1/2}(r)$</td>
<td>$(3.2^{+2.3}_{-1.7}) \cdot 10^{-3}$</td>
<td>$0.210^{+0.009}_{-0.009}$</td>
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<tr>
<td>$B_{1/2}(k)$</td>
<td>$(8.0^{+3.4}_{-2.4}) \cdot 10^{-3}$</td>
<td>$1.607^{+0.051}_{-0.052}$</td>
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Table: Numerical sensitivity of obs $\propto \hat{c}$ (parton-level).
Errors: $\mu = m_t/2 \leftrightarrow 2m_t$ (Bernreuther et al 1508.05271, 1003.3926)

- Pick two representative operators that modify $B$s and $C$s for given axes
- Parton-level expectations modified by shower, acceptance cuts, reconstruction...
- Overlap with global fit: compare sensitivity of spin vs. kinematic distributions
- Double differential: resolve $m_t\bar{t}$ dependence, enhance NP. Gains?

\[ O_{\text{CMDM}} = -\frac{g_s}{2m_t} \hat{\mu}_t \bar{t} \sigma^{\mu\nu} T^a t G_{\mu\nu}^a \]
\[ O_{VA} = \frac{g_s^2}{2m_t^2} \hat{c}_{VA} (\bar{q} \gamma^\mu T^a q)(\bar{t} \gamma_\mu \gamma_5 T^a t) \]
**Analysis Summary**

| **Leptons** | $p_T > 25$ GeV \[|\eta| < 2.5\] |
| --- | --- |
| **Jets** | anti-$k_T$ $R = 0.4$ \[p_T > 25$ GeV \[|\eta| < 2.5\] $b$-tag w/ 70% efficiency 1% fake rate w/ FASTJET |
| **Reconstruction** | Pair $b$ jets, $l^\pm$ using $M_{T2}$ $\nu$ solutions w/ MAOS \[(Cho et al. 0810.4853)\] |
| **Require** | $\geq 2$ jets w/ $\geq 1$ b-tags $\geq 1 \times l^+, l^-$ |

- ME+decays: \texttt{FEYNRULES+UFO+MG5\_AMCNLO}
- Shower: \texttt{PYTHIA8+UMEPS}
- Analysis: \texttt{Rivet+YODA}
- Rescale $\sigma_{\text{incl}}$ with NNLO $k$-factor \[(Czakon et al. 2013)\]
- Attach $\mu$ to extrapolate D6 to different $\hat{c}$ values \(\text{to } O(\Lambda^{-2})\)
- Construct binned log-likelihood, exclude $\hat{c}$ for $CL_s < 0.05$ assuming SM for toy $\mathcal{L}_{\text{int}}, \epsilon_{\text{syst}}$

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**Table:** Event selection criteria in \texttt{Rivet} analysis
\[ \cos \theta_{\pm} \text{ polarisation distributions} - c_{VA} \text{ vs } SM \]

Left (Right): Reconstructed \( \frac{1}{\sigma} \frac{d\sigma}{d(\cos \theta^+_{k(r)})} \) distributions for the SM and \( c_{VA} = 0.25 \text{ sensitive to } B_k (B_r) \).
Left (Right): Reconstructed \( \frac{1}{\sigma} \frac{d^2\sigma}{dm_{t\bar{t}}d(\cos \theta^+_{k(r)})} \) distributions for the SM (\( c_{VA} = 0.25 \)) sensitive to \( B_k \) (\( B_r \)).
$\cos \theta_+ \cos \theta_- \text{ spin correlation distributions - } \hat{\mu}_t \text{ vs. SM}$

Left (Right): \[ \frac{d\sigma}{d(\cos \theta_n^+ \cos \theta_n^-)} \left( \frac{1}{\sigma} \frac{d^2\sigma}{dm_{t\bar{t}} d(\cos \theta_n^+ \cos \theta_n^-)} \right) \] for the SM,

$\hat{\mu}_t = 0.05$. Sensitive to $C_{nn}$. 

Liam Moore CP3
TopFitter 14/30
$\hat{\mu}_t$: 1D $\cos \theta^+_n \cos \theta^-_n$

Expected exclusion limits from
\[
\frac{d\sigma}{d(\cos \theta^+_n \cos \theta^-_n)} \text{ with } \epsilon_{\text{syst}} = 10\%, 5\%
\]

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

1D differential syst. dominated, comparable results to 8TeV CMS limit
Exclusion limits from \( \frac{d\sigma}{d m_{t\bar{t}}} \) and \( \frac{d\sigma}{d(\cos \theta^+ \cos \theta^-)} \) respectively, \( \epsilon_{syst} = 10\% \)

\[-0.068 < \hat{\mu}_t < 0.029 \text{ TopFitter w/ 8TeV}\ p_T \text{ spectra (1607.04304)}\]

Numerically similar results for \( r \), \( k \) and \( n \) correlations. Spin \( \sim \) kinematic.
Backup

\[ \hat{\mu}_t: 1D \text{ vs } 2D \cos \theta^+_k \cos \theta^-_k \text{ distributions} \]

Exclusion limits for \( d(2)\sigma \)

\[
\frac{d(2)\sigma}{d \cos \theta^+_k \cos \theta^-_k (m_{t\bar{t}})} \quad 1D \text{ vs } 2D \text{ respectively, } \epsilon_{\text{syst}} = 10\% 
\]

\( \hat{\mu}_t \) marginal \( O(5\%) \) gains from resolving \( m_{t\bar{t}} \) dependence of spin correlations. 2D improves with \( L_{\text{int}} \) at similar level.

D5: weaker scaling. \( k \)-axes spin correlations degrade w/ \( m_{t\bar{t}} \) c.f. QCD.
$\hat{c}_{VA}: \text{1D } \cos \theta^{+}_{r} \text{ vs. } \cos \theta^{+}_{k}$

Exclusion limits from $\frac{d\sigma}{d \cos \theta_{r}}$ and $\frac{d\sigma}{d \cos \theta_{k}}$ respectively, $\epsilon_{\text{syst}} = 10\%$

Unconstrained in kinematic distributions, typical TopFitter $\psi^{4}$ limits $\hat{c} \lesssim 0.2$

Sensitivity hierarchy $B(k) > B(r)$ follows parton level expectation
**\( \hat{c}_{VA} \): 1D vs 2D \( \cos \theta^+_k \) distributions**

Exclusion limits from \( \frac{d^2\sigma}{dm_{t\bar{t}}d\cos \theta^+_k} \) and 1D vs 2D respectively, \( \epsilon_{\text{syst}} = 10\% \)

\( O(\Lambda^{-4}) \) effects start to become significant for \( m_{t\bar{t}} > 1 \) TeV.

Here: even cutting bins \( m_{t\bar{t}} < 1 \) TeV, factor \( \geq 2 \) improvement 1D \( \rightarrow \) 2D. Improves w/ \( L_{\text{int}} \) for \( m_{t\bar{t}} > 1 \) TeV region, but require EFT uncertainties.
Summary & Outlook

From preliminary results:

- 1D spin $\sim$ kinematic, syst. dominated, limits consistent with TopFitter
- Bound unconstrained $\psi^4$ operators at comparable level
- Double-differential: naively improve $\psi^4$ by factor $\sim 2$
- Improvements with $L_{\text{int}}$ req. lowering systematics below 10% level

Several directions for improvement:

- NLO+MadSpin $\rightarrow$ differential SM NLO k-factors + theory uncertainties
- Quantify EFT uncertainties in typical power counting scenarios
- Investigate quadratic EFT contributions to observables. . .
- Compare against lepton + jets, for all operators. . .
1 Backup
TopFitter v1.0 - Overview

Idea: perform a simultaneous fit of the \((CP - \text{even})\) 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 \(\chi^2\) 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 $\mu_{\text{central}}/2 < \mu_{R,F} < 2\mu_{\text{central}}, \mu_{\text{central}} = m_t$.

- 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 $A_{FB}$, $A_{C}$, $\Gamma_{top}$ 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 $\chi^2$/d.o.f. allowing all $C_i$ to vary (marginalized), or each to vary individually
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<th>√s (TeV)</th>
<th>Measurements</th>
<th>arXiv ref.</th>
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<th>√s (TeV)</th>
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<td>1502.00586</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CMS</td>
<td>8</td>
<td>$t\bar{t}Z$</td>
<td>1506.7830</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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:

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

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

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

with $\cos \theta_{\pm}$ measured with respect to the axes $\hat{a}, \hat{b} = \hat{r}, \hat{R}, \hat{n}$.

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

<table>
<thead>
<tr>
<th>Correlation</th>
<th>$CP$-properties</th>
<th>sensitive to</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1(r) + B_2(r)$</td>
<td>$\mathcal{P}$-odd, $\mathcal{CP}$-even</td>
<td>$\hat{c}_{VA} , \hat{c}_3$</td>
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<tr>
<td>$B_1(k) + B_2(k)$</td>
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</tr>
</tbody>
</table>

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

- 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.
Consequences of EFT Validity

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

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

- We use log-likelihood ratio $q = -2 \log \left( \frac{L_1}{L_0} \right)$ 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 $\mu$ at 95\% confidence level $\iff CL_s = \frac{CL_{s+b}}{CL_b} < 0.05$
1D vs 2D LLRs: $\hat{\mu}_t$, 5% syst, 100$fb^{-1}$

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