Interpreting top quark LHC measurements in SMEFT

Ken Mimasu
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Particle Physics Seminar, Universität Wien
28th March 2023
New physics through tops

What is the origin of electroweak symmetry breaking?
New physics through tops

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Who are the main players?

- Higgs boson, EW gauge bosons & top quark
- Most massive ⇔ strongly coupled to the Higgs
New physics through tops

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The top is special for many reasons

EW vacuum stability
[Bednyakov et al.; PRL 115 (2015) 201802]...
The LHC is a top factory

May 2021

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

Rarity

strong interaction

weak interaction

All results at: http://cern.ch/go/pNj7
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CMS Preliminary

$\tilde{t}\tilde{t} : 10^9$
$tj, tW, tb : 10^8$
$\tilde{t}\tilde{t} + Z/W/\gamma : 10^7$
$\tilde{t}\tilde{t}H : 10^6$
$\tilde{t}\tilde{t}\tilde{t} : 10^4$

$\mathcal{L}_{\text{int.}} \sim 3 \text{ ab}^{-1}$

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Decays before hadronising
- Spin/helicity information preserved

K. Mimasu - Seminar, Vienna - 28/03/2023

Interpreting LHC top data in SMEFT
Where are we?

~10 years since the start of LHC Run 1

- No clear sign of new physics at the TeV scale
- Direct searches are saturating the energy frontier
What have we learnt?

**BSM:** new states are too...
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- **Weakly coupled**
  - rate limited
- Room for improvement
  - With increasing integrated luminosity
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**Exotic**

*we aren’t looking in the right place*

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**Limited by our creativity**

*Work for theorists & experimentalists: Motivate & enable searches for new signatures*
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- **Heavy**
  - kinematically out of reach
  - Worst-case scenario
  - ...from direct search point of view
  - Complemented by indirect searches
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**SM:** a tremendous amount!

- Higgs discovery & properties $\Rightarrow$ precision LHC programme
The LHC explorer

Many new processes observed at the LHC for the first time

Main Higgs production modes

- ggF, VH, VBF, ttH

Rare top production

- tttt, ttbb
- ttV, tW, tZ

Weak boson scattering

- VBS, VVV
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Each opens a new window, through which we can

Improve our understanding of the SM

- Search for new physics via new interactions
Energy & precision

Paradigm shift at the energy frontier for BSM searches
Energy & precision

**Paradigm shift** at the energy frontier for BSM searches

Direct (bumps)
Energy & precision

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Indirect (tails)
⇒ New physics is heavy
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Heavy new physics
Precision measurements
High energy

Effective Field Theory (EFT)
Energy & precision

Paradigm shift at the energy frontier for BSM searches

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Effective Field Theory (EFT)

\[ A_{BSM}^n(E, M) \sim E^{4-n} \left( a_0 + a_1 \frac{E}{M} + a_2 \frac{E^2}{M^2} + \ldots \right), \quad E \ll M \]
SMEFT: SM v2.0

\[ \mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}^D_i}{\Lambda^{D-4}} \]

**SM = low energy effective description**

- New physics = tower of irrelevant \((D>4)\) operators
- Respecting low energy field content & symmetries

**SU(3)_c \times SU(2)_L \times U(1)_Y**

\[ \varphi = \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} : 2^{1\over 2} \]
SM = low energy effective description

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\begin{align*}
aTGC & : X^3 : \varepsilon_{i,j,k} W_{\mu\nu}^I W_{\rho}^{J,\nu} W_{\rho}^{K,\mu} \\
\lambda_h & : H^6 : (\varphi^\dagger \varphi)^3 \\
\gamma_f & : \psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i u_j \bar{\varphi}) \\
ffV & : \psi^2 H^2 D : (\varphi^\dagger D_\mu \varphi) (\bar{q}_i \gamma^\mu q_j)
\end{align*}
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SU(3)_c x SU(2)_L x U(1)_Y
$$\varphi = \left( \begin{array}{c} G^+ \\ v + h + iG^0 \end{array} \right) : {\bf 2}_{\frac{1}{2}}$$

aTGC
$$X^3 : \epsilon_{ijk} W^I_{\mu \nu} W^J_{\nu \rho} W^K_{\rho \mu}$$
$$X^2 H^2 : (\varphi^\dagger \varphi)^2 G^a_{\mu \nu} G^{a \mu \nu}$$
$$ggh(h)$$

$$\lambda_h$$
$$H^6 : (\varphi^\dagger \varphi)^3$$
$$H^4 D^2 : (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$$
$$\delta M_Z$$

$$\gamma_f$$
$$\psi^2 H^3 : (\varphi^\dagger \varphi)^2 (\bar{q}_i u_j \varphi)$$
$$\psi^2 X H : (\bar{q}_i \sigma^{\mu \nu} u_j \varphi) B_{\mu \nu}$$
‘dipole’

$$ffV$$
$$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) (\bar{q}_i \gamma^\mu q_j)$$
$$\psi^4 : (\bar{q}_i \gamma^\mu q_j) (\bar{q}_k \gamma_\mu q_l)$$
4F

More than ‘just’ a parametrisation of ignorance
- Unlike anomalous couplings
- Finite energy range (∼Λ)
- Renormalisable QFT (order-by-order)
- Well defined matching procedure
SMEFT is...

Model independent

- Underlying assumptions

\[ \mathcal{L}_{\text{eff}} = \sum_i \frac{c_i O^D_i}{\Lambda^{D-4}} \]

Heavy new physics: \( M > E_{\text{exp}} \)

SM field content & gauge symmetries

Linear EWSB: Higgs = doublet
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Systematically improvable

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\[ \frac{E^2}{\Lambda^2} \quad \& \quad \{g_S, g, g'_I\} \quad \text{more loops} \]
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  \[ \frac{E^2}{\Lambda^2} \]
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**Global**
- **Model independence**: we don’t know what operators NP will generate
- Patterns & correlations among observables are key

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- Double expansion higher dim. \( \frac{E^2}{\Lambda^2} \) & \{g_s, g, g'\} more loops

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- **Ultimate goal**: complete SMEFT likelihood confronted with HEP data

EWPO, Higgs, multiboson, top, DY, flavor,…

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\[ \frac{E^2}{\Lambda^2} \quad \& \quad \{ g_S, g, g' \} \quad \text{more loops} \]

\[ \mathcal{L}(c_i) \Rightarrow \text{indirectly constrain many UV models} \]
SMEFT interpretation

$$\Delta o_n = o_n^{\text{EXP}} - o_n^{\text{SM}} = \sum_i \frac{a_{n,i}(\mu) c_i^{(6)}(\mu)}{\Lambda^2} + O\left(\frac{1}{\Lambda^3}\right)$$
SMEFT interpretation

Improving new physics reach means improving...

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Global nature
As many observables as possible
Identify patterns & correlations in fits
Exploit energy-growth
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Global nature
As many observables as possible
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Sensitivity

Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,...)
SMEFT interpretation

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**Global nature**
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**Sensitivity**
*Experiment:* Best measurements & understanding of uncertainties and correlations
*Theory:* Best available predictions for observables (NLO, NNLO, N3LO, ...)

**Interpretation**
Relies on accurate knowledge of the size & correlation among $a_i$
Determining $c_i^{(6)}$ requires most precise available SMEFT predictions $\Rightarrow$ NLO
The wealth of data

Decays

Flavor

CPV

K. Mimasu - Seminar, Vienna - 28/03/2023

Interpreting LHC top data in SMEFT
The wealth of data

Decays
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Today’s topic
The importance of top data

\textbf{Likelihood ⇔ Fit to the Wilson coefficients}

- Search for deviations from the SM: \( \frac{C_i}{\Lambda^2} = 0 \)
- Find \textit{hints} for heavy new physics
- LHC top data has a vital role in this programme
The importance of top data

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By itself: individual bounds; top data alone

- Determine top quark properties/interactions
- Probe heavy new physics that couples preferentially to tops
The importance of top data

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Globally: marginalised; top, Higgs, diboson, LEP, ... data

- Influence determination of other couplings in EW sector,...
- Probe more realistic models connected to the EWSB puzzle
Top operator glossary
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**currents** \[ i(\phi^+ \overleftrightarrow{D}_{\mu} \phi)(\bar{Q}_{\gamma\mu} Q) \]

- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

$C_{\phi f}$
Top operator glossary

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- $ffVh$ contact interactions

\[ C_{\phi f} \]

**Yukawa**

\[ (\bar{q} t \bar{\phi})(\phi^\dagger \phi) \]

- Decouple $m_t$ & $y_t$
- $t\bar{t}hh(h)$ contact interactions

\[ C_{t\phi} \]
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**Dipole**
\[ (\bar{q} \sigma_{\mu\nu} t \bar{\phi})V^{\mu\nu} \]
- Chirality flipping \( f\bar{f}V \) couplings
- \( f\bar{f}V(V)h \) contact interactions
- \( W, B \) & \( G \) fields
Top operator glossary

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**4 fermion**
\[ (\overline{f} \gamma_\mu f)(\overline{Q} \gamma^\mu Q) \]
- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous ($\sim O(20)$ w/ top)
Fits: status & developments

Many SMEFT interpretations in experimental analyses
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Many SMEFT interpretations in experimental analyses

Global interpretations

- **Size**: 100s of data points & 10s of operators
- **Precision**: Inclusion of NLO QCD corrections & loop sensitivity
- **Breadth**: First combinations of top, Higgs & EW precision data

[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]
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Take home message

• Top sector probed around TeV scale

• EW top couplings weakly constrained

• NLO effects can be significant

• EFT validity should be studied

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Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279
Status in a nutshell

Global new physics searches via high precision/energy

- **Z & W-pole data**: handle on the EW gauge sector  
  [Han & Skiba; PRD 71 (2005) 075009]
  [Falkowski & Riva; JHEP 02 (2015) 039]

- **LHC**: thriving Higgs & top programmes

- Probing gauge interactions at high energy (V V, VBS, VVV, …)
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How much cross-talk? Where does being global matter?
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How much cross-talk? Where does being global matter?

We know that Higgs data greatly complements LEP

- **Access unconstrained directions** in parameter space
- Allows for a **closed fit** to flavor-universal SMEFT
- Crucial to combine EWPO, Diboson & Higgs data

[Corbett et al.; PRD 87 (2013) 015022]  [Ellis et al.; JHEP 06 (2018) 146]
[Pomarol & Riva; JHEP 01 (2014) 151]
[Ellis, Sanz & You; JHEP 03 (2015) 157]
[Biekkötter, Corbett & Plehn; SciPost Phys 6 (2019) 6, 064]…
Top & Higgs

Inextricably linked in the SM

- Yukawa interaction controls ggF
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\[ C_{HG} \text{ Point-like} \]
\[ C_{tH} \text{ Yukawa} \]
\[ C_{tG} \text{ Dipole} \]

Blind direction in BSM scenarios

Effective coupling degeneracy
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Need more data to break degeneracy
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$C_{th}$ Yukawa
$C_{tG}$ Dipole

Blind direction in BSM scenarios

Effective coupling degeneracy

Need more data to break degeneracy

- $t\bar{t}H$ production for direct Yukawa measurement
- $t\bar{t}$ data to constrain dipole
The role of top data

$t\bar{t}$ cross section measurements constrain $C_{tG}$

- Indirectly improve bounds on $C_{HG}$ and $C_{tH}$
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Several other new interactions can affect $t\bar{t}$
- Notably $q\bar{q}t\bar{t}$ operators, of which there are many (14)
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?
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Can only be addressed in combined fit

- Identify other cross-talk (non-trivial correlations)
- Crystallisation of knowledge gained after LHC Run 2
- Broaden range of applicability to UV models
The fit

Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory

John Ellis,\textsuperscript{a,b,c} Maeve Madigan,\textsuperscript{d} Ken Mimasu,\textsuperscript{a} Veronica Sanz\textsuperscript{e,f} and Tevong You\textsuperscript{b,d,g} [JHEP 04 (2021) 279]
Global SMEFT interpretation of 4 categories of data

14  •  Electroweak Precision Observables (EWPO): Z-pole & W-mass

118 • LEP2 & LHC diboson production: differential WW, WZ, Zjj

72  •  Higgs measurements: signal strengths & STXS

137 • Top data: single-top, ttbar & asymmetries, ttV, tZ, tW

Based on
[Ellis et al.; JHEP 06 (2018) 146]

Big thanks to authors of SMEFIT analysis
[JHEP 04 (2019) 100]
for sharing some of their top predictions
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341 measurements across categories

• Chosen to be statistically independent & maximise reach
• Correlations included when publicly available (mostly are)
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Linear EFT approximation: \[ \mu_x \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i x^i \frac{C_i}{\Lambda^2} + \mathcal{O} \left( \frac{1}{\Lambda^4} \right) \]
### Degrees of freedom

<table>
<thead>
<tr>
<th>Flavor scenario</th>
<th>Universal</th>
<th>‘Top specific’</th>
</tr>
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<tbody>
<tr>
<td><strong>EWPO:</strong></td>
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20 + 14
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<td>Yukawa: $\mathcal{O}<em>{\tau H}, \mathcal{O}</em>{\mu H}, \mathcal{O}<em>{bH}, \mathcal{O}</em>{tH}$,</td>
</tr>
<tr>
<td></td>
<td>Top 2F: $\mathcal{O}<em>{H^{(3)}}, \mathcal{O}</em>{H^{(1)}}, \mathcal{O}<em>{Ht}, \mathcal{O}</em>{tG}, \mathcal{O}<em>{tW}, \mathcal{O}</em>{tB}$,</td>
</tr>
<tr>
<td></td>
<td>Top 4F: $\mathcal{O}<em>{Q_q}^{3,1}, \mathcal{O}</em>{Q_q}^{3,8}, \mathcal{O}<em>{Q_q}^{1,8}, \mathcal{O}</em>{Q_u}, \mathcal{O}<em>{Q_d}^{8}, \mathcal{O}</em>{tQ}^{8}, \mathcal{O}<em>{tu}, \mathcal{O}</em>{td}$,</td>
</tr>
</tbody>
</table>

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**K. Mimasu - Seminar, Vienna - 28/03/2023**

**Interpreting LHC top data in SMEFT**
Top-only: top + EWPO individual

Top operators: EWPO + top EW + $t\bar{t}$ + $t\bar{t}X$

95%CL individual: $C_i \frac{(1\,\text{TeV})^2}{\Lambda^2}$

$\Lambda / \sqrt{C_i}$ [TeV]

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Interpreting LHC top data in SMEFT
Top-only: top + EWPO individual

- Some tension in $t\bar{t}$ data
- Asymmetries help to improve agreement
Top-only: breakdown

4F (ťťq) operators

Individual:
all others = 0
Top-only: breakdown

- $t\bar{t}$ asymmetries constrain orthogonal direction to cross section
- Large marginalisation effects: many similar operators
- $t\bar{t}V$ & $t\bar{t}H$ help to close the space
Top-only: breakdown

4F ($t\bar{t}qq$) operators

- $t\bar{t}$ asymmetries constrain orthogonal direction to cross section
- Large marginalisation effects: many similar operators
- $t\bar{t}V$ & $t\bar{t}H$ help to close the space
- Marginalised linear sensitivity: $C_{4F} \left[ \frac{1 \text{ TeV}^2}{\Lambda^2} \right] \sim (5 - 15)$ significant $\frac{1}{\Lambda^4}$ effects
Top-only: top + EWPO marginalised

95%CL marginalised; $C_i \frac{(1 \text{ TeV})^2}{\Lambda^2}$

$C_i = (4\pi)^2$  ---  $C_i = 1$  ---  $C_i = 0.01$
Top-only: top + EWPO marginalised

- Graph showing 95% CL marginalised limits for $C_i \left( \frac{1 \text{ TeV}}{\Lambda} \right)^2$
- Legend includes:
  - $t\bar{t}$ Run 1
  - $t\bar{t}$ Run 1 & 2 + Asym.
  - $t\bar{t}$ Run 1 & 2
  - no EWPO

- Bottom graph: previous individual limits for $C_i$ with $C_i = (4\pi)^2$, $C_i = 1$, and $C_i = 0.01$
Top-only: top + EWPO marginalised

- $C_{tH}$: $t\bar{t}H$ bound alone is quite weak
- $C_{tG}$: Strong constraint but tension with SM
- Neutral top couplings poorly constrained
Top-only: top + EWPO marginalised

- $C_{tH}$: $t\bar{t}H$ bound alone is quite weak
- $C_{tG}$: Strong constraint but tension with SM
- Neutral top couplings poorly constrained
- EWPO closes $Zb\bar{b}$ coupling direction
- Impact of asymmetries in 4F
- Somewhat low scales (validity?)
Top-Higgs interplay

2D individual constraints
Top-Higgs interplay

2D individual constraints

- All others set to 0
- $ggF/t\bar{t}H$ complementarity for $(C_{HG}, C_{tH})$
- $H+\text{jets STXS}$ & $t\bar{t}V$ not yet competitive
- Strong impact of $t\bar{t}$ evident for $(C_{tG}, C_{G})$
- Tension with SM $\sim 2\sigma$
- Significant correlations remain
- Large marginalisation effects

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Top-Higgs interplay

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- Large marginalisation effects

What is the concrete impact of 4F?
4F impact

Fit to ‘Higgs-only’ subspace

\[ C_{H^0}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H} + C_{tG} & C_{G} \]

- Allow a closed fit to Higgs data only
- Emphasises impact of \( t\bar{t}H \) & \( t\bar{t} \)
4F impact

Fit to ‘Higgs-only’ subspace
\(C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H} + C_{tG} & C_{G}\)
- Allow a closed fit to Higgs data only
- Emphasises impact of \(t\bar{t}H & t\bar{t}\)

Now add in \(t\bar{t}\) 4F operators
\(+ C_{Qq}^{3,8}, C_{Qq}^{1,8}, C_{Qu}^{8}, C_{Qd}^{8}, C_{tq}^{8}, C_{tu}^{8}, C_{td}^{8}\)
- Relatively mild impact
- Preferred \(t\bar{t}\) phase space is different
\(C_{tG} : \) low \(m_{t\bar{t}}\)
\(4F : \) high \(m_{t\bar{t}}\)
- Able to constrain them independently
SMEFiT

Top, Higgs & Diboson w/ ‘perfect’ EWPO

- NLO QCD
- top loop sensitivity

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Interpreting LHC top data in SMEFT
SMEFiT

Top, Higgs & Diboson w/ ‘perfect’ EWPO

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Interpreting LHC top data in SMEFT
Linear vs Quadratic

[K. Mimasu - Seminar, Vienna - 28/03/2023]
Linear vs Quadratic

Some bounds purely \(O(\Lambda^{-4})\)

1) imprecise data
2) non-interference
Linear vs Quadratic

Some bounds purely $O(\Lambda^{-4})$
1) imprecise data
2) non-interference

Non-Gaussian posteriors: Quadratic effects important

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Interpreting LHC top data in SMEFT
Linear vs Quadratic

Non-Gaussian posteriors:
Quadratic effects important

Dim-8 effects? EFT validity?

1) imprecise data
2) non-interference

Some bounds purely $O(\Lambda^{-4})$
NLO vs LO

Top is coloured

Non-trivial QCD corrections
Loop sensitivity

Not just higher precision: new \textit{loop-induced} sensitivity

- Especially relevant for top loops: most \textit{strongly coupled} particle
- Weakly constrained directions meet precisely measured observables
- Large allowed Wilson coefficients overcome loop factors
Loop sensitivity

Not just higher precision: new loop-induced sensitivity

- Especially relevant for top loops: most strongly coupled particle
- Weakly constrained directions meet precisely measured observables
- Large allowed Wilson coefficients overcome loop factors

Example: top couplings in $hVV$ vertex

- Yukawa, current & dipole couplings in $gg \rightarrow h \& h \rightarrow \gamma\gamma/Z\gamma$
- (Weakly) constrained at tree-level by $t\bar{t}\gamma/Z/H \& t\bar{t}$
Loop sensitivity

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Example: top couplings in $hVV$ vertex

- Yukawa, current & dipole couplings in $gg \rightarrow h$ & $h \rightarrow \gamma\gamma/Z\gamma$
- (Weakly) constrained at tree-level by $t\bar{t}\gamma/Z/H$ & $t\bar{t}$

SMEFiT: individual bounds dominated by Higgs data!

- Weak dipoles & $Ztt$ current operators $(C_{tW}, C_{tZ}, C_{\phi Q}^{(-)}, C_{\phi Q}^{3}, C_{\phi t})$
- Also contributions to $gg \rightarrow Zh/ZZ/Z\gamma/WW$
- Complementary indirect sensitivity from non-top data
Top EW interactions

![Graph showing Top EW interactions with different categories: EWPO, Bosonic, Yuk, Top 2F. The graph displays the values of a parameter $\Lambda/\sqrt{c_i}$ in TeV for various combinations of $c_i$. The graph includes two error levels: $2\sigma$ Individual and $2\sigma$ Marginalised.](image)
Top EW interactions
Top EW interactions

- Charged current interactions quite well constrained
Top EW interactions

- **Charged current** interactions quite well constrained
- **Yukawa** and **neutral current** are among the worst
Top EW interactions

- Charged current interactions quite well constrained
- Yukawa and neutral current are among the worst

How can we improve?
High energy & multiplicity

Improving sensitivity = collect more data. Is it enough?
High energy & multiplicity

Improving sensitivity = collect more data. Is it enough?

$t\bar{t}X$ for Yukawa & neutral current operators

- EFT effect $\propto \nu^2/\Lambda^2$, no energy growth (SM-kinematics)
- EFT $\times$ SM interference often suppressed

[Azatov et al.; PRD 95 (2017) no. 6, 065014]
High energy & multiplicity

Improving sensitivity = collect more data. Is it enough?

$t\bar{t}X$ for Yukawa & neutral current operators

- EFT effect $\propto \frac{v^2}{\Lambda^2}$, no energy growth (SM-kinematics)
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  [Azatov et al.; PRD 95 (2017) no. 6, 065014]

\[
\mathcal{A} \sim \mathcal{A}_{SM} \left( 1 + c_i \frac{v^2}{\Lambda^2} + c_j \frac{v E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2} \right)
\]
High energy & multiplicity

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Rate measurements will become systematics dominated
High energy & multiplicity

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$A \sim A_{SM} \left(1 + c_i \frac{v^2}{\Lambda^2} + c_j \frac{v E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2}\right)$

‘Energy helps accuracy’
  [Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated
Increasingly high-energy measurements scale with lumi.
High energy & multiplicity

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‘Energy helps accuracy’
  [Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated
Increasingly high-energy measurements scale with lumi.

There will always be some scattering amplitude
that displays maximal ($E^2$) growth w.r.t the SM
Finding the right process

Gauge invariance +
Goldstone equivalence theorem: $\partial^\mu G \leftrightarrow Z_L^\mu$
Finding the right process

Gauge invariance +
Goldstone equivalence theorem: $\partial^\mu G \leftrightarrow Z_\mu^\mu$

\[
C_{tH}(H^\dagger H)(\bar{Q}tH) \quad \langle H^\dagger H \rangle = v^2 \Rightarrow h \sim v^2/\Lambda^2
\]
Finding the right process

Gauge invariance +
Goldstone equivalence theorem: \( \partial^\mu G \leftrightarrow Z_L^\mu \)

\[ C_t H (H^t H) (\bar{Q} t \tilde{H}) \]
\[ \langle H^t H \rangle = v^2 \Rightarrow h \sim v^2/\Lambda^2 \]

Feynman gauge
\[ \langle H^t H \rangle = v^2 + 2v h + h^2 + G^+ G^- + G_0^2 \Rightarrow \sim v E/\Lambda^2 \]
Finding the right process

Gauge invariance + Goldstone equivalence theorem:

\[ \partial_\mu G \leftrightarrow Z^\mu_L + \sim v^2 \]

\[ C_{tH}(H^\dagger H)(\bar{Q}t\tilde{H}) \]

\[ \langle H^\dagger H \rangle = v^2 \Rightarrow \]

\[ \sim v^2 / \Lambda^2 \]

Feynman gauge

\[ \langle H^\dagger H \rangle = v^2 + 2vh + h^2 + G^+G^- + G_0^2 \Rightarrow \]

\[ \sim vE / \Lambda^2 \]
Finding the right process

Gauge invariance +
Goldstone equivalence theorem: \( \partial^\mu G \leftrightarrow Z_L^\mu \)

\[ C_{tH}(H^+H)(\bar{Q}t\bar{H}) \quad \langle H^+H \rangle = v^2 \quad \Rightarrow \quad h \sim v^2/\Lambda^2 \]

Feynman gauge \( \langle H^+H \rangle = v^2 + 2vh + h^2 + G^+G^- + G_0^2 \quad \Rightarrow \quad \sim vE/\Lambda^2 \)
Finding the right process

Gauge invariance +
Goldstone equivalence theorem:

$$\partial^\mu G \leftrightarrow Z_L^\mu$$

$$C_{tH}(H^\dagger H)(\tilde{Q}t\tilde{H})$$ 

$$\langle H^\dagger H \rangle = v^2 \Rightarrow h \sim v^2/\Lambda^2$$

Feynman gauge 

$$\langle H^\dagger H \rangle = v^2 + 2vh + h^2 + G^+G^- + G_0^2 \Rightarrow$$

$$C_{Ht} i(H^\dagger \overset{\rightarrow}{D}_\mu H)(\tilde{t}_R \gamma^\mu t_R) \Rightarrow z \sim v^2/\Lambda^2$$
Finding the right process

Gauge invariance +
Goldstone equivalence theorem:
\[ \partial^\mu G \leftrightarrow Z^\mu_L \]

\[ C_{t\bar{H}}(H^\dagger H)(\bar{Q}t\bar{H}) \quad \langle H^\dagger H \rangle = v^2 \quad \Rightarrow \]
\[ \sim v^2/\Lambda^2 \]

Feynman gauge
\[ \langle H^\dagger H \rangle = v^2 + 2v h + h^2 + G^+ G^- + G_0^2 \quad \Rightarrow \]
\[ \sim v E/\Lambda^2 \]

\[ C_{Ht} i(H^\dagger \bar{D}_\mu H)(\bar{t}_R \gamma^\mu t_R) \quad \Rightarrow \]
\[ \sim v^2/\Lambda^2 \]

\[ \sim E^2/\Lambda^2 \]

\[ t W_L \rightarrow t W_L \]
\[ t Z_L \rightarrow t h \]
\[ b W_L \rightarrow t Z_L \]
\[ b W_L \rightarrow t h \]
Finding the right process

Gauge invariance +
Goldstone equivalence theorem:
\[ \partial^\mu G \leftrightarrow Z^\mu_L \]

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\[ \langle H^\dagger H \rangle = v^2 \Rightarrow h \sim v^2/\Lambda^2 \]

Feynman gauge
\[ \langle H^\dagger H \rangle = v^2 + 2vh + h^2 + G^+G^- + G_0^2 \Rightarrow \]
\[ \sim vE/\Lambda^2 \]

\[ C_{Ht}i(H^\dagger \not{D}_\mu H)(\bar{t}_R\gamma^\mu t_R) \Rightarrow \]
\[ \sim v^2/\Lambda^2 \]

Unitarity non-cancellations in scattering amplitudes \[ \iff \]
Non-renormalisable contact interactions with Goldstones

\[ tW_L \rightarrow tW_L \]
\[ tZ_L \rightarrow th \]
\[ bW_L \rightarrow tZ_L \]
\[ bW_L \rightarrow th \]
Finding the right process

Gauge invariance +
Goldstone equivalence theorem:
\[ \partial^\mu G \leftrightarrow Z^\mu_L \]

\[ C_{tH}(H^+H)(\bar{Q}t\bar{H}) \quad \langle H^+H \rangle = v^2 \quad \Rightarrow \]
\[ h \quad \sim \frac{v^2}{\Lambda^2} \]

Feynman gauge
\[ \langle H^+H \rangle = v^2 + 2vh + h^2 + G^+G^- + G^0_0 \quad \Rightarrow \]
\[ tW_L \rightarrow tW_L \quad tZ_L \rightarrow th \quad bW_L \rightarrow tZ_L \quad bW_L \rightarrow th \]

\[ C_{Ht} i(H^+D_\mu H)(\bar{t}_R\gamma^\mu t_R) \quad \Rightarrow \]
\[ z \quad \sim \frac{v^2}{\Lambda^2} \quad + \]
\[ \sim \frac{E^2}{\Lambda^2} \]

Unitarity non-cancellations in scattering amplitudes
\[ \Leftrightarrow \]
Non-renormalisable contact interactions with Goldstones

Less vevs, more legs! (AKA multiplicity)

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Interpreting LHC top data in SMEFT

[Dror et al.; JHEP 01 (2016) 071]
[Mantani, Maltoni & KM; JHEP 10 (2019) 004]

[Henning et al.; PRL 123 (2019) 181801]
EW top scattering

\[ s \sim t \gg m^2 \]

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<thead>
<tr>
<th></th>
<th>Single-top</th>
<th>Two-top (( tt ))</th>
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<tr>
<td>w/o Higgs</td>
<td>( bW \rightarrow t (Z/\gamma) )</td>
<td>( tW \rightarrow tW )</td>
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</table>

2 \rightarrow 2 top EW scattering amplitudes in high energy limit:
study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT
EW top scattering

2 → 2 top EW scattering amplitudes in high energy limit:
study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT

e.g. $bW \rightarrow th$
**EW top scattering**

\[ s \sim t \gg m^2 \]

**Single-top** \[ bW \rightarrow t(Z/\gamma) \]
\[ tW \rightarrow tW \]
\[ t(Z/\gamma) \rightarrow t(Z/\gamma) \]

**Two-top \((tt)\)**
\[ bW \rightarrow th \]
\[ t(Z/\gamma) \rightarrow th \]
\[ th \rightarrow th \]

**2 → 2 top EW scattering amplitudes in high energy limit:**

- study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT

\[ A(b_L, W_L, t_R) \propto \sqrt{-t}(2m_w^2 g_{th} - g_{wh}m_t) \]

- e.g. \( bW \rightarrow th \)
EW top scattering

\[
\begin{align*}
B & \quad B' \\
\text{s} \sim t \gg m^2 & \quad f \quad f'
\end{align*}
\]

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2 \to 2 top EW scattering amplitudes in high energy limit:
study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT

\[
A(b_L, W_L, t_R) \propto \sqrt{-t(2m_w^2 g_{th} - g_{Wlh} m_t)}
\]

e.g. \(bW \to th\)  SMEFT \(\Rightarrow\)

<table>
<thead>
<tr>
<th>(\lambda_b, \lambda_W, \lambda_t)</th>
<th>SM</th>
<th>(O_{t\varphi})</th>
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**EW top scattering**

2 → 2 top EW scattering amplitudes in high energy limit: study of unitarity violating behaviour & helicity structure in dimension-6 SMEFT

**Example:** $bW \rightarrow th$

**SMEFT**

Where is max-growth?
Behaviour of interference?

**Table:**

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**Formula:**

$$A(b_L, W_L, t_R) \propto \sqrt{-t(2m_W^2 g_{th} - g_{wh} m_t)}$$
Overview of results

gauge/higgs operators ↔ top operators

<table>
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<tr>
<th></th>
<th>$O_{\varphi_D}$</th>
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Energy-growing interference

single-top

two-top w/o Higgs

two-top w/ Higgs

K. Mimasu - Seminar, Vienna - 28/03/2023

Interpreting LHC top data in SMEFT
Overview of results

gauge/higgs operators $\leftrightarrow$ top operators

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Most top operators show max growth somewhere

- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)
Embedding the amplitudes

Collider processes: high multiplicity, EW top production

(a) $t\bar{t}X$

(b) $tX_j$

(c) $tWX$

(d) $t\bar{t}X_j$

(e) $t\bar{t}XY$

(f) VBF
Embedding the amplitudes

Collider processes: high multiplicity, EW top production

Couplings \{ top EW, Higgs, triple gauge \} \Rightarrow \text{Heart of EWSB sector}
## Top EW scattering pheno

<table>
<thead>
<tr>
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### Single-top

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### Two-top w/o Higgs

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### Two-top w/ Higgs
Top EW scattering pheno

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See, e.g., $tZj/tHj$ [Degrande, Maltoni, KM, Vryonidou & Zhang; JHEP 01 (2022) 100]  
$tWZ$ [El Faham, Maltoni, KM & Zaro; JHEP 01 (2022) 100]
Rare single top modes

\[ t\bar{Z}, tWZ \]
Rare single top modes

\[ tZ \]

\[ bW \rightarrow tZ \]

neutral & charged current
top quark gauge interactions

\[ tWZ \]

\[ \bar{b}/b \rightarrow W^\pm Z \]

\[ g \rightarrow t/\bar{t} \]
Rare single top modes

$b/b \rightarrow tZ$

$tWZ$

$bW \rightarrow tZ$

neutral & charged current top quark gauge interactions

$O_{\varphi Q}^{(3)} = i (\varphi^\dagger \overleftrightarrow{D}_\mu \tau^I \varphi) (\bar{Q} \gamma^\mu \tau_I Q)$

Expectation:
Energy-growing interference
Rare single top modes

\[ b/\bar{b} \rightarrow t/Z \]

Neutral & charged current
Top quark gauge interactions

\[ tW \rightarrow t/Z \]

Expectation:
Energy-growing interference

Dedicated \( tZj \) study:

- Larger rate, differential measurements available
- Expected E-growing interference is suppressed...

[Degrande, Maltoni, KM, Vryonidou & Zhang; JHEP 10 (2018) 005]
Rare single top modes

\[ \begin{align*}
  b/\bar{b} & \rightarrow t/\bar{t} \\
  tZ & \\
  q & \rightarrow W \\
  q' & \\
\end{align*} \]

neutral & charged current
top quark gauge interactions

\[ \begin{align*}
  \bar{b}/b & \rightarrow W^\pm \\
  tWZ & \\
  g & \rightarrow Z \\
  t/\bar{t} & \\
\end{align*} \]

\[ \mathcal{O}^{(3)}_{\varphi Q} = i (\varphi^\dagger \bar{D}_\mu \tau^I \varphi) (\bar{Q} \gamma^\mu \tau_I Q) \]

Expectation:
Energy-growing interference

Dedicated \( tZj \) study:

- Larger rate, differential measurements available
- Expected E-growing interference is suppressed...

Growth recovered in \( tWZ \)

- Generally larger relative effect of all BSM interactions

[Degrande, Maltoni, KM, Vryonidou & Zhang; JHEP 10 (2018) 005]

[Mantani, Maltoni & KM; JHEP 10 (2019) 004]
$tZ$ radar plot

$p p \rightarrow tZj$

$C_i = 1$
Inclusive
$p_T(Z) > 500$ GeV

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Interpreting LHC top data in SMEFT
$tZ$ radar plot

interference/SM

$p p \rightarrow t Z j$

square/SM

$C_i = 1$
Inclusive
$p_T(Z) > 500$ GeV
$tZ$ radar plot

interference/SM

$square/SM$

$\sigma_{QCD} = \sigma_{EW} = 621.3 \text{ fb}$
$\sigma_{HE} = 794.8 \text{ ab}$

$pp \rightarrow tZj$

Total rate impact

$C_i = 1$
Inclusive
$p_T(Z) > 500 \text{ GeV}$
$tZ$ radar plot

interference/SM

$pp \rightarrow tZj$

square/SM

Total rate impact

Energy growth

$C_i = 1$

Inclusive

$p_T(Z) > 500$ GeV
$tZ$ radar plot

interference/SM

$pp \to tZj$

Cancellations

square/SM

Total rate impact

Energy growth

$C_i = 1$

Inclusive

$p_T(Z) > 500$ GeV

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$tZ$ radar plot

interference/SM

square/SM

Cancellations

Total rate impact

Energy growth

Expected growth from 2→2 absent!

$C_i = 1$
Inclusive
$p_T(Z) > 500$ GeV

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Interpreting LHC top data in SMEFT
$tZW$ radar plot

interference/SM

$pp \rightarrow tZW$

square/SM

$C_i = 1$

Inclusive

$p_T(W,Z) > 500$ GeV

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$tZW$ radar plot

interference/SM

$pp \rightarrow tZW$

Cancellations gone!

square/SM

$C_i = 1$
Inclusive
$p_T(W,Z) > 500$ GeV
**tZW radar plot**

interference/SM

\[ p p \rightarrow tZW \]

square/SM

Cancellations gone!

Expected growth is there!

\[ C_i = 1 \]

Inclusive

\[ p_T (W,Z) > 500 \text{ GeV} \]
tZW radar plot

interference/SM

$\sigma_{QCD} = -$ $\sigma_{EW} = 114.6$ fb $\sigma_{HE} = 85.3$ ab

$\log(r_i)$

$\sigma^{(1)}_{QCD}$ $\sigma^{(3)}_{QCD}$

$\theta_{Q}$ $\theta_{Q}$

$\phi_{Q}$ $\phi_{Q}$

$\phi_{t}$ $\phi_{t}$

$\phi_{tb}$ $\phi_{tb}$

$\theta_{tw}$ $\theta_{tw}$

$\theta_{tq}$ $\theta_{tq}$

Cancellations gone!

$p p \rightarrow tZW$

square/SM

$\log(r_{i,i})$

$\sigma^{(1)}_{QCD}$ $\sigma^{(3)}_{QCD}$

$\theta_{Q}$ $\theta_{Q}$

$\phi_{Q}$ $\phi_{Q}$

$\phi_{t}$ $\phi_{t}$

$\phi_{tb}$ $\phi_{tb}$

$\theta_{tw}$ $\theta_{tw}$

$\theta_{tq}$ $\theta_{tq}$

Bigger impact

Expected growth is there!

$C_i = 1$
Inclusive
$p_T(W,Z) > 500$ GeV

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**tZW radar plot**

**interference/SM**

\[ p p \rightarrow tZW \]

\[ \sigma_{QCD} = - \]
\[ \sigma_{EW} = 114.6 \text{ fb} \]
\[ \sigma_{HE} = 85.3 \text{ ab} \]

\[ \log(r_i) \]

Cancellations gone!

**square/SM**

Bigger impact

More growth

\[ C_i = 1 \]

Inclusive

\[ p_T(W,Z) > 500 \text{ GeV} \]

Expected growth is there!

K. Mimasu - Seminar, Vienna - 28/03/2023
tZW radar plot

interference/SM

square/SM

$\sigma_{QCD} = -$
$\sigma_{EW} = 114.6 \text{ fb}$
$\sigma_{HE} = 85.3 \text{ ab}$

$log(r_i)$

$p p \rightarrow tZW$

Cancellations gone!

Bigger impact

More growth

Expected growth is there!

Interesting process that should be accessible at the LHC

$C_i = 1$
Inclusive
$p_T(W,Z) > 500 \text{ GeV}$
New physics in tWZ

Rare top production with promising BSM sensitivity
- Precision differential predictions for SM & EFT
New physics in tWZ

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Well-defined NLO calculation
- Control uncertainties & check stability of BSM impact (SMEFT K-factors)
- $tWZ$ non-trivial: overlap with other processes
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NLO 5FS: real-emission includes $tWZ\bar{b}$ final state

LO $\Rightarrow$ NLO
Overlap in tWZ

\[ t\bar{t}Z(t \rightarrow W\bar{b}) \]

Overlap: **resonant** contributions from \( t\bar{t} \) & \( t\bar{t}Z \)

Contrast to our **non-resonant** \( tWZ \) topology
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- Unwanted pieces are LO contribution to other processes, interfere w/ signal
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A. Full final state, 4FS: $pp \rightarrow b\bar{b}W^+W^-Z$ ! NLO computationally intensive !
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**Analogous behaviour in any** $tW(X)$ **production process**

A. Full final state, 4FS: $pp \rightarrow b\bar{b}W^+W^-Z$ ! NLO computationally intensive!


B. Subtract resonant contributions: operative definition of signal region @ NLO
We follow: [Demartin et al.; EPJC 77 (2017) 34], [Frixione et al.; JHEP 12 (2019) 008]

tWZ in the SM

tWZ $\rightarrow tW\ell\ell$: resonant overlap = $1\rightarrow 2(3)$ & $1\rightarrow 3(4)$ decays
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- Use Diagram Removal (DR) technique to mitigate overlap
- Suppress resonant interference: veto hard or central b-quarks

$p_T > 30 \text{ GeV}$
$|\eta| < 2.5$
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$\mathbf{p_T > 30 \text{ GeV}}$

$| \eta | < 2.5$

High mass & Z-pole

w/o b-veto:
DR1/DR2 diverge at high energy.
Gauge invariance issues...

w/ b-veto:
DR1/DR2 agree.
Uncertainty under control.
\( tWZ \) in the SMEFT

**Pros**

- Sensitive to unitarity violation in \( bW \rightarrow tZ \) scattering
- Energy growth found to be more pronounced w.r.t. \( tZj, tWj, \ldots \)
- No LO contribution from 4F operators, unlike \( t\bar{t}Z \) & \( tZj \)
- Global fit: help to de-correlate 4F from top EW couplings
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- Global fit: help to de-correlate 4F from top EW couplings

**Cons**
- Rare process \(~100 \text{ fb before decays}\)
- Not yet observed
- Overlap with resonant backgrounds
- Challenging to disentangle from other rate top processes
  - \( tW, t\bar{t}Z, t\bar{t}W, tZj, \ldots \)
$O(\Lambda^{-2})$

$W_L, Z_L$

$W_L, Z_T$

$W_T, Z_L$

$W_T, Z_T$
$\mathcal{O}(\Lambda^{-2})$

$W_L, Z_L$

Expected E-growing interference

$W_T, Z_L$

Other unexpected ones... finite mass effects?

$W_T, Z_T$
LO, unpolarised \( \Lambda = 1 \text{ TeV}, C_i = 1 \)

SM: TT=56 fb, TL=47 fb & LL = 13 fb
LO, unpolarised $\Lambda = 1$ TeV, $C_i = 1$

SM: TT=56 fb, TL=47 fb & LL = 13 fb

$C_{\phi Q}^{(-)}$, $C_{\phi t}$ no energy growth: expected in interference, too mild in square
\[ \mathcal{O} = \mathcal{O}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}^i_{\text{int}} + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \mathcal{O}^{ij}_{\text{sq}} \]

<table>
<thead>
<tr>
<th></th>
<th>Inclusive</th>
<th>High-Energy $\equiv p_T^{Z,W} &gt; 500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LO</td>
<td>NLO DR1</td>
</tr>
<tr>
<td></td>
<td>SM</td>
<td>103.36(4) $^{+12.76%}_{-12.82%}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>106.80(9) $^{+5.04%}_{-5.62%}$</td>
</tr>
<tr>
<td></td>
<td>LO</td>
<td>0.073(0) $^{+15.92%}_{-14.23%}$</td>
</tr>
<tr>
<td></td>
<td>NLO DR1</td>
<td>0.036(0) $^{+26.82%}_{-45.63%}$</td>
</tr>
</tbody>
</table>
NLO inclusive \( \Lambda = 1 \text{ TeV}, C_i = 1 \)

\[
\mathcal{O} = \mathcal{O}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}^{i}_{\text{int}} + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \mathcal{O}^{ij}_{\text{sq}}
\]

<table>
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<tr>
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<th>Inclusive ( \mathcal{O}(\Lambda^{-4}) )</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>LO</td>
<td>NLO DR1</td>
</tr>
<tr>
<td>( c_{\varphi Q}^{(3)} )</td>
<td>19.78(1)(^{+12.98%}_{-13.02%} )</td>
<td>21.20(2)(^{+5.66%}_{-6.13%} )</td>
</tr>
<tr>
<td>( c_{\varphi Q}^{(-1)} )</td>
<td>2.19(0)(^{+12.65%}_{-12.72%} )</td>
<td>2.69(1)(^{+8.92%}_{-8.18%} )</td>
</tr>
<tr>
<td>( c_{\varphi t} )</td>
<td>1.77(0)(^{+13.11%}_{-13.13%} )</td>
<td>1.81(0)(^{+4.81%}_{-5.53%} )</td>
</tr>
<tr>
<td>( c_{tW} )</td>
<td>-11.34(1)(^{+12.27%}_{-12.15%} )</td>
<td>-11.49(2)(^{+5.84%}_{-5.57%} )</td>
</tr>
<tr>
<td>( c_{tZ} )</td>
<td>-0.26(0)(^{+11.03%}_{-11.01%} )</td>
<td>-0.35(2)(^{+4.99%}_{-6.66%} )</td>
</tr>
<tr>
<td>( c_{tG} )</td>
<td>7.95(0)(^{+13.00%}_{-13.04%} )</td>
<td>7.36(1)(^{+4.00%}_{-5.01%} )</td>
</tr>
</tbody>
</table>

Good DR1/DR2 agreement: stick to DR2 henceforth
NLO inclusive

$\Lambda = 1 \text{ TeV}, C_i = 1$

Inclusive vs. High energy

$\log_{10}(\mathcal{O}(\Lambda^{-2})/SM) \cdot C_{tG}$

Interference/SM $C^{(-)}_{\phi Q}$

Square/SM $C^{(-)}_{\phi Q}$

$b$-veto inclusive

$b$-veto $p_T > 500 \text{ GeV}$

$\sigma_{SM}^{DR2} = 106.80 \text{ fb}$
NLO inclusive

$\Lambda = 1 \text{ TeV}, C_i = 1$

Inclusive vs. High energy

$\log_{10}(\mathcal{O}(\Lambda^{-2})/\text{SM})$

$C_tG$

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$

Interference/SM $C_{\phi Q}^{(-)}$

Square/SM $C_{\phi Q}^{(3)}$

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<tr>
<td></td>
<td>LO</td>
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<tr>
<td>$c_{tQ}^{(3)}$</td>
<td>0.191</td>
<td>0.200</td>
</tr>
<tr>
<td>$c_{\phi Q}^{(-)}$</td>
<td>0.021</td>
<td>0.026</td>
</tr>
<tr>
<td>$c_{ct}$</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>$c_{tW}$</td>
<td>$-0.110$</td>
<td>$-0.109$</td>
</tr>
<tr>
<td>$c_{tZ}$</td>
<td>$-0.003$</td>
<td>$-0.003$</td>
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<tr>
<td>$c_{tG}$</td>
<td>0.077</td>
<td>0.068</td>
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<tr>
<td></td>
<td>LO</td>
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<tr>
<td>$c_{tQ}^{(3)}$</td>
<td>$-0.870$</td>
<td>$-0.715$</td>
</tr>
<tr>
<td>$c_{\phi Q}^{(-)}$</td>
<td>0.028</td>
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<td>$c_{tW}$</td>
<td>$-0.528$</td>
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**NLO inclusive**

\[ \Lambda = 1 \text{ TeV}, \ C_i = 1 \]

**Inclusive vs. High energy**

- **b-veto:** LO/NLO have different phase space
  - "K-factor" ill defined: compute for **relative impacts**
  - Some non-trivial NLO QCD corrections

---

**K. Mimasu - Seminar, Vienna - 28/03/2023**
NLO differential

Fixed order: relative impact stable under NLO QCD
NLO differential

Fixed order: relative impact stable under NLO QCD
- top $p_T$ not sensitive, not in relevant $tb \rightarrow WZ$ sub-amplitude
NLO differential

Dipoles, dominated by quadratic

K. Mimasu - Seminar, Vienna - 28/03/2023
NLO differential

Dipoles, dominated by quadratic

- Omitted other current operators due to lack of growth
- Potential sensitivity to gluon dipole (quite constrained by $t\bar{t}$)
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SMEFT contribution to suppressed overlap processes included!
NLO+PS

Allow tops to decay, keep W & Z stable
- Now require exactly one b-jet (veto applied to additional b-jet)
- Assumes 100% b-tagging efficiency within $|\eta| < 2.5$

K. Mimasu - Seminar, Vienna - 28/03/2023

Interpreting LHC top data in SMEFT
NLO+PS

Allow tops to decay, keep W & Z stable
- Now require exactly one b-jet (veto applied to additional b-jet)
- Assumes 100% b-tagging efficiency within $|\eta| < 2.5$

Some DR1/DR2 difference when selecting 'wrong' b-jet

Otherwise NLO stable!

K. Mimasu - Seminar, Vienna - 28/03/2023
Interpreting LHC top data in SMEFT
Prospects & challenges

EW top scattering: promising avenue for EW top couplings
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EW top scattering: promising avenue for EW top couplings

- Go beyond rate measurements & access energy growth/unitarity violation
- Increasingly high energy & multiplicity processes: future-proof
- Rare EW top modes: probe complimentary directions in SMEFT space
- Some already measured or within LHC reach ($t\bar{t}Wj$, $tHj$, $tWZ$, …)
- Others challenging, dedicated pheno studies required…
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<tbody>
<tr>
<td>ttZ(\ell^+\ell^-)</td>
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</tr>
<tr>
<td>ttH(bb)</td>
<td>ttZ, tt\bar{b}b, ttW, tZj,...</td>
</tr>
<tr>
<td>ttH(\gamma\gamma)</td>
<td>tt, b\bar{b}H, tHj, tHW</td>
</tr>
<tr>
<td>ttH(\tau^+\tau^-)</td>
<td>ttW(W), ttZ,...</td>
</tr>
<tr>
<td>tZj</td>
<td>ttV, tHj, tHW, tZW,...</td>
</tr>
<tr>
<td>tHj</td>
<td>ttH, ttZ, tt\bar{b}b, ttW, tZj,...</td>
</tr>
<tr>
<td>tt\bar{t}t</td>
<td>ttW, ttZ, ttH,...</td>
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Sig/Bkg. overlap ⇒ global measurements
Prospects & challenges

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<td>$t\bar{t}H(bb)$</td>
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</tr>
<tr>
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<td>$t\bar{t}V$, $tH_j$, $tHW$, $tZW$,...</td>
</tr>
<tr>
<td>$tHj$</td>
<td>$t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}b\bar{b}$, $t\bar{t}W$, $tZ_j$,...</td>
</tr>
<tr>
<td>$t\bar{t}\bar{t}t$</td>
<td>$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$,...</td>
</tr>
</tbody>
</table>

Sig/Bkg. overlap $\Rightarrow$ global measurements

- SMEFT contributes everywhere… blurs the lines
- Challenging to incorporate into global likelihood
- From individual to simultaneous measurements
- Signal regions based on final state properties
Conclusions

The future is bright for top physics in SMEFT
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- Global SMEFT analyses are rapidly expanding & probing model space
- New precision tools available (SMEFTatNLO): NLO & loop-induced effects
- Being incorporated into experimental interpretations
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Things I couldn’t mention!

- Future direction: global study on CP violating operators in top data
- Fantastic progress in UV model interpretations of global fits
- Automated matching tools available
- Very important for testing validity