A fit to Higgs and top data in the SMEFT

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work in collaboration
with: Juan Rojo, Cen Zhang, Eleni Vryonidou, Emma Slade, Luca Mantani, Emanuele Nocera, Jake Ethier, Jaco ter Hoeve
Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states

Search for new interactions

“Peak” or more complicated structures searches. Need for descriptive simulations for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for accurate predictions for SM and EFT.
A quote

[S]He who knows the art of the **direct** and the **indirect** approaches will be victorious.
A quote

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Riccardo Rattazzi, Granada Meeting
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Sun Tzu, The Art of War
A quote

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Sun Tzu, The Art of War
**SMEFT Lagrangian: Dim=6**

[Buchmuller and Wyler, 86]  [Grzadkowski et al, 10]

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<tr>
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<th>$\phi^6$ and $\phi^4D^2$</th>
<th>$\psi^2\phi^3$</th>
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## SMEFT Lagrangian: Dim=6

**[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]**

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<td>( Q_{dd} )</td>
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<td>( Q_{cd} )</td>
<td>( Q_{qd} )</td>
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<tr>
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**B-violating**

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<tr>
<td>( Q_{lq} )</td>
<td>( \varepsilon^{\alpha\beta\gamma}\varepsilon_{jk} [(d_\alpha^\gamma)^T C u_\alpha^\beta] [(q_\gamma^j)^T C l_\beta^k] |</td>
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<td>( Q_{q_{uu}}^{(1)} )</td>
<td>( \varepsilon^{\alpha\beta\gamma}\varepsilon_{jk} [(q_\alpha^\alpha)^T C q_\beta^j] [(u_\gamma^j)^T C e_i] |</td>
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<tr>
<td>( Q_{q_{qq}}^{(8)} )</td>
<td>( \varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn} [(q_\alpha^j)^T C q_\beta^k] [(q_\gamma^m)^T C l_\gamma^m] |</td>
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<tr>
<td>( Q_{lq_{uu}}^{(3)} )</td>
<td>( \varepsilon^{\alpha\beta\gamma}(\tau^\varepsilon)^{(j)(\tau^\varepsilon)}<em>{mn} [(q</em>\alpha^j)^T C q_\beta^k] [(q_\gamma^m)^T C l_\gamma^m] |</td>
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<td>( Q_{lq_{dd}}^{(3)} )</td>
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[Buchmuller and Wyler, 86]  [Grzadkowski et al, 10]

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SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]
Which interactions?

• Interactions between light fermions and gauge bosons tested at low energies and at LEP at below the per mill level.
• Self interactions of weak gauge bosons tested at LEP II High energy at the % level. LHC will be competitive.
• Higgs interactions with gauge bosons constrained at 10% level.
• Top-quark interactions with gauge bosons and the Higgs at 10% level.
• Higgs self interactions unexplored
• Higgs interactions with light fermions unexplored.
Higgs

- ggF
- BR_H
- ttH
- VH/VBF
- VBS
- t+H/Z/\gamma
- single top
- tt+V
- EW
- EWPO
- TGC

Jets

Decays

Flavor

CPV

HC 2019 - Oxford - 2 Oct

Ken Mimasu®
Example: tZj/tHj

- Single top rate about 1/4 of QCD tt
- Purely EW processes => no QCD contribution
- Sensitive to 2 four-fermion and 3 top/EW operators that modify tbW vertex
- Requiring the presence of an additional Z or Higgs
  - Unique possibility of probing full set of top/Higgs/EW operators at once
  - Higher thresholds may enhance EFT effects
  - Recent LHC measurement of tZj cross section at 4.2σ

[Degrande, FM, Mimasu, Vryonidou, Zhang, 2018]
Example: tZj/tHj

tHj (tZj = h→Z) : classes of operators

\[ O_{\psi W} : \varphi^\dagger \varphi W_i^{\mu \nu} W_i^{\mu \nu} \]

HWW

TGC

\[ O_{\psi W} : e^{ijk} W_{i, \mu \nu} W_{j, \mu}^\nu W_{k, \rho}^\mu \]

\[ O_{\psi t} : (\varphi^\dagger \varphi) (\bar{Q} t) \bar{\phi} \]

top Yukawa

\[ O_{\psi t} : i(\varphi^\dagger \overleftrightarrow{D}_{\mu} \varphi) (t \gamma^\mu t) \]

ttZ coupling

\[ O_{\psi Q}^{(3)} : i(\varphi^\dagger \overleftrightarrow{D}_{\mu} \varphi) (\bar{Q} \gamma^\mu \sigma_i Q) \]

Wtb vertex

\[ O_{\psi t}^{(3)} : i(\varphi^\dagger \overleftrightarrow{D}_{\mu} \varphi) (\bar{Q} \gamma^\mu \sigma_i Q) \]

Contact terms

\[ O_{tB} : (\bar{Q} \sigma_{\mu \nu} t) \bar{\phi} B^{\mu \nu} \]

• Accessing the bW→tH & bW→tZ sub-amplitudes
  • Rich interplay between EFT operators from different sectors
  • Different energy growth and interference with the SM
  • Four fermion interactions also present

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Example: $tZj/tHj$
Example: $tZj/tHj$

$\sigma_{QCD} = -\sigma_{BW} = 46.4 \text{ fb}$

$p p \rightarrow thj$

$\sigma^{(3)}_{t\varphi}$  

$\sigma^{(3)}_{t\varphi}$
Example: $tZj/tHj$

$\sigma_{\text{OCD}} = \sigma_{\text{EW}} = 646.9 \text{ fb}$

$p p \rightarrow tZj$

$\sigma_{tW}$

$\sigma_{tB}$

$\sigma_{\varphi t}$

$\sigma^{(1)}_{\varphi Q}$

$\sigma^{(3)}_{\varphi Q}$

$\sigma^{(1)}_{\varphi Q}$

$\sigma^{(3)}_{\varphi Q}$

[FM, Mantani, Mimasu, 2018]
SMEFT at the LHC

$S$ is a generic scale, which is process and operator dependent

• Large number of operators, yet a plethora of observables and final states to measure.

• Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.

• Validity issues arise, as well as for the interpretation in terms of models.
SMEFT at the LHC

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$$\text{Obs}_i = \text{Obs}_{i}^{SM} + M_{ij} \cdot \frac{s}{\Lambda^2} \cdot c_j$$
SMEFT at the LHC

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\[ S \text{ is a generic scale, which is process and operator dependent} \]

\[ \text{Obs}_i = \text{Obs}^\text{SM}_i + M_{ij} \cdot \frac{s}{\Lambda^2} c_j \]

\[ \Lambda > \sqrt{s} \sqrt{|c_i|/\delta} \]

\[ |c_i| s/\Lambda^2 < \delta \]
SMEFT at the LHC

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\[
|c_i| s/\Lambda^2 < \delta
\]

\[
\sqrt{s} < \Lambda
\]
SMEFT global fit

• **Measurements:**
  • Total as well as differential, unfolded and/or fiducial, including uncertainties and correlations.
  • Reference SMEFT interpretations done by the experimental collaboration for best sensitivity targets.

• **Theoretical predictions:**
  • SM at the best possible accuracy
  • SMEFT at least at NLO in QCD

• **Fitting:**
  • Robust and scalable fitting technology
  • Combination with low/energy, flavour and LEP measurements
SMEFT at NLO

Aim to fully automate NLO calculations in the SMEFT within public Monte Carlo generators based on:

- Warsaw basis of dimension-6 operators

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: \(U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e\)
- Successful validation with LO implementations
- 0/2F@NLO operators validated (with previous partial NLO implementations)

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- 4F@NLO operators validation: on-going

Paves the way for a precise SMEFT programme at the LHC

[In collaboration with: C. Degrande, G. Durieux, K. Mimasu, E. Vryonidou, C. Zhang]
Need for NLO

1. Operators run and mix under RGE

2. EFT scale dependence

3. Genuine NLO corrections (finite terms) are important

4. New operators arise
Need for NLO

4. New operators arise

New operators can arise at one-loop or via real corrections.

- At variance with the SM, loop-induced processes might not be finite.
- Including the full set of operators at a given order implies that no extra UV divergences appear (closure check).
- Use tree-level, loop-level, hierarchy but not gauge couplings.

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]
[Dawson, Giardino, 2018, 2019]
[Dedes et al, 2018]
[Vryonidou and Zhang, 2018]
Need for NLO

4. New operators arise

[Durieux, Gu, Vryonidou and Zhang, 2018]
Global fit Setup

Theory

(N)NLO QCD+ NLO EW for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

Methodology

Based on NNPDF
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Output

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added
Plan to extend to Higgs, gauge sector etc
A first application: A global top fit at NLO

Rich phenomenology

34 d.o.f. CP-conserving

[Hartland, FM, Nocera, Rojo, Slade, Vryonidou and Zhang, 2019]
Observables and theory predictions

**Data**

- Top-pair production
- $W$-helicities

**Theoretical predictions**

The baseline fit includes:

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$\chi^2/n_{\text{dat}}$ (prior)</th>
<th>$\chi^2/n_{\text{dat}}$ (fit)</th>
<th>$n_{\text{dat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS_tt_8TeV_ljets [ $m_{tt}$ ]</td>
<td>1.51</td>
<td>1.25</td>
<td>7</td>
</tr>
<tr>
<td>CMS_tt_8TeV_ljets [ $y_{tt}$ ]</td>
<td>1.17</td>
<td>1.17</td>
<td>10</td>
</tr>
<tr>
<td>CMS_tt2D_8TeV_dilep [ $(m_{tt}, y_{tt})$ ]</td>
<td>1.38</td>
<td>1.38</td>
<td>16</td>
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<tr>
<td>CMS_tt_13TeV_ljets2 [ $m_{tt}$ ]</td>
<td>1.09</td>
<td>1.28</td>
<td>8</td>
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<td>CMS_tt_13TeV_dilep [ $m_{tt}$ ]</td>
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<tr>
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<th>$\chi^2/n_{\text{dat}}$ (prior)</th>
<th>$\chi^2/n_{\text{dat}}$ (fit)</th>
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<td>CMS_tZ_inc_13TeV</td>
<td>0.66</td>
<td>0.34</td>
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</table>

**Baseline fit includes:**

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

One distribution from each dataset, to avoid double counting
Results

SMEFiT analysis of LHC top quark data

N. Hartland et. al. JHEP 1904 (2019) 100, updated
Results

- Correlations of fit parameters via color map
- Not all parameters completely independent!
Recent developments

• Optimisation of the MC fitting technique and correct handling of the square terms.

• New Nested Sampling (NS) algorithm implemented for MC sampling determination of posterior distributions

• Fitting to restricted scenarios

• Extension to the Higgs sector started
Comparison between fit technologies

- Agreement of 95% CL bounds rather good between the two methods
- Slight improvements in some operator bounds from previous SMEFiT publication
Linear vs quadratic

SMEFiT top quark data, global fit, marginalised

95% Confidence Level Bounds (1/TeV²)

- **NS \(\sigma(\Lambda^{-2})\)**
- **NS \(\sigma(\Lambda^{-4})\)**
• Consistent with SM within 95% CL errors
• New LHC top quark measurements may help to constrain additional operator coefficients
Comparison between fit technologies

- Slightly different correlation structure than MC fit method – currently still working to understand sources of differences and improve agreement.
Top-philic scenario

- Same flavour symmetries as baseline scenario (MFV: $U(2)_q \times U(2)_u \times U(2)_d$)
- Assumes new physics couples more strongly to 3rd-generation LH doublet and RH up-type singlet (+ bosons)

\[
\begin{align*}
&c_{tq}^{[I]}, \quad c_{\bar{P}Q}, \quad c_{\varphi Q}^3, \quad c_{\varphi t}, \quad c_{tW}^{[I]}, \quad c_{tZ}^{[I]}, \quad c_{tG}^{[I]} \\
&c_{\varphi tb}^{[I]} \quad \text{and} \quad c_{bW}^{[I]} \quad \text{appear proportional to } y_b \\
&c_{QQ}^{1}, \quad c_{QQ}^{8}, \quad c_{Qt}^{1}, \quad c_{Qt}^{8}, \quad c_{tt}^{1}, \\
&c_{QDW} = c_{Qq}^{3,1} = c_{Ql}^{3(\ell)}, \\
&c_{QDB} = 6 c_{Qq}^{1,1} = \frac{3}{2} c_{Qu}^{1} = -3 c_{Qd}^{1} = -3 c_{Qb}^{1} = -2 c_{Qe}^{1(\ell)} = -c_{Qe}^{(\ell)}, \\
&c_{tDB} = 6 c_{tq}^{1} = \frac{3}{2} c_{tu}^{1} = -3 c_{td}^{1} = -3 c_{tb}^{1} = -2 c_{te}^{1(\ell)} = -c_{te}^{(\ell)}, \\
&c_{QDG} = c_{Qq}^{1,8} = c_{Qu}^{8} = c_{Qd}^{8} = c_{Qb}^{8}, \\
&c_{tDG} = c_{tq}^{8} = c_{tu}^{8} = c_{td}^{8} = c_{tb}^{8}.
\end{align*}
\]

- 34 parameter basis reduced to 19 free parameters
Top-philic scenario

- Significantly stronger constraints with top-philic scenario
Work in progress: Higgs Fit

- Analysis of VH production data from ATLAS at 13 TeV
- Single dataset of 5 points
- Same SM prediction as ATLAS analysis

- No interference with top sector
- Total error dominated by statistical uncertainties – reflects in resulting coefficient bounds
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### Preliminary

![Graph](image)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Wilson Coefficient</th>
<th>Degree of Freedom</th>
<th>Operator Definition</th>
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<tr>
<td>$O_{pW}$</td>
<td>cpW</td>
<td>$O_{pW}$</td>
<td>$(\phi^\dagger \phi - \frac{g^2}{2}) W^\mu_{\nu} W^\nu_{\mu}$</td>
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<tr>
<td>$O_{pB}$</td>
<td>cpB</td>
<td>$O_{pB}$</td>
<td>$(\phi^\dagger \phi - \frac{g^2}{2}) B^\mu_{\nu} B^\nu_{\mu}$</td>
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<td>$O_{pWB}$</td>
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<td>$O_{pWB}$</td>
<td>$(\phi^\dagger T^I \phi) B^\mu_{\nu} W^\nu_{\mu}$</td>
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<td>$O_{pD}$</td>
<td>cpDC</td>
<td>$O_{pD}$</td>
<td>$(\phi^\dagger D^\mu \phi)^J (\phi^\dagger D^\mu \phi)$</td>
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<tr>
<td>$O_{pq}$</td>
<td>cpqi</td>
<td>$O^{(1)}_{pq}$</td>
<td>$\sum_{j=1,2} i(\phi^\dagger D^\mu_\nu \phi)(q_j \gamma^\mu q_j)$</td>
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<tr>
<td>$O_{3pq}$</td>
<td>c3pq</td>
<td>$O^{(3)}_{pq}$</td>
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<td>$O_{pQ3}$</td>
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<td>$O_{pd1}$</td>
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<td>$O_{pd1}$</td>
<td>$\sum_{j=1,2,3} i(\phi^\dagger D^\mu_\nu \phi)(d_j \gamma^\mu d_j)$</td>
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<tr>
<td>$O_{pd}$</td>
<td>cdp</td>
<td>$O_{pd}$</td>
<td>$\delta_{\mu} (\phi^\dagger \phi) \delta_{\mu} (\phi^\dagger \phi)$</td>
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<tr>
<td>$O_{3p11}$</td>
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<td>$O_{3p12}$</td>
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<td>$O^{(3)}_{p2}$</td>
<td>$i(\phi^\dagger D^\mu_\nu \phi)(\bar{l}_2 \gamma^\mu \gamma^\tau l_2)$</td>
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</tbody>
</table>

Fabio Maltoni
Work in progress: Higgs Fit

- Analysis of VH production data from ATLAS at 13 TeV
- Single dataset of 5 points
- Same SM prediction as ATLAS analysis

- No interference with top sector
- Total error dominated by statistical uncertainties – reflects in resulting coefficient bounds
Towards a global top/H/EW fit...

- Many flat directions at $1/\Lambda^2$
Summary

• A far reaching approach to new physics is that of searching for new interactions employing the SMEFT.

• The SMEFT approach provides a consistent QFT to work with. Predictions can be obtained and systematically improved at higher orders.

• To have a quantitative and meaningful interpretation framework predictions have to be available at NLO accuracy in QCD (and EW) and constraints need to be obtained in a global way.

• SMEFiT has performed a first exploratory study of the top sector at NLO in QCD in the SMEFT, using LHC data, comparing also different fitting techniques. We are on a steep learning curve!

• We are moving towards a combined top+Higgs+EW+EWPO data interpretation.
Additional information
Fitting technology I

Some remarks on Monte Carlo fitting methodology:

• Based on Bayesian statistical methods – robust determination of parameters (e.g. Wilson coefficients) and their uncertainties

\[ E[\mathcal{O}] = \int d^n a \mathcal{P}(\tilde{a} | \text{data}) \mathcal{O}(\tilde{a}) \]

\[ V[\mathcal{O}] = \int d^n a \mathcal{P}(\tilde{a} | \text{data}) \left[ \mathcal{O}(\tilde{a}) - E[\mathcal{O}] \right]^2 \]

• Bayes’ theorem defines probability \( \mathcal{P} \) as

\[ \mathcal{P}(\tilde{a} | \text{data}) = \frac{1}{Z} \mathcal{L}(\text{data}|\tilde{a}) \pi(\tilde{a}) \]

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“Evidence” \( Z = \int d^n a \mathcal{L}(\text{data}|\tilde{a}) \pi(\tilde{a}) \)
Fitting technology I

- Can sample parameter space and perform many fits to obtain representative MC sample

\[
E[\mathcal{O}(\tilde{a})] = \sum_k w_k \mathcal{O}(\tilde{a}_k) \quad V[\mathcal{O}(\tilde{a})] = \sum_k w_k (\mathcal{O}(\tilde{a}_k) - E[\mathcal{O}])^2
\]

- Generate artificial data replicas (Gaussian resampling):

\[
\mathcal{O}^{(\text{art})}_i(k) = S^{(k)}_{i,N} \mathcal{O}^{(\text{exp})}_i \left( 1 + r^{(k)}_i \sigma^{(\text{stat})}_i + \sum_{\alpha=1}^{N_{\text{sys}}} r^{(k)}_{i,\alpha} \sigma^{(\text{sys})}_{i,\alpha} \right), \quad k = 1, \ldots, N_{\text{rep}}
\]

- Minimize loss function:

\[
\chi^2 \equiv \frac{1}{N_{\text{dat}}} \sum_{i,j=1}^{N_{\text{dat}}} \left( \mathcal{O}^{(\text{th})}_i(\{\langle c_l \rangle \}) - \mathcal{O}^{(\text{exp})}_i \right) (\text{cov}^{-1})_{ij} \left( \mathcal{O}^{(\text{th})}_j(\{\langle c_l \rangle \}) - \mathcal{O}^{(\text{exp})}_j \right)
\]

\[
\text{cov}_{ij} = \text{cov}^{(\text{exp})}_{ij} + \text{cov}^{(\text{th})}_{ij}
\]

- Cross-validate to prevent over-fitting

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Fitting technology II

\[ Z = \int d^n a \mathcal{L}(\text{data}|\tilde{a}) \pi(\tilde{a}) = \int_0^1 dX \mathcal{L}(X) \quad \text{where the prior volume} \quad dX = \pi(\tilde{a}) d^n a \]

- Samples directly from prior space to locate region of maximum likelihood
- Posterior samples obtained as a by-product of computing evidence \( Z \)
- Advantage: no need for cross-validation or a minimiser (fit algorithm)
- Disadvantage: exponential increase in runtime as prior volume increases


\[ Z_i \sim \sum_i \mathcal{L}_i w_i \]

\[ w_i = \frac{1}{2} (X_{i-1} - X_{i+1}) \]
Fitting technology II

- Probability distributions from MC samples provide crucial insight to behaviour of coefficients

- Differences between the two independent methods can be studied (are MC fits underestimating or NS overestimating?)

- Provides visualisation of correlations and unconstrained parameters

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HC 2019 - Oxford - 2 Oct
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- Provides visualisation of correlations and unconstrained parameters
## SMEFiT: data set

<table>
<thead>
<tr>
<th>Process</th>
<th>Dataset</th>
<th>$\sqrt{s}$</th>
<th>Info</th>
<th>Observables</th>
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<tbody>
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<td>lepton+jets</td>
<td>$d\sigma/d</td>
<td>y_t</td>
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<tr>
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<th>Observables</th>
<th>$N_{\text{dat}}$</th>
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<tbody>
<tr>
<td>Single $t$</td>
<td>CMS$_t$ _tch$<em>8$TeV$</em>{\text{inc}}$</td>
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<td>$t$-channel</td>
<td>$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t}) \ (R_t)$</td>
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<tr>
<td>Single $t$</td>
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<td>$s$-channel</td>
<td>$\sigma_{\text{tot}}(t + \bar{t})$</td>
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<td>$t$-channel</td>
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<tr>
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<td>13 TeV</td>
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<td>$\sigma_{\text{tot}}(t), \sigma_{\text{tot}}(\bar{t}) \ (R_t)$</td>
<td>2 (1)</td>
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<td>Single $t$</td>
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<td>$t$-channel</td>
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<td>$t$-channel</td>
<td>$\frac{d\sigma}{dp_T^{(t+\bar{t})}}, \frac{d\sigma}{dy_{(t+\bar{t})}}$</td>
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<td>$tW$</td>
<td>ATLAS$_{tW}$ <em>inc$</em>{8}$TeV</td>
<td>8 TeV</td>
<td>inclusive</td>
<td>$\sigma_{\text{tot}}(tW)$</td>
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<td>$tW$</td>
<td>CMS$_{tW}$ <em>inc$</em>{8}$TeV</td>
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<td>inclusive</td>
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<td>$\sigma_{\text{tot}}(tW)$</td>
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<tr>
<td>$tZ$</td>
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<td>inclusive</td>
<td>$\sigma_{\text{fid}}(Wb\ell l^- q)$</td>
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<td>13 TeV</td>
<td>inclusive</td>
<td>$\sigma_{\text{tot}}(tZq)$</td>
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## SMEFiT: Theory input

<table>
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<tr>
<th>Process</th>
<th>SM</th>
<th>Code</th>
<th>SMEFT</th>
<th>Code</th>
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<td>$t\bar{t}$</td>
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<td>MCFM/SHERPA NLO + NNLO K-factors</td>
<td>NLO QCD</td>
<td>MG5_aMC</td>
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<tr>
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<td>LO QCD + NLO SM K-factors</td>
<td>MG5_aMC</td>
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<td>MG5_aMC</td>
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</tbody>
</table>
dof vs operators

Degrees of freedom: 4-heavy

\[ c_{QQ}^1 \equiv 2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)} \]

\[ c_{QQ}^8 \equiv 8C_{qq}^{3(3333)} \]

\[ c_{Qt}^1 \equiv C_{qu}^{1(3333)} \]

\[ c_{Qt}^8 \equiv C_{qu}^{8(3333)} \]

\[ c_{Qb}^1 \equiv C_{qd}^{1(3333)} \]

\[ c_{Qb}^8 \equiv C_{qd}^{8(3333)} \]

\[ c_{tt}^1 \equiv C_{uu}^{1(3333)} \]

\[ c_{tb}^1 \equiv C_{ud}^{1(3333)} \]

\[ c_{tb}^8 \equiv C_{ud}^{8(3333)} \]

\[ c_{QtQb}^1 \equiv \text{Re}\{C_{quqd}^{1(3333)}\} \]

\[ c_{QtQb}^8 \equiv \text{Re}\{C_{quqd}^{8(3333)}\} \]

4-fermion operators in Warsaw basis

\[ O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l) \]

\[ O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l) \]

\[ O_{qu}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l) \]

\[ O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l) \]

\[ O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l) \]

\[ O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l) \]

\[ O_{uu}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l) \]

\[ O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l) \]

\[ O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l) \]

\[ \hat{O}_{quqd}^{1(ijkl)} = (\bar{q}_i u_j) \varepsilon (\bar{q}_k d_l) \]

\[ \hat{O}_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j) \varepsilon (\bar{q}_k T^A d_l) \]
dof vs operators

Degrees of freedom: 2-heavy-2-light

\[ c_{Qq}^{1,1} \equiv C_{qq}^{1(i3i3)} + \frac{1}{6} C_{qq}^{1(i3i3)} + \frac{1}{2} C_{qq}^{3(i3i3)} \]

\[ c_{Qq}^{3,1} \equiv C_{qq}^{3(i3i3)} + \frac{1}{6} (C_{qq}^{1(i3i3)} - C_{qq}^{3(i3i3)}) \]

\[ c_{Qq}^{1,8} \equiv C_{qq}^{1(i3i3)} + 3 C_{qq}^{3(i3i3)} \]

\[ c_{Qq}^{3,8} \equiv C_{qq}^{1(i3i3)} - C_{qq}^{3(i3i3)} \]

\[ c_{tu}^1 \equiv C_{uuu}^{(i3i3)} + \frac{1}{3} C_{uuu}^{(i3i3)} \]

\[ c_{tu}^8 \equiv 2 C_{uuu}^{(i3i3)} \]

\[ c_{td}^1 \equiv C_{udd}^{(33i3)} \]

\[ c_{ud}^8 \equiv C_{udd}^{8(33i3)} \]

\[ c_{tq}^1 \equiv C_{quu}^{1(i3i3)} \]

\[ c_{Qu}^1 \equiv C_{qqu}^{1(33i3)} \]

\[ c_{Qd}^1 \equiv C_{qdd}^{1(33i3)} \]

\[ c_{tq}^8 \equiv C_{quu}^{8(i33)} \]

\[ c_{Qu}^8 \equiv C_{qqu}^{8(33i3)} \]

\[ c_{Qd}^8 \equiv C_{qdd}^{8(33i3)} \]

4-fermion operators in Warsaw basis

\[ O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l) \]

\[ O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l) \]

\[ O_{qu}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l) \]

\[ O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l) \]

\[ O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l) \]

\[ O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l) \]

\[ O_{uu}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l) \]

\[ O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l) \]

\[ O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l) \]

\[ \frac{\delta}{\delta} O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j) \in (\bar{q}_k d_l) \]

\[ \frac{\delta}{\delta} O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j) \in (\bar{q}_k T^A d_l) \]
**dof vs operators**

### Degrees of freedom: 2-heavy + gauge/Higgs

\[ c_{t\varphi} \equiv \text{Re}\{C_{u\varphi}^{(33)}\} \]

\[ c_{\varphi Q}^\perp \equiv C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)} \]

\[ c_{\varphi Q}^3 \equiv C_{\varphi q}^{3(33)} \]

\[ c_{\varphi t} \equiv C_{\varphi u}^{(33)} \]

\[ c_{\varphi tb} \equiv \text{Re}\{C_{\varphi ud}^{(33)}\} \]

\[ c_{tW} \equiv \text{Re}\{C_{uW}^{(33)}\} \]

\[ c_{tZ} \equiv \text{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\} \]

\[ c_{bW} \equiv \text{Re}\{C_{dW}^{(33)}\} \]

\[ c_{tG} \equiv \text{Re}\{C_{uG}^{(33)}\} \]

### Gauge/Higgs operators in Warsaw basis

\[ \dagger O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi} (\varphi^\dagger \varphi) \]

\[ O_{\varphi q}^{1(ij)} = (\varphi^\dagger \gamma^\mu \tilde{q}_j) (\bar{q}_i \gamma^\mu q_j) \]

\[ O_{\varphi q}^{3(ij)} = (\varphi^\dagger \gamma^\mu \tau^I \tilde{q}_j) (\bar{q}_i \gamma^\mu \tau^I q_j) \]

\[ O_{\varphi u}^{(ij)} = (\varphi^\dagger \gamma^\mu \tilde{u}_j) (\bar{u}_i \gamma^\mu u_j) \]

\[ \dagger O_{\varphi ud}^{(ij)} = (\varphi^\dagger d_j) (\bar{u}_i \gamma^\mu d_j) \]

\[ \dagger O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \tilde{\varphi} W_{\mu\nu}^I \]

\[ \dagger O_{dW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j) \varphi W_{\mu\nu}^I \]

\[ \dagger O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\varphi} B_{\mu\nu} \]

\[ \dagger O_{uG}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j) \tilde{\varphi} G_{\mu\nu}^A \]
1. Operators run and mix under RGE

**Running** means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

**Mixing** means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.
By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.
3. Genuine NLO corrections (finite terms) are important

- pp → ttH
  \[ O_{t\phi} = y_t^3 \left( \phi^\dagger \phi \right) (\bar{Q}t) \bar{\phi}, \]
  \[ O_{\phi G} = y_t^2 \left( \phi^\dagger \phi \right) G^A_{\mu\nu} G^A_{\mu\nu}, \]
  \[ O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \bar{\phi} G^A_{\mu\nu}. \]

- EFT scale uncertainties are very much reduced at NLO.

- RG are sometimes thought to be an approximation for full NLO, but it is often not the case.