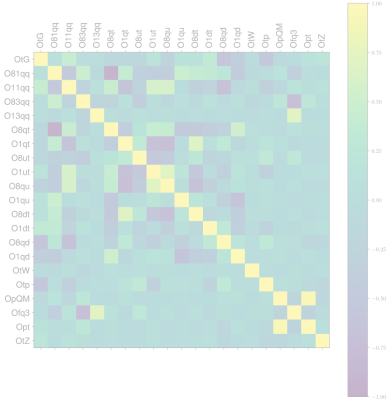
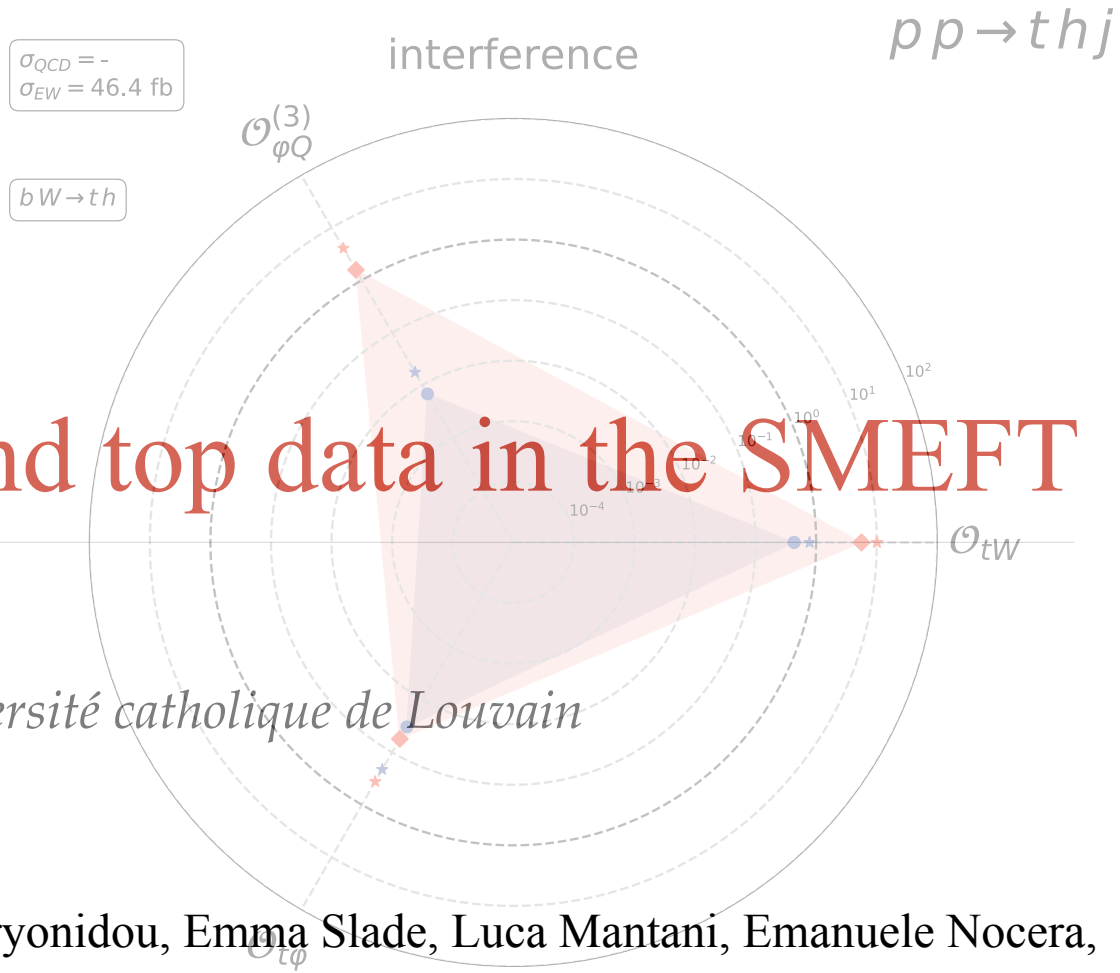


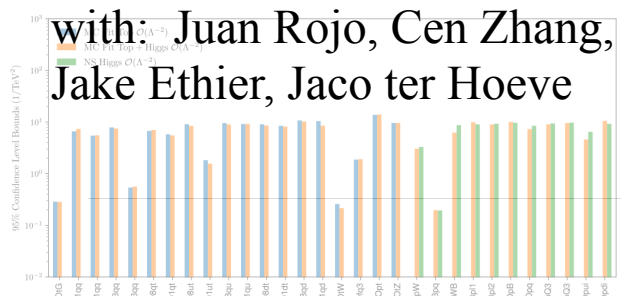



# A fit to Higgs and top data in the SMEFT


*Fabio Maltoni*

*Università di Bologna & Université catholique de Louvain*


work in collaboration
with: Juan Rojo, Cen Zhang, Eleni Vryonidou, Emma Slade, Luca Mantani, Emanuele Nocera, Jake Ethier, Jaco ter Hoeve

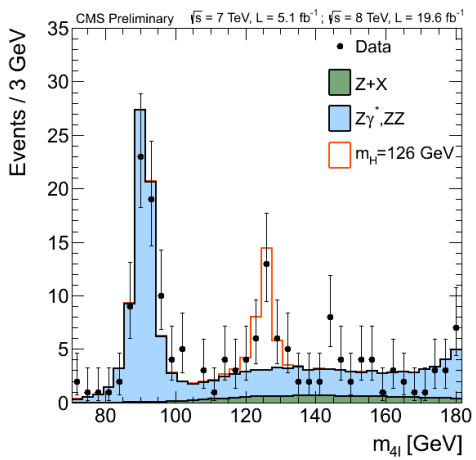


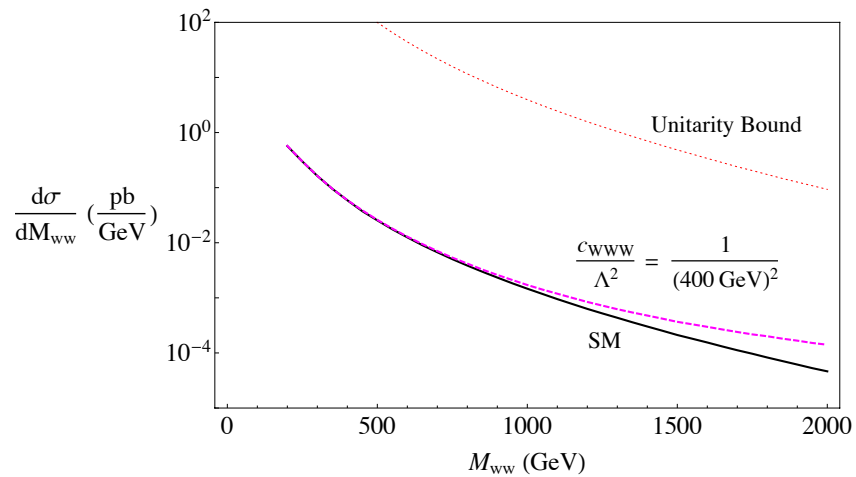
# Search for New Physics at the LHC

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.

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Riccardo Rattazzi, Granada Meeting

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Sun Tzu, The Art of War

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Sun Tzu, The Art of War

# SMEFT Lagrangian: Dim=6

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

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$ |

# SMEFT Lagrangian: Dim=6

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

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |

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| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
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| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
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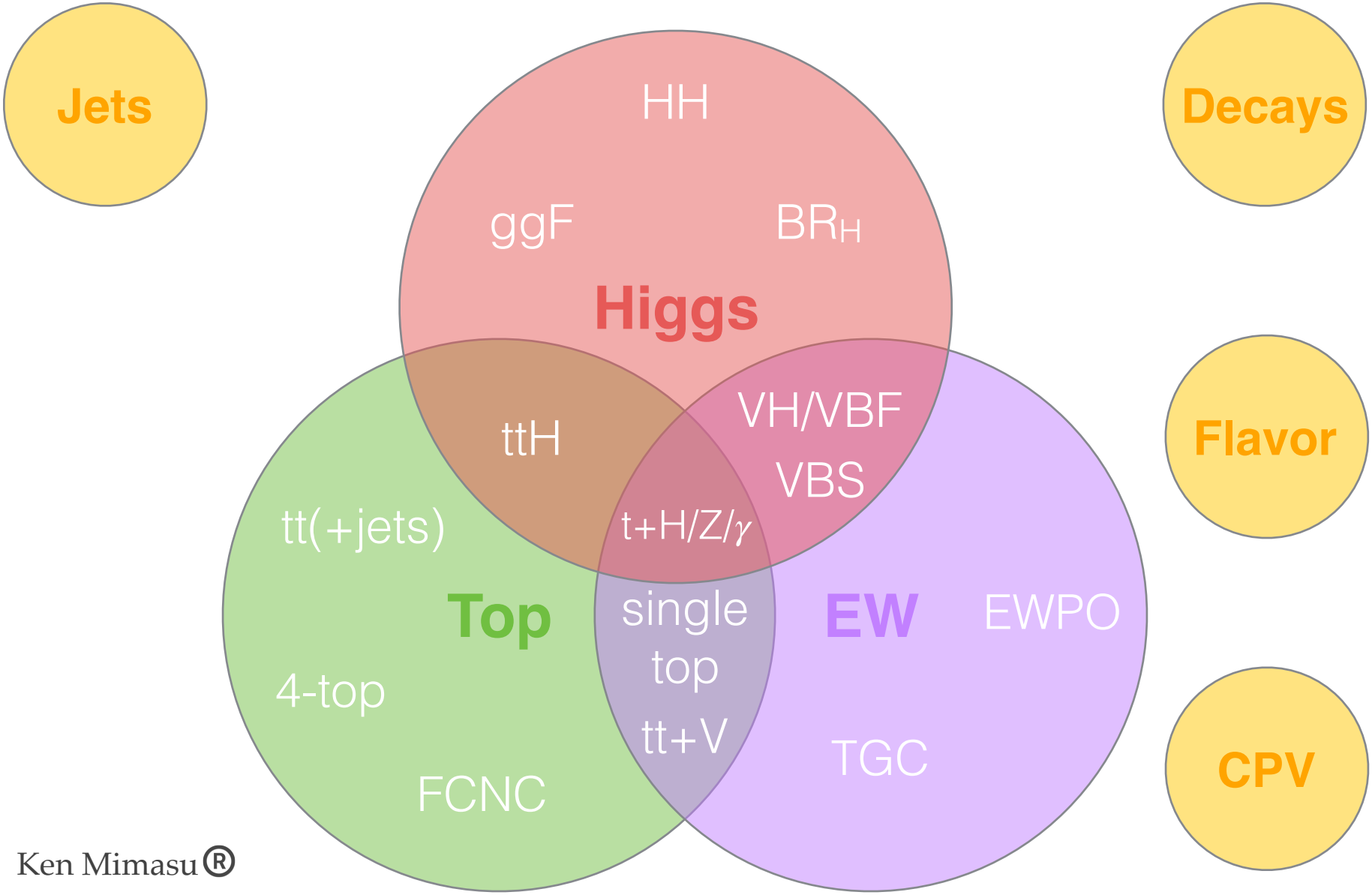
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |

# SMEFT Lagrangian: Dim=6

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

# Which interactions?

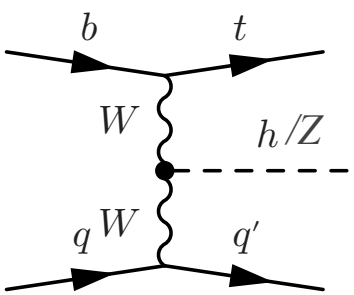
- Interactions between light fermions and gauge bosons tested at low energies and at LEP at below the per mill level.
- Self interactions of weak gauge bosons tested at LEP II High energy at the % level. LHC will be competitive.
- Higgs interactions with gauge bosons constrained at 10% level.
- Top-quark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


Jets
Decays
Flavor
CPV
HH
ggF
BR$_H$
Higgs
ttH
VH/VBF
VBS
t+H/Z/$\gamma$
tt(+jets)
Top
single top
tt+V
4-top
FCNC
EW
EWPO
TGC

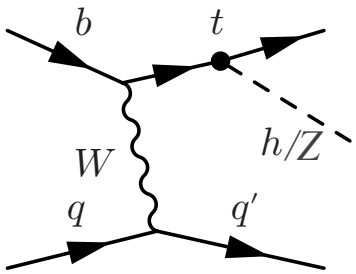
Ken Mimasu®

# Example: tZj/tHj

[Degrande, FM, Mimasu, Vryonidou, Zhang, 2018]

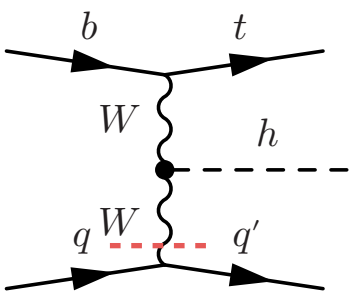



- Single top rate about 1/4 of QCD tt
- Purely EW processes => no QCD contribution
- Sensitive to 2 four-fermion and 3 top/EW operators that modify tbW vertex
- Requiring the presence of an additional Z or Higgs
  - Unique possibility of probing full set of top/Higgs/EW operators at once
  - Higher thresholds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



# Example: tZj/tHj

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

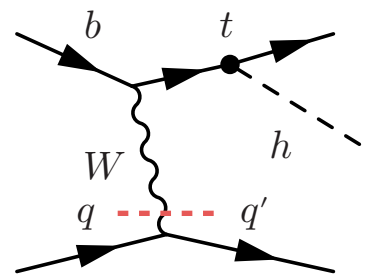



$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi\, W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

$\mathcal{O}_W \; : \; \epsilon^{ijk} W_{i,\,\mu\nu} W_j^{\nu\rho} W^\mu_{k,\,\rho}$

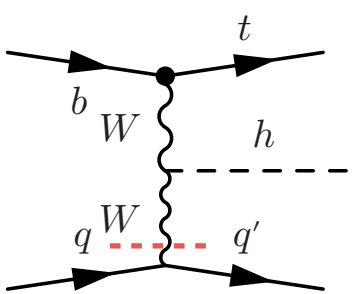



$\mathcal{O}_{t\varphi} : \; (\varphi^\dagger \varphi)\,(\bar{Q}\, t)\,\tilde{\varphi}$

top Yukawa

ttZ coupling

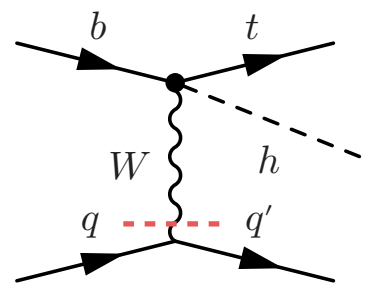
$\mathcal{O}_{\varphi t} : i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$




$\mathcal{O}^{(3)}_{\varphi Q} : \; i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Wtb vertex

$\mathcal{O}_{\varphi tb} : i(\tilde{\varphi}\, D_\mu \varphi)(\bar{b}\gamma^\mu t)$

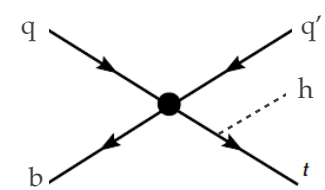



$\mathcal{O}^{(3)}_{\varphi Q} : \; i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Contact terms

$\mathcal{O}_{tB} : \; (\bar{Q}\, \sigma_{\mu\nu}\, t)\, \tilde{\varphi}\, B^{\mu\nu}$

- 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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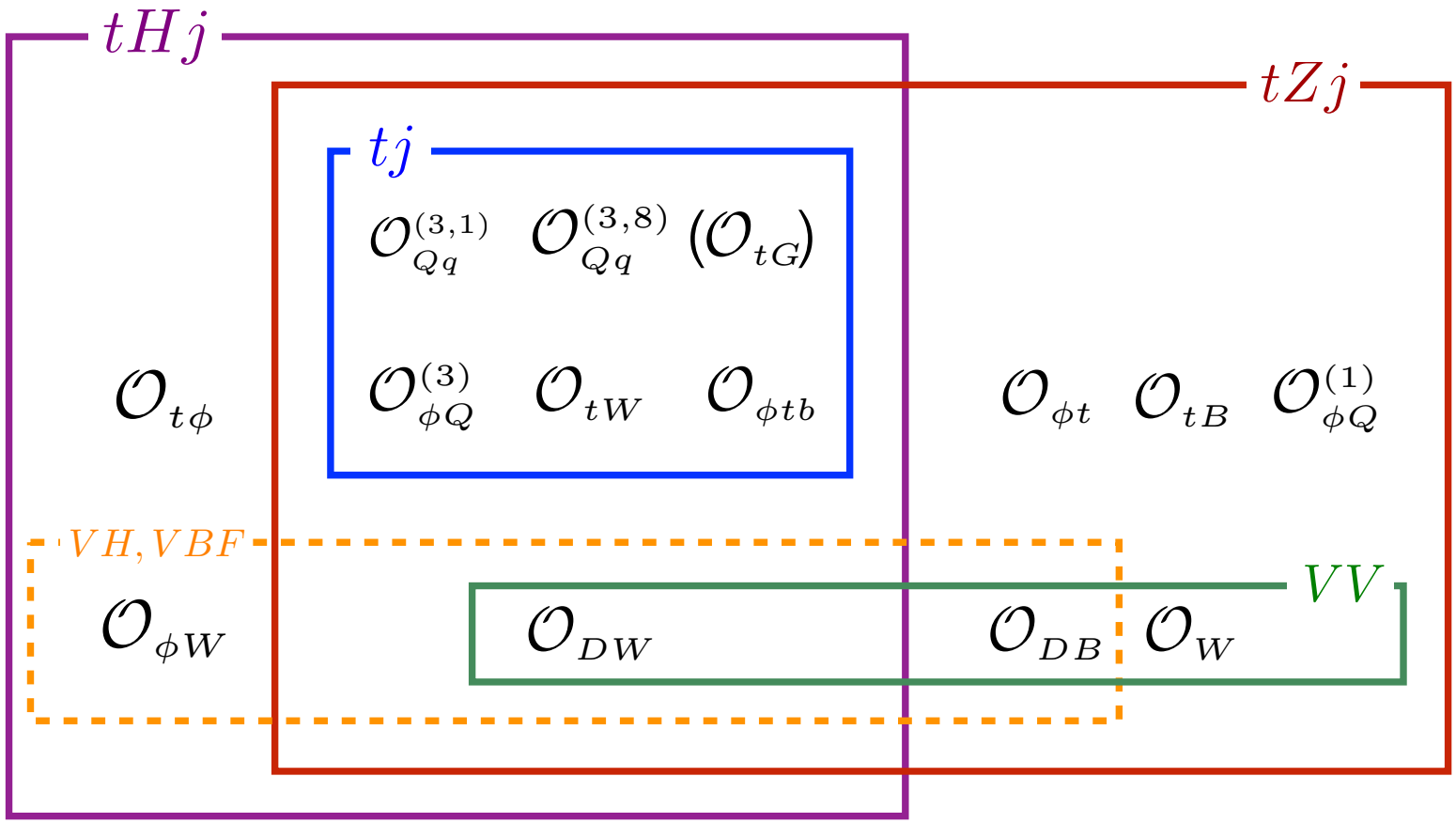


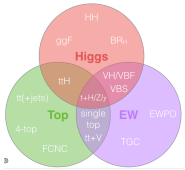

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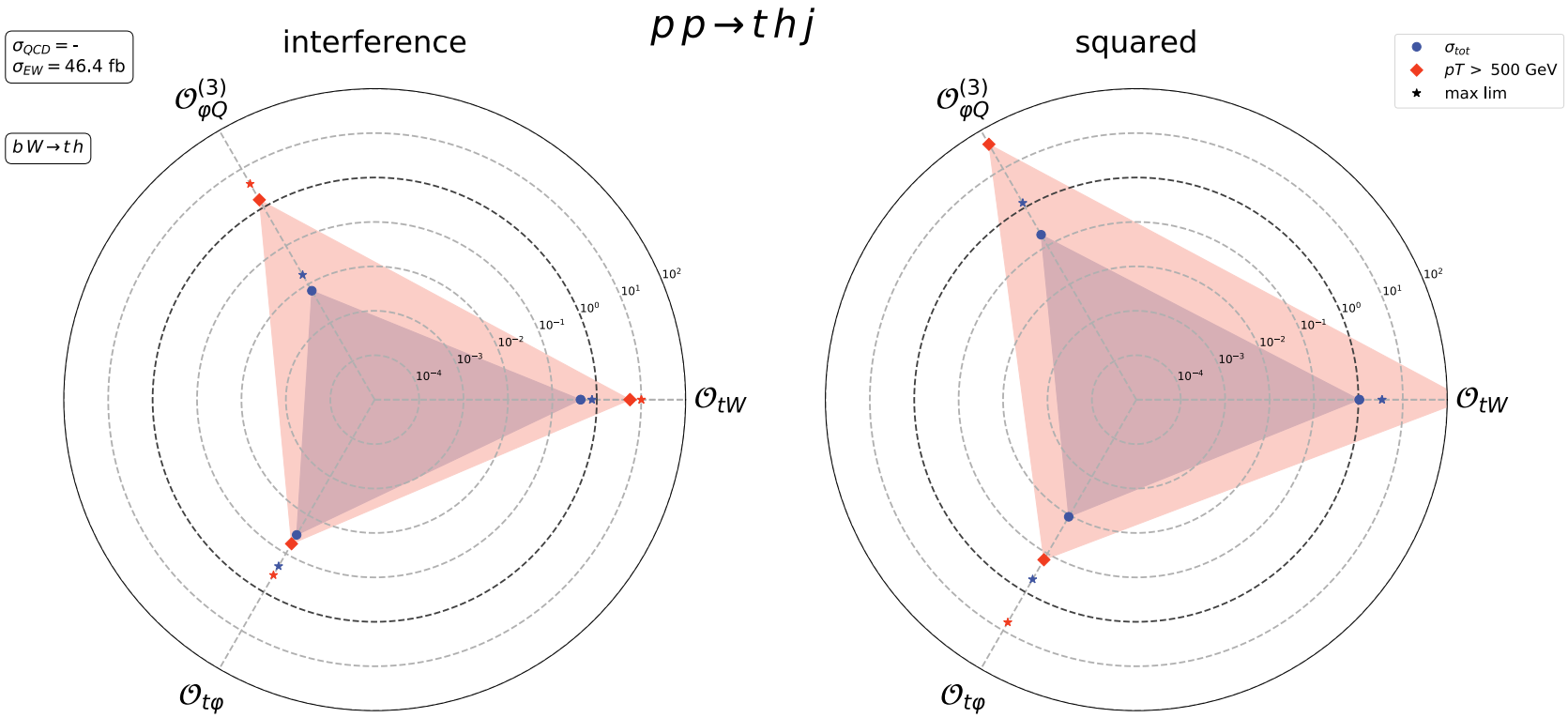
[FM, Mantani, Mimasu, 2018]



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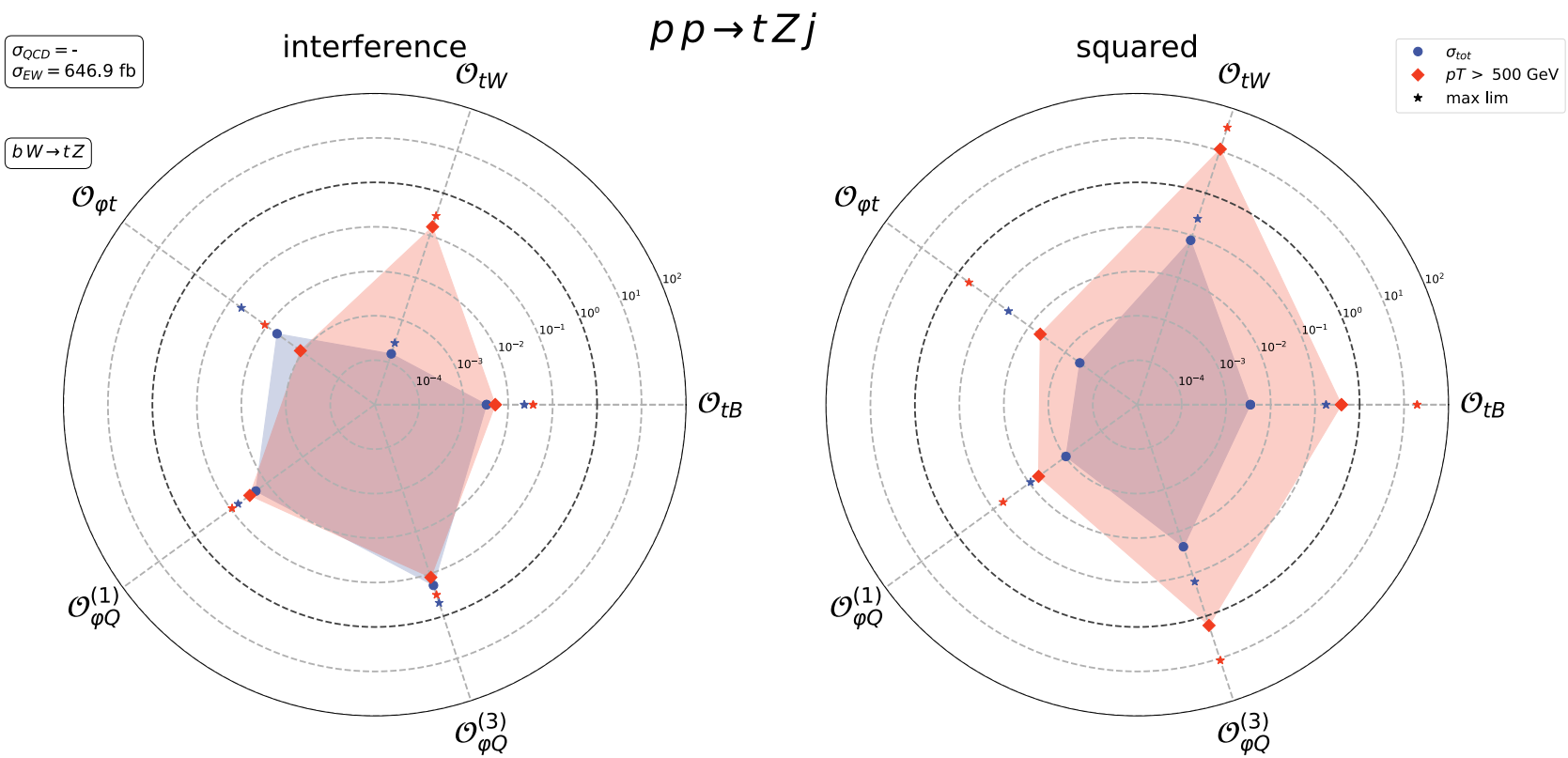

# SMEFT at the LHC

$S$ 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

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

$$\mathrm{Obs}_i = \mathrm{Obs}_i^{\mathrm{SM}} + M_{ij} \cdot \frac{s}{\Lambda^2} c_j$$

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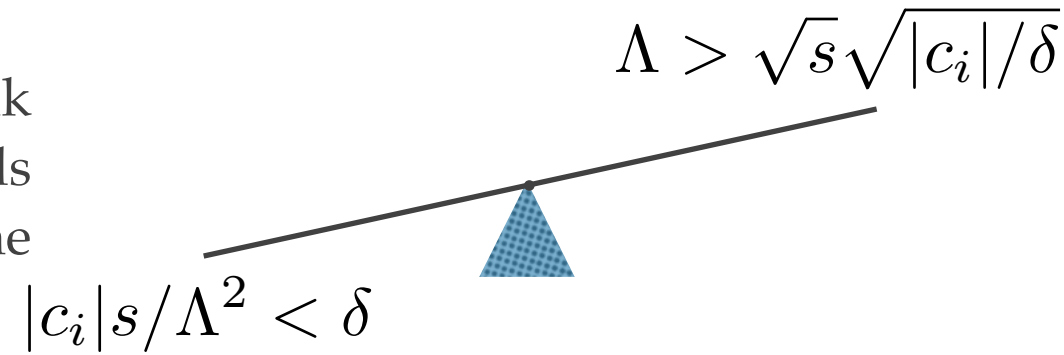

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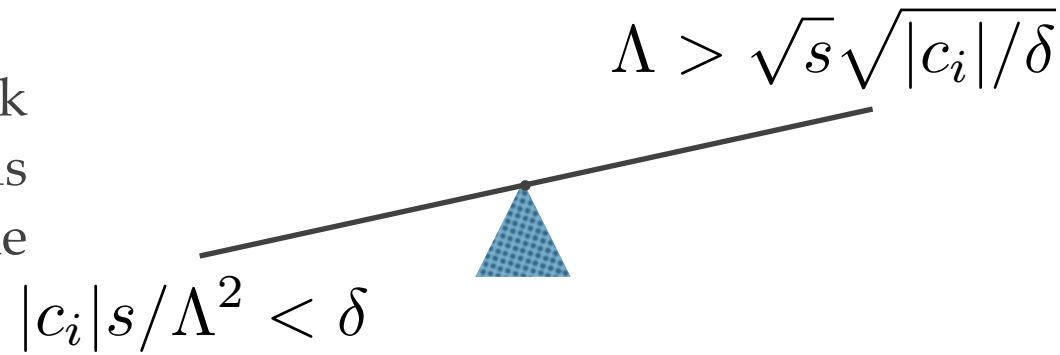
- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.
- Validity issues arise, as well as for the interpretation in terms of models.




$$\sqrt{s} < \Lambda$$

# 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**

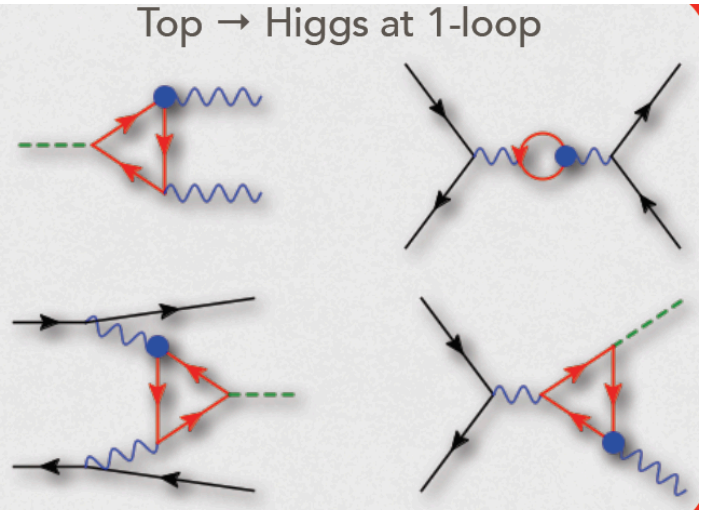
# Need for NLO

**4. New operators arise**

[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]

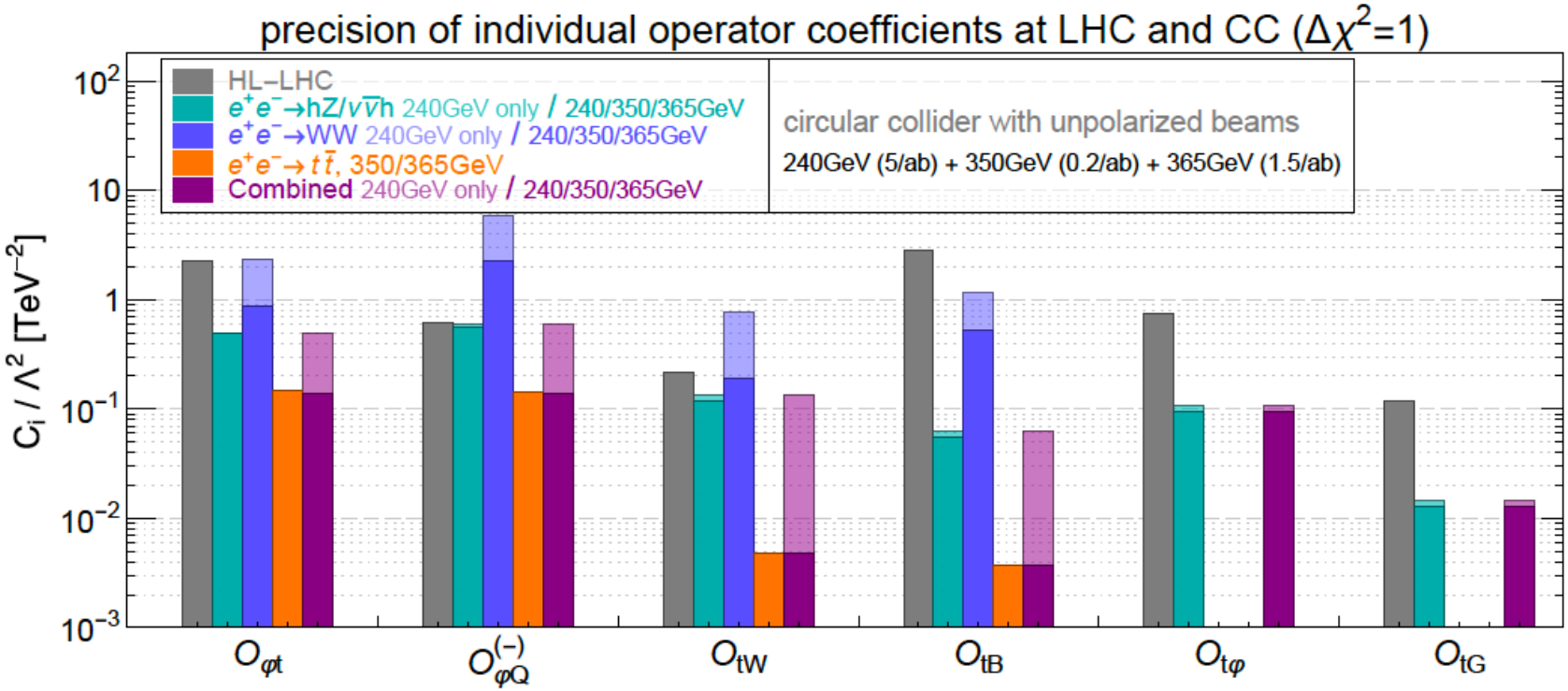
New operators can arise at one-loop or via real corrections.

- 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.



# 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

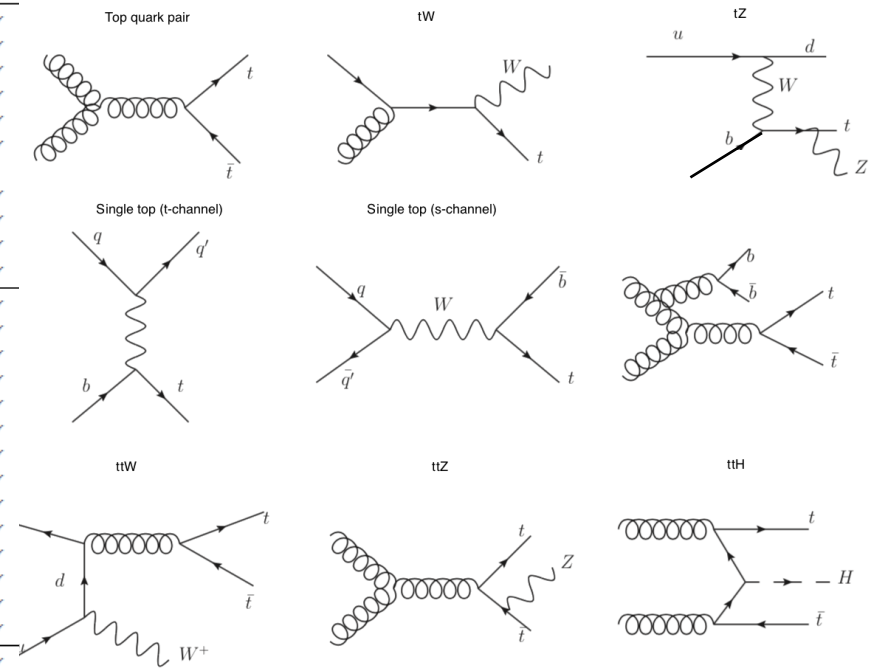
Based on NNPDF
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

## 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@NLO

| Class | Notation | Degree of Freedom | Operator Definition | Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$) $t\bar{t}$ | single-top | $tW$ | $tZ$ | $t\bar{t}W$ | $t\bar{t}Z$ | $t\bar{t}H$ | $t\bar{t}t\bar{t}$ | $t\bar{t}b\bar{b}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $QQQQ$ | OQQ1 | $c^1_{QQ}$ | $2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$ | | | | | | | | ✓ | ✓ |
| | OQQ8 | $c^8_{QQ}$ | $8C^{3(3333)}_{qq}$ | | | | | | | | ✓ | ✓ |
| | OQt1 | $c^1_{Qt}$ | $C^{1(3333)}_{qu}$ | | | | | | | | ✓ | ✓ |
| | OQt8 | $c^8_{Qt}$ | $C^{8(3333)}_{qu}$ | | | | | | | | ✓ | ✓ |
| | OQb1 | $c^1_{Qb}$ | $C^{1(3333)}_{qd}$ | | | | | | | | | ✓ |
| | OQb8 | $c^8_{Qb}$ | $C^{8(3333)}_{qd}$ | | | | | | | | | ✓ |
| | Ott1 | $c^1_{tt}$ | $C^{(3333)}_{tu}$ | | | | | | | | ✓ | |
| | Otb1 | $c^1_{tb}$ | $C^{1(3333)}_{ud}$ | | | | | | | | | ✓ |
| | Otb8 | $c^8_{tb}$ | $C^{8(3333)}_{ud}$ | | | | | | | | | ✓ |
| | OQtQb1 | $c^1_{QtQb}$ | $C^{1(3333)}_{quqd}$ | | | | | | | | | ✓ |
| | OQtQb8 | $c^8_{QtQb}$ | $C^{8(3333)}_{quqd}$ | | | | | | | | | ✓ |
| $QQqq$ | O81qq | $c^{1,8}_{Qq}$ | $C^{1(ttss)}_{qq} + 3C^{3(ttss)}_{qq}$ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | O11qq | $c^{1,1}_{Qq}$ | $C^{1(ttss)}_{qq} + \frac{1}{6}C^{1(ttss)}_{qq} + \frac{1}{2}C^{3(ttss)}_{qq}$ | (✓) | | | | (✓) | (✓) | (✓) | ✓ | ✓ |
| | O83qq | $c^{3,8}_{Qq}$ | $C^{1(ttss)}_{qq} - C^{3(ttss)}_{qq}$ | ✓ | (✓) | | (✓) | ✓ | ✓ | ✓ | ✓ | ✓ |
| | O13qq | $c^{3,1}_{Qq}$ | $C^{3(ttss)}_{qq} + \frac{1}{6}(C^{1(ttss)}_{qq} - C^{3(ttss)}_{qq})$ | (✓) | ✓ | | ✓ | (✓) | (✓) | (✓) | ✓ | ✓ |
| | O8qt | $c^8_{tq}$ | $C^{8(ttss)}_{qu}$ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | O1qt | $c^1_{tq}$ | $C^{1(ttss)}_{qu}$ | (✓) | | | | (✓) | (✓) | (✓) | ✓ | ✓ |
| | O8ut | $c^8_{tu}$ | $2C^{(ttss)}_{uu}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | O1ut | $c^1_{tu}$ | $C^{(ttss)}_{uu} + \frac{1}{3}C^{(ttss)}_{uu}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| | O8qu | $c^8_{Qu}$ | $C^{8(33tt)}_{qu}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | O1qu | $c^1_{Qu}$ | $C^{1(33tt)}_{qu}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| | O8dt | $c^8_{td}$ | $C^{8(33tt)}_{ud}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | O1dt | $c^1_{td}$ | $C^{1(33tt)}_{ud}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| | O8qd | $c^8_{Qd}$ | $C^{8(33tt)}_{qd}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | O1qd | $c^1_{Qd}$ | $C^{1(33tt)}_{qd}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| $QQ+V,G,\varphi$ | OtG | $c_{tG}$ | $\mathrm{Re}\{C^{(33)}_{uG}\}$ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | OtW | $c_{tW}$ | $\mathrm{Re}\{C^{(33)}_{uW}\}$ | | ✓ | ✓ | ✓ | | | | | |
| | ObW | $c_{bW}$ | $\mathrm{Re}\{C^{(33)}_{dW}\}$ | | (✓) | (✓) | (✓) | | | | | |
| | OtZ | $c_{tZ}$ | $\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$ | | | | ✓ | | ✓ | | | |
| | Off | $c_{\varphi tb}$ | $\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$ | | (✓) | (✓) | (✓) | | | | | |
| | Ofq3 | $c^3_{\varphi Q}$ | $C^{3(33)}_{\varphi q}$ | | ✓ | ✓ | ✓ | | | | | |
| | OpQM | $c^-_{\varphi Q}$ | $C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$ | | | | ✓ | | ✓ | | | |
| | Opt | $c_{\varphi t}$ | $C^{(33)}_{\varphi u}$ | | | | ✓ | | ✓ | | | |
| | Otp | $c_{t\varphi}$ | $\mathrm{Re}\{C^{(33)}_{u\varphi}\}$ | | | | | | | ✓ | | |




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

4 tops, ttbb, top-pair associated production

Single top
t-channel, s-channel, tW, tZ

One distribution from each dataset, to avoid double counting

| Dataset | $\chi^2/n_{\rm dat}$ (prior) | $\chi^2/n_{\rm dat}$ (fit) | $n_{\rm dat}$ |
|---|---|---|---|
| ATLAS_tt_8TeV_ljets [ $m_{t\bar{t}}$ ] | 1.51 | 1.25 | 7 |
| CMS_tt_8TeV_ljets [ $y_{t\bar{t}}$ ] | 1.17 | 1.17 | 10 |
| CMS_tt2D_8TeV_dilep [ $(m_{t\bar{t}}, y_t)$ ] | 1.38 | 1.38 | 16 |
| CMS_tt_13TeV_ljets2 [ $m_{t\bar{t}}$ ] | 1.09 | 1.28 | 8 |
| CMS_tt_13TeV_dilep [ $m_{t\bar{t}}$ ] | 1.34 | 1.42 | 6 |
| CMS_tt_13TeV_ljets_2016 [ $m_{t\bar{t}}$ ] | 1.87 | 1.87 | 10 |
| ATLAS_WhelF_8TeV | 1.98 | 0.27 | 3 |
| CMS_WhelF_8TeV | 0.31 | 1.18 | 3 |
| CMS_ttbb_13TeV | 5.00 | 1.29 | 1 |
| CMS_tttt_13TeV | 0.05 | 0.02 | 1 |
| ATLAS_tth_13TeV | 1.61 | 0.55 | 1 |
| CMS_tth_13TeV | 0.34 | 0.01 | 1 |
| ATLAS_ttZ_8TeV | 1.32 | 5.29 | 1 |
| ATLAS_ttZ_13TeV | 0.01 | 1.06 | 1 |
| CMS_ttZ_8TeV | 0.04 | 0.06 | 1 |
| CMS_ttZ_13TeV | 0.90 | 0.67 | 1 |
| ATLAS_ttW_8TeV | 1.34 | 0.27 | 1 |
| ATLAS_ttW_13TeV | 0.82 | 0.65 | 1 |
| CMS_ttW_8TeV | 1.54 | 0.54 | 1 |
| CMS_ttW_13TeV | 0.03 | 0.09 | 1 |
| CMS_t_tch_8TeV_dif | 0.11 | 0.32 | 6 |
| ATLAS_t_tch_8TeV [ $y_t$ ] | 0.91 | 0.43 | 4 |
| ATLAS_t_tch_8TeV [ $y_{\bar{t}}$ ] | 0.39 | 0.45 | 4 |
| ATLAS_t_sch_8TeV | 0.08 | 1.92 | 1 |
| ATLAS_t_tch_13TeV | 0.02 | 0.09 | 2 |
| CMS_t_tch_13TeV_dif [ $y_t$ ] | 0.46 | 0.49 | 4 |
| CMS_t_sch_8TeV | 1.26 | 0.76 | 1 |
| ATLAS_tW_inc_8TeV | 0.02 | 0.06 | 1 |
| CMS_tW_inc_8TeV | 0.00 | 0.07 | 1 |
| ATLAS_tW_inc_13TeV | 0.52 | 0.82 | 1 |
| CMS_tW_inc_13TeV | 4.29 | 1.68 | 1 |
| ATLAS_tZ_inc_13TeV | 0.00 | 0.00 | 1 |
| CMS_tZ_inc_13TeV | 0.66 | 0.34 | 1 |
| Total | **1.11** | **1.06** | **103** |

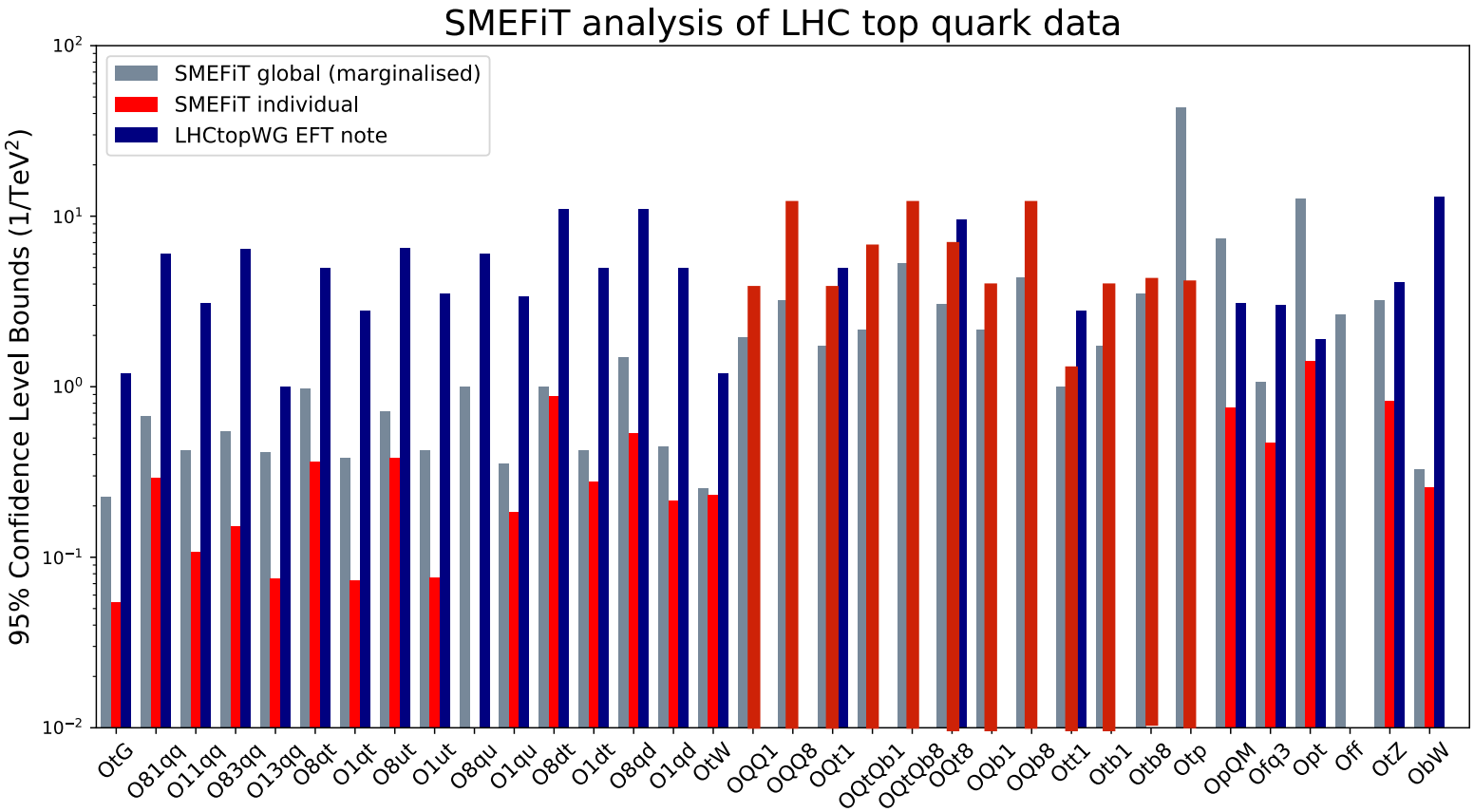
## Theoretical predictions

| Process | SM | SMEFT |
|---|---|---|
| $t\bar{t}$ | NNLO QCD | NLO QCD |
| single-$t$ ($t$-ch) | NNLO QCD | NLO QCD |
| single-$t$ ($s$-ch) | NLO QCD | NLO QCD |
| $tW$ | NLO QCD | NLO QCD |
| $tZ$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}W(Z)$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}h$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}t\bar{t}$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}b\bar{b}$ | NLO QCD | LO QCD + NLO SM $K$-factors |

Baseline fit includes:

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

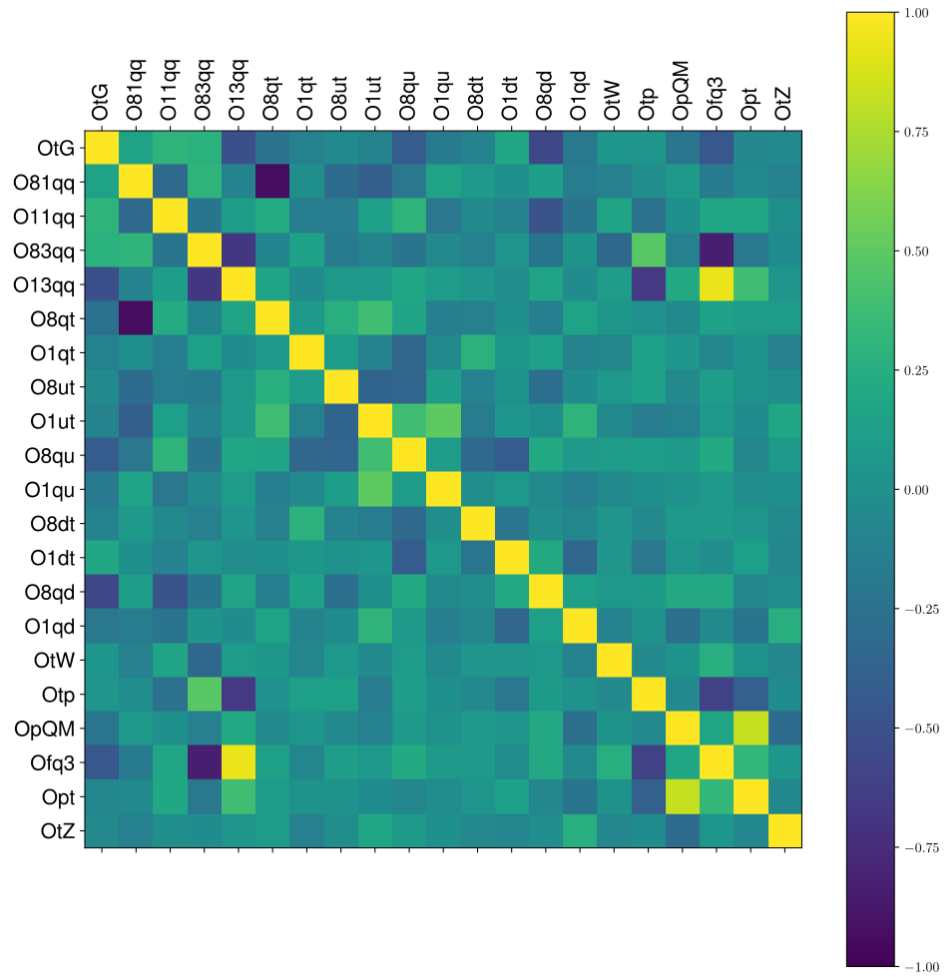
# Results




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

# Results

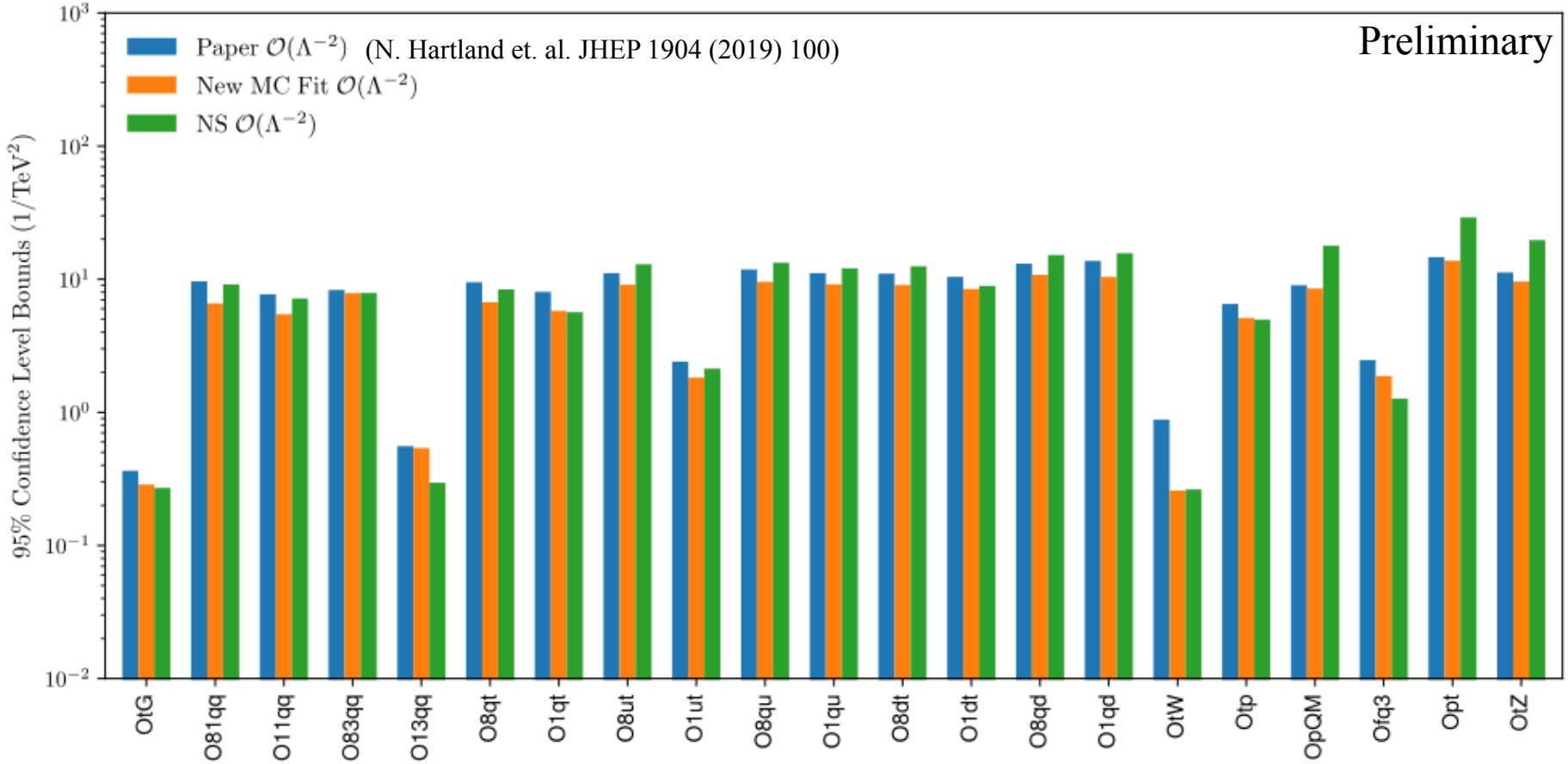
- Correlations of fit parameters via color map
- Not all parameters completely independent!



# Recent developments

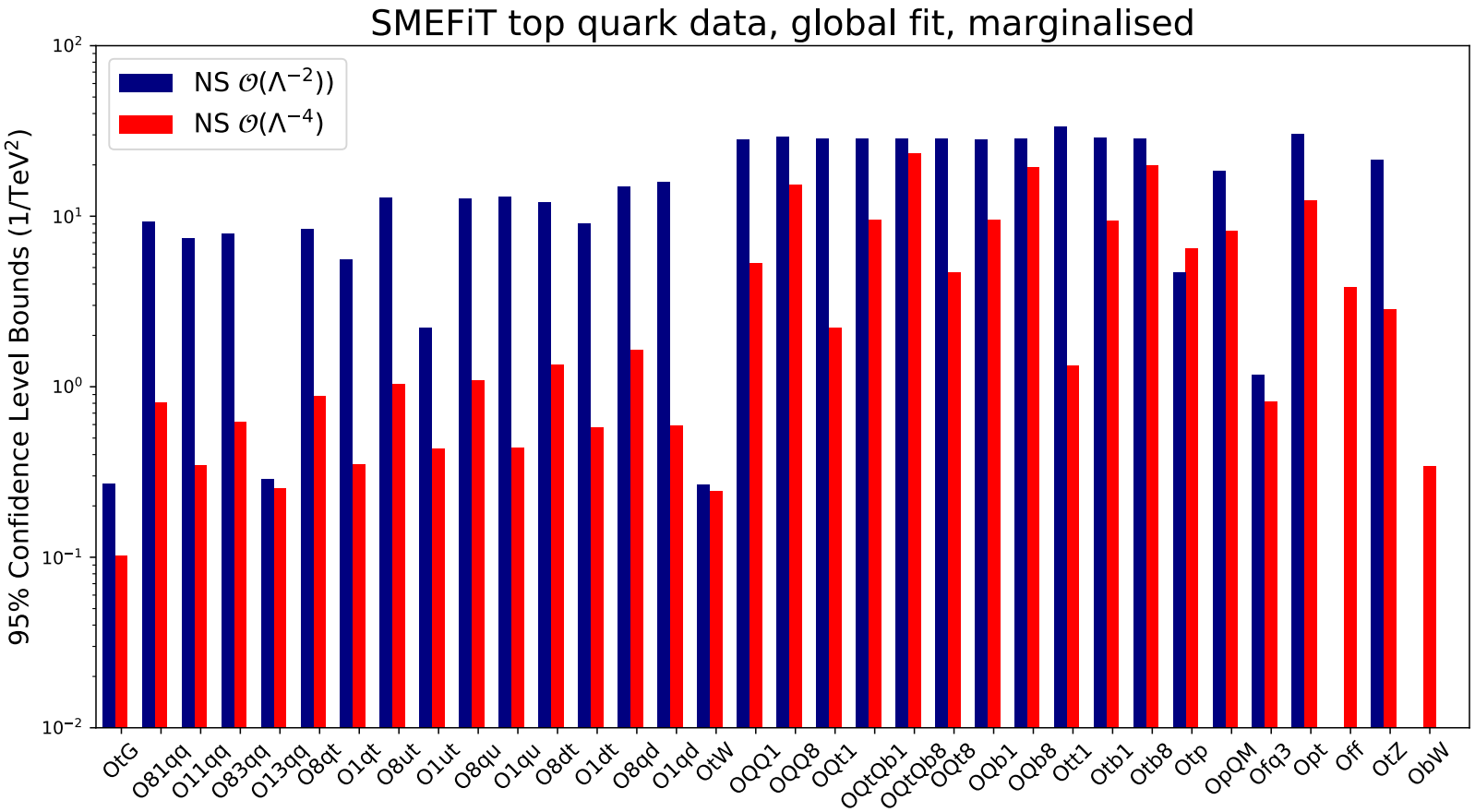
- Optimisation of the MC fitting technique and correct handling of the square terms.
- New Nested Sampling (NS) algorithm implemented for MC sampling determination of posterior distributions
- Fitting to restricted scenarios
- Extension to the Higgs sector started

# Comparison between fit technologies

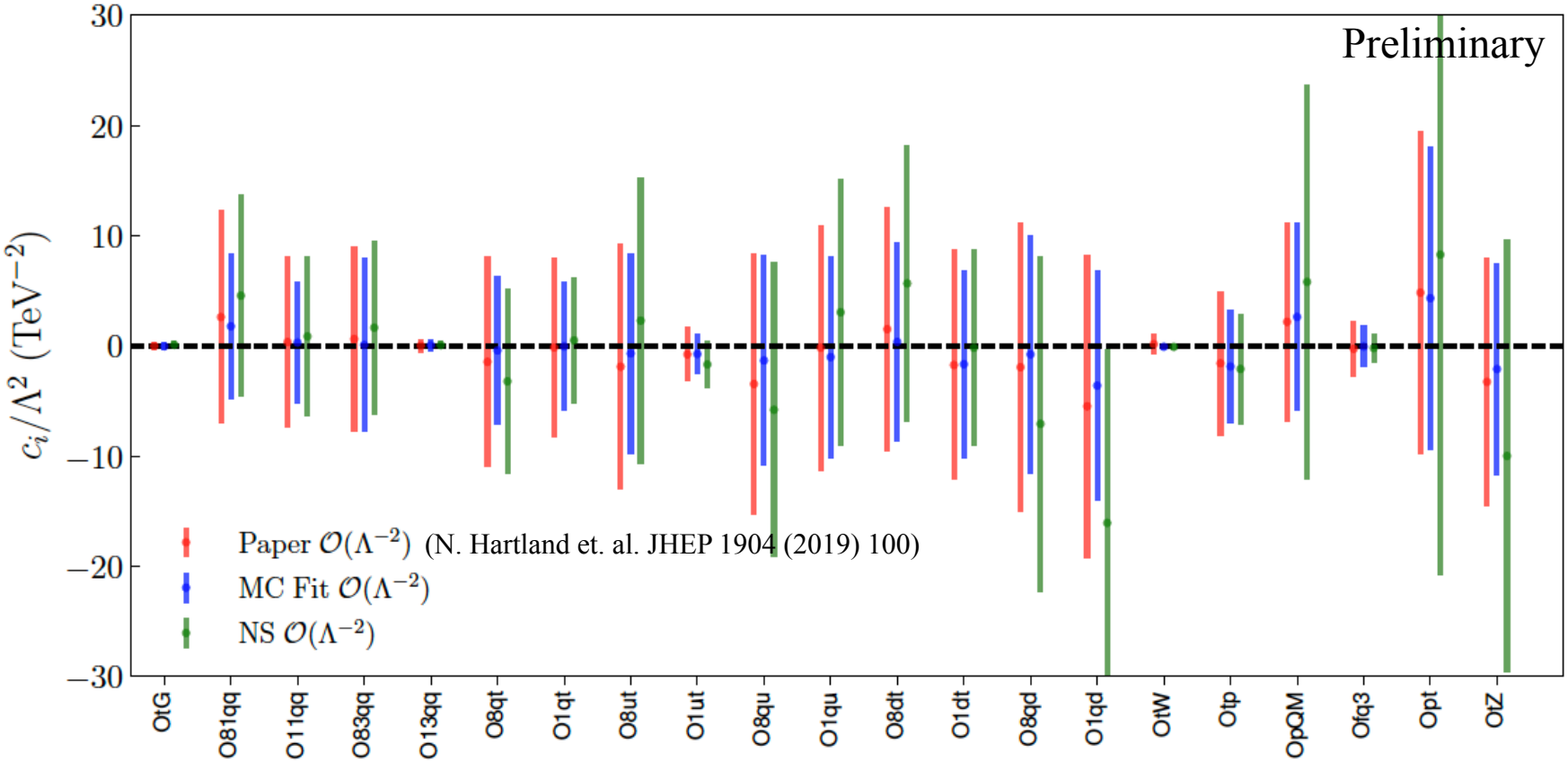



- Agreement of 95% CL bounds rather good between the two methods
- Slight improvements in some operator bounds from previous SMEFiT publication

# Linear vs quadratic

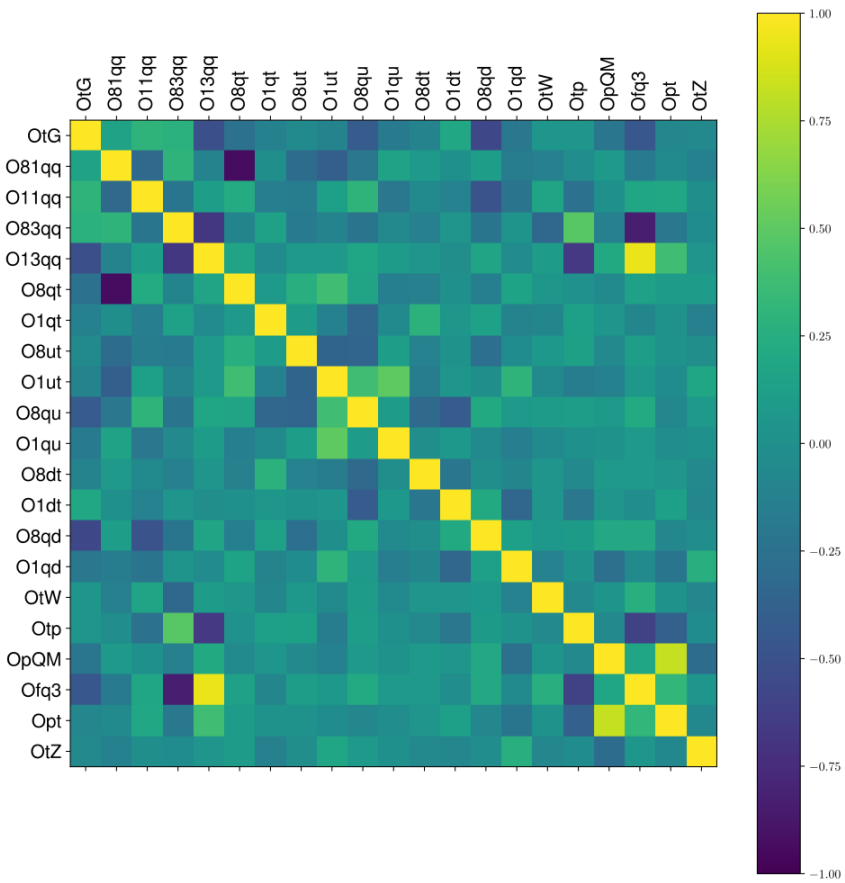


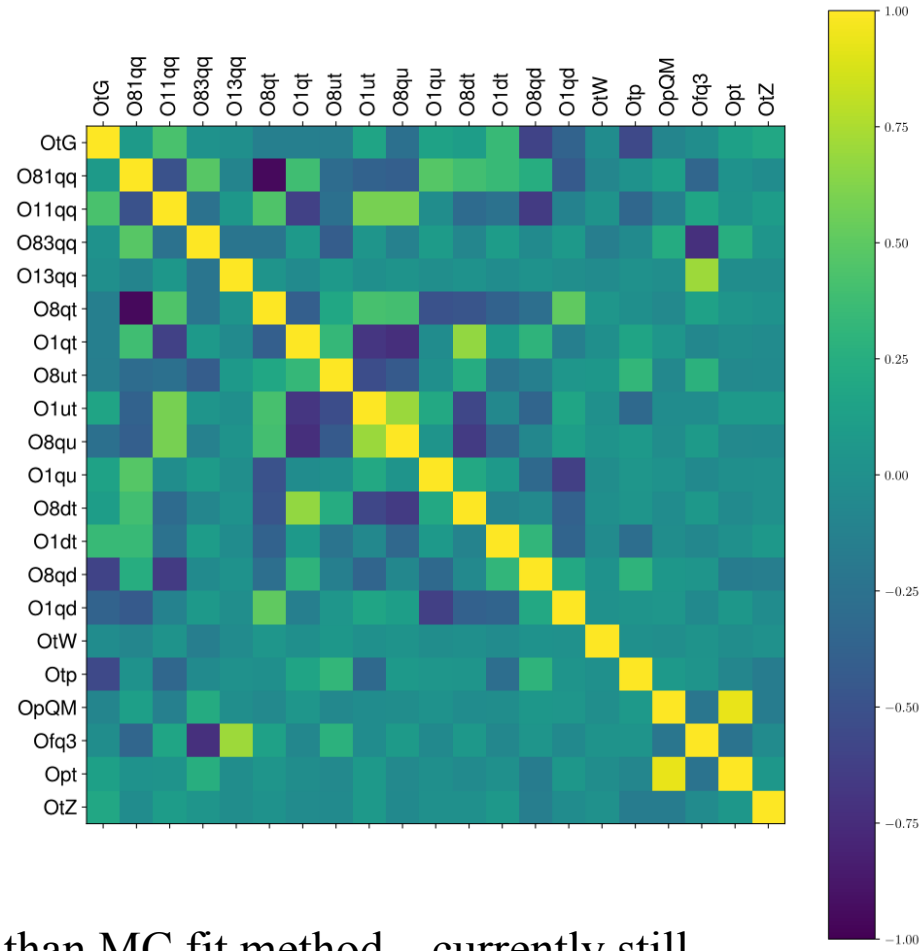
# Comparison between fit technologies




- 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)

$$c_{t\varphi}^{[I]}, \quad c_{\varphi Q}^{-}, \quad c_{\varphi Q}^{3}, \quad c_{\varphi t}, \quad c_{tW}^{[I]}, \quad c_{tZ}^{[I]}, \quad c_{tG}^{[I]},$$

$c_{\varphi tb}^{[I]}$ and $c_{bW}^{[I]}$ appear proportional to $y_b$

$$c_{QQ}^{1}, \quad c_{QQ}^{8}, \quad c_{Qt}^{1}, \quad c_{Qt}^{8}, \quad c_{tt}^{1},$$

$$c_{QDW} = c_{Qq}^{3,1} = c_{Ql}^{3(\ell)},$$

$$c_{QDB} = 6c_{Qq}^{1,1} = \frac{3}{2}c_{Qu}^{1} = -3c_{Qd}^{1} = -3c_{Qb}^{1} = -2c_{Ql}^{1(\ell)} = -c_{Qe}^{(\ell)},$$

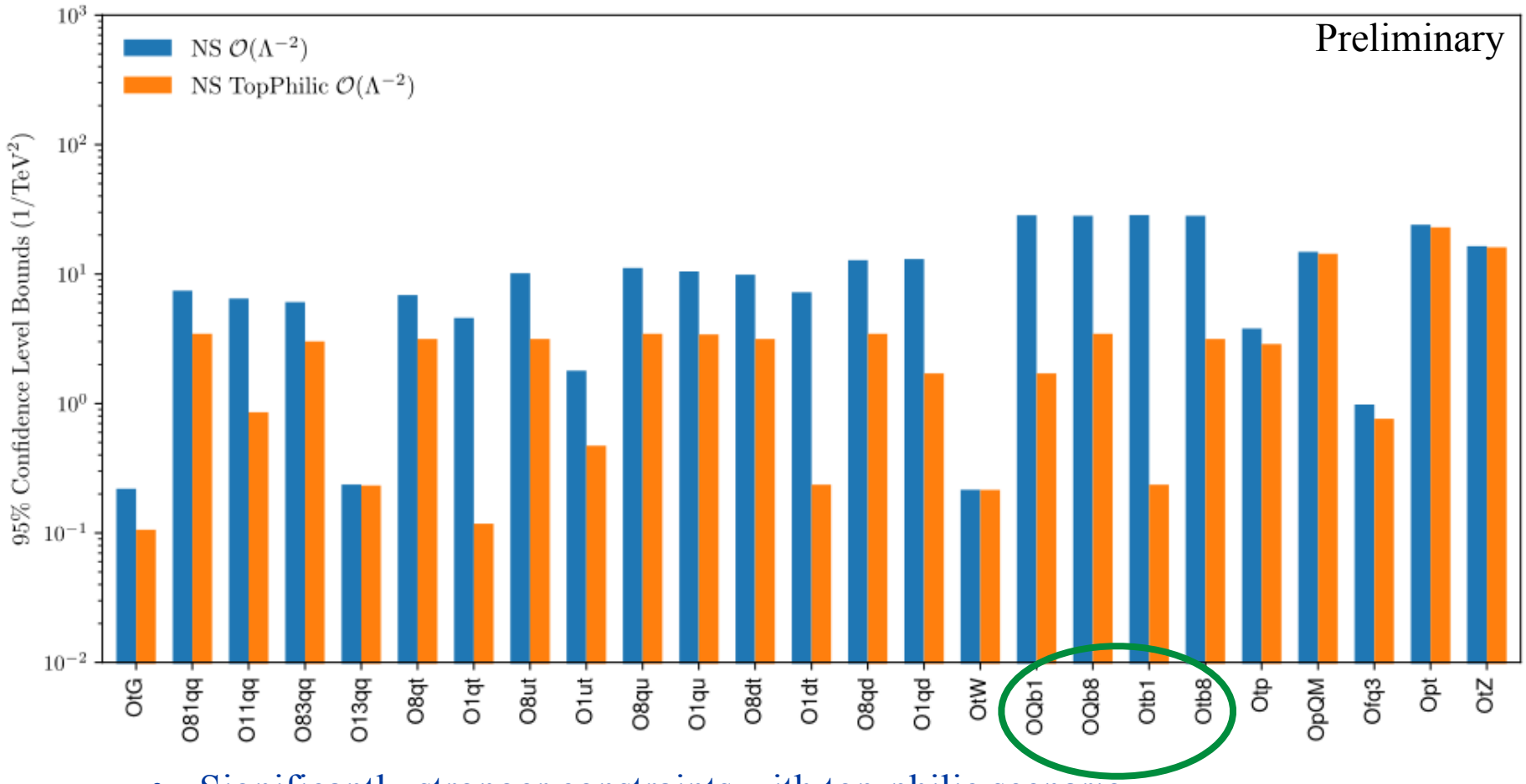
$$c_{tDB} = 6c_{tq}^{1} = \frac{3}{2}c_{tu}^{1} = -3c_{td}^{1} = -3c_{tb}^{1} = -2c_{tl}^{(\ell)} = -c_{te}^{(\ell)},$$

$$c_{QDG} = c_{Qq}^{1,8} = c_{Qu}^{8} = c_{Qd}^{8} = c_{Qb}^{8},$$

$$c_{tDG} = c_{tq}^{8} = c_{tu}^{8} = c_{td}^{8} = c_{tb}^{8}.$$

- 34 parameter basis reduced to 19 free parameters

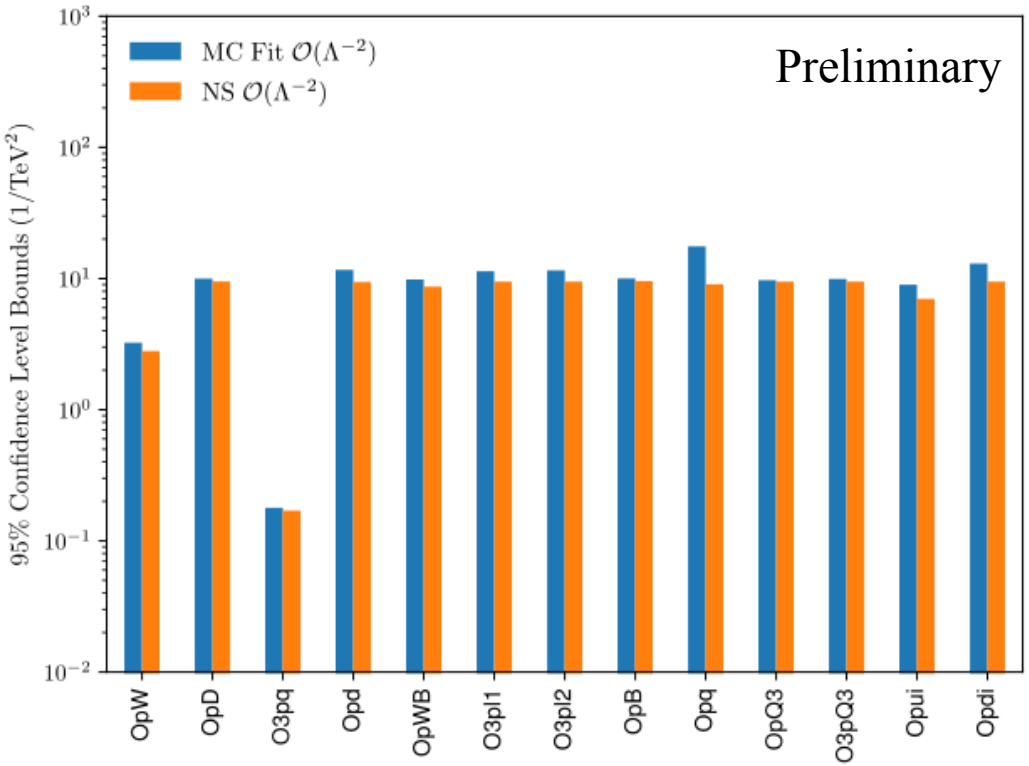
# Top-philic scenario




- 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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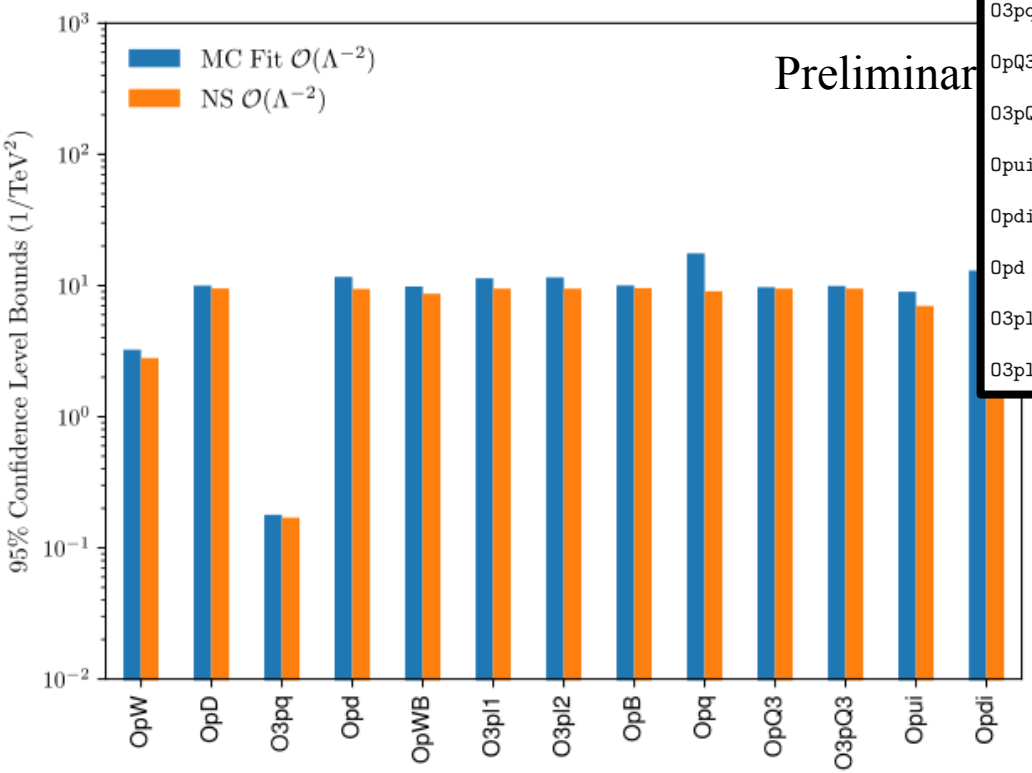
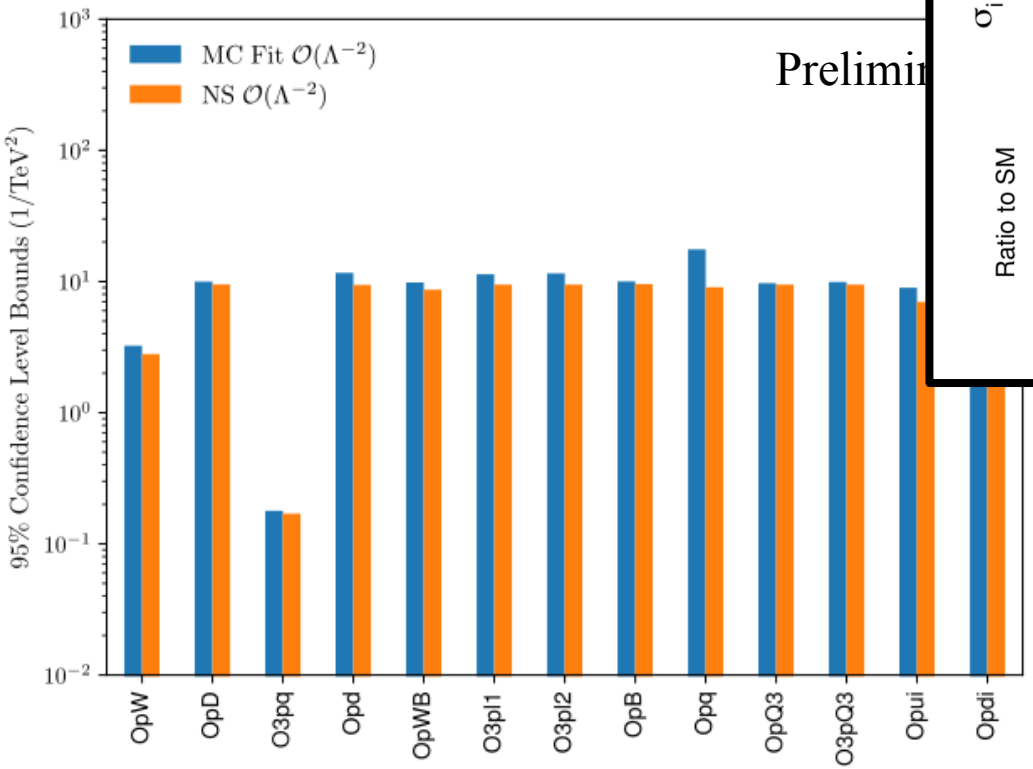



| Operator | Wilson Coefficient | Degree of Freedom | Operator Definition |
|---|---|---|---|
| OpW | cpW | $\mathcal{O}_{\varphi W}$ | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)W_I^{\mu\nu}W_{\mu\nu}^I$ |
| OpB | cpB | $\mathcal{O}_{\varphi B}$ | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)B^{\mu\nu}B_{\mu\nu}$ |
| OpWB | cpWB | $\mathcal{O}_{\varphi WB}$ | $\left(\varphi^\dagger\tau_I\varphi\right)B^{\mu\nu}W_{\mu\nu}^I$ |
| OpD | cpDC | $\mathcal{O}_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\dagger\left(\varphi^\dagger D_\mu\varphi\right)$ |
| Opq | cpqi | $\mathcal{O}_{\varphi q_i}^{(1)}$ | $\sum_{j=1,2} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)(\bar{q}_j\gamma^\mu q_j)$ |
| O3pq | c3pqi | $\mathcal{O}_{\varphi q_i}^{(3)}$ | $\sum_{j=1,2} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\bar{q}_j\gamma^\mu\tau^I q_j\right)$ |
| OpQ3 | cpQ3 | $\mathcal{O}_{\varphi Q}^{(1)}$ | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)\left(\overline{Q}\gamma^\mu Q\right)$ |
| O3pQ3 | c3pQ3 | $\mathcal{O}_{\varphi Q}^{(3)}$ | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\overline{Q}\gamma^\mu\tau^I Q\right)$ |
| Opui | cpu | $\mathcal{O}_{\varphi u_i}$ | $\sum_{j=1,2} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)(\bar{u}_j\gamma^\mu u_j)$ |
| Opdi | cpd | $\mathcal{O}_{\varphi d_i}$ | $\sum_{j=1,2(,3)} i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)\left(\bar{d}_j\gamma^\mu d_j\right)$ |
| Opd | cdp | $\mathcal{O}_{\varphi d}$ | $\partial_\mu\left(\varphi^\dagger\varphi\right)\partial^\mu\left(\varphi^\dagger\varphi\right)$ |
| O3pl1 | c3pl1 | $\mathcal{O}_{\varphi l_1}^{(3)}$ | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\bar{l}_1\gamma^\mu\tau^I l_1\right)$ |
| O3pl2 | c3pl2 | $\mathcal{O}_{\varphi l_2}^{(3)}$ | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\bar{l}_2\gamma^\mu\tau^I l_2\right)$ |

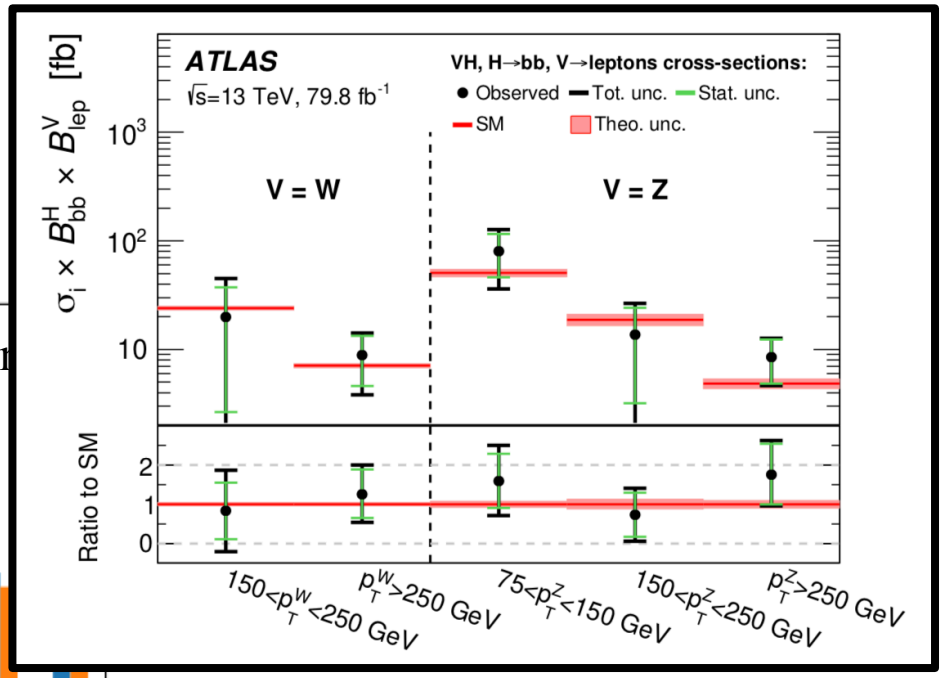
- No interference with top sector
- Total error dominated by statistical uncertainties – reflects in resulting coefficient bounds

# 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




Prelimin

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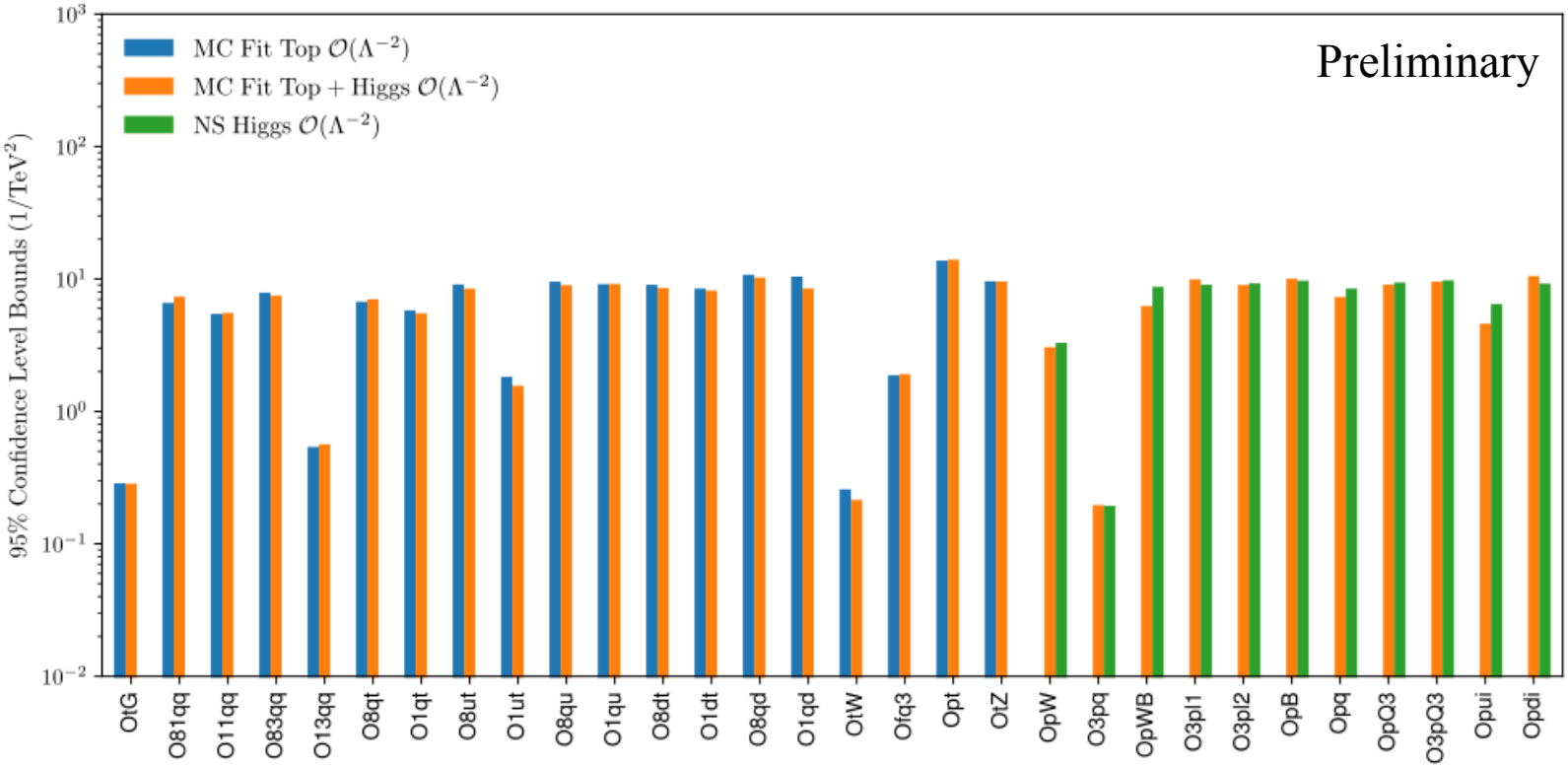
# Towards a global top/H/EW fit…




- 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

$$E\left[\mathcal{O}\right] = \int d^n a \mathcal{P}(\vec{a}|data)\mathcal{O}(\vec{a})$$

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

- Bayes' theorem defines probability $\mathcal{P}$ as

$$\mathcal{P}(\vec{a}|data) = \frac{1}{Z}\mathcal{L}(data|\vec{a})\pi(\vec{a})$$

Priors

"Evidence" $Z = \int d^n a \mathcal{L}(data|\vec{a})\pi(\vec{a})$

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# Fitting technology I

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

$$E[\mathcal{O}(\vec{a})] = \sum_k w_k \mathcal{O}(\vec{a}_k) \qquad V[\mathcal{O}(\vec{a})] = \sum_k w_k (\mathcal{O}(\vec{a}_k) - E[\mathcal{O}])^2$$

- Generate artificial data replicas (Gaussian resampling):

$$\mathcal{O}_i^{(\mathrm{art})(k)} = S_{i,N}^{(k)} \mathcal{O}_i^{(\mathrm{exp})} \left( 1 + r_i^{(k)} \sigma_i^{(\mathrm{stat})} + \sum_{\alpha=1}^{N_{\mathrm{sys}}} r_{i,\alpha}^{(k)} \sigma_{i,\alpha}^{(\mathrm{sys})} \right), \quad k = 1, \ldots, N_{\mathrm{rep}}$$

- Minimize loss function:

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

$$\mathrm{cov}_{ij} = \mathrm{cov}_{ij}^{(\mathrm{exp})} + \mathrm{cov}_{ij}^{(\mathrm{th})}$$

- Cross-validate to prevent over-fitting

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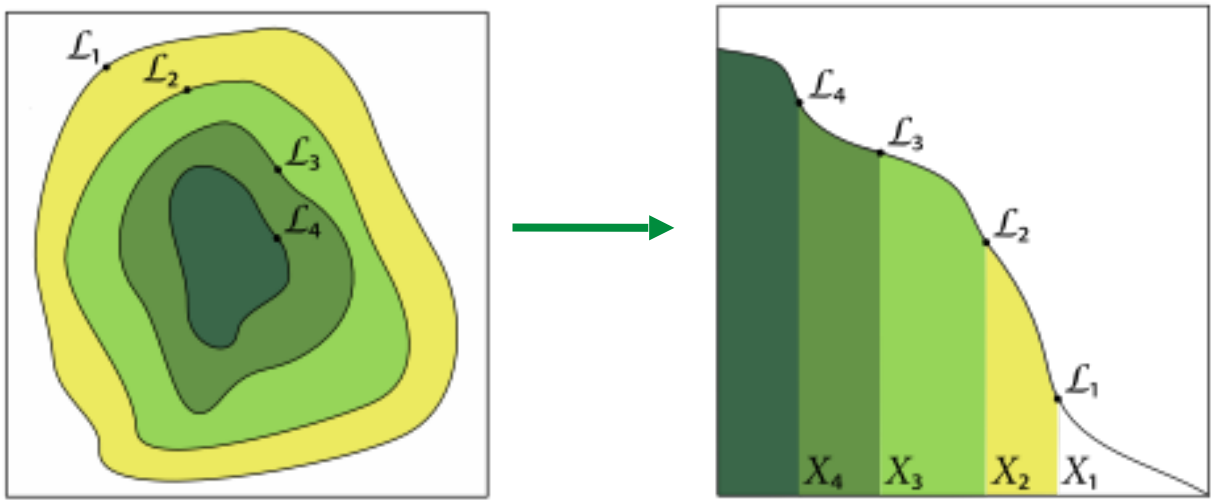
# Fitting technology II

$$Z = \int d^n a \mathcal{L}(data|\vec{a})\pi(\vec{a}) = \int_0^1 dX \mathcal{L}(X)$$

where the *prior volume* $dX = \pi(\vec{a})d^n a$




$$Z_i \sim \sum_i \mathcal{L}_i w_i$$

$$w_i = \frac{1}{2}(X_{i-1} - X_{i+1})$$

Feroz et al. arXiv:1306.2144 [astro-ph]

- 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

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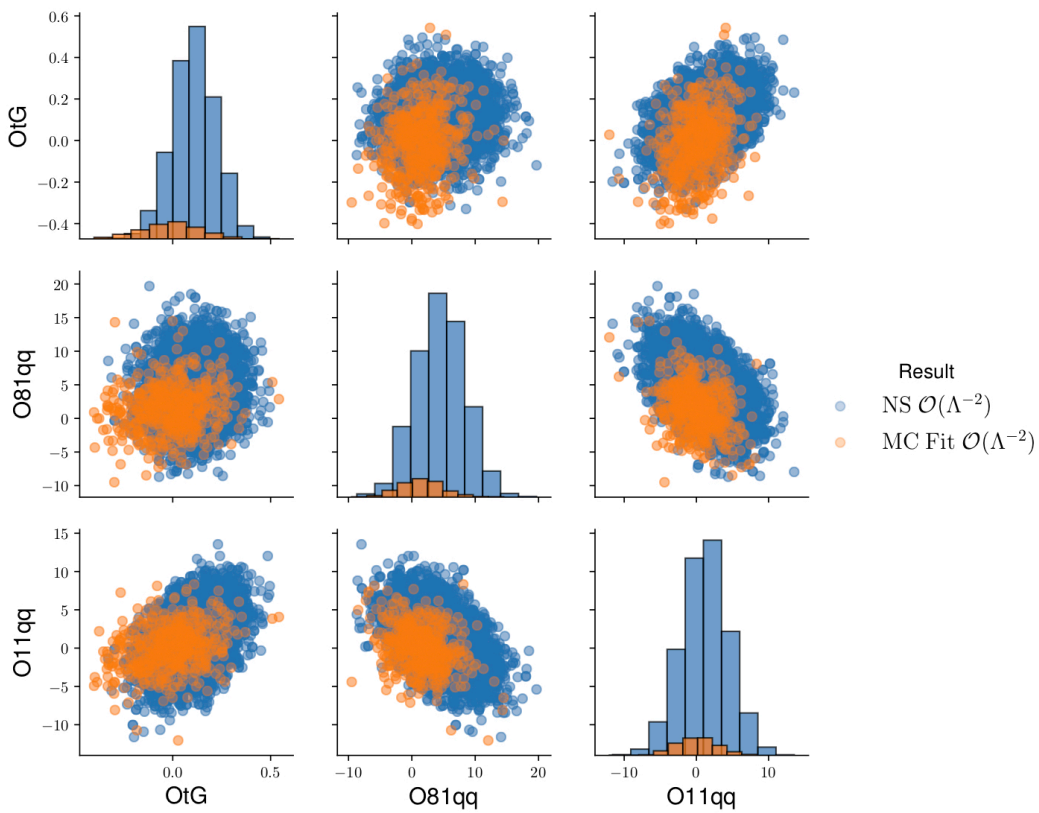
# Fitting technology II

- 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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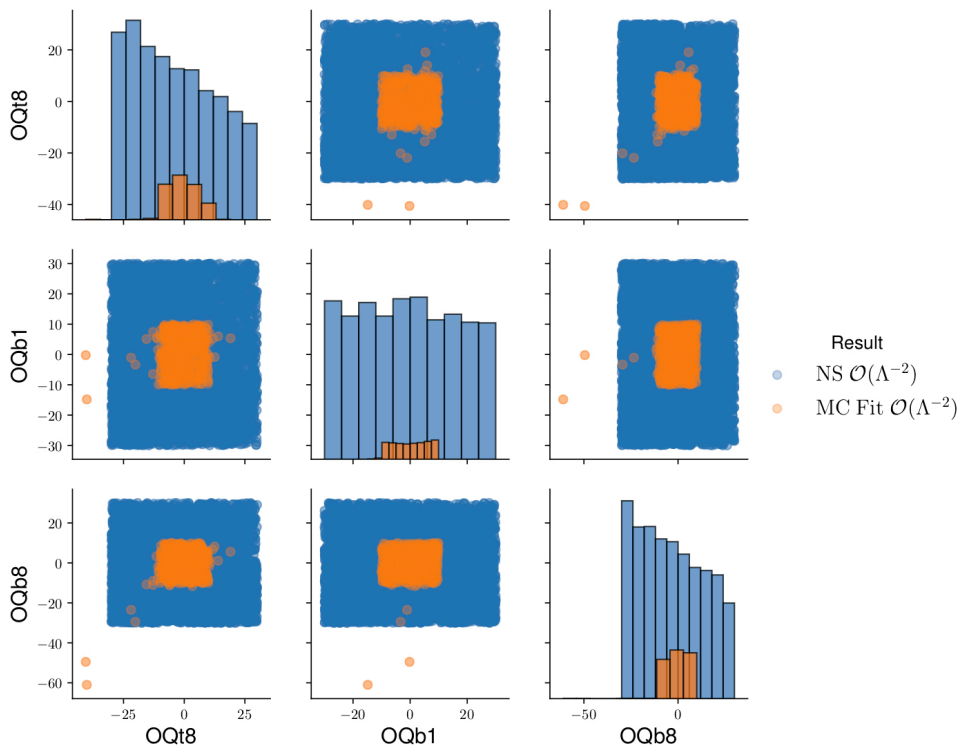
# Fitting technology II

- Probability distributions from MC samples provide crucial insight to behaviors 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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# SMEFiT : data set

| Process | Dataset | $\sqrt{s}$ | Info | Observables | $N_{\rm dat}$ |
|---|---|---|---|---|---|
| $t\bar{t}$ | ATLAS_tt_8TeV_ljets | **8 TeV** | lepton+jets | $d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$ | 5, 8, 7, 5 |
| $t\bar{t}$ | CMS_tt_8TeV_ljets | **8 TeV** | lepton+jets | $d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$ | 10, 8, 7, 10 |
| $t\bar{t}$ | CMS_tt2D_8TeV_dilep | **8 TeV** | dileptons | $d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$ | 16, 16, 16, 16 |
| $t\bar{t}$ | CMS_tt_13TeV_ljets | **13 TeV** | lepton+jets | $d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$ | 7, 9, 8, 6 |
| $t\bar{t}$ | CMS_tt_13TeV_ljets2 | **13 TeV** | lepton+jets | $d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$ | 11, 12, 10, 10 |
| $t\bar{t}$ | CMS_tt_13TeV_dilep | **13 TeV** | dileptons | $d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$ | 8, 6, 6, 8 |
| $t\bar{t}$ | ATLAS_WhelF_8TeV | **8 TeV** | $W$ helicity fract | $F_0, F_L, F_R$ | 3 |
| $t\bar{t}$ | CMS_WhelF_8TeV | **8 TeV** | $W$ helicity fract | $F_0, F_L, F_R$ | 3 |

# SMEFiT : data set

| Process | Dataset | $\sqrt{s}$ | Info | Observables | $N_{\rm dat}$ |
|---|---|---|---|---|---|
| $t\bar{t}b\bar{b}$ | CMS_ttbb_13TeV | **13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}b\bar{b})$ | 1 |
| $t\bar{t}t\bar{t}$ | CMS_tttt_13TeV | **13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}t\bar{t})$ | 1 |
| $t\bar{t}Z$ | CMS_ttZ_8_13TeV | **8+13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}Z)$ | 2 |
| $t\bar{t}Z$ | ATLAS_ttZ_8_13TeV | **8+13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}Z)$ | 2 |
| $t\bar{t}W$ | CMS_ttW_8_13TeV | **8+13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}W)$ | 2 |
| $t\bar{t}W$ | ATLAS_ttW_8_13TeV | **8+13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}W)$ | 2 |
| $t\bar{t}H$ | CMS_tth_13TeV | **13 TeV** | signal strength | $\mu_{t\bar{t}H}$ | 1 |
| $t\bar{t}H$ | ATLAS_tth_13TeV | **13 TeV** | total xsec | $\sigma_{\rm tot}(t\bar{t}H)$ | 1 |

# SMEFiT : data set

| Process | Dataset | $\sqrt{s}$ | Info | Observables | $N_{\rm dat}$ |
|---|---|---|---|---|---|
| Single $t$ | CMS_t_tch_8TeV_inc | **8 TeV** | $t$-channel | $\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ $(R_t)$ | 2 (1) |
| Single $t$ | CMS_t_sch_8TeV | **8 TeV** | $s$-channel | $\sigma_{\rm tot}(t+\bar{t})$ | 1 |
| Single $t$ | ATLAS_t_sch_8TeV | **8 TeV** | $s$-channel | $\sigma_{\rm tot}(t+\bar{t})$ | 1 |
| Single $t$ | ATLAS_t_tch_8TeV | **8 TeV** | $t$-channel | $d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$<br>$d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$ | 5, 4<br>4, 4 |
| Single $t$ | ATLAS_t_tch_13TeV | **13 TeV** | $t$-channel | $\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ $(R_t)$ | 2 (1) |
| Single $t$ | CMS_t_tch_13TeV_inc | **13 TeV** | $t$-channel | $\sigma_{\rm tot}(t+\bar{t})$ $(R_t)$ | 1 (1) |
| Single $t$ | CMS_t_tch_8TeV_dif | **8 TeV** | $t$-channel | $d\sigma/dp_T^{(t+\bar{t})}$,<br>$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$ | 6<br>6 |
| Single $t$ | CMS_t_tch_13TeV_dif | **13 TeV** | $t$-channel | $d\sigma/dp_T^{(t+\bar{t})}$,<br>$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$ | 4<br>4 |
| $tW$ | ATLAS_tW_inc_8TeV | **8 TeV** | inclusive | $\sigma_{\rm tot}(tW)$ | 1 |
| $tW$ | CMS_tW_inc_8TeV | **8 TeV** | inclusive | $\sigma_{\rm tot}(tW)$ | 1 |
| $tW$ | ATLAS_tW_inc_13TeV | **13 TeV** | inclusive | $\sigma_{\rm tot}(tW)$ | 1 |
| $tW$ | CMS_tW_inc_13TeV | **13 TeV** | inclusive | $\sigma_{\rm tot}(tW)$ | 1 |
| $tZ$ | CMS_tZ_inc_13TeV | **13 TeV** | inclusive | $\sigma_{\rm fid}(Wbl^+l^-q)$ | 1 |
| $tZ$ | ATLAS_tZ_inc_13TeV | **13 TeV** | inclusive | $\sigma_{\rm tot}(tZq)$ | 1 |

# SMEFiT : Theory input

| Process | SM | Code | SMEFT | Code |
|---|---|---|---|---|
| $t\bar{t}$ | NNLO QCD | MCFM/SHERPA NLO + NNLO $K$-factors | NLO QCD | MG5_aMC |
| single-$t$ ($t$-ch) | NNLO QCD | MCFM NLO + NNLO $K$-factors | NLO QCD | MG5_aMC |
| single-$t$ ($s$-ch) | NLO QCD | MCFM | NLO QCD | MG5_aMC |
| $tW$ | NLO QCD | MG5_aMC | NLO QCD | MG5_aMC |
| $tZ$ | NLO QCD | MG5_aMC | LO QCD + NLO SM $K$-factors | MG5_aMC |
| $t\bar{t}W(Z)$ | NLO QCD | MG5_aMC | LO QCD + NLO SM $K$-factors | MG5_aMC |
| $t\bar{t}h$ | NLO QCD | MG5_aMC | LO QCD + NLO SM $K$-factors | MG5_aMC |
| $t\bar{t}t\bar{t}$ | NLO QCD | MG5_aMC | LO QCD + NLO SM $K$-factors | MG5_aMC |
| $t\bar{t}b\bar{b}$ | NLO QCD | MG5_aMC | LO QCD + NLO SM $K$-factors | MG5_aMC |

# dof vs operators

## Degrees of freedom: 4-heavy

$$c^1_{QQ} \equiv 2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$$
$$c^8_{QQ} \equiv 8C^{3(3333)}_{qq}$$
$$c^1_{Qt} \equiv C^{1(3333)}_{qu}$$
$$c^8_{Qt} \equiv C^{8(3333)}_{qu}$$
$$c^1_{Qb} \equiv C^{1(3333)}_{qd}$$
$$c^8_{Qb} \equiv C^{8(3333)}_{qd}$$
$$c^1_{tt} \equiv C^{1(3333)}_{uu}$$
$$c^1_{tb} \equiv C^{1(3333)}_{ud}$$
$$c^8_{tb} \equiv C^{8(3333)}_{ud}$$
$$c^1_{QtQb} \equiv \mathrm{Re}\{C^{1(3333)}_{quqd}\}$$
$$c^8_{QtQb} \equiv \mathrm{Re}\{C^{8(3333)}_{quqd}\}$$

## 4-fermion operators in Warsaw basis

$$O^{1(ijkl)}_{qq} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l)$$
$$O^{3(ijkl)}_{qq} = (\bar{q}_i\gamma^\mu \tau^I q_j)(\bar{q}_k\gamma_\mu \tau^I q_l)$$
$$O^{1(ijkl)}_{qu} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l)$$
$$O^{8(ijkl)}_{qu} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l)$$
$$O^{1(ijkl)}_{qd} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l)$$
$$O^{8(ijkl)}_{qd} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l)$$
$$O^{(ijkl)}_{uu} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$$
$$O^{1(ijkl)}_{ud} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l)$$
$$O^{8(ijkl)}_{ud} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)$$
$$^\ddagger O^{1(ijkl)}_{quqd} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l)$$
$$^\ddagger O^{8(ijkl)}_{quqd} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l)$$

# dof vs operators

## Degrees of freedom: 2-heavy-2-light

$$c_{Qq}^{1,1} \equiv C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(i33i)} + \frac{1}{2}C_{qq}^{3(i33i)}$$
$$c_{Qq}^{3,1} \equiv C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)})$$
$$c_{Qq}^{1,8} \equiv C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$$
$$c_{Qq}^{3,8} \equiv C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$$
$$c_{tu}^{1} \equiv C_{uu}^{(ii33)} + \frac{1}{3}C_{uu}^{(i33i)}$$
$$c_{tu}^{8} \equiv 2C_{uu}^{(i33i)}$$
$$c_{td}^{1} \equiv C_{ud}^{1(33ii)}$$
$$c_{td}^{8} \equiv C_{ud}^{8(33ii)}$$
$$c_{tq}^{1} \equiv C_{qu}^{1(ii33)}$$
$$c_{Qu}^{1} \equiv C_{qu}^{1(33ii)}$$
$$c_{Qd}^{1} \equiv C_{qd}^{1(33ii)}$$
$$c_{tq}^{8} \equiv C_{qu}^{8(ii33)}$$
$$c_{Qu}^{8} \equiv C_{qu}^{8(33ii)}$$
$$c_{Qd}^{8} \equiv C_{qd}^{8(33ii)}$$

## 4-fermion operators in Warsaw basis

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l)$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu \tau^I q_j)(\bar{q}_k\gamma_\mu \tau^I q_l)$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l)$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l)$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l)$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l)$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l)$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)$$
$$^{\ddagger}O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l)$$
$$^{\ddagger}O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l)$$

# dof vs operators

Degrees of freedom: 2-heavy + gauge/Higgs

$$c_{t\varphi} \equiv \mathrm{Re}\{C_{u\varphi}^{(33)}\}$$
$$c_{\varphi Q}^{-} \equiv C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$$
$$c_{\varphi Q}^{3} \equiv C_{\varphi q}^{3(33)}$$
$$c_{\varphi t} \equiv C_{\varphi u}^{(33)}$$
$$c_{\varphi tb} \equiv \mathrm{Re}\{C_{\varphi ud}^{(33)}\}$$
$$c_{tW} \equiv \mathrm{Re}\{C_{uW}^{(33)}\}$$
$$c_{tZ} \equiv \mathrm{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$$
$$c_{bW} \equiv \mathrm{Re}\{C_{dW}^{(33)}\}$$
$$c_{tG} \equiv \mathrm{Re}\{C_{uG}^{(33)}\}$$

Gauge/Higgs operators in Warsaw basis

$$^{\ddagger}O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi)$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_j)$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i\gamma^\mu \tau^I q_j)$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_j)$$
$$^{\ddagger}O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i\gamma^\mu d_j)$$
$$^{\ddagger}O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi} W^I_{\mu\nu}$$
$$^{\ddagger}O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu}$$
$$^{\ddagger}O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad \tilde{\varphi} B_{\mu\nu}$$
$$^{\ddagger}O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi} G^A_{\mu\nu}$$

# Need for NLO

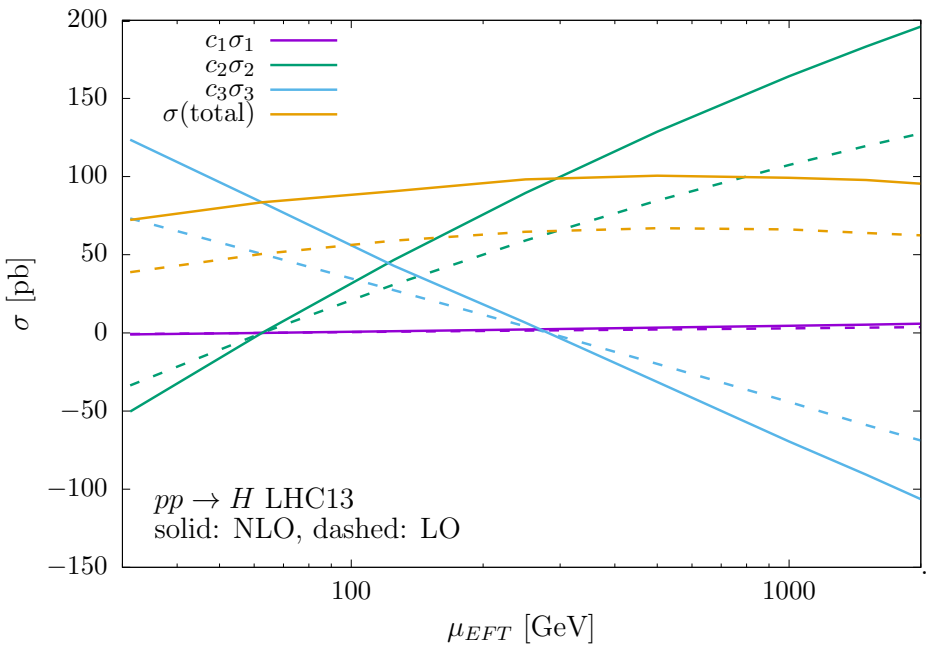
**1. Operators run and mix under RGE**

**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.

# Need for NLO

## 2. EFT scale dependence




$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

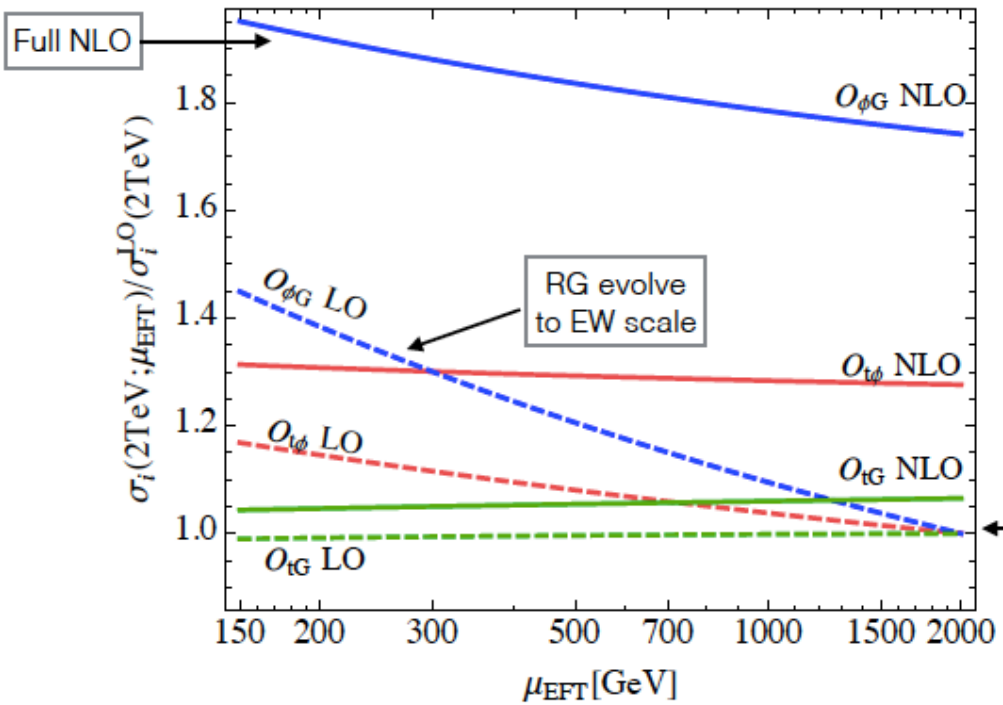
$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij} C_j(\mu),$$

$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

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.

# Need for NLO

**3. Genuine NLO corrections (finite terms) are important**




- pp → ttH

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}\,.$$

- 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.