Constraining Standard Model Effective Field Theory at colliders

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Outline

- Standard Model Effective Field Theory
- Global fits
  - CP-odd triple gauge interactions
  - Global fits of the Higgs-gauge sector

Why do we need global fits?
Why is Standard Model Effective Field Theory a good framework to perform them?
How do different sectors interact in global fits?
Why do we need global fits?

ATLAS Preliminary

\(|p_T| < 2.5\), \(m_H = 125.09\) GeV, \(|y| < 2.5\)

\(P_{\text{SM}} = 87\%\)

<table>
<thead>
<tr>
<th>Process</th>
<th>Total (\pm Stat)</th>
<th>Syst. (\pm Stat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ggF \gamma)</td>
<td>1.00 (\pm 0.07)</td>
<td>\pm 0.05 (\pm 0.05)</td>
</tr>
<tr>
<td>(ggF ZZ)</td>
<td>0.94 (\pm 0.19)</td>
<td>\pm 0.10 (\pm 0.04)</td>
</tr>
<tr>
<td>(ggF WW)</td>
<td>1.08 (\pm 0.19)</td>
<td>\pm 0.11 (\pm 0.15)</td>
</tr>
<tr>
<td>(ggF \tau\tau)</td>
<td>1.02 (\pm 0.19)</td>
<td>\pm 0.09 (\pm 0.47)</td>
</tr>
<tr>
<td>(ggF ) comb.</td>
<td>1.00 (\pm 0.19)</td>
<td>\pm 0.09 (\pm 0.30)</td>
</tr>
<tr>
<td>(VBF \gamma)</td>
<td>1.31 (\pm 0.26)</td>
<td>\pm 0.19 (\pm 0.18)</td>
</tr>
<tr>
<td>(VBF ZZ)</td>
<td>1.25 (\pm 0.26)</td>
<td>\pm 0.19 (\pm 0.15)</td>
</tr>
<tr>
<td>(VBF WW)</td>
<td>0.60 (\pm 0.23)</td>
<td>\pm 0.18 (\pm 0.06)</td>
</tr>
<tr>
<td>(VBF \tau\tau)</td>
<td>1.15 (\pm 0.23)</td>
<td>\pm 0.17 (\pm 0.21)</td>
</tr>
<tr>
<td>(VBF bb)</td>
<td>3.03 (\pm 0.19)</td>
<td>\pm 0.16 (\pm 0.12)</td>
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<tr>
<td>(VBF ) comb.</td>
<td>1.15 (\pm 0.19)</td>
<td>\pm 0.16 (\pm 0.12)</td>
</tr>
<tr>
<td>(VH \gamma)</td>
<td>1.32 (\pm 0.25)</td>
<td>\pm 0.21 (\pm 0.09)</td>
</tr>
<tr>
<td>(VH ZZ)</td>
<td>1.53 (\pm 0.25)</td>
<td>\pm 0.21 (\pm 0.09)</td>
</tr>
<tr>
<td>(VH bb)</td>
<td>1.02 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.12)</td>
</tr>
<tr>
<td>(VH ) comb.</td>
<td>1.10 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.12)</td>
</tr>
<tr>
<td>(tth+H \gamma)</td>
<td>0.90 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.06)</td>
</tr>
<tr>
<td>(tth+H VV)</td>
<td>1.72 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.06)</td>
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<tr>
<td>(tth+H \tau\tau)</td>
<td>1.20 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.06)</td>
</tr>
<tr>
<td>(tth+H bb)</td>
<td>0.79 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.06)</td>
</tr>
<tr>
<td>(tth+H ) comb.</td>
<td>1.10 (\pm 0.09)</td>
<td>\pm 0.07 (\pm 0.06)</td>
</tr>
</tbody>
</table>

\(\sigma \times B\) normalized to SM
Why do we need global fits?

![Graph showing single top quark production](image-url)

**ATLAS** Preliminary

Total Stat. Syst. SM

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma \times B$ (pb)</th>
</tr>
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<tbody>
<tr>
<td>$t\bar{t}$ + $H$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$W$ + $t\bar{t}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$Z$ + $t\bar{t}$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

*Note: Numbers are illustrative and not actual values.*

**CMS** Preliminary

May 2021

Single top quark production

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**References**

- CDF & D0, PRL 112 (2014) 231803
- CMS, JHEP 12 (2012) 035
- CMS, JHEP 06 (2014) 090
- CMS, PLB 800 (2019) 135042
- CMS, PRL 12 (2018) 221802
- CMS, JHEP 10 (2018) 117
- CMS-PAS, TOP-20-002 (Preliminary)
- Z-associated
- CMS, JHEP 07 (2017) 003
- CMS, JHEP 07 (2017) 003
- CMS, JHEP 07 (2017) 003
- CMS, JHEP 12 (2019) 132003

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[ATLAS-CONF-2020-027]
Why do we need global fits?
Why do we need global fits?

Is new physics hiding here?

$\sigma \times B$ normalized to SM

[ATLAS-CONF-2020-027]
Effective field theory - EFT
Effective field theory - EFT

\[ E_{\text{NP}} \quad E_{\text{LHC}} \quad \Lambda \quad \text{FT} \]

Hierarchy of scales
Effective field theory - EFT

Hierarchy of scales

Heavy particles that we cannot resolve live here

Describe NP by higher-order interactions of SM fields

New kinematic structures (in contrast to kappa framework)
SM effective field theory - SMEFT

- SMEFT: SM fields only, SM symmetries respected
- Higgs doublet structure (in contrast to HEFT)
- Different bases: Warsaw, HISZ, SILH, ...

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_x \frac{c_x}{\Lambda^2} \mathcal{O}_x^{(6)} \]

59 operators (MFV)
Not all of them contribute to Higgs/diboson/top physics

Fit \( c_x / \Lambda^2 \)

Odd dimensions violate lepton or baryon number
# Warsaw basis

<table>
<thead>
<tr>
<th>1 : $X^3$</th>
<th>2 : $H^6$</th>
<th>3 : $H^4D^2$</th>
<th>5 : $\psi^2H^3 + \text{h.c.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_G$</td>
<td>$f^{ABC}G_{\mu}^{A\nu}G_{\rho}^{B\sigma}G_{\mu}^{C\rho}$</td>
<td>$Q_H (H^3 H)^3$</td>
<td>$Q_{eH} (H^3H)(\bar{t}_p e_r H)$</td>
</tr>
<tr>
<td>$Q_{\bar{G}}$</td>
<td>$f^{ABC}\bar{G}<em>{\mu}^{A\nu}G</em>{\rho}^{B\sigma}G_{\mu}^{C}\bar{G}_{\rho}$</td>
<td>$Q_{H\bar{D}} (H^3 D_{\mu}^H)^* (H^3 D_{\mu}^H)$</td>
<td>$Q_{uH} (H^3 H)(\bar{q}_p u_r H)$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$\epsilon^{iJKW_{\mu}^I W_{\nu}^J W_{\rho}^K}$</td>
<td>$Q_{dH} (H^3 H)(\bar{q}_p d_r H)$</td>
<td></td>
</tr>
<tr>
<td>$Q_{\bar{W}}$</td>
<td>$\epsilon^{iJK\bar{W}<em>{\mu}^I \bar{W}</em>{\nu}^J \bar{W}_{\rho}^K}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4 : $X^2H^2$</th>
<th>6 : $\psi^2XH + \text{h.c.}$</th>
<th>7 : $\psi^2H^2D$</th>
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<tbody>
<tr>
<td>$Q_{HH}$</td>
<td>$H^3 H G_{\mu\nu}^A G_{\mu\nu}^A$</td>
<td>$Q_{iH}^{(1)} (H^3H)(\bar{t}_p \gamma^\mu l_r)$</td>
</tr>
<tr>
<td>$Q_{H\bar{G}}$</td>
<td>$H^3 H \bar{G}<em>{\mu\nu}^A G</em>{\mu\nu}^A$</td>
<td>$Q_{iH}^{(3)} (H^3H)(\bar{t}_p \tau^I \gamma^\mu l_r)$</td>
</tr>
<tr>
<td>$Q_{HW}$</td>
<td>$H^3 H W_{\mu\nu}^I W_{\mu\nu}^I$</td>
<td>$Q_{H\bar{c}} (H^3H)(\bar{t}_p \gamma^\mu e_r)$</td>
</tr>
<tr>
<td>$Q_{H\bar{W}}$</td>
<td>$H^3 H \bar{W}<em>{\mu\nu}^I \bar{W}</em>{\mu\nu}^I$</td>
<td>$Q_{H\bar{q}}^{(3)} (H^3H)(\bar{q}_p \gamma^\mu q_r)$</td>
</tr>
<tr>
<td>$Q_{HB}$</td>
<td>$H^3 H B_{\mu\nu} B_{\mu\nu}$</td>
<td>$Q_{H\bar{q}}^{(3)} (H^3H)(\bar{q}_p \tau^I \gamma^\mu q_r)$</td>
</tr>
<tr>
<td>$Q_{H\bar{B}}$</td>
<td>$H^3 H \bar{B}<em>{\mu\nu} B</em>{\mu\nu}$</td>
<td>$Q_{H\bar{u}} (H^3H)(\bar{u}_p \gamma^\mu u_r)$</td>
</tr>
<tr>
<td>$Q_{HWB}$</td>
<td>$H^3 H \tau^I H W_{\mu\nu}^I W_{\mu\nu}^I$</td>
<td>$Q_{H\bar{d}} (H^3H)(\bar{d}_p \gamma^\mu d_r)$</td>
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<tr>
<td>$Q_{H\bar{WB}}$</td>
<td>$H^3 H \tau^I W_{\mu\nu}^I W_{\mu\nu}^I$</td>
<td>$Q_{Hud} + \text{h.c.}$</td>
</tr>
<tr>
<td>$Q_{\bar{L}}$</td>
<td>$(\bar{t}_p \gamma^\mu l_r)$</td>
<td></td>
</tr>
</tbody>
</table>

8 : $(\bar{L}L)(\bar{L}L)$

$Q_{\ell\ell} = (\bar{t}_p \gamma^\mu l_r)(\bar{t}_p \gamma^\mu l_r)$

[Grzadkowski et al. (1008.4884)]
### Warsaw basis

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<th>$X^3$</th>
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<tbody>
<tr>
<td>$Q_{CG}$</td>
<td>$f^{ABC}G_\mu^A G_\nu^B G_\rho^C$</td>
<td>$Q_H$</td>
<td>$(H^\dagger H)^3$</td>
<td>$Q_{eH}$</td>
</tr>
<tr>
<td>$Q_{C\bar{G}}$</td>
<td>$f^{ABC}\bar{G}<em>\mu^A G</em>\nu^B G_\rho^C$</td>
<td>$Q_{H\Box}$</td>
<td>$(H^\dagger H)\Box(H^\dagger H)$</td>
<td>$Q_{uH}$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$e^{IJK}W_{\mu}^{I}W_{\nu}^{J}W_{\rho}^{K}$</td>
<td>$Q_{HD}$</td>
<td>$(H^\dagger D_\mu H)^* (H^\dagger D_\nu H)$</td>
<td>$Q_{dH}$</td>
</tr>
<tr>
<td>$Q_{\bar{W}}$</td>
<td>$e^{IJK}\bar{W}<em>{\mu}^{I}W</em>{\nu}^{J}W_{\rho}^{K}$</td>
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<th>$\psi^2H^2D$</th>
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<tr>
<td>$Q_{HG}$</td>
<td>$H^\dagger H G_{\mu\nu}^A G_{\lambda\sigma}^A$</td>
<td>$Q_{eW}$</td>
<td>$(\bar{t}<em>{p}\sigma</em>{\mu\nu}e_{r})\tau^I HW_{\mu\nu}^I$</td>
</tr>
<tr>
<td>$Q_{H\bar{G}}$</td>
<td>$H^\dagger H \bar{G}<em>{\mu\nu}^A G</em>{\lambda\sigma}^A$</td>
<td>$Q_{eB}$</td>
<td>$(\bar{t}<em>{p}\sigma</em>{\mu\nu}e_{r})HB_{\mu\nu}$</td>
</tr>
<tr>
<td>$Q_{HW}$</td>
<td>$H^\dagger H W_{\mu\nu}^I W_{\lambda\sigma}^I$</td>
<td>$Q_{uG}$</td>
<td>$(\bar{q}<em>{p}\sigma</em>{\mu\nu}T^A u_{r})\bar{H} G_{\mu\nu}^A$</td>
</tr>
<tr>
<td>$Q_{\bar{H}W}$</td>
<td>$H^\dagger H \bar{W}<em>{\mu\nu}^I W</em>{\lambda\sigma}^I$</td>
<td>$Q_{uW}$</td>
<td>$(\bar{q}<em>{p}\sigma</em>{\mu\nu}u_{r})\tau^I \bar{H} W_{\mu\nu}^I$</td>
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<tr>
<td>$Q_{HB}$</td>
<td>$H^\dagger H B_{\mu\nu}$</td>
<td>$Q_{uB}$</td>
<td>$(\bar{q}<em>{p}\sigma</em>{\mu\nu}u_{r})\bar{H} B_{\mu\nu}$</td>
</tr>
<tr>
<td>$Q_{H\bar{B}}$</td>
<td>$H^\dagger H \bar{B}_{\mu\nu}$</td>
<td>$Q_{dG}$</td>
<td>$(\bar{q}<em>{p}\sigma</em>{\mu\nu}T^A d_{r})H G_{\mu\nu}^A$</td>
</tr>
<tr>
<td>$Q_{HWB}$</td>
<td>$H^\dagger \tau^I H W_{\mu\nu}^I B_{\lambda\sigma}^\nu$</td>
<td>$Q_{dW}$</td>
<td>$(\bar{q}<em>{p}\sigma</em>{\mu\nu}d_{r})\tau^I H W_{\mu\nu}^I$</td>
</tr>
<tr>
<td>$Q_{\bar{H}WB}$</td>
<td>$H^\dagger \tau^I H \bar{W}<em>{\mu\nu}^I B</em>{\lambda\sigma}^\nu$</td>
<td>$Q_{dB}$</td>
<td>$(\bar{q}<em>{p}\sigma</em>{\mu\nu}d_{r})HB_{\mu\nu}$</td>
</tr>
</tbody>
</table>

8. $(\bar{\ell}\ell)(\bar{\ell}\ell)$

- Plus another 24 four-fermion operators

[Grzadkowski et al. (1008.4884)]
A 2D example:

CP-odd triple gauge couplings
CP-odd dimension-6 operators

- Linear effect of CP-odd operators on the total cross section is very small (zero before kinematic cuts)
- Influence of CP-odd operators on CP-even+CP-odd fit often negligible [Ethier et al (2101.03180)]
- Need dedicated observables
- Only few fits of CP-odd SMEFT operators
CP-odd dimension-6 operators

- Linear effect of CP-odd operators on the total cross section is very small (zero before kinematic cuts)
- Influence of CP-odd operators on CP-even+CP-odd fit often negligible [Ethier et al (2101.03180)]
- Need dedicated observables
- Only few fits of CP-odd SMEFT operators
  - Higgs production and decay [Brehmer et al (1712.02350)]
    [Bernlochner et al (1808.06577)]
    [Englert et al (1901.05982)]
  - Low-energy experiments (EDMs + LEP+ $B \rightarrow X_s \gamma$) [Cirigliano et al (1903.03625)]
  - Diboson production [Bakshi et al (2009.13394)]
    [Ethier et al (2101.03180)] (distributions)
CP-odd triple gauge couplings

\[ \mathcal{L}_{\text{SM}} = -i g_{WWV} \left[ (W_{\mu \nu}^+ W_{-\mu}^\nu - W_{\mu \nu}^- W_{+\mu}^\nu) \\
+ W_{\mu}^+ W_{\nu}^- V^{\mu \nu} \right] \]
CP-odd triple gauge couplings

\[ \mathcal{L}_{SM} = -ig_{WWV} \left[ (W_{\mu\nu}^{+} W_{-\mu}^{\nu} V^{\nu} - W_{\mu\nu}^{-} W_{+\mu}^{\nu} V^{\nu}) \\
+ W_{\mu}^{+} W_{\nu}^{-} V^{\mu\nu} \right] \]

Luckily only two dim-6 operators contribute

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{c_{\tilde{W}}}{\Lambda^2} \mathcal{O}_{\tilde{W}} + \frac{c_{H\tilde{W}B}}{\Lambda^2} \mathcal{O}_{H\tilde{W}B} \]

\[ \mathcal{O}_{\tilde{W}} = \varepsilon^{IJK} \tilde{W}_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K} \]

\[ \mathcal{O}_{H\tilde{W}B} = \tilde{H}^{I} \tau^{I} H \tilde{W}_{\mu\nu}^{I} B^{\mu\nu} \]
CP-odd triple gauge couplings

\[ \mathcal{L}_{\text{SM}} = -ig_{WWV} \left[ (W^{+\mu}_\nu W^{-\nu}_\mu - W^{-\mu}_\nu W^{+\nu}_\mu) 
+ W^{+\mu}_\nu W^{-\nu}_\mu V^{\mu\nu} \right] \]

Luckily only two dim-6 operators contribute

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_{\tilde{W}}}{\Lambda^2} O_{\tilde{W}} + \frac{c_{H\tilde{W}B}}{\Lambda^2} O_{H\tilde{W}B} \]

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}^I_\mu W^J_\nu W^K_\rho \]

\[ O_{H\tilde{W}B} = H^I \tau^I H \tilde{W}^I_{\mu\nu} B^{\mu\nu} \]

Does not exist in the SM
First contribution appears at dim-8
Triple gauge couplings

\[ \mathcal{O}_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{\mu}^{I} W_{\nu}^{J \rho} W_{\rho}^{K \mu} \]

\[ \mathcal{O}_{H\bar{W}B} = H^{\dagger} \tau^{I} H \tilde{W}_{\mu \nu}^{I}, B^{\mu \nu} \]

[AB, Gregg, Krauss, Schönherr (2102.01115)]
Triple gauge couplings

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_I^{\mu} W_J^{\nu} W^K_{\rho} \]

\[ O_{H\tilde{W}B} = H^{\dagger I} H \tilde{W}_{\mu\nu} B^{\mu\nu} \]

Interactions involve epsilon tensor

[AB, Gregg, Krauss, Schönherr (2102.01115)]
**Triple gauge couplings**

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K} \]

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Interactions involve epsilon tensor

\[ \text{ triple products on the momenta } \]
**Triple gauge couplings**

\[ \mathcal{O}_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu} \]

\[ \mathcal{O}_{H\tilde{W}B} = H^{I} \tau^{I} H \tilde{W}_{\mu\nu}^{I} B_{\mu\nu} \]

**Interactions involve epsilon tensor**

- **↓ triple products on the momenta**
- **↓ Modulation of \( \Delta \phi \) distributions**

\[ \Delta \phi_{kl} \propto \sin^{-1}\left( (\vec{p}_k - \vec{p}_l)_z (\vec{p}_k \times \vec{p}_l)_z \right) \]

[AB, Gregg, Krauss, Schönherr (2102.01115)]
Triple gauge couplings

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K} \]
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- Modulation of \( \Delta \phi \) distributions

\[ \Delta \phi_{kl} \propto \sin^{-1}((\vec{p}_k - \vec{p}_l)_z (\vec{p}_k \times \vec{p}_l)_z) \]

Observables: asymmetries
Systematic uncertainties cancel out

\[ A_{ij} = \frac{N_{i,-j} - N_{i,+j}}{N_{i,-j} + N_{i,+j}} \]
\[ i = WW, WZ, W\gamma, Zjj, Wjj \]
\[ j = 1, \ldots, 6 \]
Triple gauge couplings

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_\mu^I W_\nu^J W_\rho^K \]
\[ O_{H\tilde{W}B} = H^\dagger I H \tilde{W}_\mu^I B^{\mu\nu} \]

Interactions involve epsilon tensor

- \( \text{ triple products on the momenta } \)
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**Triple gauge couplings**

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_\mu^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu} \]

\[ O_{H\tilde{W}B} = H^\dagger I H \tilde{W}_\mu^{I\nu} B^{\mu\nu} \]

Interactions involve epsilon tensor

- **triple products on the momenta**
- **Modulation of \( \Delta \phi \) distributions**

\[ \Delta \phi_{kl} \propto \sin^{-1}((\tilde{p}_k - \tilde{p}_l)_z (\tilde{p}_k \times \tilde{p}_l)_z) \]

**Observables: asymmetries**

Systematic uncertainties cancel out

\[ A_{ij} = \frac{N_{i,-j} - N_{i,+j}}{N_{i,-j} + N_{i,+j}} \]

\[ i = WW, WZ, W\gamma, Z_{jj}, W_{jj} \]

\[ j = 1, \ldots, 6 \]
Triple gauge couplings

\[
O_{\tilde{W}} = \epsilon^{IJK} \, \tilde{W}_\mu^I W_\nu^J W_\rho^K
\]

\[
O_{H \tilde{W} B} = H^I \tau^I H \, \tilde{W}_\mu^I B^{\mu\nu}
\]

Interactions involve epsilon tensor

- triple products on the momenta
- Modulation of \(\Delta \phi\) distributions

\[
\Delta \phi_{kl} \propto \sin^{-1}((\vec{p}_k - \vec{p}_l)_Z (\vec{p}_k \times \vec{p}_l)_Z)
\]

Observables: asymmetries

Systematic uncertainties cancel out

\[
A_{ij} = \frac{N_{i,-j} - N_{i,+j}}{N_{i,-j} + N_{i,+j}}
\]

\[i = WW, WZ, W\gamma, Zjj, Wjj\]
\[j = 1, \ldots, 6\]
**Triple gauge couplings - results**

[AB, Gregg, Krauss, Schönherr (2012.01115)]

\[
\mathcal{L}_{\text{int}} = 139 \text{ ifb}
\]

\[
O_W = \epsilon^{JK} \tilde{W}_\mu^{IJ} W_\nu^{JP} W_\rho^{K\mu}
\]

\[
O_{H\tilde{W}B} = H^I J H \tilde{W}^I_{\mu\nu} B^{\mu\nu}
\]

See also: [Bakshi, Chakrabortty, Englert, Spannowsky, Stylianos (2009.13394)]
**Triple gauge couplings - results**

[AB, Gregg, Krauss, Schönherr (2102.01115)]

\[ \mathcal{L}_{\text{int}} = 139 \text{ ifb} \]

\[ \begin{align*}
W Z & \\
\text{limits too weak to appear on plots}
\end{align*} \]

\[ O_W = \epsilon^{IJK} \tilde{W}^I_{\mu} W^J_{\nu} W^K_{\rho} \]

\[ O_{H\tilde{W}B} = H^I \tau^I H \tilde{W}^I_{\mu\nu} B^{\mu\nu} \]

See also: [Bakshi, Chakrabortty, Englert, Spannowsky, Stylianos (2009.13394)]
Triple gauge couplings - results

\[ L_{\text{int}} = 139 \text{ ifb} \]

\[ \mathcal{O}_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu} \]

\[ \mathcal{O}_{H\tilde{W}B} = H^{I} \tilde{H} H \tilde{W}_\mu^{I\nu} B^{\mu\nu} \]

\[ WZ \text{ limits too weak to appear on plots} \]

\[ V\bar{jj} \text{ gives best constraints on } c_{\tilde{W}} \]

See also: [Bakshi, Chakrabortty, Englert, Spannowsky, Stylianos (2009.13394)]
Triple gauge couplings - results

[AB, Gregg, Krauss, Schönherr (2102.01115)]

\[ \mathcal{L}_{\text{int}} = 139 \text{ ifb} \]

\[ c_{W}/\Lambda^2 \text{ [TeV}^{-2}] \]
\[ c_{H\tilde{W}B}/\Lambda^2 \text{ [TeV}^{-2}] \]

\[ WZ \text{ limits too weak to appear on plots} \]

\[ Vjjj \text{ gives best constraints on } c_{\tilde{W}} \]

\[ W\gamma \text{ gives best constraints on } c_{H\tilde{W}B} \]

\[ O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K} \mu \]

\[ O_{H\tilde{W}B} = H^{IJ} H\tilde{W}_{\mu\nu}^{I} B^{\mu\nu} \]

See also: [Bakshi, Chakrabortty, Englert, Spannowsky, Stylianos (2009.13394)]
Triple gauge couplings - results

\[O \sim W Z, W \gamma \text{ gives best constraints on } c_{\tilde{W}}\]

\[V jj \text{ gives best constraints on } c_{H \tilde{W}B}\]

\[O_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{I}^{\mu} W_{J}^{\nu} W_{K}^{\rho} W_{\rho}^{\mu}\]

\[O_{H \tilde{W}B} = H_{I}^{\tau} H \tilde{W}_{I}^{\nu} B_{\mu\nu}\]

See also: [Bakshi, Chakraborty, Englert, Spannowsky, Stylianos (2009.13394)]

Limits for 3 iab at \(O(10^{-2})\)

\[|c_{H \tilde{W}B}|/\Lambda^2 < 3.1 \ T e V^{-2} \text{ Higgs WBF+\gamma}\]

\[|c_{H \tilde{W}B}|/\Lambda^2 < 1.5 \ T e V^{-2} \text{ Higgs production}\]

[AB et al (2003.06379)]

[Bernlochner et al (1808.06577)]

\(c_{\tilde{W}/\Lambda^2} \text{ [TeV]}\)
Motivates a combined fit of CP-odd operators in Higgs + diboson + X production

$WZ$ limits too weak to appear on plots

$Vjj$ gives best constraints on $c_{\tilde{W}}$

$W\gamma$ gives best constraints on $c_{H\tilde{W}B}$

$|c_{H\tilde{W}B}|/\Lambda^2 < 3.1 \text{ TeV}^{-2}$ Higgs WBF+$\gamma$

$|c_{H\tilde{W}B}|/\Lambda^2 < 1.5 \text{ TeV}^{-2}$ Higgs production

$O_{\tilde{W}} = \epsilon^{\text{IJK}} \tilde{W}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$

$O_{H\tilde{W}B} = H^{\dagger} \tau^I H \tilde{W}_{\mu\nu}^{I} B_{\mu\nu}$

See also: [Bakshi, Chakrabortty, Englert, Spannowsky, Stylianos (2009.13394)]
[Bernlochner et al (2003.06379)]
[Bernlochner et al (1808.06577)]
CP-even interactions
CP even fit (of the Higgs-gauge sector)

[Ellis, Madigan, Mimasu, Sanz, You (2012.02779)]
The operator $\mathcal{O}_{HG}$

$\mathcal{O}_{HG} = H\dagger H G^A_{\mu\nu} G^{A,\mu\nu} \rightarrow v h G^A_{\mu\nu} G^{A\mu\nu}$

Feynman rules

SM: $-i G_H \delta_{a_1,a_2} (p_1^{\mu} p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

EFT: $-i v \delta_{a_1,a_2} (p_1^{\mu} p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

Structurally the same
The operator $\mathcal{O}_{HG}$

$$\mathcal{O}_{HG} = H\dagger H G_A^{\mu\nu} G_A^{\lambda,\mu\nu} \rightarrow \nu h G_A^{\mu\nu} G_A^{A\mu\nu}$$

Feynman rules

SM: $-i G_H \delta_{a_1,a_2} (p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

EFT: $-i \nu \delta_{a_1,a_2} (p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

Structurally the same

Affects total cross section only
The operator $\mathcal{O}_{HB}$

$$\mathcal{O}_{HB} = H^\dagger H B_{\mu \nu} B^{\mu \nu} \rightarrow c_{HZZ}^{\text{EFT}} h Z_{\mu \nu} Z^{\mu \nu}$$

Feynman rules

SM: $g_{ZZh}^{\text{SM}} \eta^{\mu \nu}$

EFT: $g_{hZZ}^{\text{EFT}} \left[ \eta^{\mu \nu} p_{Z_1} \cdot p_{Z_2} \right]$

EFT contribution has additional momentum dependence
The operator $\mathcal{O}_{HB}$

$$\mathcal{O}_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu} \rightarrow c^{EFT}_{HZZ} h Z_{\mu\nu} Z^{\mu\nu}$$

Feynman rules

SM: $g^{SM}_{ZZh} \eta^{\mu\nu}$

EFT: $g^{EFT}_{hZZ} [p^\mu_{Z1} p^\nu_{Z2} - \eta^{\mu\nu} p_{Z1} \cdot p_{Z2}]$

EFT contribution has additional momentum dependence
The operator $\mathcal{O}_{HB}$

$\mathcal{O}_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu} \rightarrow c_{HZZ}^{\text{EFT}} h Z_{\mu\nu} Z^{\mu\nu}$

Feynman rules

SM: $g_{ZZh}^{\text{SM}} \eta^{\mu\nu}$
EFT: $g_{hZZ}^{\text{EFT}} [p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2]$}

EFT contribution has additional momentum dependence

Affects distributions

e.g. $m_{Zh}$ in HZ production
The operator $\mathcal{O}_{Hu}$

$$\mathcal{O}_{Hu} = (H^\dagger i \not{D}_\mu H) (\bar{u}_R \gamma^\mu u_R) \rightarrow (h + v) Z_\mu (\bar{u}_R \gamma^\mu u_R)$$

**Feynman rules**

**SM Zuu:** $g_{Zuu}^{SM} \gamma^\mu P_R$

**EFT Zuu:** $g_{Zuu}^{EFT} \gamma^\mu P_R$

**EFT Zhuu:** $g_{Zuu}^{EFT} / v \gamma^\mu P_R$

**New contact interaction**
The operator $\mathcal{O}_{Hu}$

$$\mathcal{O}_{Hu} = (H^\dagger i D_\mu H)(\bar{u}_R \gamma^\mu u_R) \rightarrow (h + \nu)Z_\mu(\bar{u}_R \gamma^\mu u_R)$$

Feynman rules

SM Zuu: $g_{Zuu}^{SM} \gamma^\mu P_R$

EFT Zuu: $g_{Zuu}^{EFT} \gamma^\mu P_R$

EFT Zhuu: $g_{Zuu}^{EFT}/\nu \gamma^\mu P_R$

New contact interaction

Affects distributions

SM: propagator suppression
Dimension-six operators - effects

- Contribution to SM-like structures (same Lorentz structure as in SM)
  Only total cross section affected
- Interactions with new Lorentz structures
- New contact interactions (not present in the SM)
  distributions affected
  Validity?
Input data

- Electroweak precision observables
- Single Higgs data
  - Signal strength
  - Simplified template cross sections
    (Differential information)
- Diboson distributions
- Dihiggs signal strength
Input data

- Electroweak precision observables
- Single Higgs data
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Input data

- Electroweak precision observables
- Single Higgs data
  - Signal strength
  - Simplified template cross sections
    (Differential information)
- Diboson distributions
- Dihiggs signal strength

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
Dihiggs

• Constrains $O_H = (H^\dagger H)^3$ which appear in many scalar extensions

• $gg\rightarrow HH$ at NLO in Powheg [Heinrich, Jones, Kerner, Scyboz (2006.16877)]

• Considered channels from ATLAS and CMS

  $HH \rightarrow b\bar{b}b\bar{b}$
  $HH \rightarrow b\bar{b}\gamma\gamma$
  $HH \rightarrow b\bar{b}\tau\tau$
**LHC Run II fit - without fermion-gauge operators**

[HISZ basis]

\[
O_{GG} = \phi^{\dagger} \phi G^{a}_{\mu\nu} G^{a\mu\nu}
\]
\[
O_{WW} = \phi^{\dagger} \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi
\]
\[
O_{BB} = \phi^{\dagger} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi
\]
\[
O_{W} = (D_{\mu} \phi)^{\dagger} \hat{W}^{\mu\nu} (D_{\nu} \phi)
\]
\[
O_{B} = (D_{\mu} \phi)^{\dagger} \hat{B}^{\mu\nu} (D_{\nu} \phi)
\]
\[
O_{\phi 2} = \frac{1}{2} \partial^{\mu}(\phi^{\dagger} \phi) \partial_{\mu}(\phi^{\dagger} \phi)
\]
\[
O_{WWW} = \text{Tr} \left( \hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\mu}_{\rho} \right)
\]
\[
O_{\tau} = \phi^{\dagger} \phi \bar{L}_{3} \phi e_{R,3}
\]
\[
O_{t} = \phi^{\dagger} \phi \bar{Q}_{3} \phi \bar{u}_{R,3}
\]
\[
O_{b} = \phi^{\dagger} \phi \bar{Q}_{3} \phi \bar{d}_{R,3}
\]

“New” data

Nothing new on the theory side
LHC Run II fit - without fermion-gauge operators

[HISZ basis]

\[ O_{GG} = \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \]
\[ O_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi \]
\[ O_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \]
\[ O_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \]
\[ O_{\phi_2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]
\[ O_{WWW} = \text{Tr} \left( \hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\rho}_\mu \right) \]
\[ O_{\tau} = \phi^\dagger \phi \bar{L}_3 \phi e_{R,3} \]
\[ O_{t} = \phi^\dagger \phi \bar{Q}_3 \phi u_{R,3} \]
\[ O_{b} = \phi^\dagger \phi \bar{Q}_3 \phi d_{R,3} \]

“New” data
Nothing new on the theory side

[SFitter Run I: Butter et al. (1604.03105)]
[Ellis, (Madigan), (Mimasu), (Murphy), Sanz, You (1803.03252, 2012.02779)]
[da Silva Almeida, Alves, (Rosa Agostinho), Éboli, Gonzalez-Garcia (1812.01009, 2108.04828)]
[Ethier, Magni, Maltoni, Mantani, Nocera Rojo, Slade, Vryonidou, Zhang (2105.00006)]

[AB, Corbett, Plehn (1812.07587)]

[99% CL]

Run I
Run I + II

BR [%]

lle, lWW, lBB, lW, lB, l\tau, lWWW

Only operators involving the Higgs or TGCs

Limits on bosonic operators improved by distributions

"New" data

"Nothing new on the theory side"
LHC Run II fit - without fermion-gauge operators

[HISZ basis]

\[ O_{GG} = \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \]
\[ O_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \]
\[ O_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi \]
\[ O_W = (D_{\mu} \phi)^\dagger \hat{W}_{\mu\nu}(D_{\nu} \phi) \]
\[ O_B = (D_{\mu} \phi)^\dagger \hat{B}_{\mu\nu}(D_{\nu} \phi) \]
\[ O_{\phi 2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_{\mu} (\phi^\dagger \phi) \]
\[ O_{WWW} = \text{Tr} \left( \hat{W}_{\mu\nu} \hat{W}_{\nu\rho} \hat{W}_{\rho} \right) \]

“New” data

Nothing new on the theory side

[AB, Corbett, Plehn (1812.07587)]

[SFitter Run I: Butter et al. (1604.03105)]
[Ellis, (Madigan), (Mimasu), (Murphy), Sanz, You (1803.03252, 2012.02779)],
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[Ethier, Magni, Maltoni, Mantani, Nocera Rojo, Slade, Vryonidou, Zhang (2105.00006)]

[99% CL]
LHC Run II fit - fermion-gauge operators

\[ \mathcal{O}_{GG} = \phi^\dagger \phi \, G_{\mu\nu}^a G^{a\mu\nu} \]
\[ \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} W^{\mu\nu} \phi \]
\[ \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} B^{\mu\nu} \phi \]
\[ \mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu}(D_\nu \phi) \]
\[ \mathcal{O}_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu}(D_\nu \phi) \]
\[ \mathcal{O}_{\phi_2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]
\[ \mathcal{O}_{WWW} = \text{Tr} \left( \hat{W}_{\mu\nu} W^{\nu\rho} \hat{W}^{\rho}_{\mu} \right) \]
\[ \mathcal{O}_{\tau} = \phi^\dagger \phi \, \bar{L}_3 \phi e_{R,3} \]
\[ \mathcal{O}_t = \phi^\dagger \phi \, \bar{Q}_3 \tilde{\phi} u_{R,3} \]
\[ \mathcal{O}_b = \phi^\dagger \phi \, \bar{Q}_3 \tilde{\phi} d_{R,3} \]

Adding more freedom

\[ \mathcal{O}_{\phi_1} = (D_\mu \phi)^\dagger \phi^\dagger (D^\mu \phi) \]
\[ \mathcal{O}_{(1)_{\phi Q}} = \phi^\dagger (iD_\mu \phi)(\bar{Q} \gamma^\mu Q) \]
\[ \mathcal{O}_{(1)_{\phi d}} = \phi^\dagger (iD_\mu \phi)(\bar{d}_R \gamma^\mu d_R) \]

\[ \mathcal{O}_{(3)_{\phi Q}} = \phi^\dagger (iD_\mu \phi)(\bar{Q} \gamma^\mu \sigma^a Q) \]
\[ \mathcal{O}_{(1)_{\phi e}} = \phi^\dagger (iD_\mu \phi)(\bar{e}_R \gamma^\mu e_R) \]

\[ \mathcal{O}_{LLLL} = (\bar{L}_\mu L)(\bar{L}_\mu L) \]
LHC Run II fit - correlations

Contributions to Zh production

\[ \mathcal{O}_B = (D_\mu \phi)^\dagger \tilde{B}^{\mu\nu}(D_\nu \phi) \]

\[ \mathcal{O}_W = (D_\mu \phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu \phi) \]

\[ \mathcal{O}_{\phi Q}^{(1)} = \phi^\dagger (i \tilde{D}_\mu \phi)(\bar{Q} \gamma^\mu Q) \]

\[ \mathcal{O}_{\phi Q}^{(3)} = \phi^\dagger (i \tilde{D}_\mu^a \phi)(Q \gamma^\mu \sigma^a Q) \]
LHC Run II fit - correlations

Contributions to Zh production

- $O_{B,W}$
- $O_{\phi Q}$

No propagator suppression

$O_B = (D_{\mu}\phi)^\dagger \bar{B}^{\mu\nu}(D_{\nu}\phi)$

$O_W = (D_{\mu}\phi)^\dagger \bar{W}^{\mu\nu}(D_{\nu}\phi)$

$O^{(1)}_{\phi Q} = \phi^\dagger (i\not\!D_{\mu}) (\bar{Q}\gamma^\mu Q)$

$O^{(3)}_{\phi Q} = \phi^\dagger (i\not\!D^a_{\mu}) (\bar{Q}\gamma^\mu \sigma^a Q)$
## SMEFT fits - a global effort!

<table>
<thead>
<tr>
<th>Linear/quadratic</th>
<th>Eboli, Gonzalez-Garcia et al</th>
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Filled to my best knowledge - apologies for any mistakes
## SMEFT fits - a global effort!

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Higgs-top combination

Combining different sectors, e.g. top + Higgs

[Ellis, Madigan, Mimasu, Sanz, You (2012.02779)]

[see also: Ethier et al. (2105.00006)]
Higgs-top combination

Combining different sectors, e.g. top + Higgs

[Ellis, Madigan, Mimasu, Sanz, You (2012.02779)]

[see also: Ethier et al. (2105.00006)]
Including NLO QCD corrections

SMEFT @ NLO, e.g. NLO QCD for diboson + Vh

Top sector fits including NLO QCD:
- [Hartland et al (1901.05965)]
- [Ellis et al. (2012.02779)]
- [Brivio et al. (1910.03606)]

\[ \sqrt{s} = 8 + 13 \text{ TeV} \]
Including NLO QCD corrections

SMEFT @ NLO, e.g. NLO QCD for diboson + Vh

[MG: Degrande et al. (2008.11743)]
Top sector fits including NLO QCD:
[Hartland et al (1901.05965)]
[Ellis et al. (2012.02779)]
[Brivio et al. (1910.03606)]

\( \sqrt{s} = 8 + 13 \text{ TeV} \)

\[ d(\Delta \sigma_{WZ}/\sigma_{SM})/dm_{WZ} \]

\( pp \rightarrow W^\pm Z \rightarrow \ell^+\ell^- \ell^- \)

\( C_{H_{q}q}/\Lambda^2 = 0.20 \text{ TeV}^{-2} \)

Interference Terms

\( \mu_R = \mu_F = M_Z/2 \)

ATLAS Cuts

\( \sqrt{s} = 13 \text{ TeV} \)

\[ C/\Lambda^2 \]

Including NLO QCD corrections

SMEFT @ NLO, e.g. NLO QCD for diboson + Vh

\[ \sqrt{s} = 8 + 13 \text{ TeV} \]

Interference Terms

\[ \mu_R = \mu_F = M_Z/2 \]

ATLAS Cuts

\[ \sigma^{\text{SM}}(pp \rightarrow W^+Z \rightarrow \ell^+\ell^-\ell^-) \]

\[ C_{Hi}/\Lambda^2 = 0.20 \text{ TeV}^{-2} \]
Global fit

Reduced set: EWPO + 2020 Higgs data (incl. ATLAS STXS data)
Full set: EWPO + 2021 Higgs data + Dihiggs

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (work in progress)]
Global fit

Reduced set: EWPO + 2020 Higgs data (incl. ATLAS STXS data)
Full set: EWPO + 2021 Higgs data + Dihiggs

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (work in progress)]

No diboson data
UV complete model fits

- Map UV complete models onto EFT
  - Extended scalar sectors
  - Quark bidoublet model
  - Vector-singlet pair model
  - Vector-like quarks

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (work in progress)]
[Gorbahn, No, Sanz (1502.07352)]
[Drozd, Ellis, Quevillon, You (1504.02409)]
[Ellis, (Madigan, Mimasu, Murphy), Sanz, You (1803.03252), (2012.02779)]
[Dawson, Homiller, Lane (2007.01296), (2102.02823)]
[Bakshi, Chakrabortty, (Englert), Spannowsky, (Stylianou) (2009.13394), (2012.03839)]
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UV complete model fits

- Map UV complete models onto EFT
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  - …
Summary

- **CP-odd interactions** in diboson and Vjj production
  - Charged TGC: (almost) orthogonal limits from $W\gamma$ and $V_{jj}$

- **Global fit for LHC run II**
  - Combinations of different sectors
    Higgs + diboson + EWPO + top + X
  - SMEFT is the framework, but not the answer
Thank you for your attention!
Individual limits

individual limits
preliminary

2012.02779 (without top data)
work in progress
Profiled limits

preliminary

2012.02779 (without top data)

work in progress

$\frac{c/\Lambda^2}{[\text{GeV}^{-2}]}$