Global fits to EW and Higgs observables at the FCC

Jorge de Blas
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In short:

- Properties of the Electroweak gauge bosons (EWPO)
- Mass and couplings of the Higgs boson

The point of this talk:

- To get an overall idea of what one could get after combining the different collider options …
- … emphasizing complementarities between them (to convince you that they are all important)

**DISCLAIMER:** All results in this talk are VERY preliminary
Theoretical framework: The dimension-6 SMEFT

Electroweak precision observables at the FCC

Higgs observables at the FCC

The Global fit to EW and Higgs observables
The dimension-6 SMEFT
The dimension-6 SMEFT

- **The dimension 6 SMEFT:**
  
  Assumes new physics is heavy + decoupling
  
  Particles and symmetries of the low-energy theory: SM
  
  Power counting: EFT expansion in canonical dimension of operators

  \[
  \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots
  \]

  \[
  \mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i
  \]

  \[\Lambda: \text{Cut-off of the EFT}\]

- **LO new physics effects “start” at dimension 6**

- **With current precision, and assuming \(\Lambda\sim\text{TeV}\), sensitivity to \(d>6\) is small**

  \[
  \frac{M_2^2}{(1\text{TeV})^2} \sim 0.8\% \quad \frac{M_4^4}{(1\text{TeV})^4} \sim 0.007\%
  \]

**Truncate at \(d=6\):** 59 types of operators (2499 counting flavor)


First complete basis, aka Warsaw basis
The dimension-6 SMEFT

- Advantages of EFTs:
  - Completely model-independent description of new physics (Consistent with assumptions of SM at low energies)
  - Well-defined perturbative expansion (can compute at $N^n\text{LO}$)
  - Well-defined way of connecting with explicit UV completions via matching/integrating out heavy degrees of freedom
  - Describes correlations of new physics effects in different types of observables, e.g.

\[
O_{\phi WB} = \phi^\dagger \sigma_\alpha \phi B^{\mu \nu} W^a_{\mu \nu}
\]  
(dim 4)

\[
v^2 B^{\mu \nu} W^3_{\mu \nu}
\]
(Modifies neutral gauge boson self-energies)

\[
v h B^{\mu \nu} W^3_{\mu \nu}
\]
(dim 5)

\[
h \rightarrow ZZ, \gamma\gamma
\]
(Higgs phys.)

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Jorge de Blas

*INFIN - University of Padova*
FCC sensitivity to New Physics

General strategy for calculation of future sensitivities

- **Fit to new physics effects** parameterized by the dimension 6 SMEFT:
  - Bayesian fit using [HEPfit]
  - **FCC sensitivity**: from posterior info (NP parameter errors/limits)
- **Assumptions**:
  - **Likelihood**: SM predictions as central values for future “experimental” measurements. Errors given by projected experimental uncertainties. (For comparison, results using current data are also shown assuming SM central values, with current uncertainties.)
  - **SM theory uncertainties**: SM intrinsic and parametric uncertainties reduced according to future projections. Included in the analysis when available.
  - **New physics effects**: Working at the linear-level in the EFT effects (interference with SM amplitudes)
    
    \[ O = O_{SM} + \delta O_{NP} \frac{1}{\Lambda^2} \]
Electroweak precision measurements at the FCC
Electroweak precision observables at FCC ee

- Electroweak precision measurements at FCC-ee

**Precision measurements at the Z pole**

See R. Tenchini’s talk for details

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected uncertainty</th>
<th>(Relative uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ [GeV]</td>
<td>$10^{-4}$</td>
<td>$(10^{-6})$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$10^{-4}$</td>
<td>$(4 \times 10^{-5})$</td>
</tr>
<tr>
<td>$\sigma^0_{\text{had}}$ [nb]</td>
<td>$5 \times 10^{-3}$</td>
<td>$(10^{-4})$</td>
</tr>
<tr>
<td>$R_e$</td>
<td>0.006</td>
<td>$(3 \times 10^{-4})$</td>
</tr>
<tr>
<td>$R_\mu$</td>
<td>0.001</td>
<td>$(5 \times 10^{-5})$</td>
</tr>
<tr>
<td>$R_\tau$</td>
<td>0.002</td>
<td>$(10^{-4})$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.000006</td>
<td>$(3 \times 10^{-4})$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.00026</td>
<td>$(15 \times 10^{-4})$</td>
</tr>
</tbody>
</table>

$Z$-lineshape parameters and normalized partial decay widths

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected uncertainty</th>
<th>(Relative uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>$10^{-4}$</td>
<td>$(7 \times 10^{-4})$</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$(10^{-3})$</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>$3 \times 10^{-4}$</td>
<td>$(2 \times 10^{-3})$</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$30 \times 10^{-4}$</td>
<td>$(32 \times 10^{-4})$</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$80 \times 10^{-4}$</td>
<td>$(12 \times 10^{-3})$</td>
</tr>
<tr>
<td>$\sin^2 \theta^e_{\text{Eff}} (P_\tau)$</td>
<td>$6.6 \times 10^{-6}$</td>
<td>$(3 \times 10^{-5})$</td>
</tr>
<tr>
<td>$\sin^2 \theta^e_{\text{Eff}} (A^\mu_{FB})$</td>
<td>$5 \times 10^{-6}$</td>
<td>$(2 \times 10^{-5})$</td>
</tr>
</tbody>
</table>

$Z$-pole left-right asymmetry parameters

Latest Results from FCC-ee CDR

Thanks to Roberto Tenchini and Alain Blondel for info about the FCC-ee EW measurements
Electroweak precision observables at FCC ee

- Electroweak precision measurements at FCC-ee

**Precision measurements at the $WW$ threshold**

See P. Azurri's talk for details

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected uncertainty $\times 10^{-3}$</th>
<th>Relative uncertainty $\times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W$ [GeV]</td>
<td>6.5</td>
<td>(8 $\times 10^{-6}$)</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>1.59</td>
<td>(8 $\times 10^{-4}$)</td>
</tr>
<tr>
<td>$R_{inv}$</td>
<td>0.002</td>
<td>(3 $\times 10^{-4}$)</td>
</tr>
</tbody>
</table>

“First Look at the Physics Case of TLEP”
JHEP 1401 (2014) 164

Latest Results from FCC-ee CDR
**EWPO sensitive to modifications of NC couplings**

\[
\mathcal{L}_{NC} = -\frac{e}{s_c}(1 + \delta^U g_{NC}) Z_\mu \sum_\psi \overline{\psi} i \gamma^\mu \left[ \left( g_L^\psi \delta_{ij} + (\delta^D g_{L}^\psi)_{ij} \right) P_L + \left( g_R^\psi \delta_{ij} + (\delta^D g_{R}^\psi)_{ij} \right) P_R + \delta^Q g_{NC} \delta_{ij} \right] \psi^i
\]

**Flavor non-universal contributions**

\[
\begin{align*}
\delta^D g_L^e &= -\frac{1}{2} \left( C_{\phi l}^{(1)} + C_{\phi l}^{(3)} \right) \frac{v^2}{\Lambda^2}, \\
\delta^D g_R^u &= -\frac{1}{2} \left( C_{\phi q}^{(1)} + C_{\phi q}^{(3)} \right) \frac{v^2}{\Lambda^2},
\end{align*}
\]

**Flavor-universal contributions**

\[
\delta^U g_{NC} = -\frac{1}{2} \left[ \Delta_{GF} + \frac{C_{\phi D}}{2} \right] \frac{v^2}{\Lambda^2}
\]

\[
\delta^Q g_{NC} = -Q \left( \frac{s_c}{c^2} C_{\phi WB} + \frac{s^2 c^2}{c^2 - s^2} \left[ \Delta_{GF} + \frac{C_{\phi D}}{2} \right] \right) \frac{v^2}{\Lambda^2}
\]

**Indirect effect associated to modifications in \( \mu \) decay (\( G_F \))**

\[
\Delta_{GF} = \left( C_{\phi l}^{(3)} \right)_{22} + \left( C_{\phi l}^{(3)} \right)_{11} - (C_{ul})_{1221}
\]

**10 Operators**

\[
\begin{align*}
\mathcal{O}_{\phi_f}^{(1)} &= (\phi^\dagger i D_{\mu} \phi) (\bar{f} \gamma^\mu f) \\
\mathcal{O}_{\phi_f}^{(3)} &= (\phi^\dagger i D^a_{\mu} \phi) (\bar{f} \gamma^\mu \sigma_a f) \\
\mathcal{O}_{\phi_D} &= |\phi^\dagger i D_{\mu} \phi|^2 \\
\mathcal{O}_{\phi_{WB}} &= (\phi^\dagger \sigma_a \phi) W^a_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{ll} &= (\bar{l} \gamma_{\mu} l)(\bar{l} \gamma^{\mu} l)
\end{align*}
\]
Electroweak precision observables at FCC ee

- **EWPO sensitive to modifications of CC couplings (Ignoring CKM effects)**

\[ \mathcal{L}_{CC} = - \frac{e}{\sqrt{2} s} (1 + \delta^U g_{CC}) W^+_{\mu} \left[ \left( \delta_{ij} + (\delta^D U_L)_{ij} \right) \overline{\nu}_L \gamma^\mu e^j_L + (\delta^D V_R)_{ij} \overline{u}_R \gamma^\mu d^j_R + \left( \delta_{ij} + (\delta^D V_L)_{ij} \right) \overline{u}_L \gamma^\mu d^j_L \right] + \text{h.c.} \]

**Flavor non-universal contributions**

\[ \delta^D U_L = C_{\phi q} \frac{v^2}{\Lambda^2}, \]
\[ \delta^D V_L = C_{\phi q} \frac{v^2}{\Lambda^2}, \quad \delta^D V_R = \frac{1}{2} C_{\phi ud} \frac{v^2}{\Lambda^2} \]

**Flavor-universal contributions**

\[ \delta^U g_{CC} = \left[ \frac{sc}{s^2 - c^2} C_{\phi WB} - \frac{c^2}{2(s^2 - c^2)} \left( \Delta G_F + \frac{C_{\phi D}}{2} \right) \right] \frac{v^2}{\Lambda^2} \]

- **\( W \) mass:**

\[ M_W^2 = M_Z^2 c^2 \left( 1 - \frac{c^2}{c^2 - s^2} \left( \frac{C_{\phi D}}{2} + \frac{2s}{c} C_{\phi WB} + \frac{s^2}{c^2} \Delta G_F \right) \frac{v^2}{\Lambda^2} \right) \]

EWPO: Z-pole + W properties
Constrain 8 independent combinations (in the FU case)
Electroweak precision observables at FCC ee

- Electroweak precision measurements at FCC-ee of SM inputs

**Precision measurements of Top and Higgs masses**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected uncertainty (Relative uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$ [GeV]</td>
<td>$50 \times 10^{-3}$ ($3 \times 10^{-4}$)</td>
</tr>
<tr>
<td>$M_H$ [GeV]</td>
<td>$7 \times 10^{-3}$ ($6 \times 10^{-5}$)</td>
</tr>
</tbody>
</table>

"First Look at the Physics Case of TLEP" JHEP 1401 (2014) 164

**Precision measurements of the EM constant from $A_{FB}^{\mu\mu}$ above and below the Z pole**

See note in P. Janot's talk for details

$$\frac{\delta \alpha_{QED}(M_Z^2)}{\alpha_{QED}(M_Z^2)} \sim 3 \times 10^{-5}$$

With a 1-year running period at 87.9/94.3 GeV (85 ab⁻¹):

Latest Results from FCC-ee CDR
Electroweak precision observables at FCC ee

- Global fit to electroweak precision measurements at FCC-ee

Interaction scale associated to each operator

Fermion flavour universality assumed
Electroweak precision observables at FCC ee

- Global fit to electroweak precision measurements at FCC-ee

Fermion flavour universality assumed
Electroweak precision observables at FCC ee

- Global fit to electroweak precision measurements at FCC-ee: Impact of theory uncertainties

Fermion flavour universality assumed
Electroweak precision observables at FCC ee

- Global fit to electroweak precision measurements at FCC-ee

No Lepton flavour universality assumed
Electroweak precision observables at FCC ee

- Global fit to electroweak precision measurements at FCC-ee

Partial Quark flavour universality assumed (1st 2 families with equal couplings)
Electroweak precision observables at FCC ee

- Electroweak precision measurements at FCC-ee

**Precision measurements of Top couplings at 365 GeV**

\[ \Gamma_{\mu}^{tX} = -i e \left\{ \gamma_\mu \left( F_{1V}^X + \gamma_5 F_{1A}^X \right) + \frac{m_t}{2m_t} (p_t + p_\nu) \nu \left( i F_{2V}^X + \gamma_5 F_{2A}^X \right) \right\} \]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Uncertainty</th>
<th>Correlation Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta g_V^t / g_V^{t,SM} )</td>
<td>0.009</td>
<td>1</td>
</tr>
<tr>
<td>( \delta g_A^t / g_A^{t,SM} )</td>
<td>0.021</td>
<td>1</td>
</tr>
<tr>
<td>( \delta g_L^t / g_L^{t,SM} )</td>
<td>0.008</td>
<td>1</td>
</tr>
<tr>
<td>( \delta g_R^t / g_R^{t,SM} )</td>
<td>0.016</td>
<td>1</td>
</tr>
</tbody>
</table>

**Assuming new physics only in Ztt couplings**

P. Janot, JHEP 1504 (2015) 182

Thanks to Patrick Janot for for info about the FCC-ee Ztt measurements
Electroweak precision observables at FCC ee

- Global fit to electroweak precision measurements at FCC-ee

Partial Quark flavour universality assumed (1st 2 families with equal couplings)
Electroweak precision observables at FCC eh

- Electroweak precision measurements at FCC-eh

**Precision measurements of couplings to light quark families**

Assuming new physics only in $Zqq$ couplings

<table>
<thead>
<tr>
<th>Observable</th>
<th>Uncertainty</th>
<th>(Relative uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g^u_V$</td>
<td>0.0022</td>
<td>(1.1%)</td>
</tr>
<tr>
<td>$g^u_A$</td>
<td>0.0031</td>
<td>(0.6%)</td>
</tr>
<tr>
<td>$g^d_V$</td>
<td>0.0049</td>
<td>(1.4%)</td>
</tr>
<tr>
<td>$g^d_A$</td>
<td>0.0049</td>
<td>(0.97%)</td>
</tr>
</tbody>
</table>

Thanks to Daniel Britzger for info about the FCC-eh EW measurements
Electroweak precision observables at FCC ee/eh

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh

No Fermion flavour universality assumed
Electroweak precision observables at FCC ee/eh

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh

No Fermion flavour universality assumed
Electroweak precision observables at FCC ee/eh

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh

No Fermion flavour universality assumed

Independent info about all 3 SM fermion families
Electroweak precision observables at FCC ee/eh

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh

No Fermion flavour universality assumed

Independent info about all 3 SM fermion families
Higgs precision measurements at the FCC
Higgs precision observables at FCC ee

- Uncertainties rescaled to 2 IP wrt. “First Look at the Physics Case of TLEP” JHEP 1401 (2014) 164

<table>
<thead>
<tr>
<th>Associated $ZH$ production</th>
<th>$W$ boson fusion (WBF) production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observable</td>
<td>Expected uncertainty</td>
</tr>
<tr>
<td>$\sigma_{ZH}$</td>
<td>0.57%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow b\bar{b})$</td>
<td>0.28%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow c\bar{c})$</td>
<td>1.7%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow gg)$</td>
<td>2.0%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow W^\pm W^{\mp*})$</td>
<td>1.3%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow \tau^+\tau^-)$</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow ZZ^*)$</td>
<td>4.4%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow \gamma\gamma)$</td>
<td>4.2%</td>
</tr>
<tr>
<td>$\sigma_{ZH} \text{ Br}(H \rightarrow \mu^+\mu^-)$</td>
<td>18.4%</td>
</tr>
</tbody>
</table>

See M. Klute’s talk for details
### Higgs precision observables at FCC eh

- **FCC-eh (60 GeV e - 50 TeV p):** Precisions for 2 ab⁻¹ of data

#### CC DIS: $W$ boson fusion (WBF)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow b\bar{b})$</td>
<td>0.27%</td>
</tr>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow c\bar{c})$</td>
<td>2.36%</td>
</tr>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow gg)$</td>
<td>1.78%</td>
</tr>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow W^\pm W^{\mp*})$</td>
<td>2.45%</td>
</tr>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow \tau^+\tau^-)$</td>
<td>1.65%</td>
</tr>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow ZZ^*)$</td>
<td>3.94%</td>
</tr>
<tr>
<td>$\sigma_{WBF} \text{Br}(H \rightarrow \gamma\gamma)$</td>
<td>4.7%</td>
</tr>
</tbody>
</table>

#### NC DIS: $Z$ boson fusion (ZBF)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow b\bar{b})$</td>
<td>0.83%</td>
</tr>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow c\bar{c})$</td>
<td>7.08%</td>
</tr>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow gg)$</td>
<td>5.62%</td>
</tr>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow W^\pm W^{\mp*})$</td>
<td>4.29%</td>
</tr>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow \tau^+\tau^-)$</td>
<td>5.25%</td>
</tr>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow ZZ^*)$</td>
<td>11.8%</td>
</tr>
<tr>
<td>$\sigma_{ZBF} \text{Br}(H \rightarrow \gamma\gamma)$</td>
<td>14.1%</td>
</tr>
</tbody>
</table>

Thanks to Max and Uta Klein for info about the FCC-eh Higgs measurements
Higgs precision observables at FCC ee and eh

- Fit to modified Higgs couplings (assuming no extra invisible decays)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>FCC-ee Relative precision</th>
<th>FCC-eh Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_b )</td>
<td>0.58%</td>
<td>0.74%</td>
</tr>
<tr>
<td>( \kappa_t )</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>( \kappa_T )</td>
<td>0.78%</td>
<td>1.10%</td>
</tr>
<tr>
<td>( \kappa_c )</td>
<td>1.05%</td>
<td>1.35%</td>
</tr>
<tr>
<td>( \kappa_\mu )</td>
<td>9.6%</td>
<td>—</td>
</tr>
<tr>
<td>( \kappa_Z )</td>
<td>0.16%</td>
<td>0.43%</td>
</tr>
<tr>
<td>( \kappa_W )</td>
<td>0.41%</td>
<td>0.26%</td>
</tr>
<tr>
<td>( \kappa_g )</td>
<td>1.23%</td>
<td>1.17%</td>
</tr>
<tr>
<td>( \kappa_\gamma )</td>
<td>2.18%</td>
<td>2.35%</td>
</tr>
<tr>
<td>( \kappa_{Z\gamma} )</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

See M. Klute’s talk for MI fit

\[ \kappa_i \equiv g_{hi}/g_{hi}^{SM} \]
Higgs precision observables at FCC ee and eh

- Fit to modified Higgs couplings (assuming no extra invisible decays)

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<td>1.10%</td>
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<td>1.17%</td>
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<tr>
<td>$\kappa_\gamma$</td>
<td>2.35%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>—</td>
</tr>
</tbody>
</table>

$\kappa_i \equiv \frac{g_{hi}}{g_{hi}^{SM}}$
Higgs precision observables at FCC ee and eh

- Fit to modified Higgs couplings (assuming no extra invisible decays)

$$ \kappa_i \equiv \frac{g_{hi}}{g_{hi}^{SM}} $$

See U. Klein’s talk for tH at FCC-eh

<table>
<thead>
<tr>
<th>Coupling</th>
<th>FCC-ee</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_b$</td>
<td>0.58%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>0.78%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>1.05%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>9.6%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.16%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>0.41%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>1.23%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>2.18%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coupling</th>
<th>FCC-eh</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_b$</td>
<td>0.74%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>—</td>
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</tr>
<tr>
<td>$\kappa_c$</td>
<td>1.10%</td>
<td></td>
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<td>—</td>
<td></td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.43%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>0.26%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>1.17%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>2.35%</td>
<td></td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>
Higgs precision observables at FCC ee and eh

- **Fit to modified Higgs couplings (assuming no extra invisible decays)**
  
  Using HLLHC Results (Only 1 Experiment) to fill the gaps

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_b$</td>
<td>10.4%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>7.6%</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>9.43%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>—</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>7.4%</td>
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<td>$\kappa_Z$</td>
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<td>$\kappa_W$</td>
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</tr>
<tr>
<td>$\kappa_g$</td>
<td>5.2%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>4.3%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>15%</td>
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</table>

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Relative precision</th>
</tr>
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<tbody>
<tr>
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<td>$\kappa_t$</td>
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<td>$\kappa_\mu$</td>
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<td>$\kappa_Z$</td>
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</tr>
<tr>
<td>$\kappa_W$</td>
<td>0.40%</td>
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<tr>
<td>$\kappa_g$</td>
<td>1.03%</td>
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<tr>
<td>$\kappa_\gamma$</td>
<td>1.41%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>14.2%</td>
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</table>

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_b$</td>
<td>0.69%</td>
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<td>$\kappa_t$</td>
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<tr>
<td>$\kappa_\tau$</td>
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<td>$\kappa_c$</td>
<td>1.33%</td>
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<td>$\kappa_\mu$</td>
<td>6.25%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.41%</td>
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<tr>
<td>$\kappa_W$</td>
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<tr>
<td>$\kappa_g$</td>
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<td>$\kappa_\gamma$</td>
<td>1.44%</td>
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<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>14.26%</td>
</tr>
</tbody>
</table>

$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$
Higgs complementarities

- Rare Higgs decays statistically limited at FCC-ee/eh
  - Can be measured at FCC-hh with 1% stat. precision (in $\delta\mu/\mu$)
  - Systematics can be further cancelled by measuring ratios of BR ($\gamma\gamma/4\mu$, $\mu\mu/4\ell$, $Z\gamma/4\ell$, $\gamma\gamma/\mu\mu$)

Robust determination by this method requires both FCC-hh and FCC-ee/eh

1% accuracy (stat + sys) within reach

Provided $BR(H\rightarrow4\ell)$ known to $<<1\%$

$(pp\rightarrow H\rightarrow4\ell$ measurable at FCC-hh to $\sim1\%$)

Measurable at FCC-ee/eh with required precision

Thanks to Michele Selvaggi for info about the FCC-hh Higgs measurements
Higgs complementarities

- Top Yukawa coupling not directly accessible at FCC-ee. Could be measured in single tH at FCC-eh
- Can be measured at FCC-hh from $\sigma(ttH)/\sigma(ttZ)$ boosted


e.g. Fit and extract $N_H/N_Z$ to 1% accuracy
$\Rightarrow \delta_{\text{stat}+\text{th}} y_t/y_t \sim 1\%$

More on this later
Higgs complementarities: Global fit to Higgs couplings at FCC

- All single Higgs couplings can be determined below the 1%

**FCC-ee/FCC-eh**
Precise determinations for the leading couplings

**HZZ**
Crucial for normalization of FCC-hh results

**FCC-hh**
Completes the picture with precise determinations of Top and coupling associated to rare decays

**NOT MODEL-INDEPENDENT:**
Results assume that, if there is New physics, it can only be in the Higgs couplings

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_b$</td>
<td>0.38%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>0.51%</td>
</tr>
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<td>$\kappa_T$</td>
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<td>$\kappa_Z$</td>
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</tr>
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<td>$\kappa_W$</td>
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</tr>
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<td>$\kappa_g$</td>
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</tr>
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<td>$\kappa_\gamma$</td>
<td>0.40%</td>
</tr>
<tr>
<td>$\kappa_Z\gamma$</td>
<td>0.52%</td>
</tr>
</tbody>
</table>

$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$
Higgs precision observables at the FCC

- Operators considered in this analysis: Higgs couplings

$$\mathcal{L}_{hVV} = g_{hgg} G_{\mu\nu}^A G_{\mu\nu}^A h + g_{hWW}^{(1)} W_{\mu\nu} W_{\mu\nu}^{\dagger} h + \left( g_{hWW}^{(2)} W^{\mu+\nu} \partial^\mu W_{\mu\nu}^{\dagger} h + \text{h.c.} \right) + g_{hWW}^{(3)} W_{\mu}^{+} W_{\mu}^{-} h$$

Vector couplings

$$+ g_{hZZ}^{(1)} Z_{\mu\nu} Z_{\mu\nu} h + g_{hZZ}^{(2)} Z_{\nu} \partial^\mu Z_{\mu\nu} h + g_{hZZ}^{(3)} Z_{\mu} Z_{\mu} h$$

$$+ g_{hZA}^{(1)} Z_{\mu\nu} F_{\mu\nu} h + g_{hZA}^{(2)} Z_{\nu} \partial^\mu F_{\mu\nu} h + g_{hAA} F_{\mu\nu} F_{\mu\nu} h$$

Several New Operators

$$\mathcal{O}_{\phi_G} = (\phi^\dagger \phi) G_{\mu\nu}^A G_{\mu\nu}^A$$

$$\mathcal{O}_{\phi_B} = (\phi^\dagger \phi) B_{\mu\nu} B_{\mu\nu}$$

$$\mathcal{O}_{\phi_W} = (\phi^\dagger \phi) W_{\mu\nu}^a W_{\mu\nu}^a$$

$$\mathcal{O}_{D\phi_B} = i D^\mu \phi^\dagger D^\nu \phi B_{\mu\nu}$$

$$\mathcal{O}_{D\phi_W} = i D^\mu \phi^\dagger \sigma^a D^\nu \phi W_{\mu\nu}^a$$

Already present in the EWPO analysis

$$\mathcal{O}_{\phi_{WB}} = (\phi^\dagger \sigma_a \phi) W_{\mu\nu}^a B_{\mu\nu}$$

$$\mathcal{O}_{\phi_D} = \left| \phi^\dagger i D^\mu \phi \right|^2$$

Modifies Higgs kinetic term. Enters in all Higgs observables

Field redefinition: trade by this 2 operators (do not enter in EWPO)
Higgs precision observables at the FCC

- **Operators considered in this analysis: Higgs couplings**

**Fermionic couplings**

\[
\mathcal{L}_{hff} = g_{hff} \bar{e}_L^i e_R^i h + g_{h uu} \bar{u}_L^i u_R^i h + g_{h dd} \bar{d}_L^i d_R^i h + \text{h.c.}
\]

\[
g_{hff} = -\frac{m_f}{v} \left( 1 + \left[ (C_{\phi} - \frac{1}{4} C_{D}) - \frac{v}{\sqrt{2} m_f} C_f \phi - \frac{1}{2} \Delta_G \right] \frac{v^2}{\Lambda^2} \right)
\]

**Higgs self-coupling**

\[
\mathcal{L}_{hhh} = g_{hhh} h^3
\]

\[
g_{hhh} = -\frac{M_h^2}{2v} \left( 1 + \left[ 3 (C_{\phi} - \frac{1}{4} C_{D}) - 2 \frac{v^2}{M_h^2} C_{f} \phi - \frac{1}{2} \Delta_G \right] \frac{v^2}{\Lambda^2} \right)
\]

**Operators**

\[
\mathcal{O}_{e\phi} = (\phi^\dagger \phi) \left( \bar{t}_L \phi e_R \right)
\]

\[
\mathcal{O}_{u\phi} = (\phi^\dagger \phi) \left( \bar{q}_L \phi u_R \right)
\]

\[
\mathcal{O}_{d\phi} = (\phi^\dagger \phi) \left( \bar{q}_L \phi d_R \right)
\]

**Higgs self-interactions only**

\[
\mathcal{O}_\phi = (\phi^\dagger \phi)^3
\]

Only enters in Higgs self-interactions
Diboson observables at FCC ee

- $W$ pair production at FCC-ee
  
  See P. Azurri’s talk and J. Gu’s poster for details

<table>
<thead>
<tr>
<th>aTGC</th>
<th>Uncertainty (stat)</th>
<th>Correlation Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{1Z}$</td>
<td>$8.1 \times 10^{-4}$</td>
<td>1</td>
</tr>
<tr>
<td>$\delta \kappa_{\gamma}$</td>
<td>$5.2 \times 10^{-4}$</td>
<td>$-0.28$</td>
</tr>
<tr>
<td>$\lambda_{Z}$</td>
<td>$7.9 \times 10^{-4}$</td>
<td>$-0.87$</td>
</tr>
</tbody>
</table>

Using full angular information of the $W$’s and decays

Statistical Analysis only

Assumes aTGC dominance

(Full EFT study in progress)

From J. Gu's Talk at FCC-ee Physics Meeting, March 19 2018
Diboson observables at FCC ee

- **Operators entering in anomalous Triple gauge couplings**

\[
\mathcal{L}_{\text{TGC}} = i e \left[ \left( W_{\mu\nu}^+ W_{\mu}^- - W_{\mu\nu}^- W_{\mu}^+ \right) A_\nu + (1 + \delta \kappa_\gamma) A_{\mu\nu} W_{\mu}^+ W_{\mu}^- \right] \\
+ i g \cos \theta_W \left[ (1 + \delta g_{1,Z}) \left( W_{\mu\nu}^+ W_{\mu}^- - W_{\mu\nu}^- W_{\mu}^+ \right) Z_\nu + (1 + \delta \kappa_Z) Z_{\mu\nu} W_{\mu}^+ W_{\mu}^- \right] \\
+ i e \frac{\lambda}{m_W^2} W_{\mu\nu}^+ W_{\nu \rho} A_{\rho \mu} + i g \cos \theta_W \frac{\lambda_Z}{m_W^2} W_{\mu\nu}^+ W_{\nu \rho} Z_{\rho \mu},
\]

2 aTGC related to Higgs couplings

\[
\delta \kappa_\gamma = -2 v c_W^2 \left( g_{hAA}^{(1)} - g_{hZZ}^{(1)} + \frac{1}{2 s_W c_w} g_{hZA}^{(1)} (c_W^2 - s_W^2) \right) \\
\delta g_{1,Z} = \frac{v}{2(c_W^2 - s_W^2)} \left( c_W^2 g_{hZZ}^{(2)} + 4 s_W^2 (g_{hAA}^{(1)} - g_{hZZ}^{(1)} + \frac{1}{4} g_{hZZ}^{(2)} + \frac{2 s_W}{c_w} g_{hZA}^{(1)} (c_W^2 - s_W^2) \right) \\
\delta \kappa_Z = \delta g_{1,Z} - \frac{g'}{g^2} \delta \kappa_\gamma \\
\lambda_\gamma = \lambda_Z = - \frac{3}{2 s_W} C_W^2 \frac{v^2}{\Lambda^2}
\]

\[
\mathcal{O}_W = i \varepsilon_{abc} W_{\mu}^a W_{\nu}^b W_{\rho}^c W_{\mu} W_{\nu} W_{\rho}
\]

Only one more operator (enters only in aNGC)
EFT fit to Higgs precision observables at the FCC-ee and FCC-eh:

- Results show only for operators non-entering in EWPO (stay unchanged)

---

**Higgs precision observables at the FCC**

- **95% Prób. Limits**

---

**Results show only for operators non-entering in EWPO (stay unchanged)**
Higgs precision observables at the FCC

- EFT fit to Higgs precision observables at the FCC-ee and FCC-eh:

At this point, it compares relatively well with the kappa analysis for the SM-like couplings.
Going back to Higgs complementarities...

- Top Yukawa coupling not directly accessible at FCC-ee. Could be measured in single tH at FCC-eh
- Can be measured at FCC-hh from $\sigma(ttH)/\sigma(ttZ)$ boosted

- Robust determination by this method requires both FCC-hh and FCC-ee

![Graphs](M.L. Mangano et al., arXiv: 1507.08169 [hep-ph])

![Graphs](e.g. Fit and extract $N_H/N_Z$ to 1% accuracy
$\Rightarrow \delta_{\text{stat+th}} y_t/y_t \sim 1\%$
Assumes no NP in $Ztt$ and $BR(H\rightarrow bb)$ know to 1%
Both measurable at FCC-ee with required precision)
Going back to Higgs complementarities...

- Top Yukawa coupling not directly accessible at FCC-ee. Could be measured in single $tH$ at FCC-eh
- Can be measured at FCC-hh from $\sigma(ttH)/\sigma(ttZ)$ boosted

Toy fit neglecting FCCee measurements

Assuming ~10% accuracy on $Ztt$ top couplings

Precise measurement ~1% of LH $Ztt$ coupling needed

e.g. Fit and extract $N_H/N_Z$ to 1% accuracy
$\Rightarrow \delta_{\text{stat+th}} y_t/y_t \sim 1\%$

Assumes no NP in $Ztt$ and $BR(H\rightarrow hh)$ known to 1%

Both measurable at FCC-ee with required precision

- Robust determination by this method requires both FCC-hh and FCC-ee
Higgs self-interaction:

- Can be tested at FCC-ee via NLO effects: Limited (~50%) precision

Direct HH production at FCC-hh:

\[ \delta \kappa = \left[ 3(C_{\phi} - \frac{1}{4}C_{\phi D}) - 2 \frac{v^2}{M_H^2} C_{\phi} - \frac{1}{2} \Delta G_F \right] \frac{v^2}{\Lambda^2} \]

Assumes all uncertainty goes into \( \kappa_\lambda \)

But other NP parameters modify HH production and decays

They can be measured at FCC-ee/eh/hh with ~1% precision \( \rightarrow \) Global FCC fit for robust estimates

M. Selvaggi, Talk at 2nd FCC Physics Workshop
Going back to Higgs complementarities...

- Higgs self-interaction:
  - Can be tested at FCC-ee via NLO effects: Limited (~50%) precision

\[ \lambda = \left[ 3(C_{\phi D} - \frac{1}{4}C_{\phi}) - 2\frac{v^2}{M_h^2}C_{\phi} - \frac{1}{2}\Delta_GF \right] \frac{v^2}{\Lambda^2} \]

Assumes all uncertainty goes into \( \kappa_\lambda \)

Other NP parameters modify HH production and decays

They can be measured at FCC-ee/eh/hh with ~1% precision → Global FCC fit for robust estimates
Going back to Higgs complementarities…

- Higgs self-interaction:
  - Can be tested at FCC-ee via NLO effects: Limited (~50%) precision

![Toy fit neglecting FCCee measurements](Image)

Indirect dependence on FCC-ee Ztt via Htt/Ztt FCC-hh measurement

Assumes all uncertainty goes into $\kappa_\lambda$

$$\lambda = \left[ 3(C_{\phi^3} - \frac{1}{4} C_{\phi D}) - 2 \frac{v^2}{M^2} C_\phi - \frac{1}{2} \Delta G_F \right] \frac{v^2}{\Lambda^2}$$

Other NP parameters modify HH production and decays

They can be measured at FCC-ee/eh/hh with ~1% precision → Global FCC fit for robust estimates

M. Selvaggi, Talk at 2nd FCC Physics Workshop

S. Di Vita et al., JHEP 1802 (2018) 178

A. Azatov et al. PRD92 (2015) no.3, 035001
The Global Electroweak and Higgs fit
The Global Electroweak and Higgs fit

- Putting all together… Fit to all 22 (EW) + 13 (Higgs+WW) operators

Dominated by FCC-ee - Complementary info from FCC-eh for light quarks
• Putting all together… Fit to all 22 (EW) + 13 (Higgs+WW) operators

Receives important contributions from all FCC options
The Global Electroweak and Higgs fit

- Putting all together… Fit to all 22 (EW) + 13 (Higgs+WW) operators

Single Higgs couplings could be known to ~1% or better

Higgs Self-coupling could be known to less than 10%

Independent information for the couplings to all fermion families

Lepton sector: precision down to ~10^{-4}

Quark sector: sub-percent level in most cases

Preliminary
Conclusions

- A global fit in a model-independent theoretical framework is required to accurately assess the sensitivity to new physics in the different EW and Higgs observables.

- The FCC can test (indirectly) new physics interaction scales at the level of several tenths to TeV and increase the precision of properties of the SM particles by, roughly, one order of magnitude.

- All three FCC options complement each other very well:
  - FCC-ee allows not only very precise measurements of the Higgs and EWPO but also provides the normalization for more precise measurements at the FCC-eh and FCC-hh.
  - FCC-eh complements FCC-ee providing information about light quark EW couplings. Similar precision in the Higgs sector.
  - FCC-hh fills gaps in precision Higgs measurements for rare decays, top and the Higgs self-coupling.
Conclusions

- All three FCC options complement each other very well and are useful to complete the whole picture:

  **FCC-ee**
  - Z-pole: EW precision NC
  - WW threshold: EW precision CC
  - Higgs: General measurements
  - Ztt: EW Top couplings

  **FCC-eh**
  - EWPO: first quark families
  - Higgs: General measurements
  - PDFs

  **FCC-hh**
  - Higgs: Rare decays
  - Higgs: Top coupling
  - Higgs: Self-coupling
  - High $q^2$
Conclusions

- All three FCC options complement each other very well and are useful to complete the whole picture:

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  **FCC-eh**
  - EWPO: first quark families
  - Higgs: General measurements
  - PDFs

  **FCC-hh**
  - Higgs: Rare decays
  - Higgs: Top coupling
  - Higgs: Self-coupling
  - High $q^2$
Conclusions

- The dimension 6 SMEFT:

\[ \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots \]

\[ \mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad [\mathcal{O}_i] = d \quad \rightarrow \quad \left( \frac{q}{\Lambda} \right)^{d-4} \]

\( \Lambda \): Cut-off of the EFT

Most of the effects discussed so far

For \( E \gg v \) these effects can provide precise constraints on EFT interactions even if experimental precision is lower

Large Energies \( \Rightarrow \) FCC-hh

Look for \( E \)-enhanced effects in differential distributions

See A. Wulzer’s talk this morning
The dimension 6 SMEFT:

\[
\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots
\]

\[
\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \quad [\mathcal{O}_i] = d \quad \text{Effects} \quad \left(\frac{q}{\Lambda}\right)^{d-4}
\]

Example: Individual 95% prob bound on

\[
\frac{C_{\phi q}^{(3)}}{\Lambda^2} \sim \pm 3 \times 10^{-3} \text{ TeV}^{-2}
\]

For \(E > \gg\) these

Contributes to WZ production via High-E primary

\[
a_q^{(3)} = 4 \frac{C_{\phi q}^{(3)}}{\Lambda^2} \sim \pm 12 \times 10^{-3} \text{ TeV}^{-2}
\]

Study of \(p_{TV}\) distrib. at FCC-hh 20 ab\(^{-1}\) \((\delta_{\text{sys}} = 5\%) \Rightarrow a_q^{(3)} \sim \pm 6 \times 10^{-3} \text{ TeV}^{-2}

Energy helps to improve precision constraints on new physics

See A. Wulzer's talk this morning

To be included in updated global fits
Thank you