Global fits to EW and Higgs observables at the FCC

Jorge de Blas
University of Padova & INFN-Sezione di Padova

FCC Week 2018
Amsterdam, April 11, 2018

Introduction

The Future Circular Collider

- In short:

FCC-ee: Experimental PRECISION **FCC-hh: ENERGY**

FCC-eh: a good mix of both

- All 3 options can do a lot in terms of improving our understanding of the electroweak sector:
  - 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

Jorge de Blas
INFN - University of Padova

Outline

- **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**

Jorge de Blas
INFN - University of Padova

The dimension-6 SMEFT

Jorge de Blas
INFN - University of Padova

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

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

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

Effects suppressed by $q = v, E < \Lambda$

Λ: Cut-off of the EFT

- LO new physics effects "start" at dimension 6
- With current precision, and assuming Λ~TeV, sensitivity to $d>6$ is small

$$\frac{M_Z^2}{(1\text{TeV})^2} \sim 0.8\% \qquad \frac{M_Z^4}{(1\text{TeV})^4} \sim 0.007\%$$

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

W. Buchmüller, D. Wyler, Nucl. Phys. B268 (1986) 621
C. Arzt, M.B. Einhorn, J. Wudka, Nucl. Phys. B433 (1995) 41
B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 (2010) 085

First complete basis, aka *Warsaw* basis

Jorge de Blas
INFN - University of Padova

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^nLO)**
  - **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.**

$$\mathcal{O}_{\phi WB} = \phi^\dagger \sigma_a \phi B^{\mu\nu} W^a_{\mu\nu}$$

EWSB

$$v^2 B^{\mu\nu} W^3_{\mu\nu}$$

(dim 4)

Modifies neutral gauge boson self-energies

EWPT

$$vhB^{\mu\nu} W^3_{\mu\nu}$$

(dim 5)

$$h \to ZZ, \gamma\gamma$$

Higgs phys.

Jorge de Blas
INFN - University of Padova

FCC sensitivity to New Physics

General strategy for calculation of future sentivities

- 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)

$$O = O_{\rm SM} + \delta O_{\rm NP} \frac{1}{\Lambda^2}$$

Jorge de Blas
INFN - University of Padova

Electroweak precision measurements at the FCC

Jorge de Blas
INFN - University of Padova

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

Observable	Expected uncertainty	(Relative uncertainty)
M_Z [GeV]	10^{-4}	(10^{-6})
Γ_Z [GeV]	10^{-4}	(4×10^{-5})
$\sigma^0_{\rm had}$ [nb]	5×10^{-3}	(10^{-4})
R_e	0.006	(3×10^{-4})
R_μ	0.001	(5×10^{-5})
R_τ	0.002	(10^{-4})
R_b	0.00006	(3×10^{-4})
R_c	0.00026	(15×10^{-4})

Z-lineshape parameters and normalized partial decay widths

Observable	Expected uncertainty	(Relative uncertainty)
A_e	10^{-4}	(7×10^{-4})
A_μ	1.5×10^{-4}	(10^{-3})
A_τ	3×10^{-4}	(2×10^{-3})
A_b	30×10^{-4}	(32×10^{-4})
A_c	80×10^{-4}	(12×10^{-3})
$\sin^2\theta^e_{\rm Eff}$ (P_τ)	6.6×10^{-6}	(3×10^{-5})
$\sin^2\theta^\ell_{\rm Eff}$ (A^μ_{FB})	5×10^{-6}	(2×10^{-5})

Z-pole left-right asymmetry parameters

Not independent

Latest Results from FCC-ee CDR

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

Jorge de Blas
INFN - University of Padova

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

Observable	Expected uncertainty	(Relative uncertainty)
M_W [GeV]	6.5×10^{-4}	(8×10^{-6})
Γ_W [GeV]	1.59×10^{-3}	(8×10^{-4})
$R_{\rm inv}$	0.002	(3×10^{-4})

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

Latest Results from FCC-ee CDR

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **EWPO sensitive to modifications of NC couplings**

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

Flavor non-universal contributions

$$\delta^D g_L^{\substack{\nu\\ e}} = -\frac{1}{2}\left(C_{\phi l}^{(1)} \mp C_{\phi l}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta^D g_R^e = -\frac{1}{2} C_{\phi e}^{(1)} \frac{v^2}{\Lambda^2}$$

$$\delta^D g_L^{\substack{u\\ d}} = -\frac{1}{2}\left(C_{\phi q}^{(1)} \mp C_{\phi q}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta^D g_R^{\substack{u\\ d}} = -\frac{1}{4} C_{\phi_d^u}^{(1)} \frac{v^2}{\Lambda^2}$$

10 Operators

$$\mathcal{O}_{\phi f}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{f}\gamma^\mu f)$$

$$\mathcal{O}_{\phi f}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^a \phi)(\overline{f}\gamma^\mu \sigma_a f)$$

Flavor-universal contributions

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

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

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

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

Indirect effect associated to modifications in μ decay (G_F)

$$\Delta_{G_F} = \left(C_{\phi l}^{(3)}\right)_{22} + \left(C_{\phi l}^{(3)}\right)_{11} - (C_{ll})_{1221}$$

$$\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

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

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

Flavor non-universal contributions

$$\delta^D U_L = C^{(3)}_{\phi l}\frac{v^2}{\Lambda^2},$$

$$\delta^D V_L = C^{(3)}_{\phi q}\frac{v^2}{\Lambda^2}, \quad \cancel{\delta^D V_R = \frac{1}{2}C_{\phi ud}\frac{v^2}{\Lambda^2}}$$

Does not interfere with SM

Operators

$$\cancel{\mathcal{O}_{\phi ud} = (\tilde{\phi}^\dagger i D_\mu \phi)(\overline{u}_R\gamma^\mu d_R)}$$

Flavor-universal contributions

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

No more operators but constraints
1 more direction

- ***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)

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **Electroweak precision measurements at FCC-ee of SM inputs**

Precision measurements of Top and Higgs masses

Observable	Expected uncertainty	(Relative uncertainty)
m_t [GeV]	50×10^{-3}	(3×10^{-4})
M_H [GeV]	7×10^{-3}	(6×10^{-5})

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

Only ~10 MeV experimental

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

See note in P. Janot's talk for details

$$\frac{\delta\alpha_{\rm QED}^{-1}(M_Z^2)}{\alpha_{\rm QED}^{-1}(M_Z^2)} \sim 3 \times 10^{-5}$$

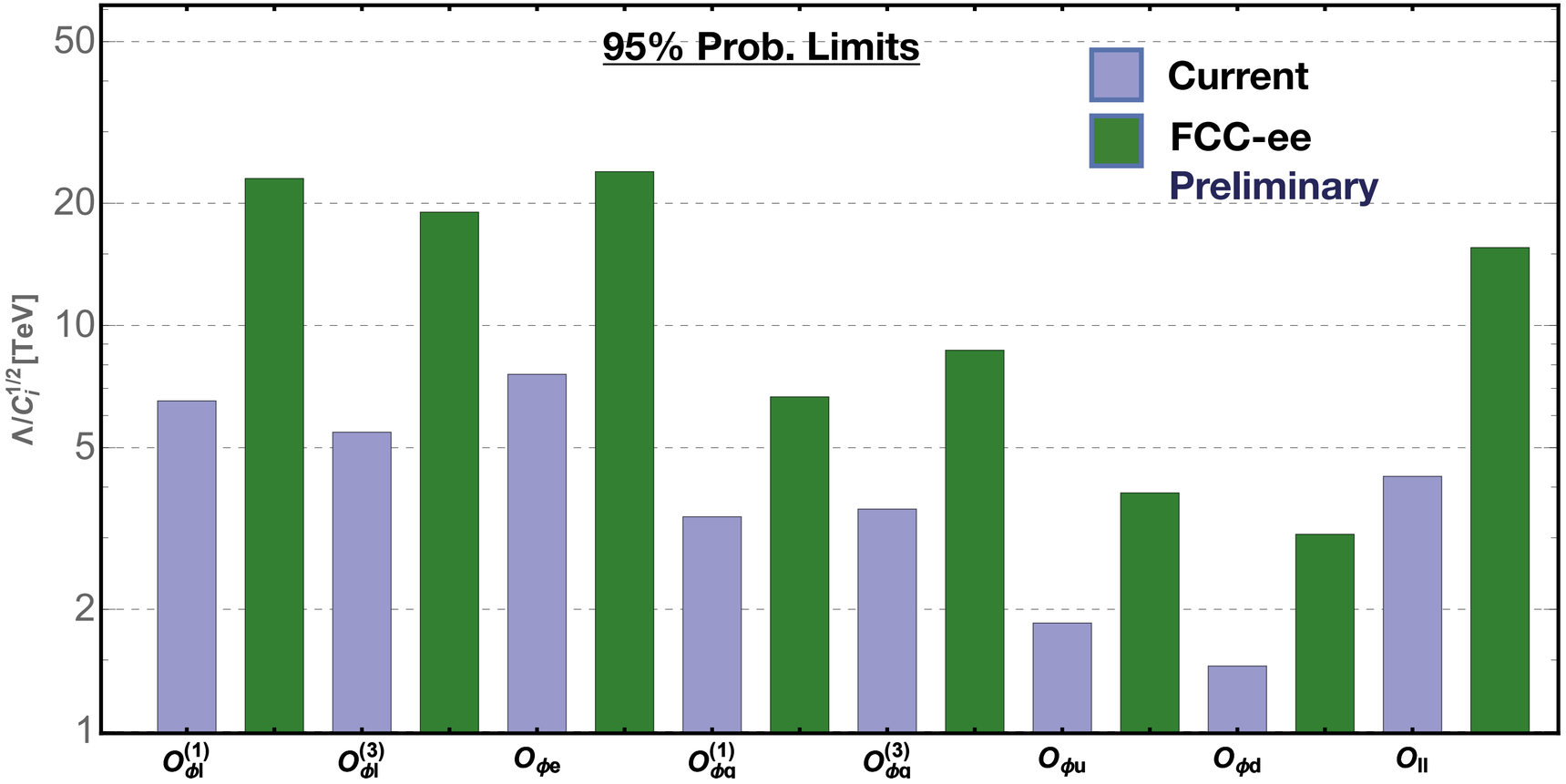
With a 1-year running period at 87.9/94.3 GeV (85 ab^{-1}):

Latest Results from FCC-ee CDR

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **Global fit to electroweak precision measurements at FCC-ee**



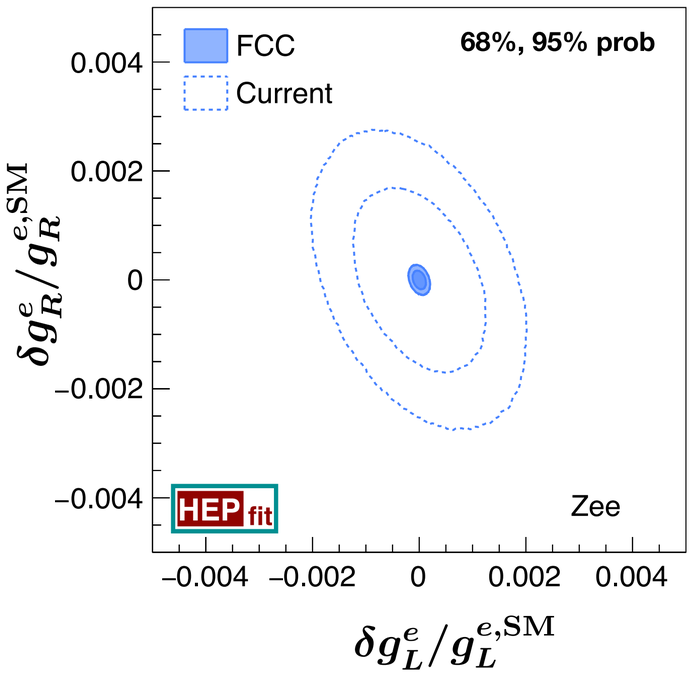
Interaction scale associated to each operator

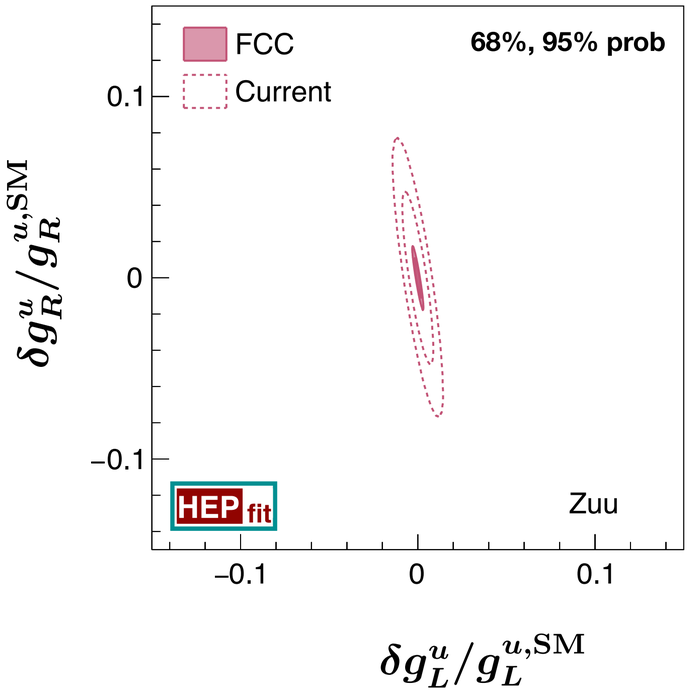
Fermion flavour universality assumed

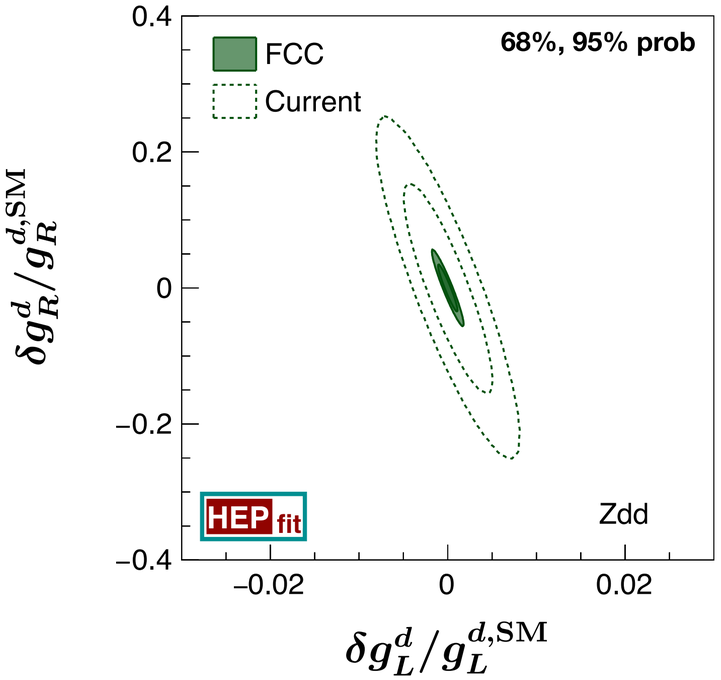
Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **Global fit to electroweak precision measurements at FCC-ee**



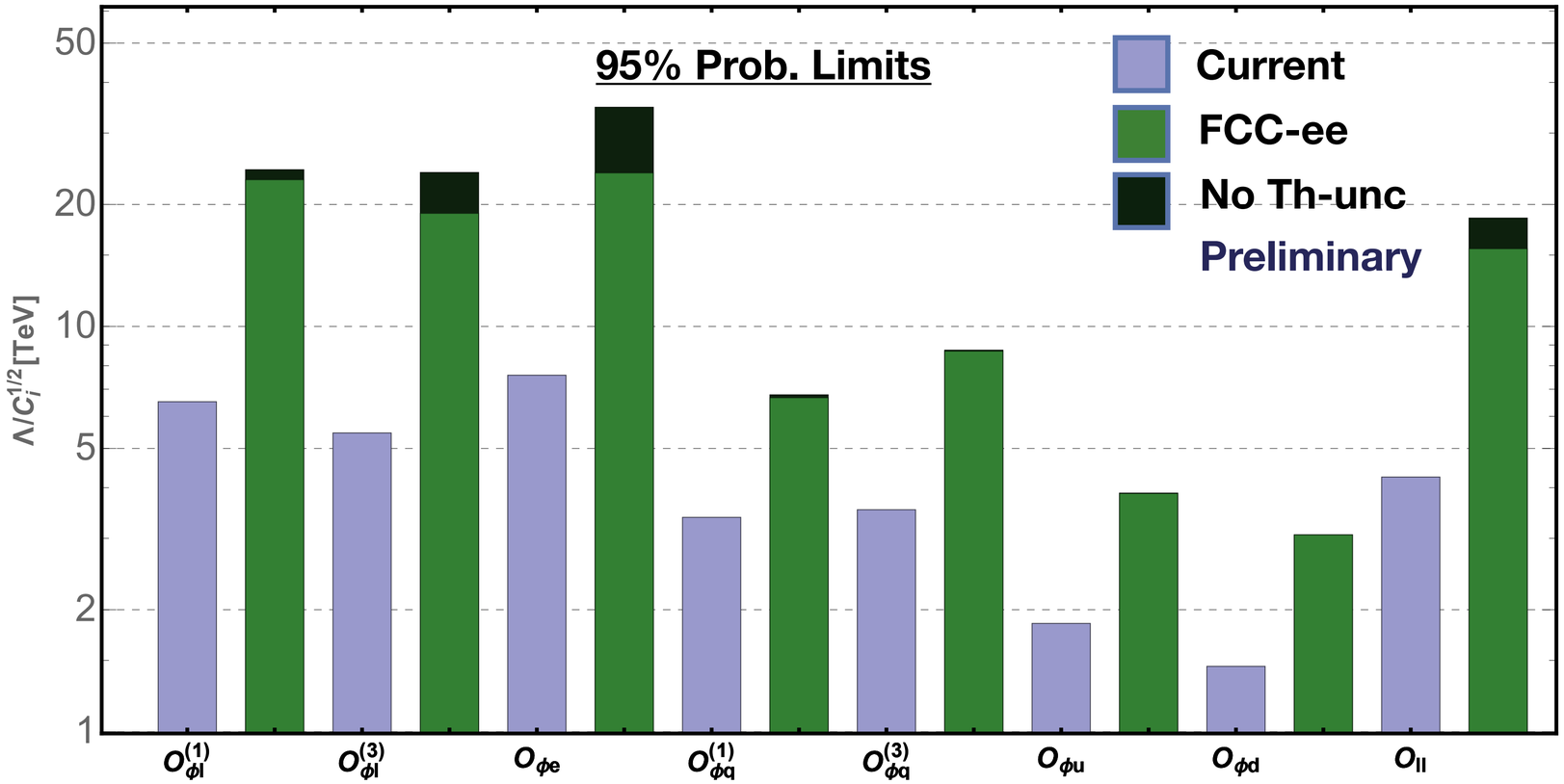


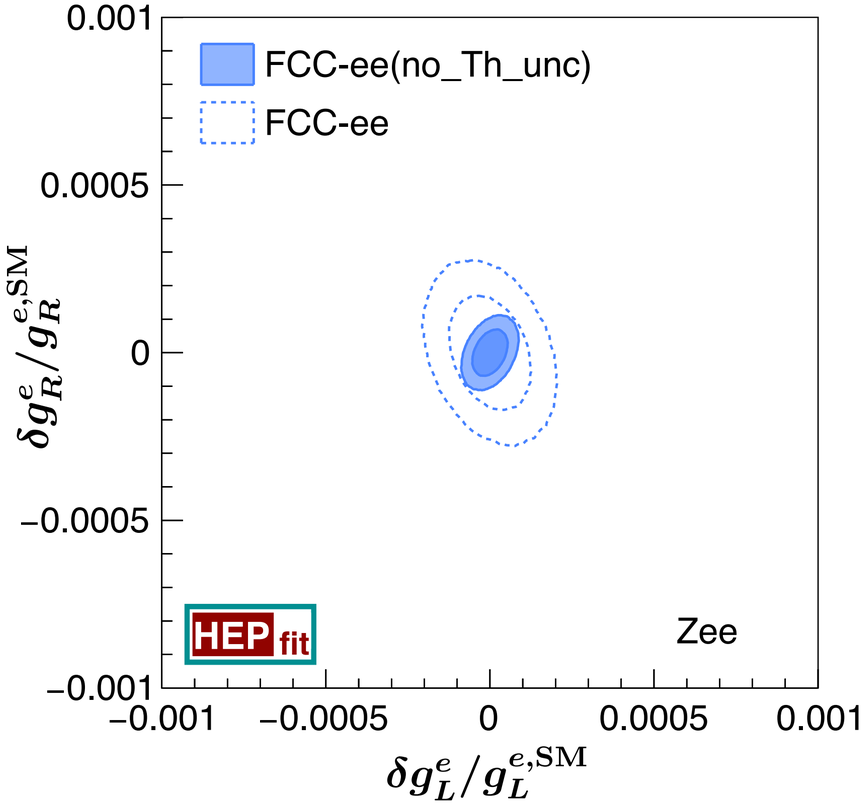


Fermion flavour universality assumed

Electroweak precision observables at FCC ee

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



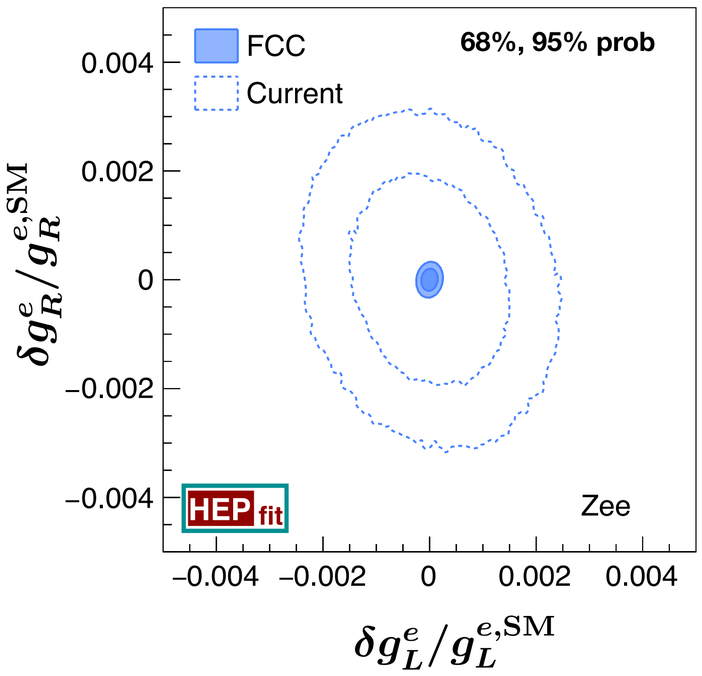


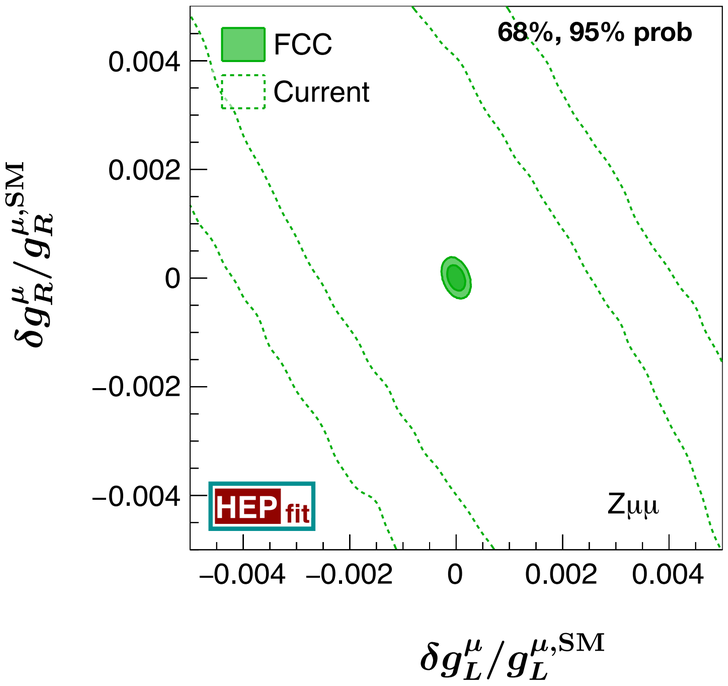
Fermion flavour universality assumed

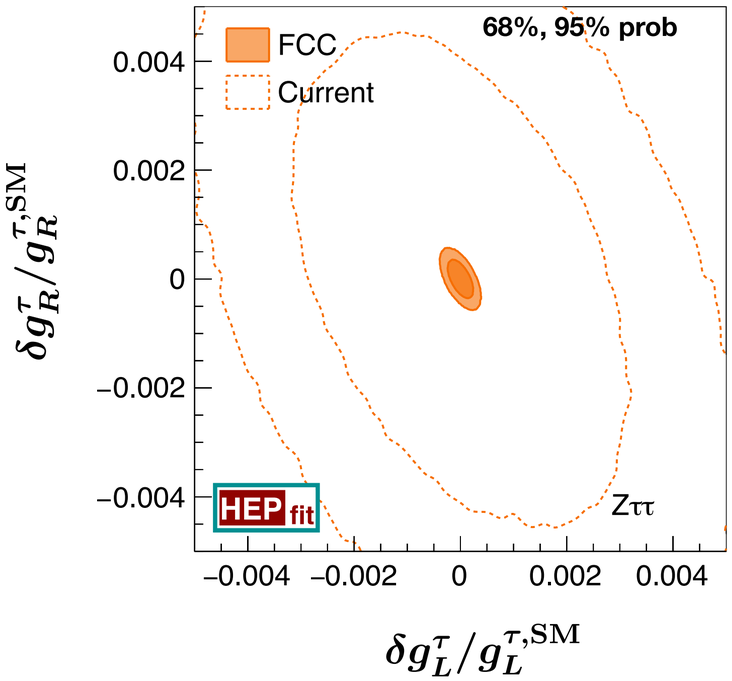
Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **Global fit to electroweak precision measurements at FCC-ee**



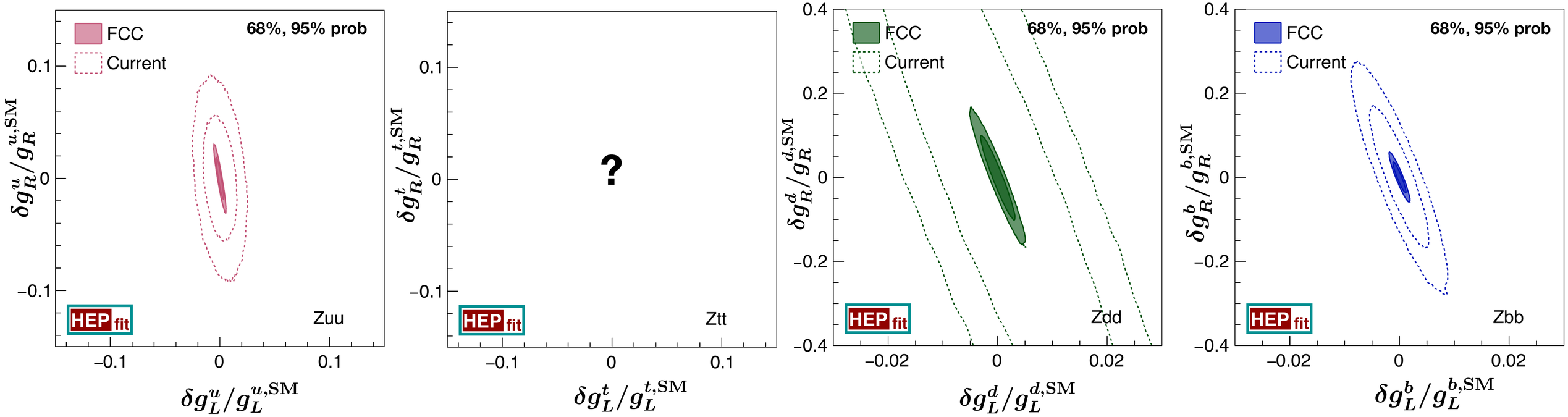




No Lepton flavour universality assumed

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)

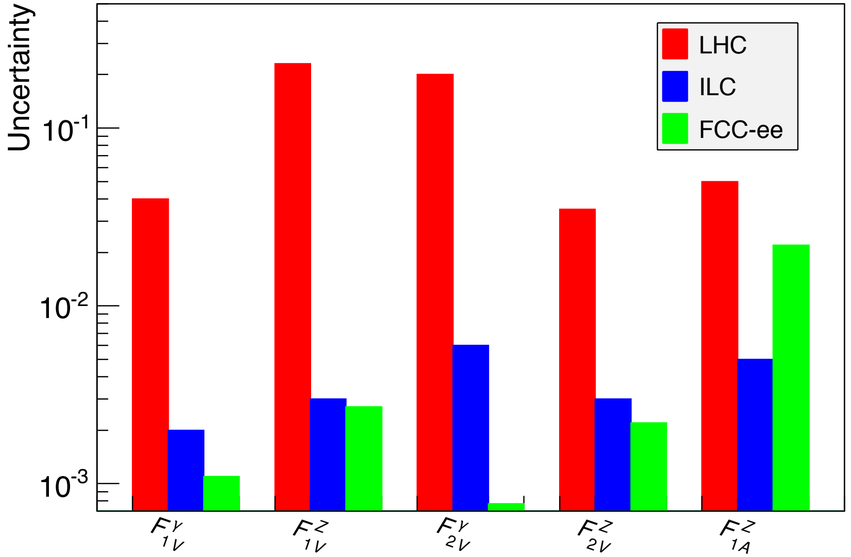
Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **Electroweak precision measurements at FCC-ee**

Precision measurements of Top couplings at 365 GeV

$$\Gamma_\mu^{ttX} = -ie\left\{\gamma_\mu\left(F_{1V}^X + \gamma_5 F_{1A}^X\right) + \frac{\sigma_{\mu\nu}}{2m_t}(p_t + p_{\bar{t}})^\nu\left(iF_{2V}^X + \gamma_5 F_{2A}^X\right)\right\}$$



Precision on	F_{1V}^γ	F_{1V}^Z	F_{1A}^γ	F_{1A}^Z
Only three $F_{1V,A}^X$	$1.2\,10^{-3}$	$2.9\,10^{-3}$	$0.0\,10^{-2}$	$2.2\,10^{-2}$

P. Janot, JHEP 1504 (2015) 182

FCC-ee 365 GeV			
Coupling	Uncertainty	Correlation Matrix	
$\delta g_V^t / g_V^{t\,\mathrm{SM}}$	0.009	1	0.25
$\delta g_A^t / g_A^{t\,\mathrm{SM}}$	0.021		1
$\delta g_L^t / g_L^{t\,\mathrm{SM}}$	0.008	1	−0.96
$\delta g_R^t / g_R^{t\,\mathrm{SM}}$	0.016		1

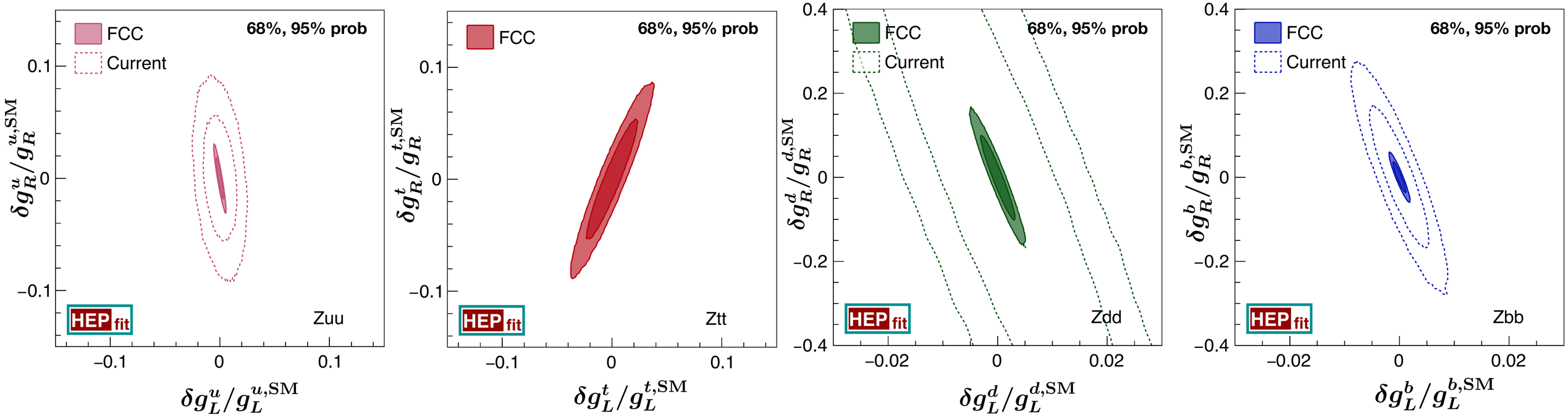
Assuming new physics only in *Ztt* couplings

Thanks to Patrick Janot for for info about the FCC-ee Ztt measurements

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee

- **Global fit to electroweak precision measurements at FCC-ee**

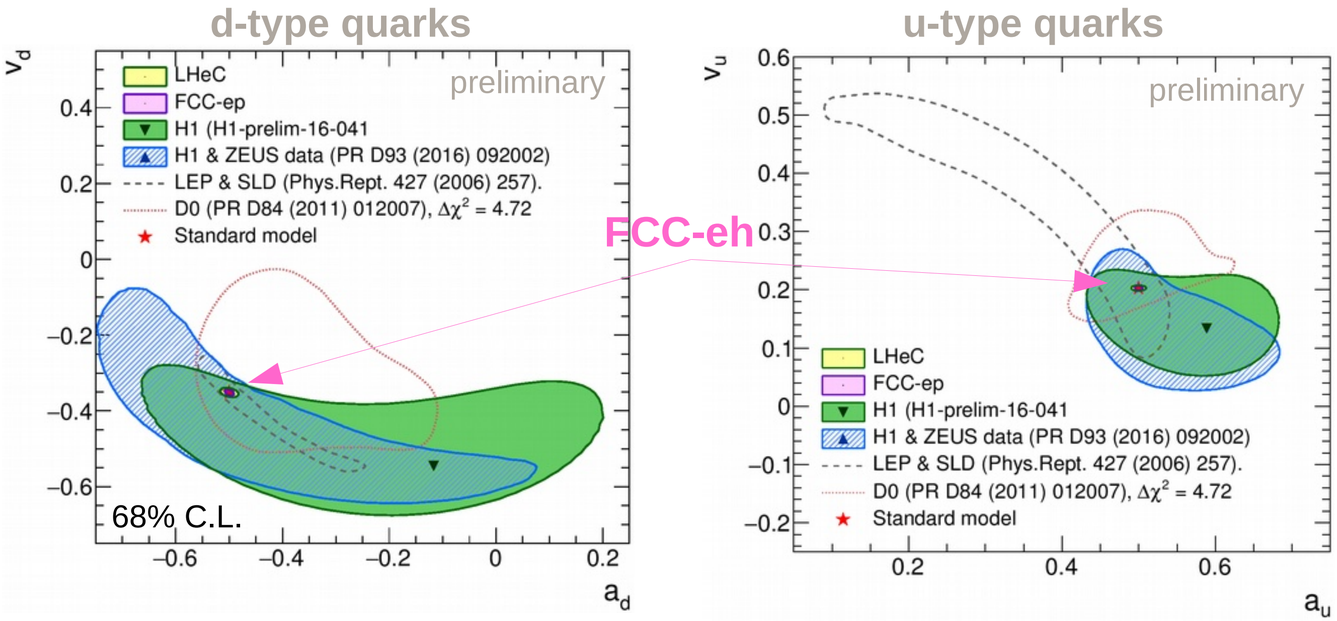


Partial Quark flavour universality assumed (1st 2 families with equal couplings)

Electroweak precision observables at FCC eh

- **Electroweak precision measurements at FCC-eh**

Precision measurements of couplings to light quark families



Observable	Uncertainty	(Relative uncertainty)
g_V^u	0.0022	(1.1%)
g_A^u	0.0031	(0.6%)
g_V^d	0.0049	(1.4%)
g_A^d	0.0049	(0.97%)

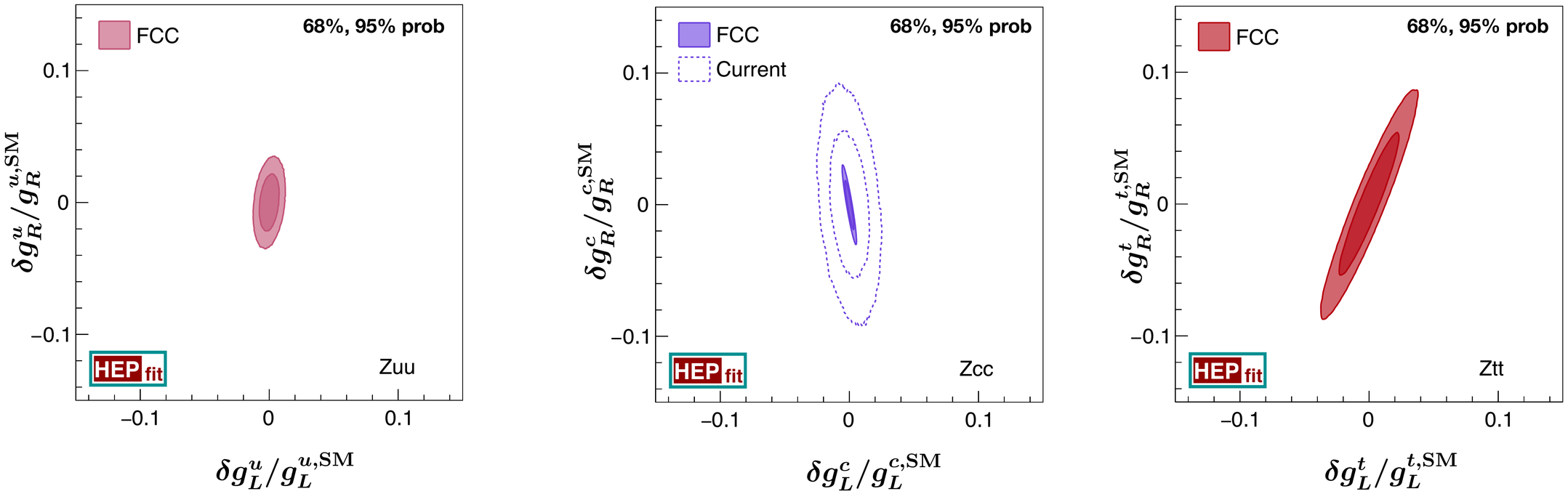
Assuming new physics only in Zqq couplings

Thanks to Daniel Britzger for info about the FCC-eh EW measurements

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee/eh

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

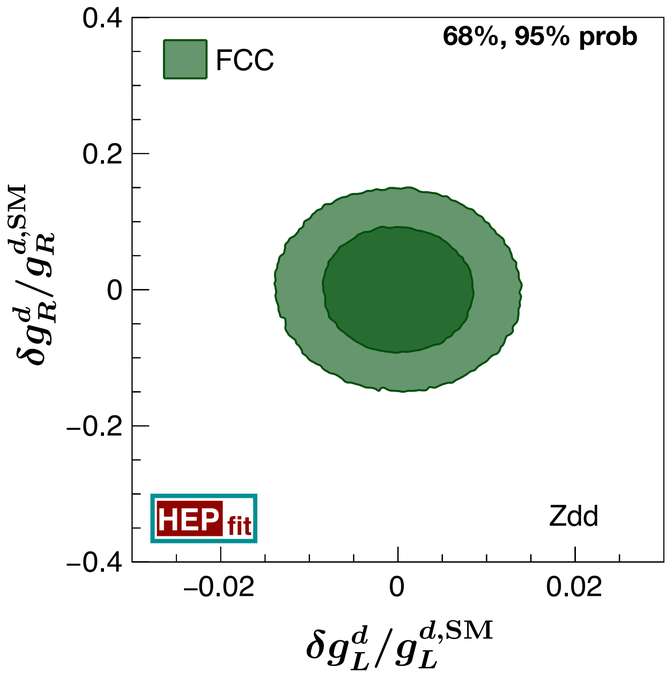


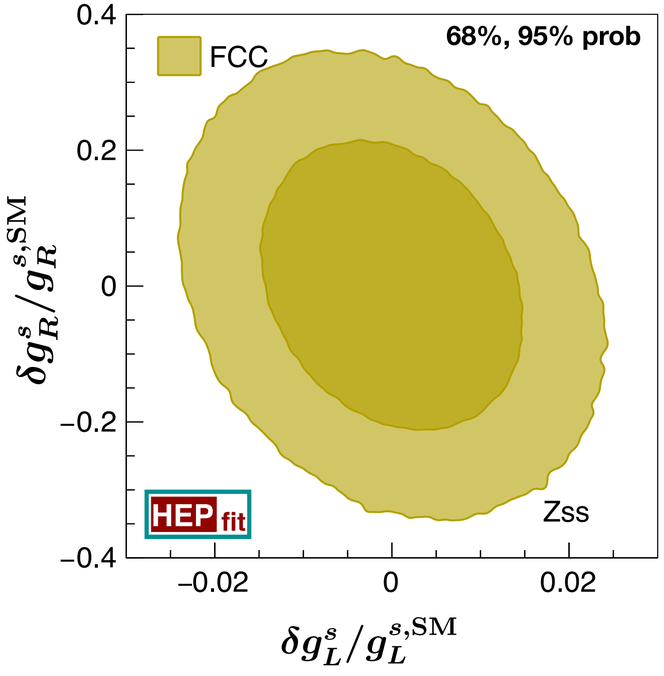
No Fermion flavour universality assumed

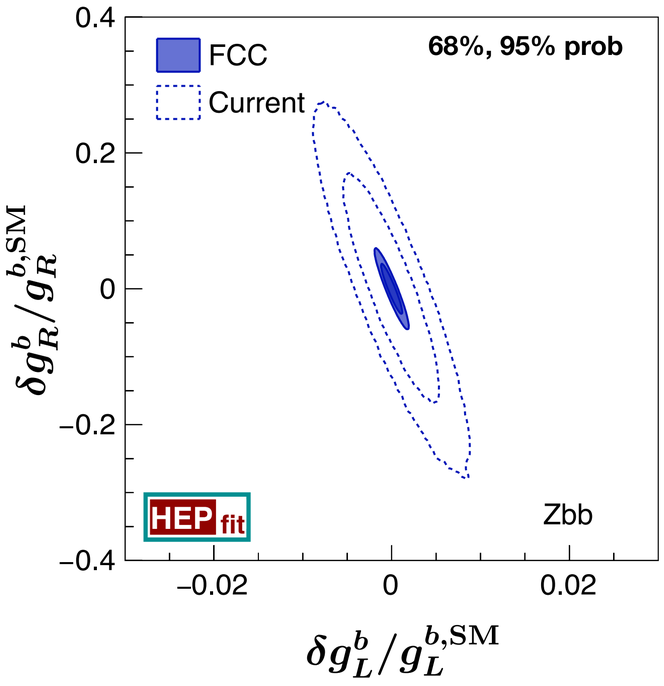
Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee/eh

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





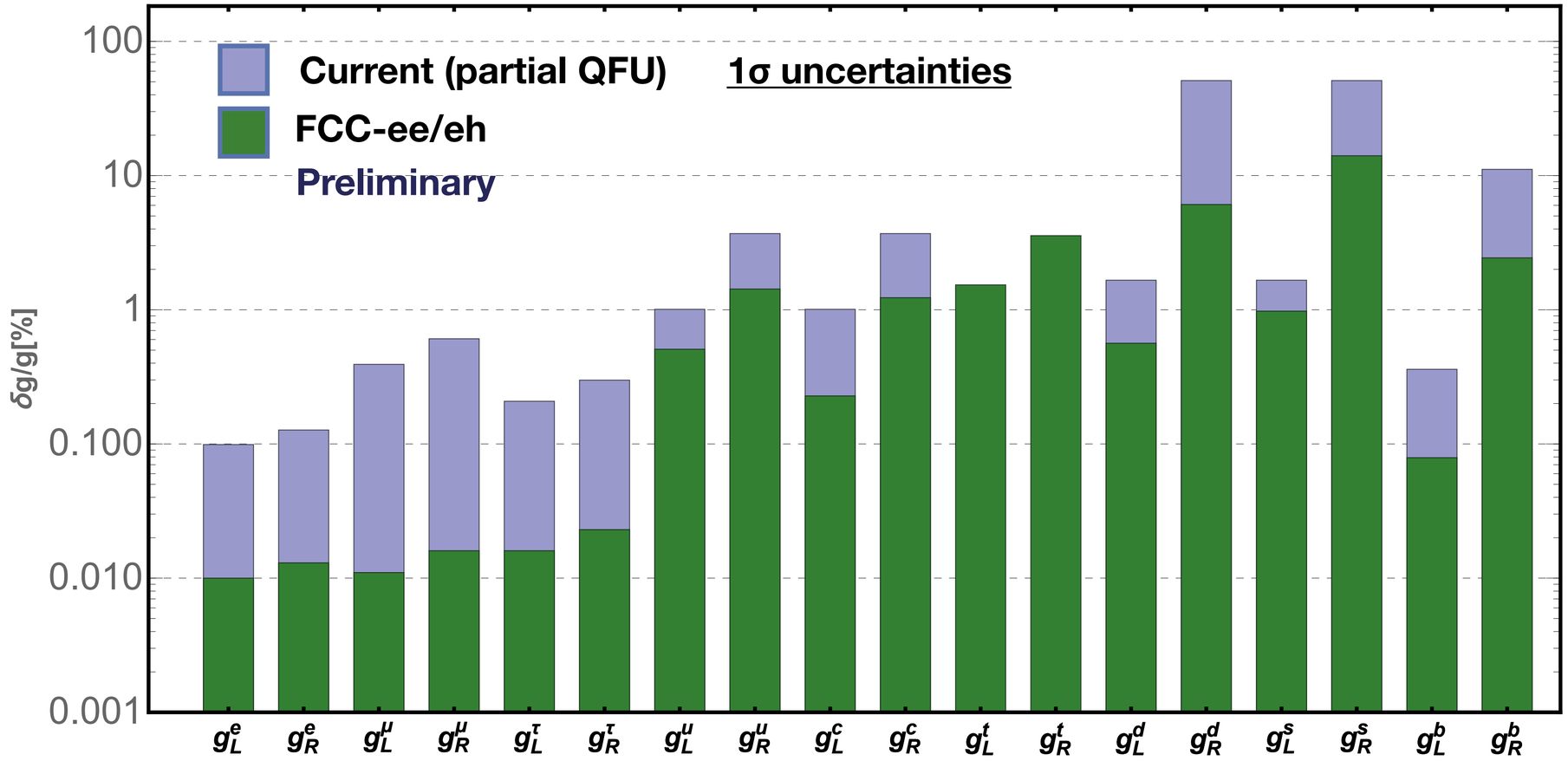


No Fermion flavour universality assumed

Jorge de Blas
INFN - University of Padova

Electroweak precision observables at FCC ee/eh

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



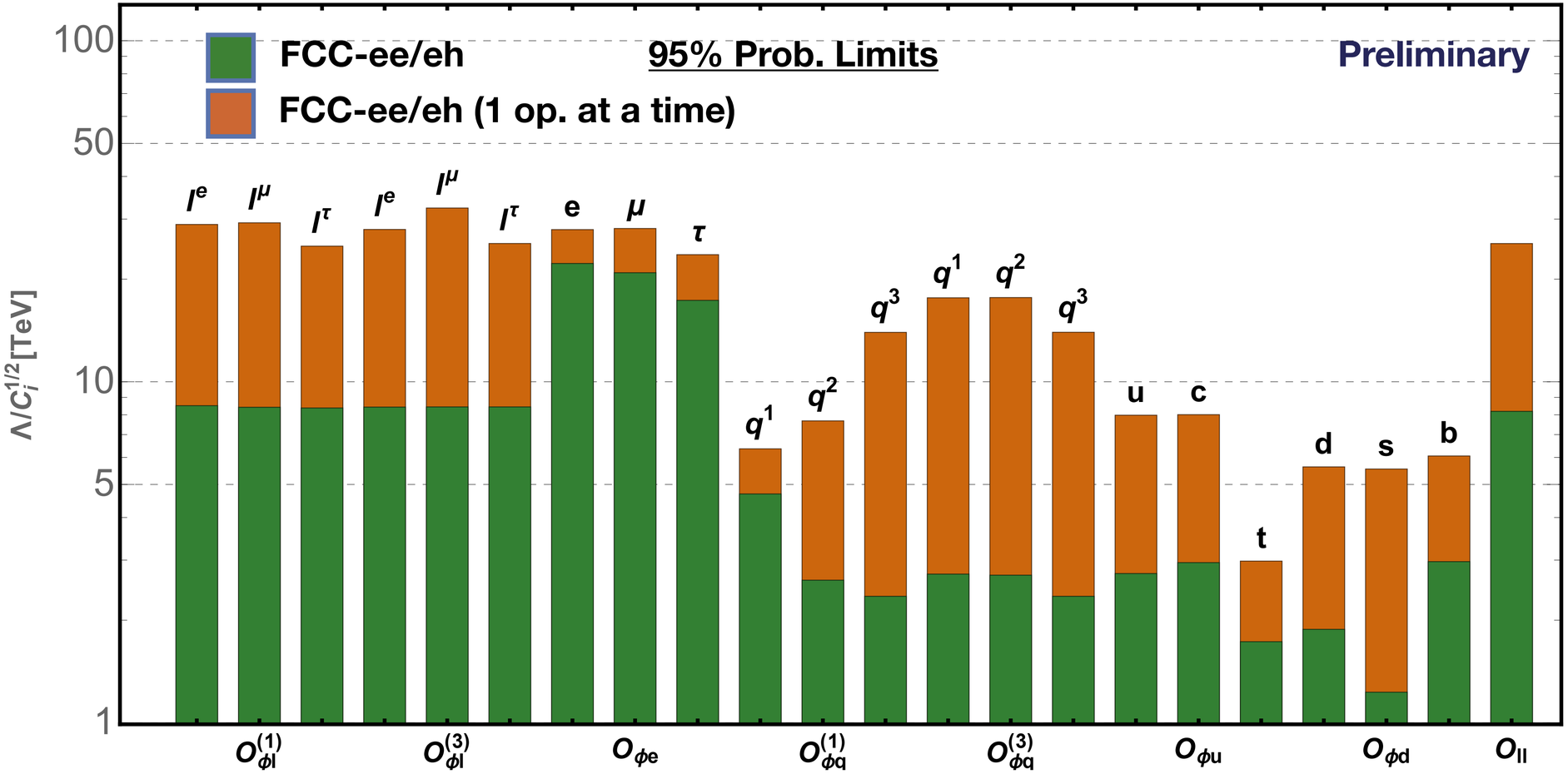
No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

Jorge de Blas
INFN - University of Padova

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

Jorge de Blas
INFN - University of Padova

Higgs precision measurements at the FCC

Jorge de Blas
INFN - University of Padova

Higgs precision observables at FCC ee

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

Associated ZH production

Observable	Expected uncertainty
σ_{HZ}	0.57%
$\sigma_{HZ}\,\mathrm{Br}(H \to b\bar{b})$	0.28%
$\sigma_{HZ}\,\mathrm{Br}(H \to c\bar{c})$	1.7%
$\sigma_{HZ}\,\mathrm{Br}(H \to gg)$	2.0%
$\sigma_{HZ}\,\mathrm{Br}(H \to W^{\pm}W^{\mp *})$	1.3%
$\sigma_{HZ}\,\mathrm{Br}(H \to \tau^{+}\tau^{-})$	1.0%
$\sigma_{HZ}\,\mathrm{Br}(H \to ZZ^{*})$	4.4%
$\sigma_{HZ}\,\mathrm{Br}(H \to \gamma\gamma)$	4.2%
$\sigma_{HZ}\,\mathrm{Br}(H \to \mu^{+}\mu^{-})$	18.4%

W boson fusion (WBF) production

Observable	Expected uncertainty
$\sigma_{WBF}^{(240\mathrm{GeV})}\,\mathrm{Br}(H \to b\bar{b})$	3.1%
$\sigma_{WBF}^{(350\mathrm{GeV})}\,\mathrm{Br}(H \to b\bar{b})$	0.79%

See M. Klute's talk for details

Jorge de Blas
INFN - University of Padova

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)

Observable	Expected uncertainty
$\sigma_{WBF}\,\mathrm{Br}(H \to b\bar{b})$	0.27%
$\sigma_{WBF}\,\mathrm{Br}(H \to c\bar{c})$	2.36%
$\sigma_{WBF}\,\mathrm{Br}(H \to gg)$	1.78%
$\sigma_{WBF}\,\mathrm{Br}(H \to W^{\pm}W^{\mp *})$	2.45%
$\sigma_{WBF}\,\mathrm{Br}(H \to \tau^{+}\tau^{-})$	1.65%
$\sigma_{WBF}\,\mathrm{Br}(H \to ZZ^{*})$	3.94%
$\sigma_{WBF}\,\mathrm{Br}(H \to \gamma\gamma)$	4.7%

NC DIS: Z boson fusion (ZBF)

Observable	Expected uncertainty
$\sigma_{ZBF}\,\mathrm{Br}(H \to b\bar{b})$	0.83%
$\sigma_{ZBF}\,\mathrm{Br}(H \to c\bar{c})$	7.08%
$\sigma_{ZBF}\,\mathrm{Br}(H \to gg)$	5.62%
$\sigma_{ZBF}\,\mathrm{Br}(H \to W^{\pm}W^{\mp *})$	4.29%
$\sigma_{ZBF}\,\mathrm{Br}(H \to \tau^{+}\tau^{-})$	5.25%
$\sigma_{ZBF}\,\mathrm{Br}(H \to ZZ^{*})$	11.8%
$\sigma_{ZBF}\,\mathrm{Br}(H \to \gamma\gamma)$	14.1%

Thanks to Max and Uta Klein for info about the FCC-eh Higgs measurements

Jorge de Blas
INFN - University of Padova

Higgs precision observables at FCC ee and eh

- **Fit to modified Higgs couplings (<u>assuming no extra invisible decays</u>)**

FCC-ee	
Coupling	Relative precision
κ_b	0.58%
κ_t	—
κ_τ	0.78%
κ_c	1.05%
κ_μ	9.6%
κ_Z	0.16%
κ_W	0.41%
κ_g	1.23%
κ_γ	2.18%
$\kappa_{Z\gamma}$	—

FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	—
κ_τ	1.10%
κ_c	1.35%
κ_μ	—
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	—

See M. Klute's talk for MI fit

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

Jorge de Blas
INFN - University of Padova

Higgs precision observables at FCC ee and eh

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

FCC-ee	
Coupling	Relative precision
κ_b	0.58%
κ_t	—
κ_τ	0.78%
κ_c	1.05%
κ_μ	9.6%
κ_Z	0.16%
κ_W	0.41%
κ_g	1.23%
κ_γ	2.18%
$\kappa_{Z\gamma}$	—

FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	—
κ_τ	1.10%
κ_c	1.35%
κ_μ	—
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	—

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

Jorge de Blas
INFN - University of Padova

Higgs precision observables at FCC ee and eh

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

FCC-ee	
Coupling	Relative precision
κ_b	0.58%
κ_t	–
κ_τ	0.78%
κ_c	1.05%
κ_μ	9.6%
κ_Z	0.16%
κ_W	0.41%
κ_g	1.23%
κ_γ	2.18%
$\kappa_{Z\gamma}$	–

FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	–
κ_τ	1.10%
κ_c	1.35%
κ_μ	–
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	–

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

See U. Klein's talk for tH at FCC-eh

Jorge de Blas
INFN - University of Padova

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

HLLHC (ATLAS)	
Coupling	Relative precision
κ_b	10.4%
κ_t	7.6%
κ_τ	9.43%
κ_c	–
κ_μ	7.4%
κ_Z	3.7%
κ_W	4.2%
κ_g	5.2%
κ_γ	4.3%
$\kappa_{Z\gamma}$	15%

HLLHC + FCC-ee	
Coupling	Relative precision
κ_b	0.55%
κ_t	5.19%
κ_τ	0.76%
κ_c	1.03%
κ_μ	5.20%
κ_Z	0.16%
κ_W	0.40%
κ_g	1.03%
κ_γ	1.41%
$\kappa_{Z\gamma}$	14.2%

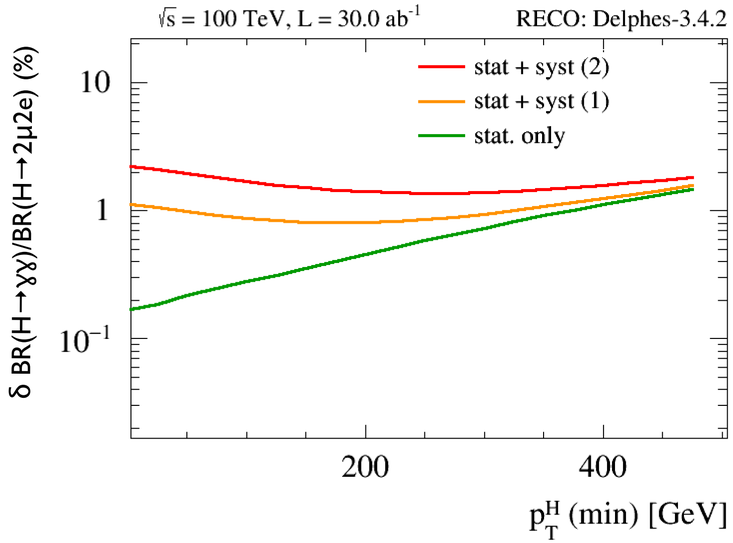
HLLHC + FCC-eh	
Coupling	Relative precision
κ_b	0.69%
κ_t	5.27%
κ_τ	1.06%
κ_c	1.33%
κ_μ	6.25%
κ_Z	0.41%
κ_W	0.25%
κ_g	1.02%
κ_γ	1.44%
$\kappa_{Z\gamma}$	14.26%

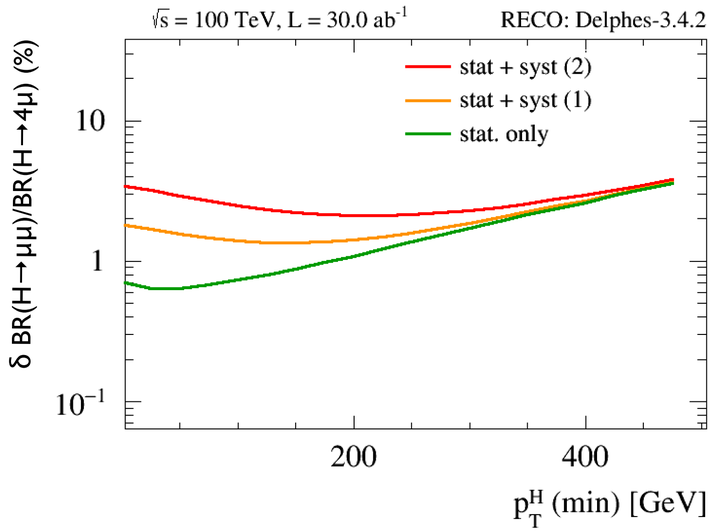
$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

Jorge de Blas
INFN - University of Padova

Higgs complementarities

- **Rare Higgs decays statistically limited at FCC-ee/eh**
  - **Can be measured at FCC-hh with 1% stat. precision (in δμ/μ)**
  - **Systematics can be further cancelled by measuring ratios of BR (γγ/4l, μμ/4l, Zγ/4l, γγ/μμ)**





M. Selvaggi, Talk at 2nd FCC Physics Workshop

1% accuracy (stat + sys) within reach

Provided *BR(H→4l)* know to <<1%

(*pp→H→4l* measurable at FCC-hh to ~1%)

Measurable at FCC-ee/eh with required precision

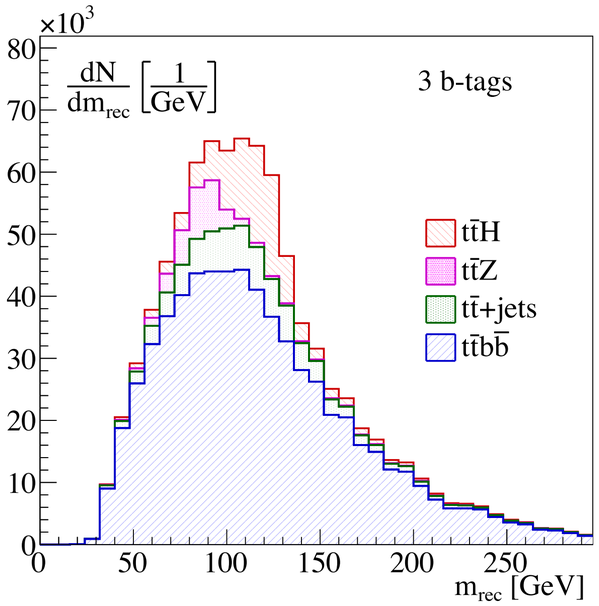
- **Robust determination by this method requires both FCC-hh and FCC-ee/eh**

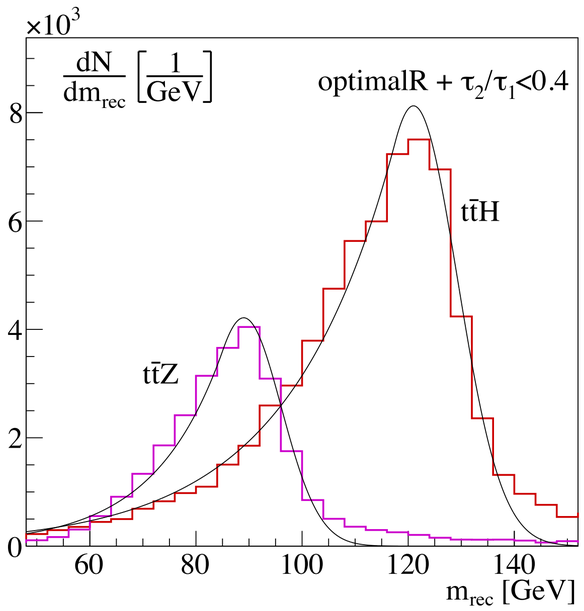
Thanks to Michele Selvaggi for info about the FCC-hh Higgs measurements

Jorge de Blas
INFN - University of Padova

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**





M.L. Mangano et al., arXiv: 1507.08169 [hep-ph]

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

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

HLLHC + FCC	
Coupling	Relative precision
κ_b	0.38%
κ_t	0.51%
κ_τ	0.58%
κ_c	0.79%
κ_μ	0.42%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	0.40%
$\kappa_{Z\gamma}$	0.52%

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

Jorge de Blas
INFN - University of Padova

Higgs precision observables at the FCC

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

Vector couplings

$$\mathcal{L}_{hVV} = g_{hgg} G^A_{\mu\nu} G^{A\mu\nu} h + g^{(1)}_{hWW} W^{\mu\nu} W^{\dagger}_{\mu\nu} h + \left(g^{(2)}_{hWW} W^{+\nu} \partial^\mu W^{\dagger}_{\mu\nu} h + \text{h.c.} \right) + g^{(3)}_{hWW} W^+_\mu W^{-\mu} h$$
$$+ g^{(1)}_{hZZ} Z_{\mu\nu} Z^{\mu\nu} h + g^{(2)}_{hZZ} Z_\nu \partial_\mu Z^{\mu\nu} h + g^{(3)}_{hZZ} Z_\mu Z^\mu h$$
$$+ g^{(1)}_{hZA} Z_{\mu\nu} F^{\mu\nu} h + g^{(2)}_{hZA} Z_\nu \partial_\mu F^{\mu\nu} h + g_{hAA} F_{\mu\nu} F^{\mu\nu} h$$

Several New Operators

$$\mathcal{O}_{\phi G} = (\phi^\dagger \phi)\, G^A_{\mu\nu} G^{A\,\mu\nu}$$
$$\mathcal{O}_{\phi B} = (\phi^\dagger \phi)\, B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{\phi W} = (\phi^\dagger \phi)\, W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$\mathcal{O}_{\phi\Box} = (\phi^\dagger \phi)\, \Box\, (\phi^\dagger \phi)$$

Modifies Higgs kinetic term.
Enters in all Higgs observables

Already present in the EWPO analysis

$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_a \phi) W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{\phi D} = \left| \phi^\dagger i D_\mu \phi \right|^2$$

$$\mathcal{O}_{D\phi B} = i D^\mu \phi^\dagger D^\nu \phi\, B_{\mu\nu}$$
$$\mathcal{O}_{D\phi W} = i D^\mu \phi^\dagger \sigma_a D^\nu \phi\, W^a_{\mu\nu}$$

Field redefinition: trade by this 2 operators (do not enter in EWPO)

Jorge de Blas
INFN - University of Padova

Higgs precision observables at the FCC

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

Fermionic couplings

$$\mathcal{L}_{hff} = g^{ii}_{hee}\,\bar{e}^i_L e^i_R h + g^{ii}_{huu}\,\bar{u}^i_L u^i_R h + g^{ii}_{hdd}\,\bar{d}^i_L d^i_R h + \text{h.c.}$$

$$g_{hff} = -\frac{m_f}{v}\left(1 + \left[(C_{\phi\Box} - \frac{1}{4}C_{\phi D}) - \frac{v}{\sqrt{2}m_f}C_{f\phi} - \frac{1}{2}\Delta_{G_F}\right]\frac{v^2}{\Lambda^2}\right)$$

Operators

$$\mathcal{O}_{e\phi} = (\phi^\dagger\phi)\,(\overline{l_L}\phi e_R)$$

$$\mathcal{O}_{u\phi} = (\phi^\dagger\phi)\,(\overline{q_L}\tilde{\phi} u_R)$$

$$\mathcal{O}_{d\phi} = (\phi^\dagger\phi)\,(\overline{q_L}\phi d_R)$$

Higgs self-coupling

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

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

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

Only enters in Higgs self-interactions

Jorge de Blas
INFN - University of Padova

Diboson observables at FCC ee

- ***W*** **pair production at FCC-ee**

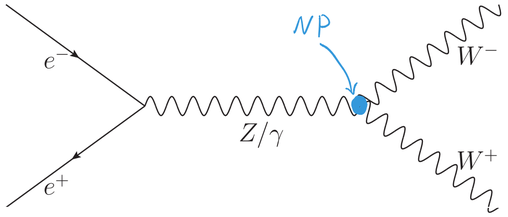
See P. Azurri's talk and J. Gu's poster for details

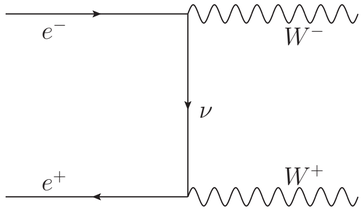
FCC-ee 161/240/350/365 GeV				
aTGC	Uncertainty (stat)	Correlation Matrix		
δg_{1Z}	8.1×10^{-4}	1	-0.28	-0.87
$\delta \kappa_\gamma$	5.2×10^{-4}		1	-0.12
λ_Z	7.9×10^{-4}			1

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**

$$
\begin{aligned}
\mathcal{L}_{\rm TGC} &= ie\left[\left(W^+_{\mu\nu}W^-_{\mu} - W^-_{\mu\nu}W^+_{\mu}\right)A_\nu + (1+\delta\kappa_\gamma)A_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\
&+ ig\cos\theta_W\left[(1+\delta g_{1,Z})\left(W^+_{\mu\nu}W^-_{\mu} - W^-_{\mu\nu}W^+_{\mu}\right)Z_\nu + (1+\delta\kappa_Z)\;Z_{\mu\nu}\,W^+_\mu W^-_\nu\right] \\
&+ ie\frac{\lambda_\gamma}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + ig\cos\theta_W\frac{\lambda_Z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu},
\end{aligned}
$$

2 aTGC related to Higgs couplings

$$
\begin{aligned}
\delta\kappa_\gamma &= -2vc_W^2\left(g_{hAA} - g^{(1)}_{hZZ} + \frac{1}{2s_Wc_W}g^{(1)}_{hZA}(c_W^2 - s_W^2)\right) \\
\delta g_{1,Z} &= \frac{v}{2(c_W^2-s_W^2)}\left(c_W^2 g^{(2)}_{hZZ} + 4s_W^2(g_{hAA} - g^{(1)}_{hZZ} + \tfrac{1}{4}g^{(2)}_{hZZ}) + \frac{2s_W}{c_W}g^{(1)}_{hZA}(c_W^2 - s_W^2)\right) \\
\delta\kappa_Z &= \delta g_{1,Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma \\
\lambda_\gamma = \lambda_Z &= -\frac{3}{2}\frac{e}{s_W}C_{3W}\frac{v^2}{\Lambda^2}
\end{aligned}
$$

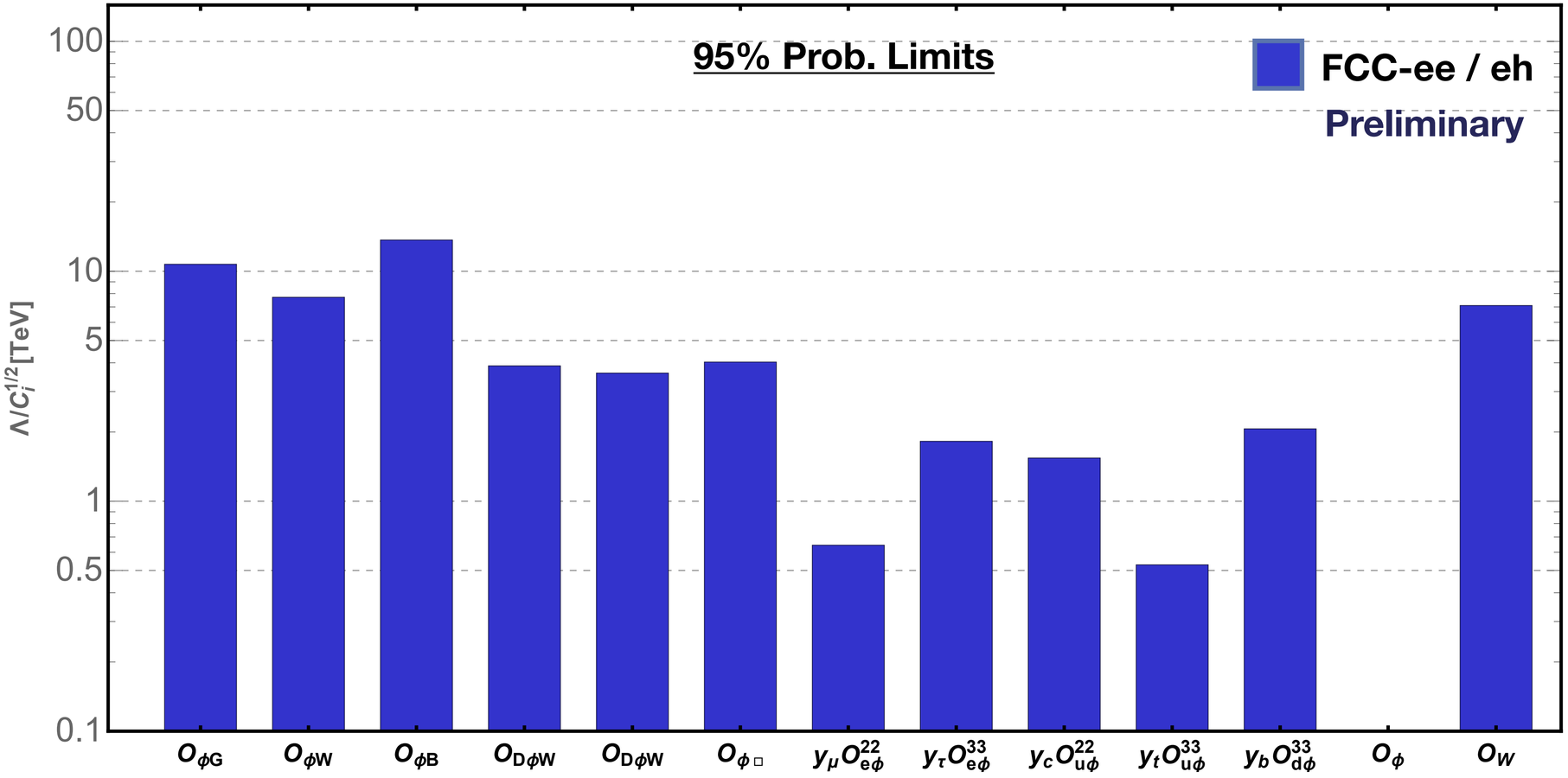
$$\mathcal{O}_W = i\epsilon_{abc}W^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$$

Only one more operator (enters only in aNGC)

Jorge de Blas
INFN - University of Padova

Higgs precision observables at the FCC

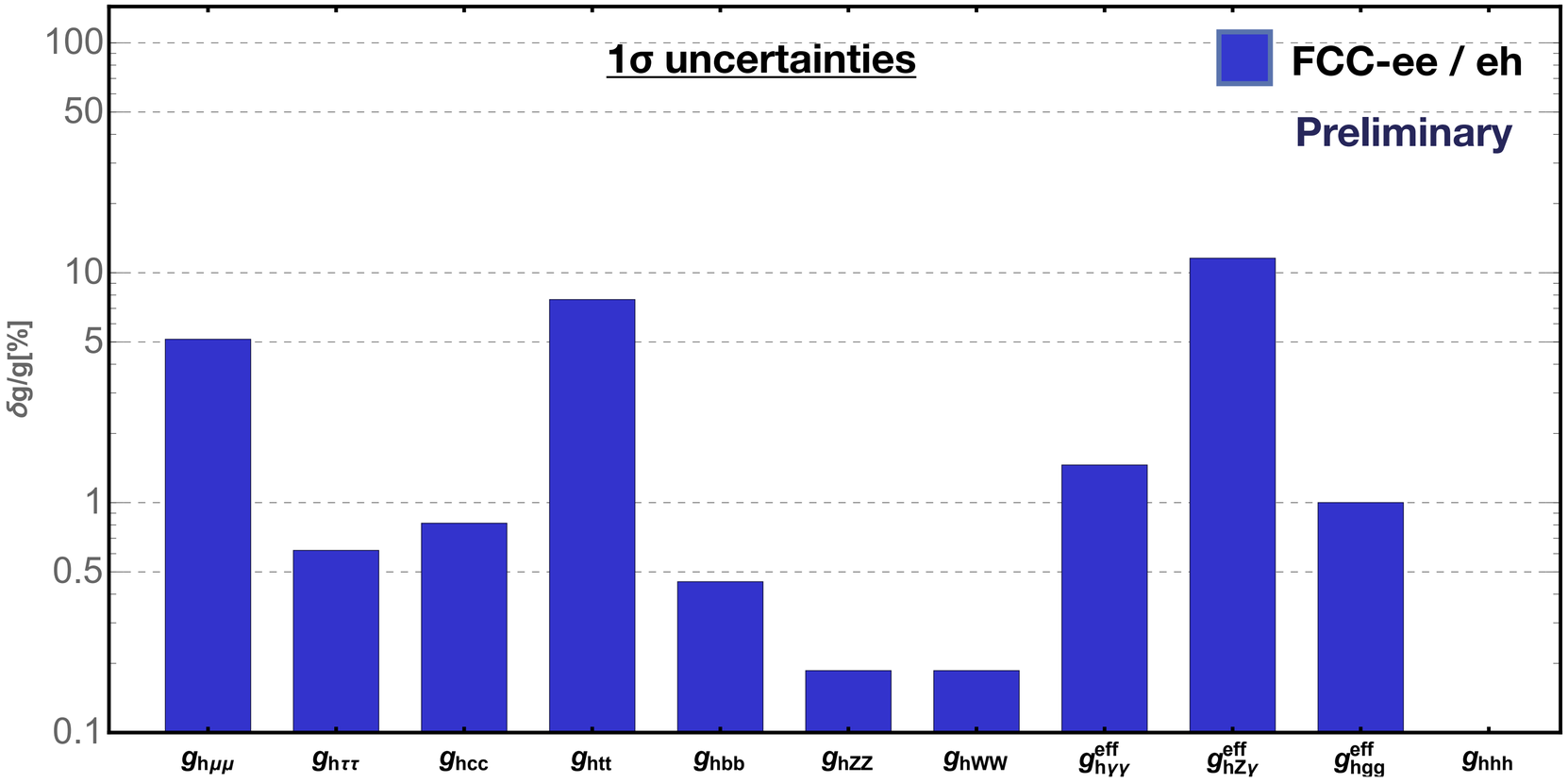
- **EFT fit to Higgs precision observables at the FCC-ee and FCC-eh:**



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

Higgs precision observables at the FCC

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



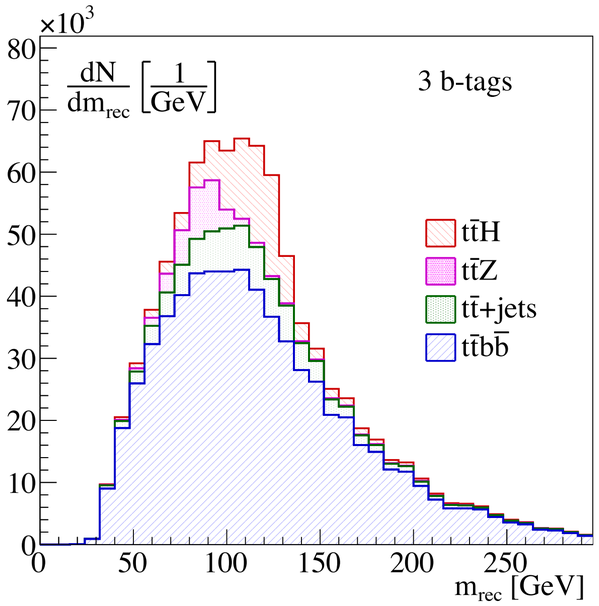
HLLH+FCC-ee/FCC-eh	
Coupling	Relative precision
κ_b	0.39%
κ_t	5.16%
κ_τ	0.59%
κ_c	0.79%
κ_μ	5.17%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	1.19%
$\kappa_{Z\gamma}$	14.3%

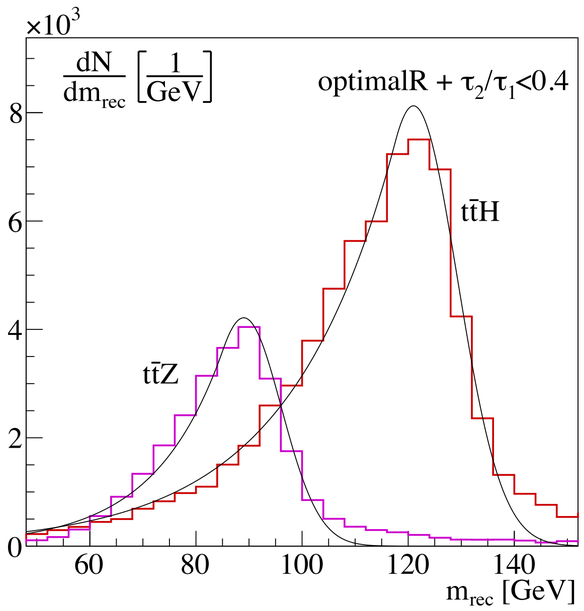
At this point, it compares relatively well with the kappa analysis for the SM-like couplings

Jorge de Blas
INFN - University of Padova

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**





M.L. Mangano et al., arXiv: 1507.08169 [hep-ph]

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

Assumes no NP in *Ztt* and *BR(H→bb)* know to 1%

Both measurable at FCC-ee with required precision

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

Jorge de Blas
INFN - University of Padova

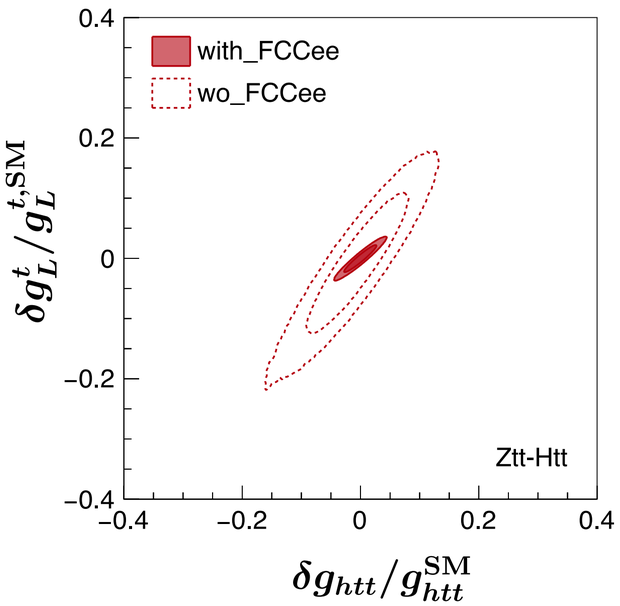
Going back to Higgs complementarities…

- **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
$\Rightarrow \delta_{stat+th}\, y_t/y_t \sim 1\%$

Assumes no NP in *Ztt* and *BR(H→bb)* know to 1%

Both measurable at FCC-ee with required precision

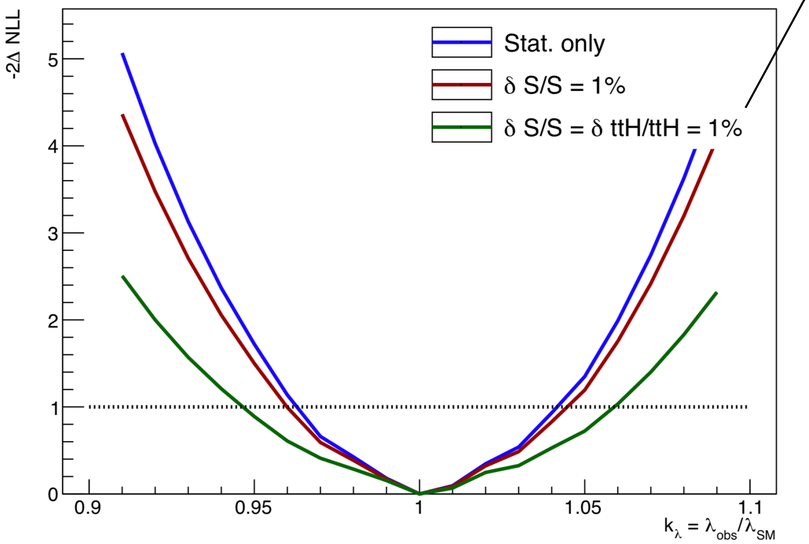
  - **Robust determination by this method requires both FCC-hh and FCC-ee**

Jorge de Blas
INFN - University of Padova

Going back to Higgs complementarities…

- **Higgs self-interaction:**
  - **Can be tested at FCC-ee via NLO effects: Limited (~50%) precision** S. Di Vita et al., JHEP 1802 (2018) 178
  - **Direct HH production at FCC-hh:**

pp→HH→bbγγ



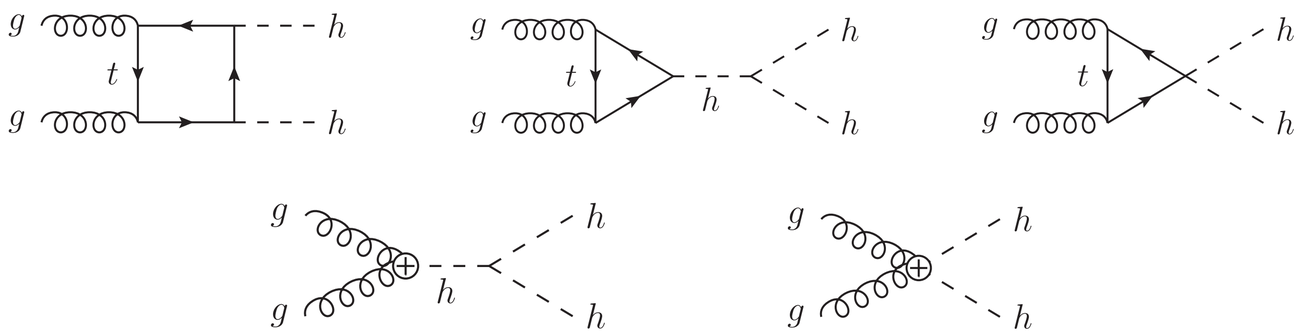
$\delta\kappa_\lambda(\text{stat}) \approx 3.5\ \%$
$\delta\kappa_\lambda(\text{stat + syst}) \approx 6\ \%$

M. Selvaggi, Talk at 2nd FCC Physics Workshop

Assumes all uncertainty goes into κ_λ

$$\delta\kappa_\lambda = \left[3(C_{\phi\Box} - \tfrac{1}{4}C_{\phi D}) - 2\frac{v^2}{M_h^2}C_\phi - \tfrac{1}{2}\Delta_{G_F}\right]\frac{v^2}{\Lambda^2}$$

But other NP parameters modify HH production and decays



A. Azatov et al. PRD92 (2015) no.3, 035001

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

Jorge de Blas
INFN - University of Padova

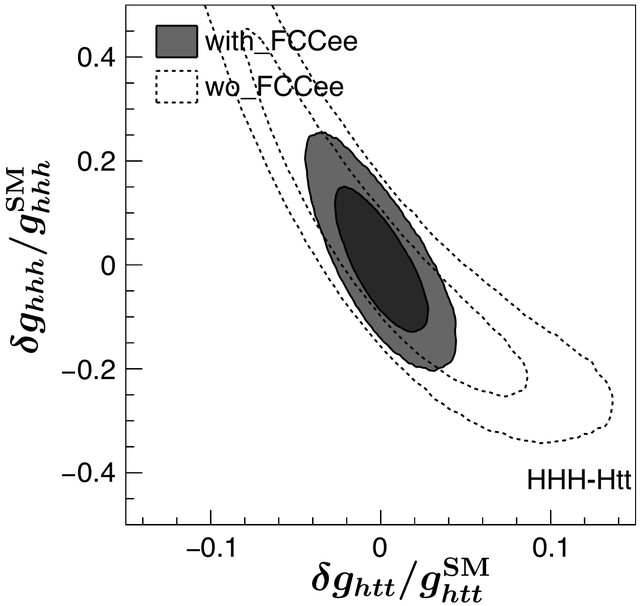
Going back to Higgs complementarities…

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

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

Toy fit neglecting FCCee measurements

Precise determination of operators modifying *Htt* interactions needed



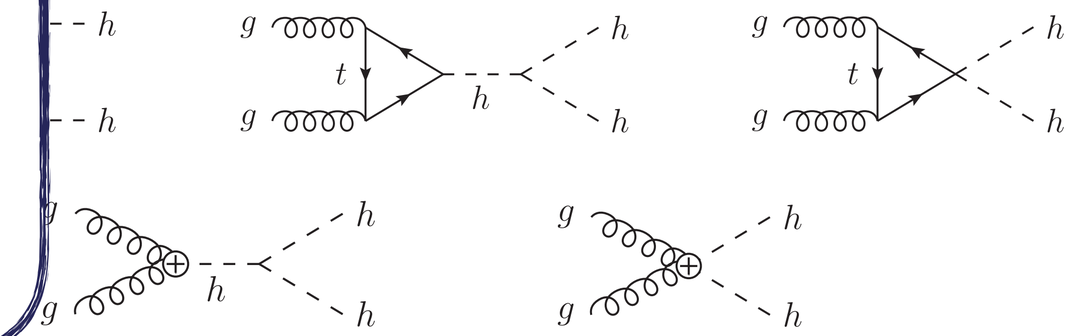
$\delta\kappa_\lambda(\text{stat} + \text{syst}) \approx 6\,\%$

M. Selvaggi, Talk at 2nd FCC Physics Workshop

Assumes all uncertainty goes into κ_λ

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

ther NP parameters modify HH production and decays



A. Azatov et al. PRD92 (2015) no.3, 035001

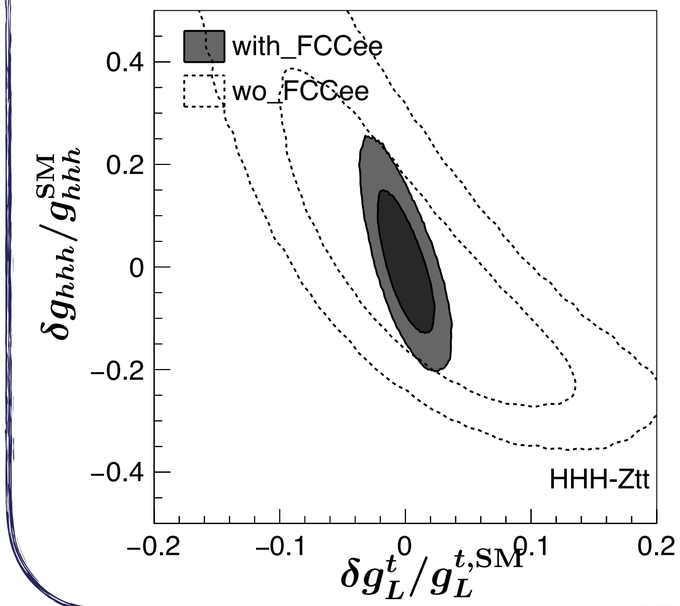
They can be measured at FCC-ee/eh/hh with ~1% precision → Global FCC fit for robust estimates

Going back to Higgs complementarities…

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

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

Toy fit neglecting FCCee measurements



$\delta\kappa_\lambda$(stat + syst) ≈ 6 %

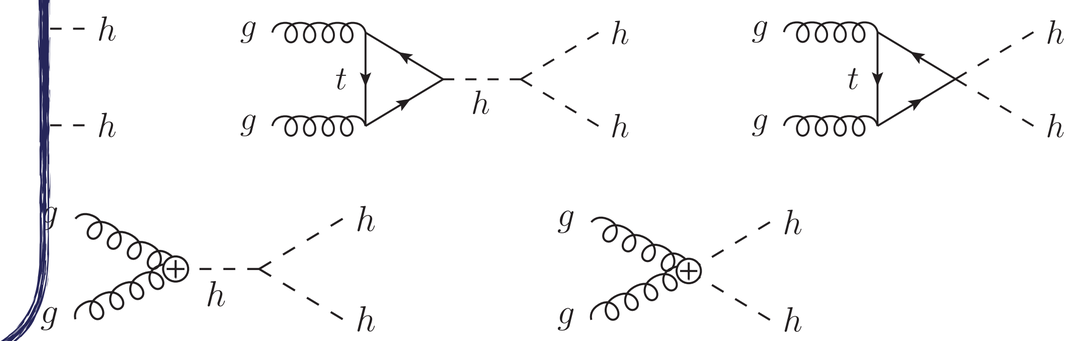
Indirect dependence on FCC-ee *Ztt* via *Htt/Ztt* FCC-hh measurement

M. Selvaggi, Talk at 2nd FCC Physics Workshop

Assumes all uncertainty goes into κ_λ

$$\lambda = \left[3(C_{\phi\Box} - \tfrac{1}{4}C_{\phi D}) - 2\tfrac{v^2}{M_h^2}C_\phi - \tfrac{1}{2}\Delta_{G_F}\right]\tfrac{v^2}{\Lambda^2}$$

ther NP parameters modify HH production and decays



A. Azatov et al. PRD92 (2015) no.3, 035001

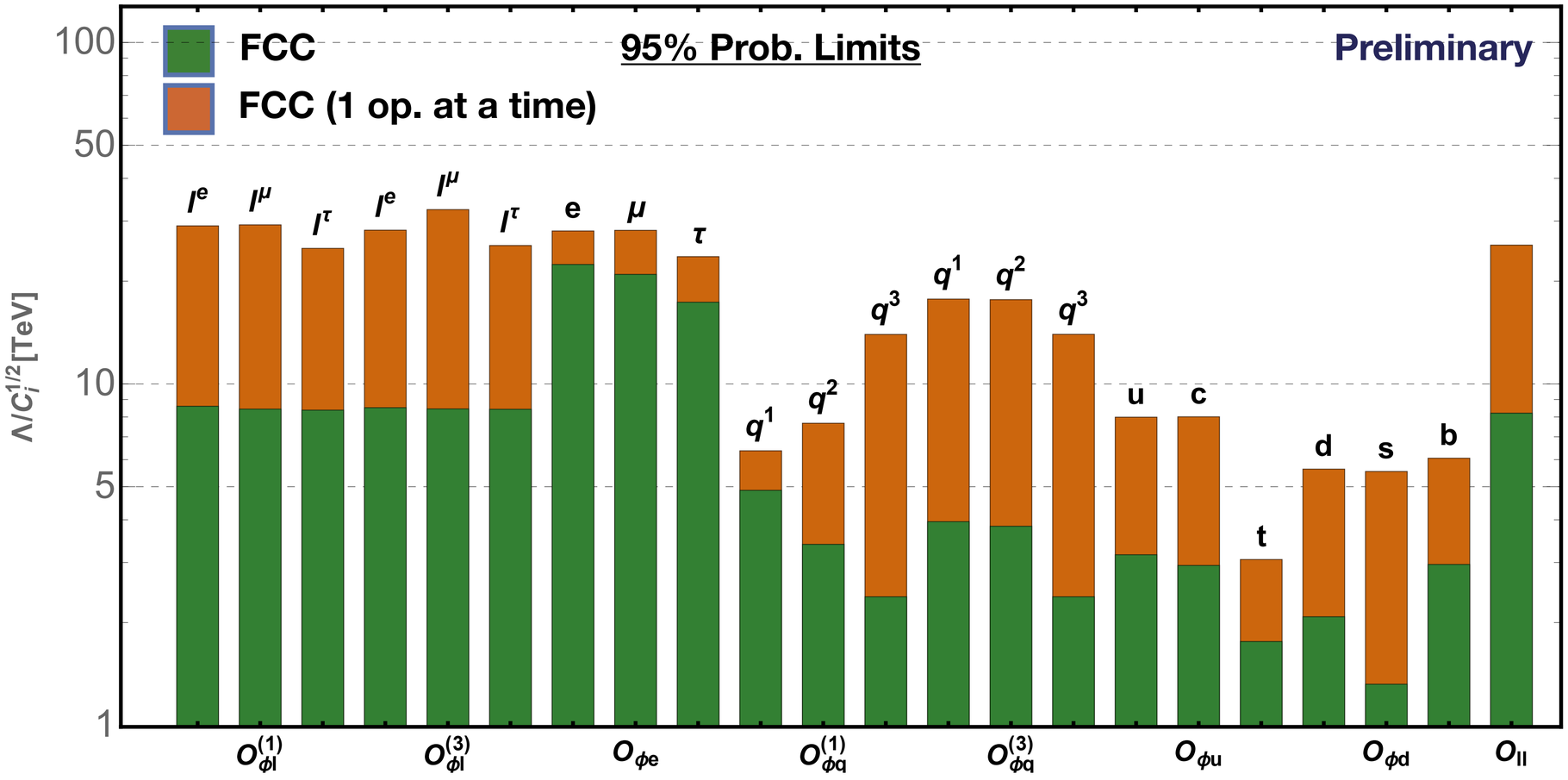
They can be measured at FCC-ee/eh/hh with ~1% precision → Global FCC fit for robust estimates

The Global Electroweak and Higgs fit

Jorge de Blas
INFN - University of Padova

The Global Electroweak and Higgs fit

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

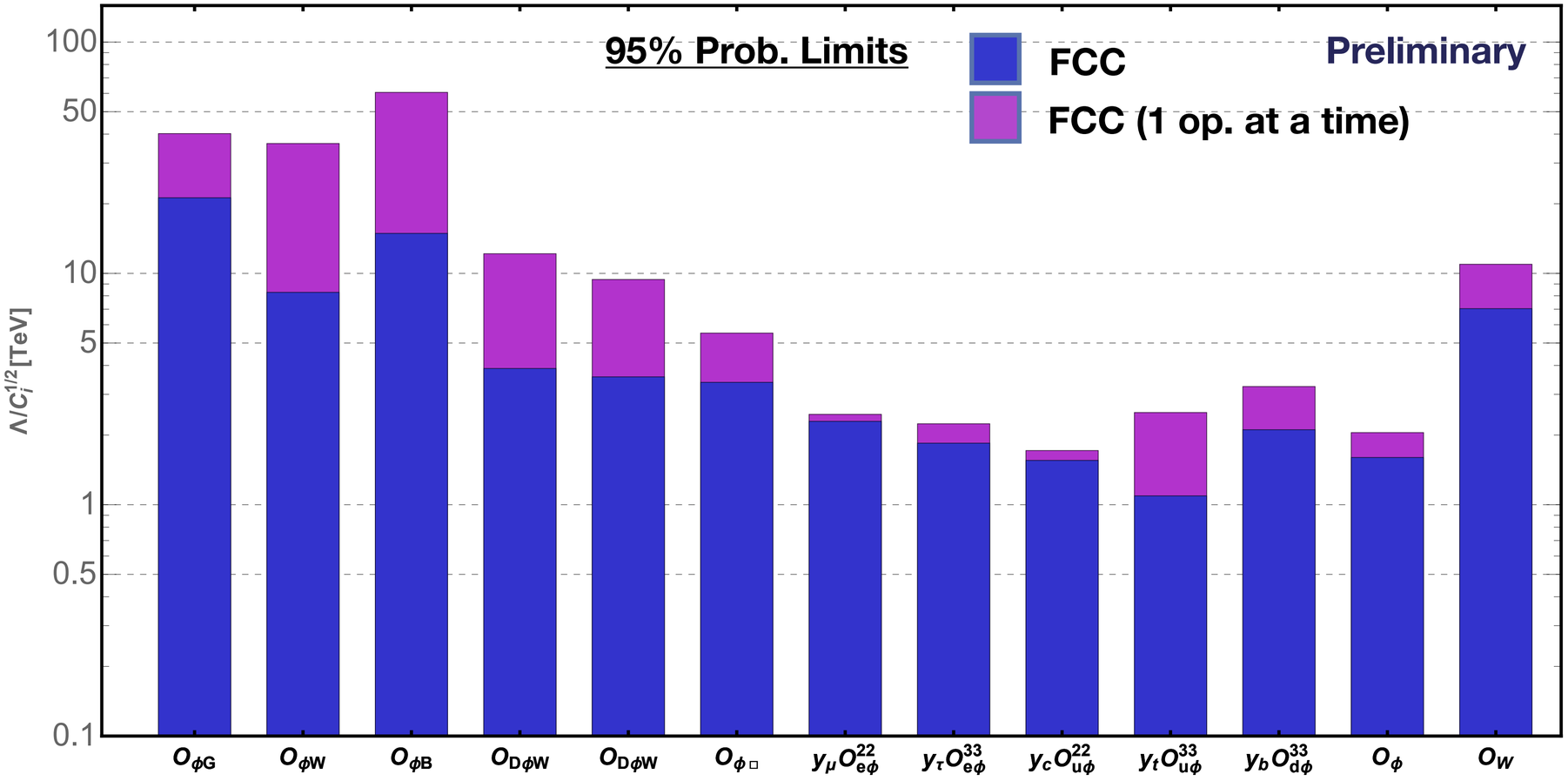


Dominated by FCC-ee - Complementary info from FCC-eh for light quarks

Jorge de Blas
INFN - University of Padova

The Global Electroweak and Higgs fit

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

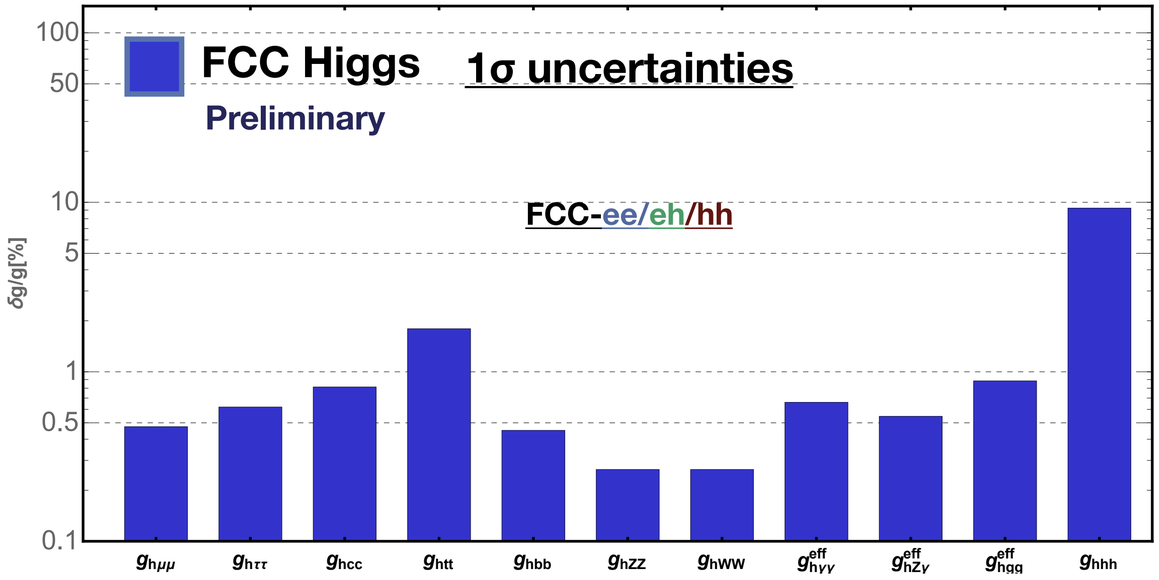


Receives important contributions from all FCC options

Jorge de Blas
INFN - University of Padova

The Global Electroweak and Higgs fit

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

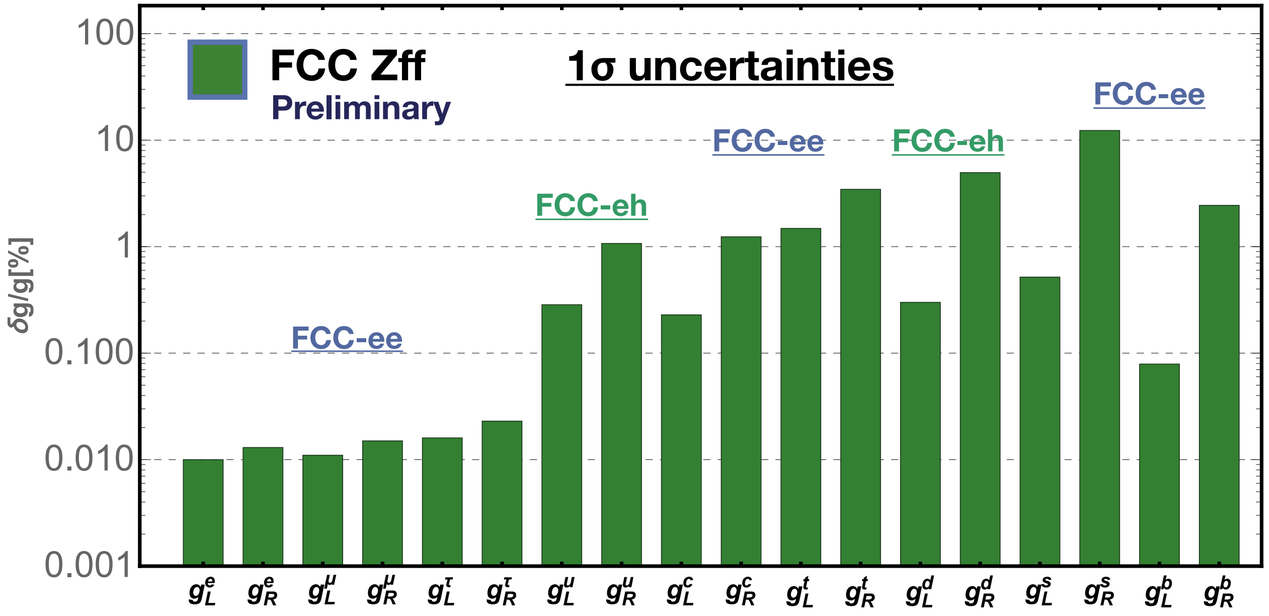


Single Higgs couplings could be known to ~1% or better

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



Jorge de Blas
INFN - University of Padova

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

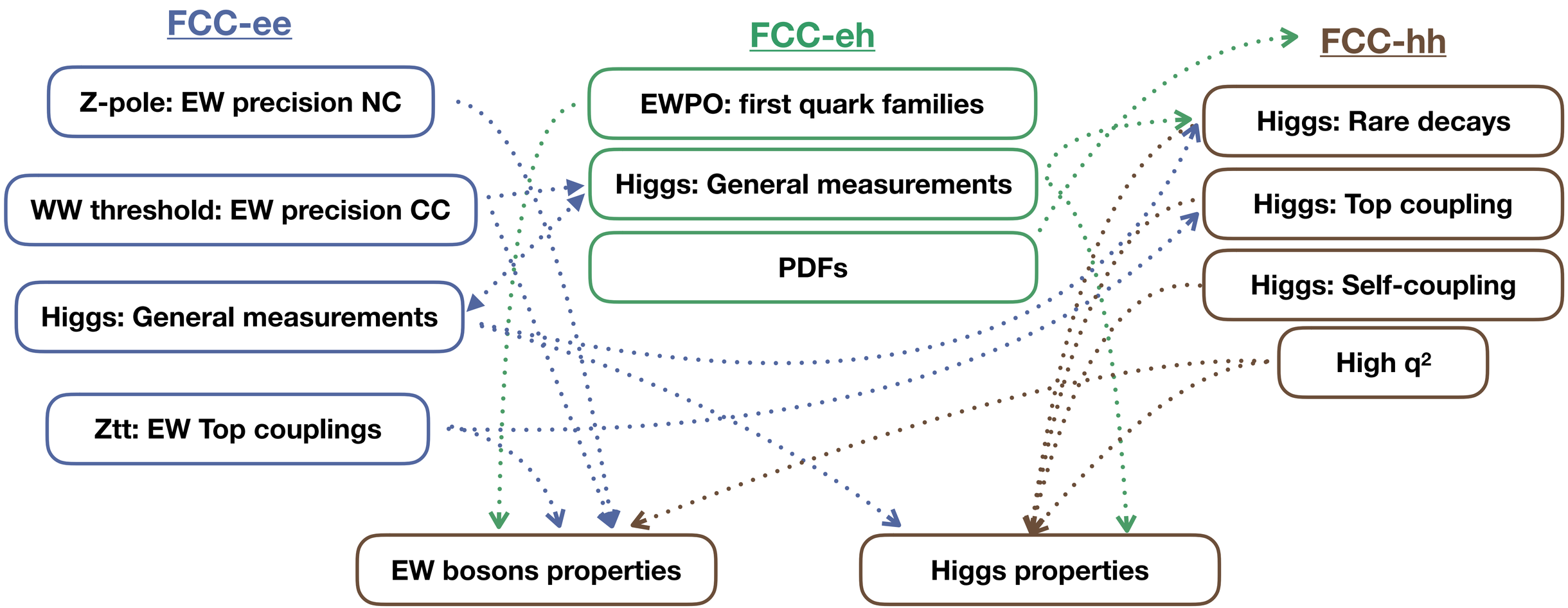
- The FCC can test (indirectly) new physics interaction scales at the level of several tenths to TeV and increase the precision of properties of the SM particles by, roughly, one order of magnitude

- 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

Jorge de Blas
INFN - University of Padova

Conclusions

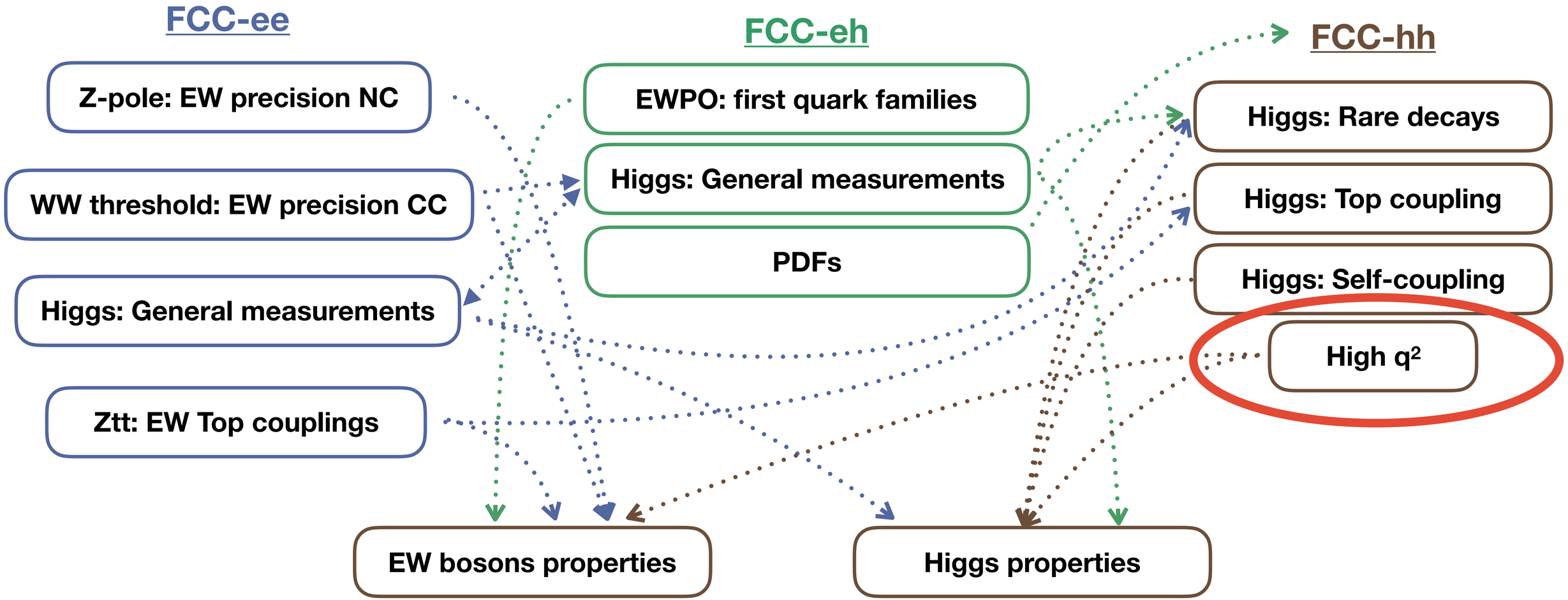
- **All three FCC options complement each other very well and are useful to complete the whole picture:**



Jorge de Blas
INFN - University of Padova

Conclusions

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



Jorge de Blas
INFN - University of Padova

Conclusions

- **<u>The dimension 6 SMEFT:</u>**

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

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

Effects suppressed by $q = v, E < \Lambda$

Λ: Cut-off of the EFT

Most of the effects discussed so far

For E>>v these effects can provide precise constraints on EFT interactions even if experimental precision is lower

Large Energies ⇒ FCC-hh

<u>Look for E-enhanced effects in differential distributions</u>

See A. Wulzer's talk this morning

Jorge de Blas
INFN - University of Padova

Conclusions

- **The dimension 6 SMEFT:**

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

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

Example: Individual 95% prob bound on $\frac{C_{\phi q}^{(3)}}{\Lambda^2}$ ~ ±3 x 10^{-3} TeV^{-2}

For $E \gg v$ these

Contributes to WZ production via High-E primary $a_q^{(3)} = 4\frac{C_{\phi q}^{(3)}}{\Lambda^2} \sim \pm 12 \times 10^{-3}\text{TeV}^{-2}$

Look

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

Energy helps to improve precision constraints on new physics

See A. Wulzer's talk this morning

To be included in updated global fits

Jorge de Blas
INFN - University of Padova

Thank you

Jorge de Blas
INFN - University of Padova