SMEFT fits at the FCC

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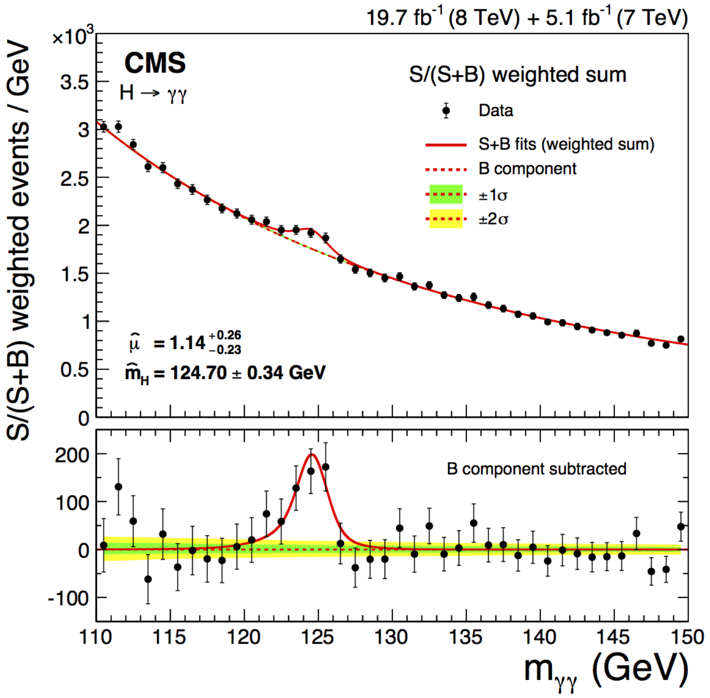
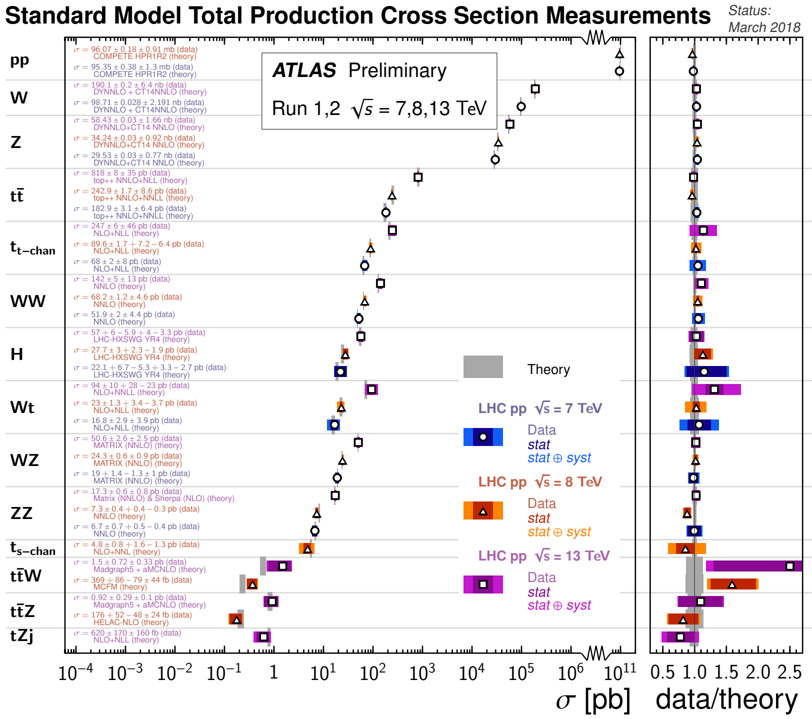
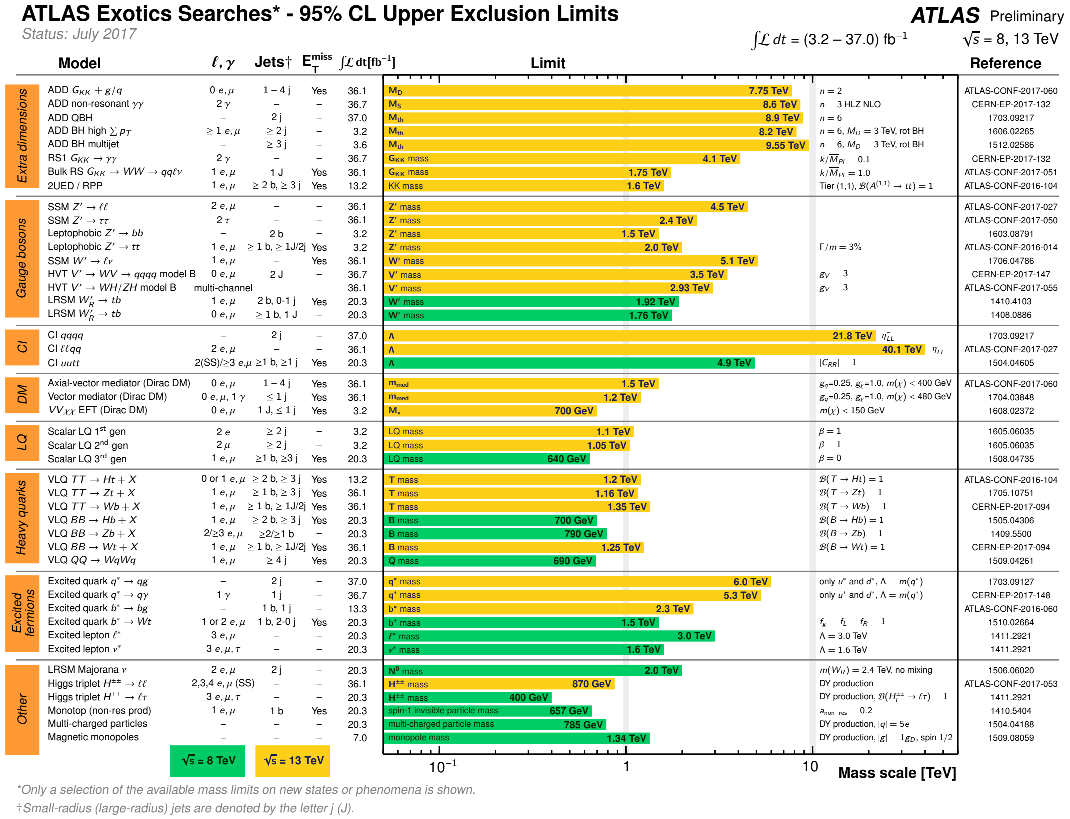
Introduction

Particle Physics Today

- The LHC after Run I & II:







We found the Higgs **(almost) everything looks SM like…** **… no sign of NP in Direct searches**

- But we have good reasons to believe there must be new physics

Neutrino masses
Dark Matter/Dark Energy
Matter/Anti-Matter asymmetry

Hierarchy problem
EW vacuum is metastable
…

Introduction

If there is New Physics

- Most of the data seems to be well reproduced by the SM predictions (within experimental and theoretical accuracy)

Its effects in measured observables must be small wrt current precision

- LHC direct searches: **No sign of New Physics…**

No preference for any particular BSM model

New Physics mass scale seems to be well above the electroweak scale

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Future experiments like FCC-ee will take care of providing extremely high-precision

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New Physics mass scale seems to be well above the electroweak scale

Effective Field Theories provide optimal framework for model-independent studies in problems with very different mass scales

Optimal framework for model-independent studies of indirect sensitivity to New Physics at FCC-ee

The dimension 6 SMEFT

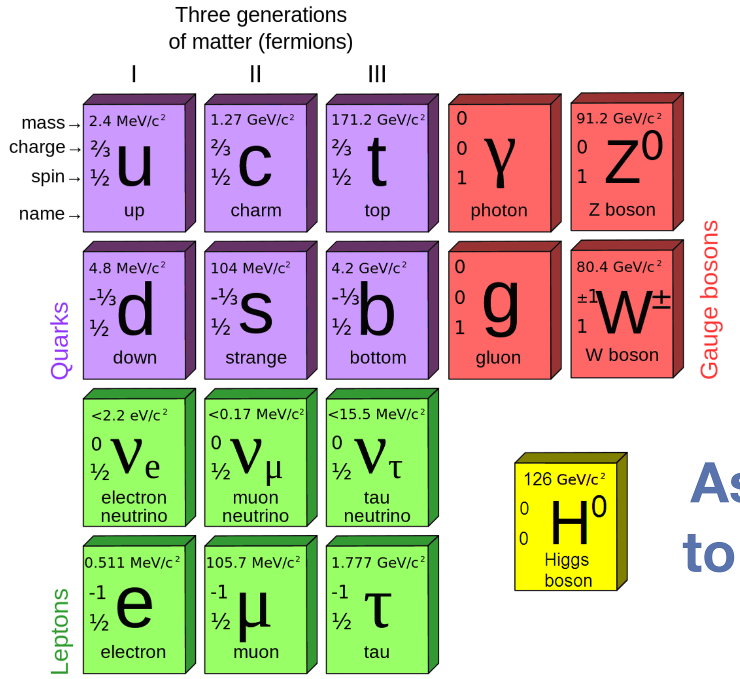
The dimension 6 SMEFT

- **The Standard Model Effective Field Theory (SMEFT):**
  - **Particles and Symmetries of the "Low-Energy" Theory:**

Poincare symmetry

SM gauge invariance

$SU(3)_c \times SU(2)_L \times U(1)_Y$



Assumed to belong to an $SU(2)_L$ doublet

  - **Power counting rules:** 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

The dimension 6 SMEFT

- **The dimension 6 SMEFT:**

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

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

$$q = v, E < \Lambda$$

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

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

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

The dimension 6 SMEFT

- **SMEFT operators directly testable at FCC-ee (non-exhaustive list):**

$h \to VV$

$$\begin{aligned}
\mathcal{O}_{\phi\Box} &= (\phi^\dagger\phi)\,\Box\,(\phi^\dagger\phi)\\
\mathcal{O}_{\phi G} &= (\phi^\dagger\phi)\,G^A_{\mu\nu}G^{A\,\mu\nu}\\
\mathcal{O}_{\phi W} &= (\phi^\dagger\phi)\,W^a_{\mu\nu}W^{a\,\mu\nu}\\
\mathcal{O}_{\phi B} &= (\phi^\dagger\phi)\,B_{\mu\nu}B^{\mu\nu}\\
\mathcal{O}_{\phi WB} &= (\phi^\dagger\sigma_a\phi)W^a_{\mu\nu}B^{\mu\nu}\\
\mathcal{O}_{\phi D} &= \left|\phi^\dagger iD_\mu\phi\right|^2
\end{aligned}$$

Also enter in EWPO & *VV* prod.

$h \to ff$

$$\begin{aligned}
\mathcal{O}_{\phi\Box} &= (\phi^\dagger\phi)\,\Box\,(\phi^\dagger\phi)\\
\mathcal{O}_{e\phi} &= (\phi^\dagger\phi)\,(\overline{l_L}\phi e_R)\\
\mathcal{O}_{u\phi} &= (\phi^\dagger\phi)\,\left(\overline{q_L}\tilde{\phi}u_R\right)\\
\mathcal{O}_{d\phi} &= (\phi^\dagger\phi)\,(\overline{q_L}\phi d_R)
\end{aligned}$$

Not directly testable with EWPO nor *VV* prod.

$$\mathcal{O}_{3W} = \epsilon_{abc}W^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$$

Enters only in *VV* prod.

$h \to Vff$

$$\begin{aligned}
\mathcal{O}^{(1)}_{\phi f} &= (\phi^\dagger i\overset{\leftrightarrow}{D}_\mu\phi)(\overline{f}\gamma^\mu f)\\
\mathcal{O}^{(3)}_{\phi f} &= (\phi^\dagger i\overset{\leftrightarrow}{D}{}^a_\mu\phi)(\overline{f}\gamma^\mu\sigma_a f)
\end{aligned}$$

Strongly constrained by EWPO
(induce modified *Vff* couplings)

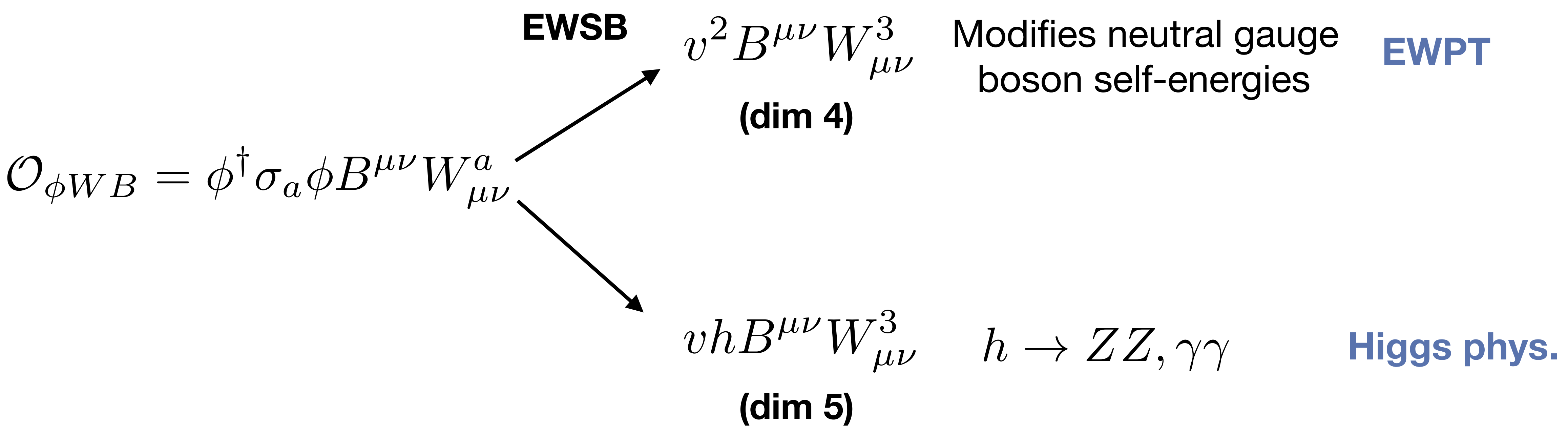
Indirect

$$\begin{aligned}
\mathcal{O}_{ll} &= (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)\\
\mathcal{O}^{(3)}_{\phi l} &= (\phi^\dagger i\overset{\leftrightarrow}{D}{}^a_\mu\phi)(\bar{l}\gamma^\mu\sigma_a l)\\
\mathcal{O}_{\phi D} &= \left|\phi^\dagger iD_\mu\phi\right|^2\\
\mathcal{O}_{\phi WB} &= (\phi^\dagger\sigma_a\phi)W^a_{\mu\nu}B^{\mu\nu}
\end{aligned}$$

Modify SM inputs:
Enter in all EW processes

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)**
    - **Describes correlations of new physics effects in different types of observables, e.g.**



EWSB

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

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

(dim 4)

Modifies neutral gauge boson self-energies

EWPT

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

(dim 5)

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

Higgs phys.

The dimension 6 SMEFT

- **Advantages of EFTs:**
  - Well-defined way of connecting with explicit UV completions via matching/integrating out heavy degrees of freedom

Full UV/EFT dictionary known at tree level:

48 different types of fields (different quantum numbers) contribute at dim. 6
    19 scalar fields
    13 vector-like fermion fields: 6 leptons + 7 quarks
    16 vector boson fields

J.B., J.C. Criado, M. Pérez-Victoria and J. Santiago, arXiv:1711.10391 [hep-ph]

General results also known at loop level (Universal 1-loop effective action)

Henning, Lu, Murayama, arXiv:1411.1837 [hep-ph]
Drozd, Ellis, Quevillon, You, arXiv:1511.03003 [hep-ph]
Ellis, Quevillon, You, Zhang, arXiv:1604.02445, 1706.07765 [hep-ph]

Tools available or in development for automatized matching

⇒ **Straightforward to connect EFT results with particular models**

EFT fits at FCC-ee

Fitting framework

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.
  - **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)

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

Fit inputs: Theory and Experiment

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

SM input

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and dominant exp. error
m_Z (keV)	91186700±2200	5	100	Z line shape scan; beam energy calibration
Γ_Z (keV)	2495200±2300	8	100	Z line shape scan; beam energy calibration
R_l^Z ($\times 10^3$)	20767±25	0.06	0.2-1.0	ratio hadrons / leptons, lepton acceptance
α_s (m_Z) ($\times 10^4$)	1196±30	0.1	0.4-1.6	from R_l^Z above
R_b ($\times 10^6$)	216290±660	0.3	<60	ratio $b\bar{b}$/hadrons, stat. extrapol. from SLD
$\sigma_{\rm had}^0$ ($\times 10^3$) (nb)	41541±37	0.1	4	peak hadronic cross section, luminosity meas.
N_ν ($\times 10^3$)	2991±7	0.005	1	Z peak cross sections, luminosity measurement
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	231480±160	3	2-5	from $A_{FB}^{\mu\mu}$ at Z peak, beam energy calibration
$1/\alpha_{\rm QED}(m_Z)$ ($\times 10^3$)	128952±14	4	Small	from $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992±16	0.02	1-3	b-quark asymmetry at Z pole, from jet charge
$A_{FB}^{{\rm pol},\tau}$ ($\times 10^4$)	1498±49	0.15	<2	τ polarisation, charge asymmetry, τ decay physics
m_W (MeV)	80350±15	0.6	0.3	WW threshold scan; beam energy calibration
Γ_W (MeV)	2085±42	1.5	0.3	WW threshold scan; beam energy calibration
α_s (m_W) ($\times 10^4$)	1170±420	3	Small	from R_l^W
N_ν($\times 10^3$)	2920±50	0.8	Small	ratio invisible to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740±500	20	Small	$t\bar{t}$ threshold scan; QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410±190	40	Small	$t\bar{t}$ threshold scan; QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2±0.3	0.08	Small	$t\bar{t}$ threshold scan; QCD errors dominate
ttZ couplings	±30%	0.5 – 1.5%	Small	from E_{CM} = 365 GeV run

Fit inputs: Theory and Experiment

- **DiBoson (WW) precision measurements at FCC-ee**

Decay mode relative precision	$B(\mathrm{W} \to e\nu)$	$B(\mathrm{W} \to \mu\nu)$	$B(\mathrm{W} \to \tau\nu)$	$B(\mathrm{W} \to qq)$
LEP2	1.5%	1.4%	1.8%	0.4%
FCC-ee	$3{\cdot}10^{-4}$	$3{\cdot}10^{-4}$	$4{\cdot}10^{-4}$	$1{\cdot}10^{-4}$

Relevant to constrain CC couplings + NC for each neutrino flavour

Fit inputs: Theory and Experiment

Intrinsic theory uncertainties: EWPO

FCC-ee-Z EWPO error estimations				
	$\delta\Gamma_Z$ [MeV]	δR_l $[10^{-4}]$	δR_b $[10^{-5}]$	$\delta \sin^2\theta_{\rm eff}^{\rm l}$ $[10^{-5}]$
FCC-ee	0.1	10	$2 \div 6$	6
TH1-new	0.4	60	10	45
TH2	0.15	15	5	15
TH3	< 0.07	< 7	< 3	< 7

Standard Model Theory for the FCC-ee: The Tera-Z, arXiv:1809.01830 [hep-ph]

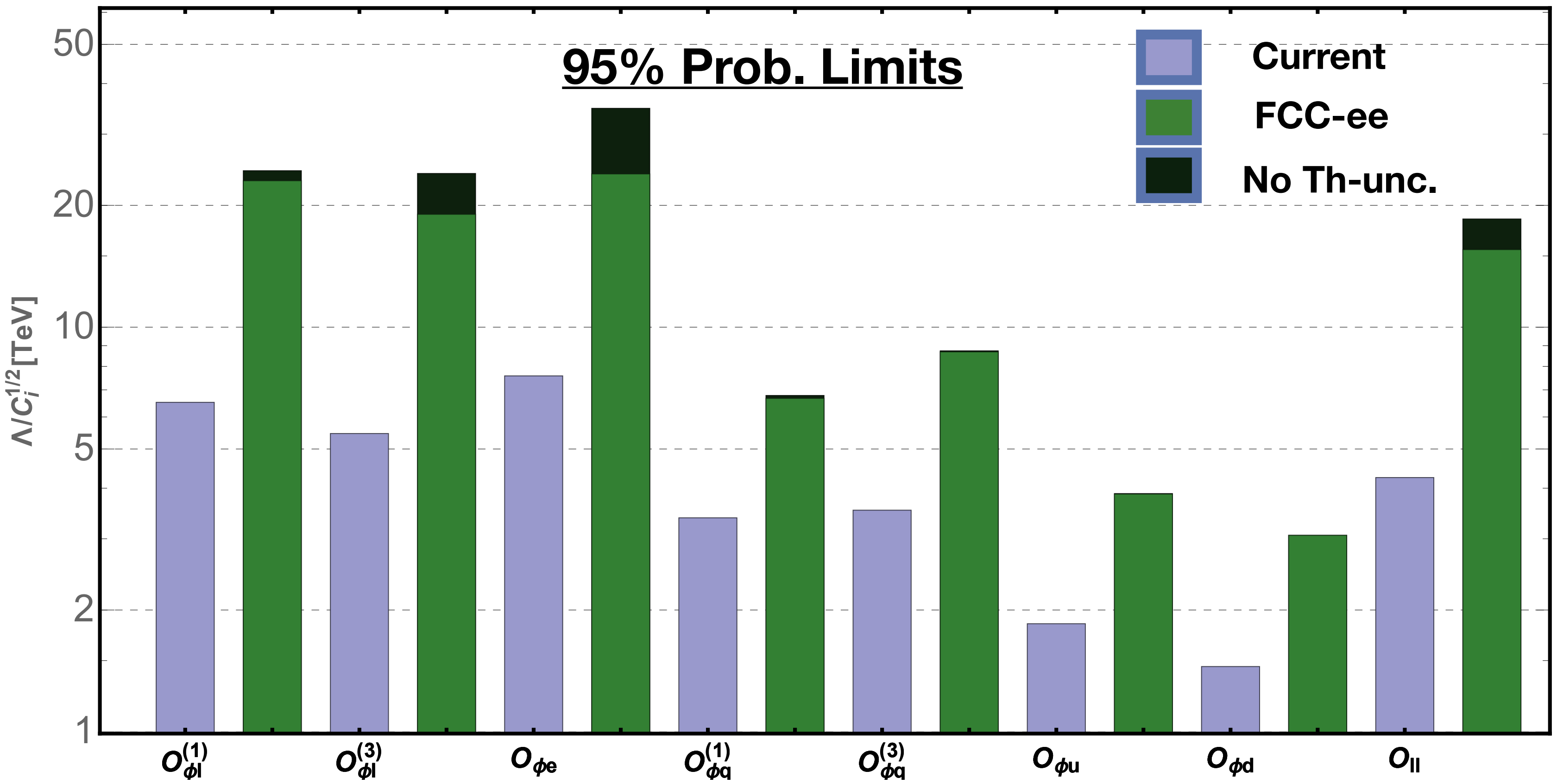
- TH1: Current intrinsic uncertainty
- TH2: Extrapolation assuming EW 3-loop corrections are known
- TH3: Same as TH2 assuming dominant 4-loop corrections are known

Modeled via nuisance parameters modifying the SM predictions

The Global EW fit at FCC-ee

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

Impact of theory uncertainties



Theory uncertainties have a significant impact in the sensitivity to New Physics (not easy to see in this global fit)

	Current		FCCee		
	Exp.	SM	Exp.	SM (par.)	SM (th.)
δM_W [MeV]	±15	±8	±1	$\pm0.6/\pm1$	±1
$\delta\Gamma_Z$ [MeV]	±2.3	±0.73	±0.1	±0.1	±0.2
$\delta\mathcal{A}_\ell$ [$\times10^{-5}$]	±210	±93	±2.1	$\pm8/\pm14$	±11.8
δR_b^0 [$\times10^{-5}$]	±66	±3	±6	±0.3	$\pm$ 5

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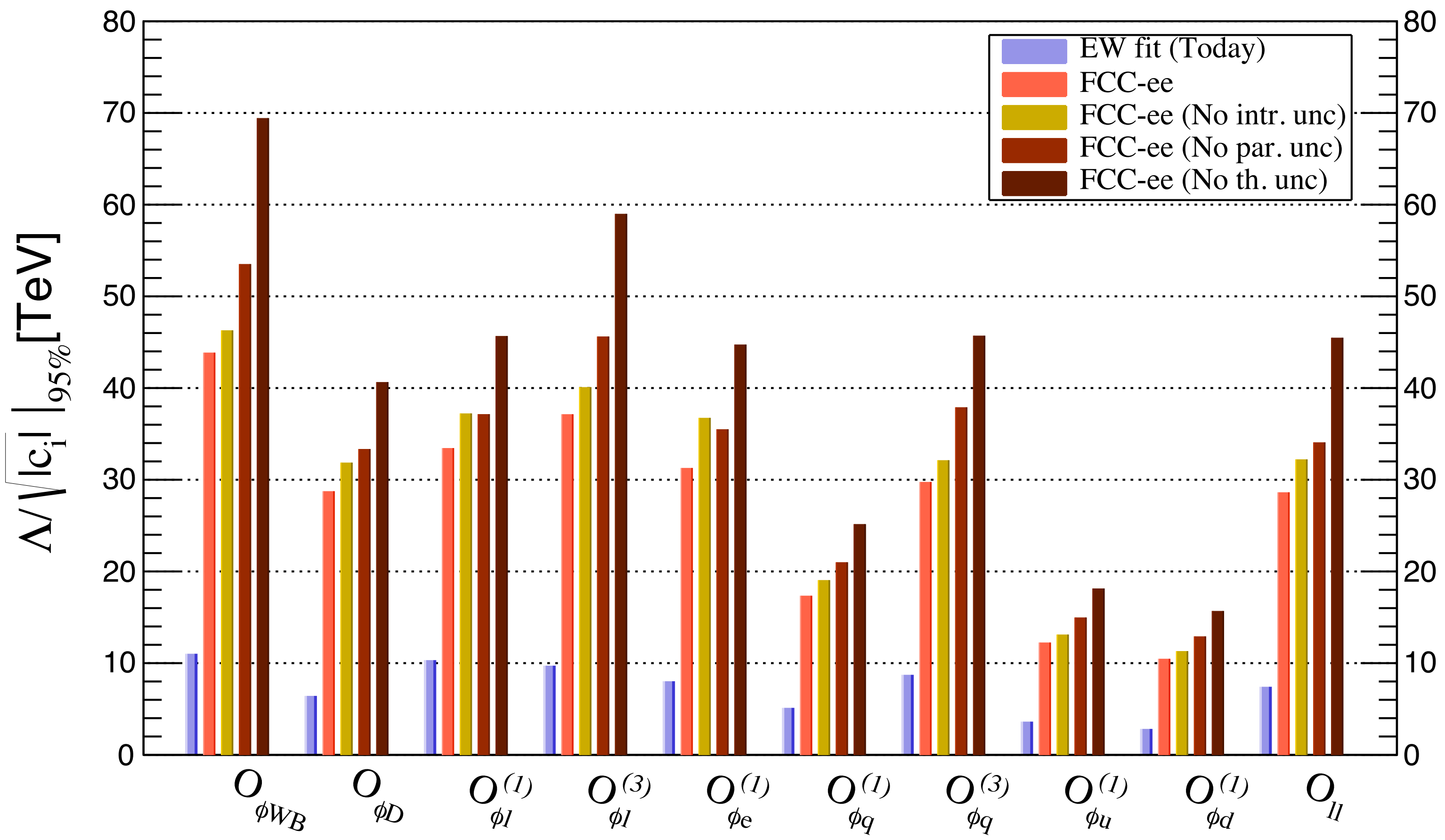
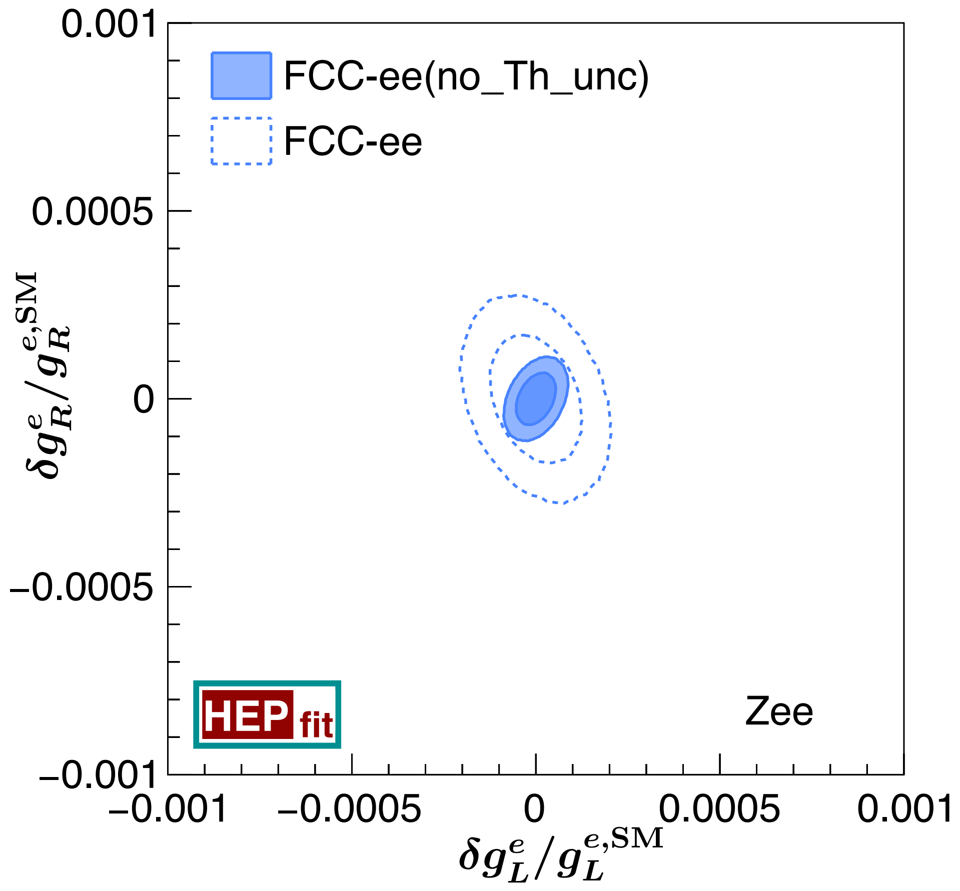


Fit 1 operator at a time



Eff. couplings in the SMEFT

$$\mathcal{L}_{\mathrm{NC}} = -\frac{e}{sc}\left(1+\delta^U g_{\mathrm{NC}}\right) Z_\mu \sum_\psi \overline{\psi}\gamma^\mu\left[\left(g_{L,R}^\psi + \delta^D g_{L,R}^\psi\right) P_{L,R} + \delta^Q g_{\mathrm{NC}}\right]\psi$$

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

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

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

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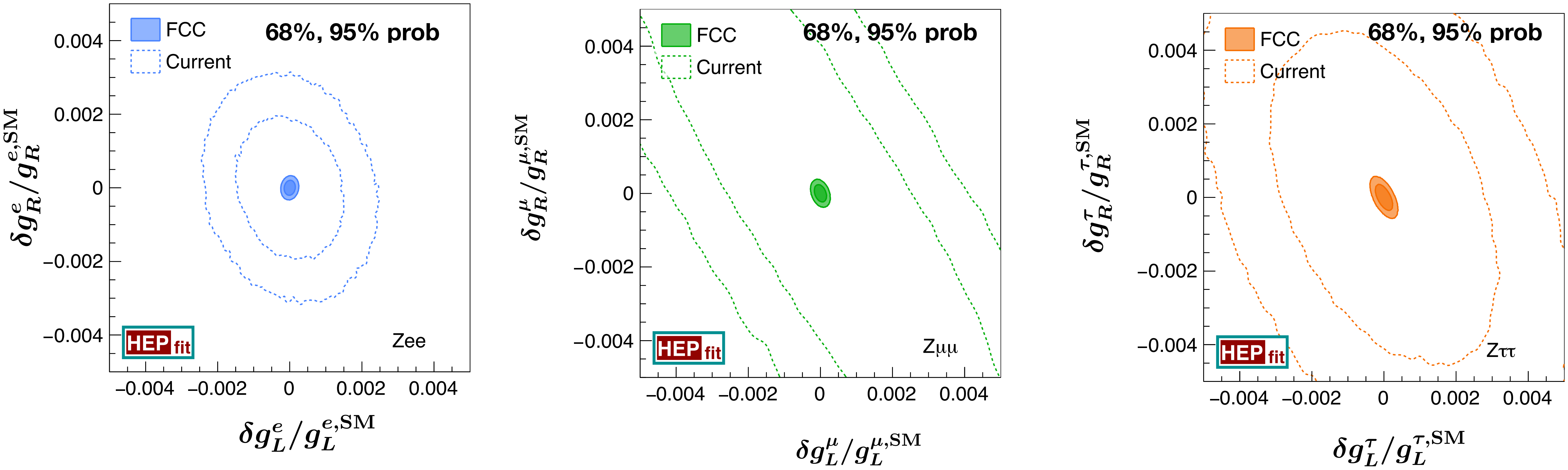


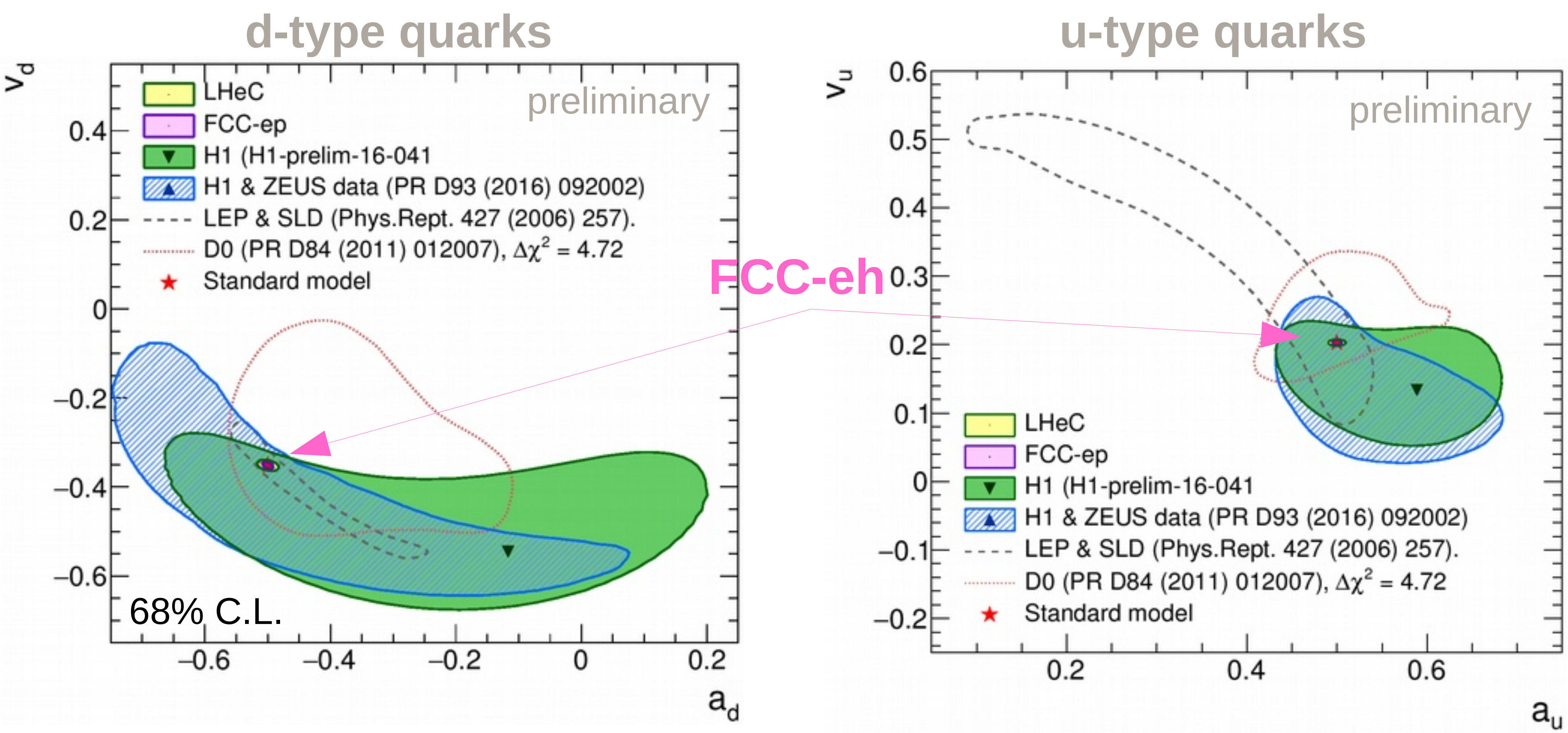
No Lepton flavour universality assumed

We can also lift the assumption of quark universality and constraint the couplings to all quark families independently using FCC-ee + FCC-eh

The Global EW fit at FCC

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

Precision measurements of couplings to light quark families



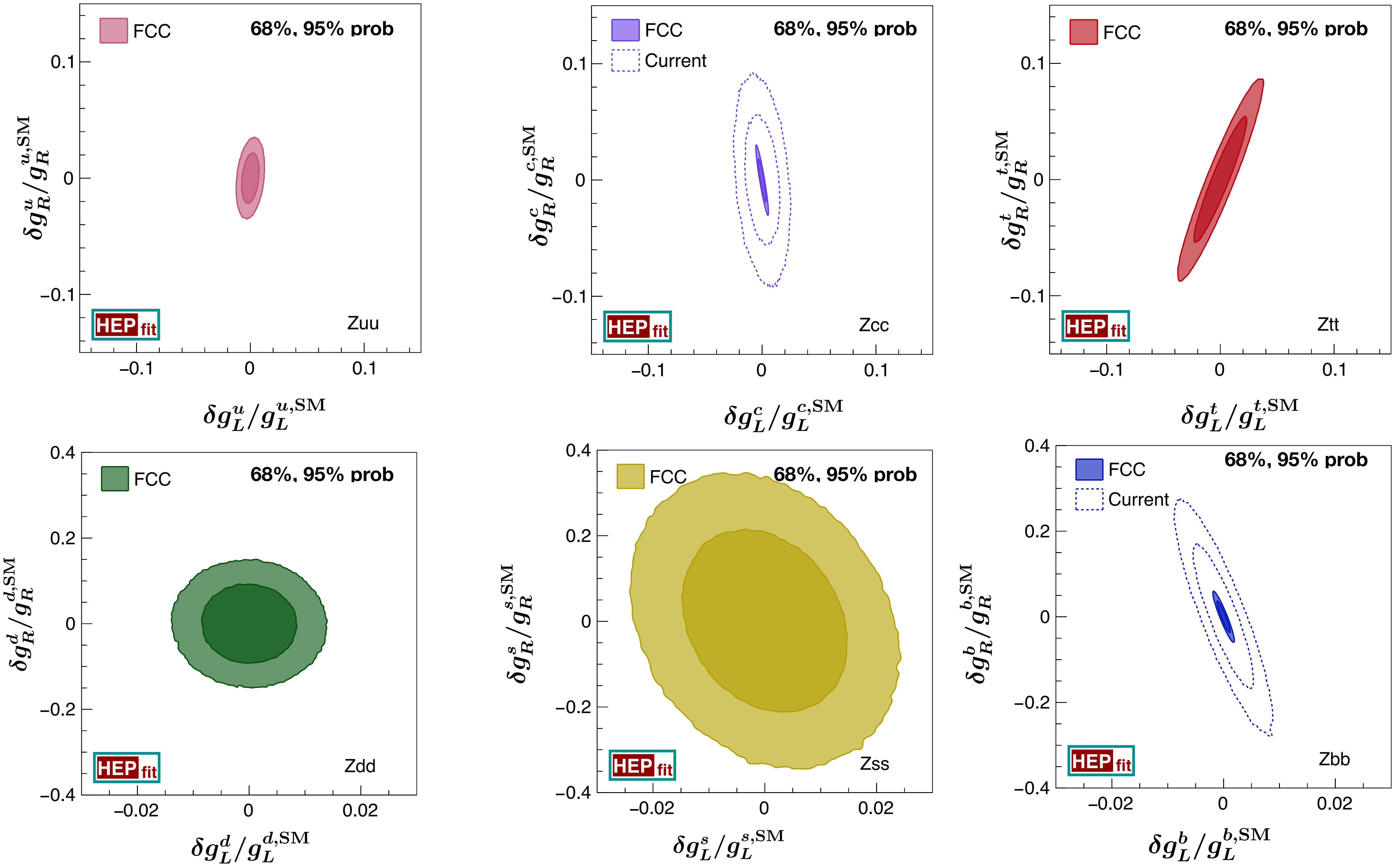
Observable	Uncertainty	(Relative uncertainty)
g_V^u	0.0022	(1.1%)
g_A^u	0.0031	(0.6%)
g_V^d	0.0049	(1.4%)
g_A^d	0.0049	(0.97%)

Assuming new physics only in Zqq couplings

The Global EW fit at FCC

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

No Fermion flavour universality assumed



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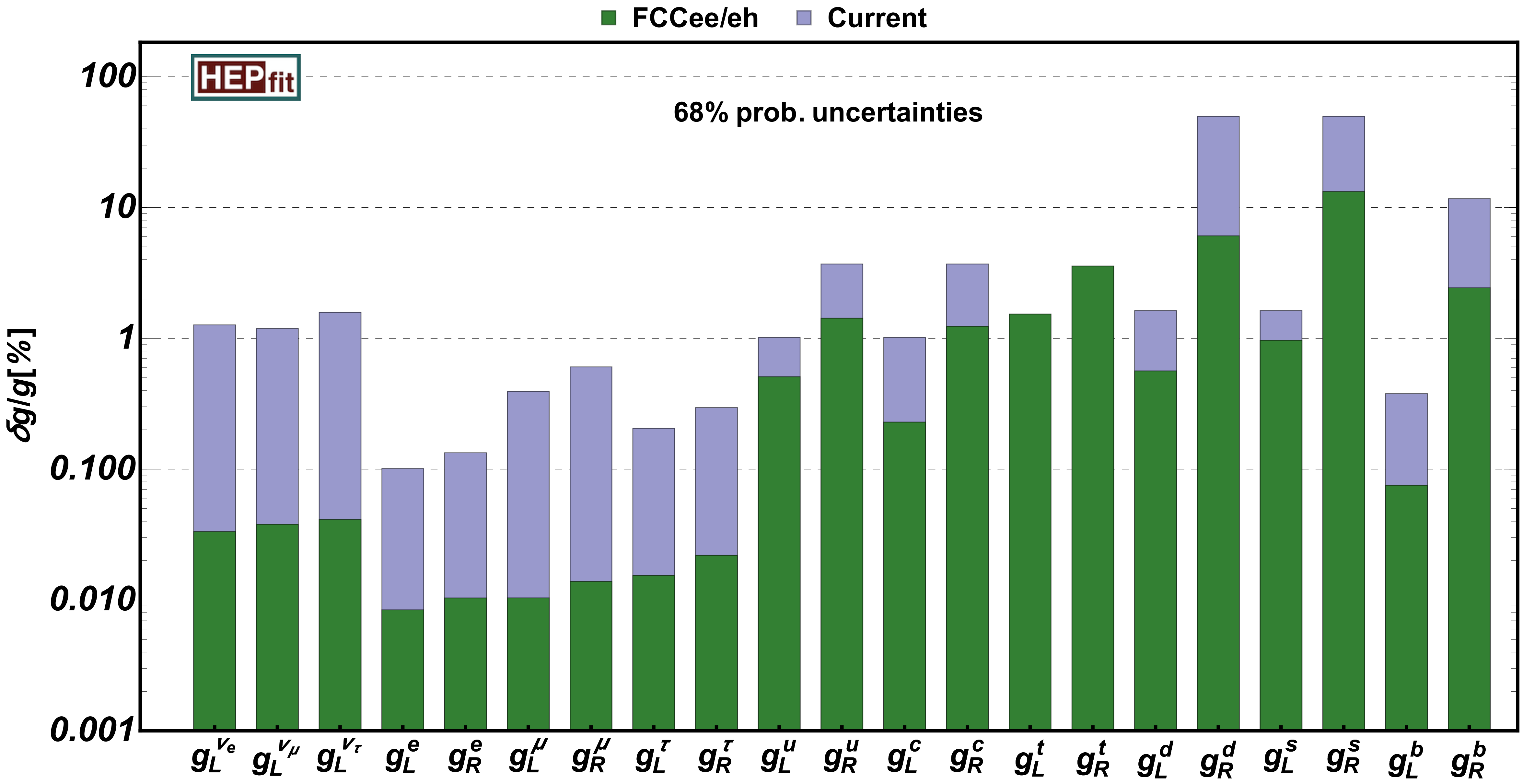


No Fermion flavour universality assumed

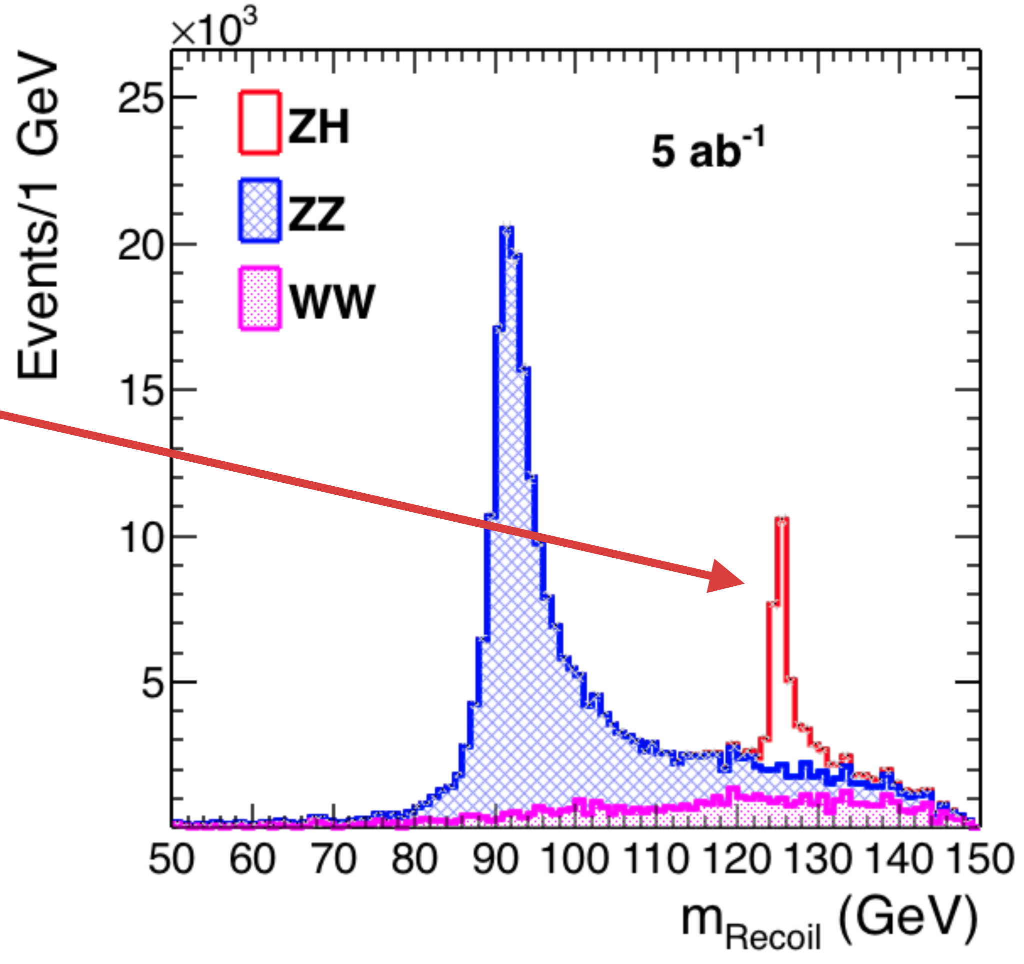
Independent info about all 3 SM fermion families

Fit inputs: Theory and Experiment

- **Higgs precision measurements at FCC-ee**

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \to$ any	±0.5		±0.9	
$H \to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \to c\bar{c}$	±2.2		±6.5	±10
$H \to gg$	±1.9		±3.5	±4.5
$H \to W^+W^-$	±1.2		±2.6	±3.0
$H \to ZZ$	±4.4		±12	±10
$H \to \tau\tau$	±0.9		±1.8	±8
$H \to \gamma\gamma$	±9.0		±18	±22
$H \to \mu^+\mu^-$	±19		±40	
$H \to$ invis.	< 0.3		< 0.6	

Absolute measurement of HZZ couplings (σ_{ZH})



Allows model-independent measurement of Higgs width

Fit inputs: Theory and Experiment

Theory uncertainties: Higgs observables

Decay	Intrinsic	Param. m_q	Param. α_s	Para. M_H
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	$-$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	$-$
$H \to \tau^+\tau^-$	$< 0.1\%$	$-$	$-$	$-$
$H \to \mu^+\mu^-$	$< 0.1\%$	$-$	$-$	$-$
$H \to gg$	$\sim 1\%$		0.5%	$-$
$H \to \gamma\gamma$	$< 1\%$	$-$	$-$	$-$
$H \to Z\gamma$	$\sim 1\%$	$-$	$-$	
$H \to WW$	$\lesssim 0.4\%$	$-$	$-$	$\sim 0.1\%$
$H \to ZZ$	$\lesssim 0.3\%^\dagger$	$-$	$-$	$\sim 0.1\%$
$\Gamma_{\rm tot}$	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$

† From $e^+e^- \to HZ$ production

FCC-ee CDR

Fit inputs: Theory and Experiment

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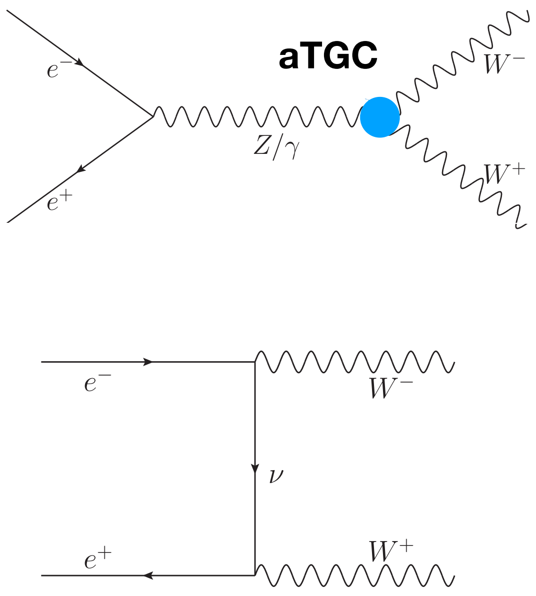
LEP2	1.5%	1.4%	1.8%	0.4%
FCC-ee	$3 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$1 \cdot 10^{-4}$

Relevant to constrain CC couplings + NC for each neutrino flavour

FCC-ee $e^+e^- \to WW$ semileptonic channel all angles								
	240 GeV only				**365 GeV only**			
	uncertainty	correlation matrix			uncertainty	correlation matrix		
		$\delta g_{1,Z}$	$\delta\kappa_\gamma$	λ_Z		$\delta g_{1,Z}$	$\delta\kappa_\gamma$	λ_Z
$\delta g_{1,Z}$	11.2×10^{-4}	1	0.08	-0.90	13.9×10^{-4}	1	-0.57	-0.80
$\delta\kappa_\gamma$	8.6×10^{-4}		1	-0.42	8.3×10^{-4}		1	0.10
λ_Z	12.3×10^{-4}			1	11.9×10^{-4}			1

	240/350/365 GeV				**161/240/350/365 GeV**			
	uncertainty	correlation matrix			uncertainty	correlation matrix		
		$\delta g_{1,Z}$	$\delta\kappa_\gamma$	λ_Z		$\delta g_{1,Z}$	$\delta\kappa_\gamma$	λ_Z
$\delta g_{1,Z}$	8.1×10^{-4}	1	-0.28	-0.87	8.1×10^{-4}	1	-0.28	-0.87
$\delta\kappa_\gamma$	5.2×10^{-4}		1	-0.12	5.2×10^{-4}		1	-0.12
λ_Z	7.9×10^{-4}			1	7.9×10^{-4}			1

Assumes aTGC dominance

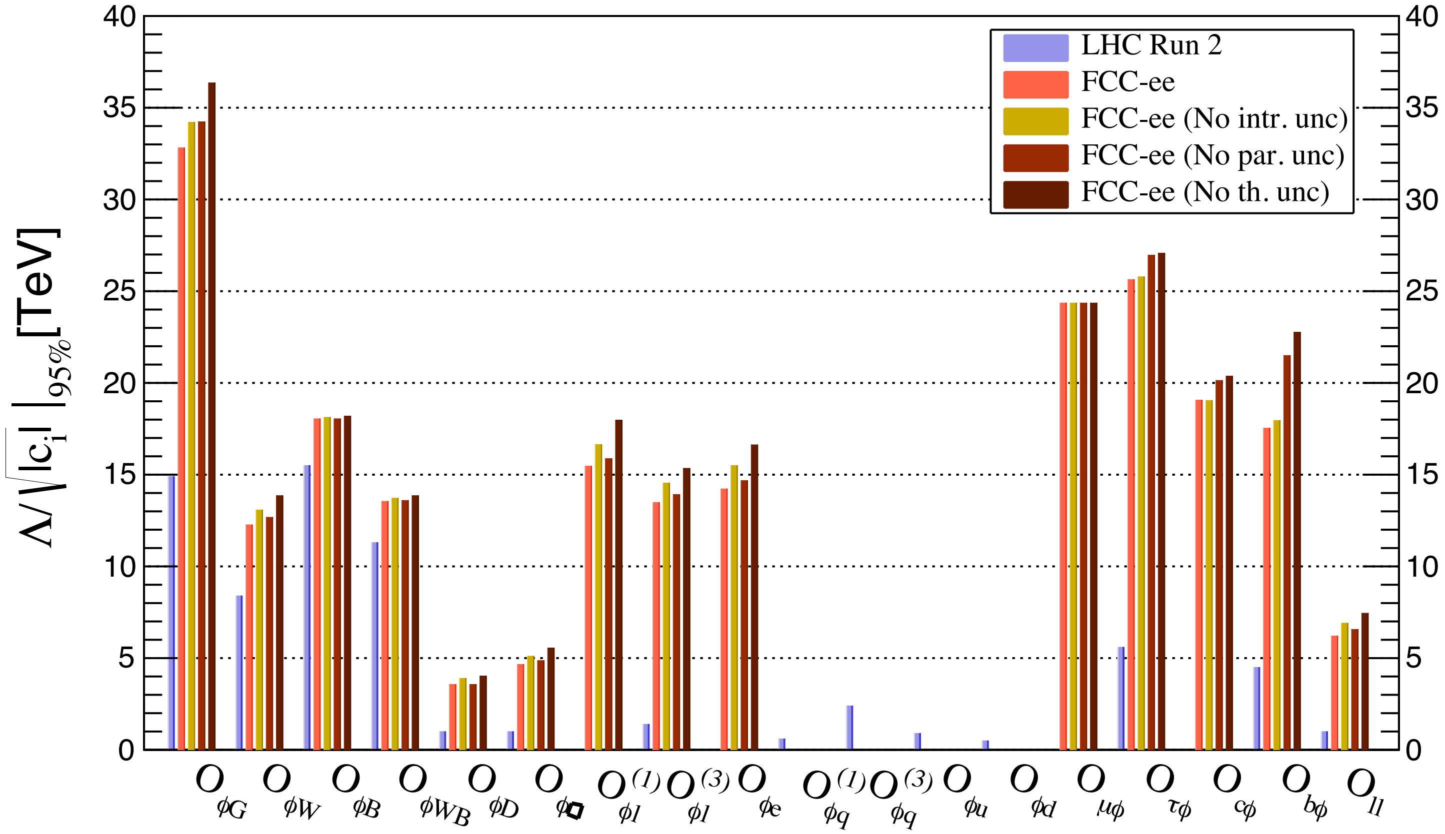


aTGC δg_{1Z} and $\delta\kappa_\gamma$ receive contributions from same interactions entering in hVV couplings ⇒ Relevant for Global Higgs fit

The Global Higgs fit at FCC

- **Fit to Higgs precision measurements at FCC-ee**

Impact of theory uncertainties



Fit 1 operator at a time

Decay	Intrinsic	Param. m_q	Param. α_s	Para. M_H
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–
$H \to gg$	$\sim 1\%$		0.5%	–
$H \to \gamma\gamma$	$< 1\%$	–	–	–
$H \to Z\gamma$	$\sim 1\%$	–	–	
$H \to WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$
$H \to ZZ$	$\lesssim 0.3\%^\dagger$	–	–	$\sim 0.1\%$
$\Gamma_{\rm tot}$	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$

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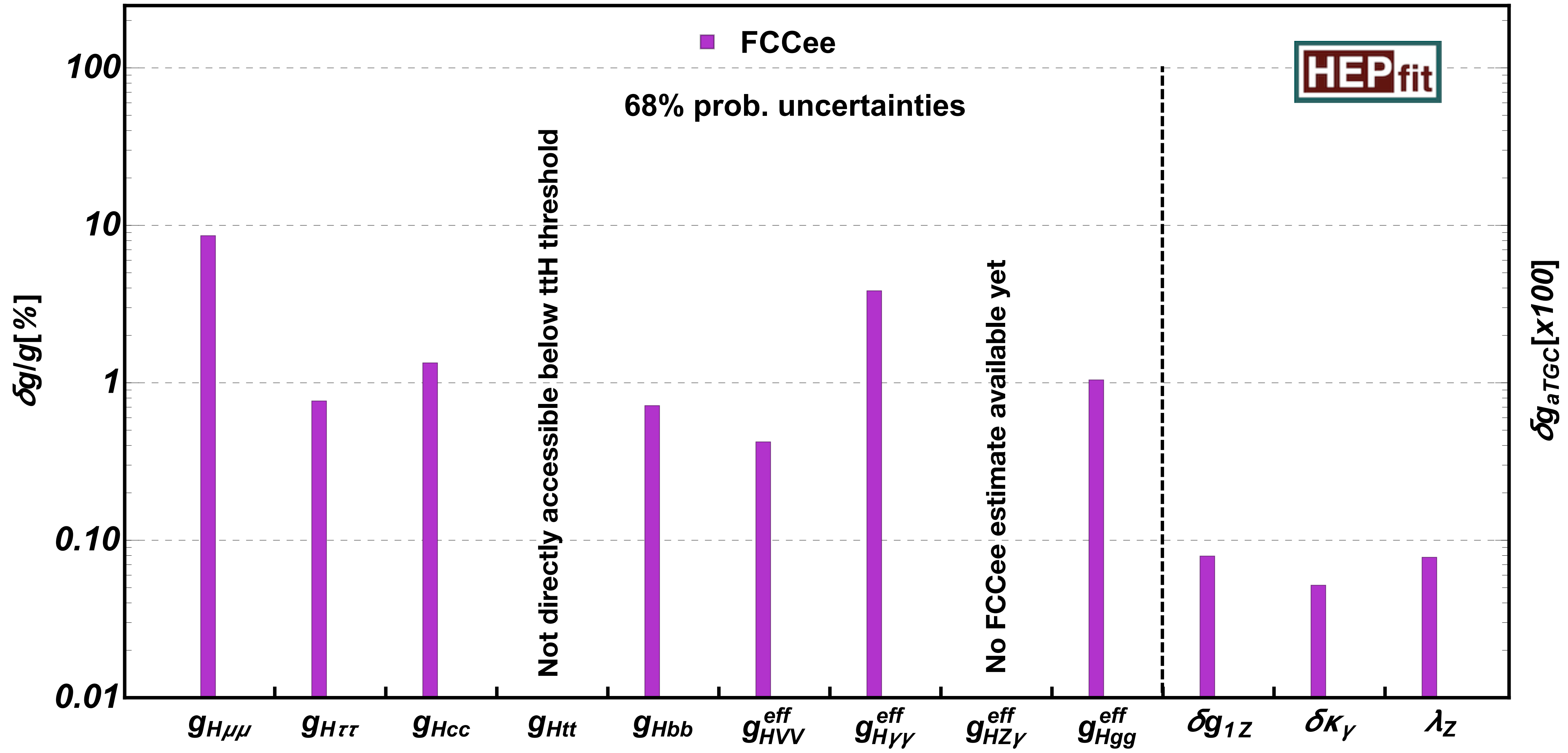
- **Fit to Higgs precision measurements at FCC-ee**



Sensitivity to NP in effective couplings in the SMEFT framework

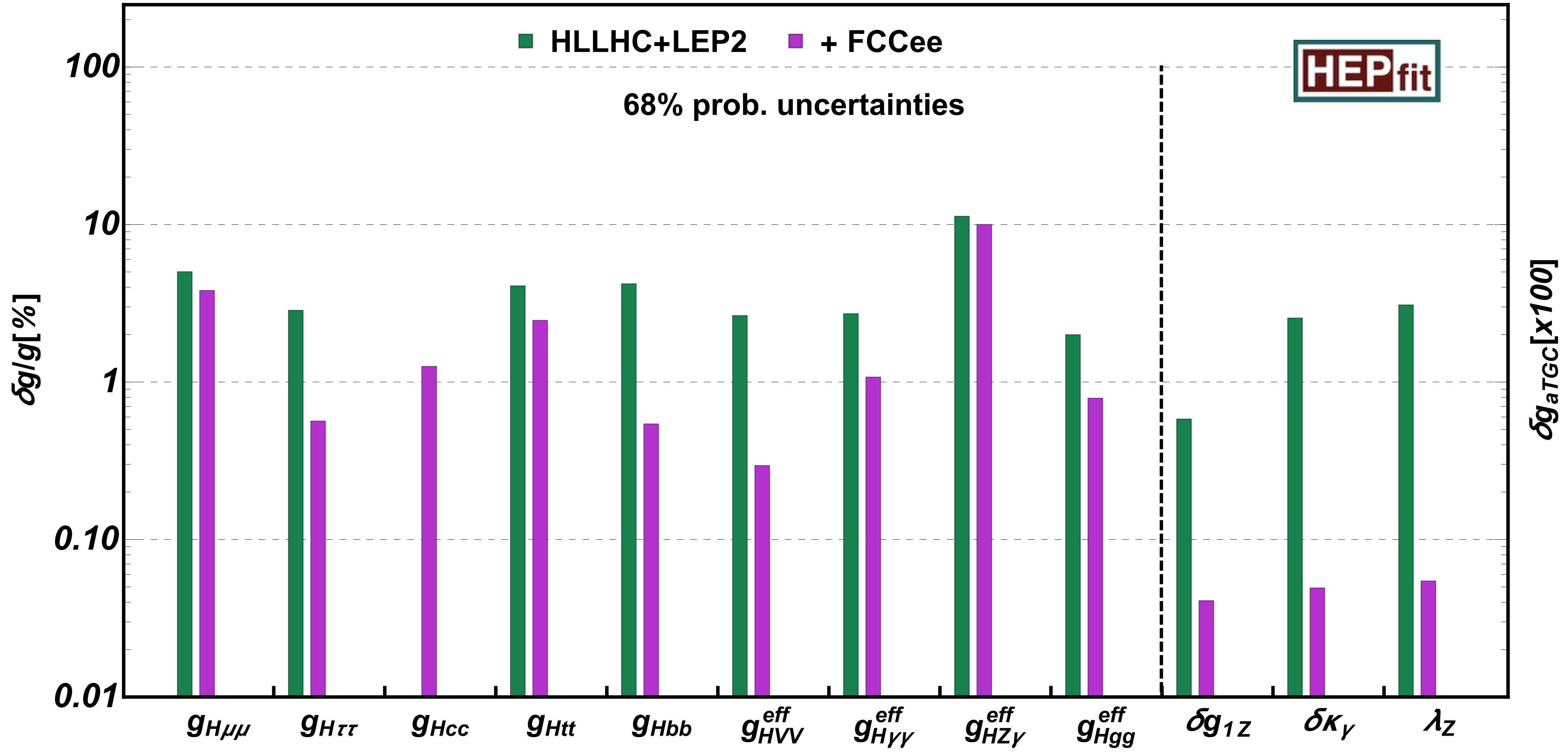
$$g^{\text{eff}\;2}_{hXX} = \frac{\Gamma_{H\to XX}}{\Gamma^{\text{SM}}_{H\to XX}}$$

e.g.

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

The Global Higgs fit at FCC

- **Fit to Higgs precision measurements at HLLHC + FCC-ee**



Sensitivity to NP in effective couplings in the SMEFT framework

$$g^{\text{eff}\ 2}_{hXX} = \frac{\Gamma_{H\to XX}}{\Gamma^{\rm SM}_{H\to XX}}$$

e.g.

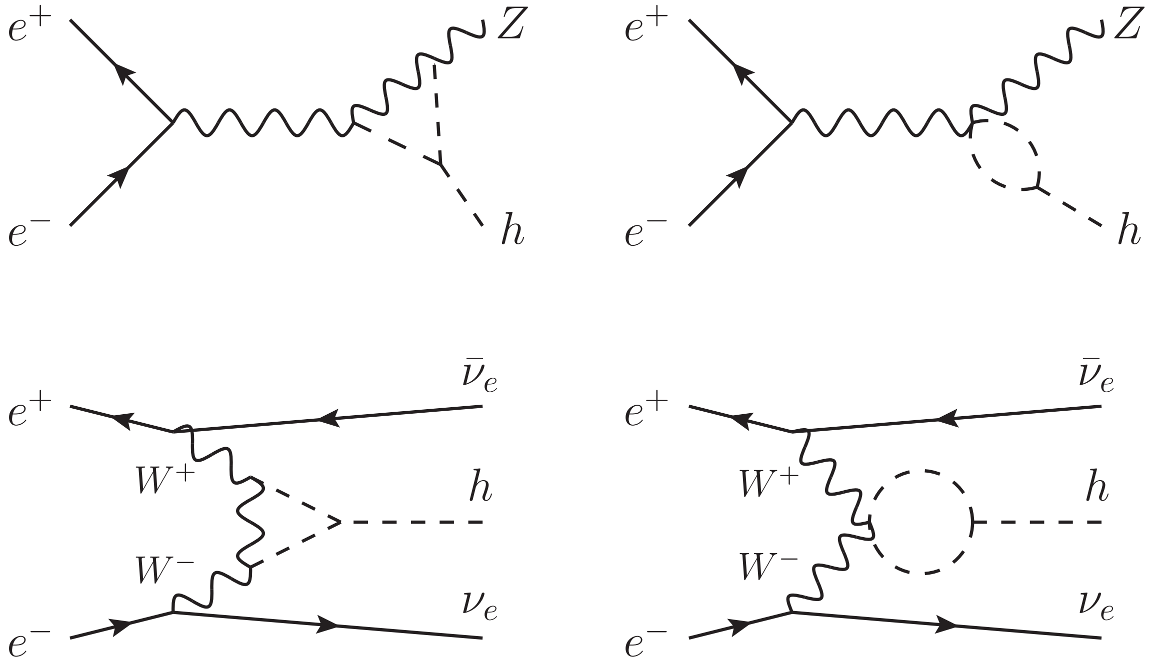
$$g_{hff} = -\frac{m_f}{v}\left(1+\left[(C_{\phi\Box}-\tfrac{1}{4}C_{\phi D}) - \frac{v}{\sqrt{2}m_f}C_{f\phi} - \tfrac{1}{2}\Delta_{G_F}\right]\frac{v^2}{\Lambda^2}\right)$$

The Global Higgs fit at FCC

FCCee sensitivity to Higgs trilinear coupling

- **Can be tested at FCC-ee via NLO effects**

M. McCullough, PRD90 (2014) no.1, 015001
S. Di Vita et al., JHEP 1802 (2018) 178



NP in the effective Higgs trilinear coupling in the SMEFT framework

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

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

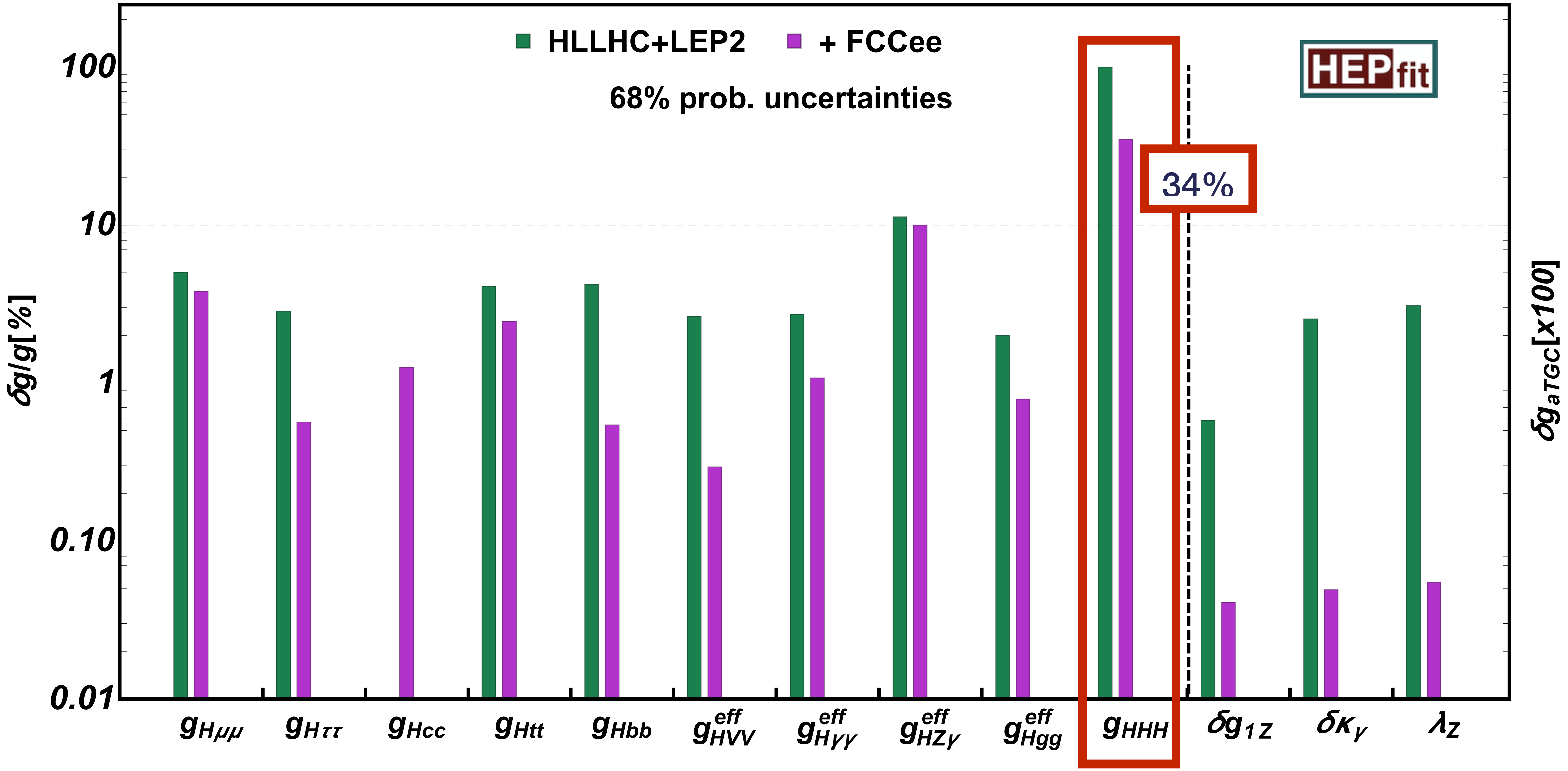
From a global fit to the FCCee Higgs + Diboson data:

$$\delta g_{hhh}/g_{hhh}^{\mathrm{SM}} \approx 40\% \qquad (\,\delta g_{hhh}/g_{hhh}^{\mathrm{SM}} \approx 25\% \quad \mathbf{4\ IPs})$$

Indirect FCC-ee sensitivity to Higgs trilinear better than direct at HLLHC

The Global Higgs fit at FCC

FCCee sensitivity to Higgs trilinear coupling



Sensitivity to NP in effective couplings in the SMEFT framework

Indirect FCC-ee sensitivity to Higgs trilinear better than direct at HLLHC

The Global Higgs fit at FCC

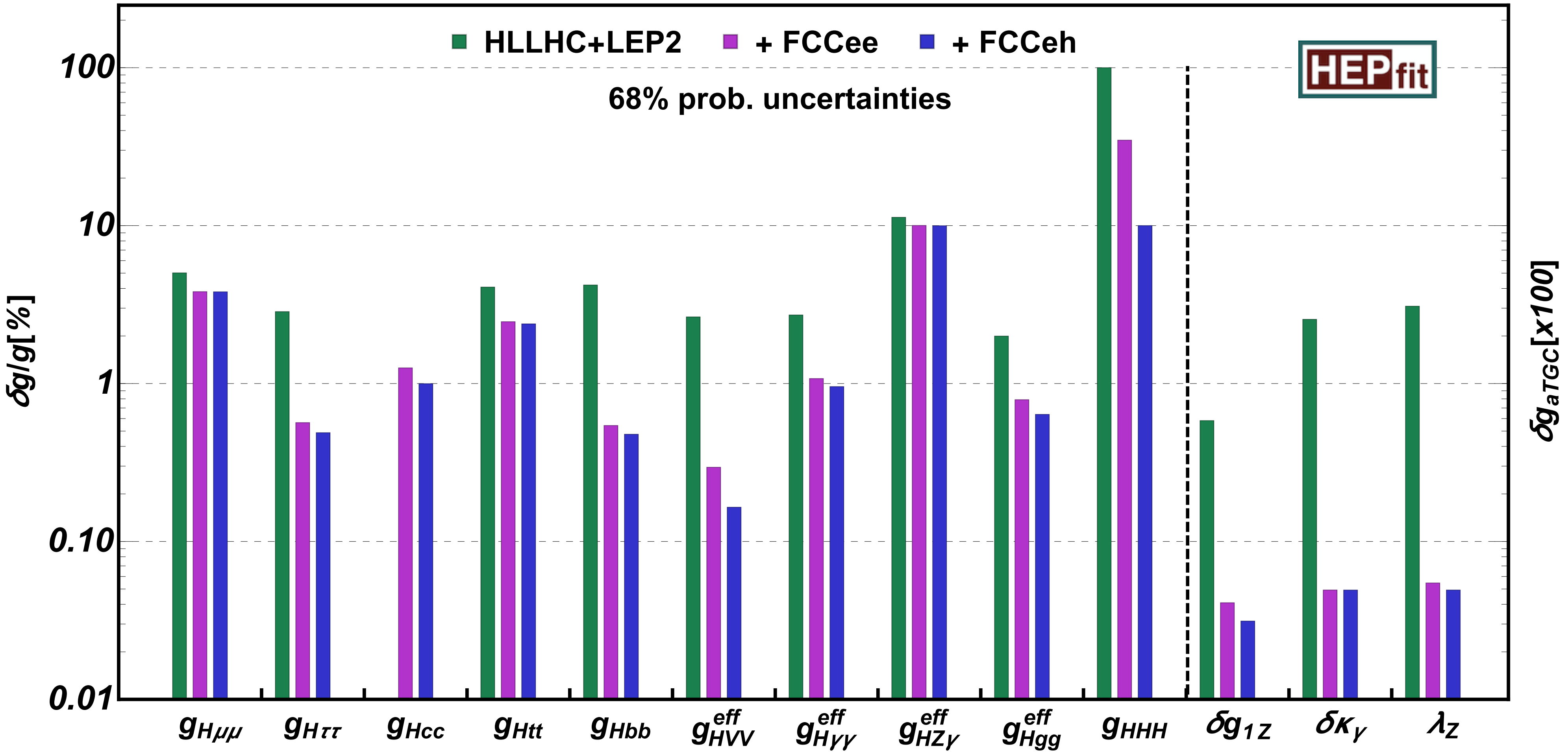
- **FCC-eh (60 GeV e - 50 TeV p): Precisions for 2 ab^{-1} of data**

CC DIS: W boson fusion

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%

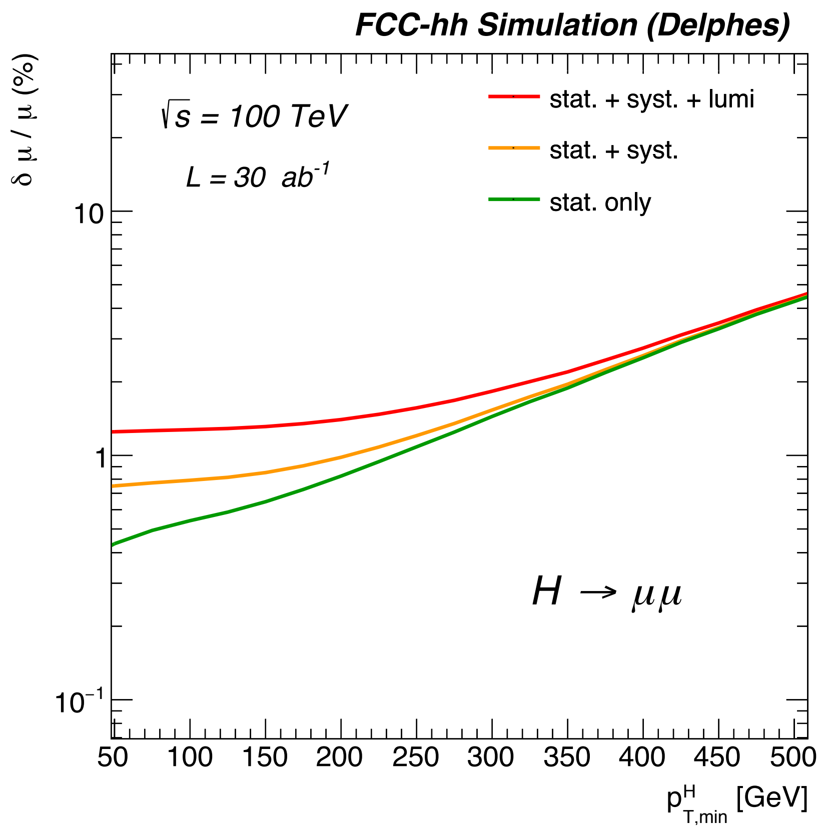
NC DIS: Z boson fusion

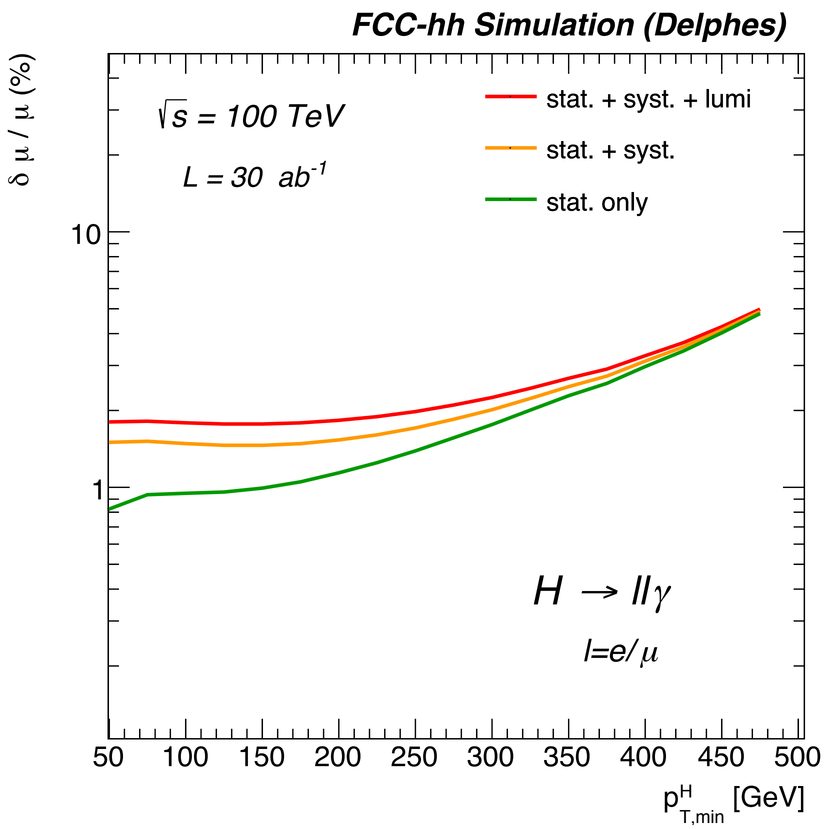
Observable	Expected uncertainty
$\sigma_{ZBF}\,\mathrm{Br}(H \to b\bar{b})$	0.83%
$\sigma_{ZBF}\,\mathrm{Br}(H \to c\bar{c})$	7.08%
$\sigma_{ZBF}\,\mathrm{Br}(H \to gg)$	5.62%
$\sigma_{ZBF}\,\mathrm{Br}(H \to W^{\pm}W^{\mp *})$	4.29%
$\sigma_{ZBF}\,\mathrm{Br}(H \to \tau^{+}\tau^{-})$	5.25%
$\sigma_{ZBF}\,\mathrm{Br}(H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



The Global Higgs fit at FCC

- **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)**





1% accuracy (stat + sys) within reach

Provided *BR(H→4l)* know to <<1%

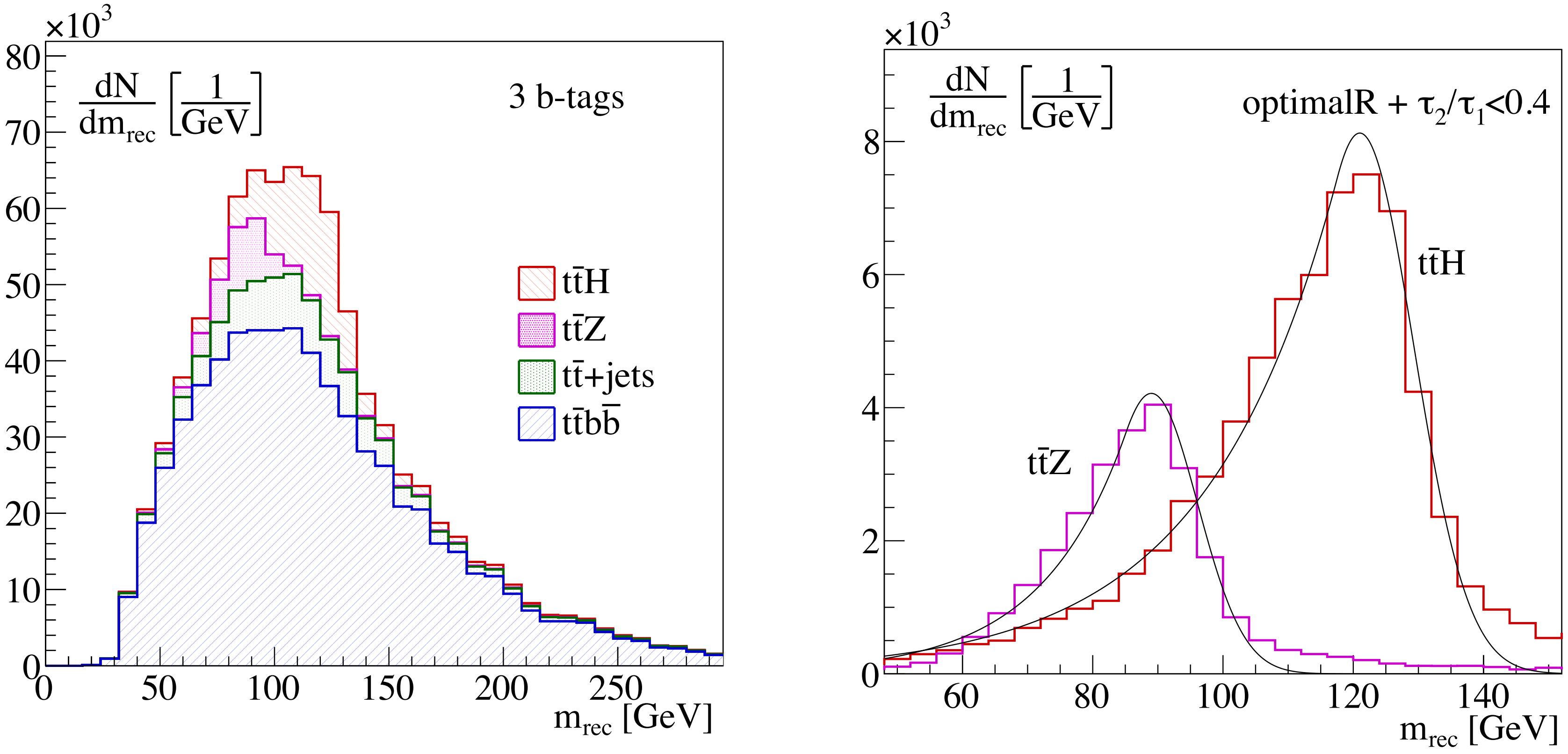
(*pp→H→4l* at FCC-hh ~1%)

Measurable at FCC-ee/eh with required precision

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

The Global Higgs fit at FCC

- **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 *σ(ttH)/σ(ttZ)* (boosted)**



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

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

Assumes no NP in *Ztt* and *BR(H→bb)* known <<1%

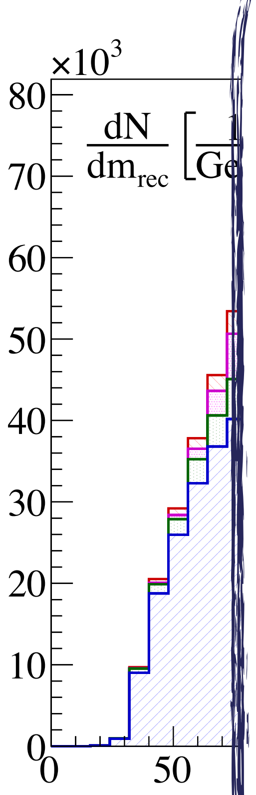
Both measurable at FCC-ee with required precision

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

The Global Higgs fit at FCC

- **Top Yukawa coupling not directly accessible at FCC-ee. Could be measured in single tH at FCC-eh**

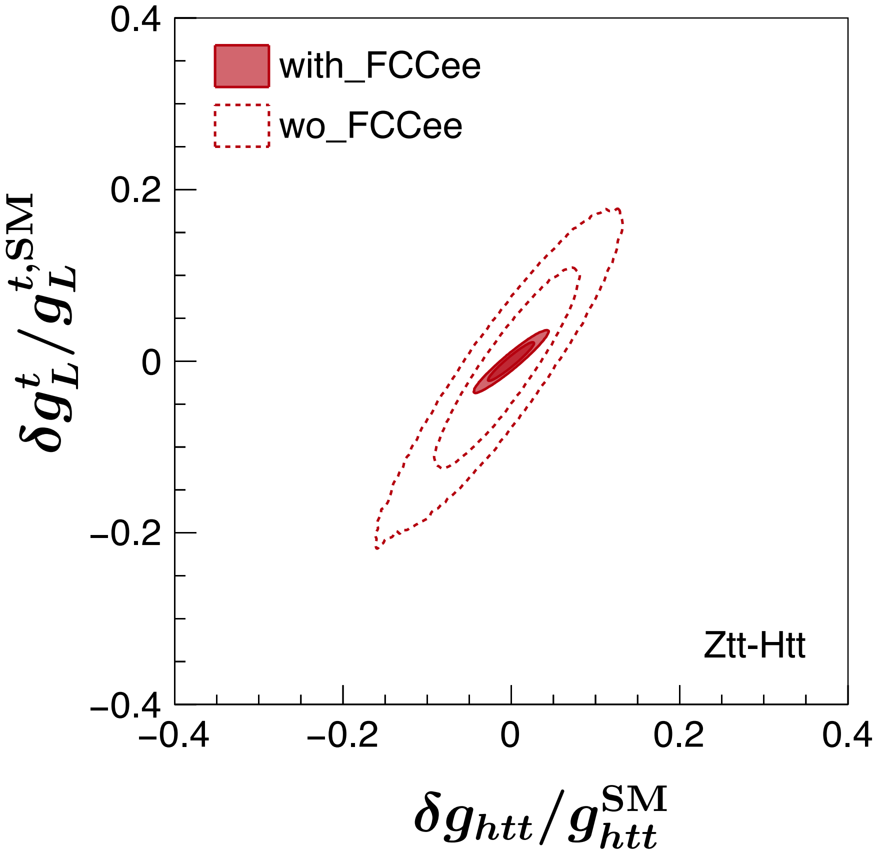
- **Can be measured at FCC-hh from *σ(ttH)/σ(ttZ)* (boosted)**



Toy fit neglecting FCCee

Assuming ~10% accuracy on Ztt top couplings

Precise measurement ~1% of LH Ztt coupling needed



ct N_H/N_Z

at+th y_t/y_t ~ 1%

in *Ztt* and

n <<1%

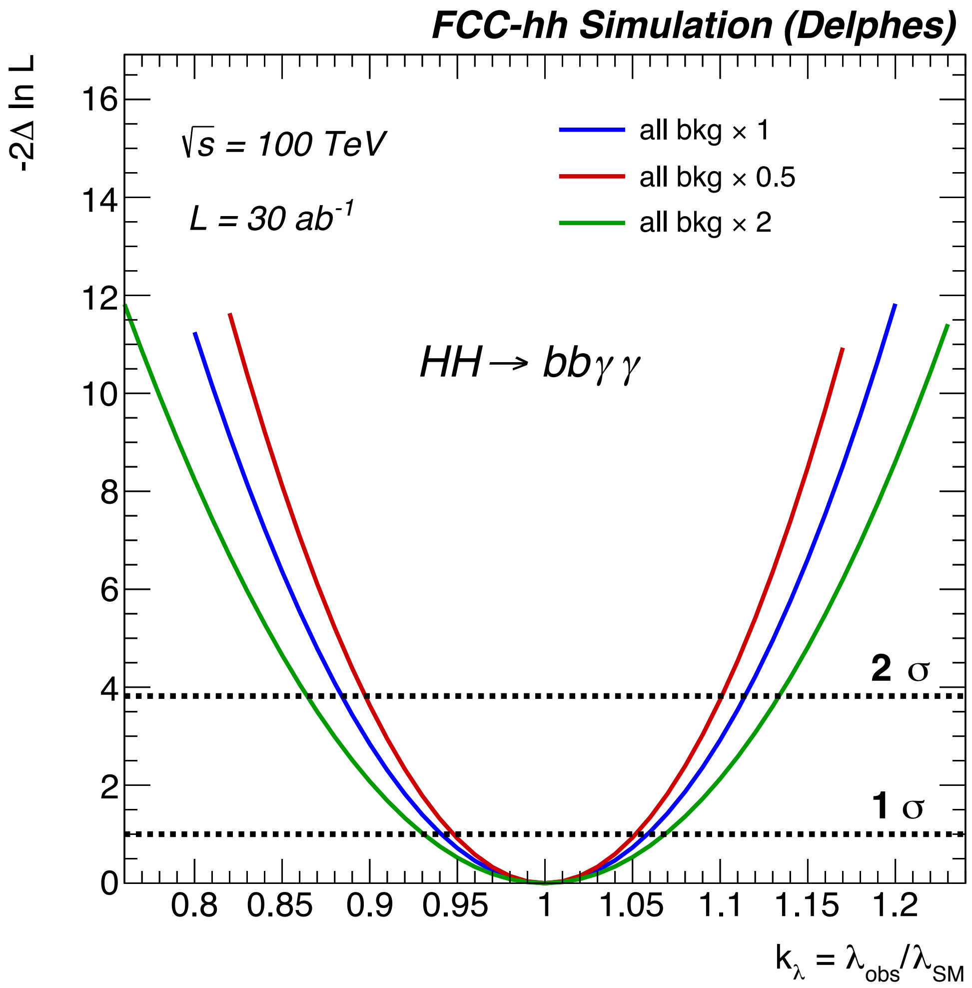
at FCC-ee

recision

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

The Global Higgs fit at FCC

- **Higgs self-interaction:**
  - **Direct HH production at FCC-hh:**

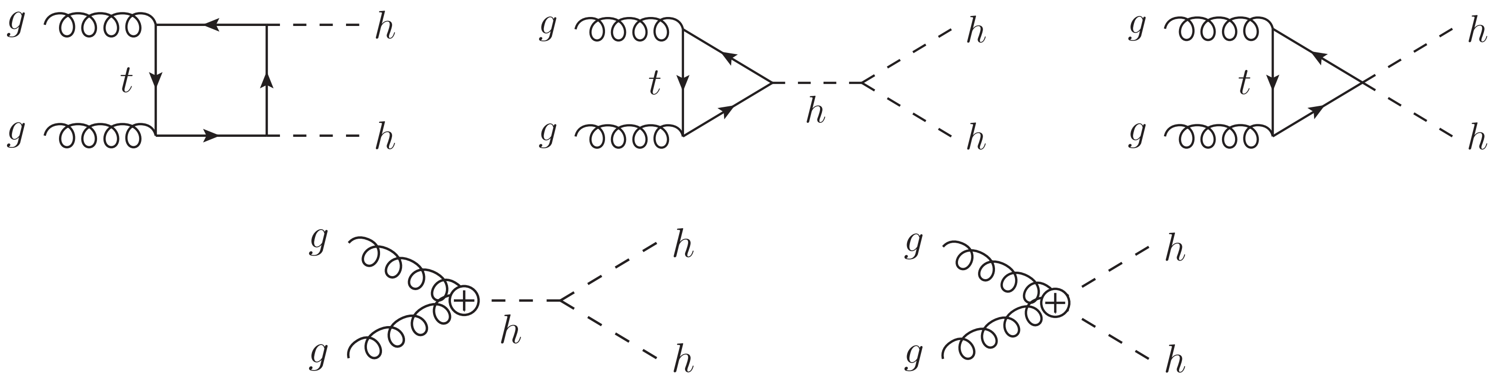


$\delta\kappa_\lambda \sim 5\%$

Assumes all uncertainty goes into κ_λ

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

But other NP parameters modify HH production and decays

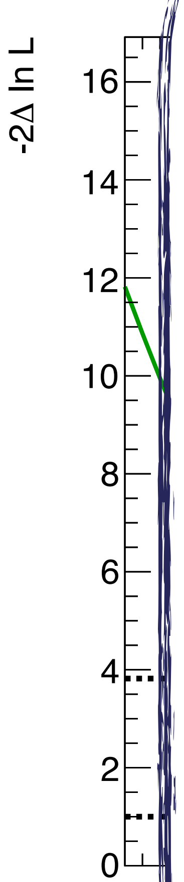


A. Azatov et al. PRD92 (2015) no.3, 035001

They can be measured at FCC-ee/eh/hh with ~1% precision

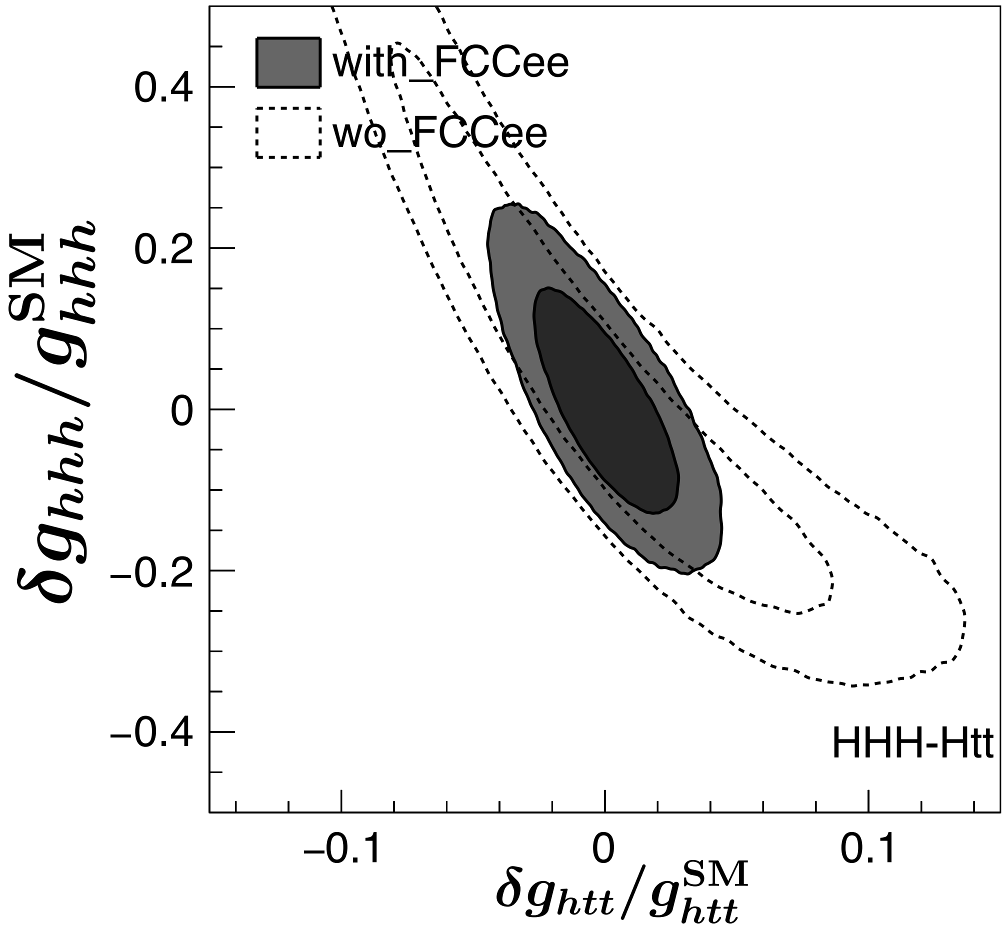
The Global Higgs fit at FCC

- **Higgs self-interaction:**
  - **Direct HH production at FCC-hh:**

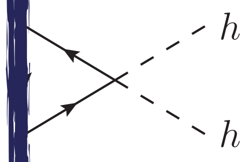


Toy fit neglecting FCCee measurements and using simple HH inclusive observable

Precise determination of operators modifying *Htt* interactions needed



$G_F \Big] \quad \frac{v^2}{\Lambda^2}$



.3, 035001

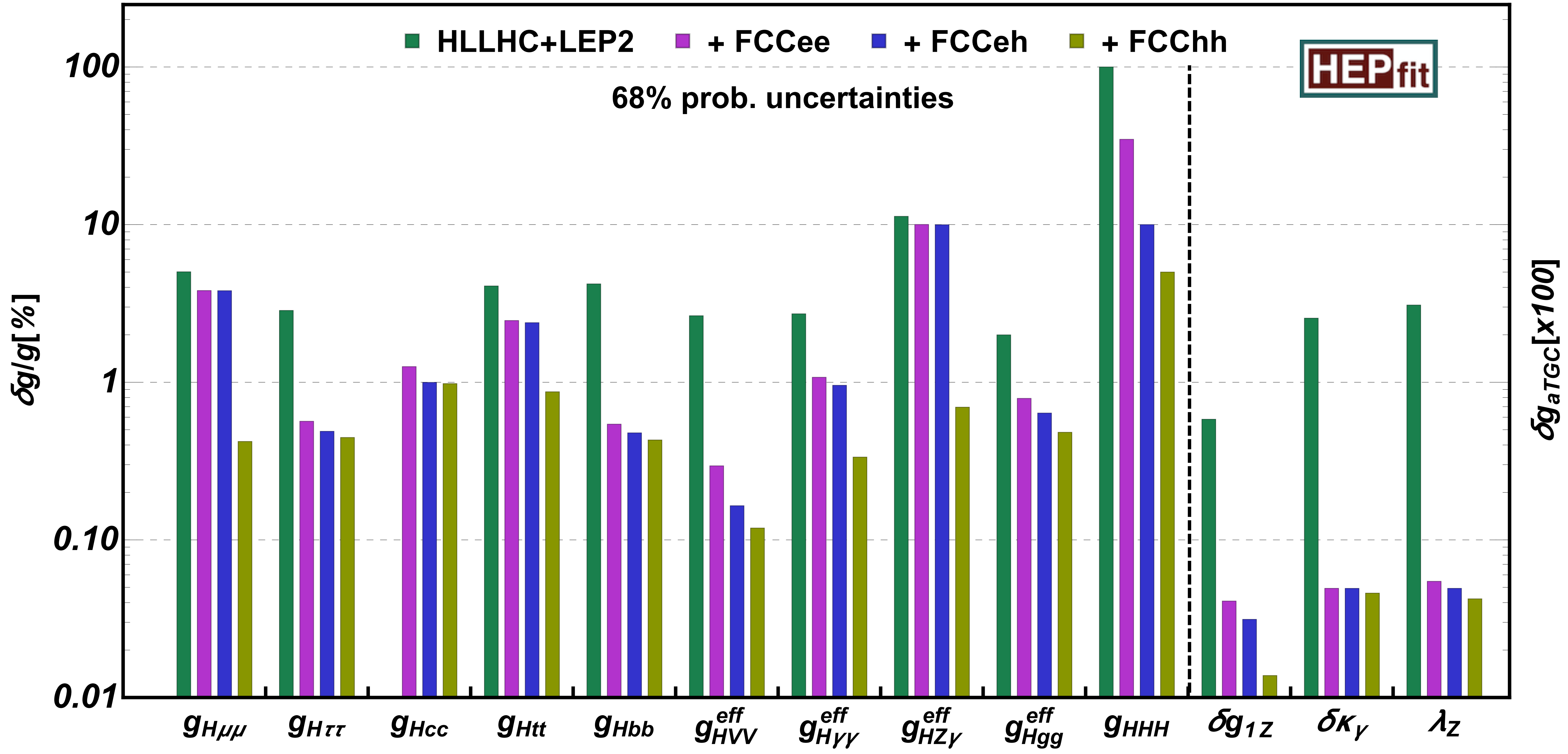
nh

with ~1% precision

$\delta\kappa_\lambda$~5%

The Global Higgs fit at FCC

Assuming perfect EW measurements



Sensitivity to NP in effective couplings in the SMEFT framework

The Global EW/Higgs fit at FCC

- **FCC-hh gives access to high-energy frontier in precision constraints**

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

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

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

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

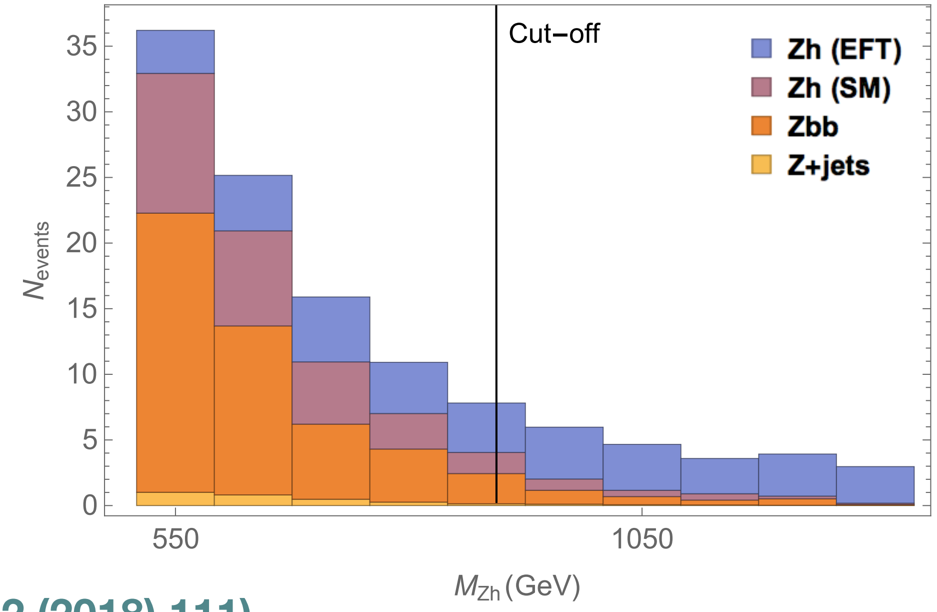
Look for E-enhanced effects in differential distributions

Example: Boosted ZH: Sensitive to 1 EFT direction

$$g_{\mathbf{p}}^Z = g_{Zu_L}^h - 0.76\ g_{Zd_L}^h - 0.45\ g_{Zu_R}^h + 0.14\ g_{Zd_R}^h$$

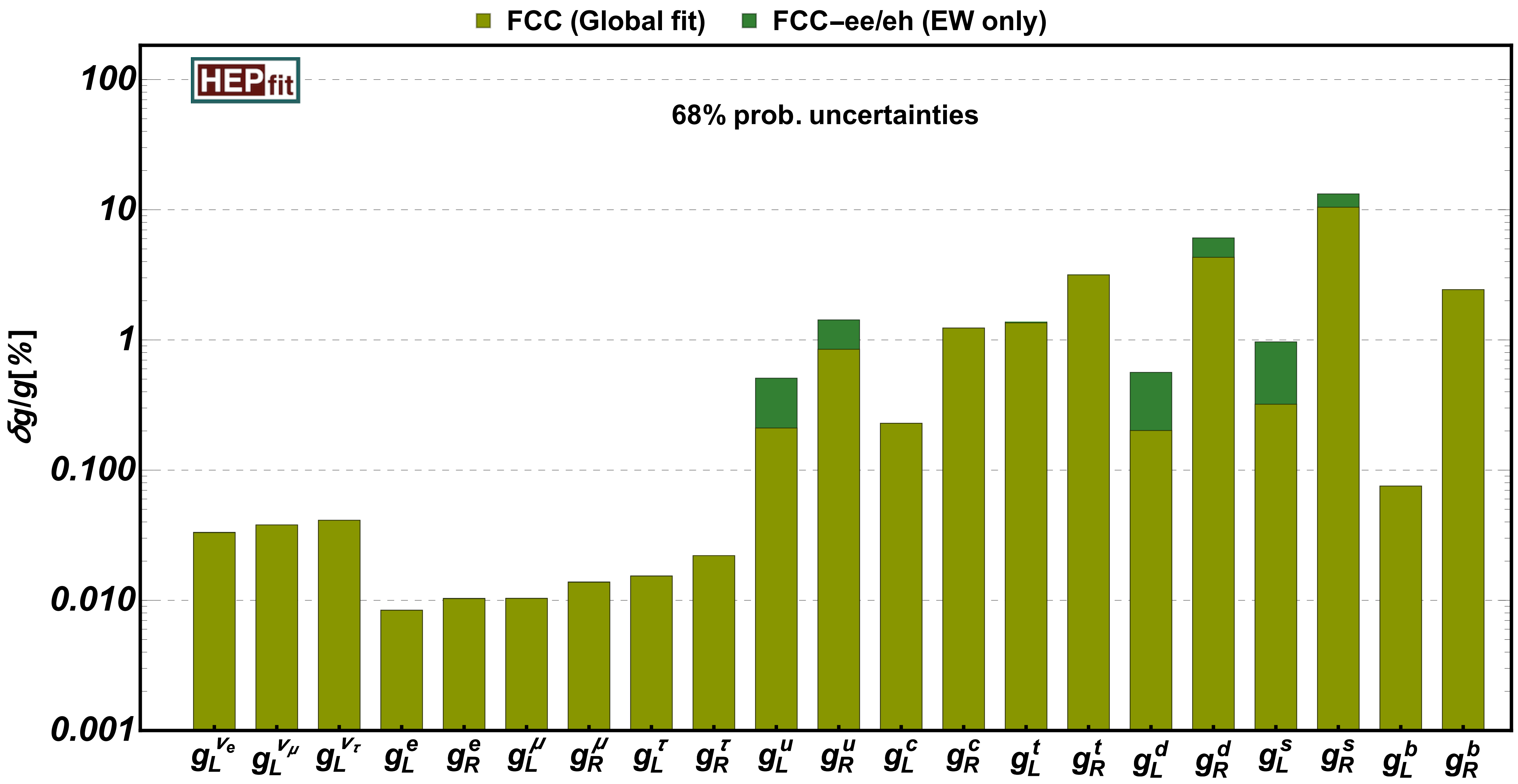
$$hZqq \quad \leftrightarrow \quad Zqq$$

S. Banerjee et al., arXiv: 1807.01796 [hep-ph]



(We also include in the fit pp → WZ from R. Franceschini et al., JHEP 1802 (2018) 111)

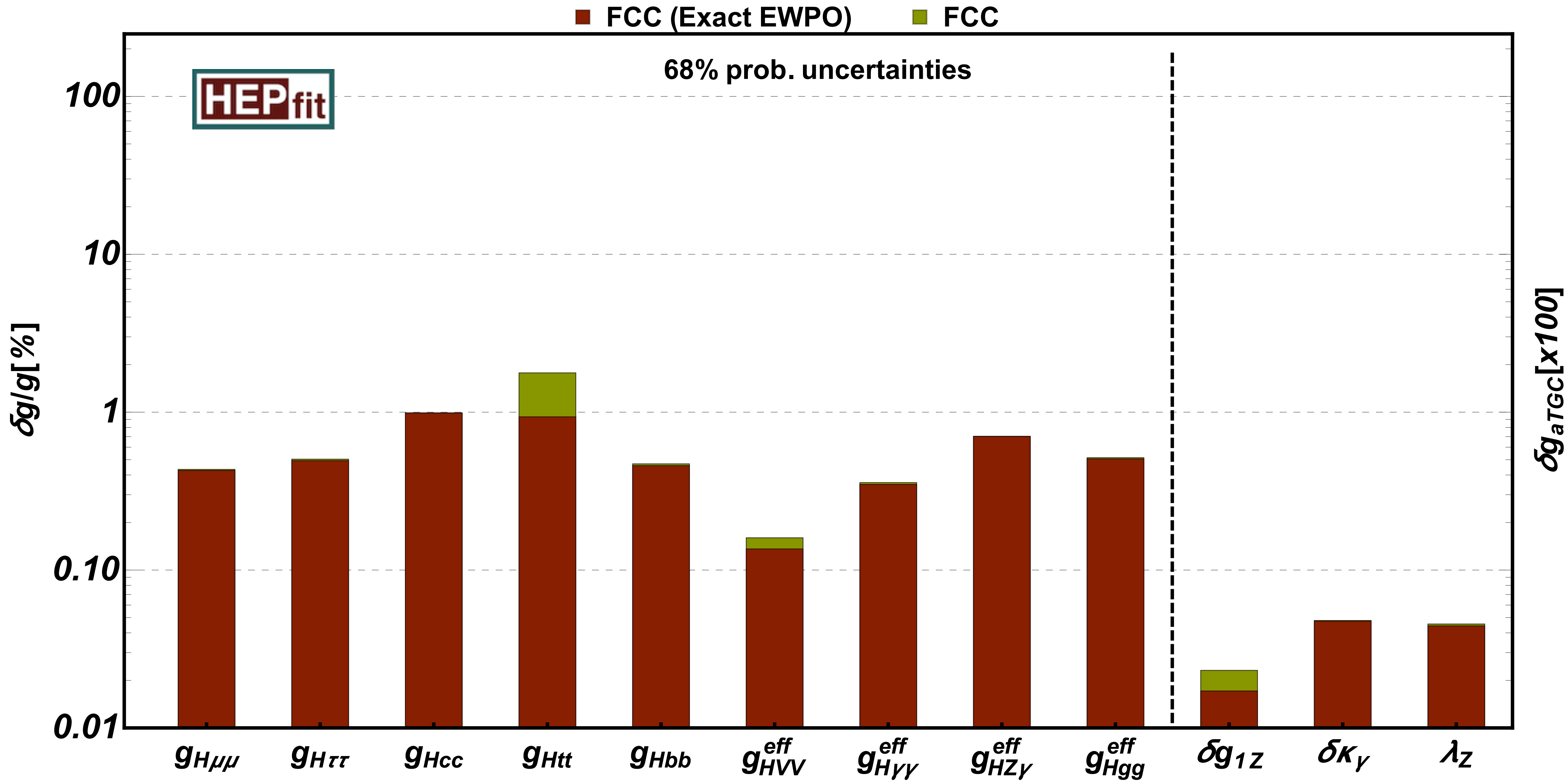
The Global EW/Higgs fit at FCC



Sensitivity to NP in effective couplings in the SMEFT framework

Differential pp observables help to improve 1st fam. quark couplings

The Global EW/Higgs fit at FCC



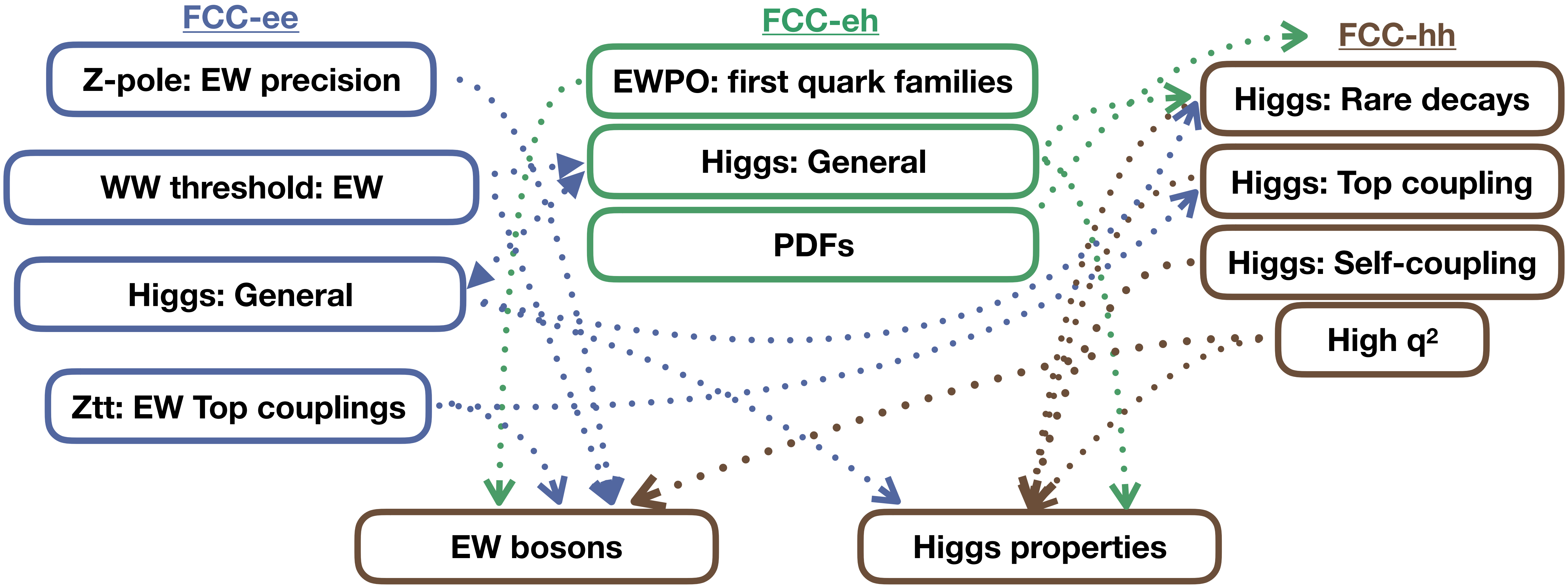
Sensitivity to NP in effective couplings in the SMEFT framework

Finite precision of FCC-ee *Ztt* only slightly reduces sensitivity to *Htt*

Summary

- Current data (LEP/LHC) sensitive to NP in EW (Higgs) $\lesssim$1% (~10%)

- FCC can largely improve our knowledge of the EW/Higgs sectors. As with current data, no single machine can do all the work…



- Apart from a strong EW/Higgs program, FCC-ee is also fundamental to maximize the physics output of the FCC-eh/hh

Backup slides

EWPO in the SMEFT

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

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

Flavor non-universal contributions

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

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

Flavor-universal contributions

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

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

Indirect effect associated to modifications in μ

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

10 Operators in Warsaw basis

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

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

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

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

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

EWPO in the SMEFT

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

$$\mathcal{L}_{\mathrm{CC}} = -\frac{e}{\sqrt{2}s}\left(1+\delta^U g_{\mathrm{CC}}\right) W_\mu^+ \left[\left(\delta_{ij} + (\delta^D U_L)_{ij}\right)\overline{\nu_L^i}\gamma^\mu e_L^j + (\delta^D V_R)_{ij}\,\overline{u_R^i}\gamma^\mu d_R^j + \left(\delta_{ij} + (\delta^D V_L)_{ij}\right)\overline{u_L^i}\gamma^\mu d_L^j\right] + \mathrm{h.c.}$$

Flavor non-universal contributions

Operators

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

Does not interfere with SM

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

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

Flavor-universal contributions

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

- ***W* mass:**

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

No more operators but constraints 1 more direction

EWPO: Z-pole + W properties

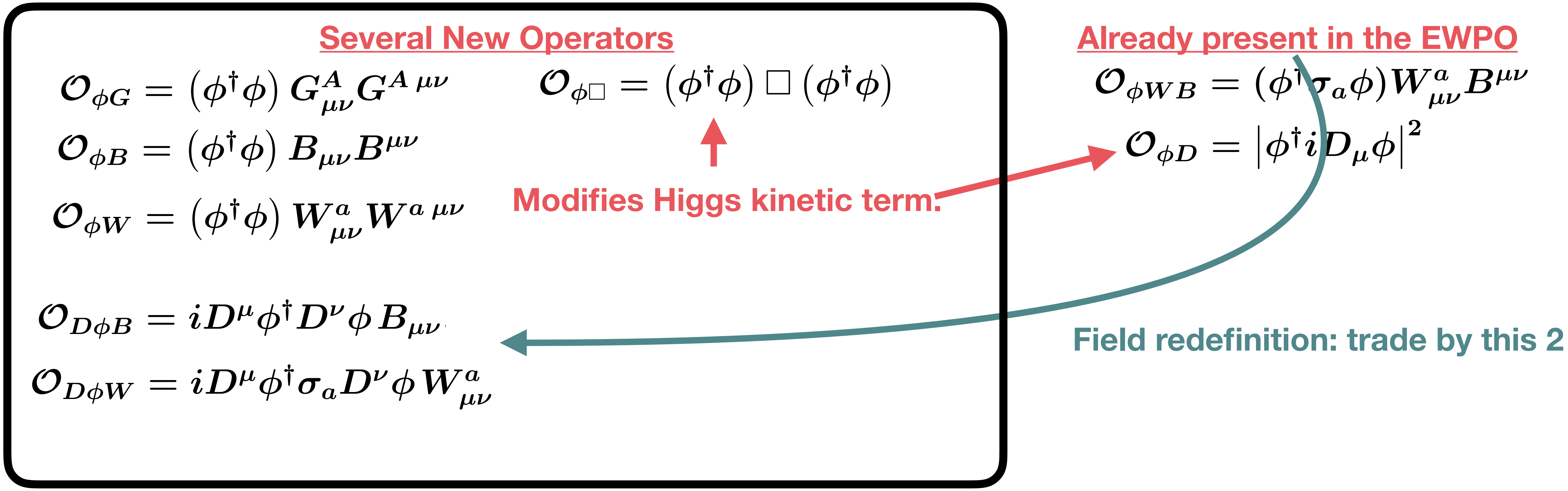
Constrain 8 independent combinations (in the FU case)

Higgs couplings in the SMEFT

- **Operators contributing to 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

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

Modifies Higgs kinetic term.

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

Already present in the EWPO

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

Field redefinition: trade by this 2

Higgs couplings in the SMEFT

- **Operators contributing to Higgs couplings:**

Fermionic couplings

$$\mathcal{L}_{hff} = g_{hee}^{ii}\,\bar{e}_L^i e_R^i h + g_{huu}^{ii}\,\bar{u}_L^i u_R^i h + g_{hdd}^{ii}\,\bar{d}_L^i d_R^i h + \text{h.c.}$$

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

Operators

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

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

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

Higgs self-coupling

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

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

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

Only enters in
Higgs self-interactions

Plus ALL operators entering in EWPO modify EW Higgs production or decay
⇒ Need Global EW+Higgs fit

aTGC in the SMEFT

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

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

2 aTGC related to Higgs couplings

Help to constrain anomalous Higgs boson coupling to vector bosons

$$\delta\kappa_\gamma = -2vc_W^2\left(g_{hAA} - g^{(1)}_{hZZ} + \frac{1}{2s_Wc_W}g^{(1)}_{hZA}(c_W^2 - s_W^2)\right)$$

$$\delta g_{1,Z} = \frac{v}{2(c_W^2-s_W^2)}\left(c_W^2 g^{(2)}_{hZZ} + 4s_W^2(g_{hAA} - g^{(1)}_{hZZ} + \frac{1}{4}g^{(2)}_{hZZ}) + \frac{2s_W}{c_W}g^{(1)}_{hZA}(c_W^2 - s_W^2)\right)$$

$$\delta\kappa_Z = \delta g_{1,Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma$$

$$\lambda_\gamma = \lambda_Z = -\frac{3}{2}\frac{e}{s_W}C_{3W}\frac{v^2}{\Lambda^2} \longrightarrow$$

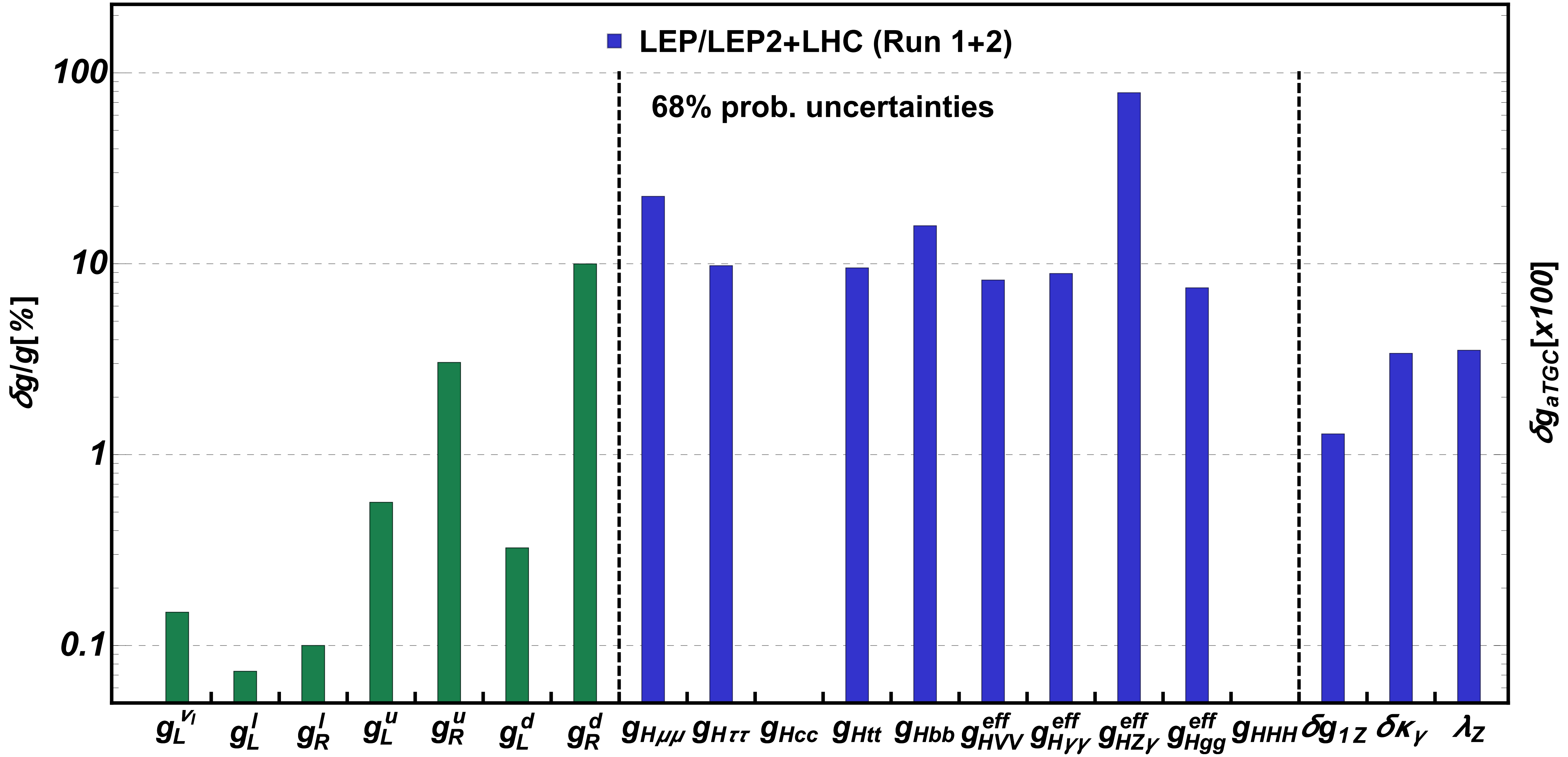
$$\mathcal{O}_W = i\epsilon_{abc}W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$$

Only one more operator

Current EWPO+Higgs signal strengths+aTGC fit sensitive to 19 combinations of EFT operators

The Global EW and Higgs fit

Status of the Global Electroweak and Higgs fit: Constraints on the SMEFT



Sensitivity to NP in effective couplings in the SMEFT framework