EW/Higgs precision probes at the FCC-ee: Status after the CDR

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<u>**Based on the results presented in:**</u>

FCC CDR Volume 1, Physics Opportunities, https://fcc-cdr.web.cern.ch/
FCC CDR Volume 2, The Lepton Collider, https://fcc-cdr.web.cern.ch/

Introduction

- **FCC-CDR:** First study of the FCC capabilities to constraint the EW/Higgs sector in a global manner, taking advantage of the complementarities between the different FCC collider options (ee/eh/hh)
- In this presentation:
  - Summary of the status of the Global EW/Higgs studies in the CDR with emphasis in the contribution from FCC-ee
  - A few aspects of current studies that could be improved? Limitations?
  - A couple of topics that did not make it to CDR but could be added

- Disclaimer: No new results in this talk. Only discussion of issues and WiP.
- Physics perspective in this talk presented from the point of view of the formalism of Effective Field Theories (EFT)

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 dim. of operators

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

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

Λ: Cut-off of the EFT

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

- LO new physics effects "start" at dimension 6: 59 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 1st complete basis, aka *Warsaw* basis

- SMEFT 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/Diboson
- $v h B^{\mu\nu} W^3_{\mu\nu}$ (dim 5): $h \to ZZ, \gamma\gamma$ — Higgs phys.

⇒ Use global EW/Higgs fits to estimate sensitivity to NP effects

The dimension 6 SMEFT

- **Assumptions in Higgs/Diboson/EWPO EFT studies:**
  CP-even, 4-fermion/dipole better tested in other processes

List of operators and their effects (e.g. in Warsaw basis)

$h \to VV$

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

Also enter in EWPO & VV prod.

$h \to ff$

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

Not directly testable with EWPO

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

Enters only in VV prod.

$h \to Vff$

$$\mathcal{O}^{(1)}_{\phi f} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{f}\gamma^\mu f)$$
$$\mathcal{O}^{(3)}_{\phi f} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{f}\gamma^\mu\sigma_a f)$$

Strongly constrained by EWPO (induce modified Vff couplings)

Indirect

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

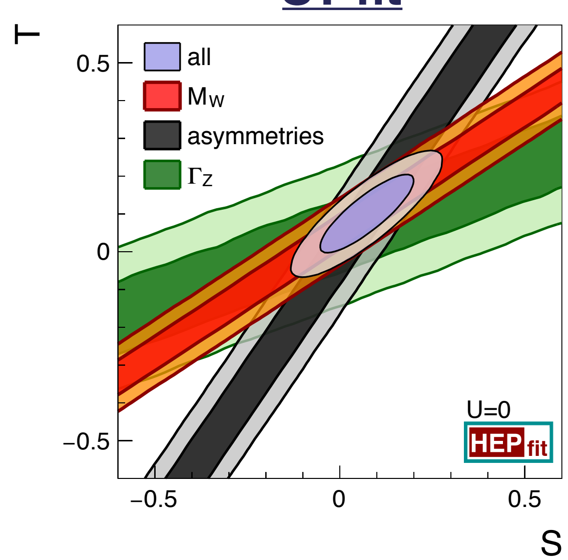
Modify SM inputs: Enter in all EW processes

EFT fits to precision EW measurements

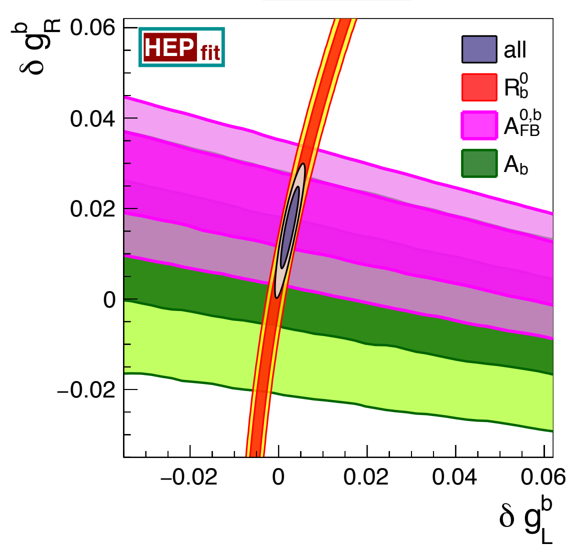
Global Fits to EW precision measurements

- **EWPO:** very precise measurements of W and Z boson properties
  - Current knowledge dates back to the LEP era…
  - …but also receives inputs from Tevatron/LHC
  - Crucial in the confirmation of the validity of the SM descriptions of EW interactions…
  - …in guiding Higgs and Top searches…
  - … and setting strong constraints on new physics modifying the EW sector, e.g.

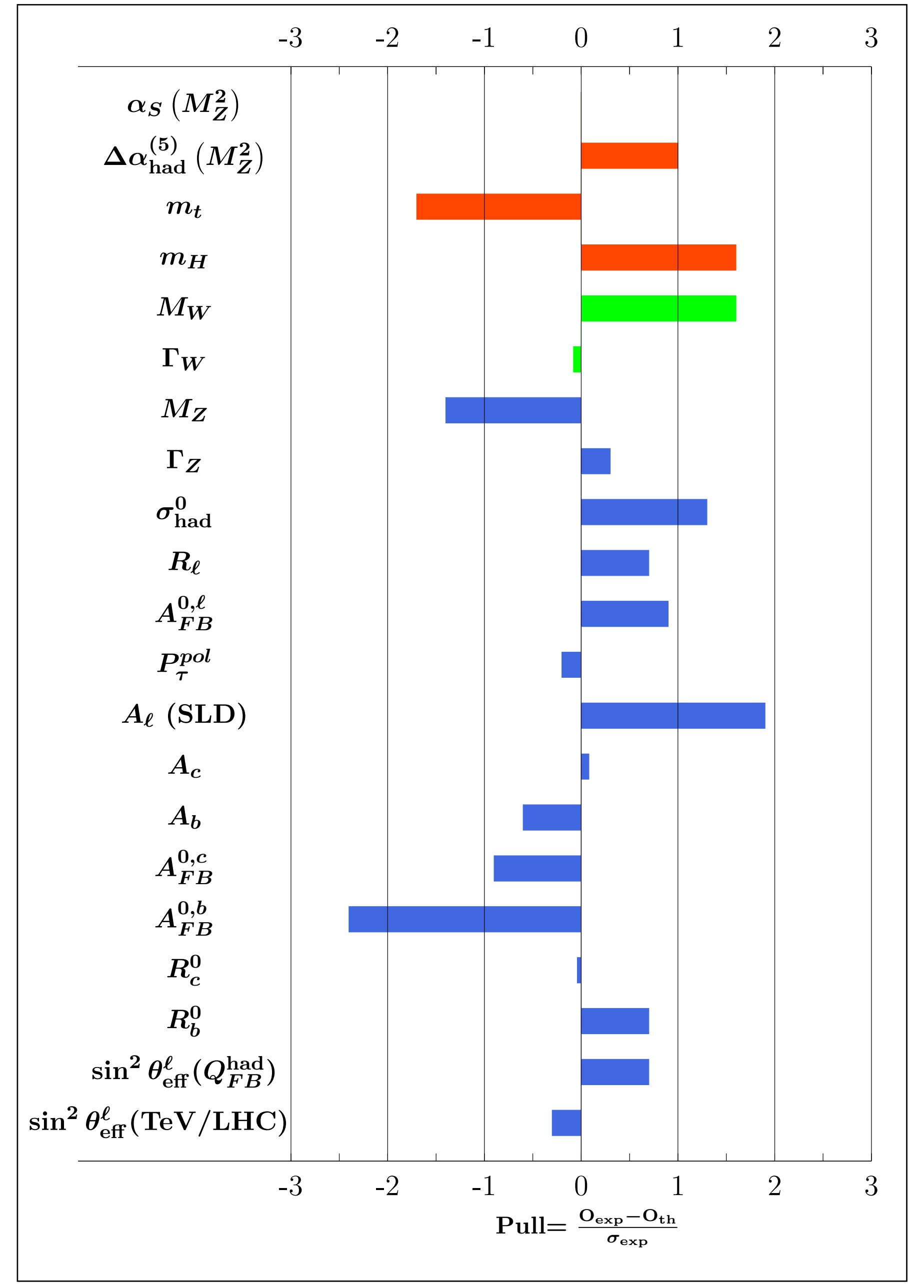
ST fit



Zbb fit



The SM EW fit



- The core of the EWPO program at FCC comes from FCC-ee…

Fit inputs: Theory and Experiment

Electroweak Precision measurements at FCC-ee: CDR summary

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 (×10³)	20767±25	0.06	0.2-1.0	ratio hadrons / leptons, lepton acceptance
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6	from R_l^Z above
R_b (×10⁶)	216290±660	0.3	<60	ratio $b\bar{b}$/hadrons, stat. extrapol. from SLD
σ^0_{had} (×10³) (nb)	41541±37	0.1	4	peak hadronic cross section, luminosity meas.
N_ν (×10³)	2991±7	0.005	1	Z peak cross sections, luminosity measurement
$\sin^2\theta_W^{\mathrm{eff}}$ (×10⁶)	231480±160	3	2-5	from $A_{FB}^{\mu\mu}$ at Z peak, beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z)$ (×10³)	128952±14	4	Small	from $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ (×10⁴)	992±16	0.02	1-3	b-quark asymmetry at Z pole, from jet charge
$A_{FB}^{\mathrm{pol},\tau}$ (×10⁴)	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) (×10⁴)	1170±420	3	Small	from R_l^W
N_ν(×10³)	2920±50	0.8	Small	ratio invisible to leptonic in radiative Z returns
m_{top} (MeV)	172740±500	20	Small	$t\bar{t}$ threshold scan; QCD errors dominate
Γ_{top} (MeV)	1410±190	40	Small	$t\bar{t}$ threshold scan; QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	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

SM input

Z-pole

WW

tt

Fit inputs: Theory and Experiment

Electroweak Precision measurements at FCC-ee

From the defunct FCC CDR Volume 5

Z-lineshape

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

Asymmetries

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})
$\sin^2\theta^e_{\text{Eff}}$ (P_τ)	6.6×10^{-6}	(3×10^{-5})
~~$\sin^2\theta^\ell_{\text{Eff}}$ (A^μ_{FB})~~	~~5×10^{-6}~~	~~(2×10^{-5})~~

Not independent

WW and above

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})
$N_\nu \leftarrow$ R_{inv}	0.002	(3×10^{-4})

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

WW and above

Theory uncertainties (missing H.O. corrections): EWPO

FCC-ee-Z EWPO error estimations				
	$\delta\Gamma_Z$ [MeV]	δR_l $[10^{-4}]$	δR_b $[10^{-5}]$	$\delta \sin^2\theta^{l}_{\mathrm{eff}}$ $[10^{-5}]$
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]

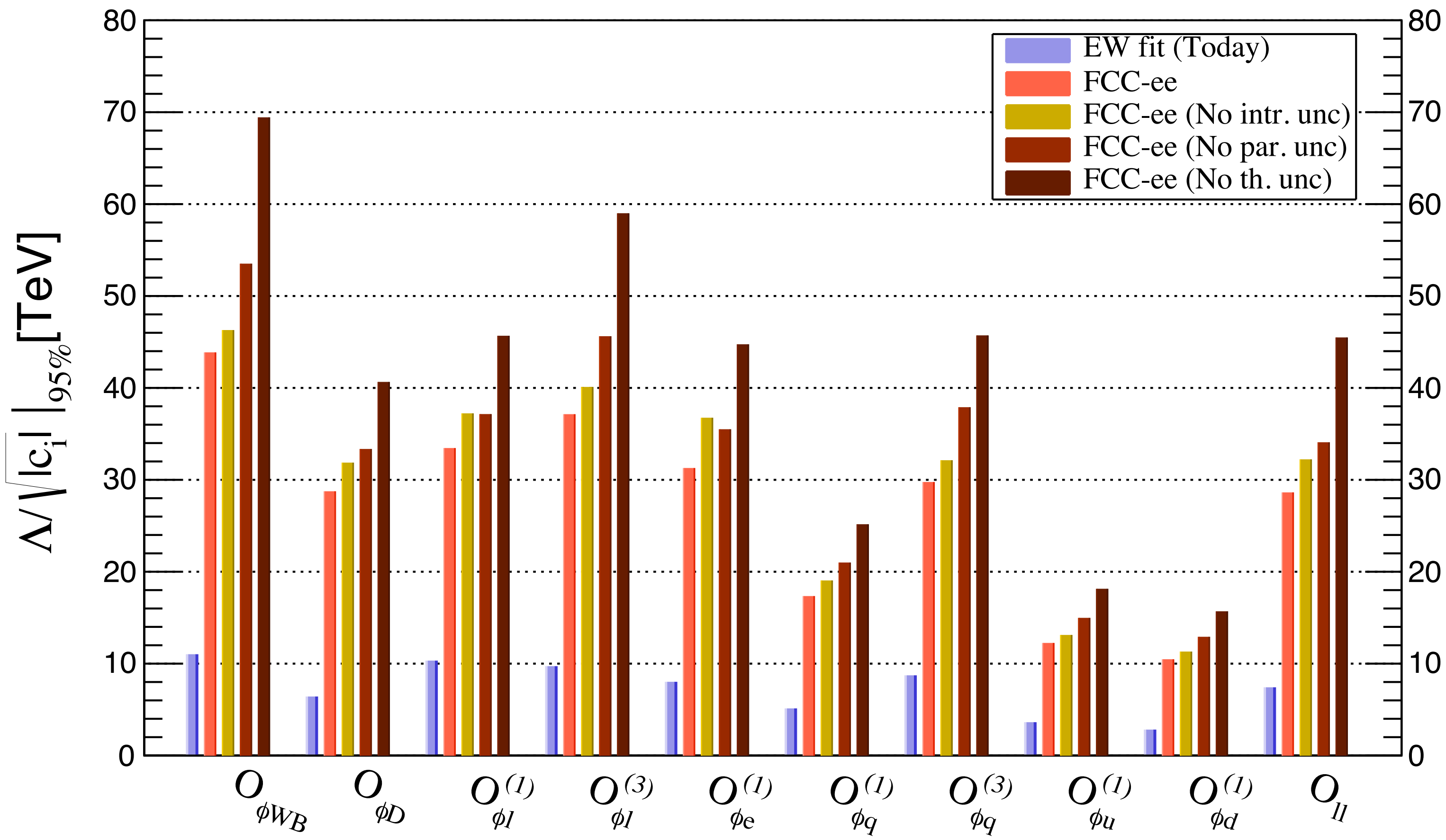
- **TH1:** Current intrinsic uncertainty
- **TH2:** Extrapolation assuming EW 3-loop corrections are known
- **TH3:** Same as TH2 assuming dominant 4-loop corrections are known

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



Effects clearly visible in fits 1 operator at a time…

…or along the physical directions probed by the EWPO

Effect in the global fit better seen in terms of modifications of *Zff* couplings

$\Downarrow$

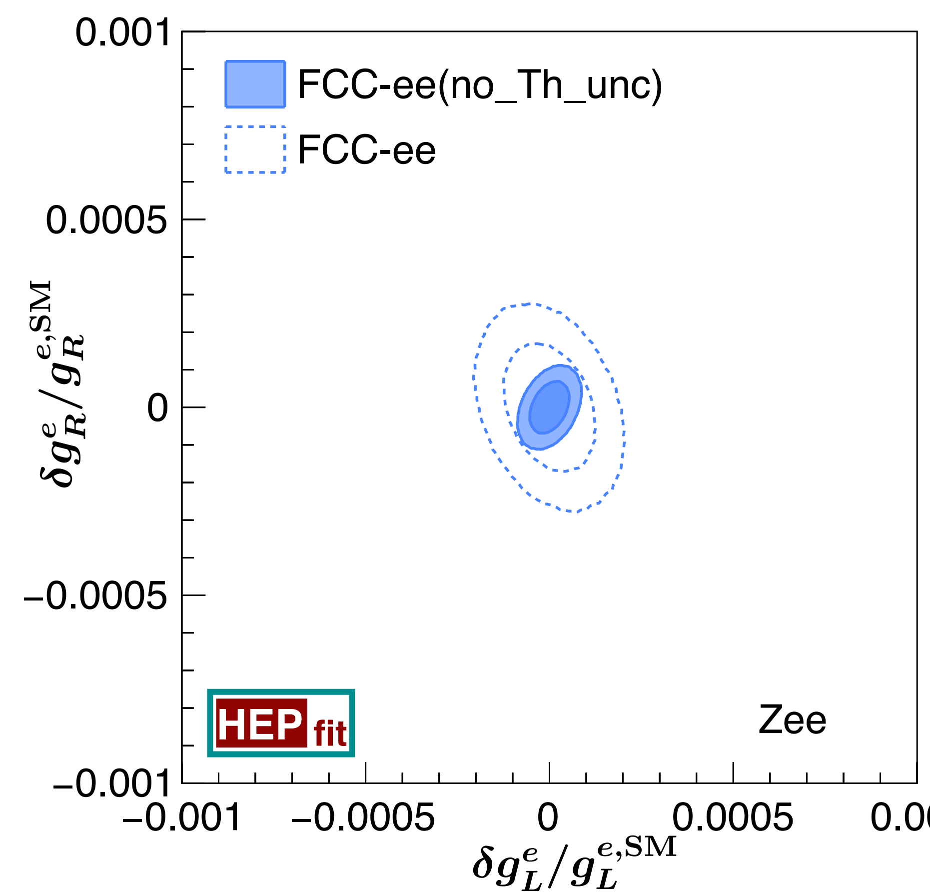
Eff. couplings in the SMEFT

$$\mathcal{L}_{\rm NC}=-\frac{e}{sc}(1+\delta^U g_{\rm NC})Z_\mu\sum_\psi\overline{\psi}\gamma^\mu\Big[\Big(g^\psi_{L,R}+\delta^D g^\psi_{L,R}\Big)P_{L,R}+\delta^Q g_{\rm NC}\Big]\psi \quad\Rightarrow$$

$$\delta^D g^e_L=-\frac{1}{2}\left(C^{(1)}_{\phi l}+C^{(3)}_{\phi l}\right)\frac{v^2}{\Lambda^2},\qquad \delta^D g^e_R=-\frac{1}{2}C^{(1)}_{\phi e}\frac{v^2}{\Lambda^2}$$

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

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



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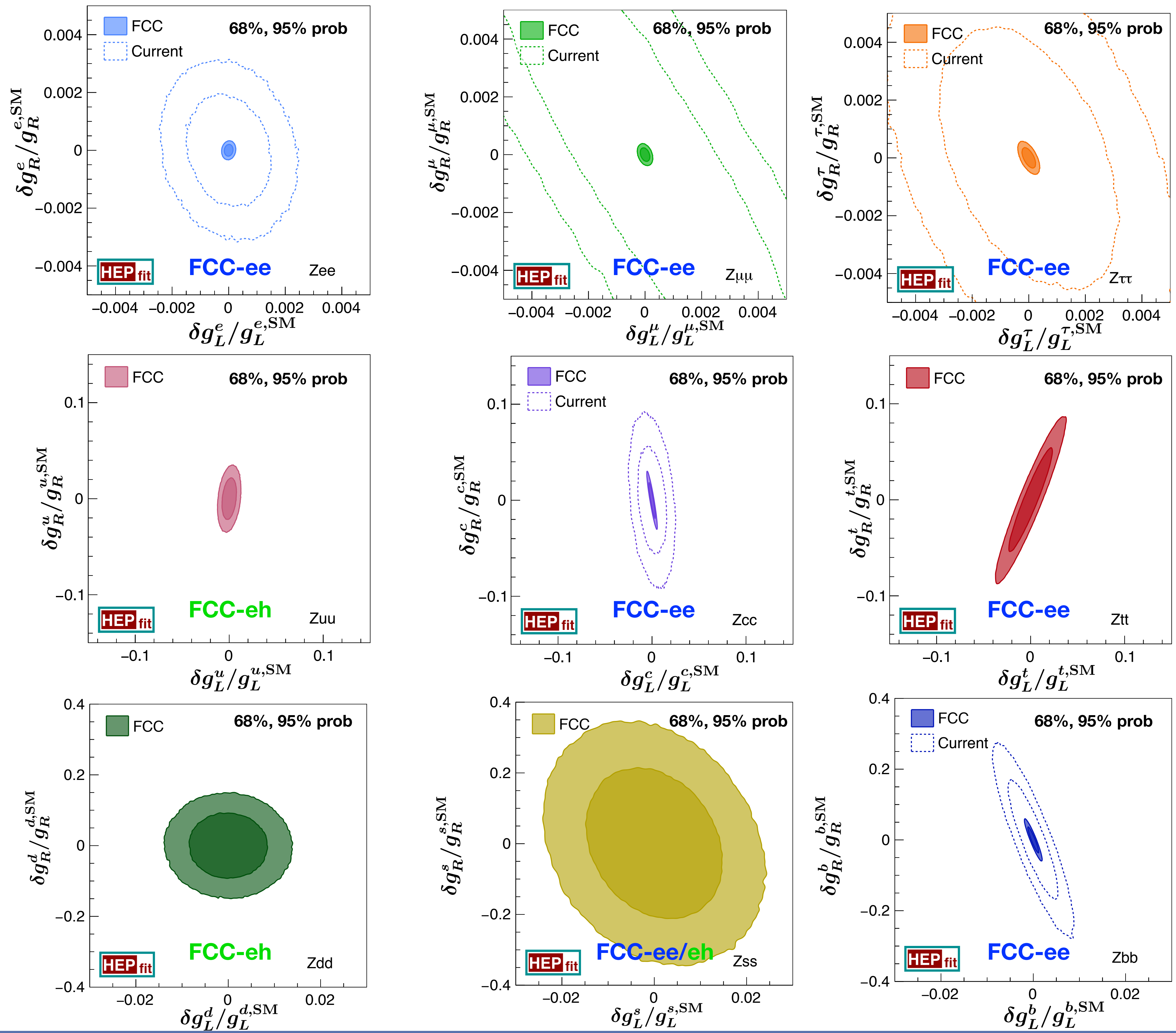
The Global EW fit at FCC-ee/eh

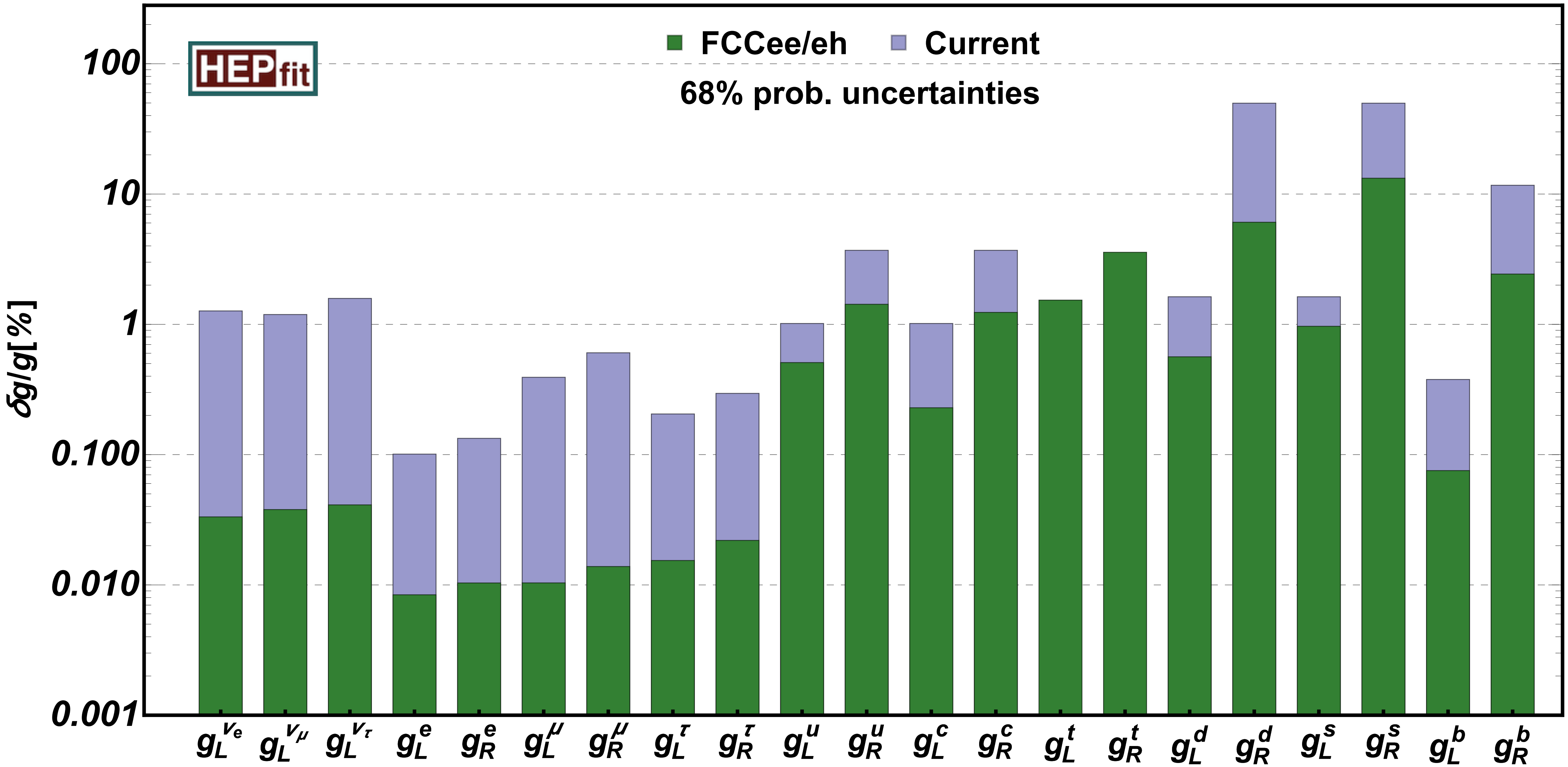
Sensitivity to deviations in NC couplings from SMEFT fit:
No fermion flavour universality assumed



The Global EW fit at FCC-ee/eh

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

Current vs FCC-ee/eh



1-σ sensitivity to deviations in NC couplings from SMEFT fit: No flavour universality assumed

Independent info about all 3 SM fermion families

Beyond the CDR studies

A few questions

- **Parametric uncertainties:**

	α_s	$\alpha_{QED}/\Delta\alpha_{had}^{(5)}$	M_Z	m_t	Total	FCCee
δM_W [MeV]	±0.14	$\pm0.53/\pm0.92$	±0.1	±0.3	$\pm0.64/\pm0.98$	±0.6
$\delta\Gamma_Z$ [MeV]	±0.099	$\pm0.03/\pm0.05$	±0.01	±0.01	$\pm0.1\ /\pm0.11$	±0.1
$\delta\mathcal{A}_\ell\ [\times10^{-5}]$	±0.54	$\pm8\ /\pm14$	±0.56	±1.2	$\pm8.1\ /\pm14$	±2.1
$\delta R_b^0\ [\times10^{-5}]$	±0.22	$\pm0.04/\pm0.07$	±0.003	±0.17	$\pm0.28/\pm0.29$	±6

Even if theory calculation improve such that higher order contributions are negligible wrt FCC-ee precision, parametric uncertainties will remain

SM input

Observable	present value ± error	FCC-ee stat.	FCC-ee syst.
m_Z (keV)	91186700±2200	5	100
Γ_Z (keV)	2495200±2300	8	100
R_l^Z (×10³)	20767±25	0.06	0.2-1.0
α_s (m_Z) (×10⁴)	1196±30	0.1	0.4-1.6
R_b (×10⁶)	216290±660	0.3	<60
σ^0_{had} (×10³) (nb)	41541±37	0.1	4
N_ν (×10³)	2991±7	0.005	1
$\sin^2\theta_W^{eff}$ (×10⁶)	231480±160	3	2-5
$1/\alpha_{QED}(m_Z)$ (×10³)	128952±14	4	Small
$A_{FB}^{b,0}$ (×10⁴)	992±16	0.02	1-3

α_{QED} still limiting factor but

Statistically limited

How low can we go?

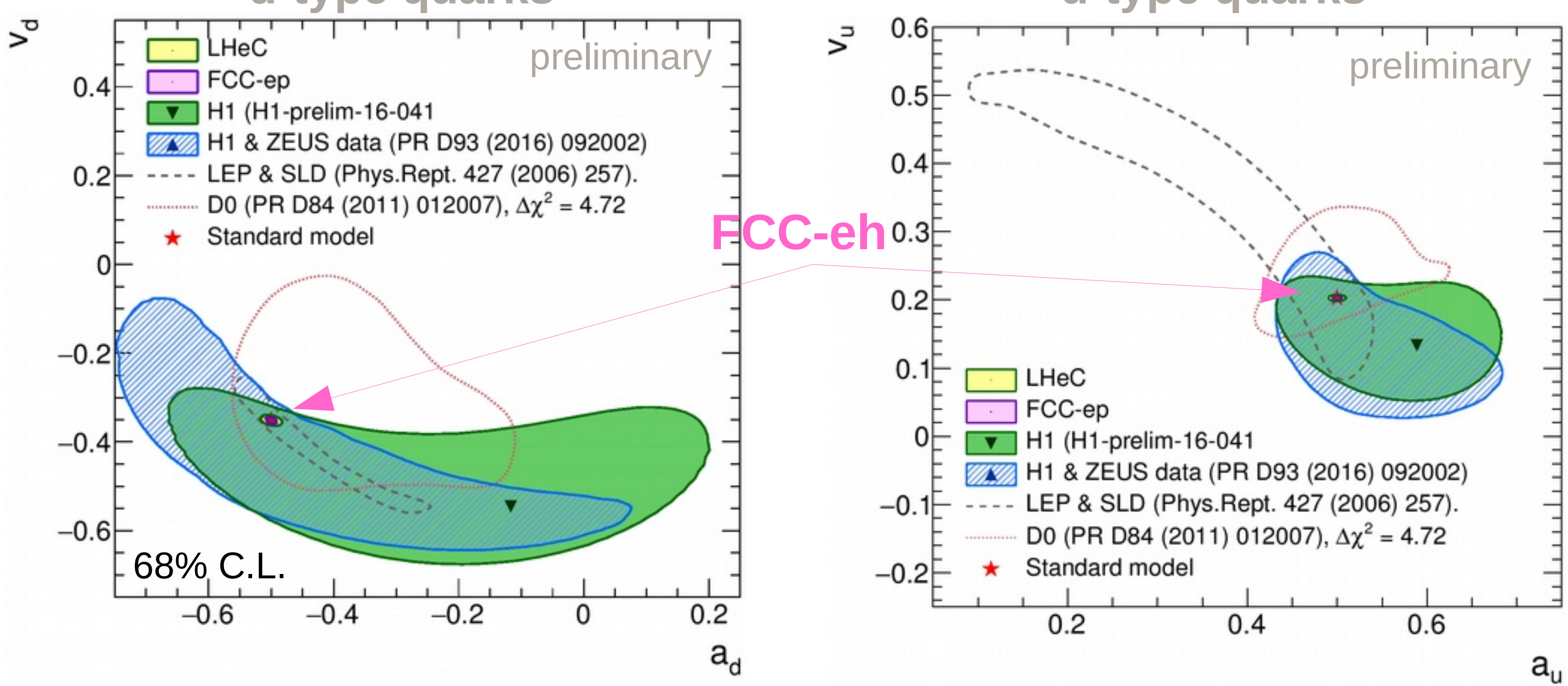
(More time running off-pole, 4IP?)

Beyond the CDR studies

A few questions

- **Determination of Z couplings to light quarks relies on FCC-eh**

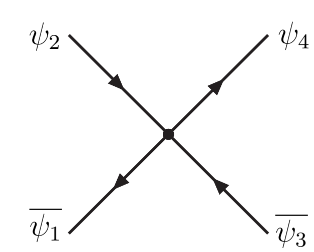
d-type quarks　　　　u-type quarks



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%)

Precise determination (~1%) but not model-independent

Sensitive to 4-Fermion contact interactions (CI)



- **4-Fermion effects suppressed at the Z-pole**

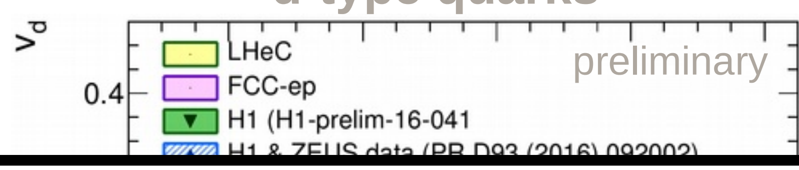
What is the FCC-ee Z-pole run potential to measure light quark interactions?

Beyond the CDR studies

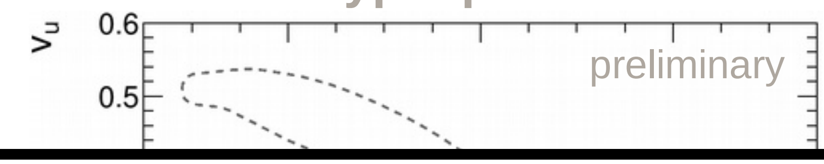
A few questions

- **Determination of Z couplings to light quarks relies on FCC-eh**

d-type quarks



u-type quarks



Old LEP studies of light flavours (u,d,s) studies relied either on SM assumptions (DELPHI) or partial flavour universality constraints (OPAL)

$$\frac{R_{\rm u}}{R_{\rm d}+R_{\rm u}+R_{\rm s}} = 1-\frac{2R_{\rm d,s}}{R_{\rm d}+R_{\rm u}+R_{\rm s}} = 0.258\pm 0.031\pm 0.032$$

$$A_{\rm FB}^{0,\,{\rm d,s}} = 0.072\pm 0.035\pm 0.011 - 0.0119(A_{\rm FB}^{0,\,{\rm c}}-0.0722)/0.0722\,,$$

$$A_{\rm FB}^{0,\,{\rm u}} = 0.044\pm 0.067\pm 0.018 - 0.0334(A_{\rm FB}^{0,\,{\rm c}}-0.0722)/0.0722\,.$$

2019->FCC-ee time : Can these assumptions be removed?

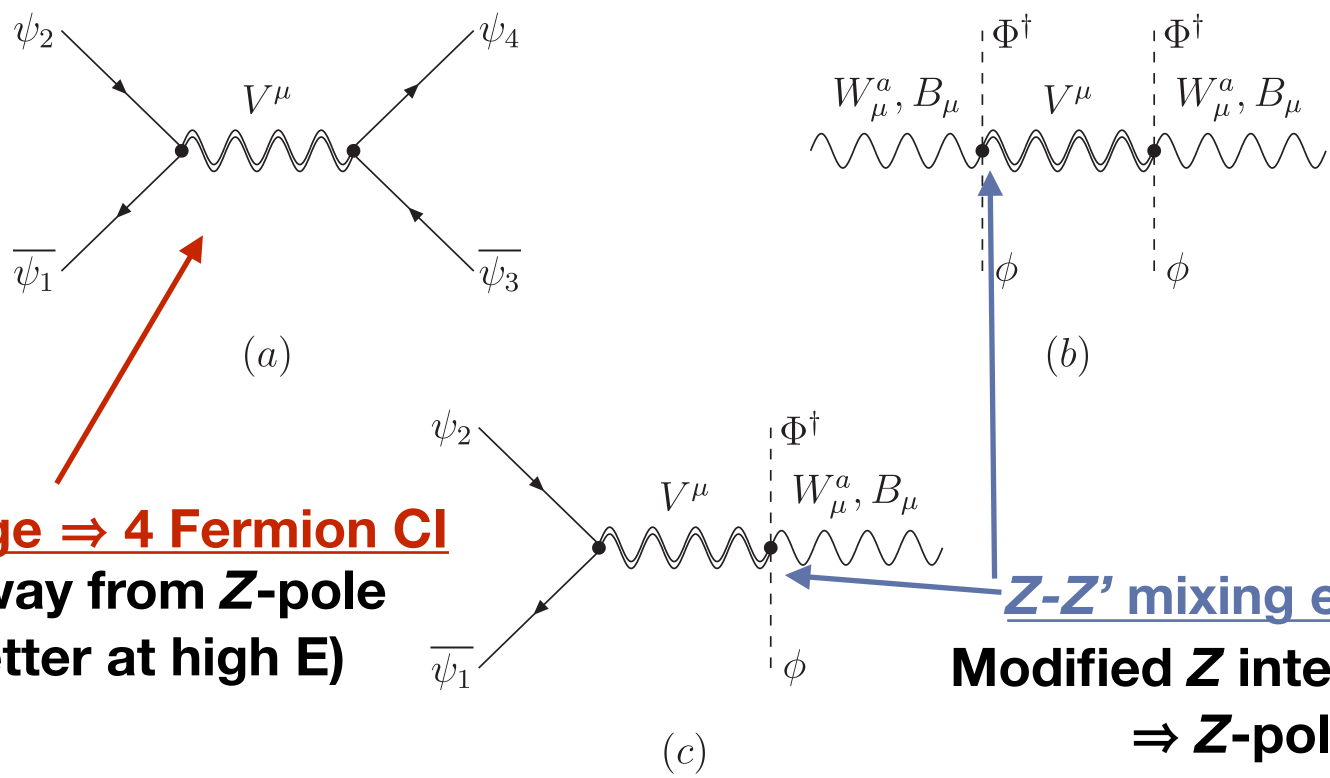
FCC-ee checks on light flavour couplings could strengthen the model-independence of FCC-eh results and robustness of Global FCC EW fit

What is the FCC-ee Z-pole run potential to measure light quark interactions?

Beyond the CDR studies

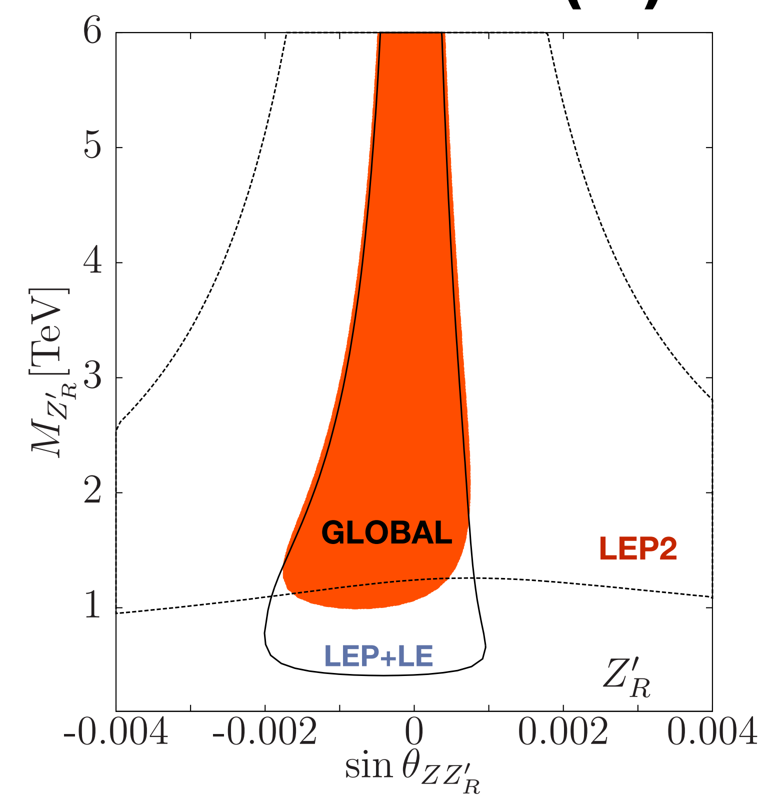
Difermion production ($e^+e^-\to ff$) above the Z pole

- CDR EWPO studies focus mostly on ff production around the Z pole
- Complementarity: Data off the pole sensitive to physics suppressed at the Z-pole because of the resonance, e.g. extra vector bosons (*Z'*)



Z' exchange ⇒ 4 Fermion CI
Better away from *Z*-pole
(and better at high E)

Z-Z' mixing effects
Modified *Z* interactions
⇒ *Z*-pole



- What is the sensitivity of FCC-ee data to CI at WW, ZH, tt threshold?
- HL-LHC will probably outperform FCC-ee for (some) Lepton-Quark CI

But testing 4-Lepton interactions is for Lepton colliders

Beyond the CDR studies

Four-fermion interactions at tt threshold

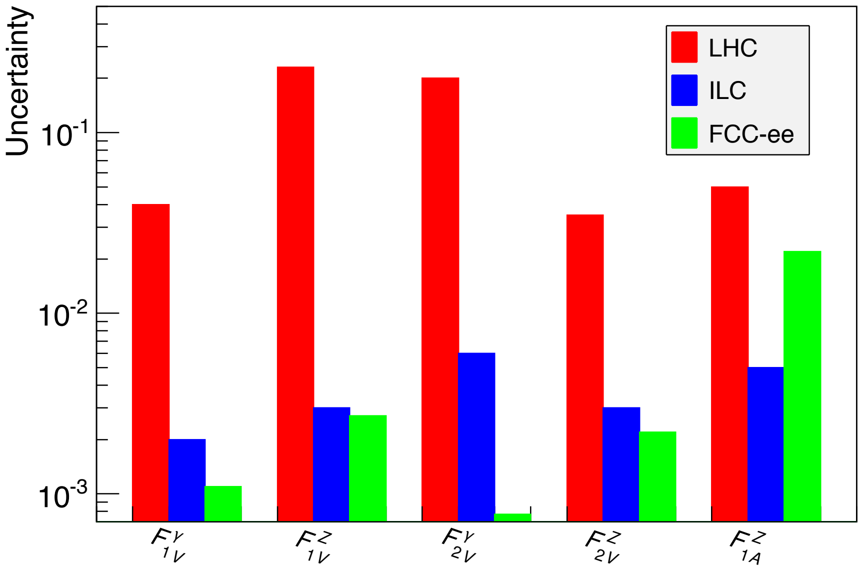
- **As in the light quark case, the extraction of the EW Top couplings is also not completely model-independent:**

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

BSM: generated at 1 Loop

(Functions of q^2)

Using only one energy one cannot disentangle contributions to Ztt from those to $e^+e^- t\, t$ CI



Precision on	F^γ_{1V}	F^Z_{1V}	F^γ_{1A}	F^Z_{1A}
Only three $F^X_{1V,A}$	$1.2\,10^{-3}$	$2.9\,10^{-3}$	$0.0\,10^{-2}$	$2.2\,10^{-2}$

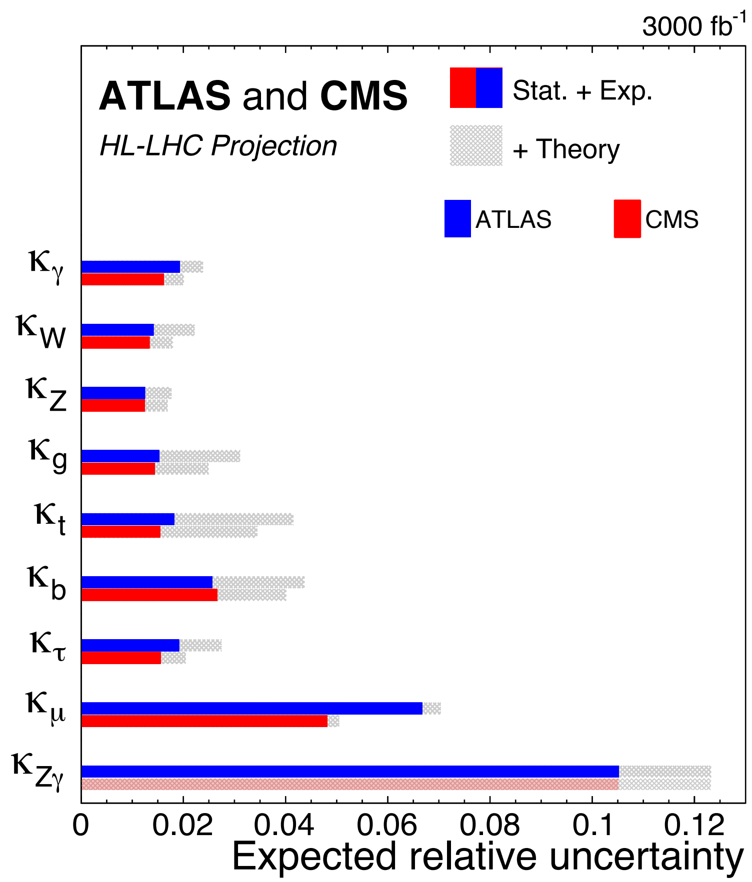
P. Janot, JHEP 1504 (2015) 182

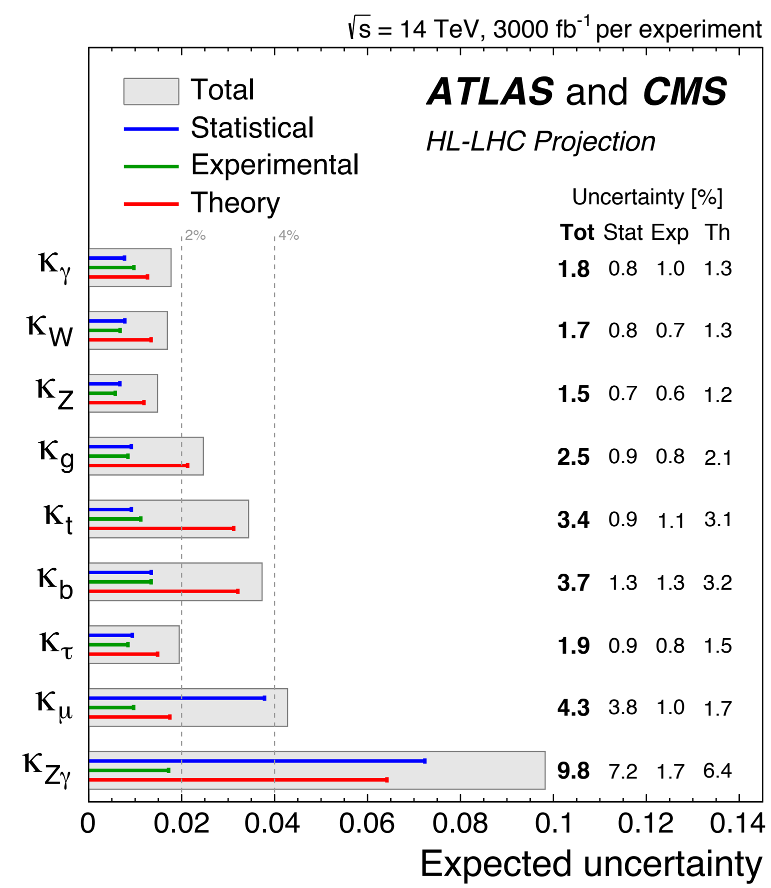
FCC-ee runs at 2 energies very close to each other: 350 GeV (0.2/ab) and 365 GeV (1.5/ab)
⇒ limitation for model-independent extraction?

EFT fits to precision Higgs measurements at FCC

Global Fits to Higgs observables

- **Measuring the Higgs couplings is an integral part of the physics program of the LHC/HL-LHC:**
  - **Expected precision ~few/several percent (κ framework)**





  - **but not model-independent (either ratios or need extra assumptions: e.g. No exotic decays)**

- **FCC can push the precision below 1% plus more model-independent**

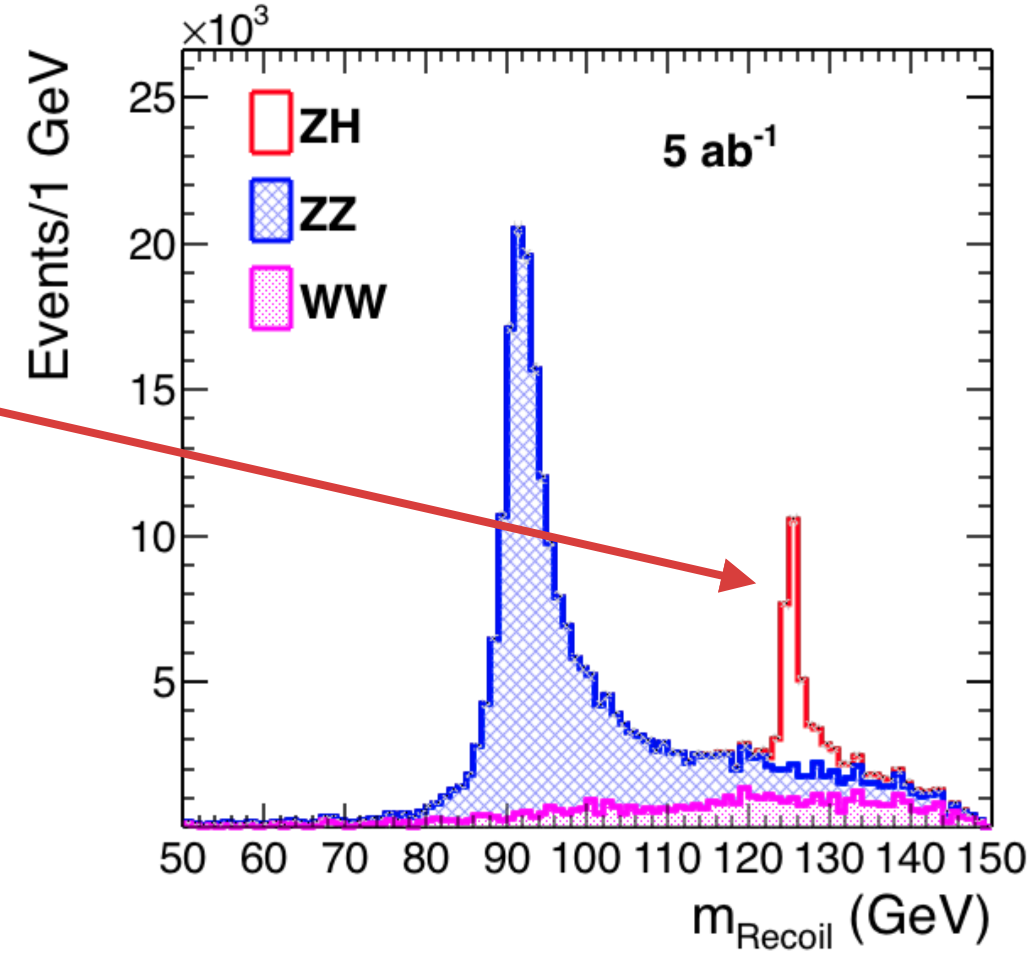
Fit inputs: Theory and Experiment

Higgs Precision measurements at FCC-ee

(See. P. Janot's talk)

$\sqrt{s}$ (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 to normalize H couplings (no ratios)

κ-framework: model-independent determination of Higgs width

Fit inputs: Theory and Experiment

Theory uncertainties: Higgs observables

From the defunct FCC CDR Volume 5

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%	$-$
$H \to \gamma\gamma$	$< 1\%$	$-$	$-$	$-$
$H \to Z\gamma$	$\sim 1\%$	$-$	$-$	
$H \to WW$	$\lesssim 0.4\%$	$-$	$-$	$\sim 0.1\%$
$H \to ZZ$	$\lesssim 0.3\%^\dagger$	$-$	$-$	$\sim 0.1\%$
Γ_{tot}	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$

† From $e^+e^- \to HZ$ production

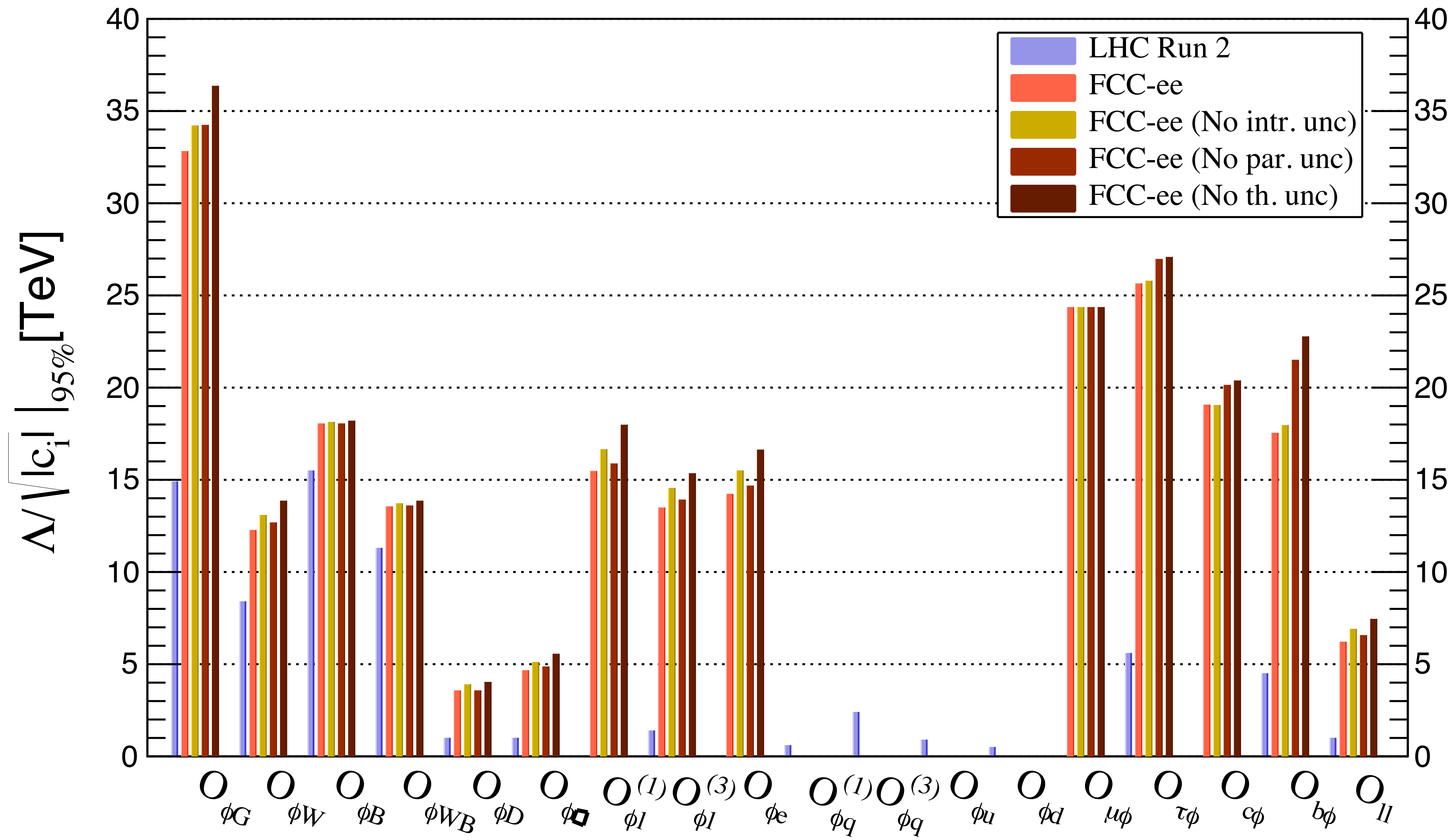
Projections from Heinemeyer et al.

We studied the impact of these uncertainties on the FCC-ee projections in Volume 2

Higgs fits at FCC-ee

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

Impact of theory uncertainties

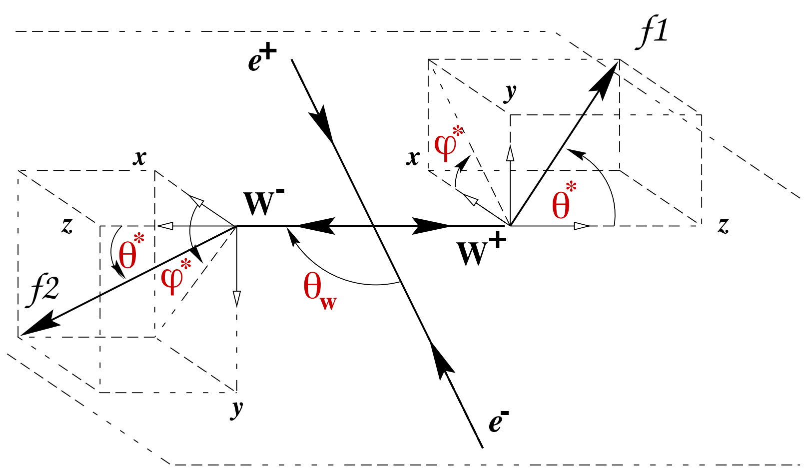


Fit 1 operator at a time

Small or moderate impact of theory uncertainties (compared to the case of EWPO)

Diboson (WW) precision measurements at FCC-ee: aTGC

From fit to diff. distribution in all angles



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

aTGC

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

$$\left(\begin{array}{c}\delta\kappa_Z = \delta g_{1,Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma\\ \lambda_\gamma = \lambda_Z\end{array}\right)$$

Fit inputs: Theory and Experiment

Diboson (WW) precision measurements at FCC-ee: aTGC

From fit to diff. distribution in all angles

FCC-ee $e^+e^- \to WW$ semileptonic channel all angles

240 GeV only — uncertainty | correlation matrix

365 GeV only — uncertainty | correlation matrix

$\delta\kappa_\gamma$ λ_Z

-0.80

0.10

1

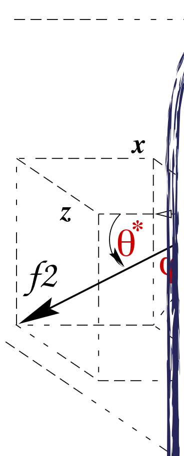
matrix

λ_Z

-0.87

-0.12

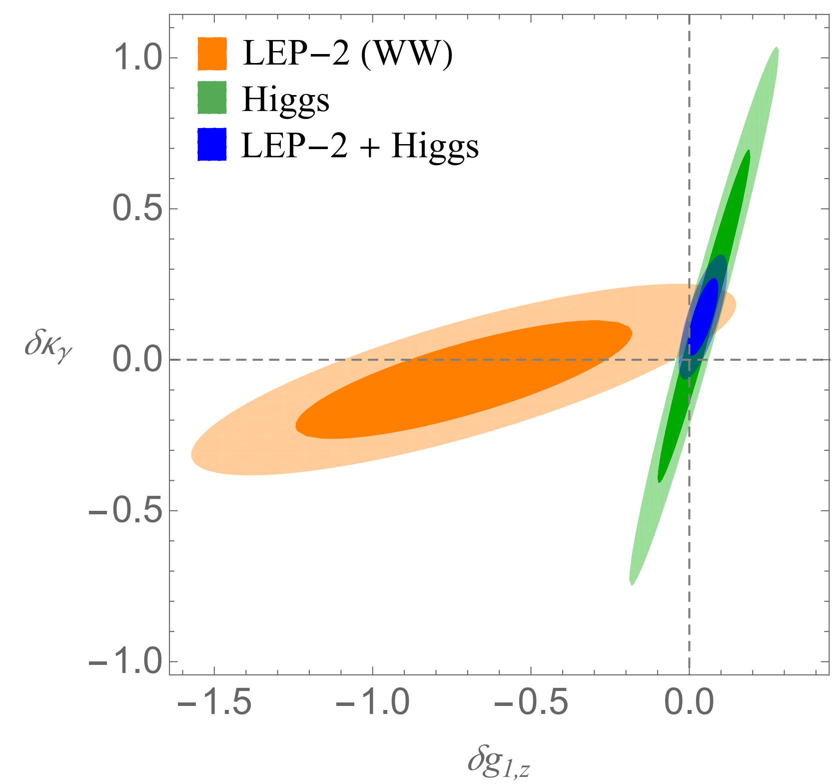
1



$\mathcal{L}_{\mathrm{TGC}}$

SMEFT: aTGC δg_{1Z} and $\delta\kappa_\gamma$ receive contributions from the same interactions entering in hVV couplings

⇒ **WW measurements relevant for Global Higgs fit**



A. Falkowski et al., PRL 116 (2016) 011801

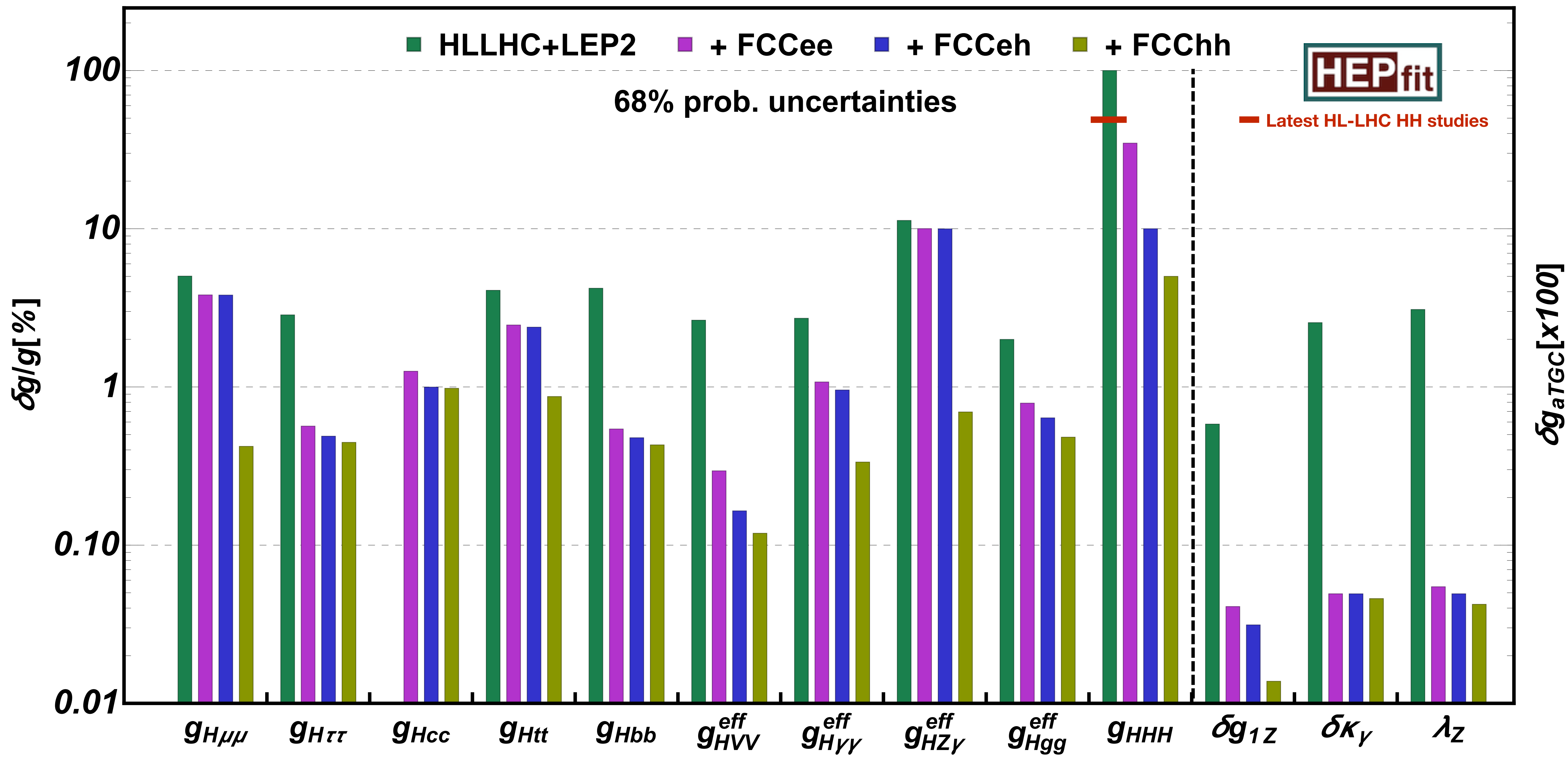
$+ \quad \ldots_{Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma \;)$ $\quad \lambda_\gamma = \lambda_Z$

$$+ \quad ie\frac{\lambda_\gamma}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + ig\cos\theta_W\frac{\lambda_Z}{m_W^2}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu},$$

The Global Higgs fit at FCC

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

Assuming perfect EW measurements



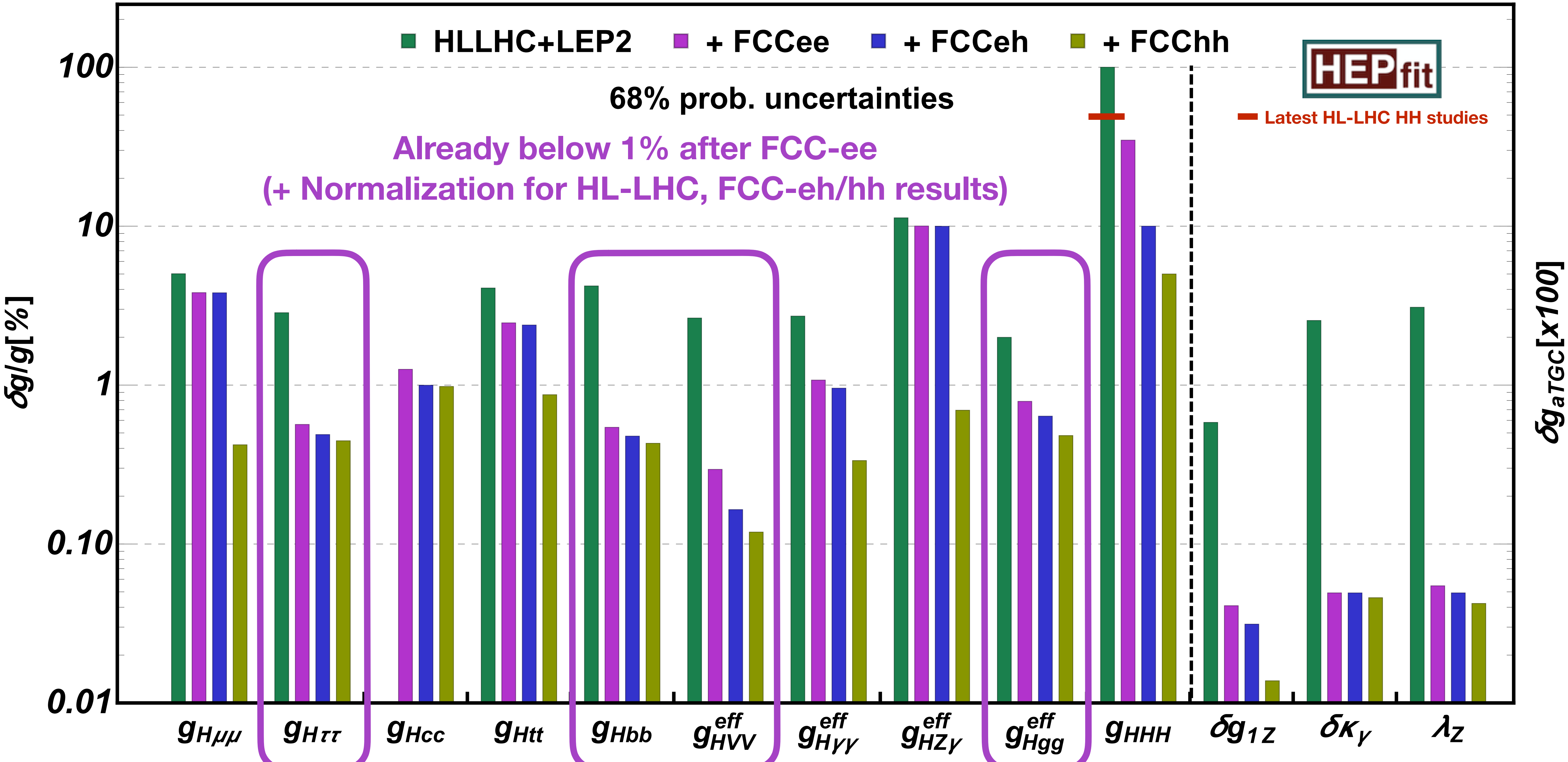
1-σ sensitivity to NP in effective couplings $g_{hXX}^{\mathrm{eff}\ 2} = \frac{\Gamma_{H\to XX}}{\Gamma_{H\to XX}^{\mathrm{SM}}}$ in the SMEFT framework

After FCC-ee/eh/hh: most couplings to be known with a precision below 1%

The Global Higgs fit at FCC

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

Assuming perfect EW measurements



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The Global Higgs fit at FCC

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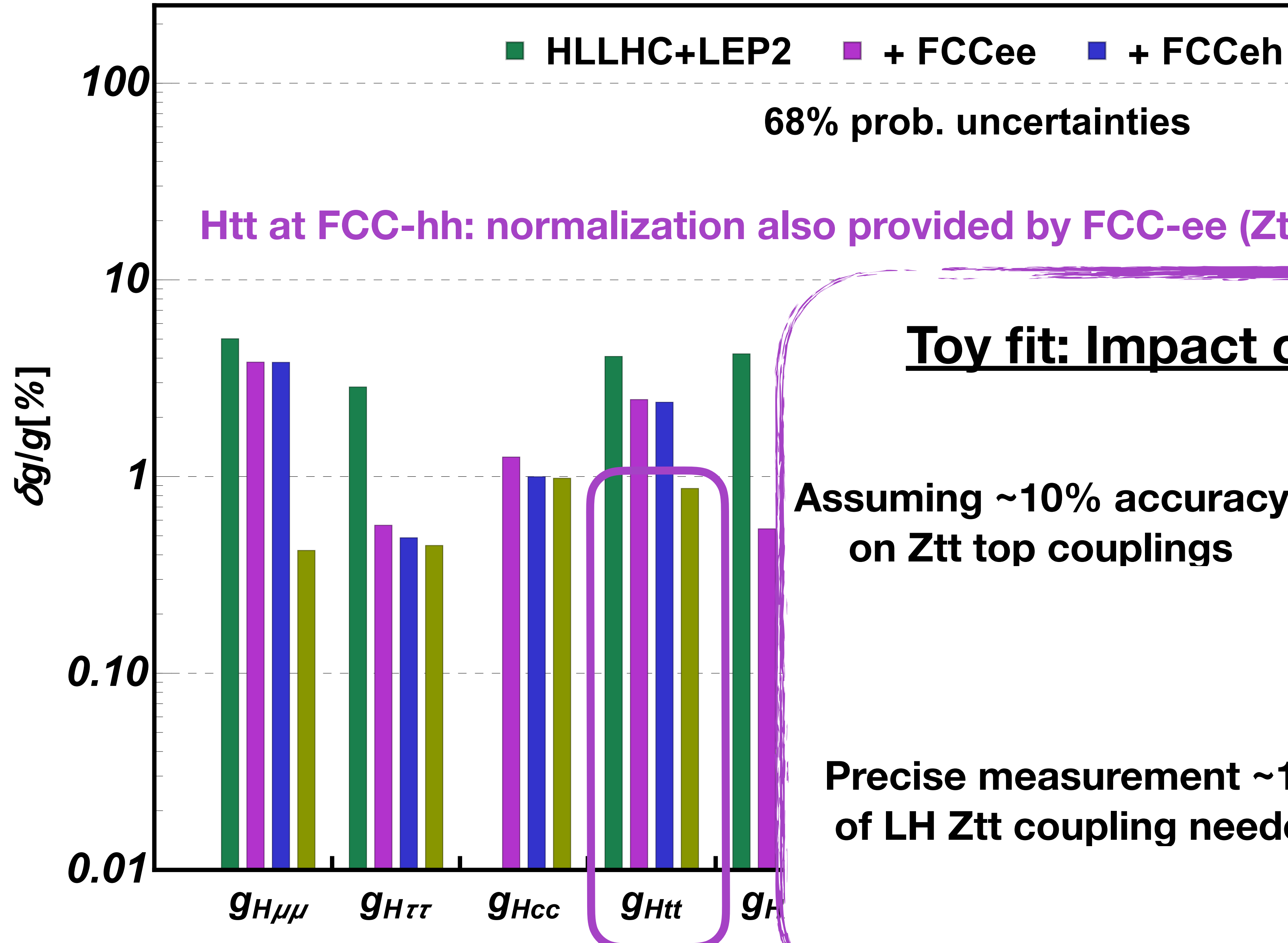
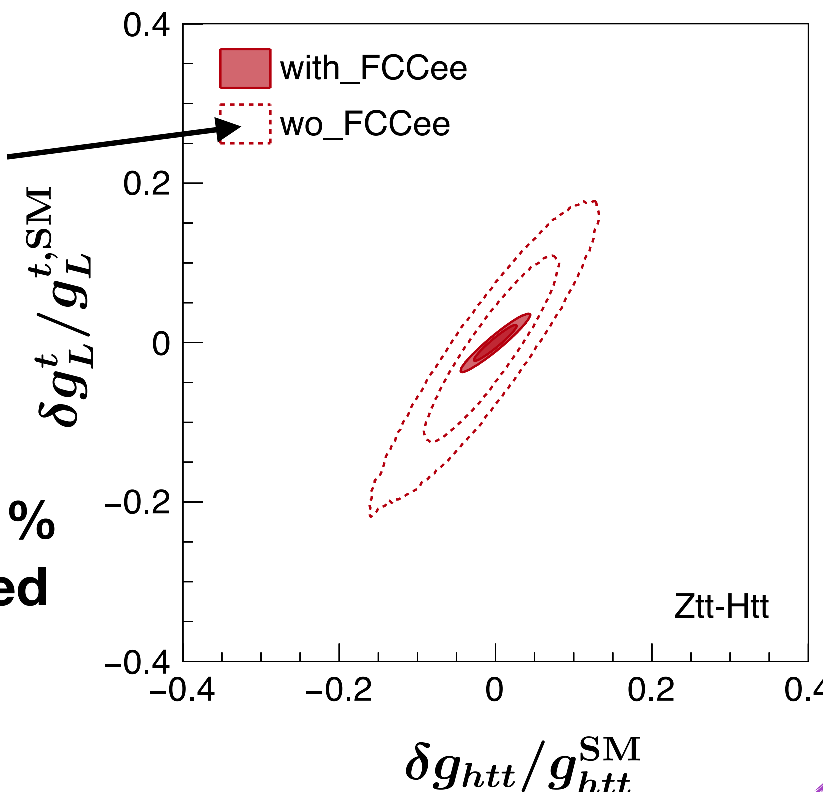


Toy fit: Impact of *ttZ* measurements

Assuming ~10% accuracy on Ztt top couplings

Precise measurement ~1% of LH Ztt coupling needed



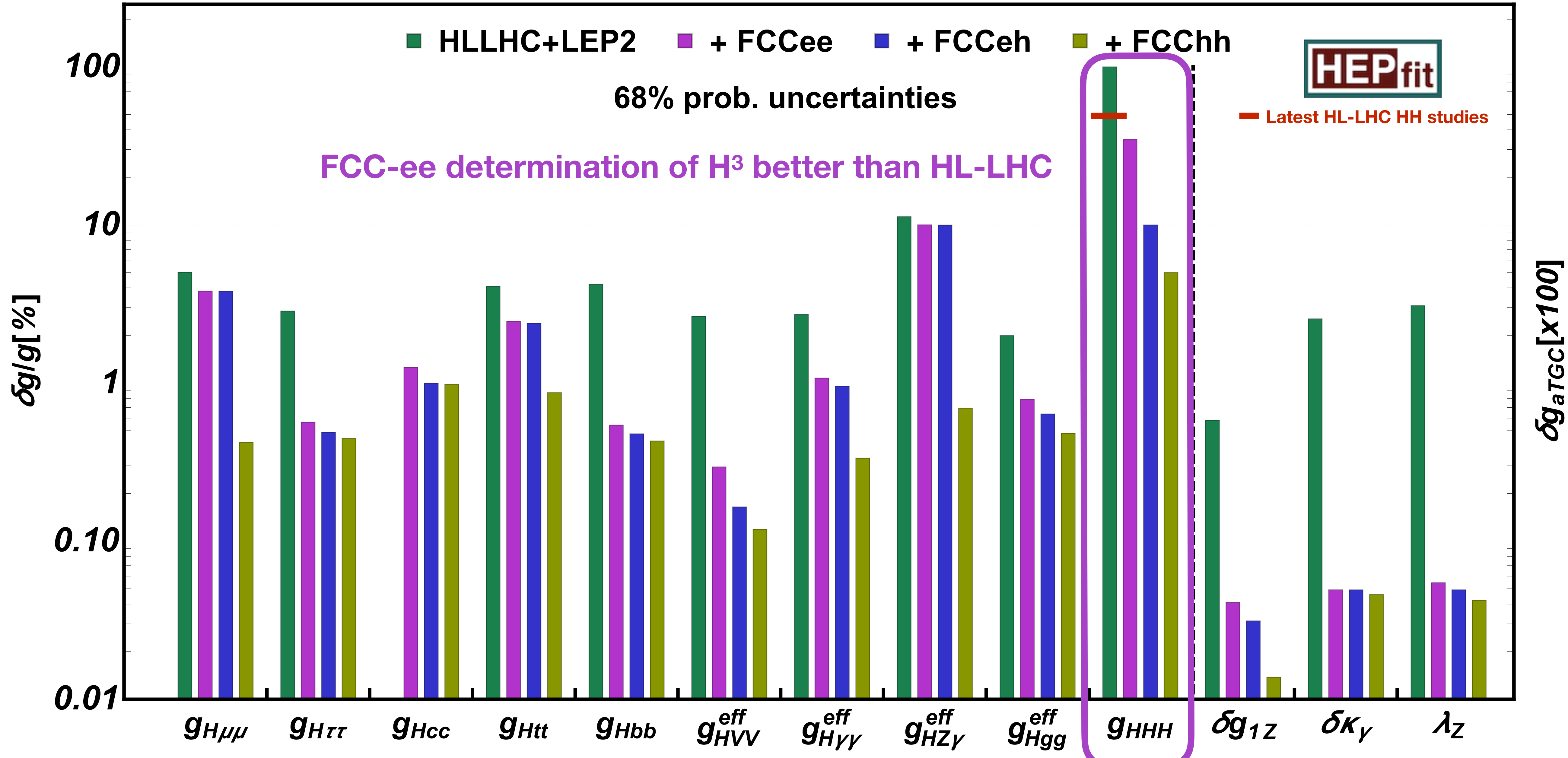
1-σ sensitivity to NP in effective ... $\Gamma_{H\to XX}$

After FCC-ee/eh/hh: most couplings to be known with a precision below 1%

The Global Higgs fit at FCC

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

Assuming perfect EW measurements



1-σ sensitivity to NP in effective couplings $g_{hXX}^{\mathrm{eff}\ 2} = \frac{\Gamma_{H\to XX}}{\Gamma_{H\to XX}^{\mathrm{SM}}}$ **in the SMEFT framework**

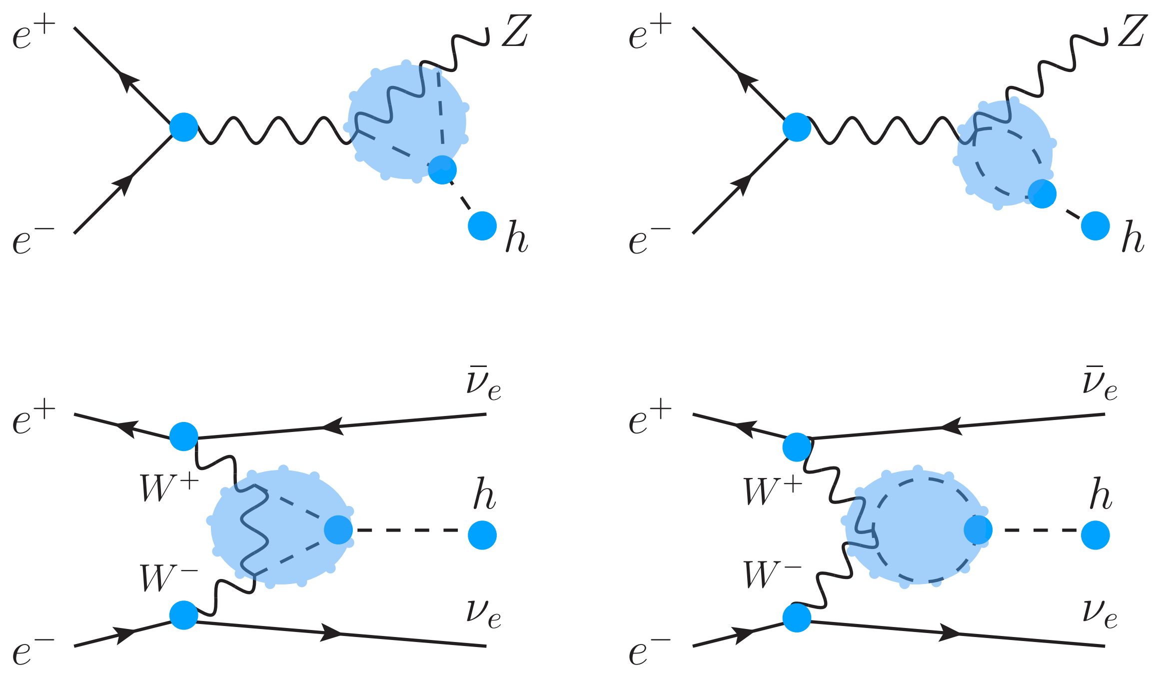
After FCC-ee/eh/hh: most couplings to be known with a precision below 1%

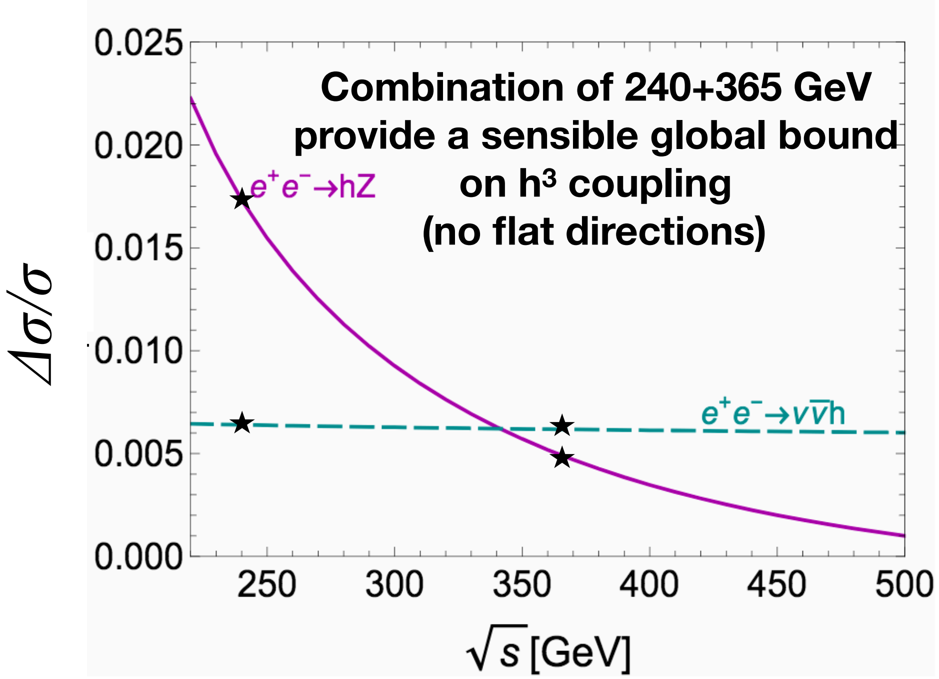
The Global Higgs fit at FCC-ee

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

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

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

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

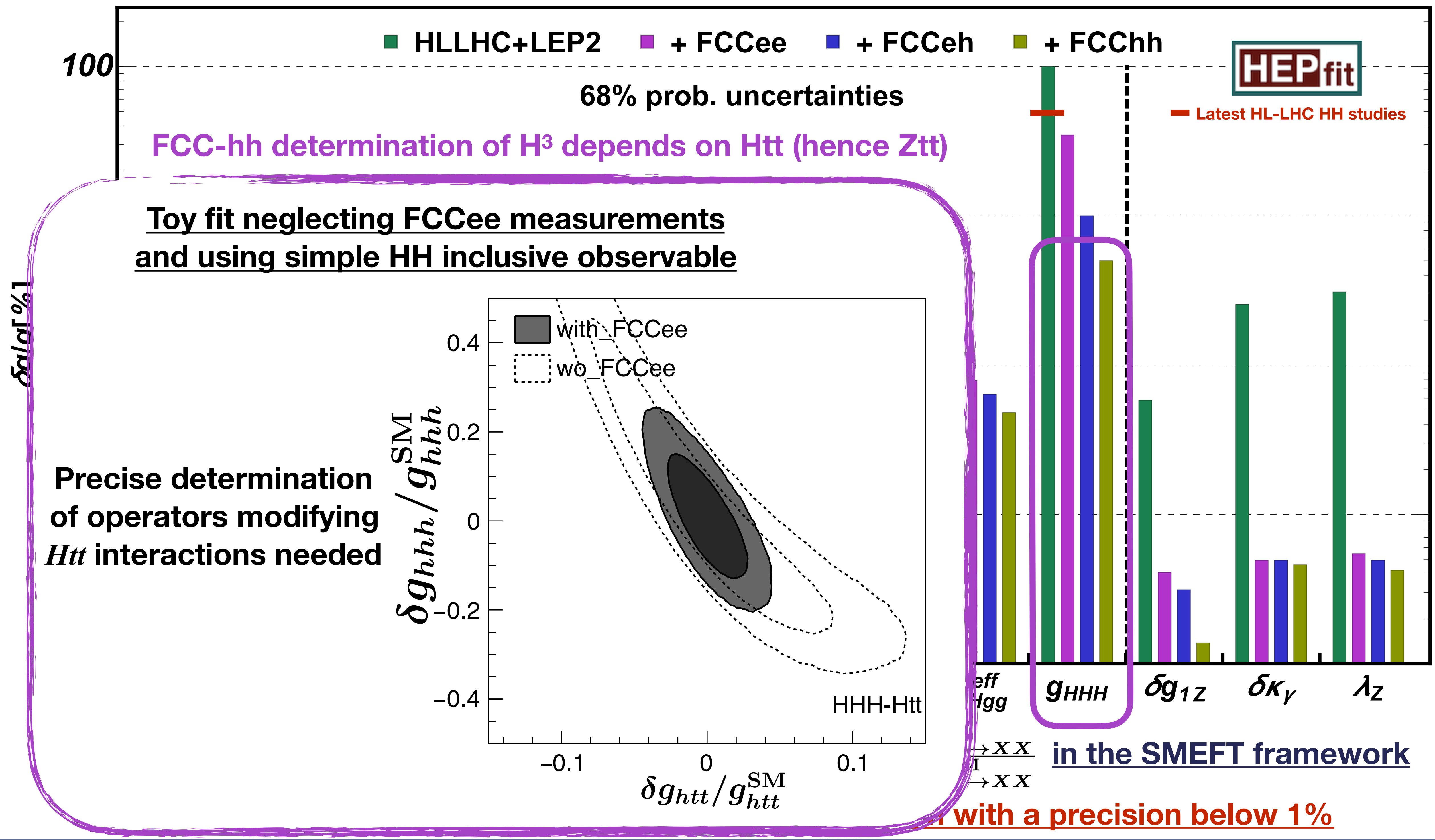
$$\delta g_{hhh}/g_{hhh}^{\rm SM} \approx 40\% \qquad (\,\delta g_{hhh}/g_{hhh}^{\rm SM} \approx 25\% \quad \textbf{4 IPs})$$

Indirect FCC-ee sensitivity to Higgs trilinear better than direct at HL-LHC (~50%)

The Global Higgs fit at FCC

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

Assuming perfect EW measurements

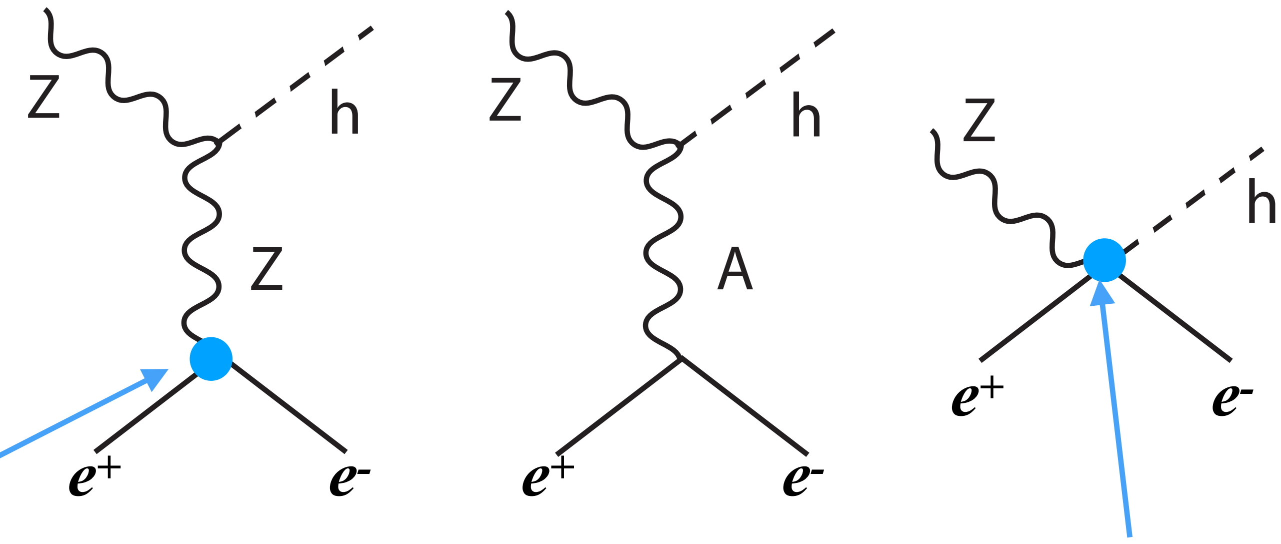


in the SMEFT framework

with a precision below 1%

The Global EW+Higgs fit at FCC

- **In previous Higgs results we assumed perfect EW measurements, e.g.**



Perfect EW: Known to be SM-like with ∞ precision. Also implies these contact int. are absent

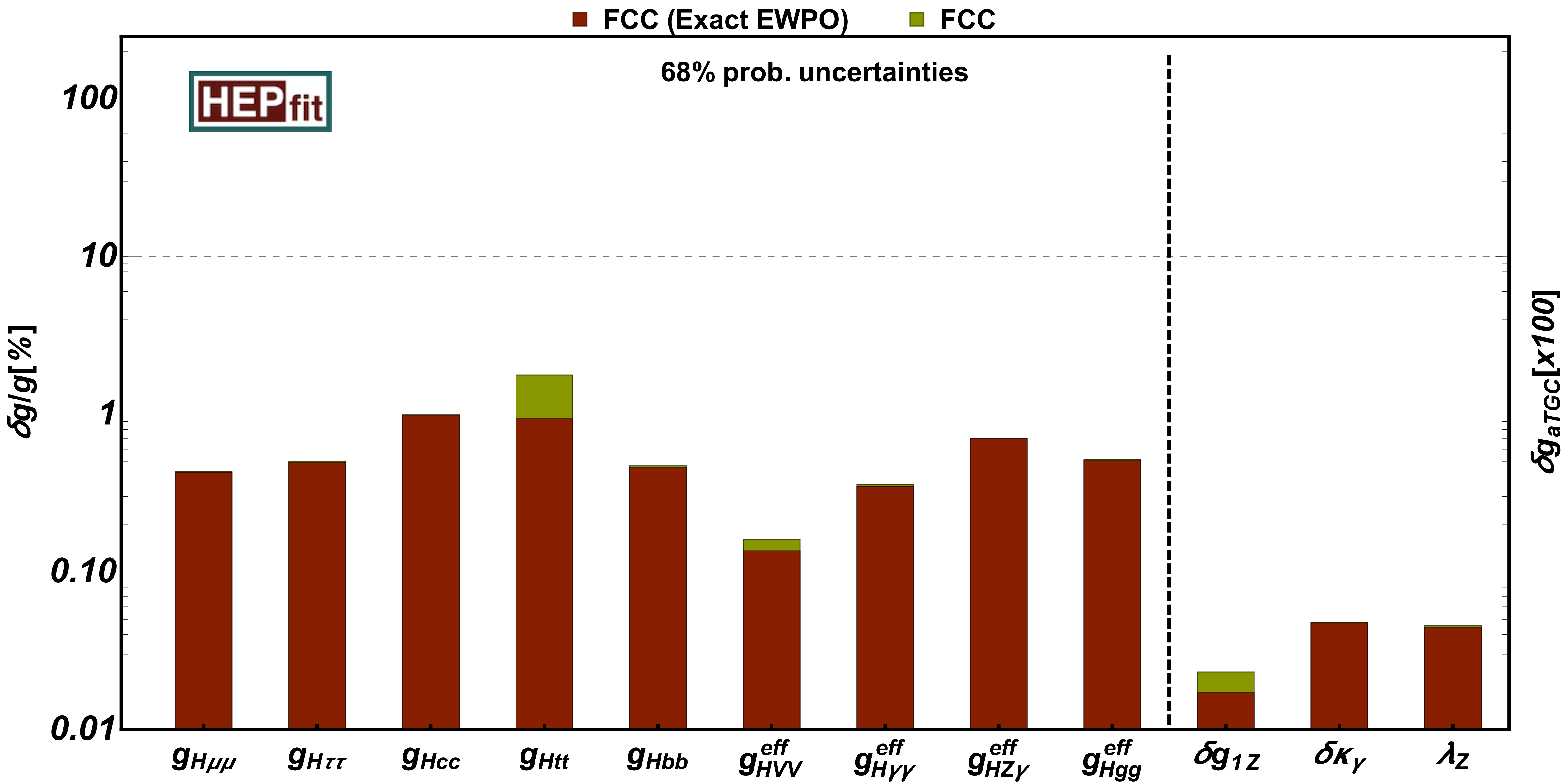
- **Also misses impact of finite precision of *Ztt* in *σ(ttH)/σ(ttZ)***

- **A robust analysis of Higgs couplings requires to add finite precision for all those interactions ⇒ Global EW + Higgs fit**

- **FCC-ee EWPO ≈ perfect EW measurements from the point of view of Higgs measurements**

The Global EW+Higgs fit at FCC

- **Fit to EW and Higgs precision measurements at FCC:**

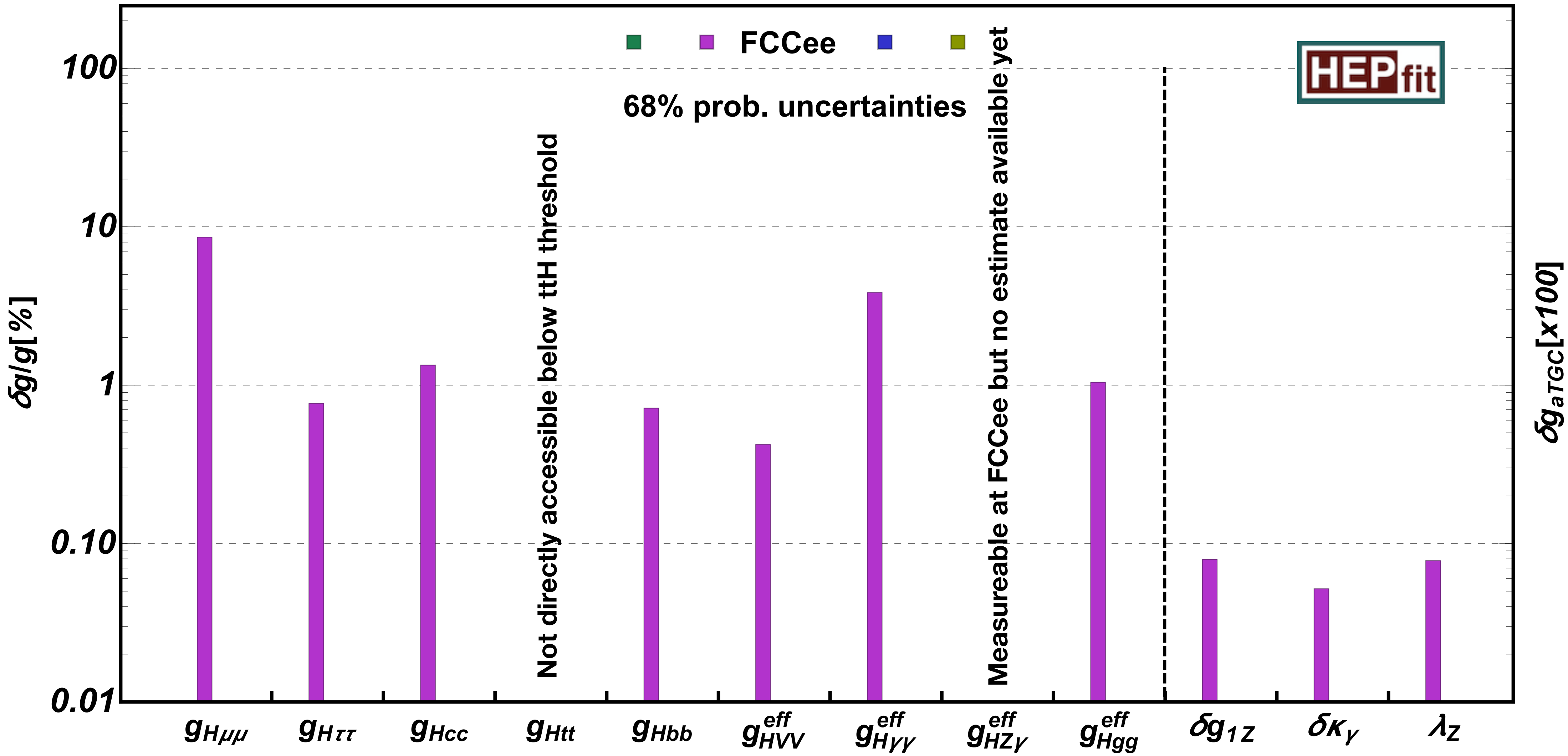


1-σ sensitivity to NP in effective couplings $g^{\text{eff}\ 2}_{hXX} = \frac{\Gamma_{H\to XX}}{\Gamma^{\text{SM}}_{H\to XX}}$ in the SMEFT framework

Only finite precision of FCC-ee *Ztt* slightly reduces sensitivity to *Htt*

Beyond the CDR studies

Still missing: HZγ interactions



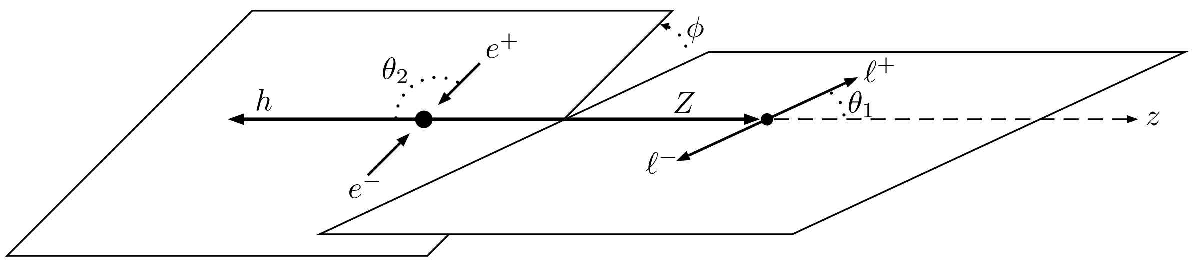
Independent from other interactions in κ analysis but not in EFT

- **CEPC (only 240 GeV):** $\mu_{Z\gamma} \sim 16\%$. **FCC-ee (240+365 GeV)??**

Beyond the CDR studies

Angular information in $e^+e^- \to ZH$

N. Craig, J. Gu, Z. Liu, K. Wang, arXiv: 1512.06877 [hep-ph]



6 angular observables

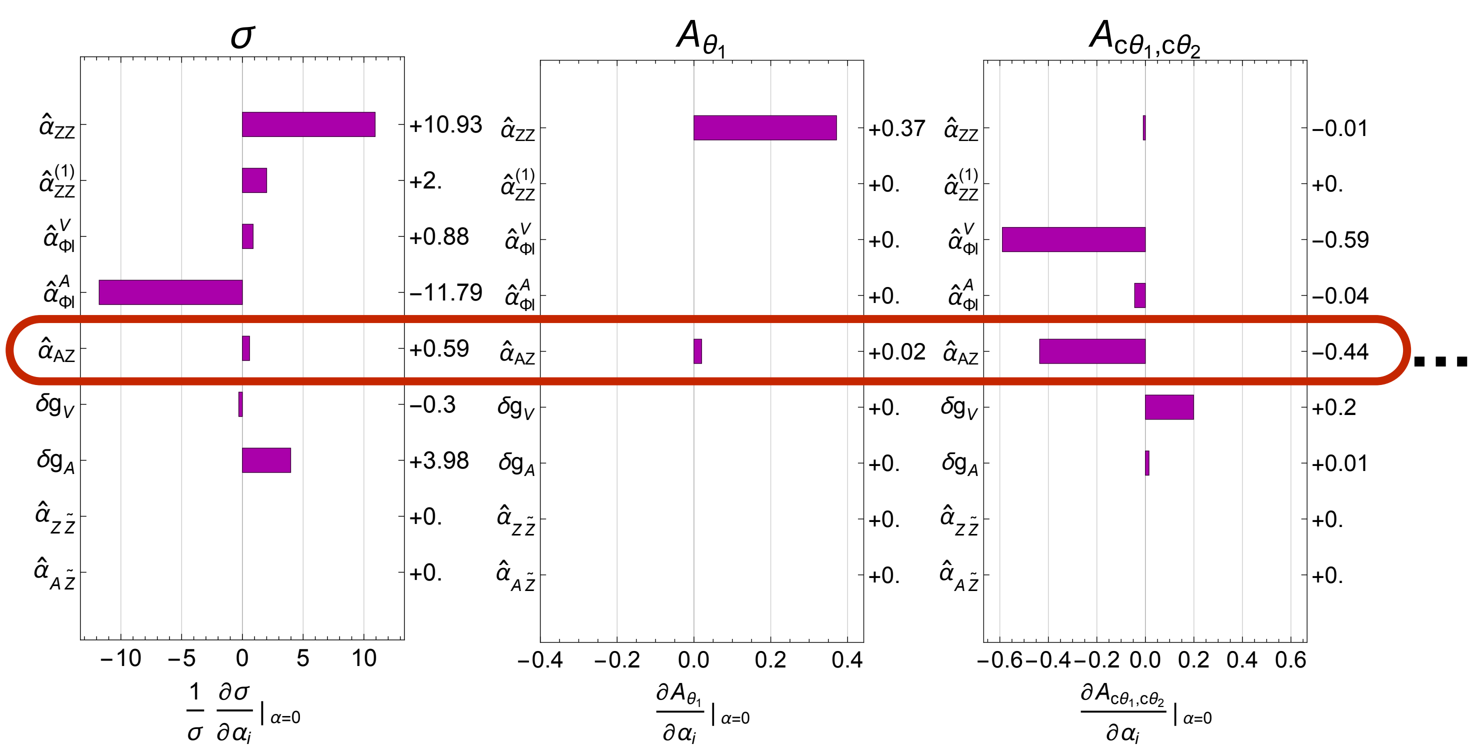
$$\mathcal{A}_{\theta_1} = \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\, \mathrm{sgn}(\cos(2\theta_1))\, \frac{d\sigma}{d\cos\theta_1}$$

$$\mathcal{A}_{\phi}^{(1)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\sin\phi)\, \frac{d\sigma}{d\phi} \qquad \mathcal{A}_{\phi}^{(2)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\sin(2\phi))\, \frac{d\sigma}{d\phi}$$

$$\mathcal{A}_{\phi}^{(3)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\cos\phi)\, \frac{d\sigma}{d\phi} \qquad \mathcal{A}_{\phi}^{(4)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\cos(2\phi))\, \frac{d\sigma}{d\phi}$$

$$\mathcal{A}_{c\theta_1,c\theta_2} = \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\, \mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\, \mathrm{sgn}(\cos\theta_2)\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2}$$

$$\mathcal{L}_{\rm eff} \supset c_{ZZ}^{(1)} h Z_\mu Z^\mu + c_{ZZ}^{(2)} h Z_{\mu\nu} Z^{\mu\nu} + c_{Z\widetilde{Z}} h Z_{\mu\nu}\widetilde{Z}^{\mu\nu} + c_{AZ} h Z_{\mu\nu} A^{\mu\nu} + c_{A\widetilde{Z}} h Z_{\mu\nu}\widetilde{A}^{\mu\nu}$$
$$+ h Z_\mu \bar{\ell}\gamma^\mu (c_V + c_A\gamma_5)\,\ell + Z_\mu\bar{\ell}\gamma^\mu(g_V - g_A\gamma_5)\ell - g_{\rm em} Q_\ell A_\mu \bar{\ell}\gamma^\mu \ell,$$



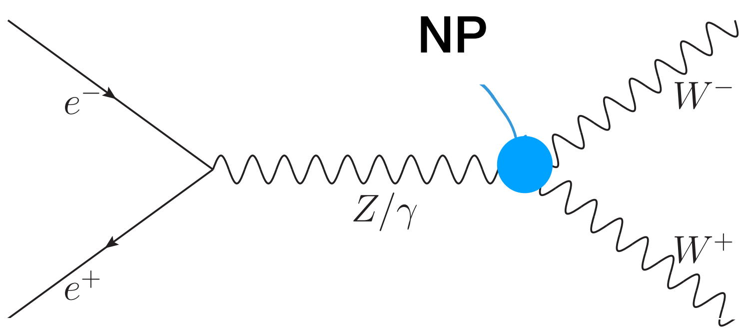
Asymmetries compensate lack of sensitivity of unpolarized rate to hZγ or vector lepton interactions

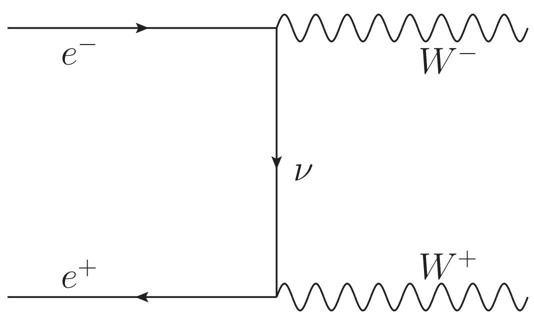
Complementary test of anomalous contributions to h→Zγ

Beyond the CDR studies

Full EFT study of $e^+e^- \to W^+W^-$ production

- **Current FCC-ee aTGC results: Fit to binned angular distr. (no corr.). Also assume aTGC dominance, i.e.**





- **Good approx. at LEP2. Probably good approx. at FCC-ee too…**

Beyond the CDR studies

Full EFT study of $e^+e^- \to W^+W^-$ production

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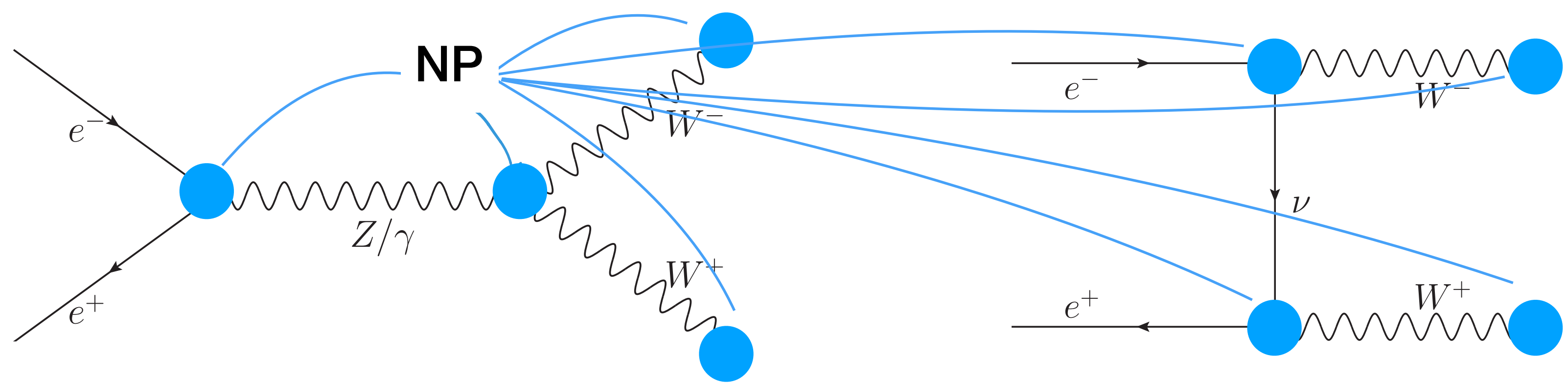
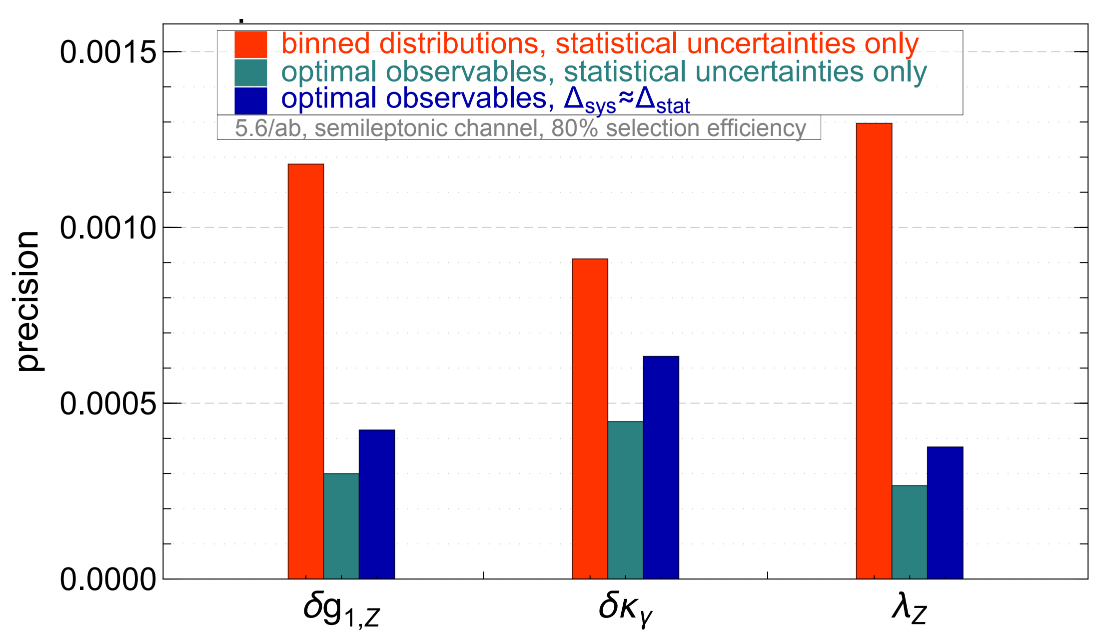


- **Good approx. at LEP2. Probably good approx. at FCC-ee too…**
- **…testing using full EFT parameterization… plus statistical optimal observable analysis** JB, G. Durieux, C. Grojean, J. Gu, A. Paul, In preparation



OO study is idealized: only take care of statistics part

How large are sys. expected to be in WW at FCC-ee?

$$\Delta_{\rm sys} \approx \Delta_{\rm stat} \ ?$$

Did we miss anything?

- **Probably… There was certainly more we wanted to do:**

From the defunct Volume 5

16	Higgs boson mass measurement
17	Higgs boson CP Measurement
18	Exotic Higgs boson decays

No info of M_H in CDR!

Precision of ~10 MeV needed to push parametric uncertainties in $h \to VV^*$ to an acceptable level (CEPC claims 5.9 MeV)

4	Lepton Flavour violation in Z decays

(and Higgs)

- **…Looking forward to see the results that were in preparation for those sections**