EFT FITS FOR HIGGS AND EW @FCC-ee

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two paths to the throne:
–find a new degree of freedom
–find a modified coupling

OVERVIEW

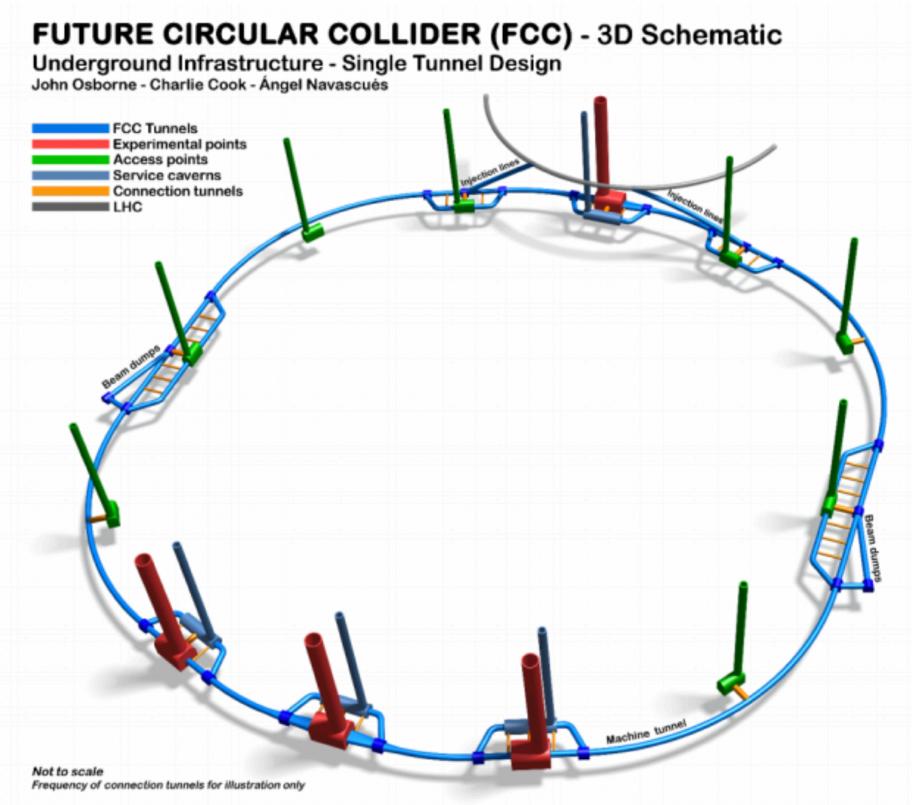
FCC–ee projections

-- FCC-ee run configurations

-- primary physics processes probed

-- the precision of Electroweak Precision Observables at FCC-ee

-- aTGC and trilinear measurements



FCC–ee CDR vols. 1 & 2

EFT fits

-- defining the EFT bases

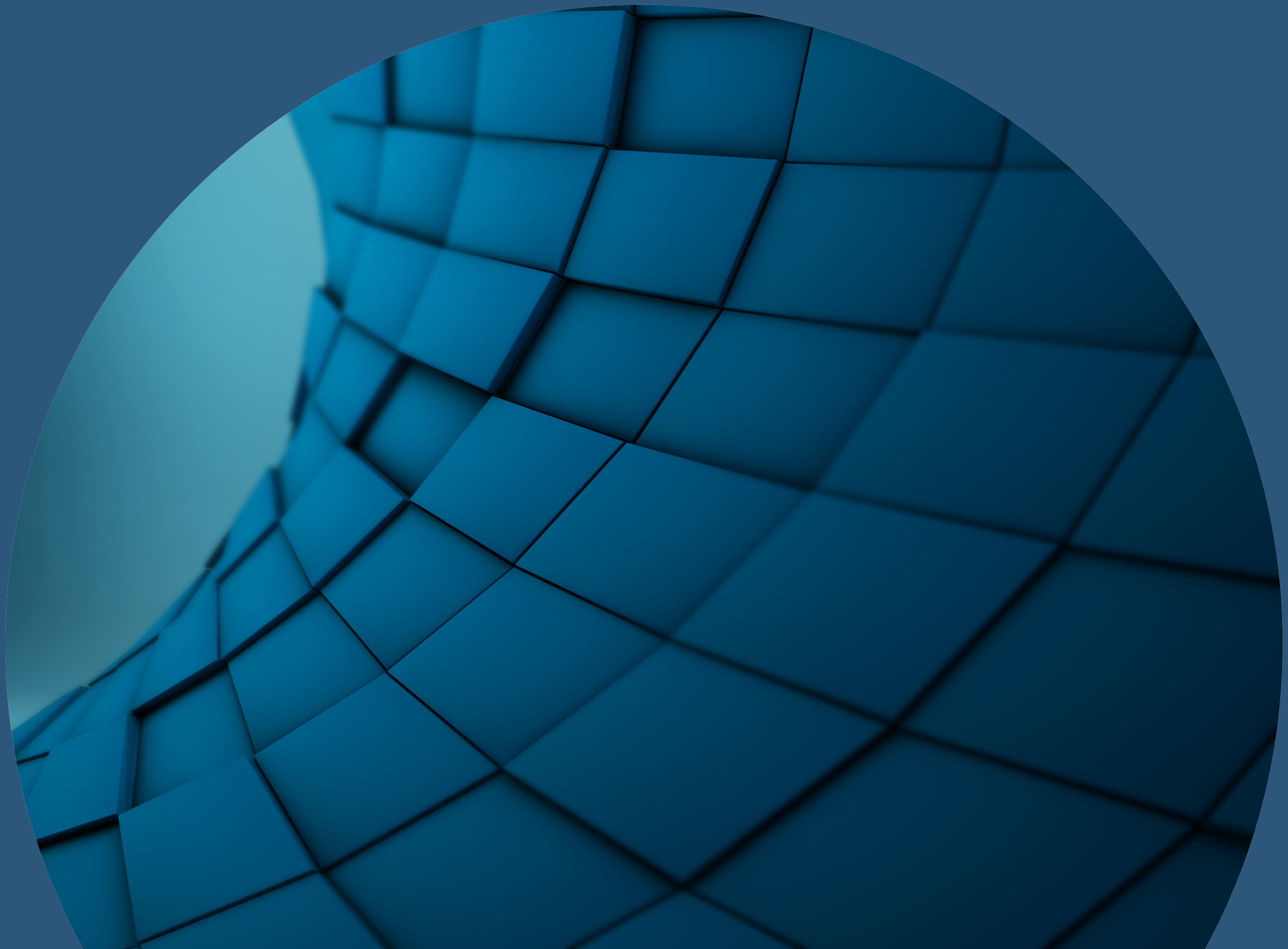
-- fits in the EFT framework

-- correlations between the EW and Higgs sectors

-- comparison with other proposed colliders

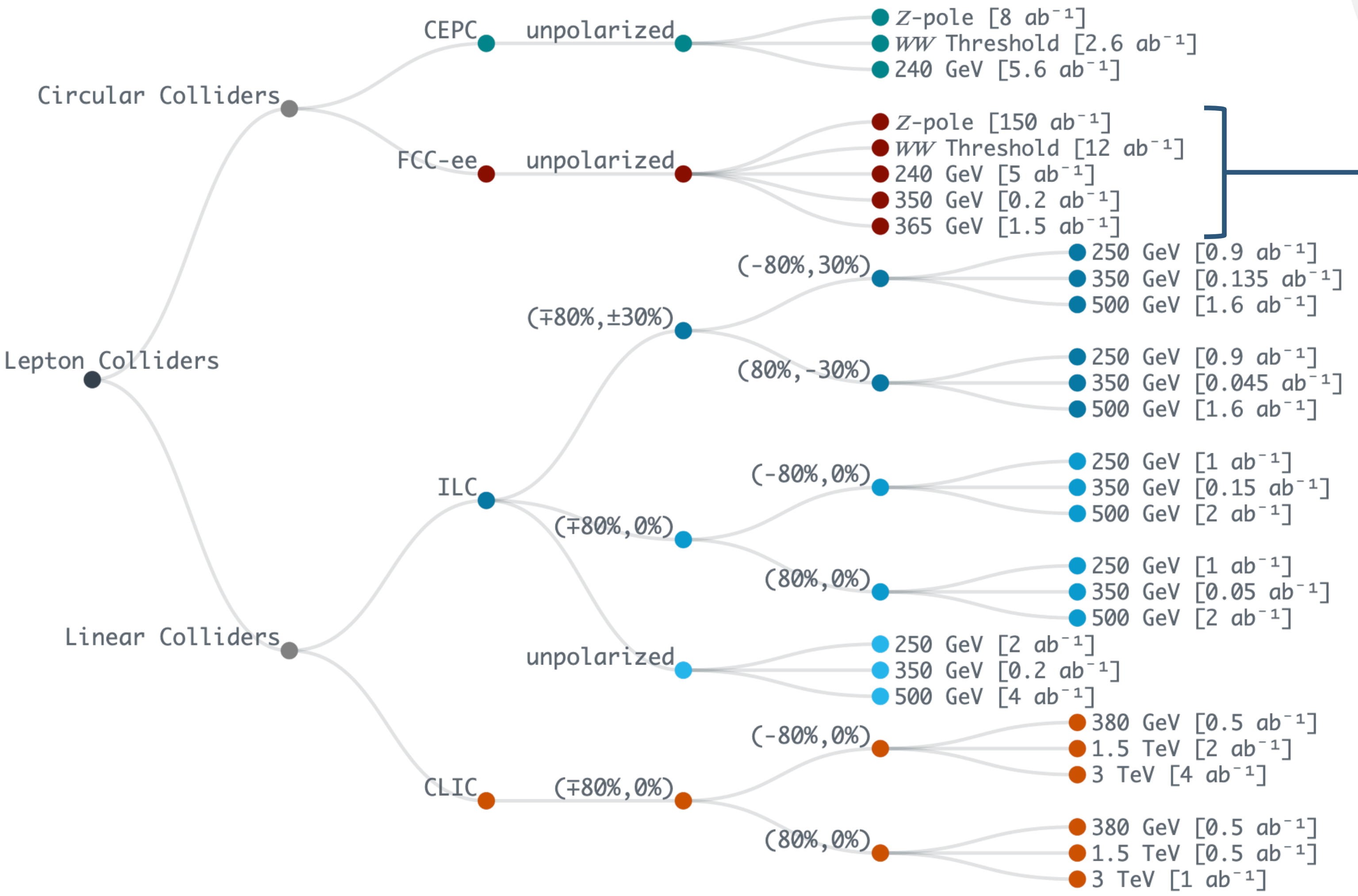
THE COLLIDER

Operating energies, luminosities and physics goals.



RUN CONFIGURATIONS

Comparison between the different proposed collider and runs

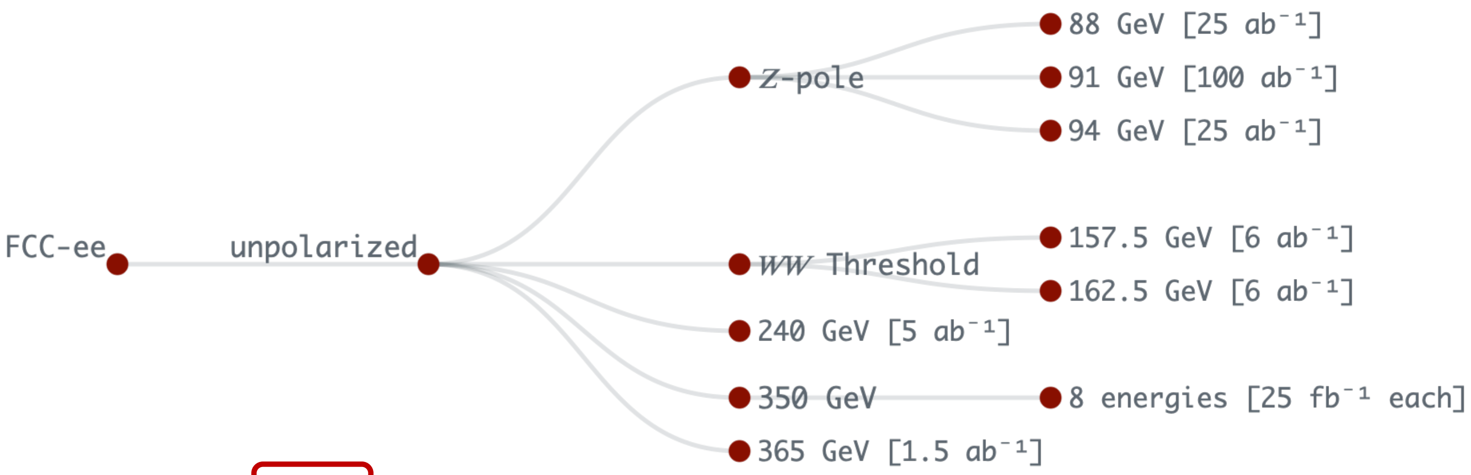


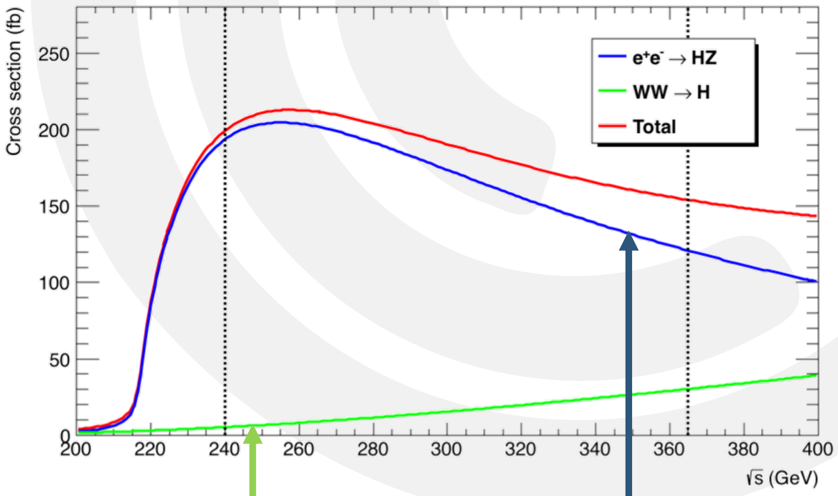
- The FCC-ee has a very comprehensive program at several energies to probe EW, Higgs and top physics.
- Z-pole run is, by far, of the highest luminosity: improvements over LEP/SLD measurements by several orders of magnitude.
- Higgs program at several energies: possible to make measurement of the trilinear coupling.

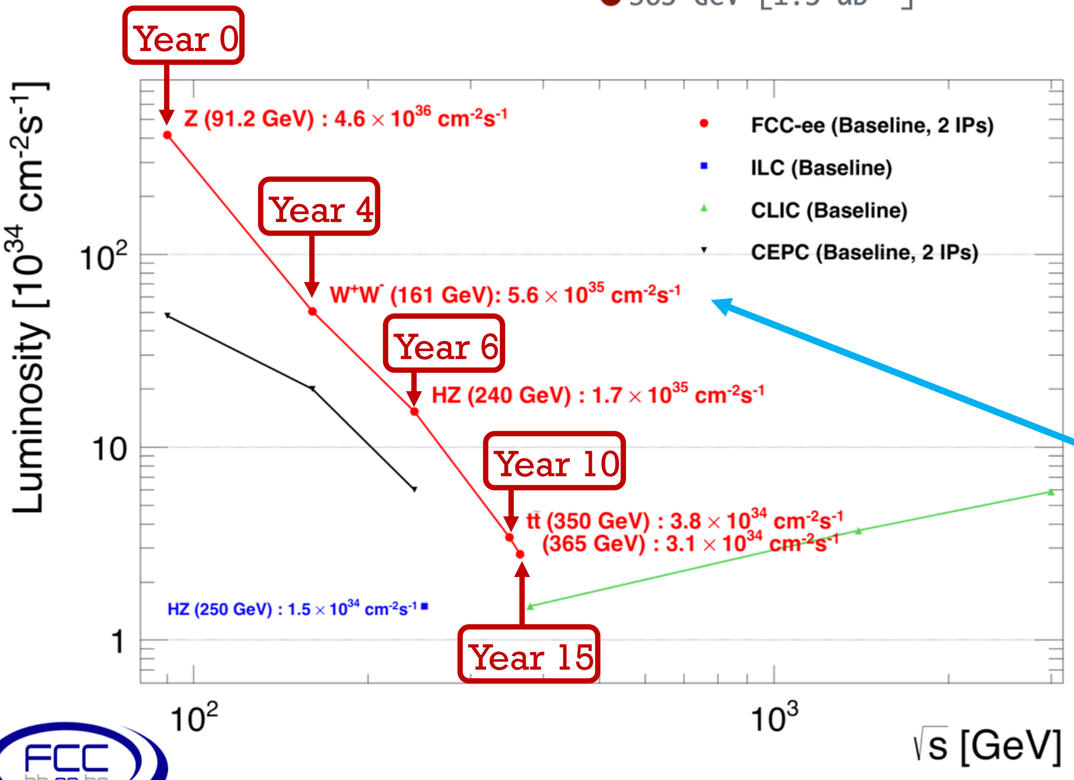
Particle production @ FCC-ee

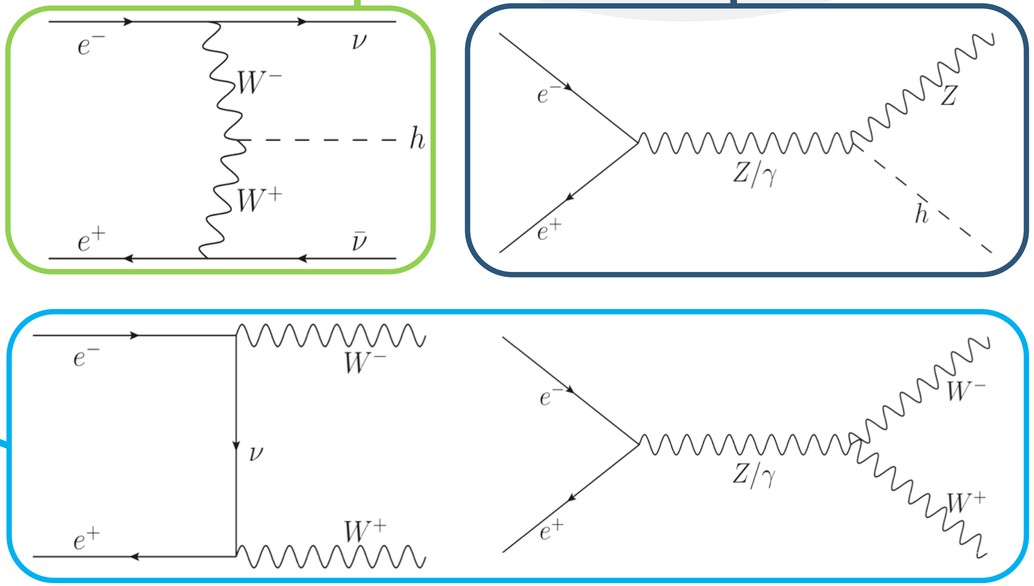
Phase	Run duration (years)	Event statistics
FCC-ee-Z	4	3×10^{12} visible Z decays
FCC-ee-W	2	10^8 WW events
FCC-ee-H	3	10^6 ZH events
FCC-ee-tt(1)	1	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	10^6 $t\bar{t}$ events

RUN CONFIGURATIONS









Primary production modes

EWPO MEASUREMENTS

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
σ^0_{had} ($\times 10^3$) (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
$\sin^2\theta_W^{\mathrm{eff}}$ ($\times 10^6$)	231480±160	3	2-5	from $A_{FB}^{\mu\mu}$ at Z peak, beam energy calibration
$1/\alpha_{QED}(m_Z)$ ($\times 10^3$)	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
$A_{FB}^{\mathrm{pol},\tau}$ ($\times 10^4$)	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_{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

Z–pole

WW

tt

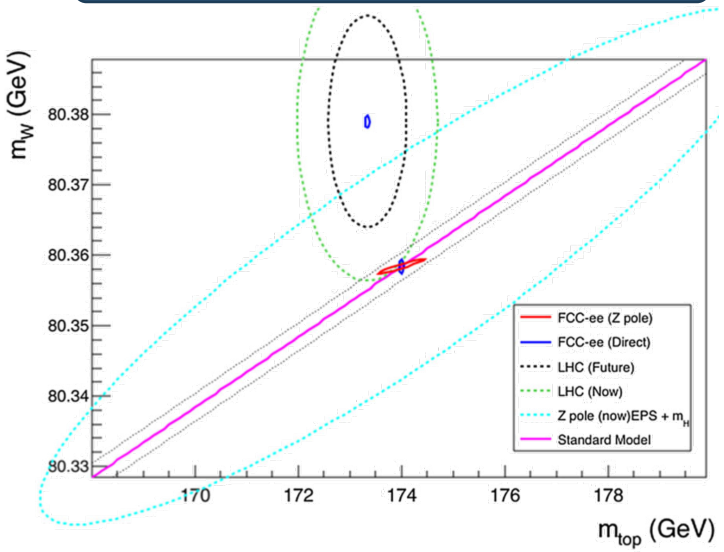
List of EWPO measurements and sensitivities projected for FCC-ee

FCC-ee will redefine "precision" for Electroweak Precision Observables!

systematics dominated

statistics dominated

W and top mass measurements



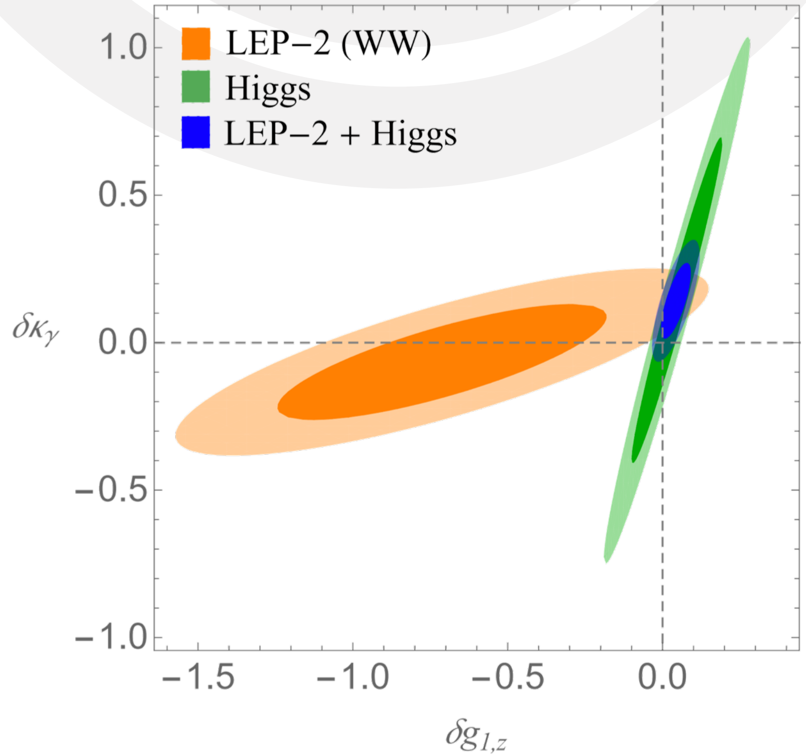
DIBOSON MEASUREMENTS

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

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

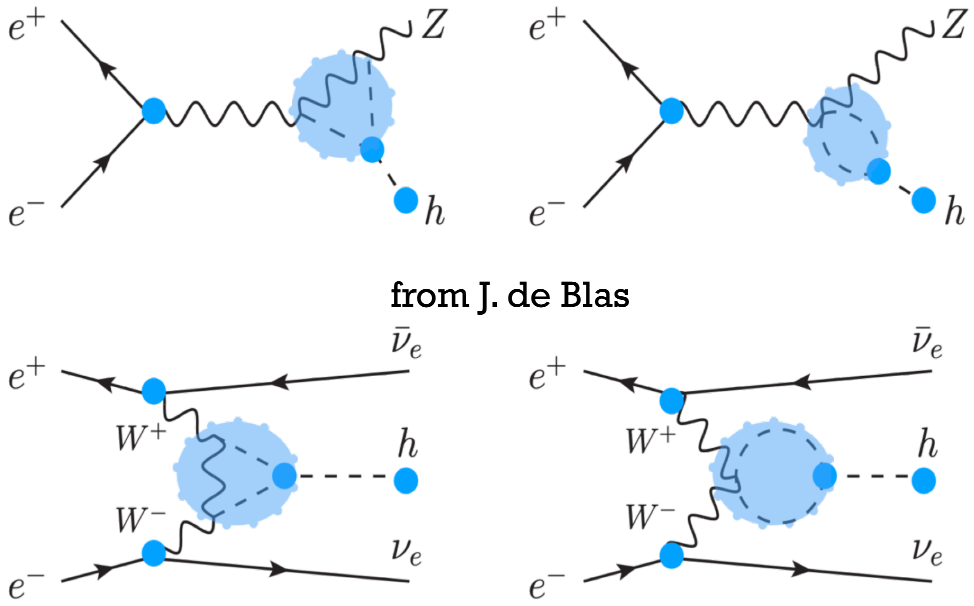
	240 GeV only				**365 GeV only**			
	uncertainty	correlation matrix			uncertainty	correlation matrix		
		$\delta g_{1,Z}$	$\delta\kappa_\gamma$	λ_Z		$\delta g_{1,Z}$	$\delta\kappa_\gamma$	λ_Z
$\delta g_{1,Z}$	11.2×10^{-4}	1	0.08	-0.90	13.9×10^{-4}	1	-0.57	-0.80
$\delta\kappa_\gamma$	8.6×10^{-4}		1	-0.42	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

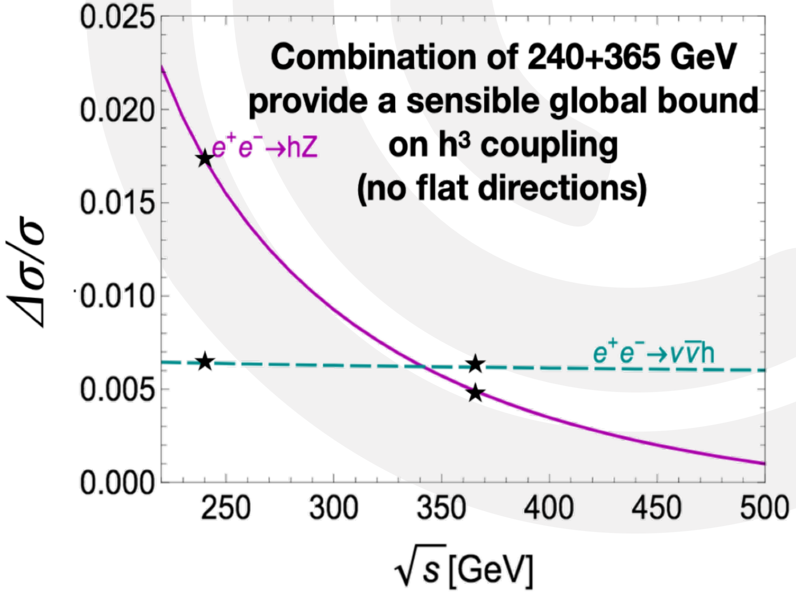


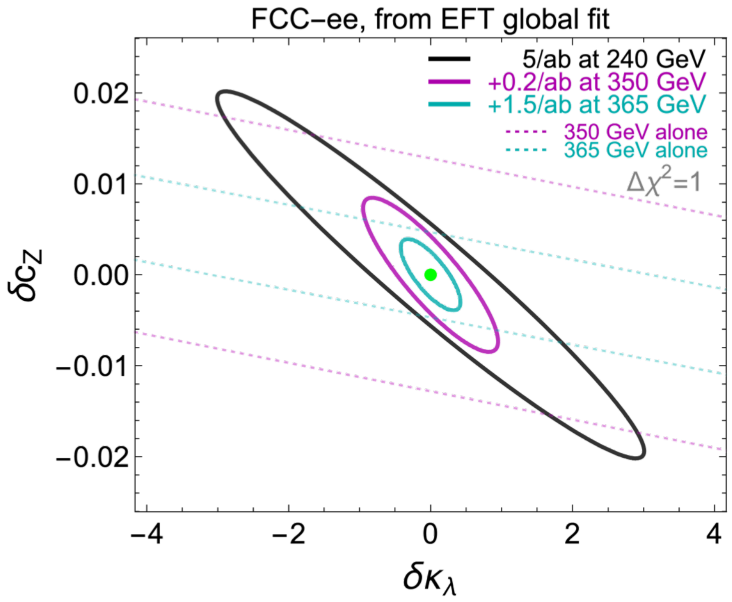
A. Falkowski et. al. arXiv:1508.00518

TRILINEAR HIGGS COUPLING



from J. de Blas

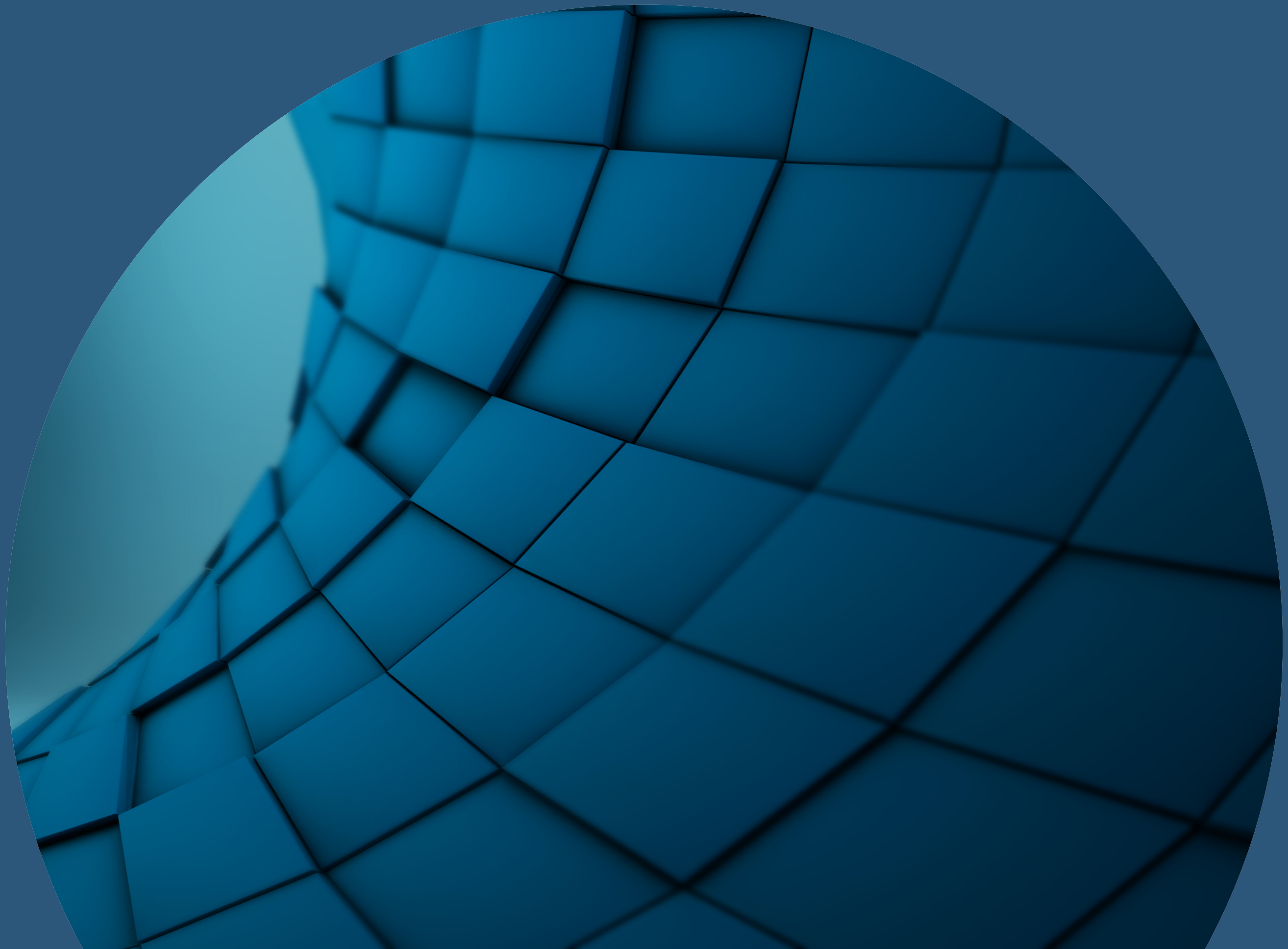




FCC-ee can measure the trilinear using two energies.
Bounds competitive with those from higher energies at linear colliders

EFT FITS

Blending EW, diboson and Higgs precision physics.



EFT BASIS

Basis of operators in an EFT

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = i H^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

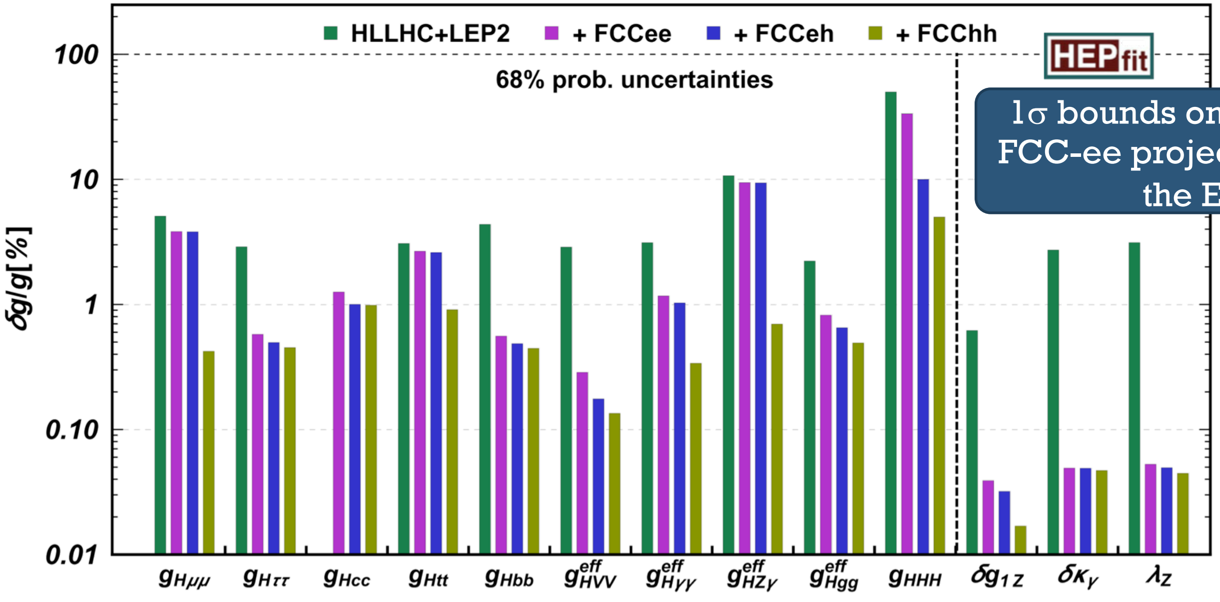
not present in the SILH’ basis

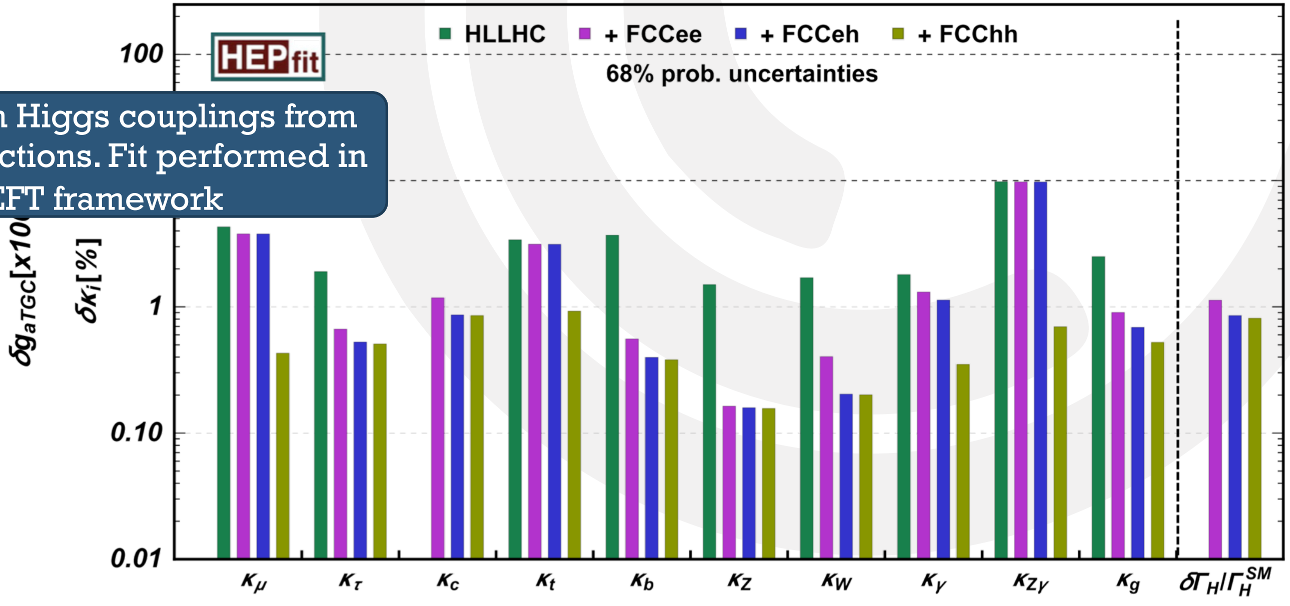
not present in the modified-SILH’ basis

not present in the Warsaw basis

- Any theoretical framework comes with some assumptions and an EFT is not an exception!
- However, it is a consistent framework to relate physics in at different scales for different productions and decays.
- In the absence of a coherent UV-completion, an EFT framework can miss the correlations between different operators in any basis
- An EFT is an attempt to minimize “model assumptions”, not to completely remove it.
- A global fit has to be able to incorporate measurements in different sectors, like the Higgs and EW, simultaneously.
- An EFT fit and a “κ” fit should present the same physics results if the Higgs and EW sectors are decoupled (as it is with current measurement).

GLOBAL FIT





1σ bounds on Higgs couplings from FCC-ee projections. Fit performed in the EFT framework

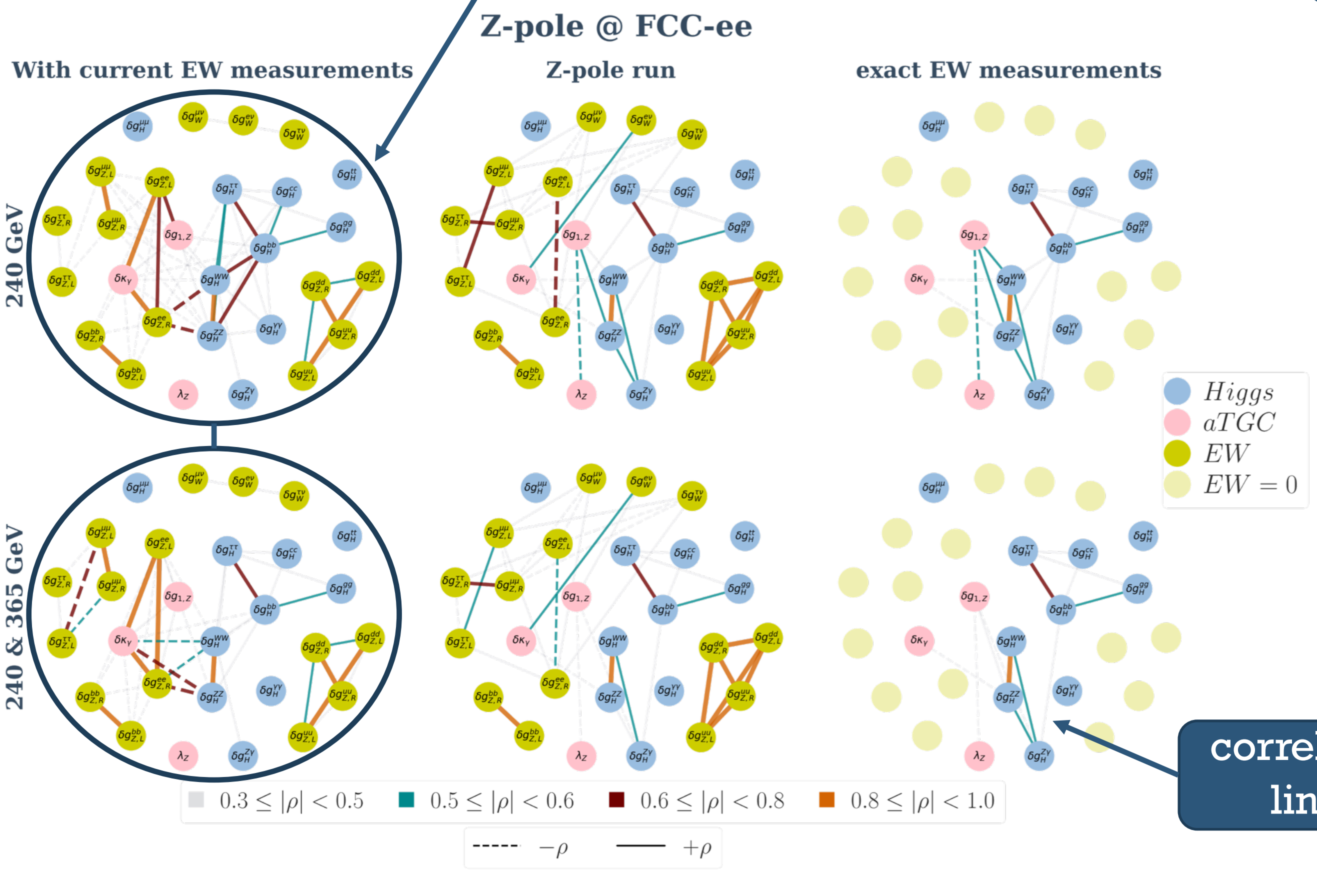
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	**< 1.0**	< 1.0

(sub-)% precision in the Higgs couplings

J. de Blas et. al. arXiv:1907.04311

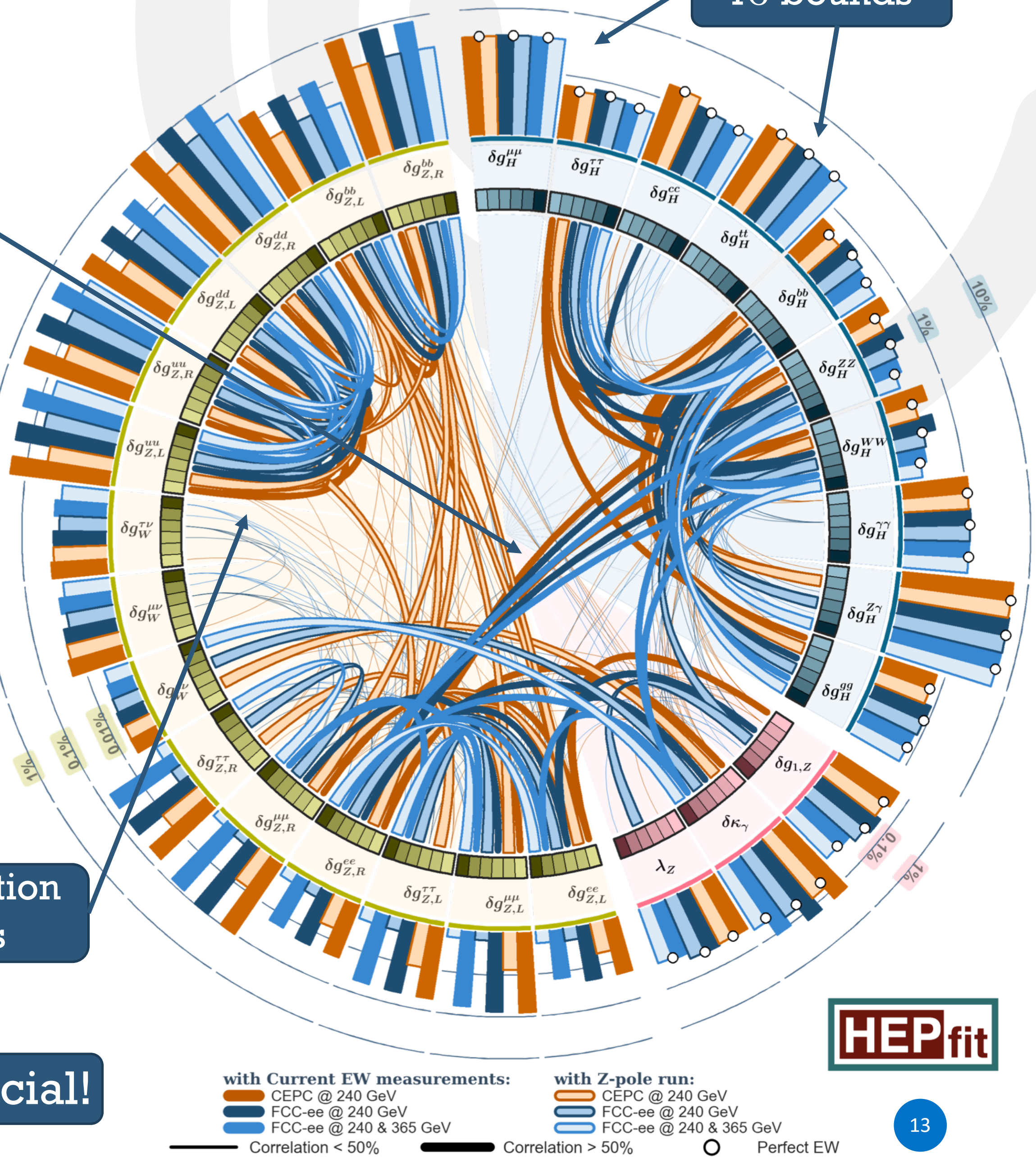
HIGGS−EW INTERPLAY

Correlation between the Higgs and EW sector without a *Z*-pole run



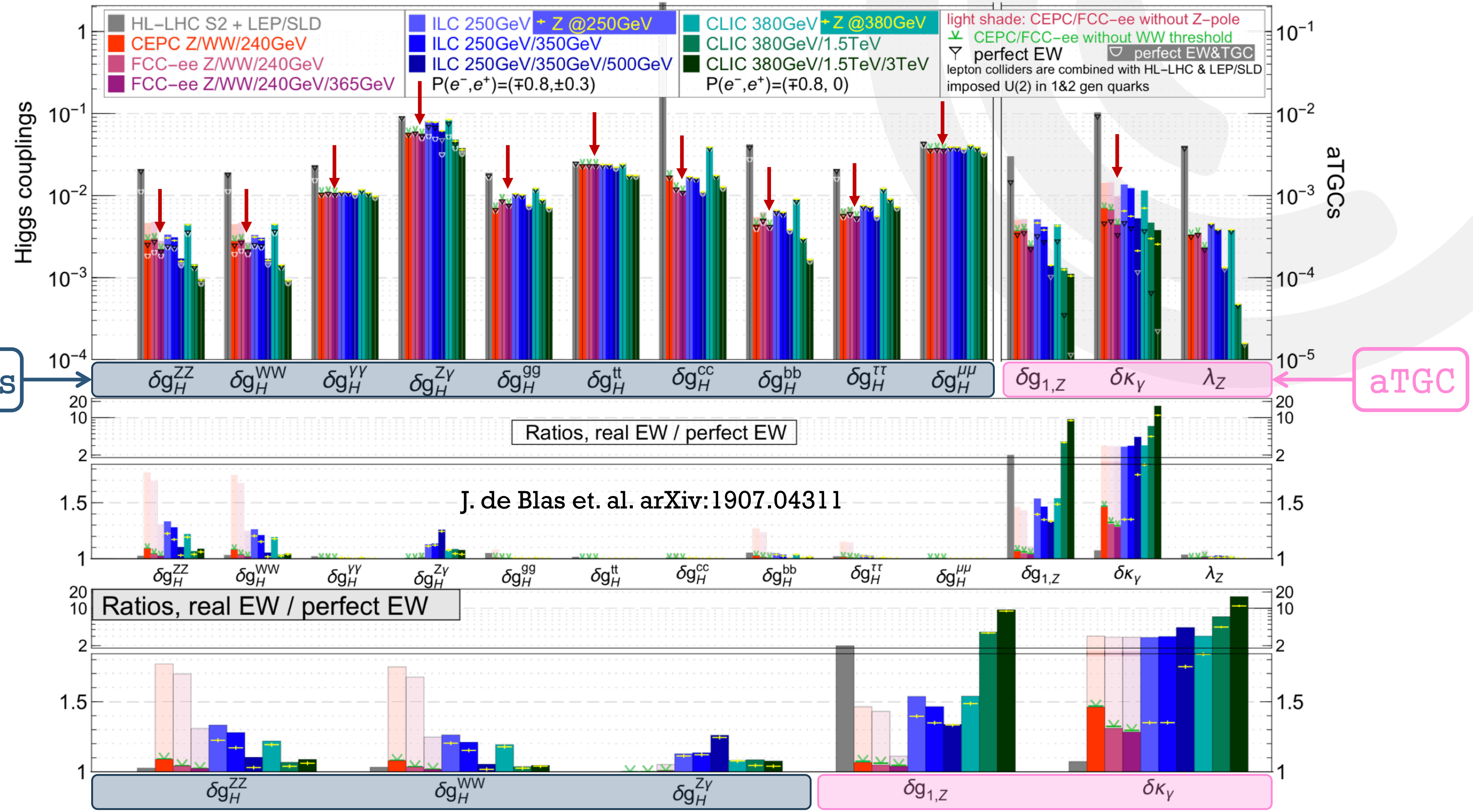
correlation links

1σ bounds



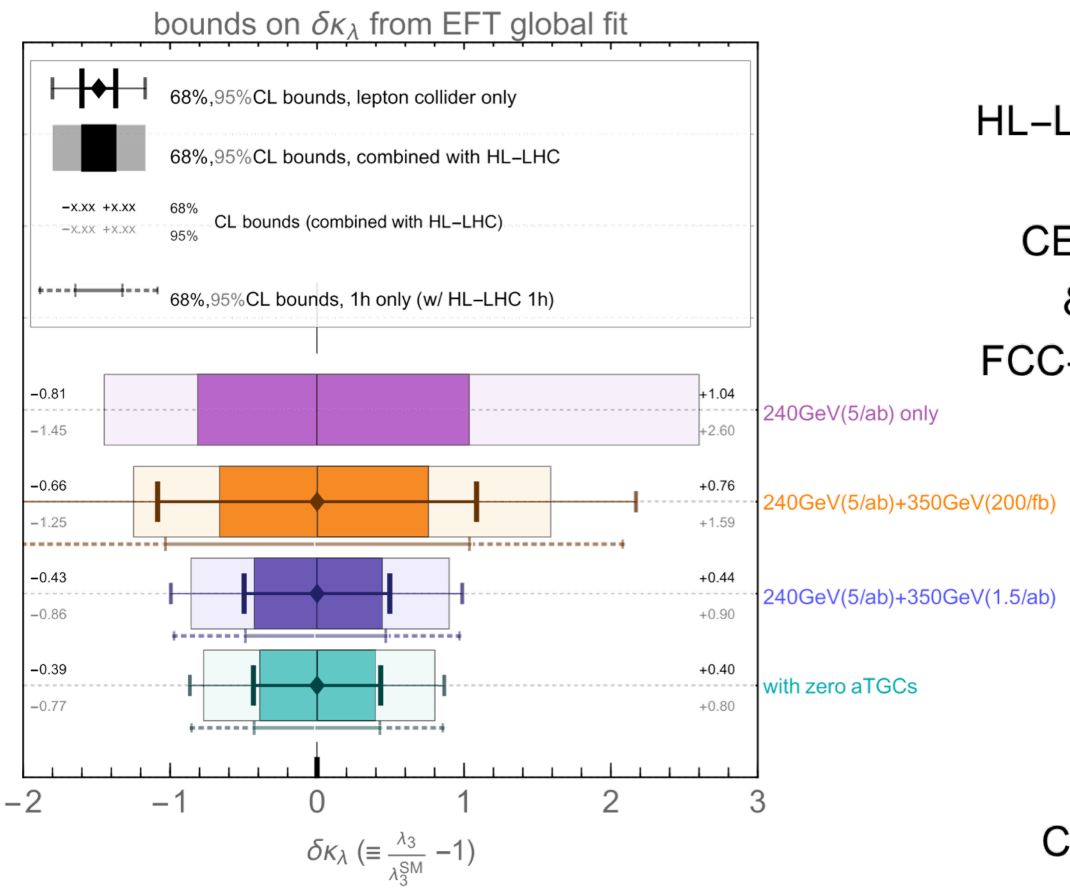
Improved EWPO measurement is crucial!

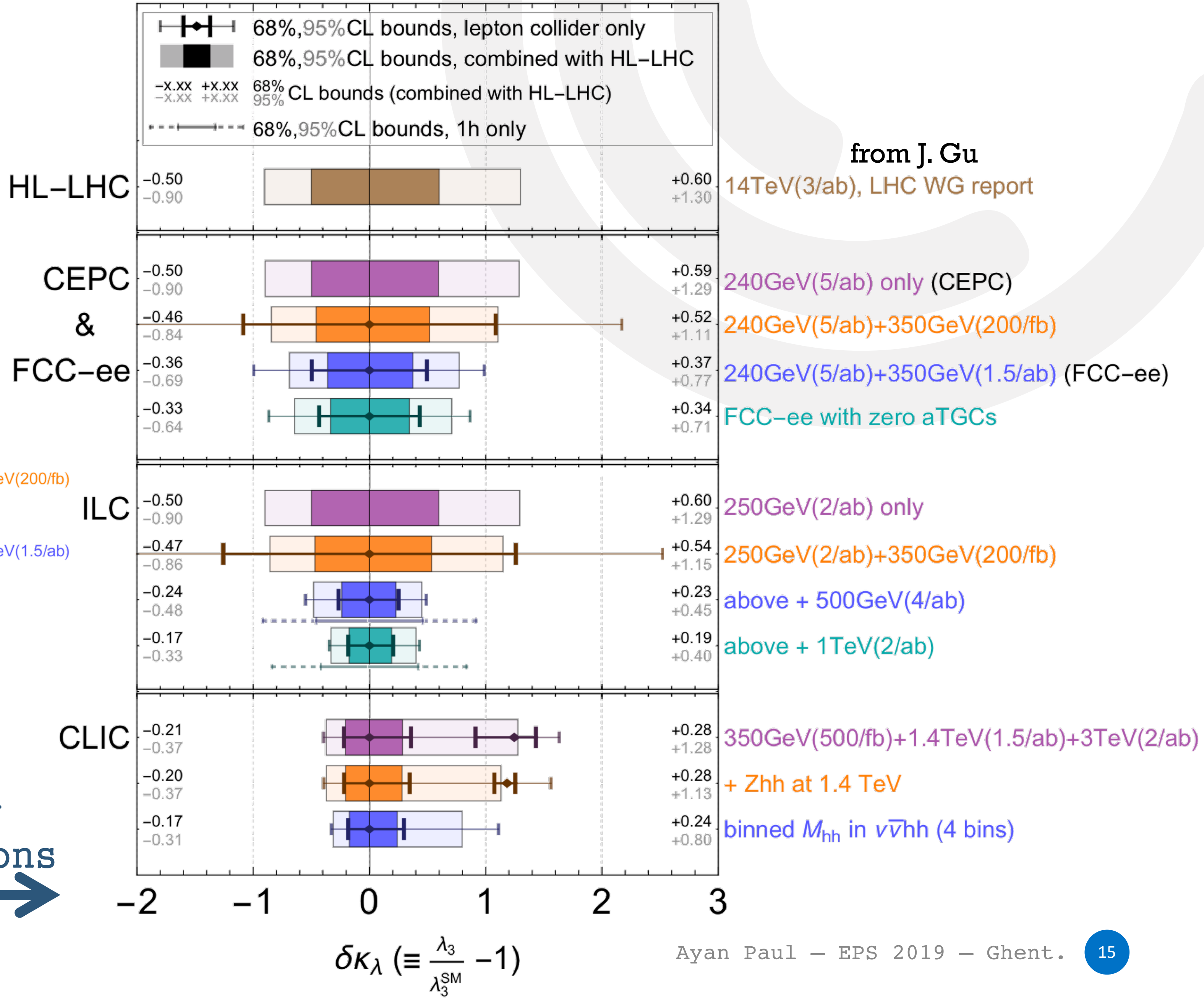
FCC−ee vs. OTHER FUTURE COLLIDERS



↓ -- FCC-ee performance

TRILINEAR HIGGS COUPLING





from J. Gu

Updated with new HL−LHC projections

SUMMARY

MEASUREMENTS

- FCC-ee will take Higgs measurements to the precision regime.
- One order of magnitude or more enhanced precision compared to HL-LHC in several Higgs couplings.
- Orders of magnitude better precision for EWPO compared to LEP/SLD.
- Measurements made at several energies from the *Z*-pole to above the top pair production threshold

GLOBAL FITS

- Precision measurement of both the Higgs and EWPO interlock the two sectors.
- A global fit is *necessary* for a complete picture of the constraints on all the Higgs couplings.
- Higher precision from a *Z*-pole run can reduce the cross-talk between the Higgs and EW sectors.
- Ideally, all Higgs, EWPO and Diboson measurements should be considered in a consistent EFT framework.

THANK YOU

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