

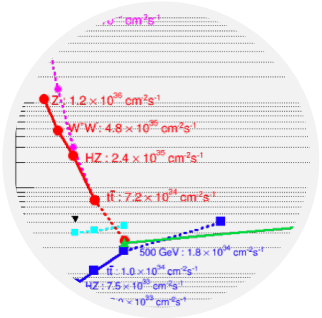
# Disentangling Higgs and EW Measurements at Future Lepton Colliders



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# Overview



## The Colliders

a brief overview of the legacy we can leave behind for the future generations



## The Framework

a discussion of the theoretical and statistical framework that we use



## The Results

elaborations and interpretations of our projections for the future

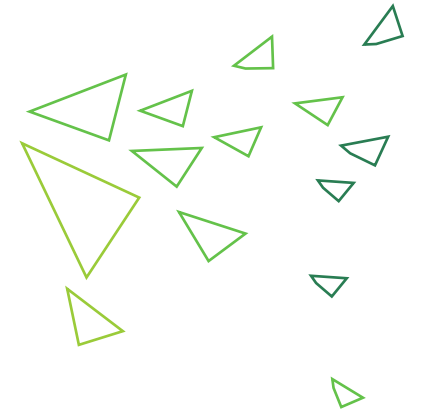
Disclaimer: This is an academic study of the physics that can be probed at future lepton colliders. I do not make any prediction on which ones will exist in reality or their final run configurations.





# Future Lepton Colliders

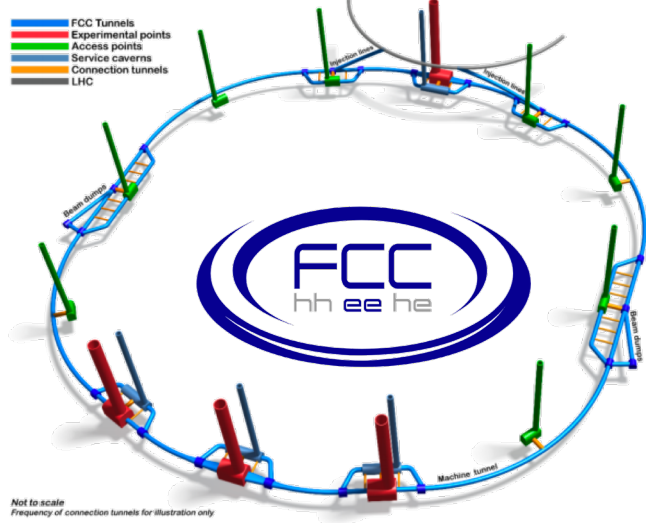
a brief overview of the possible future  
lepton colliders and the configurations we  
explore



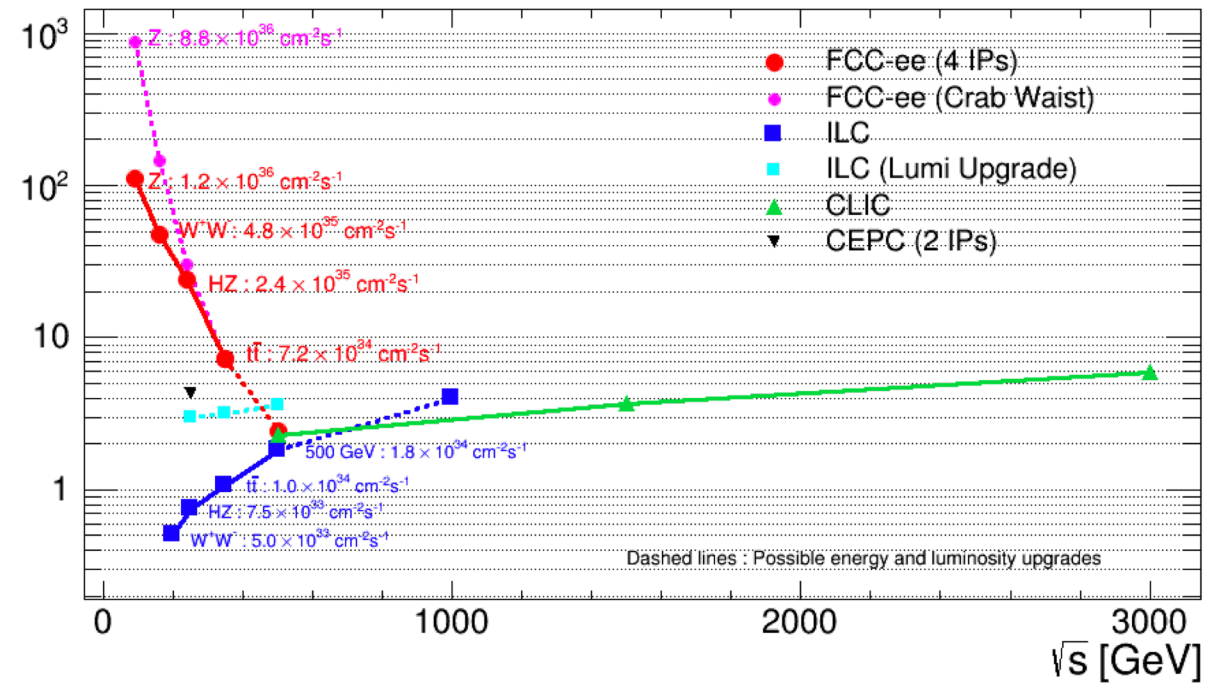
# proposed colliders

**circular colliders** → higher luminosity at lower energies

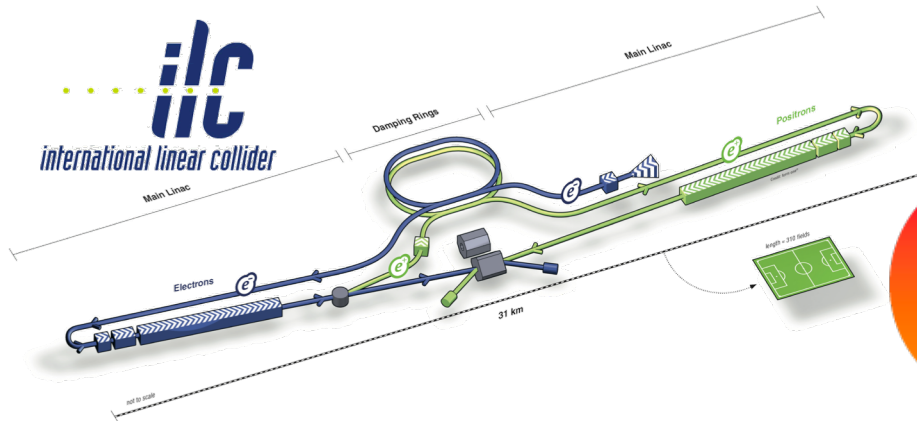
**FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic**  
Underground Infrastructure - Single Tunnel Design  
John Osborne - Charlie Cook - Angel Navascués



Luminosity [ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ]

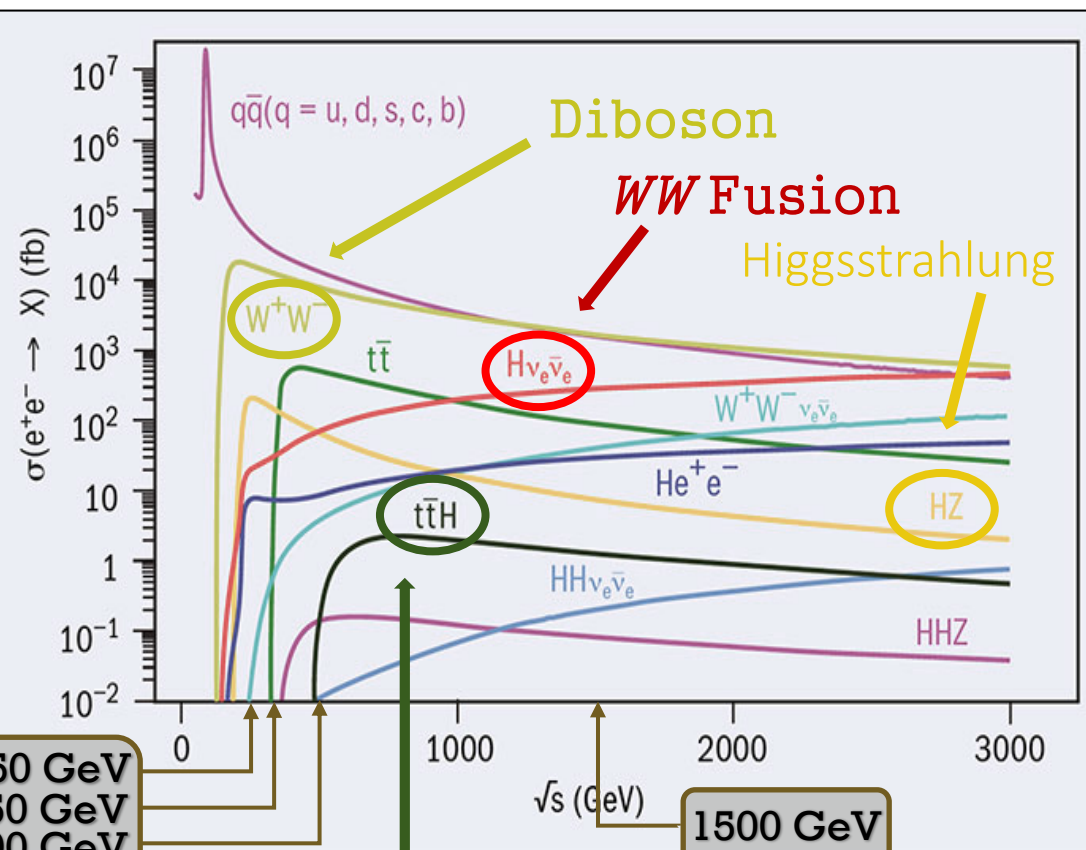


**linear colliders** → higher energy reach

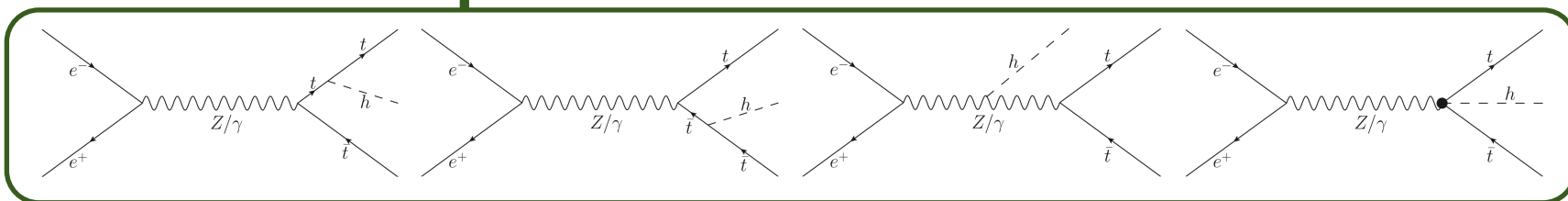
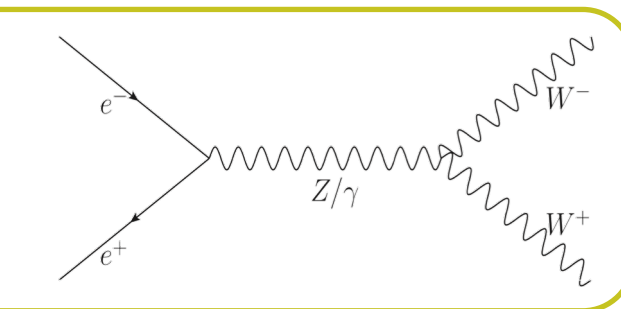
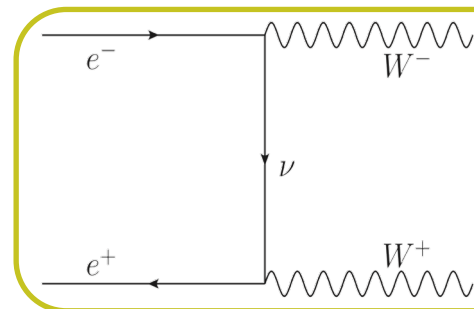
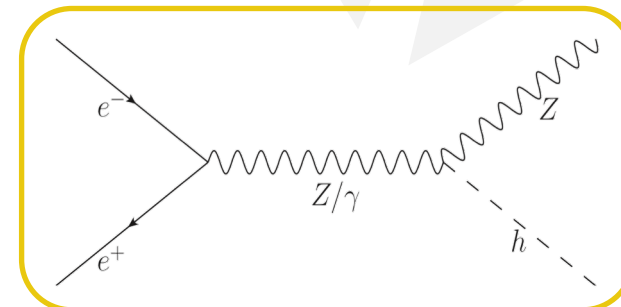
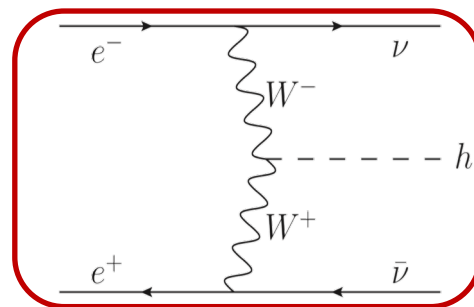




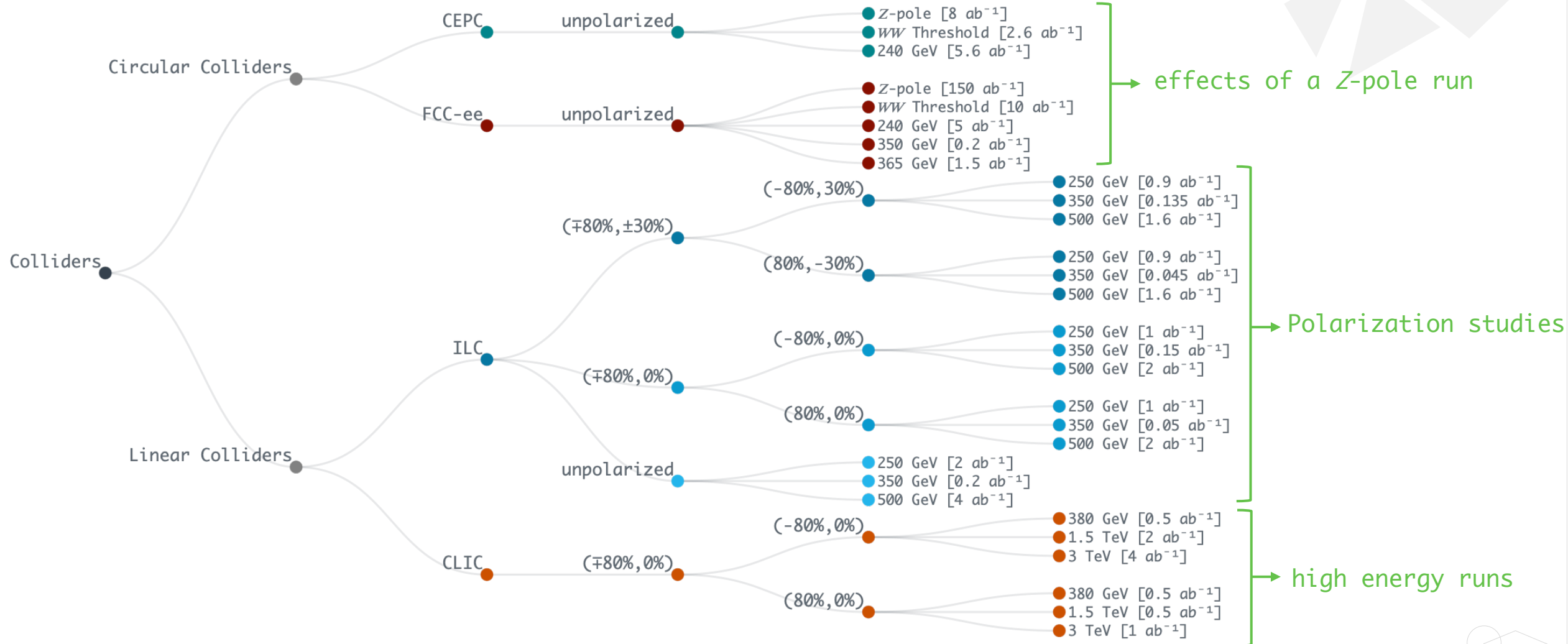
# single Higgs production

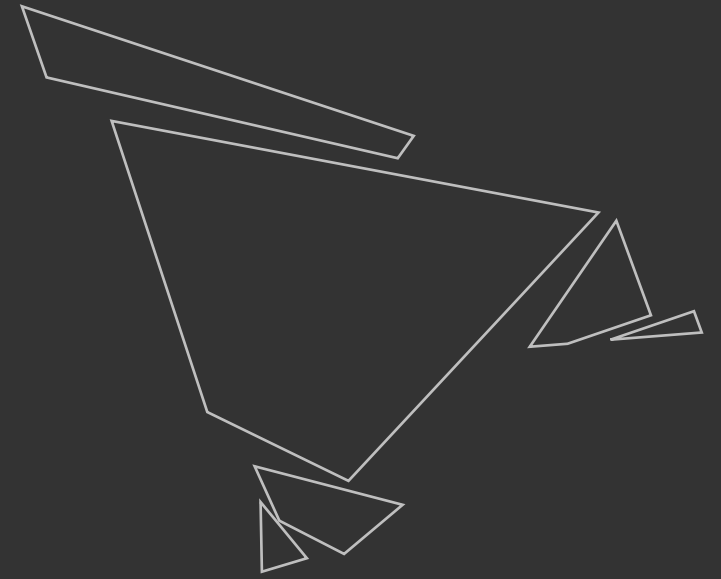


## Primary production modes



# collider configurations





# Theoretical & Statistical Framework

introducing the SMEFT and the analysis  
framework used

# “what?”, “why?” and “how?”

## the problems

- traditionally Higgs fits are done in the “ $\kappa$ ” framework.
- this works if:
  - Higgs and EW couplings are decoupled
  - one ignores questions like custodial protection in the gauge couplings of the Higgs (i.e.,  $hZZ$  and  $hWW$  independent)
- for the Higgs sector to be decoupled from the EW sector one has to assume infinite precision in the EW couplings
- the question is: are LEP/SLD measurements precise enough for the goodness of this assumption?
- can precision measurement of the Higgs couplings complete with the precision in EWPO

## the solution

- focus on HL-LHC + lepton collider + LEP/SLD
- study scenarios with and without Z-pole runs at future circular colliders
- study effects of polarization and measurements from radiative returns at ILC
- study the effects of higher energy runs at CLIC
- use the SMEFT d-6 framework varying all possible operators for the Higgs and EW sector but assuming U(2) symmetry in the light quark couplings ( $[C_{Hu}^{(1,3)}]_{11} = [C_{Hu}^{(1,3)}]_{22}$ )
- fits were done in both **HEPfit** and an independent home-grown code in two different statistical framework.



# HEPfit: a MCMC based Bayesian analysis framework

HEPfit website:  
<http://hepfit.roma1.infn.it>

The screenshot shows the HEPfit website homepage. At the top is a teal header with the HEPfit logo and navigation links: home, developers, samples, and documentation. Below the header is a white box with the text: "HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models." Underneath this are four physics categories, each with a plot and a description:

- Higgs Physics**: HEPfit can be used to study Higgs couplings and analyze data on signal strengths. The plot shows  $\kappa_V$  vs  $\kappa_A$  for various Higgs decays.
- Precision Electroweak**: Electroweak precision observables are included in HEPfit. The plot shows  $S$  vs  $U$  for various observables.
- Flavour Physics**: The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics. The plot shows  $A_{FB}$  vs  $q^2$  for various decays.
- BSM Physics**: Dynamics beyond the Standard Model can be studied by adding models in HEPfit. The plot shows  $m_{H^\pm}$  vs  $m_{A/H}$  for various models.

At the bottom are two sections: "References" and "Downloads".

**References**

- Core@HEPfit  
The User Manual is coming soon!
- Physics@HEPfit  
papers describing our physics goals and contents coming soon!

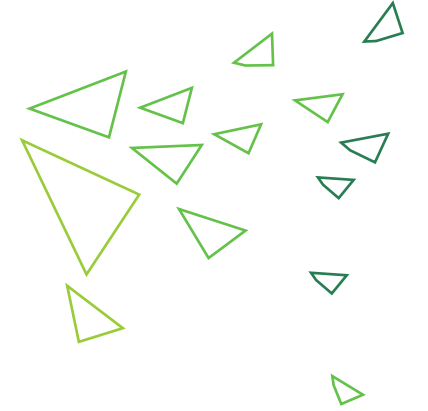
**Downloads**

- Current Version: HEPfit v1.0-RC1
- Developer Version: HEPfit @ GitHub
- Previous Versions:
- Dependencies: GSL, ROOT, BOOST, BAT
- For installation please follow the instructions here



## Results & Interpretations

discussions of the effects of EW  
measurements on the Higgs couplings  
and the effects of beam polarization



$$\delta g_H^{\mu\mu}, \delta g_H^{\tau\tau}, \delta g_H^{cc}, \delta g_H^{tt}, \delta g_H^{bb},$$

$$\delta g_H^{ZZ}, \delta g_H^{WW}, \delta g_H^{\gamma\gamma}, \delta g_H^{Z\gamma}, \delta g_H^{gg},$$

$$\delta g_{1,Z}, \delta \kappa_\gamma, \lambda_Z,$$

$$\delta g_{Z,L}^{ee} \equiv (\delta g_{Z,L}^\ell)_{11}, \quad \delta g_{Z,L}^{\mu\mu} \equiv (\delta g_{Z,L}^\ell)_{22}, \quad \delta g_{Z,L}^{\tau\tau} \equiv (\delta g_{Z,L}^\ell)_{33},$$

$$\delta g_{Z,R}^{ee} \equiv (\delta g_{Z,R}^\ell)_{11}, \quad \delta g_{Z,R}^{\mu\mu} \equiv (\delta g_{Z,R}^\ell)_{22}, \quad \delta g_{Z,R}^{\tau\tau} \equiv (\delta g_{Z,R}^\ell)_{33},$$

$$\delta g_W^{e\nu} \equiv (\delta g_W^\ell)_{11}, \quad \delta g_W^{\mu\nu} \equiv (\delta g_W^\ell)_{22}, \quad \delta g_W^{\tau\nu} \equiv (\delta g_W^\ell)_{33},$$

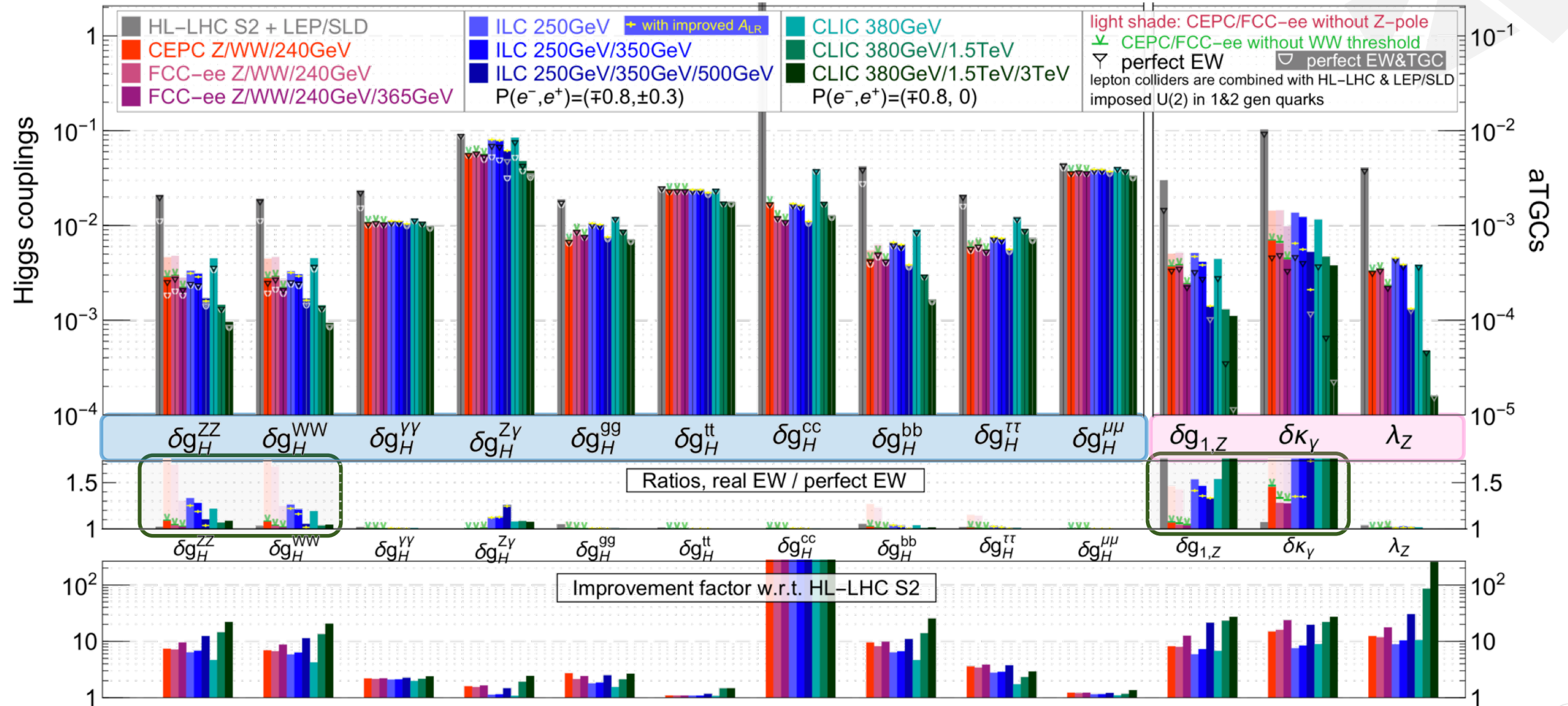
$$\delta g_{Z,L}^{uu} \equiv (\delta g_{Z,L}^u)_{11} = (\delta g_{Z,L}^u)_{22}, \quad \delta g_{Z,L}^{dd} \equiv (\delta g_{Z,L}^d)_{11} = (\delta g_{Z,L}^d)_{22}, \quad \delta g_{Z,L}^{bb} \equiv (\delta g_{Z,L}^d)_{33},$$

$$\delta g_{Z,R}^{uu} \equiv (\delta g_{Z,R}^u)_{11} = (\delta g_{Z,R}^u)_{22}, \quad \delta g_{Z,R}^{dd} \equiv (\delta g_{Z,R}^d)_{11} = (\delta g_{Z,R}^d)_{22}, \quad \delta g_{Z,R}^{bb} \equiv (\delta g_{Z,R}^d)_{33},$$

$$\delta g_H^x \equiv \sqrt{\frac{\Gamma(h \rightarrow x)}{\Gamma(h \rightarrow x)^{\text{SM}}}} - 1$$

# constraints on Higgs couplings

## precision reach on effective couplings from full EFT global fit





# Regular Colliders

exact EW measurements

correlations differ between  
CEPC and FCC-ee because  
of different inputs

dominated by HL-LHC measurements

correlations between  
the Higgs and EW  
couplings

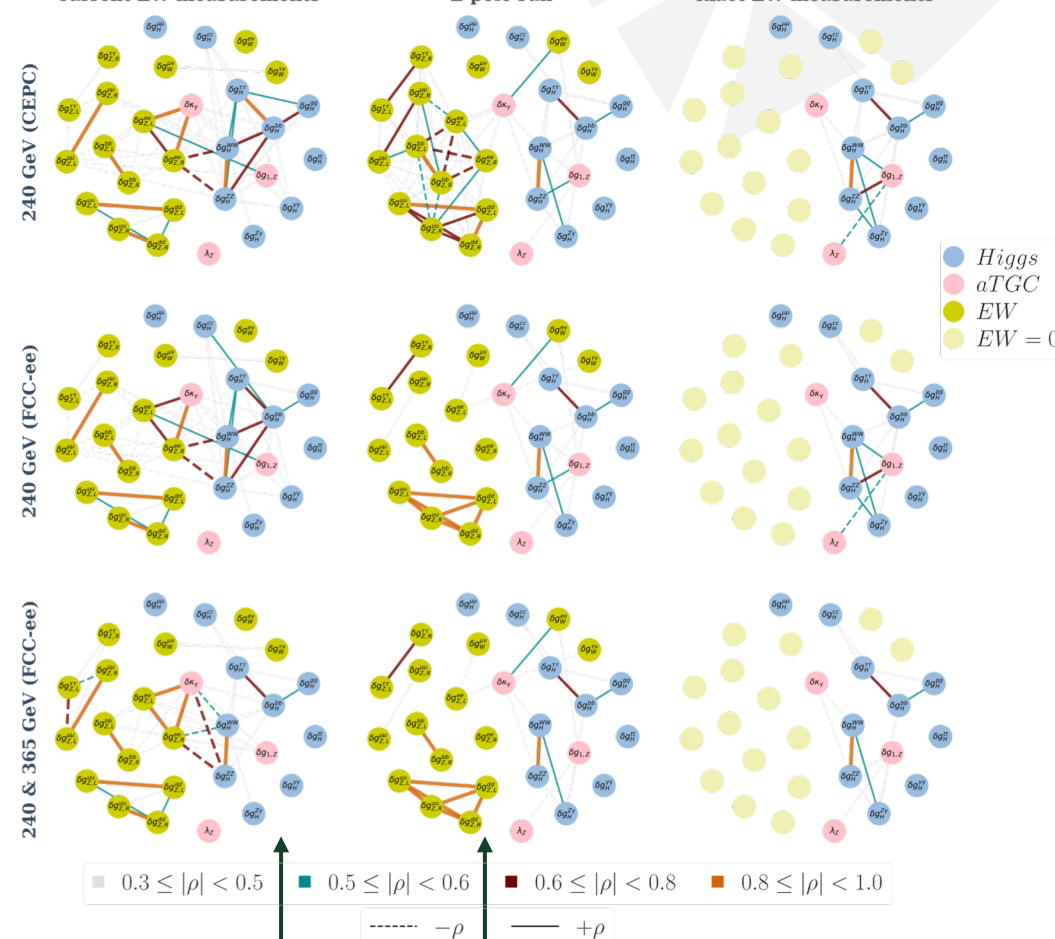
significant constraints  
from HL-LHC

## Z-pole @ Future Circular Colliders

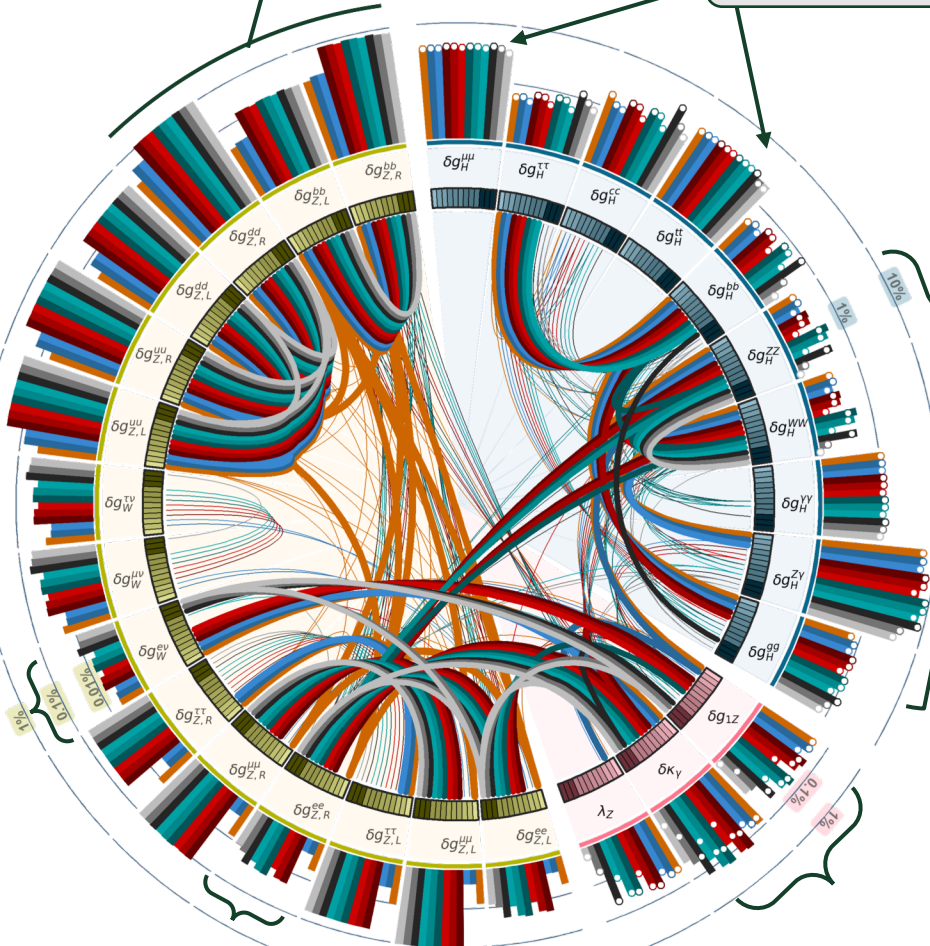
current EW measurements

### Z-pole run

exact EW measurements



Higgs and EW sectors get decorrelated after inclusion of Z-pole measurements



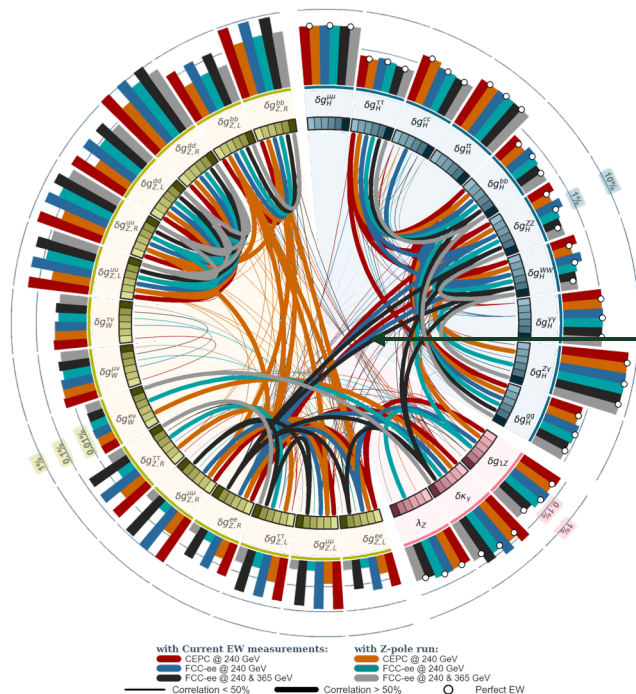
CEPC: 240 GeV  
FCC-ee: 240 GeV, 240 & 365 GeV  
ILC ( $\pm 80\%$ ,  $\mp 30\%$ ): 250 GeV, 250 & 350 GeV, 250 & 350 & 500 GeV  
ILC Unpolarized: 250 GeV, 250 & 350 GeV, 250 & 350 & 500 GeV  
CLIC ( $\pm 80\%$ , 0%): 380 GeV, 380 & 1500 GeV, 300 & 1500 & 3000 GeV

Correlation < 50% Correlation > 50% Perfect EW



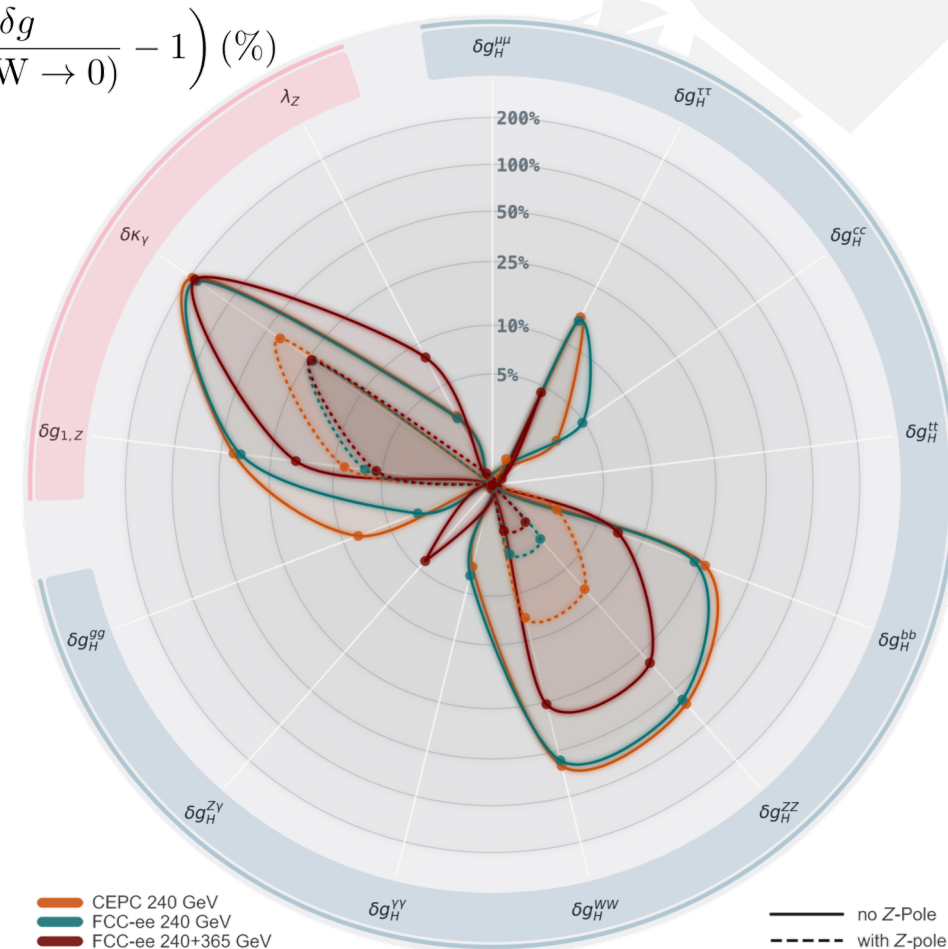
# effects of EW measurements on Higgs couplings

- Without EW measurements beyond LEP/SLD the Higgs and EW sectors are correlated.
- Decoupling them, essentially requires more precise EWPO measurements which can be done at the circular colliders.
- For the effective Higgs couplings, there are almost no differences between the case of a Z-pole run and the assumption of perfect EW measurements.
- For the aTGCs, even a Z-pole run does not completely eliminate the differences from the assumption of perfect EW measurement.



correlations between the Higgs and EW sectors in the absence of Z-pole run at FCC-ee and CEPC at all energies

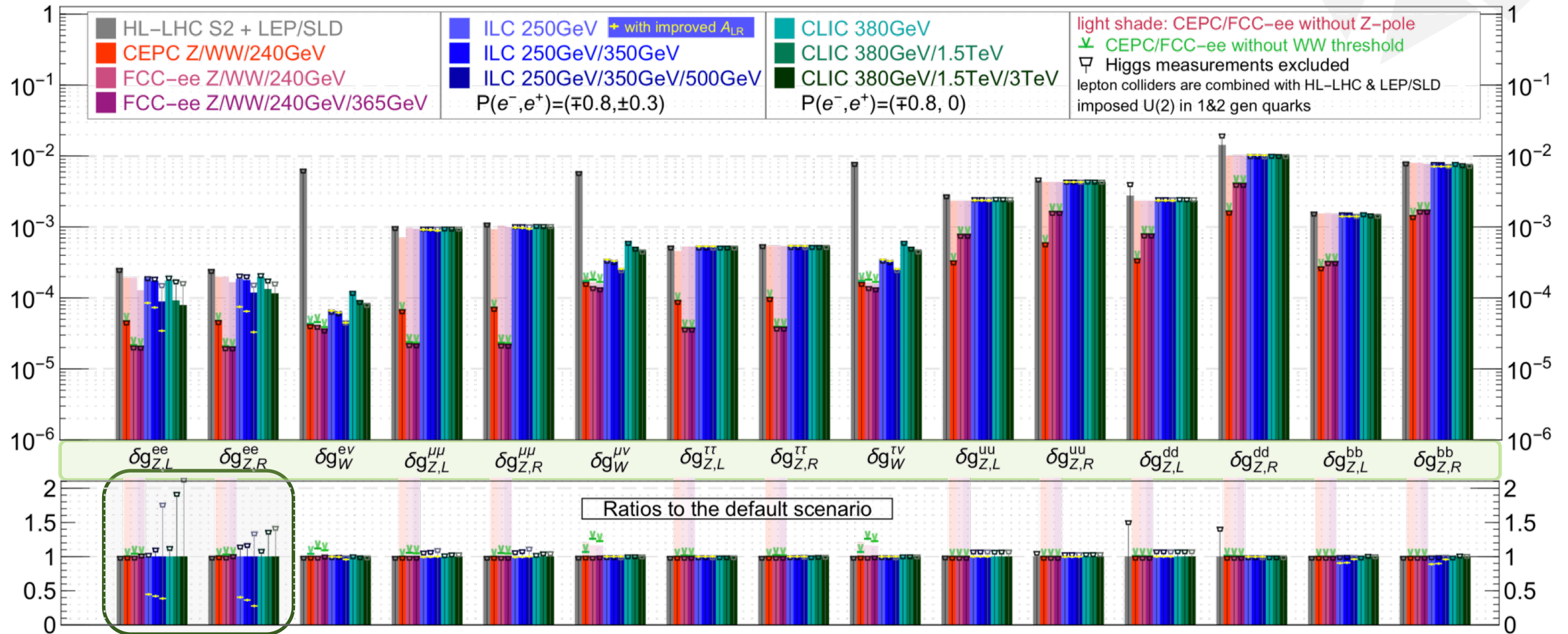
$$\left( \frac{\delta g}{\delta g(\text{EW} \rightarrow 0)} - 1 \right) (\%)$$



shift in constraints to couplings when compared with those assuming perfect EW measurement (in %)

# constraints on EW couplings

precision reach on EW couplings from full EFT global fit



# effects of polarization

$$\sigma_{P_{e^+}P_{e^-}} = \sigma_0(1 - P_{e^+}P_{e^-}) \left[ 1 - A_{LR} \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}} \right]$$

process dependent

$$\begin{aligned} A_{LR}^{Zh} &= 0.151 \\ A_{LR}^{\nu\bar{\nu}h} &= 1 \\ A_{LR}^{WW} &= 0.98 \end{aligned}$$

statistical scaling factor  $\approx 1.24$   
when summed over both  
polarization with equal luminosities  
as in the ILC 250 GeV run

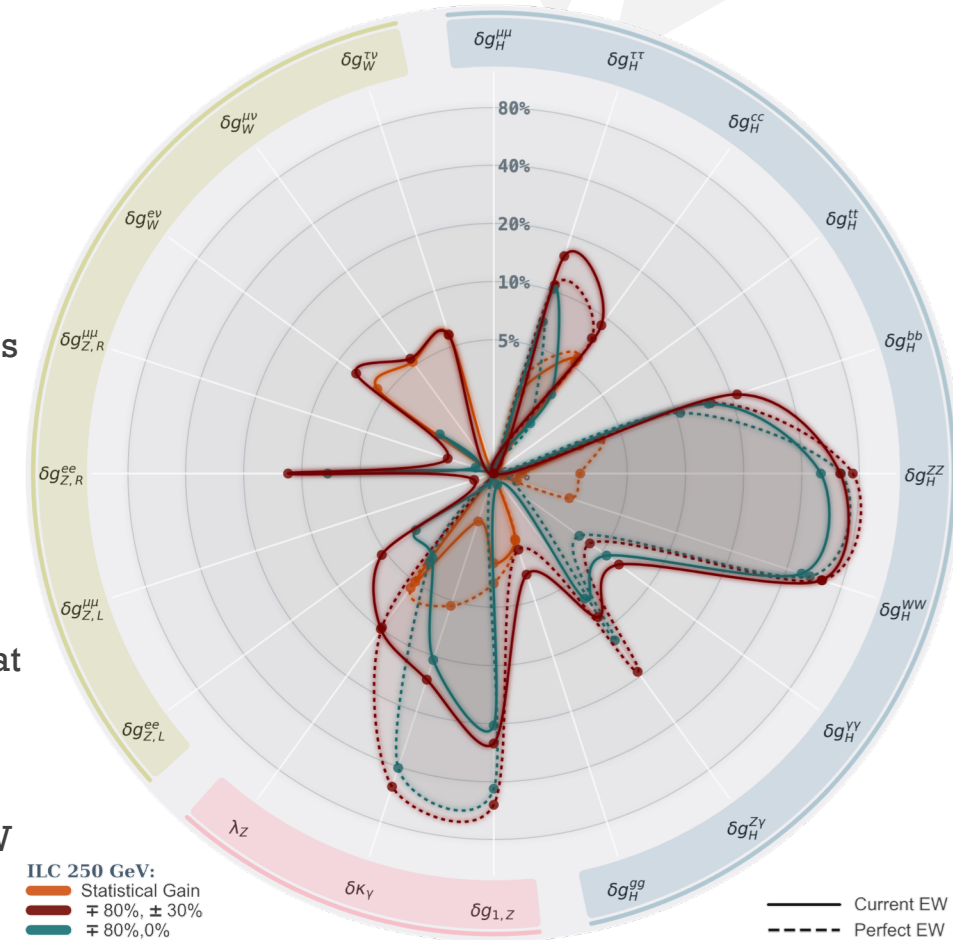
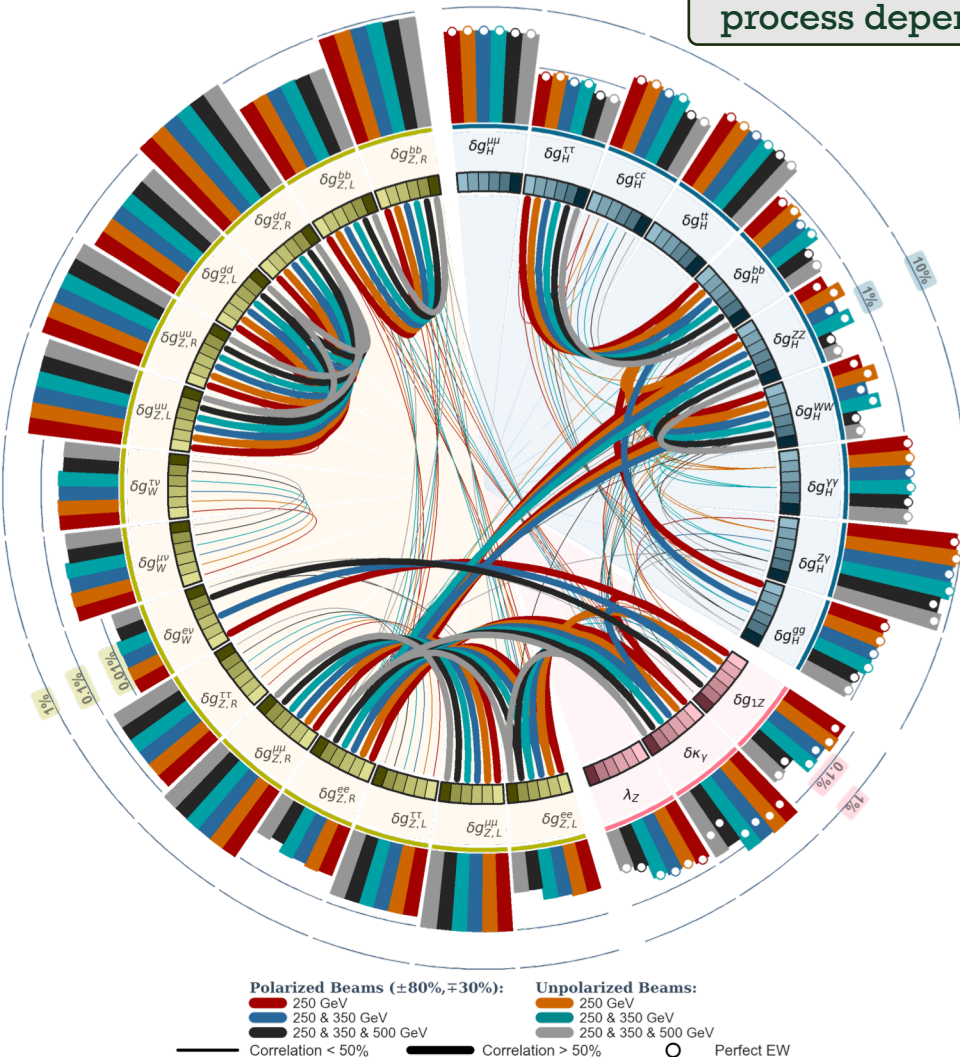
effective Higgs couplings get  
decorrelated from EW at higher  
energies.

aTGCs retain correlation with EW at  
higher energies

polarization does not fully  
compensate for the absence of EW  
measurements

polarization is important mostly for  
250 GeV

$$\left( \frac{\delta g \text{ (unpolarized)}}{\delta g \text{ (polarized)}} - 1 \right) (\%)$$







# Summary

build the collider(s)!

- When precision in Higgs coupling measurement come close to the precision of EWPO then there is significant cross-talk between the two sectors.
- We study several scenarios in all the proposed future lepton colliders to see what effect a  $Z$ -pole run, a  $WW$  threshold run and polarization can have on Higgs couplings measurements.
- We use the SMEFT d-6 framework varying all necessary operators and perform fits in two completely independent implementations.



- To disentangle the two sectors one way out is to measure EWPO with much greater precision. This is possible at circular colliders.
- At linear colliders this can possibly be compensated by higher energy runs for the effective Higgs couplings but not for all the aTGCs.
- Polarization is important at 250 GeV as it gives a significant boost to constraints on the couplings. With higher energies the benefits of polarization diminish.



# The Contributors



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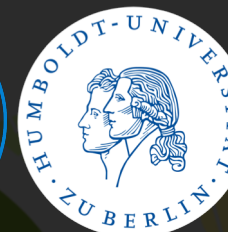
DESY & HU–Berlin



\*idea shamelessly stolen from Jiayin

Ayan Paul, 7<sup>th</sup> June – WIN 2019

# Thank you!



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To my Mother and Father, who showed me what I could do,  
and to Ikaros, who showed me what I could not.

“To know what no one else does, what a pleasure it can be!”

– adopted from the words of  
Eugene Wigner.

