Electroweak couplings of the Z boson at CLIC

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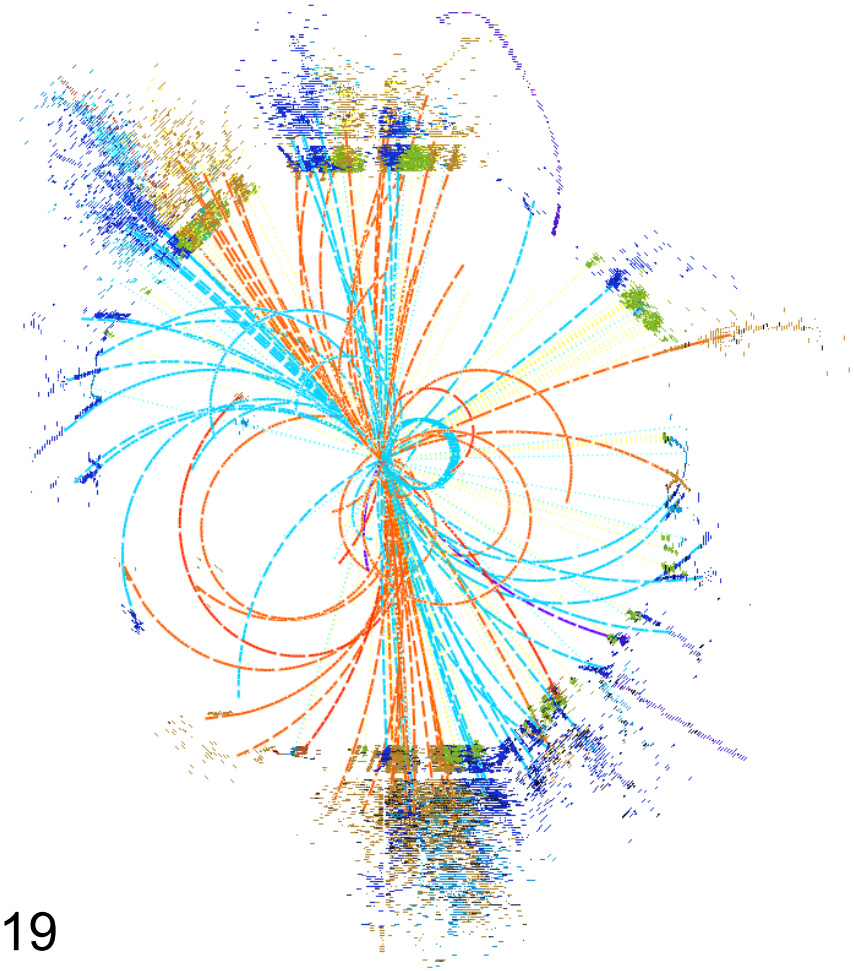
CLIC Detector and Physics
Collaboration Meeting



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EWPO from LEP / SLD in EFT fit

Observable	Experimental value	Ref.	SM prediction	Definition
m_Z [GeV]	91.1875 ± 0.0021	27	$\times$	$\sqrt{\frac{(g_L^2+g_Y^2)v^2}{4} + \delta\Pi_{ZZ}(m_Z^2)}$
Γ_Z [GeV]	2.4952 ± 0.0023	27	2.4950	$\sum_f \Gamma(Z \to f\bar{f})$
$\sigma_{\rm had}$ [nb]	41.540 ± 0.037	27	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_ℓ	20.767 ± 0.025	27	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \ell^+\ell^-)}$
A_ℓ	0.1499 ± 0.0018	28	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	27	0.01626	$\frac{3}{4}A_\ell^2$
R_b	0.21629 ± 0.00066	27	0.21578	$\frac{\Gamma(Z\to dd)}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b	0.923 ± 0.020	27	0.93463	$\frac{\Gamma(Z\to d_Ld_L)-\Gamma(Z\to d_Rd_R)}{\Gamma(Z\to d\bar{d})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	27	0.1032	$\frac{3}{4}A_\ell A_b$
R_c	0.1721 ± 0.0030	27	0.17226	$\frac{\Gamma(Z\to u\bar{u})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_c	0.670 ± 0.027	27	0.668	$\frac{\Gamma(Z\to u_L\bar{u}_L)-\Gamma(Z\to u_R\bar{u}_R)}{\Gamma(Z\to u\bar{u})}$
$A_c^{\rm FB}$	0.0707 ± 0.0035	27	0.0738	$\frac{3}{4}A_\ell A_c$
m_W [GeV]	80.385 ± 0.015	29	80.364	$\sqrt{\frac{g_L^2v^2}{4} + \delta\Pi_{WW}(m_W^2)}$
Γ_W [GeV]	2.085 ± 0.042	30	2.091	$\sum_f \Gamma(W \to f f')$
$\mathrm{Br}(W \to \mathrm{had})$	0.6741 ± 0.0027	31	0.6751	$\frac{\sum_q \Gamma(W\to qq')}{\sum_f \Gamma(W\to ff')}$

Z pole

WW production

NB: The ECFA Higgs@FutureColliders group does not assume lepton universality

arXiv:1411.0669

Z-pole operation

Fully-installed 380 GeV collider operated at Z-pole:
L = 2.3 x 10^{32} $cm^{-2}s^{-1}$ → very useful for calibration

Initial installation of linac for Z-pole energy + adapted beam delivery system:
L = 0.36 x 10^{34} $cm^{-2}s^{-1}$ for 50 Hz operation → 100 fb^{-1} in a few years

100 fb^{-1} with 50:50 splitting of the -80% and +80% electron beam polarisations:
- about 4.5 billion Z bosons
- about 3 billion Z decays in hadronic final states

Uncertainty on beam polarisation:
- 0.1% from polarimeter upstream and downstream of the interaction point
- Blondel scheme (as foreseen at ILC) would require positron polarisation

Z-pole: asymmetry parameters (1)

Left-right asymmetry:

$$A_{LR} = \frac{1}{|P|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e$$

→ using hadronic Z decays limited by systematic uncertainties

Uncertainty on beam polarisation:

$$\frac{\Delta A_{LR}}{A_{LR}} = \frac{\Delta P}{P}$$

Impact of collision energy:

$$dA_{LR}/d\sqrt{s} \approx 2 \times 10^{-5}/\,\mathrm{MeV}$$

→ collision energy needs to be controlled to a few MeV (1 MeV possible using $e^+e^- \to \mu^+\mu^-\gamma$)

Reconstruction of beam energy spread (several per mille) to be demonstrated

Other fermions → combined forward-backward left-right asymmetry:

$$A^f_{FB,LR} = \frac{1}{P}\frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4}A_f$$

Same impact of polarisation uncertainty as for A_{LR}

Z-pole: asymmetry parameters (2)

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
A_e	0.1515	0.00002	0.00015
A_μ	0.142	0.00014	0.00014
A_τ	0.143	0.00021	0.00014
A_c	0.670	0.00013	0.00067
A_b	0.923	0.00007	0.00092

Assumptions:
- 80% b-tagging efficiency
- 50% c-tagging efficiency
- Only hadronic tau decays

Z-pole: decay ratios

$$R_{\mathrm{c,b}} = \frac{\Gamma(\mathrm{Z} \to \mathrm{c\bar{c}}, \mathrm{b\bar{b}})}{\sum_{\mathrm{q=u,d,s,c,b}} \Gamma(\mathrm{Z} \to \mathrm{q\bar{q}})} \qquad R_{\mathrm{e,\mu,\tau}} = \frac{\sum_{\mathrm{q=u,d,s,c,b}} \Gamma(\mathrm{Z} \to \mathrm{q\bar{q}})}{\Gamma(\mathrm{Z} \to \mathrm{e^+e^-}, \mu^+\mu^-, \tau^+\tau^-)}$$

→ Uncertainties on total luminosity and beam polarisation cancel in these ratios

Systematic uncertainties assumed for illustration:

- Overall systematic uncertainties of the SLD measurements (flavour tagging more similar to CLIC than LEP experiments) of R_b and R_c can be improved by a factor 5
- Systematic uncertainties for decays to lepton pairs at LEP (dominated by understanding of detector acceptance) scaled with the integrated luminosity

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
$1/R_{\mathrm{e}}$	0.0481	4×10^{-6}	2×10^{-5}
$1/R_{\mu}$	0.0481	4×10^{-6}	1×10^{-5}
$1/R_{\tau}$	0.0482	6×10^{-6}	2×10^{-5}
R_c	0.172	1.5×10^{-5}	4×10^{-4}
R_b	0.216	1.1×10^{-5}	1.5×10^{-4}

Return-to-Z events

• The energy loss due to ISR and beamstrahlung provides large samples of return-to-Z events at the 380 GeV stage
→ In particular, significant improvement compared to LEP / SLD possible on A_e

• Generator-level study (Whizard 2) with cuts to simulate the geometric acceptance of the CLIC detector and suppress backgrounds from γγ and eγ interactions

• For example, more than 3.5 million hadronic Z decays pass the event selection assuming 1 ab^{-1} of integrated luminosity and 50:50 splitting of the -80%/+80% electron-beam polarisation configurations
(for comparison about 400000 hadronic Z decays at SLC, 16 million at LEP)

• 0.1% uncertainty on the electron beam polarisation from polarimeters or $e^+e^- \rightarrow W^+W^-$ events
→ also potential validation of the polarisation measurement at 380 GeV

Return-to-Z: asymmetry parameters

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
A_e	0.1515	0.0006	0.00015
A_μ	0.142	0.0039	0.00014
A_τ	0.143	0.0055	0.00014
A_c	0.670	0.0019	0.00067
A_b	0.923	0.0036	0.00092

- Study of b- and c-jet charge reconstruction left for future investigation

Assumptions:
- 80% b-tagging efficiency
- 50% c-tagging efficiency
- Only hadronic tau decays

Return-to-Z: ratios

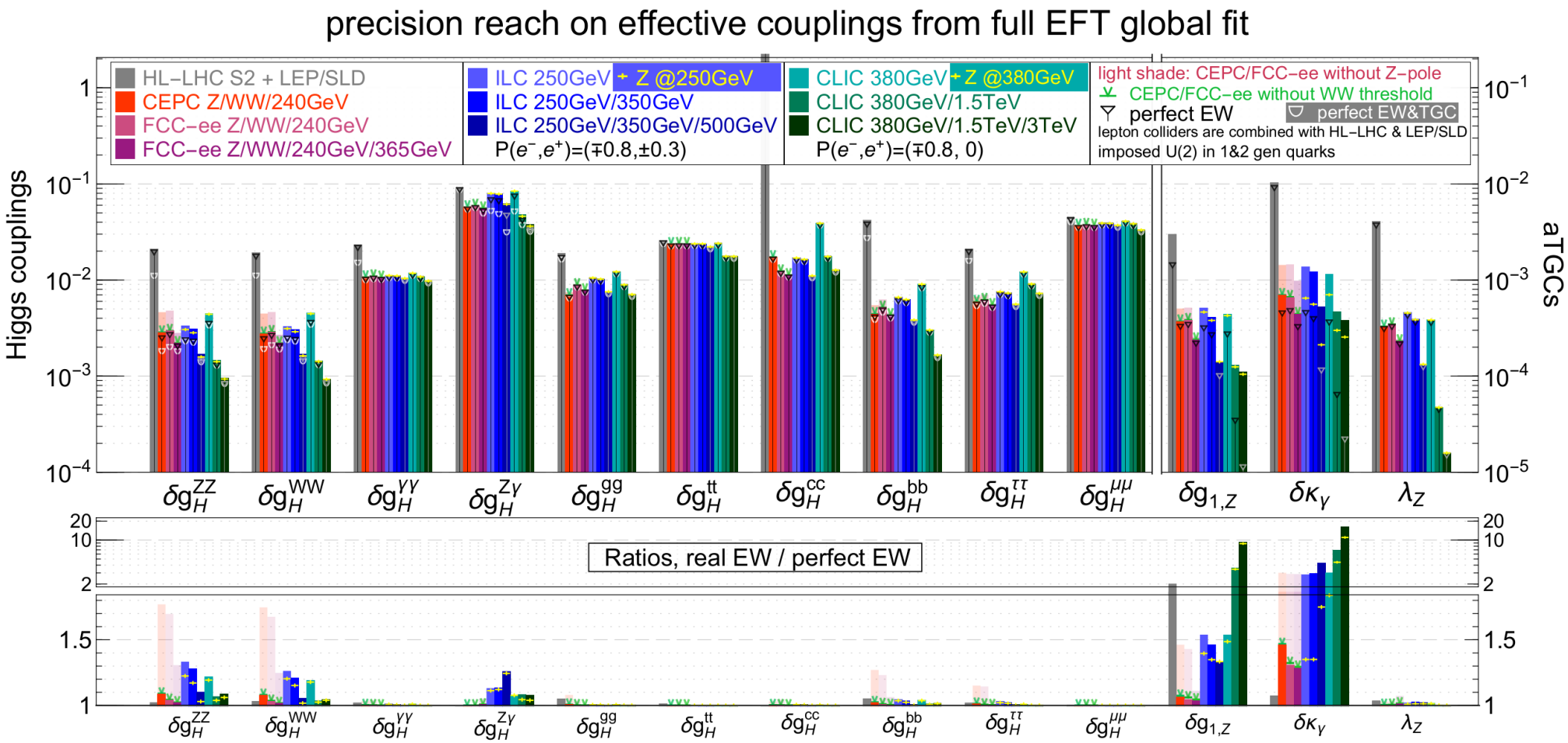
- Presence of hard neutrino also gives access to neutrino coupling:

$$R_\nu = \frac{\Gamma(\mathrm{Z} \to \nu\bar{\nu})}{\sum_{\mathrm{q=u,d,s,c,b}} \Gamma(\mathrm{Z} \to \mathrm{q}\bar{\mathrm{q}})}$$

- For illustration we assume 0.1% systematic uncertainty for final states with electrons, muons, photons or b-jets, and 0.5% systematic uncertainty for final states with tau leptons or charm quarks

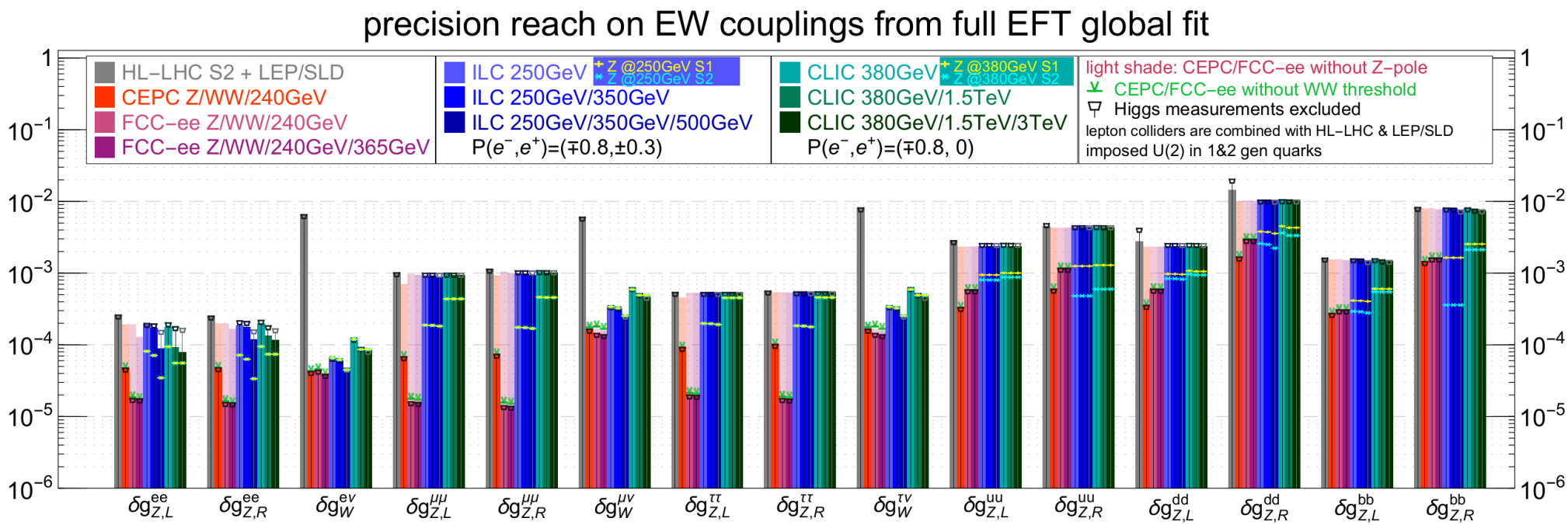
Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
$1/R_\mathrm{e}$	0.0481	0.00012	0.00005
$1/R_\mu$	0.0481	0.00012	0.00005
$1/R_\tau$	0.0482	0.00016	0.00024
R_c	0.172	0.00042	0.00086
R_b	0.216	0.00031	0.00022
R_ν	0.286	0.0027	0.00029

Impact on EFT fit: Higgs and aTGCs



Jiayin Gu

Impact on EFT fit: (H)Vff couplings



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Thank you!