Discussion session on two-fermion final state

Emanuele Bagnaschi (INFN LNF/CERN)
on behalf of the two-fermion final state team

ECFA
European Committee for Future Accelerators

11 October 2023
Second ECFA workshop on e+e- Higgs/EW/Top factories

`Paestum, Italy`

Two-fermion final state focus group

Team

- Freya Blekman [FCC-ee]
- Adrian Irles [ILC]
- Daniel Jean [ILC/ILD]
- Eram Rizvi [LHC]
- Jorge de Blas [theory/GLOBAL-WG1/CLIC]
- Emanuele Bagnaschi [theory]
- Alessandro Vicini [theory]

Team

Coordinated by: Chris Hays [HTE], Karsten Koeneke [HTE], Patrick Koppenburg [WG1], Jenny List [WG1], Fabio Maltoni [HTE-WG1]

Topics

- bb, cc, ss, tautau final states
- constraints on four-fermion interactions
- tau polarization,
- asymmetries
- strange tagging
- separating up and down quarks
- Kaon-ID
- vertex charge
- Complementarity between HL-LHC and e^+e^- colliders
- ...

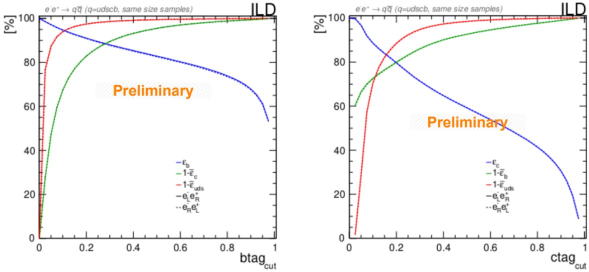
ILC -- ongoing work

- Group in IJCLab, Tohoku U, IFIC (Y. Okugawa, A. Irles,, H. Yamamoto, F. Richard, R. Pöschl)
- $e^+e^- \to q\bar{q}$ with $q = s$ at 250 GeV, not using the radiative return

Topics

- LD full simulation with LO MC
- A_{FB} observables
- Ongoing PhD to be finished by beginning 2024 (Y. Okugawa)
- K-ID at relatively high momentum is primordial
- With pion/K separation they are also exploring the prospects of AFBud
- Outlook: extension to different energies?

Flavor tagging

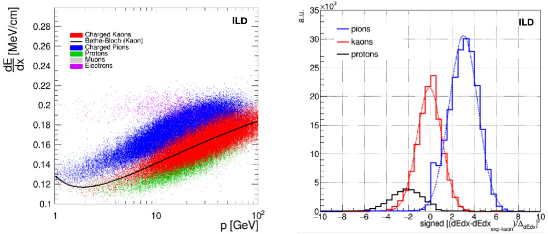


(a) (b)

Figure 2: Flavor tagging performance for b (left) and c (right). ϵ_c (ϵ_b) is the tagging efficiency after c (b) tag cuts. $1-\tilde{\epsilon}_b$ ($1-\tilde{\epsilon}_c$) are the c (b) tagging purity under b (c) background. $1-\tilde{\epsilon}_{uds}$ is the flavor tagging efficiency under uds background. Finally, dotted and solid lines represent the same quantity with $e^-_R e^+_L$ and $e^-_L e^+_R$ beam polarization, respectively.

[Okugawa et al., PoS ICHEP2022 871]

Kaon ID



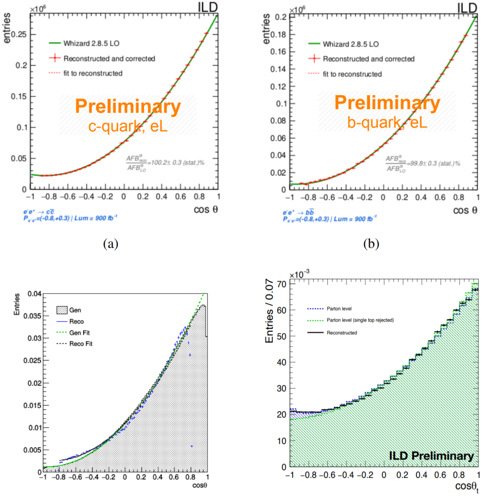
(a)

(b)

Figure 3: (a) dE/dx vs. momentum for each particle ($e, \mu, K^{\pm}, p, \pi$). (b) dE/dx distances from kaon Bethe-Bloch formula.

[Okugawa et al., PoS ICHEP2022 871]

Asymmetries



(a)

(b)

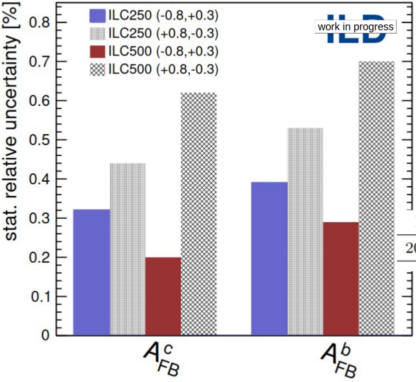
(c)

(d)

Figure 4: Reconstructed and generated polar angle distributions of the process (a) $c\bar{c}$, (b) $b\bar{b}$, (c) $s\bar{s}$, and (d) $t\bar{t}$. Superimposed is a fit inspired by the differential cross section. (see text for details)

[Okugawa

Asymmetries systematics



ILC250	ILC500	ILC1000
2000 fb^{-1}	4000 fb^{-1}	8000 fb^{-1}

[Irles '23, this workshop]

Ongoing work: TwoF above Z-pole (ILD)

- ILD note and previous works https://inspirehep.net/literature/2669897
  - ILC50, b and c studies
- Work presented in LCWS (J.P. Márquez)
  - Proceeding https://inspirehep.net/literature/2682331
  - Talk https://indico.slac.stanford.edu/event/7467/contributions/5977/attachments/2862/8042/LCWS2023_JPMH.pdf
  - ILC250+ILC500 comparing scenarios with different PID (no PID, dEdx, dNdx)
- Work presented in EPS-HEP (J.P. Márquez)
  - First theory prospects
  - https://indico.desy.de/event/34916/contributions/147224/
- GHU studies
  - A models: (arxiv:1705.05282)
  - B models: (2309.01132) (arxiv:2301.07833)

$$A_1 : \theta_H = 0.0917, m_{KK} = 8.81 \text{ TeV} \rightarrow m_{Z'} = 7.19 \text{ TeV};$$
$$A_2 : \theta_H = 0.0737, m_{KK} = 10.3 \text{ TeV} \rightarrow m_{Z'} = 8.52 \text{ TeV},$$

$$B_1^+ : \theta_H = 0.10, m_{KK} = 13 \text{ TeV} \rightarrow m_{Z'} = 10.2 \text{ TeV};$$
$$B_1^- : \theta_H = 0.10, m_{KK} = 13 \text{ TeV} \rightarrow m_{Z'} = 10.2 \text{ TeV};$$
$$B_2^+ : \theta_H = 0.07, m_{KK} = 19 \text{ TeV} \rightarrow m_{Z'} = 14.9 \text{ TeV};$$
$$B_2^- : \theta_H = 0.07, m_{KK} = 19 \text{ TeV} \rightarrow m_{Z'} = 14.9 \text{ TeV};$$
$$B_3^+ : \theta_H = 0.05, m_{KK} = 25 \text{ TeV} \rightarrow m_{Z'} = 19.6 \text{ TeV};$$
$$B_3^- : \theta_H = 0.05, m_{KK} = 25 \text{ TeV} \rightarrow m_{Z'} = 19.6 \text{ TeV},$$

Today, HTE session --> A. Irles

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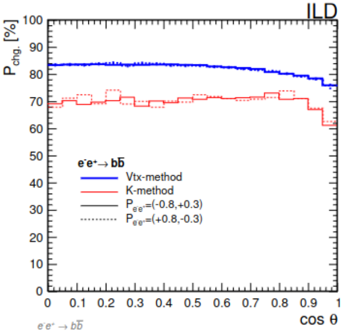
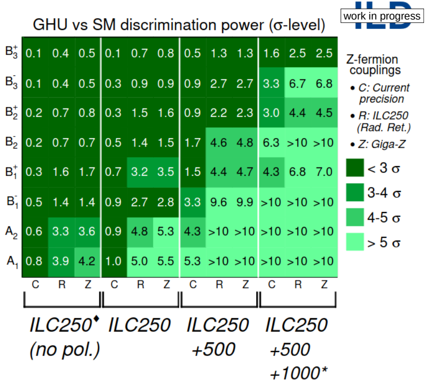
Optimization of detector: jet charge



GHU vs SM discrimination power



GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.)			ILC250			ILC250 +500			ILC250 +500 +1000*		
	C	R	Z	C	R	Z	C	R	Z	C	R	Z
B_3^+	0.1	0.4	0.5	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
B_3^-	0.1	0.4	0.5	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
B_2^+	0.2	0.7	0.8	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
B_2^-	0.2	0.7	0.7	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
B_1^+	0.3	1.6	1.7	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
B_1^-	0.5	1.4	1.4	0.9	2.7	2.8	3.3	9.6	9.9	>10	>10	>10
A_2	0.6	3.3	3.6	0.9	4.8	5.3	4.3	>10	>10	>10	>10	>10
A_1	0.8	3.9	4.2	1.0	5.0	5.5	5.3	>10	>10	>10	>10	>10

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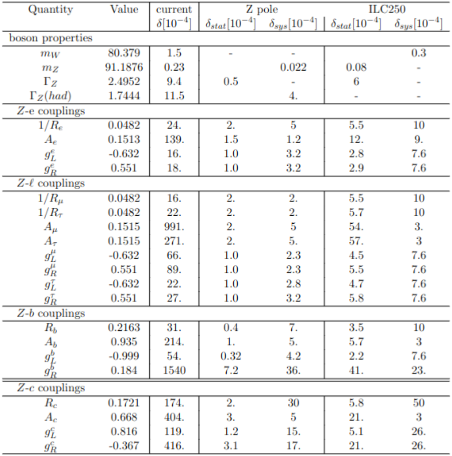
Z-couplings

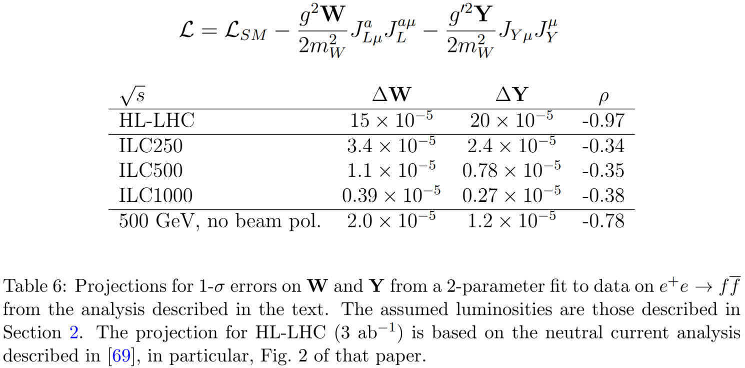
- ILC Snowmass 21 report

  https://arxiv.org/pdf/2203.07622.pdf



Quantity	Value	current	Z pole		ILC250	
		$\delta[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$
boson properties						
m_W	80.379	1.5	-	-		0.3
m_Z	91.1876	0.23		0.022	0.08	-
Γ_Z	2.4952	9.4	0.5	-	6	-
$\Gamma_Z(had)$	1.7444	11.5		4.	-	-
Z-e couplings						
$1/R_e$	0.0482	24.	2.	5	5.5	10
A_e	0.1513	139.	1.5	1.2	12.	9.
g_L^e	-0.632	16.	1.0	3.2	2.8	7.6
g_R^e	0.551	18.	1.0	3.2	2.9	7.6
Z-ℓ couplings						
$1/R_\mu$	0.0482	16.	2.	2.	5.5	10
$1/R_\tau$	0.0482	22.	2.	2.	5.7	10
A_μ	0.1515	991.	2.	5	54.	3.
A_τ	0.1515	271.	2.	5.	57.	3
g_L^μ	-0.632	66.	1.0	2.3	4.5	7.6
g_R^μ	0.551	89.	1.0	2.3	5.5	7.6
g_L^τ	-0.632	22.	1.0	2.8	4.7	7.6
g_R^τ	0.551	27.	1.0	3.2	5.8	7.6
Z-b couplings						
R_b	0.2163	31.	0.4	7.	3.5	10
A_b	0.935	214.	1.	5.	5.7	3
g_L^b	-0.999	54.	0.32	4.2	2.2	7.6
g_R^b	0.184	1540	7.2	36.	41.	23.
Z-c couplings						
R_c	0.1721	174.	2.	30	5.8	50
A_c	0.668	404.	3.	5	21.	3
g_L^c	0.816	119.	1.2	15.	5.1	26.
g_R^c	-0.367	416.	3.1	17.	21.	26.

Four fermion interactions: flavour universal



$$\mathcal{L} = \mathcal{L}_{SM} - \frac{g^2\mathbf{W}}{2m_W^2} J^a_{L\mu} J^{a\mu}_L - \frac{g'^2\mathbf{Y}}{2m_W^2} J_{Y\mu} J^\mu_Y$$

$\sqrt{s}$	$\Delta\mathbf{W}$	$\Delta\mathbf{Y}$	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

Table 6: Projections for 1-σ errors on **W** and **Y** from a 2-parameter fit to data on $e^+e \to f\overline{f}$ from the analysis described in the text. The assumed luminosities are those described in Section 2. The projection for HL-LHC (3 ab^{-1}) is based on the neutral current analysis described in [69], in particular, Fig. 2 of that paper.

[LCC Physics Working Group, 1908.11299]

Four fermion interactions: flavour non-universal

$$\mathcal{L}_{LL} = \frac{g^2_{\text{contact}}}{2\Lambda^2}\sum_j \eta^j_{LL}(\bar{e}_L\gamma_\mu e_L)(\overline{\psi}^j_L\gamma^\mu\psi^j_L),$$

$$\mathcal{L}_{LR} = \frac{g^2_{\text{contact}}}{2\Lambda^2}\sum_j \eta^j_{LR}(\bar{e}_L\gamma_\mu e_L)(\overline{\psi}^j_R\gamma^\mu\psi^j_R),$$

$$\mathcal{L}_{RL} = \frac{g^2_{\text{contact}}}{2\Lambda^2}\sum_j \eta^j_{RL}(\bar{e}_R\gamma_\mu e_R)(\overline{\psi}^j_L\gamma^\mu\psi^j_L),$$

$$\mathcal{L}_{RR} = \frac{g^2_{\text{contact}}}{2\Lambda^2}\sum_j \eta^j_{RR}(\bar{e}_R\gamma_\mu e_R)\overline{\psi}^j_R\gamma^\mu\psi^j_R),$$

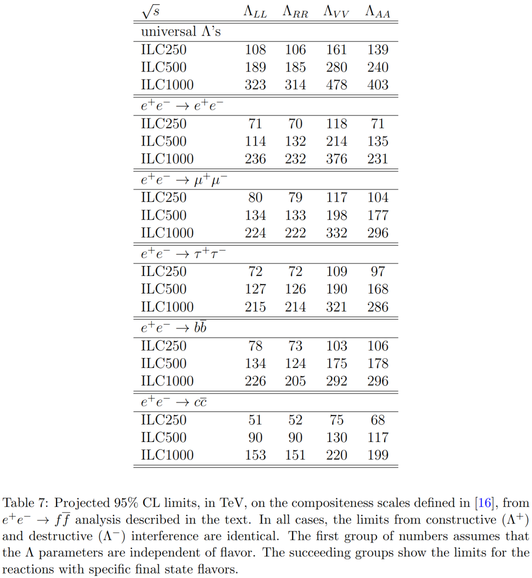
$$\Lambda = \Lambda^\pm_{LL} \text{ for } (\eta_{LL},\eta_{RR},\eta_{LR},\eta_{RL}) = (\pm1,0,0,0),$$
$$\Lambda = \Lambda^\pm_{RR} \text{ for } (\eta_{LL},\eta_{RR},\eta_{LR},\eta_{RL}) = (0,\pm1,0,0),$$

$$\Lambda = \Lambda^\pm_{VV} \text{ for } (\eta_{LL},\eta_{RR},\eta_{LR},\eta_{RL}) = (\pm1,\pm1,\pm1,\pm1),$$
$$\Lambda = \Lambda^\pm_{AA} \text{ for } (\eta_{LL},\eta_{RR},\eta_{LR},\eta_{RL}) = (\pm1,\pm1,\mp1,\mp1),$$

- Limits derived for fixed values of η
- $g^2_{contact}/(4\pi) = 1$

[LCC Physics Working Group, 1908.11299]

Four fermion interactions: flavour non-universal



$\sqrt{s}$	Λ_{LL}	Λ_{RR}	Λ_{VV}	Λ_{AA}
universal Λ's				
ILC250	108	106	161	139
ILC500	189	185	280	240
ILC1000	323	314	478	403
$e^+e^- \to e^+e^-$				
ILC250	71	70	118	71
ILC500	114	132	214	135
ILC1000	236	232	376	231
$e^+e^- \to \mu^+\mu^-$				
ILC250	80	79	117	104
ILC500	134	133	198	177
ILC1000	224	222	332	296
$e^+e^- \to \tau^+\tau^-$				
ILC250	72	72	109	97
ILC500	127	126	190	168
ILC1000	215	214	321	286
$e^+e^- \to b\bar{b}$				
ILC250	78	73	103	106
ILC500	134	124	175	178
ILC1000	226	205	292	296
$e^+e^- \to c\bar{c}$				
ILC250	51	52	75	68
ILC500	90	90	130	117
ILC1000	153	151	220	199

Table 7: Projected 95% CL limits, in TeV, on the compositeness scales defined in [16], from $e^+e^- \to f\bar{f}$ analysis described in the text. In all cases, the limits from constructive (Λ^+) and destructive (Λ^-) interference are identical. The first group of numbers assumes that the Λ parameters are independent of flavor. The succeeding groups show the limits for the reactions with specific final state flavors.

CLIC: 2F study

$$\Delta\mathcal{L}_{\text{Universal}} = \frac{S}{16\pi v^2}\mathcal{O}_{WB} - \frac{2\alpha T}{v^2}\mathcal{O}_{HD} - \frac{Y}{2M_W^2}\mathcal{O}_{2B} - \frac{W}{2M_W^2}\mathcal{O}_{2W},$$

$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$$

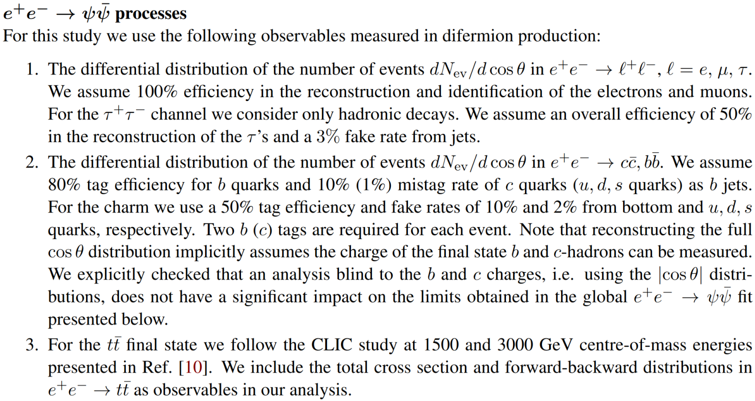
$$\mathcal{O}_{B} = \tfrac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} \qquad \mathcal{O}_{WB} = gg'(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$\mathcal{O}_{2B} = \tfrac{1}{2}\left(\partial_\rho B_{\mu\nu}\right)^2 \qquad \mathcal{O}_{2W} = \tfrac{1}{2}\left(D_\rho W^a_{\mu\nu}\right)^2$$

[The CLIC potential for new physics, 1812.02093]

CLIC: 2F study



$e^+e^- \to \psi\bar{\psi}$ processes

For this study we use the following observables measured in difermion production:

1. The differential distribution of the number of events $dN_{\text{ev}}/d\cos\theta$ in $e^+e^- \to \ell^+\ell^-$, $\ell = e, \mu, \tau$. We assume 100% efficiency in the reconstruction and identification of the electrons and muons. For the $\tau^+\tau^-$ channel we consider only hadronic decays. We assume an overall efficiency of 50% in the reconstruction of the τ's and a 3% fake rate from jets.
2. The differential distribution of the number of events $dN_{\text{ev}}/d\cos\theta$ in $e^+e^- \to c\bar{c}, b\bar{b}$. We assume 80% tag efficiency for b quarks and 10% (1%) mistag rate of c quarks (u, d, s quarks) as b jets. For the charm we use a 50% tag efficiency and fake rates of 10% and 2% from bottom and u, d, s quarks, respectively. Two b (c) tags are required for each event. Note that reconstructing the full $\cos\theta$ distribution implicitly assumes the charge of the final state b and c-hadrons can be measured. We explicitly checked that an analysis blind to the b and c charges, i.e. using the $|\cos\theta|$ distributions, does not have a significant impact on the limits obtained in the global $e^+e^- \to \psi\bar{\psi}$ fit presented below.
3. For the $t\bar{t}$ final state we follow the CLIC study at 1500 and 3000 GeV centre-of-mass energies presented in Ref. [10]. We include the total cross section and forward-backward distributions in $e^+e^- \to t\bar{t}$ as observables in our analysis.

[The CLIC potential for new physics, 1812.02093]

CLIC: 2F study

Table 19: (Right) 68% C.L. Gaussian errors on the different oblique parameters. In parenthesis, the results assuming the other oblique parameters are set to 0. All numbers obtained from the fit assuming $\delta_{\text{sys}} = 0.3\%$ for the light fermion channels and $\delta^{(O)}_{\text{sys},tt} = 1\%$ systematics for $e^+e^- \to t\bar{t}$. (Left) The correlations between the different oblique parameters from the fit for the CLIC Baseline scenario.

Scenario (P_{e^-}, P_{e^+})	Current	CLIC Baseline $(\mp 80\%, 0\%)$	CLIC Unpolarized $(0\%, 0\%)$
S	0.13	0.09 (0.05)	0.16 (0.10)
T	0.08	0.10 (0.05)	0.12 (0.07)
$W\,[\times 10^6]$	600	1.7 (1.5)	3.0 (2.2)
$Y\,[\times 10^6]$	900	2.0 (1.8)	2.3 (1.7)

CLIC Baseline Correlation matrix				
S	1			
T	0.86	1		
W	0.08	0.19	1	
Y	0.10	0.05	-0.41	1

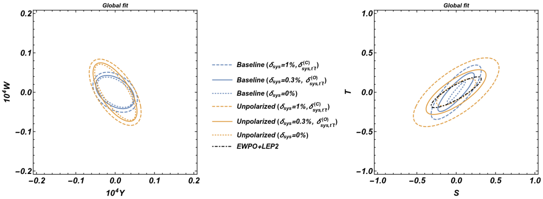


Figure 24: (Left) 95% C.R. in the W-Y plane, profiling over S and T, for the different CLIC scenarios and assumptions on the systematic errors. (Right) 95% C.R. in the S-T plane, profiling over W and Y, for the different CLIC scenarios and assumptions on the systematic errors.

[The CLIC potential for new physics, 1812.02093]

Example of EW measurements @ Tera Z

Couplings measured from ratio of hadronic and leptonic partial widths

→ need control on detector acceptances: detector precision ~ 10 μm

	Statistical uncertainty	Systematic uncertainty
R_μ (R_ℓ)	10^{-6}	5×10^{-5}
R_τ	1.5×10^{-6}	10^{-4}
R_e	1.5×10^{-6}	3×10^{-4}
R_b	5×10^{-5}	3×10^{-4}
R_c	1.5×10^{-4}	15×10^{-4}

Relative stat. and syst. unc. (similar)

fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10
c	2×10^{-3}	1×10

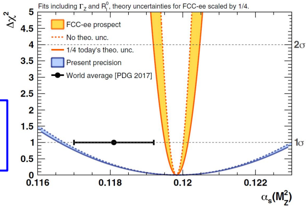
Relative unc. on couplings

1-2 orders of magnitude
Improvement w.r.t. LEP

Extract strong coupling constant $\alpha_S(m_Z^2)$ using leptonic/hadronic width ratio: $R_l = \Gamma_{had}/\Gamma_{lep}$

→ $\Delta\alpha_S(m_Z)$ ~ 1×10^{-5} (stat) + 1.5×10^{-4} (syst) abs. (current value $\Delta\alpha_S$ 30×10^{-4})

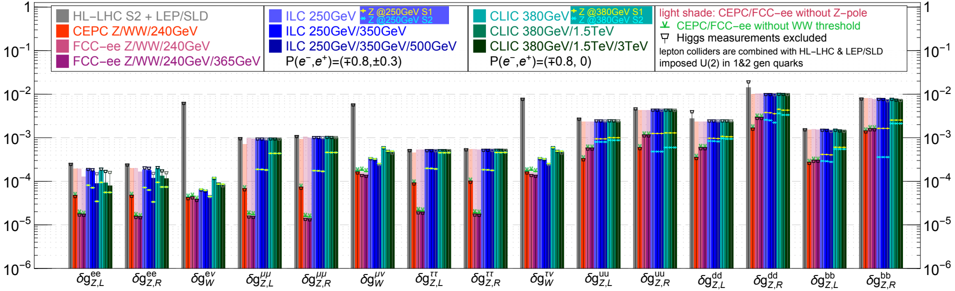
→ Systematically dominated (acceptance)



J. Eysermans @ EPS2021

Sensitivity on EW couplings

J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



Sensitivity on EW couplings

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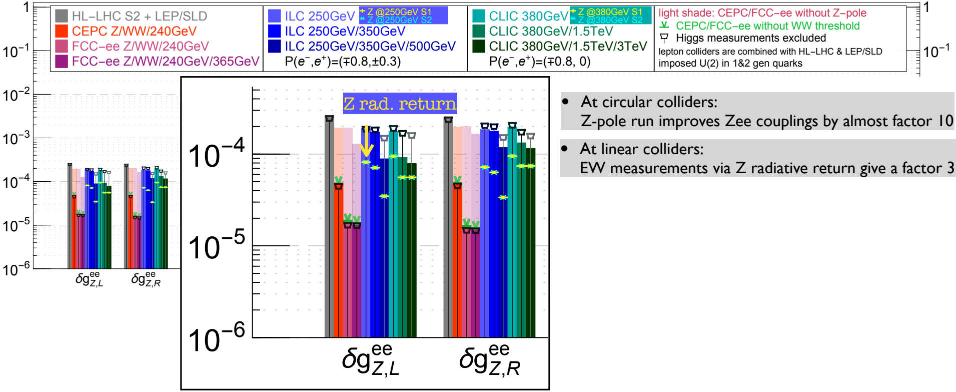
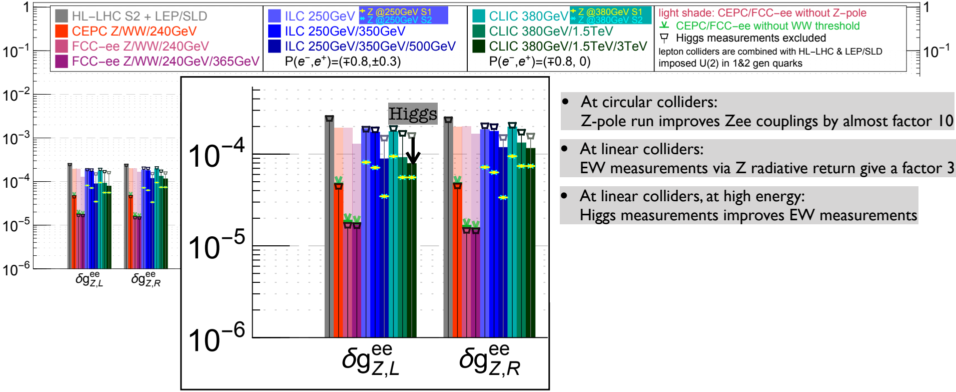


- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3

Sensitivity on EW couplings

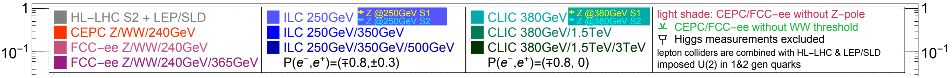
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- At circular colliders:
  Z-pole run improves Zee couplings by almost factor 10
- At linear colliders:
  EW measurements via Z radiative return give a factor 3
- At linear colliders, at high energy:
  Higgs measurements improves EW measurements

Sensitivity on EW couplings

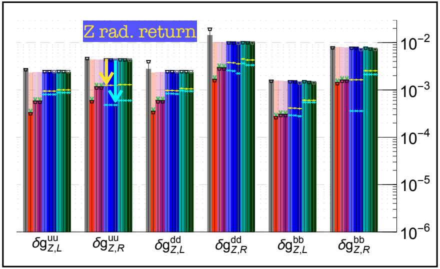
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311



- At linear colliders, at high energy:
  EW measurements via Z-radiative return has a large impact on Zqq couplings
- Improvements depend a lot on hypothesis on systematic uncertainties

  Yellow: LEP/SLD systematics / 2

  Blue: small EXP and TH systematics



Theory

Open questions

- MC benchmarking?
- Benchmarking precision by constraining four fermion interactions or explicit simplified UV models?
- Possibility of using energy growth to compensate for decrease number of events?
- Any interesting WILP scenarios to be directly tested on data?
- Any sensitivity to anything coming from "heavy quarks" compared to flavour factories?
- FCNC sensitivity? For quarks and leptons
- 2F+photon sensitivity to new physics

Outlook

- Important questions not yet addressed?
- Developments on the exp. side?
- Can we measure other observables?
- Issues and opportunities from tau polarization? Tau spin correlations?
- Accuracy of SM calculations? sufficient?
- More BSM theory benchmarking?
- Get involved!