Electroweak precision measurements at the ILC

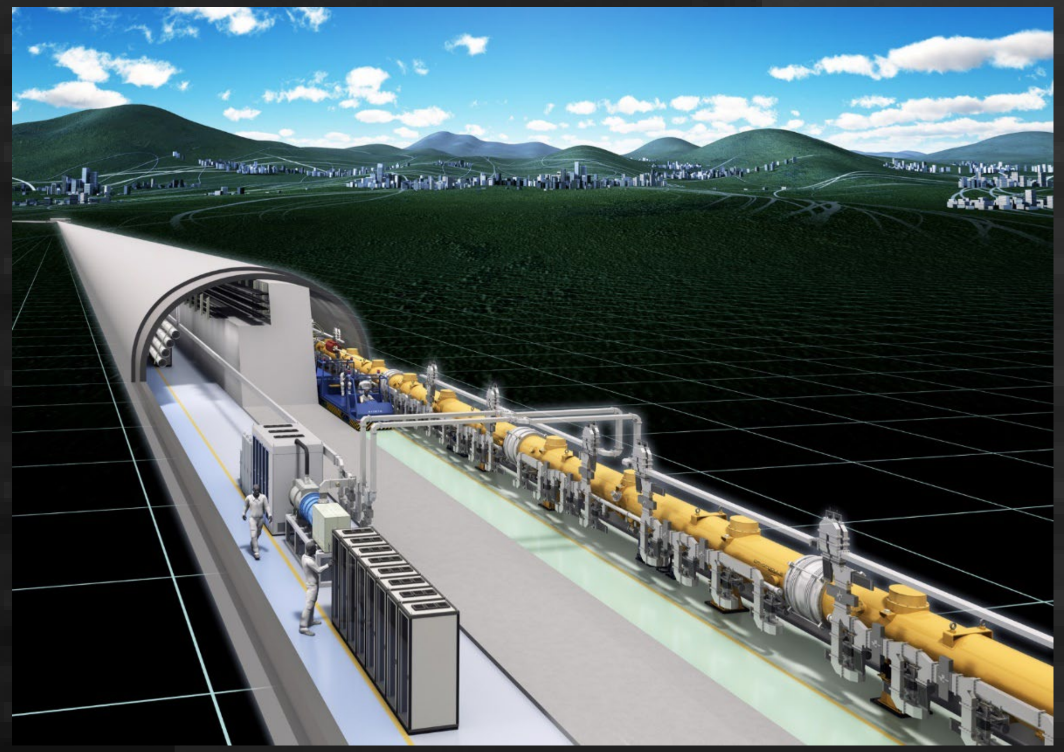
T. Suehara (Kyushu University)

on behalf of ILC IDT-WG3 Physics Potential and Opportunities subgroup
based on arXiv:2203.07622 (ILC Snowmass white paper)

e^+e^- Higgs factories and the ILC

e^+e^- Higgs factory

- The next EF machine after HL-LHC in 2030-40s
- Solid physics cases (Higgs, BSM…)
- Powerful machine for EW precise measurements



Circular machine

- FCCee, CEPC
- Upgrade path to hadron colliders
- More luminosity in Z-pole and WW
- Multiple detectors (like LHC)
- Feasibility studies in Europe until ~2025
- ~100 km tunnel

Linear machine

- ILC, CLIC, C^3 etc.
- Upgrade path to TeV e^+e^- colliders
- More luminosity in higher energy
- Polarization
- Long development technically mature
- < 20 km tunnel

ILC in Japan

- Pity not concrete statement yet
- (Still) the earliest machine possible to be realized
- Restructuring of strategy ongoing (expect first feedback this year)
- Construction start aimed at (late) 2020s → operation in 2030s
- Support from US (and Europe) mandatory (the concern of MEXT)

EW precise measurements at Higgs Factories

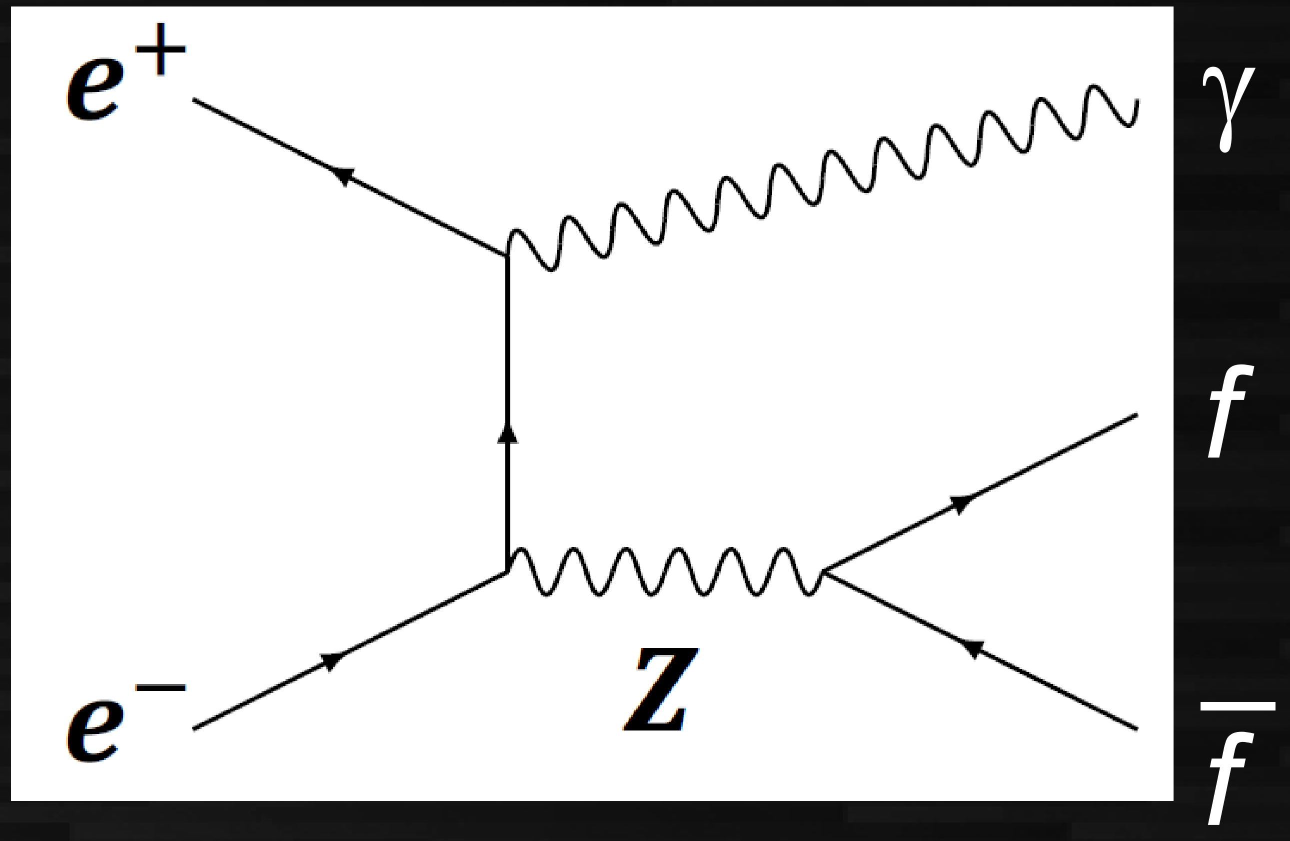
- Electroweak precision observables (EWPOs):
  LEP results still alive → supreme channels for lepton colliders
  - 1-2 order-of-magnitude improvement foreseen with Higgs Factories
- Direct probe for new physics (eg. Z' bosons)
  - Collision energy is important
- Triple/quartic coupling of gauge bosons
  - Better for higher energies
- Important inputs for SM Effective Field Theory
  - Essential for model-independent NP search with EW/Higgs sectors

Topics

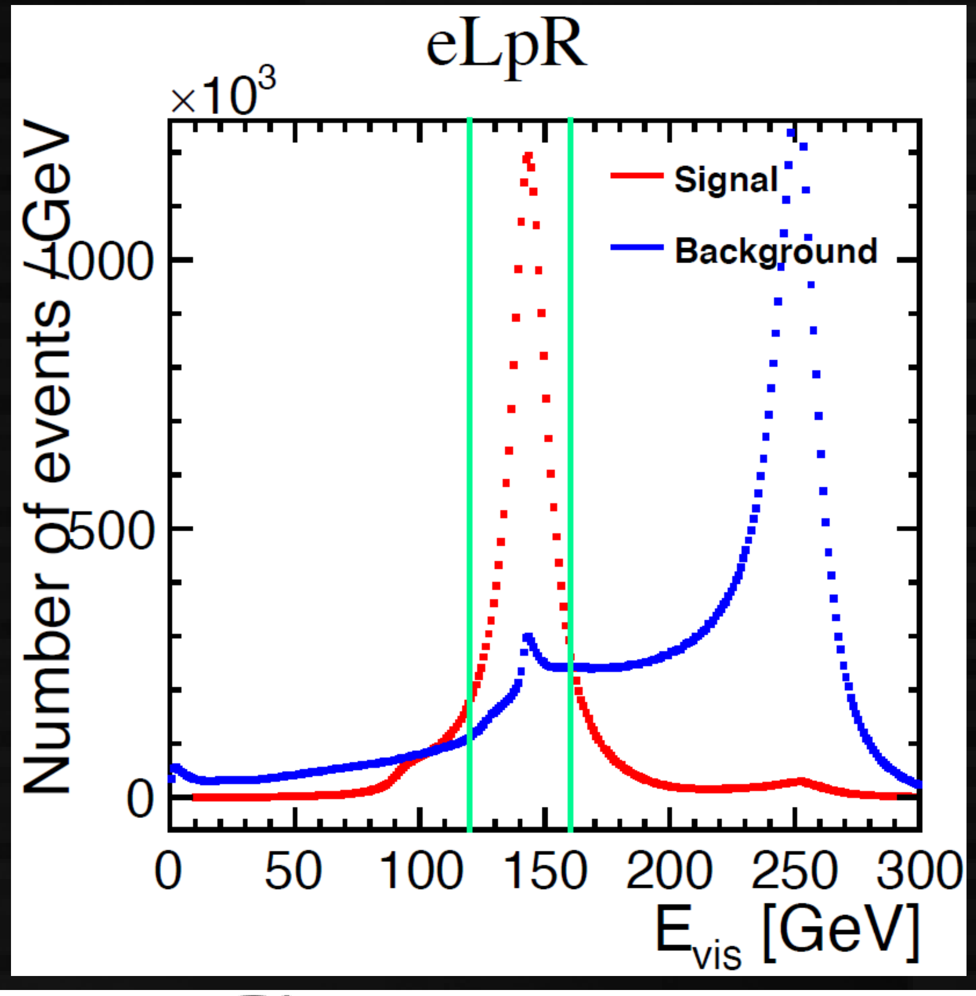
- $e^+e^- \rightarrow 2f$ measurements
  - – Radiative return at 250 GeV
  - – Z-pole (Giga-Z)
  - – 2f at 250/500/1000 GeV
    - Sensitivity to Z' models
    - Sensitivity to indirect DM search
- Triple gauge couplings
- W mass measurements (Z mass/width: the next talk)
- Applying to Higgs analysis (SMEFT)
- Summary

Radiative Return at 250 GeV, 2 ab^{-1}

arXiv:2203.07944
ILD full simulation



Real Z produced with γ at single energy



$$\text{Cut 2} \quad 120\,\text{GeV} < E_{vis} < 160\,\text{GeV}$$

Z → qq only

(−0.8, +0.3) polarization, assuming $\int Ldt = 900\,\text{fb}^{-1}$.

$\times 10^6$ events	Signal	Signal (Core)	2f_l	4f_l	4f_sl	4f_h	2f_h	Bkg.
Expected	46.0	32.5	12.7	9.34	17.2	15.1	23.6	78.1
Cut 1	32.7	31.1	10.1	5.96	16.0	14.8	21.6	68.3
Cut 2	24.6	24.4	2.55	1.46	3.22	0.00422	1.09	8.32
Cut 3	24.5	24.4	1.93	0.366	0.526	0.00352	1.04	3.87
Cut 4	24.4	24.3	0.299	0.0574	0.523	0.00352	1.00	1.88
Cut 5	24.3	24.2	0.0651	0.0102	0.520	0.00352	0.977	1.58
Cut 6	24.2	24.2	0.0571	0.00807	0.470	0.00210	0.694	1.23
Cut 7	24.2	24.1	0.0534	0.00647	0.463	0.00204	0.682	1.21

24 M events after selection with $e_L p_R$ (16 M with $e_R p_L$), negligible bkg.

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

100% pol.

$$A_{LRobs} \equiv \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}}$$

observables

$$A_{LR} = A_{LRobs} \frac{1 + |P_-||P_+|}{|P_-| + |P_+|}$$

P: polarization w/ uncertainty

$A_{LR} = 0.22810 \pm \mathbf{0.00018}$ (stat)

total error on A_{LR} is $\mathbf{2.5 \times 10^{-4}}$

Including pol. error and other systematics
Stat. error and syst. error comparable

Analysis fully utilizing polarization

Radiative Return: other variables

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

δm_Z (0.7 MeV): Using Z → $\mu\mu$ only
(if including Z → qq statistical power 0.2-0.3 MeV, but jet energy scaling should be an issue)

A_f (f = μ, τ, b, c): from A_{LRFB} (no simulation done yet)
Estimating (flavor/charge) tagging efficiencies from full-simulation studies of 250/500 GeV 2f
(τ: 80%, μ: 88%, b: 40%, c: 7.3%).
g_{LR}: calculated from A_f

R_f: $R_q \equiv \Gamma(Z \to q\bar{q})/\Gamma(Z \to \text{ hadrons})$ and $1/R_\ell \equiv \Gamma(Z \to \ell^+\ell^-)/\Gamma(Z \to \text{ hadrons})$
Same as above but do not need charge tagging
(efficiency on quarks much better)
Γ_Z: calculated from R_f
Can be improved by line shape (by some factor)

Z-pole run (Giga-Z)

Quantity	Value	current $\delta[10^{-4}]$	Zpole $\delta_{stat}[10^{-4}]$	Zpole $\delta_{sys}[10^{-4}]$
boson properties				
m_W	80.379	1.5	-	-
m_Z	91.1876	0.23		0.022
Γ_Z	2.4952	9.4	0.5	-
$\Gamma_Z(had)$	1.7444	11.5		4.
Z-e couplings				
$1/R_e$	0.0482	24.	2.	5
A_e	0.1513	139.	2.8	5.
g_L^e	-0.632	16.	1.0	3.2
g_R^e	0.551	18.	1.0	3.2
Z-ℓ couplings				
$1/R_\mu$	0.0482	16.	2.	2.
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g_L^b	-0.999	54.	0.32	4.2
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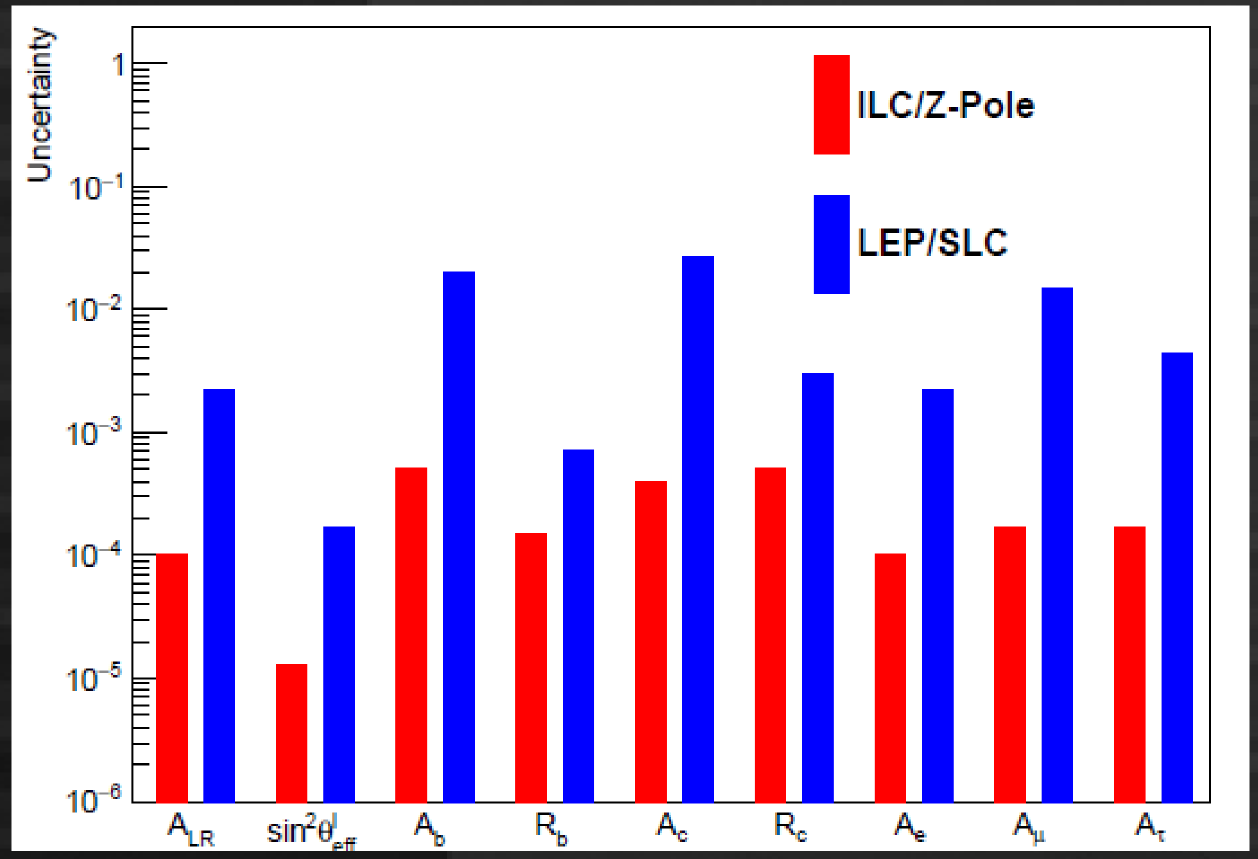
Z-c couplings				
R_c	0.1721	174.	2.	30
A_c	0.668	404.	3.	5
g_L^c	0.816	119.	1.2	15.
g_R^c	-0.367	416.	3.1	17.

Number of Zs and luminosity

	sign$(P(e^-), P(e^+))$ = $(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	60.4	46.1	35.9	29.4	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

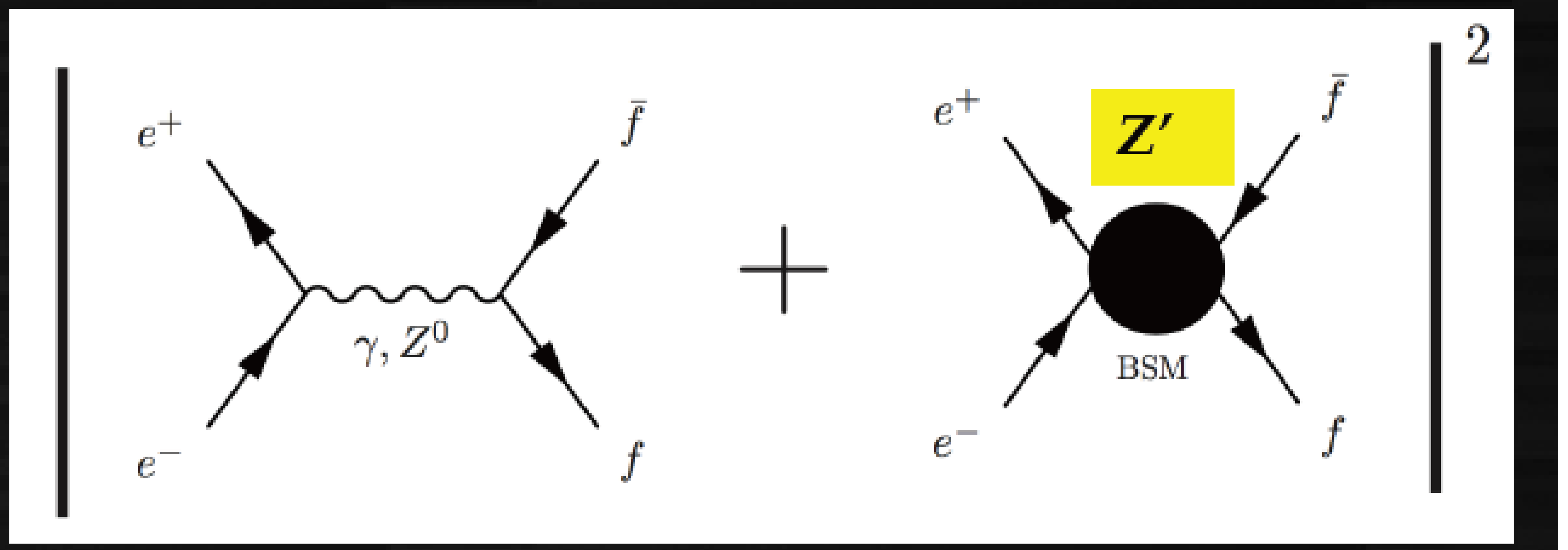


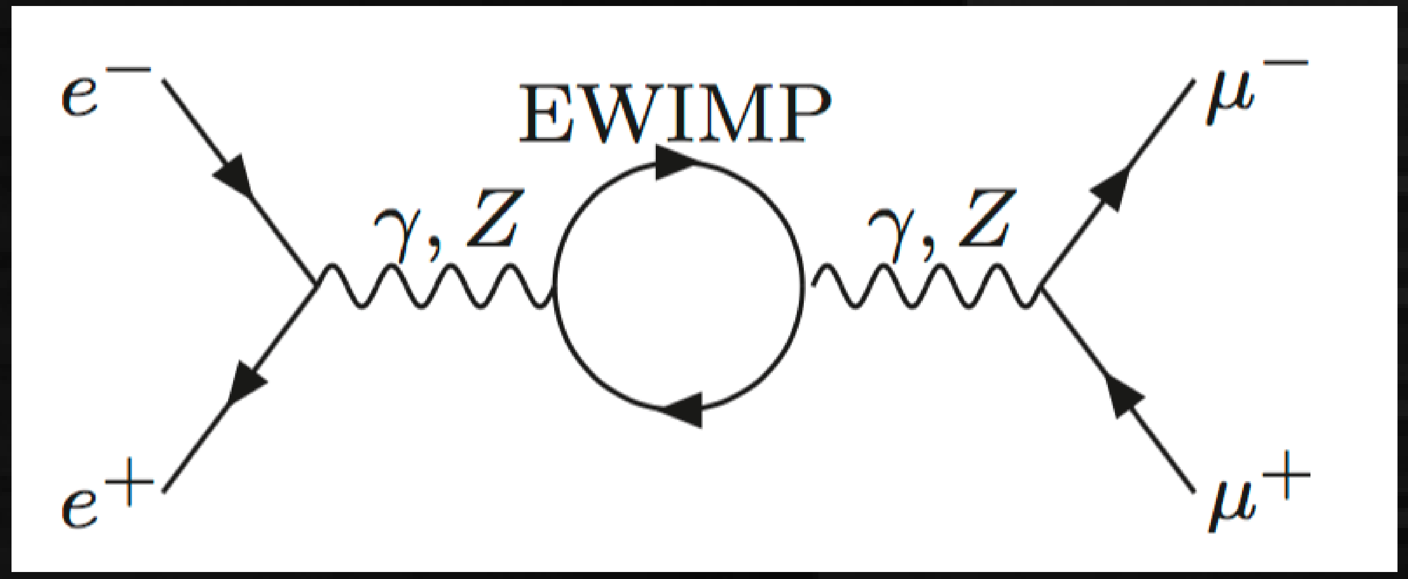
0.1 ab^{-1} assumed (~1.5 years run)
~50 times more Zs than 250 GeV
Electron polarization maintained
Positron may not be polarized
(depending on positron production method)

No serious simulation studies done
Mostly dominated by systematic uncertainty
of polarization uncertainty (~0.1%)

2f at 250- GeV (no Radiative Return)

Probe for high energy particles (Z’, WIMP,…)





Efficiency assumed based on full-simulation studies

$$c_b = 0.29, c_c = 0.07,$$

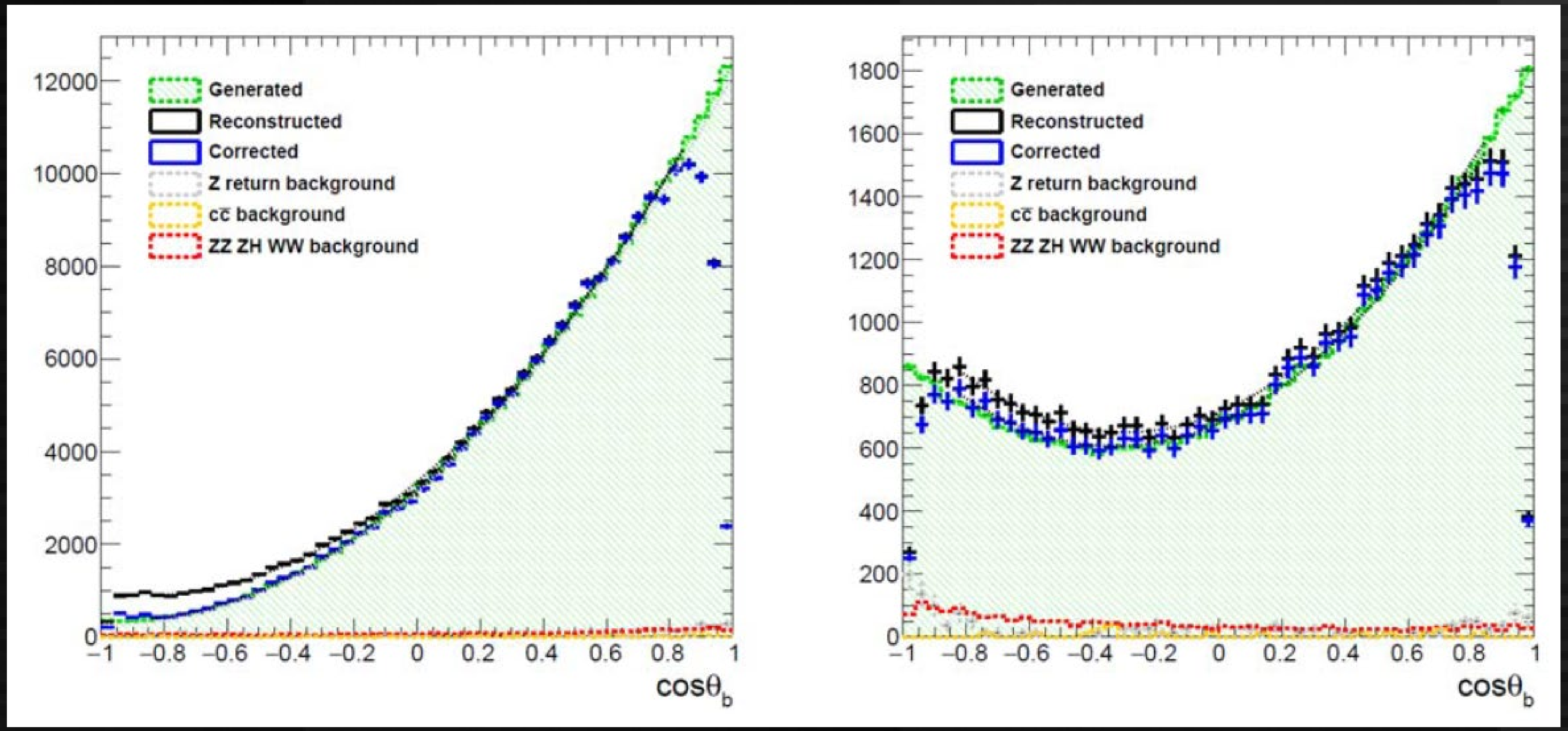
$$c_e = 0.97, c_\mu = 0.98, c_\tau = 0.65$$

Gives difference in σ and angular/polarization dependence

→ precise measurement to 0.1% possible

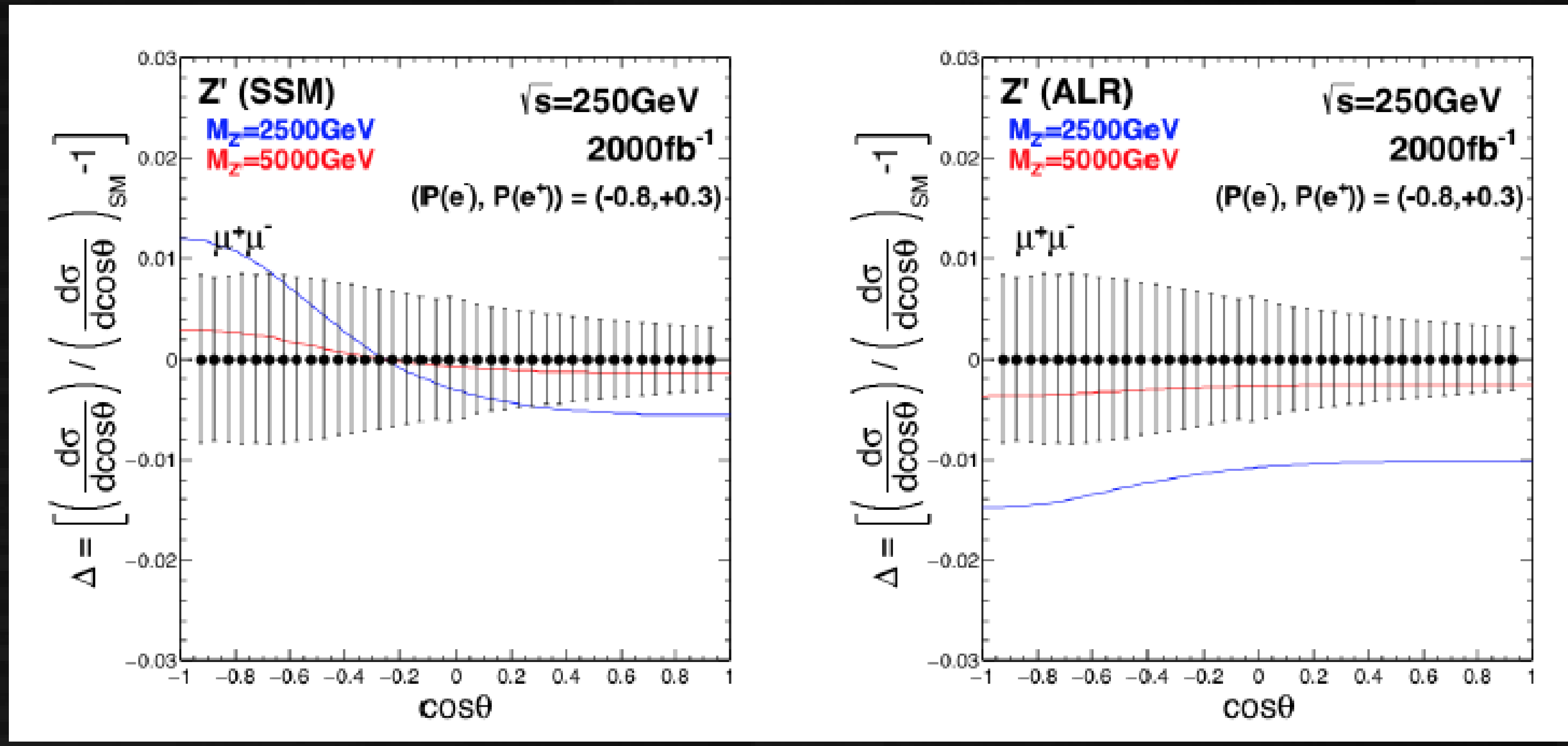
Sqrt(s)	Process	N ($e^-_L e^+_R$)	N ($e^-_R e^+_L$)
250 GeV, 2 ab^{-1}	e^+e^- → qq	43 M	27 M
	e^+e^- → ll (μ, τ)	7.2 M	5.7 M
500 GeV, 4 ab^{-1}	e^+e^- → qq	18 M	10 M
	e^+e^- → ll (μ, τ)	4.2 M	3.1 M
1 TeV, 8 ab^{-1}	e^+e^- → qq	10 M	6.1 M
	e^+e^- → ll (μ, τ)	2.4 M	1.7 M

Measurement with < 0.1% possible



Study of charge assignment of e^+e^- → bb

2f study: limits to Z' and WIMPs



Angular distributions are checked to obtain significance

Model	250 GeV, 2 ab^{-1} excl.	250 GeV, 2 ab^{-1} disc.	500 GeV, 4 ab^{-1} excl.	500 GeV, 4 ab^{-1} disc.	1 TeV, 8 ab^{-1} excl.	1 TeV, 8 ab^{-1} disc.
SSM	7.7	4.9	13	8.3	22	14
ALR	9.4	5.9	16	10	25	18
χ	7.0	4.4	12	7.7	21	13
ψ	3.7	2.3	6.3	4.0	11	6.7
η	4.1	2.6	7.2	4.6	12	7.8

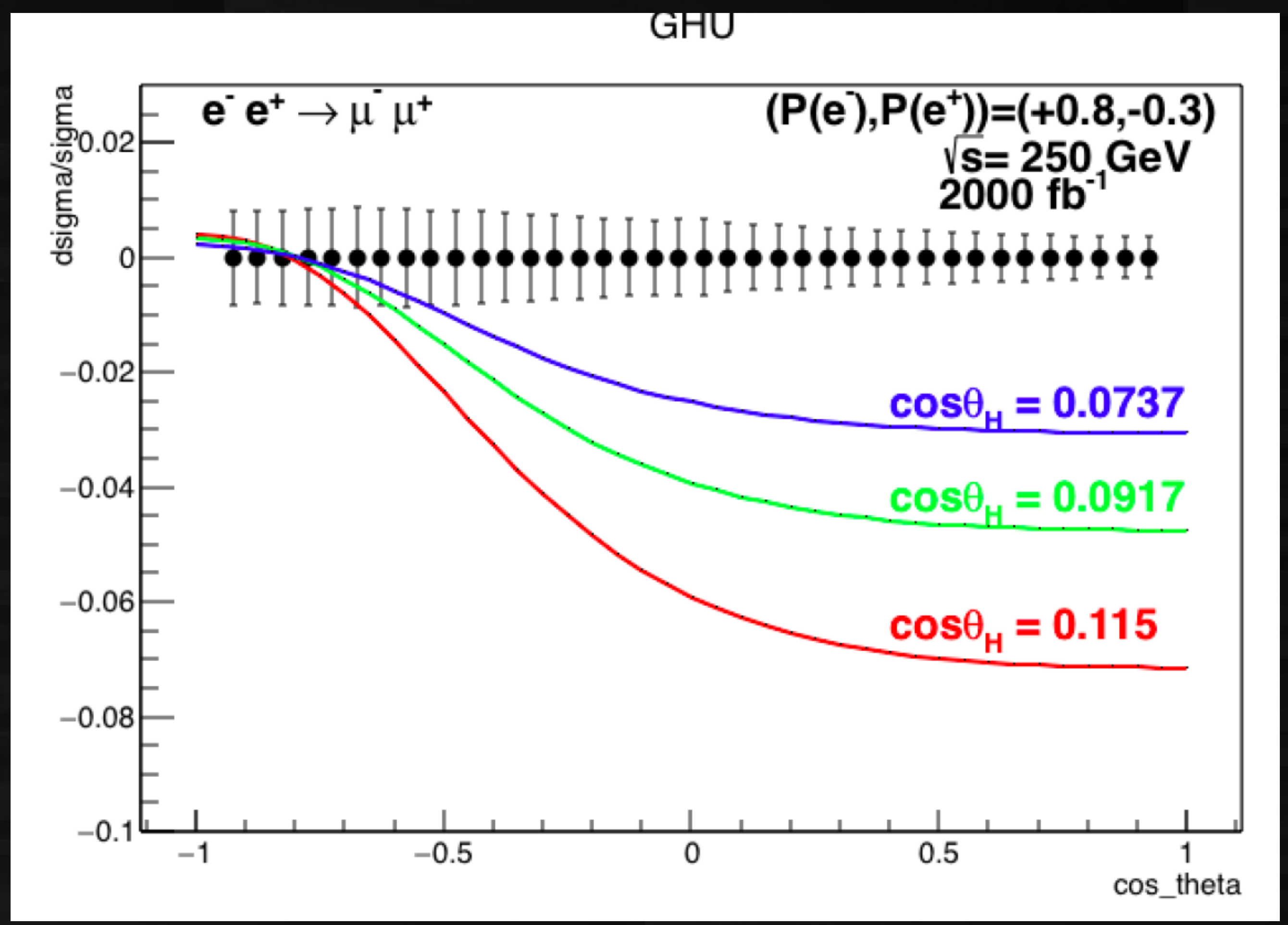
Table 10.1: Projected limits on Z' bosons in standard models, from the study of $e^+e^- \to f\bar{f}$. The values presented, given in TeV, are the 95% exclusion limits and the 5σ discovery limits for the successive stages of the ILC program up to 1 TeV.

Limit for Z' models in TeV: SSM, ALR (alternative left-right model) and E_6 models

Table 5: Mass reach of EWIMP

BSM	mass reach (90% CL)
MDM	500 GeV
Higgsino	180 GeV
Wino	240 GeV

Mass reach of WIMPs at 250 GeV: to be updated



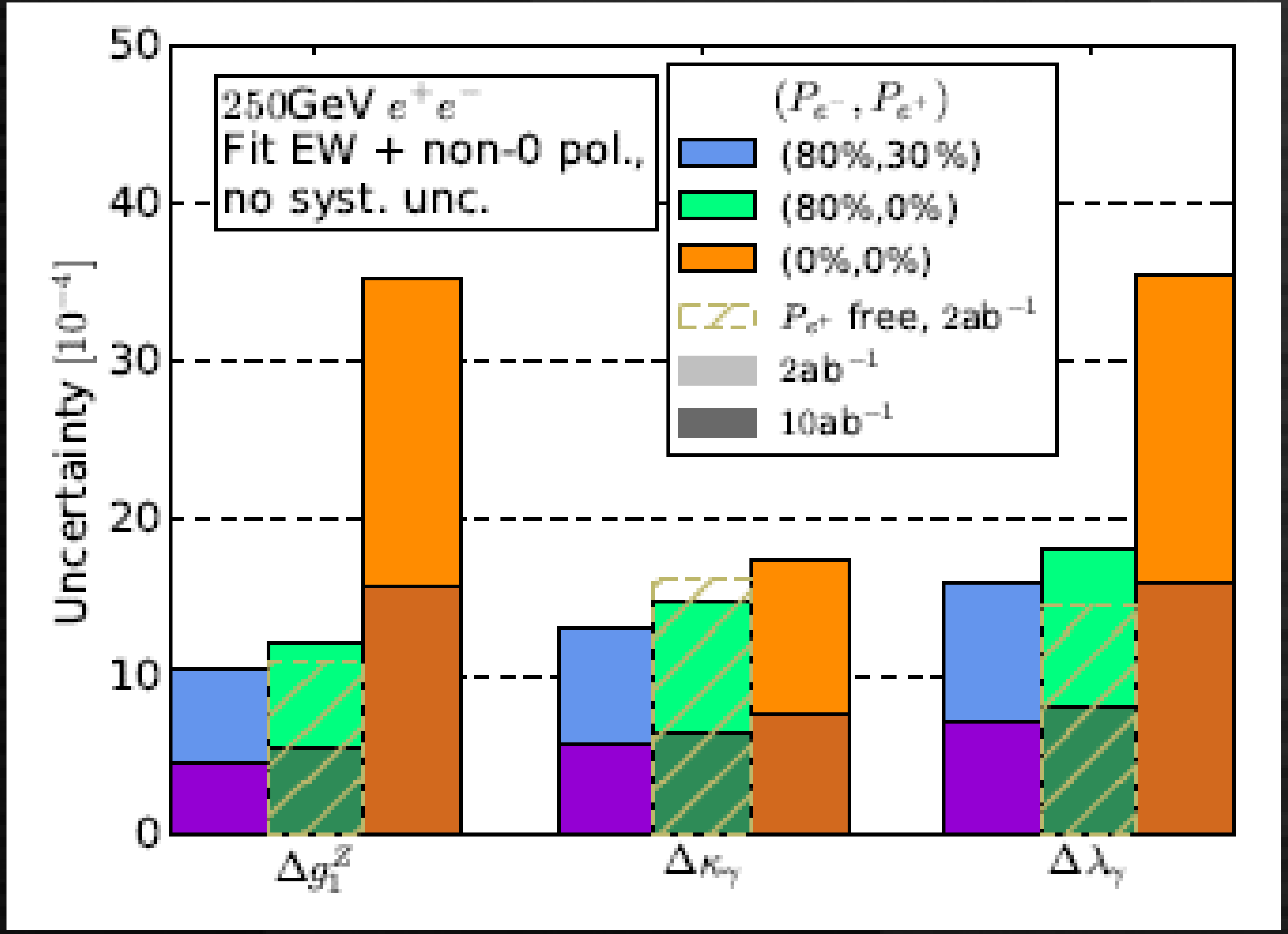
Z' in GHU (Gauge Higgs Unification) model (arXiv:1705.05282,1801.04671)
Big deviation with $e_R p_L$ polarization: easy to identify deviation with 250 GeV linear colliders

arXiv:2002.02777

Triple gauge couplings at 250- GeV

Table 1: List of processes used in the fitting framework, including the considered values of chiral chross-sections and the differential distributions with corresponding binning. A starred observable (*) is extracted in the rest frame of the corresponding W boson. ($q = u, d, s, c, b$) Cross sections where calculated with `WHIZARD` [7] and are supplied by the ILD generator group [8].

Process ($e^+e^- \to X$)	σ_{LR} [fb^{-1}]	σ_{RL} [fb^{-1}]	σ_{LL} [fb^{-1}]	σ_{RR} [fb^{-1}]	Diff. observ. # Bins		
$W^+W^- \to \mu\nu q\bar{q}'$	9390	86.4	0	0	$\cos(\theta_{W^-})$, 20 $\otimes$	$\cos(\theta^*_\mu)$, 10 $\otimes$	ϕ^*_l 10
$W^+e^-\bar{\nu} \to q\bar{q}'e^-\bar{\nu}$	5000	42.8	0	119	$\cos(\theta_{W^+})$, 20 $\otimes$	$\cos(\theta^*_{e^-})$, 10 $\otimes$	$m_{e^-\bar{\nu}}$ 20
$W^-e^+\nu \to q\bar{q}'e^+\nu$	500	42.9	120	0	$\cos(\theta_{W^-})$, 20 $\otimes$	$\cos(\theta^*_{e^+})$, 10 $\otimes$	$m_{e^+\bar{\nu}}$ 20
$ZZ \to q\bar{q}\mu^+\mu^-$	356	178	0	0	θ^l_Z, 20 $\otimes$	$\theta^*_{\mu^-}$, 10 $\otimes$	$\phi^*_{\mu^-}$ 10
$q\bar{q}$	12900	71300	0	0	θ_q 20		
l^+l^- ($l = \mu/\tau$)	21200	16500	0	0	θ_{l^-} 20		



Higher energy: significant improvement

	250 GeV W^+W^-	350 GeV W^+W^-	500 GeV W^+W^-	1000 GeV W^+W^-
g_{1Z}	0 .062	0.033	0.025	0.0088
κ_A	0.096	0.049	0.034	0.011
λ_A	0.077	0.047	0.037	0.0090
$\rho(g_{1Z}, \kappa_A)$	63.4	63.4	63.4	63.4
$\rho(g_{1Z}, \lambda_A)$	47.7	47.7	47.7	47.7
$\rho(\kappa_A, \lambda_A)$	35.4	35.4	35.4	35.4

Table 13: Projected statistical errors, in %, for $e^+e^- \to W^+W^-$ measurements input to our fits. The errors are quoted for luminosity samples of 500 fb^{-1} divided equally between beams with -80% electron polarisation and +30% positron polarisation and brams with +80% electron polarisation and -30% positron polarisation. Please see the text of Appendix B for further explanation of this table.

Result on constrained TGCs (LEP constraint ~10^{-2})

(Electron) polarization is important in the TGC

W mass measurement

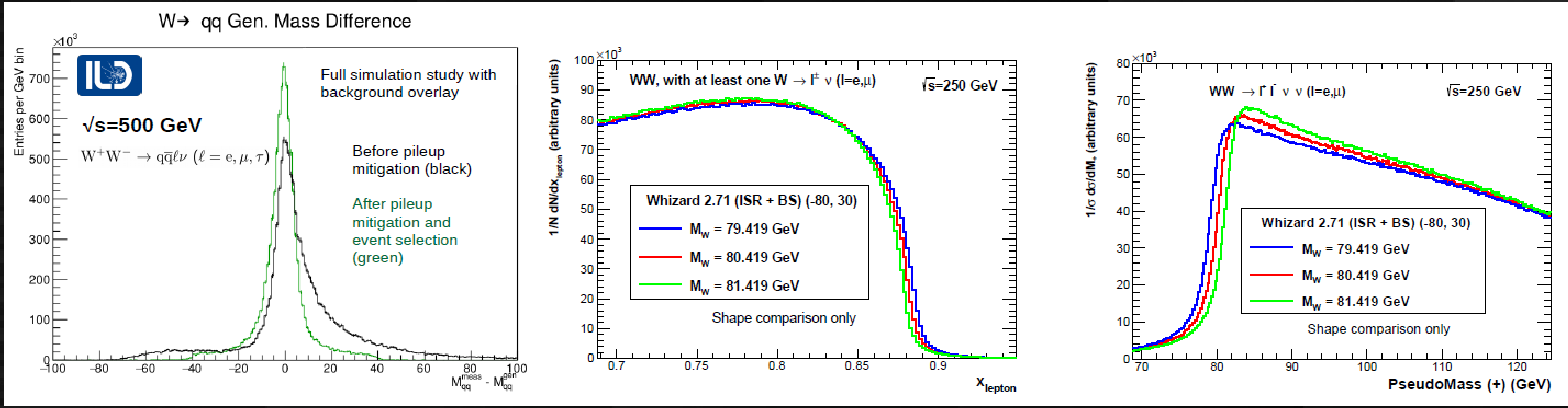
ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	2000	200	4000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.4	0.55	0.8
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.3	2.7	3.3
statistical	30	0.75	2.8	0.9
total	36	2.4	3.9	3.4

Methods to measure W mass with ILC:

1. Constrained reconstruction (kinematic constraints with W^+W^-)
2. Hadronic mass (single W or semileptonic W-pair)
3. Lepton endpoints
4. Dilepton pseudomass
5. Polarized threshold scan (at WW threshold)

Numbers with method 1.

2 MeV precision should be in reach



Hadronic mass at 500 GeV

Lepton endpoints and dilepton pseudomass at 250 GeV

Comparisons

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	64
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	570
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	200
$\Delta\sigma^0_{\mathrm{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

Table 3: EWPOs at future e^+e^-: statistical error (estimated experimental systematic error). Δ (δ) stands for absolute (relative) uncertainty, while * indicates inputs taken from current data [1]. See Refs. [17, 24, 26, 27, 36, 37].

Snowmass electroweak summary for EWPOs

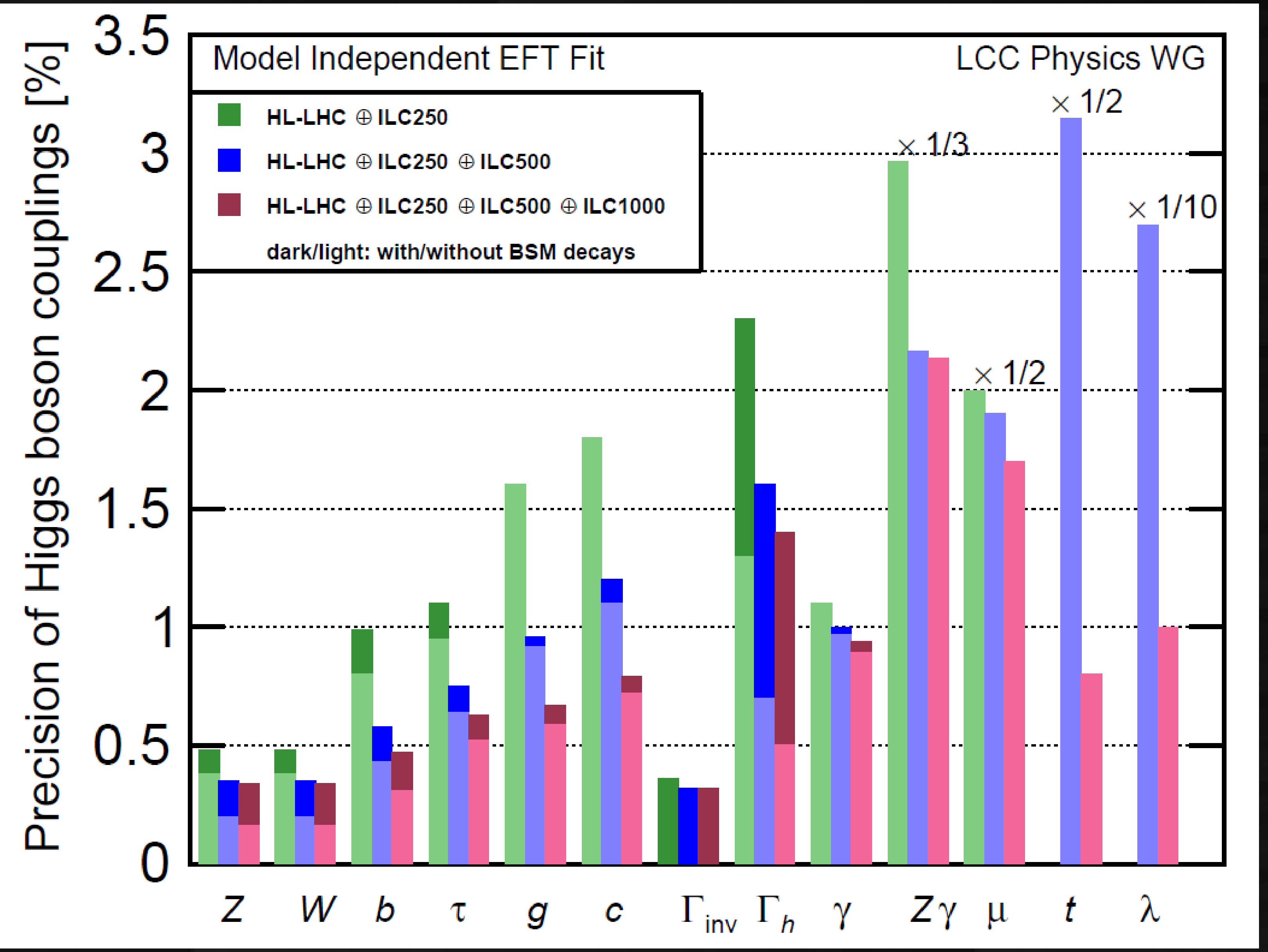
- No easy comparison: just take order-of-magnitude difference
- Circular collider has much higher luminosity at < 250 GeV
- Polarization partially compensates difference of luminosity
- Mostly dominated by systematics - effect of too much luminosity is rather limited
- TGC/VBS better in higher energy LC would give better numbers (but ~10^{-3} with 250 GeV for TGC)
- Input to SMEFT with Higgs measurements

SM Effective Field Theory fits

Assumed SMEFT Lagrangian (22 params)

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_H + \mathcal{L}_{W,B} + \underbrace{\mathcal{L}_{\Phi\ell} + \mathcal{L}_{\Phi q} + \mathcal{L}_{\Phi f} + \mathcal{L}_g}_{\text{Anomalous Higgs-fermion/gluon couplings}}$$

$$\begin{aligned}
\mathcal{L}_H &= \frac{c_H}{2v^2}(\partial_\mu \Phi^\dagger \Phi)^2 + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{\lambda c_6}{v^2}(\Phi^\dagger\Phi)^3 \\
\mathcal{L}_{W,B} &= \frac{g^2 c_{WW}}{v^2}(\Phi^\dagger\Phi)W^a_{\mu\nu}W^{a\mu\nu} + \frac{2gg' c_{WB}}{v^2}(\Phi^\dagger t^a \Phi)W^a_{\mu\nu}B^{\mu\nu} \\
&\quad + \frac{g'^2 c_{BB}}{v^2}(\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu} + \frac{c_{3W}}{6v^2}\epsilon_{abc}W^{a\nu}_{\mu}W^{b\rho}_{\nu}W^{c\mu}_{\rho} .
\end{aligned}$$



SMEFT results for Higgs couplings

coupling	ILC250 RadRtrn	ILC250 GigaZ	ILC250 TeraZ	ILC500 RadRtrn	ILC500 GigaZ	ILC500 TeraZ
hZZ	0.38	0.35	0.30	0.20	0.20	0.19
hWW	0.38	0.35	0.31	0.20	0.20	0.19
hbb	0.80	0.78	0.77	0.43	0.43	0.43
$h\tau\tau$	0.95	0.94	0.92	0.63	0.63	0.63
hgg	1.6	1.6	1.6	0.91	0.91	0.91
hcc	1.7	1.7	1.7	1.1	1.1	1.1
$h\gamma\gamma$	1.0	1.0	1.0	0.96	0.96	0.96
$h\gamma Z$	8.9	8.5	7.9	6.5	6.4	5.8
$h\mu\mu$	4.0	3.9	3.9	3.7	3.7	3.7
Γ_{tot}	1.29	1.26	1.21	0.70	0.70	0.69

Effect of EWPOs for Higgs couplings

Summary

- Electroweak measurements are one of the important programs in Higgs factories
  - Necessary for SMEFT – eventually for Higgs precision
  - W mass puzzle can be cleared
- 1-2 order-of-magnitude improvement from LEP expected
- Circular collider better for EWPOs, LC upgrade for TGC/VBS
- Systematics important in most of variables
  - Need more detailed investigation
- Some study including full detector simulation exists
  - But not fully covered yet, a lot of work still needed