Physics around the Z-pole at e+e- future colliders

- Introduction
- Impact of high precision observables
- Physics Case for a Z-run with polarized beams
- Conclusions

What is the current status?

* 29.5.1929 † 8.4.2024

- **One Higgs particle discovery on 4.7.2012**
  - strongly consistent with Standard Model (SM) predictions
- **Few excesses around…..(e.g. a light scalar at about 95 GeV)**
  - but not (yet) confirmed discoveries
- **Still strong motivation for Beyond SM (BSM) physics**
  - Dark Matter, Gravitational Waves, Baryon-Asymmetry, etc.
- **However, scale of new physics window still unclear**
  - …..the research field might be in great danger

  ➡Therefore, high precision and/or high energy in specific areas needed and additional tools complementary to (HL)LHC analyses required to identify the promising windows

  LLParticles,2203.05502, Aiko, Endo, 2302.11377

  ➡Z-pole running crucial as telescope to high AND lower energy scales!

➡e+e- collider designs with sane beam polarization crucial!

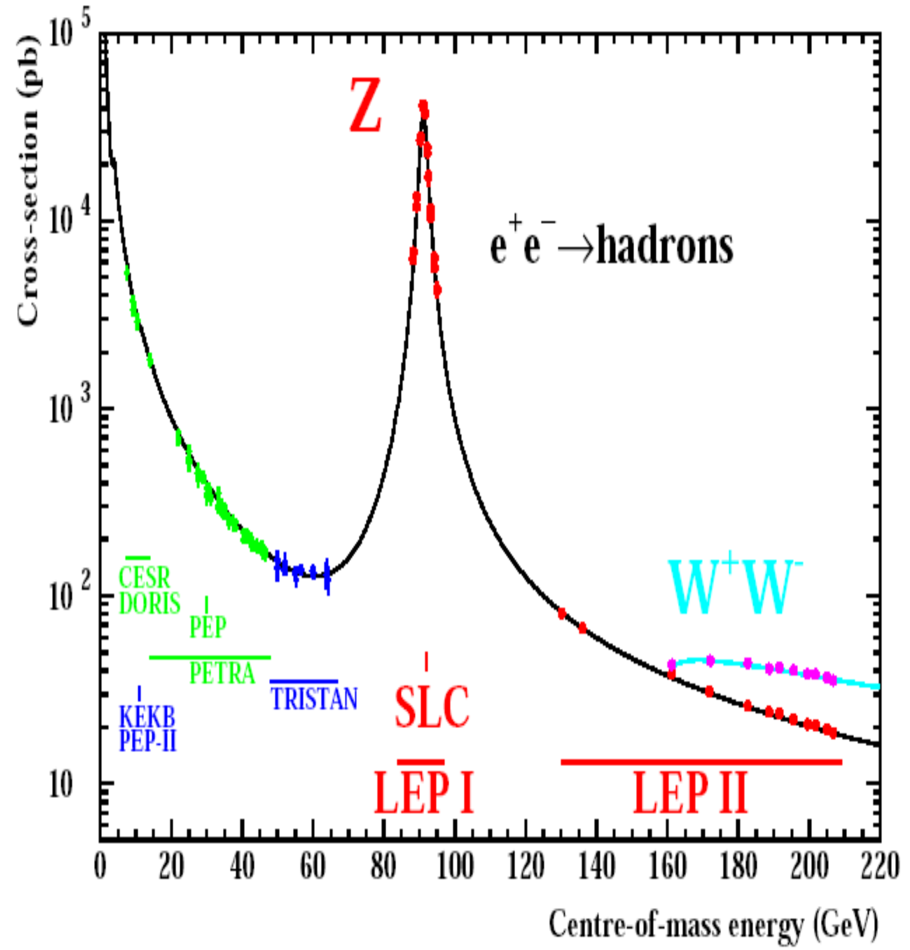
Z-factory: high precision physics at the Z-pole

- Z-boson = carrier of the weak force

- Electroweak theory tested at quantum level via electroweak precision observables

- Clean environment enables also measurements of e.g. α_S

- High sensitivity to effects of new physics

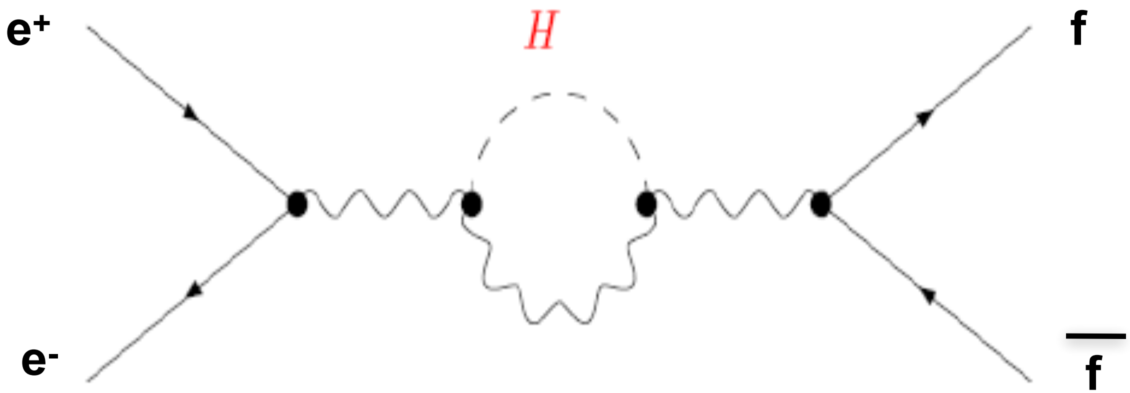


Strong case for new programme of high precision measurements

- Z-run at CEPC
- GigaZ option at the ILC
- dedicated Z-factory

Why a 'new' e^+e^- Z-factory?

- **Electroweak precision physics**



  - **Sensitivity to quantum effects of new physics**
    - **All states contribute, including the ones that are too heavy to be produced directly**
    - **Probing the underlying physics and the properties of new particles**

Electroweak precision observables

- EWPO: α, G_F, M_Z, M_W, Γ_l , $\sin^2\theta_{eff}$, g_μ-2, …
  - One example: precise measurement of
    M_W = 80.377±0.012 GeV
    - *accuracy of 0.2 ‰*
    - *leading to sensitivity to 1- and 2-loop quantum effects …*
- Previous experimental results at the Z-pole:
    - *LEP: very precise measurement of M_Z, Γ_Z, $A_{FB}(l)$, $A_{FB}(b,c)$,…*
    - *SLD: $A_{LR}(e)$, $A_{LR}(\mu)$, …*
- Of particular interest: $\sin^2\theta_{eff} = 1-M_W^2/M_Z^2$ + loop effects
    - *Determined from A_{FB} , A_{LR}*

→ ***High sensitivity to effects of new physics !***

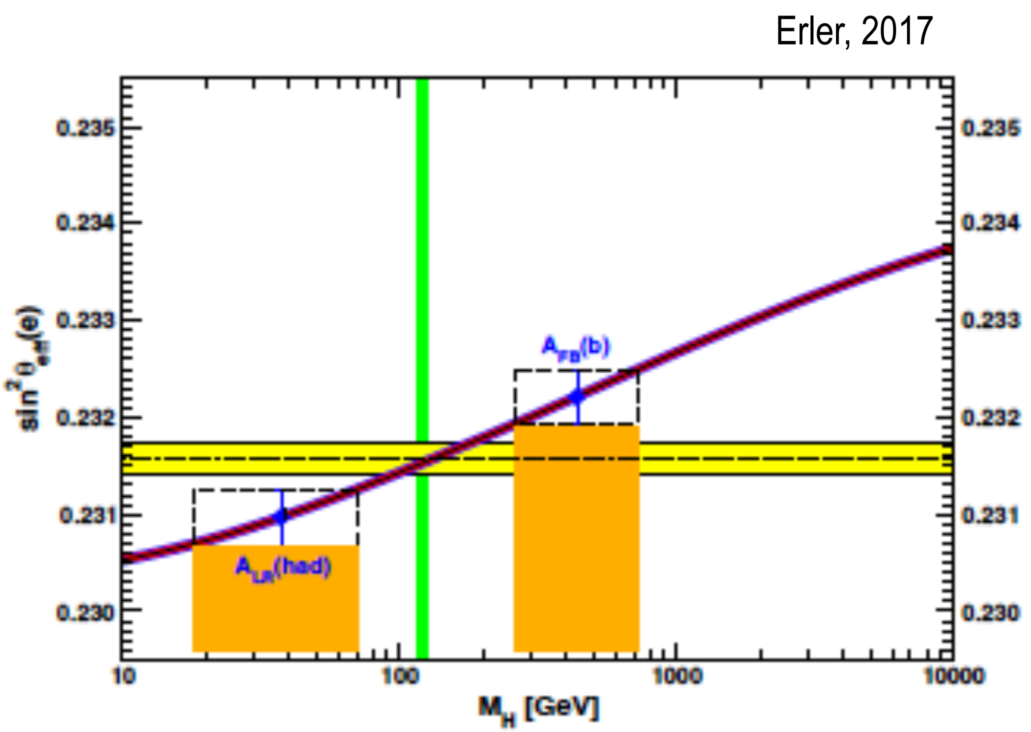
Remember the past: physics gain of polarized beams

- **Past experience:**
  - excellent e- polarization ~78% at SLC:
  - led to best single measurement of $\sin^2\theta = 0.23098 \pm 0.00026$ on basis of $L \sim 10^{30}\ cm^{-2}s^{-1}$ (~600000 Z's)

- **Compare with results from unpolarized beams at LEP:**
  - $\sin^2\theta = 0.23221 \pm 0.00029$ but with $L \sim 2 \times 10^{31} cm^{-2}s^{-1}$ (~ 17 million Z's)

→ polarization can even compensate order of magnitude in luminosity for specific observables!

Experimental situation



LEP:
$\sin^2\theta_{eff}(A_{FB}^b)$= 0.23221±0.00029

SLC:
$\sin^2\theta_{eff}(A_{LR})$= 0.23098±0.00026

Current central values:
$\sin^2\theta_{eff}$ = 0.23105±0.00087 (LHC)
0.23179±0.00035 (Tevatron)

➡ **Discrepancy between the most precise measurements**
Central value has large impact on physics predictions!

courtesy slide S. Heinemeyer

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: $\Gamma(H \to b\bar{b})$
   $\to$ at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $e^+e^- \to ZH$
   $\to$ better than then "pure" experimental precision

Two types of theory uncertainties:

1. intrinsic: missing higher orders

2. parametric: uncertainty due to exp. uncertainty in SM input parameters
   Example: m_t, m_b, α_s, $\Delta\alpha_{\text{had}}$, ...

courtesy slide S. Heinemeyer

2. SM parameter determination

⇒ intrinsic uncertainties ⇒ more details in back-up

1. M_H: better than 20 MeV ⇒ negligible
2. M_Z: ~ 0.1 MeV with negligible theory uncertainties ⇒ negligible
3. $\alpha_s(M_Z)$: from (mainly) R_ℓ
   $\delta\alpha_s^{\text{exp}} \sim 10^{-4}$, $\delta\alpha_s^{\text{theo}} \sim 1.5 \times 10^{-4}$
4. m_t: from threshold scan
   $\delta m_t^{\text{exp/theo}} \lesssim 50$ MeV
5. m_b: from lattice calculations
   $\delta m_b \sim 10$ MeV
6. $\Delta\alpha_{\text{had}}$: BES III and Belle II: $\delta(\Delta\alpha_{\text{had}}) \sim 5 \times 10^{-5}$
   better from measurements "around the Z pole? $\sim 3 \times 10^{-5}$?

2. EWPOs in concrete BSM models

The by far best worked out model: SM

Intrinsic uncertainties:

Quantity	current experimental unc.	current intrinsic unc.
M_W [MeV]	12	4 $(\alpha^3, \alpha^2\alpha_s)$
$\sin^2\theta^{\ell}_{\rm eff}$ $[10^{-5}]$	16	4.5 $(\alpha^3, \alpha^2\alpha_s)$
Γ_Z [MeV]	2.3	0.5 $(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$
R_b $[10^{-5}]$	66	15 $(\alpha^3, \alpha^2\alpha_s)$
R_l $[10^{-3}]$	25	5 $(\alpha^3, \alpha^2\alpha_s)$

Parametric uncertainties:

Quantity	$\delta m_t = 0.9$ GeV	$\delta(\Delta\alpha_{\rm had}) = 10^{-4}$	$\delta M_Z = 2.1$ MeV
$\delta M_W^{\rm para}$ [MeV]	5.5	2	2.5
$\delta\sin^2\theta^{\ell,\rm para}_{\rm eff}$ $[10^{-5}]$	3.0	3.6	1.4

$\Rightarrow$ Current intrinsic/parametric uncertainties are substantially smaller than current experimental uncertainties :-) in the SM!

Improvements with the ILC/FCC-ee/CEPC

Experimental errors of the precision observables:

	today	Tev./LHC	ILC/GigaZ	FCC-ee/TeraZ
$\delta \sin^2\theta_{\text{eff}}(\times 10^5)$	15	15	1.3	0.6
δM_W [MeV]	12	$\lesssim 12$	2-3	0.5
δm_t [GeV]	0.6	$\lesssim 0.5$	0.05	0.05

M_W: from direct reconstruction and threshold scan
(not taken into account here: M_W^{CDF})

$\sin^2\theta_{\text{eff}}$: 1/2 year TeraZ/GigaZ run (GigaZ: polarization important)

α_s : Improvement from GigaZ/TeraZ run

$\Rightarrow$ no theory uncertainties included $\Rightarrow$ visible effect for FCC-ee/TeraZ

Polarization basics

- **Longitudinal polarization:** $\mathcal{P} = \frac{N_R - N_L}{N_R + N_L}$

- **Cross section:**

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = \frac{1}{4}\{(1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\rm RR} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\rm LL} + (1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\rm RL} + (1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\rm LR}\}$$

- **Unpolarized cross section:**

$$\sigma_0 = \frac{1}{4}\{\sigma_{\rm RR} + \sigma_{\rm LL} + \sigma_{\rm RL} + \sigma_{\rm LR}\}$$

- **Left-right asymmetry:**

$$A_{\rm LR} = \frac{(\sigma_{\rm LR} - \sigma_{\rm RL})}{(\sigma_{\rm LR} + \sigma_{\rm RL})}$$

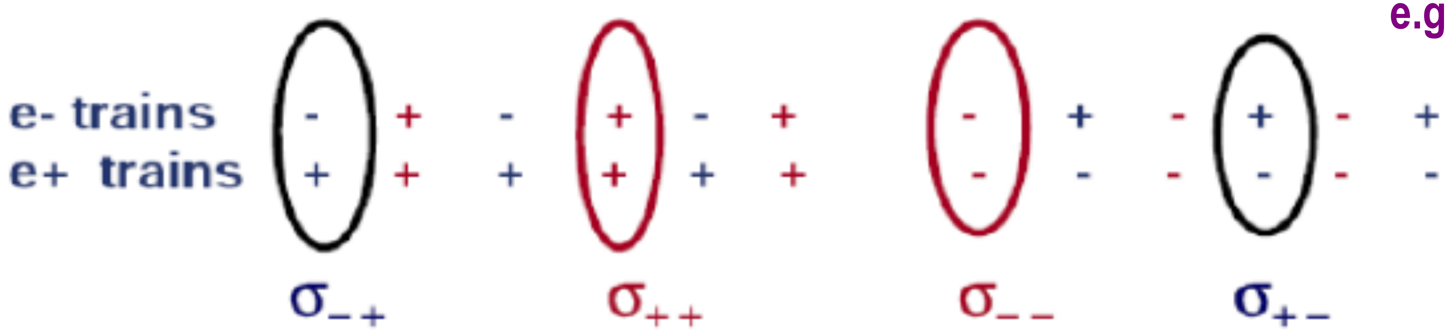
- **Effective polarization and luminosity:**

$$\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_{e^-} - \mathcal{P}_{e^+}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}} \qquad \mathcal{L}_{\rm eff} = \frac{1}{2}(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})\mathcal{L}$$

Why is helicity flipping required?

- **Gain in effective lumi lost if no flipping available**

e.g. S. Riemann



  – 50% spent to 'inefficient' helicity pairing (most SM, BSM)
  – Similar flip frequency for both beams ~ pulse-per-pulse
- **Gain in ΔP_{eff} remains, but flipping required to understand:**
  – Systematics and correlations P_{e-} x P_{e+}
- **Spin rotators needed,….well experienced at HERA, e.g.…!**

Why is helicity flipping required?

- **With both beams polarized we gain in**
  - Higher effective polarization (higher effect of polarization)

$$P_{eff} := (P_{e-} - P_{e+})/(1 - P_{e-}P_{e+})$$

  - Higher effective luminosity (higher fraction of collisions)

$$L_{eff}/L = 1 - P_{e-}\, P_{e+}$$

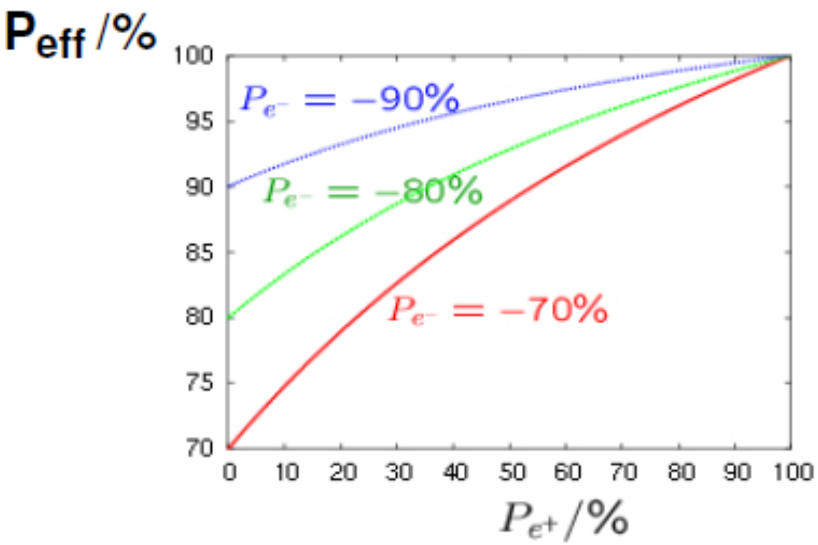
$\sqrt{s}$	$P(e^-)$	$P(e^+)$	P_{eff}	$\mathcal{L}_{eff}/L$	$\frac{1}{x}\Delta P_{eff}/P_{eff}$
total range	∓80%	0%	∓80%	1	1
250 GeV	∓80%	±40%	∓91%	1.3	0.43
≥350 GeV	∓80%	±55%	∓94%	1.4	0.30

- **Applicable for V,A processes, e.g. @Z=pole (most SM, some BSM)**

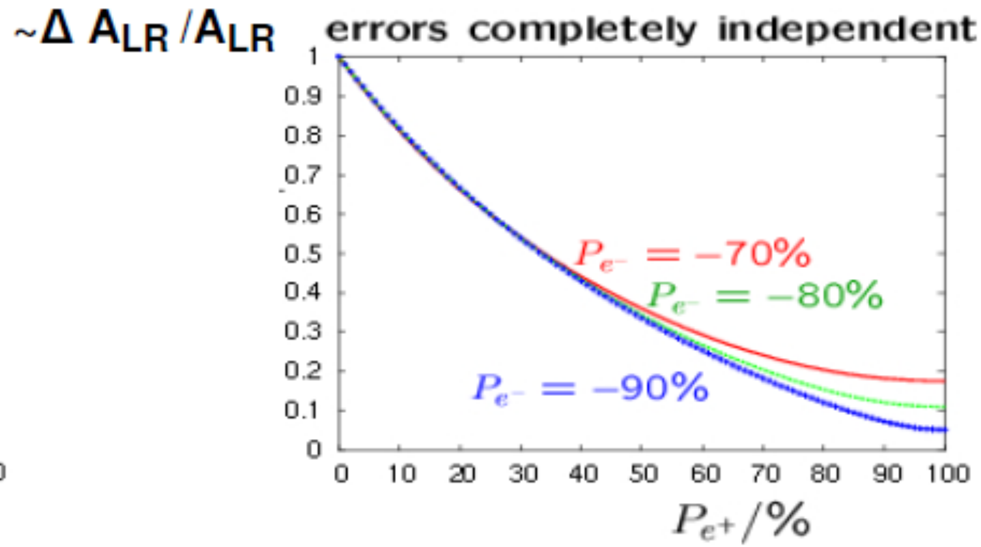
$$\sigma\,(Pe-,Pe+) = (1 - Pe-\; Pe+)\; \sigma_{unpol}\,[1 - P_{eff}\, A_{LR}]$$

Impact of P(e+)

- **Statistics**



- **And gain in precision**



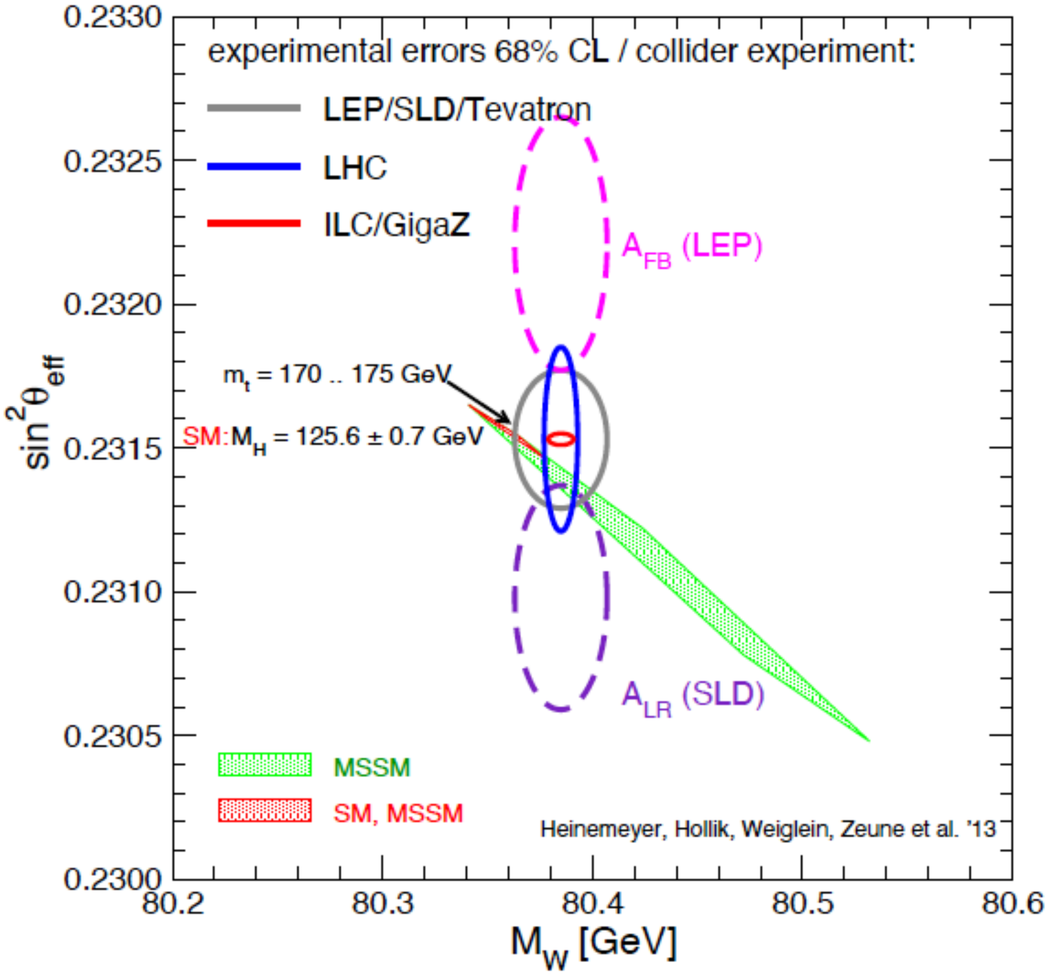
- (80%,60): P_{eff} = 95% (90%,60%): P_{eff} =97% (90%, 30%): P_{eff} =94 %

	(80%,60)	(90%,60%)	(90%, 30%)
	P_{eff} = 95%	P_{eff} =97%	P_{eff} =94 %
	$\Delta A_{LR}/A_{LR}$ = 0.3	$\Delta A_{LR}/A_{LR}$ = 0.27	$\Delta A_{LR}/A_{LR}$ =0.5
gain:	factor~3	factor>3	factor~2

- **NO gain with only pol. e- (even if '100% ') !**

Which precision do we need?

- Supersymmetry as a showcase:



MSSM band:
scan over
SUSY masses

SM band:
variation of M_H^{SM}

Effective leptonic mixing angle

- Experimental uncertainty:

Today: LEP, SLD: $\sin^2\theta_{\text{eff}}^{\text{exp}} = 0.23153 \pm 0.00016$

GigaZ/TeraZ: both beams polarized, Blondel scheme

$$\delta\sin^2\theta_{\text{eff}}^{\text{exp,ILC(CEPC...)}} = 13\,(3)\times 10^{-6} \quad \Leftarrow \text{TU neglected}$$

- Theoretical uncertainty [10^{-6}]:

intrinsic today: $\delta\sin^2\theta_{\text{eff}}^{\text{SM,theo}} = 47 \quad \delta\sin^2\theta_{\text{eff}}^{\text{MSSM,today}} = 50-70$

intrinsic future: $\delta\sin^2\theta_{\text{eff}}^{\text{SM,theo,fut}} = 15 \quad \delta\sin^2\theta_{\text{eff}}^{\text{MSSM,fut}} = 25-35$

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta\sin^2\theta_{\text{eff}}^{\text{para},m_t} = 30, \quad \delta\sin^2\theta_{\text{eff}}^{\text{para},\Delta\alpha_{\text{had}}} = 36, \quad \delta\sin^2\theta_{\text{eff}}^{\text{para},M_Z} = 14$$

parametric future: $\delta m_t^{\text{fut}} = 0.05$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5\times 10^{-5}$, $\delta M_Z^{\text{ILC/CEPC}} = 1/0.1$ MeV

$$\Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},m_t} = 2, \ \Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},\Delta\alpha_{\text{had}}} = 18, \ \Delta\sin^2\theta_{\text{eff}}^{\text{para,fut},M_Z} = 6.5/0.7$$

Short reminder: why are polarized $e^{\pm}$ needed?

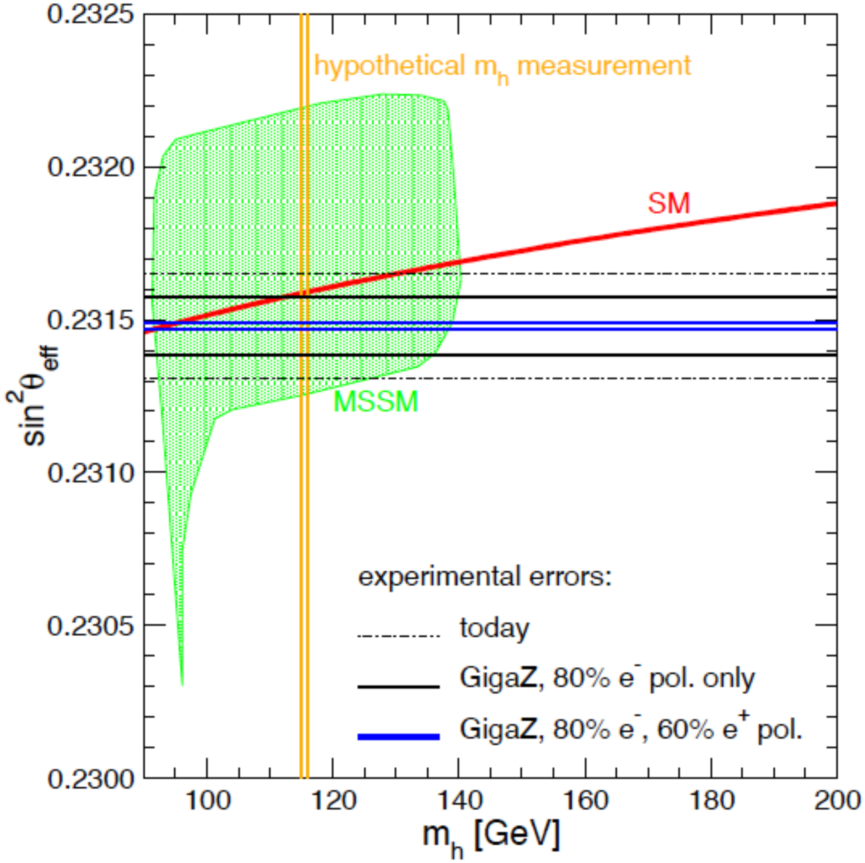
- **Important issue: measuring amount of polarization**
  - **limiting systematic uncertainty for high statistics measurements**
  - **Compton polarimeters (up- /downstream): envisaged uncertainties of ΔP/P=0.25%**
- **Advantage of adding positron polarization:**
  - **Substantial enhancement of eff. luminosity and eff. polarization**
  - **new independent observables**
  - **handling of limiting systematics and access to in-situ measurements: ΔP/P=0.1% achievable!**
  - **Windows to new physics already at low energy!**
- **Physics impact: EWPO, Higgs-Physics, WW/Z/top-Physics, New Physics !**

Literature: polarized e+e- beams at a LC (only a few examples)

- *LCC-Physics Group: 'The role of positron polarization for the initial 250 GeV stage of ILC', arXiv: 1801.02840*
- *G. Moortgat-Pick et al. (~85 authors) : `Pol. positrons and electrons at the LC', Phys. Rept. 460 (2008), hep-ph/0507011*
- *G. Wilson: `Prec. Electroweak measurements at a Future e+e- LC', ICHEP2016, R. Karl, J. List, LCWS2016, 1703.00214*
- *many more (only few examples): 1206.6639, 1306.6352 (ILC TDR), 1504.01726, 1702.05377, 1908.11299,2001.03011, …*
- *G. Moortgat-Pick, H. Steiner, `Physics opportunities with pol. e- and e+ beams at TESLA, Eur.Phys.J direct 3 (2001)*
- *T. Hirose, T. Omori, T. Okugi, J. Urakawa, Pol. e+ source for the LC, JLC, Nucl. Instr. Meth. A455 (2000) 15-24,….*

Polarized e± for $\sin^2\theta_{eff}$

- Precision depends crucially on polarization!

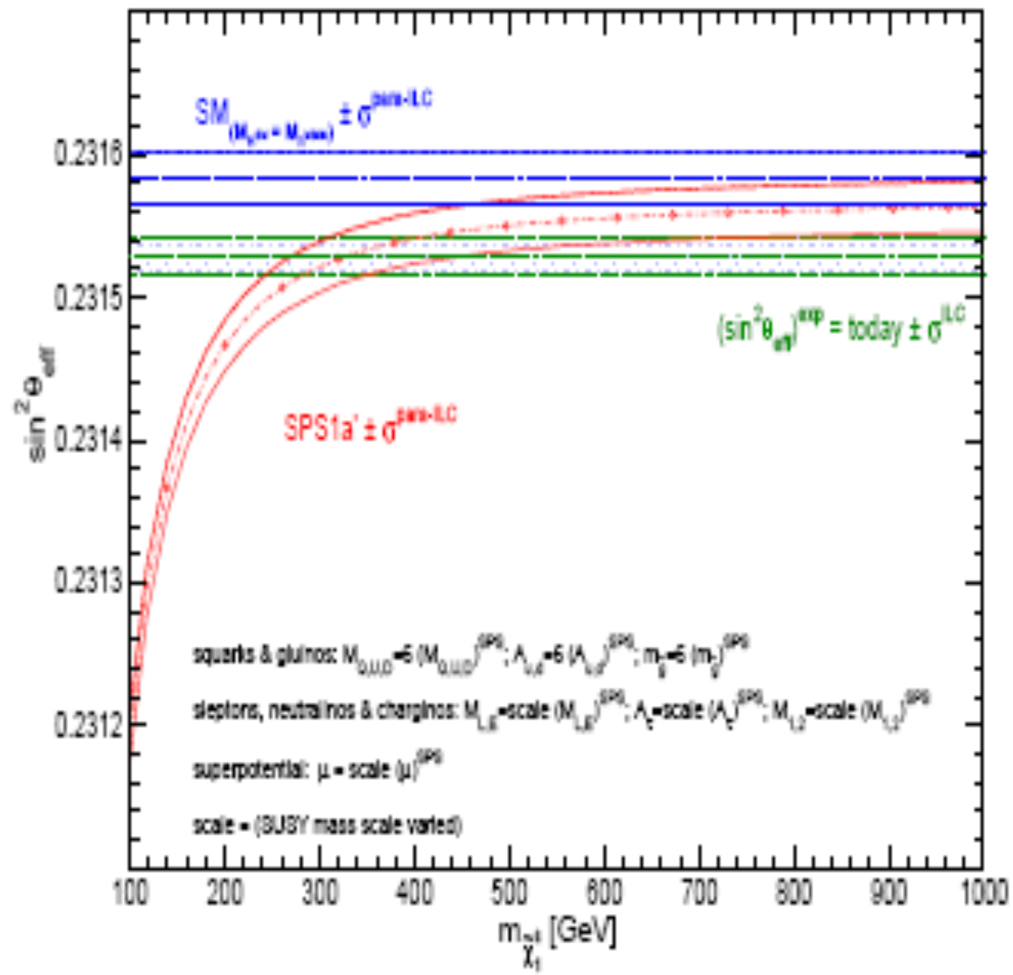


Heinemeyer, Weiglein '05

Help in challenging HL-LHC scenarios ?

- **Assume only Higgs@LHC but no hints for SUSY:**
  - Really SM?
  - Help from $\sin^2\theta_{eff}$?

Heinemeyer, Weber, Weiglein



- **If GigaZ precision:**
  - i.e. Δm_{top}=0.1 GeV…
  - Deviations measurable

- **$\sin^2\theta_{eff}$ can be the crucial quantity !**

➡ **telescope to NP!**

$\sin^2\theta_{eff}$ at the Z-factory

- **Measure both A_{FB} and A_{LR} in same experiment !**

→ **with improved precision w.r.t. LEP and SLC:**
- ALR: large gain from polarization of both beams and higher luminosity
- AFB: gain from higher luminosity, better b-tagging, etc.

→ **resolve unclear situation:**
- New physics affecting AFB(b) and ALR(l) in different ways?
- Resolution of experimental discrepancy:
  reliable central value+ improved precision

→ **large impact also on interpretation of LHC results …**

Which precision should one aim for?

- **Theoretical uncertainties:** $\Delta \sin 2\theta_{eff}^{ho} \sim 5\text{x}10^{-5}$ (currently)

- **Uncertainties from input parameters: Δm_Z, $\Delta\alpha_{had}$, m_{top}**
  - Δm_Z=2.1 MeV: $\Delta \sin^2\theta_{eff}^{para} \sim 1.4\text{x}10^{-5}$
  - $\Delta\alpha_{had} \sim 10$ (5 future) x 10^{-5} : $\Delta \sin^2\theta_{eff}^{para} \sim 3.6$ (1.8 future)$\text{x}10^{-5}$
  - $\Delta m_{top} \sim 1$ GeV (LHC): $\Delta \sin^2\theta_{eff}^{para} \sim 3\text{x}10^{-5}$
  - $\Delta m_{top} \sim 0.1$ GeV (ILC): $\Delta \sin^2\theta_{eff}^{para} \sim 0.3\text{x}10^{-5}$

→ ***If $\Delta \sin^2\theta_{eff} \sim <3\text{x}10^{-5}$ achievable: big physics impact***

What else at the Z-factory? …α_S, Γ_l, R_b

- **α_S is a key parameter in QCD:**

  $\alpha_S = 0.1180(9) \pm 0.0076$ (Particle data 2022)

  - **Big progress via measuring event shapes variables as thrust**
  - **Reduction of uncertainty via higher order calculations and hadronization corrections**
  - **theoretical (SCET) models to reduce non-perturbative uncertainty**

  promising to measure **α_S if >10x lumi_{LEP} and better detectors**

- **Γ_l : uncertainties in leptonic event selection mainly stat. limited**

  e.g. Moenig '01

  - **improvements from higher luminosity ≥10xlumi_{LEP} expected**

- **$R_{b,c,e,\mu,\tau}$, $A_{b,c,e,\mu,\tau}$: systematically limited**

  - **exploitation of beam polarization…**

  ➡ ***Pol@CEP: see talk Zhe Duan***

Further topics for a Z-factory

- **Flavour physics at a Z-factory:**
  - about 40% of Z-decays lead to B-hadrons
  - large boost allows good separation of the 2 B's in clean environment
  - large A_{FB} allows tagging of initial state flavour from event axis only
  - unique studies in B_S to check syst. in $|V_{cb}|$, $|V_{ub}|$
  - unique studies in weak decays in polarized beauty hadrons
- **Rare Z decays**
  - study of lepton flavour violating decays with high luminosity
- **Z' physics**
  - realized in many scenarios of new physics
  - Sensitivity to mixing between Z and Z'

Irles et al., arXiv: 190500220

In many cases detailed studies are still ongoing for a Z-factory…

CEPC Operation Plan and Goals in TDR

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. per year (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

*** Calculated using 3,600 hours per year for data collection.

CEPC-SppC Proposals-J. Gao ICFA Seminar 2023, Nov. 30, 2023, DESY 4

CEPC Operation Plan and Goals in TDR

	E...		SR	Lumi. per IP	Integrated Lumi.	Total	Total no. of
	360	5	30	0.5	0.13	0.65	0.4×10^6

FCC-ee Run Plan

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345–365	1.5	10^6 $t\bar{t}$ events

$\approx \frac{\Delta_{LEP,S}}{500}$

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*** Calculated using 3,600 hours per year for data collection.

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What's the role of polarization?

'Gedankenexperiment' if start with Z-run instead of Higgs@CEPC:

Irles et al., arXiv: 190500220

- **Statistical uncertainty of A_{LR}**
  - If only polarized electrons:

    → ΔA_{LR} depends mainly on polarimeter resolution $\Delta P/P \sim 0.5$-1%
  - If combined with run@250: polarimetry ΔP/P reduced by order of magnitude via WW channel….
  - If both beams are polarized: apply Blondel scheme: $A_{LR} = f(\sigma_{LR}, \sigma_{RL}, \sigma_{LL}, \sigma_{RR})$

    → uncertainty depends on $\Delta\sigma_{LL}$, $\Delta\sigma_{LR}$, $\Delta\sigma_{RL}$, $\Delta\sigma_{RR}$ not on ΔP/P !

    → Some running in LL and RR required: ~10% of time
- **Results comparable with 250 run…….**
  - Z-run could already provide deep insights in lepton universality, fermion properties, etc. if polarized beams are available!

Conclusions

- **A dedicated Z-run@CEPC has a great physics potential**
  - resolve discrepancy between $A_{LR}(l)$ and $A_{FB}(b)$ and improve world av.!
  - significant increase of precision on $\sin^2\theta_{eff}$
  - high sensitivity to effects of new physics (SUSY, Z', etc.)
  - improved measurements of α_S, Γ_l, R_b ,rare Z-decays, B decays,…

***Z-factory measurements could be a* great help for pointing to the nature of any new physics observable at HL-LHC (or elsewhere) !**

- **Technical requirements**
  - polarization (best both beams) and high luminosity are mandatory

→ **Z-run serves as telescope to new physics at high as well as lower energies……**

start a.s.a.p. is of extremely high physics gain!