Physics at future Lepton Colliders

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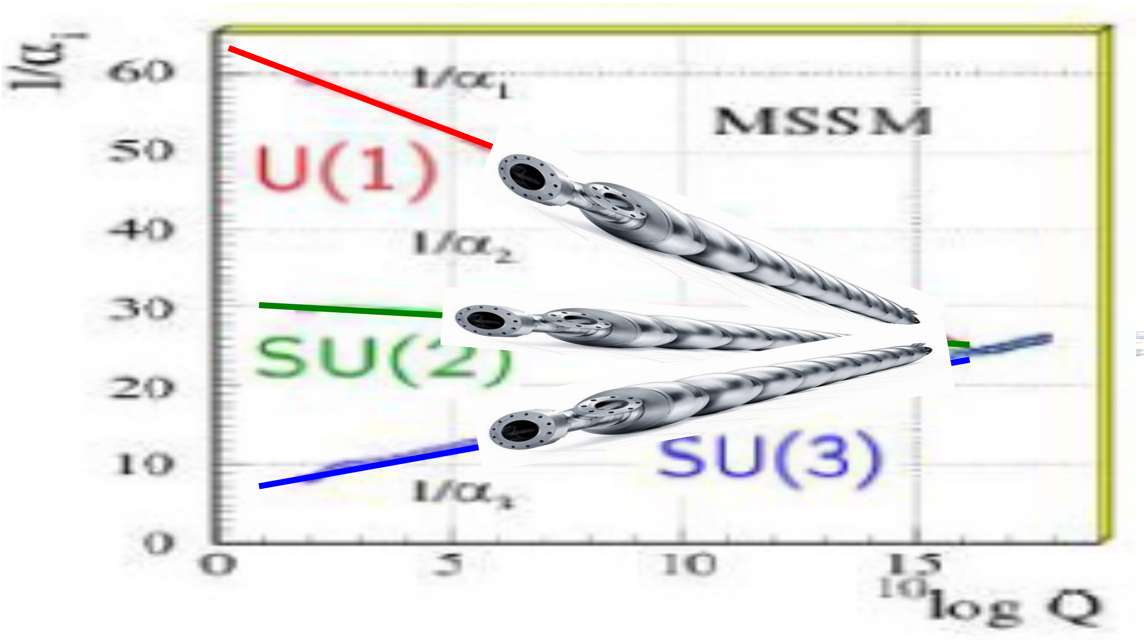


LINEAR COLLIDER COLLABORATION

Lecture 3

What if nothing else than H is found now?

- Since m_H is free parameter in SM at tree level
  - Crucial relations exist, however, between m_{top}, m_W and $\sin^2\theta_{eff}$
  - If nothing else appears in the electroweak sector, these relations have to be urgently checked in order to
    - a) distinguish between SM and Higgs in BSM models (remember $\Delta m_H \sim m^4_{top}$ in BSM!)
    - b) Close the SM picture ?
- Which strategy should one aim?
  - exploit precision observables and check whether the measured values fit together at quantum level
  - m_Z ,m_W,α_{had}, $\sin^2\theta_{eff}$ und m_{top}
- Exploit `GigaZ' option: high lumi run at $\sqrt{s}$ = 91 GeV
  - 10^9 Z in 50-100 days of running

Pe-=80% and Pe+=60% required ! (If only Pe-=90% : precision ~factor 4 less!)

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

- Z-boson = carrier of the weak force

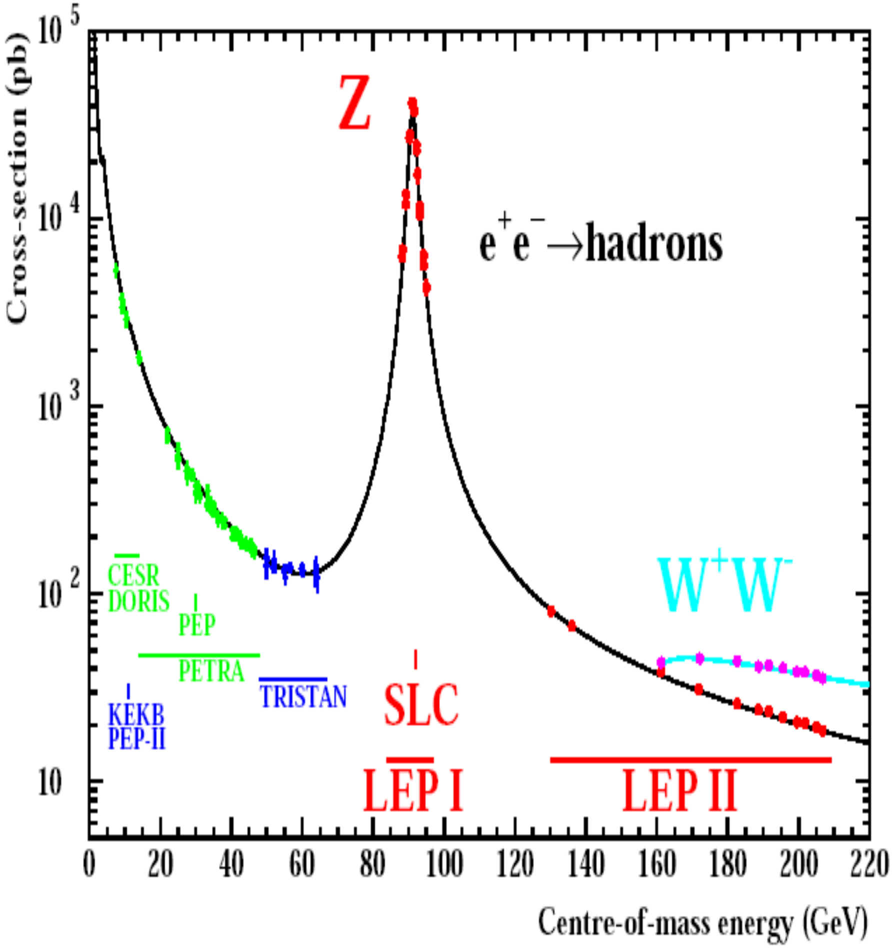
- Electroweak theory tested at quantum level via electroweak precision observables

- 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

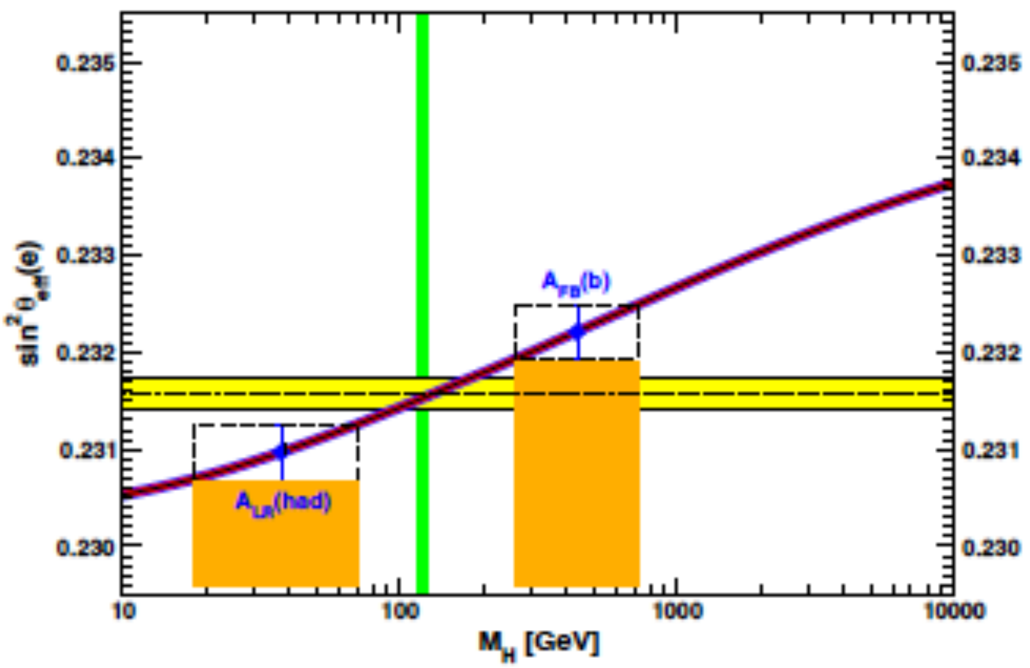
- GigaZ option at the ILC
- dedicated Z-factory
- Z-run at CEPC, FCC-ee



Experimental situation

$\sqrt{s}$=91 GeV

Erler, 2017



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!

$\sin^2\theta_{eff}$ 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:**

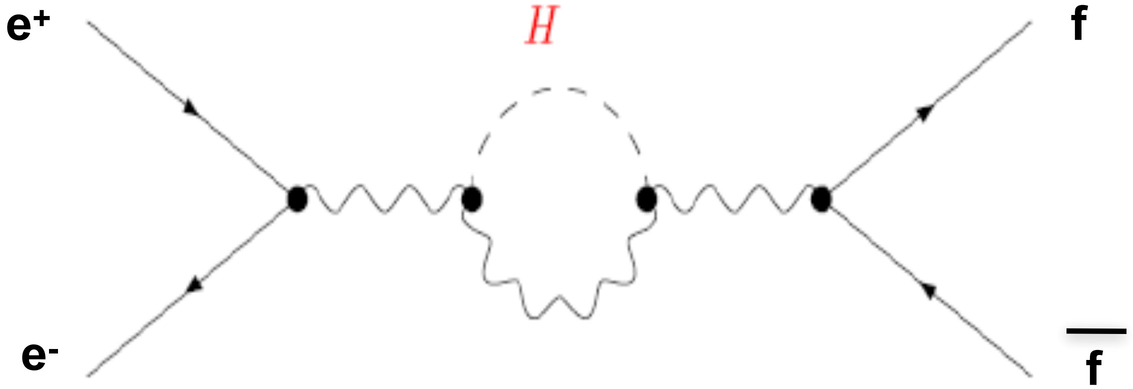
  - New physics affecting AFB(b) and ALR(l) in different ways?
  - Resolution of experimental discrepancy:

    reliable central value+ improved precision

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

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

Impact of high precision observables

Two types of uncertainties

- intrinsic: missing higher order calculations

- parametric: uncertainties due to experimental uncertainties of SM input parameters!

➡ m_t, m_b, m_H, m_Z, m_W, α_s, $\Delta\alpha_{had}$,….

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 !*

courtesy of S. Heinemeyer

2. SM parameter determination

⇒ intrinsic uncertainties

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? $\sim 3 \times 10^{-5}$?

courtesy of S. Heinemeyer

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 $(\alpha^3, \alpha^2\alpha_s)$
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	16	4.7 $(\alpha^3, \alpha^2\alpha_s)$
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	$\delta m_t = 0.3$ GeV	$\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$	$\delta M_Z = 2.1$ MeV
δM_W^{para} [MeV]	5.5	2	2.5
$\delta\sin^2\theta^{\ell,\text{para}}_{\text{eff}}$ $[10^{-5}]$	3.0	3.6	1.4

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

courtesy of S. Heinemeyer

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: $\delta m_t = 0.3$ 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

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

courtesy of S. Heinemeyer

Improvements with the ILC/FCC-ee/CEPC

Experimental errors of the precision observables:

	today	Tev./LHC	ILC/GigaZ	FCC-ee/TeraZ
$\delta \sin^2\theta_{\rm eff} (\times 10^5)$	16	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: $M_W^{\rm CDF}$)

$\sin^2\theta_{\rm eff}$: 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:**

$$\begin{aligned}\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) \;&=\; \frac{1}{4}\{(1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\mathrm{RR}} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\mathrm{LL}} \\ &\quad +(1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\mathrm{RL}} + (1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\mathrm{LR}}\}\end{aligned}$$

- **Unpolarized cross section:**

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

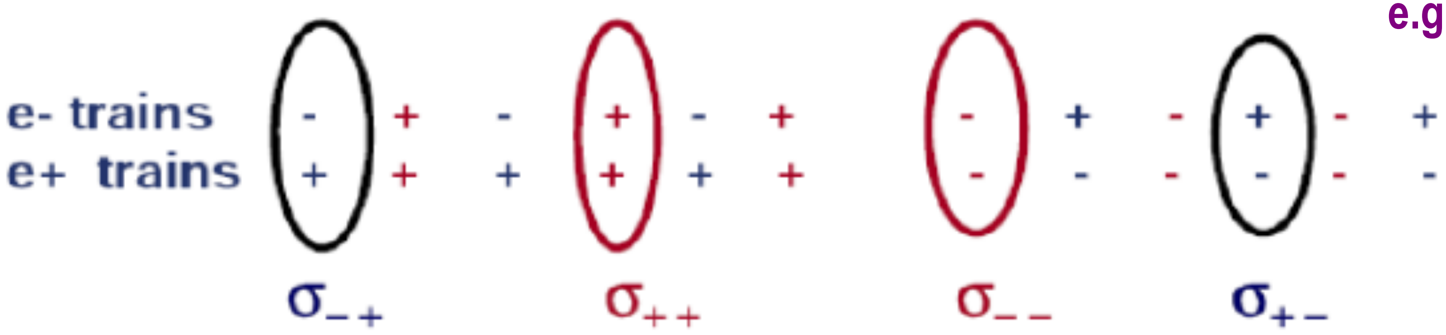
- **Left-right asymmetry:** $A_{\mathrm{LR}} \;=\; \frac{(\sigma_{\mathrm{LR}} - \sigma_{\mathrm{RL}})}{(\sigma_{\mathrm{LR}} + \sigma_{\mathrm{RL}})}$
- **Effective polarization and luminosity:**

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

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.…!

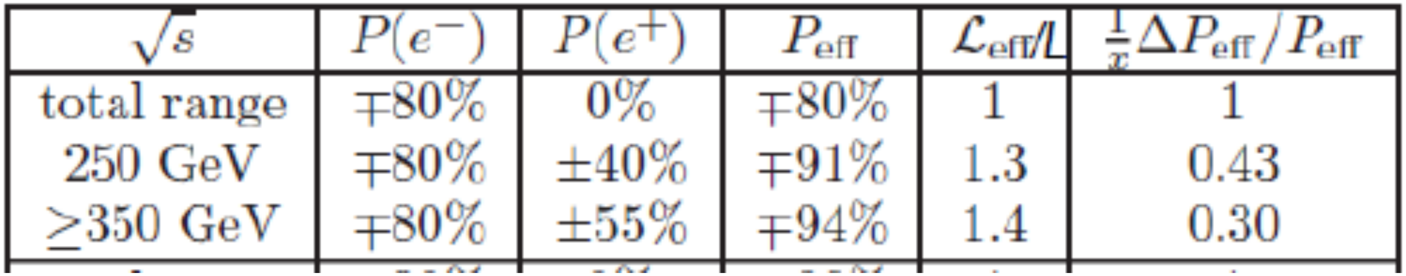
Why is helicity flipping required?

- **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)

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



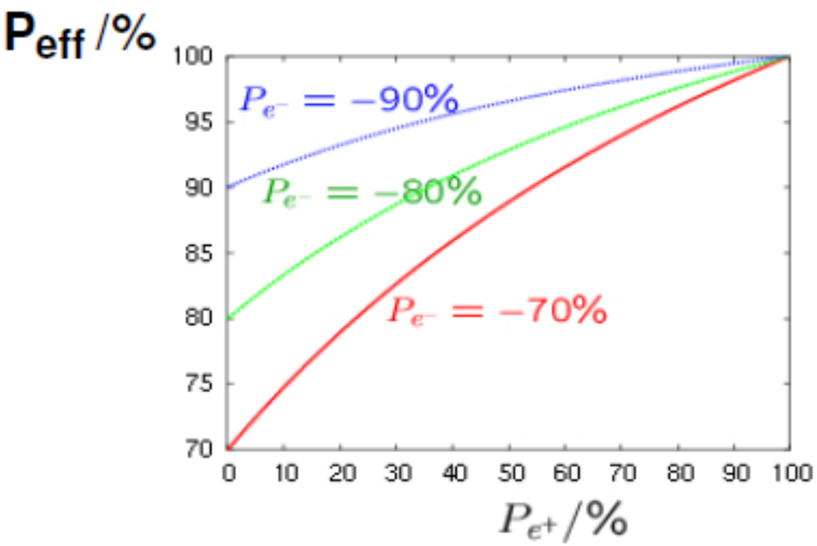
$\sqrt{s}$	$P(e^-)$	$P(e^+)$	$P_{\rm eff}$	$\mathcal{L}_{\rm eff}/\mathcal{L}$	$\frac{1}{x}\Delta P_{\rm eff}/P_{\rm eff}$
total range	∓80%	0%	∓80%	1	1
250 GeV	∓80%	±40%	∓91%	1.3	0.43
≥350 GeV	∓80%	±55%	∓94%	1.4	0.30

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

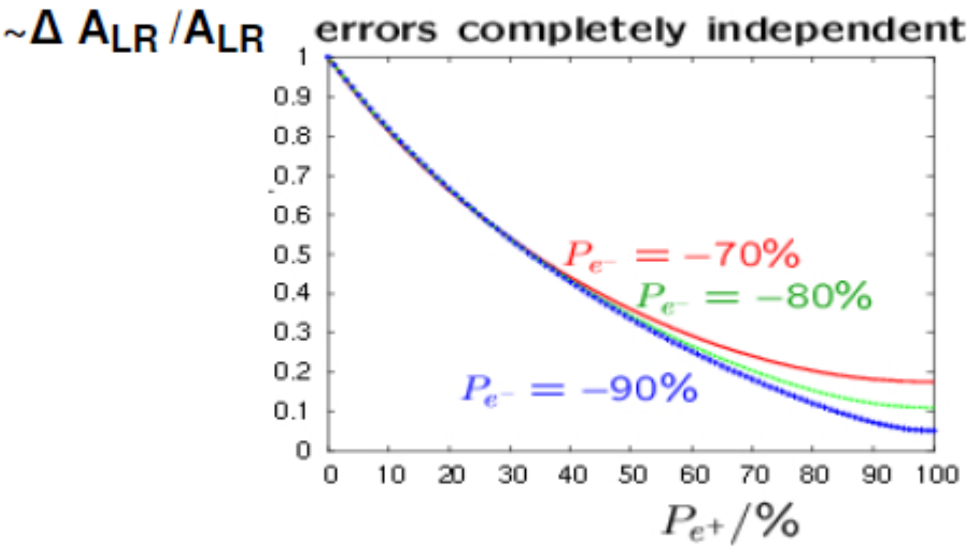
$$\sigma\,(Pe-,Pe+)=(1-Pe-\,Pe+)\,\sigma_{unpol}\,[1-P_{eff}\,A_{LR}]$$

Impact of P(e+)

- **Statistics**



- **And gain in precision**



	(80%,60): P_{eff} = 95%	(90%,60%): P_{eff} =97%	(90%, 30%): P_{eff} =94 %
	$\Delta A_{LR}/A_{LR}$ = 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% ') !

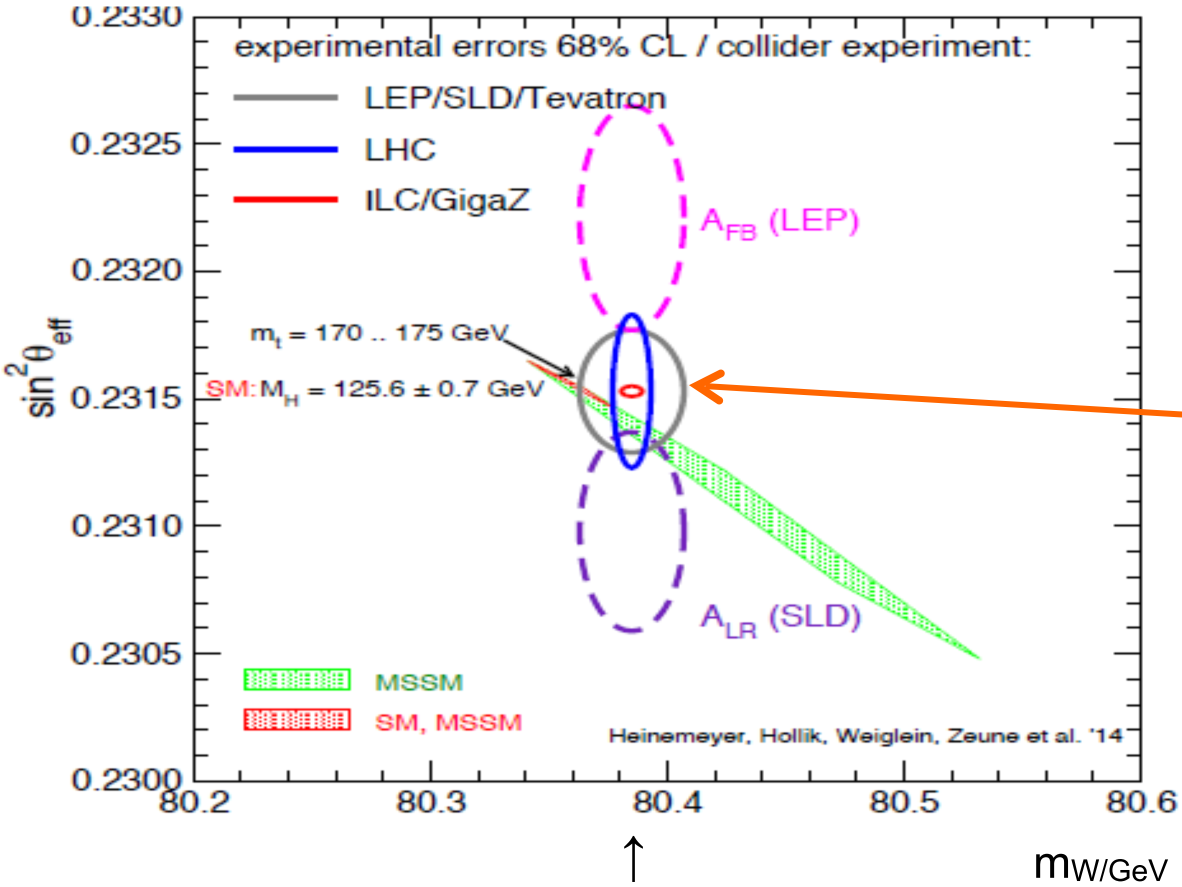
To close the story… GigaZ

$\sqrt{s}=91$ GeV

- **Measure $\sin^2\theta_{\mathrm{eff}}$ via A_{LR} with high precision: $\Delta\sin\theta=1.3\ 10^{-5}$**

World average
→
happy with both!

Central valu has large impact !!!



← *LEP value disfavours both, SM+MSSM*

GigaZ precision!

↑
SLD value disfavours SM

Help in challenging HL-LHC scenarios ?

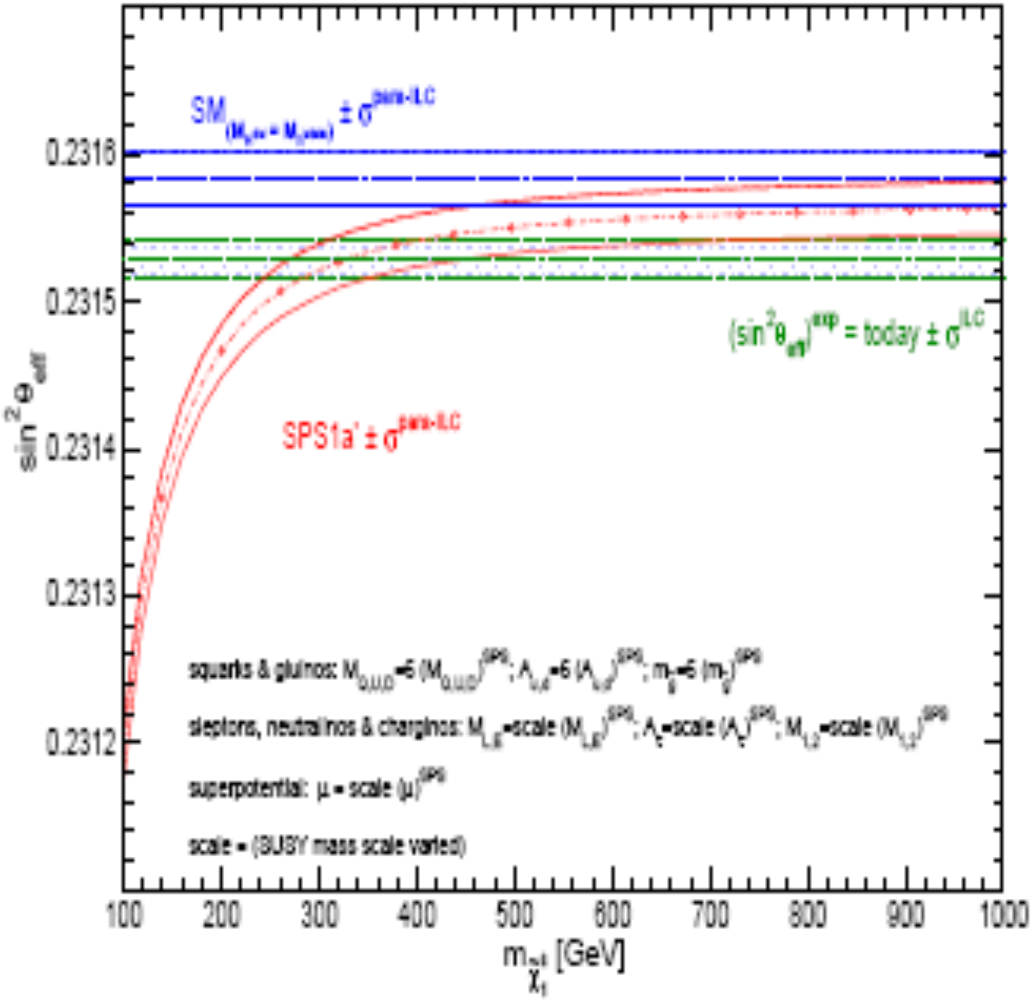
- **Assume only Higgs@LHC but no hints for SUSY:**
  - Really SM?
  - Help from $\sin^2\theta_{eff}$?

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

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

➡ **telescope to NP!**

Heinemeyer, Weber, Weiglein



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…

Further topics for a Z-factory

- **Flavour physics at a Z-factory:**
  - about 15% 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: 1905.00220

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

LC Physics Conclusions

LC offers Physics ‘add-ons’:

- tuneable energy stages, threshold scans, polarized $e^{\pm}$ beams, offers eγ, γγ-option, large flexibility
- Higgs factory at low energy (250 GeV): precise measurement of the h125 couplings to fermions, gauge bosons, HZ cross section, sensitivity to extended Higgs sector
- at higher energy (350,500 GeV): measurement of the width and top Yukawa coupling and trilinear couplings beyond SM
- exploration of the Higgs potential $\longrightarrow$ ‘structure of Universe’
- Precise measurements e.g. of m_t, m_W, $\sin^2\theta_{eff}$, SUSY properties,…
- Access to high precision observables
- GigaZ: telescope to NP even at high scales *(if m_t known precisely…)*

➡ In principle: needed as soon as possible …. !

courtesy of G. Weiglein

e^+e^- Higgs factories

Linear

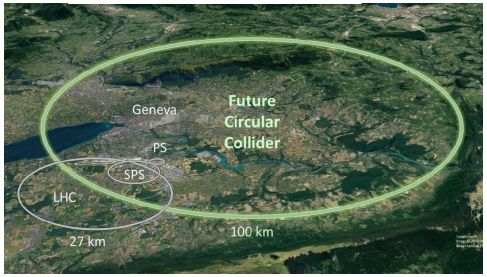
ILC
Japan

International **L**inear **C**ollider

Circular

FCC-ee
CERN

Future **C**ircular **C**ollider

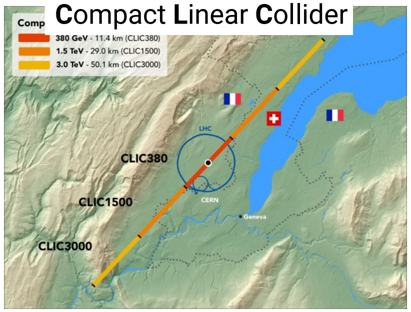


High-level differences:

- Energy reach
- Luminosity

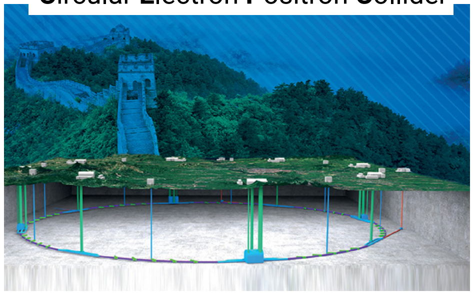
CLIC
CERN

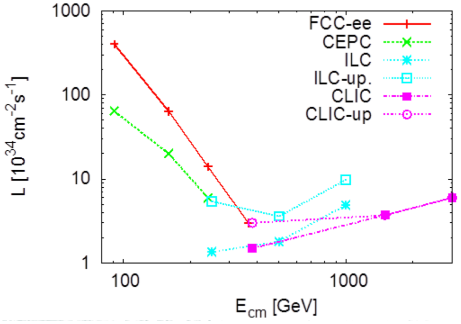
Compact **L**inear **C**ollider



CEPC
China

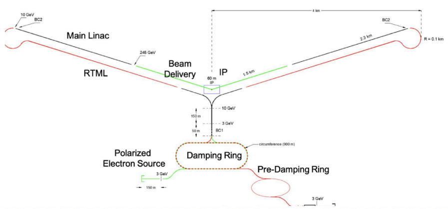
Circular **E**lectron **P**ositron **C**ollider





CCC

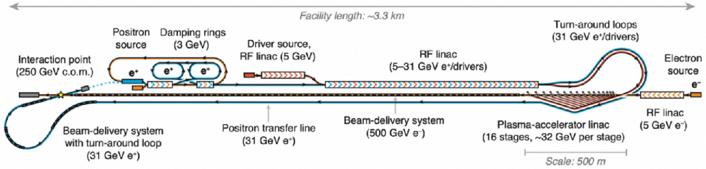
C^3 - 8 km Footprint for 250/550 GeV



- 250 GeV — *ZH* threshold
- 350 GeV — *tt* threshold
- 550 GeV — *HHH* coupling
- ca. 1.5 TeV technology limit

- Based on superconducting RF (liquid nitrogen)
- Proposed at SLAC; very compact machine

HALHF



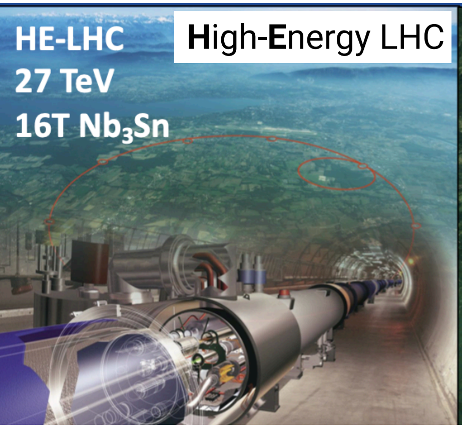
Source: **Foster, D'Arcy & Lindstrøm,** preprint at arXiv:2303.10150 (2023)

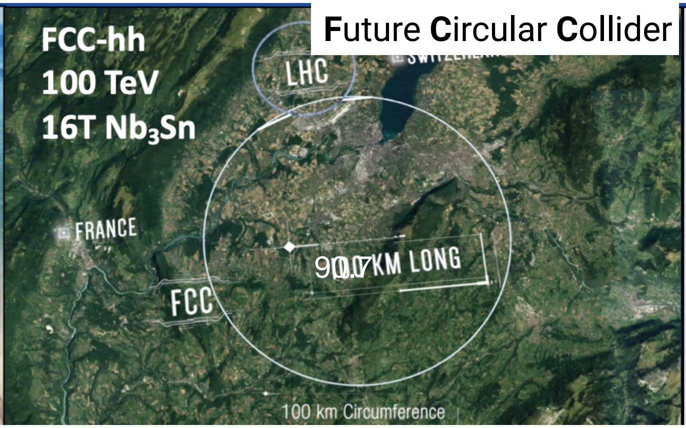
- 250 GeV — *ZH* threshold
- 365 GeV — *tt* threshold
- 10-30 TeV ?? technology limit

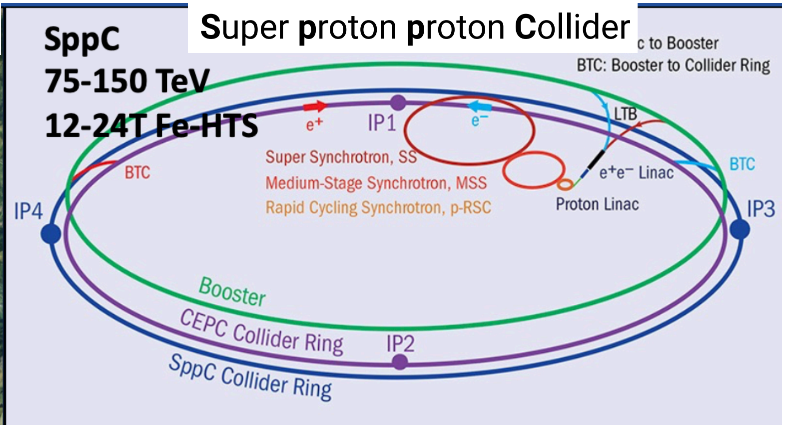
- New idea: e^- plasma acceleration, e^+ conventional LinAc
- ca. 10 years R&D needed to demonstrate feasibility
- Extremely compact: 3-4 km size, suitable for national lab

courtesy of G. Weiglein

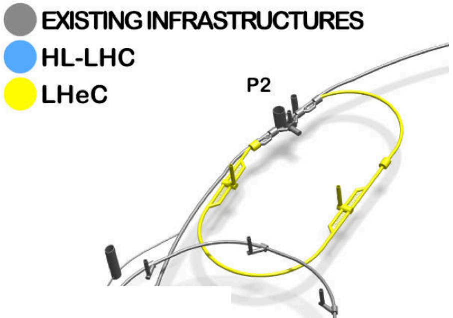
Future hadron colliders

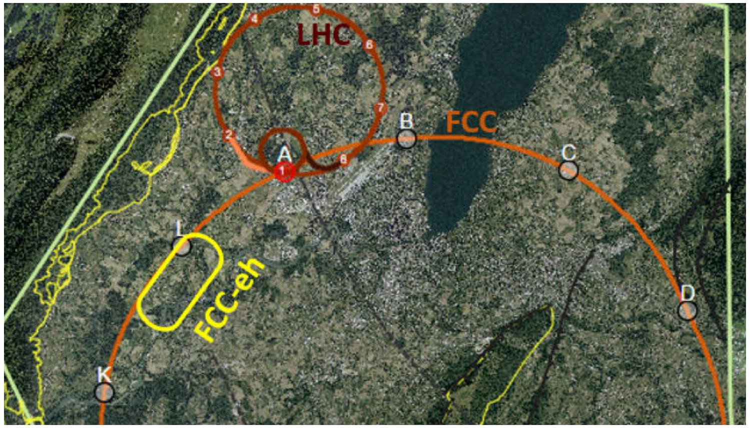


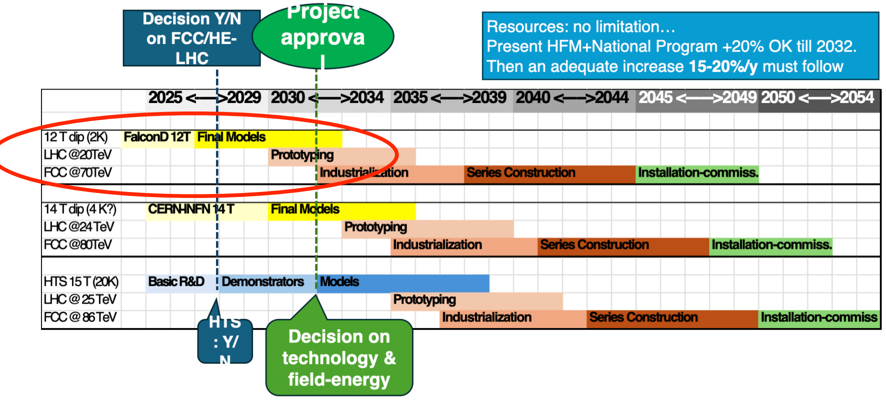




- The main challenge:
  high-field magnets: ~ 16+ T
- Electron-hadron collisions when combined with ERLs: LHeC, FCC-eh at CERN







Resources: no limitation…
Present HFM+National Program +20% OK till 2032.
Then an adequate increase **15-20%/y** must follow

[L. Rossi ’24]

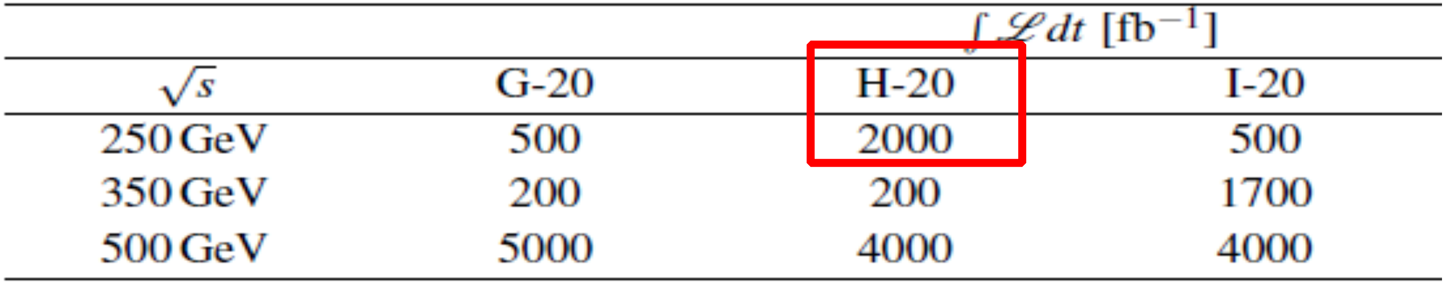
Be prepared for the ‘Unexpected’…

- Great team: LC +LHC are mandatory………!

Lumi scenarios

- Running time based on 20 years physics data, lumi upgrade included after 8 (10) years……..but

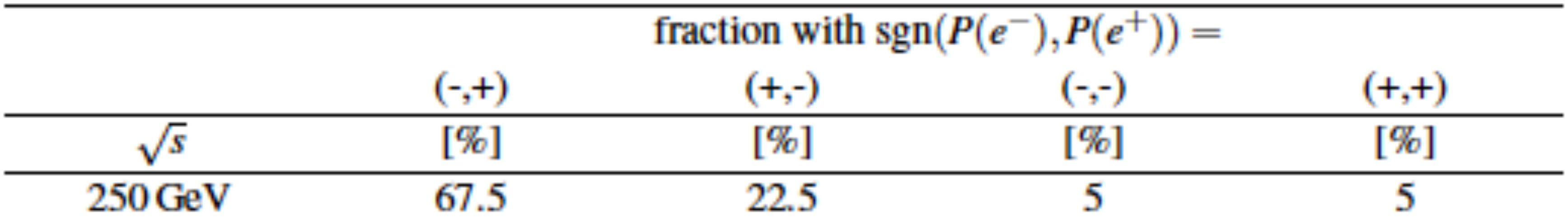
T. Barklow ea,:1506.07830



	$\int \mathscr{L} dt$ [fb^{-1}]		
$\sqrt{s}$	G-20	H-20	I-20
250 GeV	500	2000	500
350 GeV	200	200	1700
500 GeV	5000	4000	4000

- Most popular ‘H-20’: but stick to √s=250 GeV….
- Prospects LHC: 300 fb-1 in 2023

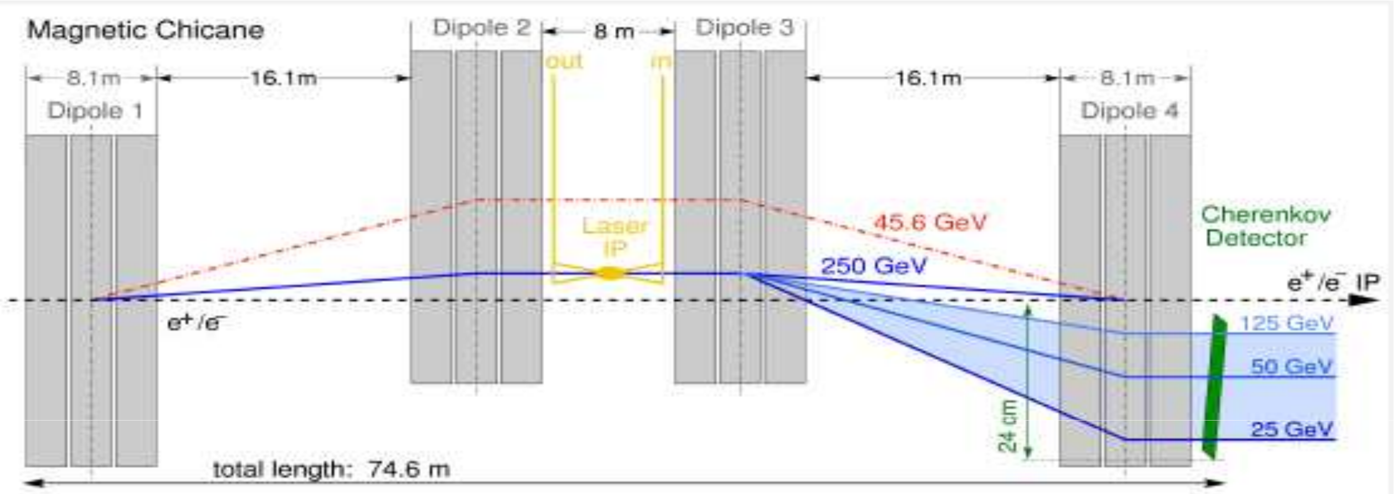
  HL-LHC: 3000 fb-1 in 2037 (start HL-LHC: 2027)
- Request: ‘Physics results improve/complement LHC, HL-LHC results’



	fraction with sgn$(P(e^-),P(e^+))$ =			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV	67.5	22.5	5	5

Compton polarimetry at ILC

- Upstream polarimeter: use chicane system



  - Can measure individual e± bunches
  - Prototype Cherenkov detector tested at ELSA!
- Downstream polarimeter: crossing angle required
  - Lumi-weighted polarization (via w/o collision)
  - Spin-tracking simulations required

Polarimetry requirements

- SLC experience: measured ΔP/P=0.5%
  - Compton scattered e- measured in magnetic spectrometer
- Goal at ILC: measure ΔP/P≤0.25%
  - Dedicated Compton polarimeters and Cherenkov detectors
  - Use upstream and downstream polarimeters
    - ➢ Machine feedback and access to luminosity-weighted polarization

  - Use also annihilation data: \`average polarization’
    - ➢ Longterm absolute calibration scale, up to ΔP/P=0.1%

Free Parameters in the MSSM

- mass matrices are 3 x 3 hermitian

→ m^2_Q , m^2_u , m^2_d , m^2_L , m^2_e : 45 parameters

- gaugino masses M_1, M_2, M_3 are complex numbers: 6
- trilinear couplings a_u, a_d, a_e are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses m^2_{Hu}, m^2_{Hd} : 2

→ altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to'rotations':

-4 non-trivial field redifinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

→ remain 105 free new parameters in the MSSM!