Why are simultaneously-polarized e^- and e^+ beams needed for HEP?

- **Motivation**
- **Polarization basics**
- **Physics cases for polarized beams**
- **Status e+ sources at linear collider**
- **Conclusions**

LINEAR COLLIDER COLLABORATION

What is the current status of HEP?

- One Higgs particle discovered in 2012
  - strongly consistent with Standard Model (SM) predictions
- Few excesses around…..(e.g. a scalars at ~95, 350 GeV)
  - but not (yet) confirmed discoveries
- Still strong motivation for Beyond SM (BSM) physics
  - Higgs Sector: crucial for history of Universe!
  - Dark Matter, Gravitational Waves, Baryon-Asymmetry, etc.
- However, scale of new physics window still unclear
  - …..high precision and/or high energy in specific areas needed and additional tools complementary to (HL)LHC analyses required to identify the promising windows
- Required by HEP
  - stageable, tuneable high cms, precision lepton collider(s) with polarized beams and high lumi mandatory

➡Mature e+e- collider design(s) with sane polarization!

(Reasonable) strategy

Proposal:

- ***build a Linear Collider, upgradeable to HALHF***
- ***'in parallel' to HL-LHC and FCC!***

would cover precision & energy frontier simultaneously and provide new (and more sustainable(?)) technologies !

Immediate (a.s.a.p.!) need for e+e- collider for

- ***Higgs sector high precision measurements***
- ***Top quark high precision measurements***
- ***Electroweak high precision measurements***
- ***Opening new windows to BSM physics, CP-violating effects,…***

➡√s=Z-pole, WW,250, 350, ≥500 GeV with polarized beams

Remember the past: physics gain of polarized beams

- **Past experience:**
  - **excellent e- polarization ~78% at SLC:**
  - **led to best single measurement of $\sin^2\theta=0.23098\pm0.00026$ on basis of $L\sim10^{30}$ cm^{-2}s^{-1} (~600000 Z's)**

- **Compare with results from unpolarized beams at LEP:**
  - **$\sin^2\theta=0.23221\pm0.00029$ but with $L\sim2\times10^{31}$cm^{-2}s^{-1} (~ 17 million Z's)**

➡ **Polarization essential for suppression of systematics**

➡ **can even compensate order of magnitude in luminosity for specific observables!**

➡ ***Polarized e- sources well under control, why also polarized e+ required.....?***

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:**

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

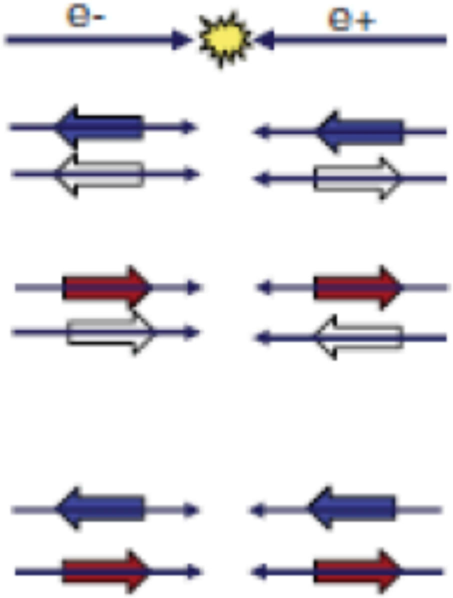
Statistical arguments

- Effective polarization

$$P_{eff} := (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$$
$$= (\#LR - \#RL)/(\#LR + \#RL)$$

- Fraction of colliding particles

$$\mathcal{L}_{eff}/\mathcal{L} := \tfrac{1}{2}(1 - P_{e^-}P_{e^+}) = (\#LR + \#RL)/(\#all)$$



P_{e^-}	P_{e^+}	h_{e^-}	h_{e^+}	cross section
-1	0	-1	+1	σ_{LR}
		-1	-1	$\sigma_{LL} \rightarrow 0$
+1	0	+1	-1	σ_{RL}
		+1	+1	$\sigma_{RR} \rightarrow 0$
-1	+1	-1	+1	σ_{LR}
+1	-1	+1	+1	σ_{RL}

½ of events do not react !

⇒ Enhancing of $\mathcal{L}_{eff}$ with $P(e^-)$ and $P(e^+)$!

Short reminder: why 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!**
  - ***allows exploitation of transversely-polarized beams!*** *see talk G. Weiglein*
- **Physics impact: Higgs-Physics, WW/Z/top-Physics, New Physics !**

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

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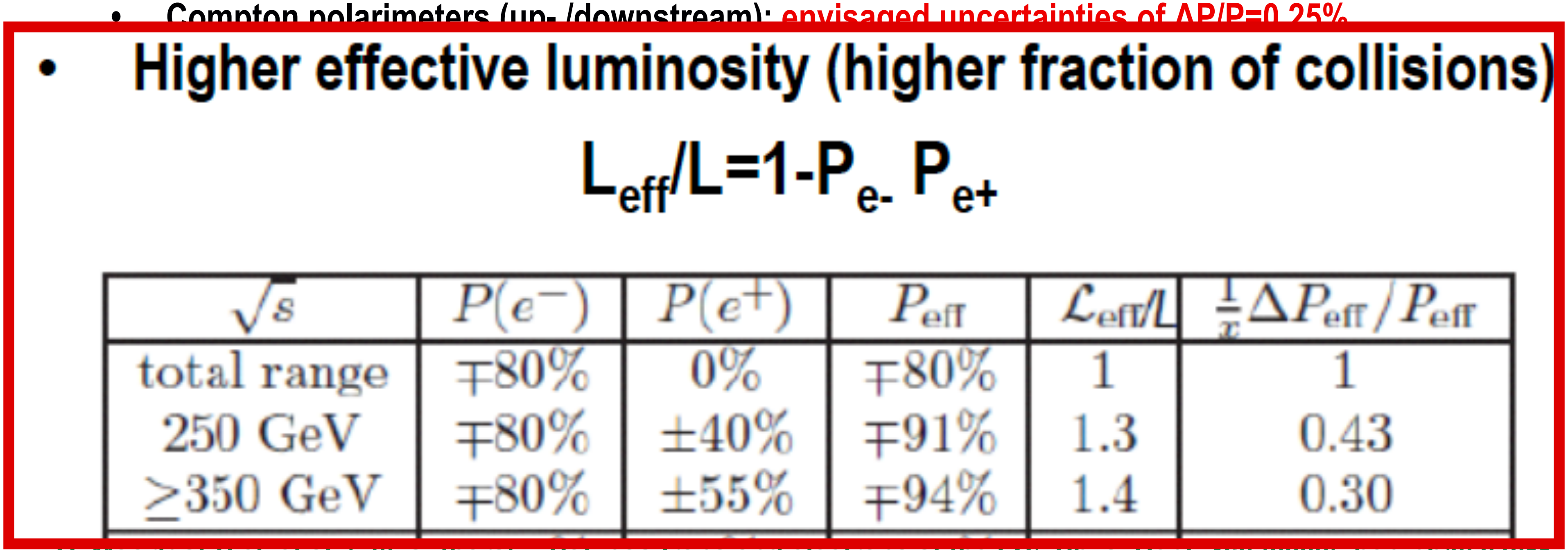

- **Higher effective luminosity (higher fraction of collisions)**

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

$\sqrt{s}$	$P(e^-)$	$P(e^+)$	$P_{\rm eff}$	$\mathcal{L}_{\rm eff}/L$	$\frac{1}{x}\Delta P_{\rm eff}/P_{\rm eff}$
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

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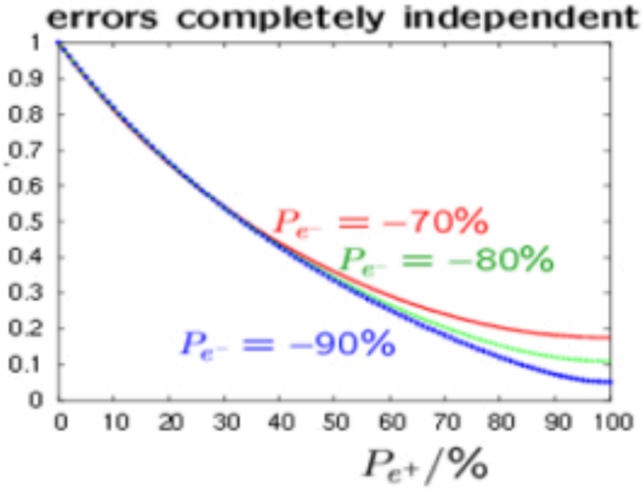
- **Higher precision and better control of systematics**
  - ➡ $\Delta A_{LR}/A_{LR} \sim \Delta P_{eff}/P_{eff}$
  - ➡ (90%,60%): P_{eff}=97%

    $\Delta A_{LR}/A_{LR}$ =0.27 ‘gain factor ~3’
  - ➡ (90%,30%): P_{eff}=94%

    $\Delta A_{LR}/A_{LR}$ =0.5 ‘gain factor ~2’



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Transversely polarized beams

Transversely polarized beams

→ enables to exploit azimuthal asymmetries in fermion production !

- the process $e^+e^- \to W^+W^-$:

  $\Rightarrow$ azimuthal asymmetry projects out $W_L^+W_L^-$ *e.g. Fleischer et al,*

- the process e+e- ⟶ tt:

  ➡ probe leptoquark models *e.g. Rindani, Poulose, et al.*

- the process e+e- ⟶ ff:

  ➡ probe extra dimensions *e.g. Hewett, Rizzo et al.*

- the construction of CP violating oservables:

  $\Rightarrow$ matrix elements $|M|^2 \sim \mathcal{C}\times\Delta(\alpha)\Delta^*(\beta)\times\mathcal{S}$($\mathcal{C}$=coupl., Δ=prop., $\mathcal{S}$=momenta)

  if CP violation: contributions of $Im(\mathcal{C})\times Im(\mathcal{S})$(e.g. contributions of ϵ tensors!)

  $\Rightarrow$ azimuthal dependence ('not only in scattering plane')

  $\Rightarrow$ observables are e.g. asymmetries of CP-odd quantities: $\vec{p}_a(\vec{p}_b\times\vec{p}_c)$

  $\vec{s}^{2\mu} := \vec{p}_1 \times \vec{p}_3$ perpendicular scattering plane, CP even

  $\vec{s}^{1\mu} := \vec{p}_1 \times \vec{s}^2(p_1)$ transverse in plane, CP odd

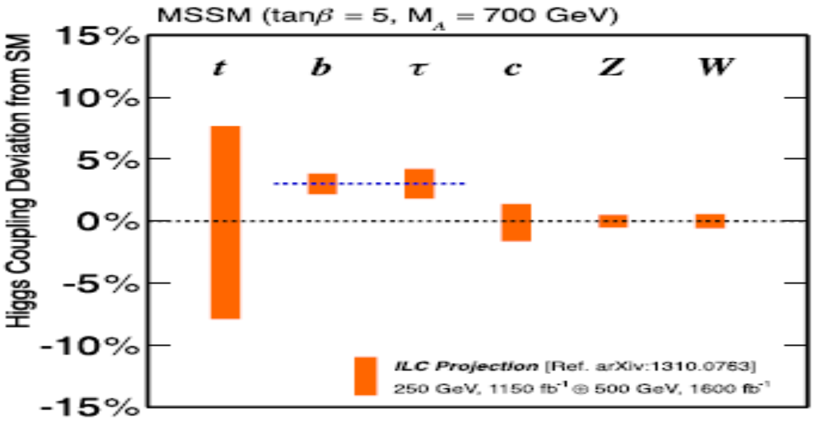
e.g. Cheng Li et al.

Expected deviation in Higgs measurements

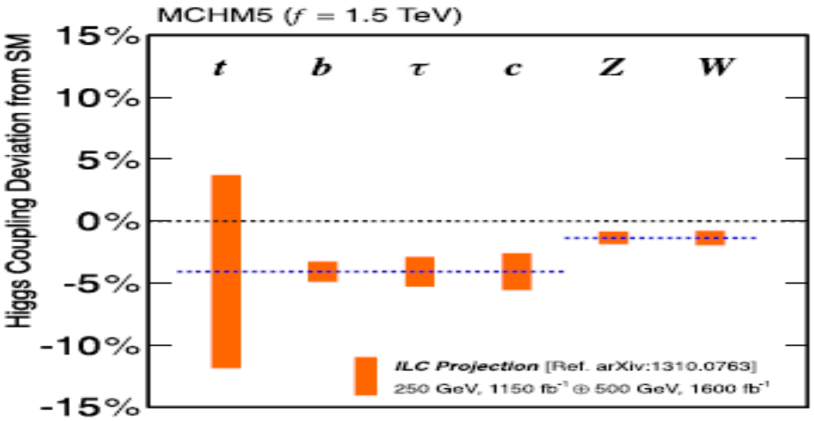
- **Higgs couplings achievable at LHC:**
  - Could be the only SM Higgs (what's about DM? gauge unification?)
  - Could be a SUSY Higgs (one has to be close to a SM-like one)
  - Could be a composite state

S. Komamiya,

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)

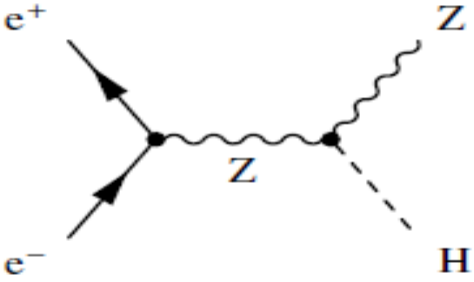


ILC 250+500 LumiUp

- *Determination of Higgs couplings in 1% level essential for ILC250!*

Process: Higgs Strahlung

$\sqrt{s}$=250 GeV



- $\sqrt{s}$=250 GeV: dominant process
- Why crucial?
  - allows model-independent access!
  - Absolute measurement of Higgs cross section σ(HZ) and g_{HZZ}:

    crucial input for all further Higgs measurement!

  - Allows access to H-> invisible/exotic
  - Allows with measurement of Γ^h_{tot} absolute measurement of BRs!
  - If no P(e+): 20% longer running time!…..*~few years and less precision!*

courtesy of G. Weiglein

CP properties of h125

$\mathcal{CP}$ properties: more difficult than spin, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1,q_2)g^{\mu\nu} + a_2(q_1,q_2)\left[(q_1 q_2)\,g^{\mu\nu} - q_1^\mu q_2^\nu\right] + a_3(q_1,q_2)\epsilon^{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}$$

SM, pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

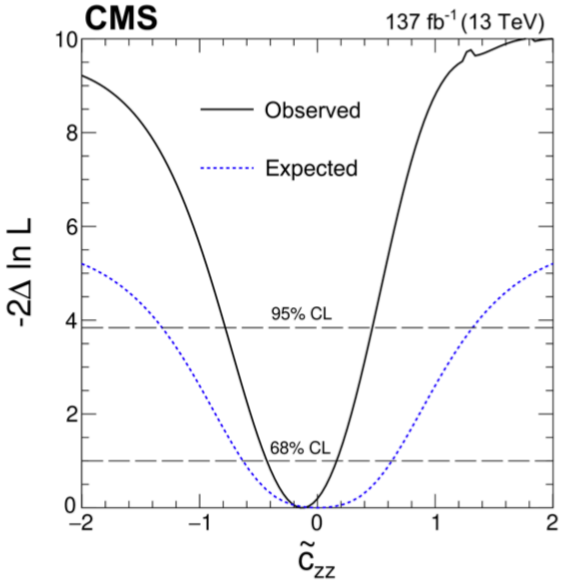
However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP in Higgs-Gauge-boson couplings

$$\mathcal{L}_{\mathrm{EFF}} = c_{\mathrm{SM}}\, Z_\mu Z^\mu H - \frac{c_{HZZ}}{v} Z_{\mu\nu} Z^{\mu\nu} H - \frac{\tilde{c}_{HZZ}}{v} Z_{\mu\nu} \tilde{Z}^{\mu\nu} H$$

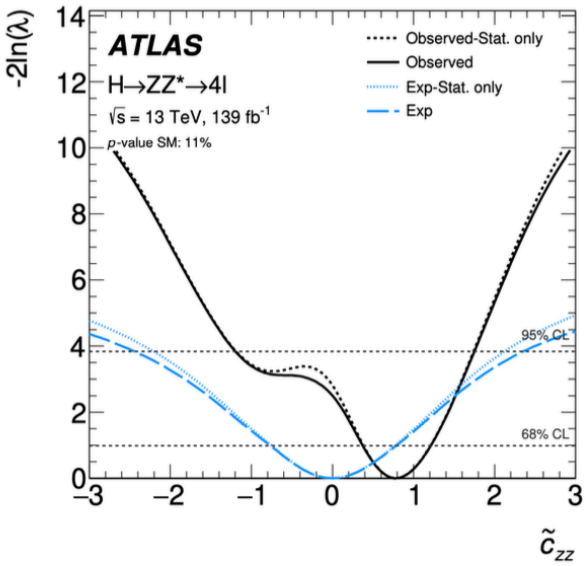
At LHC: H → 4 l measurement:

[*CERN-EP-2021-054*]



$$(\tilde{c}_{ZZ})_{\mathrm{CMS}} \sim [-0.66, 0.51]$$

[*CERN-EP-2023-030*]

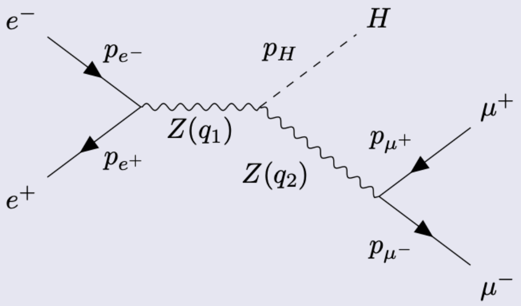


$$(\tilde{c}_{ZZ})_{\mathrm{ATLAS}} \sim [-1.2, 1.75]$$

Probing CP at the e+e- collider

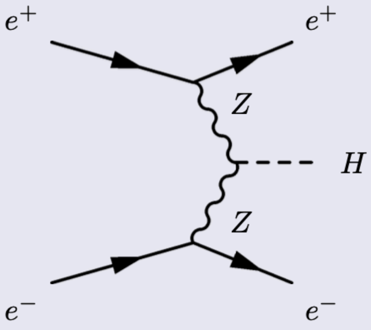
- CP probes of HZZ via Z-decay from HZ or Z fusion

Higgs Strahlung



- Unpolarised study at CEPC [*Q. Sha et al.* 22']
- The spin information of the initial transversely polarised electrons is carried by the Z boson and transferred to the $\mu^+\mu^-$ pair by the Z decay

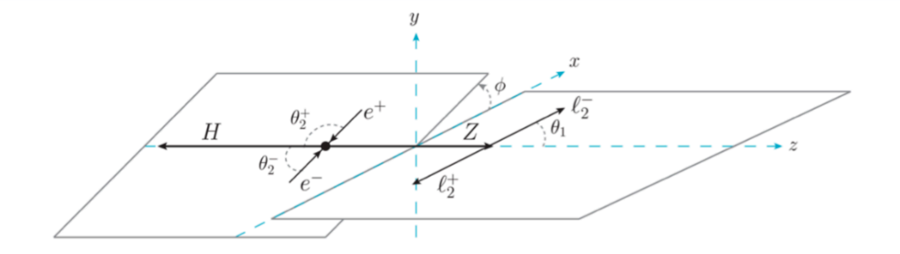
Z fusion



- Z-fusion study at 1 TeV [*I. Bozovic et al.* 24']
- Z-fusion process **cannot** carry the spin information of initial transversely polarised beams, since the final state electron and positron are unpolarised

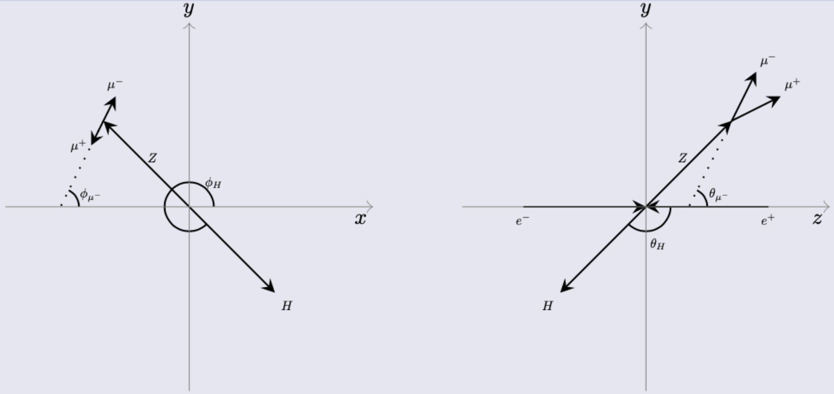
CP-sensitive observables

Coordinate systems with unpolarised or longitudinal polarised beams



- The ϕ is the azimuthal angle difference between the μ^--μ^+ plane and the Z-H plane

Coordinate systems with transversely polarised beams ($\vec{n}_y \propto \vec{s}_{e^-}$, $\vec{n}_x \propto \vec{s}_{e^-} \times \vec{p}_{e^-}$, $\vec{n}_z \propto \vec{p}_{e^-}$)



- The ϕ_{μ^-} is the azimuthal angle of the μ^--μ^+ plane with fixing the y-axis orientation to $\vec{s}_{e^-}$

Comparison of both methods

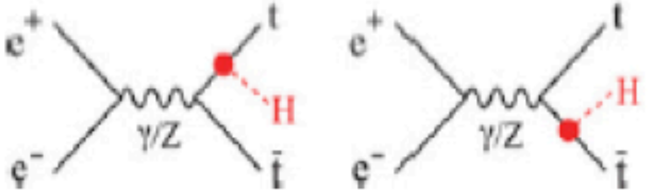
	95% C.L. (2σ)limit						
Experiments	ATLAS	CMS	HL-LHC	CEPC	CLIC	CLIC	ILC
Processes	$H \to 4\ell$	$H \to 4\ell$	$H \to 4\ell$	HZ	W-fusion	Z-fusion	$HZ,\ Z \to \mu^+\mu^-$
$\sqrt{s}$ [GeV]	13000	13000	14000	240	3000	1000	250
Luminosity [fb^{-1}]	139	137	3000	5600	5000	8000	5000
$(\lvert P_-\rvert, \lvert P_+\rvert)$							$(90\%, 40\%)$
$\widetilde{c}_{HZZ}$ $(\times 10^{-2})$	[-16.4, 24.0]	[-9.0, 7.0]	[-9.1, 9.1]	[-1.6, 1.6]	[-3.3, 3.3]	[-1.1, 1.1]	[-1.1, 1.0]
$f_{CP}^{HZZ}(\times 10^{-5})$	[-409.82, 873.58]	[-123.78, 74.91]	[-126.54, 126.54]	[-3.92, 3.92]	[-16.66, 16.66]	[-1.85, 1.85]	[-1.85, 1.53]
$\tilde{c}_{ZZ}$	[-1.2, 1.75]	[-0.66, 0.51]	[-0.66, 0.66]	[-0.12, 0.12]	[-0.24, 0.24]	[-0.08, 0.08]	[-0.08, 0.07]

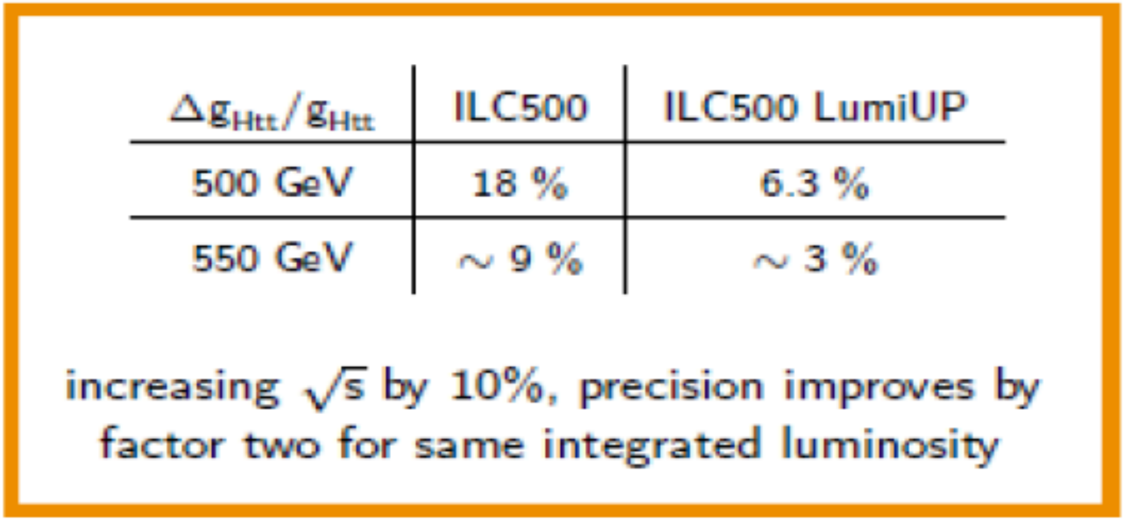
- The e^+e^- colliders can significantly improve the sensitivity to CP-odd HZZ coupling compared to the LHC or HL-LHC.
- The sensitivity with polarised beams is better than the analysis with unpolarised beams, where the center-of-mass energy and luminosity are similar.
- The Z-fusion process can have similar sensitivity but with much higher center-of-mass energy.

Top Yukawa Coupling

- **top-Yukawa coupling crucial:**
  - since strongest coupling to Higgs sector
  - g_{ttH} offers new surprises, needs model-independent measurement

see, e.g. C. Duerig, EPS'15





$\Delta g_{Htt}/g_{Htt}$	ILC500	ILC500 LumiUP
500 GeV	18 %	6.3 %
550 GeV	∼ 9 %	∼ 3 %

increasing $\sqrt{s}$ by 10%, precision improves by factor two for same integrated luminosity

  - Numbers very ambitous
  - Used so far: (±80,-+30)
  - Further improvement with (+-80,-+60):

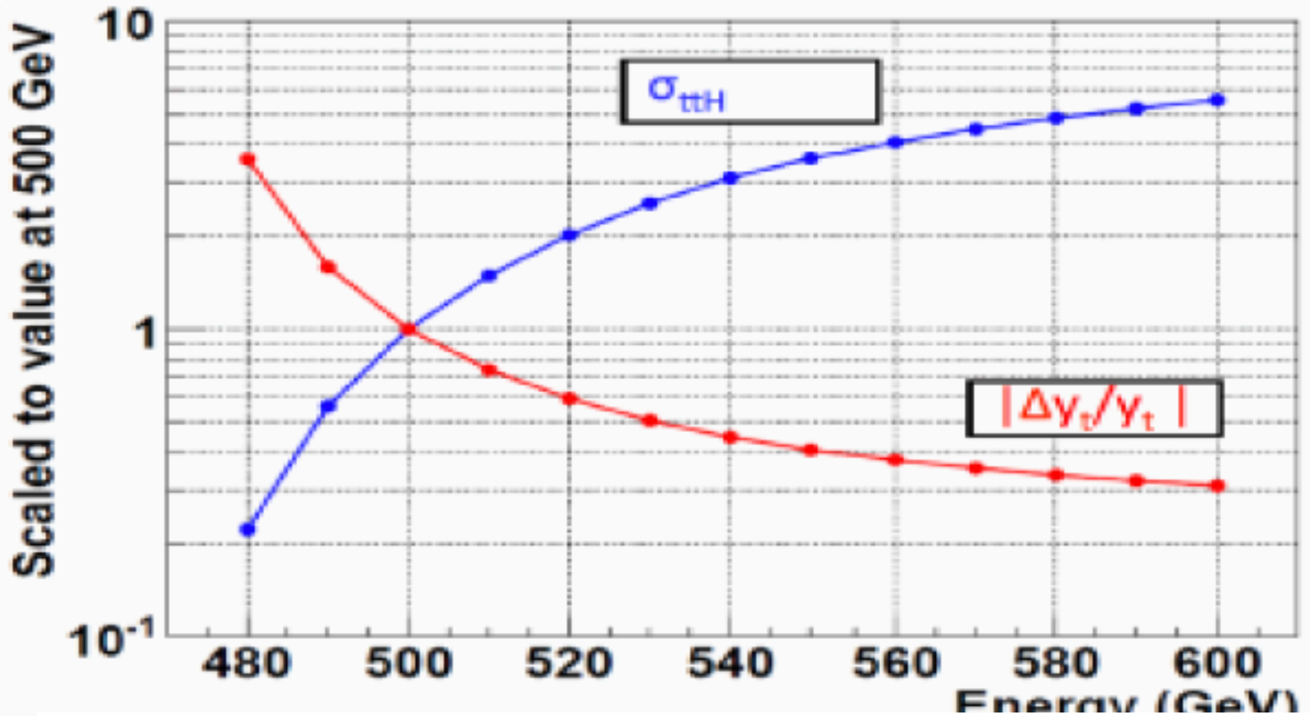
    S increases by 24% if from (80,30) to (80,60)

    S/√B increases by 50%
  - *If no P_{e+}.: S decreases by about 20%*

Top Yukawa Coupling

- top-Yukawa coupling crucial:
  - sin
  - g_{ttH}

urement
rig, EPS'15



umiUP
%
%
proves by
minosity

$\sqrt{s} = 550$ GeV better precision on g_{Htt}

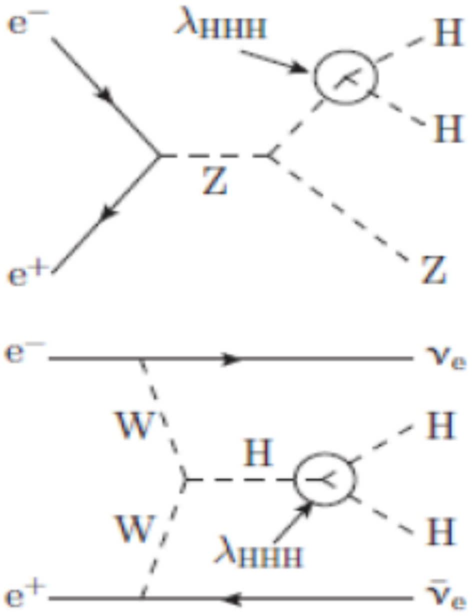
- by factor 4 enhanced cross section
- main backgrounds decrease

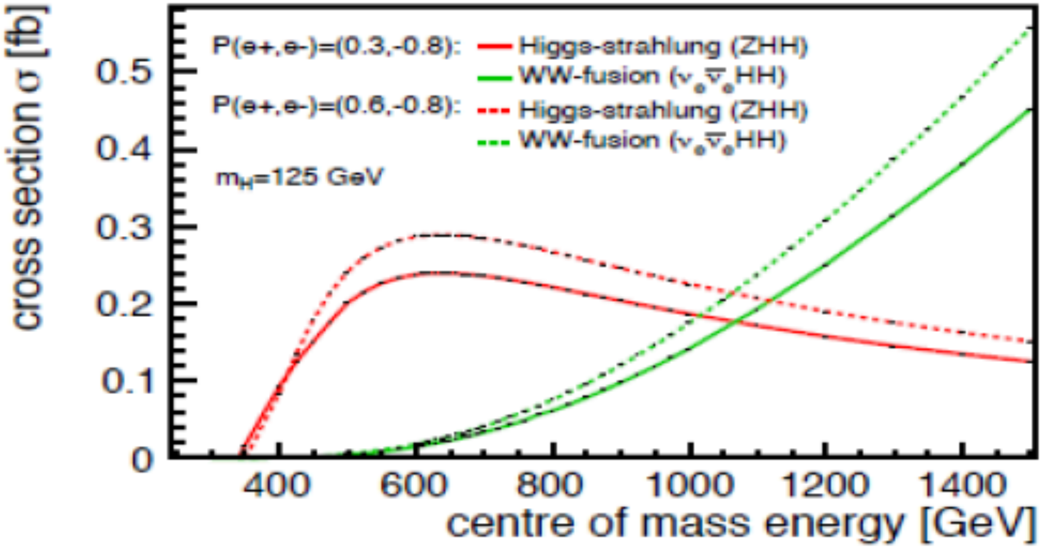
  - Num
  - Use
  - Further
    S inc
    $S/\sqrt{B}$
  - *If no P*

Another hot topic: Trilinear Higgs Couplings

Very important for establishing Higgs mechanism!

- LHC estimates:
  - about $\Delta\lambda_{HHH}$~32% at HL-LHC (14 TeV, 3000fb^{-1})
- At LC: Very challenging (small rates ~0.2fb, lots of dilution+backg.)





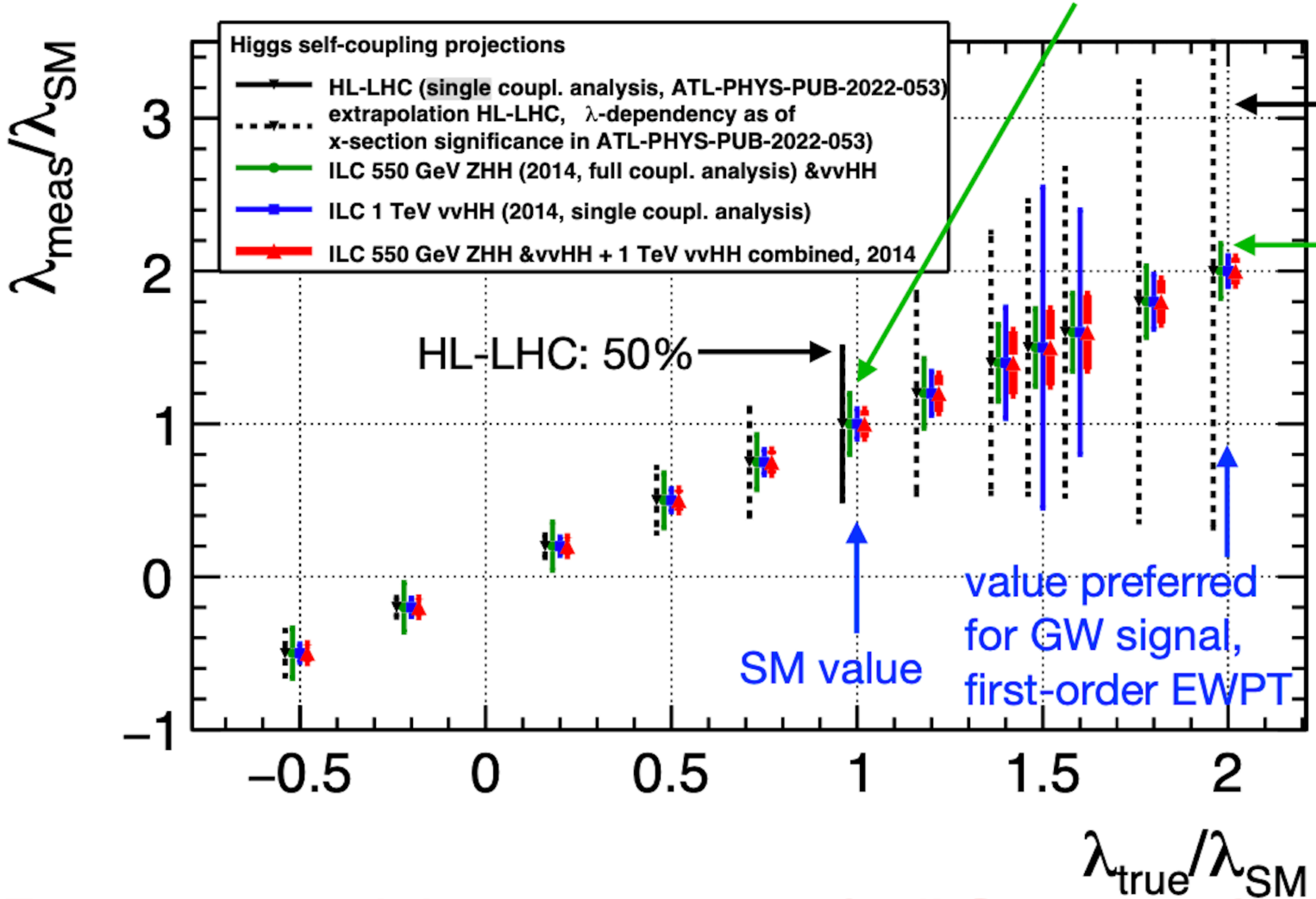
- At cms=1TeV $\Delta\lambda_{HHH}$~10% achievable

In total: about 50% enhancement comp. to P_{e+}=0% !

courtesy of G. Weiglein

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC (550 GeV, Higgs pair production)

[J. List et al. '24]



ILC550: 20%

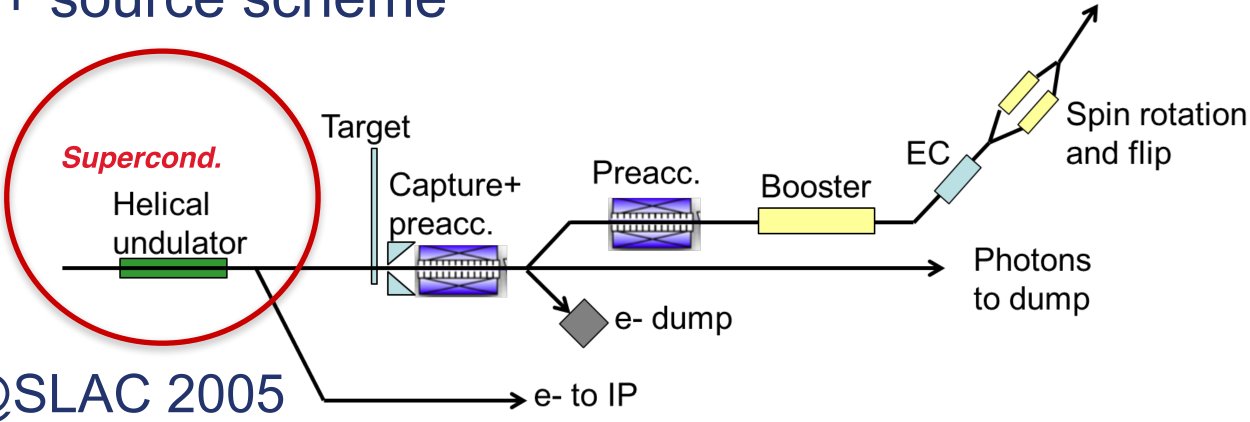
HL-LHC: 84%

ILC550: 9%

⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC550 than for HL-LHC

Most mature polarized e+ for LC: ILC

- The polarized e+ source scheme



Principle tested with
E-166 experiment @SLAC 2005

G. Alexander et al., NIMA 610 (2009), G. Alexander et al., Phys.Rev.Lett.100 (2008)

- ILC e+ beam parameters (nominal luminosity)

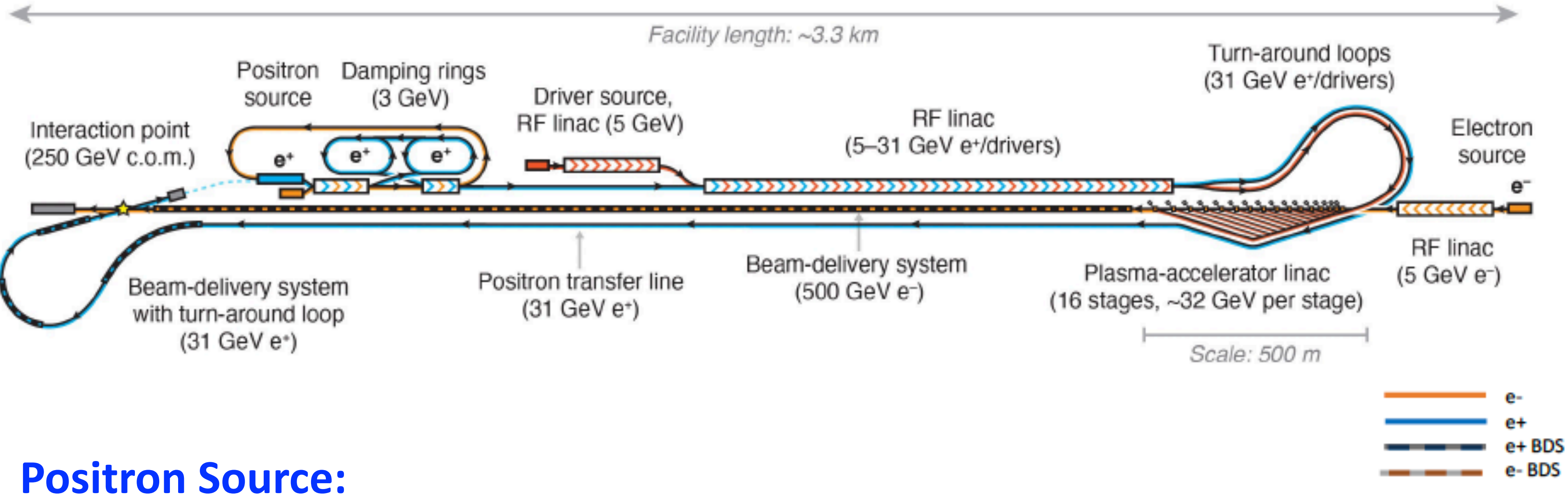
Number of positrons per bunch at IP	2×10^{10}
Number of bunches per pulse	1312
Repetition rate	5 Hz
Positrons per second at IP	1.3×10^{14}

That's about a factor 100 more compared to SLC!

  - Required positron yield: Y = 1.5e+/e- at damping ring

HALHF Design: upgrade of ILC250…?

B. Foster, R. D'Arcy, C.A. Lindstrom



Positron Source:

- **Conventional e+ source with up to 31 GeV e- drive beam**
  - **needs RF**
- **Undulator-based source: mature for ILC parameters**
  - **'sustainable' double-use of electron drive beam**
  - **higher physics potential**

see talk of Carl Lindstrom

Overview positron requirements

	rep rate/Hz	#bunch/pulse	#e+/bunch	#e+/pulse	#e+/s
SLC	120	1	$5x10^{10}$	$5x10^{10}$	$6x10^{12}$
ILC/Tesla	5	1312	$2x10^{10}$	$2.6x10^{13}$	$1.3x10^{14}$
FCC/CEPC	100	1	$2x10^{10}$	$2x10^{10}$	$2x10^{12}$
CLIC	50	312	$4\ x10^{9}$	$1.2x10^{12}$	$6x10^{13}$
HALHF	10000	1	$2\text{-}3x10^{10}$	$2\text{-}3x10^{10}$	$2\text{-}3x10^{14}$

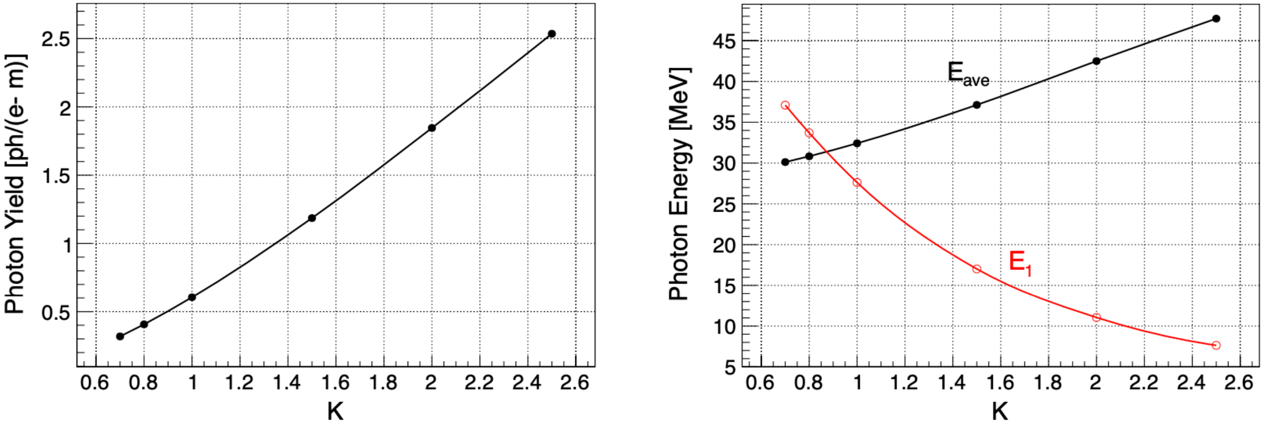
Undulator with E(e-)=500 GeV

Goals: high #e+@DR, high P(e+)>30%, target lifetime~1y :

Use new undulator parameters

- ➡ e.g. higher K = 2.5, period λ=43 mm
- ➡ leads to more higher harmonics, higher yield,

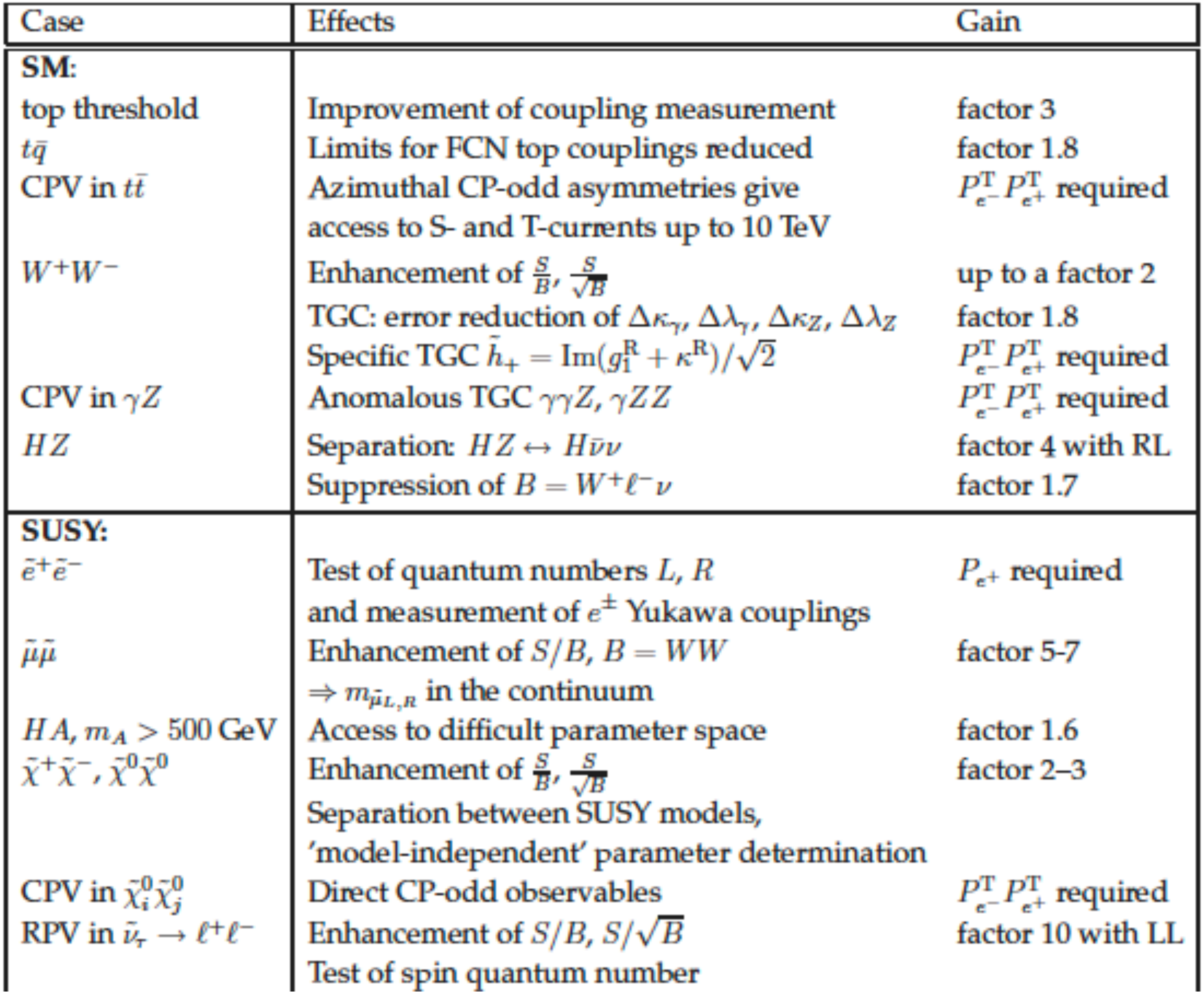
Ushakov ea 1301.1222



- ➡ higher γ_{ave} energy and higher energy spread
- ➡larger γ spot size
- ➡ e+ capture more difficult…..but more know-how (PS, PL) now!
- ➡simulations with CAIN ongoing!

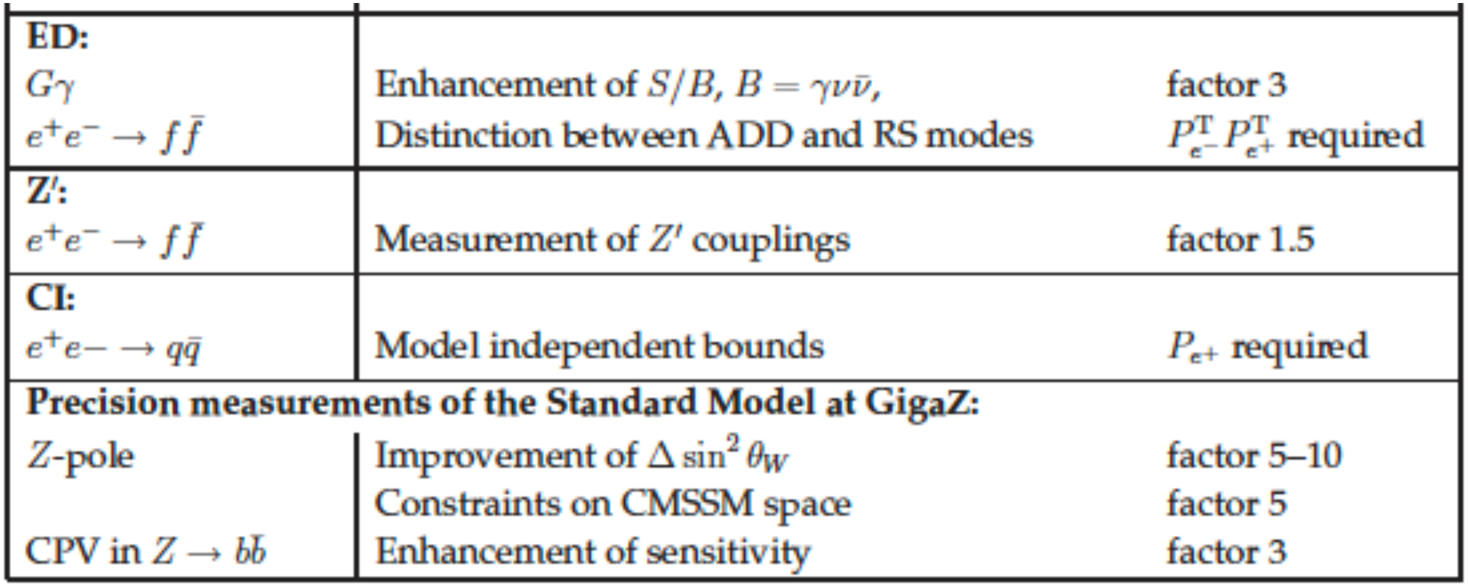
Big thanks to Yokoya-san and Takahashi-san!!!

Further Physics Examples



Case	Effects	Gain
SM:		
top threshold	Improvement of coupling measurement	factor 3
$t\bar{q}$	Limits for FCN top couplings reduced	factor 1.8
CPV in $t\bar{t}$	Azimuthal CP-odd asymmetries give access to S- and T-currents up to 10 TeV	$P_{e^-}^{\mathrm{T}} P_{e^+}^{\mathrm{T}}$ required
W^+W^-	Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$	up to a factor 2
	TGC: error reduction of $\Delta\kappa_\gamma$, $\Delta\lambda_\gamma$, $\Delta\kappa_Z$, $\Delta\lambda_Z$	factor 1.8
	Specific TGC $\tilde{h}_+ = \mathrm{Im}(g_1^{\mathrm{R}} + \kappa^{\mathrm{R}})/\sqrt{2}$	$P_{e^-}^{\mathrm{T}} P_{e^+}^{\mathrm{T}}$ required
CPV in γZ	Anomalous TGC $\gamma\gamma Z$, γZZ	$P_{e^-}^{\mathrm{T}} P_{e^+}^{\mathrm{T}}$ required
HZ	Separation: $HZ \leftrightarrow H\bar{\nu}\nu$	factor 4 with RL
	Suppression of $B = W^+\ell^-\nu$	factor 1.7
SUSY:		
$\tilde{e}^+\tilde{e}^-$	Test of quantum numbers L, R and measurement of $e^\pm$ Yukawa couplings	P_{e^+} required
$\tilde{\mu}\tilde{\mu}$	Enhancement of S/B, $B = WW$	factor 5-7
	$\Rightarrow m_{\tilde{\mu}_{L,R}}$ in the continuum	
HA, $m_A > 500$ GeV	Access to difficult parameter space	factor 1.6
$\tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^0\tilde{\chi}^0$	Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$	factor 2–3
	Separation between SUSY models, 'model-independent' parameter determination	
CPV in $\tilde{\chi}_i^0\tilde{\chi}_j^0$	Direct CP-odd observables	$P_{e^-}^{\mathrm{T}} P_{e^+}^{\mathrm{T}}$ required
RPV in $\tilde{\nu}_\tau \to \ell^+\ell^-$	Enhancement of S/B, $S/\sqrt{B}$	factor 10 with LL
	Test of spin quantum number	

Further Physics Examples



ED:		
$G\gamma$	Enhancement of S/B, $B = \gamma\nu\bar{\nu}$,	factor 3
$e^+e^- \to f\bar{f}$	Distinction between ADD and RS modes	$P^T_{e^-} P^T_{e^+}$ required
Z′:		
$e^+e^- \to f\bar{f}$	Measurement of Z' couplings	factor 1.5
CI:		
$e^+e- \to q\bar{q}$	Model independent bounds	P_{e^+} required
Precision measurements of the Standard Model at GigaZ:		
Z-pole	Improvement of $\Delta \sin^2 \theta_W$	factor 5–10
	Constraints on CMSSM space	factor 5
CPV in $Z \to b\bar{b}$	Enhancement of sensitivity	factor 3

- **Many new physics examples**
- **Beam polarization always provides ‘physics gain’**
- **Crucial sensitivity to coupling structures**
- **Still further new studies ongoing……..**

Conclusions

- Beam polarization e^- and e^+ gives 'added-value' to ILC
  - Crucial 'new' analysis tools compared to LHC physics
  - Access to chirality: since E≫m: chirality=helicity='polarization'
- P_{e+} important at $\sqrt{s}=250$ GeV (Higgs!) and higher $\sqrt{s}$
  - Saves running time
  - Essential to control systematics
  - Crucial to compete with LHC options
  - Essential to match precision promises/expectations!
  - ➢ Precision allows sensitivity to beyond SM physics
- Exploitation of both longitudinally-&transversely-pol. beams *e.g. LCC physics group,1801.02840*
  - CP-violating pheno, etc.

Polarized e+ and e- beams needed for all LC-designs (ILC, CLIC,HALHF)!

(Outlook: shorter tunnel .... reach cms 550 GeV in ILC tunnel envisaged.....)

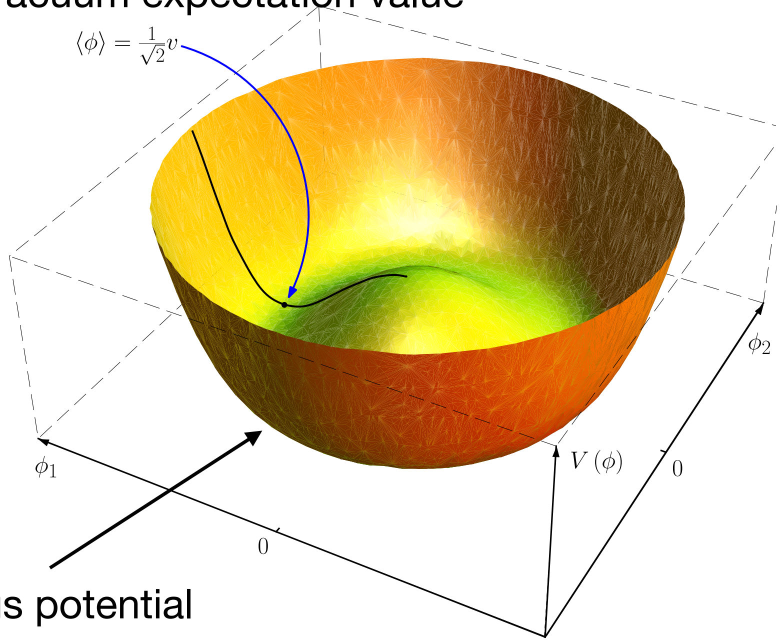
- Not covered today: polarization to determine properties of new particles directly, as chiral quantum numbers, CP quantities, large extra dimensions etc. as well as dark matter also at 250!

courtesy of G. Weiglein

Higgs potential: the "holy grail" of particle physics

Crucial questions related to electroweak symmetry breaking: what is the form of the Higgs potential and how does it arise?

Vacuum expectation value



Higgs potential

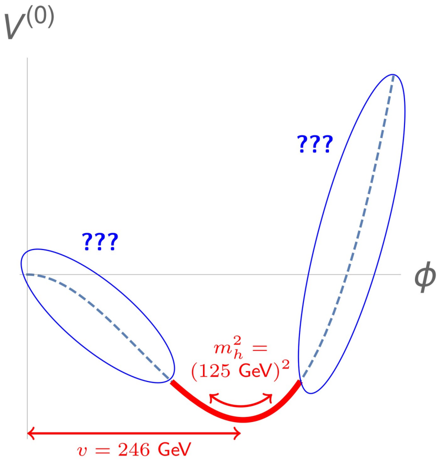
Only known so far:

→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

m_h = 125 GeV



Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

Higgs sector@250 GeV

- **What if no polarization / no P_{e+} available?**
  - Higgsstrahlung dominant $\sigma_{pol}/\sigma_{unpol}$~(1-0.151 P_{eff}) * L_{eff}/L

    With P_{e+}=0%: $\sigma_{pol}/\sigma_{unpol}$~1.13

    With P_{e+}=40%: $\sigma_{pol}/\sigma_{unpol}$~1.55 (about 37% increase comp. to 0%
  - Background: mainly ZZ (if leptonic), WW (if hadronic)
  - S/B: 1.14 (+,0) 4.35 (+,0)

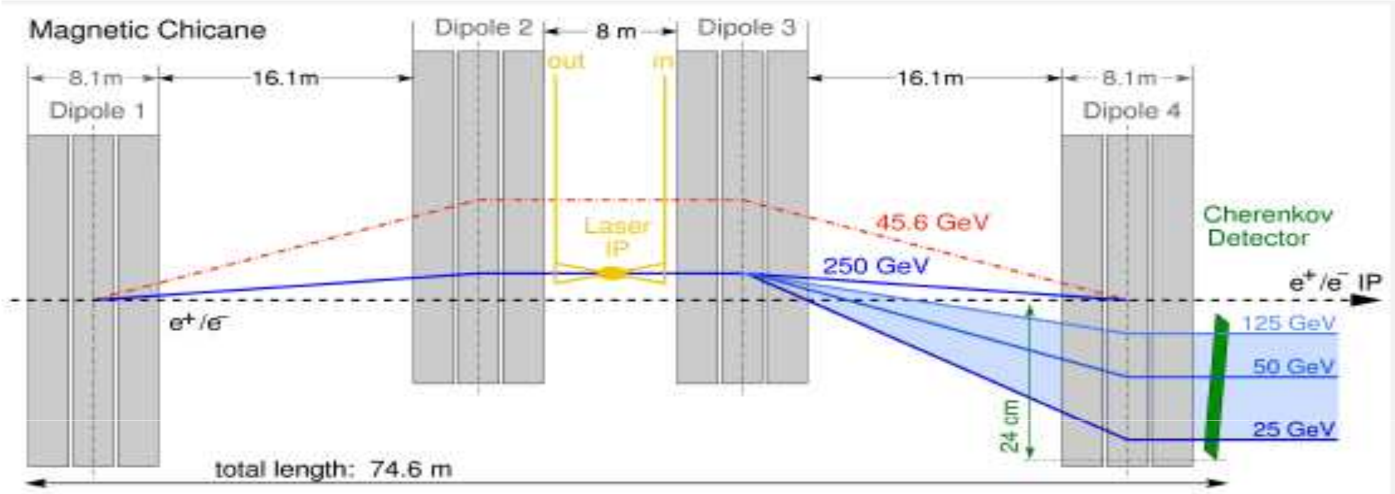
    1.20 (+,-) 12.6 (+,-)
  - S/√B: 0.99 (+,0) 1.95 (+,0)

    1.22 (+,-) 3.98 (+,-)

  ➢ *Loss if no P_{e+} :* ~20% ~ factor 2
  - If no P(e+): much longer running time required to achieve precision!

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

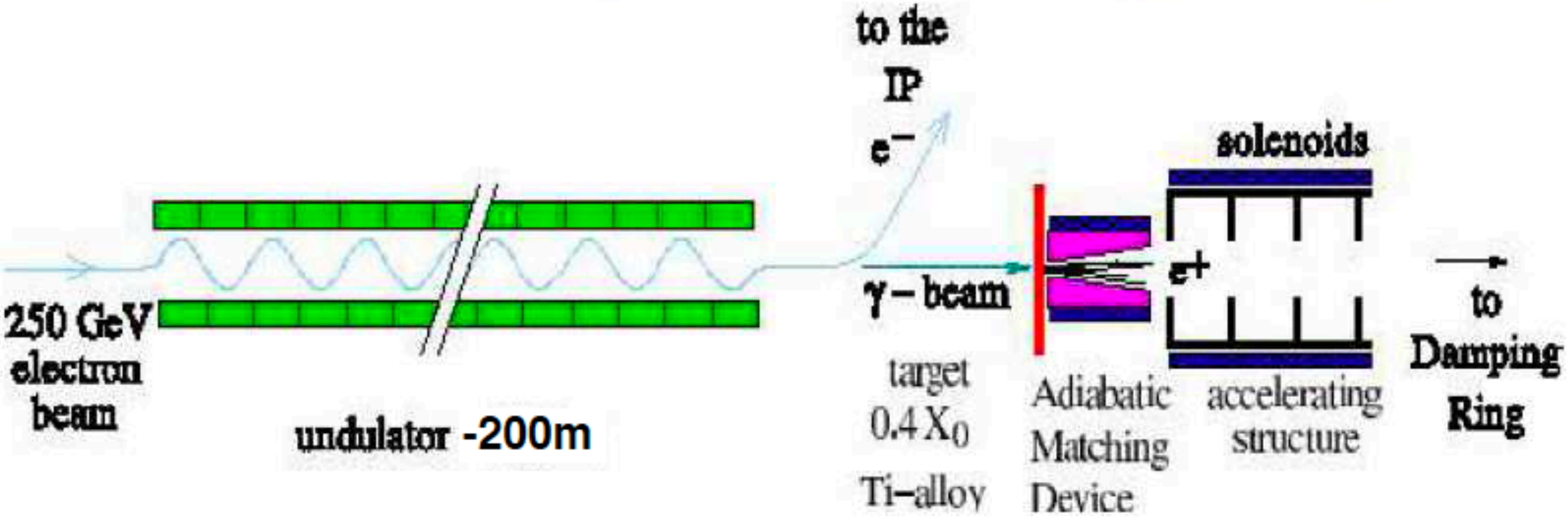
Polarimetry requirements

- 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%

Short overview: e^+ sources at ILC

- Conventional source: e- scattering in target → pair production → e+
- Undulator-based scheme: polarized e+ via circularly polarized photons

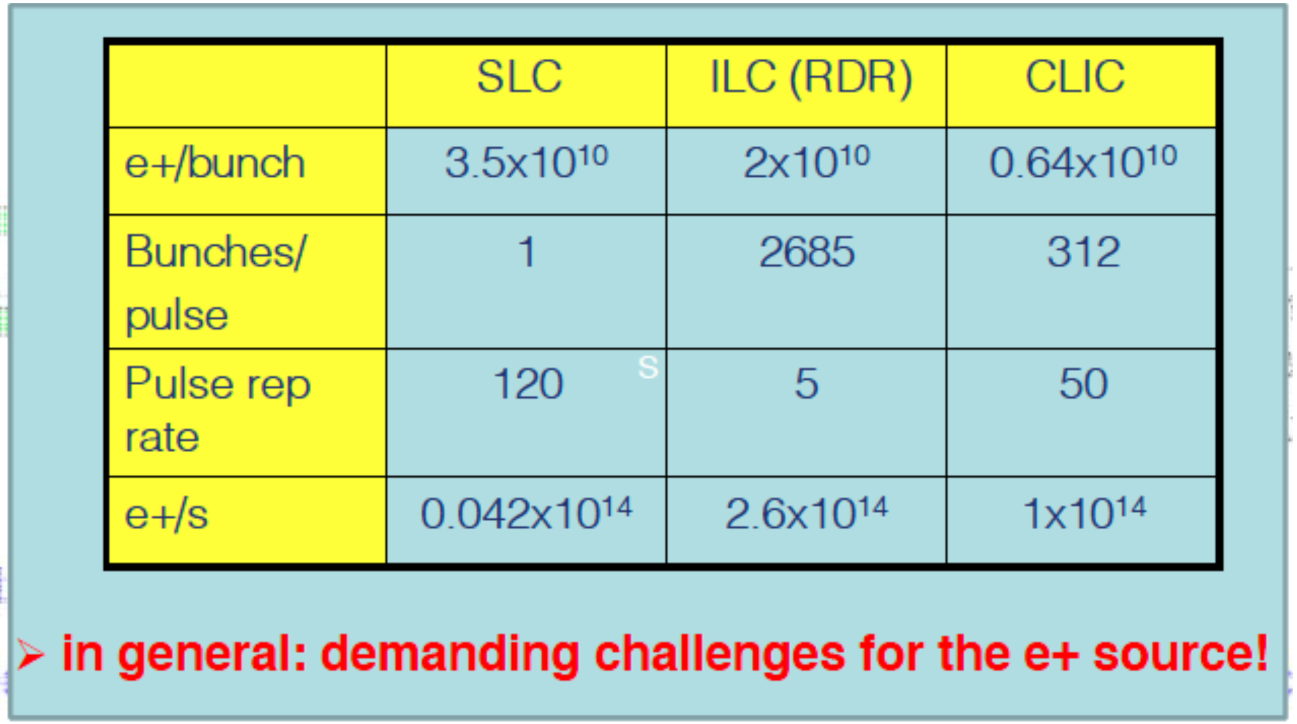


→ deviation of e- beam via helical magnetic field in undulator

→ radiated circularly polarized photons onto thin target, pair production

→ e+ yield and polarization depends on beam energy and undulator length

Short overview: e^+ sources at ILC



	SLC	ILC (RDR)	CLIC
e+/bunch	3.5×10^{10}	2×10^{10}	0.64×10^{10}
Bunches/ pulse	1	2685	312
Pulse rep rate	120	5	50
e+/s	0.042×10^{14}	2.6×10^{14}	1×10^{14}

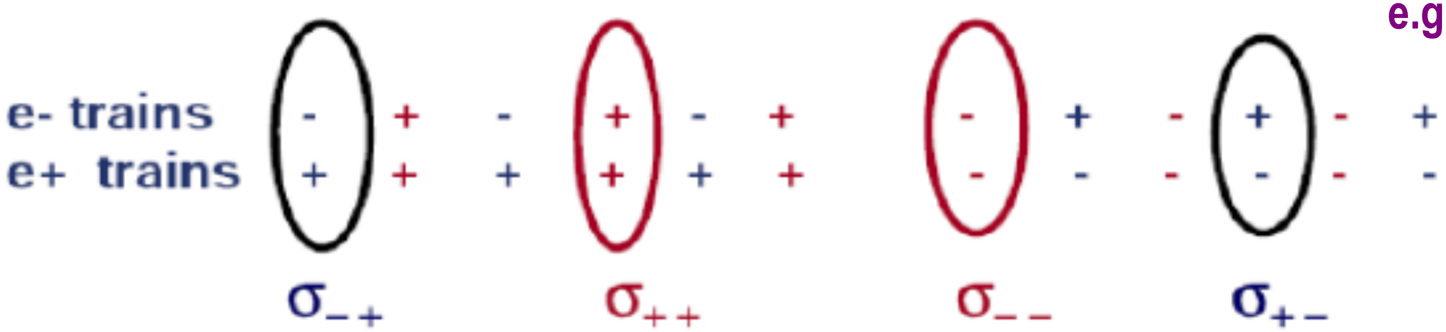
- **in general: demanding challenges for the e+ source!**

- **Beam polarization status: at cms=250 GeV: $P(e^-)$~80-90%, $P(e^+)$~30%**
  =350, 500 GeV: $P(e^-)$~80-90%, $P(e^+)$=40% (60% with collimator)
  (with chosen undulator parameters for cms=500 GeV)

Caution: helicity flipping is 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 rotator before DR and spinflipper in set-up for baseline!**
  - done!

Conclusions

- Beam polarization e^- and e^+ gives 'added-value' to ILC
  - Crucial 'new' analysis tools compared to LHC physics
  - Access to chirality: since $E \gg m$: chirality=helicity='polarization'
- P_{e+} important at $\sqrt{s}=250$ GeV (Higgs!) and higher $\sqrt{s}$
  - Saves running time
  - Essential to control systematics
  - Crucial to compete with LHC options
  - Essential to match precision promises/expectations!
  - ➢ Precision allows sensitivity to beyond SM physics! *e.g. LCC physics group,1801.02840*
- Access to new/specific asymmetries (*e.g. also access to heavy leptons etc…..LC notes*)
  - $$A_{\text{double}} = \frac{\sigma(P_1,-P_2)+\sigma(-P_1,P_2)-\sigma(P_1,P_2)-\sigma(-P_1,-P_2)}{\sigma(P_1,-P_2)+\sigma(-P_1,P_2)+\sigma(P_1,P_2)+\sigma(-P_1,-P_2)},$$
- Exploitation of both longitudinally-&transversely-pol. beams
  - Access to tensor-like interactions, CP-violating pheno, specific TGC,….

- Not covered today: polarization to determine properties of new particles directly, as chiral quantum numbers, CP quantities, large extra dimensions etc. as well as dark matter also at 250!more details see talk by J.Beyer/J. List and A. Zarnecki

Back to longitudinally polarized beams

- Important issue: measuring amount of polarization
  - limiting systematic uncertainty for high statistics measurements
- Compton polarimeters: up- and downstream
  - envisaged uncertainties of $\Delta P/P=0.25\%$. Essential for monitoring, but need to correct wrt IP.
- (Differential) Cross-section based in-situ measurements
  - need some physics assumptions
  - often under assumption of perfect helicity reversal
- Adding positron polarization helps in several ways:
  - Providing additional measurements, improving limiting systematics
  - Enhancing effective polarization
  - ‘Allow’ in-situ measurements: ‘ultimate’ measurements, but require running time in same-sign configurations

Polarization measurement

- Compton polarimeters: up- and downstream
  - envisaged uncertainties of ΔP/P=0.25% (at polarimeters!)
  - But that’s is not enough for IP!
- Use collision data to derive luminosity-weighted polarization
  - single W, WW, ZZ, Z, etc.: combined fit

$$P^{-}_{e\pm} = -|P_{e\pm}| + \tfrac{1}{2}\delta_{e\pm} \qquad P^{+}_{e\pm} = |P_{e\pm}| + \tfrac{1}{2}\delta_{e\pm}$$

  - assume H-20 set-up concerning lumi
  - helicity reversal is important
  - non-perfect helicity-reversal can be compensated
  - 0.1% accuracy in ΔP/P is achievable at IP!
  - *NOT achievable without Pe+!*

Karl, List,1703.00214

Remember: even if no Pe+ (SLC! dedicated experiment at SLACs Endstation A), the P_{e+}~0.0007 had to be derived a posteriori for physics reason!

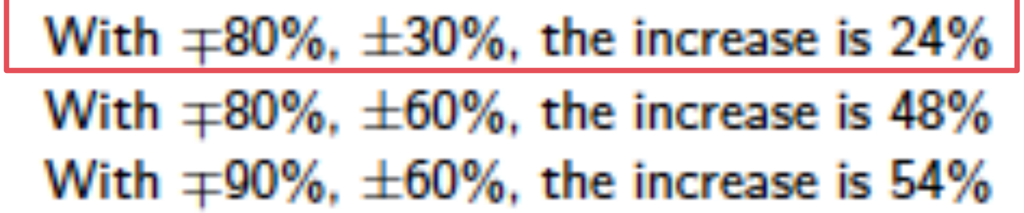
L_{eff} and P_{eff}

- More concrete: If only LR and RL contributions: only 50 % of collisions useful

effective luminosity: $L_{\text{eff}}/L = \frac{1}{2}(1 - P_{e-} P_{e+})$

This quantity = the effective number of collisions, can only be changed with P_{e-} and P_{e+}:

here:



With ∓80%, ±30%, the increase is 24%

With ∓80%, ±60%, the increase is 48%

With ∓90%, ±60%, the increase is 54%

In other words: *no P_{e+} means 24% more running time (!)*

and

10% loss in P_{eff} = 10% loss in analyzing power!

Quite substantial in Higgs strahlung and electroweak 2f production !

L_{eff} and P_{eff}: further example

- **Charged currents, i.e. t-channel W- or v-exchange (A_{LR}=1):**

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = 2\sigma_0(\mathcal{L}_{\text{eff}}/\mathcal{L})[1 - \mathcal{P}_{\text{eff}}]$$

In other words: ***no P_{e+} means 30% more running time needed !***

Quite substantial in Higgs production via WW-fusion!

Main benefits of simultaneous e^+ polarization?

- **Better Statistics: Less running time/operation cost for same physics**
  - higher rates, lower background, higher analyzing power for chosen channels

- **Lower Systematics**

  see also talk
  J.Beyer/J. List

  - key role for reduction of systematics originating from polarization measurement

- **More Observables**
  - Four distinct data-sets: opposite-site polarization collisions plus like-sign configuration ⟶ unique feature of ILC (including transversely but also unpolarized configurations!)

Statistics Suppression of WW and ZZ production

WW, ZZ production = large background for NP searches!

W^- couples only left–handed:
→ WW background strongly suppressed with right polarized beams!

Scaling factor= $\sigma^{pol}/\sigma^{unpol}$ for WW and ZZ:

$P_{e^-} = \mp 80\%$, $P_{e^+} = \pm 60\%$	$e^+e^- \rightarrow W^+W^-$	$e^+e^- \rightarrow ZZ$
(+0)	0.2	0.76
(−0)	1.8	1.25
(+−)	0.1	1.05
(−+)	2.85	1.91

'No lose theorem':
scaling factors for
signals&background

	S	B	S/B	$S/\sqrt{B}$
Example 1	×2	×0.5	×4	$\times 2\sqrt{2}$
Example 2	×2	×2	Unchanged	$\times\sqrt{2}$

Higgs Sector @250 GeV

- What if no polarization / no P_{e+} available?
  - Higgsstrahlung dominant $\sigma_{pol}/\sigma_{unpol} \sim (1-0.151\ P_{eff}) * L_{eff}/L$

    With $P_{e+}=0\%$: $\sigma_{pol}/\sigma_{unpol} \sim 1.13$

    With $P_{e+} = 30\%$ $\sigma_{pol}/\sigma_{unpol} \sim 1.51$ (about 33% increase comp. to 0%)
  - Background: mainly ZZ (if leptonic), WW (if hadronic)

– S/B:	1.14 (+,0)	4.35 (+,0)
	1.20 (+,-)	12.6 (+,-)
– S/√B:	0.99 (+,0)	1.95 (+,0)
	1.22 (+,-)	3.98 (+,-)

➢ *Loss if no P_{e+} :* ~20% ~ factor 2

- Physics Panel used both beams polarized! P_{e+} is important …

What did we promise for e+e- colliders?

Bechtle et al.

- **Precision of 1-2% achievable in Higgs couplings !!!**
- **Crucial input from ILC**
  - total cross section σ(HZ)
  - Has to be measured at √s=250GeV
  - Input parameter for all further Higgs studies (Higgs width etrc.) !
- **Lots of improvement if only σ(HZ) from ILC is added**