Impact of Polarized Beams for Higgs, Electroweak und Dark Matter Physics

- Motivation
- Polarization basics
- Some physics examples: Higgs, EW, DM
- Conclusions

G. Moortgat-Pick, Hamburg
Jasmin Becks, Robin Heine, Sven Heinemeyer, Cheng Li, Florian Lika,

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, light SUSY fermions,etc….)**
  - but not (yet) confirmed discoveries…
- **Still strong motivation for Beyond Standard Model (BSM) physics**
  - Higgs Potential & phase transition: trilinear Higgs couplings crucial
  - Dark Matter, Gravitational Waves, Baryon-Asymmetry, etc.
- **However, scale of new physics window still unclear…**
  - additional tools complementary to (HL)LHC analyses required
  - stageable, tuneable high energy, precision e^+e^- collider(s) including polarized beams and high lumi

➡**Mature e+e- linear collider design(s) with sane polarization available**

LCvision, C. Balazs, arXiv: 2503.19983

	91 GeV	250 GeV	350 GeV	550 GeV	1-3 TeV
$\int \mathcal{L}$ (ab^{-1})	0.1	3	0.2	8	8
beam polarisation (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(−+, −−, ++, +−) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)

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:** $\mathcal{P} = \dfrac{N_R - N_L}{N_R + N_L}$

- **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:**

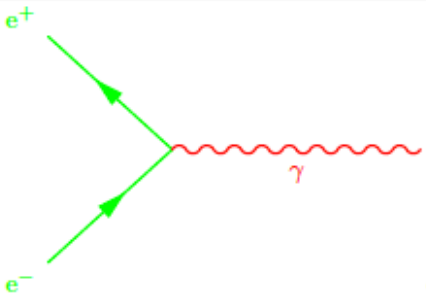
$$\sigma_0 = \frac{1}{4}\{\sigma_{\rm RR} + \sigma_{\rm LL} + \sigma_{\rm RL} + \sigma_{\rm LR}\}$$

- **Left-right asymmetry:** $A_{\rm LR} = \dfrac{(\sigma_{\rm LR} - \sigma_{\rm RL})}{(\sigma_{\rm LR} + \sigma_{\rm RL})}$

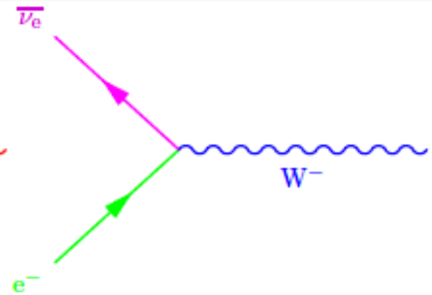
- **Effective polarization and luminosity:**

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

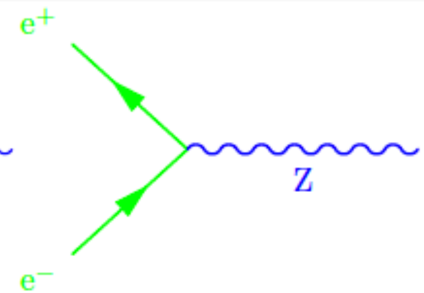
SM Vertices & some Processes



QED: parity conserved, A=0

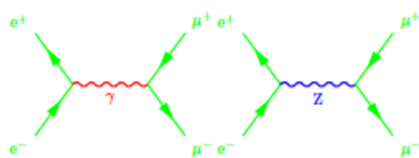


Charged currents: A=1
Parity violating
only left-handed e^- couple

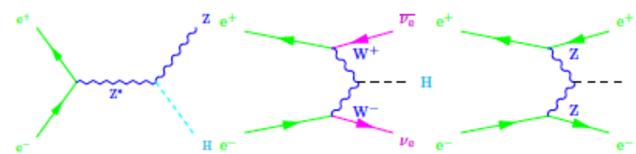


Neutral currents: A=0.15
Parity violating
left-handed e^-, right-handed e^+

2 Fermion: LR, RL

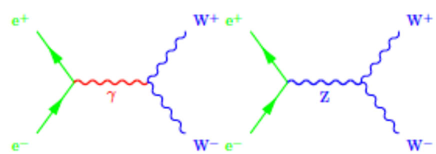


Higgs: LR, RL

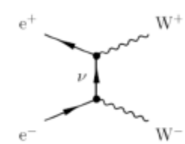


W-production:

LR, RL:

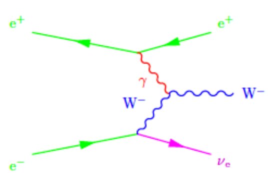


only LR:



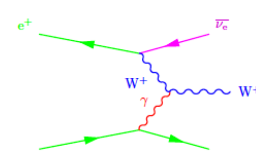
Single W-:

only LR and LL!:



Single W^+:

only RL and RR!:



Statistical arguments

- Effective polarization

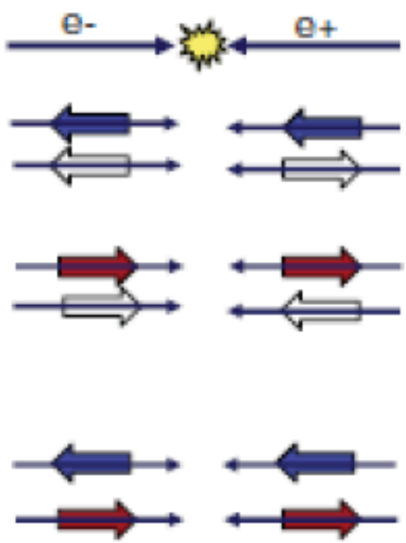
$$P_{eff} := (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$$
$$= (\#LR - \#RL)/(\#LR + \#RL)$$

'analyzing power'

- Fraction of colliding particles

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

'running time'



P_{e-}	P_{e+}	h_{e-}	h_{e+}	cross section
-1	0	-1	+1	σ_{LR}
		-1	-1	σ_{LL} → 0
+1	0	+1	-1	σ_{RL}
		+1	+1	σ_{RR} → 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 $P(e^+)$!

➡ less running time only with both beams polarized !

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!***
- **Physics impact: Higgs-Physics, WW/Z/top-Physics and on 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,….*

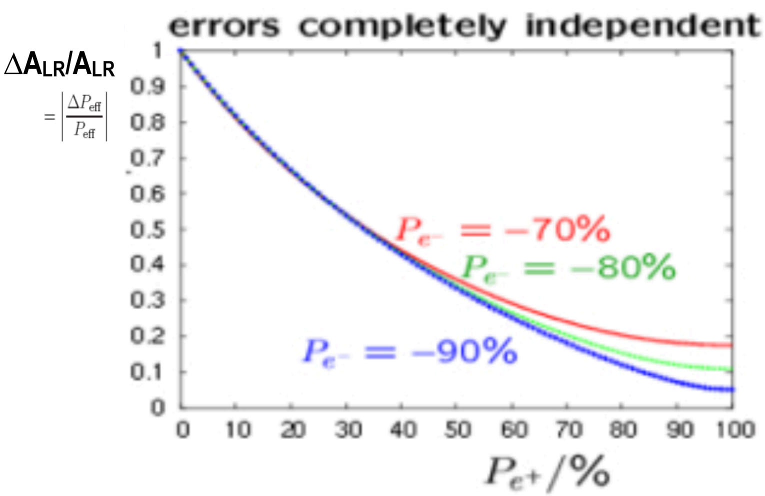
Short reminder: why polarized e± needed?

- **Important issue: measuring amount of polarization**
  - **limiting systematic uncertainty for high statistics measurements**
  - **Compton polarimeters (up-,/downstream): envisaged uncertainties of $\Delta P/P=0.25\%$**

- **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.

e.g. Cheng Li 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!)

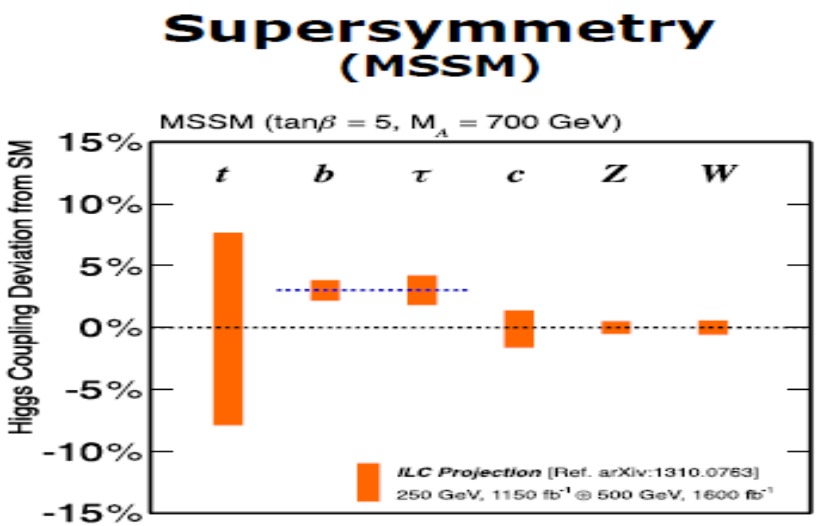
  $\Rightarrow$ azimuthal dependence ('not only in scattering plane')

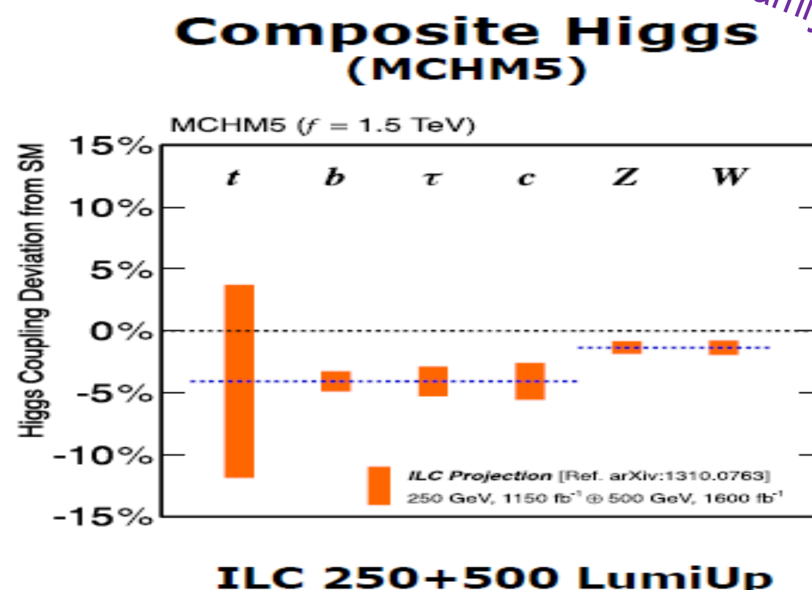
  $\Rightarrow$ observables are e.g. asymmetries of CP-odd quantities: $\vec{p}_a(\vec{p}_b \times \vec{p}_c)$

Physics Examples: Impact of polarization

- **Expected BSM deviations in Higgs measurements:**
  - Could be the only SM Higgs….but 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,

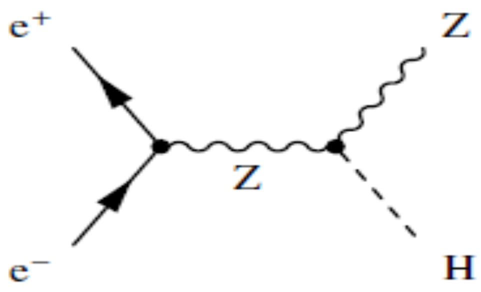




- ***Determination of Higgs couplings in 1% level essential for ILC250!***

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!*

Higgs Sector @250 GeV

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

    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

- **P_{e+} is important for achieving best precision**

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: $a_1 = 1, a_2 = 0, a_3 = 0$,

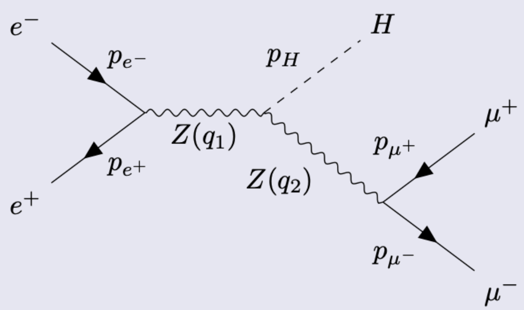
Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

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

Probing CP at the e+e- collider

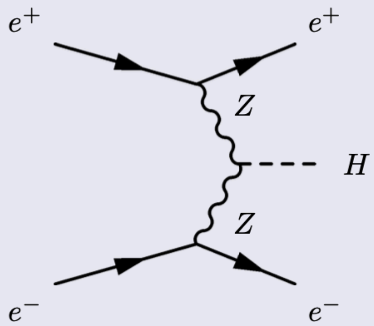
- CP probes of HZZ via Z-decay from HZ or Z fusion

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

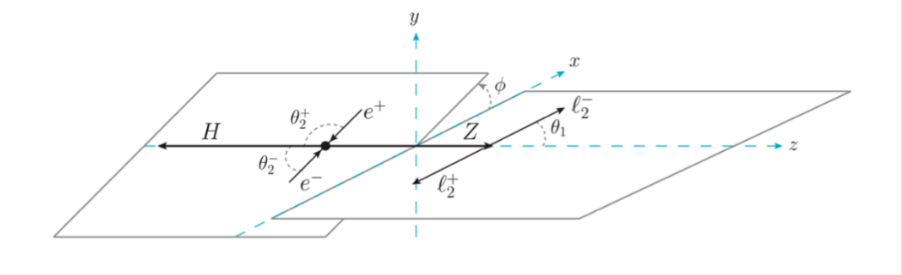
Z fusion



- 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

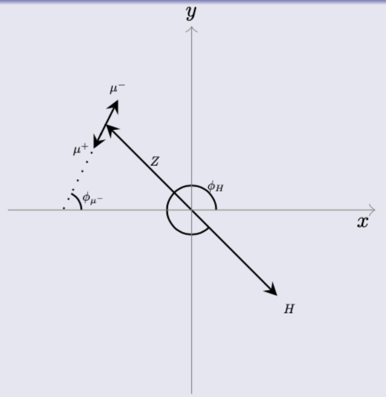
CP-sensitive observables

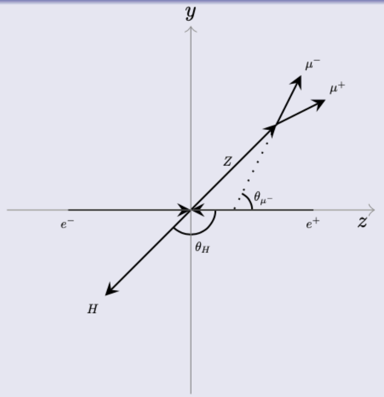
Coordinate systems with unpolarised or longitudinal polarised beams



- 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

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

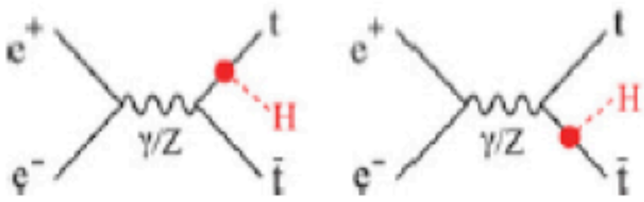
	95% C.L. (2σ)limit						
Experiments	ATLAS	CMS	HL-LHC	CEPC	CLIC	CLIC	ILC
Processes	$H \to 4\ell$	$H \to 4\ell$	$H \to 4\ell$	HZ	W-fusion	Z-fusion	$HZ,\ Z \to \mu^+\mu^-$
$\sqrt{s}$ [GeV]	13000	13000	14000	240	3000	1000	250
Luminosity [fb^{-1}]	139	137	3000	5600	5000	8000	5000
$(\lvert P_-\rvert, \lvert P_+\rvert)$							(90%, 40%)
$\tilde{c}_{HZZ}$ ($\times 10^{-2}$)	[-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

LCvision, C. Balazs, arXiv: 2503.19983

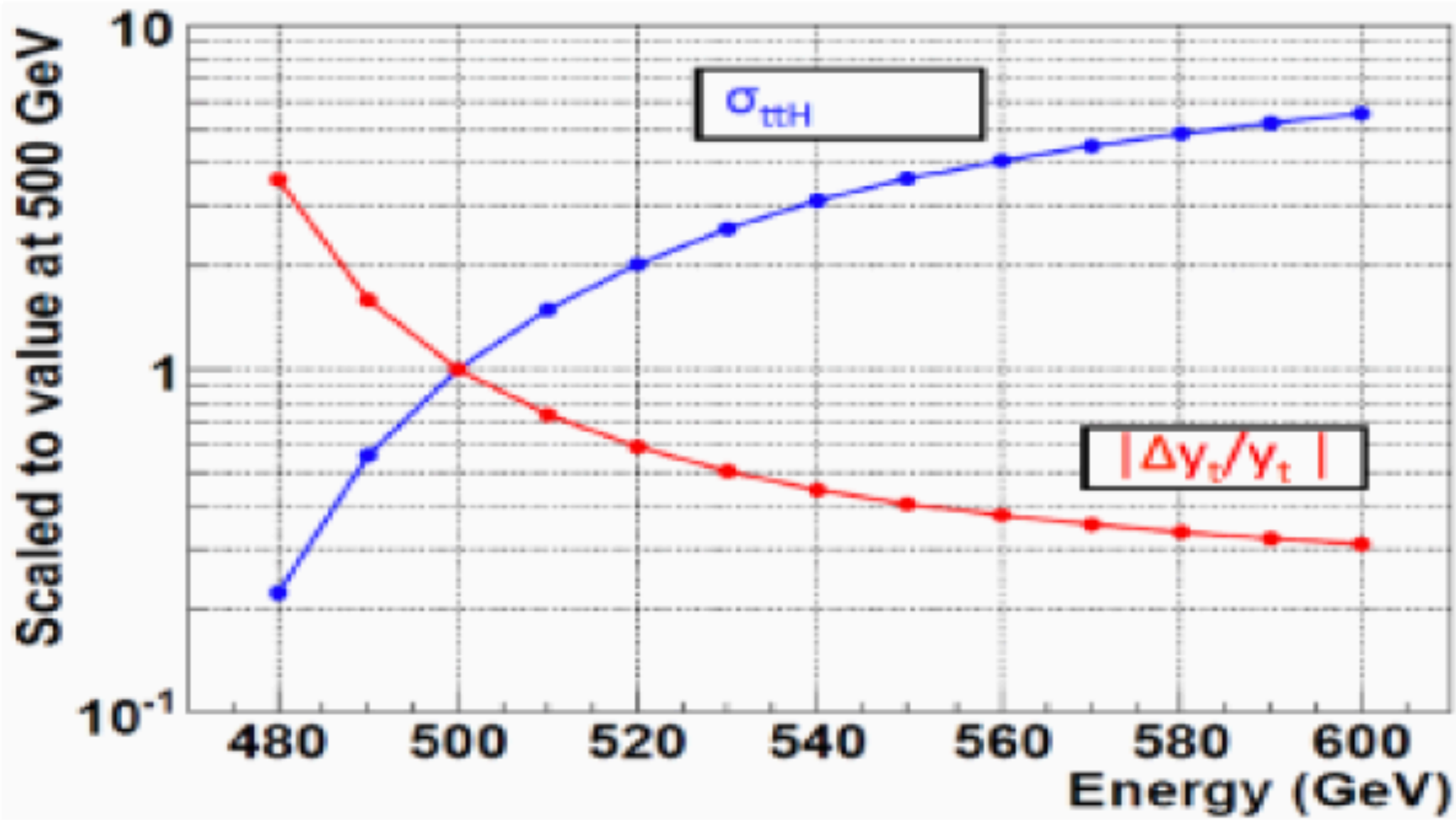


$\Delta g_{Htt}/g_{Htt}$	ILC500	ILC500 LumiUP
500 GeV	18 %	6.3 %
550 GeV	∼ 9 %	∼ 3 % @4 ab-1
1 TeV		~1% @ 8 ab-1

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



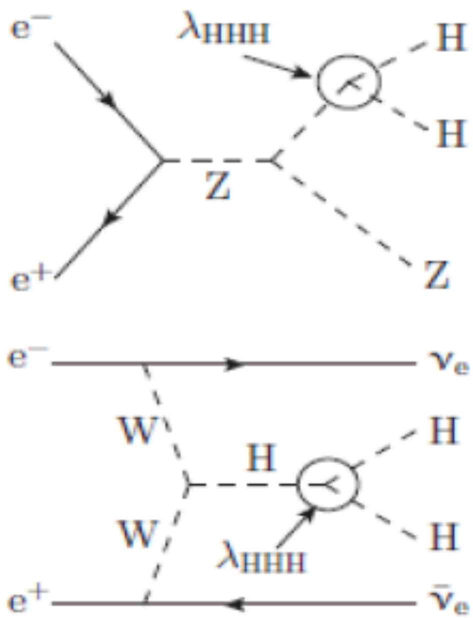
S/√B increases by 50%

– *If no P_{e+}: S decreases by about 20%*

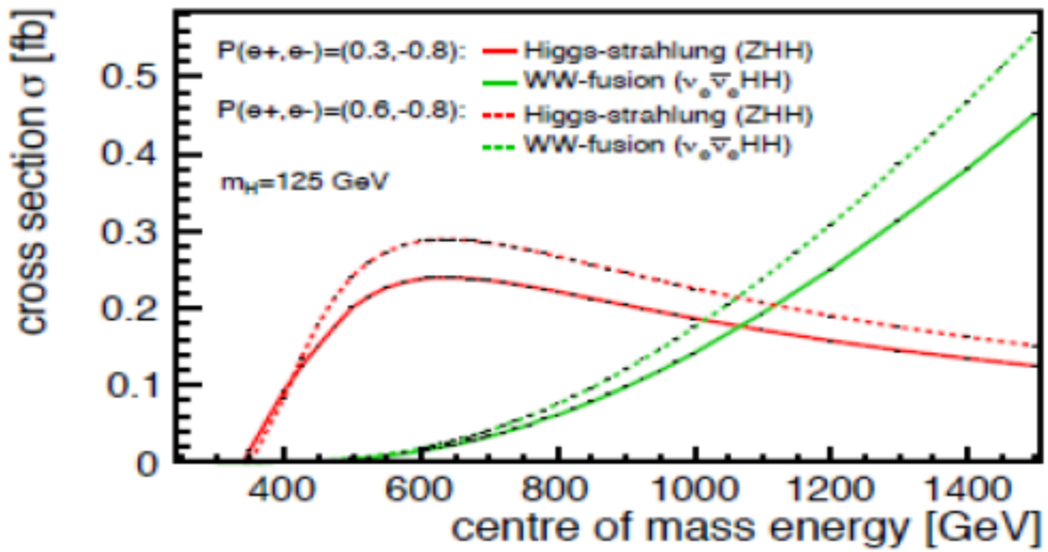
Another hot topic: Trilinear Higgs Couplings

Very important for establishing Higgs mechanism!

- LHC estimates:
  - about $\Delta\lambda_{HHH}$~ 25% at HL-LHC (14 TeV, $3000fb^{-1}$)
- At LC: Very challenging (small rates ~0.2fb, lots of dilution+backg.)



J.Beyer/J. List



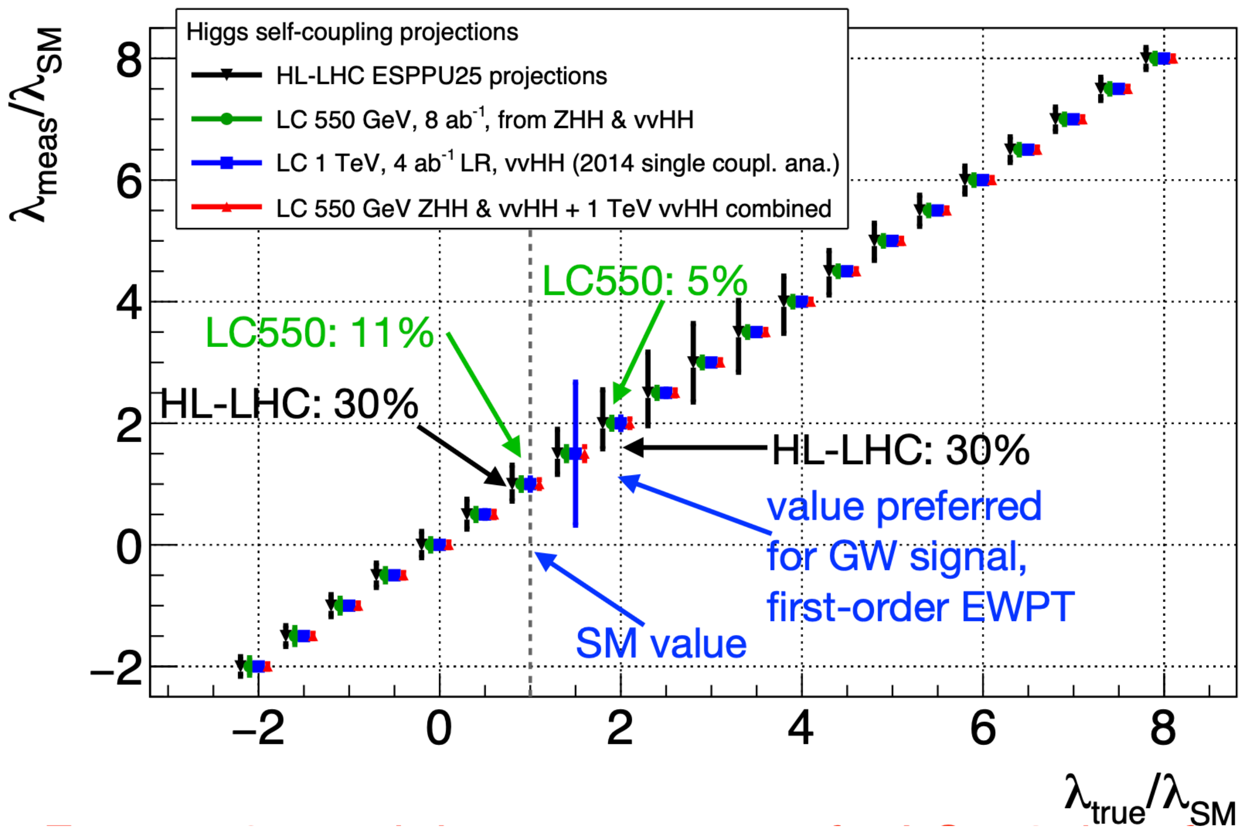
- At cms=550GeV $\Delta\lambda_{HHH}$~11% @$8ab^{-1}$ achievable

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)

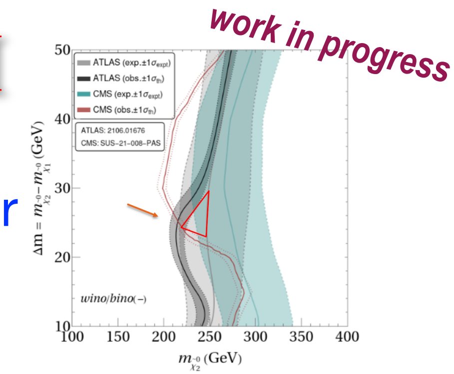
LCvision, C. Balazs, arXiv: 2503.19983



⇒ For $\varkappa_\lambda \approx 2$: much better prospects for LC550 than for HL-LHC
Reason: different interference contributions

Excellent prospects and guaranteed success!

BSM parameter determination: SUSY DM

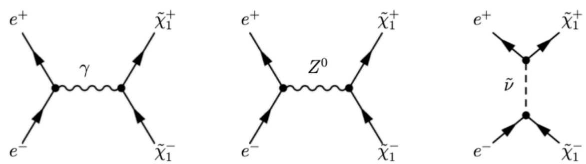


Let's assume current 'excesses' get reality: test chargino sector

- Mixing angles and cross-section are related via

$$\sigma^{\pm}\{ij\} = c_1 \cos^2(2\Phi_L) + c_2 \cos(2\Phi_L) + c_3 \cos^2(2\Phi_R) + c_4 \cos(2\Phi_R) + c_5 \cos(2\Phi_L)\cos(2\Phi_R) + c_6$$

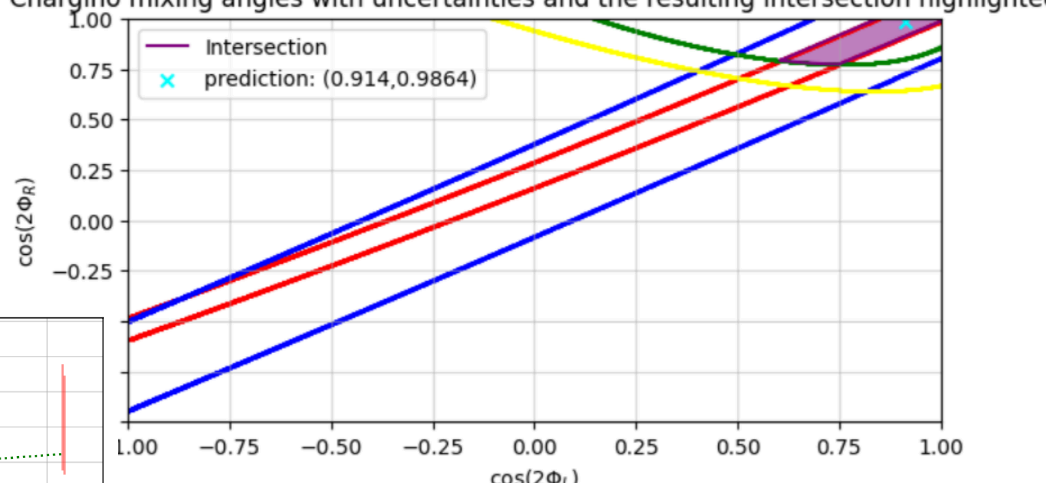
- Feynman diagrams:



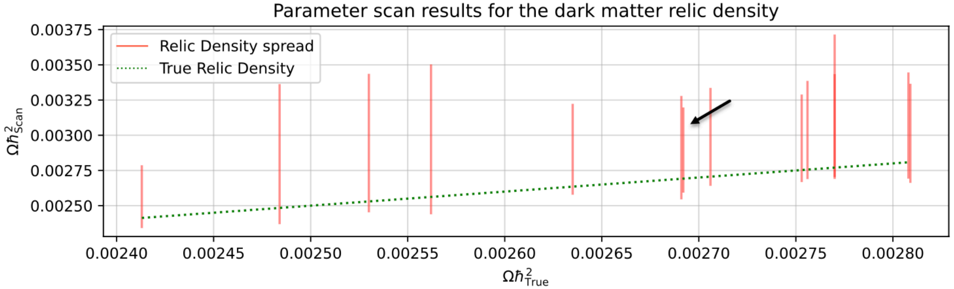
M_1	-238.36 GeV	$\sigma^{500}_{-.8,+.6}$	948.2923 fb
M_2	246.46 GeV	$\sigma^{500}_{+.8,-.6}$	26.6215 fb
μ	632.64 GeV	$\sigma^{550}_{-.8,+.6}$	263.7656 fb
$\tan\beta$	51.97	$\sigma^{550}_{+.8,-.6}$	7.3801 fb
$M_{\tilde{\nu}}$	496.78 GeV	$m_{\tilde{\chi}_1^{\pm}}$	270.65 GeV

$\sqrt{s}$	P_{e^-}	P_{e^+}
500 GeV	-0.8	+0.6
500 GeV	+0.8	-0.6
550 GeV	-0.8	+0.6
550 GeV	+0.8	-0.6

Chargino mixing angles with uncertainties and the resulting intersection highlighted



Parameter scan results for the dark matter relic density



- Beam polarization = crucial analysing tool of BSM properties and parameters!

Further Physics Examples

GMP et al, Phys.Rept. 460 (2008)

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	$P^T_{e^-} P^T_{e^+}$ 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 $\tilde{h}_+ = \mathrm{Im}(g_1^R + \kappa^R)/\sqrt{2}$	$P^T_{e^-} P^T_{e^+}$ required
CPV in γZ	Anomalous TGC $\gamma\gamma Z$, γZZ	$P^T_{e^-} P^T_{e^+}$ 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, $B = WW$ $\Rightarrow m_{\tilde{\mu}_{L,R}}$ in the continuum	factor 5-7
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 $\tilde{\chi}^0_i\tilde{\chi}^0_j$	Direct CP-odd observables	$P^T_{e^-} P^T_{e^+}$ 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

GMP et al, Phys.Rept. 460 (2008)

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 provides additional 'physics gain' !!!**
- **Crucial sensitivity to coupling structures**
- **Relevant for practically all BSM models……..**

Conclusions

- **Beam polarization e^- and e^+ gives 'added-value' to LCF, ILC,CLIC,HALHF**
  - **Crucial 'new' analysis tools compared to LHC physics**
  - **Access to chirality: since E≫m: chirality=helicity='polarization'**
- **P_{e+} important at$\sqrt{s}$=250,350,550 GeV (Higgs!) as well as at higher $\sqrt{s}$**
  - **Saves running time**
  - **Essential to control systematics**
  - **Provides crucial 'add-on' to LHC analyses**
  - **Important o match precision promises/expectations!**
  - ➢ **Precision allows sensitivity to beyond SM physics**

e.g. LCC physics group, 1801.02840

- **Exploitation of both longitudinally-&transversely-pol. beams**
  - **CP-violating pheno, etc.**

Polarized e+ and e- beams included in all LC-designs: LCF, ILC, CLIC,HALHF!

Circular e+e- designs: CEPC (Z, 250,350) also tries to get polarization for physics analyses

- **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! (see e.g. Phys. Rept. 460 (2008), hep-ph/0507011)**