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Determination of CP-violating Higgs couplings with transversely-polarized beams at the ILC250

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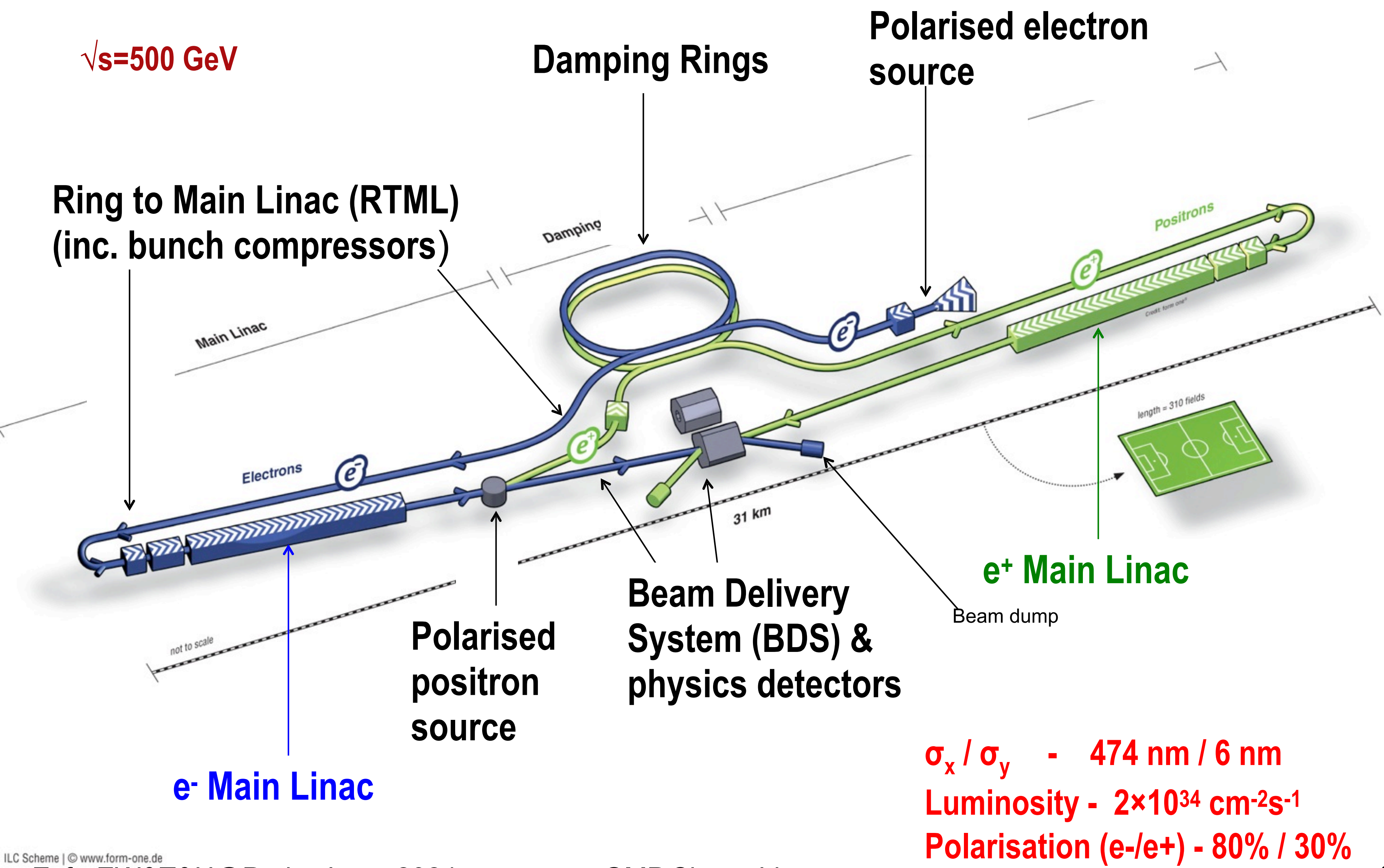
- Polarization Basics
- CP-odd observables via transversely-polarized beams
- Two approaches for HZZ
- Conclusion & Outlook

Most mature Design: ILC

$\sqrt{s}$=500 GeV



σ_x / σ_y - 474 nm / 6 nm

Luminosity - 2×10^{34} $cm^{-2}s^{-1}$

Polarisation (e-/e+) - 80% / 30%

Polarization basics

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

- **Cross section:**

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

- **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:**

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

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: $\vec{p}_a(\vec{p}_b \times \vec{p}_c)$

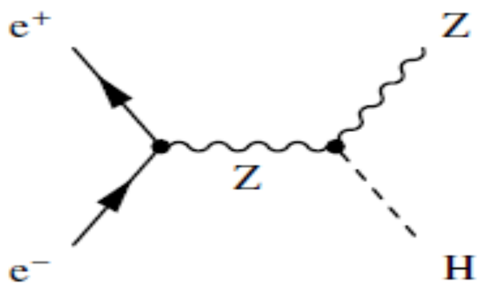
  $\vec{s}^{2\mu} := \vec{p}_1 \times \vec{p}_3$ perpendicular scattering plane, CP even

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

e.g. Cheng Li et al.

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!

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

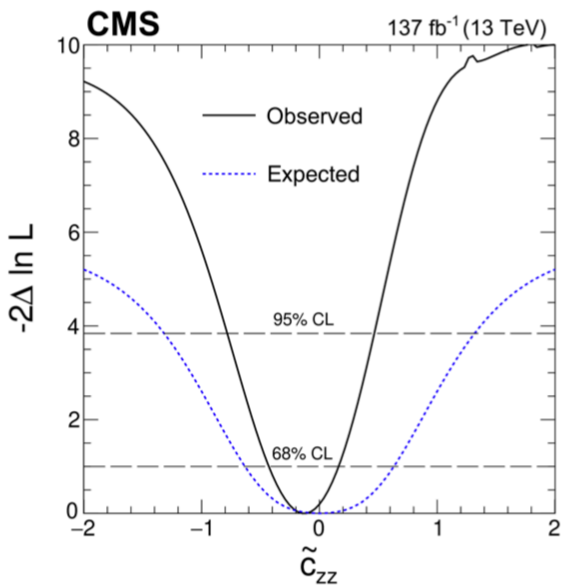
However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP in Higgs-Gauge-boson couplings

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

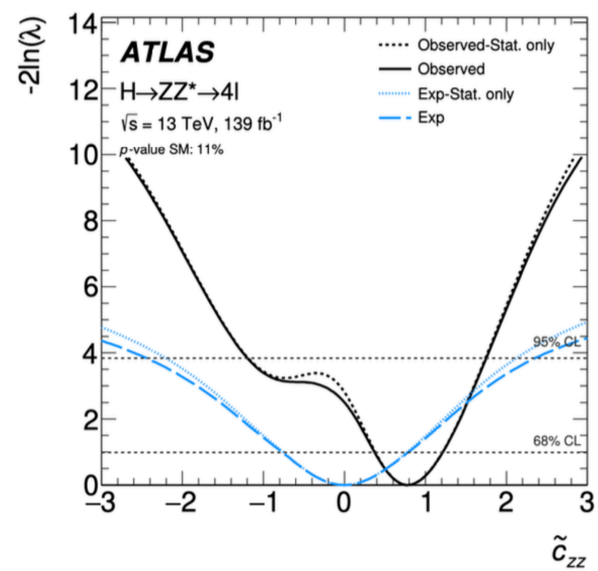
At LHC: H → 4 l measurement:

[CERN-EP-2021-054]



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

[CERN-EP-2023-030]

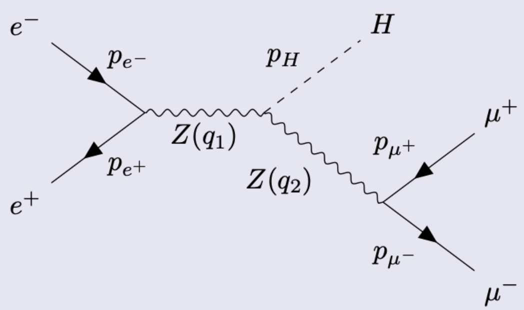


$$(\tilde{c}_{ZZ})_{\text{ATLAS}} \sim [-1.2, 1.75]$$

Probing CP at the e+e- collider

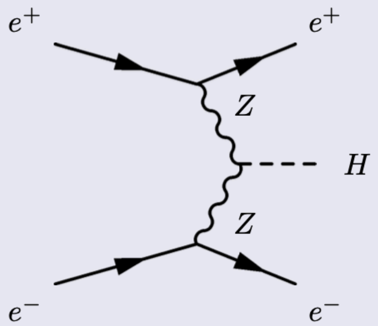
- CP probes of HZZ via Z-decay from HZ or Z fusion

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

Spindensity Formalism

H. Haber, 1994

- **Spin-density initial beams:**

$$\frac{1}{2}(1-\sigma\cdot P)_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1-P^3 & P^1-iP^2 \\ P^1+iP^2 & 1+P^3 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1-f\cos\theta_P & f\sin\theta_P e^{-i\phi_P} \\ f\sin\theta_P e^{i\phi_P} & 1+f\cos\theta_P \end{pmatrix}$$

- **Bouchiat-Michel:**

$$u(p,\lambda')\bar{u}(p,\lambda) = \frac{1}{2}(1+2\gamma_5)\not{p}\delta_{\lambda\lambda'} + \frac{1}{2}\gamma_5(\not{s}_-^1\sigma_{\lambda\lambda'}^1 + \not{s}_-^2\sigma_{\lambda\lambda'}^2)\not{p}$$

$$v(p,\lambda')\bar{v}(p,\lambda) = \frac{1}{2}(1-2\gamma_5)\not{p}\delta_{\lambda\lambda'} + \frac{1}{2}\gamma_5(\not{s}_+^1\sigma_{\lambda\lambda'}^1 + \not{s}_+^2\sigma_{\lambda\lambda'}^2)\not{p}$$

- **Higgsstrahlung:**

$$\rho^{ii'}(e^+e^-\to ZH) = \frac{1}{2}(\delta_{\lambda_r\lambda_r'} + P_-^m\sigma_{\lambda_r\lambda_r'}^m)\frac{1}{2}(\delta_{\lambda_u\lambda_u'} + P_+^n\sigma_{\lambda_u\lambda_u'}^n)M_{\lambda_r\lambda_u}^i M^{*i'}_{\lambda_r'\lambda_u'}$$

$$= (1-P_-^3P_+^3)A^{ii'} + (P_-^3-P_+^3)B^{ii'} + \sum_{mn}^{1,2} P_-^m P_+^n C_{mn}^{ii'}$$

➡both beams polarized required!

Amplitude Level

- Concentrate on additional CP-odd terms

$$|\mathcal{M}|^2 = |c_{\rm SM}\mathcal{M}_{\rm SM} + \tilde{c}_{HZZ}\widetilde{\mathcal{M}}_{HZZ}|^2$$
$$= |c_{\rm SM}\mathcal{M}_{\rm SM}|^2 + |c_{\rm SM}\tilde{c}_{HZZ}\mathcal{M}_{\rm SM}\widetilde{\mathcal{M}}_{HZZ}| + |\tilde{c}_{HZZ}\widetilde{\mathcal{M}}_{HZZ}|^2$$

$$c_{\rm SM} \propto \cos\xi_{CP}, \qquad \tilde{c}_{HZZ} \propto \sin\xi_{CP}$$

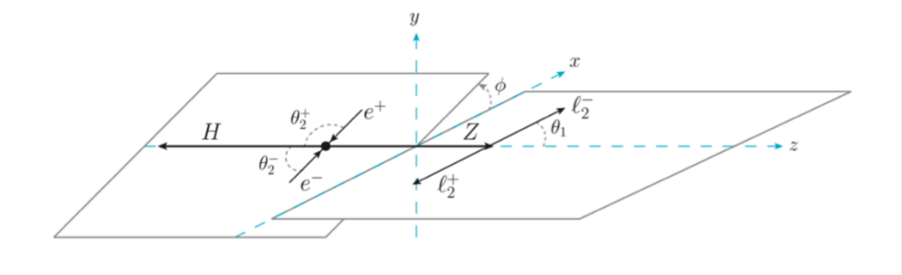
$$|\mathcal{M}|^2 = (1 - P_-^3 P_+^3)(\cos^2\xi_{CP}\,\mathcal{A}_{\text{CP-even}} + \sin 2\xi_{CP}\,\mathcal{A}_{\text{CP-odd}} + \sin^2\xi_{CP}\,\widetilde{\mathcal{A}}_{\text{CP-even}})$$
$$+ (P_-^3 - P_+^3)(\cos^2\xi_{CP}\,\mathcal{B}_{\text{CP-even}} + \sin 2\xi_{CP}\,\mathcal{B}_{\text{CP-odd}} + \sin^2\xi_{CP}\,\widetilde{\mathcal{B}}_{\text{CP-even}})$$
$$+ \sum_{mn}^{1,2} P_-^m P_+^n \left(\cos^2\xi_{CP}\,\mathcal{C}^{mn}_{\text{CP-even}} + \sin 2\xi_{CP}\,\mathcal{C}^{mn}_{\text{CP-odd}} + \sin^2\xi_{CP}\,\widetilde{\mathcal{C}}^{mn}_{\text{CP-even}}\right)$$

$$\mathcal{A}_{\text{CP-odd}}, \mathcal{B}_{\text{CP-odd}} \propto \epsilon_{\mu\nu\alpha\beta}[p^\mu_{e-} p^\nu_{e+} p^\alpha_{\mu+} p^\beta_{\mu-}] \propto (\vec{p}_{\mu+} \times \vec{p}_{\mu-}) \cdot \vec{p}_{e-}$$
$$\mathcal{C}^{mn}_{\text{CP-odd}} \propto \epsilon_{\mu\nu\rho\sigma}[(p_{e-} + p_{e+})^\mu p^\nu_{\mu+} p^\rho_{\mu-} s^\sigma_{e-}] \propto (\vec{p}_{\mu+} \times \vec{p}_{\mu-}) \cdot \vec{s}_{e-}$$

S. Biswal et al, '09

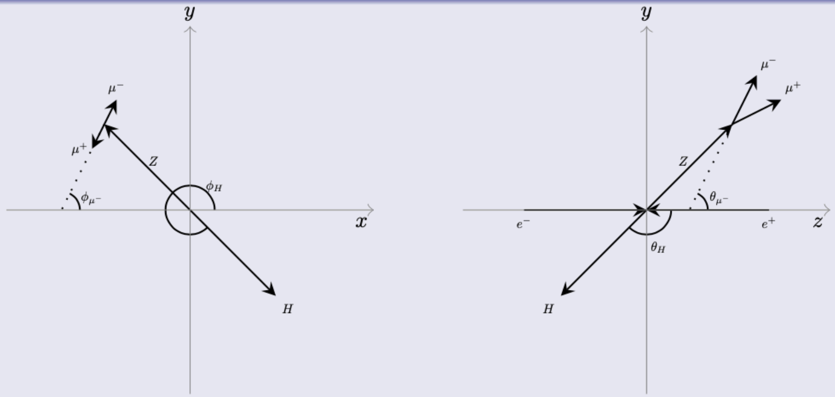
CP-sensitive observables

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 ($\vec{n}_y \propto \vec{s}_{e^-}$, $\vec{n}_x \propto \vec{s}_{e^-} \times \vec{p}_{e^-}$, $\vec{n}_z \propto \vec{p}_{e^-}$)

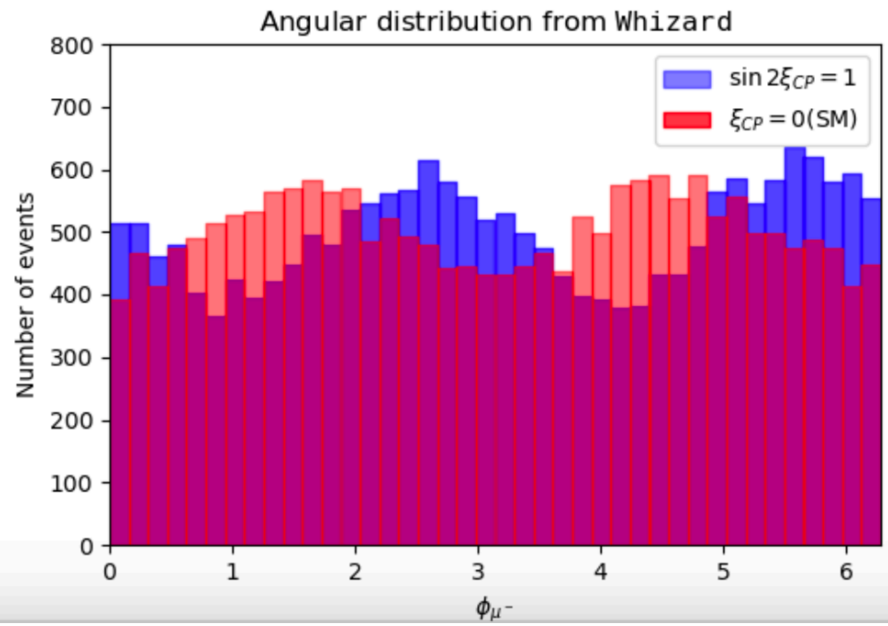


- The ϕ_{μ^-} is the azimuthal angle of the μ^--μ^+ plane with fixing the y-axis orientation to $\vec{s}_{e^-}$

Angular distribution (MC@WHIZARD)

- We fix the total cross-section to the SM tree-level cross-section, and use 100% parallel transverse polarisation

$$\sigma_{\text{tot}} = \cos^2 \xi_{CP}\, \sigma_{\text{SM}} + \sin^2 \xi_{CP} \tilde{\kappa}^2_{HZZ}\, \tilde{\sigma}_{\text{HZZ}} = \sigma_{\text{SM}},$$
$$P^2_- = P^2_+ = 100\%$$



➡ ***The angular distribution of muon azimuthal angle is sensitive to the CP-violation***

Azimuthal asymmetry

Construct the observables sensitive to CP-violation:

$$\mathcal{O}_{CP}^{T} \propto \cos\theta_H \sin 2\phi_{\mu^-}, \qquad \mathcal{O}_{CP}^{UL} \propto \cos\theta_\mu \sin\phi$$

We can define the following asymmetries:

$$\mathcal{A}_{CP}^{T} = \frac{N(\mathcal{O}_{CP}^{T} < 0) - N(\mathcal{O}_{CP}^{T} > 0)}{N_{\text{tot}}}$$

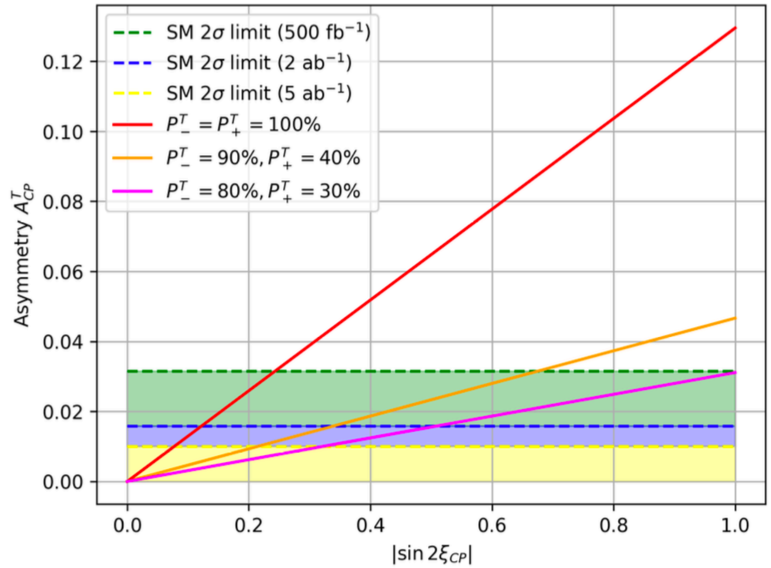
$$\mathcal{A}_{CP}^{UL} = \frac{N(\mathcal{O}_{CP}^{UL} < 0) - N(\mathcal{O}_{CP}^{UL} > 0)}{N_{\text{tot}}}$$

Statistical uncertainty (based on binomial distribution) of the Asymmetry:

$$\Delta\mathcal{A} = \sqrt{\frac{1-\mathcal{A}^2}{N_{\text{tot}}}}$$

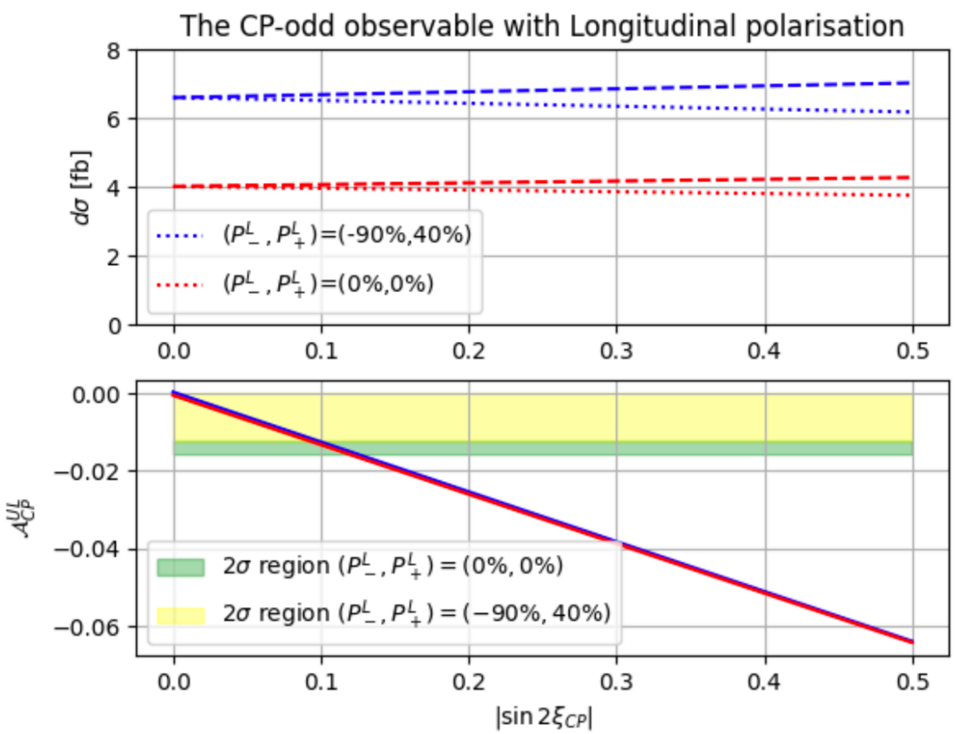
Variation of CP-mixing angle

We fix the total cross-section, and vary the CP-mixing angle ξ_{CP}



- This $\mathcal{A}^T_{CP}$ is linearly depending on the CP-mixing angle $\sin 2\xi_{CP}$
- The stronger transverse polarisation leads to larger $\mathcal{A}^T_{CP}$.
- For $(P^T_{e^-}, P^T_{e^+}) = (80\%, 30\%)$ and $L = 500\ \mathrm{fb}^{-1}$, one cannot distinguish the CP-violating case from CP-conserving case for any CP-mixing angle ξ_{CP} with only using $\mathcal{A}^T_{CP}$ observable.

Variation of CP-mixing angle



- The $\mathcal{A}^{UL}_{CP}$ linearly depends on the $\sin 2\xi_{CP}$ as well, while the beams polarisation cannot change the $\mathcal{A}^{UL}_{CP}$.
- One can also simultaneously measure the $\mathcal{A}^{UL}_{CP}$ when initial beams are transversely polarised.

Determination of CP-mixing angle

- Simply combine the two asymmetries

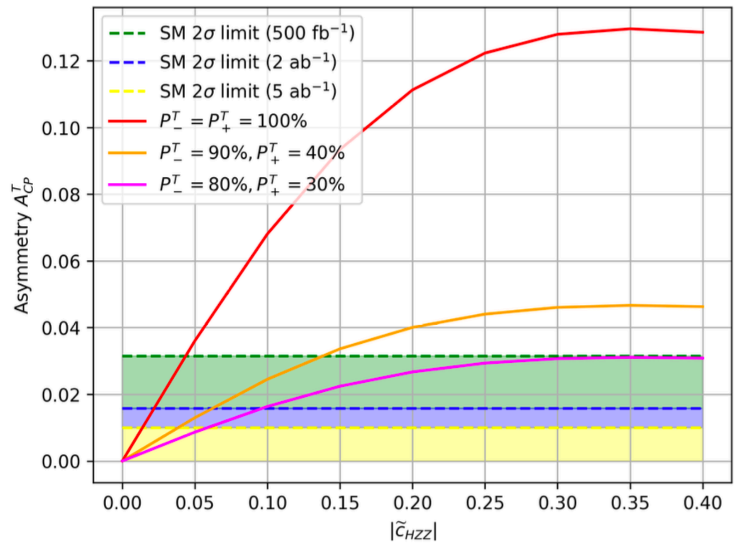
$$\chi^2_{\mathcal{A}_{\mathcal{CP}}} = (\frac{\mathcal{A}^T_{CP}}{\Delta\mathcal{A}^T_{CP}})^2 + (\frac{\mathcal{A}^{UL}_{CP}}{\Delta\mathcal{A}^{UL}_{CP}})^2 < 3.81$$

(P_-, P_+) Observables	$\mathcal{L}$ [ab^{-1}]	$\sin 2\xi_{CP}$ limit (95% C.L.) $\mathcal{A}^T_{CP}$	Combine $\mathcal{A}^T_{CP}$ & $\mathcal{A}^{UL}_{CP}$	$\mathcal{A}^{UL}_{CP}$
Transverse polarisation				
(80%, 30%)	2.0	[-0.50, 0.53]	[-0.113, 0.125]	
(80%, 30%)	5.0	[-0.36, 0.36]	[-0.068, 0.079]	
(90%, 40%)	2.0	[-0.33, 0.34]	[-0.118, 0.110]	
(90%, 40%)	5.0	[-0.23, 0.22]	[-0.066, 0.077]	
(100%, 100%)	5.0	[-0.082, 0.069]	[-0.056, 0.051]	
Longitudinal polarisation				
(−80%, 30%)	2.0			[-0.119,0.082]
(−80%, 30%)	5.0			[-0.066,0.063]
(−90%, 40%)	2.0			[-0.085,0.106]
(−90%, 40%)	5.0			[-0.059,0.062]
(−100%, 100%)	5.0			[-0.047,0.053]

➡ The systematic uncertainties can be cancelled out by the CP-odd asymmetry, since the background contribution is basically CP-even.

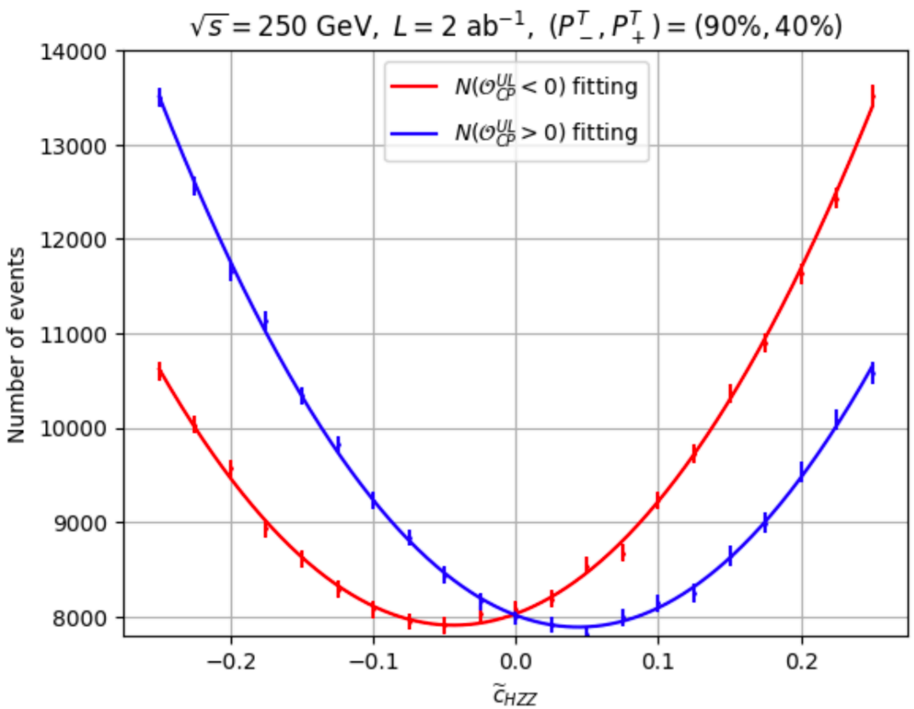
Variation of CP-odd coupling

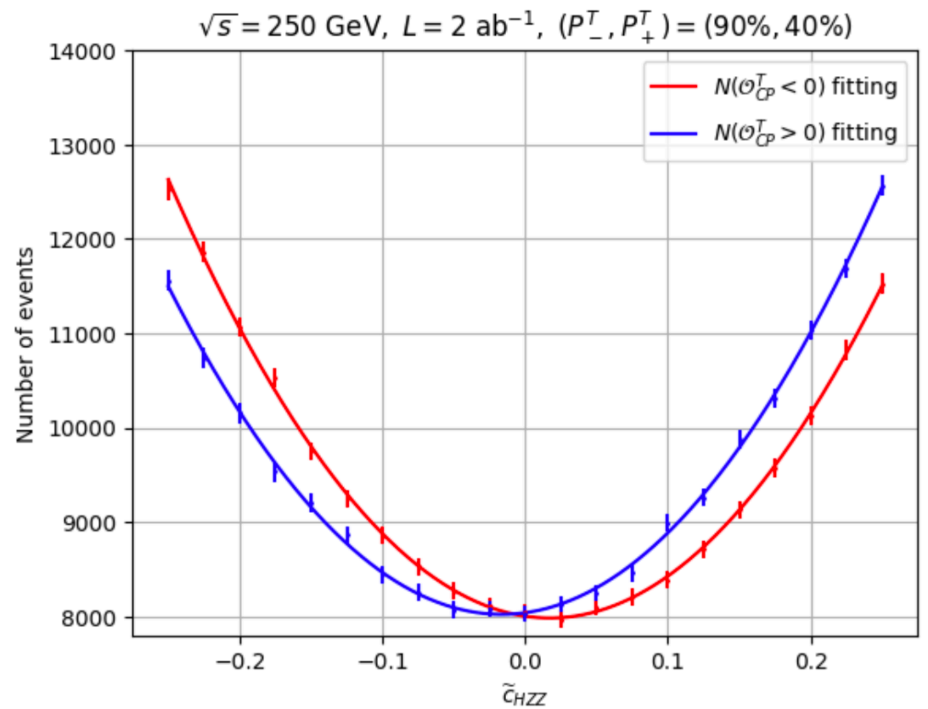
We fix $c_{\rm SM} = 1$ and vary $\widetilde{c}_{HZZ}$, in this case $\sigma_{\rm tot}$ would be increased by $\widetilde{c}_{HZZ}$



- The $\mathcal{A}^T_{CP}$ can reach to maximal when $\widetilde{c}_{HZZ} \sim 0.35$, and asymmetry $\mathcal{A}^T_{CP}$ would decrease for much higher $\widetilde{c}_{HZZ}$.
- For $(P^T_{e^-}, P^T_{e^+}) = (80\%, 30\%)$ and $L = 500\ \mathrm{fb}^{-1}$, one still cannot determine any CP-odd coupling $\widetilde{c}_{HZZ}$.

Determination of CP-odd coupling





- We made the quadratic function fit for the signal regions with varying $\tilde{c}_{HZZ}$

$$N_i = a\tilde{c}_{HZZ}^2 + b\tilde{c}_{HZZ} + c$$

Determination of CP-odd coupling

- One can combine the signal regions

$$\chi^2_N = \sum_i \left(\frac{(N(\mathcal{O}_i < 0) - N^{\mathrm{SM}}(\mathcal{O}_i < 0))^2}{N(\mathcal{O}_i < 0)} + \frac{(N(\mathcal{O}_i > 0) - N^{\mathrm{SM}}(\mathcal{O}_i > 0))^2}{N(\mathcal{O}_i > 0)} \right)$$

(P_-, P_+)	Luminosity [ab^{-1}]	$\widetilde{c}_{HZZ}$ ($\times 10^{-2}$) limit (95% C.L.)		
Observables		$\mathcal{O}^T_{CP}$	Combine $\mathcal{O}^{UL}_{CP}$ & $\mathcal{O}^T_{CP}$	$\mathcal{O}^{UL}_{CP}$
Transverse polarisation				
(80%, 30%)	2.0	[-4.45,4.65]	[-2.26, 1.93]	
(80%, 30%)	5.0	[-3.55,3.85]	[-1.29, 1.06]	
(90%, 40%)	2.0	[-4.55,4.15]	[-2.24, 1.69]	
(90%, 40%)	5.0	[-2.65,3.75]	[-1.12, 0.98]	
Longitudinal polarisation				
$(-80\%, 30\%)$	2.0			[-1.55,1.96]
$(-80\%, 30\%)$	5.0			[-1.01,1.16]
$(-90\%, 40\%)$	2.0			[-1.73,1.53]
$(-90\%, 40\%)$	5.0			[-0.93,1.18]

* The explicit combined results can be obtained by the background simulation and log-likelihood estimation

Comparison of both methods

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

* 29.5.1929 † 8.4.2024

Conclusion & Outlook

- CP-Structure of the Higgs sector still unresolved and sensitive to NP
- e+e- collider with polarized beams can achieve high precision for determining the CP-structure of HZZ
- Transversely-polarized beams provide new CP-odd observables to enhance sensitivity
- Longitudinally-polarized beams enhance x-section, lower stat. uncertainty → higher sensitivity to CP-observables!
- High luminosity and high degree of polarization needed!
- Apply concrete model studies to future designs, including HALHF (250 GeV to 500 GeV and higher!)

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+}=40%: $\sigma_{pol}/\sigma_{unpol} \sim 1.55$ (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+): 20% longer running time!…..** *~few years and less precision!*

In general: Interactions and Polarization

- **Different Interaction structures:** $\sigma \sim T_k T_l^*$ *hep-ph/0507011*

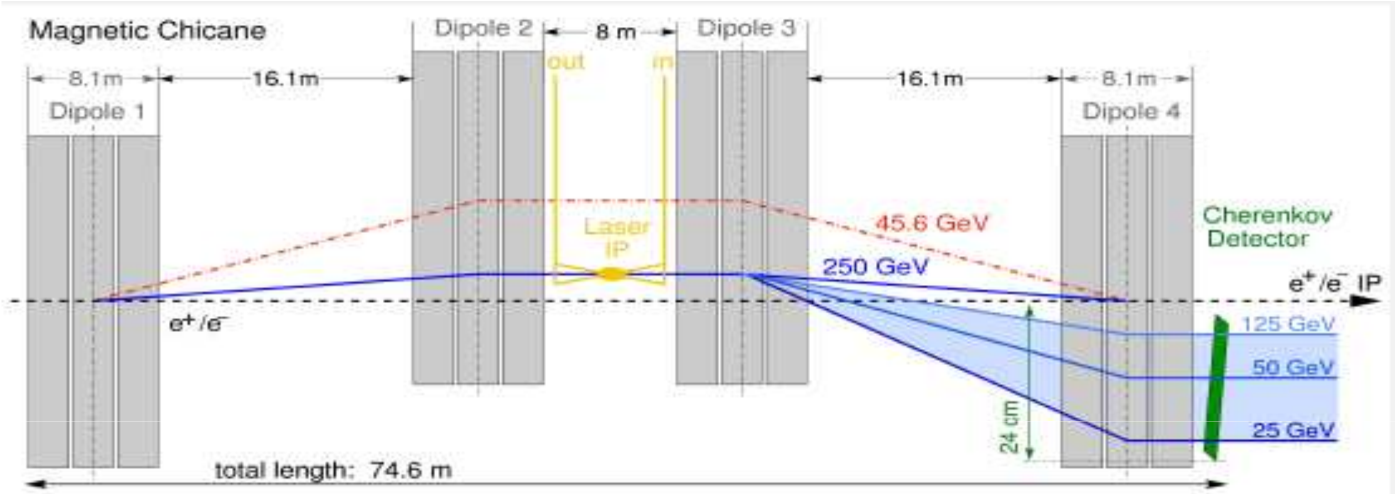
S=scalar-, P=pseudoscalar-, V=vector-, A=axial-vector-, T=tensor- like interactions

Interaction structure		Longitudinal		Transverse		Longitudinal/Transverse
Γ_k	$\bar{\Gamma}_\ell$	Bilinear	Linear	Bilinear	Linear	Interference
S	S	$\sim P_{e^-}P_{e^+}$	–	$\sim P^T_{e^-}P^T_{e^+}$	–	–
S	P	–	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	–	–
S	V,A	–	–	–	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
S	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$		–
P	P	$\sim P_{e^-}P_{e^+}$	–	$\sim P^T_{e^-}P^T_{e^+}$	–	–
P	V,A	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
P	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$		–
V,A	V,A	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	–	–
V,A	T	–	–	–	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
T	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	–	–

- **dependence on polarization provides information on kind of interaction**

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%

Statistics Suppression of WW and ZZ production

WW, ZZ production = large background for NP searches!

W^- couples only left–handed:
$\rightarrow$ 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	$\times 2$	$\times 0.5$	$\times 4$	$\times 2\sqrt{2}$
Example 2	$\times 2$	$\times 2$	Unchanged	$\times\sqrt{2}$

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

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

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

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

Quite substantial in Higgs production via WW-fusion!

L_{eff} and P_{eff}

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

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

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

ILC baseline: With $\mp 80\%$, $\pm 30\%$, the increase is 24% — $P_{eff} \sim 89\%$

With $\mp 80\%$, $\pm 60\%$, the increase is 48% — $P_{eff} \sim 95\%$

With $\mp 90\%$, $\pm 60\%$, the increase is 54% — $P_{eff} \sim 97\%$

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 Higgsstrahlung and electroweak 2f production !

- 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!

Polarization basics

- **Applicable for V,A processes (most SM, some BSM)**

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

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

$\sqrt{s}$	$P(e^-)$	$P(e^+)$	P_{eff}	$\mathcal{L}_{\text{eff}}/L$	$\Delta A_{LR}/A_{LR}$
total range	$\mp 80\%$	0%	$\mp 80\%$	0.5	1
250 GeV	$\mp 80\%$	$\pm 40\%$	$\mp 91\%$	0.65	0.43
$\geq$350 GeV	$\mp 80\%$	$\pm 55\%$	$\mp 94\%$	0.7	0.30

CP-violating admixtures in the Higgs sector

Sensitivity at the LHC and e^+e^- Higgs factories

[C. Li, G. Moortgat-Pick '24]

$e^+e^- \to HZ \to H\mu^-\mu^+$ with transverse and longitudinal beam pol.

Experiments	ATLAS[24]	CMS[19]	HL-LHC[25]	CEPC[29]	CLIC[30]	CLIC [31, 40]	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
$(\lvert P_-\rvert, \lvert P_+\rvert)$							$(90\%, 40\%)$
$\tilde{c}_{HZZ}$ $(\times 10^{-2})$ 95% C.L. (2σ)limit	[-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]

$\tilde{c}_{HZZ} = a_3$