The Central Role of Beam Polarization at Future e+e- Linear Colliders

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

More details on:
- interplay of pol&syst ➔ see talk Beyer/List
- pol and dark matter ➔ see talk Zarnecki
Required features at LHC & ILC

In order to reveal the structure of the underlying (new) physics:

- high energy desirable to reach the scale of new physics
- high luminosity needed to get sufficient statistics
- high level of experimental flexibility needed
- high precision measurements needed to get access to the quantum structure

Spin and polarization physics is important
- access to quantum properties, structure of couplings, etc.

How to exploit spin effects in particle reactions?

- initial particles: \( e^+ e^- \)
- short-living, intermediate states: \( \text{fermion}_1 + \text{fermion}_2 \)
- final particles: quarks, leptons

- beam polarization
- spin correlations
- polarization of top, \( \tau \)

\( \text{LC, today only} \)
\( \text{LHC, LC: CP e.g.} \)
\( \text{LC, partially LHC} \)
Why are polarized beams required?

• Please remember: excellent e- polarization ~78% at SLC:
  – led to best measurement of $\sin^2\theta = 0.23098 \pm 0.00026$ on basis of $L \sim 10^{30} \text{ cm}^{-2}\text{s}^{-1}$

• Compare with results from unpolarized beams at LEP:
  – $\sin^2\theta = 0.23221 \pm 0.00029$ but with $L \sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$

› polarization essential for suppression of systematics!

see also talk J.Beyer/J. List

Literature: polarized e+e- beams at a LC

• 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/0507122
• many more (only few examples): 1206.6639, 1306.6352 (ILC TDR), 1504.01726, 1702.05377, 1908.11299, 2001.03011, ...
Polarization basis

- **Formalism:** Use e.g. helicity spinors \( u(p, \lambda), v(p, \lambda) \rightarrow \) density matrix

- **Definition:** Basis of Spinvektors \( s^a, a = 1, 2, 3 \) with \( (s^a p) = 0 \):
  
  - **Longitudinal Spinvektors:** \( s^{3\mu}(p_{1,2}) := \frac{1}{m_{1,2}}(|p_{1,2}|, E\hat{p}_{1,2}) \)
  
  - **Transverse Spinvektors:**
    
    \( s^{2\mu}(p_1) := (0, \vec{p}_1 \times \vec{p}_3), \quad s^{2\mu}(p_2) = s^{2\mu}(p_1) \)
    
    \( s^{1\mu}(p_1) := (0, \vec{p}_1 \times \vec{s}^2(p_1)), \quad s^{1\mu}(p_2) = -s^{1\mu}(p_1) \)

  ![Diagram of polarization basis](image)

- **Definition:** ‘left-handed’ and ‘right-handed’ \( \equiv \) with respect to \( \hat{p} \)

  If Spinvektor \( \vec{s}^3 \parallel \vec{p} \) \( \equiv \) (‘right-handed’: \( P > 0 \))
  
  \( \vec{s}^3 \parallel \) (antiparallel \( \vec{p} \)) \( \equiv \) (‘left-handed’: \( P < 0 \))

- **Polarization** = ensemble of particles with definite helicity \( \lambda = -\frac{1}{2} \) left- or \( +\frac{1}{2} \) right-handed:

\[
\mathcal{P} = \frac{\#N_R - \#N_L}{\#N_R + \#N_L}
\]
General remarks: coupling structure

s-channel:

\[ e^+ \]

\[ J=1 \]

\[ J=0 \]

only from RL, LR: SM (\( \gamma, Z \))

only from LL, RR: NP!

⇒ In principle: \( P(e^-) \) fixes also helicity of \( e^+ \)!

t-channel:

\[ e^+ \]

depends on \( P(e^+) \)!

⇒ helicity of \( e^- \) not coupled with helicity of \( e^+ \)!

\[ e^- \]

depends on \( P(e^-) \)!

b) Bhabha scattering

⇒ \( \gamma, Z \) exchange in s-channel:
selects LR, RL

⇒ \( \gamma, Z \) exchange in t-channel:
LL, RR possible!

Two examples:

a) Single W production

only influenced by \( P(e^+) \)!

\[ e^+ \]

\[ \bar{\nu} \]

\[ W^+ \]

\[ e^- \]

unpolarised

\( P_{e^-} = -80\% \) | 4.50 pb

\( P_{e^-} = -80\%, P_{e^+} = -60\% \) | 4.69 pb

\( P_{e^-} = -80\%, P_{e^+} = +60\% \) | 4.58 pb
Physics: pol. cross sections in general

Polarized cross sections can be subdivided in:

\[ \sigma_{P_e^-P_e^+} = \frac{1}{4} \left\{ (1 + P_{e^-})(1 + P_{e^+}) \sigma_{RR} + (1 - P_{e^-})(1 - P_{e^+}) \sigma_{LL} + (1 + P_{e^-})(1 - P_{e^+}) \sigma_{RL} + (1 - P_{e^-})(1 + P_{e^+}) \sigma_{LR} \right\} \]

\( \sigma_{RR}, \sigma_{LL}, \sigma_{RL}, \sigma_{LR} \) are contributions with fully polarized L, R beams.

If (axial)vector-like (i.e. \( \gamma, Z \)): only (LR) and (RL) configurations contribute:

\[ \sigma_{P_e^-P_e^+} = \frac{1 + P_{e^-}}{2} \frac{1 - P_{e^+}}{2} \sigma_{RL} + \frac{1 - P_{e^-}}{2} \frac{1 + P_{e^+}}{2} \sigma_{LR} \]

\[ = (1 - P_{e^-}P_{e^+}) \frac{\sigma_{RL} + \sigma_{LR}}{4} \left[ 1 - \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}} \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}} \right] \]

\[ = (1 - P_{e^+}P_{e^-}) \sigma_0 \left[ 1 - P_{\text{eff}} A_{LR} \right], \]
Statistical arguments

- Effective polarization

\[ P_{\text{eff}} := \frac{(P_{e^-} - P_{e^+})}{(1 - P_{e^-}P_{e^+})} = \frac{(#LR - #RL)}{( #LR + #RL)} \]

- Fraction of colliding particles

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

\[
\begin{array}{c|c|c|c|c|c}
\hline
 P_{e^-} & P_{e^+} & e^- & e^+ & h_{e^-} & h_{e^+} & \text{cross section} \\
\hline
 -1 & 0 & \includegraphics[width=3cm]{example1} & \includegraphics[width=3cm]{example2} & -1 & 1 & \sigma_{LR} \\
 +1 & 0 & \includegraphics[width=3cm]{example3} & \includegraphics[width=3cm]{example4} & 1 & -1 & \sigma_{RL} \\
 -1 & 1 & \includegraphics[width=3cm]{example5} & \includegraphics[width=3cm]{example6} & -1 & 1 & \sigma_{LR} \\
 +1 & -1 & \includegraphics[width=3cm]{example7} & \includegraphics[width=3cm]{example8} & 1 & 1 & \sigma_{RL} \\
\hline
\end{array}
\]

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

- Effective polarization

\[ P_{\text{eff}} := \frac{(P_{e^-} - P_{e^+})}{(1 - P_{e^-}P_{e^+})} = \frac{(#LR - #RL)}{(#LR + #RL)} \]

- Fraction of colliding particles

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

Colliding particles:

<table>
<thead>
<tr>
<th></th>
<th>RL</th>
<th>LR</th>
<th>RR</th>
<th>LL</th>
<th>( P_{\text{eff}} )</th>
<th>( \mathcal{L}_{\text{eff}} / \mathcal{L} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P(e^-) = 0, )( P(e^+) = 0 )</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.</td>
<td>0.5</td>
</tr>
<tr>
<td>( P(e^-) = -1, )( P(e^+) = 0 )</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
<td>-1</td>
<td>0.5</td>
</tr>
<tr>
<td>( P(e^-) = -0.8, )( P(e^+) = 0 )</td>
<td>0.05</td>
<td>0.45</td>
<td>0.05</td>
<td>0.45</td>
<td>-0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>( P(e^-) = -0.8, )( P(e^+) = +0.6 )</td>
<td>0.02</td>
<td>0.72</td>
<td>0.08</td>
<td>0.18</td>
<td>-0.95</td>
<td>0.74</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \text{Enhancing of } \mathcal{L}_{\text{eff}} \text{ with } P(e^-) \text{ and } P(e^+)! \]
Impact of $P(e^+)$

And gain in precision

Statistics

$P_{\text{eff}} / \%$

$P_e^- = -90\%$

$P_e^- = -80\%$

$P_e^- = -70\%$

$P_{e^+} / \%$

$\Delta A_{LR} / A_{LR} \approx 0.3$

$\Delta A_{LR} / A_{LR} \approx 0.27$

$\Delta A_{LR} / A_{LR} \approx 0.5$

gain: factor $\approx 3$

factor $>3$

factor $\approx 2$

NO gain with only pol. e- (even if '100% ')!
QED: parity conserved, $A_{LR}=0$

Charged currents: $A_{LR}=1$
Parity violating
only left-handed $e^-$ couple

Neutral currents: $A_{LR}=0.15$
Parity violating
left-handed $e^-$, right-handed $e^+$
SM Processes: coupling structures

2 Fermion: LR, RL

Higgs: LR, RL

W-production:
- only LR:
- LR, RL:

Single W:
- only LR and LL!

Single W⁺:
- only RL and RR!
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:

<table>
<thead>
<tr>
<th>$P_{e^-} = \mp 80%$, $P_{e^+} = \pm 60%$</th>
<th>$e^+e^- \rightarrow W^+W^-$</th>
<th>$e^+e^- \rightarrow ZZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+0)</td>
<td>0.2</td>
<td>0.76</td>
</tr>
<tr>
<td>(−0)</td>
<td>1.8</td>
<td>1.25</td>
</tr>
<tr>
<td>(+−)</td>
<td>0.1</td>
<td>1.05</td>
</tr>
<tr>
<td>(−+)</td>
<td>2.85</td>
<td>1.91</td>
</tr>
</tbody>
</table>

‘No lose theorem’: scaling factors for signals & background

<table>
<thead>
<tr>
<th>Example</th>
<th>$S$</th>
<th>$B$</th>
<th>$S/B$</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example 1</td>
<td>$\times 2$</td>
<td>$\times 0.5$</td>
<td>$\times 4$</td>
<td>$\times 2\sqrt{2}$</td>
</tr>
<tr>
<td>Example 2</td>
<td>$\times 2$</td>
<td>$\times 2$</td>
<td>Unchanged</td>
<td>$\times \sqrt{2}$</td>
</tr>
</tbody>
</table>
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**
  - 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!)

see also talk J.Beyer/J. List
Transversely polarized beams

Transversely polarized beams enables to exploit azimuthal asymmetries in fermion production!

- the process $e^+e^- \rightarrow W^+W^-:$
  $\Rightarrow$ azimuthal asymmetry projects out $W_L^+W_L^-$

- the process $e^+e^- \rightarrow tt:$
  $\Rightarrow$ probe leptoquark models

- the process $e^+e^- \rightarrow ff:$
  $\Rightarrow$ probe extra dimensions

- the construction of CP violating observables:
  $\Rightarrow$ matrix elements $|M|^2 \sim C \times \Delta(\alpha)\Delta^*(\beta) \times S(c=\text{coupl.}, \Delta=\text{prop.}, S=\text{momenta})$

  if CP violation: contributions of $Im(C) \times Im(S)$ (e.g. contributions of $\epsilon$ tensors!)

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

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

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

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

- **Different Interaction structures:** 

  \( S = \text{scalar-}, \ P = \text{pseudoscalar-}, \ V = \text{vector-}, \ A = \text{axial-vector-}, \ T = \text{tensor-} \) like interactions

<table>
<thead>
<tr>
<th>Interaction structure</th>
<th>Longitudinal</th>
<th>Transverse</th>
<th>Longitudinal/Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_k )</td>
<td>( \bar{\Gamma}_\ell )</td>
<td>Bilinear</td>
<td>Linear</td>
</tr>
<tr>
<td>S</td>
<td>S</td>
<td>(~ P_e^- P_e^+)</td>
<td>(~ P_e^\pm)</td>
</tr>
<tr>
<td>S</td>
<td>P</td>
<td>–</td>
<td>(~ P_e^\pm)</td>
</tr>
<tr>
<td>S</td>
<td>V, A</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>S</td>
<td>T</td>
<td>(~ P_e^- P_e^+)</td>
<td>(~ P_e^\pm)</td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>(~ P_e^- P_e^+)</td>
<td>–</td>
</tr>
<tr>
<td>P</td>
<td>V, A</td>
<td>(~ P_e^- P_e^+)</td>
<td>(~ P_e^\pm)</td>
</tr>
<tr>
<td>P</td>
<td>T</td>
<td>(~ P_e^- P_e^+)</td>
<td>(~ P_e^\pm)</td>
</tr>
<tr>
<td>V, A</td>
<td>V, A</td>
<td>(~ P_e^- P_e^+)</td>
<td>(~ P_e^\pm)</td>
</tr>
<tr>
<td>V, A</td>
<td>T</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>T</td>
<td>T</td>
<td>(~ P_e^- P_e^+)</td>
<td>(~ P_e^\pm)</td>
</tr>
</tbody>
</table>

- dependence on polarization provides information on kind of interaction
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

**Supersymmetry (MSSM)**

MSSM ($\tan\beta = 5$, $M_A = 700$ GeV)

- $t$, $b$, $\tau$, $c$, $Z$, $W$

**Composite Higgs (MCHM5)**

MCHM5 ($f = 1.5$ TeV)

- $t$, $b$, $\tau$, $c$, $Z$, $W$

**ILC 250+500 LumiUp**

- Determination of Higgs couplings in 1% level essential for ILC250!
What did we promise for e+e- colliders?

- Precision of 1-2% achievable in Higgs couplings !!!

- Crucial input from ILC
  - total cross section $\sigma(\text{HZ})$
  - Has to be measured at $\sqrt{s}=250\text{GeV}$
  - Input parameter for all further Higgs studies (Higgs width etc.) !

- Lots of improvement if only $\sigma(\text{HZ})$ from ILC is added
Process: Higgs Strahlung

- $\sqrt{s}=250$ GeV: dominant process
- Why crucial?
  - allows model-independent access!
  - Absolute measurement of Higgs cross section $\sigma(HZ)$ and $g_{HZZ}$: crucial input for all further Higgs measurement!
  - Allows access to $H \rightarrow$ invisible/exotic
  - Allows with measurement of $\Gamma^h_{\text{tot}}$ 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
    \[ \frac{\sigma_{\text{pol}}}{\sigma_{\text{unpol}}} \sim (1 - 0.151 \, P_{\text{eff}}) \times \frac{L_{\text{eff}}}{L} \]
    With $P_{e^+} = 0\%$: \[ \frac{\sigma_{\text{pol}}}{\sigma_{\text{unpol}}} \sim 1.13 \]
    With $P_{e^+} = 30\%$: \[ \frac{\sigma_{\text{pol}}}{\sigma_{\text{unpol}}} \sim 1.51 \]
    (about 33\% increase compared to 0\%)
  - Background: mainly ZZ (if leptonic), WW (if hadronic)
  - $S/B$: \[
  \begin{array}{ll}
  & 1.14 (+,0) & 4.35 (+,0) \\
  & 1.20 (+,-) & 12.6 (+,-) \\
  \end{array}
  \]
  - $S/\sqrt{B}$: \[
  \begin{array}{ll}
  & 0.99 (+,0) & 1.95 (+,0) \\
  & 1.22 (+,-) & 3.98 (+,-) \\
  \end{array}
  \]

- Loss if no $P_{e^+}$: ~20\% ~ factor 2

- Physics Panel used both beams polarized! $P_{e^+}$ is important ...

Spin2021 @ Matsue, Japan

G. Moortgat-Pick/IDT-WG3

9
Trilinear Higgs Couplings

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

At $\text{cms}=1$TeV $\Delta \lambda_{HHH} \sim 10\%$ achievable

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

see also talk J.Beyer/J. List
Top Yukawa Coupling

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

- **Numbers very ambitious**
  - Used so far: $(\pm 80, -30)$
  - Further improvement with $(\pm 80, -60)$:
    - $S$ increases by 24% if from $(80, 30)$ to $(80, 60)$
    - $S/\sqrt{B}$ increases by 50%
    - If no $P_{e^+}$: $S$ decreases by about 20%

---

see, e.g. C. Duerig, EPS’15

<table>
<thead>
<tr>
<th>$\Delta g_{Htt}/g_{Htt}$</th>
<th>ILC500</th>
<th>ILC500 LumiUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 GeV</td>
<td>18 %</td>
<td>6.3 %</td>
</tr>
<tr>
<td>550 GeV</td>
<td>$\sim 9 %$</td>
<td>$\sim 3 %$</td>
</tr>
</tbody>
</table>

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

top-Yukawa coupling crucial:

- since
- $g_{tth}$

$e^+ \gamma/Z \rightarrow e^-$

- Num
- Used
- Further improvements
  - $S$ increases
  - $S/\sqrt{B}$ increases

If no $P_{e^+}$: $S$

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

- by factor 4 enhanced cross section
- main backgrounds decrease
### Further Physics Examples

<table>
<thead>
<tr>
<th>Case</th>
<th>Effects</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SM:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>top threshold</td>
<td>Improvement of coupling measurement</td>
<td>factor 3</td>
</tr>
<tr>
<td>$t\bar{q}$</td>
<td>Limits for FCN top couplings reduced</td>
<td>factor 1.8</td>
</tr>
<tr>
<td>CPV in $t\bar{t}$</td>
<td>Azimuthal CP-odd asymmetries give access to S- and T-currents up to 10 TeV</td>
<td>$P_{e^-}P_{e^+}^T$ required</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$</td>
<td>up to a factor 2</td>
</tr>
<tr>
<td></td>
<td>TGC: error reduction of $\Delta \kappa_\gamma$, $\Delta \lambda_\gamma$, $\Delta \kappa_Z$, $\Delta \lambda_Z$</td>
<td>factor 1.8</td>
</tr>
<tr>
<td></td>
<td>Specific TGC $\tilde{h}_+ = \text{Im}(g^R_1 + \kappa R)/\sqrt{2}$</td>
<td>$P_{e^-}P_{e^+}^T$ required</td>
</tr>
<tr>
<td>CPV in $\gamma Z$</td>
<td>Anomalous TGC $\gamma \gamma Z$, $\gamma ZZ$</td>
<td>$P_{e^-}P_{e^+}^T$ required</td>
</tr>
<tr>
<td>$H_\gamma$</td>
<td>Separation: $H\gamma \leftrightarrow H\bar{\nu}\nu$</td>
<td>factor 4 with RL</td>
</tr>
<tr>
<td></td>
<td>Suppression of $B = W^+\ell^-\nu$</td>
<td>factor 1.7</td>
</tr>
<tr>
<td><strong>SUSY:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{e}^+\tilde{e}^-$</td>
<td>Test of quantum numbers $L$, $R$ and measurement of $e^\pm$ Yukawa couplings</td>
<td>$P_{e^+}$ required</td>
</tr>
<tr>
<td>$\tilde{\mu}\tilde{\mu}$</td>
<td>Enhancement of $S/B$, $B = WW$</td>
<td>factor 5–7</td>
</tr>
<tr>
<td>$H_A$, $m_A &gt; 500$ GeV</td>
<td>⇒ $m_{\tilde{\mu}_{L,R}}$ in the continuum</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^0\tilde{\chi}^0$</td>
<td>Access to difficult parameter space</td>
<td>factor 1.6</td>
</tr>
<tr>
<td></td>
<td>Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$</td>
<td>factor 2–3</td>
</tr>
<tr>
<td>CPV in $\tilde{\chi}^0_{i}\tilde{\chi}^0_j$</td>
<td>Separation between SUSY models, ‘model-independent’ parameter determination</td>
<td></td>
</tr>
<tr>
<td>RPV in $\tilde{\nu}_\tau \rightarrow \ell^+\ell^-$</td>
<td>Direct CP-odd observables</td>
<td>$P_{e^-}P_{e^+}^T$ required</td>
</tr>
<tr>
<td></td>
<td>Enhancement of $S/B$, $S/\sqrt{B}$</td>
<td>factor 10 with LL</td>
</tr>
<tr>
<td></td>
<td>Test of spin quantum number</td>
<td></td>
</tr>
</tbody>
</table>
# Further Physics Examples

<table>
<thead>
<tr>
<th>ED:</th>
<th>Enhancement of $S/B$, $B = \gamma \nu \bar{\nu}$, Distinction between ADD and RS modes</th>
<th>factor 3, $P_e^T P_{e^+}^T$ required</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G\gamma$</td>
<td>$e^+e^- \rightarrow f \bar{f}$</td>
<td></td>
</tr>
<tr>
<td>$Z'$:</td>
<td>Measurement of $Z'$ couplings</td>
<td>factor 1.5</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow f \bar{f}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CI:</td>
<td>Model independent bounds</td>
<td>$P_{e^+}$ required</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow q\bar{q}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Precision measurements of the Standard Model at GigaZ:

<table>
<thead>
<tr>
<th></th>
<th>Improvement of $\Delta \sin^2 \theta_W$</th>
<th>factor 5–10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$-pole</td>
<td>Constraints on CMSSM space</td>
<td>factor 5</td>
</tr>
<tr>
<td>CPV in $Z \rightarrow b\bar{b}$</td>
<td></td>
<td>factor 3</td>
</tr>
<tr>
<td></td>
<td>Enhancement of sensitivity</td>
<td></td>
</tr>
</tbody>
</table>

- Many new physics examples
- Beam polarization always provides ‘physics gain’
- Crucial sensitivity to coupling structures
- Still further new studies ongoing……..
Short overview: $e^+$ sources at ILC

- Conventional source: $e^-$ scattering in target $\xrightarrow{\text{pair production}} e^+$
- 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

- Beam polarization status: at $\text{cms}=250$ GeV: $P(e^-)\sim 80\text{-}90\%$, $P(e^+)\sim 30\%$
  - $=350, 500$ GeV: $P(e^-)\sim 80\text{-}90\%$, $P(e^+)=40\%$ (60\% with collimator)

(with chosen undulator parameters for $\text{cms}=500$ GeV)

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>ILC (RDR)</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+/\text{bunch}$</td>
<td>$3.5 \times 10^{10}$</td>
<td>$2 \times 10^{10}$</td>
<td>$0.64 \times 10^{10}$</td>
</tr>
<tr>
<td>Bunches/pulse</td>
<td>1</td>
<td>2685</td>
<td>312</td>
</tr>
<tr>
<td>Pulse rep rate</td>
<td>120</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>$e^+/s$</td>
<td>$0.042 \times 10^{14}$</td>
<td>$2.6 \times 10^{14}$</td>
<td>$1 \times 10^{14}$</td>
</tr>
</tbody>
</table>

➤ in general: demanding challenges for the $e^+$ source!
Caution: helicity flipping is required

• Gain in effective lumi lost if no flipping available
  - 50% spent to ‘inefficient’ helicity pairing (most SM, BSM)
  - Similar flip frequency for both beams ~ pulse-per-pulse

• Gain in $\Delta P_{\text{eff}}$ remains, but flipping required to understand:
  - Systematics and correlations $P_{e^-} \times P_{e^+}$

• Spin rotator before DR and spinflipper in set-up for baseline!
  - done!

E.g. S. Riemann

Spin2021 @ Matsue, Japan
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 $\Delta P/P = 0.25\%$ (at polarimeters!)
  • But that’s is not enough for IP!

• Use collision data to derive luminosity-weighted polarization
  • single $W, WW, ZZ, Z, \text{ etc.}$: combined fit

\[
P_e^- = -|P_e^\pm| + \frac{1}{2}\delta_e^\pm \\

P_e^+ = |P_e^\pm| + \frac{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 $\Delta P/P$ is achievable at IP!

• NOT achievable without $P_{e+}$!

Remember: even if no $P_{e+}$ (SLC! dedicated experiment at SLACs Endstation A), the $P_{e+} \sim 0.0007$ had to be derived a posteriori for physics reason!
**$L_{\text{eff}}$ and $P_{\text{eff}}$**

- 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 $\pm 80\%$, $\pm 30\%$, the increase is 24%
- With $\pm 80\%$, $\pm 60\%$, the increase is 48%
- With $\pm 90\%$, $\pm 60\%$, the increase is 54%

In other words: no $P_{e^+}$ means 24% more running time (!) and
10% loss in $P_{\text{eff}}$ = 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 ν-exchange (A_{LR}=1):

\[ \sigma(P_{e-}, P_{e+}) = 2\sigma_0(L_{eff}/L)[1 - P_{eff}] \]

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

Quite substantial in Higgs production via WW-fusion!