Physics Motivation and Polarisation Measurements with $e^+e^-$ Annihilation Data

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- Why polarisation and how accurate?
- Polarisation measurements with annihilation data
- Experimental issues
- Conclusions
Why polarisation?

- In the SM the left and right handed states are different particles
- A LC with $e^-$ and $e^+$ polarisations in fact is four machines
- In detail:
  - only left handed electrons (right handed positrons) couple to the W
  - $\gamma$, Z and hypothetical new particles couple differently to left- and right handed states
  - polarisation is thus useful to enhance signal, suppress background and measure couplings
- Many processes proceed through s-channel vector particle exchange
  - electron polarisation in principle sufficient
  - however higher and more accurate effective polarisation with positron polarisation ($P_{\text{eff}} = (P_{e^+} + P_{e^-})/(1 + P_{e^+}P_{e^-})$)
  - processes with more complicated structure (e.g. t-channel) depend on both polarisations separately
How accurate?

Rule of thumb: $\Delta \mathcal{P}/\mathcal{P} < 1/\sqrt{N}$

- The polarisation accuracy is driven by the high statistics processes
- For Higgs, SUSY, etc. $\mathcal{O}(1\%)$ is sufficient
- For high statistics channels like $Z'$ searches or triple gauge couplings $\mathcal{O}(0.1\%)$ is required
- $\sin^2 \theta$ from GigaZ even requires $\Delta \mathcal{P}/\mathcal{P} < 10^{-4}$
- If $e^+$ polarisation is available the effective polarisation is known a factor three to four better than the individual polarisations
Polarisation measurements with annihilation data

- Polarisation can be measured with polarimeters to $0.25 - 0.5\%$ precision

- Depolarisation of colliding electrons $\sim 0.5\%$, of outgoing beam $\sim 2\%$

- Neither upstream nor downstream polarimeter measures the polarisation we need

- This problem can be overcome if the polarisation can be measured from annihilation data

- The large luminosity at LC offers also a better precision for data driven methods
Processes involving W bosons

- Ws couple to left handed electrons only
- In principle left-right asymmetry can measure electron polarisation directly
- Two processes:
  - single W production

\[ W^- (W^+) \text{ asymmetry measures directly } e^- (e^+) \text{ polarisation} \]
- W pair production:
  * complicated mixture of $\nu$ t-channel and $Z$, $\gamma$ s-channel exchange
  * large left-right asymmetry, depending on production angle and assumed couplings

* however forward peak dominated by $\nu$-exchange and basically independent of anomalous couplings

→ can fit for anomalous couplings and $P_{e^-}$ simultaneously
Achievable precision:

- $e^-$ polarisation only:
  \[ \frac{\delta \mathcal{P}}{\mathcal{P}} \sim 0.1\% \text{ from W-pairs and } \frac{\delta \mathcal{P}}{\mathcal{P}} \sim 0.15\% \text{ from single Ws} \]

- Both beam polarised:
  similar precision for both beams separately as for $e^-$ only
Blondel scheme with 2-fermion events

Assume only \( s \)-channel vector exchange

Four independent measurements:
(4 combinations with positive/negative electron/ positron polarisation)

\[
\begin{align*}
\sigma_{++} &= \sigma_u [1 - \mathcal{P}_{e+}\mathcal{P}_{e-} + A_{LR}(\mathcal{P}_{e+} - \mathcal{P}_{e-})] \\
\sigma_{--} &= \sigma_u [1 + \mathcal{P}_{e+}\mathcal{P}_{e-} + A_{LR}(-\mathcal{P}_{e+} - \mathcal{P}_{e-})] \\
\sigma_{+-} &= \sigma_u [1 + \mathcal{P}_{e+}\mathcal{P}_{e-} + A_{LR}(\mathcal{P}_{e+} + \mathcal{P}_{e-})] \\
\sigma_{-+} &= \sigma_u [1 - \mathcal{P}_{e+}\mathcal{P}_{e-} + A_{LR}(-\mathcal{P}_{e+} + \mathcal{P}_{e-})]
\end{align*}
\]

\[\implies \text{Can measure } \mathcal{P}_{e+}, \mathcal{P}_{e-} \text{ simultaneously with } A_{LR} \text{ if } A_{LR} \neq 0\]

\[
\mathcal{P}_{e\pm} = \frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{++} - \sigma_{--}) (\pm \sigma_{+} \pm \sigma_{++} - \sigma_{--})}{(\sigma_{+-} + \sigma_{-+} + \sigma_{++} + \sigma_{--}) (\pm \sigma_{+} \pm \sigma_{+} + \sigma_{++} - \sigma_{--})}
\]

Only difference between \(|\mathcal{P}_{e\pm}^+|\) and \(|\mathcal{P}_{e\pm}^-|\) needs to be known from polarimetry
Available event samples

• $f \bar{f}$ events at the highest energy (HE)
  - easy and background free to select
  - large $A_{LR}$ reduces error on $P$
  - however physics assumption on s-channel vector exchange
    (not valid e.g. for RPV $\tilde{\nu}$)

• radiative return events $e^+e^- \rightarrow Z\gamma \rightarrow f\bar{f}\gamma$ (RR)
  - large cross section
  - well known physics (LEP, SLC)
  - however large ($\sim 30\%$) Zee background at high energies when photon
    not reconstructed
  - Way out: photon reconstruction
    • only 9% efficiency with cut at $\theta_\gamma > 7^\circ$
Results:

\( \mathcal{P}_{e^-} = 0.80, \mathcal{P}_{e^+} = 0.60, \sqrt{s} = 340 \text{ GeV} \) (results scale with \( \sqrt{\sigma} \)), \( \mathcal{L} = 500 \text{ fb}^{-1} \)

Luminosity ratio \(+ - / - +/ + +/ - - = 1/1/1/1\)

- Radiative return:
  \[
  \frac{\delta \mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} = 0.0051 \quad \frac{\delta \mathcal{P}_{e^+}}{\mathcal{P}_{e^+}} = 0.0053 \quad \text{corr.} = -0.91
  \]

- High energy:
  \[
  \frac{\delta \mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} = 0.0010 \quad \frac{\delta \mathcal{P}_{e^+}}{\mathcal{P}_{e^+}} = 0.0012 \quad \text{corr.} = -0.49
  \]

Luminosity ratio \(+ - / - +/ + +/ - - = 9/9/1/1\)

- Errors \( \sim \) factor two larger
**Experimental issues**

**Assumptions involved:**

- absolute values of right- and left-handed polarisations are the same.
- no correlations between electron and positron polarisation exists

\[ |\mathcal{P}(L)| \neq |\mathcal{P}(R)| \] Assume \( \mathcal{P} = \pm \langle |\mathcal{P}| \rangle + \delta \mathcal{P} \)

- Ws with \( e^- \) polarisation only: \( \Delta \mathcal{P}/\mathcal{P} = \delta \mathcal{P} \)
- \( e^- \) and \( e^+ \) polarisation with Blondel scheme:
  - high energy sample:
    \[
    \begin{align*}
    \Delta \mathcal{P}_{e^-} &= 1.0 \delta \mathcal{P}_{e^-} + 0.6 \delta \mathcal{P}_{e^+} \\
    \Delta \mathcal{P}_{e^+} &= -0.5 \delta \mathcal{P}_{e^-} - 0.7 \delta \mathcal{P}_{e^+}
    \end{align*}
    \]
  - radiative return sample
    \[
    \begin{align*}
    \Delta \mathcal{P}_{e^-} &= 2.4 \delta \mathcal{P}_{e^-} + 2.1 \delta \mathcal{P}_{e^+} \\
    \Delta \mathcal{P}_{e^+} &= -1.7 \delta \mathcal{P}_{e^-} - 1.7 \delta \mathcal{P}_{e^+}
    \end{align*}
    \]
— Large effect, but partial cancellation in effective polarisation

- have to get $\delta \mathcal{P}$ from polarimeters
  - $\mathcal{P}(L)$ and $\mathcal{P}(R)$ can be measured individually flipping laser polarisation
  - have to assure that laser-electron luminosity does not depend on laser polarisation
  - can be unfolded internally in multichannel polarimeter with large lever-arm in analysing power
  - easier upstream?

Analysing power range of TESLA polarimeter
Correlations

In formulae for the Blondel scheme and in effective polarisations products of $P_{e+}$ and $P_{e-}$ enter

$\Rightarrow$ have to understand correlations between $P_{e+}$ and $P_{e-}$

- correlated time dependencies
  - effect quadratic with polarisation change
  - changed both polarisations for $\pm 5\%$ for half of the time
  $\Rightarrow 0.25\%$ effect on polarisation
  - Blondel scheme reproduces effective polarisation worse than polarimeter measurement.
    $(\Delta P_{\text{eff}} = 0.16\%$ for polarimeter, $\Delta P_{\text{eff}} = 0.25\%$ for Blondel scheme)$
  - need polarimeters to track time dependencies (e.g. inside a train) and possibility to change polarisation fast, e.g. parallel spin rotators for positrons
• correlations due to depolarisation at IP
  – depolarisation for interacting particles \( \sim 0.3\% \)
  – depolarisation of spent beam \( \sim 1\% \)
  – can be different for realistic beams
  – for ideal beams no effect on Blondel scheme according to CAIN

**Depolarisation as function of x–offset**

![Depolarisation graph](image)

\( \theta_{\text{Spin}} = 50 \text{ mrad} \)

• can there be spatial correlations from bends etc.?
**Special case: GigaZ**

- GigaZ: $10^9$ Z decays to measure $\sin^2 \theta_{eff}^l$ with a precision of $10^{-5}$ via $A_{LR}$
- $e^+$ polarisation with Blondel scheme is a must if this precision shall be reached
- $A_{LR}$ will be unfolded internally $\Rightarrow$ no additional physics assumption
  
  $A_{LR} = \sqrt{\frac{(\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+})(-\sigma_{++} + \sigma_{--} - \sigma_{+-} + \sigma_{-+})}{(\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+})(-\sigma_{++} + \sigma_{--} + \sigma_{+-} - \sigma_{-+})}}$

- main challenge from polarimetry: difference between left- and right-handed polarisation needs to be understood to $< 10^{-4}$
- for time dependences 1% precision is sufficient
- other polarisation systematics seem negligible
- non polarisation systematics not discussed in this talk
Conclusions

- Polarimetry in the per mille region is required for ILC

- Positron polarisation helps a lot to achieve this

- The polarisation can also be measured from the data themselves with per mille errors.

- Each measurement from data involves physics assumptions which have to be justified within the specific analyses.

- Also in this case polarimeters are needed for corrections

- Polarimeter and data methods are largely complementary and both are needed to get the ultimate precision.