Measuring beam polarisation with e^+e^- interactions at high energy

Klaus Mönig

DESY -Zeuthen

- Introduction
- W-pairs with e^- polarisation only
- Positron polarisation and effective polarisations
- The Blondel scheme with 2-fermion events and W-pairs
- Experimental issues
- Special case: GigaZ
- Conclusions

Introduction

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

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

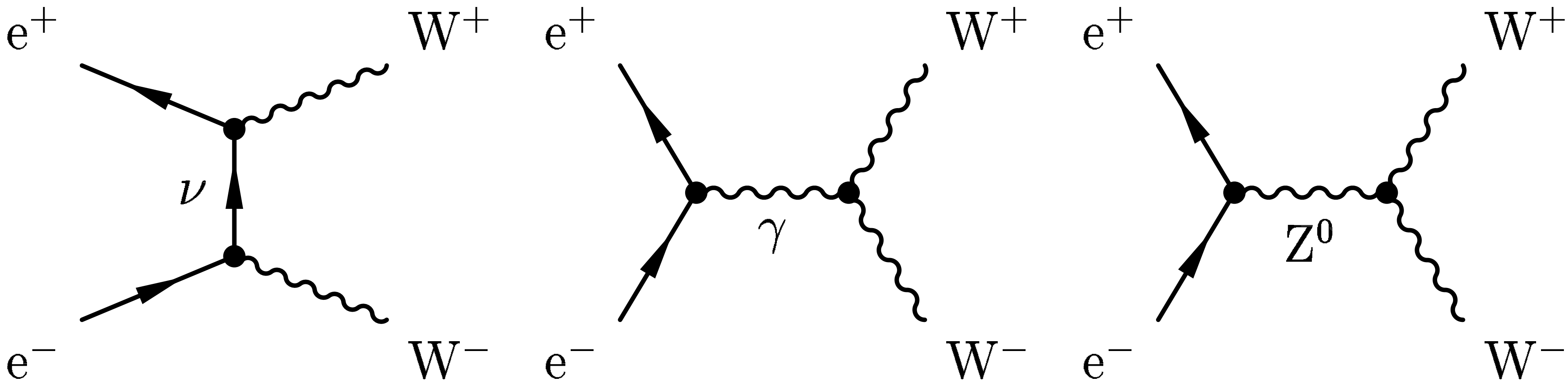
➠ neither upstream nor downstream polarimeter measures the polarisation we need

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

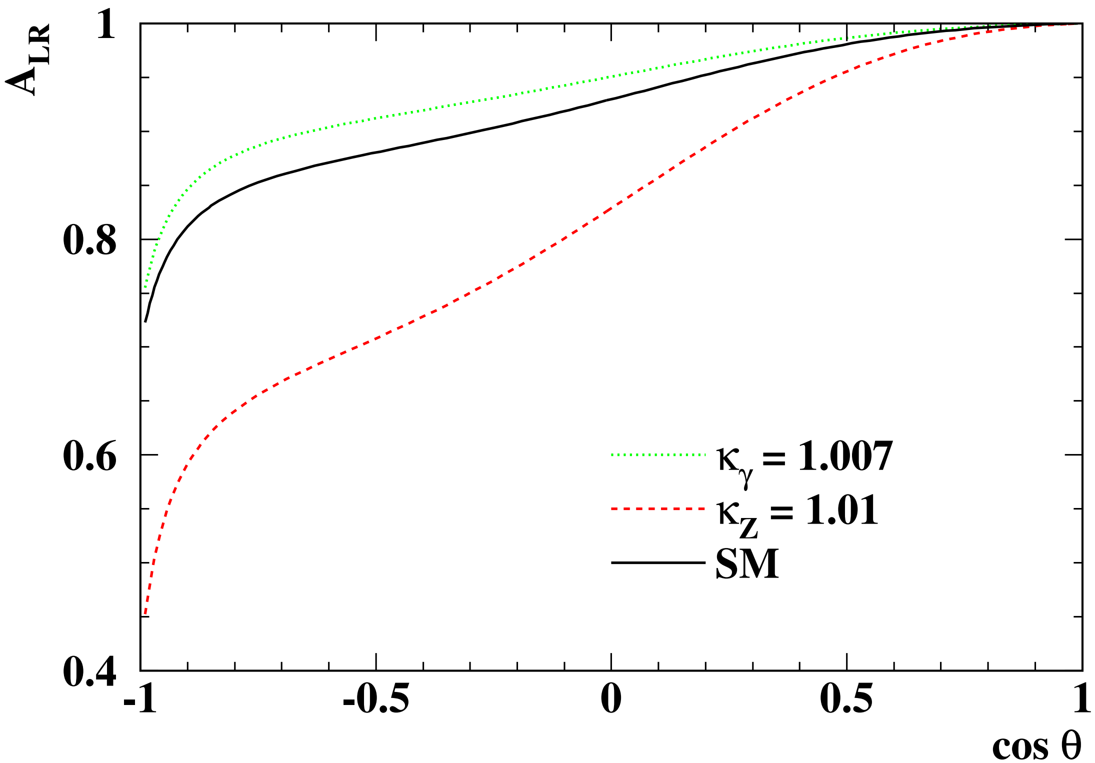
- the large luminosity at LC offers also a better precision for data driven methods

Polarisation measurement with Ws

W-pairs



- Cross section $\sigma = 12 - 7\,\text{pb}$ at $\sqrt{s} = 350 - 500\,\text{GeV}$
- complicated mixture of ν t-channel and Z, γ s-channel exchange
- large left-right asymmetry, depending on production angle and assumed couplings



- However forward peak dominated by ν-exchange and basically independent of anomalous couplings

➠ can fit for anomalous couplings and $\mathcal{P}_{e^-}$ simultaneously

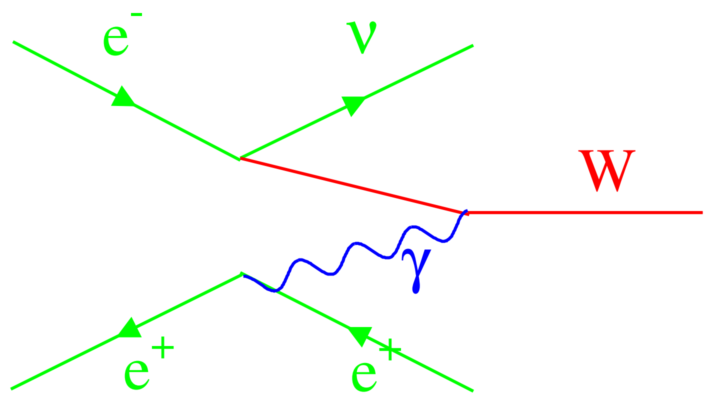
- result with $\mathcal{L} = 500$ fb^{-1} at $\sqrt{s} = 340\,\mathrm{GeV}$:

$$\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} = 0.1\%$$

correlations with the couplings negligible

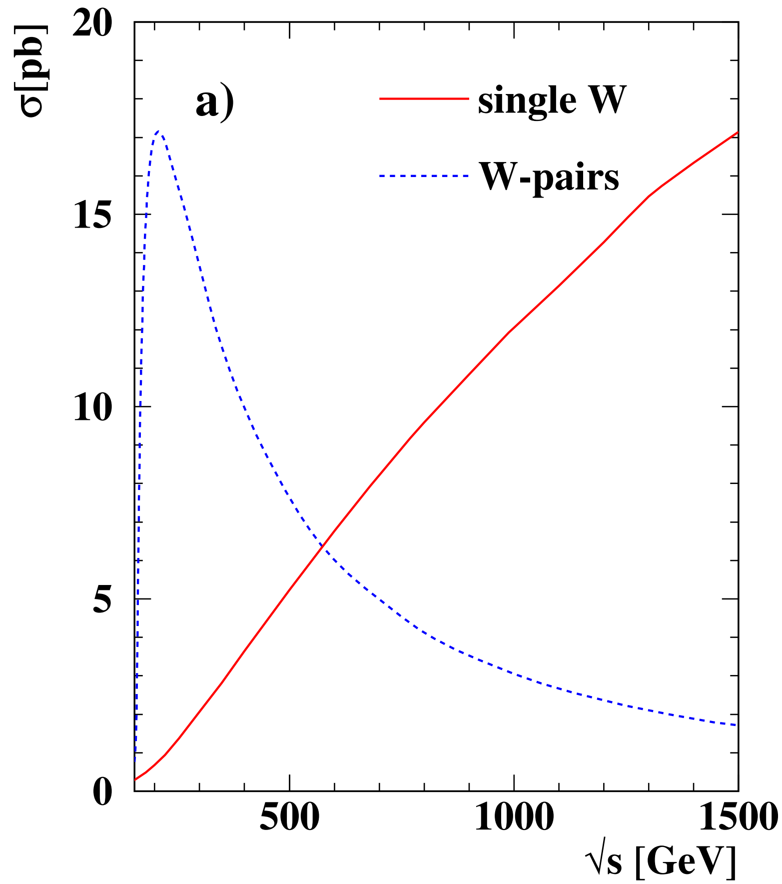
Single W production

Dominating Feynman graph:



➡ W^- (W^+) asymmetry measured directly e^- (e^+) polarisation

➡ Only leptonic Ws are useful



- Cross section large for high energies
- W energy stays low

$\Rightarrow$ large acceptance and little confusion/interference with W- and Z-pair production

Sensitivity estimate for $\sqrt{s} = 500\,\mathrm{GeV}$

($\mathcal{L} = 1$ ab^{-1}, $W^- \to e^-, \mu^-$, 100% efficiency)

$$\Delta\mathcal{P}_{e^-}/\mathcal{P}_{e^-} \sim 0.15\%$$

$\sqrt{s} = 1000\,\mathrm{GeV}$ factor $\sqrt{2}$ better, detailed study started

Positron Polarisation and Effective Polarisations

If both beams are polarised in most cases an "effective polarisation" can be defined that describes the polarisation is a given analysis

e.g. cross section for s-channel vector particle exchange

$$\sigma = \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right]$$

$\mathcal{P}_{e^+}$ ($\mathcal{P}_{e^-}$) = longitudinal polarisations of the positrons (electrons)

Relevant combination for A_{LR} measurements:

$$\mathcal{P}_{\mathrm{eff}} = \frac{\mathcal{P}_{e^+} + \mathcal{P}_{e^-}}{1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-}}$$

Relevant combination for s-channel cross section enhancement/ suppression ($A_{\mathrm{LR}} = 0$):

$$\mathcal{P}_{\sigma} = \mathcal{P}_{e^-}\mathcal{P}_{e^+}$$

Relevant combination for pure left-handed cross section enhancement/suppression

$$\mathcal{P}_L = \mathcal{P}_{e^+} - \mathcal{P}_{e^-} - \mathcal{P}_{e^+}\mathcal{P}_{e^-}$$

Polarimeter measurements and effective polarisations

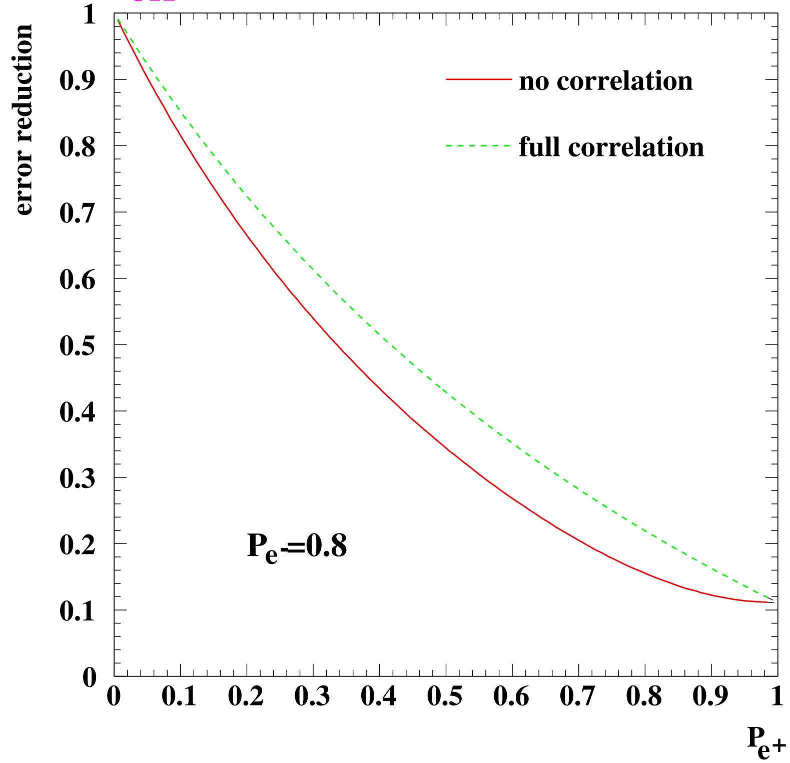
- if positron polarisation is available the error on the effective polarisations is usually smaller than the single polarisation error
- with $\Delta\mathcal{P}/\mathcal{P} = x$ for both polarimeters:
  - if the error is uncorrelated:

$$\frac{\Delta\mathcal{P}_{\text{eff}}}{\mathcal{P}_{\text{eff}}} = x\frac{\sqrt{\left(1-\mathcal{P}_{e^+}^2\right)^2\mathcal{P}_{e^-}^2 + \left(1-\mathcal{P}_{e^-}^2\right)^2\mathcal{P}_{e^+}^2}}{(\mathcal{P}_{e^+}+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+}\mathcal{P}_{e^-})}$$

  - if the error is fully correlated:

$$\frac{\Delta\mathcal{P}_{\text{eff}}}{\mathcal{P}_{\text{eff}}} = x\frac{1-\mathcal{P}_{e^+}\mathcal{P}_{e^-}}{1+\mathcal{P}_{e^+}\mathcal{P}_{e^-}}$$

Gain in $\mathcal{P}_{\text{eff}}$ due to positron polarisation



With $\mathcal{P}_{e^+} = 60\%$ a factor 3-4 is gained in the precision of $\mathcal{P}_{\text{eff}}$

Blondel scheme with 2-fermion events

Assume only s-channel vector exchange

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

$$\begin{aligned}
\sigma_{++} &= \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(\ \ \mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right] \\
\sigma_{-+} &= \sigma_u \left[1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(-\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\right] \\
\sigma_{+-} &= \sigma_u \left[1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(\ \ \mathcal{P}_{e^+} + \mathcal{P}_{e^-})\right] \\
\sigma_{--} &= \sigma_u \left[1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + A_{\mathrm{LR}}(-\mathcal{P}_{e^+} + \mathcal{P}_{e^-})\right]
\end{aligned}$$

$\Longrightarrow$ Can measure $\mathcal{P}_{e^+}$, $\mathcal{P}_{e^-}$ simultaneously with A_{LR} if $A_{\mathrm{LR}} \neq 0$

$$\mathcal{P}_{e^\pm} = \sqrt{\frac{(\sigma_{+-} + \sigma_{-+} - \sigma_{++} - \sigma_{--})(\mp\sigma_{+-} \pm \sigma_{-+} - \sigma_{++} + \sigma_{--})}{(\sigma_{+-} + \sigma_{-+} + \sigma_{++} + \sigma_{--})(\mp\sigma_{+-} \pm \sigma_{-+} + \sigma_{++} - \sigma_{--})}}$$

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)
- radiative return events $e^+e^- \to Z\gamma \to f\bar{f}\gamma$ (RR)

$\sqrt{s}$	σ_{RR}	$A_{\rm LR}(RR)$	σ_{HE}	$A_{\rm LR}(HE)$
340 GeV	17 pb	0.19	5 pb	0.50
500 GeV	7 pb	0.19	2 pb	0.50

HE events

- easy and background free to select
- large $A_{\rm LR}$ reduces error on $\mathcal{P}$
- however physics assumption on s-channel vector exchange (not valid e.g. for RPV $\tilde{\nu}$)

RR events

- 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 $\theta_\gamma > 7^\circ$

Radiative corrections

- for HE sample depolarising effects of ISR are small
- for RR sample they are about 1% if photon is not reconstructed
- if photon is reconstructed, they are negligible

Results:

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

Luminosity ratio $+-/-+/++/--\ = 1/1/1/1$

- Radiative return:

$$\frac{\delta\mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} = 0.0051 \quad \frac{\delta\mathcal{P}_{e^+}}{\mathcal{P}_{e^+}} = 0.0053 \quad corr. = -0.91$$

- High energy:

$$\frac{\delta\mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} = 0.0010 \quad \frac{\delta\mathcal{P}_{e^+}}{\mathcal{P}_{e^+}} = 0.0012 \quad corr. = -0.49$$

Luminosity ratio $+-/-+/++/--\ = 9/9/1/1$

- Errors $\sim$factor two larger

Positron polarisation and W-pairs

- Principle similar to 2-fermion case
- however sensitivity depends strongly on polar angle
- fit simultaneously polarisations and anomalous couplings
- right-handed electron-W coupling still forbidden

Up to now only analysis with analytic Born level formulae and approximate acceptance cuts
(It has however been checked to reproduce the anomalous couplings)

$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.5$

$$\frac{\delta\mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} = 0.0007 \quad \frac{\delta\mathcal{P}_{e^+}}{\mathcal{P}_{e^+}} = 0.0011 \quad corr. = 0$$

$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.1$

$$\frac{\delta\mathcal{P}_{e^-}}{\mathcal{P}_{e^-}} = 0.0011 \quad \frac{\delta\mathcal{P}_{e^+}}{\mathcal{P}_{e^+}} = 0.0021 \quad corr. = -0.52$$

Results for the effective polarisations:

	value	Rel. error [%]							
		$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.5$			$\mathcal{L}_{\pm\pm}/\mathcal{L} = 0.1$			Polarimeter	
		HE	rr	WW	HE	rr	WW	$\rho=0$	$\rho=0.5$
$\mathcal{P}_{\text{eff}}$	0.95	0.02	0.08	0.02	0.05	0.17	0.02	0.13	0.16
$\mathcal{P}_\sigma$	0.48	0.11	0.22	0.13	0.18	0.42	0.18	0.71	0.87
$\mathcal{P}_L$	0.92	0.03	0.12	0.03	0.06	0.25	0.03	0.19	0.21

$$\mathcal{P}_{\text{eff}} = \frac{\mathcal{P}_{e^+} + \mathcal{P}_{e^-}}{1 + \mathcal{P}_{e^+}\mathcal{P}_{e^-}}$$
$$\mathcal{P}_\sigma = \mathcal{P}_{e^-}\mathcal{P}_{e^+}$$
$$\mathcal{P}_L = \mathcal{P}_{e^+} - \mathcal{P}_{e^-} - \mathcal{P}_{e^+}\mathcal{P}_{e^-}$$

Data methods have a high potential if positron polarisation available

The large anticorrelation between $\mathcal{P}_{e^-}$ and $\mathcal{P}_{e^+}$, especially for the radiative return sample, reduces significantly the error on the effective polarisations

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:

$$\Delta\mathcal{P}_{e^-} = 1.0\delta\mathcal{P}_{e^-} + 0.6\delta\mathcal{P}_{e^+}$$
$$\Delta\mathcal{P}_{e^+} = -0.5\delta\mathcal{P}_{e^-} - 0.7\delta\mathcal{P}_{e^+}$$

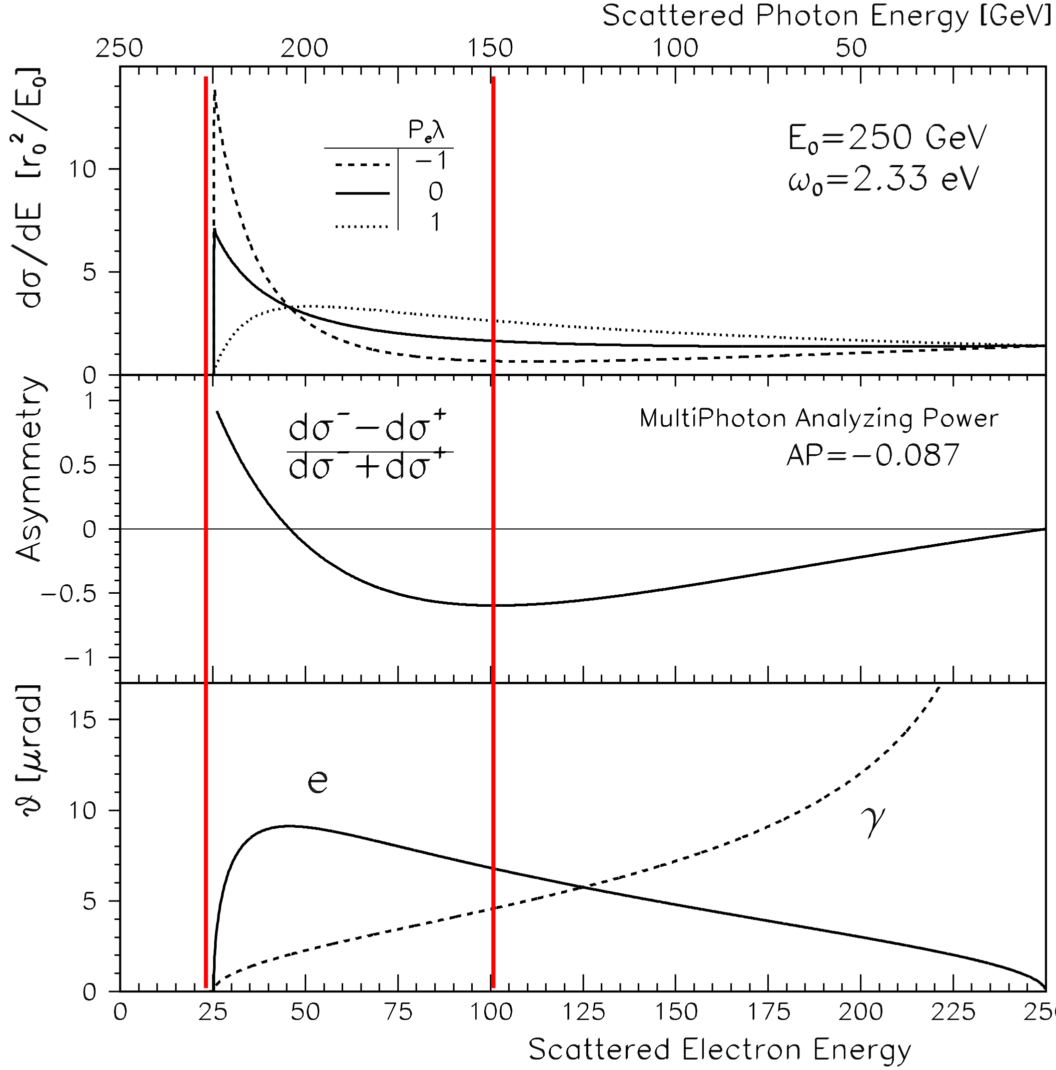
  - radiative return sample

$$\Delta\mathcal{P}_{e^-} = 2.4\delta\mathcal{P}_{e^-} + 2.1\delta\mathcal{P}_{e^+}$$
$$\Delta\mathcal{P}_{e^+} = -1.7\delta\mathcal{P}_{e^-} - 1.7\delta\mathcal{P}_{e^+}$$

– 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

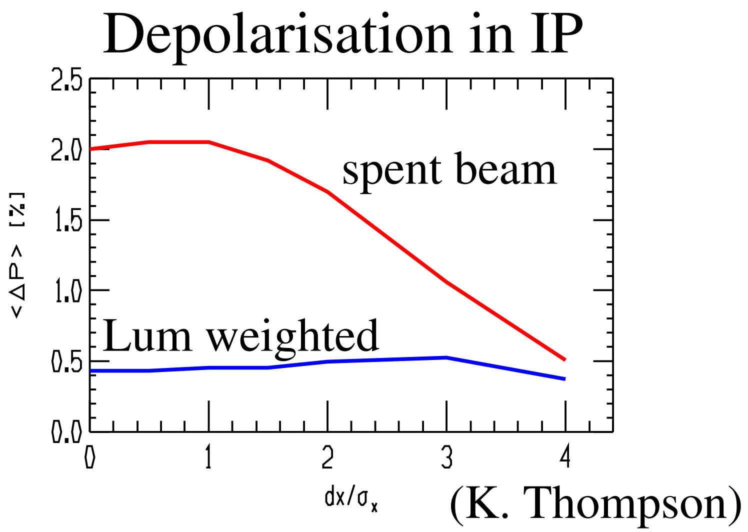
In formulae for the Blondel scheme and in effective polarisations products of $\mathcal{P}_{e^+}$ and $\mathcal{P}_{e^-}$ enter

$\Rightarrow$ have to understand correlations between $\mathcal{P}_{e^+}$ and $\mathcal{P}_{e^-}$

- correlation inside bunch, e.g. via interaction time
  ➡ negligible according to CAIN
- correlated time dependencies
  - effect quadratic with polarisation change
  - changed both polarisations for $\pm 5\%$ for half of the time

  ➡ 0.25% effect on polarisation
  - Blondel scheme reproduces effective polarisation worse than polarimeter measurement.
    ($\Delta\mathcal{P}_{\mathrm{eff}} = 0.16\%$ for polarimeter, $\Delta\mathcal{P}_{\mathrm{eff}} = 0.25\%$ for Blondel scheme)
  - need polarimeters to track time dependencies and possibility to change polarisation fast, e.g. parallel spin rotators for positrons

- correlation in depolarisation from realistic bunches
  no detailed study yet, but study of K. Thompson indicated that effect is small



- can there be spatial correlations from bends etc.?

Special case: GigaZ

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

$$A_{\rm LR} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$$

- 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

- The polarisation can be measured from the data themselves.
- Each measurement from data involves some physics assumptions.
- The errors are in the per mille region for 500 fb^{-1}
- The exact requirements have to be studied by the different analyses separately
- Polarimeters are needed for corrections
- Polarimeter and data methods are largely complementary and both are needed to get the ultimate precision.