Beam Polarisation at the LC

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Some references:

- F. Renard, Basics of Electron Positron Collisions
- H. Haber, *Spin Formalism and Applications to New Physics Searches*, Proc. of 21st SLAC Summer Inst. on Part. Phys.,Stanford 1993
- T. Omori, ‘A Polarized Positron Beam for Linear Colliders’, KEK 98-237
- Further news, references and links: http://www.ippp.dur.ac.uk/~gudrid/power/

Outline

Goal of the Linear Collider

'Precision physics in the energy range between LEP and O(1 TeV)'

* High precision measurements: tests of the SM
* Discovery of New Physics (NP) (together with Hadron Colliders)
* 'Unveiling' the structure of NP: precise determination!

$\Rightarrow$ Beam polarization = decisive tool!

1. Introduction: overview and some definitions
2. Statistical arguments for polarisation of both beams
3. Use of polarised beams e.g. for Susy searches
4. Use of transversely polarised beams
5. Some technical details for polarising e^- and e^+ at a LC

Introduction: Overview

History: First polarised e^- beam at a LC: 3-km SLC at SLAC (1992-98)
$\rightarrow P(e^-) = [60\%, 78\%]$

Planned design for a future LC:

- polarized electron source: similar design as for SLC!
  $\longrightarrow$ strained photocathode technology
  $\Rightarrow P(e^-) \approx 80\%$ expected

- polarized positrons at a LC: complete novelty!
  $\longrightarrow$ helical undulator: source for polarized γ
  $\longrightarrow$ photoproduction of polarized e^+:
  $\Rightarrow P(e^+) \approx 40 - 60\%$ expected

- Measurement of polarization:
  Compton polarimetry: $\Delta P(e^\pm) \leq 0.5\%$
  (Møller polarimetry: under discussion)
  'Blondel scheme': high precision polarimetry

Some definitions

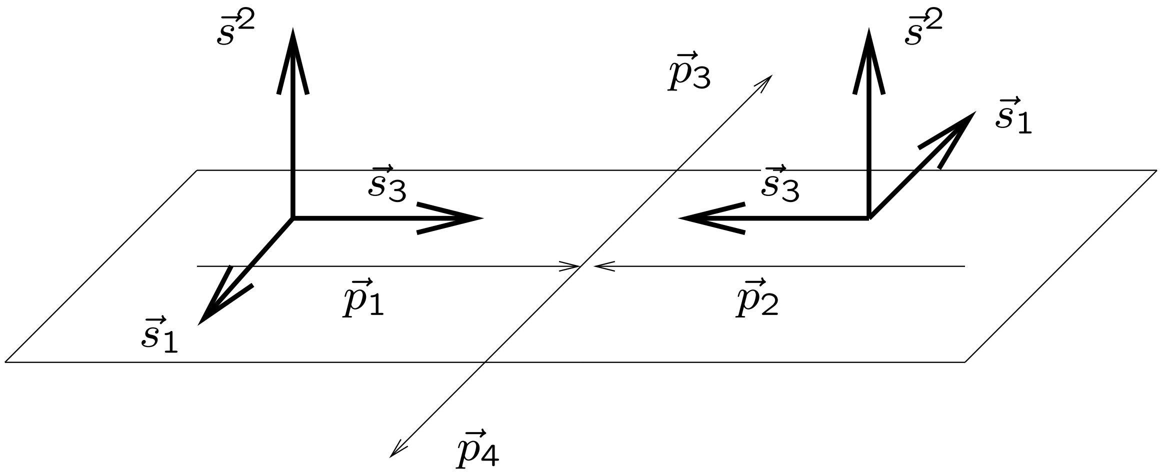
- Formalism: Use e.g. helicity spinors $u(p,\lambda)$, $v(p,\lambda)$ $\rightarrow$ density matrix
- Definition: Basis of Spinvektors s^a, $a = 1,2,3$ with $(s^a p) = 0$:

  build 'right-hand-system' in the CMS of $e^-(p_1)e^+(p_2) \rightarrow X(p_3)Y(p_4)$

  longitudinal Spinvektors: $s^{3\mu}(p_{1,2}) := \frac{1}{m_{1,2}}(|\vec{p_{1,2}}|, E\hat{p}_{1,2})$

  transverse Spinvektors: $s^{2\mu}(p_1) := (0, \vec{p}_1 \times \vec{p}_3)$, $\qquad s^{2\mu}(p_2) = s^{2\mu}(p_1)$

  $s^{1\mu}(p_1) := (0, \vec{p}_1 \times \vec{s}^2(p_1))$, $s^{1\mu}(p_2) = -s^{1\mu}(p_1)$



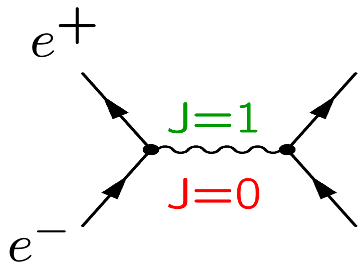
- Definition: 'left-handed'and 'right-handed' $\equiv$ with respect to $\hat{p}$

  If Spinvektor $\vec{s}^3 = \begin{pmatrix} \text{parallel } \vec{p} \\ \text{antiparallel } \vec{p} \end{pmatrix} \equiv \begin{pmatrix} \text{'right-handed': } P>0 \\ \text{'left-handed': } P<0 \end{pmatrix}$

General remarks about the coupling structure

Def.: left-handed $\equiv P(e^{\pm}) < 0$ right-handed $\equiv P(e^{\pm}) > 0$

Which configurations are possible in principle?
s–channel:



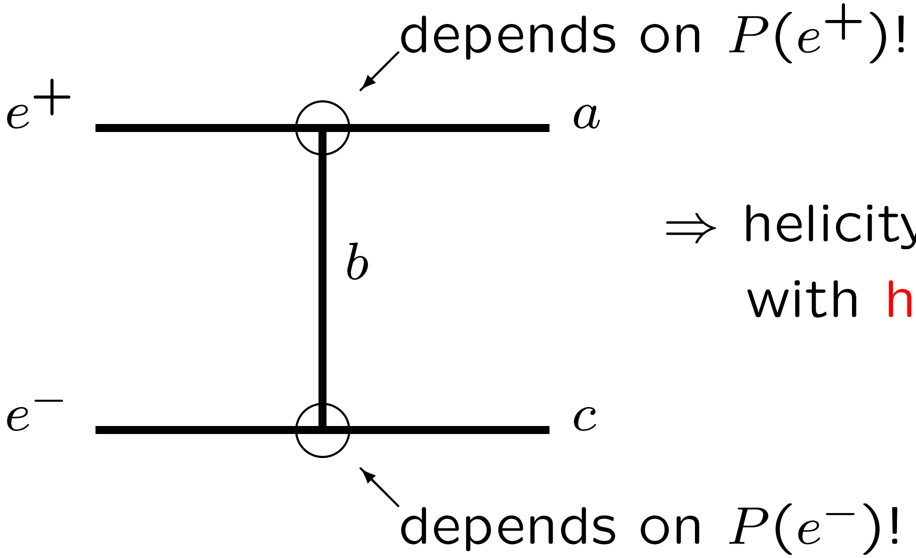
$\leftarrow$ only from RL,LR: SM (γ, Z)

$\leftarrow$ only from LL,RR: NP!

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

Which configurations are possible in the crossed channels?

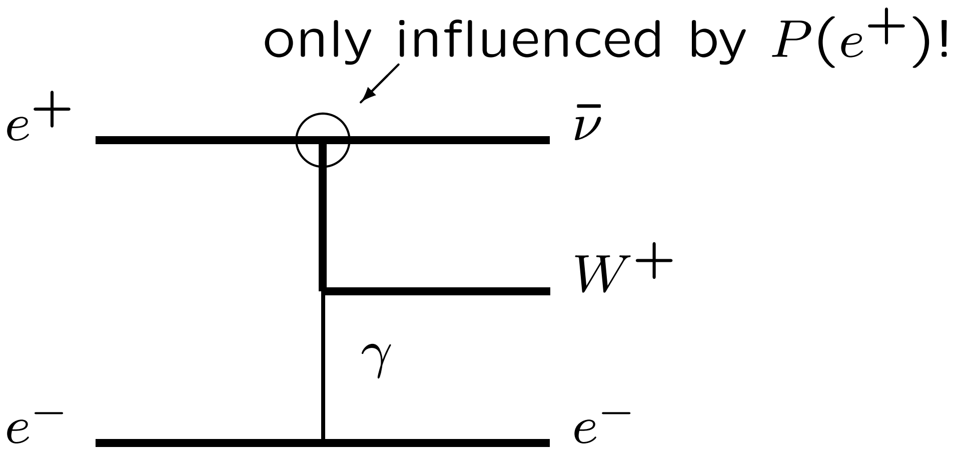
t–channel:



$\Rightarrow$ helicity of e^- not coupled with helicity of e^+!

Two examples:

a) Single W production



b) Bhabha scattering

$\Rightarrow$ γ, Z exchange in s–channel: selects LR, RL

$\Rightarrow$ γ, Z exchange in t–channel: LL,RR possible!

unpolarised	4.50 pb
$P_{e^-} = -80\%$	4.63 pb
$P_{e^-} = -80\%$, $P_{e^+} = -60\%$	4.69 pb
$P_{e^-} = -80\%$, $P_{e^+} = +60\%$	4.58 pb

Statistical arguments for polarisation of both beams

$P(e^+)$ can increase the effects:

- Effective polarisation:

$$\sigma = (1 - P_{e^-})(1 + P_{e^+})\sigma_{LR} + (1 + P_{e^-})(1 - P_{e^+})\sigma_{RL}$$

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

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

- Effective luminosity $\equiv$ fraction of colliding particles

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

Statistical arguments

- Effective polarization

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

- Fraction of colliding particles

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

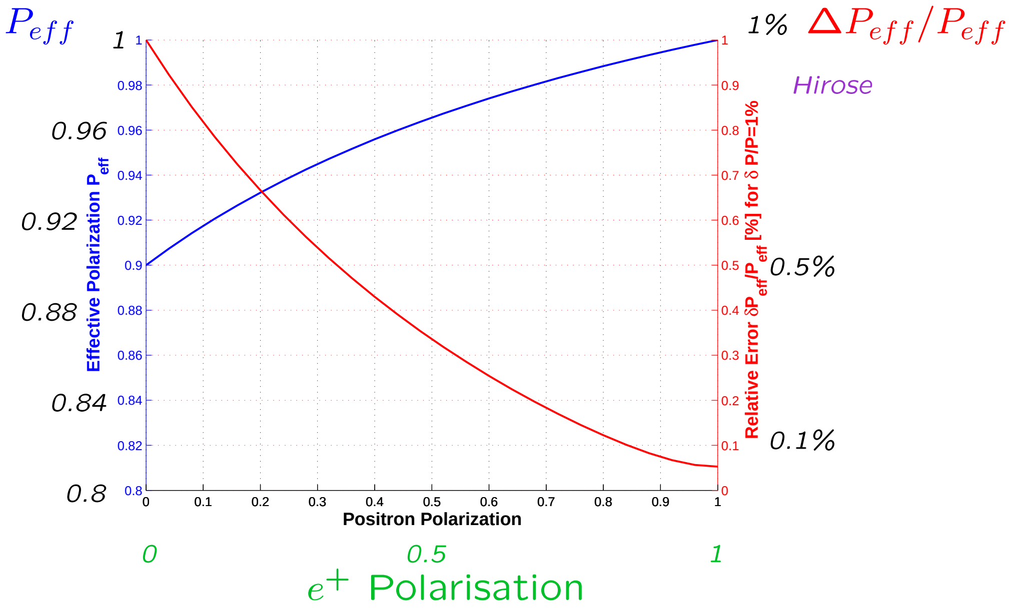
Colliding particles:

	RL	LR	RR	LL	P_{eff}	$\mathcal{L}_{eff}/\mathcal{L}$
$P(e^-) = 0$, $P(e^+) = 0$	0.25	0.25	0.25	0.25	0.	0.5
$P(e^-) = -1$, $P(e^+) = 0$	0	0.5	0	0.5	−1	0.5
$P(e^-) = -0.8$, $P(e^+) = 0$	0.05	0.45	0.05	0.45	−0.8	0.5
$P(e^-) = -0.8$, $P(e^+) = +0.6$	0.02	0.72	0.08	0.18	−0.95	0.74

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

What else do we gain with P_{e^+} and using P_{eff}?

→ systematic error of polarisation determination decreases strongly!:



$$\Delta P_{eff} = \left(\frac{\partial P_{eff}}{\partial P_{e^-}}\right)\Delta P_{e^-} + \left(\frac{\partial P_{eff}}{\partial P_{e^+}}\right)\Delta P_{e^+}$$
$$= \left(\frac{\partial P_{eff}}{\partial P_{e^-}}\right)\left(\frac{\Delta P_{e^-}}{P_{e^-}}\right)P_{e^-} + \left(\frac{\partial P_{eff}}{\partial P_{e^+}}\right)\left(\frac{\Delta P_{e^+}}{P_{e^+}}\right)P_{e^+}$$

Two approximations (here):

- linear: systematics $\gg$ statistics
- $\Delta P_{e^-}/P_{e^-} = \Delta P_{e^+}/P_{e^+} \equiv \Delta P/P$

$$\Rightarrow \frac{\Delta P_{eff}}{P_{eff}} = \frac{1+P_{e^-}P_{e^+}}{1-P_{e^-}P_{e^+}}\left(\frac{\Delta P}{P}\right)$$

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

Further statistics: Using the Blondel Scheme

Process: $e^+e^- \to Z \to f\bar{f}$ at the Z-pole (s-channel)

Measurement of effective mixing angle $\sin\Theta^{\ell}_{eff}$ via A_{LR}:

$$\sigma = \sigma_u[1 - P_{e^-}P_{e^+} + A_{LR}(P_{e^+} - P_{e^-})], \qquad A_{LR} = \frac{2(1 - 4\sin^2\Theta^{\ell}_{eff})}{1 + (1 - 4\sin^2\Theta^{\ell}_{eff})^2}$$

Gain in statistical power of 'Z-factory' only if $\Delta A_{LR}(pol) < \Delta A_{LR}(stat)$!

$\Rightarrow \Delta P_{eff} \sim 10^{-4}$ needed! ... not possible with only polarimetry.....

- Blondel Scheme: $A_{LR} = \sqrt{\frac{(\sigma^{RR}+\sigma^{RL}-\sigma^{LR}-\sigma^{LL})(-\sigma^{RR}+\sigma^{RL}-\sigma^{LR}+\sigma^{LL})}{(\sigma^{RR}+\sigma^{RL}+\sigma^{LR}+\sigma^{LL})(-\sigma^{RR}+\sigma^{RL}+\sigma^{LR}-\sigma^{LL})}}$

$\Rightarrow \Delta A_{LR} \sim 10^{-4}$

$\Delta \sin^2\theta^{\ell}_{eff} = 0.000013$

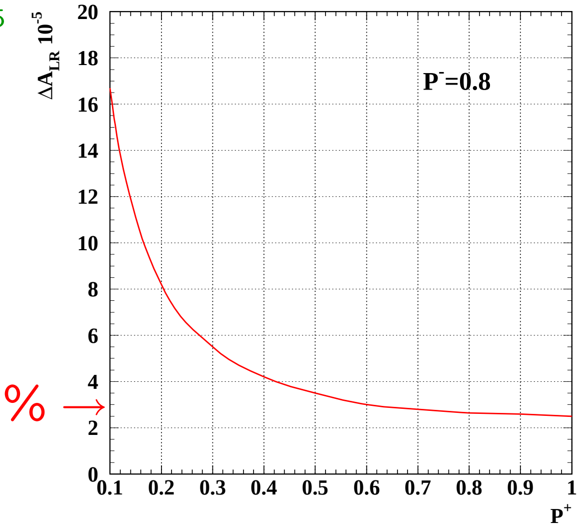
For comparison:

At LEP/Tev./LHC: $\Delta \sin^2\theta^{\ell}_{eff} = 0.00017$

$\Rightarrow$ O of magnitude better!

$\Delta A^{stat}_{LR} 10^{-5}$

Moenig



$P_{e^+} = 60\% \rightarrow$

P_{e^+}

Use of polarised beams e.g. for Susy searches and model tests

E.g. test of the SUSY assumption:

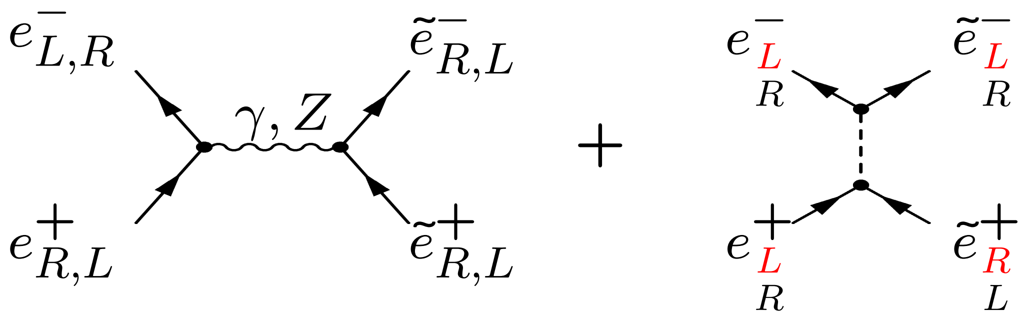
SM $\leftrightarrow$ SUSY have same quantum numbers!

$\Rightarrow e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$

Scalar partners $\leftrightarrow$ chiral quantum numbers!

How to test this association?

Strategy: $\sigma(e^+e^- \to \tilde{e}^+_{L,R}\tilde{e}^-_{L,R})$ with polarized beams



$\Rightarrow$ t–channel: unique relation between chiral fermion $\longleftrightarrow$ scalar partner

Use e.g. $e^+_L e^-_L$

$\rightarrow$ t-channel: $\tilde{e}^+_R \tilde{e}^-_L \longrightarrow \tilde{e}^+_R \leftrightarrow \tilde{e}^-_L$

$\rightarrow$ no s–channel

Physics Case for $P(e^+)$: Tests of Susy cont.

- precise analysis of non–standard couplings

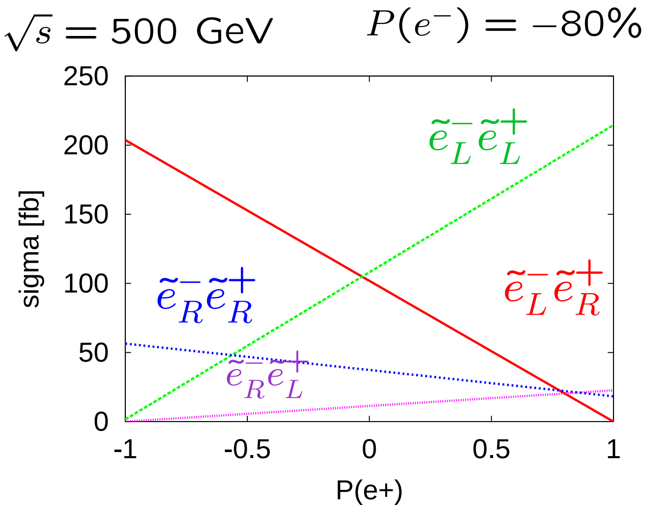
Polarised cross sections: $\sigma(e^+e^- \to \tilde{e}^+_{L,R}\tilde{e}^-_{L,R})$

Tricky case: $m_{\tilde{e}_L}$ $m_{\tilde{e}_R}$ close together:

$m_{\tilde{e}_L} = 200$ GeV, $m_{\tilde{e}_R} = 190$ GeV

$\to$ same decay kinematics!

Moortgat-Pick



In our example:

$P(e^-) = -80\%$ but $P(e^+) = 0$: no separation!

$P(e^-) = -80\%$ and $P(e^+) = -40\%$: ratio 163 fb/66 fb!

$\Rightarrow$ Separation of $\tilde{e}^-_L\tilde{e}^+_L$ and $\tilde{e}^-_L\tilde{e}^+_R$ not possible with only $P(e^-)$!

Physics Case for Polarised Positrons at a LC

- option of using transversely polarised beams!

Ratesare given by:

$\sigma = (1 - P_{e^+} P_{e^-}) \sigma_{unp} + (P^L_{e^-} - P^L_{e^+}) \sigma^L_{pol} + P^T_{e^-} P^T_{e^+} \sigma^T_{pol}$

$\Rightarrow$ only possible with both beam polarised!

Example here: $e^+e^- \rightarrow f\bar{f}$

Observable: azimuthal asymmetry

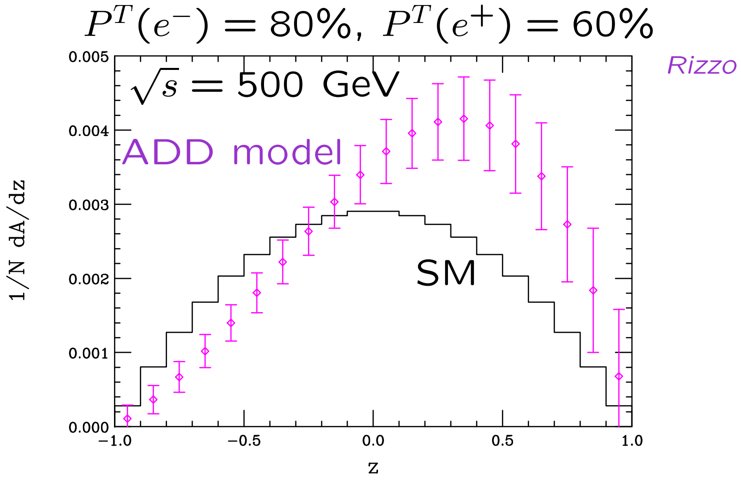
exact symmetric in the SM!

However: if e.g. large extra dimensions

$\rightarrow$ Graviton Spin=2 ('tensor') exchange

$\rightarrow$ asymmetric behaviour!!!!

$\Rightarrow$ clear separation of different models of NP



(→ see also e.g. TESLA TDR, JLC Roadmap, Snowmass '01 Resource Book, Moortgat-Pick '03, etc.)

$\Rightarrow$ Polarised e^+ in addition to polarised e^- needed at a LC

Further examples: Tranverse beams and their impact on ...

- the process $e^+e^- \to W^+W^-$:
  $\Rightarrow$ azimuthal asymmetry projects out $W_L^+W_L^-$
  at high energy asymmetry peaks a 'large' polar angles (not in beam direction!)
  $\Rightarrow$ sensitive to effects of the origin of electroweak symmetry breaking
  without complicated final spin state analysis!

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

Remember: $\vec{s}^{2\mu} := \vec{p}_1 \times \vec{p}_3$ perpendicular scattering plane, CP even
$\vec{s}^{1\mu} := \vec{p}_1 \times \vec{s}^2(p_1)$ transverse in plane, CP odd

$\Rightarrow$ Combination of transverse beam polarisation provide CP odd observables!

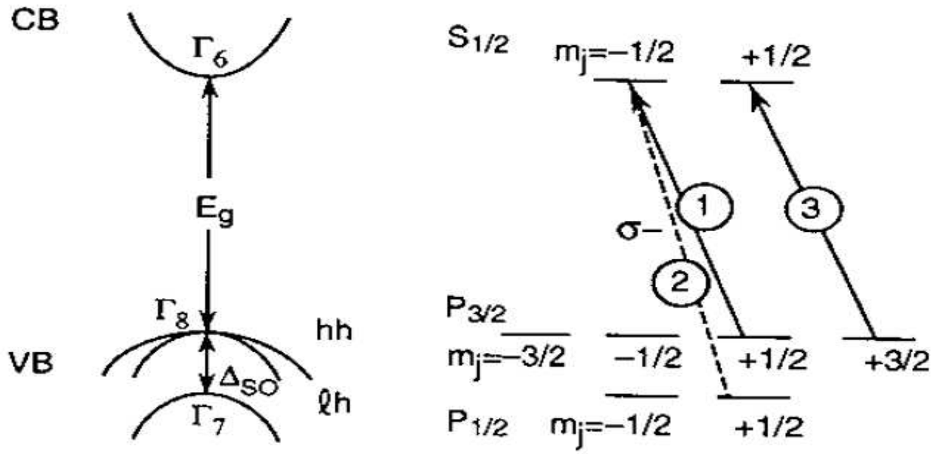
Some technical details for polarising e^- and e^+ at a LC

Remember again: First polarised e^- beam at a LC at SLAC (1992-98) with $P(e^-) = [60\%, 78\%]$

How did they polarise the e^-?

$\rightarrow$ circ. polarised light ($I_z = +1$ or -1) on GaAs cathode

$\Rightarrow P^{-1} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{3-1}{3+1} = +0.5$



How to get higher polarisation?

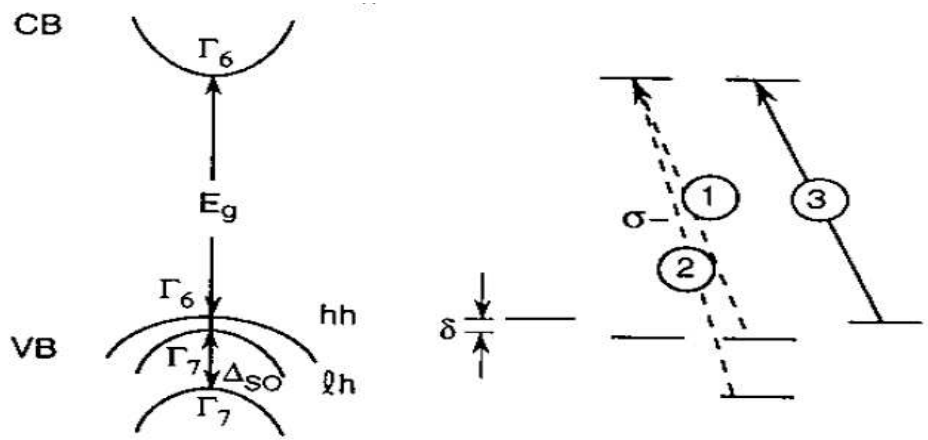
$\rightarrow$ use strained lattice: grow GaAs on substrate with diff. crystal spacing

$\Rightarrow$ removes degeneracy in lower level

If $h\nu = [E_g, (E_g + \delta)]$:

$\rightarrow$ in principle $P^{-1} = 100\%$ possible...

$\Rightarrow P^{-1} = 80 - 90\%$ expected at LC



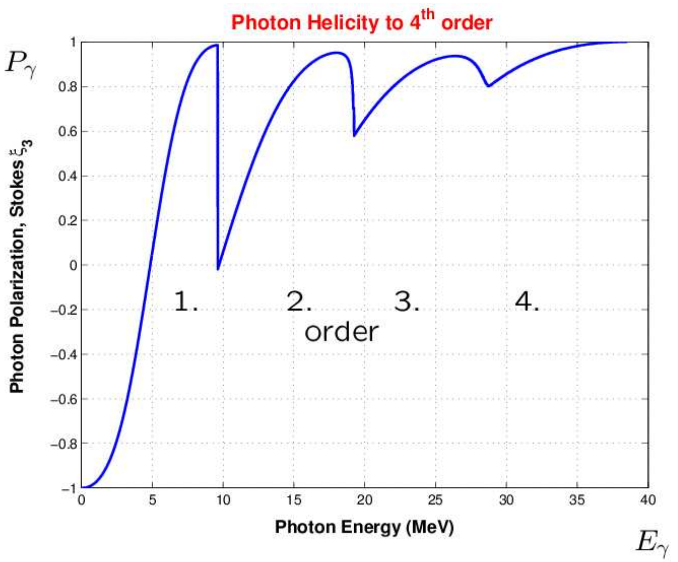
How to polarise the e^+ beam at a Linear Collider?

Complete novelty!!!

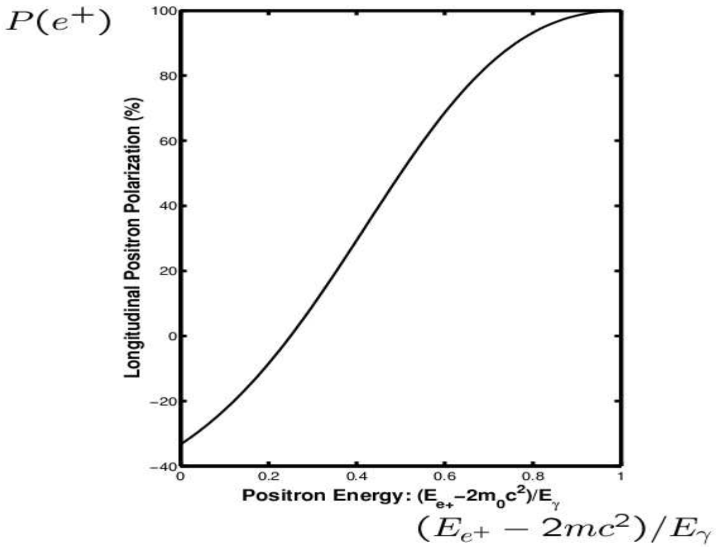
Principle (now quasi same design for all LC designs!)

- high energy beam (150-250 GeV) through helical undulator ($\sim$ 100 m)
  (TESLA baseline uses planar undulator anyway for production of unpol. e^+)
  $\rightarrow$ circ. pol. photons with $\sim$ 20 MeV (TESLA) or $\sim$ 10 MeV (NLC)
  $\rightarrow$ pol. γ on target (Ti): conversion to pol. e^+ (and e^-)

Photon Pol. of Undulator radiation



Polarisation transfer from $\gamma \rightarrow e^+$



‘Exciting’ $R\&D$ in the Polarisation Business in the next years

Demonstration experiment needed for $P(e^+)$: ‘proof of principle’

1. Approval (in June 2003!) of the international project E166@SLAC:
   - E-166 uses the 50 GeV, low emittance FFTB@SLAC in conjunction with a 1 m-long, 2.4 mm period helical undulator ($K = 0.17$) to make polarised photons with 0-10 MeV
   - These photons are converted in a ~ 0.5 rad. length thick target into polarised positrons
   - The polarisation of the positrons and photons will be measured
   - Performance expectations are for positron polarisation of about 60%

2. Superconducting helical undulator for the TESLA scheme
   - ASTeC@Daresbury: construction of a prototype for a ~30 cm s.c. helical undulator with 14 mm period, 4 mm aperture, K=1

     → could be tested at TTF2 in 2004

Summary of the Polarisation Lecture

Beam polarisation of e^- and e^+ is an important tool at a LC!

- Theo. tools: use helicity spinors $u(p,\lambda)$, $v(p,\lambda)$ and orthogonal of spinvectors $(s^a p) = 0$
- Pheno. results: Focussing out the signals , background suppression, analysis of chiral coupling structure , gain in statistics
- $P(e^+)$ needed: Electroweak precision tests with unprecedented accuracy!
- $P(e^+)$ needed: Discovery and 'unveiling' of SUSY and any NP
- $P(e^+)$ needed: additional gain in statistics, better accuracy in determining P_{eff}
- $P(e^+)$ needed: exploring transversely polarised beams ($W_L W_L$, CP, ...)
- Techn. Realis. of a high $P(e^-)$ seems to be straight forward
- Techn. Realis. of $P(e^+)$ seems to work, but still an exciting challenge!

Further news and information, please have a look:

POWER working group: close contact between Th/Exp/Machine

($\rightarrow$ http://www.ippp.dur.ac.uk/~gudrid/power)