Polarized positrons for the International Linear Collider

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DESY, Zeuthen

3rd February 2006

Outline

Motivation
- The International Linear Collider
- Why do we need polarized positrons at the ILC?
- How are polarized positrons produced?
- Polarization at Zeuthen?

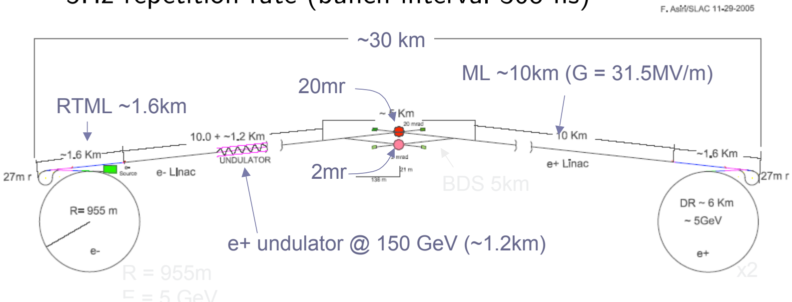
The E166 Experiment
- Experimental setup
- Preliminary results

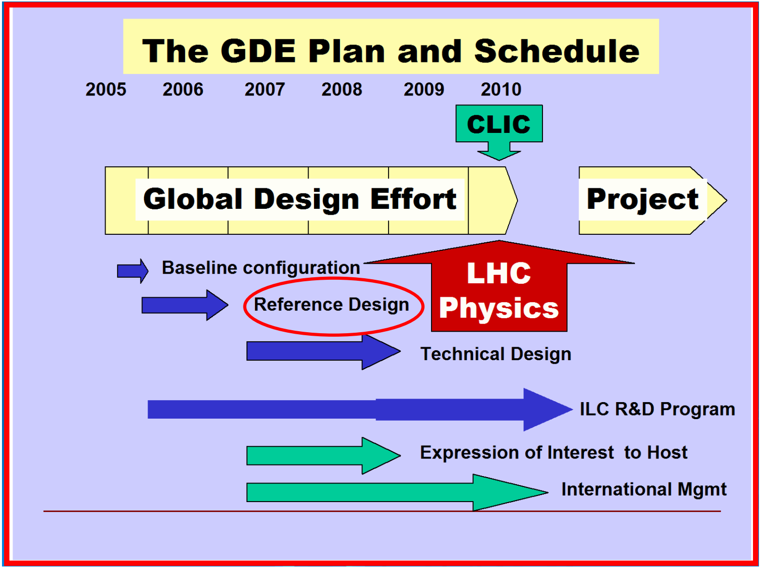
Polarization in Geant4
- Simulation package Geant4
- Back to the basics
- Examples

Summary

ILC layout

- luminosity $\mathcal{L} = 2 \cdot 10^{34}\, cm^{-2} s^{-1}$, $E_{\text{cms}} = 500 \ldots 1000\, GeV$ (remember LEP1 $\mathcal{L} = 2.4 \cdot 10^{31}\, cm^{-2} s^{-1}$)
- goal integrated luminosity in first 4 years : $500\, fb^{-1}$
- machine parameters very flexible
- nominal operation: 1ms bunch trains with 2820 bunches, 5Hz repetition rate (bunch interval 308 ns)



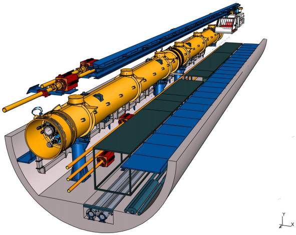

The GDE Plan and Schedule
2005 2006 2007 2008 2009 2010
CLIC
Global Design Effort
Project
Baseline configuration
Reference Design
LHC Physics
Technical Design
ILC R&D Program
Expression of Interest to Host
International Mgmt

ILC

- clean environment
- precision measurements
- polarized beams

different options

- GigaZ
- ee, $e\gamma$ and $\gamma\gamma$ option

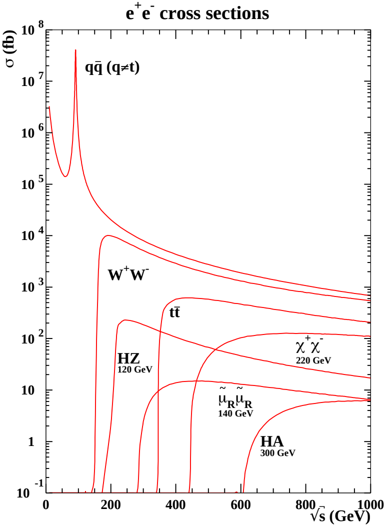


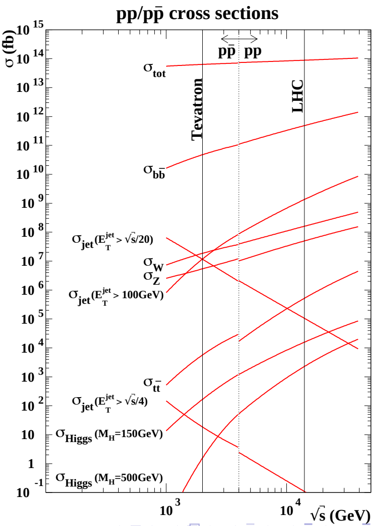
LHC

- huge QCD background
- discovery machine
- high cms energy

LHC & ILC complementarity

G. Weiglein *et al.*, arXiv:hep-ph/0410364.



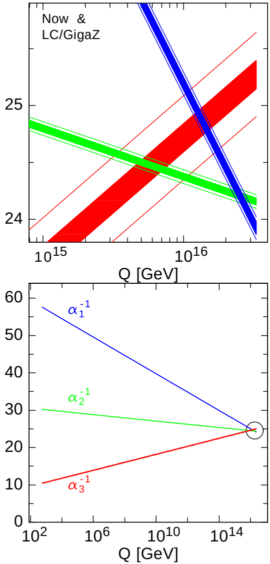


Precision measurements

Unique access to EWSB

- weak mixing angle $\sin^2\theta_W$
- mass of weak bosons
- top mass
- higgs mass and couplings

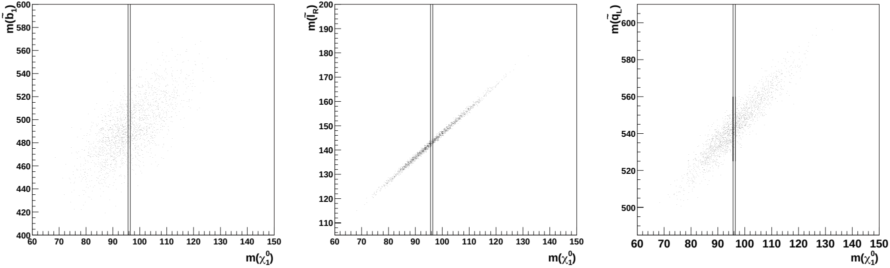
	now	Tev. Run IIA	Run IIB	LHC	LC	GigaZ
$\delta\sin^2\theta_{\text{eff}}\,(\times 10^5)$	17	78	29	14–20	(6)	1.3
δM_W [MeV]	34	27	16	15	10	7
δm_t [GeV]	5.1	2.7	1.4	1.0	0.2–0.1	0.1
δm_h [MeV]	—	—	$\mathcal{O}(2000)$	200	50	50



LHC & ILC complementarity

MSSM

- precision on $m(\tilde{\chi}_1^0)$ increases by $\mathcal{O}(10^2)$



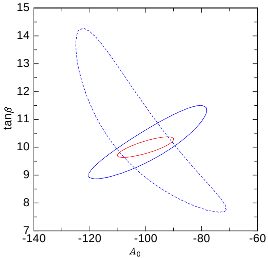
LHC & ILC complementarity

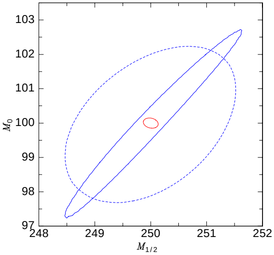
- measurements of particles not (or difficult) accessible at LHC
- precision on $m(\tilde{\chi}_1^0)$ increases by $\mathcal{O}(10^2)$
- climbing up LHC chain $\Rightarrow$ reconstruction of entire SUSY world

	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{\chi}_3^0$	364.7		3-5	3-5
$\tilde{\chi}_4^0$	381.9	5.1	3-5	2.23
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\mu}_L$	207.1	5.0	0.5	0.5
$\tilde{\nu}_\mu$	191.3	–		
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{\nu}_\tau$	190.4	–	–	–
$\tilde{q}_R$	547.6	7-12	–	5-11
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{b}_1$	515.1	7.5	–	5.7
$\tilde{b}_2$	547.1	7.9	–	6.2
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
H^0	399.8		1.5	1.5
A^0	399.4		1.5	1.5
$H^\pm$	407.7	–	1.5	1.5

Top-Down approach

- fitting high-scale parameters to experimental data
- χ^2 analysis gives probability that model is wrong
  $\Rightarrow$ exclusion of models
- example mSUGRA SPS1a





	"LHC"	"LC"	"LHC+LC"
$M_{1/2}$	250.0 ± 2.1	250.0 ± 0.4	250.0 ± 0.2
M_0	100.0 ± 2.8	100.0 ± 0.2	100.0 ± 0.2
A_0	-100.0 ± 34	-100.0 ± 27	-100.0 ± 14
$\tan\beta$	10.0 ± 1.8	10.0 ± 0.6	10.0 ± 0.4

Why do we need polarized positrons at the ILC?

- higher effective luminosity $\mathcal{L}_{\mathrm{eff}}$
- higher effective polarization P_{eff} and less dependence on polarization uncertainty
- improved signal/background ratio
- unique understanding of non-standard couplings
- option of using transversely polarized beams

G. Moortgat-Pick *et al.*, CERN-PH-TH-2005-036, arXiv:hep-ph/0507011.

Higher effectiv luminosity and higher effective polarization

e^+e^- annihilation into vector particle (γ/Z^o)
only $\sigma_{\rm LR}$ and $\sigma_{\rm RL}$ contribute

$$\sigma_{p_{e^-}p_{e^+}} = (1 - P_{e^+}P_{e^-})\ \sigma_0\ [1\ -\ P_{\rm eff}\ A_{\rm LR}]$$

$$\sigma_0 = \frac{\sigma_{\rm RL} + \sigma_{\rm LR}}{4} \quad A_{\rm LR} = \frac{\sigma_{\rm LR} - \sigma_{\rm RL}}{\sigma_{\rm LR} + \sigma_{\rm RL}} \quad P_{\rm eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}$$

		$P_{\rm eff}$	$(1 - P_{e^+}P_{e^-})$
$P_{e^-} = 0,$	$P_{e^+} = 0$	0%	1.00
$P_{e^-} = -100\%,$	$P_{e^+} = 0$	-100%	1.00
$P_{e^-} = -80\%,$	$P_{e^+} = 0$	-80%	1.00
$P_{e^-} = -80\%,$	$P_{e^+} = +60\%$	-95%	1.48

Higher effectiv luminosity and higher effective polarization

e^+e^- annihilation into vector particle (γ/Z^o)

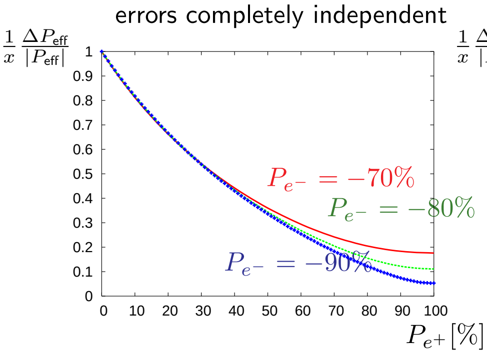
only σ_{LR} and σ_{RL} contribute

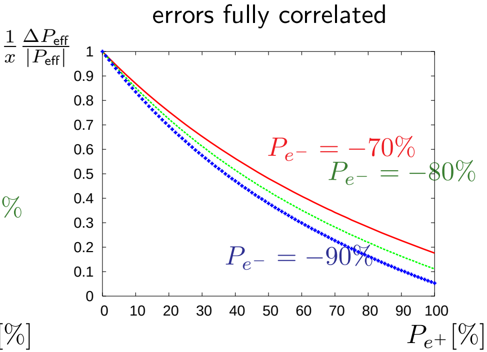
$$\sigma_{p_{e^-}p_{e^+}} = (1 - P_{e^+}P_{e^-})\ \sigma_0\ [1\ -\ P_{\mathrm{eff}}\ A_{\mathrm{LR}}]$$

$$\sigma_0 = \frac{\sigma_{\mathrm{RL}} + \sigma_{\mathrm{LR}}}{4} \quad A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{LR}} - \sigma_{\mathrm{RL}}}{\sigma_{\mathrm{LR}} + \sigma_{\mathrm{RL}}} \quad P_{\mathrm{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}$$

		P_{eff}	$(1 - P_{e^+}P_{e^-})$
$P_{e^-} = 0,$	$P_{e^+} = 0$	0%	1.00
$P_{e^-} = -100\%,$	$P_{e^+} = 0$	-100%	1.00
$P_{e^-} = -80\%,$	$P_{e^+} = 0$	-80%	1.00
$P_{e^-} = -80\%,$	$P_{e^+} = +60\%$	-95%	1.48

Precision improvement due to positron beam polarization e.g. in the measurement of A_{LR}





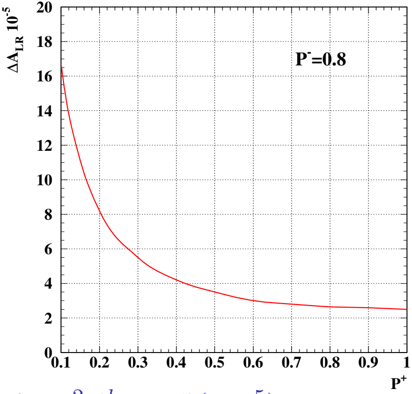
Positron Polarisation needed to reach $\Delta \sin^2 \vartheta^l_{\text{eff}} = \mathcal{O}(10^{-5})$

Precision improvement due to positron beam polarization e.g. in the measurement of A_{LR}

$$A_{\mathrm{LR}} = \frac{2(1-4\sin^2\theta_W^{\mathrm{eff}})}{1+(1-4\sin^2\theta_W^{\mathrm{eff}})}$$

- measurement of $\sin^2\theta_W^{\mathrm{eff}}$ at GigaZ
- employ *Blondel scheme* with 10% run time at σ_{++} and σ_{--}

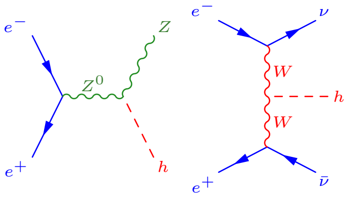
K. Mönig



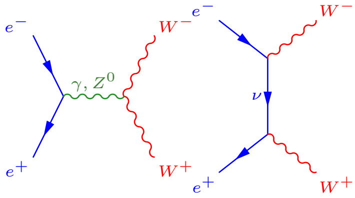
Positron Polarisation needed to reach $\Delta\sin^2\vartheta^l_{\mathrm{eff}} = \mathcal{O}(10^{-5})$

Separation of production processes

(P_{e^-}, P_{e^+})	$e^+e^- \to H\nu\bar{\nu}$	$e^+e^- \to HZ$
$(+0.8, 0)$	0.20	0.87
$(-0.8, 0)$	1.80	1.13
$(+0.8, -0.6)$	0.08	1.26
$(-0.8, +0.6)$	2.88	1.70



Suppression of background

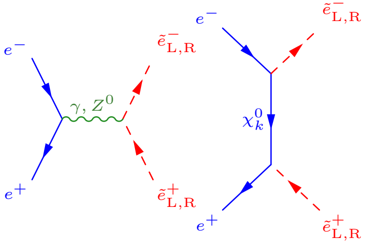


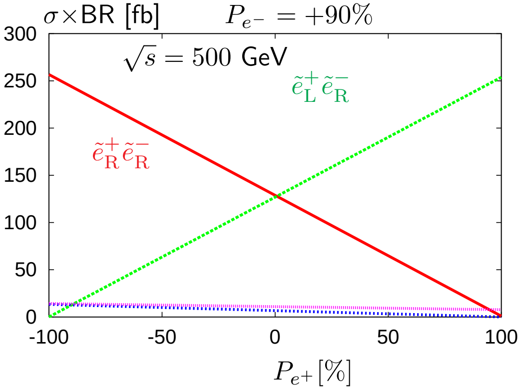
(P_{e^-}, P_{e^+})	$e^+e^- \to W^+W^-$
$(+0.8, 0)$	0.20
$(-0.8, 0)$	1.80
$(+0.8, -0.6)$	0.10
$(-0.8, +0.6)$	2.85

Unique understanding of non-standard couplings

Separation of $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm L}$ and $\tilde{e}^+_{\rm L}\tilde{e}^-_{\rm R}$

- check SUSY assumptions $e^+_{\rm L,R} \leftrightarrow \tilde{e}^+_{\rm L,R}$ and $e^-_{\rm L,R} \leftrightarrow \tilde{e}^-_{\rm R,L}$



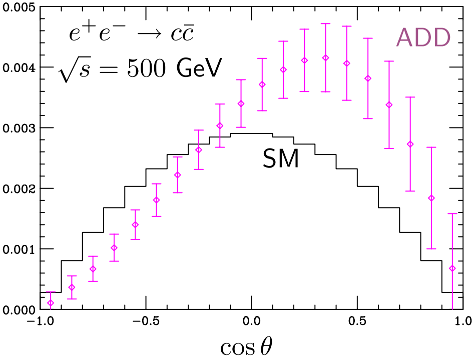


Separation of selectron pairs only posible with both beams polarized.

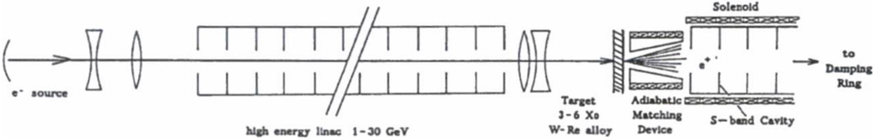
Option of using transversely polarized beams

signatures of extra dimensions in fermion production

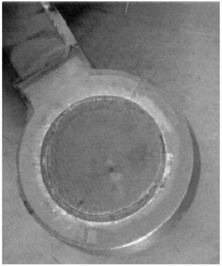
$$\frac{1}{N}\frac{dA^T}{d(\cos\theta)} = \frac{1}{\sigma}\left[\int_+ d\phi\,\frac{d\sigma}{d\cos\theta d\phi} - \int_- d\phi\,\frac{d\sigma}{d\cos\theta d\phi}\right]$$

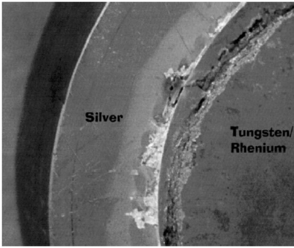


Positron source at SLAC

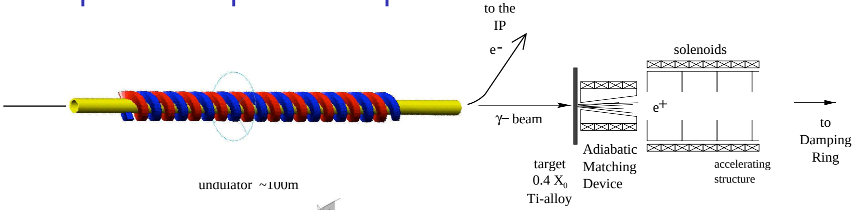


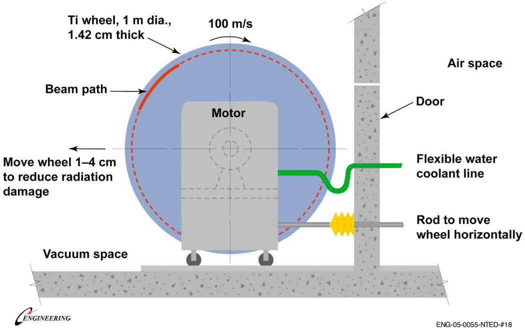
- 30 GeV electron beam hits W-Re target
- pulsed at 120Hz, 1 bunch/pulse
- heat load 24kW





How are polarized positrons produced?



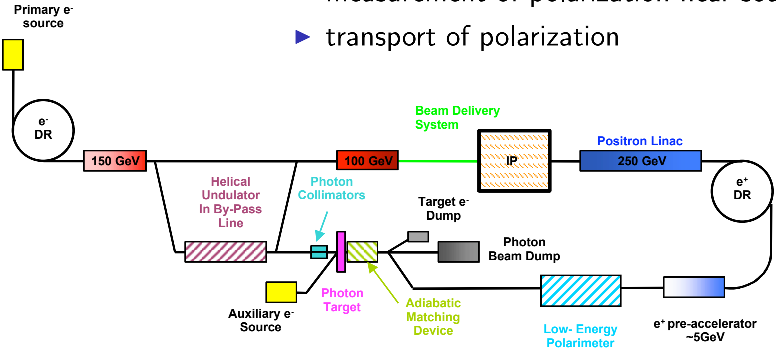


- electron beam through *helical undulator* ⇒ polarized photons
- photon beam hits thin Ti target
- pulsed at 5Hz, 2820 bunches/pulse
- heat load 135kW

Positron source for the ILC

DESY, Zeuthen

- optimization of polarization at production
- measurement of polarization near source
- transport of polarization



Positron source for the ILC

DESY, Zeuthen

- optimization of polarization at production
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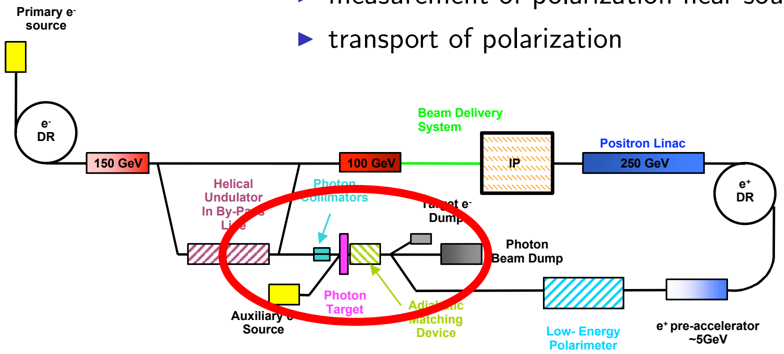

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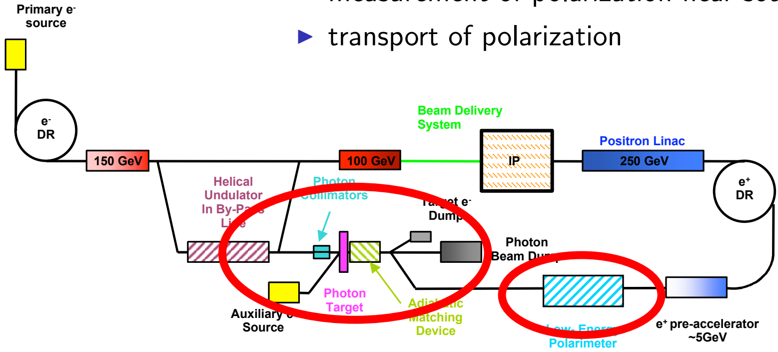


Polarization at Zeuthen?

EUROTeV WP4 : Polarized Positron Source

- Low-energy polarimeter
- Spin rotation and flip system
- Contribution to overall-design

Demonstration Experiment E166

- Helical undulator
- Production of polarized positrons
- Positron polarimeter

The E166 Experiment

Proposal:

- Demonstration of polarized positron production with a helical undulator

Status:

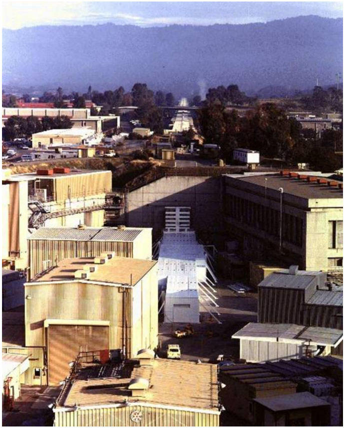
- approved in June 2003
- two runs, June and September 2005
- ≈ 8.5 million events on tape
- analysis is ongoing

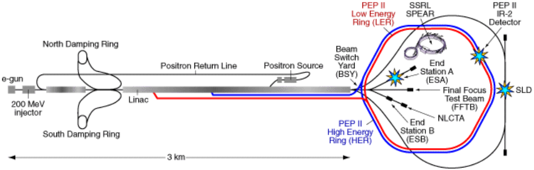
Collaboration:

- about 50 people
- 15 institutes
- from 3 continents

G. Alexander *et al.*, 2003, SLAC-PROPOSAL-E-166.

SLAC FFTB:



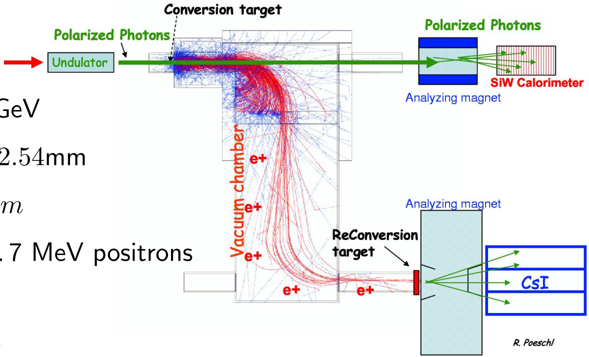


Final Focus Test Beam

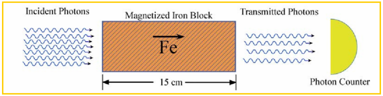
- beam energy $E_{\text{beam}} = 46.6\,GeV$
- electrons/bunch $n_e = 0.5 \cdot 10^{10}$
- beam size $\sigma = 40\,\mu m$
- rep. rate 10Hz

Experimental setup

- initial e^- beam at 46.6 GeV
- helical undulator period 2.54mm
- W target $.5\,X_0 = 1.75mm$
- spectrometer selects 3…7 MeV positrons
- reconversion to photons
- magnetised iron analyser
- CsI calorimeter



Compton transmission polarimetry



$$\sigma_{tot} = \sigma_{phot} + \sigma_{comp} + \sigma_{pair} \quad \text{with} \quad \sigma_{comp} = \sigma_0 + P_\gamma P_e \sigma_{pol}$$

Transmission

$$T^{\pm}(L) = e^{-nL\sigma} = e^{-nL\left(\sigma_{phot}+\sigma_{pair}+\sigma_0\right)} e^{\pm nL P_\gamma P_e \sigma_{pol}}$$

Asymmetry

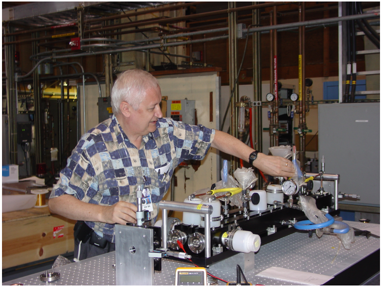
$$\delta(L) = \frac{T^+ - T^-}{T^+ + T^-} \approx nL P_\gamma P_e \sigma_{pol}$$

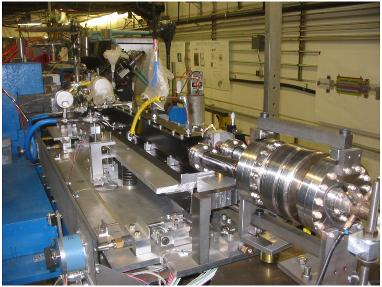
Photon Polarisation

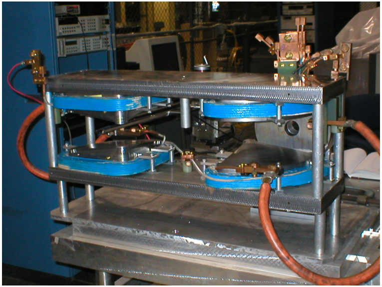
$$P_\gamma = \frac{\delta}{nL\sigma_{pol} P_e} = \frac{\delta}{A_\gamma P_e}$$

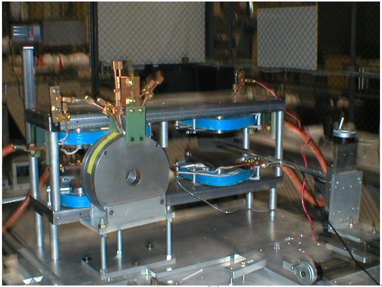
A_γ = Analysing power

Experimental setup









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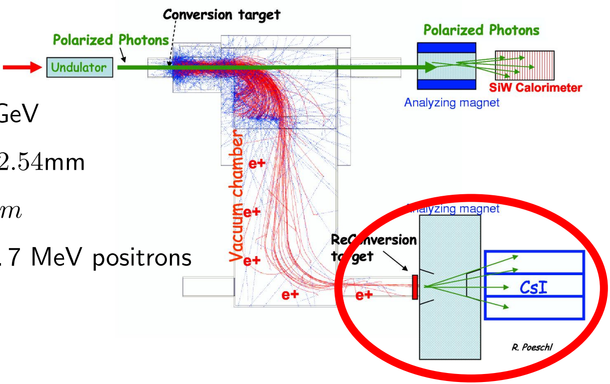
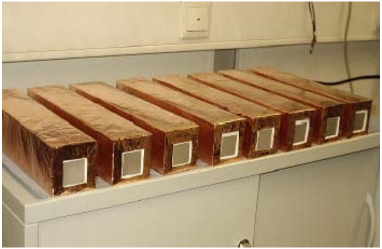
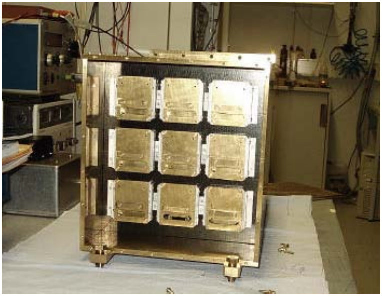
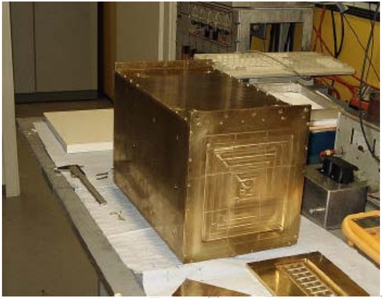


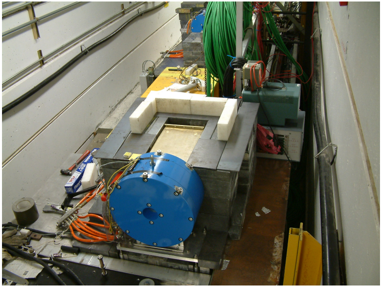
Experimental setup

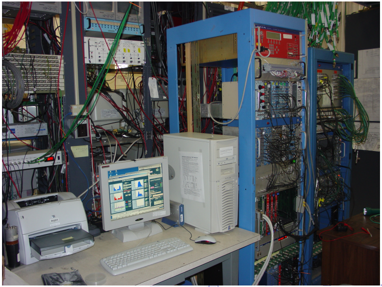






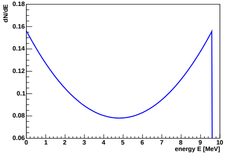
Experimental setup



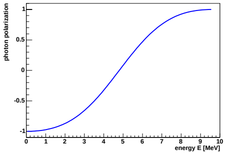


Expected positron polarization

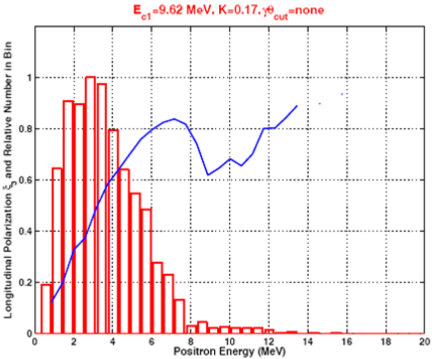
γ energy



γ polarization

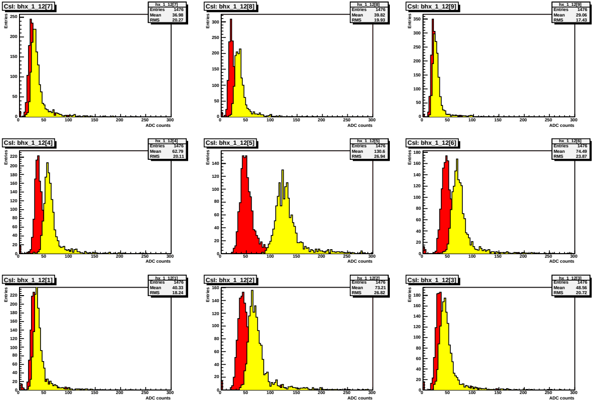


e^+ energy & polarization



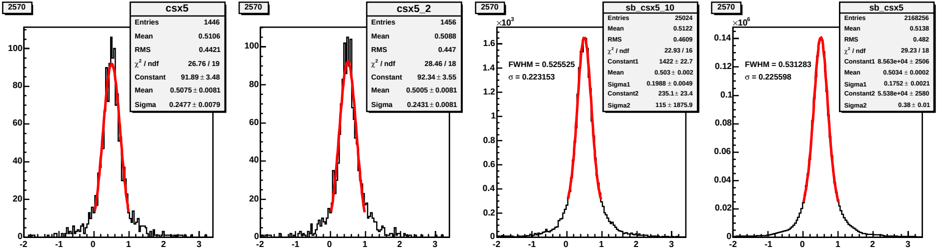
Preliminary results

Energy deposition in CsI crystals



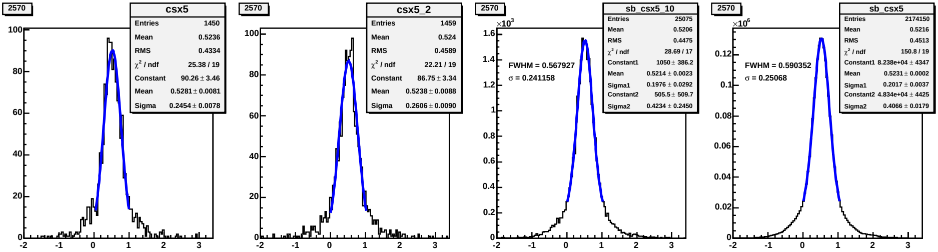
- all 9 crystals see positron signal
- good signal background separation in central crystal
- detail analysis needed to obtain asymmetry

Background substraction



- analyser polarity is fliped from plus to minus
- different analysis methods and cuts give similar results

Background substraction

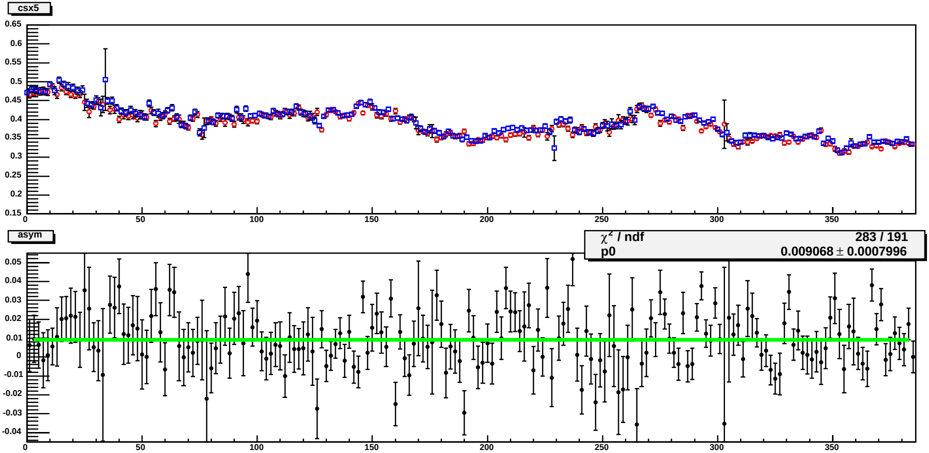


- analyser polarity is fliped from plus to minus
- different analysis methods and cuts give similar results

Preliminary results

Spectrometer current : 120 A

approx. number of signal points : $550\,000$



	Positrons					Electrons	
	100 A	120 A	140 A	160 A	180 A	160 A	
Method A	0.55	0.82	1.05	0.95	0.91	1.36	
	0.19	0.09	0.07	0.09	0.12	0.05	
	283/206	361/191	681/229	237/158	411/169	252/144	
	0.22	0.12	0.12	0.11	0.18	0.07	
Method B	0.60	0.89	1.00	0.84	0.97	1.32	
	0.18	0.09	0.07	0.09	0.12	0.05	
	241/206	302/191	647/229	237/158	370/169	271/144	
	0.20	0.11	0.11	0.11	0.17	0.07	
Method C	0.62	0.89	0.99	0.90	0.89	1.35	
	0.15	0.07	0.05	0.07	0.09	0.04	
	223/206	342/191	905/229	252/158	481/169	309/144	
	0.15	0.10	0.11	0.09	0.16	0.07	
Method D	0.62	0.91	1.00	0.89	0.96	1.32	A
	0.16	0.08	0.06	0.08	0.10	0.05	ΔA
	185/206	283/191	660/229	230/158	360/169	252/144	χ^2/ndf
	0.15	0.10	0.10	0.09	0.15	0.06	$\Delta A \cdot \sqrt{\chi^2/ndf}$

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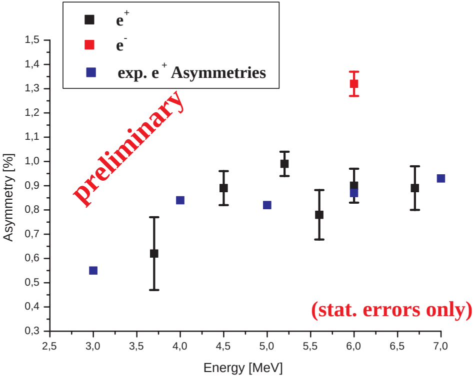
Positron/Electron asymmetries



- asymmetries in expected range
- simulation of analysing power needed to derive degree of polarization

Simulation package Geant4

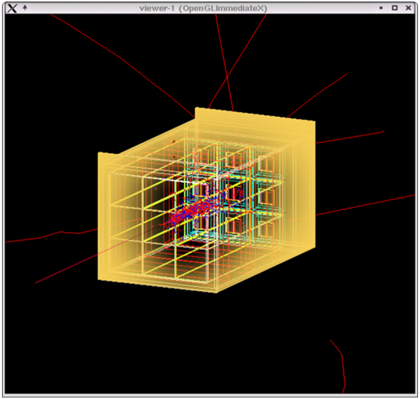
- toolkit for the simulation of the passage of particles through matter

Application in

- high energy physics
- nuclear experiments
- medical and space physics studies

Simulation method

- define geometry of detector environment
- track single particle step by step



Why do we need Polarization in Geant4

Where do we study polarized processes?

- Polarized Positron source for an International Linear Collider
- Demonstration experiment E166 at SLAC

Why are polarized interactions at low energy important?

- Target studies
  i.e. if a polarized beam hits a target
- Polarimetry
  i.e. if polarization causes observable azimuthal correlations

We want :

- to gain detailed understanding of all processes involved!

TARGET

Gammas:

- GammaConversion
- ComptonScattering
- PhotoElectricEffect

Electrons and Positrons:

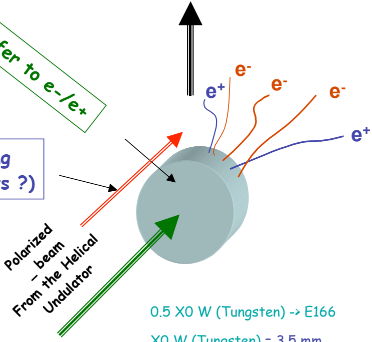
- MultipleScattering
- Ionization
- Bremsstrahlung

Polarization transfer to e-/e+

Diagnostics (Polarimetry)
Cross sections polarization dependent

- Compton Scattering
- Bhabha Scattering
- Moller Scattering
- Positron annihilation in Flight
- ....

Polarization tracking
(depolarization effects ?)



0.5 X0 W (Tungsten) -> E166

X0 W (Tungsten) = 3.5 mm

MAGNETIC FIELD:

Existing Monte Carlo codes

- EGS, *polarization extension by K. Flöttmann*
  - considers polarization transfer only
  - simulates Pair production, Bremsstrahlung, Compton
  - suitable for target studies
- Geant3, *polarization extension by V. Gharibyan/P. Schüler*
  - concentrates on asymmetries
  - simulates Bremsstrahlung, Compton (polarized target)
  - suitable for low-energy Compton polarimetry

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no complete simulation tool for low-energy polarization studies!

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no complete simulation tool for low-energy polarization studies!

- *new polarization extension Geant4*
  - aim for a complete treatment of polarization
  - polarization transfer and asymmeteries
  - suitable for polarimetry and target studies

G. Stokes, Trans. Cambridge Phil. Soc. **9** (1852) 399

Stokes parameter

Wave function :

$$\Psi(\boldsymbol{x}, t) = a_1 \Psi_1 + a_2 \Psi_2$$

Jones vector :

$$|a_1|^2 + |a_2|^2 = 1 \qquad \boldsymbol{a} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

Spin density matrix :

$$\rho = \boldsymbol{a} \otimes \boldsymbol{a}^* = \begin{pmatrix} a_1 a_1^* & a_1 a_2^* \\ a_2 a_1^* & a_2 a_2^* \end{pmatrix} = \frac{1}{2}(1 + \boldsymbol{\xi\sigma})$$

$$\sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\sigma_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_3 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Stokes parameter :

$$\boldsymbol{\xi} = \begin{pmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{pmatrix} = \boldsymbol{a}^\dagger \boldsymbol{\sigma}\, \boldsymbol{a}$$

Matrix formalism

W. H. McMaster, Rev. Mod. Phys. **33** (1961) 8

$$\begin{pmatrix} I \\ \xi \end{pmatrix} = T \begin{pmatrix} I_0 \\ \xi_0 \end{pmatrix}$$

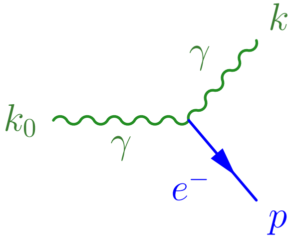
Transformation Matrix :

$$T = \begin{pmatrix} S & A_1 & A_2 & A_3 \\ P_1 & M_{11} & M_{21} & M_{31} \\ P_2 & M_{12} & M_{22} & M_{32} \\ P_3 & M_{13} & M_{23} & M_{33} \end{pmatrix}$$

- Differential cross section
- Asymmetry
- Polarization
- Depolarization and polarization transfer

Compton scattering on electron at rest

$$T = \begin{pmatrix} I & A & 0 & E \\ A & B & 0 & H_1 \\ 0 & 0 & C & H_2 \\ F & G_1 & G_2 & D \end{pmatrix}$$



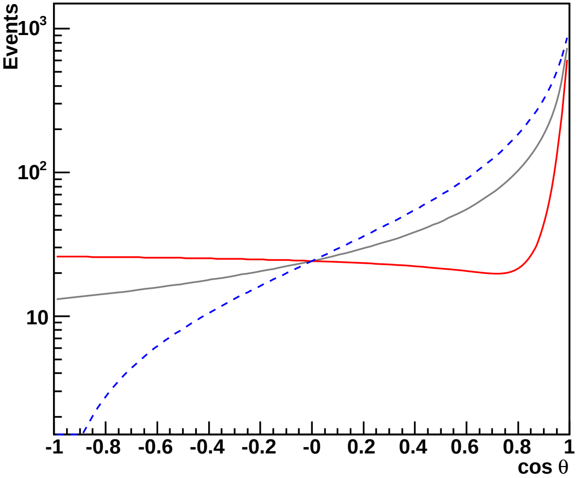
Independent of electron spin $\boldsymbol{S}$: (I,A,B,C,D)

$$I = 1 + \cos^2\theta + (k_0 - k)(1 - \cos\theta)$$
$$A = \sin^2\theta$$
$$D = 2\cos\theta + (k_0 - k)(1 - \cos\theta)\cos\theta$$

Dependent on electron spin $\boldsymbol{S}$: (E,F,G_i,H_i)

$$E = -(1 - \cos\theta)(\boldsymbol{k}_0\cos\theta + \boldsymbol{k}) \cdot \boldsymbol{S}$$
$$F = -(1 - \cos\theta)(\boldsymbol{k}\cos\theta + \boldsymbol{k}_0) \cdot \boldsymbol{S}$$

Compton scattering – Asymmetry

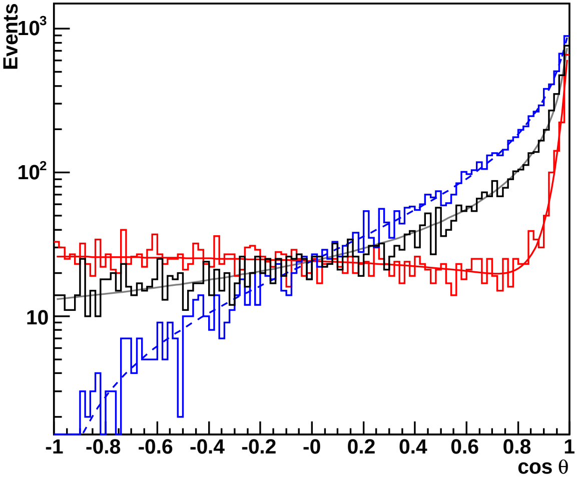


$P_\gamma \cdot P_e = +1$

$P_\gamma \cdot P_e = -1$

$P_\gamma \cdot P_e = 0$

Compton scattering – Asymmetry



$P_\gamma \cdot P_e = +1$

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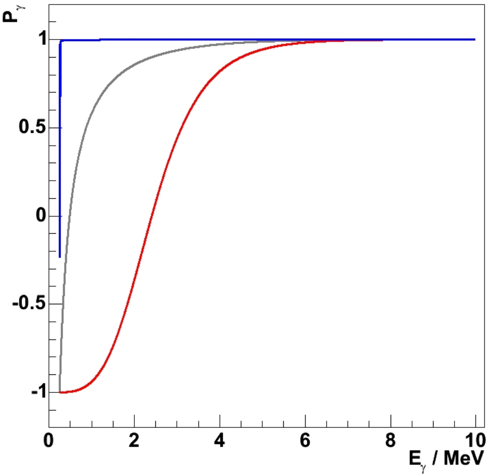
$P_\gamma \cdot P_e = 0$

Compton scattering – Polarization transfer



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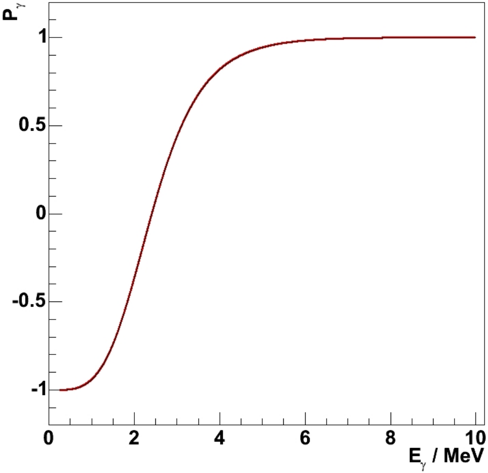
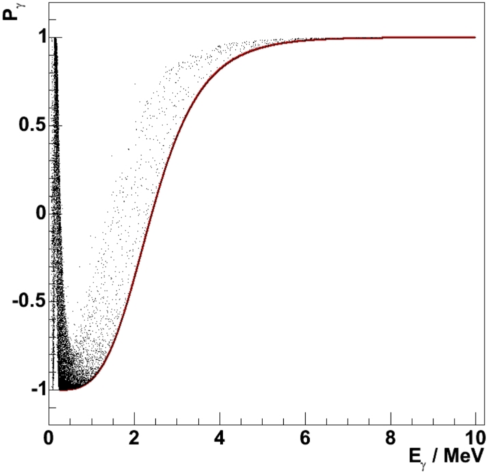
Compton scattering – Polarization transfer



$$P_\gamma \cdot P_e = +1$$

single scattering

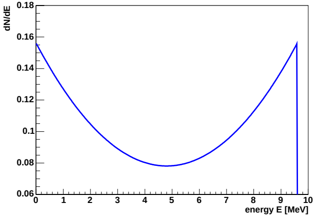
Compton scattering – Polarization transfer

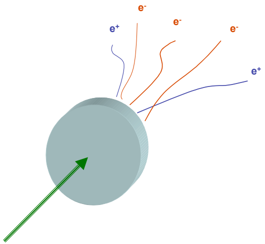


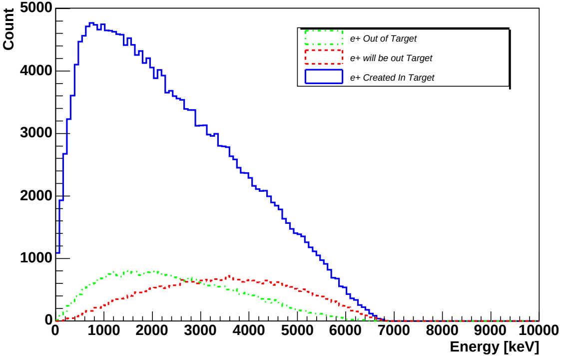
$$P_\gamma \cdot P_e = +1$$

multiple scattering

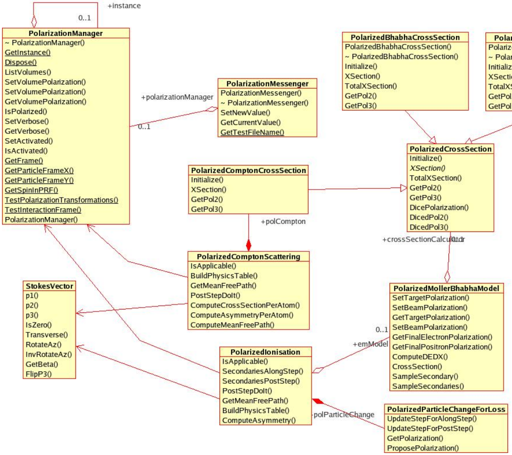
Target studies







Polarization Library for Geant4



- independent library
- provides polarized QED process
- can assigns a polarization to any logical volume
- simple to include in existing Geant4 application

Summary & Outlook

- International linear collider
  - polarized positrons crucial for many physics studies
  - undulator based positron source
- E166 analysis
  - asymmetry data analysis
  - analysing power will be recalculated with Geant4
  - determine real positron polarization
- Outlook
  - Low-energy polarimeter
  - Target optimisation
  - Source efficiency studies

G4 polarization group:
R. Dollan, H. Kolanoski, K. Laihem, T. Lohse, S. Riemann, A.S., A. Stahl, P. Starovoitov

"It is remarkable that it is more difficult to think of methods of detecting polarization, which seems apt for realization, than of methods of producing polarization."

H. A. Tolhoek, Rev. Mod. Phys. **28** (1956) 277.