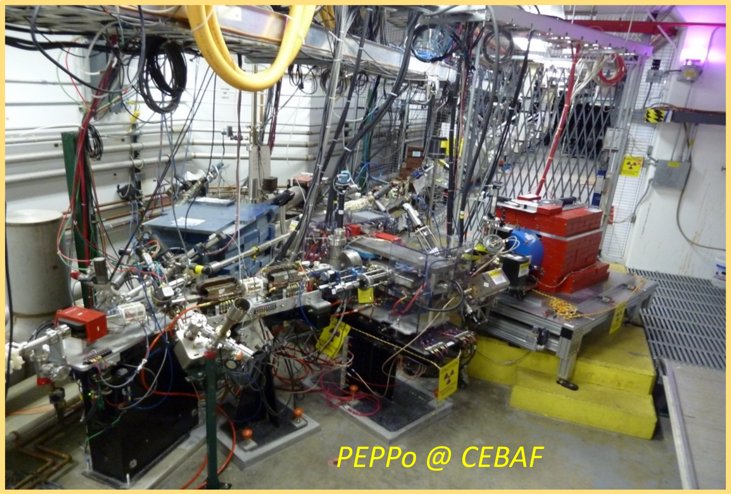
Positron Production, Polarization, and Polarimetry

Eric Voutier

Université Paris-Saclay, CNRS/IN2P3/IJCLab, Orsay, France



(i) Why ?
(ii) How ?
(iii) PEPPo
(iv) Polarimetry
(v) Summary

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Positron Physics Opportunities

U = Unpolarized
P = Polarized

Interference Physics
- Two-photon physics (U,P)
- Generalized parton distributions (U,P)

Charged Current Physics
- Deep inelastic scattering (U,P)
- Charm production (P)

Test of the Standard Model
- Search for a U-boson coupling to dark matter (U,P)
- Electroweak neutral coupling C_{3q} (U,P)
- Lepton flavor violation (U,P)

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Slow Positron Applications
- Positron annihilation spectroscopy (U,P)
- Spintronics (P)
- Positronium spectroscopy (U,P)
- Antimatter spectroscopy
- Antimatter gravity
- Energy production
- ...

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e^+e^- Colliders Physics

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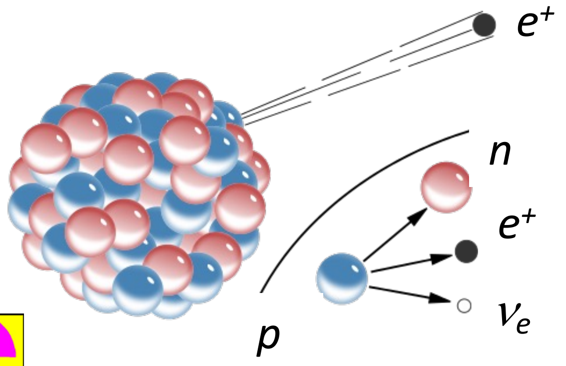
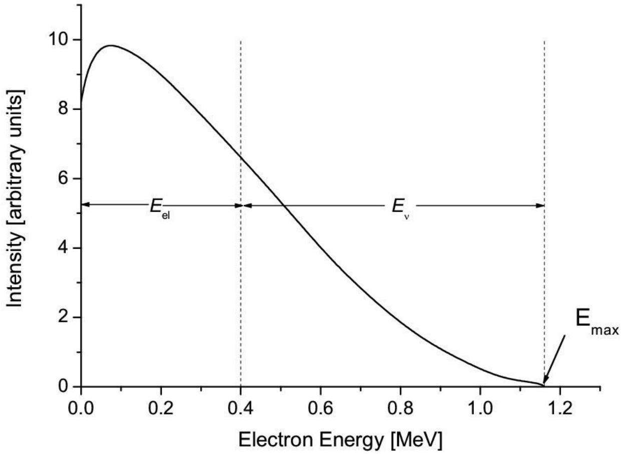
β^+ Decay





$$p \longrightarrow n + e^+ + \nu_e$$

- **Positron emission** from a **radioactive source** is an electroweak process, non-conserving parity, and creating **right-handed positrons**.
- The magnitude of the **positron polarization increases with the positron energy**, however at the expense of the flux intensity.
  - The life-time of the source is limited (months/years)
  - The flux intensity is limited (10^6-10^8 e^+/s)

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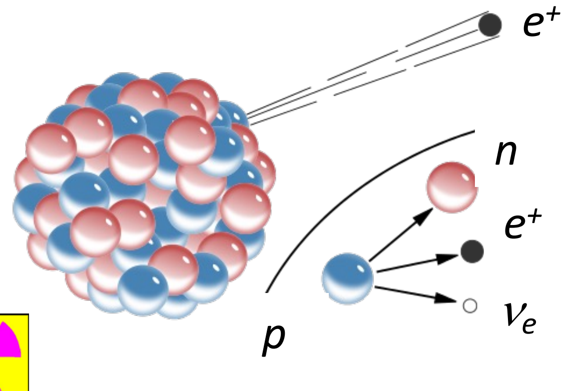

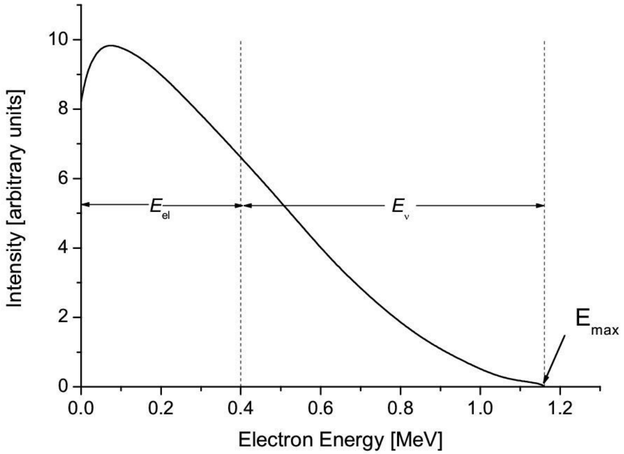

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Not performant enough for an accelerator source.

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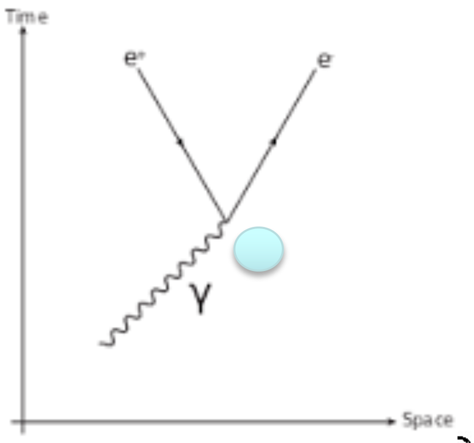
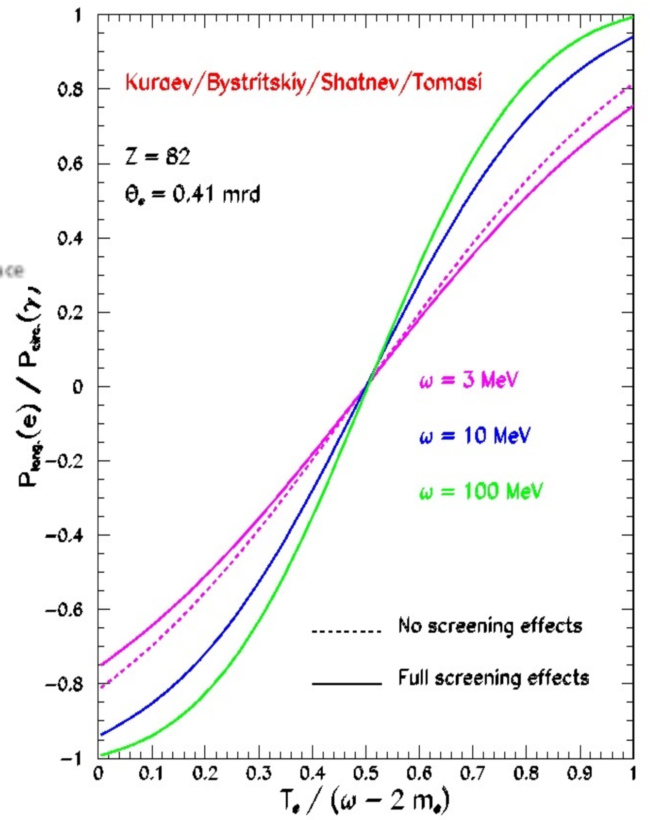
Photon Materialisation

H. Olsen, L. Maximon PR 114 (1959) 887 E.A. Kuraev et al. PRC 81 (2010) 055208



Polarization Transfer



$$\gamma + A \longrightarrow e^+ + e^- + X$$

- In the vicinity of the **electromagnetic field of a nucleus**, energetic enough photons (E_γ >1.022 MeV) create **e^+e^--pairs**.

- The circular polarization of photons transfer to the pair into longitudinal polarization.

  - The life-time is intrinsically unlimited
  - High fluxes can be achieved (10^{10}-10^{13} e^+/s)

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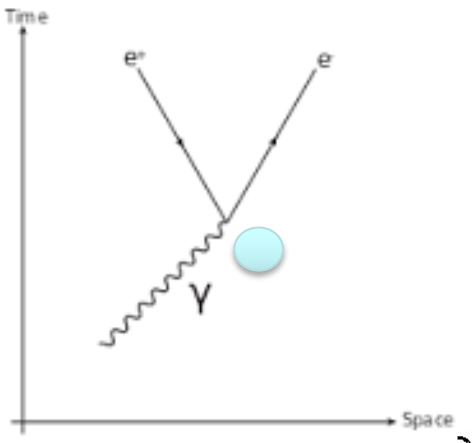

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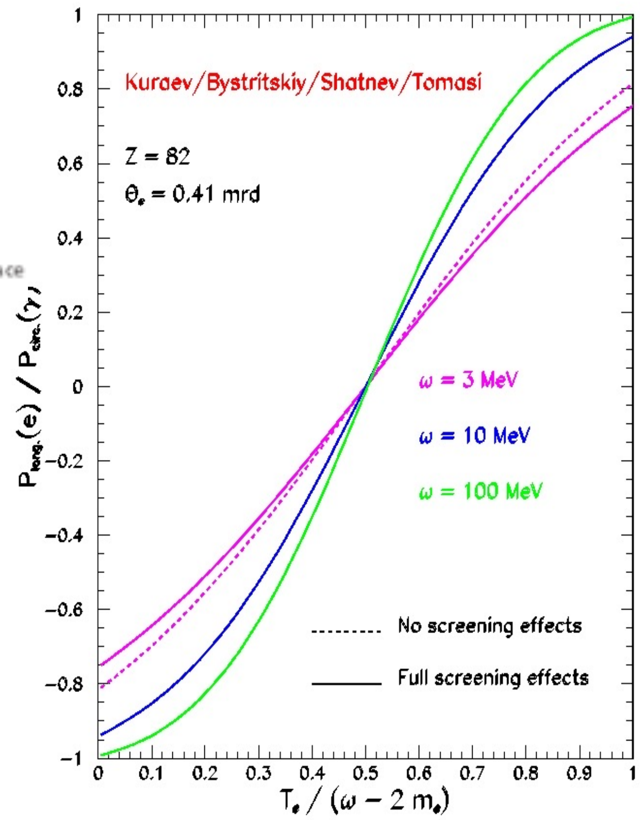

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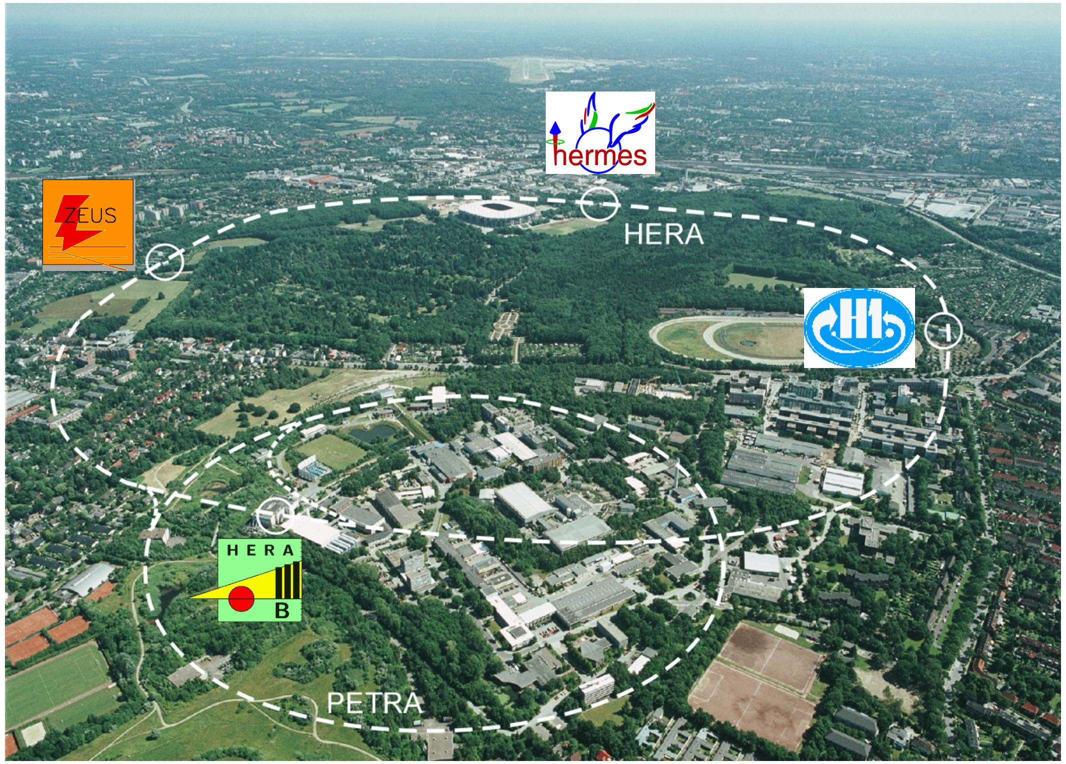
Sokolov-Ternov Effect

A.A. Sokolov, I.M. Ternov Sov. Phys. Dokl. 8 (1964) 1203

- The **synchrotron radiation** of **unpolarized positrons** (electrons) in the magnetic field of a storage ring builds up **positron polarization** in the opposite direction to the magnetic field.



Polarization builds up exponentially with a time constant characteristic of the energy and the curvature of the positrons

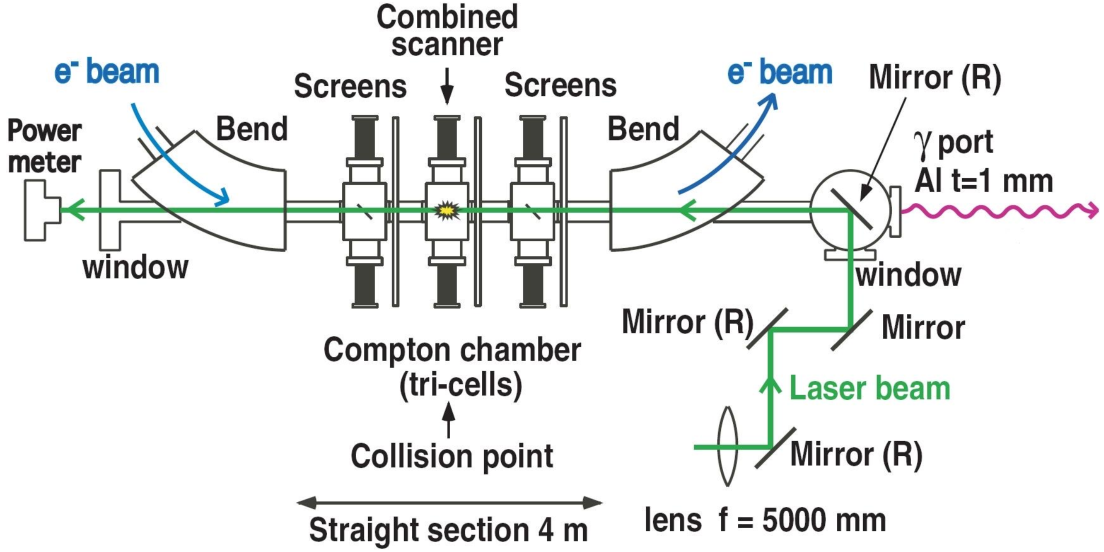
$$\tau = \frac{8}{5\sqrt{3}} \frac{m_e^2 c^2}{\hbar e^2} \frac{\rho^3}{\gamma^5} \qquad \text{(\textasciitilde 20mn@HERA)}$$

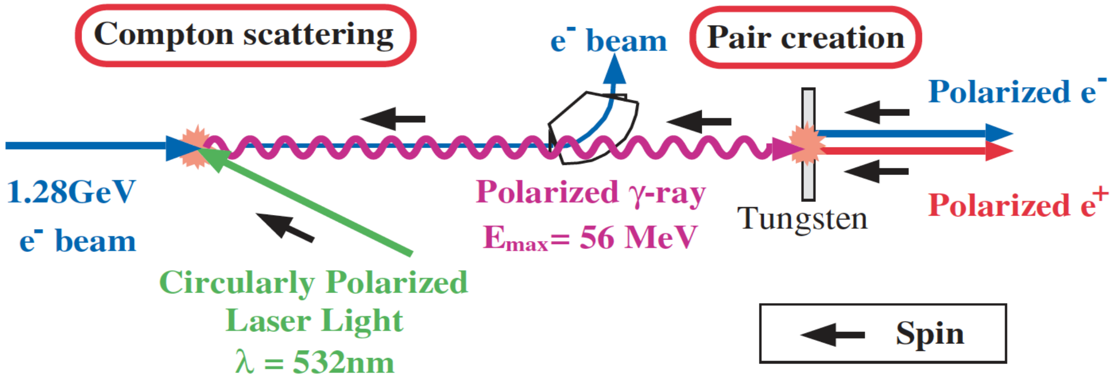
Requires a ring at **multi-GeV energies.**

Compton Backscattering

T. Omori et al. PRL 96 (2006) 114801

- The **scattering** of a **polarized laser** light on a **GeV electron** beam generates high energy photons capable of **pair creation**, while the initial **laser polarization** transfers to the **photons**.





The **demonstration experiment** was performed at **KEK** and reported an **efficient propagation of the laser polarization** to the produced positron featuring a high longitudinal polarization degree.

$$P(e^+) = 73 \pm 15 \pm 19\ \%$$

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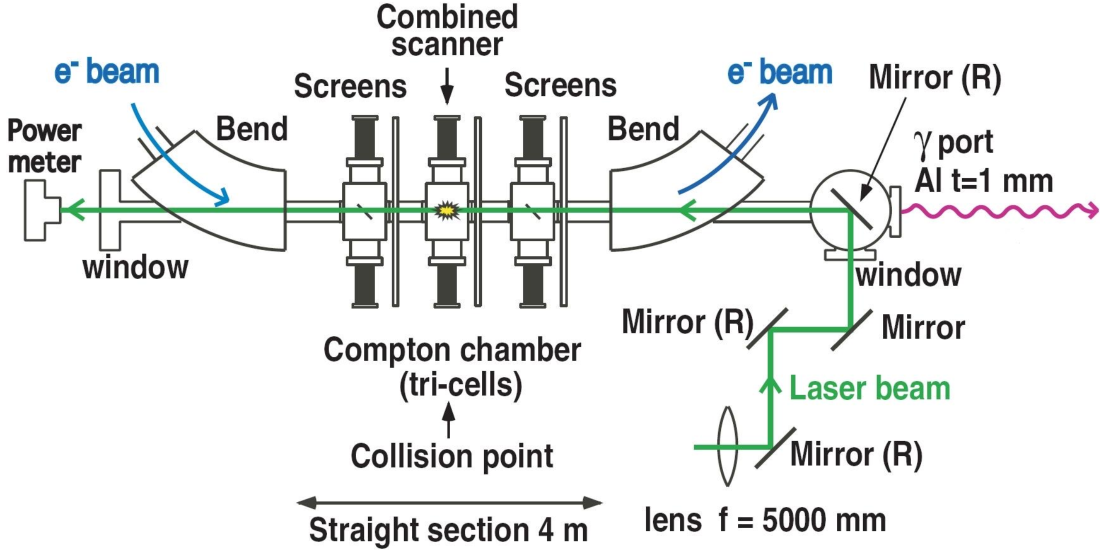

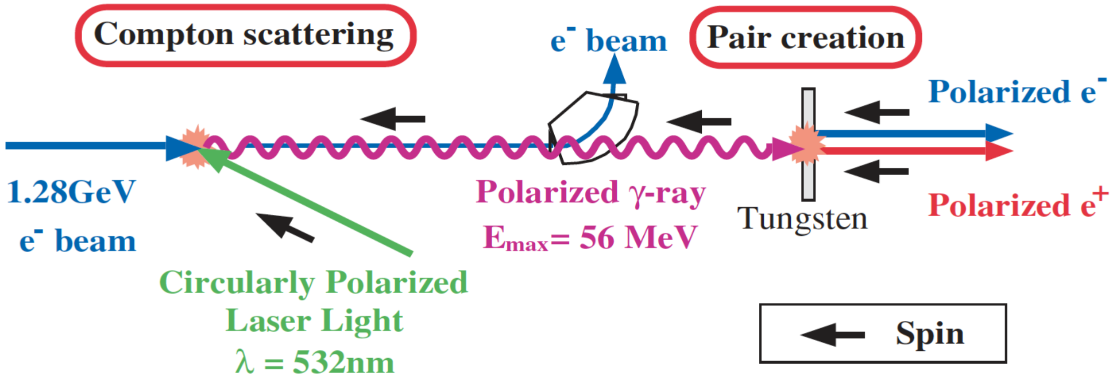

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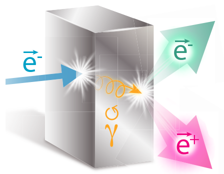
Requires few-GeV energies.

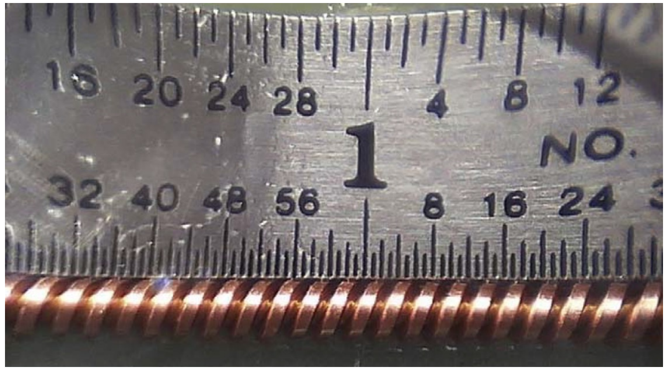
$P(e^+) = 73 \pm 15 \pm 19\ \%$



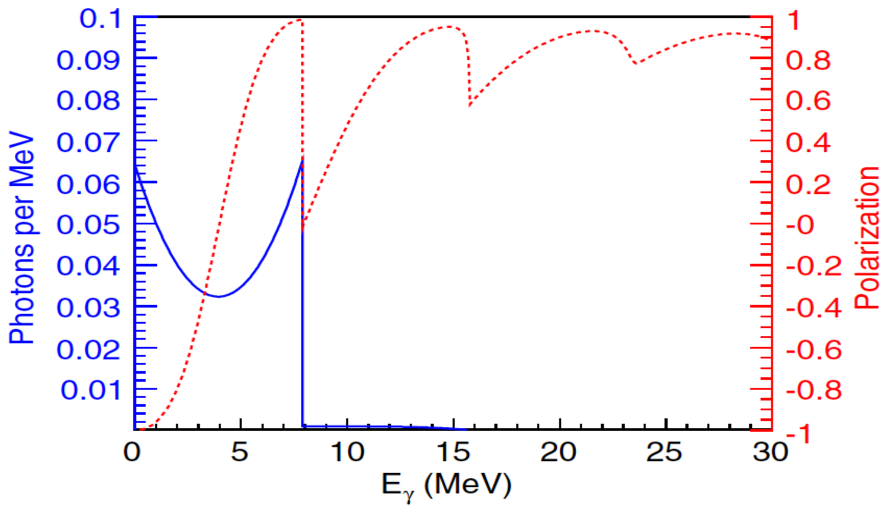
Undulator Photons

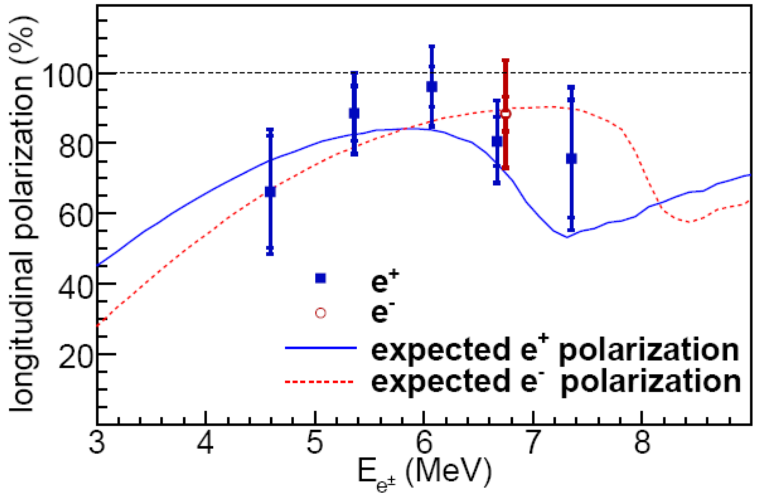
G. Alexander et al. PRL 100 (2008) 210801 G. Alexander et al. NIMA 610 (2009) 451

- A **high energy electron** beam (multi tens of GeV) traveling through a **helical undulator** generates **circularly polarized photons** suitable for polarized positron production.



0.6x0.6 mm^2 wire with 2.54 mm period





The **demonstration experiment** was conducted at **SLAC** with a **46.6 GeV** electron beam and reported high longtudinal polarization degree.

The polarized positron source at the International Linear Collider involves a 150 GeV electron beam with a 231 m long undulator.

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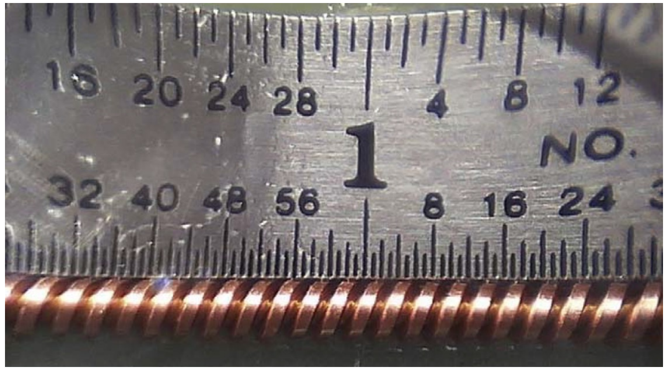

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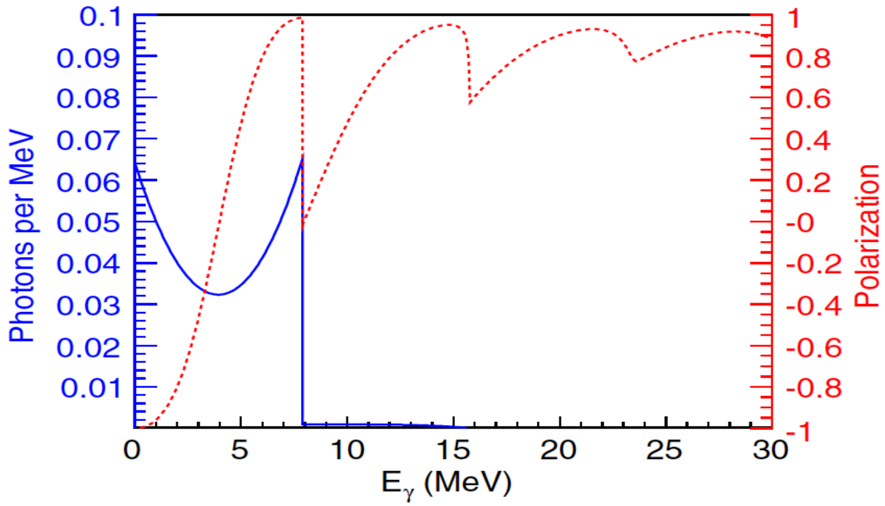

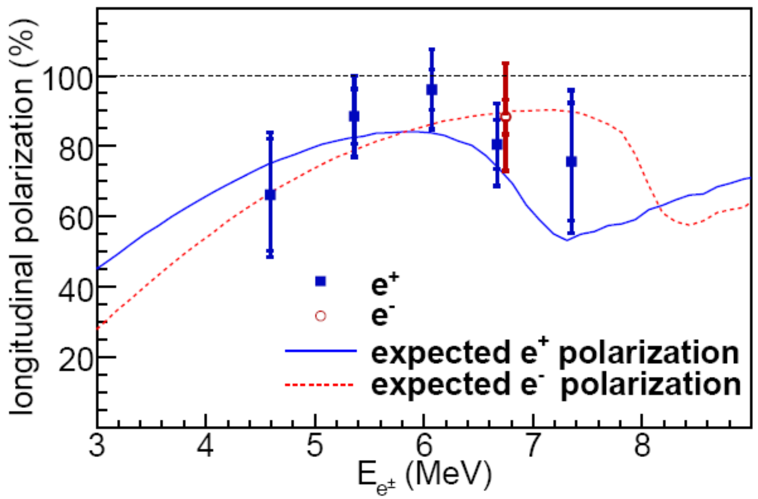

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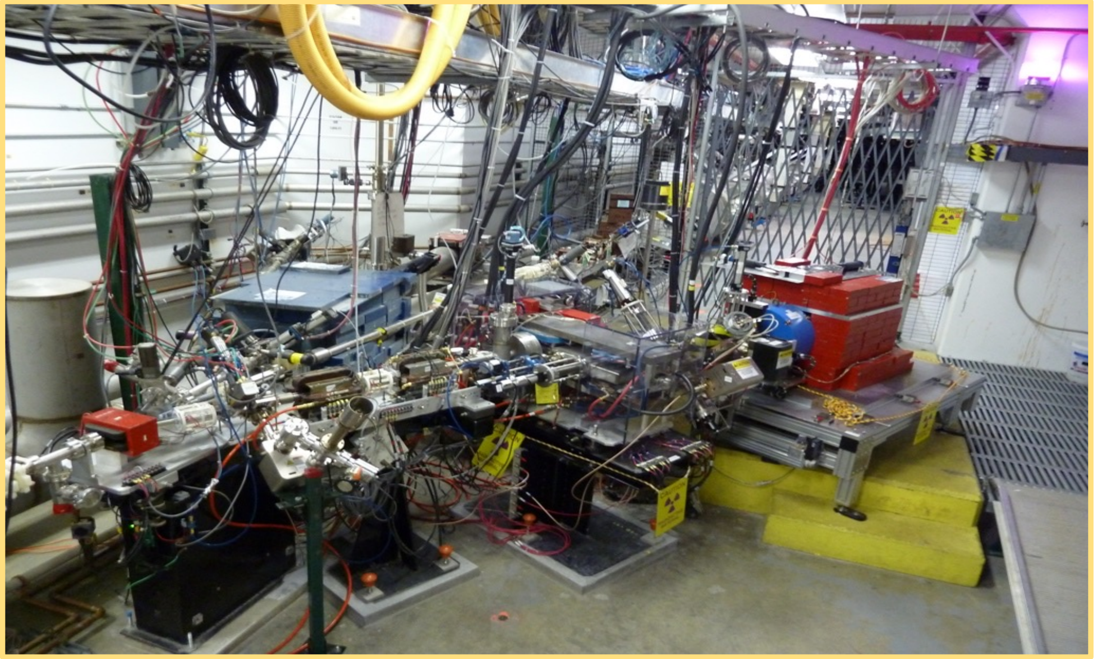
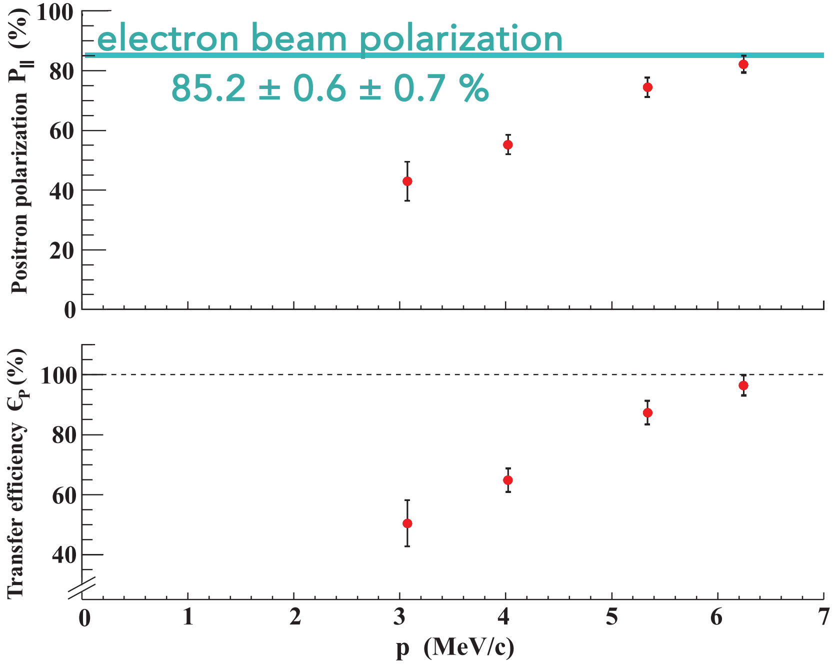
Polarized Bremsstrahlung

(PEPPo Collaboration) D. Abbott et al. PRL 116 (2016) 214801

- A longitudinally polarized electron beam generates in the vicinity of a nuclear field circularly polarized photons which create within the same target longitudinally polarized e^+e^--pairs.



J. Grames, E. Voutier et al. JLab Experiment E12-11-105 (2011)



The **demonstration experiment** was conducted at the **CEBAF** injector with a **8.2 MeV/*c*** electron beam reporting the **lagest ever** achieved **polarization**.

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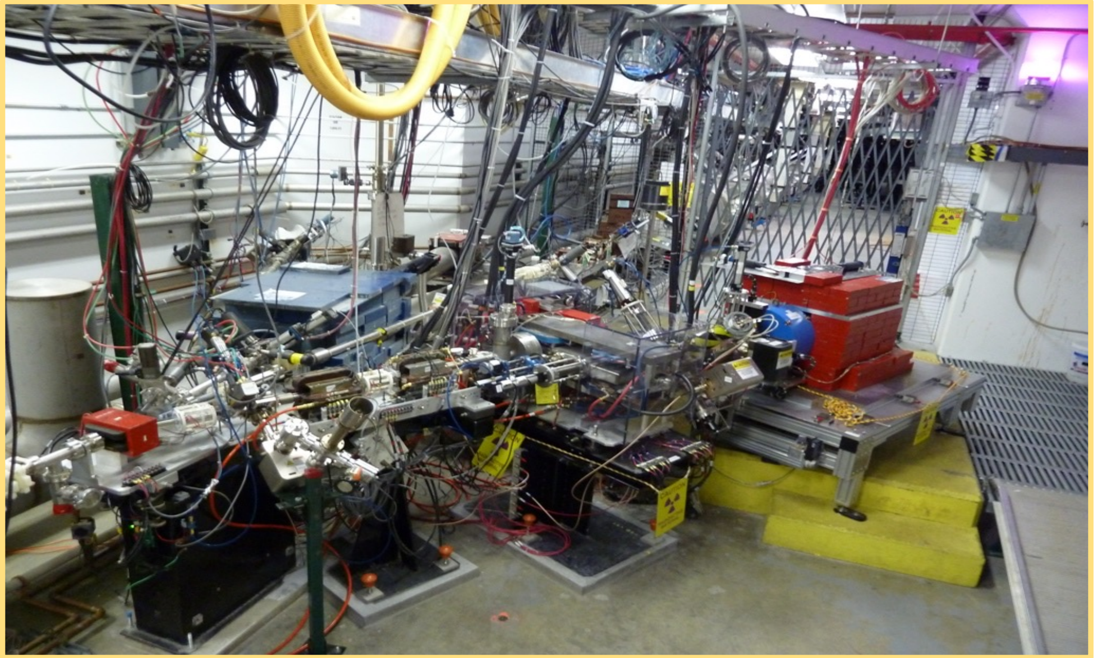

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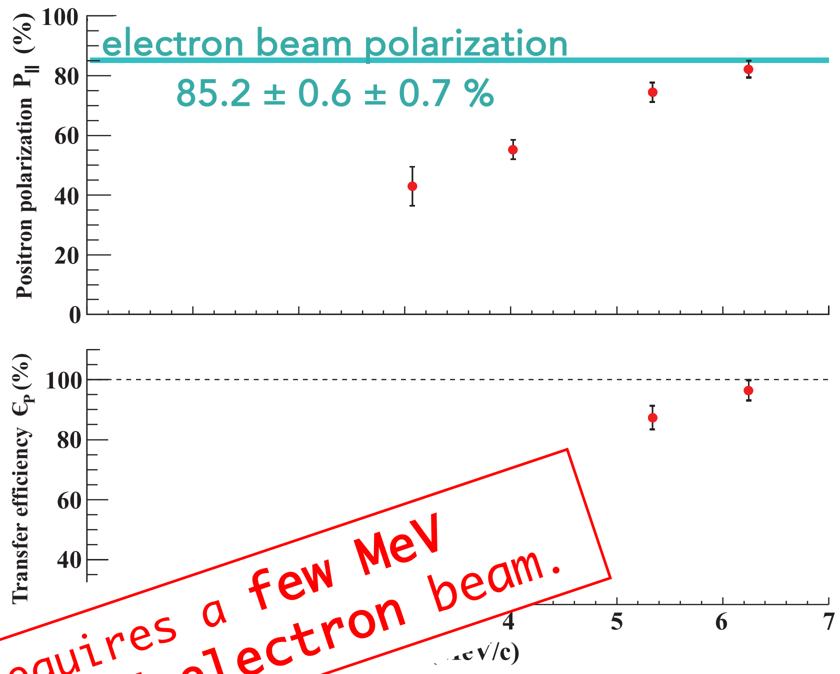

Requires a few MeV polarized electron beam.

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(PEPPo Collaboration) D. Abbott et al. PRL 116 (2016) 214801

- A **longitudinally polarized electron** beam generates in the vicinity of a nuclear field **circularly polarized photons** which create within the same target **longitudinally polarized e^+e^--pairs**.

- ✓ The PEPPo technique has been selected for the **Ce$^+$BAF** positron source.
- ✓ The Ce$^+$BAF design involves a **120 MeV** highly polarized electron beam with a **1 mA** beam intensity.
- ✓ The **technique** is intrinsically **unlimited** in polarization and intensity.
- ✓ Practical/technological limitations apply in terms of the performances of the **polarized electron source** and the capabilities of the **positron production target**.

(Ce$^+$BAF Working Group) J. Grames et al. JACoW IPAC (2023) MOPL152

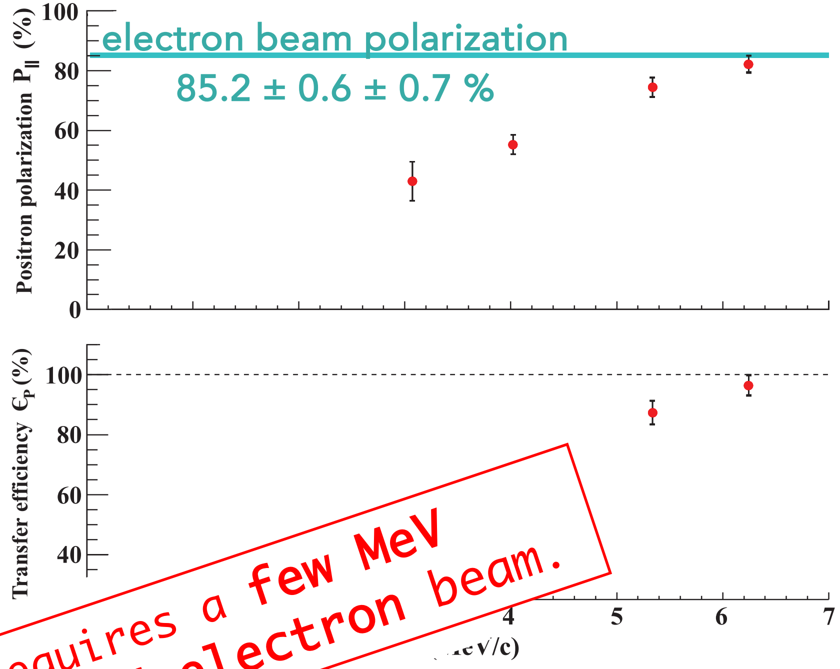

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Figure-of-Merit

- The **Figure-of-Merit** (FoM) quantifies the *polarized performance* of a **source** or a **polarimeter** from the statistical uncertainty of a measurement.

$\mathcal{A}_m$ is the measured asymmetry
P is the beam polarization
A_p is the physics asymmetry

$N^{\pm} = N_0(1 \pm PA_p)$

$$\boldsymbol{\mathcal{A}_m} = \frac{N^+ - N^-}{N^+ + N^-} = PA_p$$

$PA_p \ll 1$

$$\boldsymbol{\delta\mathcal{A}_m} = \frac{2}{N^+ + N^-}\sqrt{\frac{N^+N^-}{N^+ + N^-}} \approx \sqrt{\frac{1}{2N_0}}$$

- N_0 is proportionnal to the beam intensity, the cross section of the process, the detector efficiency, and the duration of the measurement.

Physics

$$A_p = \mathcal{A}_m / P$$

$$\delta A_p = \sqrt{\frac{1}{2N_0P^2}} = \sqrt{\frac{1}{\mathrm{FoM}}}$$

Polarization

$$P = \mathcal{A}_m / A_p$$

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Analyzing power

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Analyzing power

The FoM is defined as the **convolution** of the **unpolarized yield** and the **squared polarization capabilities**.

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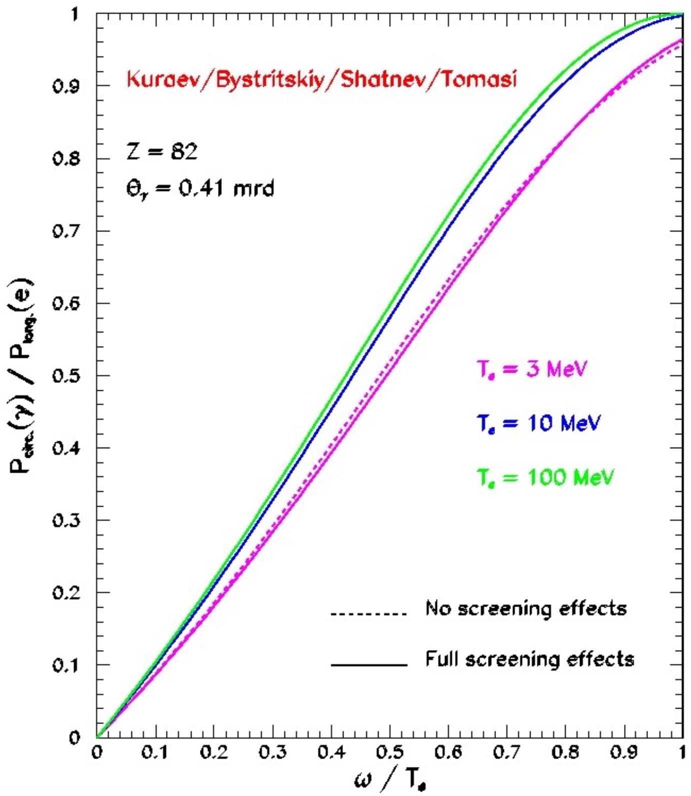
Polarized Yield

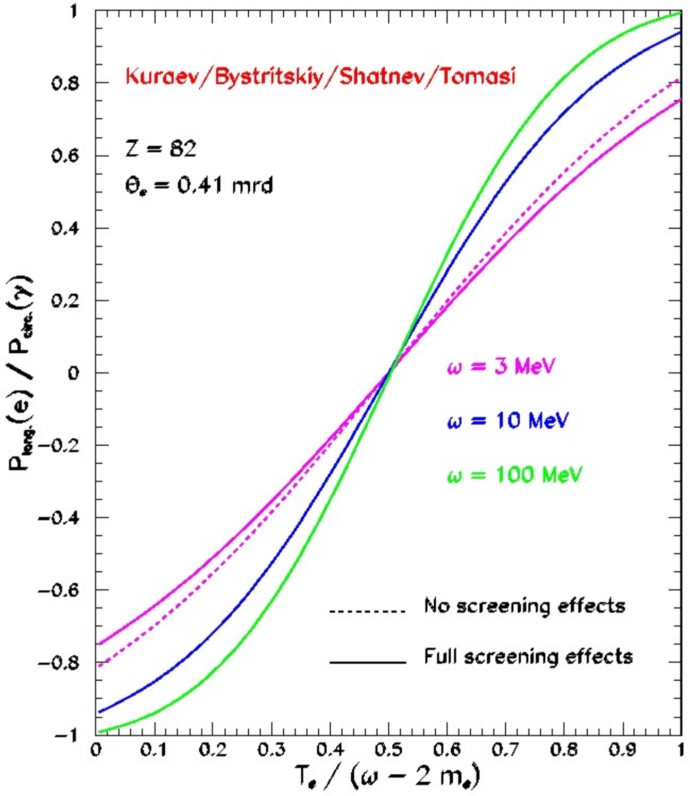
H. Olsen, L. Maximon PR 114 (1959) 887   E.A. Kuraev et al. PRC 81 (2010) 055208

- The positron **yield** (e^+/e^-) and **polarization** results from the convolution of two processes : the initial **polarized electron** beam **bremsstrahlung** and the **creation of e^+e^--pairs** by the bremsstrahlung **polarized photons**.

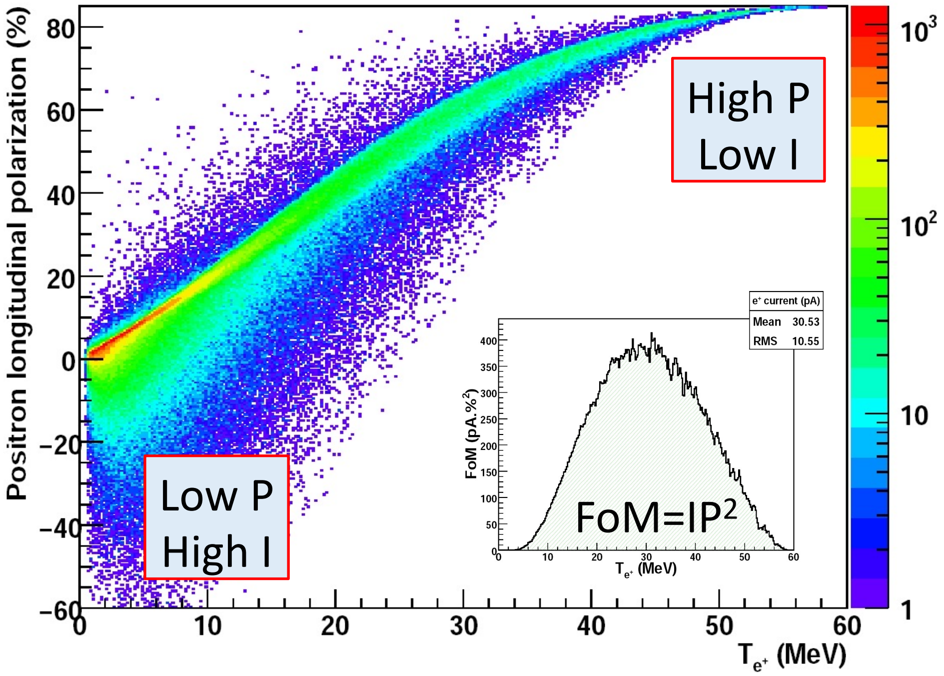
BREMSSTRAHLUNG



PAIR CREATION



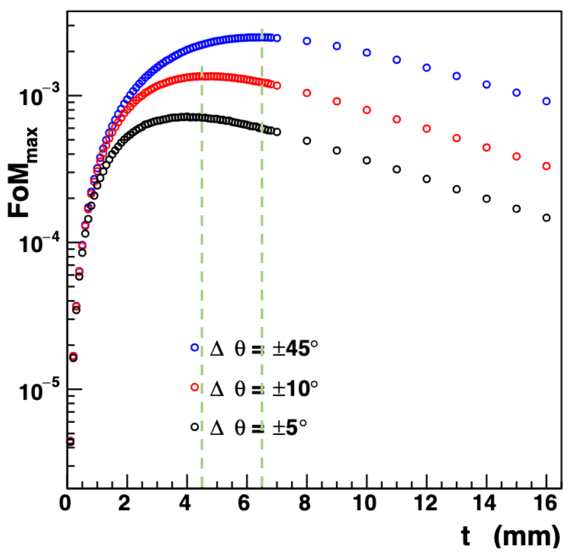
$T_{e^-} = 60$ MeV $t_W = 10$ μm

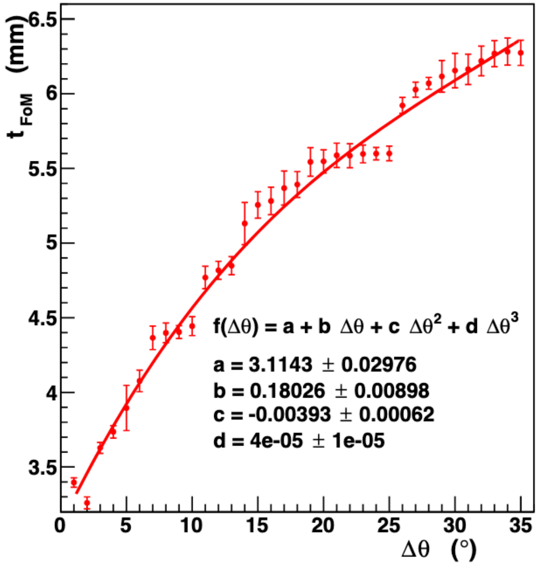


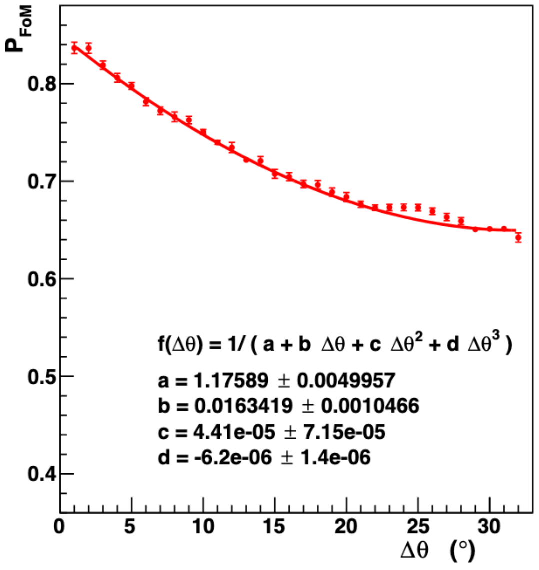
e^+ Source Optimization

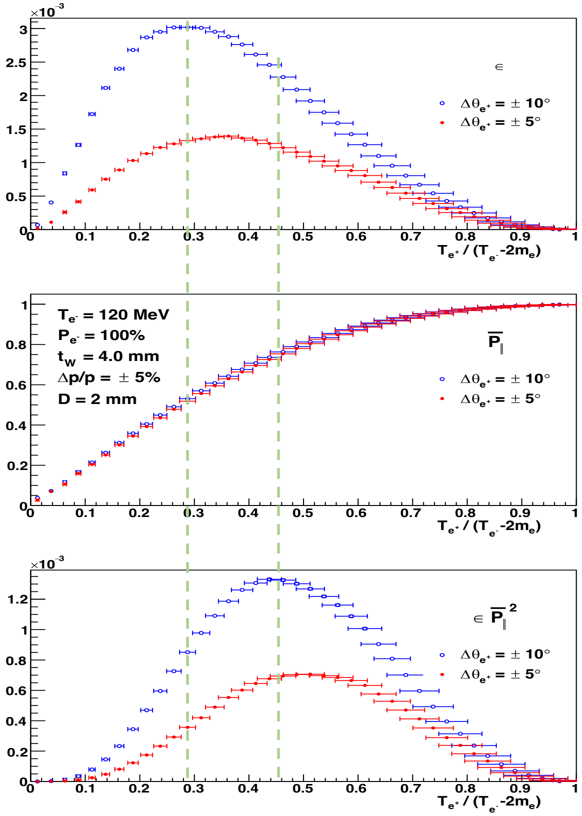
S. Habet et al. JLAB-ACC-23-3794 (2023) arXiv:2401.04484

- The positron **yield** (e^+/e^-) scales with the beam power (**Beam Energy × Beam Intensity**) and depends on the thickness of the production target.
- The **optimum target thickness** depends and the properties of the **positron collection system** which can mimic by angular ($\Delta\theta_{e^+}$) and momentum ($\Delta p/p$) acceptances.









✓ The **selection of the positron momentum** allows to operate either with **optimum FoM** (polarized mode) or **optimum efficien**cy (unpolarized mode).

(Jefferson Lab Positron Working Group) A. Accardi *et al.* EPJ A 57 (2021) 261

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Mott

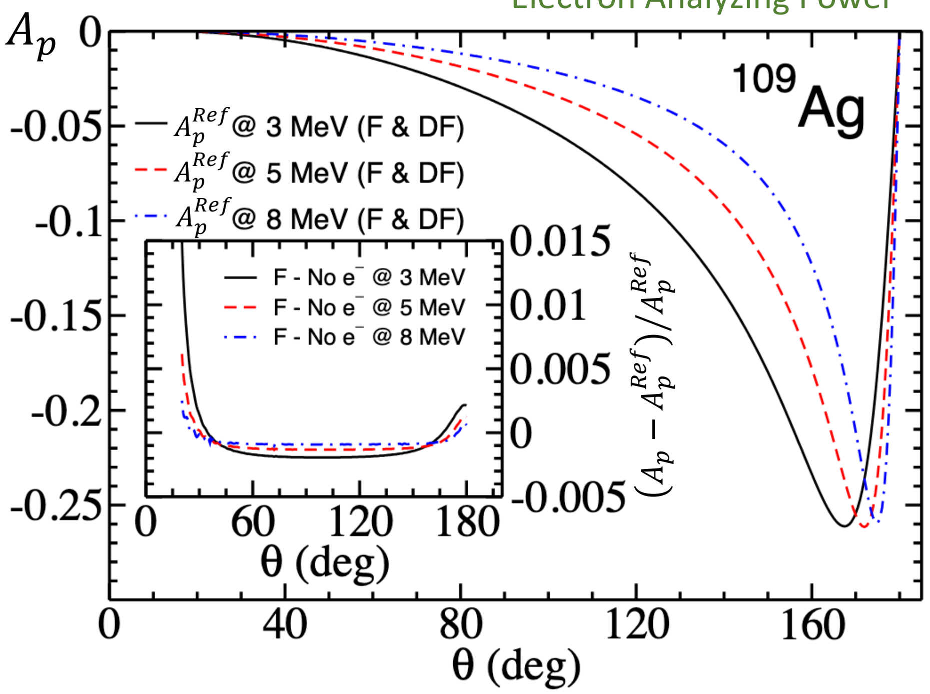
J.M. Hoogduin PhD Thesis, Groningen University (1997)   X. Roca-Maza EPL 120 (2017) 33002

- At low energies (up to a few MeV), the Mott scattering is a well-established method to measure the polarization of an electron beam.
- It involves the elastic scattering of electrons off a heavy nucleus and the interaction of the electron spin with the Coulomb field of the nucleus.
- The asymmetry is measured with respect to the beam polarization orientation.
- Mott polarimetry requires transversely polarized beams.

$$\frac{d\sigma}{d\Omega} = \frac{Z^2 e^4}{4m^2c^4} \frac{\left(1-\beta^2 \sin^2(\theta/2)\right)(1-\beta^2)}{\beta^4 \sin^2(\theta/2)} \left[1 \pm P_e A_p\right]$$

The **sensitivity** of the Mott process to positron polarisation Is expected to be **strongly reduced** because of the **repulsive interaction** with the Coulomb field.

Electron Analyzing Power



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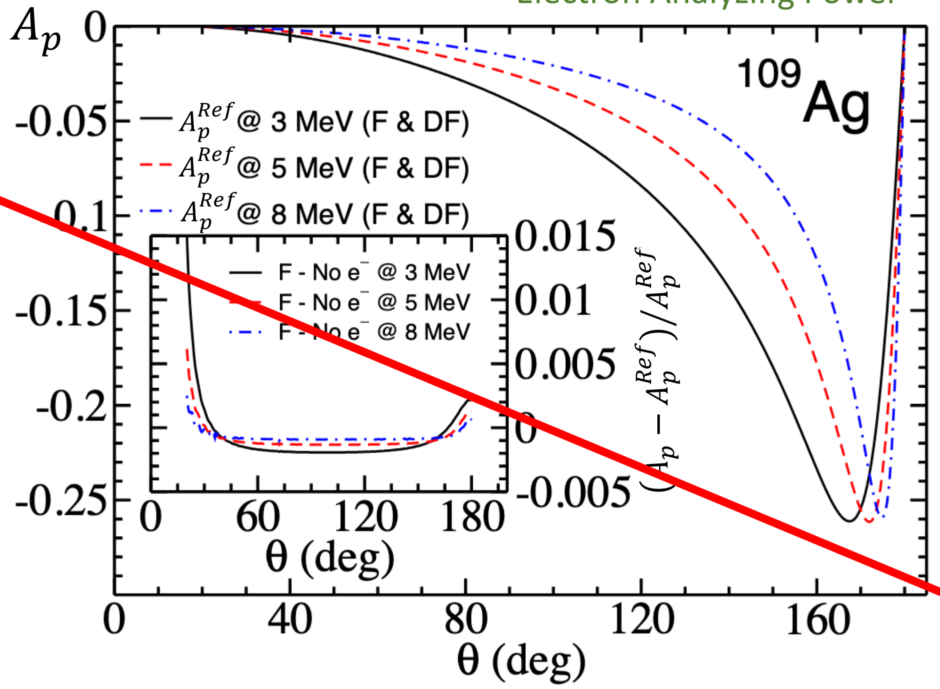

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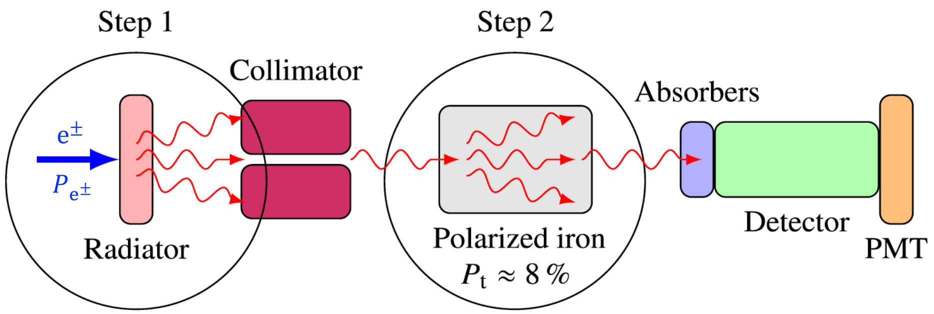
Compton Transmission

G. Blume et al. NIMA 1062 (2024) 169224

Step 2

- The absorption of circularly polarized photons (P_γ) inside a polarized target (P_t) generates an asymmetry which is proportional to the photon polarization.
- The asymmetry is measured with respect to the parallel/anti-parallel target polarization orientation.



$$\varepsilon_T = \exp\left[-\rho_e L\left(\sigma_{phot} + \sigma_{pair}\right)\right] \times \exp\left[-\rho_e L\, \sigma_C^0\left(1 \pm \rho_e L P_t P_\gamma A_p\right)\right]$$

$$A_p = \int d\Omega \left[\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right] \cos\theta$$

(ω,ω_0) are the initial and scattered photon energies

Step 2 $\mathcal{A}_m \approx \rho_e L P_t P_\gamma A_p$

Step 1+2 $\mathcal{A}_m \approx \rho_e L P_t P_{e^\pm} \langle T_\gamma^e A_p \rangle$

- ✓ Compton transmission polarimeters can operate either with electrons or positrons for the measurement of the longitudinal polarization of a beam.
- ✓ The optimum energy range is up to a few tens of MeV where the cross section of the Compton process is significant.

E. Voutier
IJCLab Irène Joliot-Curie

Positron Annihilation

W.H. McMaster RMP 33 (1961) 8 J.M. Hoogduin PhD Thesis, Groningen University (1997)

- The annihilation into γ-pairs of polarized positrons (P_x,P_y,P_z) with electrons in a polarized metallic target (S_x,S_y,S_z) generates an asymmetry suitable for the measurement of the beam polarization.
- The sensitivity of the annihilation process to the 3 different components of the positron polarization is similar in magnitude.
- The asymmetry is measured with respect to the parallel/anti-parallel target polarization orientation.

$$\left.\frac{d\sigma}{d\Omega}\right|_{cm} = \frac{\alpha^2}{s}\frac{1}{\beta}\frac{A_0\left(1 \pm P_x S_x A_x \pm P_y S_y A_y \pm P_z S_z A_z\right)}{\left(1-\beta^2\cos^2(\theta)\right)^2}$$

$$A_0 = 1 + 2\beta^2\sin^2(\theta) - \beta^4[1+\sin^4(\theta)]$$

$$A_x = \left(-1 + 2\beta^2 - \beta^4[1+\sin^4(\theta)]\right)\Big/A_0$$

$$A_y = \left(-1 + 2\beta^2 - \beta^4[1-\sin^4(\theta)]\right)\Big/A_0$$

$$A_z = \left(-1 + 2\beta^2\sin^2(\theta)\left(1-\sin^2(\theta)\right) + \beta^4[1+\sin^4(\theta)]\right)\Big/A_0$$

A possible solution
for positron polarimetry
of **few hundreds MeV**.

E. Voutier
IJCLab Irène Joliot-Curie

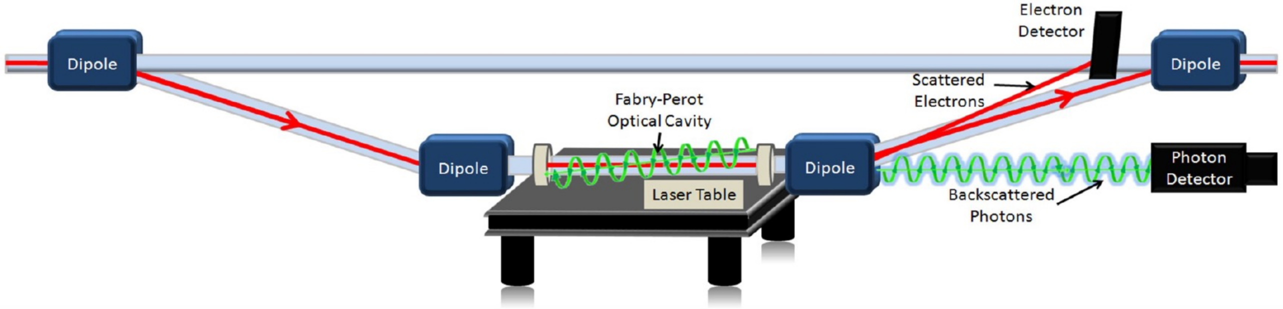
Compton Backscattering

D. Gaskell, Positron Working Group Workshop, Charlottesville (2023)

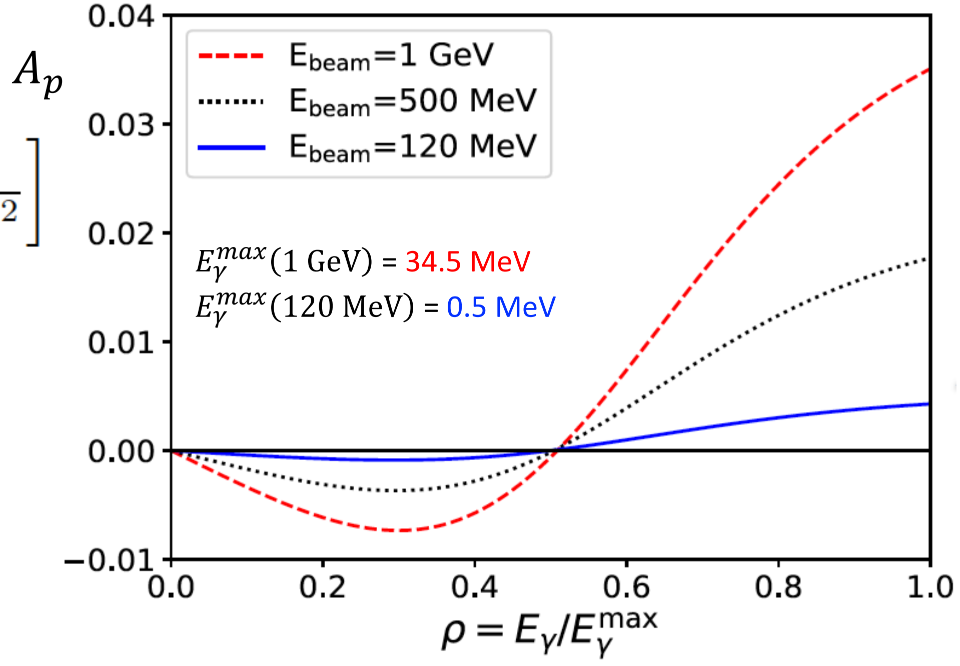
- The backscattering of a **circularly polarized laser** (P_γ) onto a **longitudinally polarized** (P_{e^+}) **positron beam** generates an asymmetry of the photon number.
- The asymmetry is measured with respect to the **left/right orientation** of the **laser polarization**.
- Compton backscattering requires **enough beam energy** (>1GeV) for sizeable analyzing power and energetic photon generation, as well as **reasonable beam intensity** for precise measurement.

$$\frac{d\sigma}{d\rho} = 2\pi r_o^2 a \left[\frac{\rho^2(1-a)^2}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]$$

$$a = \frac{1}{1+4\gamma E_{\rm laser}/m_e} \qquad A_p = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^2} \right]$$



Hall A & C Compton polarimeter



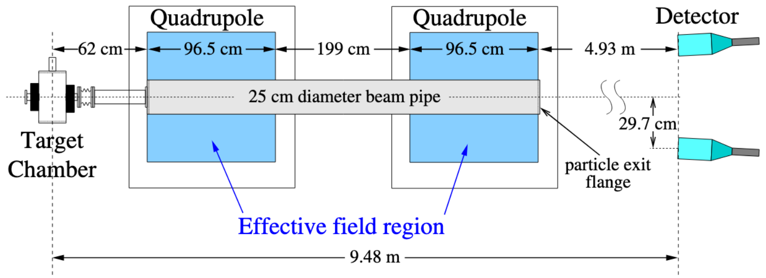
Bhabha Scattering

G. Alexander, I. Cohen NIMA 486 (2002) 552

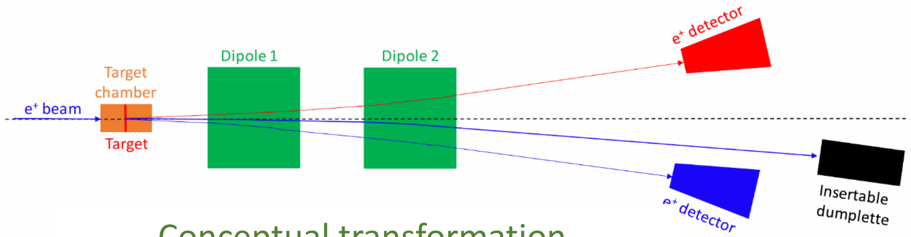
- Similarly to the Møller scattering of polarized electrons, the scattering of polarized positrons off electrons (Bhabha) in a polarized metallic target can be used to measure the beam polarization.
- Bhabha scattering is sensitive to longitudinal and transverse beam polarization, however transverse sensitivity is much smaller.
- The asymmetry is measured with respect to the parallel/anti-parallel target polarization orientation.

$$\left.\frac{d\sigma}{d\Omega}\right|_{cm} = \frac{\alpha^2}{s}\frac{[3+\cos^2(\theta)]^2}{\sin^4(\theta)}\left[1 \pm P^l_{e^+}P_t A_p \pm P^t_{e^+}P_t A_t \cos(2\phi - \phi_{e^+} - \phi_t)\right]$$

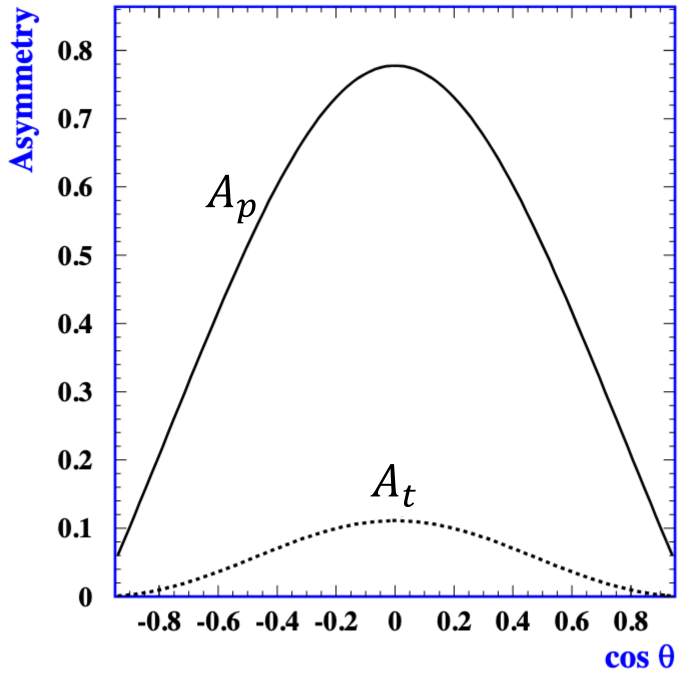
$$A_p = \frac{[7+\cos^2(\theta)]\sin^2(\theta)}{\left(3+\cos^2(\theta)\right)^2} \qquad A_t = \frac{\sin^4(\theta)}{\left(3+\cos^2(\theta)\right)^2}$$



Hall B Møller polarimeter



Conceptual transformation of the Møller into Bhabha polarimeter



Summary

- **Positron beams** are **important tools** allowing us to investigate the many faces of physics.
- They are optimally produced by the **bremsstrahlung radiation** of an electron beam which **polarization transfers** efficiently to the produced **positrons**.
- The optimization of their production is a multi-dimensionnal problem which dominant parameter is the **angular acceptance** of the positron **collection system**.
- **Positron polarimetry** is similar **to electron polarimetry**, apart Mott scattering and positron annihilation.

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Questions ?