γ-Ray Polarimetry with e^+e^- Pairs

Technology investment FIGSAG meeting, 23 May 2024

Denis Bernard,

Laboratoire Leprince-Ringuet (LLR)
Ecole Polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

γ-Ray Polarimetry with e^+e^- Pairs

- Science drivers

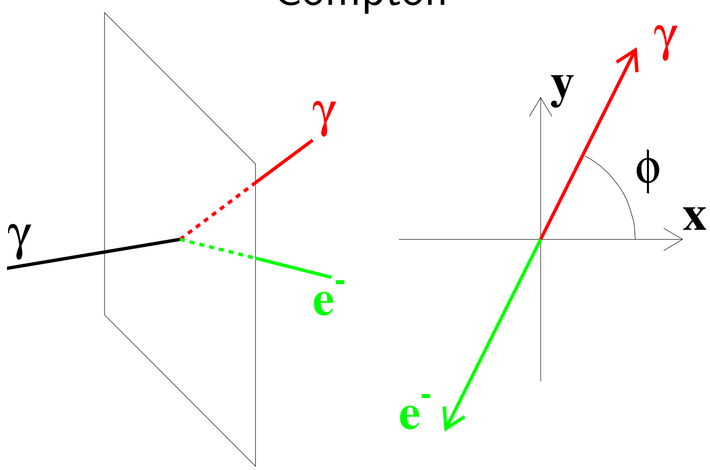
- Measurement Techniques

  - Compton scattering, $E < 1\,\mathrm{MeV}$
  - e^+e^- pair conversion, $E > 1\,\mathrm{MeV}$ $\Leftarrow$ This talk

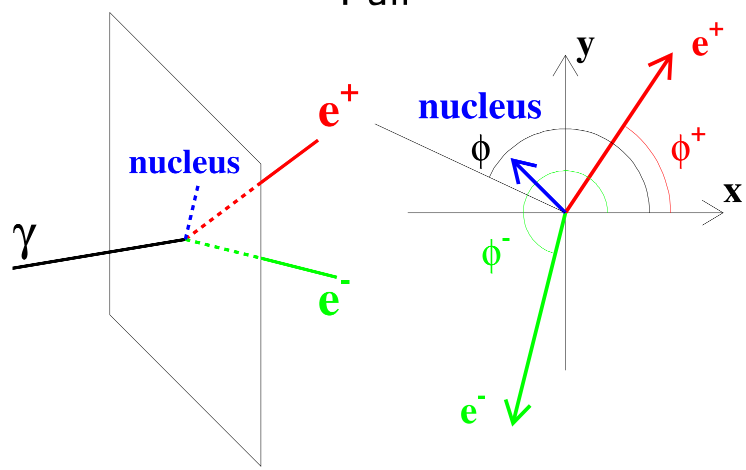
γ-Ray Linear Polarimetry

- $\frac{d\Gamma}{d\phi} \propto (1 + AP\cos[2(\phi - \phi_0)])$,
  - P source linear polarization fraction
  - ϕ_0 source polarization direction
  - A process polarization asymmetry
  - ϕ event azimuthal angle

Compton



Pair



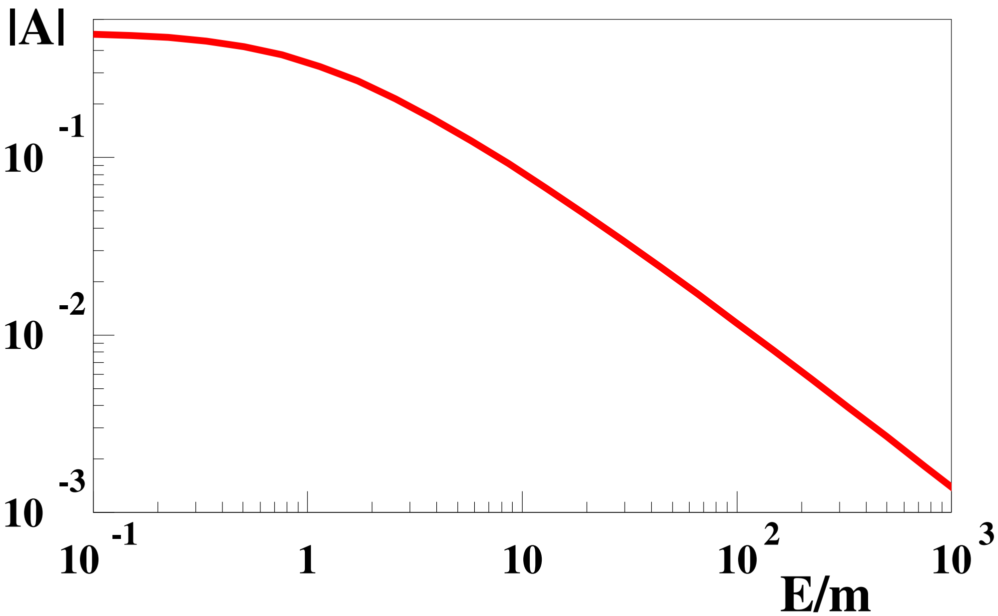
	Compton	Pair
Final state	2 particles	3 particles
Variables	2 (ϕ, θ)	5 (ϕ_+, ϕ_-, θ_+, θ_- and x_+)

$\phi \equiv (\phi_+ + \phi_-)/2$, "bissectrix", optimal

P. Gros+, Astropart.Phys. 88 (2017) 30

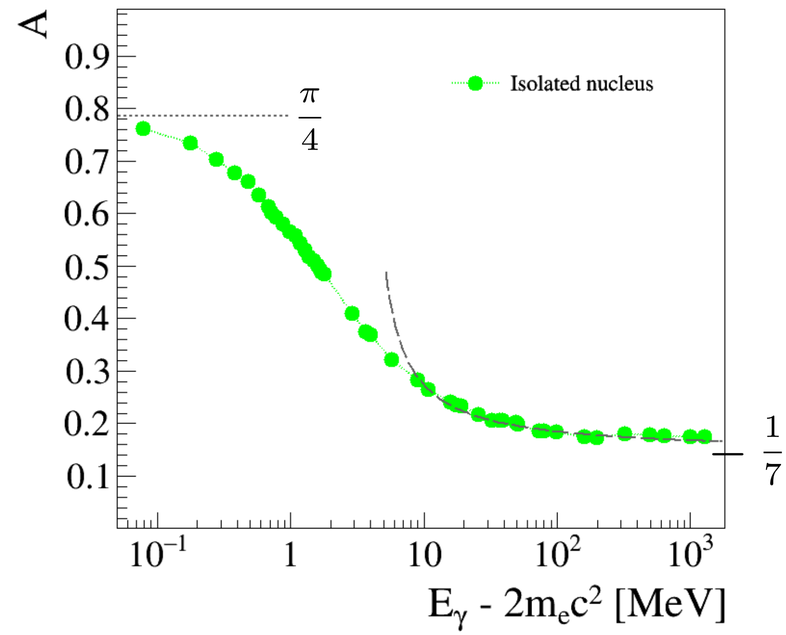
QED Polarization Asymmetry

Compton



D.B., Nucl. Instrum. Meth. A **799** (2015) 155

Pair

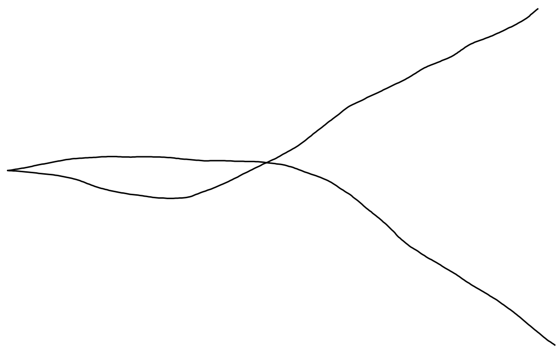


Asymptotes

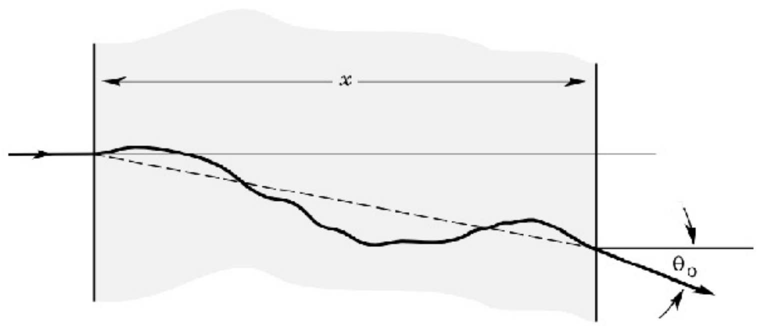
- low E, P. Gros+, Astropart.Phys. 88 (2017) 30
- high E, V. F. Boldyshev+, Yad. Fiz. **14** (1971) 1027

Lepton (e^+ and e^-) Multiple Scattering

Simulated γ-ray conversion in Argon



Summation of numerous Rutherford scatterings $\Rightarrow$ Gaussian-distributed deflection $\mathcal{N}(0, \theta_0)$,



$$\theta_0 = \frac{13.6\,\mathrm{MeV}/c}{\beta p} \sqrt{\frac{x}{X_0}}\,(1 + \text{small term})$$

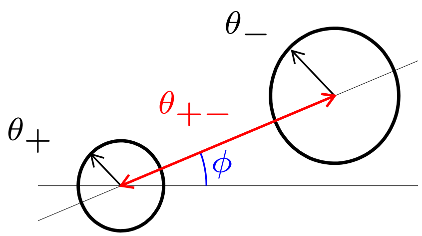
The Particle Data Group pdf

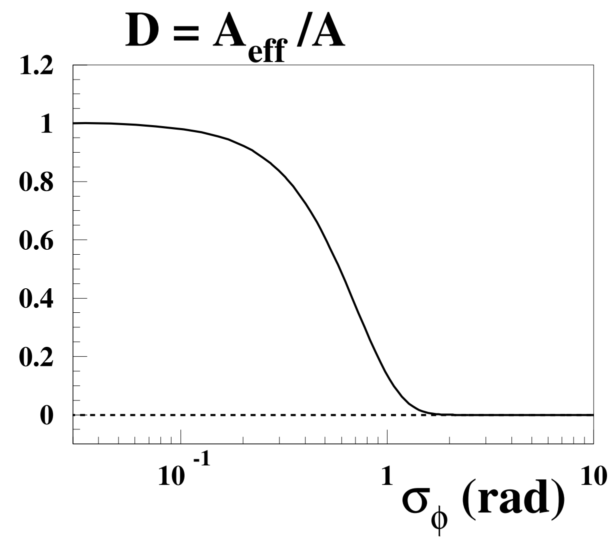
p, βc particle momentum and velocity; x, X_0, slab thickness and radiation length.

Multiple Scattering: Polarization Asymmetry Dilution

- $(1 + AP\cos(2\phi)) \otimes e^{-\phi^2/2\sigma_\phi^2} = (1 + A\, e^{-2\sigma_\phi^2}\, P\, \cos(2\phi))$

  $\Rightarrow A_{\text{eff}} = A\, e^{-2\sigma_\phi^2}, \qquad D = A_{\text{eff}}/A = e^{-2\sigma_\phi^2}$





- Azimuthal angle RMS, $\sigma_\phi = \dfrac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$, $\qquad \theta_0 \approx \dfrac{13.6\,\text{MeV}/c}{\beta p}\sqrt{\dfrac{x}{X_0}}$,
- **Pair most probable opening angle**, $\hat{\theta}_{+-} = 1.6\,\text{rad}\cdot\text{MeV}/E$ $\qquad$ Olsen, Phys.Rev. 131 (1963) 406

  $p \approx E/2$,

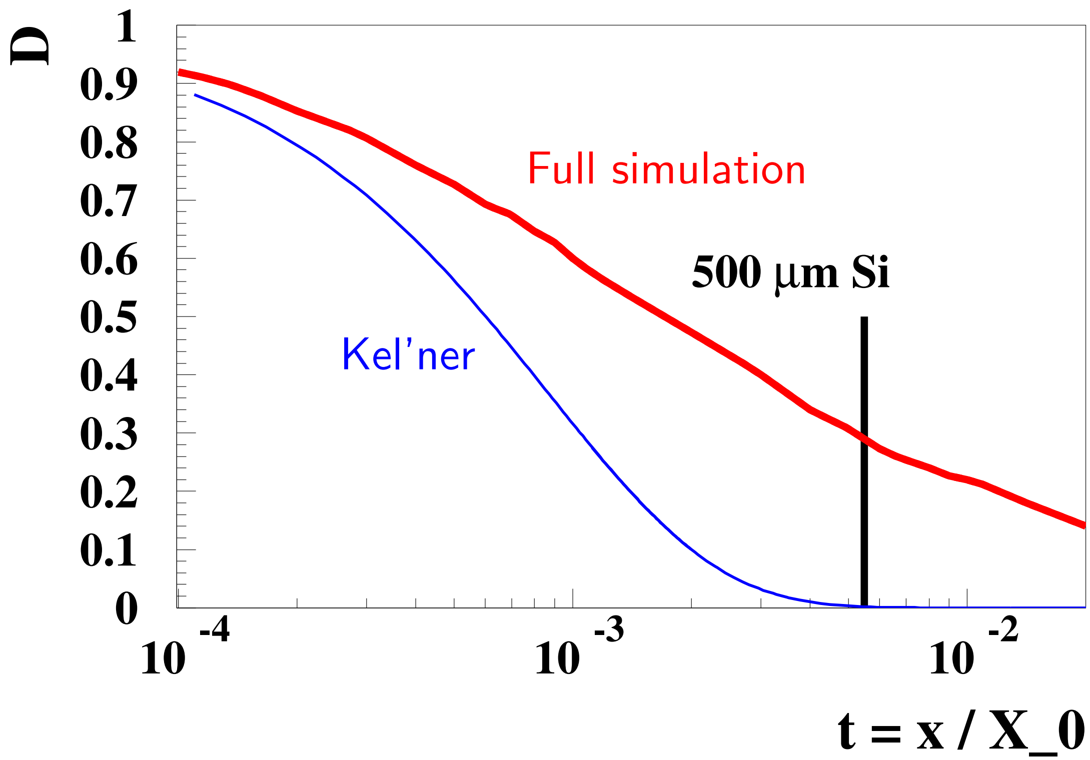
  $\Rightarrow \sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$,
- **Dilution factor**, $D \approx \exp\left(-2(24.^2) \times x/X_0\right)$,

$A_{\text{eff}}/A \approx 0.007$ for $x = 400\,\mu\text{m}$ of Si

Conventional wisdom: γ polarimetry impossible with nuclear conversions to pairs, $\gamma Z \to e^+e^-$

Kel'ner, Yad. Fiz. 21 (1975) 604 $\qquad$ Kotov, Space Science Reviews 49 (1988) 185, $\qquad$ Mattox, Astrophys. J. 363 (1990) 270

Dilution: Full Simulation



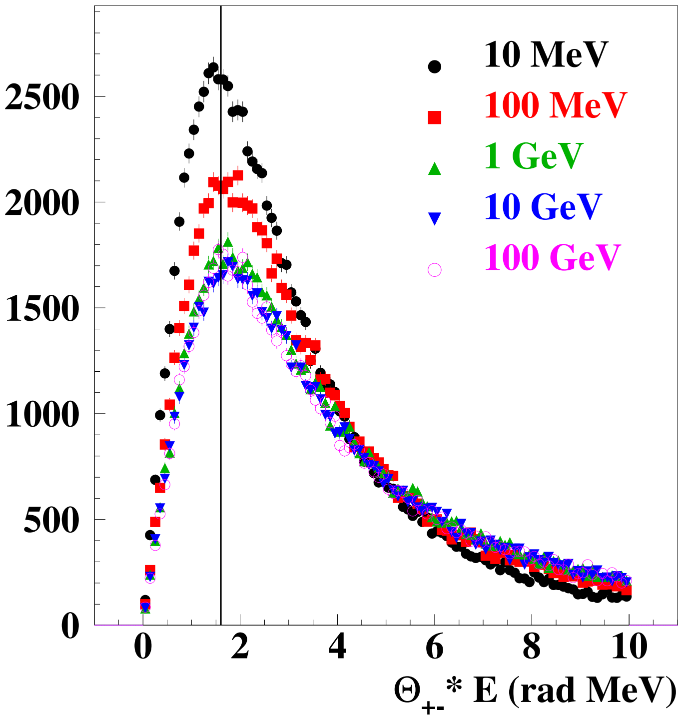
Full (5D) simulation of the dilution of the polarization asymmetry as a function of wafer thickness normalized to radiation length

5D polarized differential cross section, in Bethe-Heitler variables, M. M. May, Phys. Rev. 84 (1951) 265

Adapted from D.B., Nucl. Instrum. Meth. A 729 (2013) 765 with $\phi \equiv (\phi_+ + \phi_-)/2$,

P. Gros+, Astropart.Phys. 88 (2017) 30

Pair Opening Angle



(pair opening angle) × (photon energy)

D. B., Nucl. Instrum. Meth. A **899** (2018) 85

Asymptotically, θ_{+-} distribution scales with $1/E$

Vertical line: high-energy asymptotic most probable value

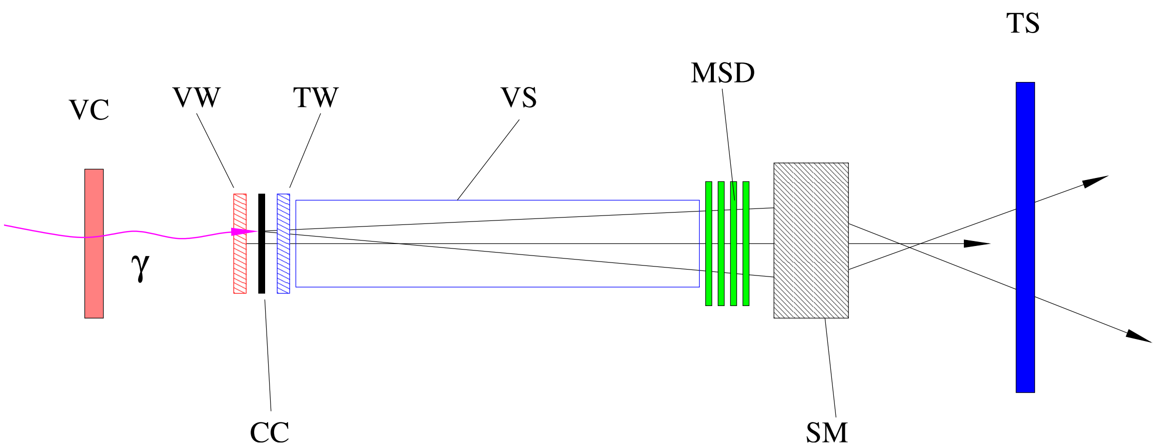
$$\hat{\theta}_{+-} = \frac{1.6 \text{ rad} \cdot \text{MeV}}{E}$$ H. Olsen, Phys. Rev. 131 (1963) 406

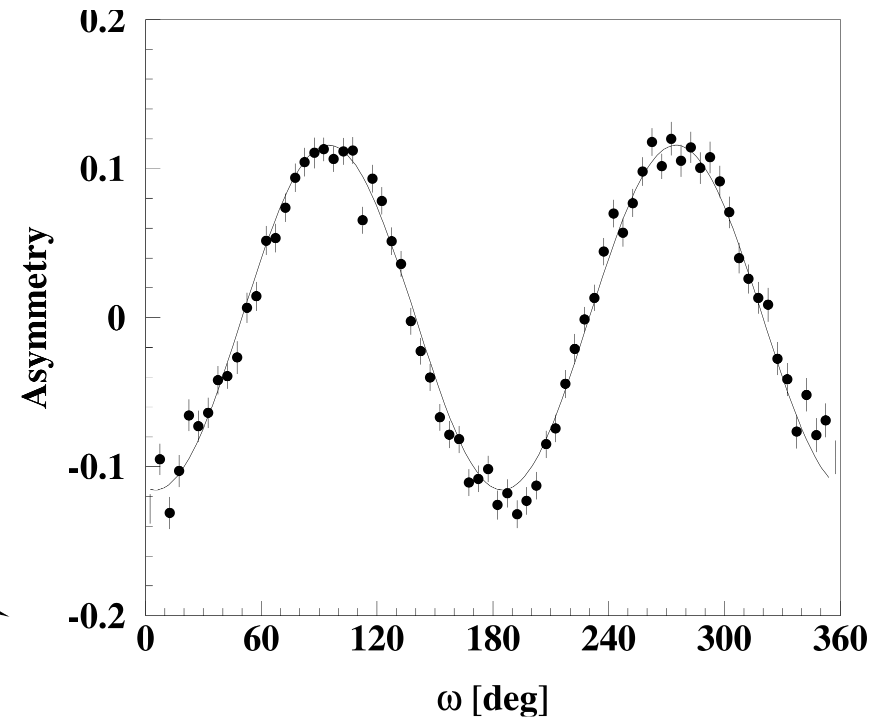
Huge high-θ_{+-} tail.

Past Achievements (1) Small Acceptance Polarimeter on Beam

JLab polarimeter prototype characterization

- 1.5 – 2.4 GeV γ-ray beam @ SPring8, Inverse Compton of linearly polarized 351 nm laser on 8 GeV e^- .
- **100 micron Carbon converter** (CC)
- Leptons travel away in vacuum straight section (VS)
- Silicon micro-strip detectors (MSD) meters downtream.
- 0.02% efficiency





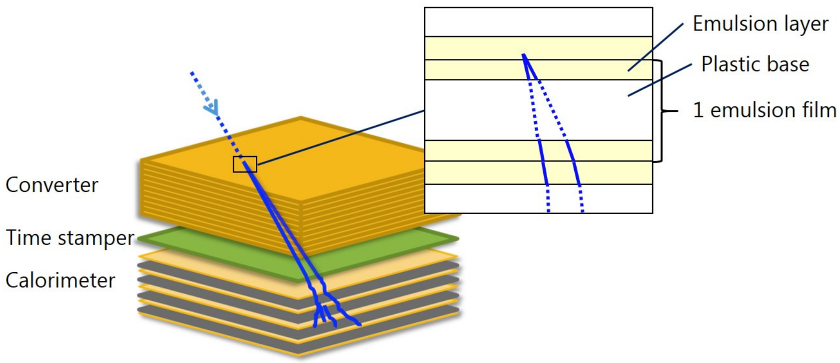
C. de Jager *et al.*, Eur. Phys. J. A 19 (2004) 275.

Past Achievements (2) Large Acceptance Homogeneous Detectors

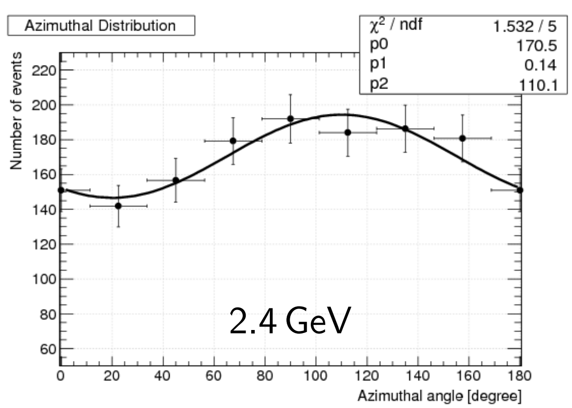
Emulsions (GRAINE)

sub-μm resolution, high density converter

S. Takahashi *et al.*, PTEP **2015** (2015) 043H01



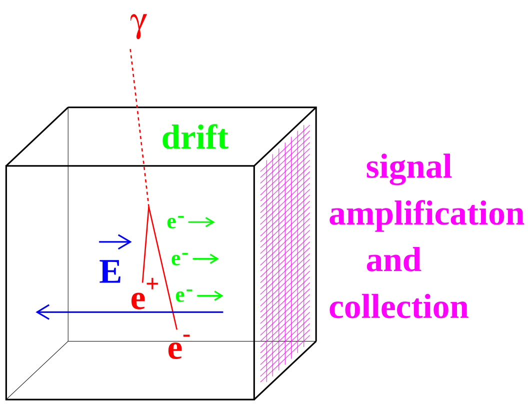
K. Ozaki *et al.*, NIM A **833** (2016)165



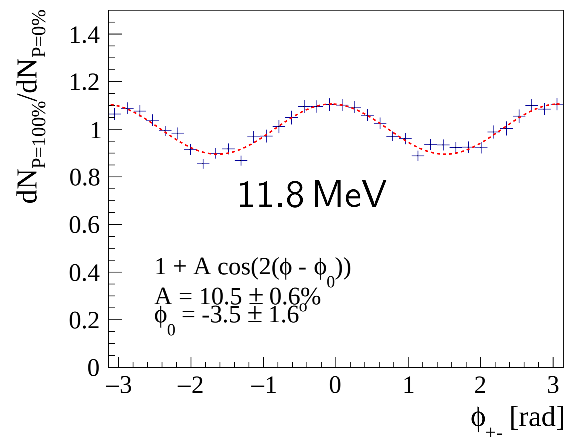
Gas time-projection chambers (TPC) (HARPO)

sub-mm resolution, low density converter

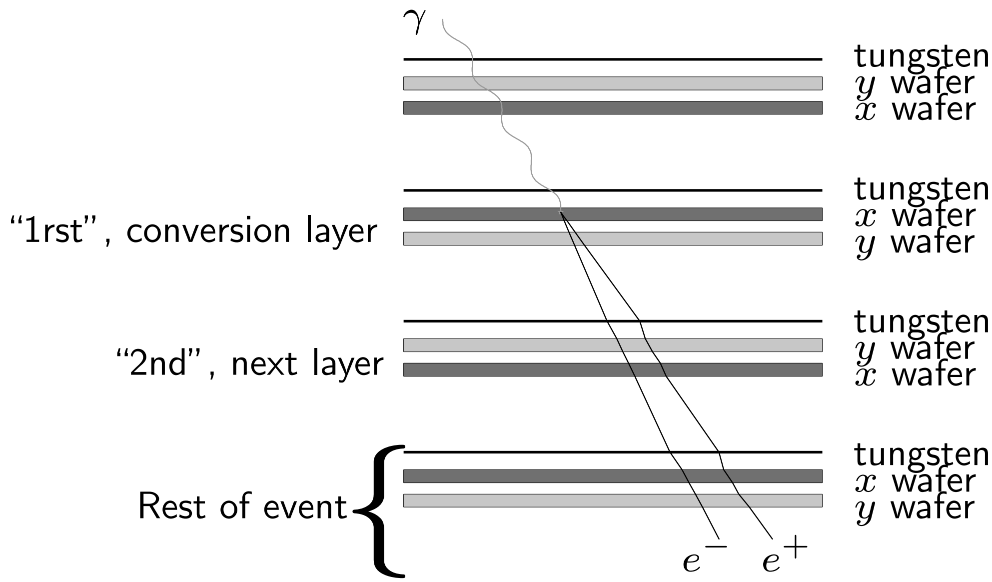
D.B., NIM A 936 (2019) 405



P. Gros *et al.*, Astropart.Phys. 97 (2018) 10

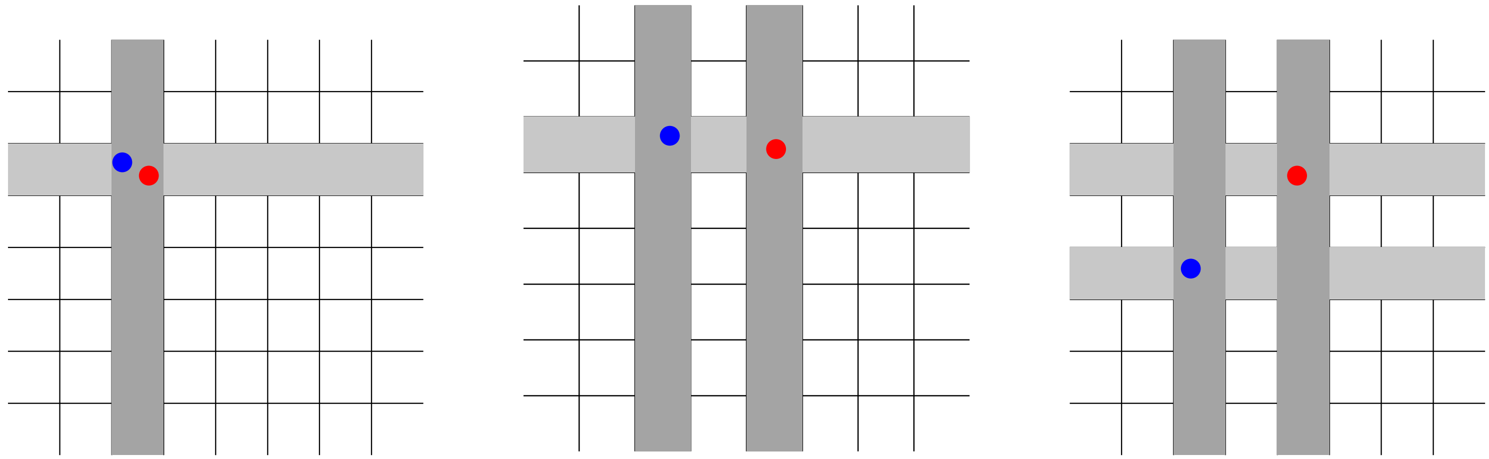


Layer ≡ pair of single-sided SSD + W foil W. B. Atwood *et al.* [Fermi-LAT Collaboration], Ap. J. 697 (2009) 1071.



Analysis based on 2 first layers.

Event Configuration in Next Layer



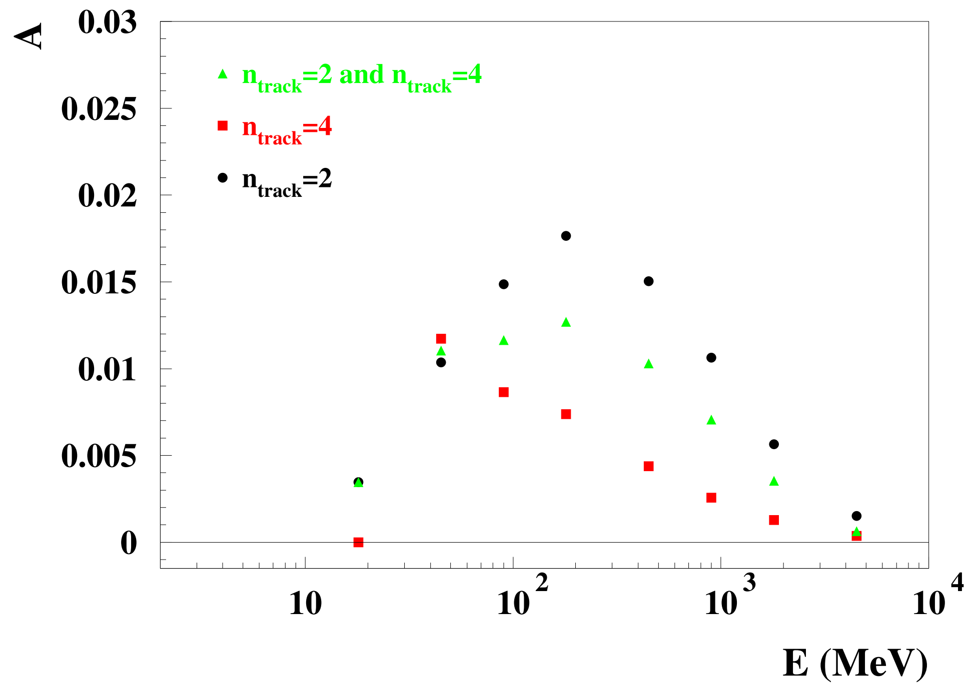
Reconstructed track #	$n_{\rm track} = 1$	$n_{\rm track} = 2$	$n_{\rm track} = 4$
Reco'ed γ candidate #	1	1	2
Azimuthal information ?	No	Yes	Yes Order-2 ambiguity Use both γ candidates with weight 1/2

Gray: hit strip(s)

e^- track, e^+ track (true track positions)

$$\text{Critical angle} = \frac{\rm pitch}{\rm spacing} = \frac{0.0228\,\rm cm}{3\,\rm cm} \approx 7.6\,\rm mrad, \text{ corresponds to peak}(\theta_{+-}) \text{ for } E \approx 210\,\rm MeV$$

Fermi-LAT: Effective Polarization Asymmetry



– **The Fermi-LAT is a γ-ray polarimeter !** D.B., Nucl.Instrum.Meth.A 1042 (2022) 167462

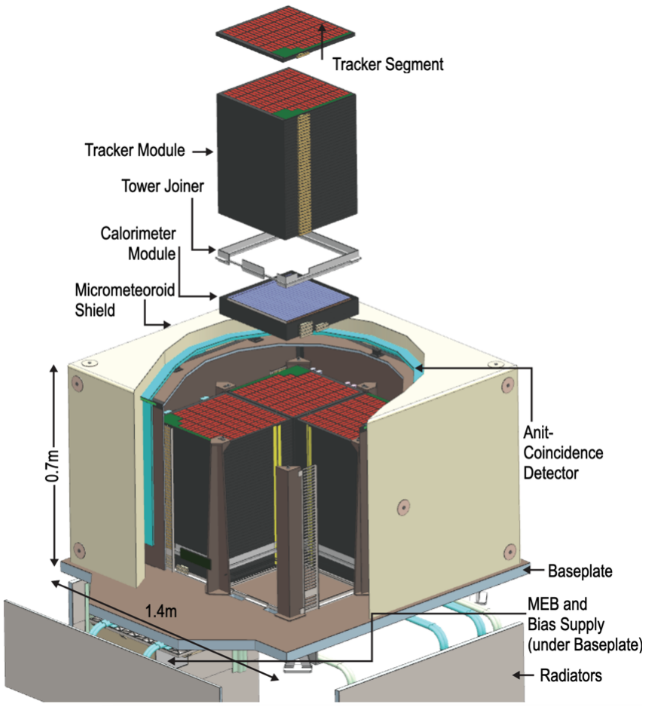
Also Fermi Symposium, Johannesburg, 2022

– A small; peaks at $A \approx 0.02$ for $E \approx 200\,\mathrm{MeV}$ $(D \approx 0.1)$

– Results confirmed by full (GLEAM + G4BetheHeitler5DModel + dedicated event reconstruction and event selection) analysis, Adrien Laviron+ [Fermi-LAT Collaboration], PoS ICRC2023 (2023) 721

Pixel detectors

The All-sky Medium Energy Gamma-ray Observatory eXplorer (AMEGO-X)



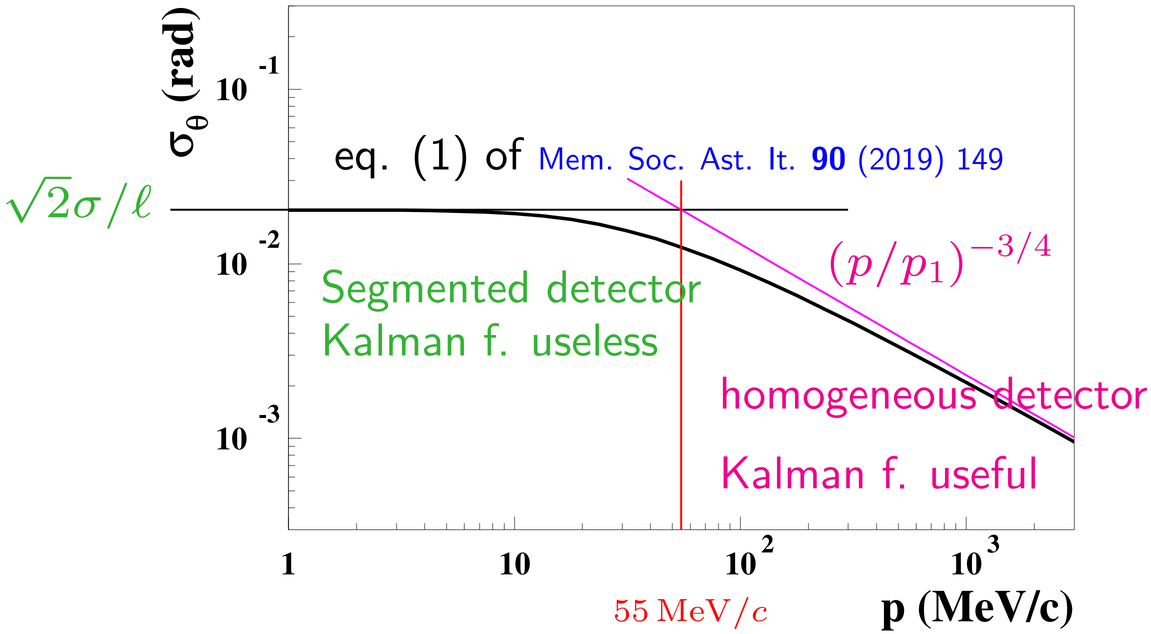
pixel pitch	500 μm
wafer thickness	500 μm
layer spacing	1 cm

pixels: no ambiguity
no W foil

R. Caputo+, J. Astron. Telesc. Instrum. Syst. **8** (2022) 044003

Kalman-filter optimal tracking: Single-track polar-angle precision

(conversion at bottom of wafer) AMEGO-X detector parameters



σ, single layer precision (pitch $/\sqrt{12}$)

ℓ, wafer spacing

p_1, "characteristic" detector tracking momentum (D.B. Nucl. Instrum. Meth. A **729** (2013) 765)

$\Rightarrow$ **Use of the 2-layer method**

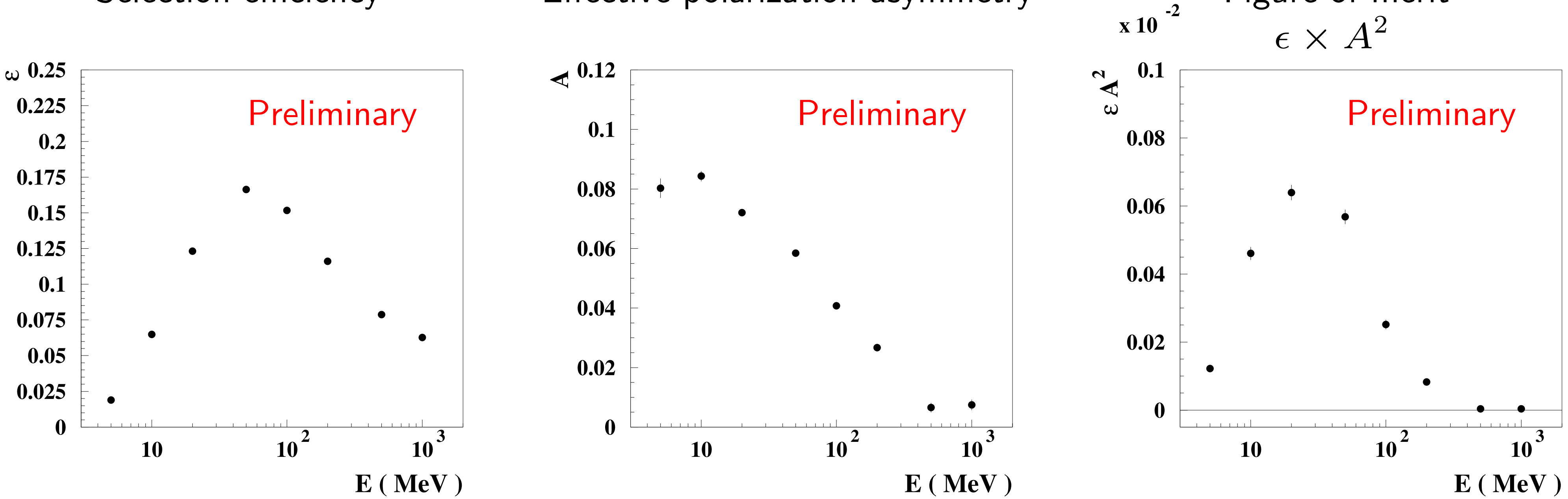
If conversion in the fat of the wafer, in addition MS inside the wafer, see slides 5 – 7.

Pixel detectors: Performance

– Cluster hit pixels having a side in common

– Request 1 cluster in conversion wafer, 2 clusters in next wafer

Selection efficiency | Effective polarization asymmetry | Figure of merit $\epsilon \times A^2$



– $A \approx 0.08$ at low energy

– Figure of merit sizeable between 10 and 100 MeV

Conclusion

No doubt high-energy γ-ray polarimetry has a bright future.

Non polarized Astronomy | Polarization

Compton

Pair

Silicon-detector active-targets, the 4-leaf clover γ-ray telescopes of the 21st Century ?

Back-up slides

Differential Cross Section; Simulation Thereof

- Differential Cross Section
  - Non Polarized Bethe and Heitler, Proc.Roy.Soc.Lond. A146 (1934) 83
  - Polarized Berlin and Madansky, Phys. Rev. 78 (1950) 623
    (in Bethe-Heitler variables May, Phys. Rev. 84 (1951) 265.)

- G4BetheHeitler5DModel, a Geant4 "Physics Model" (Event Generator)
  - PDF sampling characterization Nucl. Instrum. Meth. A **899** (2018) 85
  - Implementation Nucl. Instrum. Meth. A **936** (2019) 290
  - Geant4 documentation Physics Reference Manual
  - Example: TestEm15 examples/extended/electromagnetic/TestEm15
  - G4BetheHeitler5DModel talk Journées Théorie PNHE 2018
  - Geant4 EM talk at CHEP 2018, V. Ivantchenko EPJ Web Conf. 214 (2019) 02046

Optimal Measurement with Moments

- $p(\Omega)$ the pdf of set of variables Ω
- Weight $w(\Omega)$, $\mathrm{E}(w)$ function of P, and variance σ_P^2 minimal;
- A solution, $w_{\mathrm{opt}} = \dfrac{\partial \ln p(\Omega)}{\partial P}$

e.g.: Tkachov, Part. Nucl. Lett. 111 (2002) 28

- Polarimetry: $p(\Omega) \equiv f(\Omega) + P \times g(\Omega)$, $\quad w_{\mathrm{opt}} = \dfrac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}$.
  - If $\mathcal{A} \ll 1$, $w_0 \equiv 2\dfrac{g(\Omega)}{f(\Omega)}$, and
  - 1D "projection", $\Omega \equiv \phi$, $p(\Omega) = (1 + \mathcal{A}P\cos[2(\phi)])$:

$$w_1 = 2\cos 2\phi, \qquad \mathrm{E}(w_1) = \mathcal{A}P, \qquad \sigma_P = \frac{1}{\mathcal{A}\sqrt{N}}\sqrt{2 - (\mathcal{A}P)^2},$$

D.B., Nucl. Instrum. Meth. A 729 (2013) 765

Unknown polarization angle ϕ_0

$$P = \frac{2}{A}\sqrt{\langle\cos 2\phi\rangle^2 + \langle\sin 2\phi\rangle^2} \qquad \sigma_P \approx \frac{1}{A}\sqrt{\frac{2-(A\times P)^2}{N}}$$

$$\phi_0 = \tfrac{1}{2}\arctan\left(\frac{\langle\sin 2\phi\rangle}{\langle\cos 2\phi\rangle}\right) \qquad \sigma_{\phi_0} \approx \frac{1}{AP\sqrt{2N}}.$$

F. Kislat+, Astropart. Phys. **68** (2015) 45

Circular Polarization ?

– The "Bethe-Heitler" polarized differential cross section used here
  - Involves photon **linear** polarization only
  - Sums on the polarizations of the final leptons
  - Uses the first term of the Born series

– To measure the photon **circular** polarization, either
  - Perform triplet conversion ($\gamma e^- \rightarrow e^+ e^- e^-$) on a tank of polarized electrons ?
    G.I. Gakh et al., Prob. Atomic Sci. Technol. **2012N1** (2012), 97 ?
  - Analyze the polarization of the final leptons ?
    H. Olsen and L. C. Maximon, Phys. Rev. 114 (1959) 887.
  - Tackle the second order of the Born series ?
    H. Olsen and L. C. Maximon, Il Nuovo Cimento 24(1962) 186 , H Kolbenstvedt, H Olsen Il Nuovo Cimento A 40 (1965) 13