

De la polarimétrie gamma avec conversion en paire e^+e^-

Denis Bernard,

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris

Séminaire LAPP, 29 janvier 2021

links

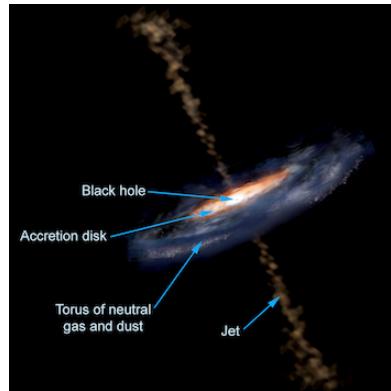


Talk Lay-out

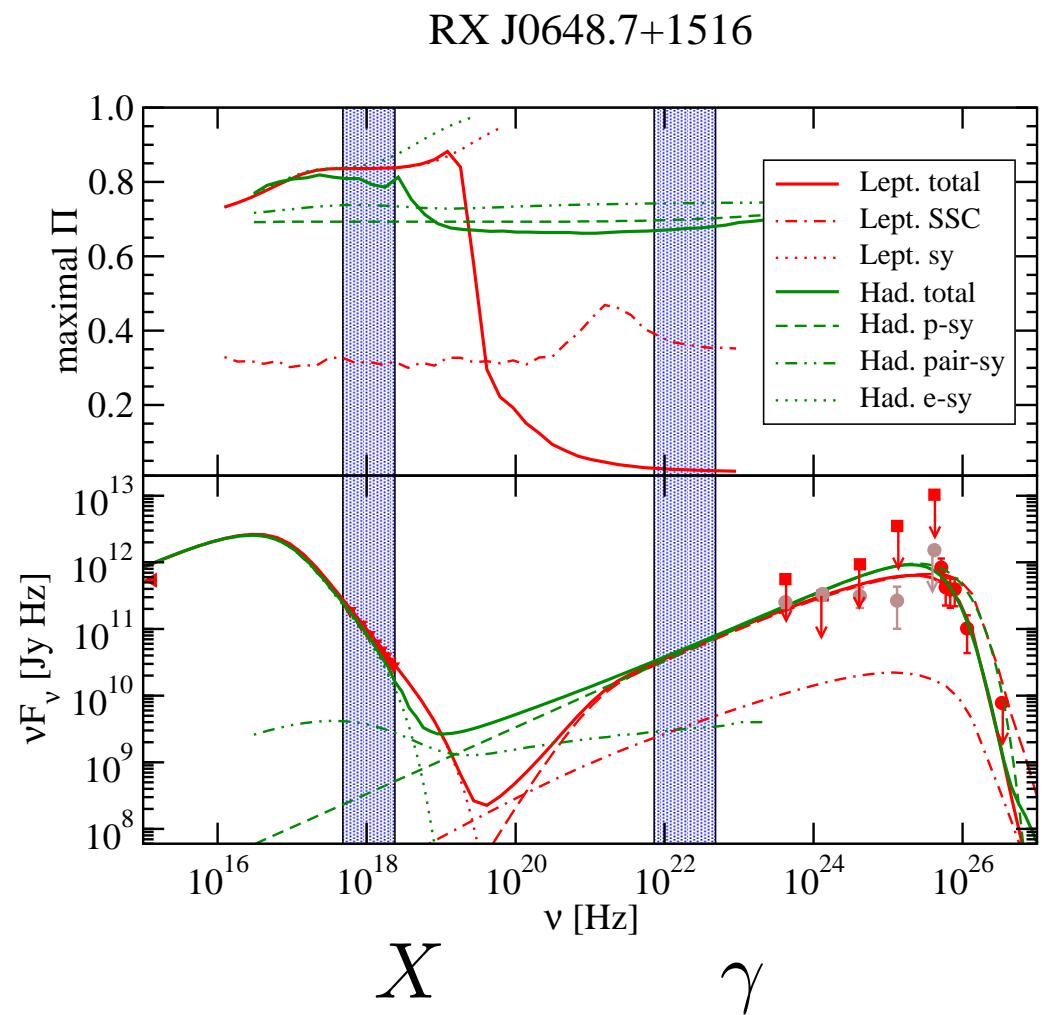
- Micro introduction: science case for (linear) γ -ray polarimetry
- Linear polarimetry with $\gamma \rightarrow e^+e^-$
- The CNRS-CEA-NewSUBARU-SPring8 “HARPO” (Hermetic ARgon POlarimeter) instrument project
- G4BetheHeitler5DModel: a 5D Bethe-Heitler γ -conversion Geant4 physics model

Deciphering emission mechanism in Blazars with γ -ray polarimetry

- Blazars: active galactic nuclei (AGN) with one jet pointing (almost) to us
leptonic synchrotron self-Compton (SSC) or **hadronic** (proton-synchrotron) ?

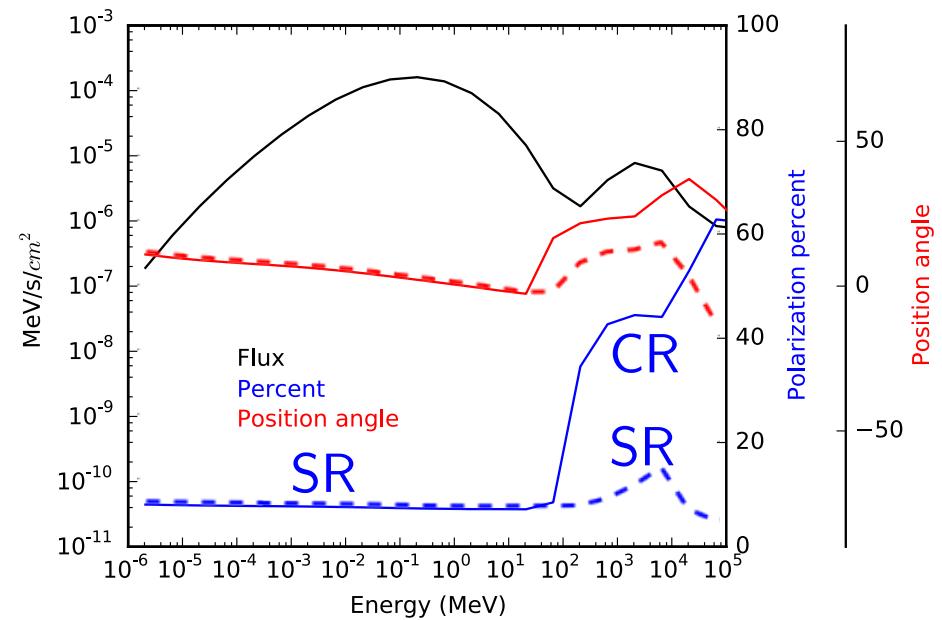
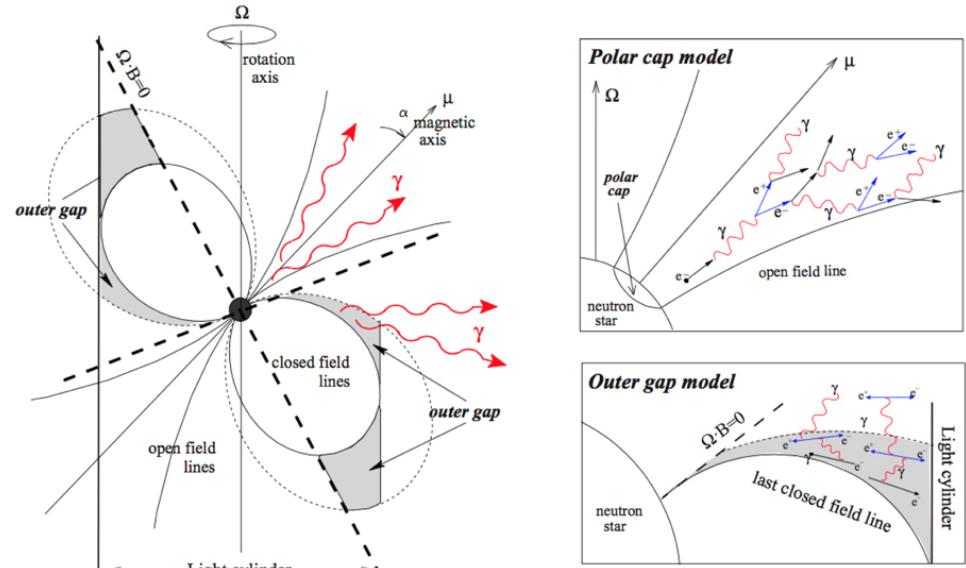


- high-frequency-peaked BL Lac
- X band: 2 -10 keV
- γ band: 30 - 200 MeV
- SED's indistinguishable, but
 - X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$
 - γ -ray: $P_{\text{lept}} \ll P_{\text{hadr}}$



H. Zhang and M. Böttcher,
A.P. J. 774, 18 (2013)

Tagging the (curvature radiation CR – synchrotron radiation SR) transition in pulsars



Polar-cap model of Crab-like pulsar

- MeV component is SR from pairs
GeV component is either CR (solid line) or SR (dashed line)
- “Polarization of MeV and GeV emission is a powerful, independent diagnostic, capable of constraining both the location and mechanism of the radiation” .

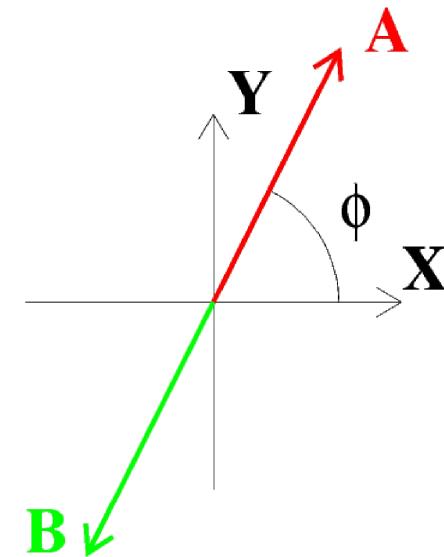
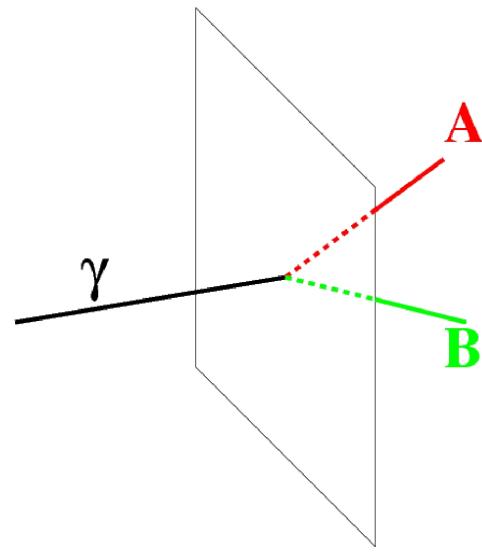
Harding and Kalapotharakos, *Astrophys. J.* 840 73 (2017)

Polarimetry

- Modulation of azimuthal angle distribution

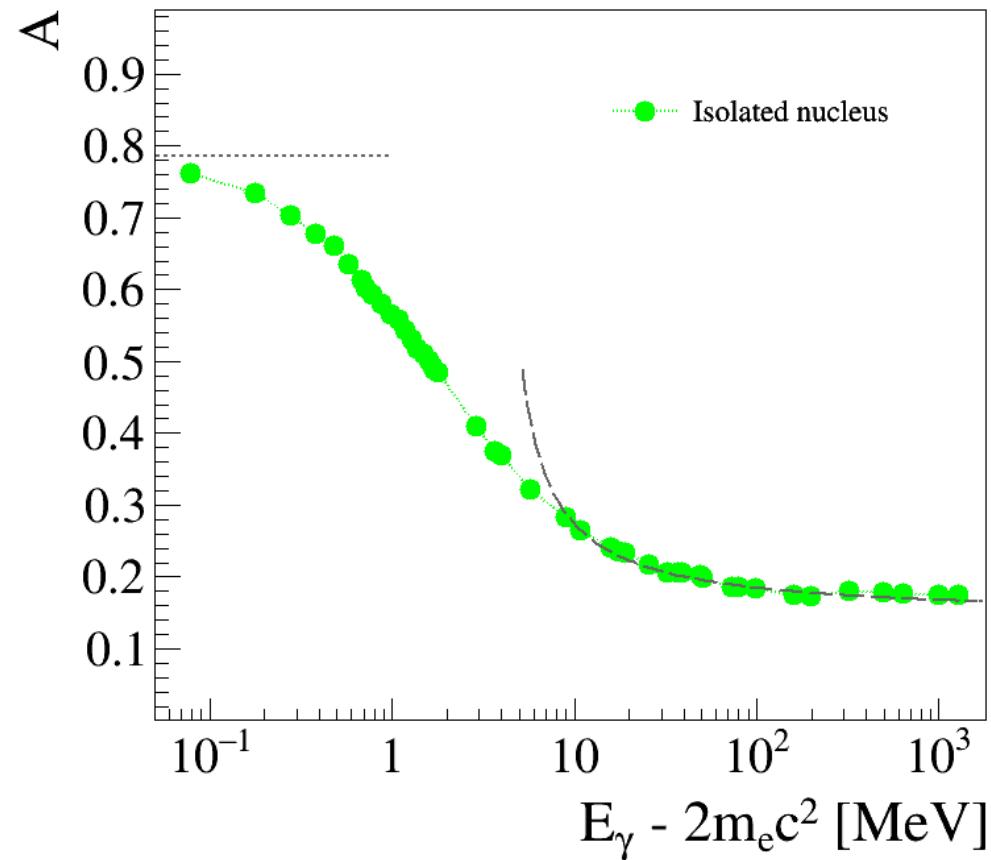
$$\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P \cos [2(\phi - \phi_0)]),$$

$$\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}},$$



- P source linear polarisation fraction
- \mathcal{A} γ -ray conversion polarization asymmetry
- ϕ event azimuthal angle
- ϕ_0 source polarization angle.

$$A(E)$$

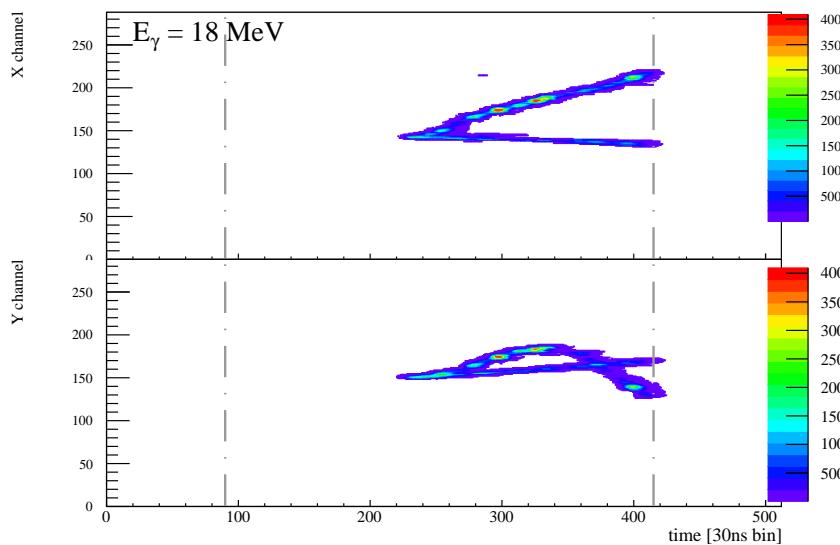


Polarisation asymmetry as a function of available energy,
compared to published asymptotic expressions

Astroparticle Physics 88 (2017) 60

The enemy: multiple scattering

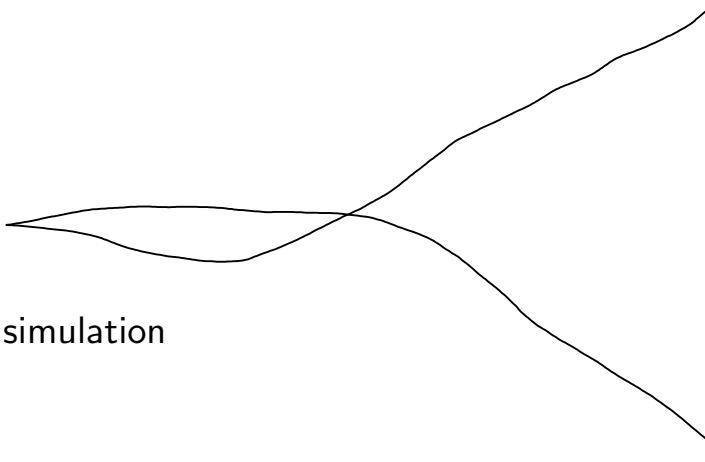
- Data



(x, t) and (y, t) views of a 18 MeV γ -ray from the BL01 beam line at NewSUBARU (LASTI, Hyôgo U., Japan) converting to e^+e^- in the 2.1 bar Ar:Isobutane 95:5 gas of the HARPO TPC prototype

- MC simulation

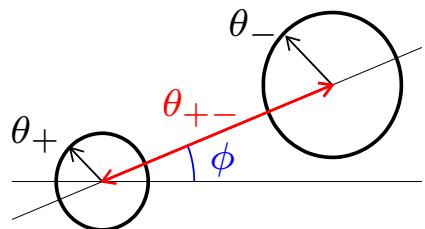
γ -ray conversion in argon, EGS5 simulation



Conversion in a Slab and Multiple Scattering: Dilution of the Polarisation Asymmetry

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

$$\Rightarrow \mathcal{A}_{\text{eff}} = \mathcal{A} e^{-2\sigma_\phi^2}, \quad D = \mathcal{A}_{\text{eff}}/\mathcal{A} = e^{-2\sigma_\phi^2}$$



- azimuthal angle RMS $\sigma_\phi = \frac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$,

$$\bullet \theta_0 \approx \frac{13.6 \text{ MeV}/c}{\beta p} \sqrt{\frac{x}{X_0}},$$

$$\bullet \text{most probable opening angle } \hat{\theta}_{+-} = 1.6 \text{ MeV}/E$$

Olsen, PR. 131, 406 (1963).

$$\Rightarrow \sigma_\phi \approx 24 \text{ rad} \sqrt{x/X_0},$$

$$\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2 \text{ for } x \approx 10^{-3} X_0$$

(100 μm of Si, 4 μm of W)

- This dilution is energy-independent.

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

Yu. D. Kotov, Space Science Reviews 49 (1988) 185,

Mattox J. R. Astrophys. J. 363 (1990) 270

γ Polarimetry with a Homogeneous Detector and Optimal Fits

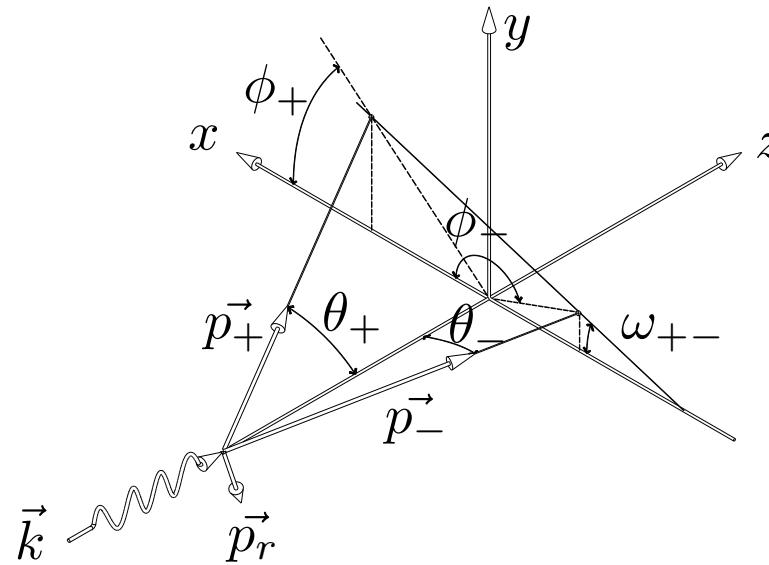
- $\sigma_\phi = \frac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, azimuthal angle resolution
- $\sigma_{\theta,\text{track}} = (\textcolor{red}{p}/p_1)^{-3/4}$, angular resolution due to multiple scattering
- $p_1 = 13.6 \text{ MeV}/c \left(\frac{4\sigma^2 l}{X_0^3} \right)^{1/6}$, Argon ($\sigma = l = 1\text{mm}$): $p_1 = 50 \text{ keV}/c$ (1 bar),
 $p_1 = 1.45 \text{ MeV}/c$ (liquid).
- $\hat{\theta}_{+-} = 1.6 \text{ MeV}/\textcolor{red}{E}$ most probable opening angle
- $\sigma_\phi = \left[x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}} \right] \frac{(p_1)^{\frac{3}{4}} \textcolor{red}{E}^{\frac{1}{4}}}{1.6 \text{ MeV}}$. azimuthal angle resolution
- x_+ fraction of the energy carried away by the positron,

There is hope .. at low p_1 (gas) .. at low energy.

Need study beyond the most probable opening angle $\theta_{+-} = \hat{\theta}_{+-}$ approximation

Developed, Validated, Event Generator

- Development of a full (5D) polarized evt generator
- First order of Born development “Bethe-Heitler”: linear polarization.
- Variables: azimuthal (ϕ_+ , ϕ_-) and polar (θ_+ , θ_-) angles of e^+ and e^- , and $x_+ \equiv E_+/E$



- Verification against published 1D distributions (nuclear and triplet conversions)

Nucl. Instrum. Meth. A 729 (2013) 765
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Bethe-Heitler differential cross section: divergences

- Non-polarised photons

Bethe and Heitler, Proc. R. Soc. Lond. A 146 (1934) 83

$$\begin{aligned} d\sigma = & \frac{-\alpha Z^2 r_0^2 m^2}{(2\pi)^2 \omega^3} dE_+ d\Omega_+ d\Omega_- \frac{|p_-||p_+|}{|\vec{q}|^4} \\ & \left[\left(\frac{p_+ \sin \theta_+}{E_+ - p_+ \cos \theta_+} \right)^2 (4E_-^2 - q^2) + \left(\frac{p_- \sin \theta_-}{E_- - p_- \cos \theta_-} \right)^2 (4E_+^2 - q^2) + \right. \\ & \left. \frac{2p_+ p_- \sin \theta_+ \sin \theta_- \cos(\phi_+ - \phi_-)}{(E_- - p_- \cos \theta_-)(E_+ - p_+ \cos \theta_+)} (4E_+ E_- + q^2 - 2\omega^2) - 2\omega^2 \frac{(p_+ \sin \theta_+)^2 + (p_- \sin \theta_-)^2}{(E_+ - p_+ \cos \theta_+)(E_- - p_- \cos \theta_-)} \right] \end{aligned}$$

with: $|\vec{q}|^2 = |\vec{p}_+ + \vec{p}_- - \vec{k}|^2$.

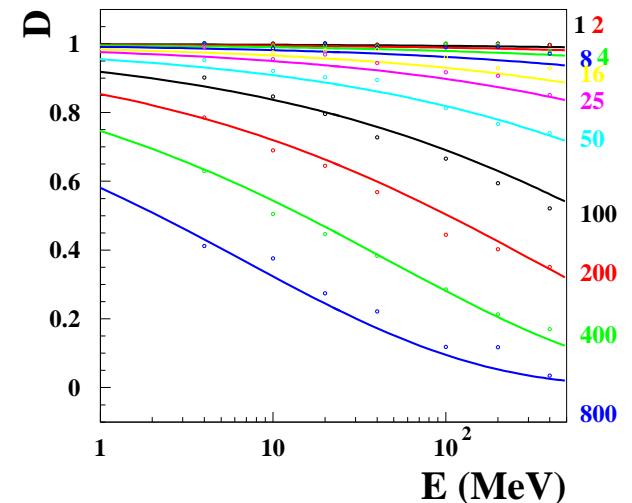
- Divergences:

- For e^+ and e^- $\frac{1}{(E - p \cos \theta)}$ forward divergence at high energies
- $\frac{1}{q^4}$ small recoil divergence

Dilution of Polarization Asymmetry due to Multiple Scattering: Optimal Fits and Full MC

- Track angular resolution $(p/p_1)^{-3/4}$,
 - $D \equiv \frac{\mathcal{A}_{\text{eff}}(p_1)}{\mathcal{A}(p_1 = 0)}$

$$p_1 = 13.6 \text{ MeV}/c \left(\frac{4\sigma^2 l}{X_0^3} \right)^{1/6}$$

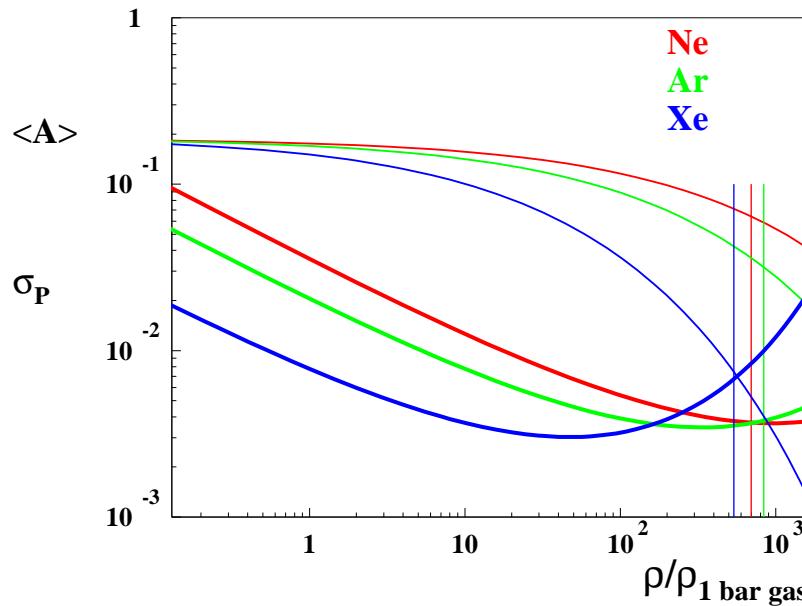


Energy variation of D for various values of $p_1(\text{keV}/c)$

- Curves are $D(E, p_1) = \exp[-2(a p_1^b E^c)^2]$ parametrizations, a, b, c constants
 - Liquid: **nope** (Ar, $p_1 = 1.45 \text{ MeV}/c$); gas: **Possible !** (1 bar, $p_1 = 50 \text{ keV}/c$)

Polarimetry Performance (no Experimental Cuts)

- Crab-like source, $T = 1$ year, $V = 1 \text{ m}^3$, $\sigma = l = 0.1 \text{ cm}$, $\eta = \epsilon = 1$).
- \mathcal{A}_{eff} (thin line), σ_P (thick line);



- Argon, 5 bar, $\mathcal{A}_{\text{eff}} \approx 15\%$, $\sigma_P \approx 1.0\%$

Nucl. Instrum. Meth. A 729 (2013) 765

The HARPO (Hermetic ARgon POlarimeter) instrument project

- France: the detector

Denis Bernard, Philippe Bruel, Mickael Frotin, Yannick Geerebaert, Berrie Giebels, Philippe Gros, Deirdre Horan, Marc Louzir, Frédéric Magniette, Patrick Poilleux, Igor Semeniouk, Shaobo Wang ^a

^aLLR, Ecole Polytechnique and CNRS/IN2P3, France

David Attié, Pascal Baron, David Baudin, Denis Calvet, Paul Colas, Alain Delbart, Ryo Yonamine ^b

^bIRFU, CEA Saclay, France

Diego Götz ^{b,c}

^cAIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp, CEA Saclay, France

- Japan: the beam.

S. Amano, T. Kotaka, S. Hashimoto, Y. Minamiyama, A. Takemoto, M. Yamaguchi,
S. Miyamoto^e

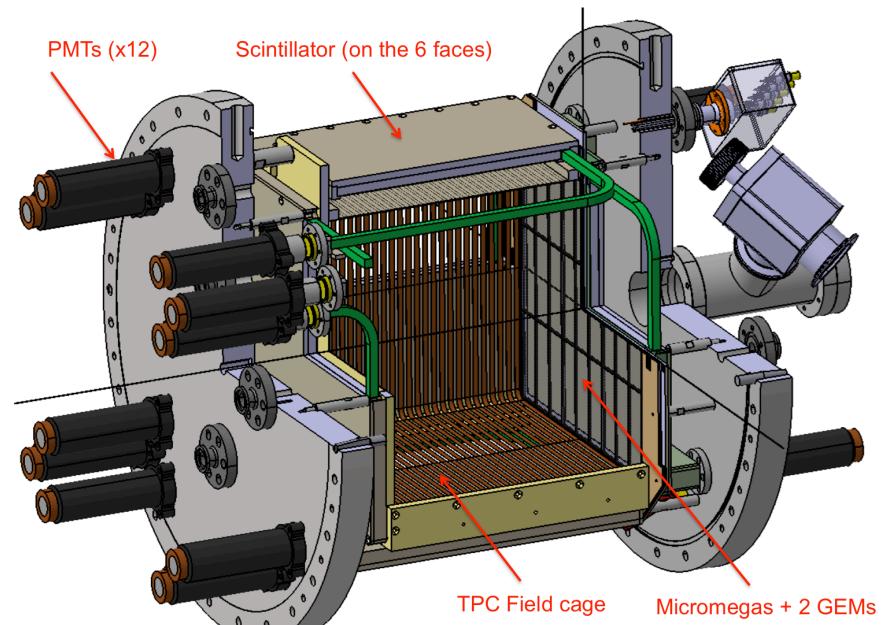
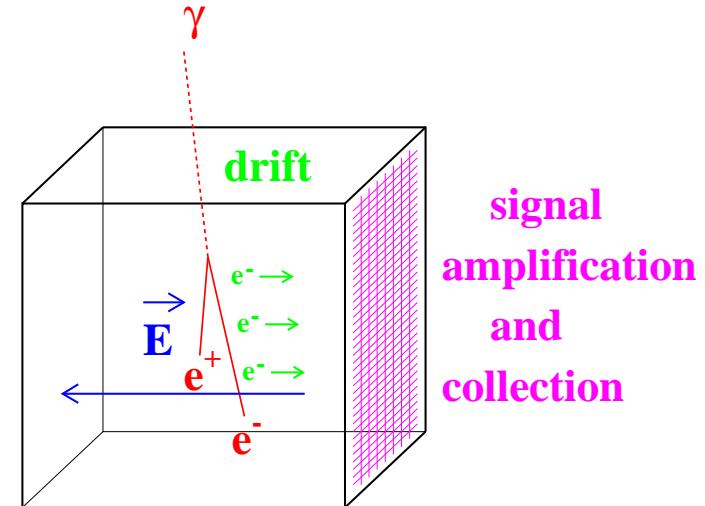
^e LASTI, University of Hyôgo, Japan

S. Daté, H. Ohkuma^f

^f JASRI/SPring8, Japan

HARPO: the Demonstrator

- Time Projection Chamber (TPC)
- $(30\text{cm})^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on x, y strips, pitch 1 mm.
- AFTER chip readout, up to 100 MHz.
- Scintillator / WLS / PMT based trigger

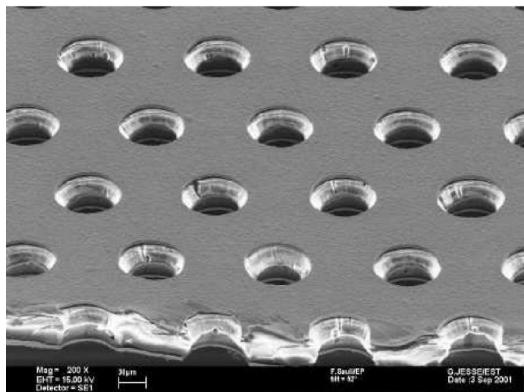


Nucl. Instrum. Meth. A 695 (2012) 71,

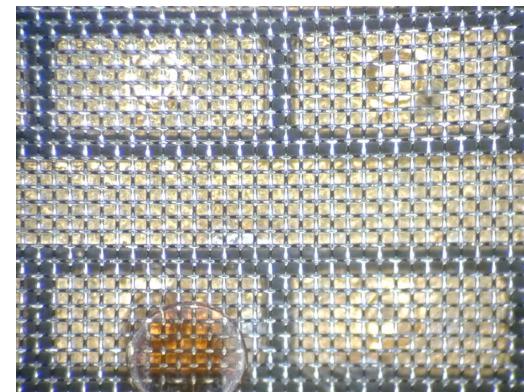
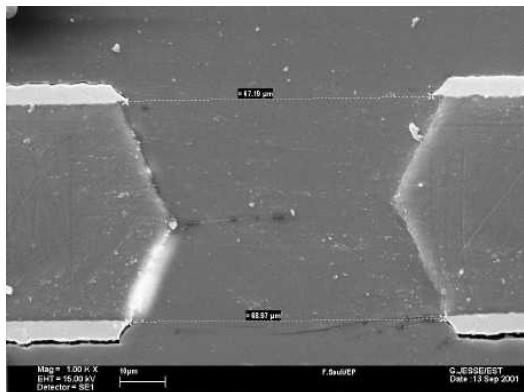
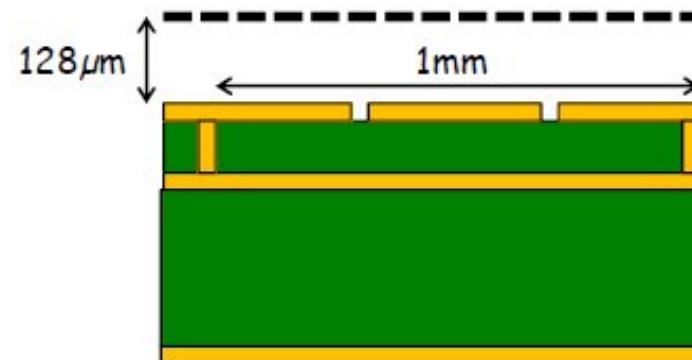
Nucl. Instrum. Meth. A 718 (2013) 395

Gas amplification: micromegas + 2 GEM

Gas Electron Multiplier
50 μm Kapton, copper clad,
pitch 140 μm , $\Phi 70 \mu\text{m}$



“bulk” micromegas
gap 128 μm

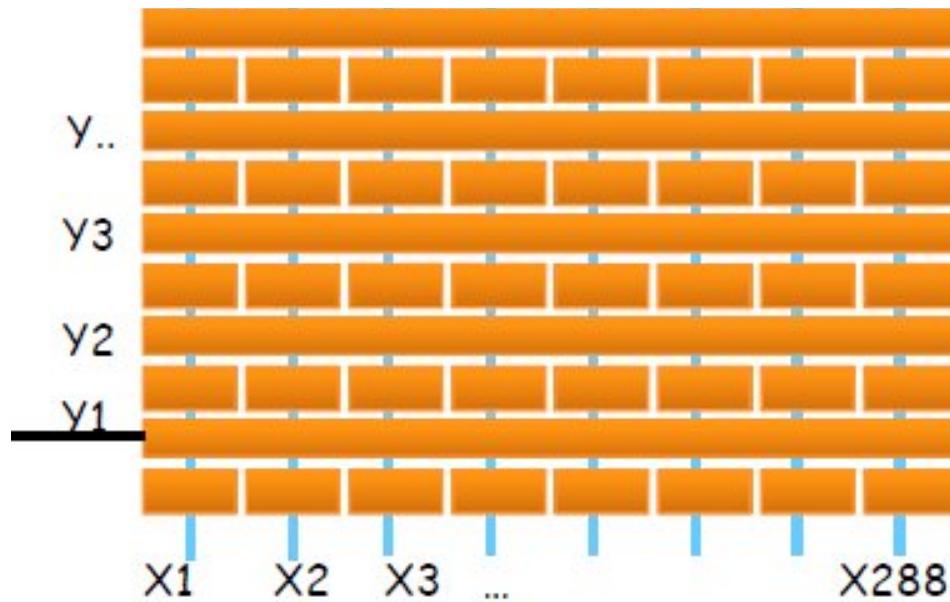


F. Sauli, Nucl. Instrum. Meth. A 386, 531 (1997)

I. Giomataris et al., Nucl. Instrum. Meth. A 560, 405 (2006)

Anode segmentation

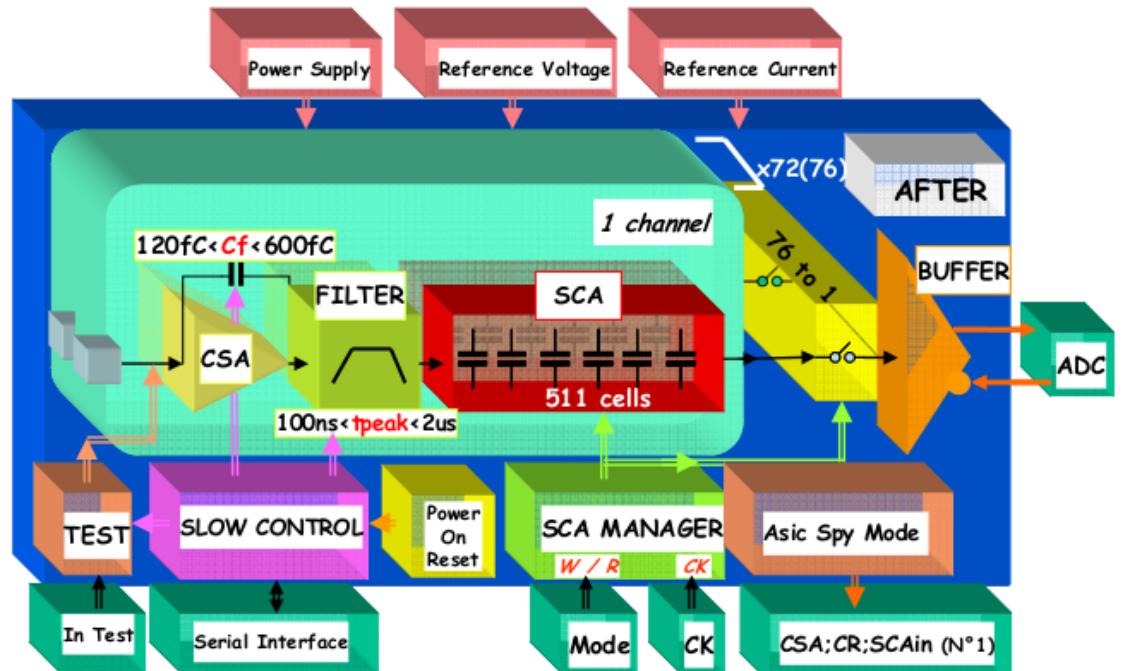
- Avalanche electrons collected on a segmented anode.



- Cu-clad PCB, strip pitch 1 mm, strip width $\approx 400 \mu\text{m}$

Read-Out: AFTER chips

- 2 directions x, y , 288 strips (channels) / direction
- 72 channels /chip
- 4 chips / direction
- 511 time bins, “circular” SCA (Switched Capacitor Array)
- Input: 120 fC to 600 fC
- Up to 100 MHz sampling
- Shaping time 100 ns to 2 μ s
- 12 bit ADC.

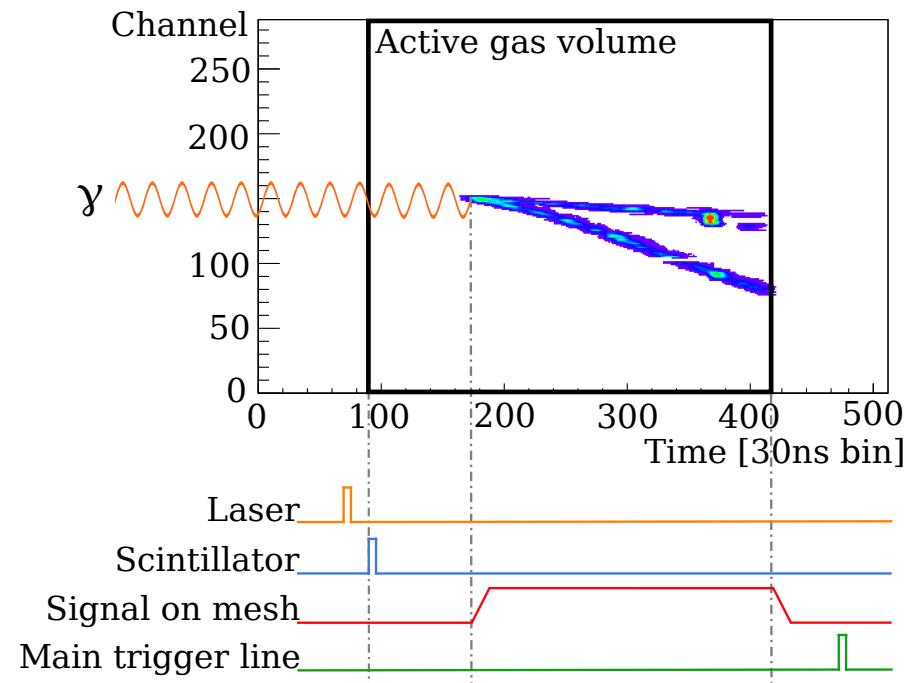
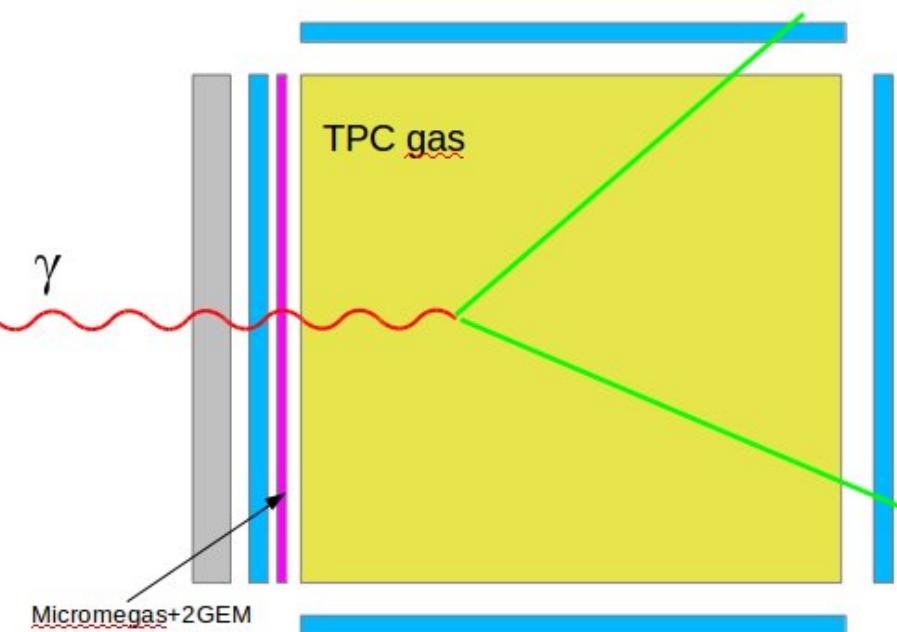


Out set-up: 30 ns sampling, $v_{\text{drift}} = 3.3 \text{ cm/s}$, $\Rightarrow 1 \text{ mm longitudinal sampling}$

100 ns shaping time, digitization 1.67 ms.

P. Baron et al., IEEE Trans. Nucl. Sci. 55, 1744 (2008).

“Beam” trigger system



- S_{up} upstream scintillator
- O one of the 5 other scintillators
- M_{slow} : a delayed ($> 1\mu\text{s}$) signal on the micromegas mesh
- L laser trigger pulse

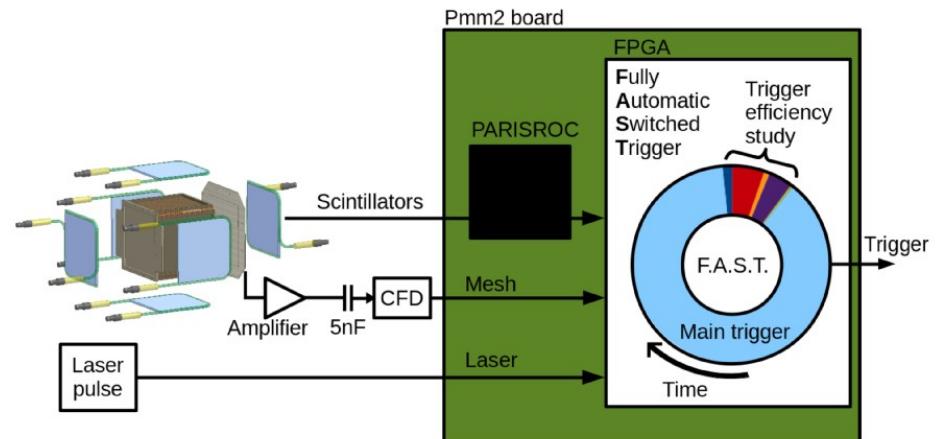
“Main line”: $T_{\gamma, \text{laser}} = \overline{S}_{up} \cap O \cap M_{slow} \cap L$

Wang et al., J. Phys. Conf. Ser. 650 (2015) 012016

“Beam” trigger system: additional lines

- Additional trigger lines:

7	$T_{\gamma, \text{laser}}$	$\bar{S}_{\text{up}} \cap O \cap M_{\text{slow}} \cap L$
8	$T_{\text{noMesh}, \text{laser}}$	$\bar{S}_{\text{up}} \cap O \cap L$
9	$T_{\text{invMesh}, \text{laser}}$	$\bar{S}_{\text{up}} \cap O \cap M_{\text{quick}} \cap L$
10	$T_{\text{noUp}, \text{laser}}$	$O \cap M_{\text{slow}} \cap L$
11	$T_{\text{noPM}, \text{laser}}$	$\bar{S}_{\text{up}} \cap M_{\text{slow}} \cap L$
12	T_{noLaser}	$\bar{S}_{\text{up}} \cap O \cap M_{\text{slow}} \cap \bar{L}$

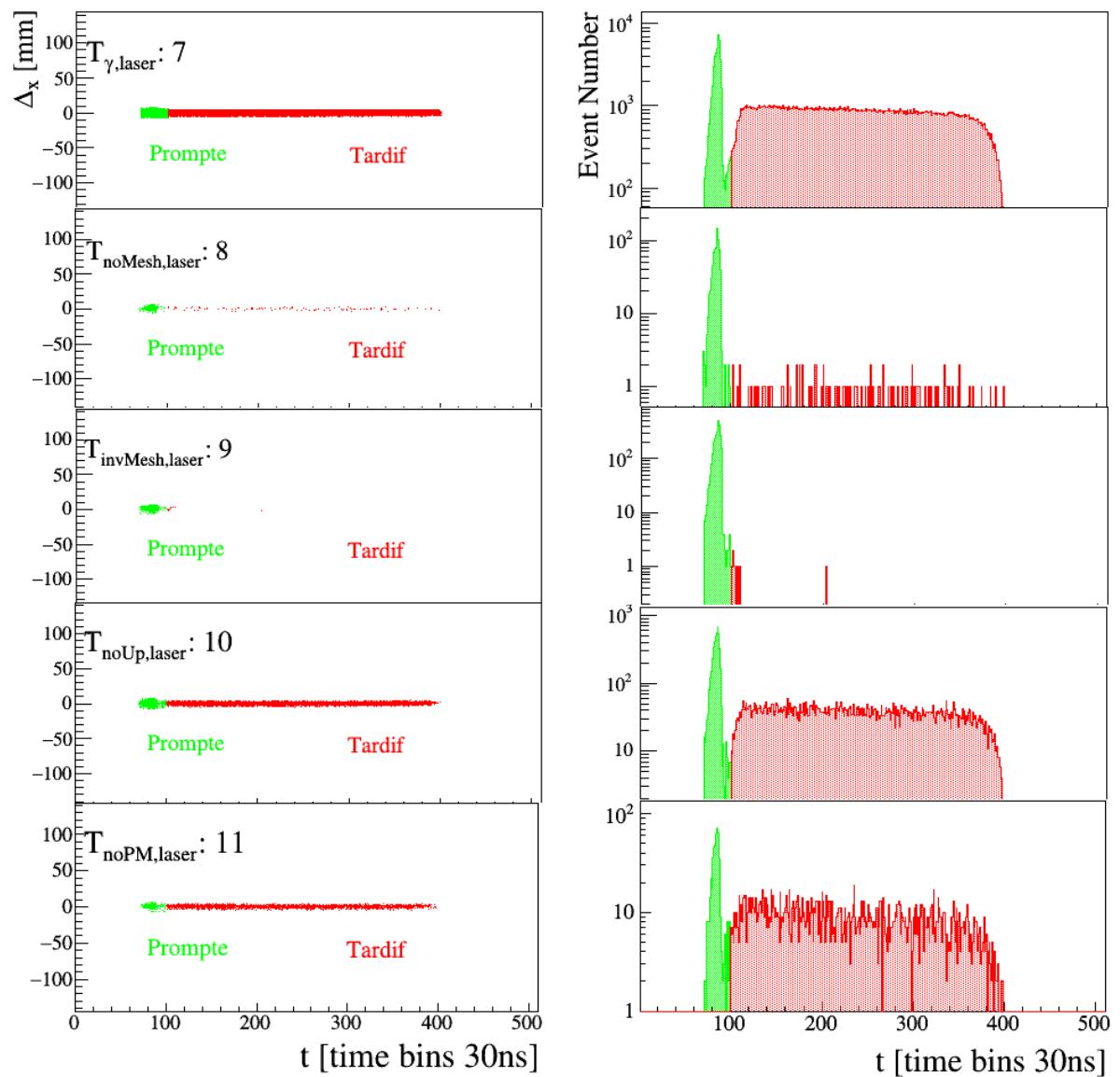


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

Y. Geerebaert et al., Real Time Conference (RT), 2016 IEEE-NPSS

“Beam” trigger system: conversion point distributions

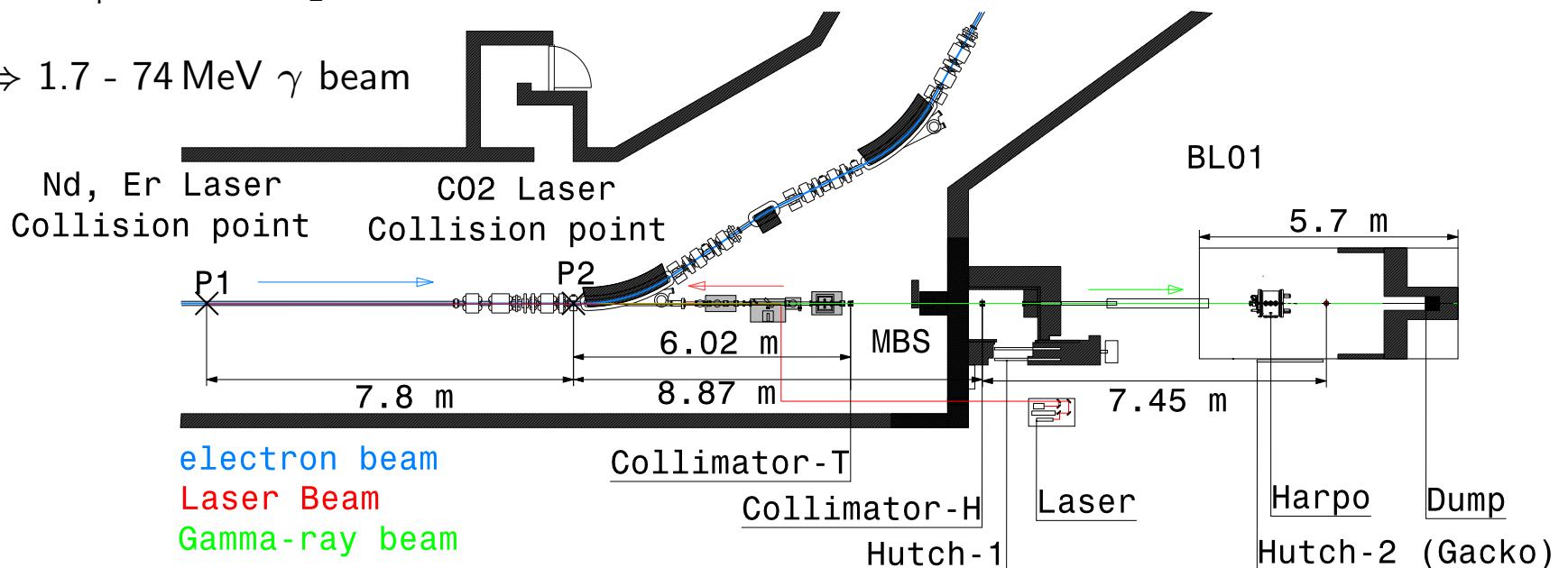
- signal efficiency 51 %
- background rejection 99.3 %
- incident rate 2 kHz
- signal on disk 50 Hz



S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015, in French

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

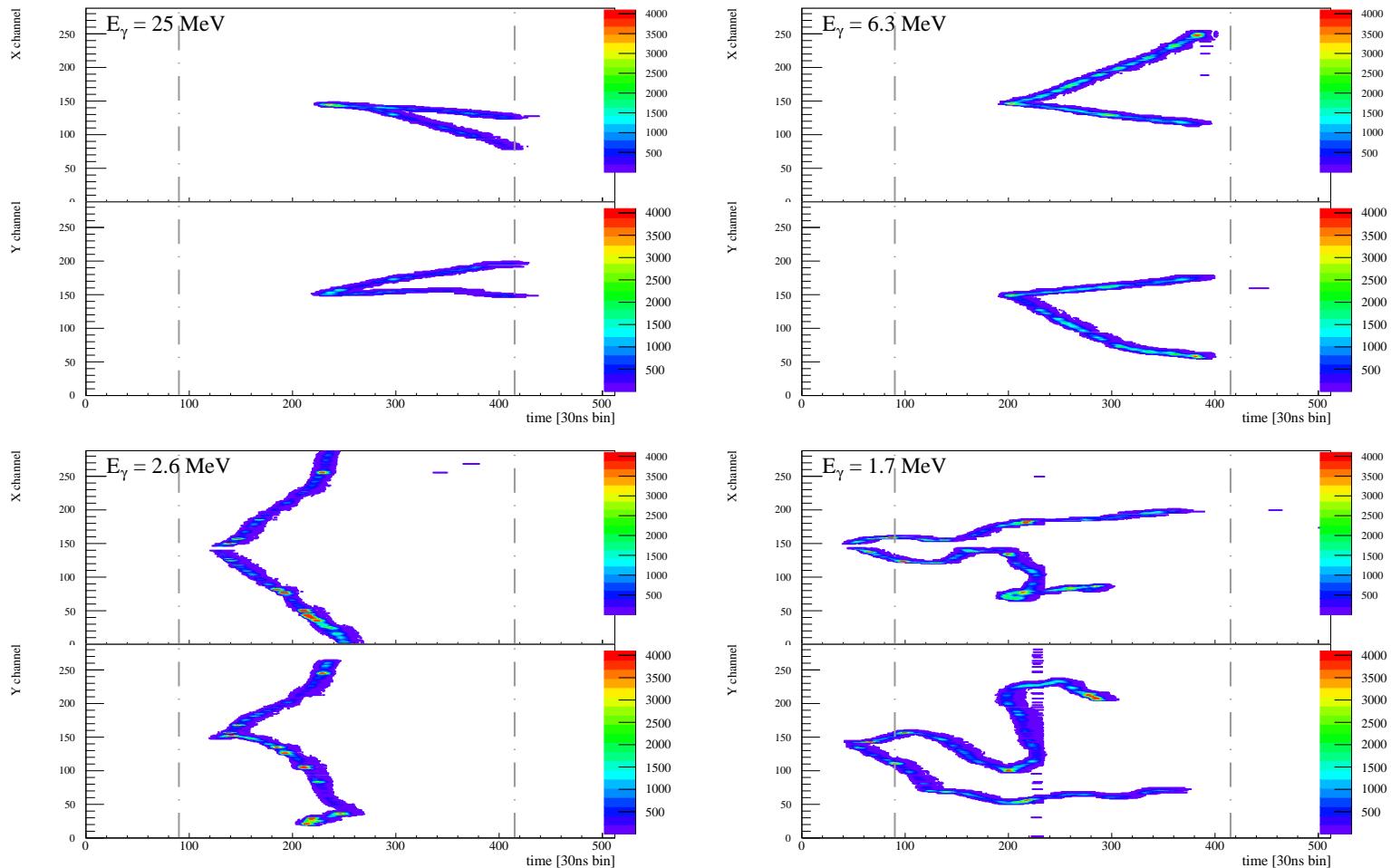
- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- 0.532 μm and 1.064 μm 20 kHz pulsed Nd:YVO₄ (2ω and 1ω),
1.540 μm 200 kHz pulsed Er (fibre) and
10.55 μm CW CO₂ lasers
- \Rightarrow 1.7 - 74 MeV γ beam



- Monochromaticity by collimation on axis
- Fully polarized or random polarization beams ($P = 0, P = 1$)
- 2.1 bar Ar:isoC₄H₁₀ 95:5 (+ a 1-4 bar scan).

A. Delbart et al., ICRC2015, PoS(ICRC2015)1016

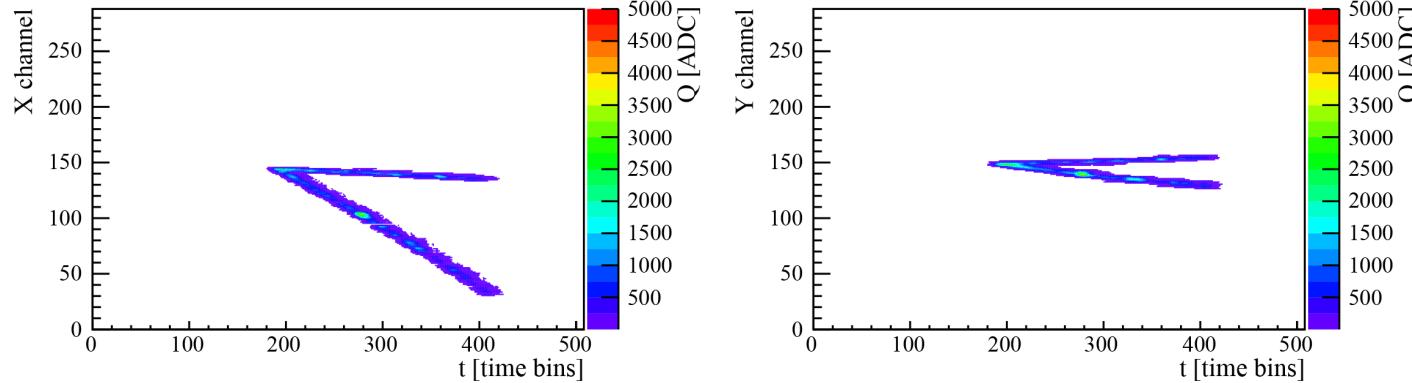
4 events



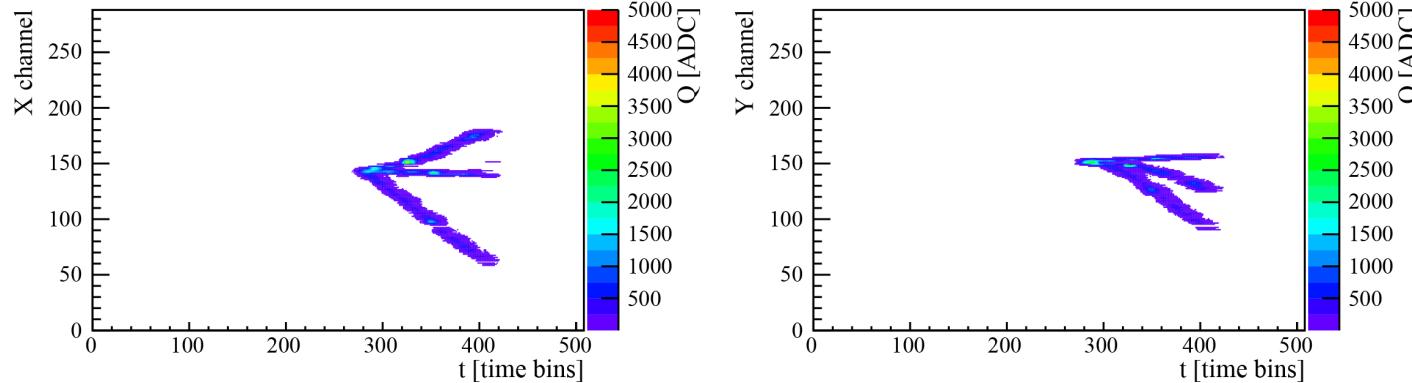
- Sample of γ -rays from the BL01 beam line at NewSUBARU (LASTI, Hyôgo U., Japan) converting to e^+e^- in the 2.1 bar Ar:Isobutane 95:5 gas of the HARPO TPC
- Ability to image low energy (MeV) γ -ray conversion to pairs.

“Nuclear” and “triplet” conversions

$$\gamma Z \rightarrow e^+ e^- Z$$

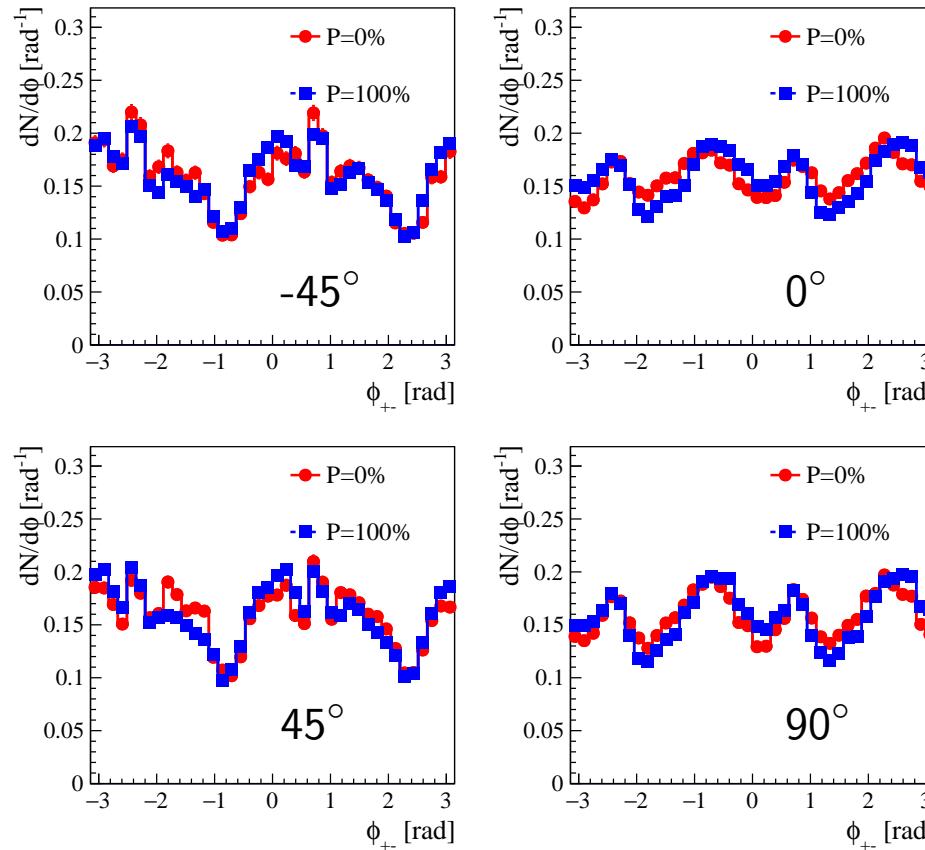


$$\gamma e^- \rightarrow e^+ e^- e^-$$



74 MeV γ -rays from the BL01 NewSUBARU γ -ray beam line, converting in the 2.1 bar Ar:Isobutane 95:5 mixture of the HARPO TPC prototype

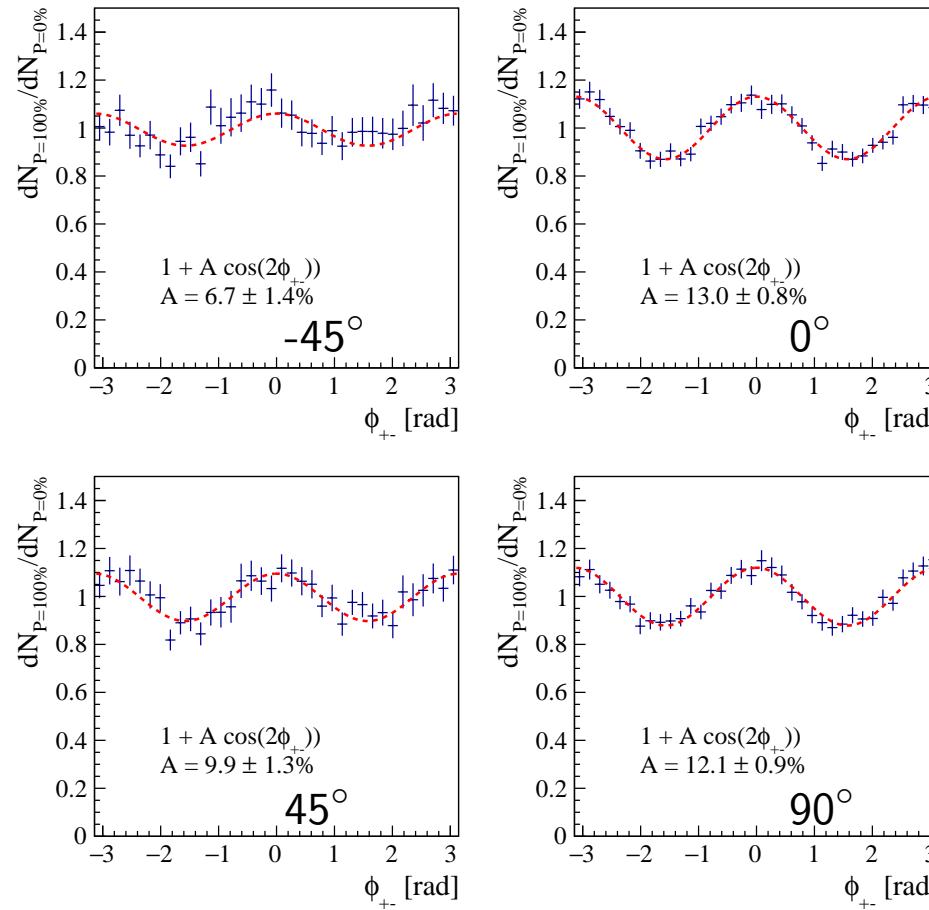
Polarimetry: azimuthal angles for 4 detector orientations



ϕ distributions for four detector orientations (11.8 MeV γ rays in 2.1 bar argon)

- Strong biases due to (x, y) detector structure lead to non-cosine shape.
- Some difference between ($P = 0$) and ($P = 1$) distributions though

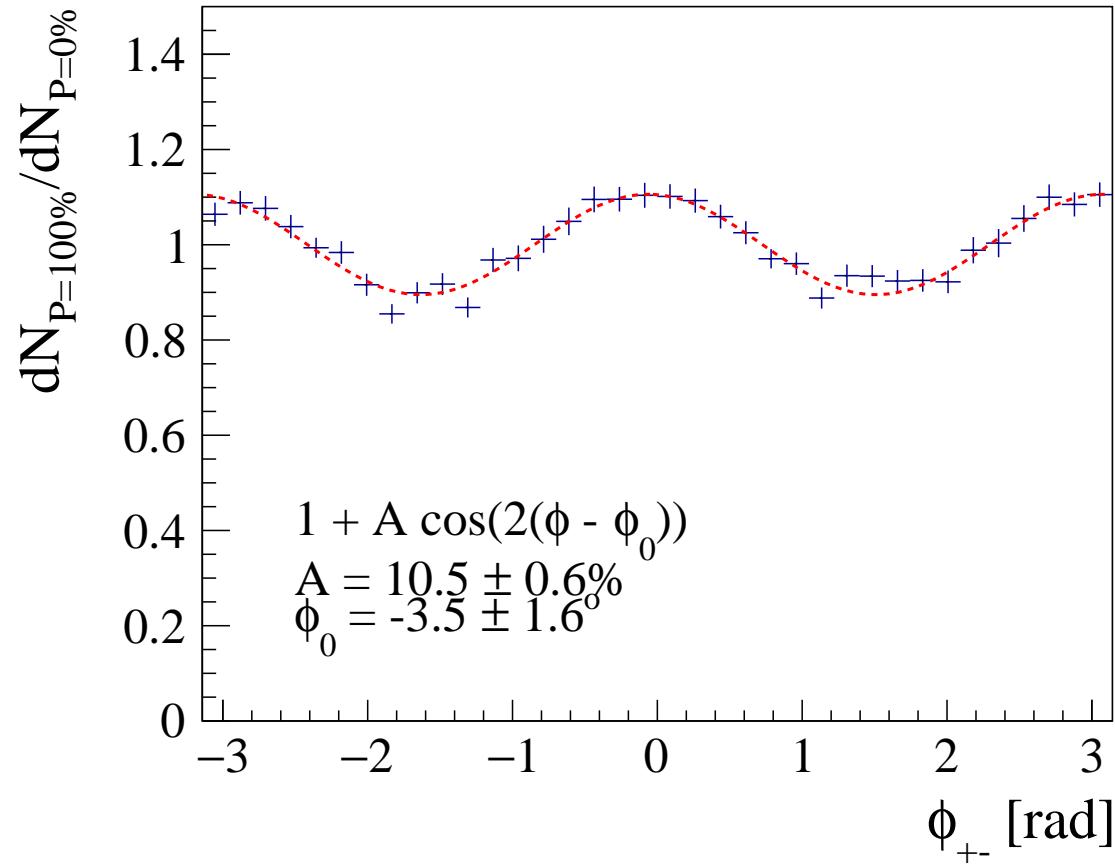
Polarimetry: $(P = 1)/(P = 0)$ ratios



Ratios of ϕ distributions for four detector orientations
(11.8 MeV γ rays in 2.1 bar Ar)

P. Gros et al. Astroparticle Physics 97 (2018) 10

Polarimetry: $(P = 1)/(P = 0)$ ratios, orientation averaged

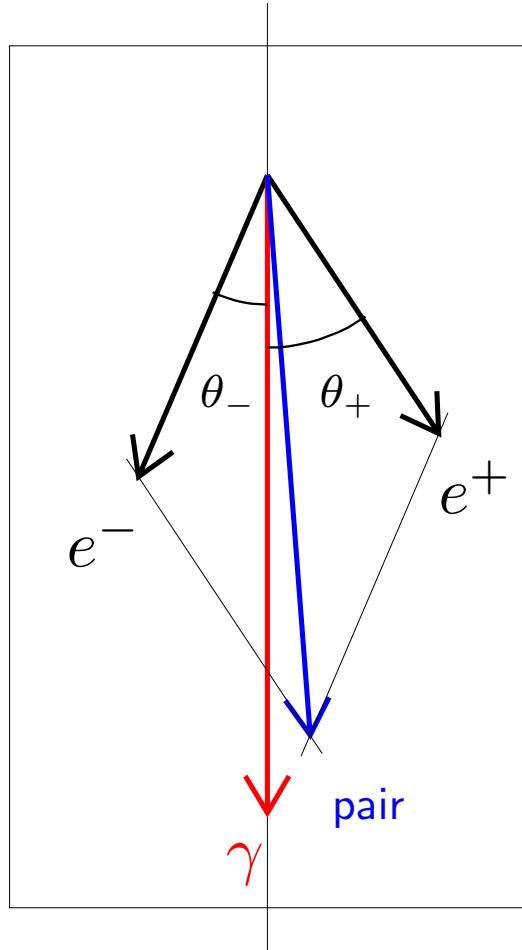


Whole sample, Ratios of ϕ distributions (11.8 MeV γ rays in 2.1 bar argon)

P. Gros et al. Astroparticle Physics 97 (2018) 10

G4BetheHeitler5DModel: a 5D Bethe-Heitler γ -conversion Geant4 physics model

Pre-existing event generators



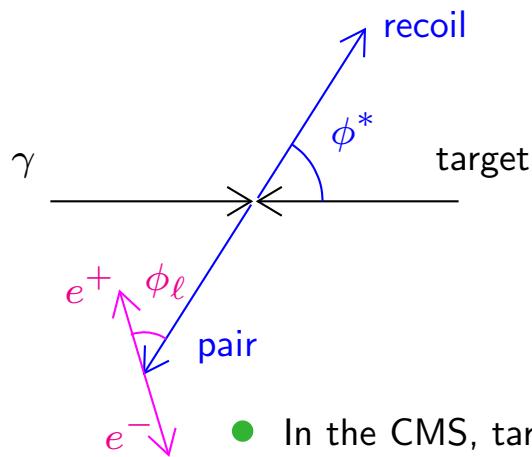
"conversion plane"

- pdf = product of 1D pdf's
- No recoil explicitly generated ($E_+ + E_- = E$)
 - \Rightarrow conversion wrongly generated in a plane that contains \vec{k}_γ
 - \Rightarrow no kick transverse to the plane
- e^+ and e^- polar angles generated independently
 - \Rightarrow energy-momentum not conserved !
 - \Rightarrow artificial kick in the plane (and wrong distribution)
- Attempts to verify polarized models failed
- Single-particle polar angle θ distribution, OK.
- "Energy share", x_+ distribution, OK. $x_+ \equiv E_+/E_\gamma$
- Geant4 Physics Reference Manual, release 10.4 (Dec. 2017, pdf)
Sects. 6.5 – 6.6. & 13.9

Gros and Bernard, Astroparticle Physics 88 (2017) 60

G4BetheHeitler5DModel: Sampling Method

- Perform each step in appropriate Lorentz frame
 - Center-of-mass system (CMS) boost determined from photon energy E and target mass M .
 - Five variables are taken at random, $(\ell: \text{lepton, that is, } e^+ \text{ or } e^-)$



variable	name	Lorentz frame
θ	target and pair polar angle	CMS
ϕ	target and pair azimuthal angle	CMS
μ	e^+e^- invariant mass	
θ_ℓ	electron and positron polar angle	pair frame
ϕ_ℓ	electron and positron azimuthal angle	pair frame

- In the CMS, target (mass M) and pair (mass μ) are back-to-back with opposite momenta.
 - “Decay” of the pair to an electron and a positron performed in the pair Lorentz frame.
 - The lepton 4-vectors are boosted “back” to the CMS.
 - The three final particle 4-vectors are boosted “back” to the laboratory Lorentz frame.
 - The Bethe-Heitler variables are obtained from the 4-vectors.
 - The probability density function (pdf) is computed.
- Final-state phase space normalization for this set of cascade decays:

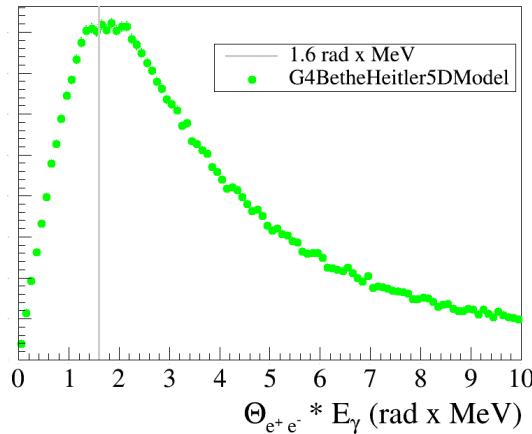
Review of Particle Physics (Particle Data Group) See eqs. (1)-(3) in Nucl. Instrum. Meth. A 899 (2018) 85

- In contrast to Bethe-Heitler we **do conserve energy momentum**, $E = E_- + E_+ + E_r$

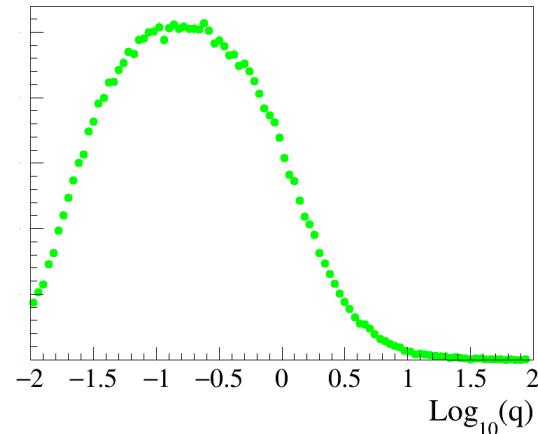
Implementation

- Provide final state: SampleSecondaries
- Inherit total cross section from G4BetheHeitlerModel
- Models flags provided via G4EmParameters flags and UI commands
 - Recoil particle (ion or electron): Nuclear / triplet / ($Z / 1$) natural mixture
 - Isolated targets (QED checks), charged targets in atoms (detector simulation)
- Linearly polarised / non polarised photons
- Since release 10.6, G4EmStandardPhysics_option4 uses 5D model for gamma conversion.

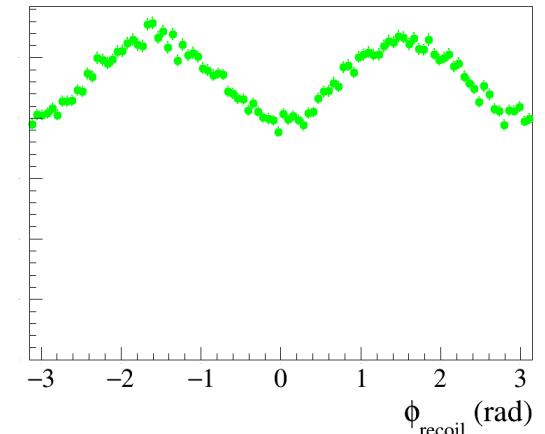
TestEm15



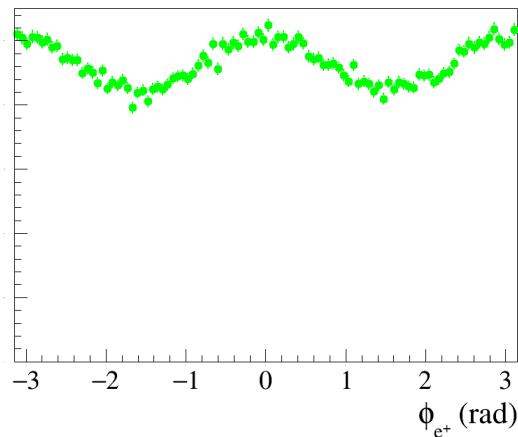
Olsen, Phys. Rev. 131 (1963) 406



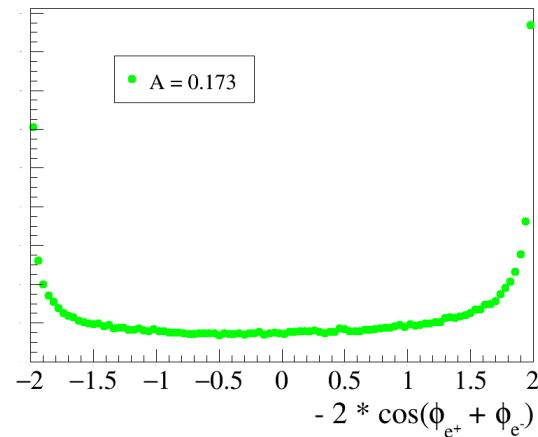
q (MeV/c) is recoil momentum



recoil preferentially \perp pol



e^+ and e^- preferentially along pol

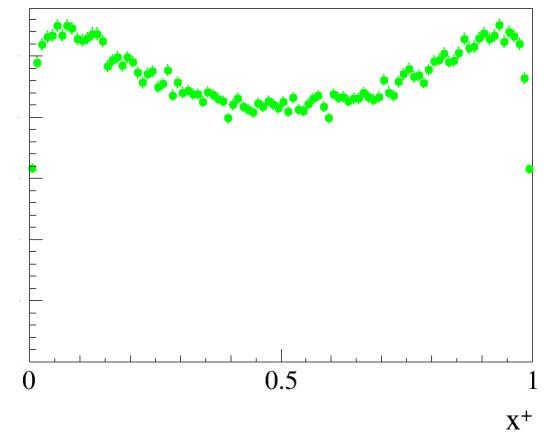


$$A = \langle -2 \cos 2\phi \rangle, \quad \phi = (\phi_+ + \phi_-)/2$$

minus sign due to π e^+/e^- shift

1 GeV, argon

Astropart. Phys. 88 (2017) 30



energy share $x_+ \equiv E_+/E_\gamma$

TestEm15/README.gamma

Documentation

- Geant4 Physics Reference Manual, release 10.7 (Dec. 2020, pdf) Sects. 6.5.4 & 13.10
- Talks / publications
 - Geant4 electromagnetic physics progress, Ivana Hrivnacova, CHEP 2019, November 2019, Adelaide link, EPJ Web Conf. **245** (2020), 02009
 - Progress of Geant4 electromagnetic physics developments and applications, Vladimir Ivantchenko, CHEP 2018, Sofia, July 2018 (link) EPJ Web Conf. **214** (2019), 02046
 - “C++ implementation of Bethe–Heitler, 5D, polarized, $\gamma \rightarrow e^+e^-$ pair conversion event generator,” I. Semeniouk and D. Bernard, Nucl. Instrum. Meth. A **936** (2019), 290
 - “A 5D, polarised, Bethe-Heitler event generator for $\gamma \rightarrow e^+e^-$ conversion,” D. Bernard, Nucl. Instrum. Meth. A **899** (2018), 85
 -

G4BetheHeitler5DModel extended to $\gamma \rightarrow \mu^+ \mu^-$

The gamma factory project @ CERN

- $1 < E_\gamma < 400 \text{ MeV}$
- $10^{17} \gamma/\text{s}$
- 7 orders of magnitude larger than presently operating light-sources
- A powerful muon source by $\gamma \rightarrow \mu^+ \mu^-$ conversions \Rightarrow also neutrino source

M. Krasny *et al.*, 9th IPAC Vancouver 2018

- Geant4 G4GammaConversionToMuons $\gamma \rightarrow \mu^+ \mu^-$ uses high-energy approximations
Verified $E_\gamma > 10 \text{ GeV}$ H. Burkhardt *et al.*, CERN-SL-2002-016-AP, CLIC-NOTE-511.
- A Geant4 physics model for $\gamma \rightarrow \mu^+ \mu^-$, valid down to threshold was needed
V. Ivantchenko,. “Muon pair production Monte Carlo”, Gamma Factory meeting, CERN, 2019 (indico).
- G4BetheHeitler5DModel extended to $\gamma \rightarrow \mu^+ \mu^-$ arXiv:1910.12501 (release 10.6)

Conclusion

- Gas TPC THE choice detector for $\gamma \rightarrow e^+e^-$ astronomy and polarimetry
- Use of a “Fast” gas ($v_{\text{drift}} \gg 1 \text{ cm}/\mu\text{s}$) mitigates background pile-up
- 4π acceptance, \approx isotropic performances (x, y, z), $< 30 \text{ ns}$ event time resolution
- Low number of electronics modules by use of projections – strips.
 - induced track matching issue easily solved.
- **Polarimetry demonstrated with excellent dilution factor.**
- **5D, polarized, γ conversion evt generator in Geant4**

Back-up Slides

Search for Axions

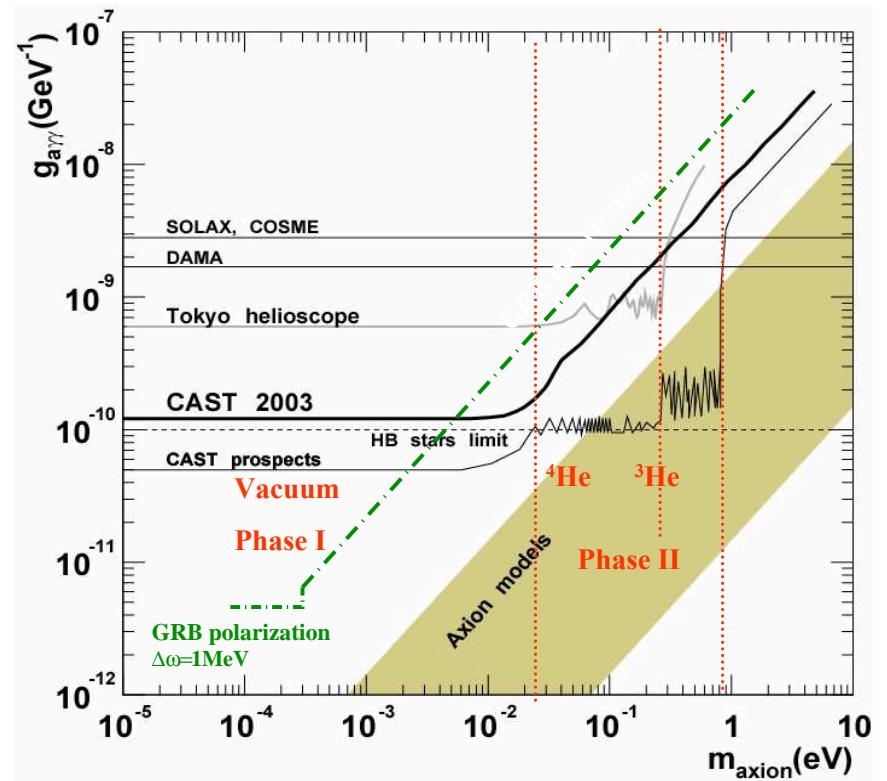
- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to 2γ through triangle anomaly.
- γ propagation through $B \Rightarrow$ Dichroism $\Rightarrow E$ dependant rotation of linear polarization \Rightarrow linear polarization dilution.

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B \sqrt{\Delta\omega L_{GRB}}}$$

- Saturation over $L = 2\pi\omega/m_a^2 > L_{GRB}$ for $m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}}$

and the limit $g_{a\gamma\gamma}$ reaches a ω -independent constant.

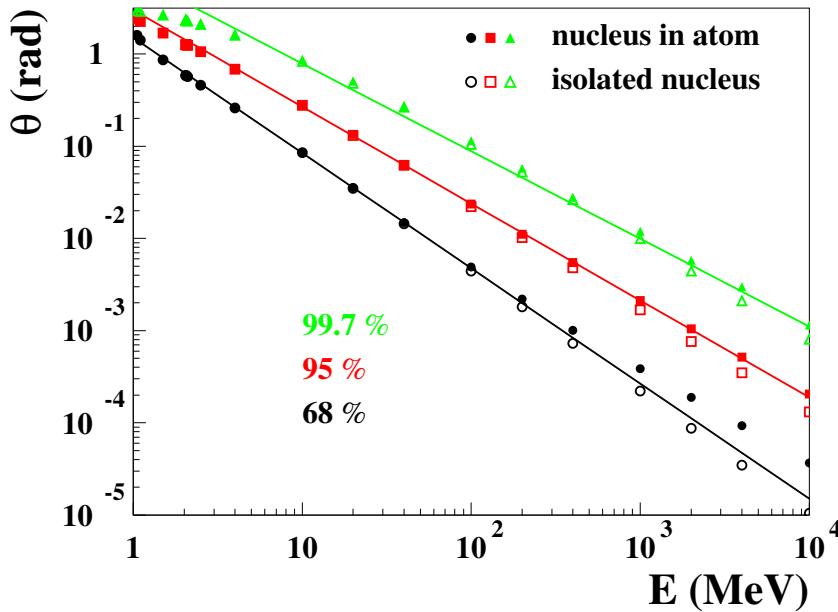
A. Rubbia and A. S. Sakharov, Astropart. Phys. 29, 20 (2008)



LIV: Search for Lorentz Invariance Violation

- Particle (photon) dispersion relations modified in LIV effective field theories (EFT)
- Additional term to the QED Lagrangian parametrized by ξ/M , M Planck mass.
- ξ bounds:
 - time of flight from the Crab: $\Delta t = \xi(k_2 - k_1)D/M$, $\xi \leq \mathcal{O}(100)$.
 - birefringence $\Delta\theta = \xi(k_2^2 - k_1^2)D/2M$
LIV induced birefringence would blurr the linear polarization of GRB emission.
 $\xi \leq 3.4 \times 10^{-16}$ with IBIS on Integral (250 – 800 keV)
D. Götz, *et al.*, MNRAS 431 (2013) 3550
- Bound $\propto 1/k^2$!

*Angular resolution at: 68, 95 and 99.7 % containment angles
(Un-measured nucleus recoil momentum)*



Approximate parametrizations:

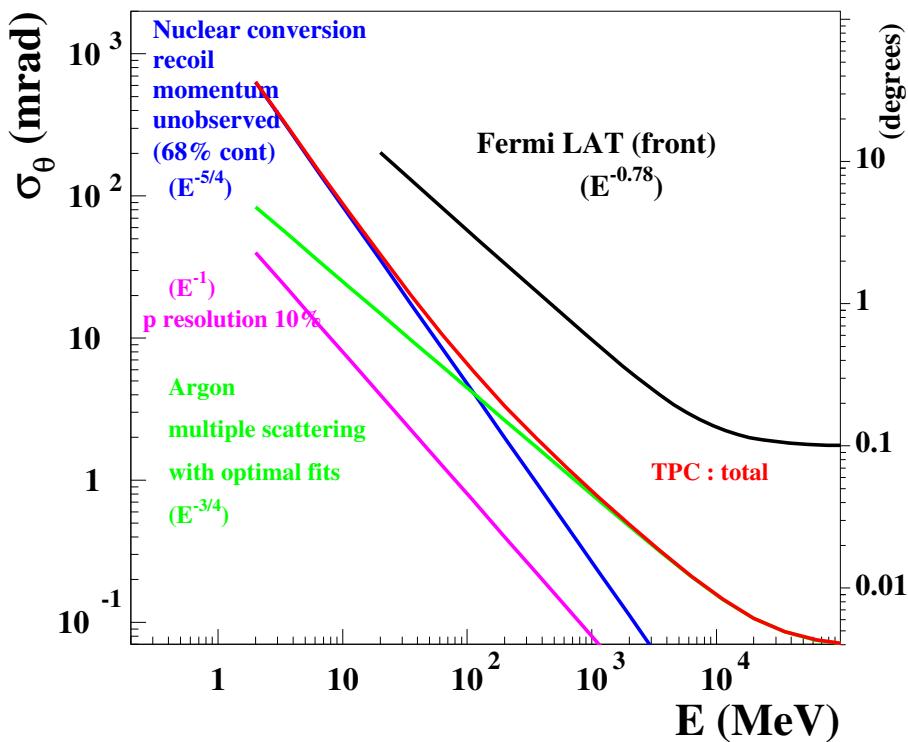
- $\theta_{68\%} \approx 1.5 \text{ rad } (E/\text{MeV})^{-5/4}$
- $\theta_{95\%} \approx 3.0 \text{ rad } (E/\text{MeV})^{-1.05}$
- $\theta_{99.7\%} \approx 7.0 \text{ rad } (E/\text{MeV})^{-0.95}$

Gros and Bernard, Astroparticle Physics 88 (2017) 60

Performances with Low-Density Homogeneous Detectors and Optimal Fits

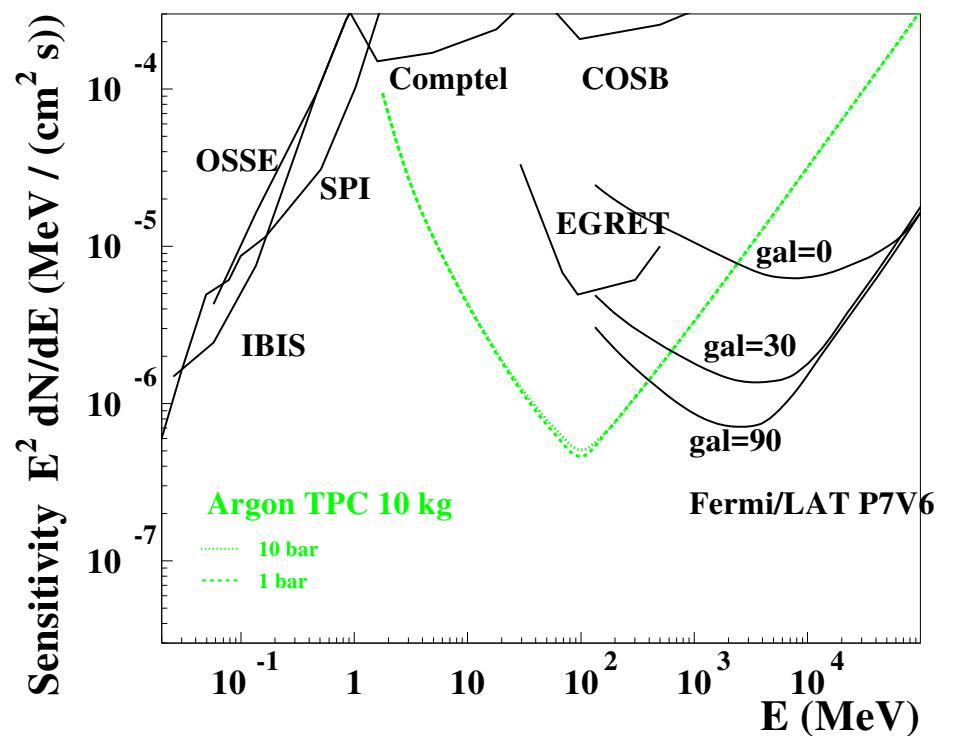
Angular resolution

- nucleus recoil $\propto E^{-5/4}$
- multiple scattering (optimal fits) $\propto E^{-3/4}$



point-source differential sensitivity

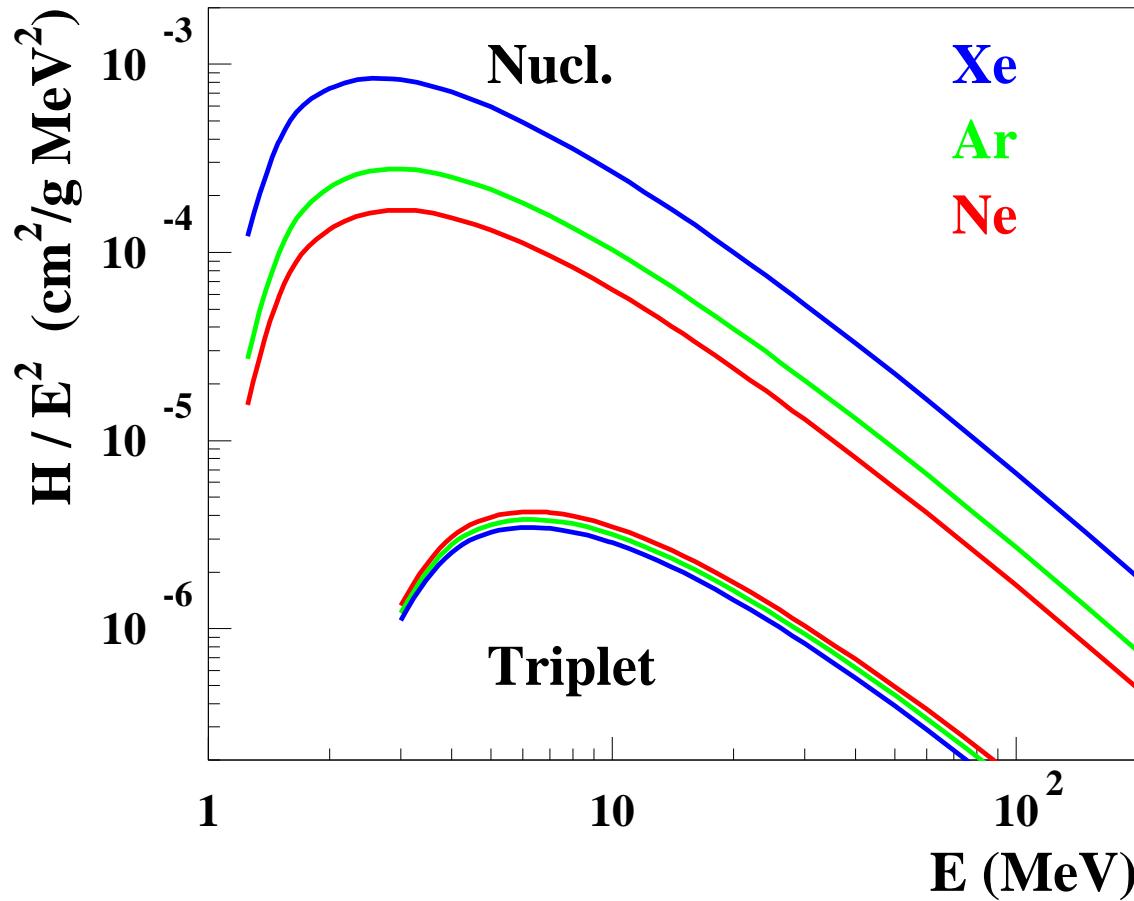
limit detectable $E^2 dN/dE$, à la Fermi: 4 bins/decade, 5σ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. “against” extragalactic background



“thin” detector: effective area $A_{\text{eff}} \propto$ mass, not to geometrical surface

Nucl. Instrum. Meth. A 701 (2013) 225

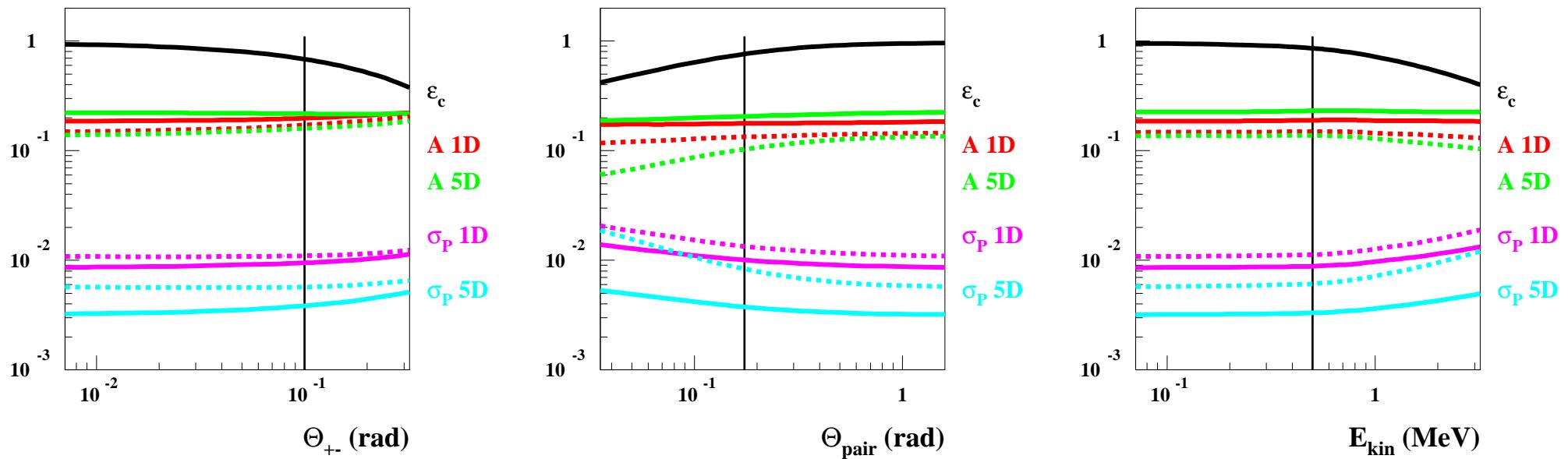
Polarimetry Demanding for Huge Statistics: Ability to take data at low energy critical



- Photon attenuation length (NIST) \times a typical cosmic-source spectrum $1/E^2$

Polarimetry: Effects of Experimental Cuts

- opening angle, $\theta_{+-} > 0.1 \text{ rad}$ (easy pattern recognition)
- source selection $\theta_{pair} < 10^\circ$
- kinetic leptons energy $E_{kin} > 0.5 \text{ MeV}$, (path length in 5 bar argon $\approx 30 \text{ cm}$)



- All cuts: $\epsilon = 45\%$, (1D) $\mathcal{A}_{\text{eff}} \approx 16.6\%$ $\sigma_P \approx 1.4\%$,

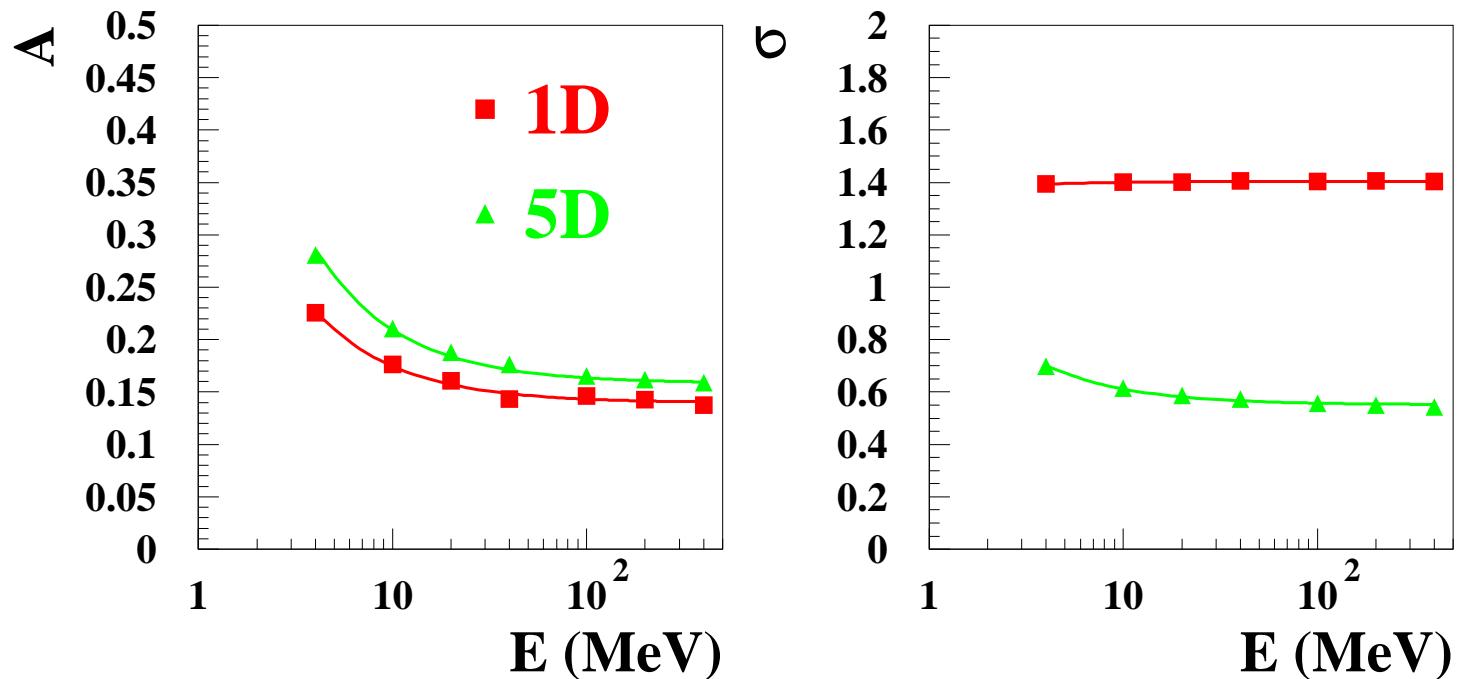
Nucl. Instrum. Meth. A 729 (2013) 765

Polarimetry: Optimal Measurement

- Remember, fit of $\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P \cos [2(\phi)])$ yields $\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}}$,
- Optimal measurement; Ω
 - let's define $p(\Omega)$ the pdf of set of (here 5) variables Ω
 - search for weight $w(\Omega)$, $E(w)$ function of P , and variance σ_P^2 minimal;
 - a solution is $w_{\text{opt}} = \frac{\partial \ln p(\Omega)}{\partial P}$ e.g.: F. V. Tkachov, Part. Nucl. Lett. 111, 28 (2002)
 - polarimetry: $p(\Omega) \equiv f(\Omega) + P \times g(\Omega)$, $w_{\text{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}$.
 - If $\mathcal{A} \ll 1$, $w_0 \equiv 2 \frac{g(\Omega)}{f(\Omega)}$, and
 - for the 1D “projection” $p(\Omega) = (1 + \mathcal{A}P \cos [2(\phi)])$:
 $w_1 = 2 \cos 2\phi$, $E(w_1) = \mathcal{A}P$, $\sigma_P = \frac{1}{\mathcal{A}\sqrt{N}} \sqrt{2 - (\mathcal{A}P)^2}$,

Nucl. Instrum. Meth. A 729 (2013) 765

Polarization asymmetry and measurement uncertainty



Nucl. Instrum. Meth. A 729 (2013) 765

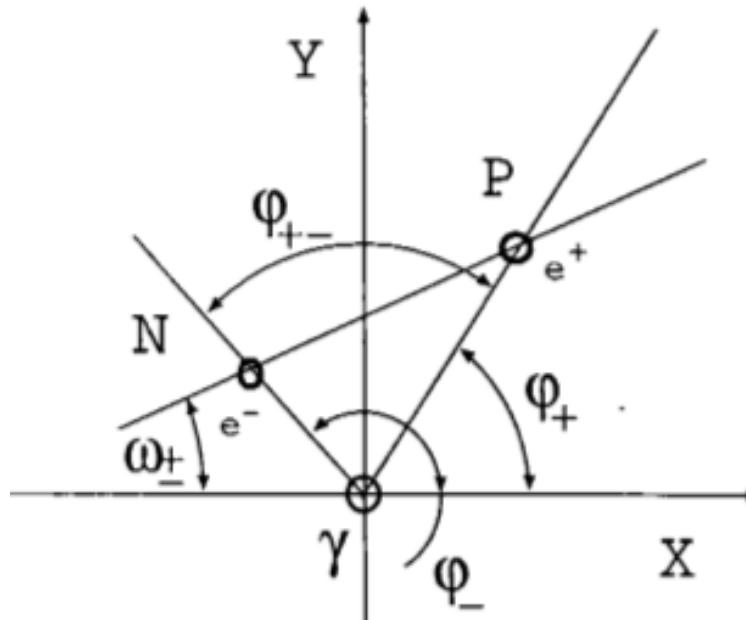
- Asymptotically $\mathcal{A} \approx 1/7 \approx 14\%$.

Boldyshev & Peresunko, Yad. Fiz. 14, 1027 (1971).

$$\frac{d\sigma}{d\phi} \propto \alpha r_0^2 \left(\left[\frac{28}{9} \ln 2(E/m) - \frac{218}{27} \right] - P \cos [2(\phi - \phi_0)] \left[\frac{4}{9} \ln (2E/m) - \frac{20}{27} \right] \right)$$

Polarimetry: Defining the Azimuthal Angle ?

- ω , most often used in publications since 2000's

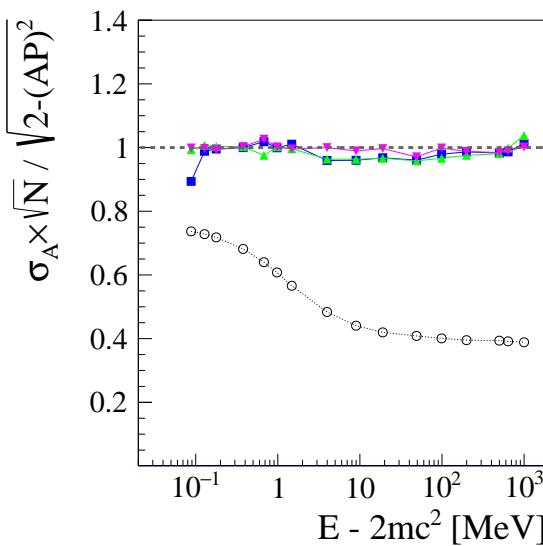
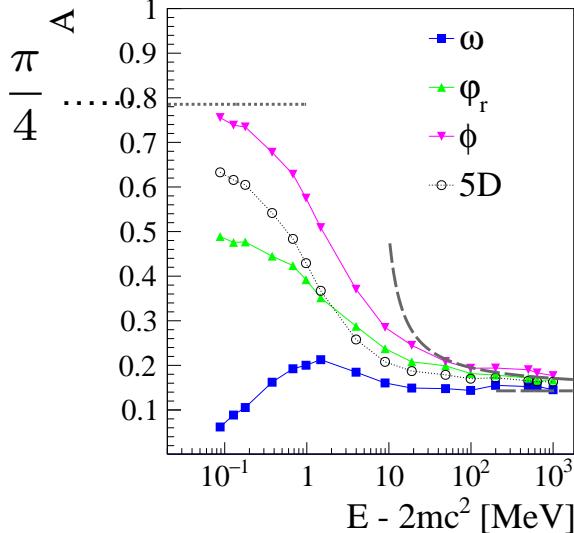


“polarized beams and polarimeters”, B. Wojtsekhowski (2000)

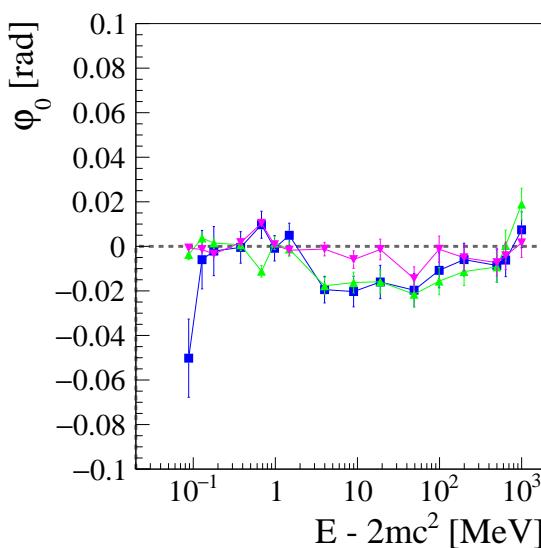
- φ_r recoil angle, $\varphi_r = \varphi_{\text{pair}} \pm \pi$
- $\phi = (\varphi_+ + \varphi_-)/2$, bisector of e^+ and e^- direction

Polarimetry: Defining the Azimuthal Angle ? Bisector Optimal !

polarization asymmetry



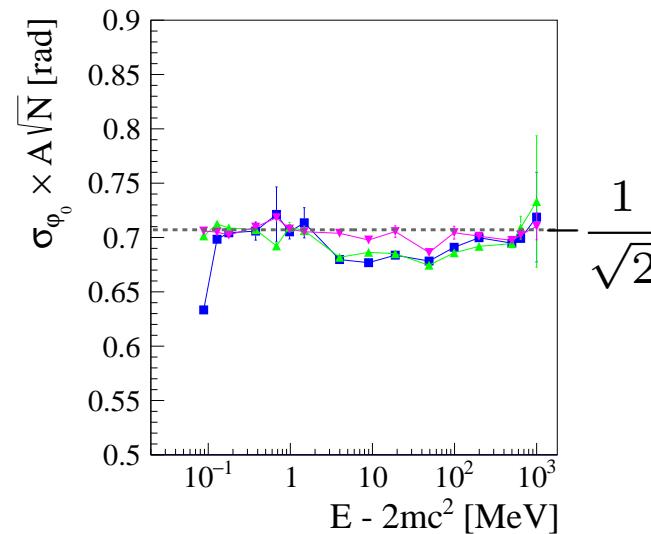
polarization angle



ω

φ_r recoil angle, $\varphi_r = \varphi_{\text{pair}} \pm \pi$

$\phi = (\varphi_+ + \varphi_-)/2$, bisector of e^+ and e^- direction



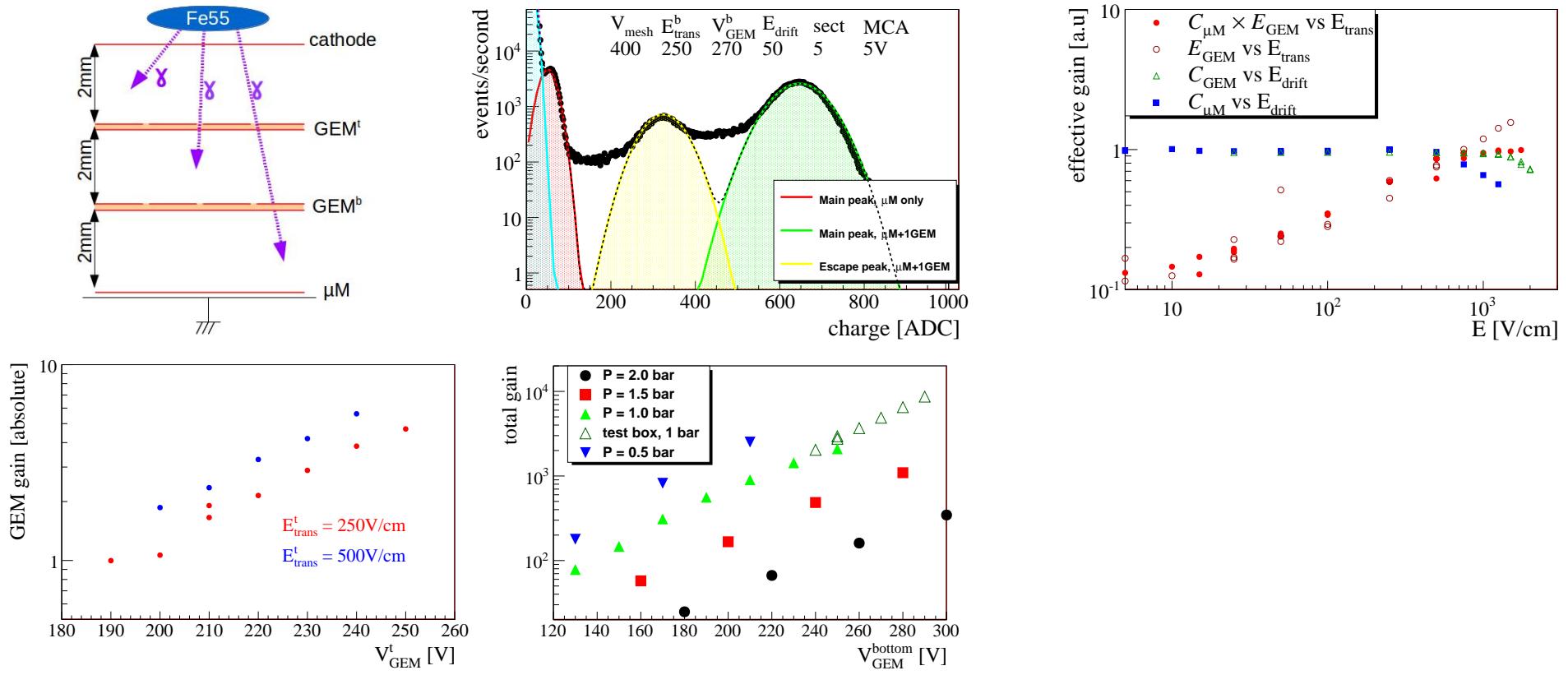
E (MeV)	loss factor wrt ϕ	
	ω	φ_r or φ_{pair}
10	0.56	0.67
100	0.74	0.94

Ph. Gros & D. Bernard,
Astropart. Phys. 88 (2017) 30

We checked that on a $P = 0$ MC sample, the measured value is found to be $\mathcal{A} \times P \approx 0$
 We checked that form factors do not affect the polarization asymmetry

Micromegas + 2 GEM assemblies: characterization

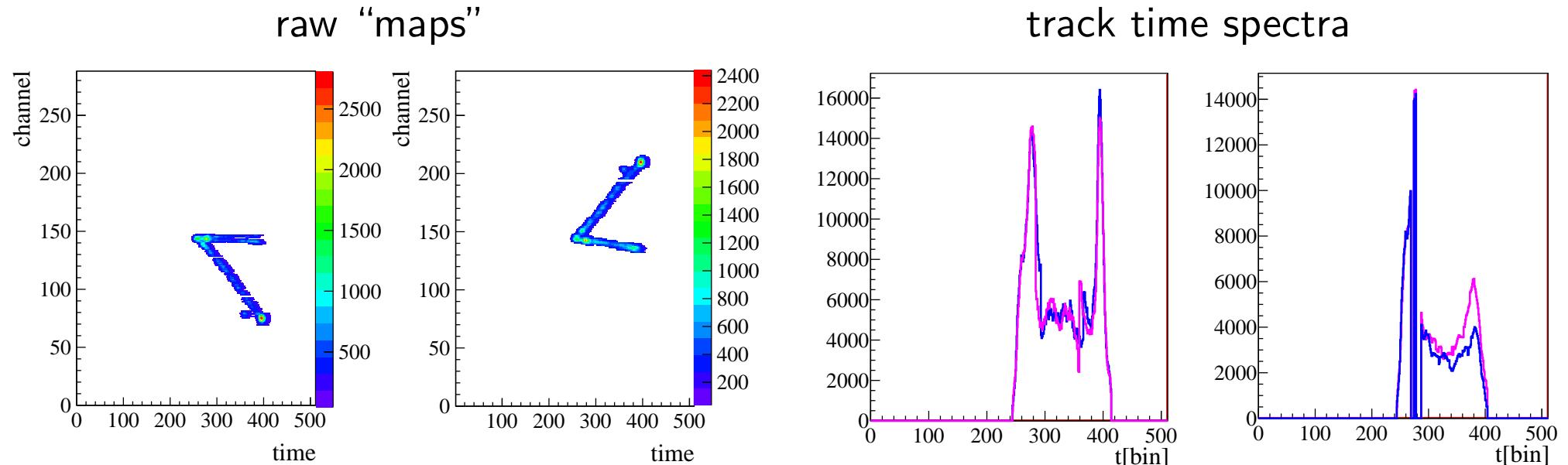
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)



Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

Track matching

A 16.7 MeV γ -ray converting to e^+e^- in 2.1 bar Ar:isobutane 95:5

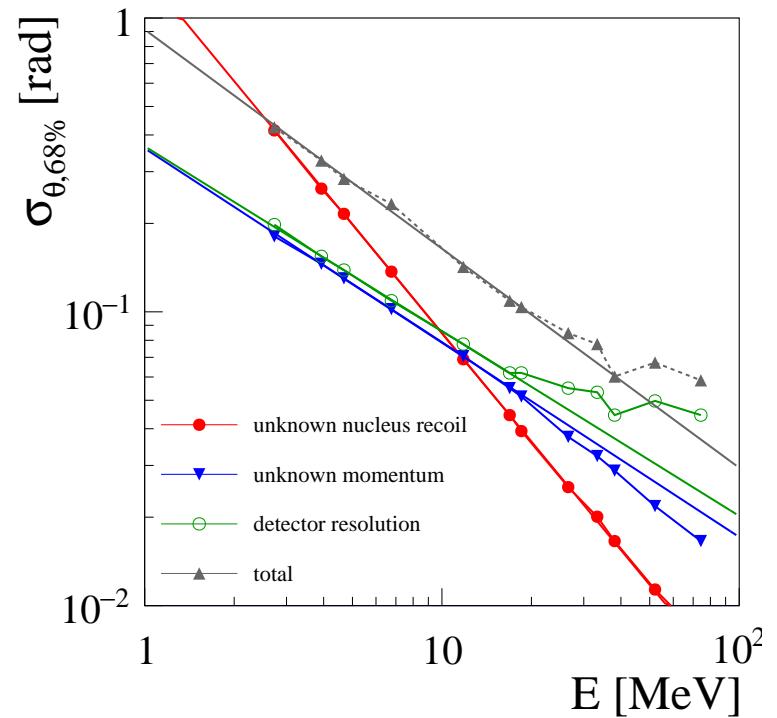
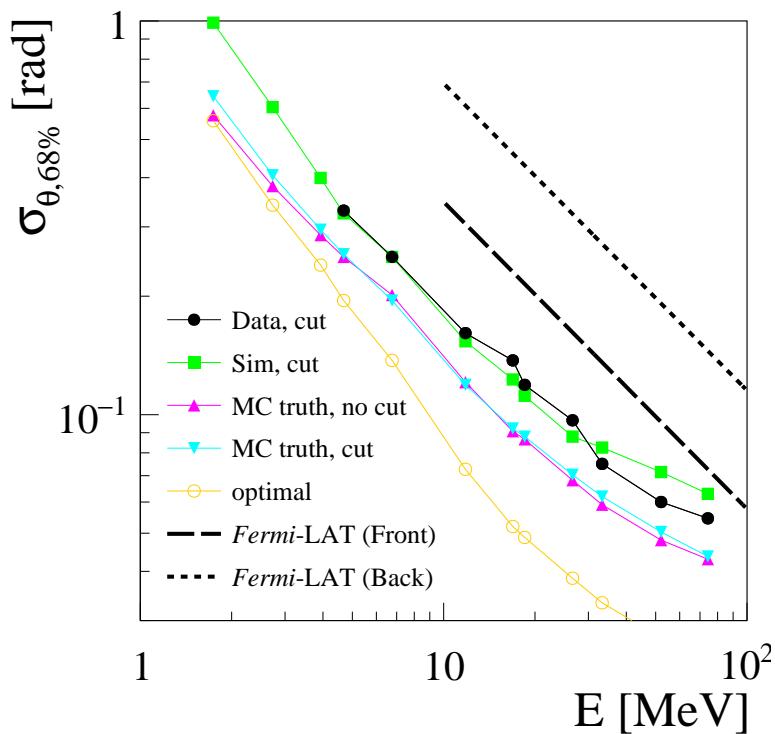


- x, y two-track ambiguity solved by track time spectra matching
- 1 channel = 1 mm.
- 1 time bin = 30 ns, $v_{\text{drift}} \approx 3.3 \text{ cm}/\mu\text{s}$ \Rightarrow 1 time bin \propto 1 mm

Nucl. Instrum. Meth. A 718 (2013) 395

Angular resolution

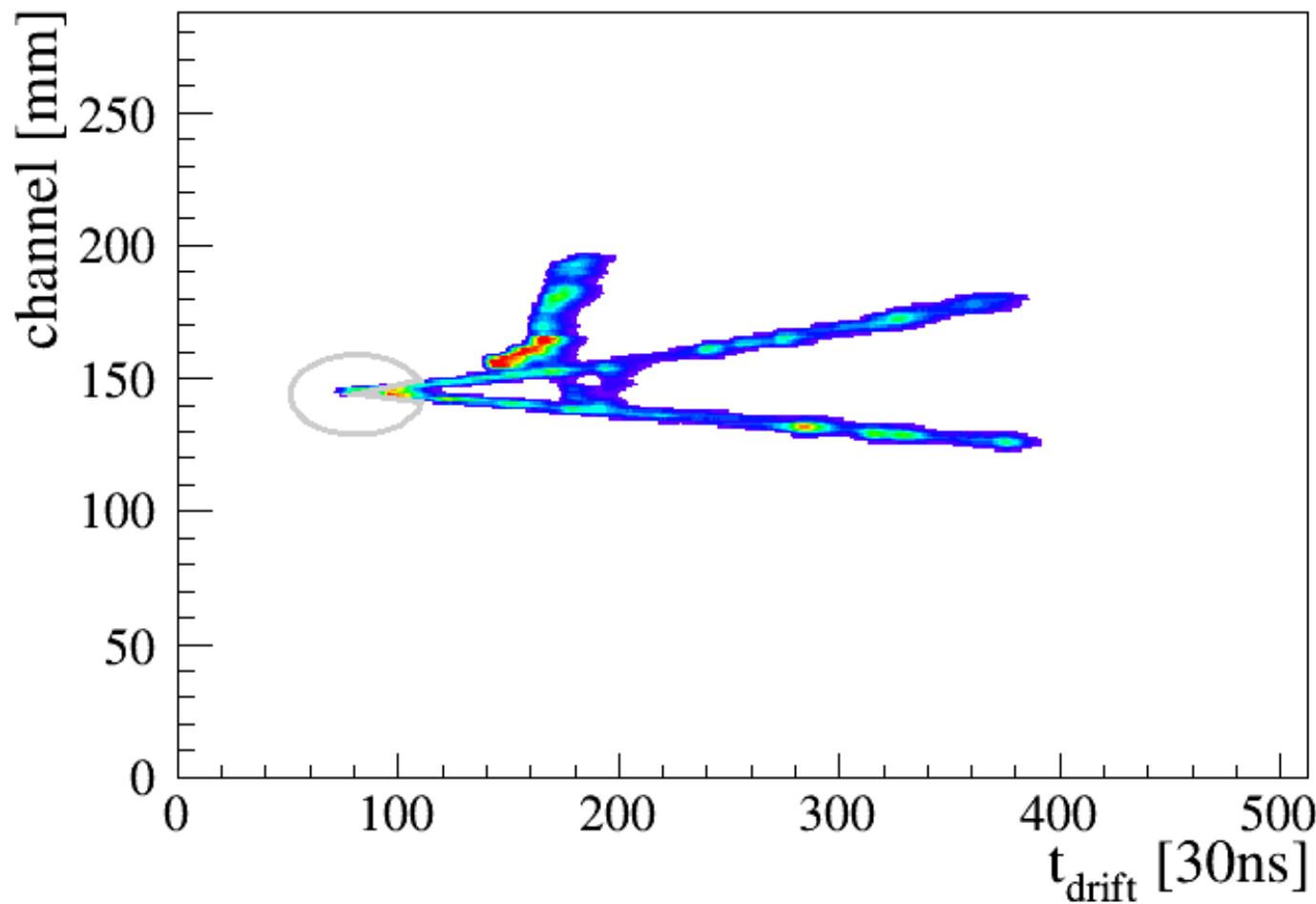
Pseudo-tracking: vertex analysis



Optimal: QED. (nucleus recoil)

P. Gros et al. Astroparticle Physics 97 (2018) 10

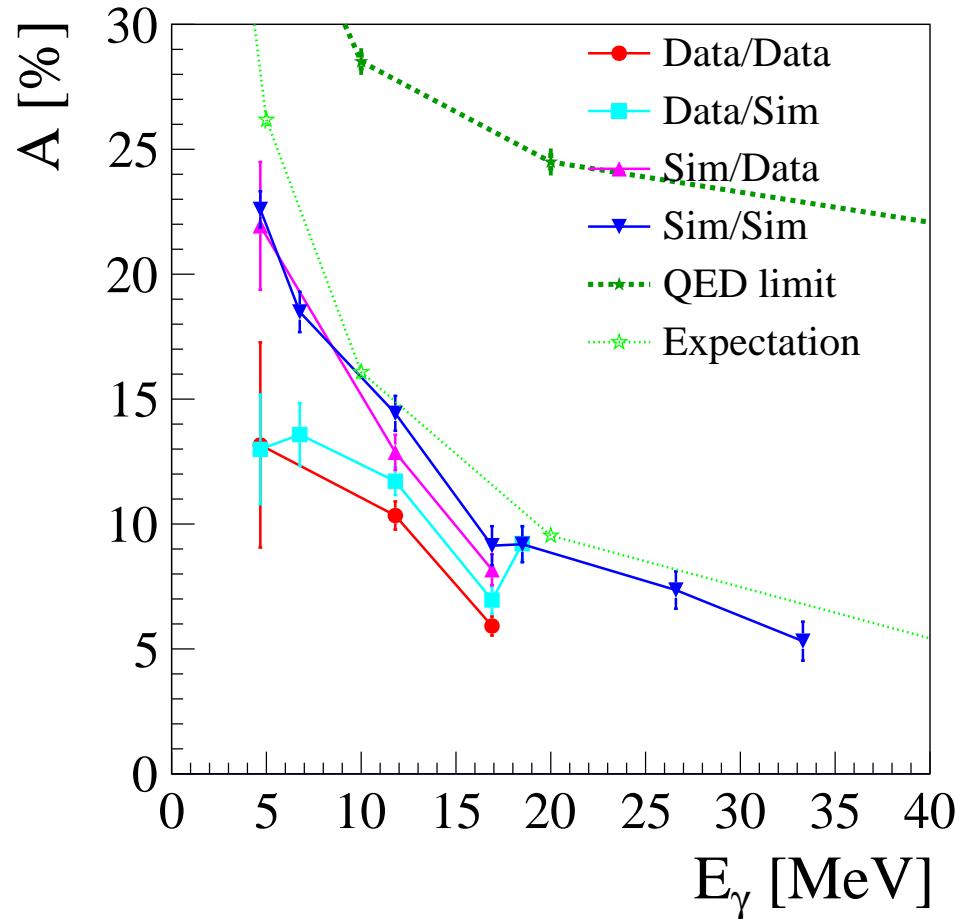
Event reconstruction



- Pseudo-tracking: vertex analysis

P. Gros, J.Phys.Conf.Ser. 1029 (2018) 012003

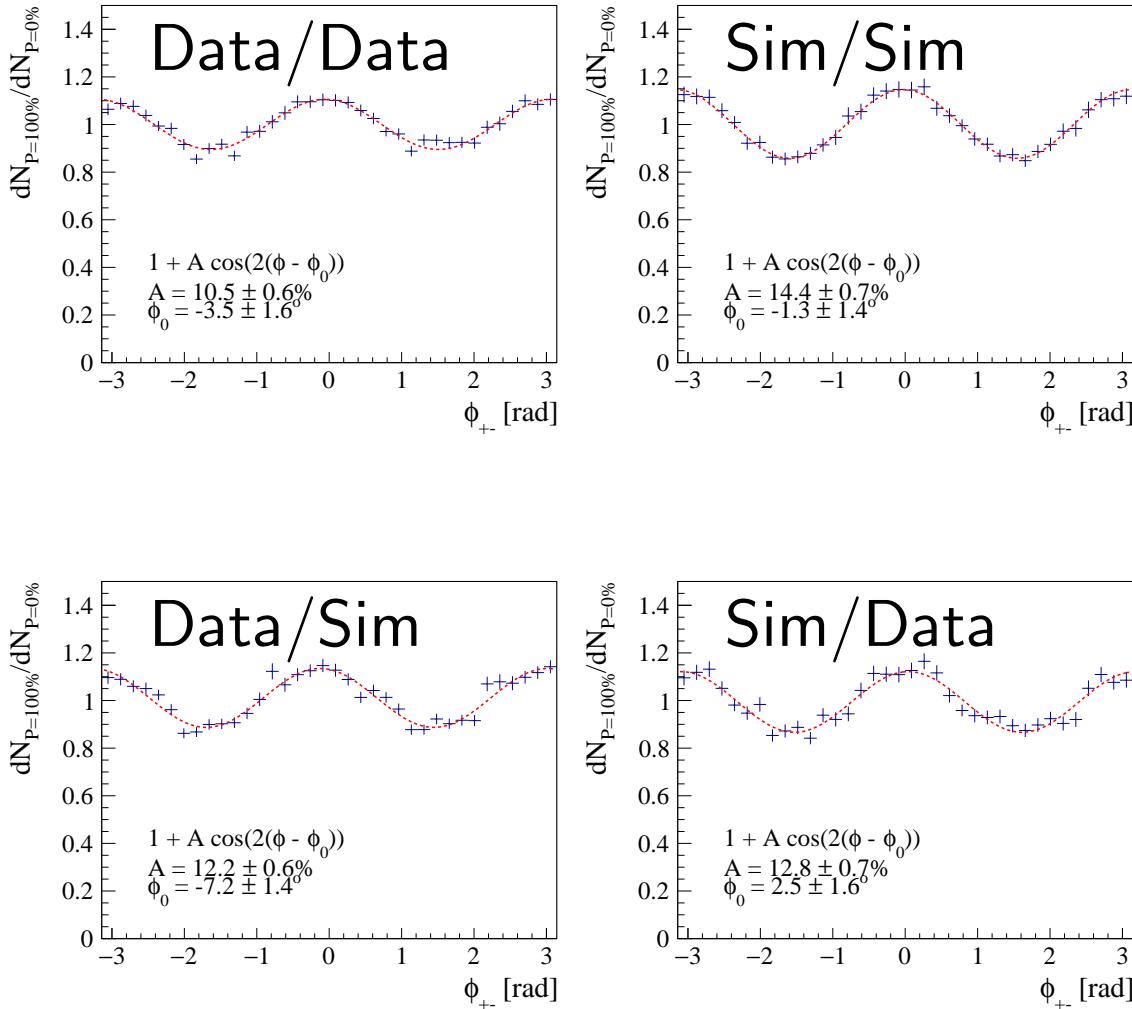
Polarization asymmetry dilution



- Measured polarization asymmetry (“Data”) compatible with QED value when dilution due to single-track resolution taken into account (“expectation”) (Kotov expression, slide 7)

P. Gros et al., Astroparticle Physics 97 (2018) 10

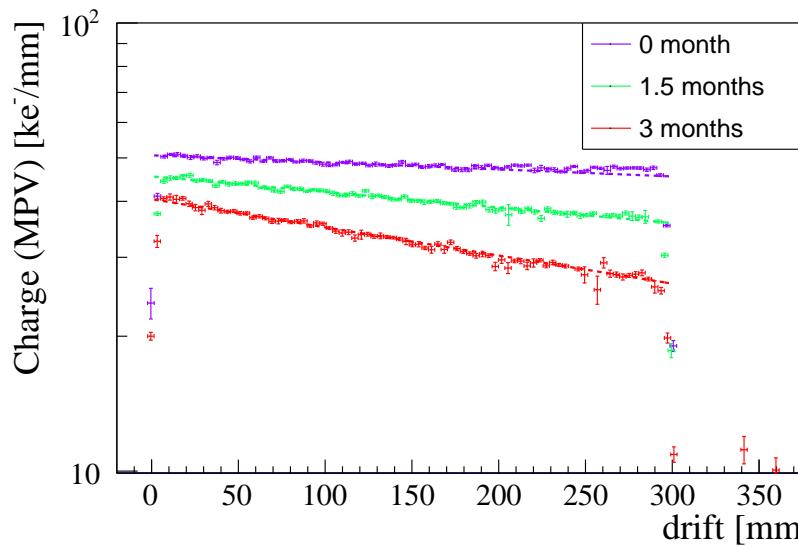
Bias correction by normalization to $P = 0$ distribution: effectiveness of Monte Carlo simulation



P. Gros et al., Astroparticle Physics 97 (2018) 10

Gas purity on the long term

- HARPO pressure vessel extremely dirty: scintillator, WLS, PVC box, PCB, epoxy, O-rings ..
- We have observed the evolution of the gaz quality in sealed mode [Fev. - Jun.] 2015 (2.1 bar).

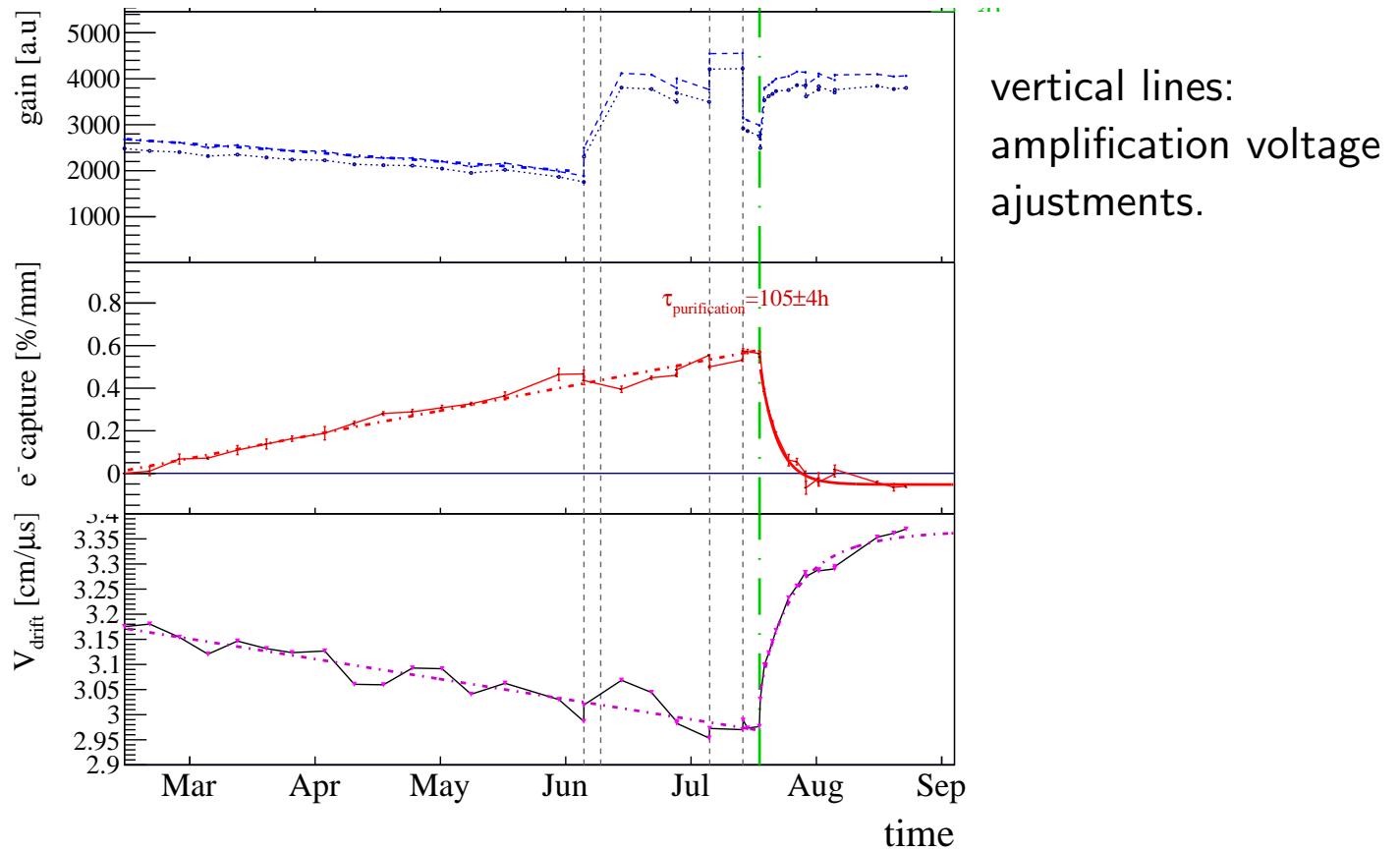


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- O_2 fraction peaked at 180 ppm on Jul. 08. $O_2/(O_2 + N_2) = 0.225$, compatible with air.
- Then we switched an oxisorb recirculation to operation. O_2 fraction disappeared (< 20 ppm)

M. Frotin et al., EPJ Web Conf. 174 (2018) 05002

Gas purity on the long term: results



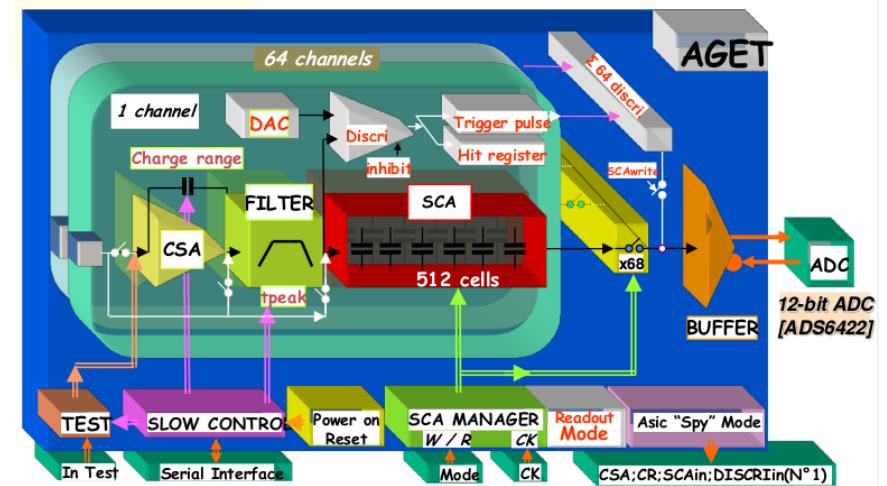
Time evolution of the amplification gain, of the electron capture and of the drift velocity as measured with cosmic-rays through [Fev. - Sept.] 2015.

- Interpreted as air leak or air outgassing, with complete gas cleaning upon purification
- Good prospects to run a TPC for years with a simple oxisorb cleaning

M. Frotin et al., EPJ Web Conf. 174 (2018) 05002

AGET: ASIC for Generic Electronics for TPC

- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- shaping: 16 peaking time values: 70 ns to 1 μ s
- 512 analog memory cells / channel
- Fsampling: 1 MHz to 100 MHz; Fread: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real time (25 MHz) Multiplicity signal: analog OR of the 64 discri Outputs
- Readout:
 - Address of the hit channel(s)
 - 3 readout modes: All, hit or specific channels
 - Predefined number of analog cells / trigger (1 to 512)



S. Anvar *et al.*, NSS/MIC, 2011 IEEE 745.

- AGET → **radhard** ASTRE: “Asic with SCA & Trigger for detector Readout Electronics” :
Prototype series tested, including latch-up in beam D. Baudin *et al.*, Nucl. Instrum. Meth. A 912 (2018) 66

Circular Polarization ?

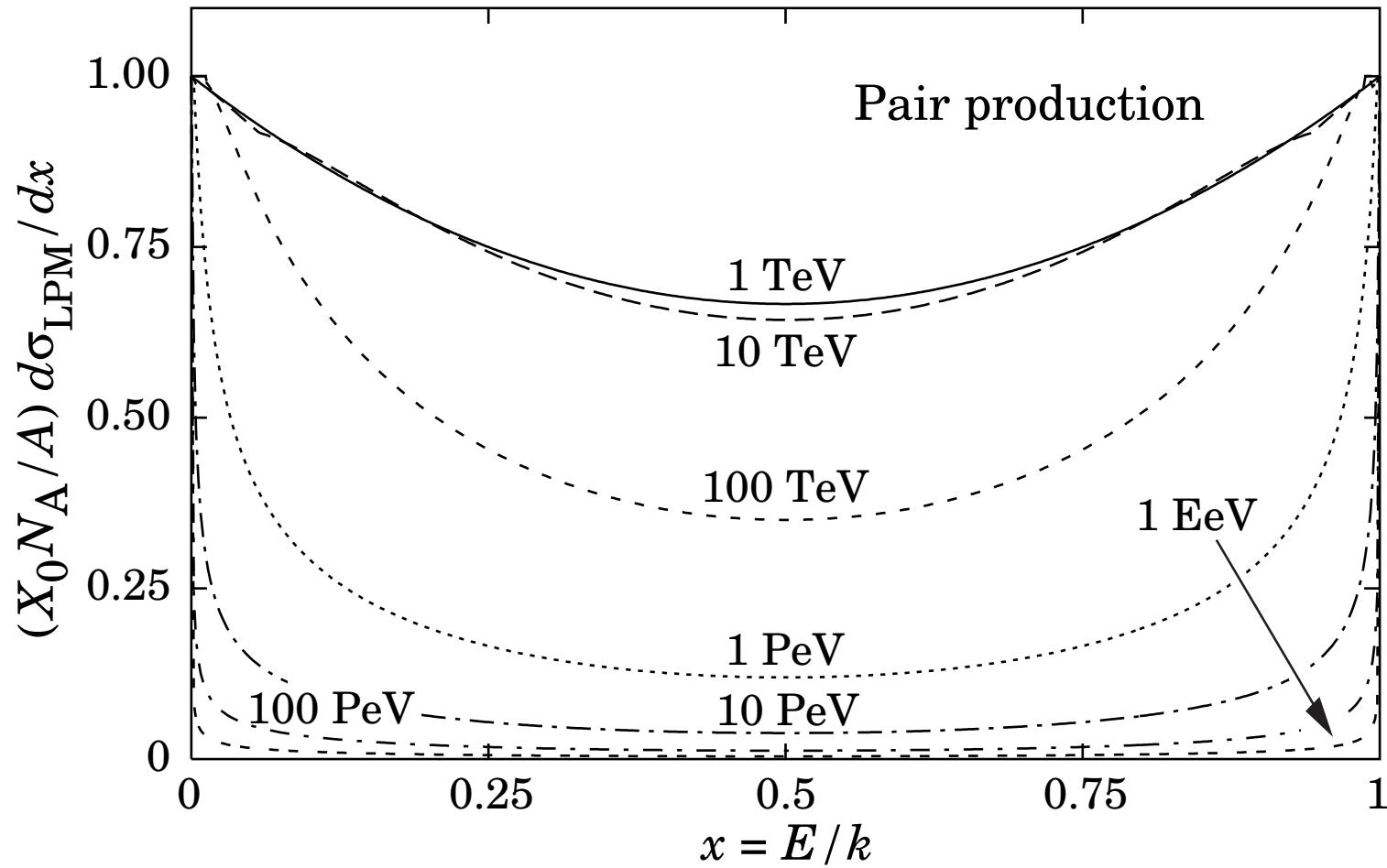
The “Bethe-Heitler” polarized differential cross section used here

- Involves photon **linear** polarization only
- Sums on the polarizations of the final leptons
- Uses the first term of the Born series

To measure the **circular** polarization of the final lepton, 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, II Nuovo Cimento 24\(1962\) 186](#) , [H Kolbenstvedt, H Olsen II Nuovo Cimento A 40 \(1965\) 13](#)

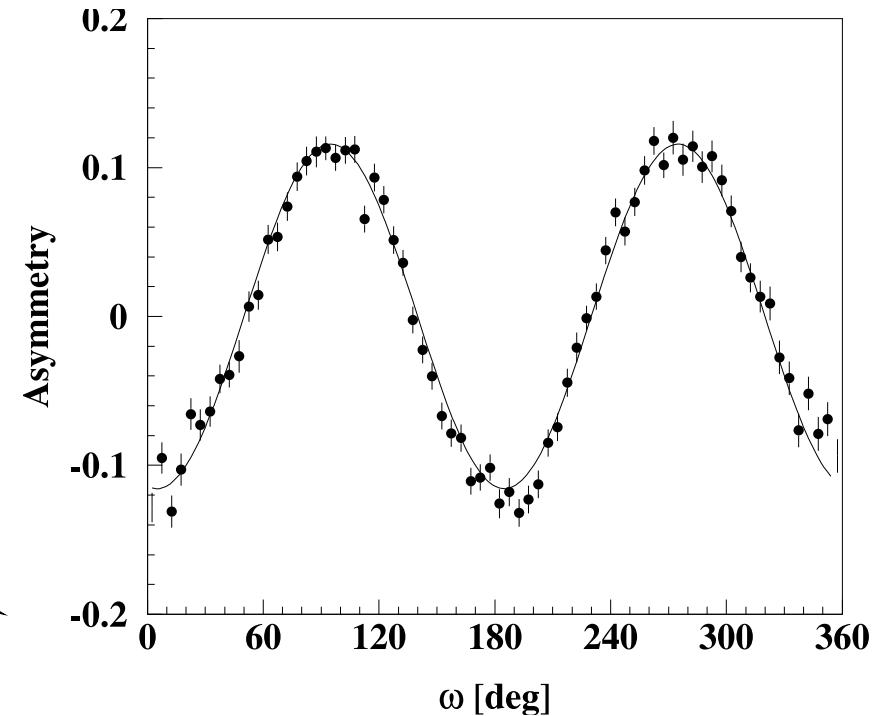
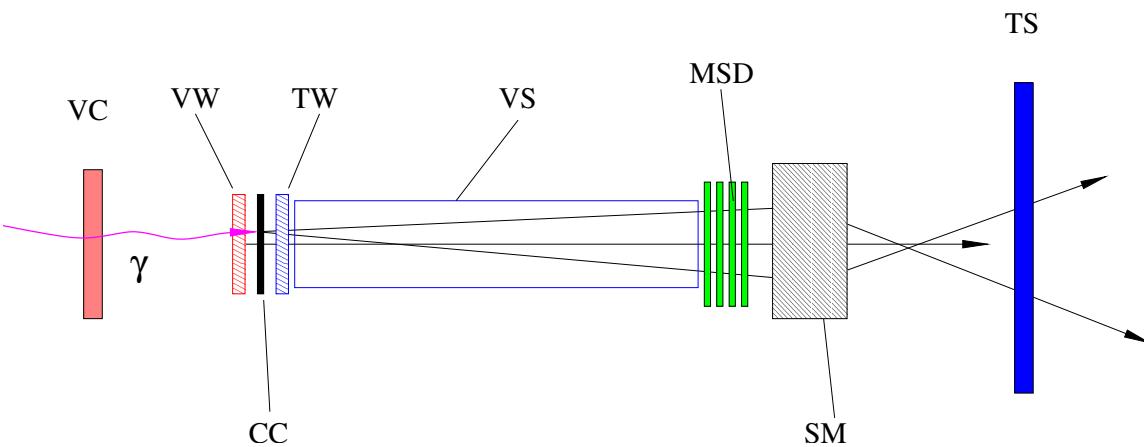
LPM



Landau-Pomeranchuk-Migdal [Review of Particle Physics \(Particle Data Group\)](#)

JLab γ Beam Polarimeter : Tests at LEPS @ SPRing8

- 1.5 – 2.4 GeV γ -ray beam, produced by ICS of linearly polarized 351 nm laser beam on 8 GeV e^- beam.
- 0.1 mm Carbon converter (CC)
- leptons travel away in vacuum straight section (VS)
- silicon micro-strip detectors (MSD) meters downstream.
- 0.02% efficiency

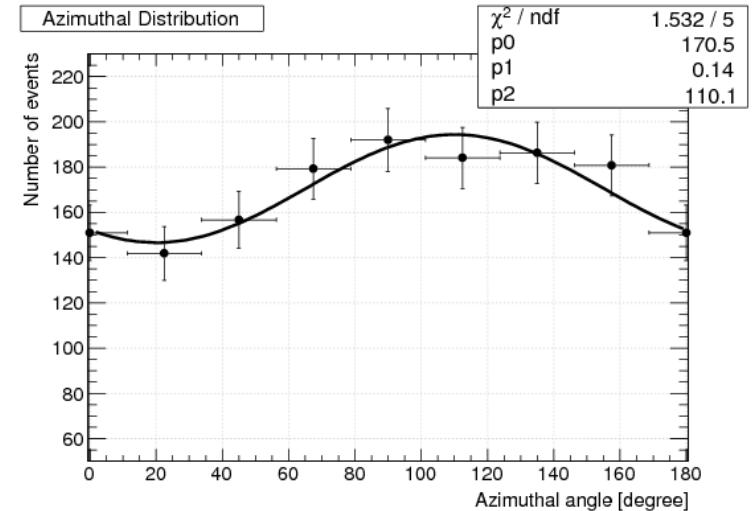
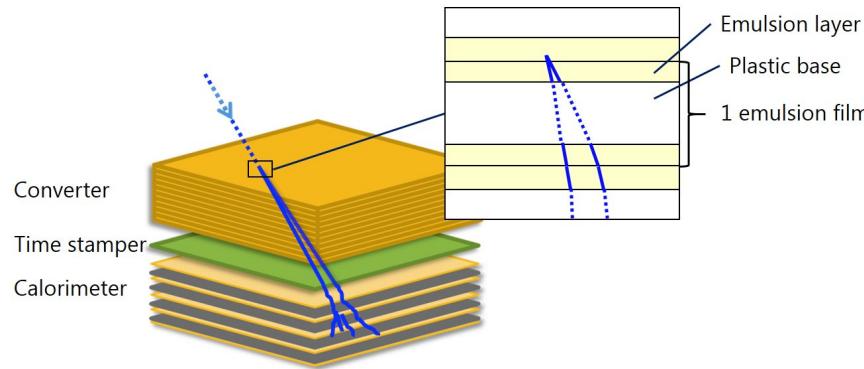


C. de Jager *et al.*, Eur. Phys. J. A 19 (2004) 275.

Emulsions: GRAINE project

(Gamma-Ray Astro-Imager with Nuclear Emulsion)

- Kôbe University - Nagoya University Collaboration



- 2.4 GeV SPring-8/LEPS gamma-ray beam
- Emulsion thickness 200 – 300 μm , bromide crystal size 200 nm; single grain position accuracy 60 nm;
 - $\mathcal{A}_{\text{eff}} \times P = 0.14^{+0.07}_{-0.06}$ measured
 - beam $P = 0.66$ estimated
 - $\mathcal{A}_{\text{eff}} = 0.21^{+0.11}_{-0.09}$ calculated, a 3.06σ non-zero polarization observation

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

Ozaki *et al.*, Nucl. Instrum. Meth. A 833 (2016)165