Gamma ray polarimetry in astrophysics
$\gamma \to e^+e^-$

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TPC 2018,
9th symposium on Large TPCs for low-energy rare event detection
Dec. 2018, Paris

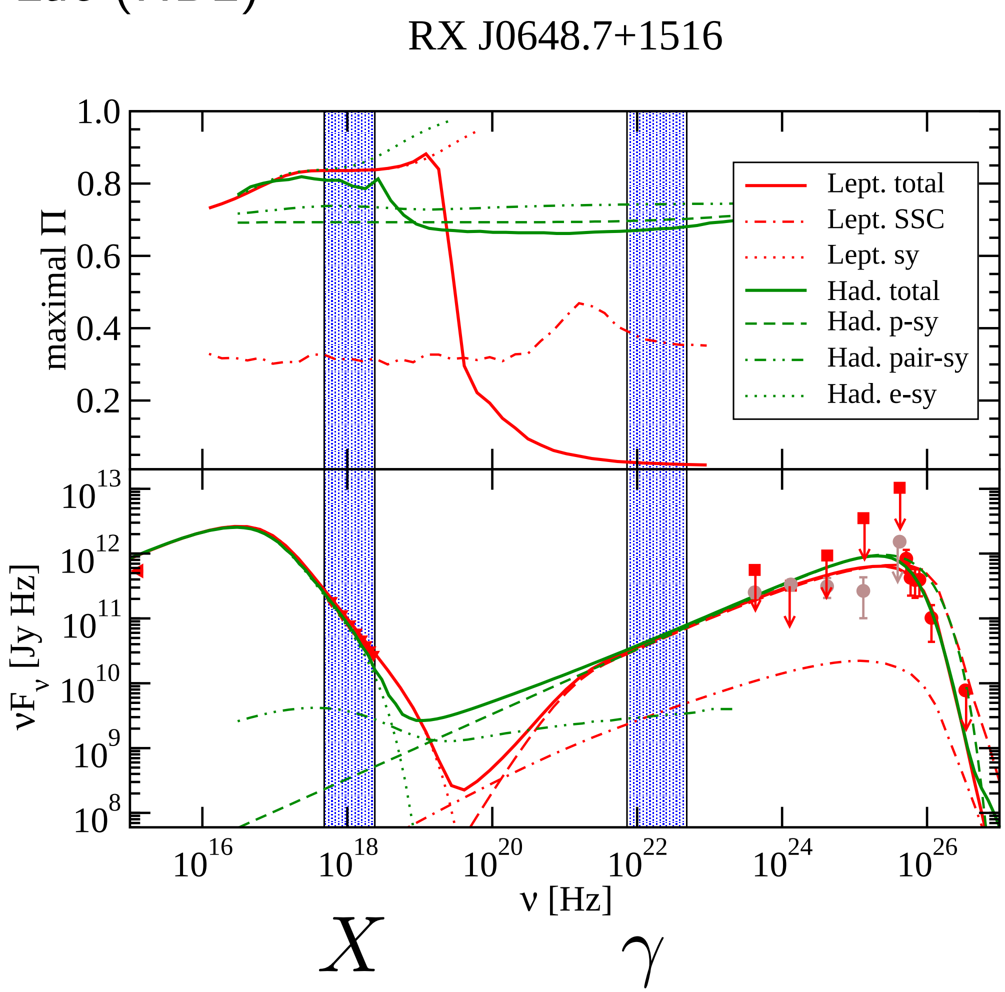
llr.in2p3.fr/∼dbernard/polar/harpo-t-p.html

Talk Lay-out

- Short introduction on the science case
- Polarimetry with $\gamma \to e^+e^-$
- Gas detectors: The "HARPO" (Hermetic ARgon POlarimeter) instrument project
- Emulsions: The GRAINE project
- All-silicon detectors: e-ASTROGAM, AMEGO

Science Case: Polarimetry: Astrophysics

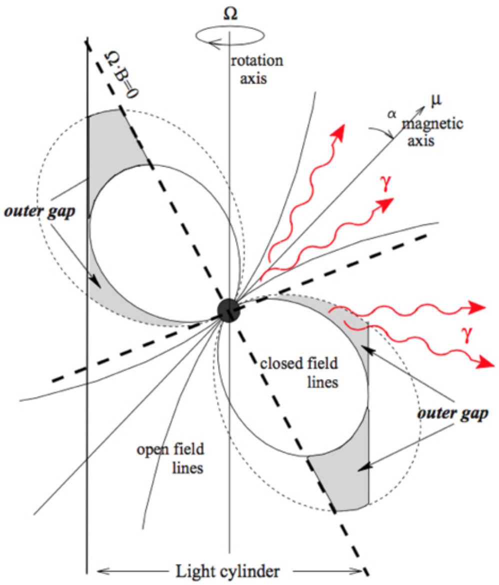
- Blazars: decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models
  - high-frequency-peaked BL Lac (HBL)
  - X band: 2 -10 keV
  - γ band: 30 - 200 MeV

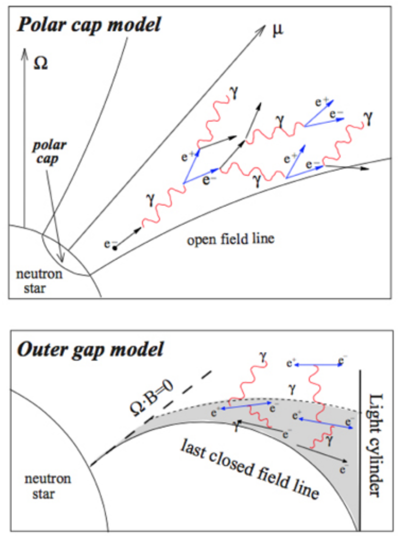


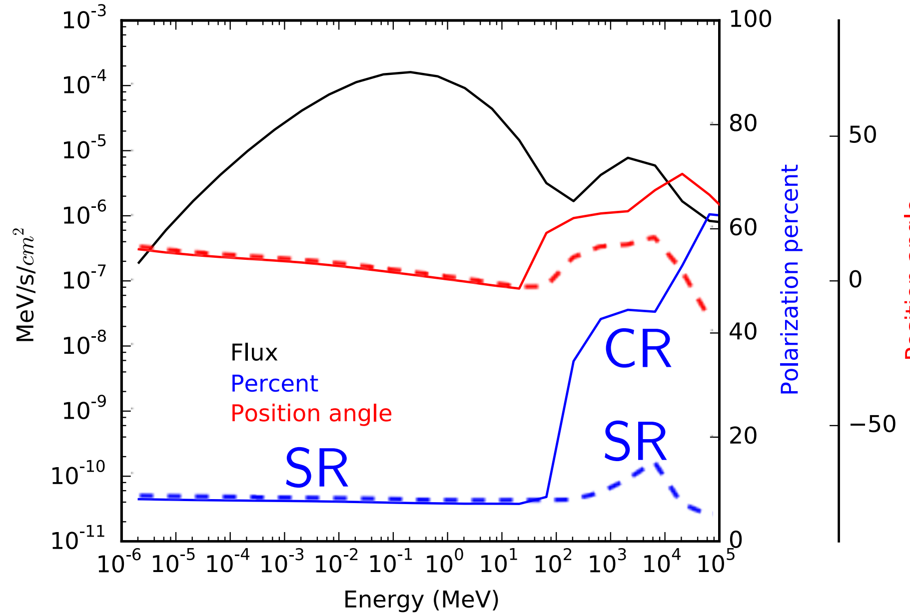
- SED's indistinguishable, but
- X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$
- γ-ray: $P_{\text{lept}} \ll P_{\text{hadr}}$

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".

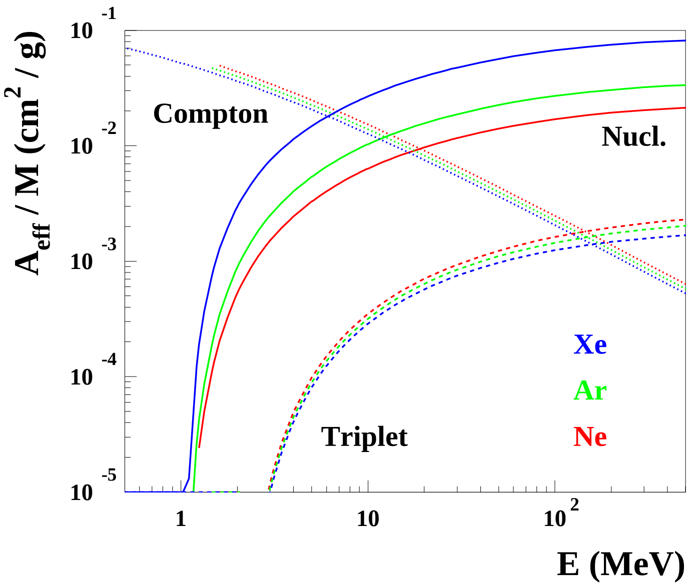
A. K. Harding and C. Kalapotharakos, PoS IFS 2017 (2017) 006, and Astrophys. J. 840 73 (2017)

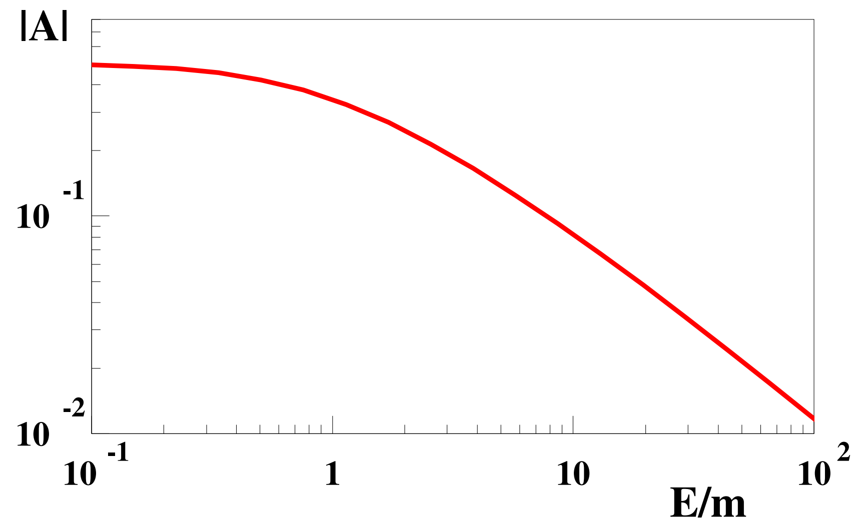
LIV: Search for Lorentz Invariance Violation

- 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: $\Delta t = \xi(k_2 - k_1)D/M$, $\xi \le \mathcal{O}(100)$.
  - birefringence $\Delta\theta = \xi(k_2^2 - k_1^2)D/2M$
    LIV induced birefringence would blurr the linear polarization of GRB emission.
    $\xi \le 3.4 \times 10^{-16}$ with IBIS on Integral (250 – 800 keV)
    D. Götz, *et al.*, MNRAS 431 (2013) 3550
- Bound $\propto 1/k^2$!

Processes, photon energy

- A number of (excellent) Compton polarimeter projects





Photon attenuation   Compton polarization asymmetry

- Sensitive below 1 MeV.

- In this talk, pair creation only.

X-rays: Bragg reflection

- Crab nebula 2.6 keV, $P = 19.5 \pm 2.8\,\%$, OSO 8 graphite crystal polarimeters

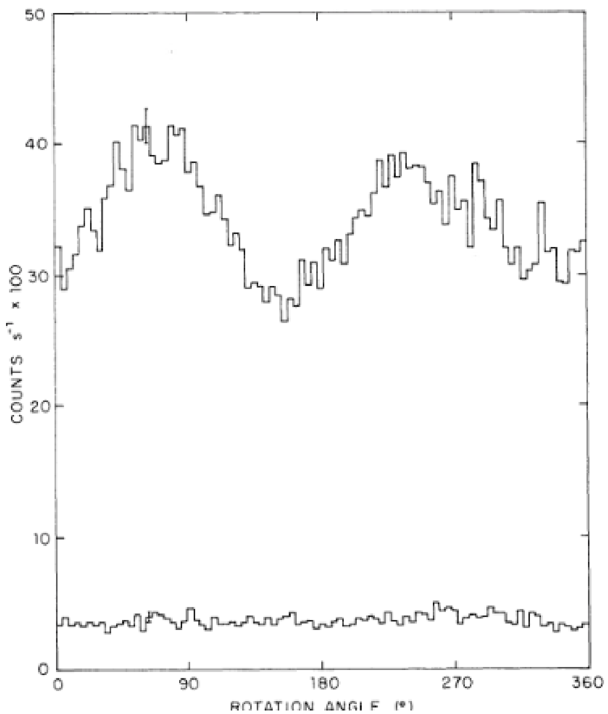


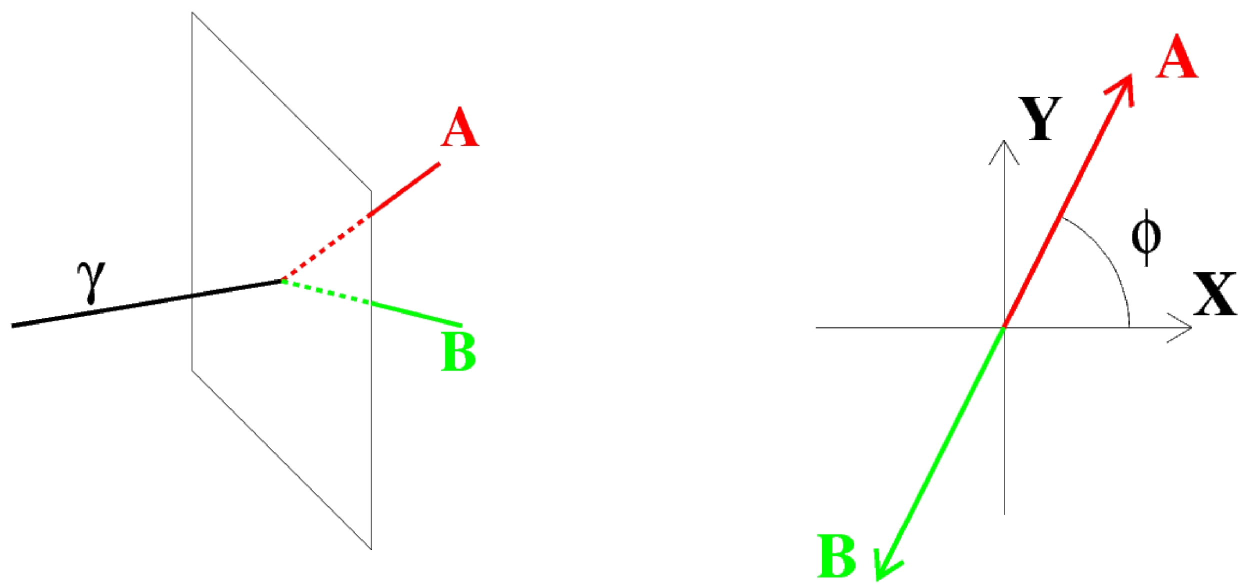
FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (*upper curve*) observations of the Crab Nebula and during (*lower curve*) observations of the Earth-occulted instrumental background.

M. C. Weisskopf *et al.*, "A precision measurement of the X-ray polarization of the Crab Nebula without pulsar contamination", Astrophysical Journal 220 (1978) 117.

Polarimetry

- Modulation of azimuthal angle distribution

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P\cos[2(\phi - \phi_0)]), \qquad \sigma_P \approx \frac{1}{\mathcal{A}}\sqrt{\frac{2}{N}},$$

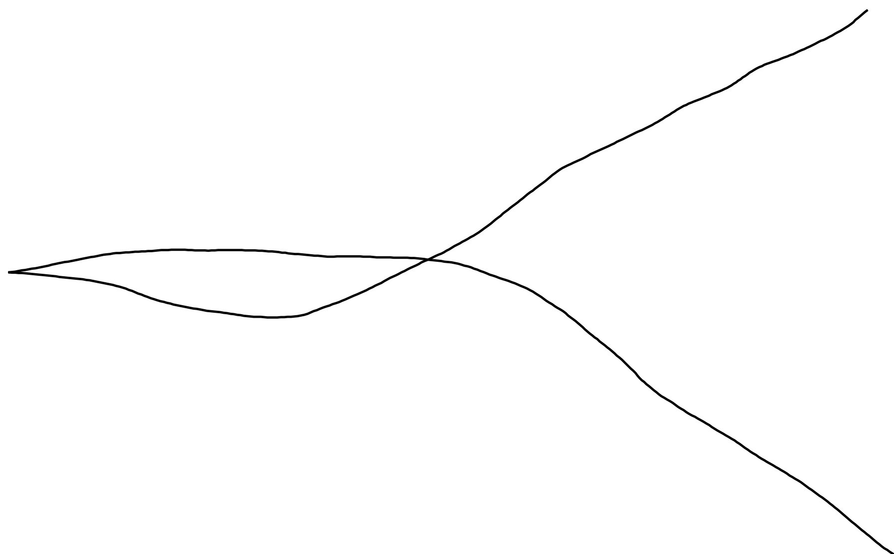


- P source linear polarisation fraction
- $\mathcal{A}$ Polarization asymmetry
- ϕ azimuthal angle

The enemy: multiple scattering

- Data

- MC simulation



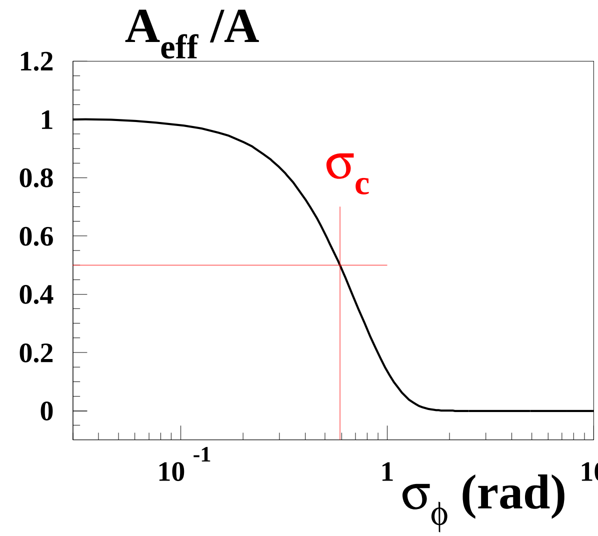
γ-ray conversion in argon, EGS5 simulation

The Glycine effect

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

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

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



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

$\Rightarrow \sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$ (e.g. $\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2$ for $110\,\mu\text{m}$ of Si, $4\,\mu\text{m}$ of W)

- This dilution is energy-independent.

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

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*

- $\sigma_\phi = \dfrac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, azimuthal angle resolution
- $\sigma_{\theta,\text{track}} = (p/p_1)^{-3/4}$, angular resolution due to multiple scattering
  - $p_1 = 13.6\,\text{MeV}/c \left(\dfrac{4\sigma^2 l}{X_0^3}\right)^{1/6}$, Argon ($\sigma = l = 1\text{mm}$): $p_1 = 50\,\text{keV}/c$ (1 bar),

    $p_1 = 1.45\,\text{MeV}/c$ (liquid).
- $\hat{\theta}_{+-} = 1.6\,\text{MeV}/E$ most probable opening angle
- $\sigma_\phi = \left[x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}}\right] \dfrac{(p_1)^{\frac{3}{4}} E^{\frac{1}{4}}}{1.6\,\text{MeV}}$. azimuthal angle resolution
  - x_+ fraction of the energy carried away by the positron,

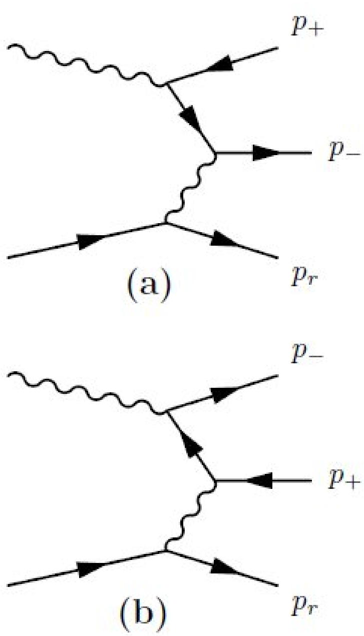
There is hope .. at low p_1 (gas) .. at low energy.

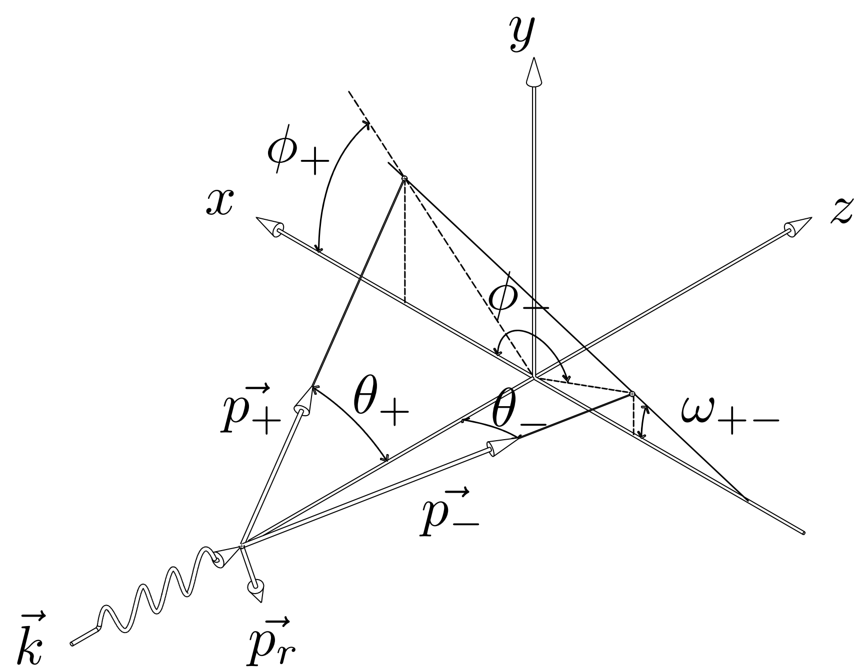
Also need study beyond the most probable opening angle $\theta_{+-} = \hat{\theta}_{+-}$ approximation

D. Bernard, NIM A 729 (2013) 765

Developed, Validated, Event Generator

- Development of a full (5D) exact (down to threshold) polarized evt generator
- Variables: azimuthal (ϕ_+, ϕ_-) and polar (θ_+, θ_-) angles of e^+ and e^-, and $x_+ \equiv E_+/E$





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

D. Bernard, NIM A 729 (2013) 765, P. Gros & D. Bernard, Astroparticle Physics 88 (2017) 60

Evt Generator: One Example of Validation Plot

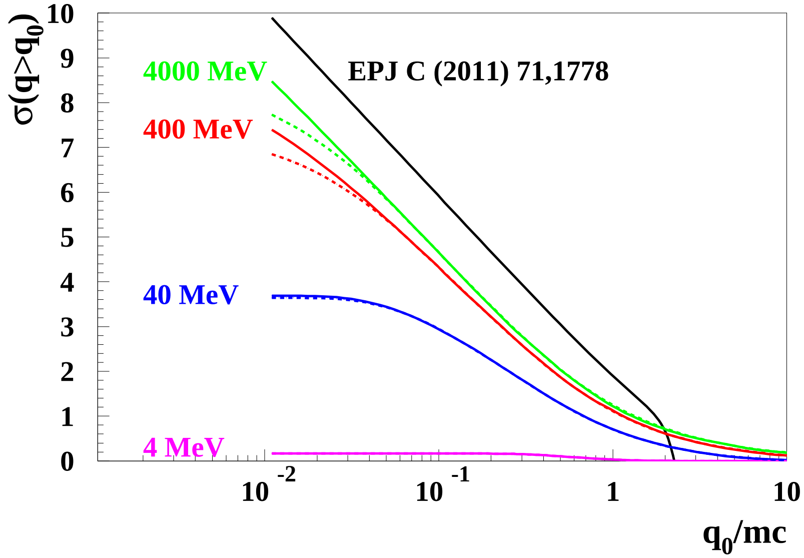
- Triplet conversion: $\gamma e^- \rightarrow e^- e^+ e^-$

  cross section for recoil electron momentum larger than q_0,
  $\sigma(q > q_0)$, as a function of q_0/mc, for various photon energies E;

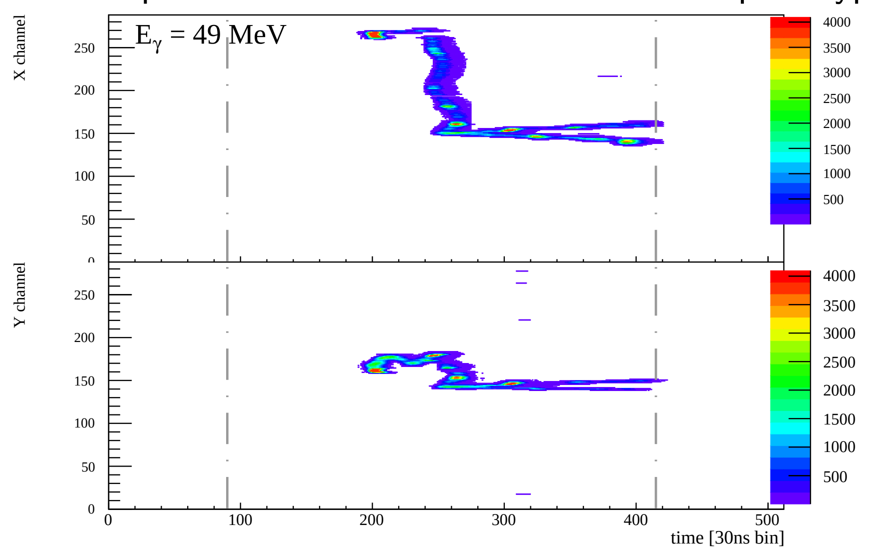
Compared with:

- High photon energy asymptote by M. L. Iparraguirre et al. Eur. Phys. J. C 71, 1778 (2011).

  Dashed curves are with electron screening form factor applied



A triplet conversion event in the HARPO prototype

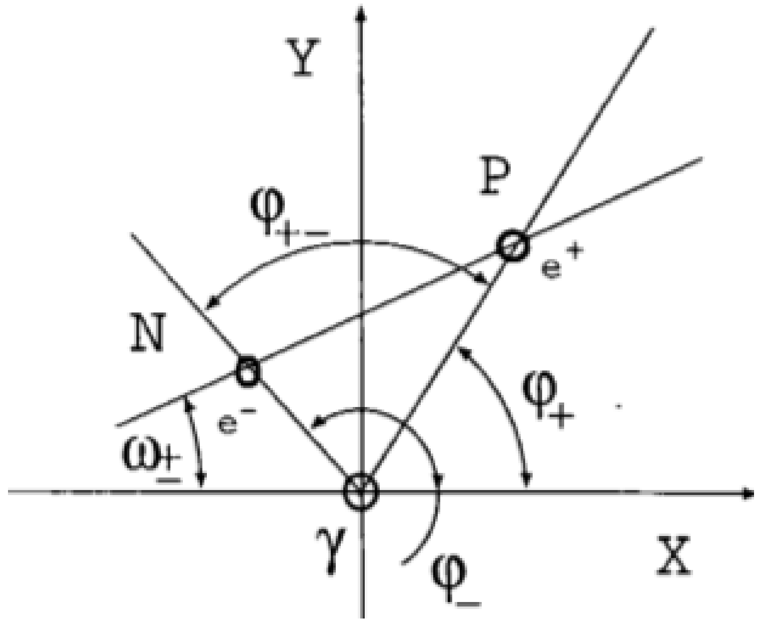


- "recoil" electron at large polar angle. Polarimetry ? Nope. (useful X-section tiny).

  D. Bernard, NIM A 729 (2013) 765

Polarimetry: Defining the Azimuthal Angle ?

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

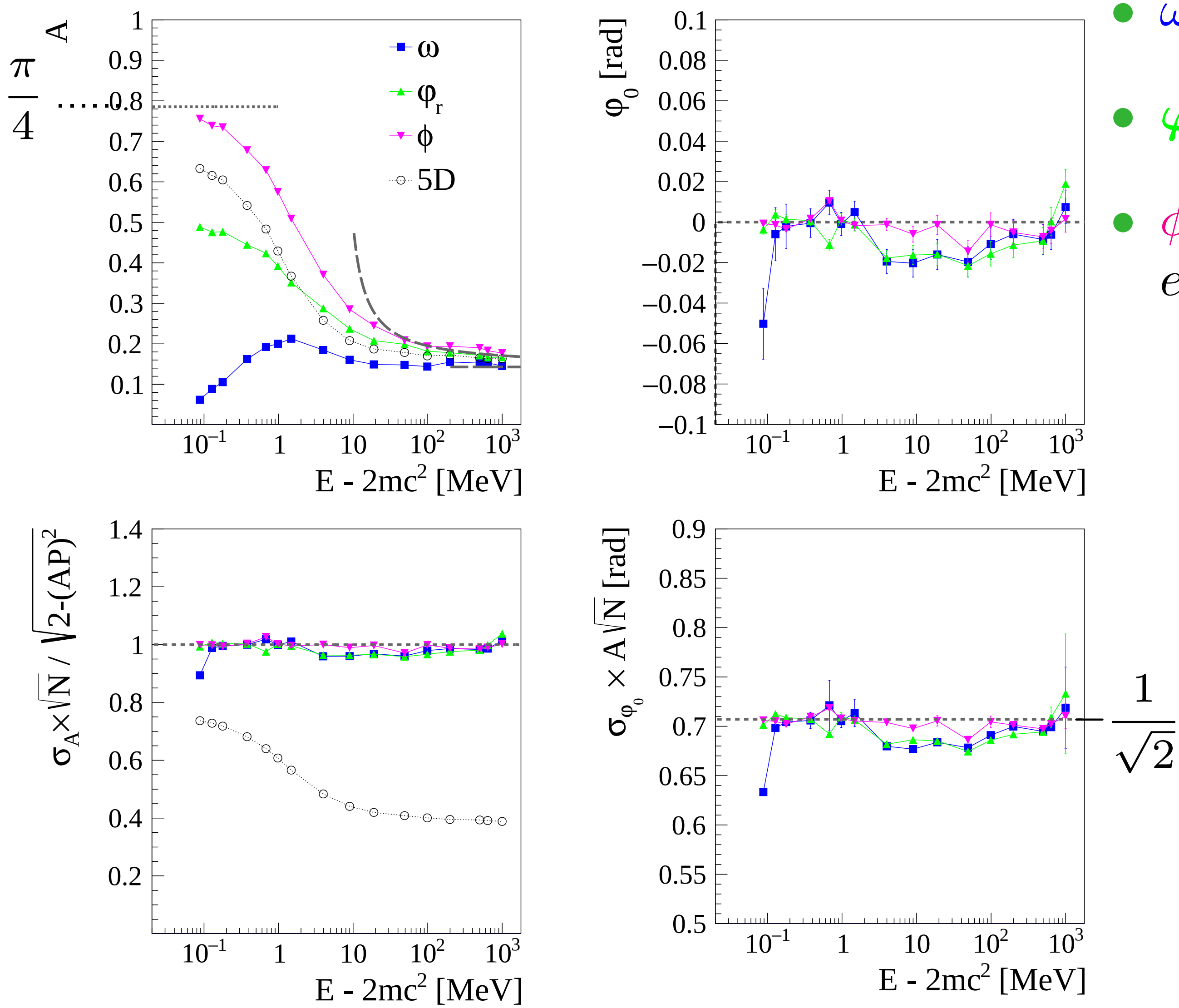


"polarized beams and polarimeters", B. Wojtsekhowski (2000)

- 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 ?

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

loss factor wrt ϕ

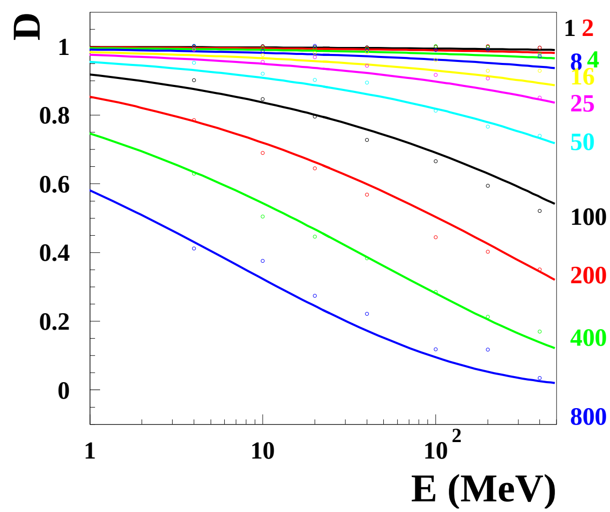
E (MeV)	ω	φ_r or φ_{pair}
10	0.56	0.67
100	0.74	0.94

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

High-energy asymptote from Boldyshev & Peresunko, Yad. Fiz. 14, 1027 (1971).

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

- Remember: track angular resolution $(p/p_1)^{-3/4}$, $p_1 = 13.6\,\mathrm{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$
- $D \equiv \frac{\mathcal{A}_{\text{eff}}(p_1)}{\mathcal{A}(p_1 = 0)}$



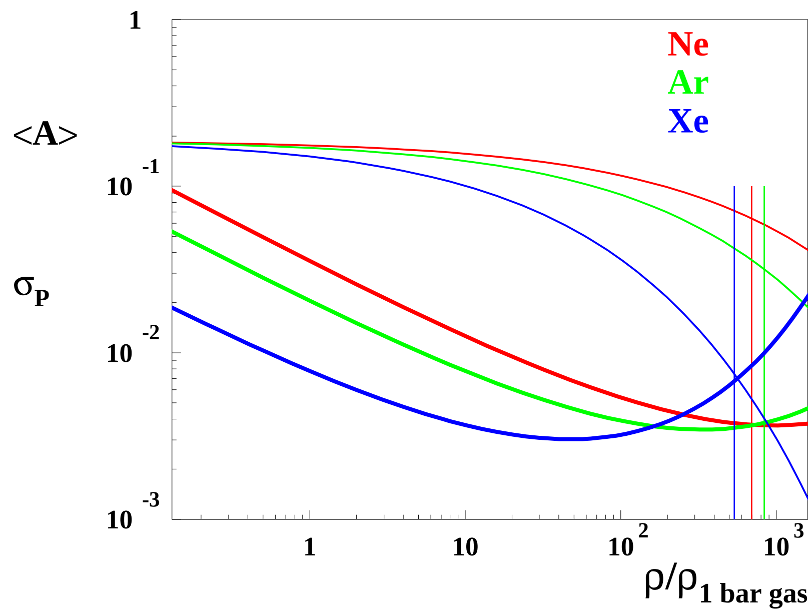
Energy variation of D for various values of $p_1(\mathrm{keV}/c)$

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

D. Bernard, NIM A 729 (2013) 765

Polarimetry Performance

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



- Argon, 5 bar, $\mathcal{A}_{\text{eff}} \approx 15\%$, $\sigma_P \approx 1.0\%$, (no Experimental Cuts)
- $\mathcal{A}_{\text{eff}} \approx 17\%$, $\sigma_P \approx 1.4\%$, (with experimental cuts, $\epsilon = 45\%$)

D. Bernard, NIM 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]
[a]LLR, Ecole Polytechnique and CNRS/IN2P3, France

David Attié, Pascal Baron, David Baudin, Denis Calvet, Paul Colas, Alain Delbart, Ryo Yonamine [b]
[b]IRFU, CEA Saclay, France

Diego Götz [b,c]
[c]AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp, CEA Saclay, France

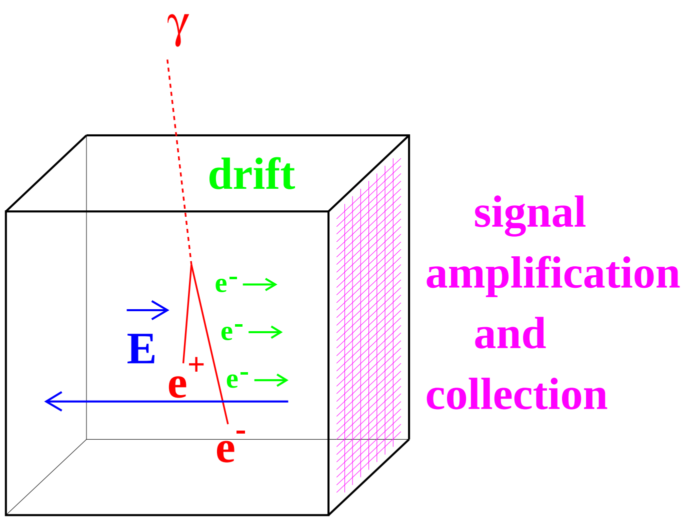
- Japan: the beam.

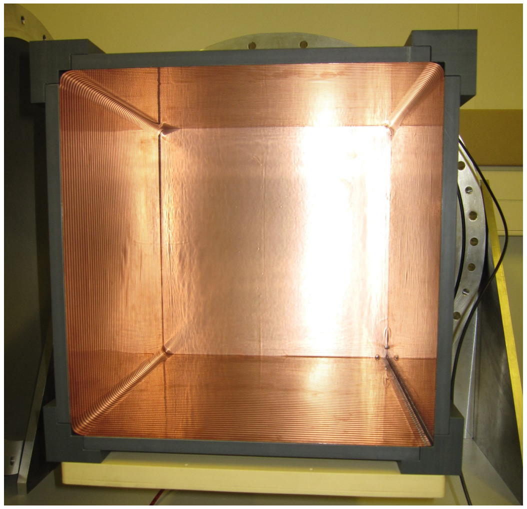
S. Amano, T. Kotaka, S. Hashimoto, Y. Minamiyama, A. Takemoto, M. Yamaguchi, S. Miyamoto[e]
[e] LASTI, University of Hyôgo, Japan

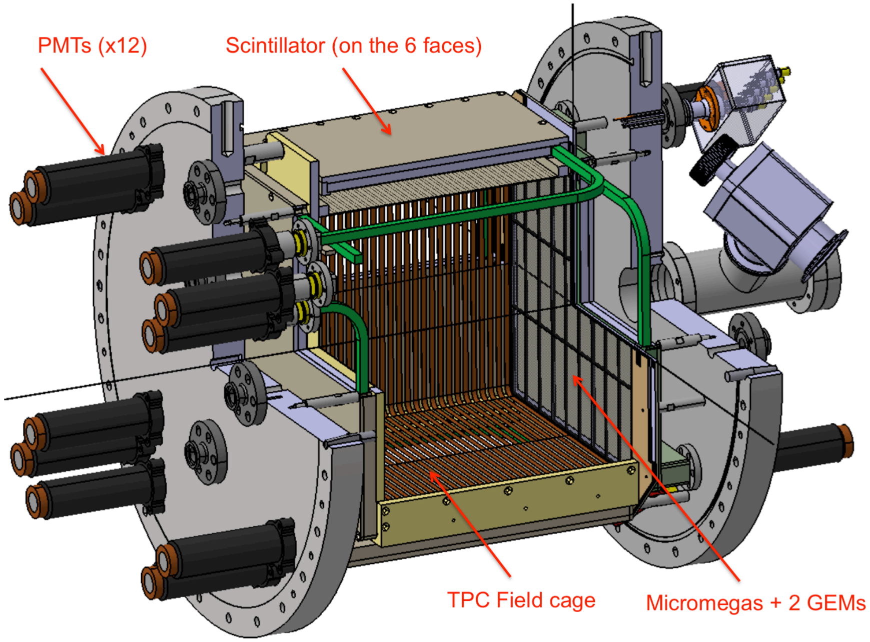
S. Daté, H. Ohkuma[f]
[f] JASRI/SPring8, Japan

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 digitization, up to 100 MHz.
- Scintillator / WLS / PMT based trigger





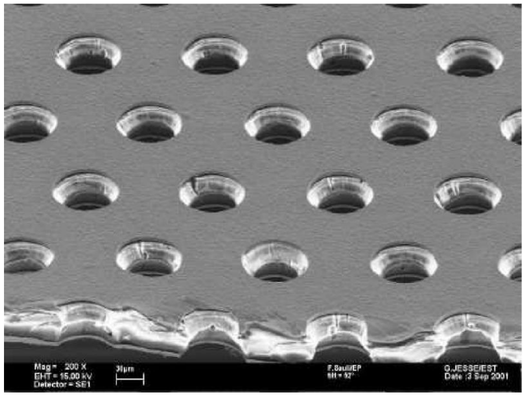


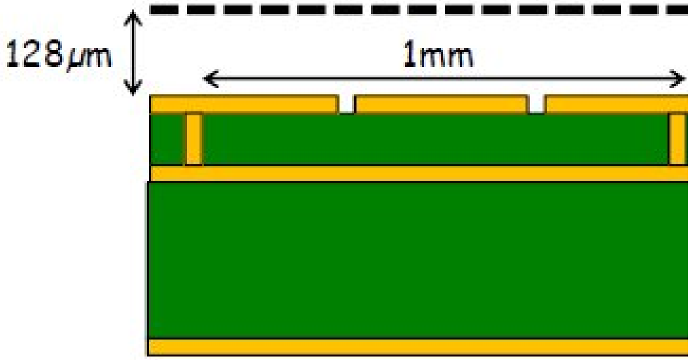
NIM A 695 (2012) 71, NIM A 718 (2013) 395

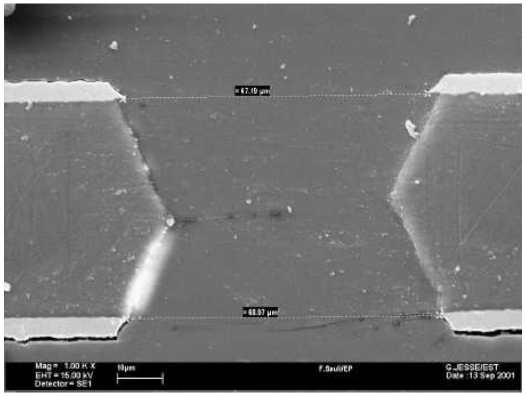
Gas amplification: micromegas + 2 GEM

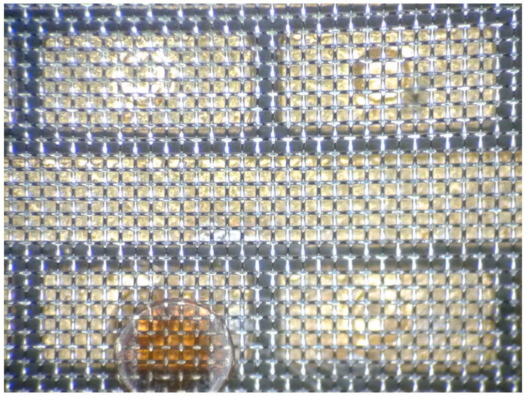
Gas Electron Multiplier
$50\,\mu\mathrm{m}$ Kapton, copper clad,
pitch $140\,\mu\mathrm{m}$, $\Phi 70\,\mu\mathrm{m}$

"bulk" micromegas
gap $128\,\mu\mathrm{m}$







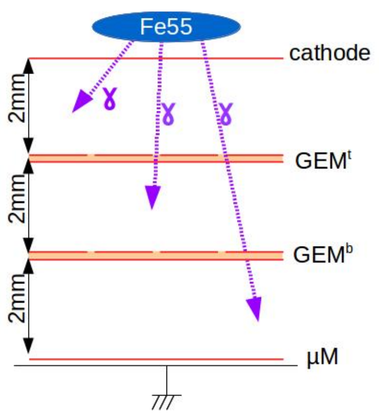


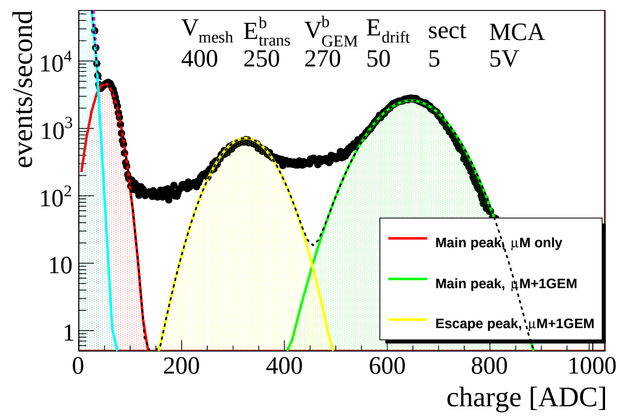
F. Sauli, NIM A 386, 531 (1997)

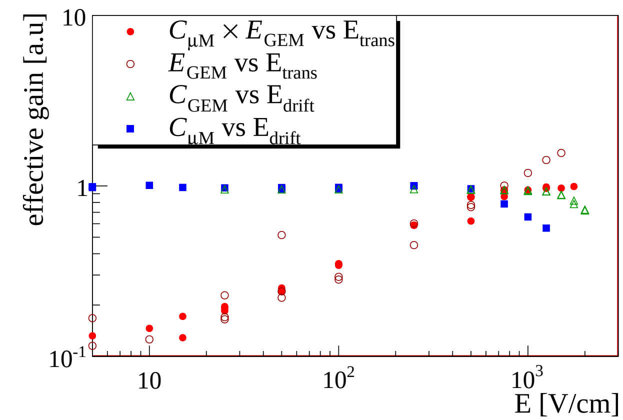
I. Giomataris et al., NIM A 560, 405 (2006)

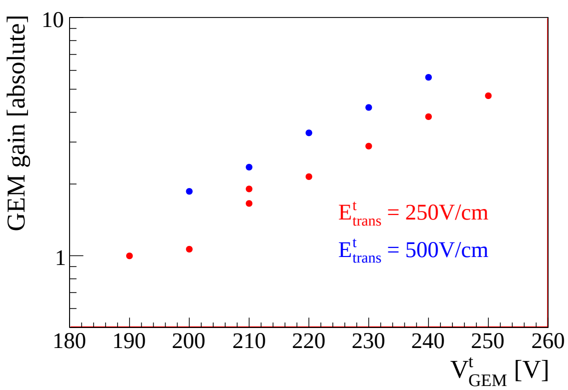
Micromegas + 2 GEM assemblies: characterization

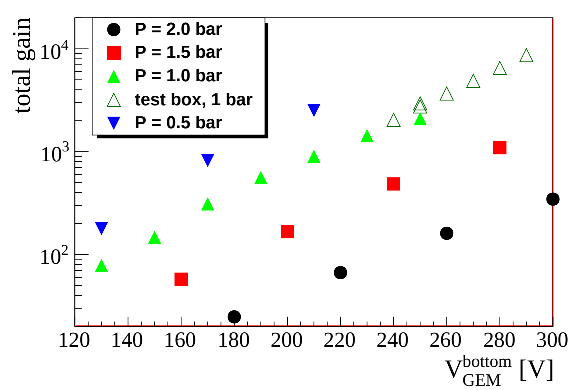
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)







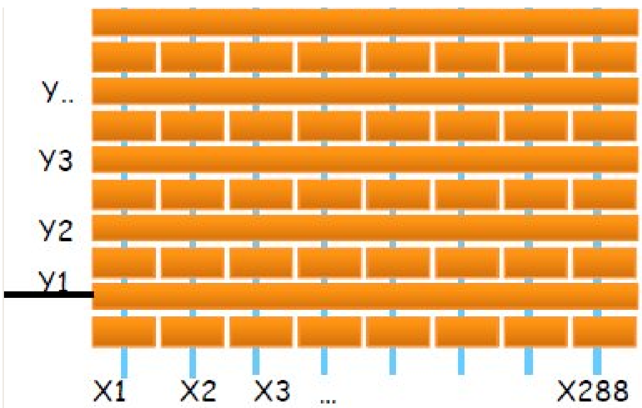


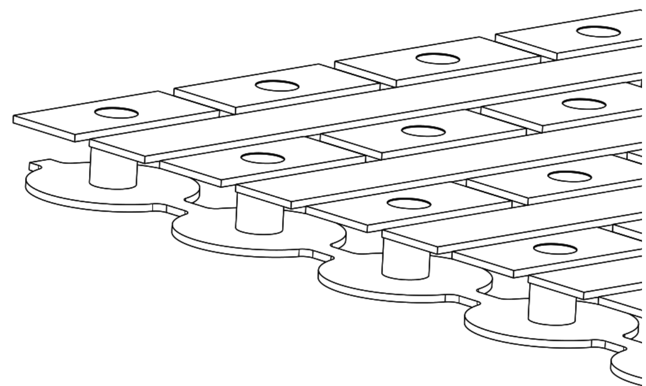


Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

Anode segmentation

- Avalanche electrons collected on a segmented anode.

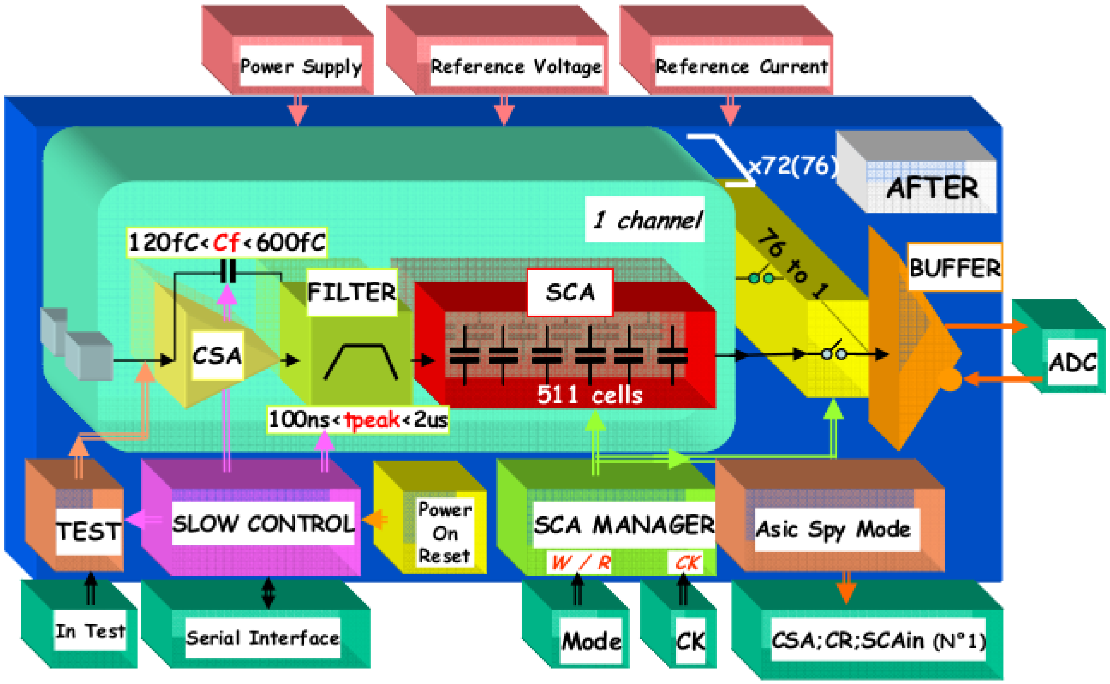




- Cu-clad PCB, strip pitch 1 mm, strip width $\approx 400\,\mu\mathrm{m}$

Signal digitization

- 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 µs
- 12 bit ADC.

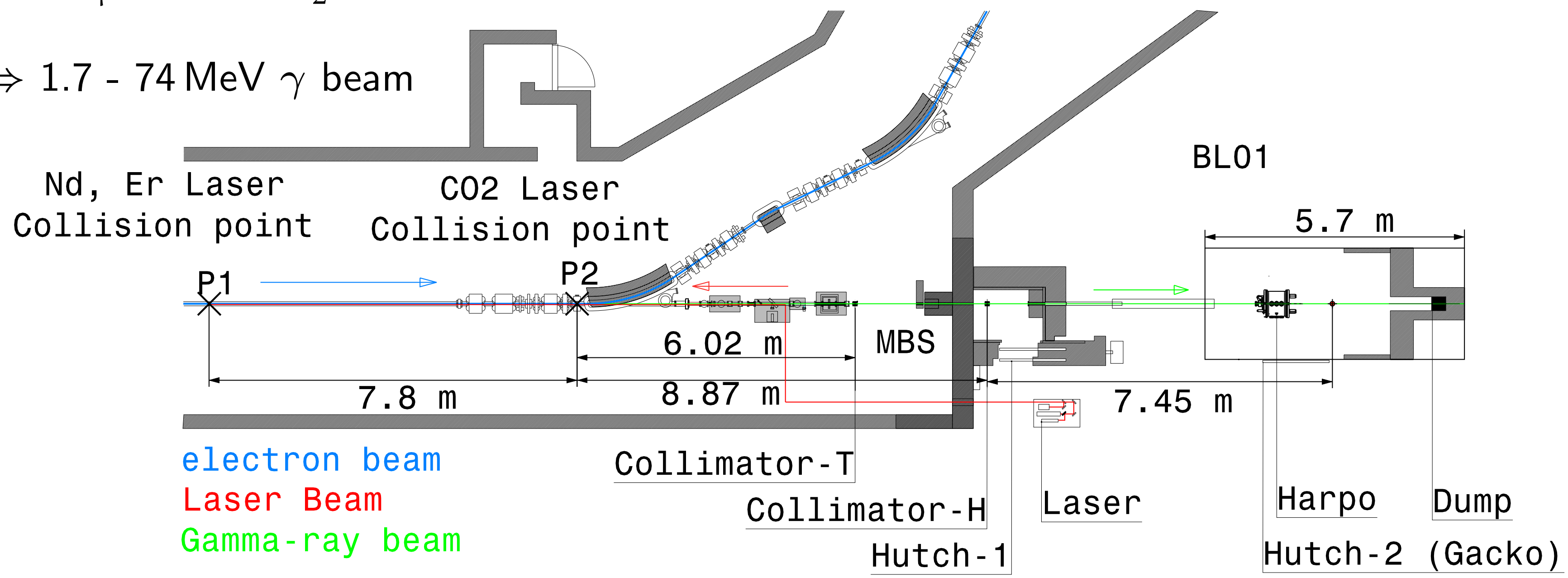


Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

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

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

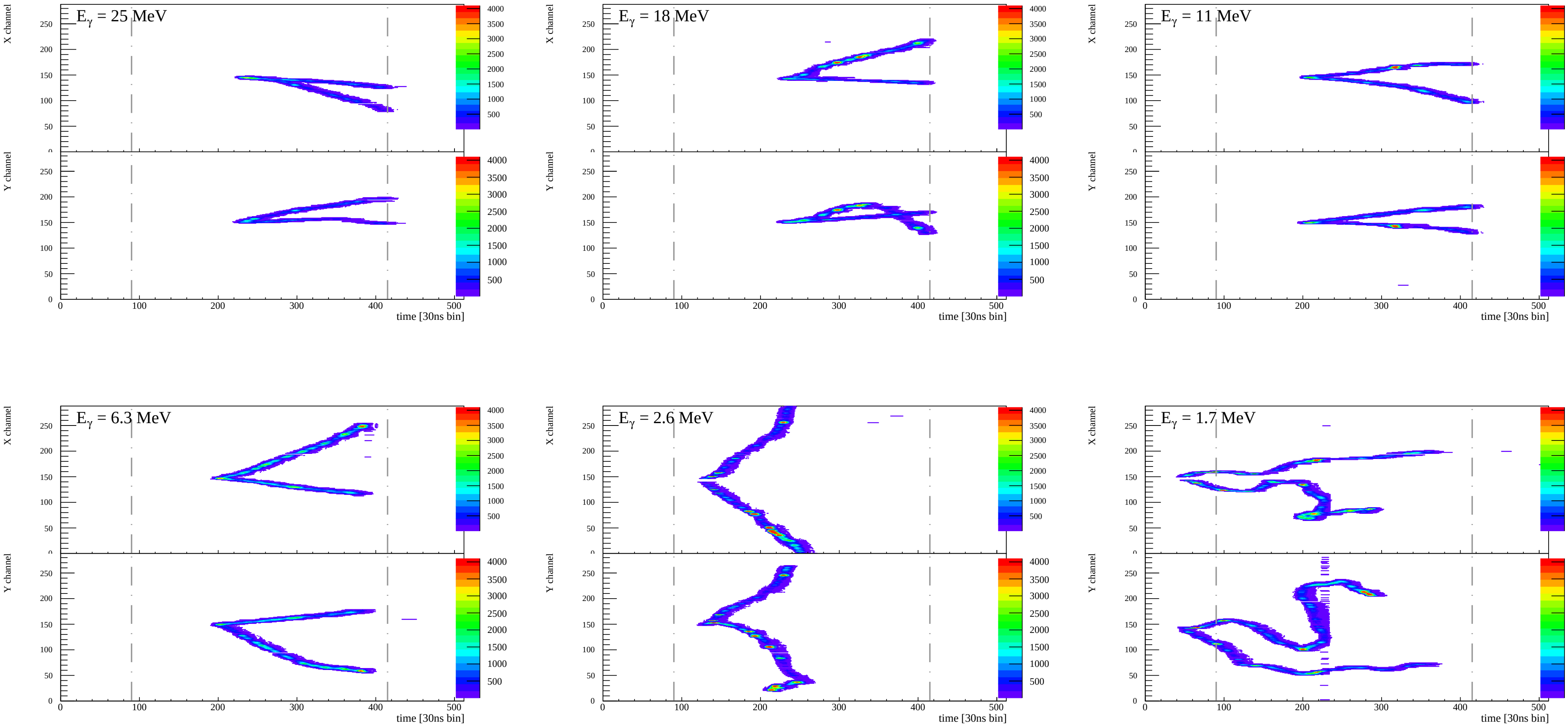
- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- $0.532\,\mu\text{m}$ and $1.064\,\mu\text{m}$ $20\,\text{kHz}$ pulsed Nd:YVO_4 (2ω and 1ω),
  $1.540\,\mu\text{m}$ $200\,\text{kHz}$ pulsed Er (fibre) and
  $10.55\,\mu\text{m}$ CW CO_2 lasers
- $\Rightarrow$ 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:isoC_4H_{10} 95:5 (+ a 1-4 bar scan).

A. Delbart et al., ICRC2015, The Hague, 2015

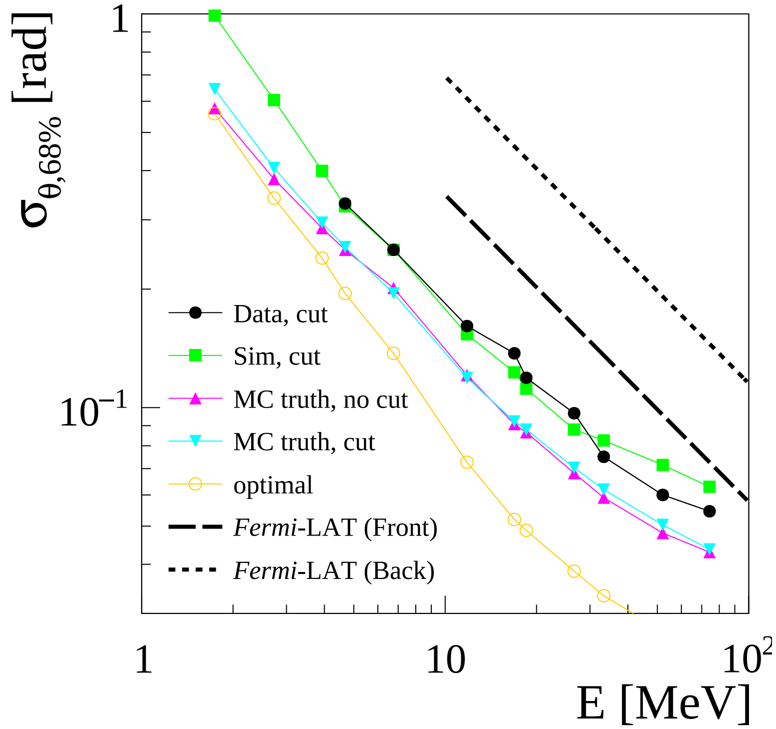
6 events

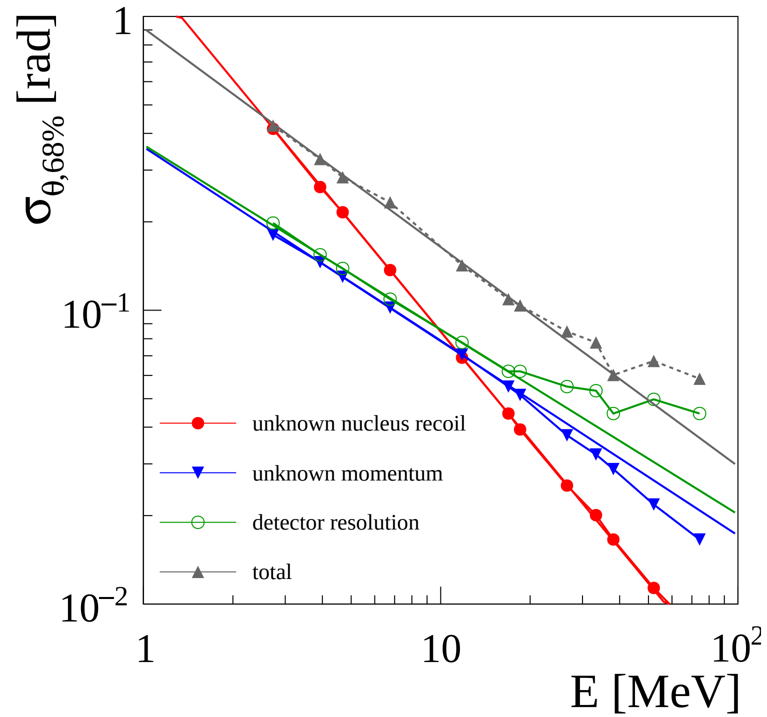


Sample of γ-rays from the BL01 beam line at NewSUBARU (LASTI, Hyôgo Kenritsu Daigaku) converting to e^+e^- in the 2.1 bar Ar:Isobutane 95:5 gas of the HARPO TPC

Ability to image conversions of very low energy γ

Angular resolution

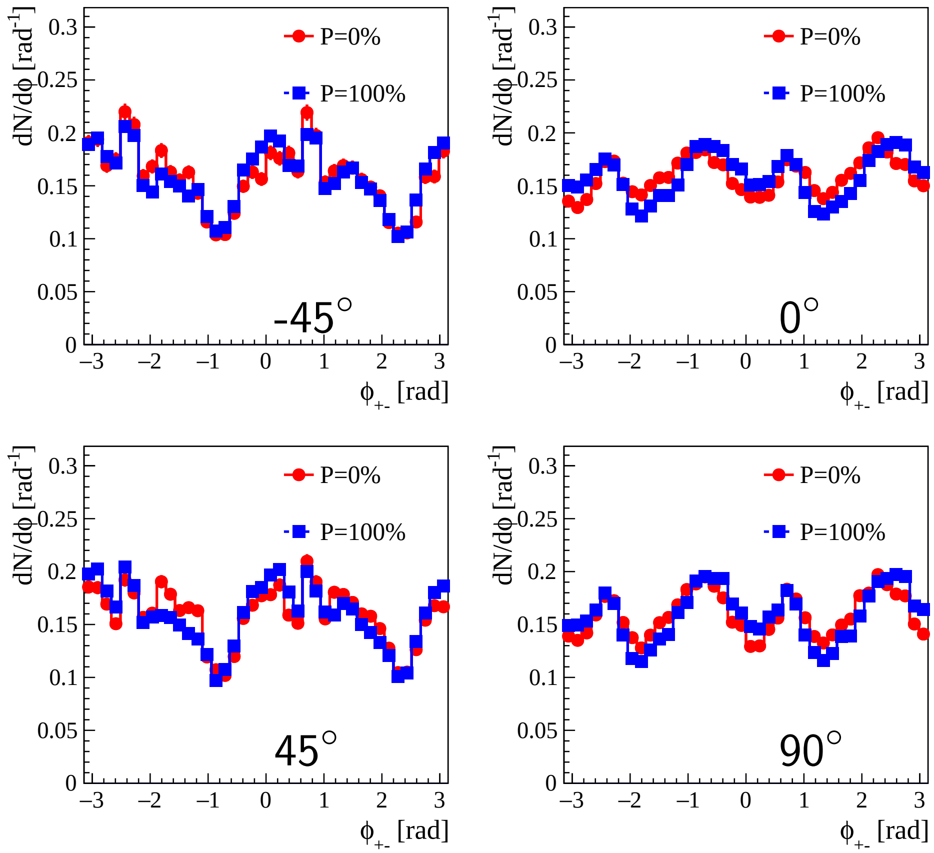




Optimal: QED.

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

Polarimetry

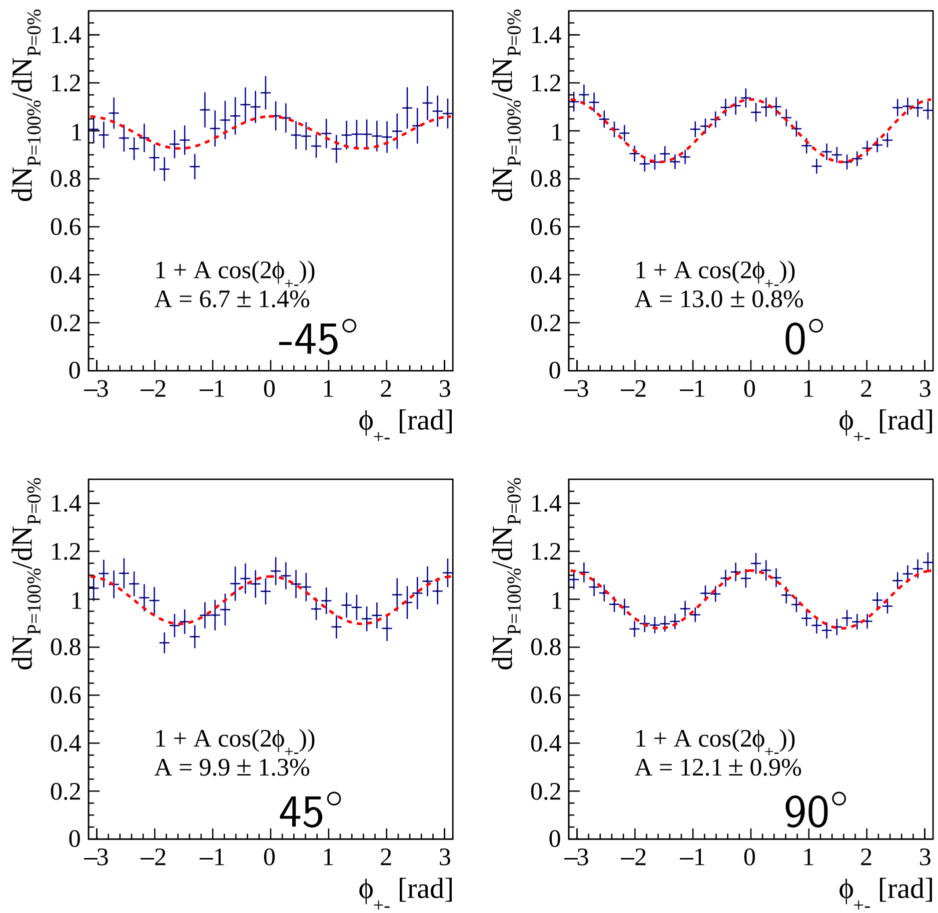


ϕ distributions for four detector orientations (11.8 MeV γ rays in 2.1 bar argon)

- Strong biases lead to non-cosine shape.
- Some difference between $(P = 0)$ and $(P = 1)$ distributions though

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

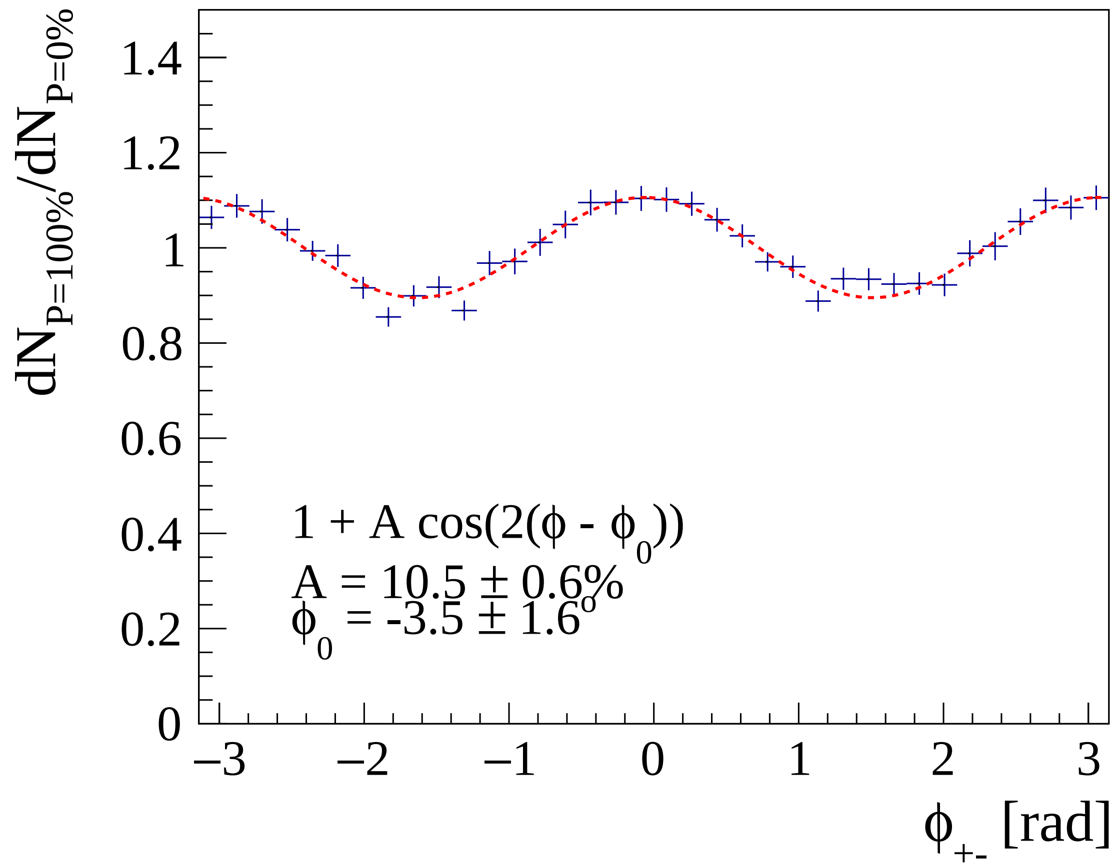
Polarimetry: $(P = 1)/(P = 0)$ *ratios*



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)

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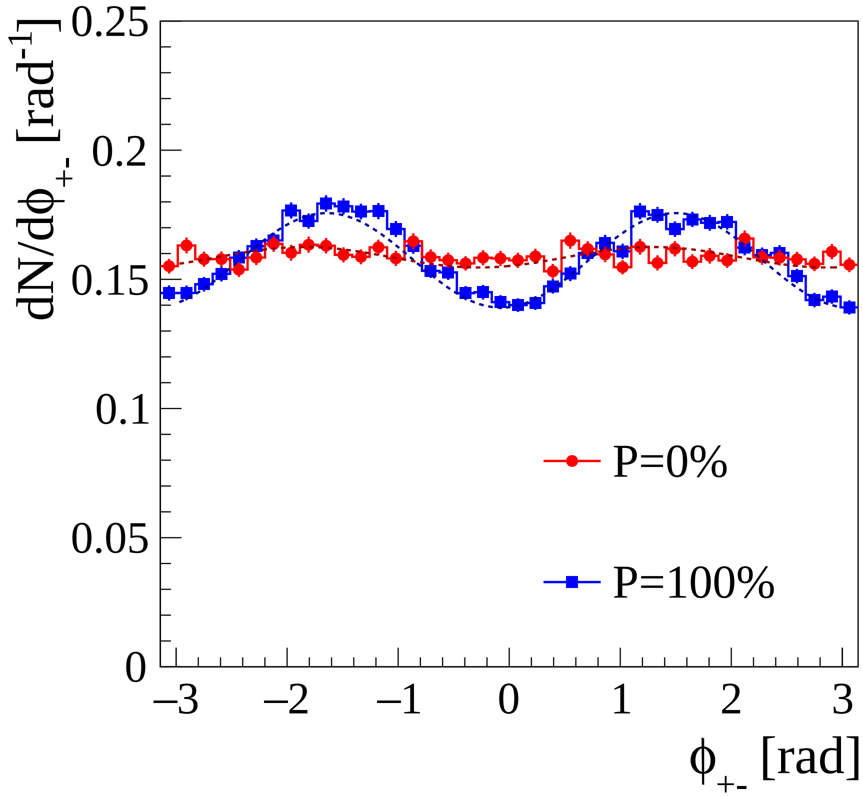
And in space ?

- No non-polarized "candle" cosmic source available ("AGN stacks" though ..)



- In practice isotropic exposure cancels bias to 1rst order

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

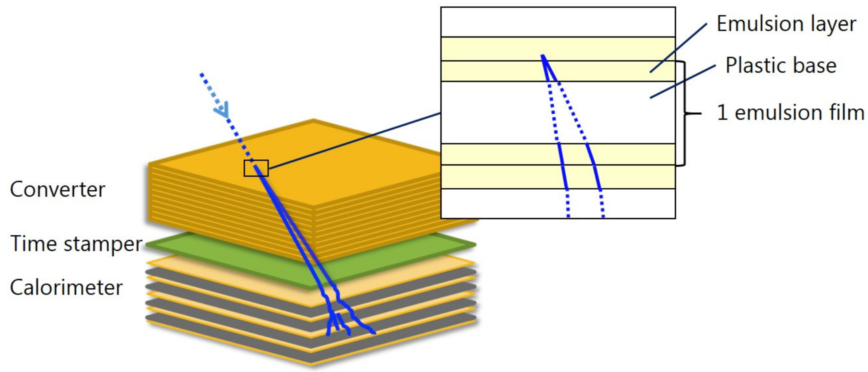
G4BetheHeitler5DModel: Geant4 version of HARPO 5D event generator

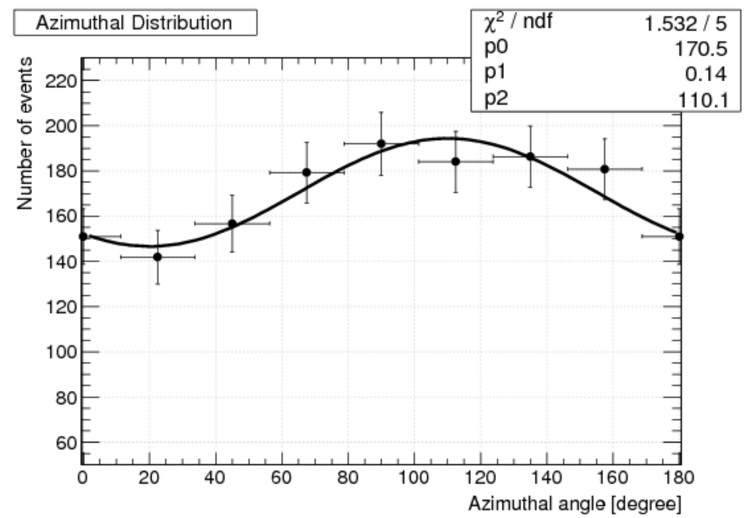
- Samples the full five-dimensional, 1rst order Born, "Bethe-Heitler" differential cross section
- Exact: no approximation (small angle, high energy ..), strictly energy-momentum conserving
- 3D final state: Generates recoil momentum out of photon-pair plane
- (Polarized, non-polarized), (nuclear, triplet), (isolated charge, inside an atom)

- Fortran demonstration model: Nucl. Instrum. Meth., A 899 (2018) 85
- C++ version: I. Semeniouk & D. Bernard 14th Pisa Meeting on advanced detectors, 27 May - 02 June 2018, Elba
- Geant4 10.5 release 7 Dec. 2018

Emulsions: GRAINE project (Gamma-Ray Astro-Imager with Nuclear Emulsion)

- Kôbe University - Nagoya University Collaboration



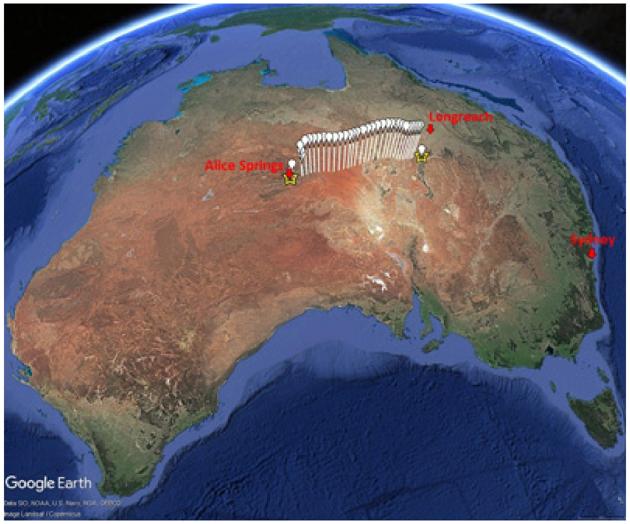


- 2.4 GeV SPring-8/LEPS gamma-ray beam
- Emulsion thickness $200 - 300\mu\mathrm{m}$, bromide crystal size $200\,\mathrm{nm}$; single grain position accuracy $60\,\mathrm{nm}$; S. Takahashi *et al.*, PTEP **2015** (2015) 043H01
  - $\mathcal{A}_{\text{eff}} \times P = 0.14 + 0.07 - 0.06$ measured
  - beam $P = 0.66$ estimated
  - $\mathcal{A}_{\text{eff}} = 0.21 + 0.11 - 0.09$ calculated, a $3.06\,\sigma$ non-zero polarization observation

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

GRAINE balloon test flight

- Goal: see the Vela pulsar gamma-ray emission
- JAXA balloon flight on 26 April 2018, altitude 38 km
- 7 hours of data taken within the Vela pulsar window



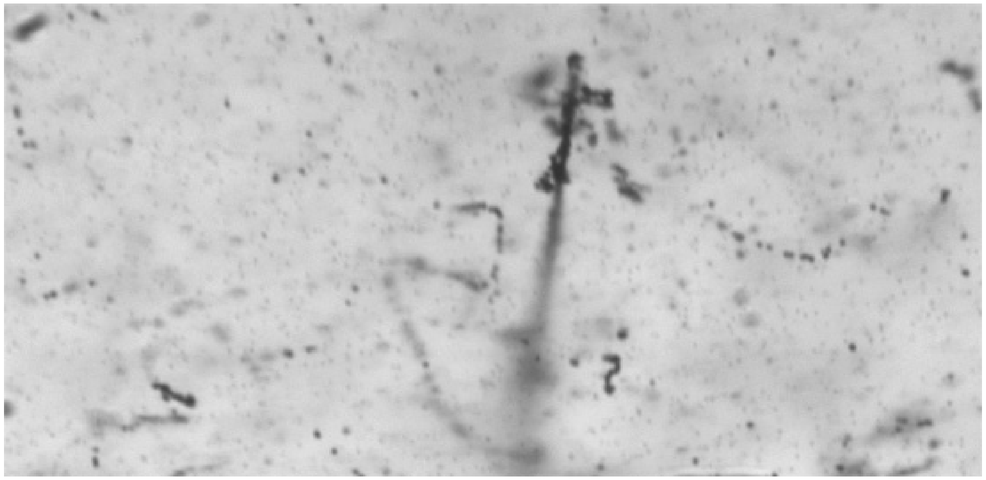


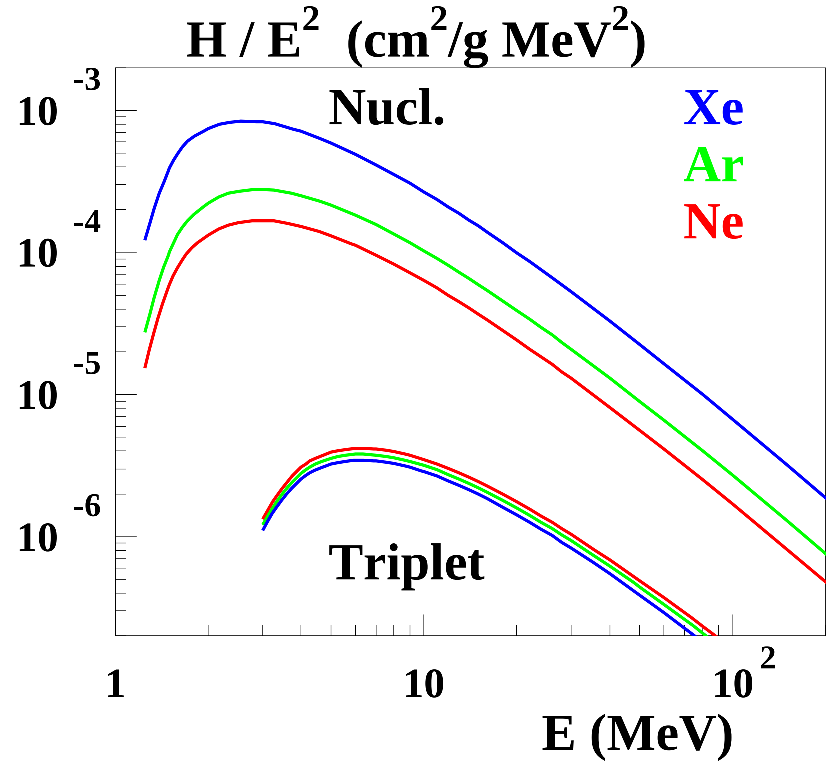
image width $\approx 100\,\mu\mathrm{m}$

- Stay tuned ..

“Balloon-borne telescope looks for cosmic gamma rays”, http://www.kobe-u.ac.jp/ August 8, 2018

Polarimetry with emulsions

- Sub-micron single-track single-point measurement $\Rightarrow$ excellent polarisation asymmetry



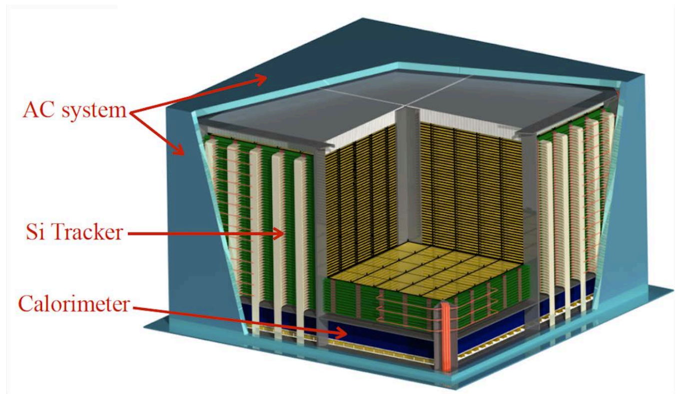
Photon attenuation $\times$ $1/E^2$ typical cosmic source spectrum.

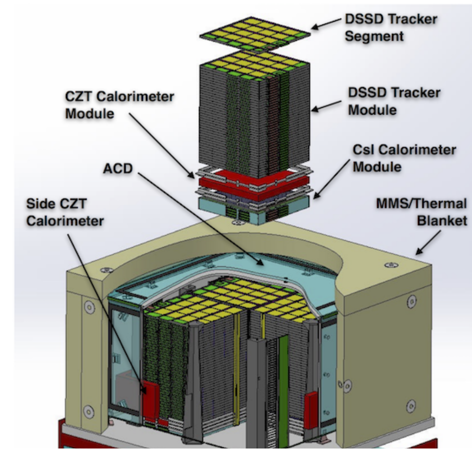
- Main issue, the ability to collect data at low energy (50 MeV, says S. Takahashi *et al.*, PTEP **2015** (2015) 043H01)

Silicon stack detector projects

- Extend *Fermi*-LAT below 100 MeV (pair conversions)
- Extend COMPTEL to a 1/10 - 1/30 sensitivty (Compton up to 30 MeV)
- Complement COMPTEL to Polarimetry (Compton, up to few MeV)
- Polarimetry with pairs never demonstrated

- AC, ACD Anti-Coincidence Detector
- DSSD double-sided silicon detector
- CZT calorimeter
- CsI(Tl) Cesium-Iodide calorimeter

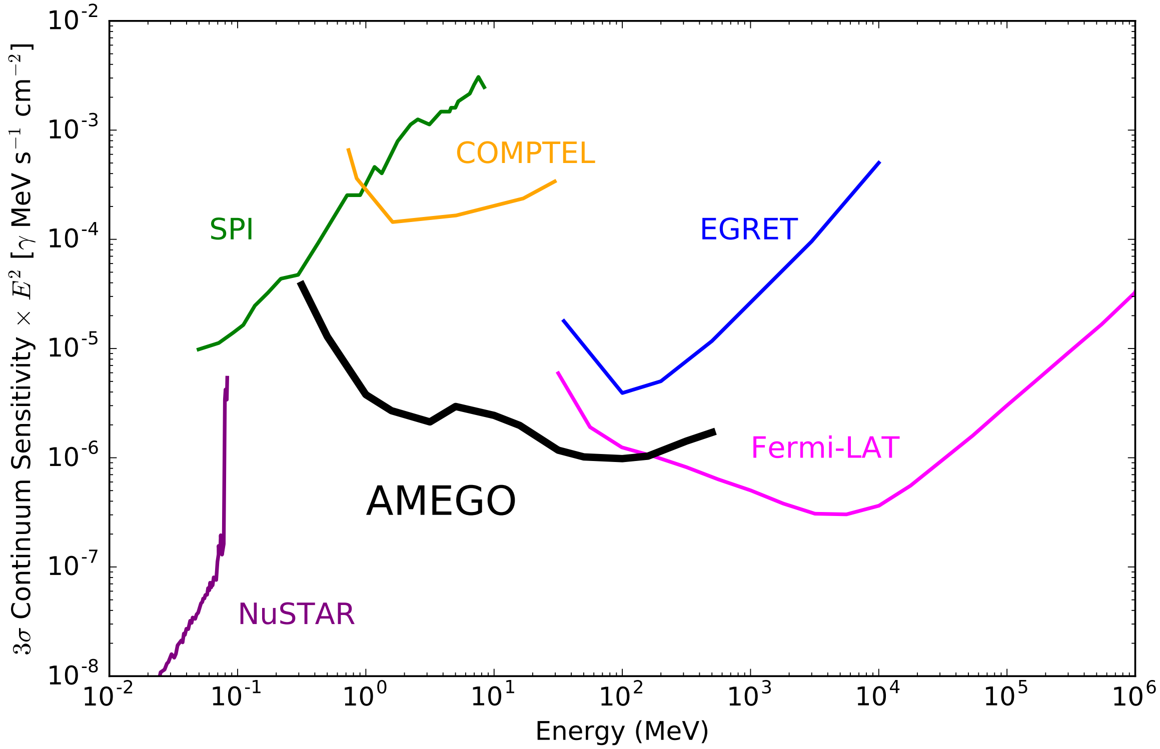




		e-ASTROGAM	AMEGO	
Reading		DSSD	DSSD	
Wafer thickness	t	500		μm
Layers	N	56	60	
Distance	D	10	10	mm
Strip pitch	p	0.24	0.50	mm
Aspect ratio	D/p	42	20	
		A. De Angelis *et al.*, JHEAp 19 (2018) 1	A. Moiseev *et al.*, PoS ICRC2017 (2018) 798	

Silicon stack detectors: Sensitivity

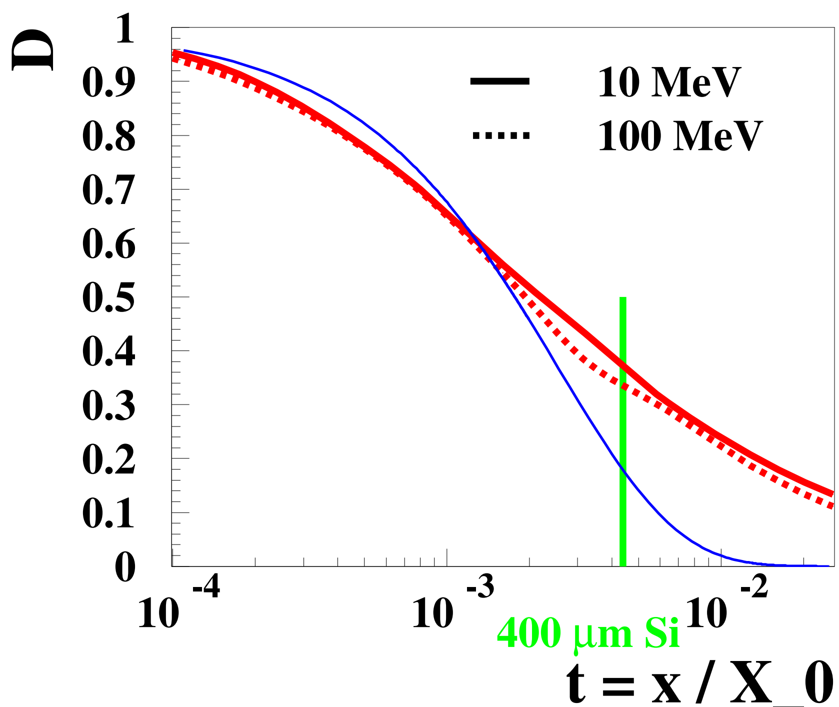
- 3 σ, 3 year, 20 % efficiency, limit detectable flux for a point-like source.



A. Moiseev *et al.*, PoS ICRC2017 (2018) 798

Silicon stack detectors: polarimetry ? 1

- Multiple scattering in the conversion wafer.



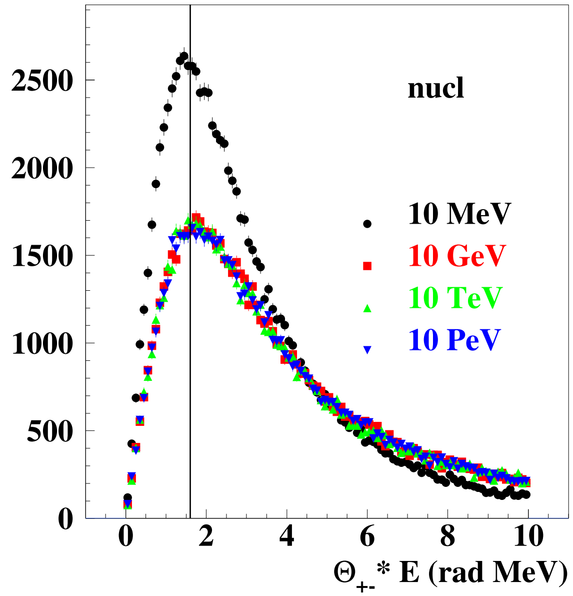
Full (5D) simulation of the dilution of the polarization asymmetry as a function of wafer thickness normalized to converter radiation length

Thin line is Kotov's E-independent, $\hat{\theta}_{+-}$-based approximation.

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

Silicon stack detectors: polarimetry ? 2

- Ability to measure the azimutal angle in the 2nd wafer ?
- Pair opening angle distribution scales like $1/E$



Distributions of the product of the pair opening angle and of the photon energy, $\theta_{+-} \times E$

D. Bernard, NIM A 899 (2018) 85

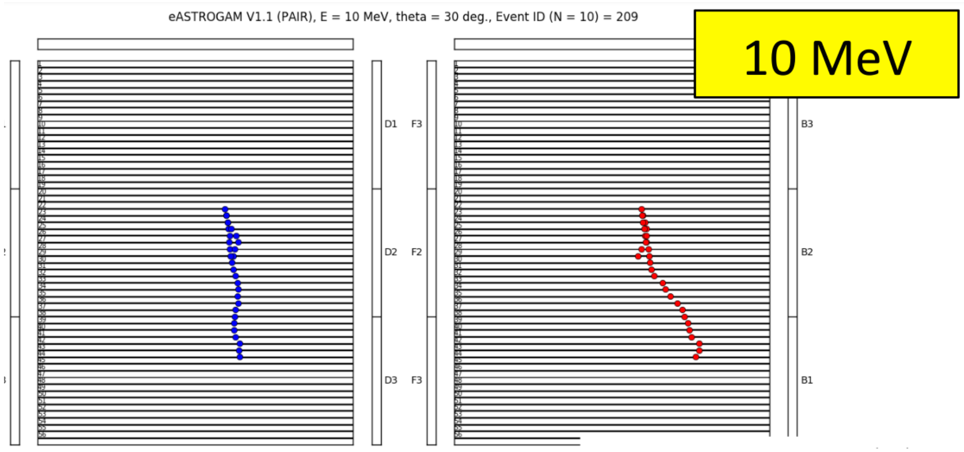
Most probable value $\hat{\theta}_{+-} = 1.6\,\mathrm{MeV}\cdot\mathrm{rad}/E$

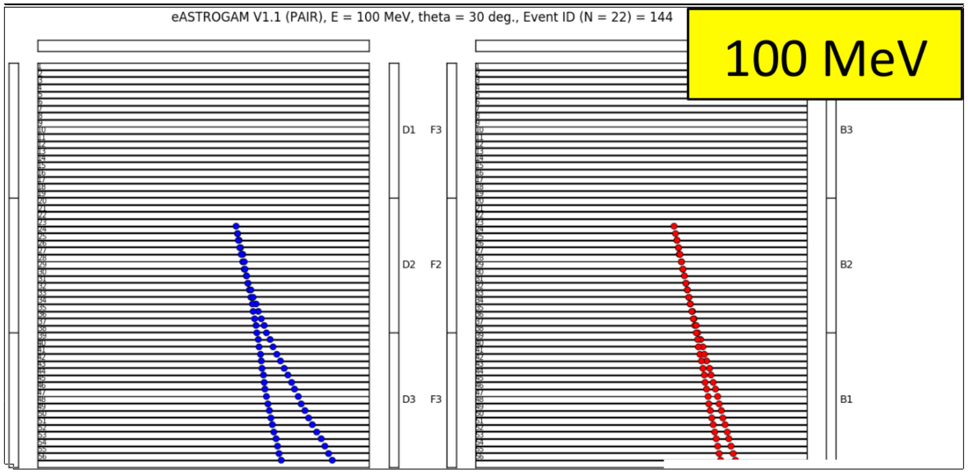
Olsen, PR. 131, 406 (1963).

		e-ASTROGAM	AMEGO	
Reading		DSSD	DSSD	
Distance	D	10	10	mm
Strip pitch	p	0.24	0.50	mm
Aspect ratio	D/p	42	20	

- Ability to take data at low energy will be an issue

Silicon stack detectors: polarimetry ? On the pitch

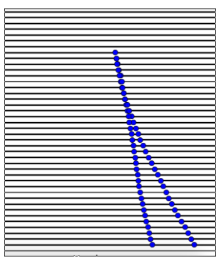




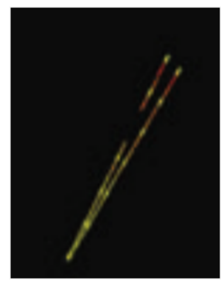
"Simulation of e-ASTROGAM", V. Fioretti, eASTROGAM Workshop: the extreme Universe, 28/02 - 02/03/2017 Padova

Polarimetry with High-Angular Resolution $\gamma \rightarrow e^+e^-$ Telescopes ?

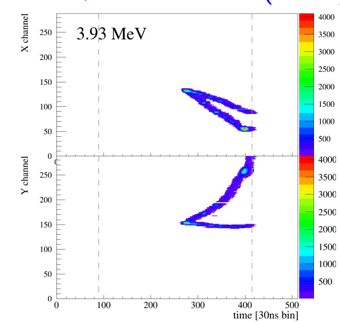
W-less, Si-stack detectors
AMEGO, e-ASTROGAM
1.3°@ 100 MeV
A. De Angelis *et al.*, Exp. Astr. **44** (2017) 25



Emulsions
GRAINE
1°@ 100 MeV
S. Takahashi *et al.*, PTEP **2015** (2015) 043H01



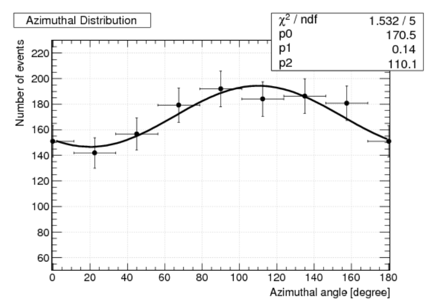
Gas TPC
HARPO
0.4°@ 100 MeV
D. Bernard, NIM A 701 (2013) 225



Polarimetry with $\gamma \rightarrow e^+e^-$:

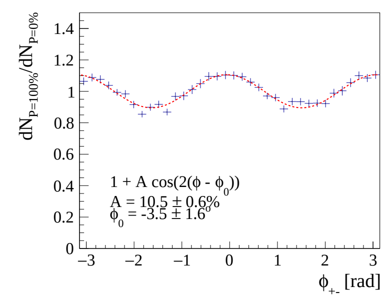
?

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



2.4 GeV (50 MeV threshold ?)

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



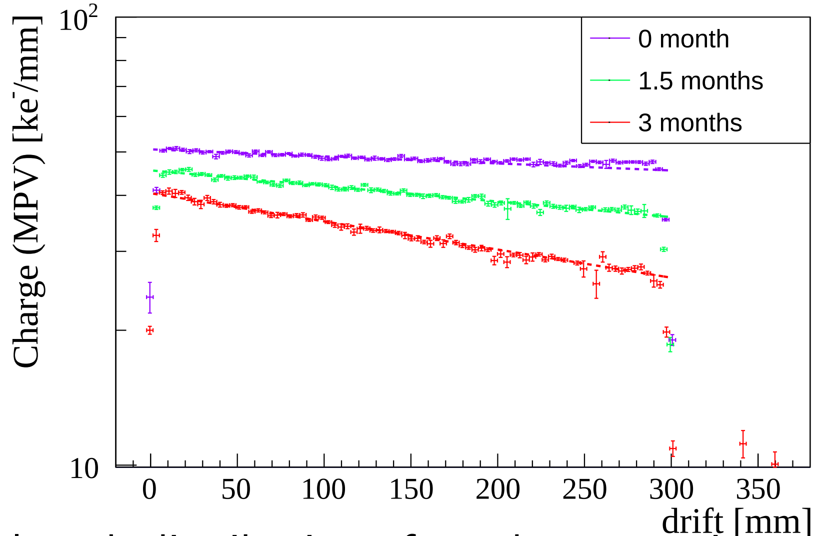
11.8 MeV

Je vous remercie de votre attention

Back-up Slides

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).

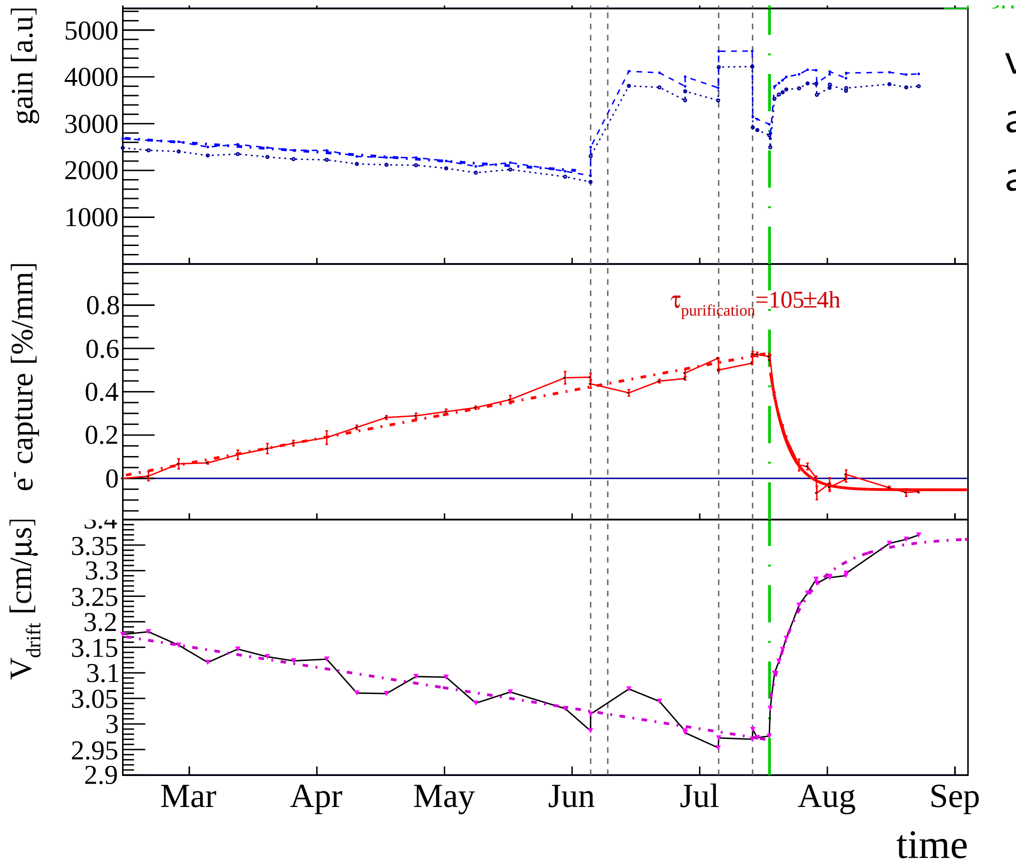


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- 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., arXiv:1512.03248 [physics.ins-det], MPGD2015, EPJ Web of Conferences

Gas purity on the long term: results



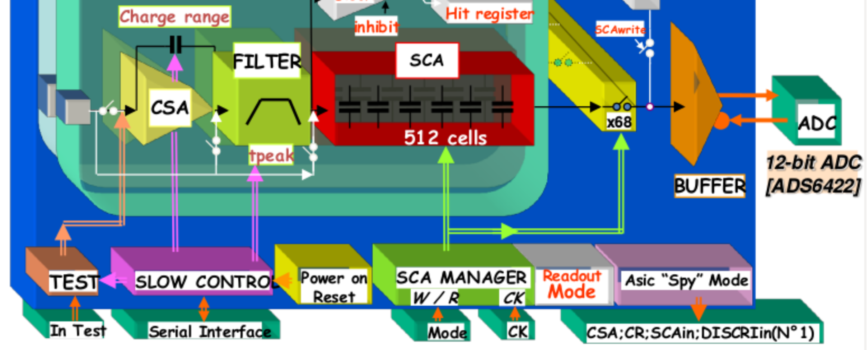
vertical lines: amplification voltage ajustments.

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., arXiv:1512.03248 [physics.ins-det], MPGD2015, EPJ Web of Conferences

AGET: ASIC for Generic



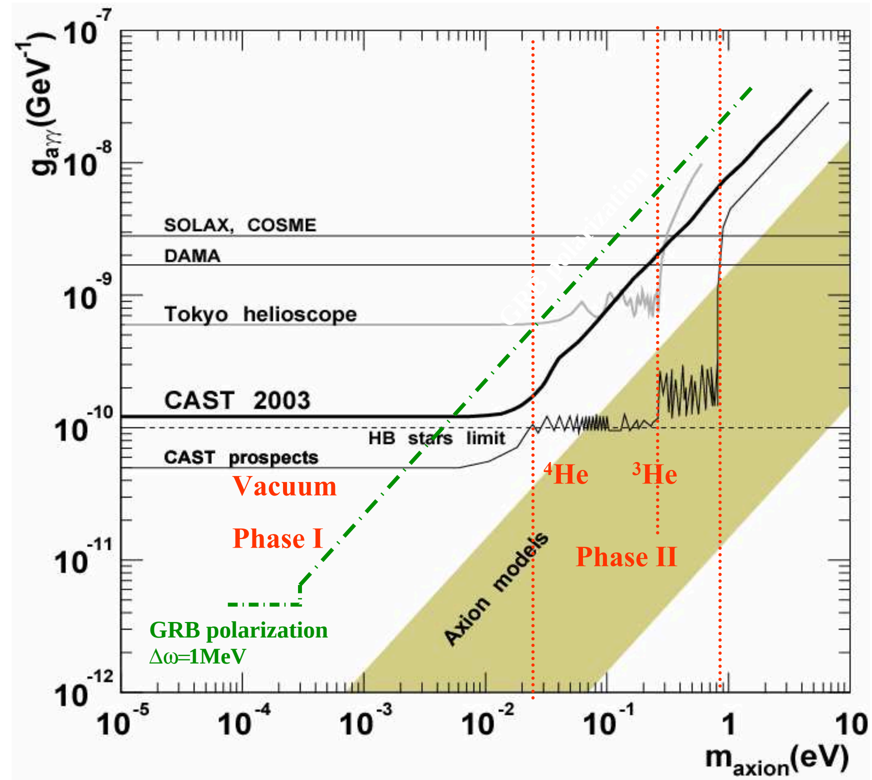
- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- shaping: 16 peaking time values: 70 ns to 1μs
- 512 analog memory cells / channel
- Fsampling: 1 MHz to 100 MHz; Fread: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real time (25 MHz) Multiplicity signal: analog OR of the 64 discri Outputs
- Readout: S. Anvar *et al.*, NSS/MIC, 2011 IEEE 745 - 749.
    - Address of the hit channel(s)
    - 3 readout modes: All, hit or specific channels
    - Predefined number of analog cells / trigger (1 to 512)

- AGET $\rightarrow$ radhard ASTRE: "Asic with SCA & Trigger for detector Readout Electronics":

Prototype series tested, D. Baudin *et al.*, HARPO collaboration, NDIP 2017, doi.org/10.1016/j.nima.2017.10.043

Search for Axions

- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to 2 γ 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)

Polarimetry: Optimal Measurement with Moments

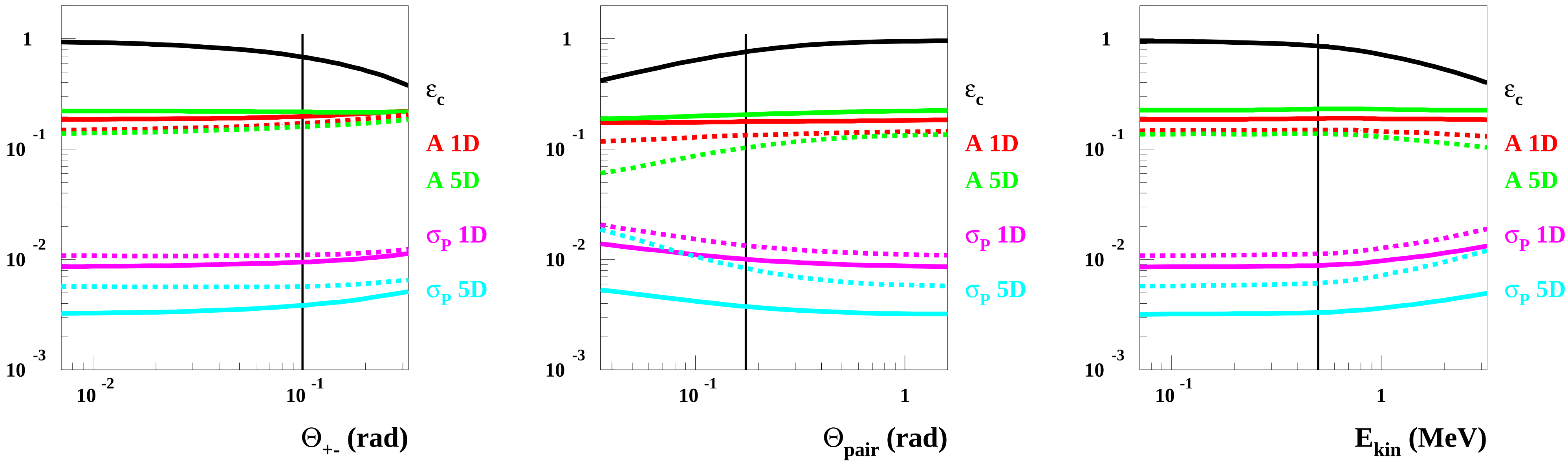
- Remember, fit of $\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P\cos[2(\phi)])$ yields $\sigma_P \approx \frac{1}{\mathcal{A}}\sqrt{\frac{2}{N}}$,
- Optimal measurement; Ω
  - let's define $p(\Omega)$ the pdf of set of (here 5) variables Ω
  - search for weight $w(\Omega)$, $\mathrm{E}(w)$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

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

D. Bernard, NIM A 729 (2013) 765

Polarimetry: Effects of Experimental Cuts

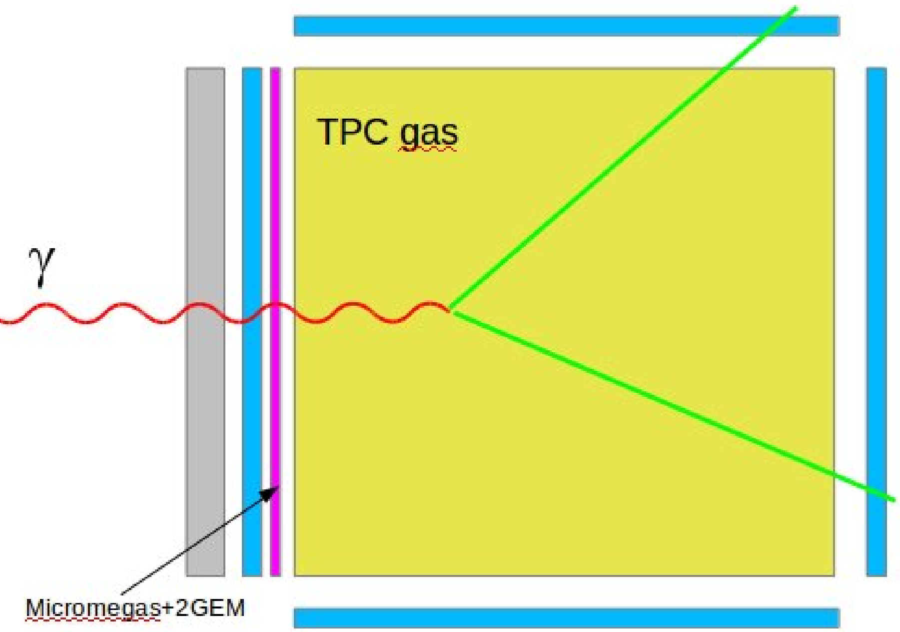
- opening angle, $\theta_{+-} > 0.1\,\mathrm{rad}$ (easy pattern recognition
- source selection $\theta_{pair} < 10\,^\circ$
- kinetic leptons energy $E_{kin} > 0.5\,\mathrm{MeV}$, (path length in 5 bar argon $\approx 30\,\mathrm{cm}$)

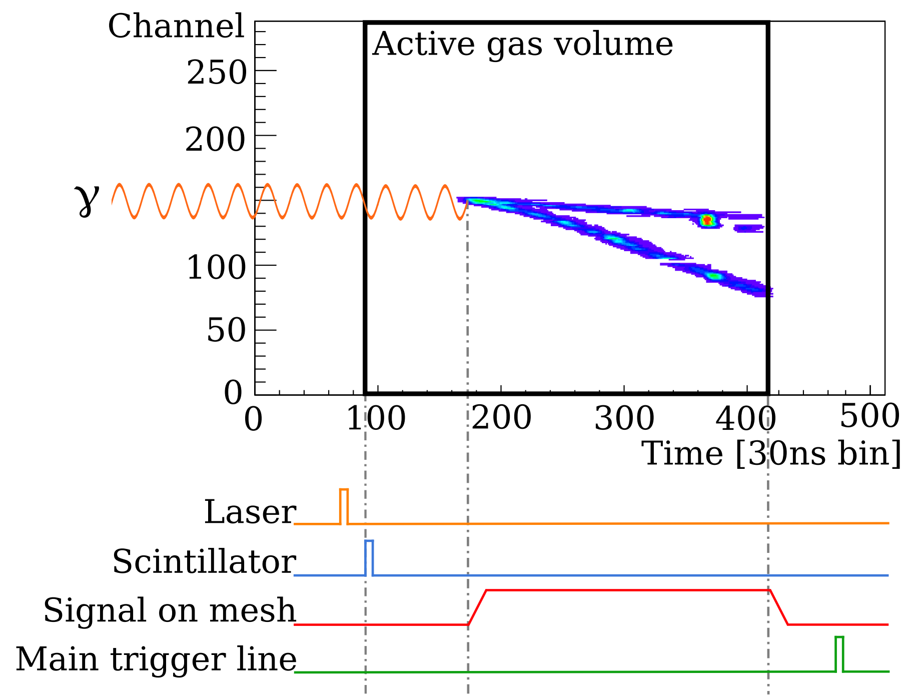


- All cuts: $\epsilon = 45\%$, (1D) $\mathcal{A}_{\mathrm{eff}} \approx 16.6\%$ $\sigma_P \approx 1.4\%$,

D. Bernard, NIM A 729 (2013) 765

“Beam” trigger system





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

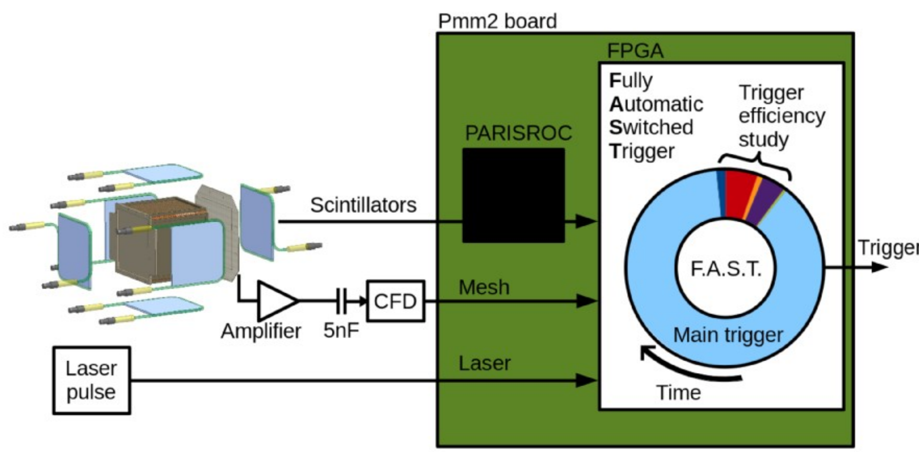
“Main line”: $T_{\gamma,laser} = \overline{S}_{up} \cap O \cap M_{slow} \cap L$

Wang et al., TPC2014, Paris, J. Phys. Conf. Ser. 650 (2015) 012016, arXiv:1503.03772 [astro-ph.IM]

“Beam” trigger system: additional lines

- Additional trigger lines:

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

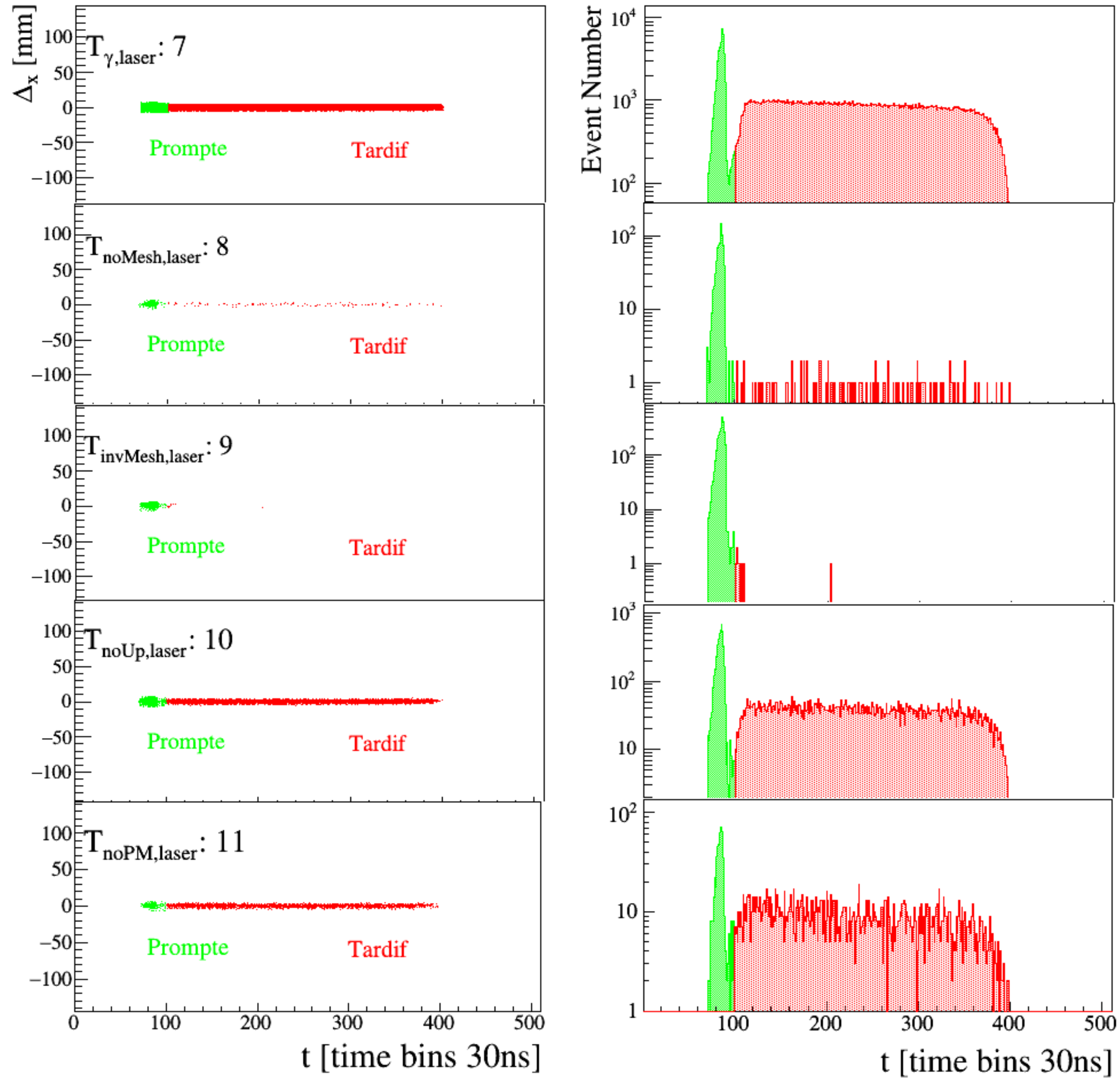


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

Y. Geerebaert, P. Gros, et al., Vienna Conference on Instrumentation 2016

"Beam" trigger system: conversion point distributions

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

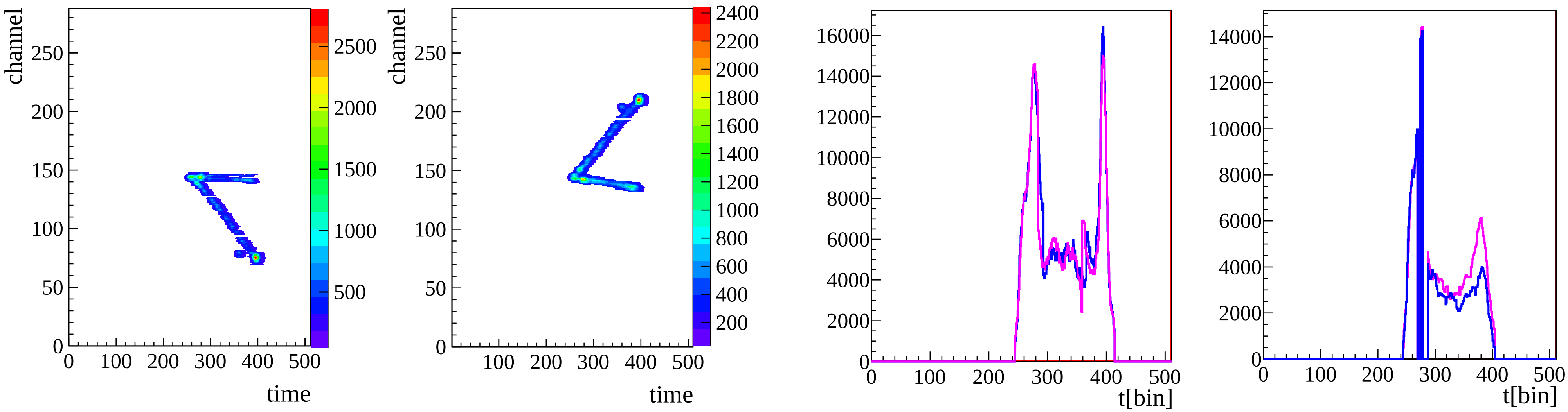


S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015, in French

Track matching

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

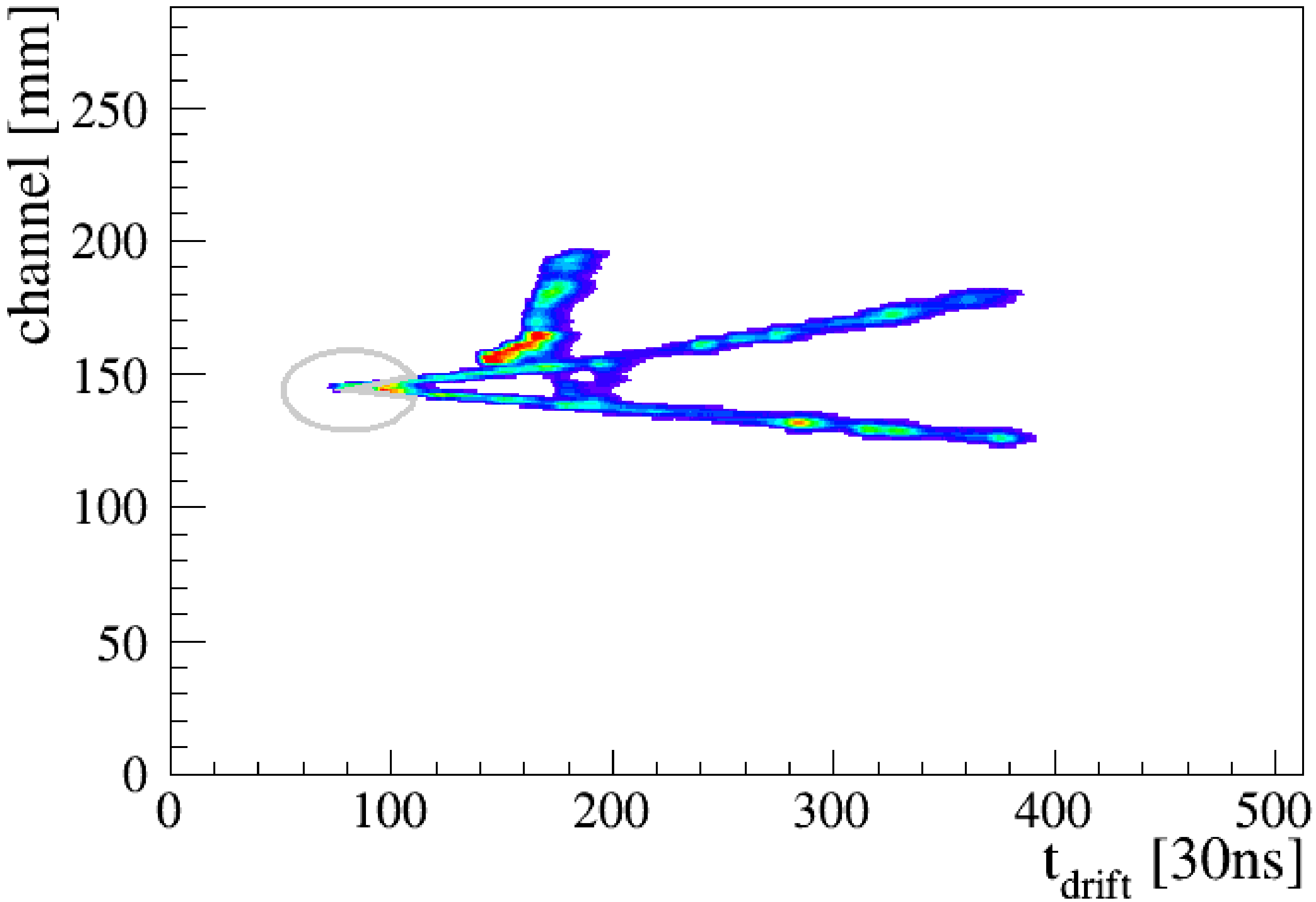
raw "maps" track time spectra



- 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 $\propto 1\,\text{mm}$

NIM A 718 (2013) 395

Event reconstruction



- Pseudo-tracking: vertex analysis

P. Gros, TPC 2016 conference, Paris 5-7 Dec. 2016, J.Phys.Conf.Ser. 1029 (2018) 012003