HARPO
A gas TPC active target for high-performance γ-ray astronomy
Demonstration of the polarimetry of MeV $\gamma \rightarrow e^{+}e^{-}$

Denis Bernard,
LLR, Ecole Polytechnique and CNRS/IN2P3, France

14th Pisa Meeting on advanced detectors, 27 May - 02 June 2018, Isola d'Elba (Italy) ,

proceedings arXiv:1805.10003 [astro-ph.IM]

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

Talk Lay-out

- Micro introduction: science case: (linear) γ-ray polarimetry
- Gas TPCs for $\gamma \rightarrow e^+e^-$ astronomy and polarimetry
- The CNRS-CEA-NewSUBARU-SPring8 "HARPO" (Hermetic ARgon POlarimeter) instrument project
- Spin-offs (companion posters @ PisaMeeting2018)
  - Kalman meets Molière: Optimal measurement of track momentum, from multiple scattering, in a $\vec{B} = 0$ tracker by a Bayesian analysis of the innovations of a series of Kalman filters applied to the track D. Bernard

    Nucl. Instrum. Meth. A 867 (2017) 182
  - C++ implementation of Bethe-Heitler, 5D, Polarized, $\gamma \rightarrow e^+e^-$ Pair Conversion Event Generator , I. Semeniouk et al.

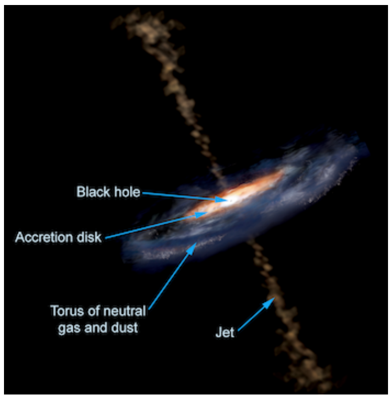
    Watch for G4BetheHeitler5DModel in 10.5 beta Geant4 release, end of June !

    (Fortran demonstration model, Nucl. Instrum. Meth. A 899 (2018) 85)

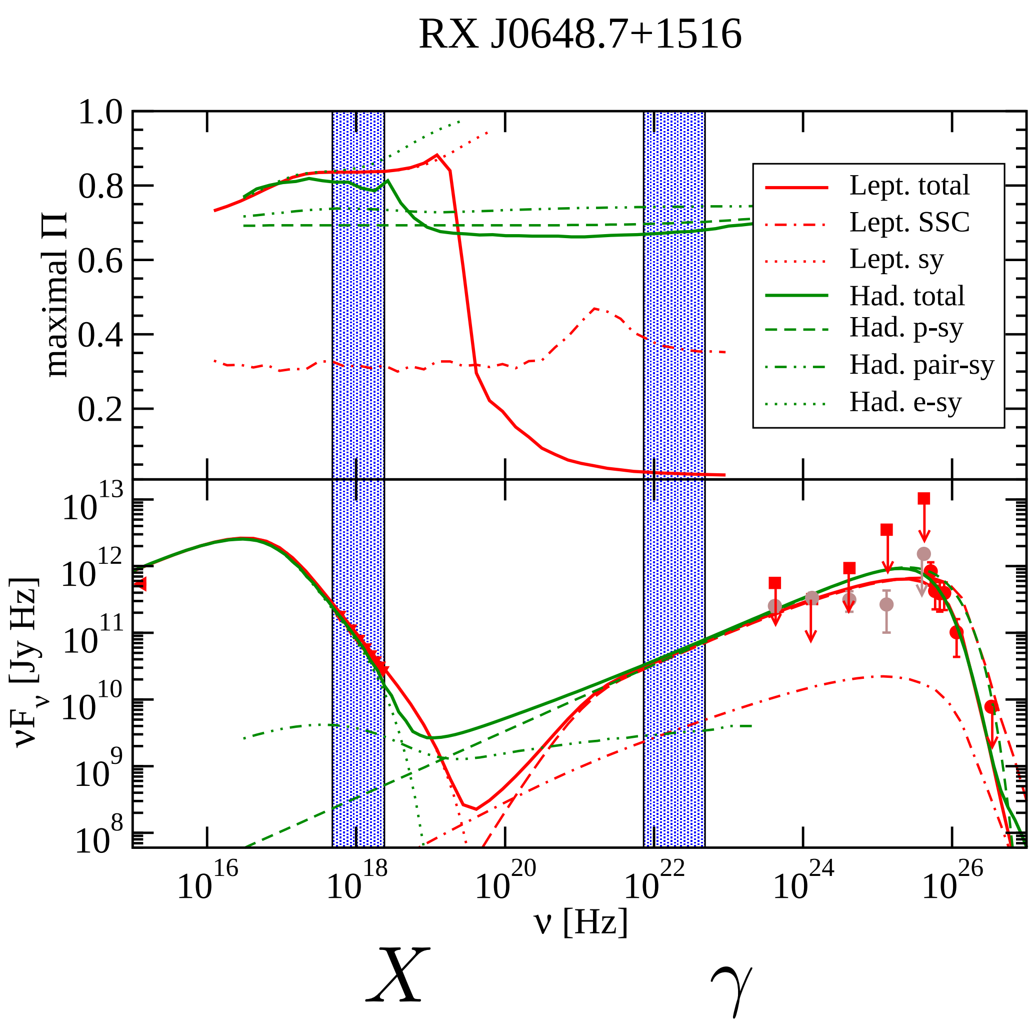
Deciphering emission mechanism in Blazars with γ-ray polarimetry

- Blazars: active galactic nuclei (AGN) with one jet pointing (almost) to us

leptonic synchrotron self-Compton (SSC) or **hadronic** (proton-synchrotron) ?

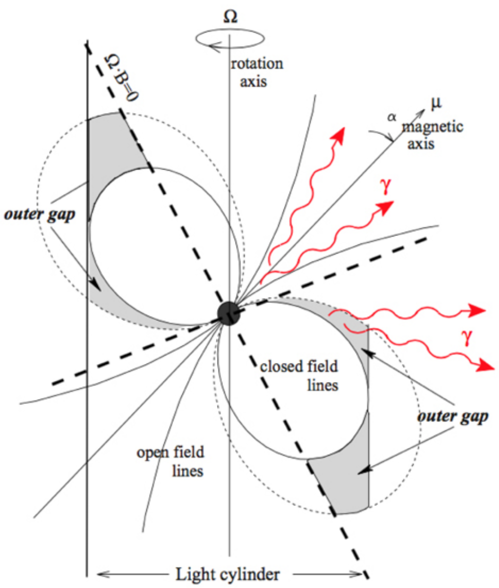


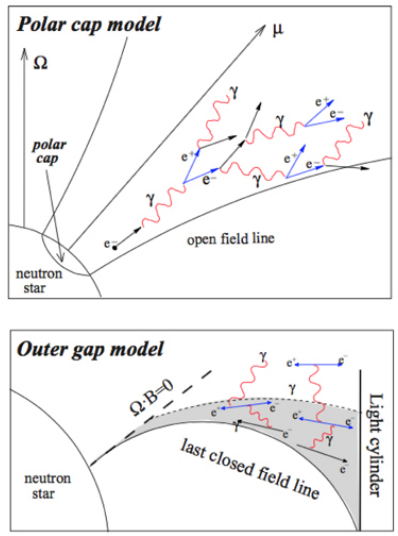
- high-frequency-peaked BL Lac
- X band: 2 -10 keV
- γ band: 30 - 200 MeV
- SED's indistinguishable, but
  - X-ray: $P_{\mathrm{lept}} \approx P_{\mathrm{hadr}}$
  - γ-ray: $P_{\mathrm{lept}} \ll P_{\mathrm{hadr}}$

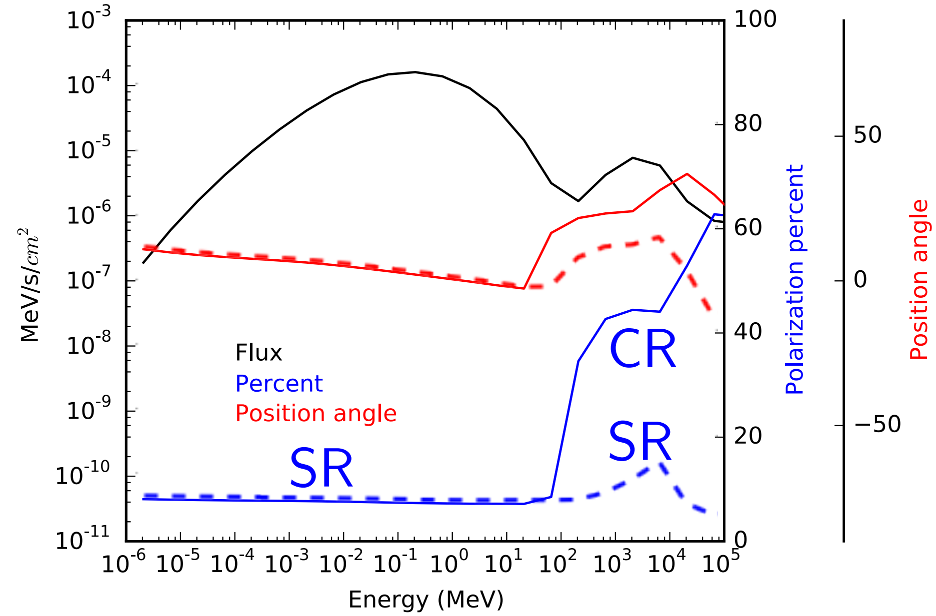


H. Zhang and M. Böttcher,
A.P. J. 774, 18 (2013)

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







Polar-cap model of Crab-like pulsar

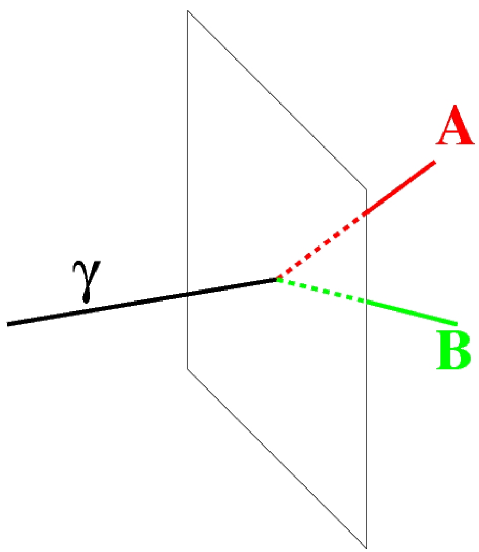
- MeV component is SR from pairs
  GeV component is either CR (solid line) or SR (dashed line)
- "Polarization of MeV and GeV emission is a powerful, independent diagnostic, capable of constraining both the location and mechanism of the radiation".

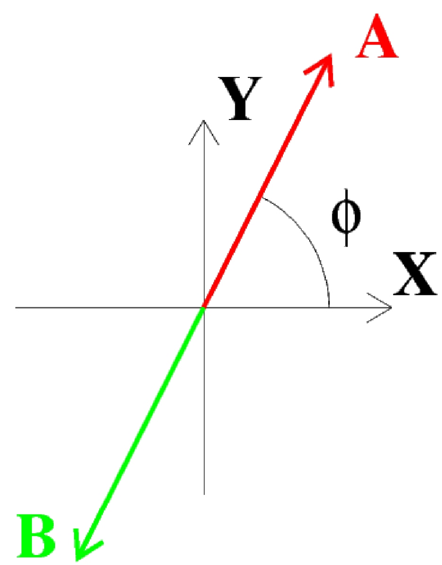
A. K. Harding and C. Kalapotharakos, PoS IFS 2017 (2017) 006, and Astrophys. J. 840 73 (2017)

Polarimetry

- Modulation of azimuthal angle distribution

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



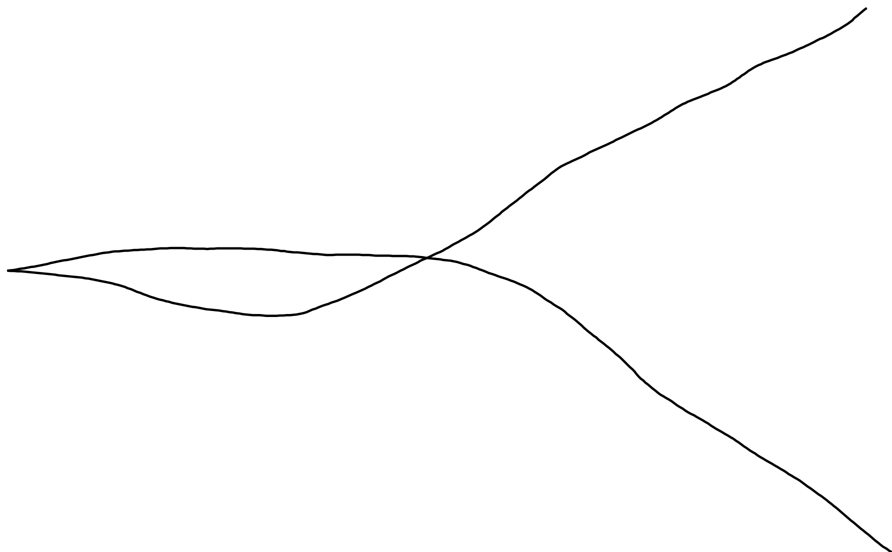


- P source linear polarisation fraction
- $\mathcal{A}$ γ-ray conversion polarization asymmetry
- ϕ event azimuthal angle
- ϕ_0 source polarization angle.

The enemy: multiple scattering

- Data

- MC simulation



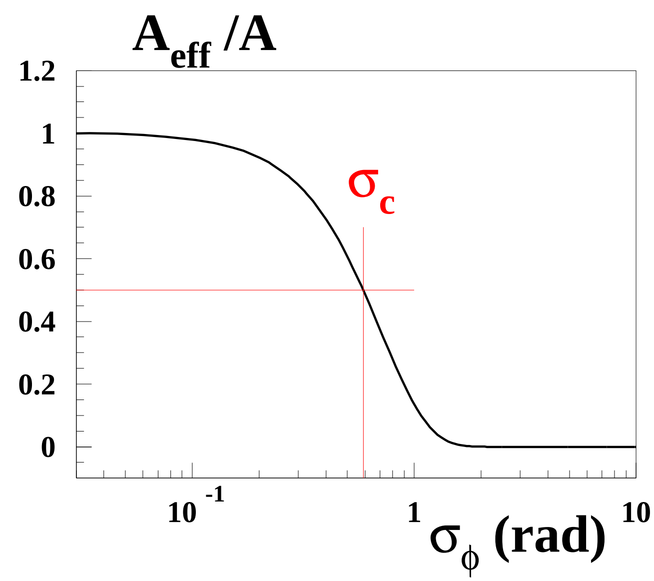
γ-ray conversion in argon, EGS5 simulation

The Wisteria effect

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

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

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



- 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).

$\Rightarrow \sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$, $\boxed{\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2 \text{ for } x \approx 10^{-3} X_0}$ (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*

- $\sigma_\phi = \dfrac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, 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,

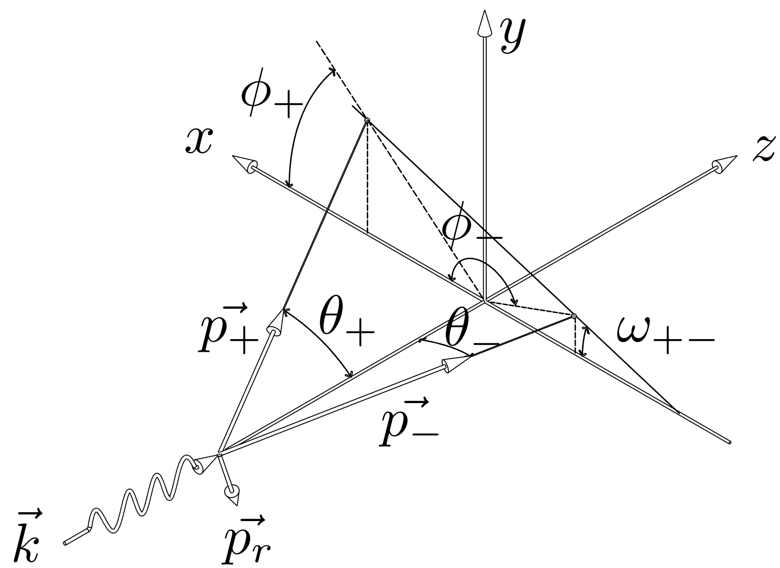
There is hope .. at low p_1 (gas) .. at low energy.

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

NIM A 729 (2013) 765

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 $x_+ \equiv E_+/E$



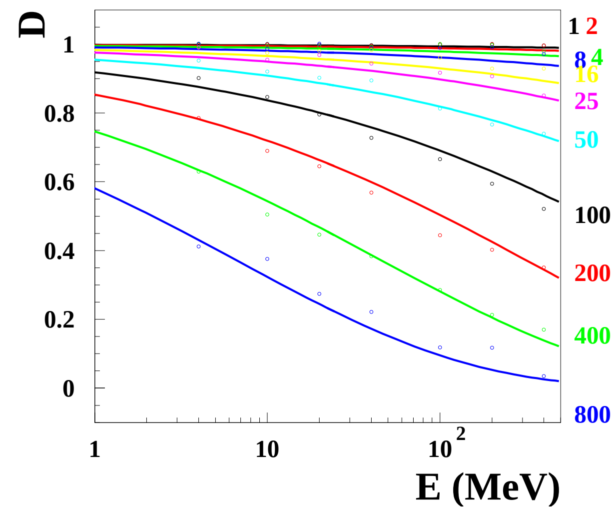
- Verification against published 1D distributions (nuclear and triplet conversions)

NIM A 729 (2013) 765
Astroparticle Physics 88 (2017) 60

- Verification recently extended down to $2mc^2 + 1\,\mathrm{keV}$ and up to 1 EeV with Geant4-compatible version Nucl. Instrum. Meth. A 899 (2018) 85

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

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



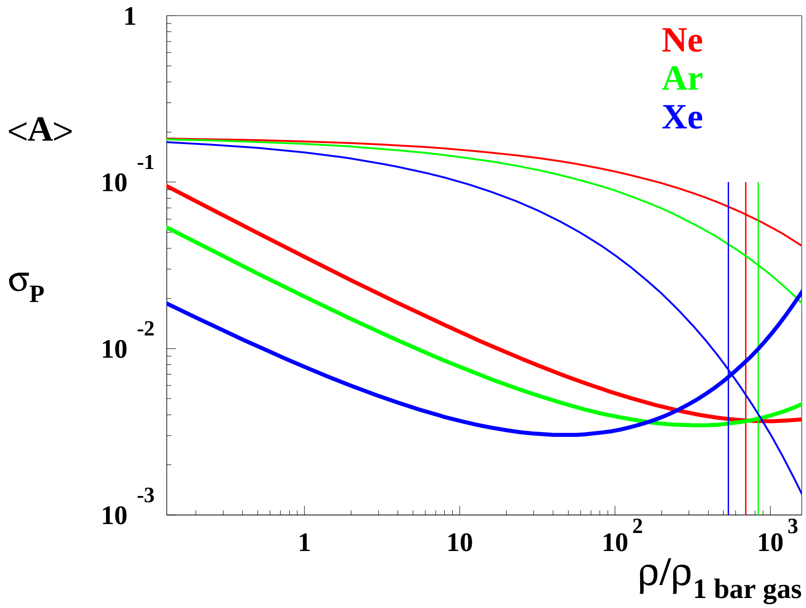
Energy variation of D for various values of $p_1(\mathrm{keV}/c)$

- 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, $p_1 = 50\,\mathrm{keV}/c$)

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

Polarimetry Performance (no Experimental Cuts)

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

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]
[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 Time line

- PisaMeeting 2012 (D. Bernard)

  Dreams, plans, a little bit of Monte Carlo,

  cosmic rays (single tracks) seen in TPC prototype.

- PisaMeeting 2015 (Ph. Gros)

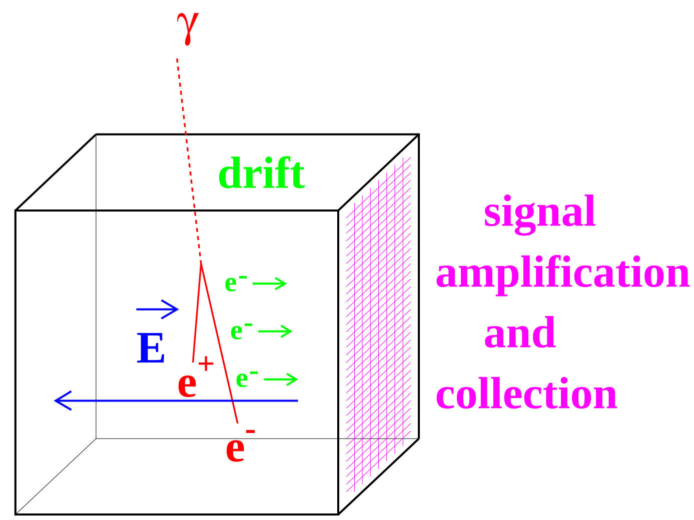
  Preliminary analysis of 2014 data-taking campaing on polarized γ-ray beam.

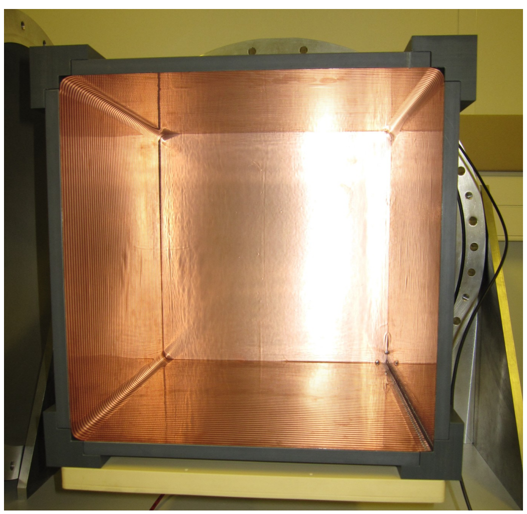
- PisaMeeting 2018 (D. Bernard)

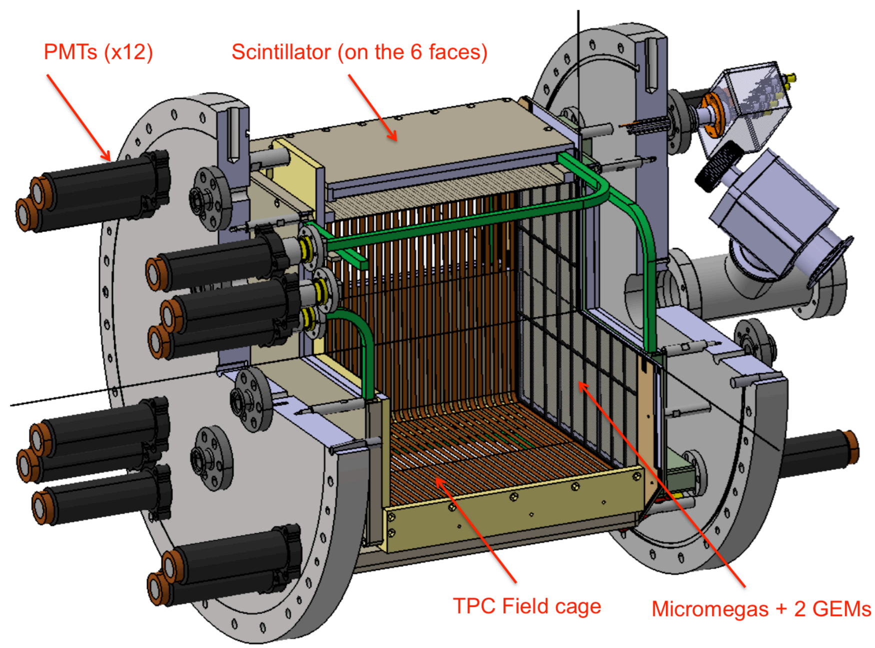
  Final results.

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



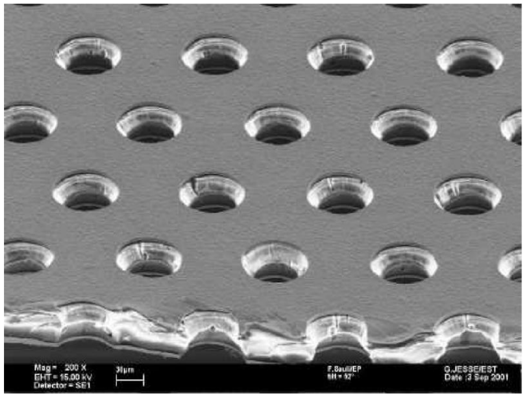


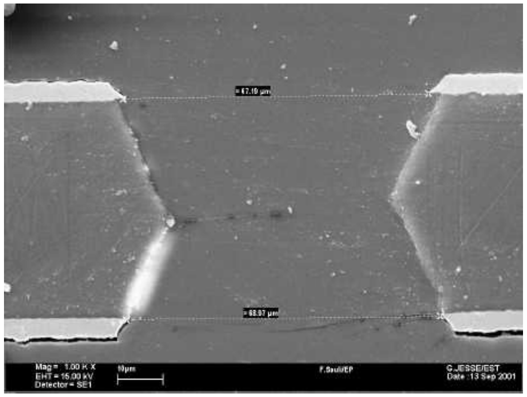


Nucl. Instrum. Meth. A 695 (2012) 71, Nucl. Instrum. Meth. A 718 (2013) 395

Gas amplification: micromegas + 2 GEM

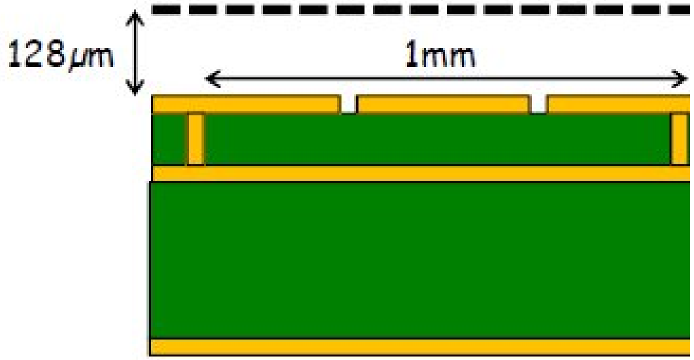
Gas Electron Multiplier
$50\,\mu m$ Kapton, copper clad,
pitch $140\,\mu m$, $\Phi 70\,\mu m$

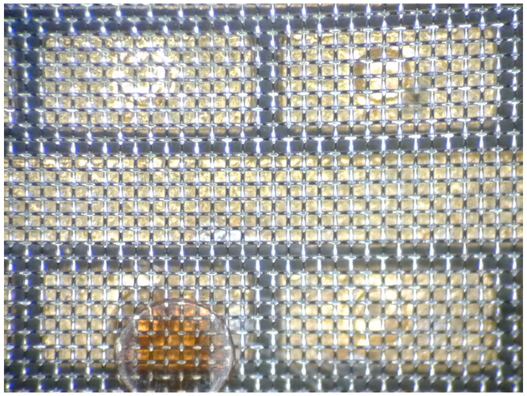




F. Sauli, Nucl. Instrum. Meth. A 386, 531 (1997)

"bulk" micromegas
gap $128\,\mu m$

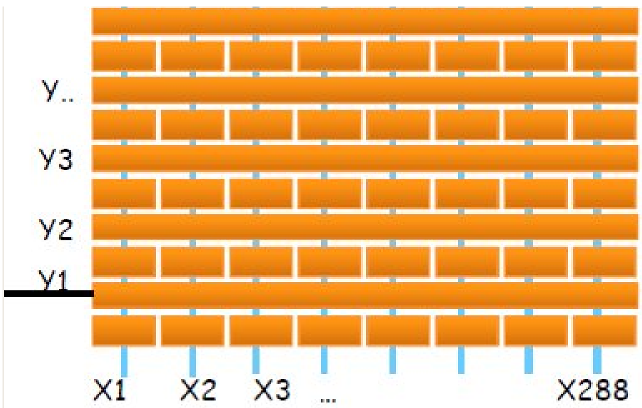


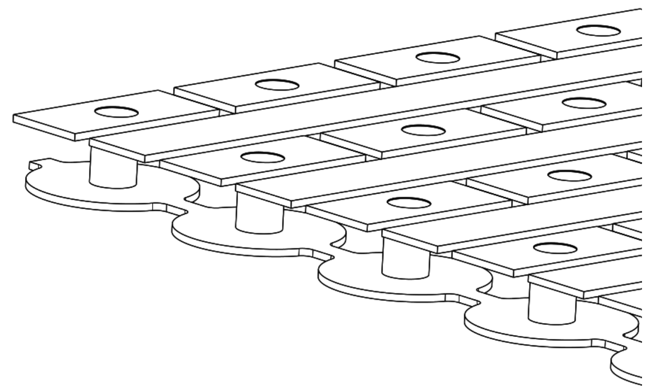


I. Giomataris et al., Nucl. Instrum. Meth. A 560, 405 (2006)

Anode segmentation

- Avalanche electrons collected on a segmented anode.

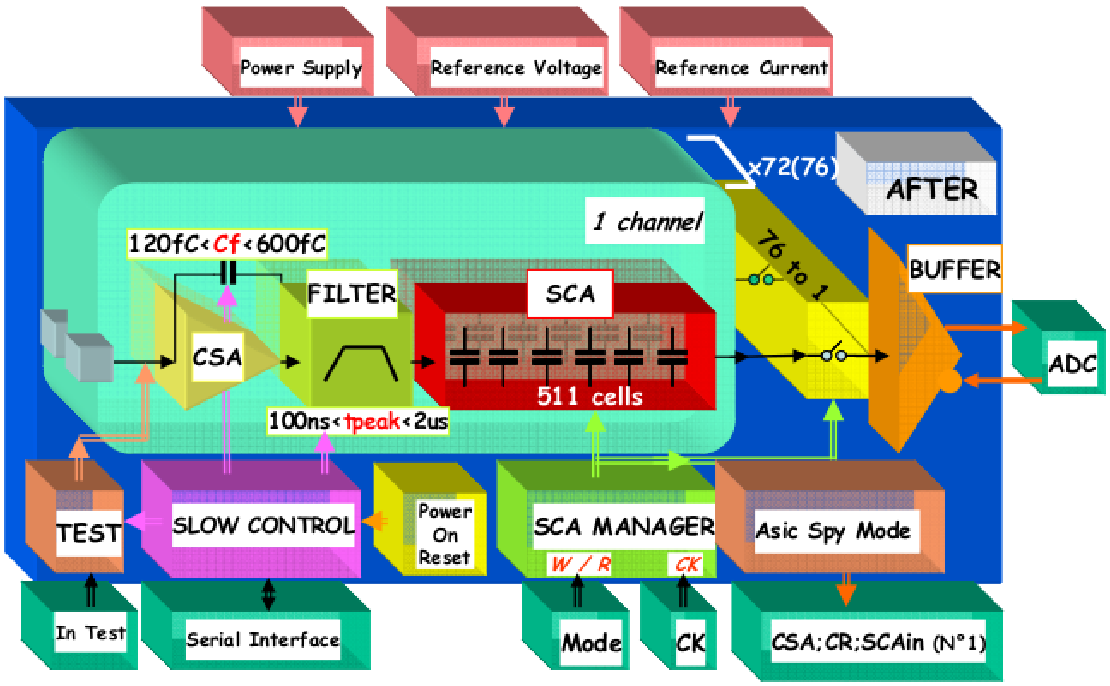




- Cu-clad PCB, strip pitch 1 mm, strip width $\approx 400\,\mu\mathrm{m}$

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 µs
- 12 bit ADC.

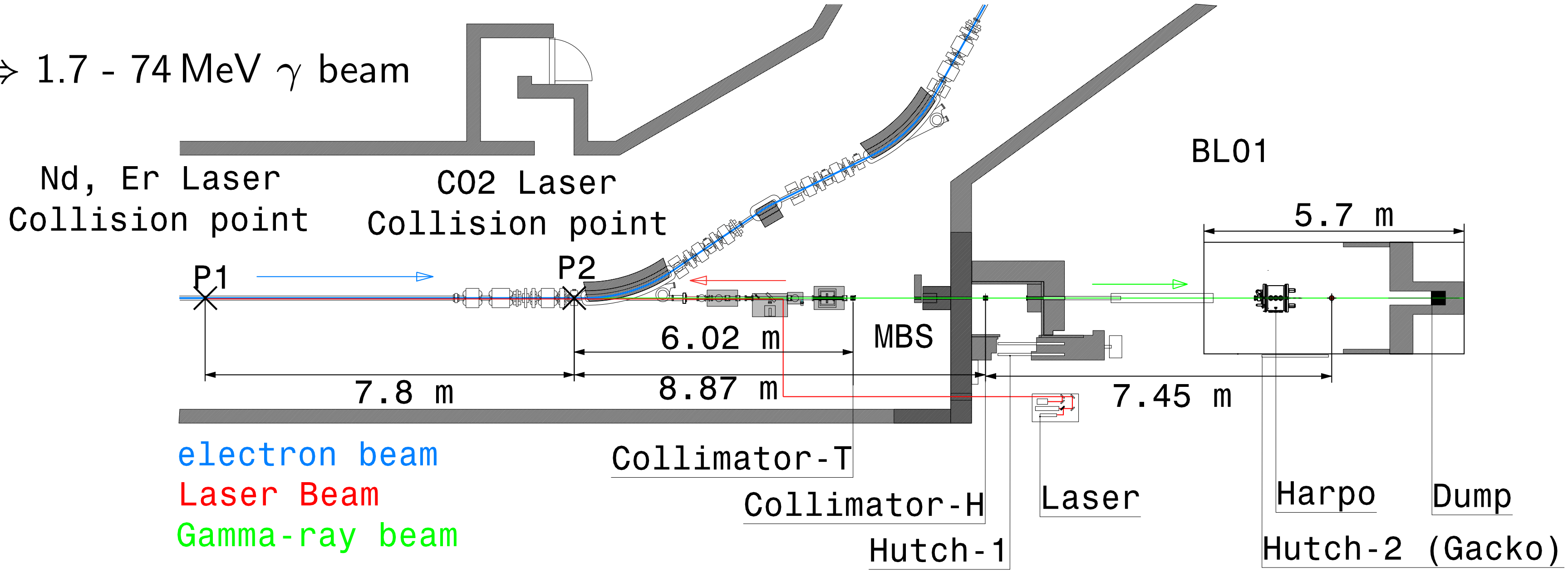


Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

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

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

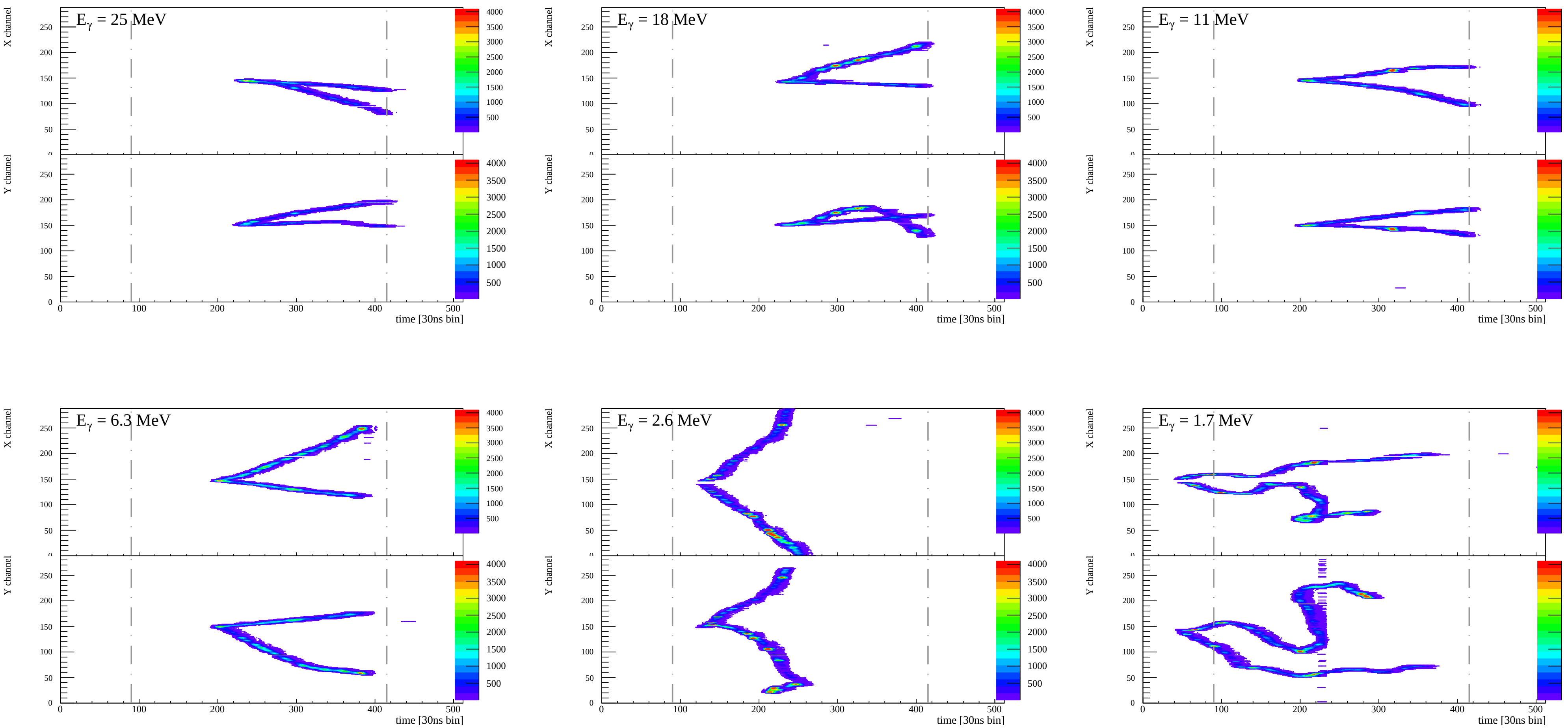
- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- $0.532\,\mu\mathrm{m}$ and $1.064\,\mu\mathrm{m}$ $20\,\mathrm{kHz}$ pulsed Nd:YVO_4 (2ω and 1ω),
  $1.540\,\mu\mathrm{m}$ $200\,\mathrm{kHz}$ pulsed Er (fibre) and
  $10.55\,\mu\mathrm{m}$ CW CO_2 lasers
- $\Rightarrow$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

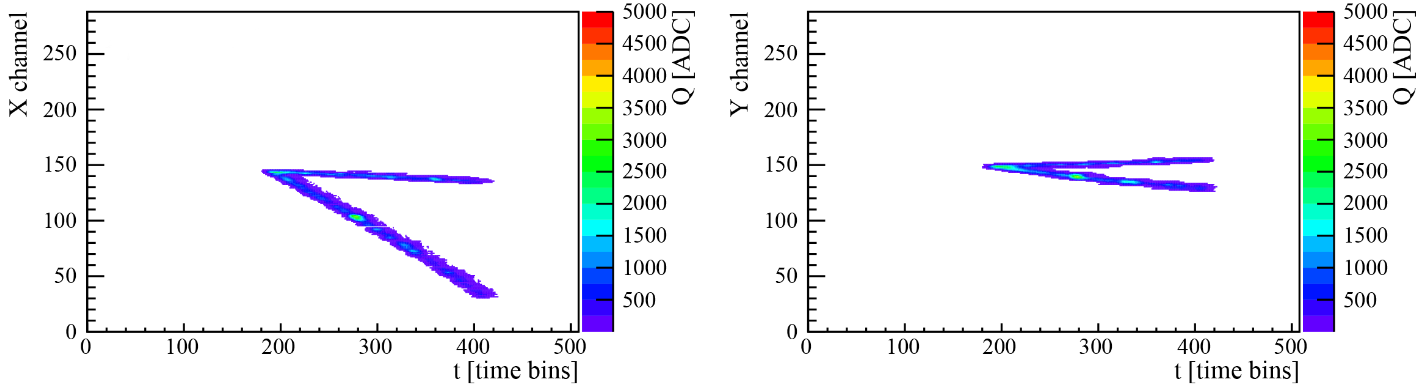
6 events



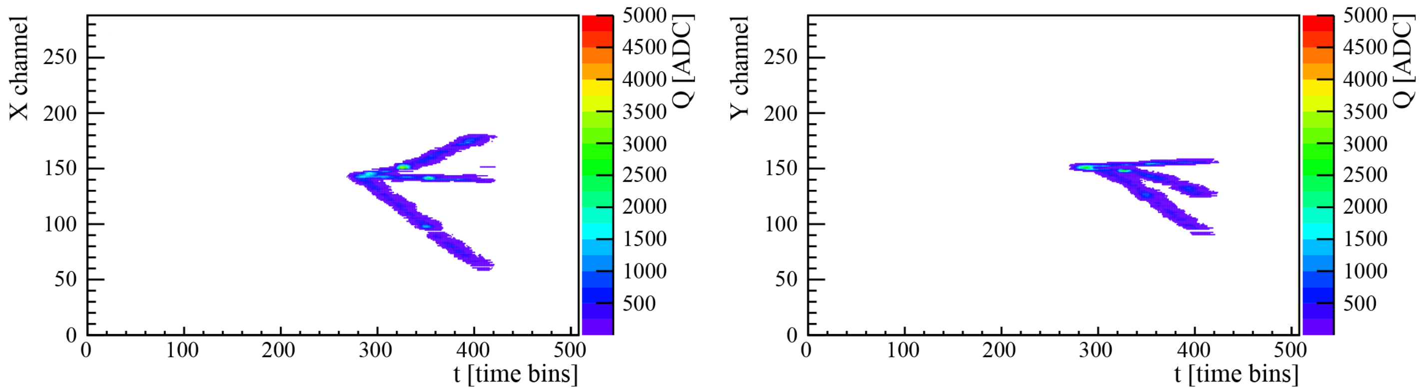
- Sample of γ-rays from the BL01 beam line at NewSUBARU (LASTI, Hyôgo Kenritsu Daigaku) converting to e^+e^- in the 2.1 bar Ar:Isobutane 95:5 gas of the HARPO TPC
- Ability to image low energy (MeV) γ-ray conversion to pairs.

"Nuclear" and "triplet" conversions

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

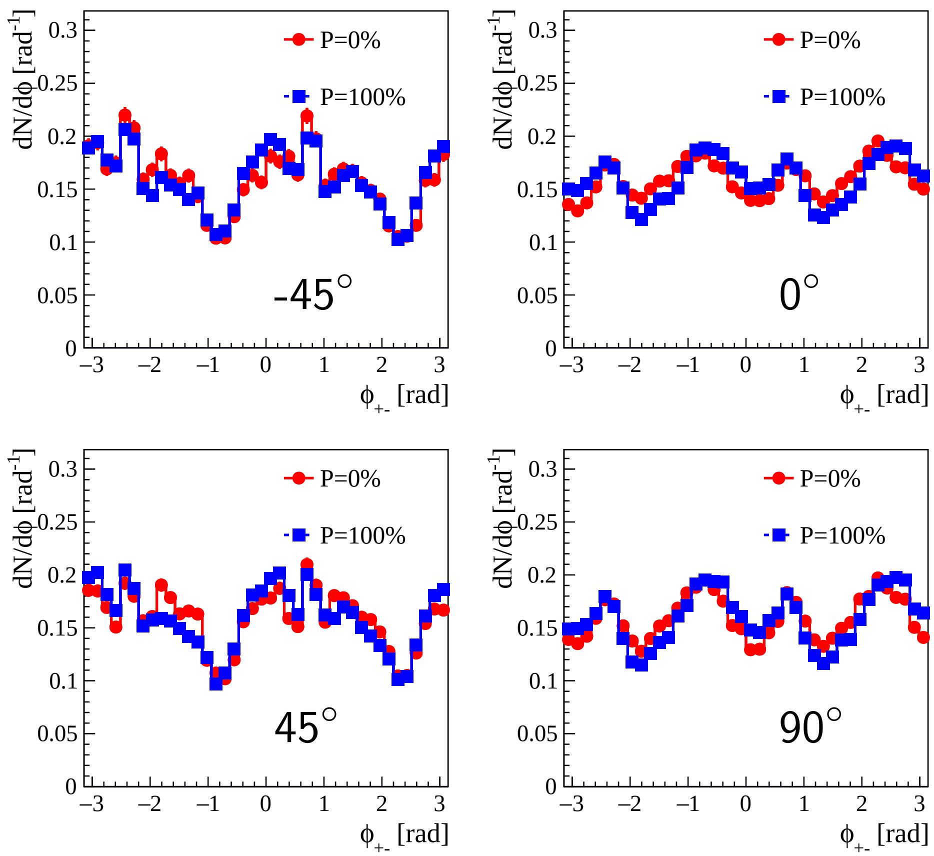


$$\gamma e^- \rightarrow e^+ e^- e^-$$



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

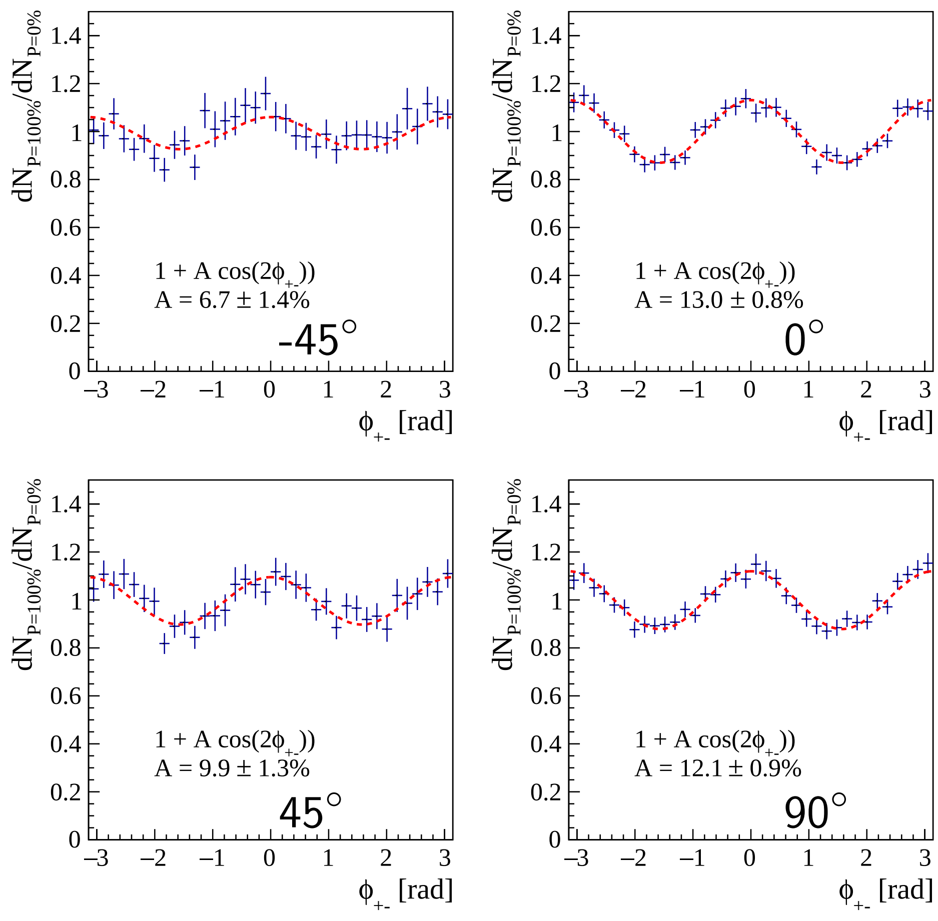


ϕ distributions for four detector orientations (11.8 MeV γ rays in 2.1 bar argon)

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

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

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

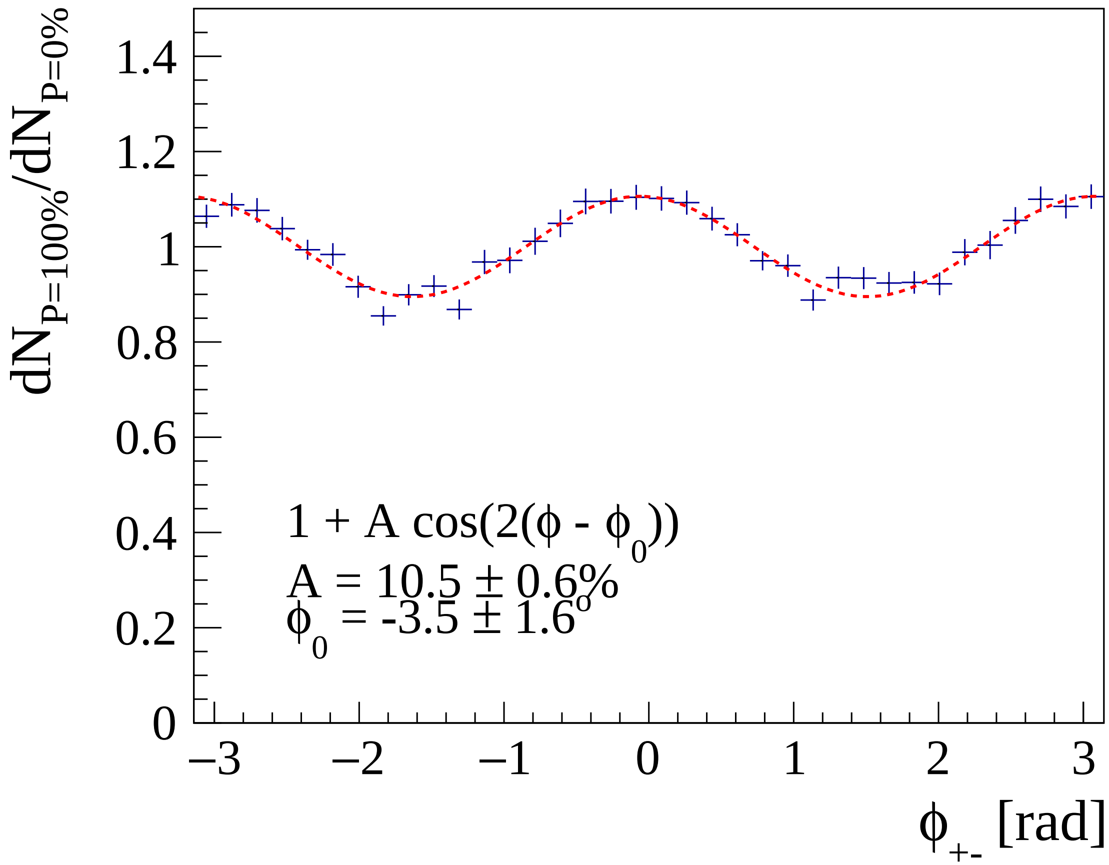


Ratios of ϕ distributions for four detector orientations

(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)

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

Conclusion

- Gas TPC THE choice detector for ultimate angular resolution $\gamma \rightarrow e^+e^-$ 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.
- Ability to cope with intense GRB – dedicated buffer needed

- Data taken:
    - with a $(30\text{cm})^3$ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
    - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, γ beam

Polarimetry demonstrated with excellent dilution factor.

Back-up Slides

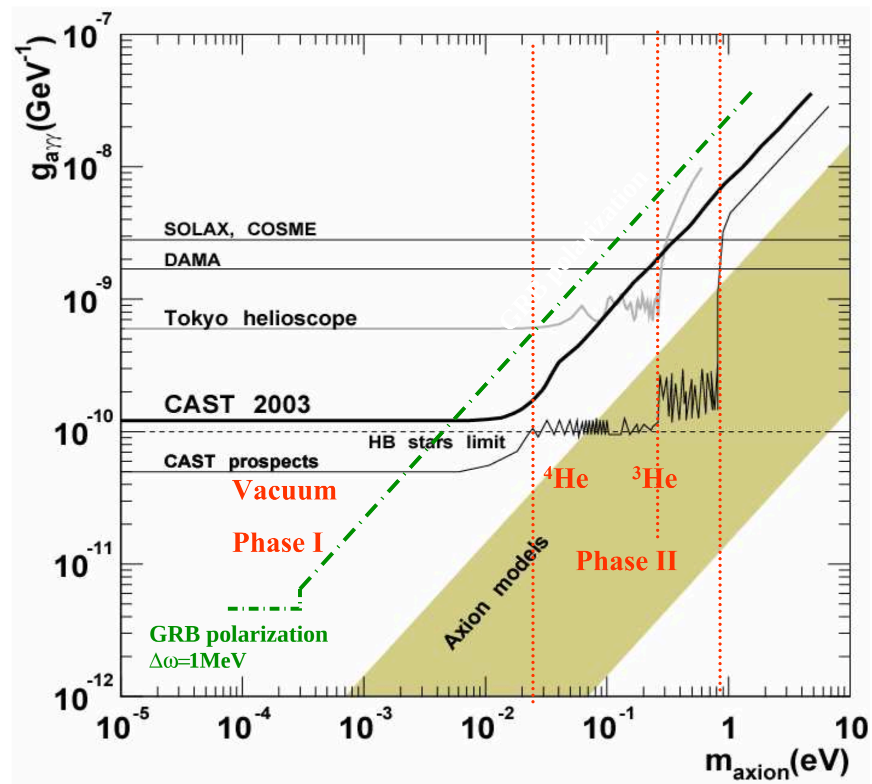
Search for Axions

- 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)

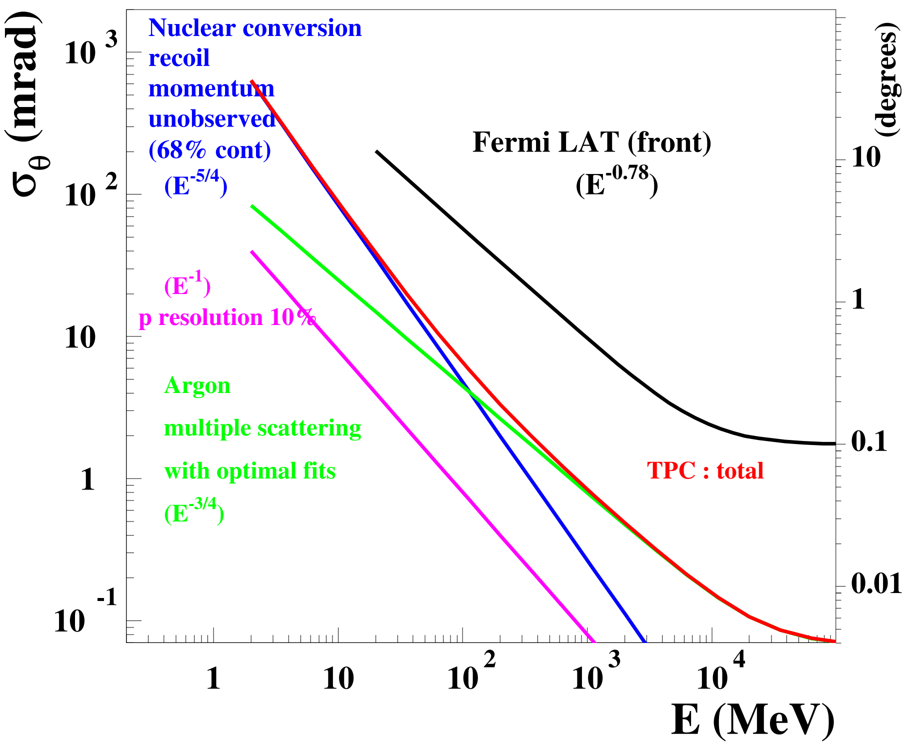
LIV: Search for Lorentz Invariance Violation

- 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 $\propto 1/k^2$!

Performances with Low-Density Homogeneous Detectors and Optimal Fits

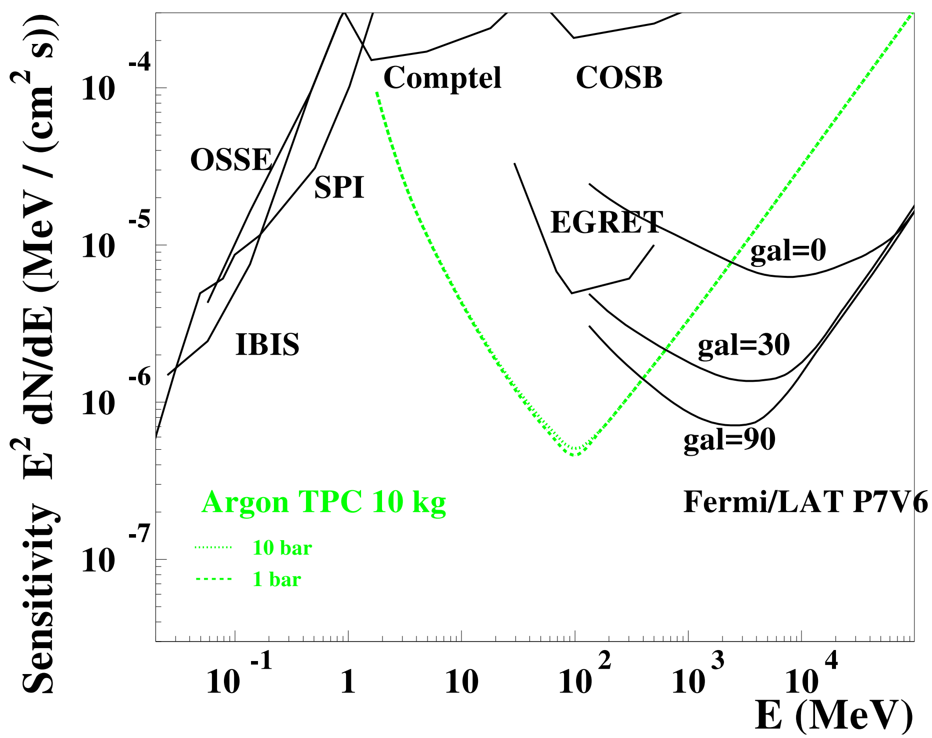
Angular resolution

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



point-source differential sensitivity

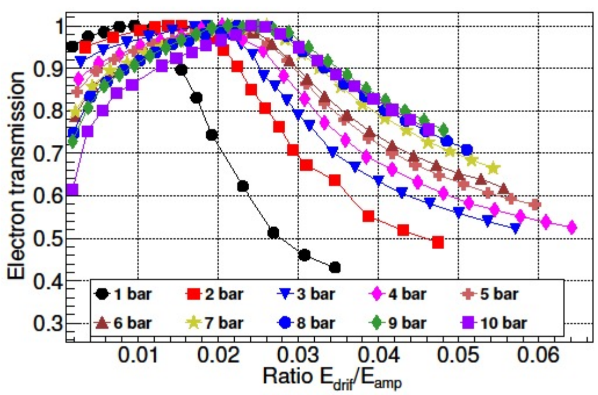
limit detectable $E^2 \mathrm{d}N/\mathrm{d}E$, à la Fermi: 4 bins/decade, 5σ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. "against" extragalactic background

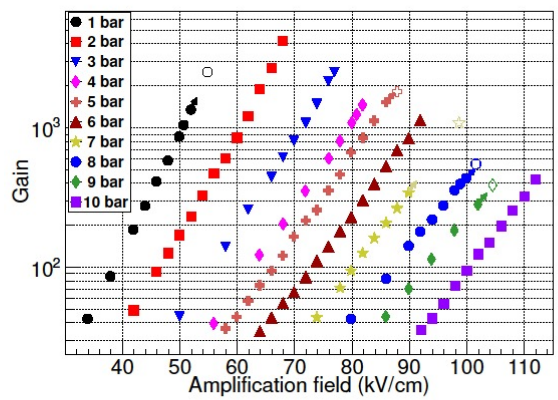


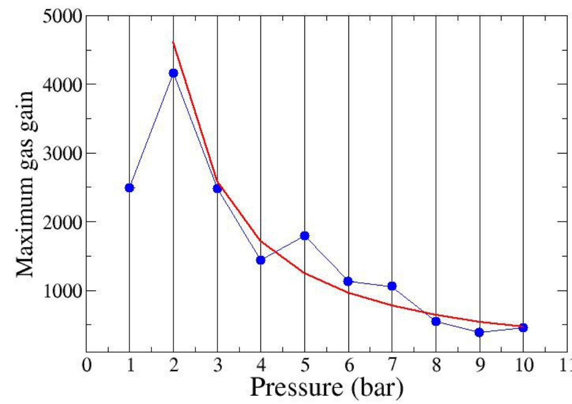
NIM A 701 (2013) 225

Which Pressure ?

- **Science**. Rising the pressure:
  - degrades the angular resolution and (mildly) point like source sensitivity
  - Increases the effective area improves the precision on the polarization
- Maximum **micropattern gas amplification gain** (micromegas, GEM) known to decrease with pressure .. but dE/dx increases ..







D. C. Herrera, *et al.*, "Micromegas-TPC operation at high pressure in Xenon-trimethylamine mixtures," J. Phys. Conf. Ser. 460, 012012 (2013).

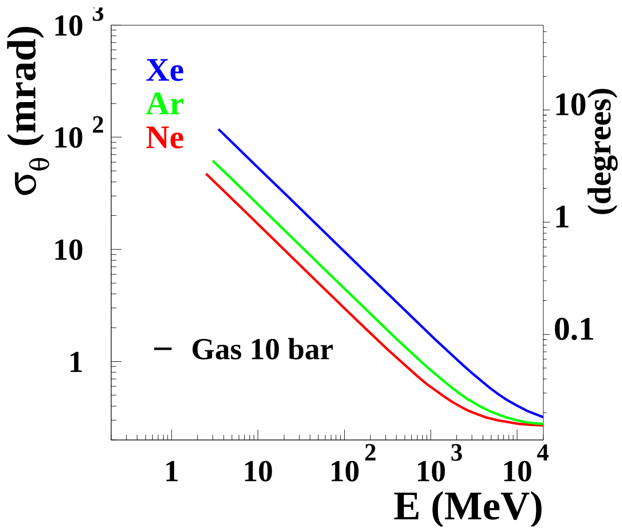
micropattern gas amplification above 10 bar a concern, unless very small gap devices can be produced.

- **Vessel Mass** $\propto$ gas mass to 1rst order.
  - For a given mission: which limit will we touch first (volume, mass) ?

In this talks, examples given at 1, 5, 10 bar. Data taken mostly at 2.1 bar, + a 1-4 bar scan.

Gas composition: light / heavy Z ? Gas pressure ?

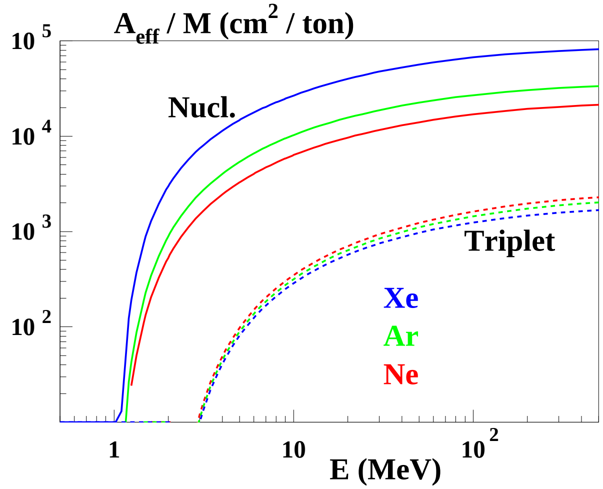
- $\rho \times X_0 = \frac{A}{Z^2} b, \quad \rho = aAP, \quad M = V\rho = VaAP, \quad X_0 = \frac{b}{aZ^2P} \quad a, b$ constants.



angular resolution degrades with Z

$\sigma_\theta \propto X_0^{-3/8} \propto Z^{3/4} P^{3/8}$

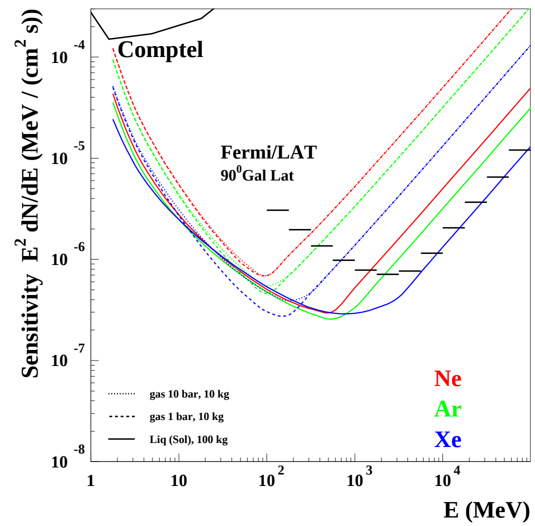
(multiple scattering)



effective area improves with Z

$A_{\text{eff}} \propto \frac{V}{X_0} \propto VPZ^2$

(asymptotically)



sensitivity mildly affected

$s \propto \frac{\sigma_\theta}{\sqrt{A_{\text{eff}}}} \propto \frac{X_0^{1/8}}{\sqrt{V}} \propto \frac{1}{V^{1/2} Z^{1/4} P^{1/8}}$

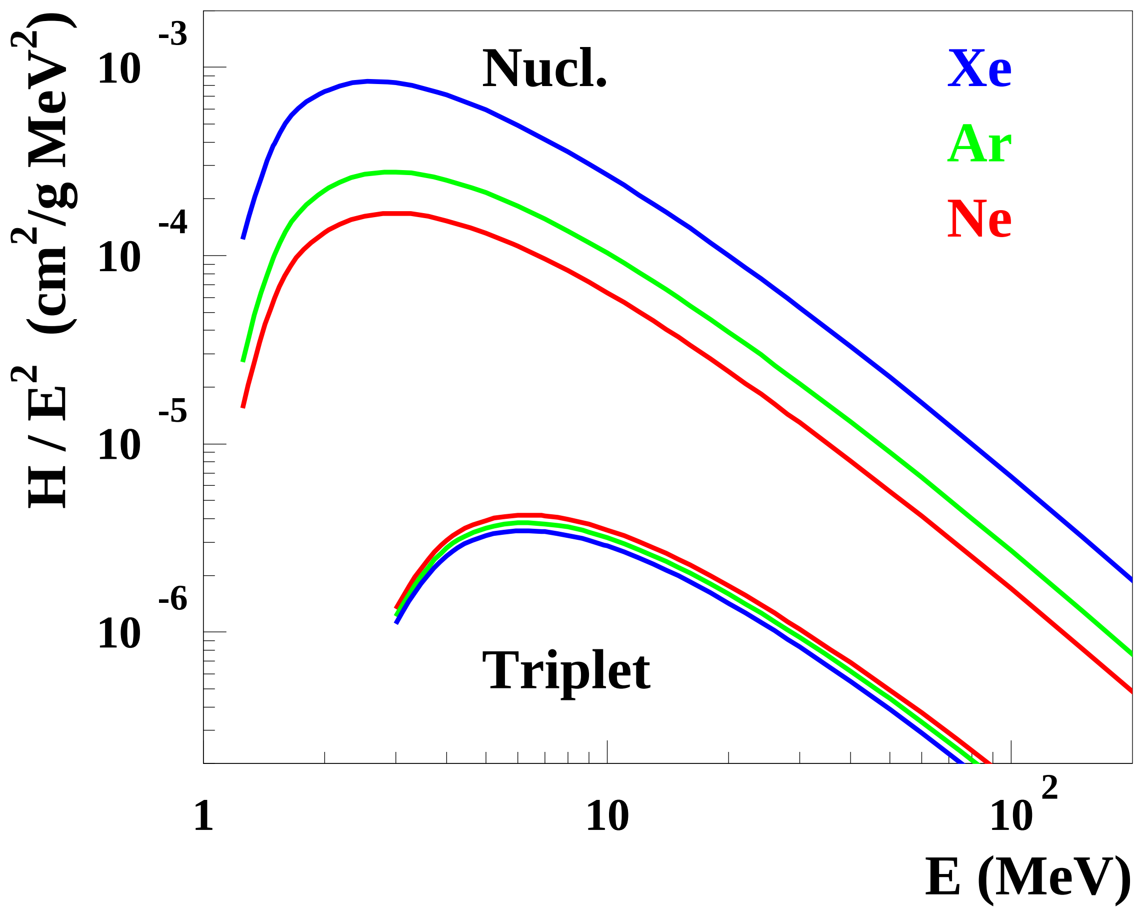
(asymptotically)
(assuming gaussian stats.)

- Note that $M_{\text{vessel}} \propto P$ and $M_{\text{gas}} \propto P$ so $M_{\text{vessel}} \propto M_{\text{gas}}$

  $M_{\text{vessel}}/M_{\text{gas}} \approx 0.36$ for Ti alloy sphere at elastic limit / Argon.

NIM A 701 (2013) 225

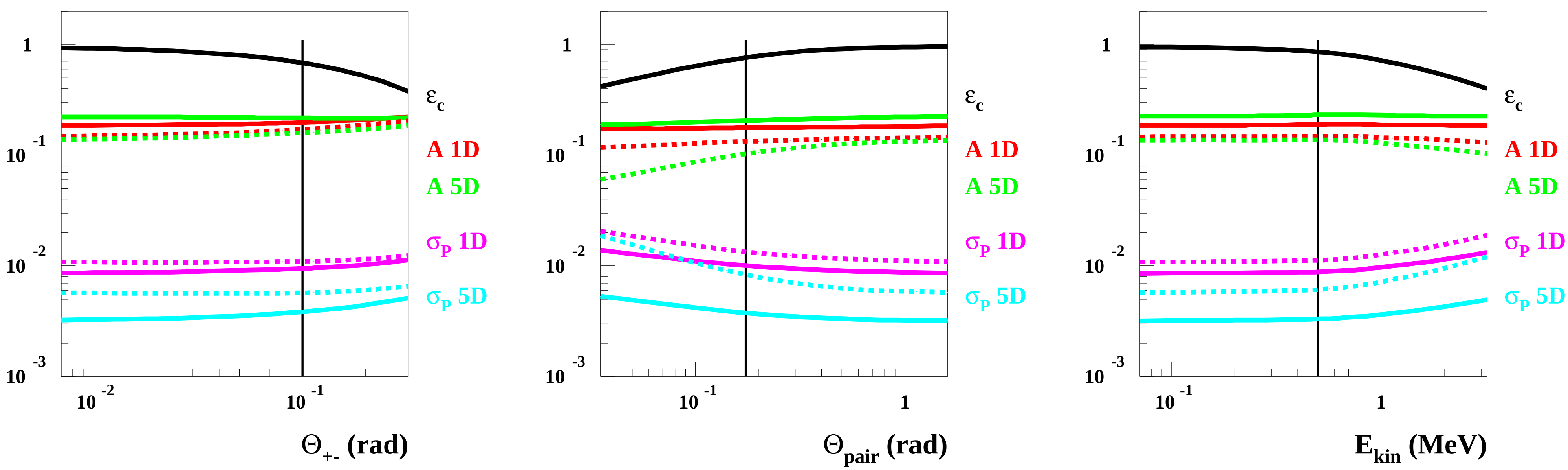
Polarimetry Demanding for Huge Statistics: Ability to take data at low energy critical



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

Polarimetry: Effects of Experimental Cuts

- opening angle, $\theta_{+-} > 0.1\,\mathrm{rad}$ (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) $\mathcal{A}_{\text{eff}} \approx 16.6\%$ $\sigma_P \approx 1.4\%$,

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

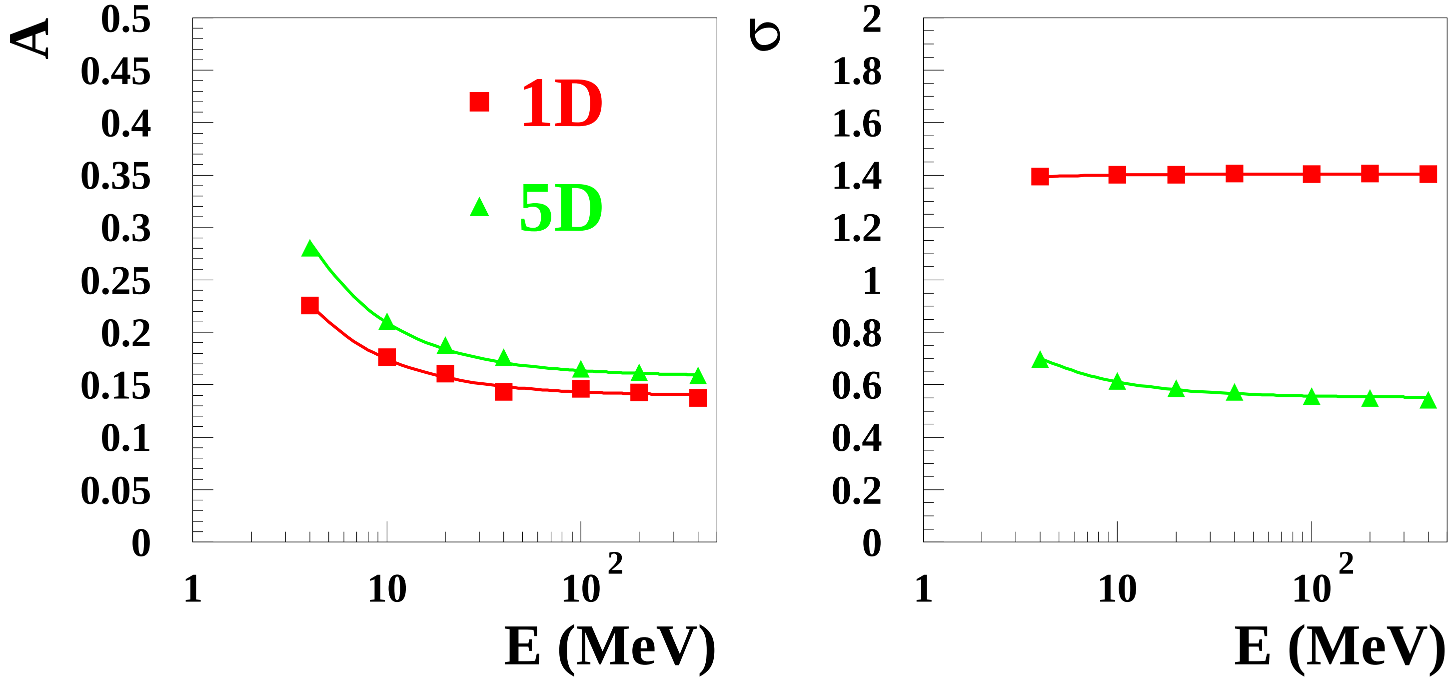
Polarimetry: Optimal Measurement

- 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" $p(\Omega) = (1 + \mathcal{A}P\cos[2(\phi)])$:

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

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

Polarization asymmetry and measurement uncertainty



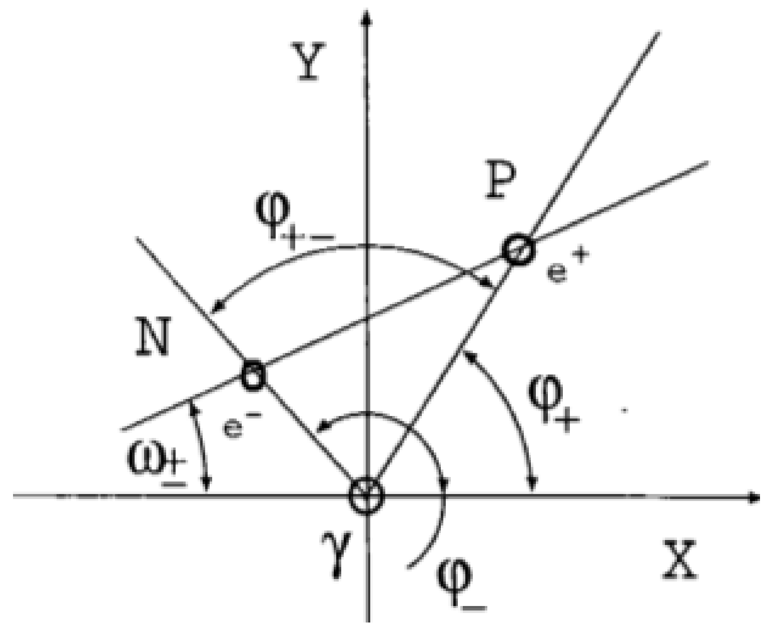
Nucl. Instrum. Meth. A 729 (2013) 765

- Asymptotically $\mathcal{A} \approx 1/7 \approx 14\%$. Boldyshev & Peresunko, Yad. Fiz. 14, 1027 (1971).

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

Polarimetry: Defining the Azimuthal Angle ?

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

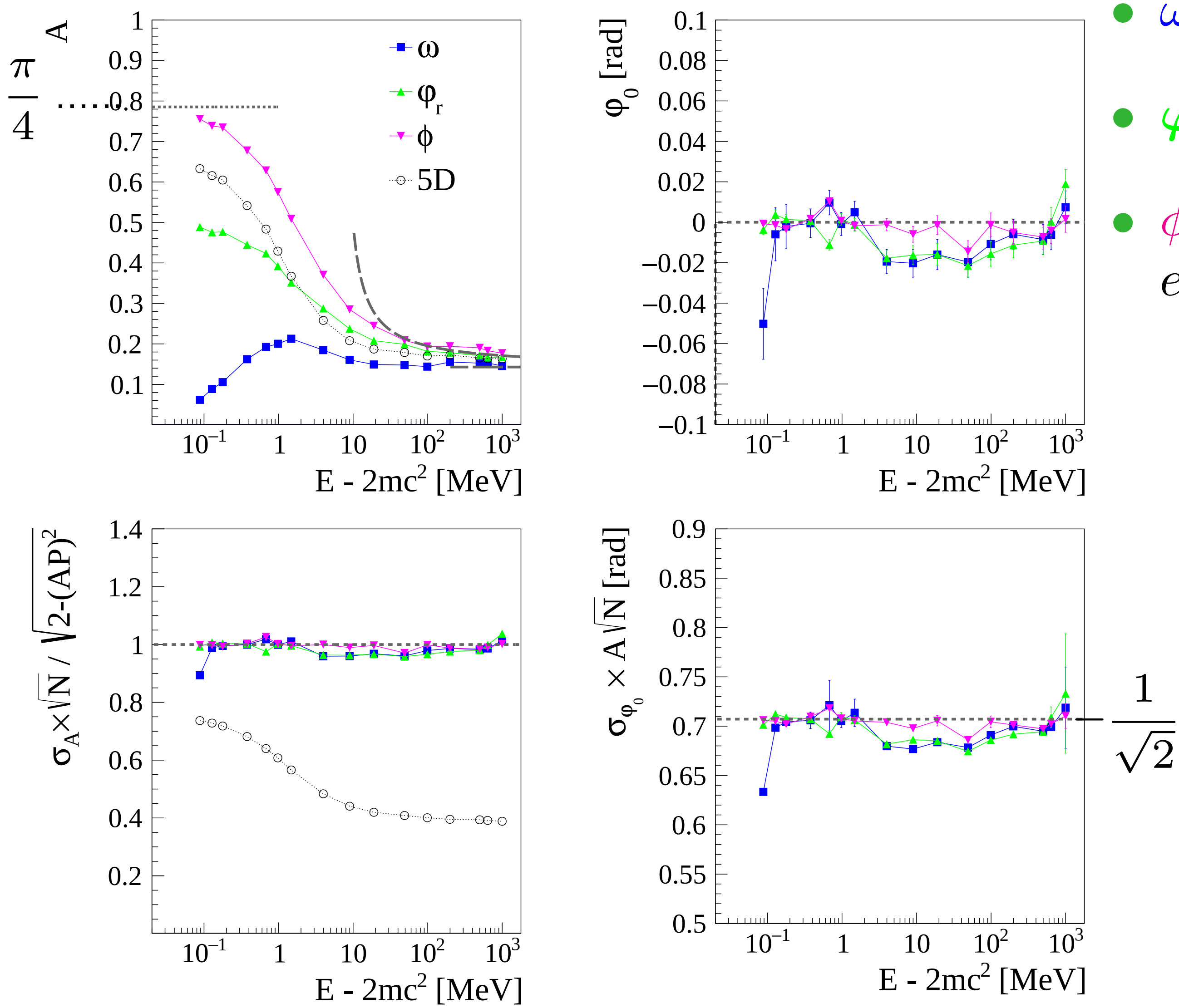


"polarized beams and polarimeters", B. Wojtsekhowski (2000)

- φ_r recoil angle, $\varphi_r = \varphi_{\rm pair} \pm \pi$
- $\phi = (\varphi_+ + \varphi_-)/2$, 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

loss factor wrt ϕ

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

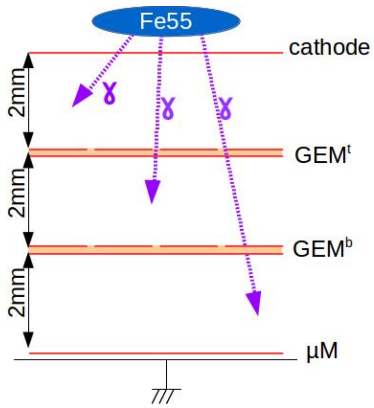
Ph. Gros & D. Bernard,

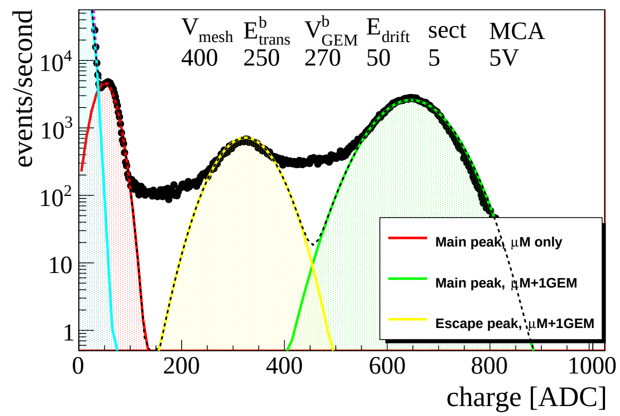
Astropart. Phys. 88 (2017) 30

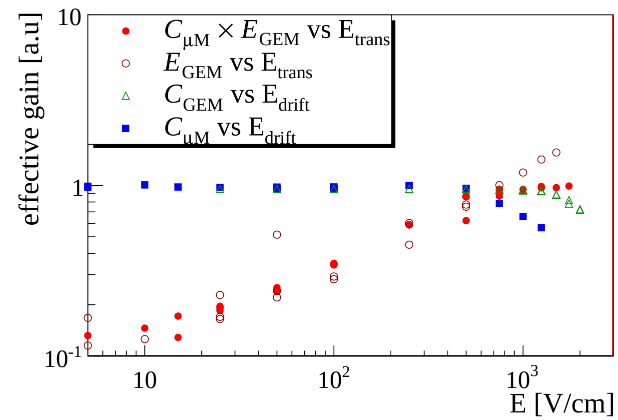
We checked that on a $P = 0$ MC sample, the measured value is found to be $\mathcal{A} \times P \approx 0$
We checked that form factors do not affect the polarization asymmetry

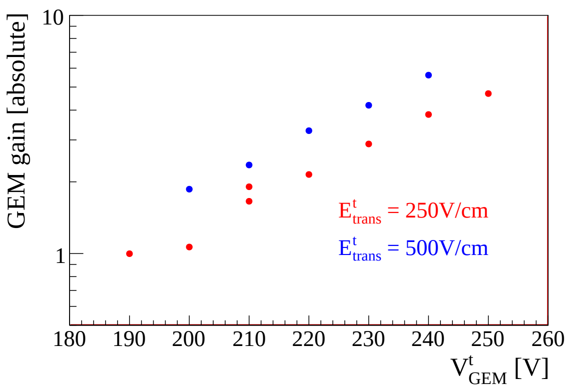
Micromegas + 2 GEM assemblies: characterization

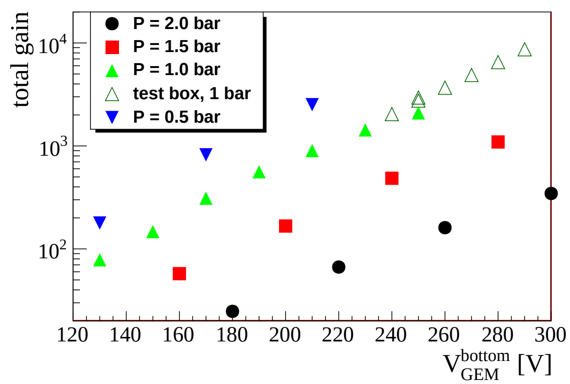
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)





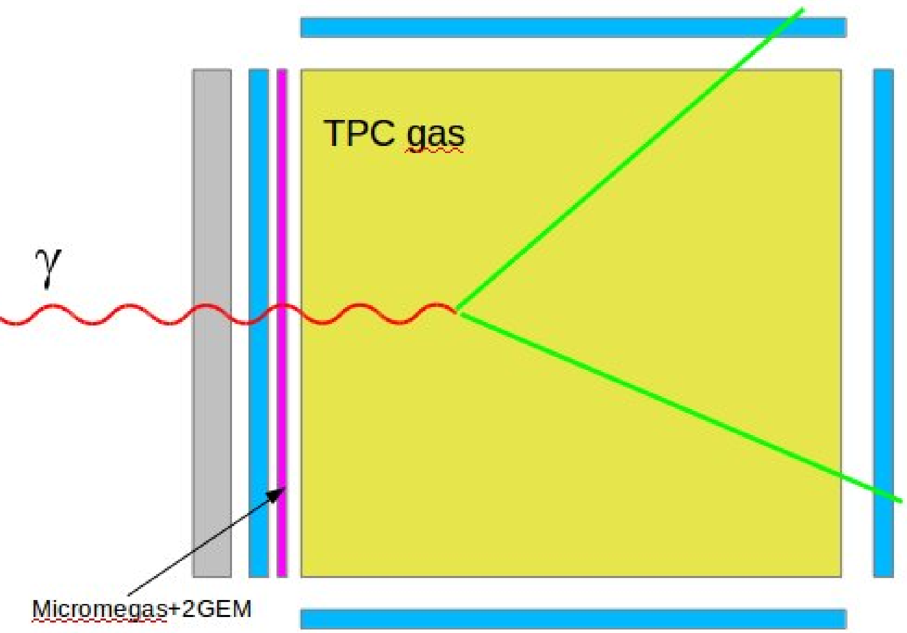


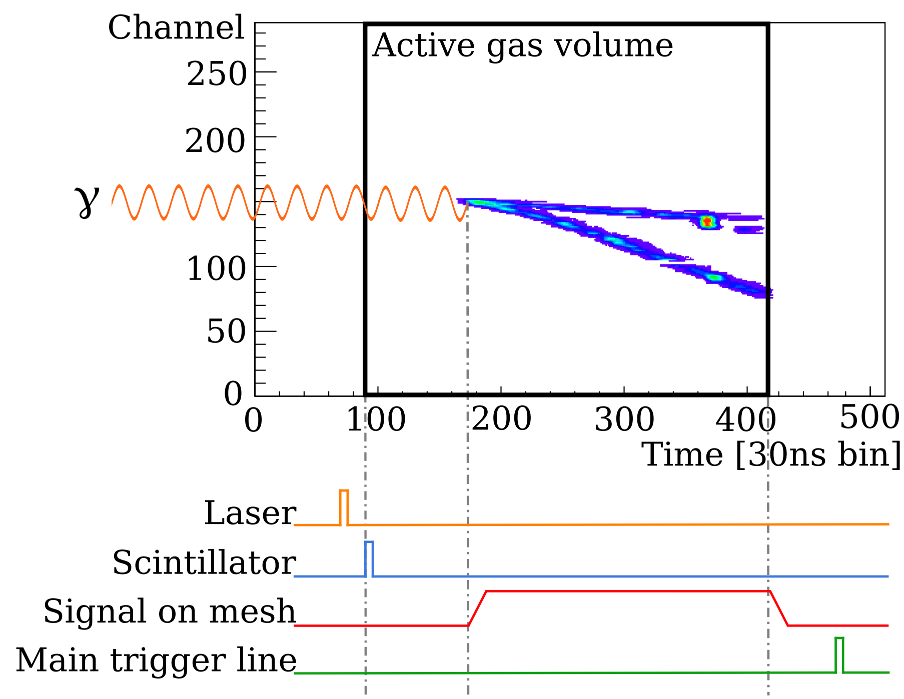




Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

"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

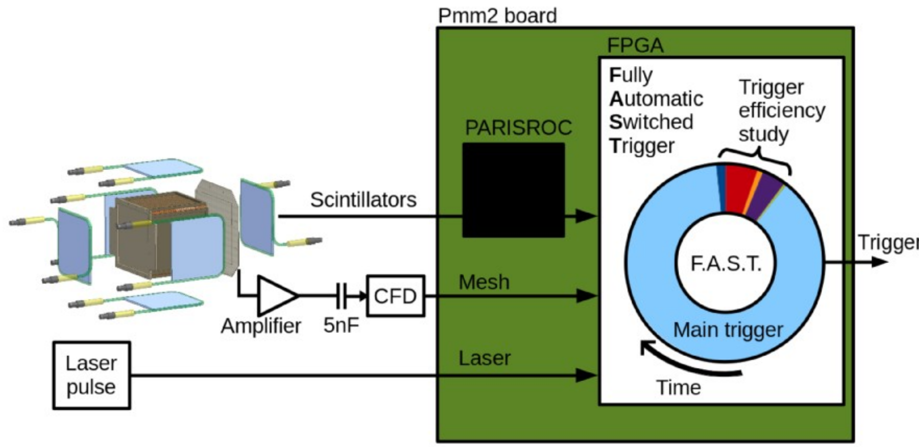
"Main line": $T_{\gamma,laser} = \overline{S}_{up} \cap O \cap M_{slow} \cap L$

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	$T_{noLaser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap \overline{L}$

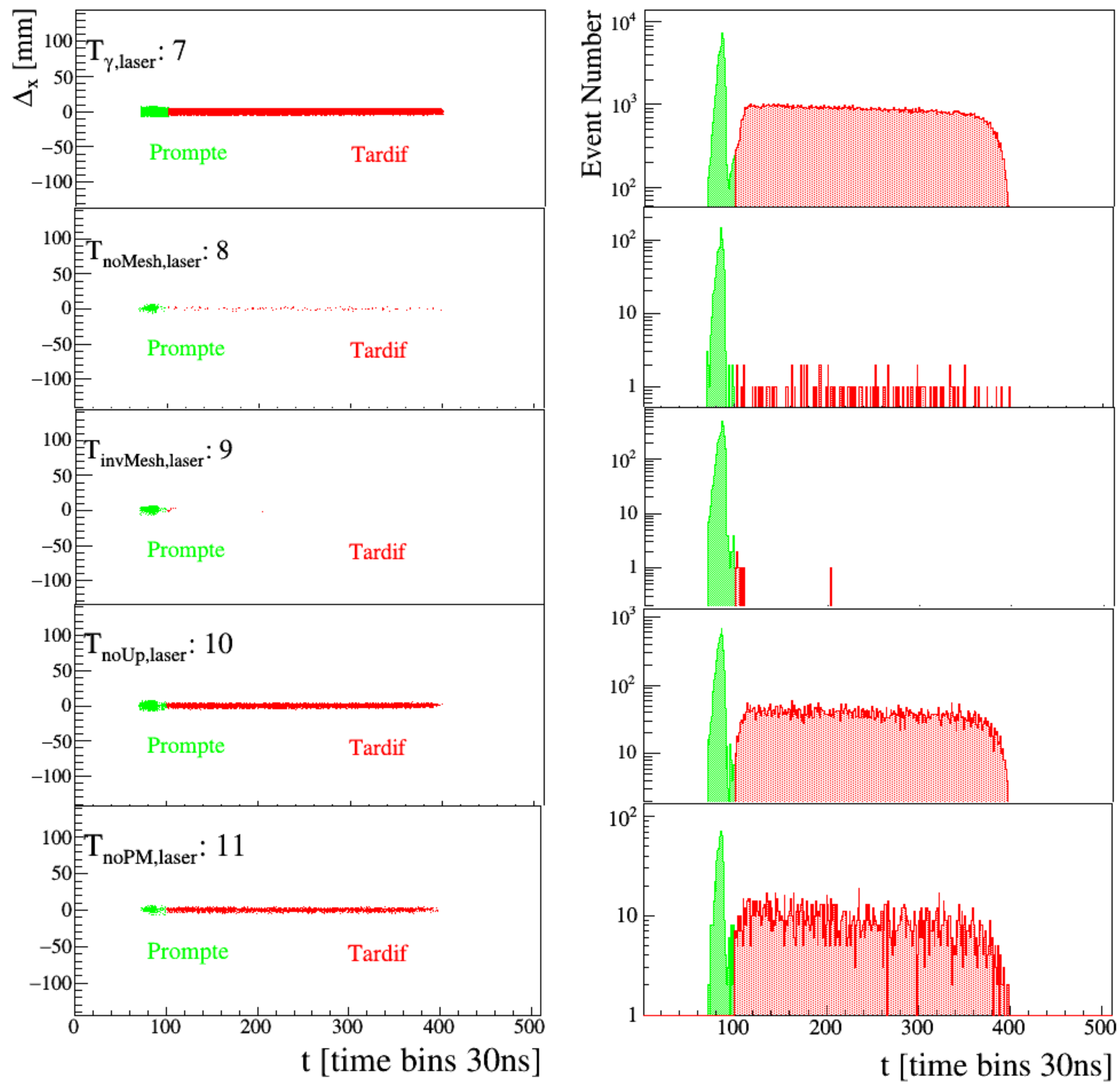


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

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

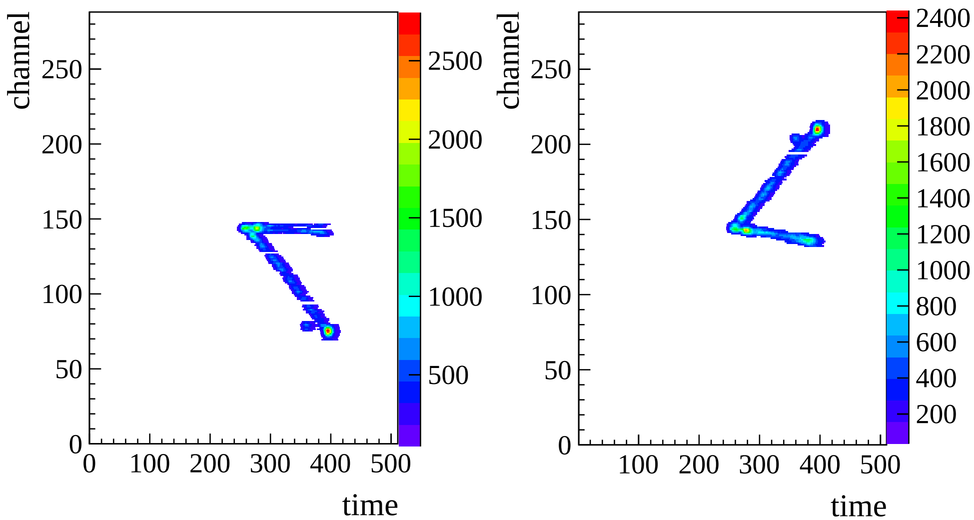


S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015, in French

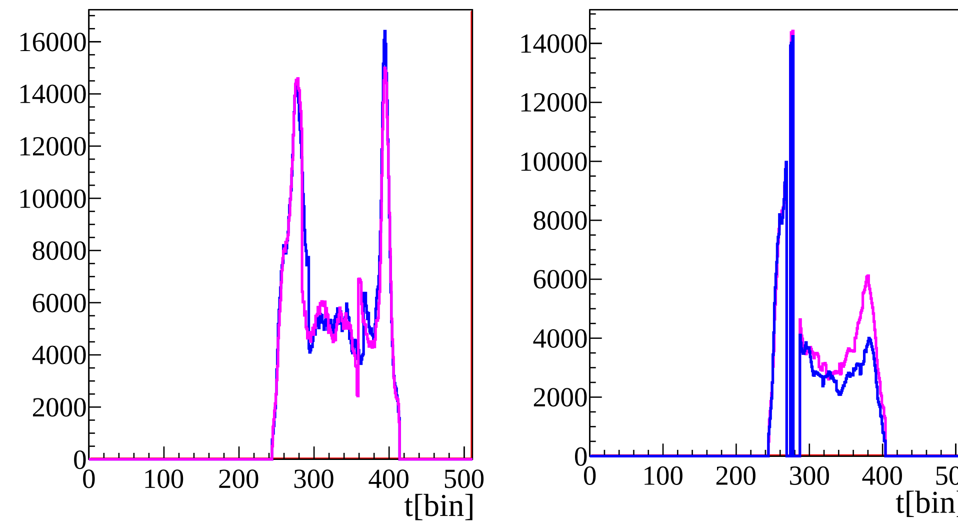
Track matching

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

raw "maps"



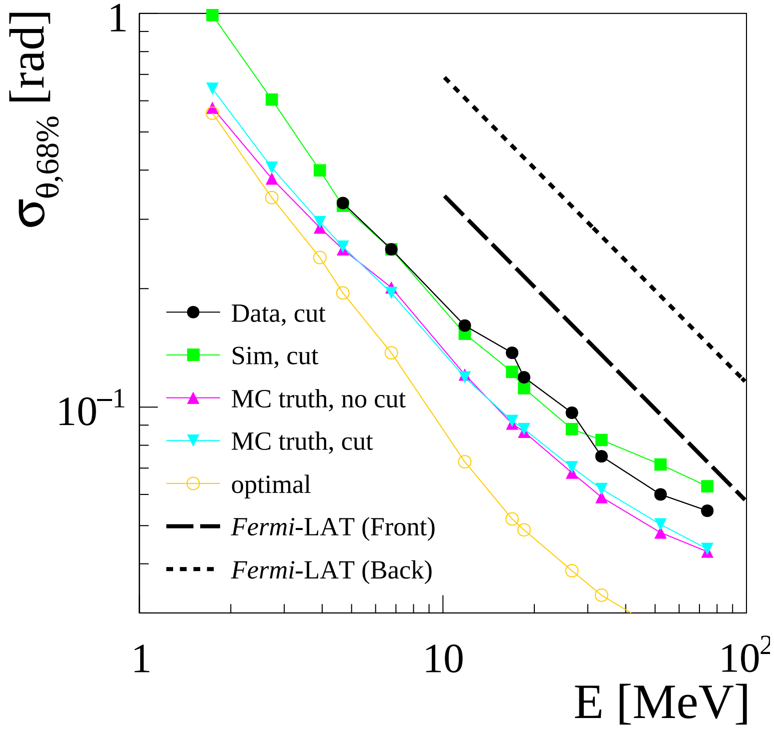
track time spectra

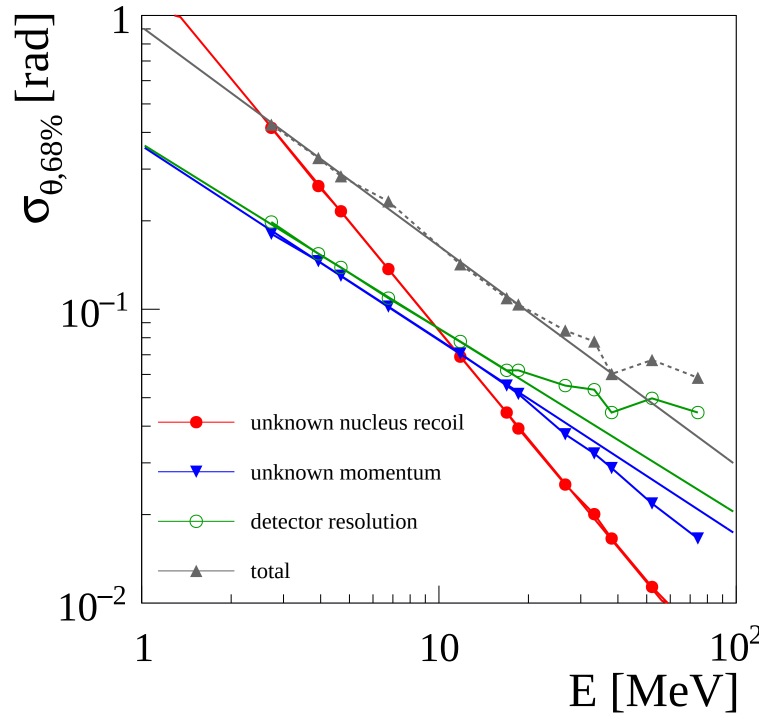


- x, y two-track ambiguity solved by track time spectra matching
- 1 channel $=$ 1 mm.
- 1 time bin $=$ 30 ns, $v_{\text{drift}} \approx 3.3\,\text{cm}/\mu\text{s}$ $\Rightarrow$ 1 time bin $\propto 1\,\text{mm}$

12th Pisa Meeting on Advanced Detectors, Elba, 2012, NIM A 718 (2013) 395

Angular resolution

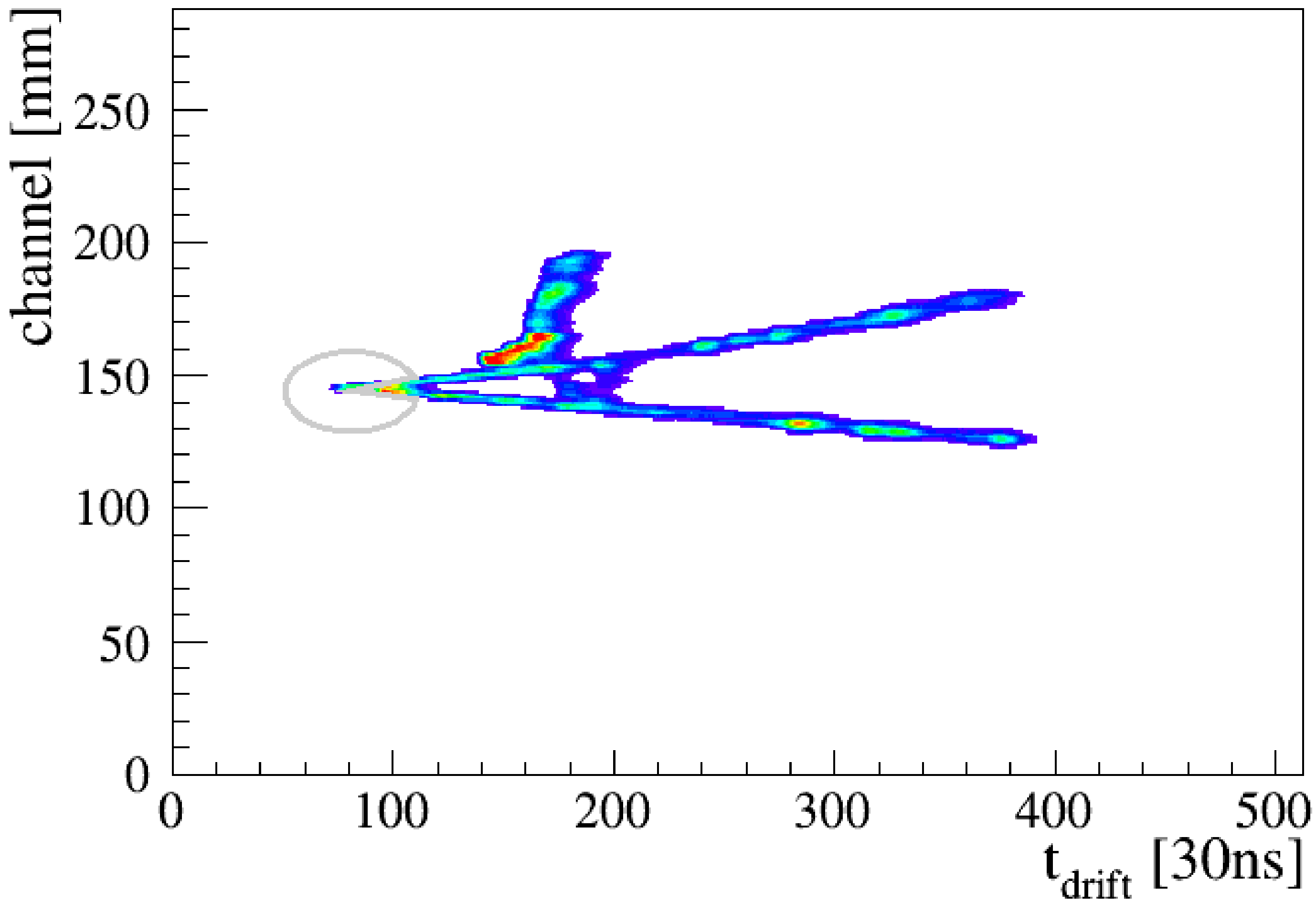




Optimal: QED. (nucleus recoil)

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

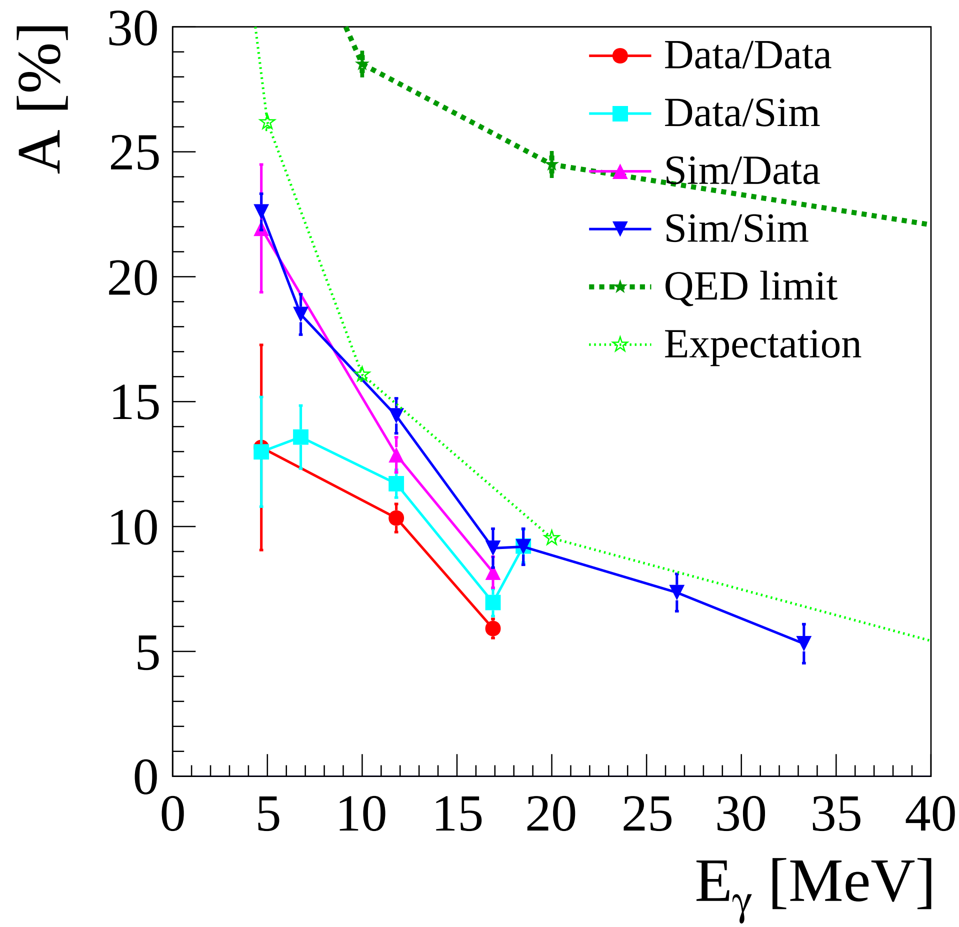
Event reconstruction



- Pseudo-tracking: vertex analysis

P. Gros, TPC 2016 conference, Paris, Dec. 2016, procs JPCS

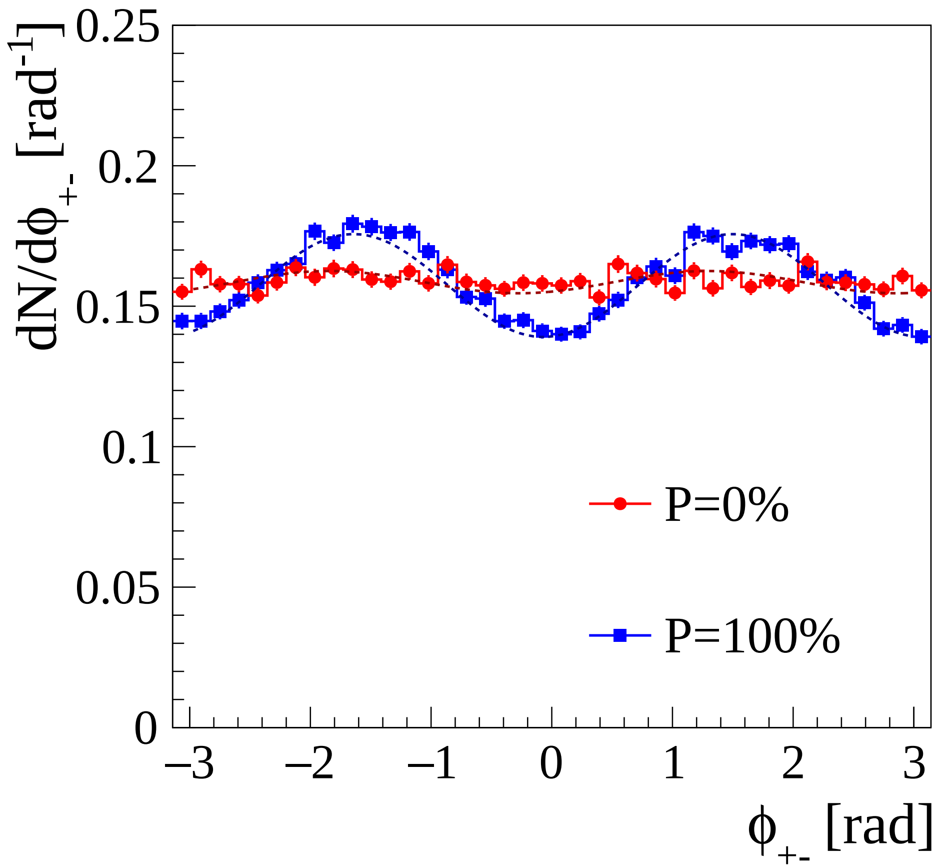
Polarization asymmetry dilution



- 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

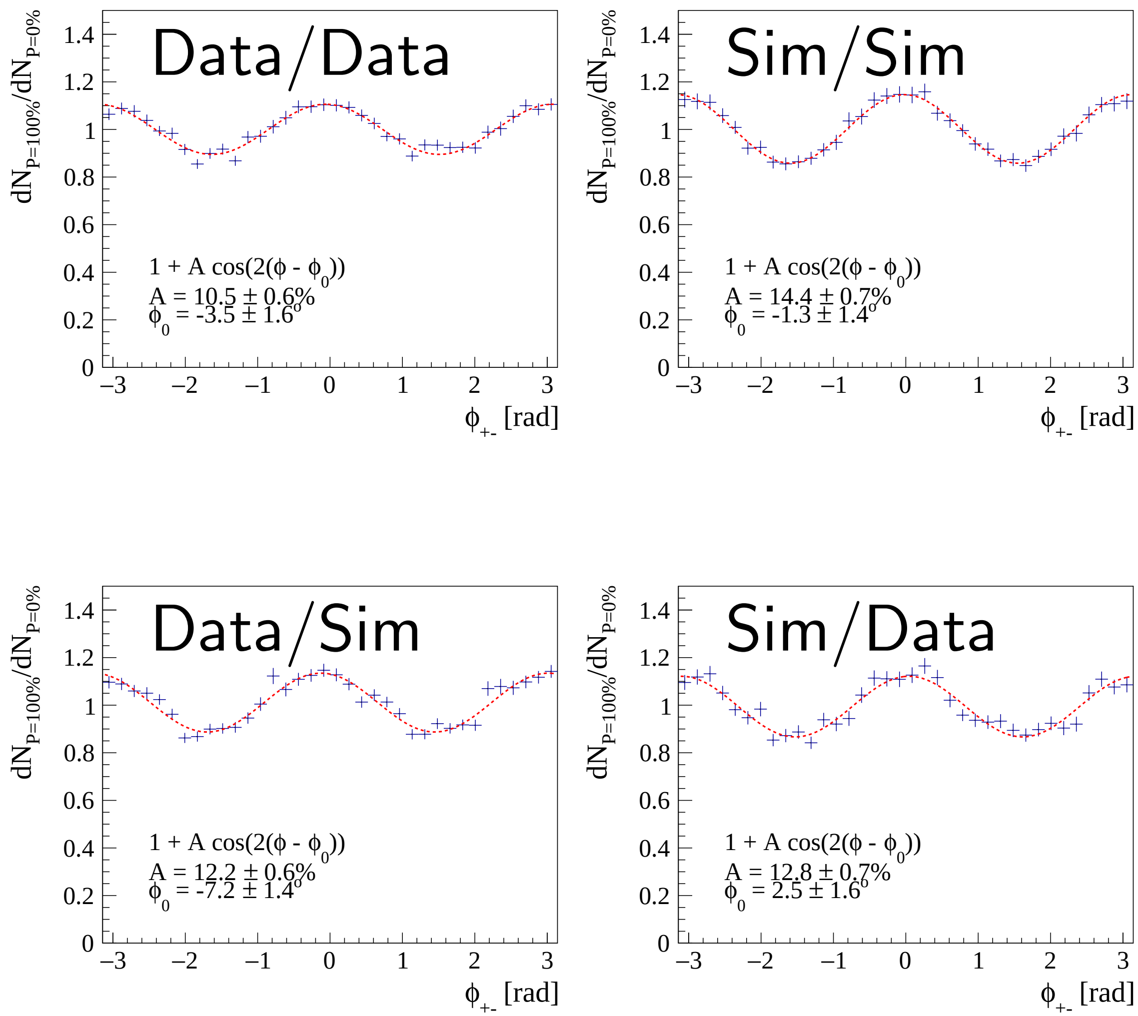
Absence of polarization bias for time-averaged data taking in orbit



- Simulated distribution of ϕ_{+-} for $11.8\,\mathrm{MeV}$ photons, for isotropic photons.
- The interaction points are uniformly distributed in the detector.

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

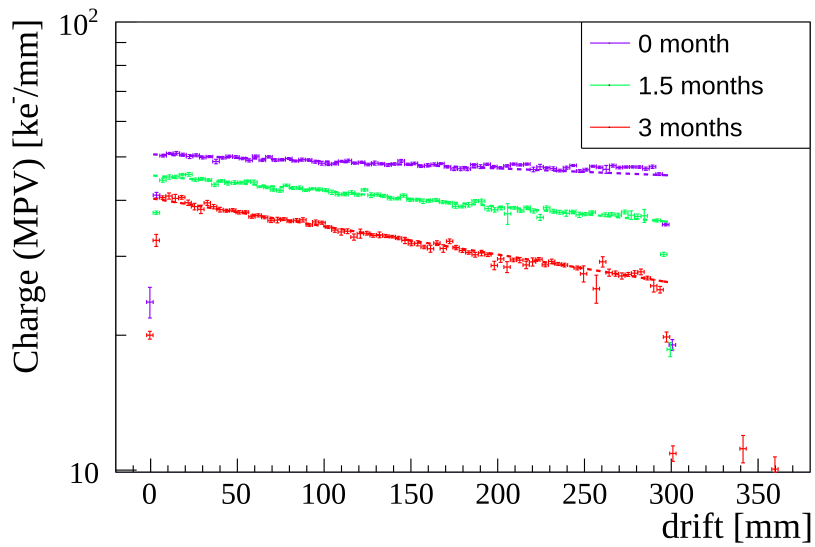
Bias correction by normalization to $P = 0$ distribution: effectiveness of Monte Carlo simulation



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).

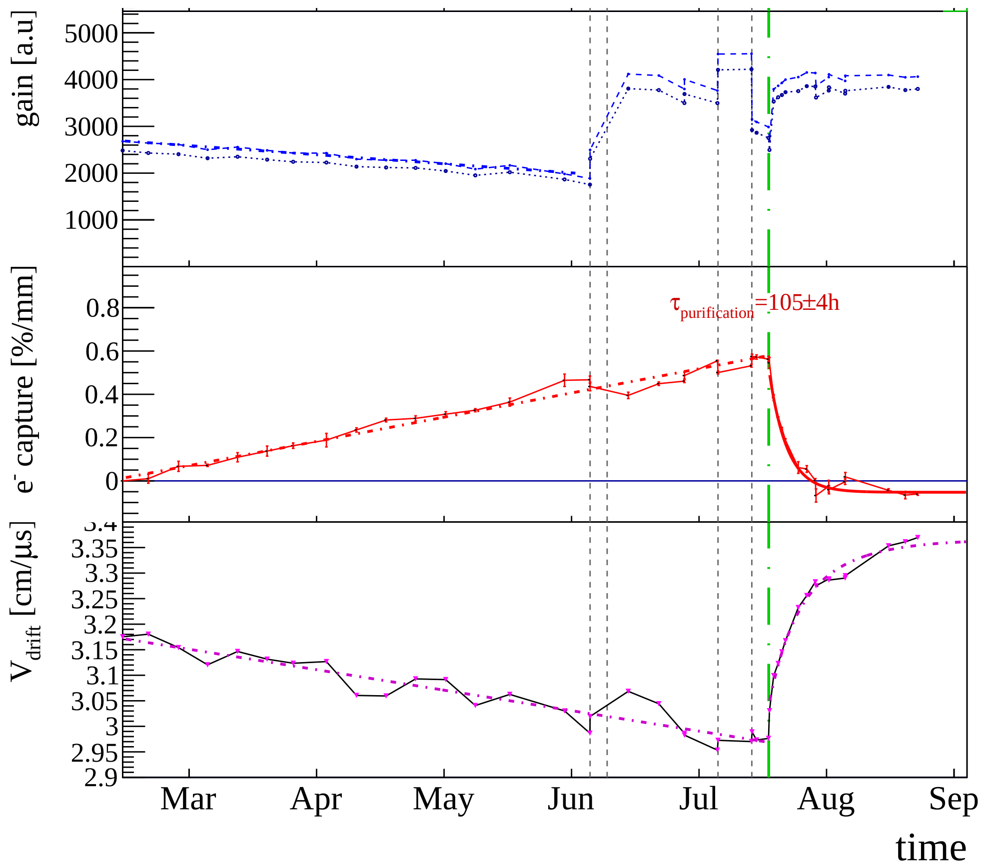


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

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

Gas purity on the long term: results



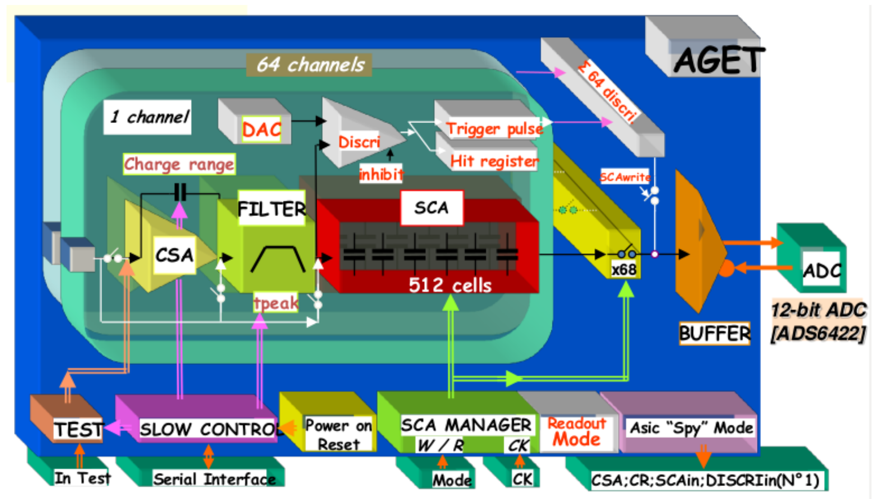
vertical lines: amplification voltage ajustments.

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 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 μs
- 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 → 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