Linear Polarimetry with $\gamma \rightarrow e^+e^-$ conversions

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Polarised Emission from Astrophysical Jets,
12-16 June 2017, Ierapetra, Greece

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

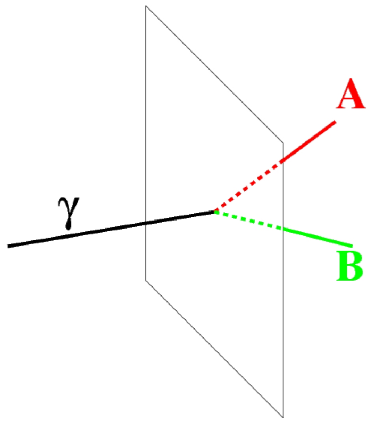
One Workshop, 3 presentations

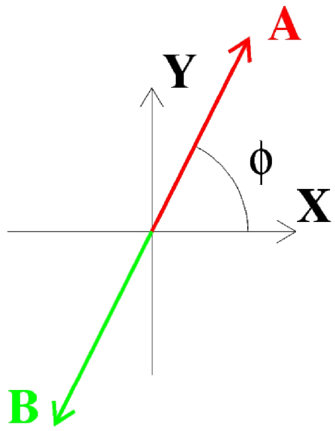
- What I had planned
  - Poster : High angular-resolution high sensitivity γ-ray astronomy and linear polarimetry with low density (gas) detectors in the MeV-GeV energy range
    - Talk : A Bethe-Heitler 5D polarized $\gamma \rightarrow e^+e^-$ conversion event generator
    - Poster : γ-ray astronomy with magnetic-field-free active targets: Optimal measurement of charged particle momentum from multiple scattering with a Bayesian analysis of filtering innovations
- Talk refurbished : some elements on γ-ray polarimetry with e^+e^- pairs.
- γ-ray polarimetry for jet astrophysics science case : see Haocheng's talk.

High-energy Polarimetry

- Here photons detected individually (Photo-electric, Compton, pair production)
- $J^{PC} = 1^{--}$:

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





  - P (cosmic source) linear polarisation fraction
  - ϕ_0 (cosmic source) polarisation angle
  - $\mathcal{A}$ (conversion process) polarization asymmetry
  - ϕ (event) azimuthal angle

- Polarimetry by analysis of ϕ distribution

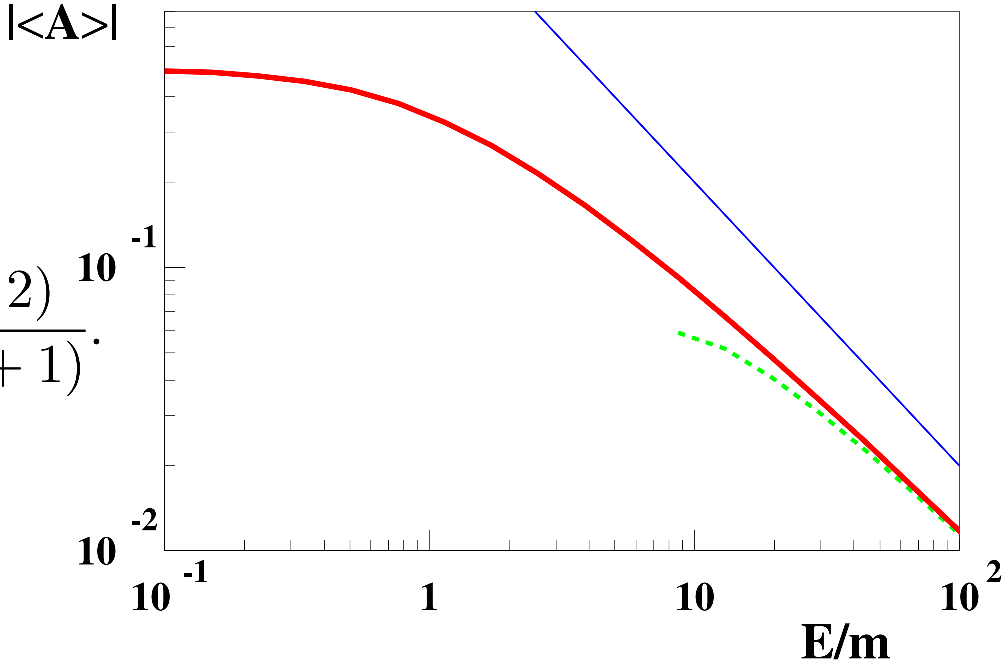
Compton scattering : Polarisation Asymmetry

Current and past Compton telescopes sensitive below 1 MeV

- Cross section decreasing
- Polarization asymmetry :
  - Exact expression
  - HE approximation

$$\langle \mathcal{A} \rangle = -\frac{4(\log 2k_0 - 2)}{k_0(2\log 2k_0 + 1)}.$$

  - $\langle \mathcal{A} \rangle \approx -\dfrac{2}{k_0}.$



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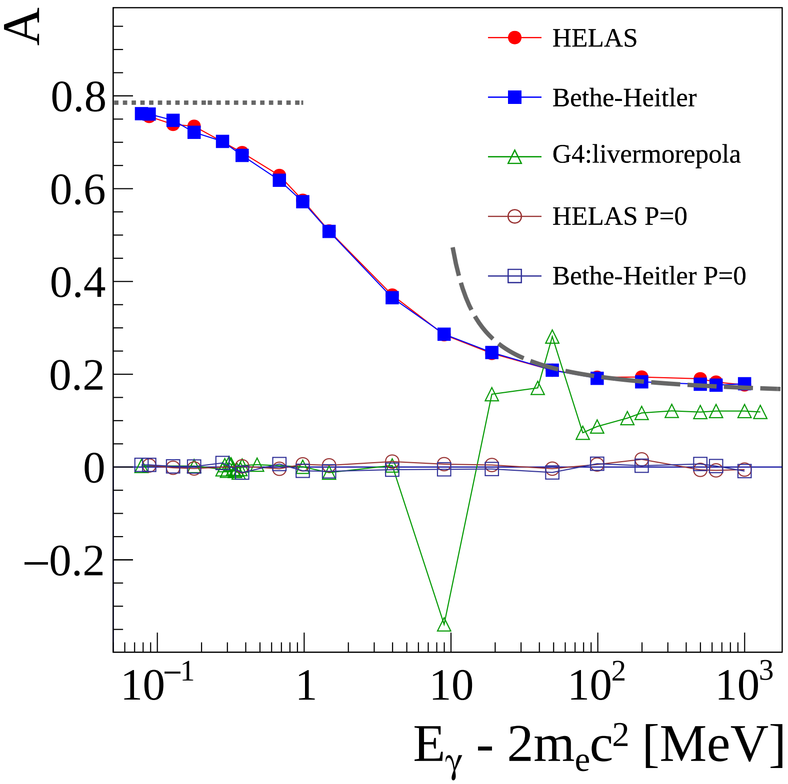
Pair Conversion : Polarisation Asymmetry

- HELAS : all Feynman diagrams
- Bethe-Heitler analytical expression

  (2 dominant diagrams)



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Asymptotes :

- Low energy

$$A = \frac{\pi}{4}.$$

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- High energy

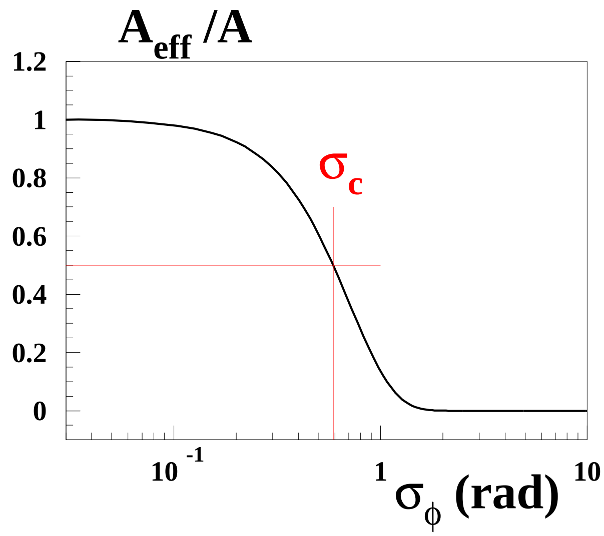
$$A \approx \frac{\frac{4}{9}\ln 2E - \frac{20}{28}}{\frac{28}{9}\ln 2E - \frac{218}{27}} \rightarrow \frac{1}{7} \approx 0.14$$

V. F. Boldyshev et al., Yad. Fiz. **14** (1971) 1027, (Sov.J.Nucl.Phys. **14** (1972) 576).

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

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

$\Rightarrow \mathcal{A}_{\text{eff}} = \mathcal{A} \; e^{-2\sigma_\phi^2}$

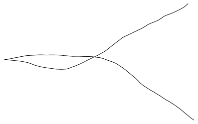


- azimuthal angle RMS $\sigma_\phi = \dfrac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$,
  - $\theta_0 \approx \dfrac{13.6\,\text{MeV}/c}{\beta p} \sqrt{\dfrac{x}{X_0}}$,
  - most probable opening angle $\hat{\theta}_{+-} = 1.6\,\text{MeV}/E$ Olsen, PR. 131, 406 (1963).

$\Rightarrow \sigma_\phi \approx 24\,\text{rad} \sqrt{x/X_0}$ (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 $\gamma Z \rightarrow e^+ e^-$



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
- $\sigma_{\theta,\mathrm{track}} = (p/p_1)^{-3/4}$, angular resolution due to multiple scattering
  - $p_1 = 13.6\,\mathrm{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$, Argon ($\sigma = l = 1\mathrm{mm}$): $p_1 = 50\,\mathrm{keV}/c$ (1 bar),

    $p_1 = 1.45\,\mathrm{MeV}/c$ (liquid).
- $\hat{\theta}_{+-} = 1.6\,\mathrm{MeV}/E$ most probable opening angle
- $\sigma_\phi = \left[x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}}\right] \frac{(p_1)^{\frac{3}{4}} E^{\frac{1}{4}}}{1.6\,\mathrm{MeV}}$. 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

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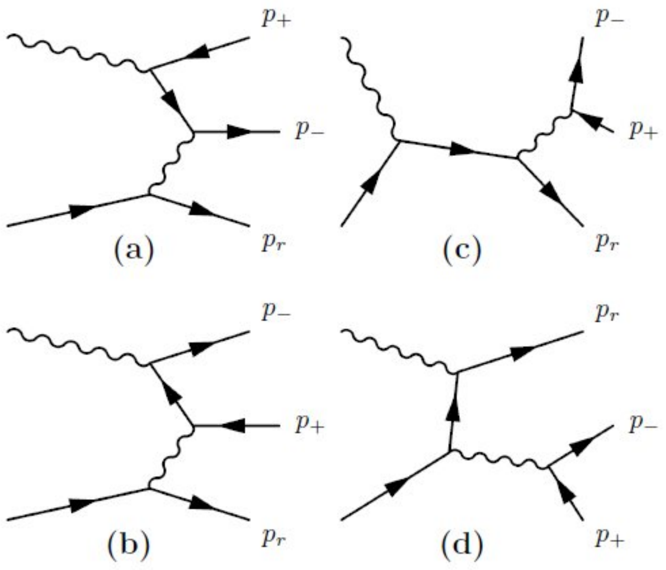
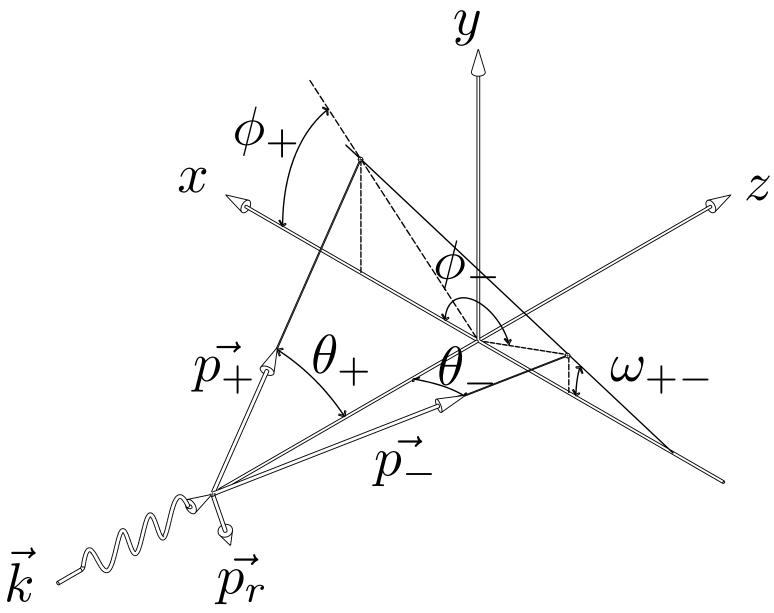
Developed, Validated, Event Generator

- 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 $x_+ \equiv E_+/E$





- Uses:
  - HELAS amplitude computation H. Murayama, *et al.*, KEK-91-11.
  - SPRING event generator S. Kawabata, Comput. Phys. Commun. **88**, 309 (1995).
- Validation against published 1D distributions (nuclear and triplet conversions)

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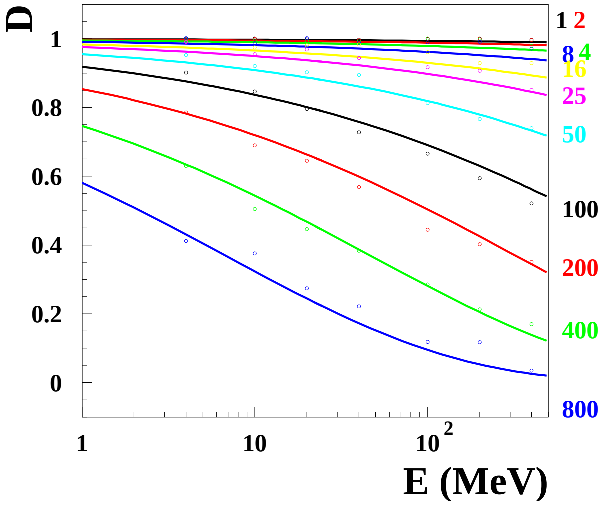
Dilution of Polarization Asymmetry due to Multiple Scattering: Optimal Fits and Full MC

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

- $D \equiv \dfrac{\mathcal{A}_{\text{eff}}(p_1)}{\mathcal{A}(p_1 = 0)}$



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

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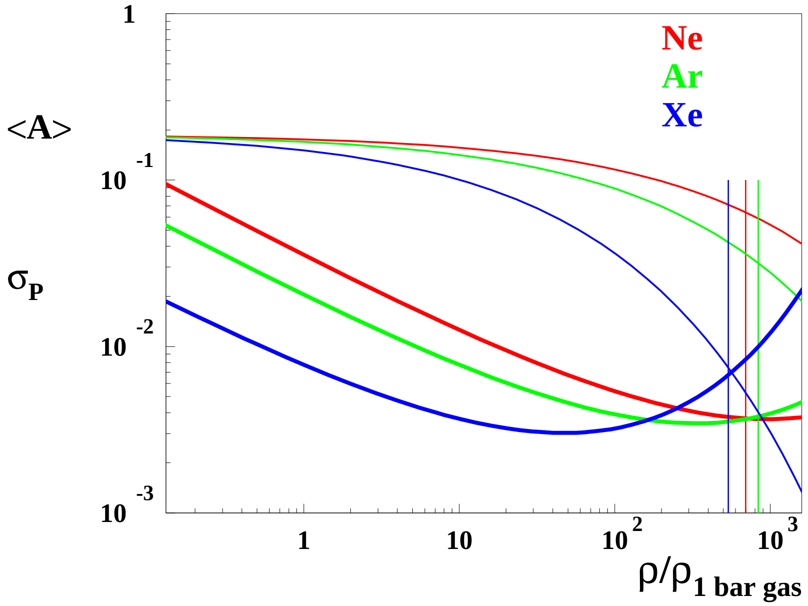
Polarimetry Performance

- 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, $\mathcal{A}_{\text{eff}} \approx 15\%$, $\sigma_P \approx 1.0\%$,
- With experimental cuts: $\epsilon = 45\%$, $\mathcal{A}_{\text{eff}} \approx 16.6\%$, $\sigma_P \approx 1.4\%$,

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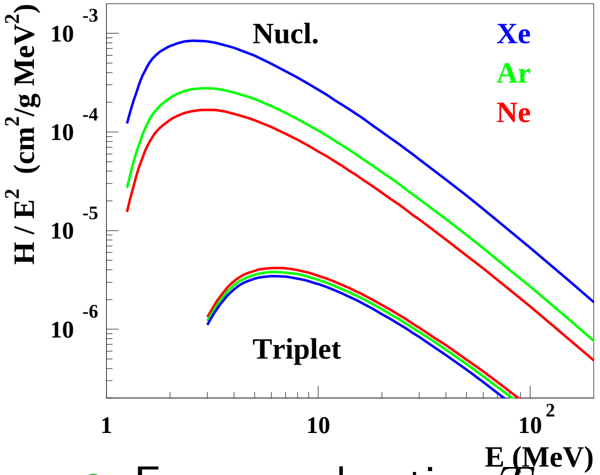
Polarization sensitivity in a nut shell

- Effective area $A_{\mathrm{eff}} = H \times M$, $V = 1\,\mathrm{m}^3$, 5 bar argon, $M = 8.3\,\mathrm{kg}$
- Crab-like source, $\Gamma = 2$, $E^2 \dfrac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}t\mathrm{d}S} = F = 10^{-3}\mathrm{MeV\,cm}^{-2}\mathrm{s}^{-1}$.



	Ne	Si	Ar	Ge	Xe
$\int \frac{H(E)}{E^2}\mathrm{d}E$ $\mathrm{cm}^2/(\mathrm{g\,MeV})$	0.0019	0.0027	0.0032	0.0053	0.0083

- Exposure duration $T = 1$ year, exposure fraction $\eta = 1$
- Polarimetry sensitive for bright sources : zero background assumption
- $N = \eta T M F \displaystyle\int \frac{H(E)}{E^2}\mathrm{d}E \approx 830\,000$ events, $A \approx 0.2$, $\sigma_P \approx \dfrac{1}{\mathcal{A}}\sqrt{\dfrac{2}{N}} \approx 0.01$.
- Reasonable $\eta \approx 1/7$, (7 year, $1\,\mathrm{m}^3$) or (1 year, $7\,\mathrm{m}^3$) → $\sigma_P \approx 0.01$.
- year → day, $0.01 \rightarrow 0.20$

Pair conversion : circular polarimetry ?

- γ-ray circular polarization does not take part in the electron-polarization-averaged differential cross section

  (to first order Born approximation)

- γ-ray circular polarization transfered to electron and positron polarization

  V. V. Bytev et al., JETP Lett. **75** (2002) 452, [Pisma Zh. Eksp. Teor. Fiz. **75** (2002) 542]

- Polarization analysis would need magnetized detectors

  I. Sakai et al., in Proceedings of the 21st ICFA Workshop, Stony Brook, 2001.

On a space mission : nope, IMHO.

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,
Patrick Sizun, 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

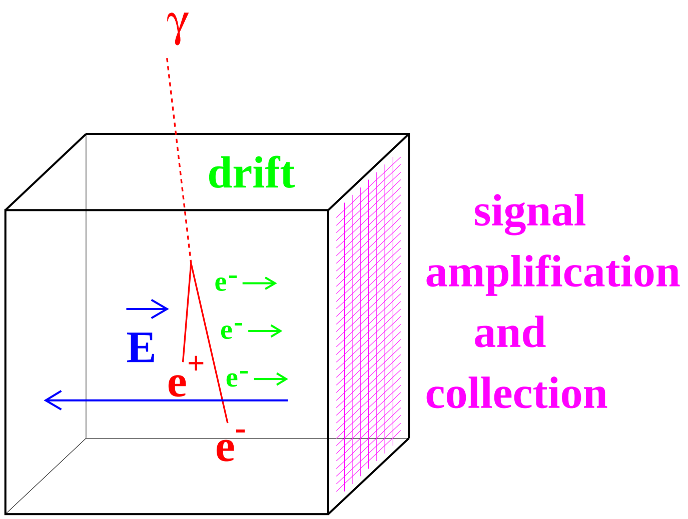
- Japan: the beam.

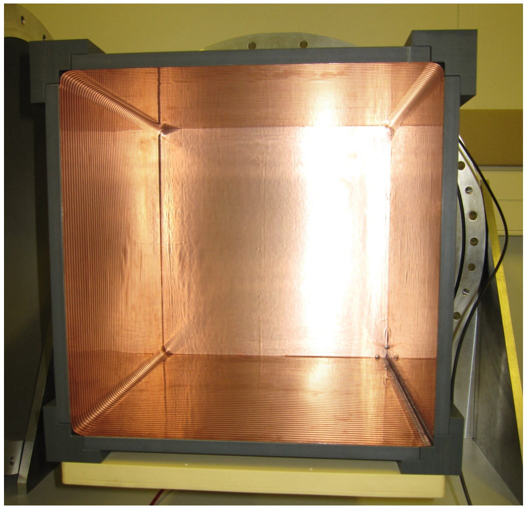
S. Amano, T. Kotaka, S. Hashimoto, Y. Minamiyama, A. Takemoto, M. Yamaguchi,
S. Miyamoto[e]
[e] LASTI, University of Hyôgo, Japan

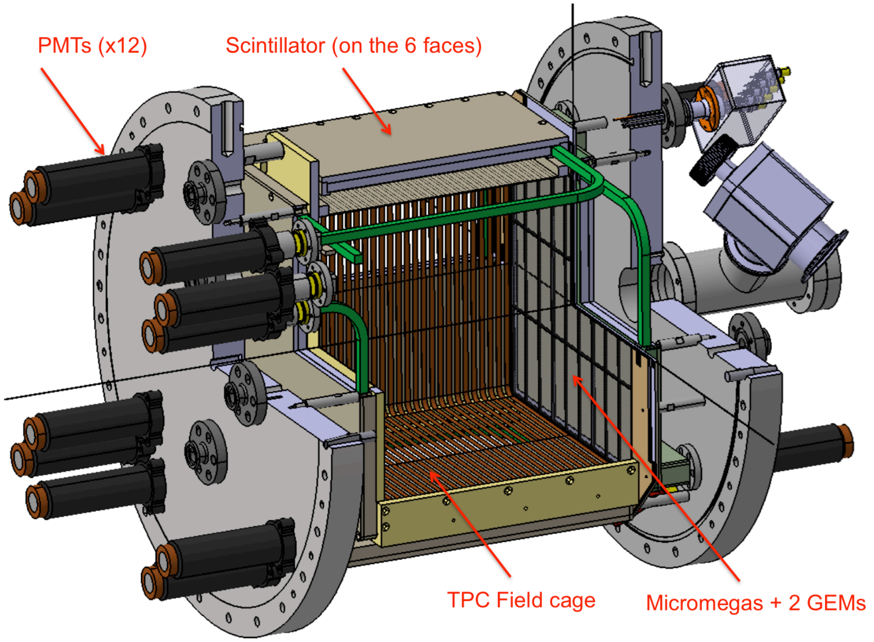
S. Daté, H. Ohkuma[f]
[f] JASRI/SPring8, Japan

HARPO: the Demonstrator

- Time Projection Chamber (TPC)
- $(30\mathrm{cm})^3$ 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



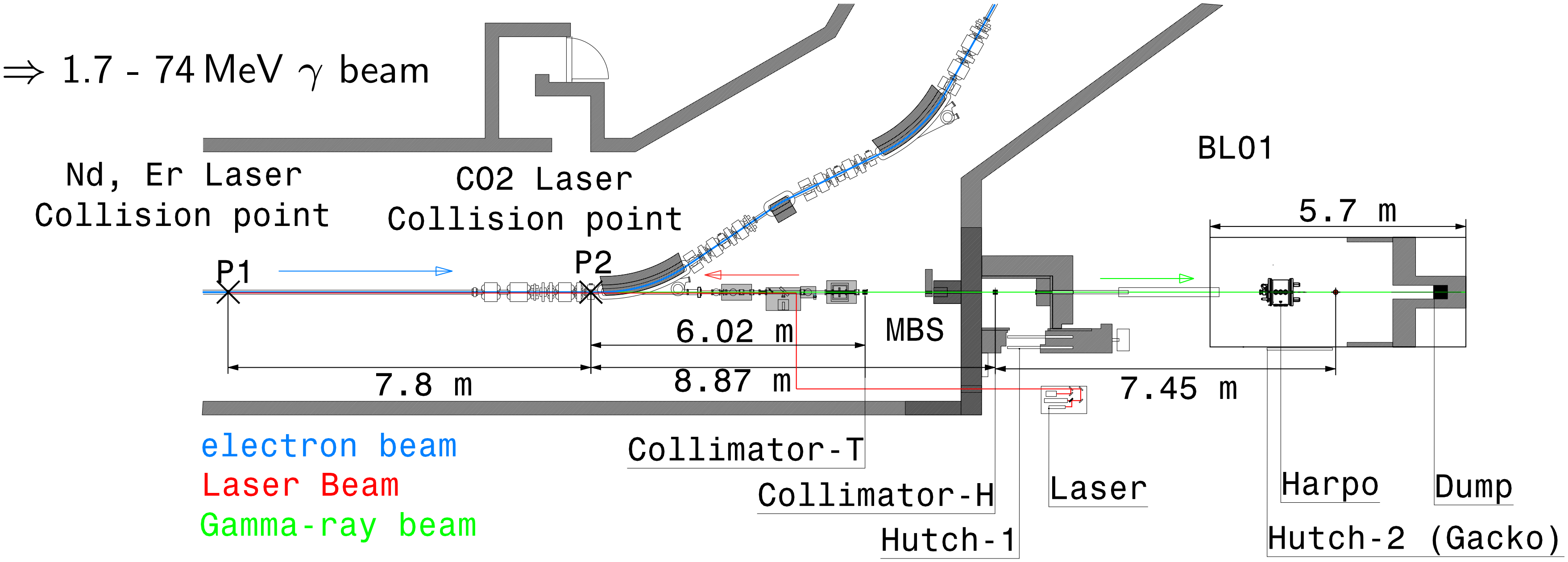




NIM A 695 (2012) 71,   NIM A 718 (2013) 395

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

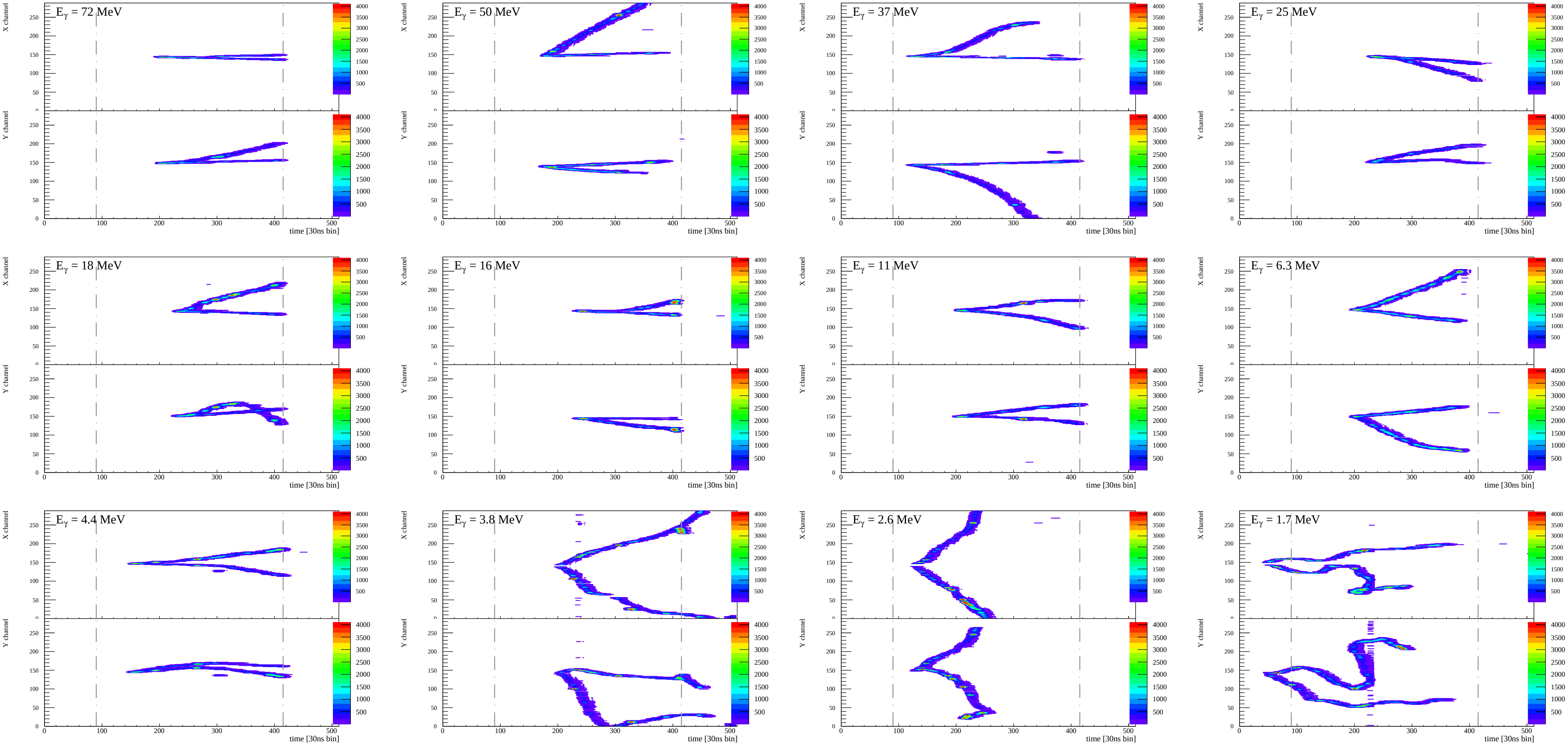
- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- $0.532\,\mu\mathrm{m}$ and $1.064\,\mu\mathrm{m}$ $20\,\mathrm{kHz}$ pulsed Nd:YVO_4 (2ω and 1ω),
  $1.540\,\mu\mathrm{m}$ $200\,\mathrm{kHz}$ pulsed Er (fibre) and
  $10.55\,\mu\mathrm{m}$ CW CO_2 lasers
- $\Rightarrow$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

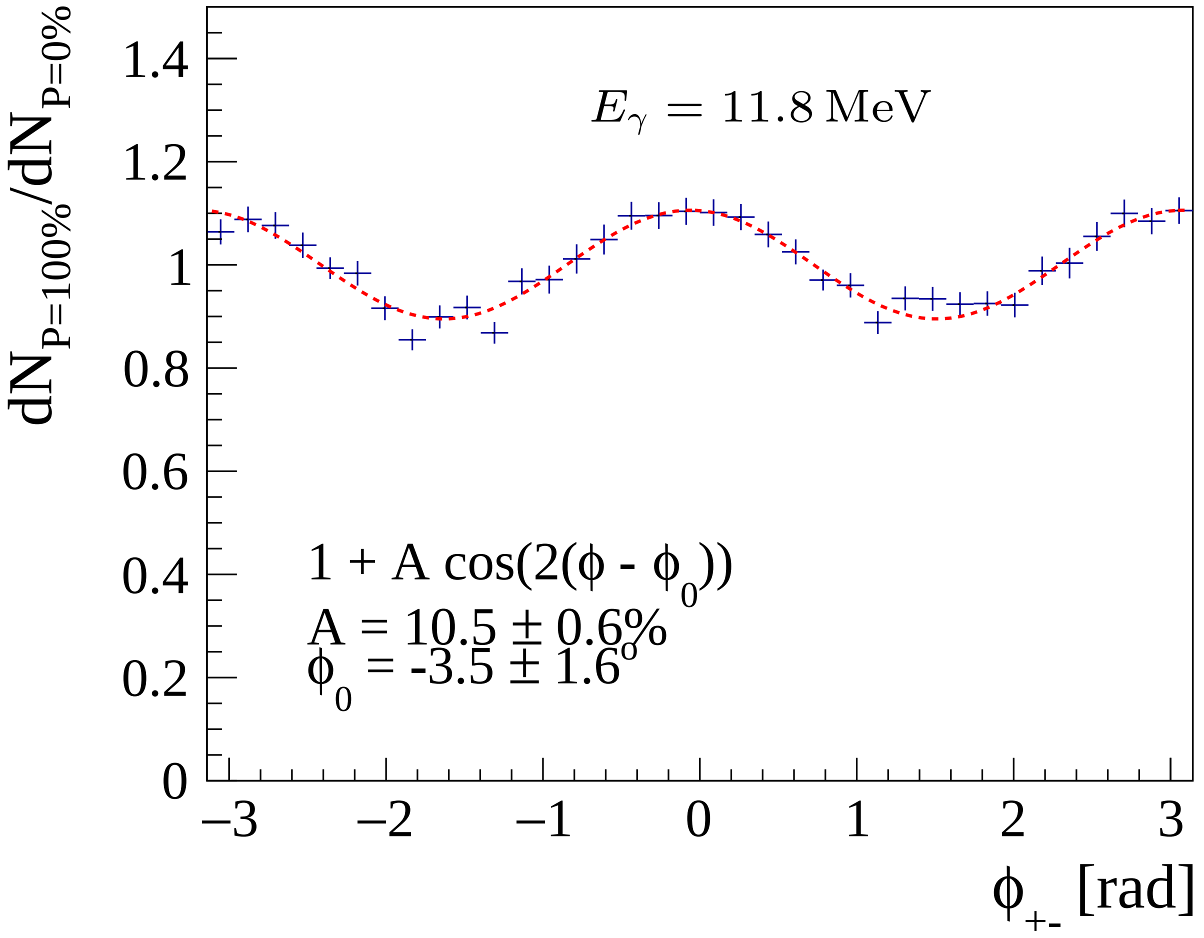
Japan beam Data: gallery



Sample of γ-rays from 74 to 1.7 MeV converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5 detected by the HARPO TPC

(pre-beam-calibration γ-ray energy on plots)

Polarimetry : HARPO results



$11.8\,\mathrm{MeV}$ γ-rays converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5

Preliminary, publication in preparation

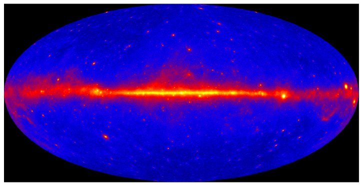
Conclusion

- Gas TPC is THE choice detector for ultimate angular resolution $\gamma \rightarrow e^+e^-$ astronomy and polarimetry
- 4π acceptance detector, low pile-up, zero deadtime
- Data taken:
  - with a $(30\mathrm{cm})^3$ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
  - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, γ beam
- First demonstration of low energy $(E < 1\,\mathrm{GeV})$ γ-ray polarimetry with pairs
- Cosmic-source polarisation-fraction precision statistics dominated.

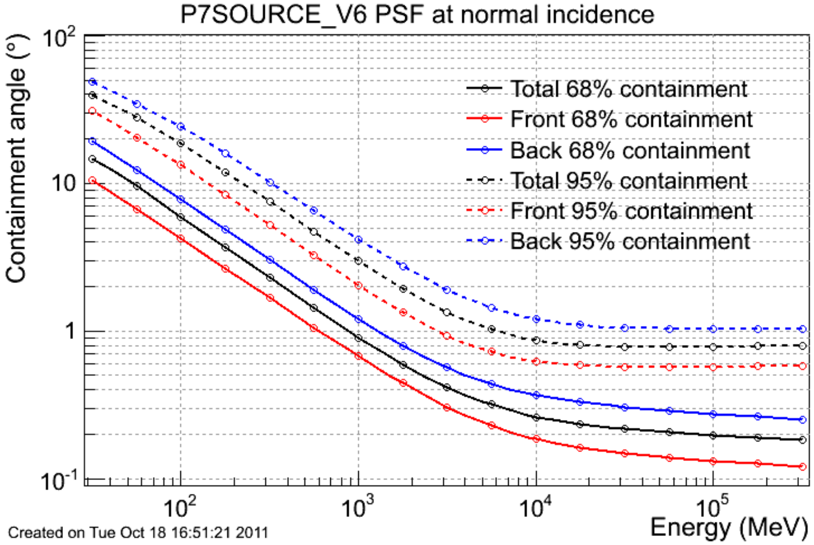
Thanks

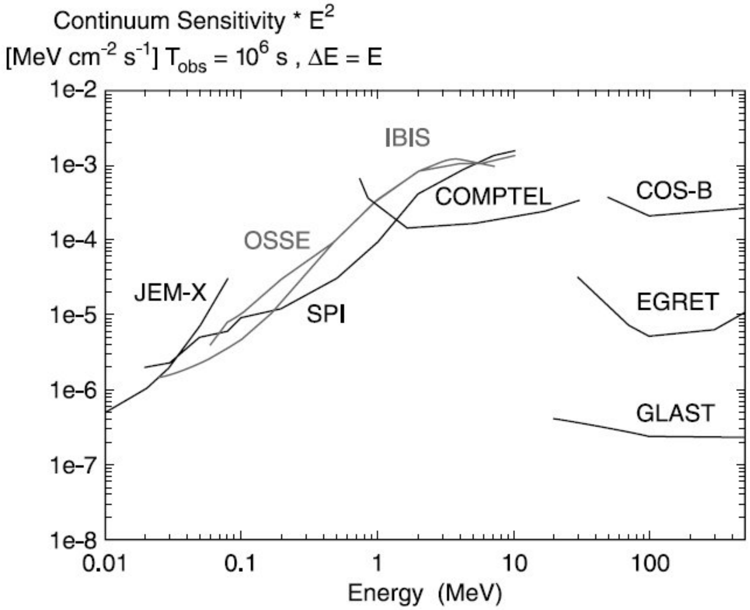
Back-up Slides

Non polarized astronomy



- Improve angular resolution – crowded sky regions



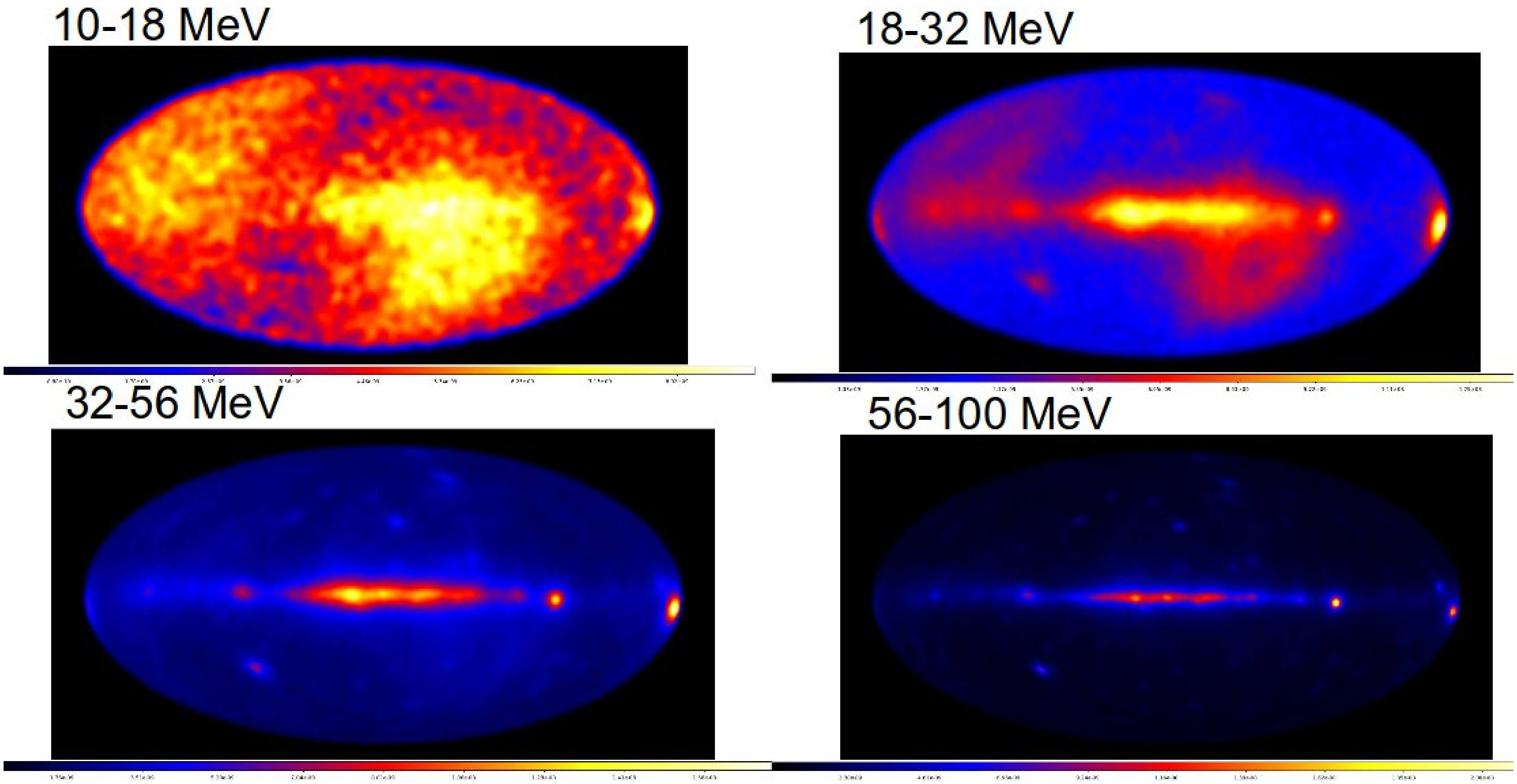


Fermi/LAT

V. Schönfelder, New Astr. Rev. 48 (2004) 193

- Solve sensitivity gap between Compton and pair telescopes
  - Actually Fermi was publishing mostly in the range $0.1 - 300\mathrm{GeV}$
  - Improvement expected from PASS8

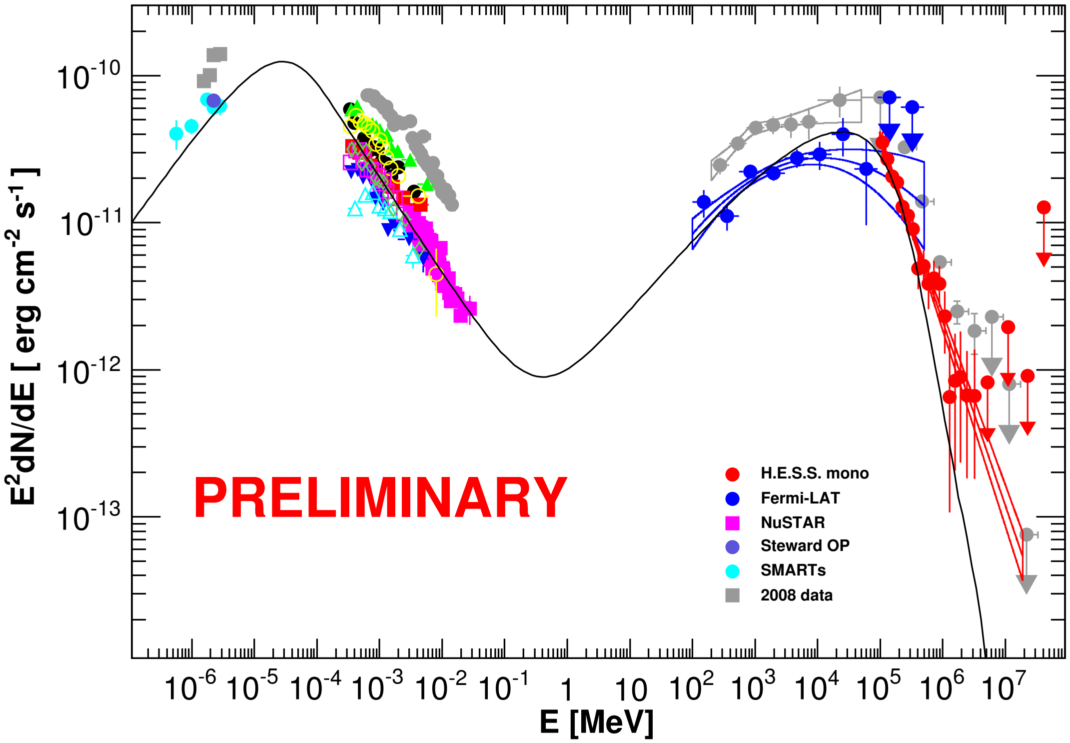
Angular resolution and sensitivity



“Fermi-LAT below 100 MeV (Pass8 data)”, Julie McEnery,

“e-ASTROGAM workshop: the extreme Universe”, Padova Feb-March 2017

γ-ray sensitivity gap: HBL PKS 2155-304 example



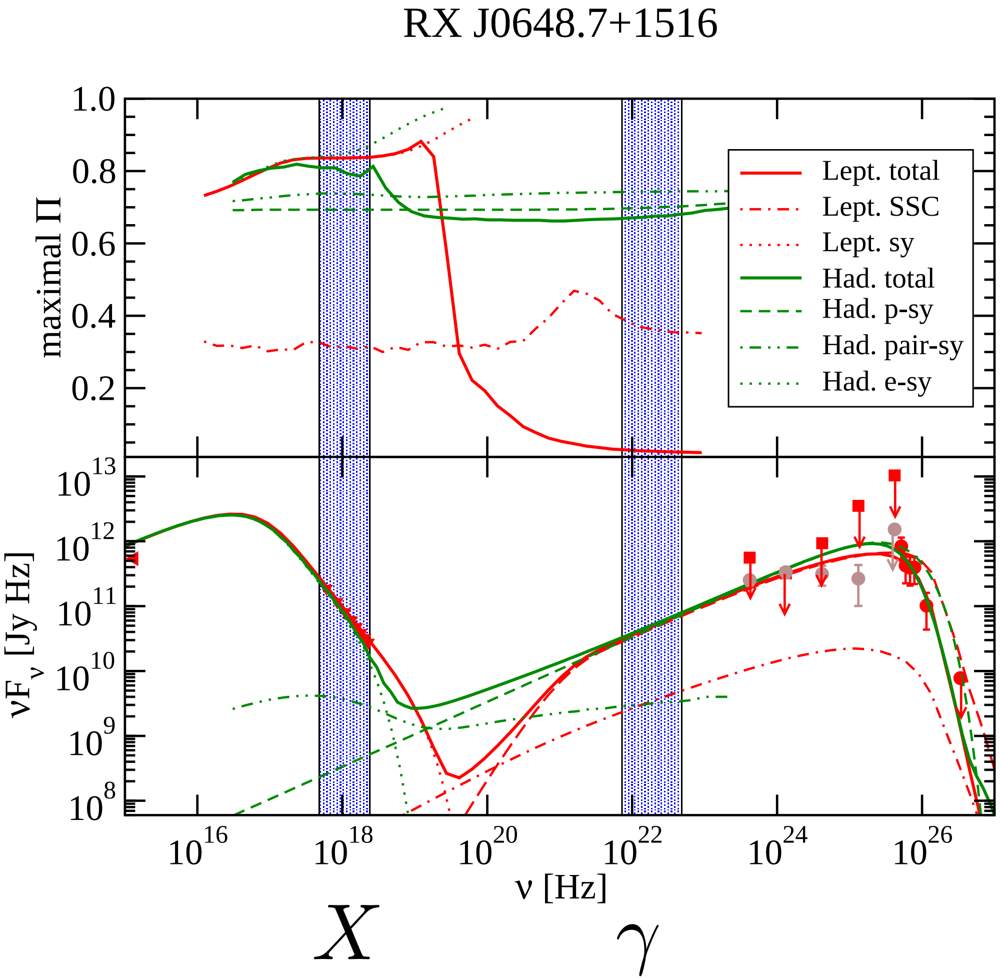
Grey points: dedicated Multiwavelength campaign 2013:

- NuSTAR satellite (3-79 keV),
- the Fermi Large Area Telescope (LAT, 100 MeV-300 GeV)
- (H.E.S.S.) array phase II

D. A. Sanchez *et al.*, 5th Fermi Symposium: Nagoya, Oct 2014 arXiv:1502.02915v2 [astro-ph.HE]

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

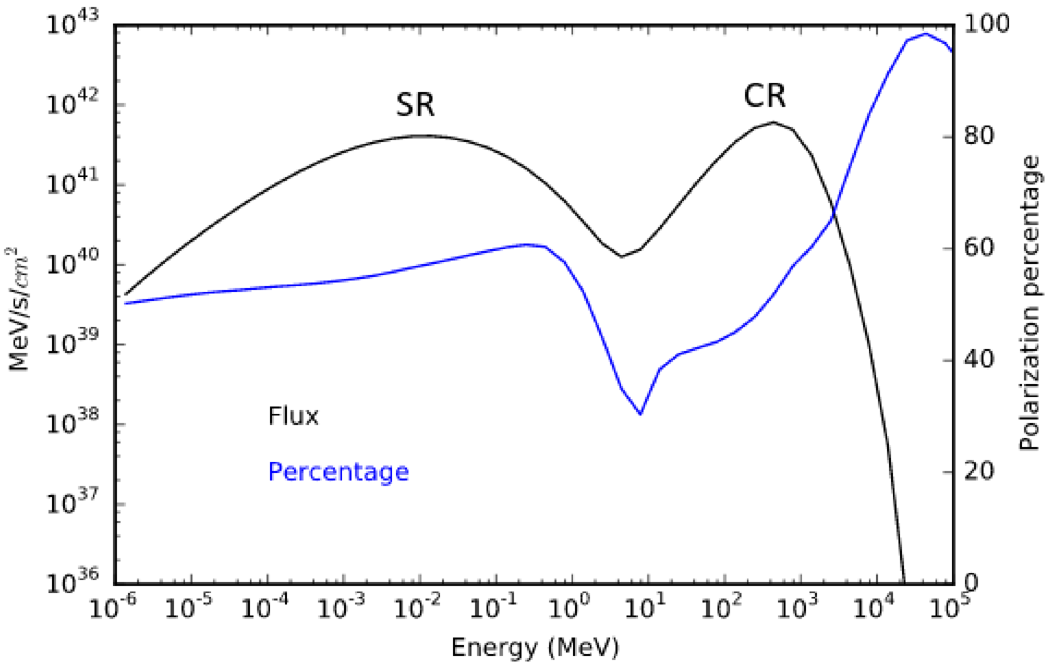


- SED's indistinguishable, but
- X-ray: $P_{\rm lept} \approx P_{\rm hadr}$
- γ-ray: $P_{\rm lept} \ll P_{\rm hadr}$

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

Pulsars

- Phase-averaged polarization
- Tag transition energy between synchrotron and curvature radiation at 1 – 100 MeV in Crab-like pulsars



A. K. Harding, Future Space-based Gamma-ray Observatories Workshop, NASA GSFC 2016.

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 $\propto 1/k^2$!

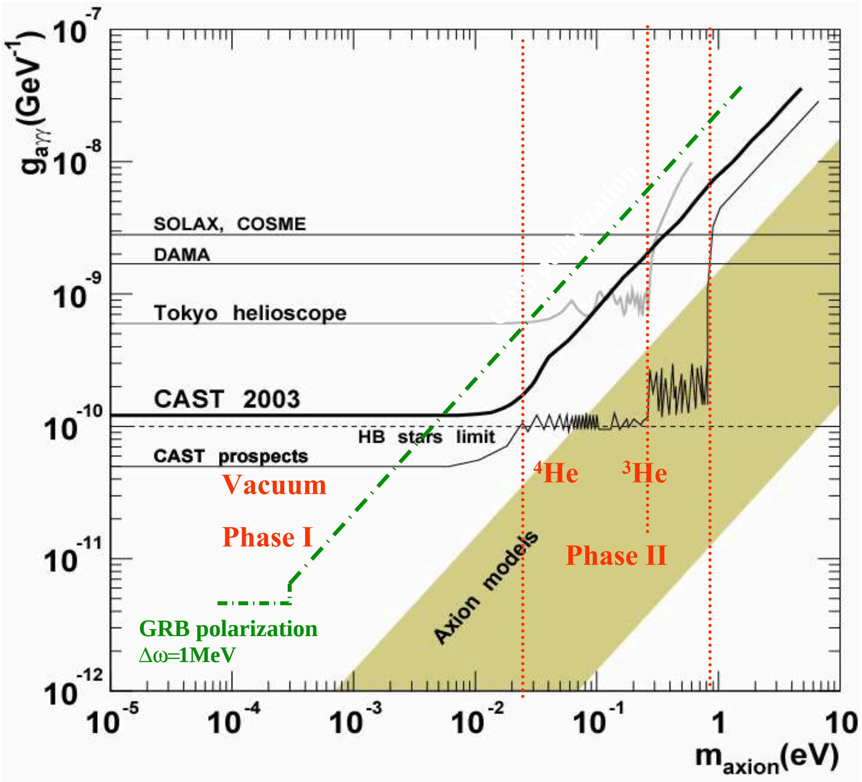
Search for Axions

- 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)

Photon angular resolution

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

$$\vec{k} = \vec{p_{e^+}} + \vec{p_{e^-}} + \vec{p_r}$$

<u>Contributions:</u>

- Single-track angular resolution,
- Un-measured nucleus recoil momentum for “nuclear” conversion
- Single-track momentum resolution

Single-track angular resolution

Hypotheses:

- Thin homogeneous detector;
- Tracking with optimal treatment of multiple-scattering-induced correlations (e.g., à la Kalman);
- Low energy, multiple-scattering-dominated, regime

$$\sigma_{\theta t} = (p/p_1)^{-3/4} \qquad \text{with} \qquad p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6},$$

With:

- p track momentum $[\mathrm{MeV}/c]$;
- $p_0 = 13.6\,\mathrm{MeV}/c$, multi-scattering constant;
- p_1 detector "multiple-scattering momentum" parameter $[\mathrm{MeV}/c]$;
- σ single measurement detector spatial resolution [cm];
- l track longitudinal sampling (pitch) [cm].

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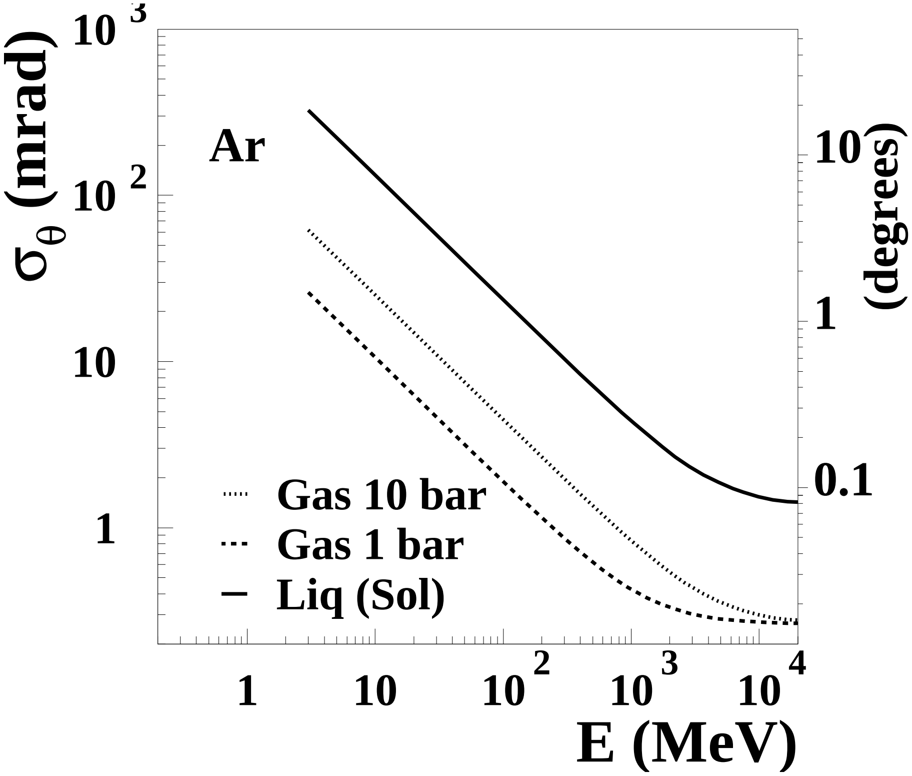
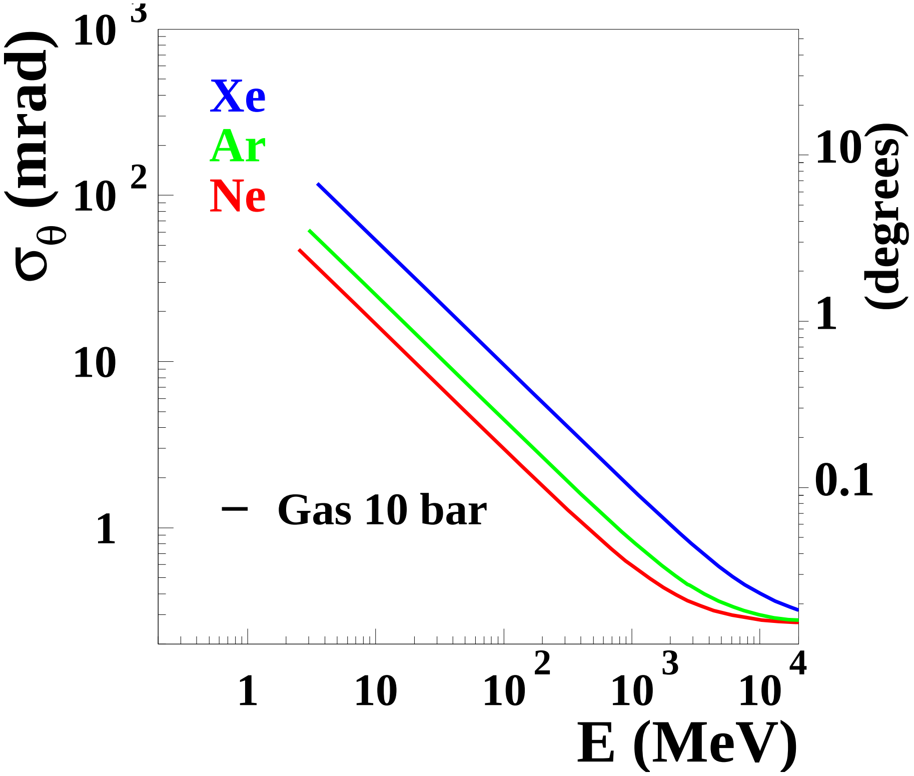
Single-track angular resolution

- Dependence of the RMS photon angular resolution on photon energy
- Sampling pitch $l = 1\,\mathrm{mm}$, point resolution $\sigma = 0.1\,\mathrm{mm}$,



For various densities (argon)

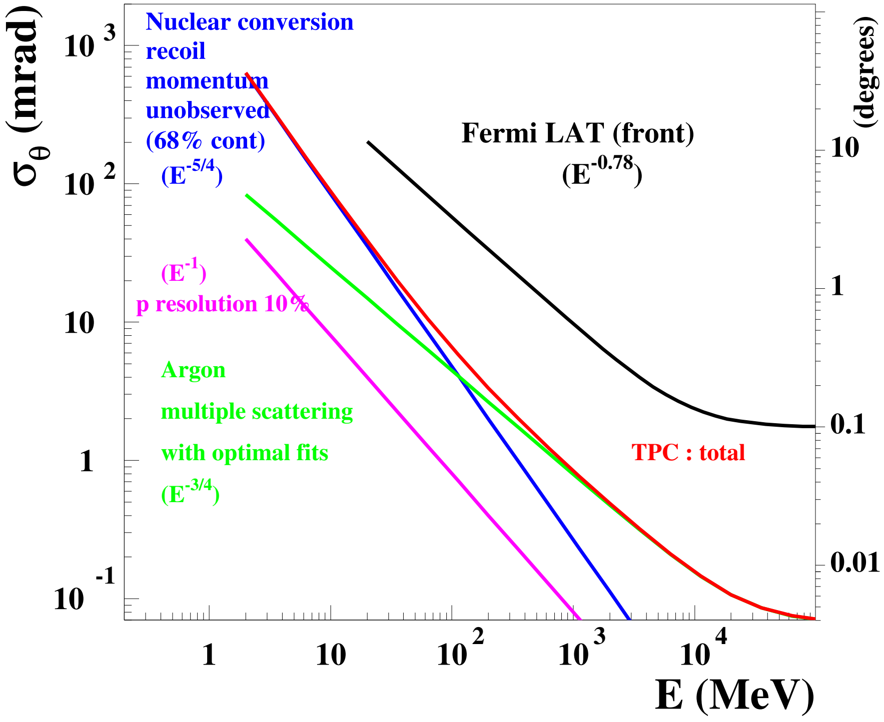


for various gases

NIM A 701 (2013) 225

Angular resolution

- Argon-based gas, $P = 10\,\mathrm{bar}$ $X_0 = 1180\,\mathrm{cm}$
- Sampling pitch $l = 1\,\mathrm{mm}$, point resolution $\sigma = 0.1\,\mathrm{mm}$,

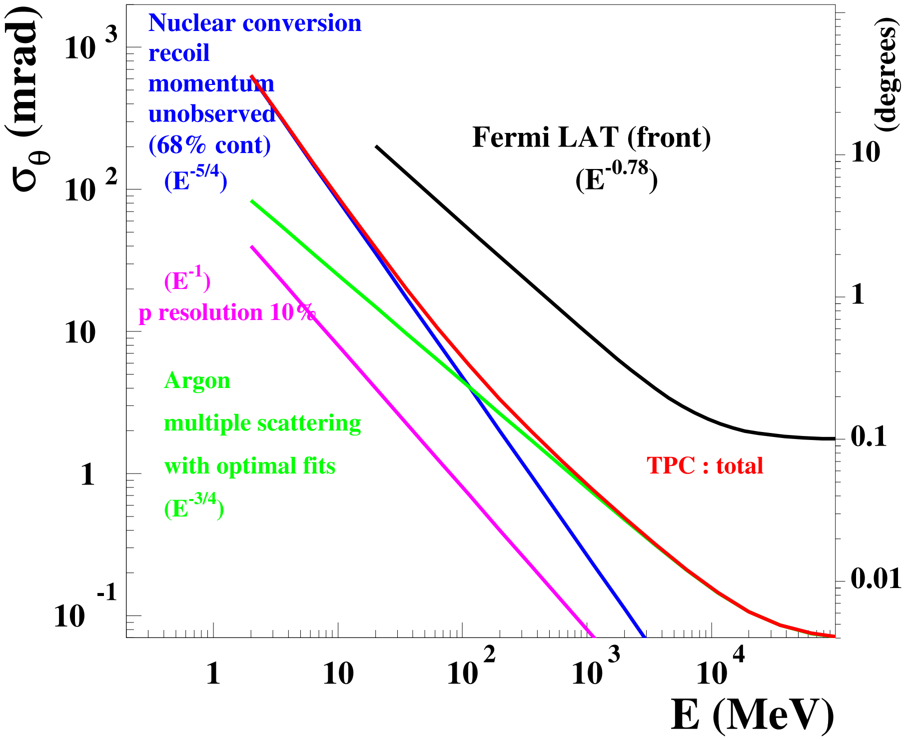


NIM A 701 (2013) 225

Performances with Thin Homogeneous Detector and Optimal Fits

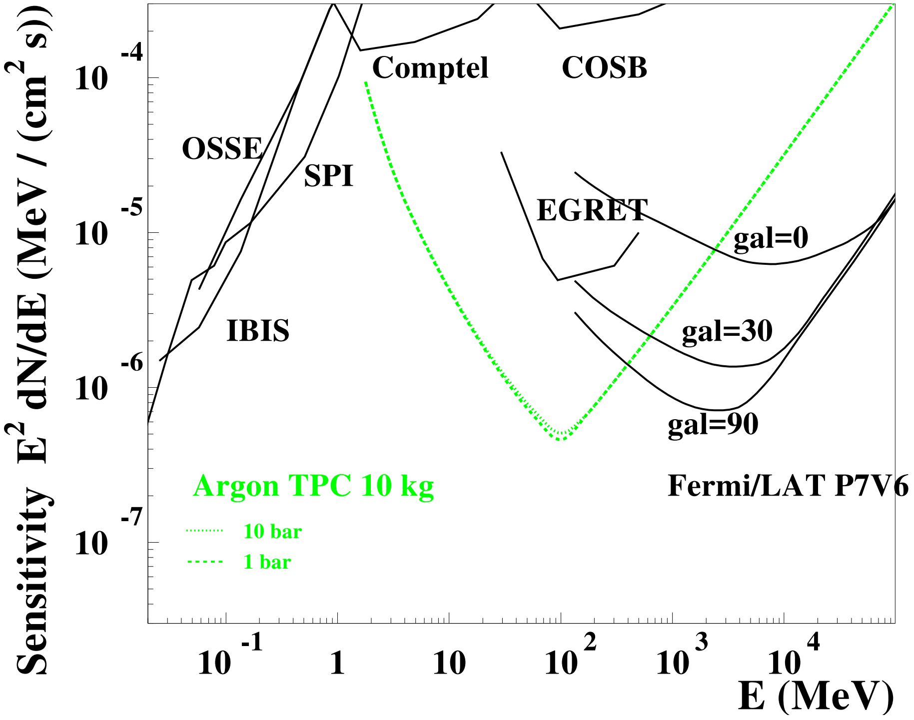
Angular resolution

- 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



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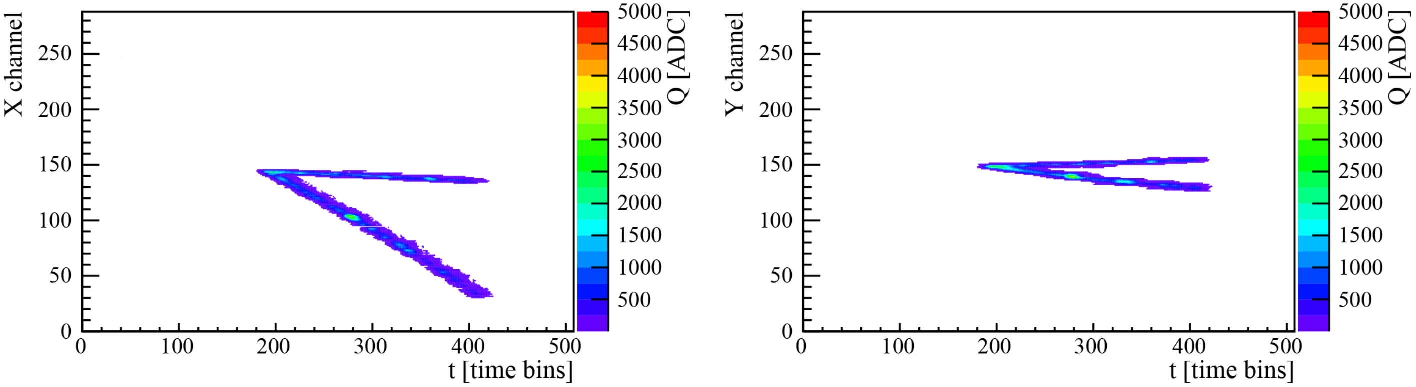
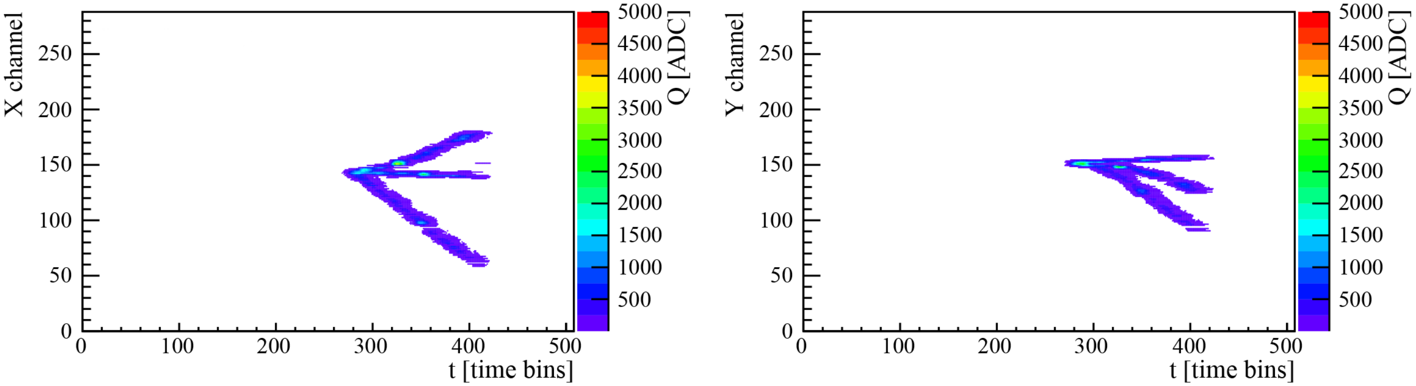
"Nuclear" and "triplet" pair conversion

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



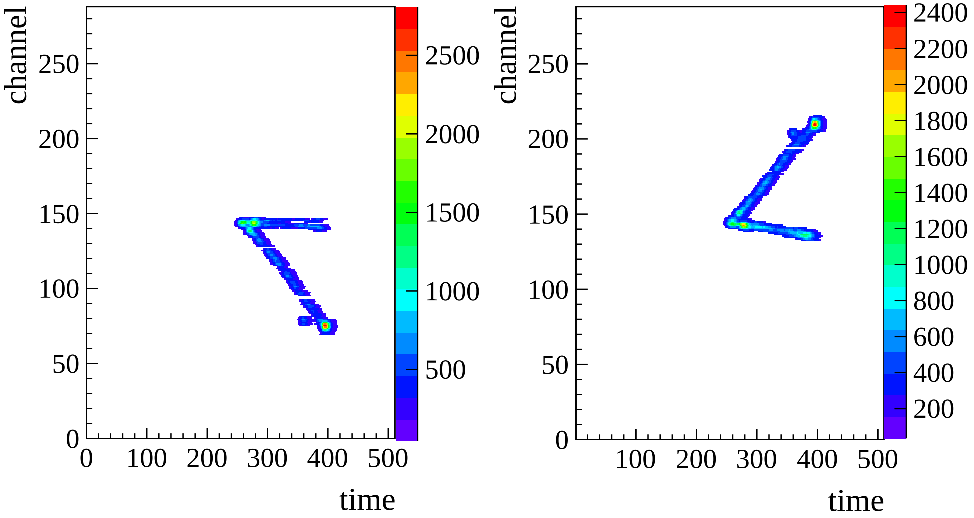
$$\gamma e^- \rightarrow e^+ e^- e^-$$



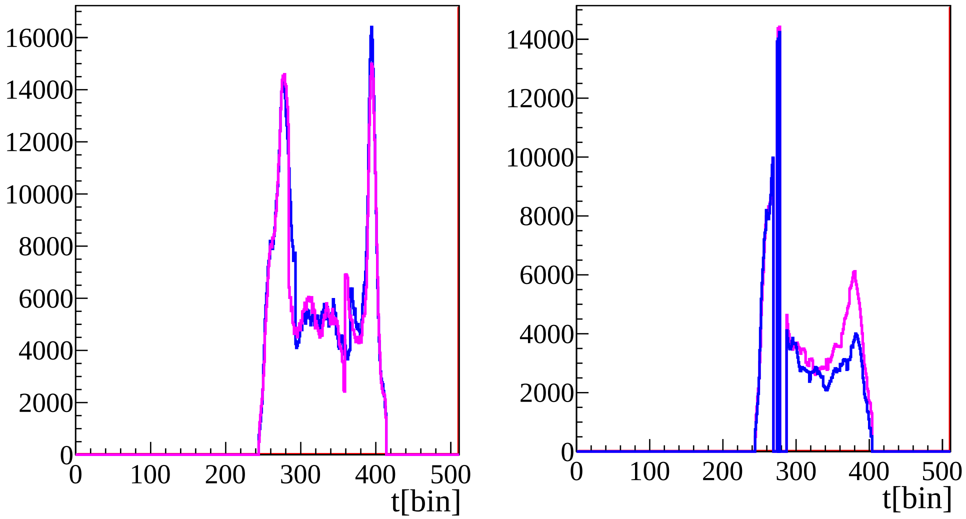
74 MeV γ-rays from NewSUBARU conversions in 2.1 bar Ar:Isobutane 95:5

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 $= 1\,\text{mm}$.
- 1 time bin $= 30\,\text{ns}$, $v_{\text{drift}} \approx 3.3\,\text{cm}/\mu\text{s}$ $\Rightarrow$ 1 time bin $\propto 1\,\text{mm}$

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

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

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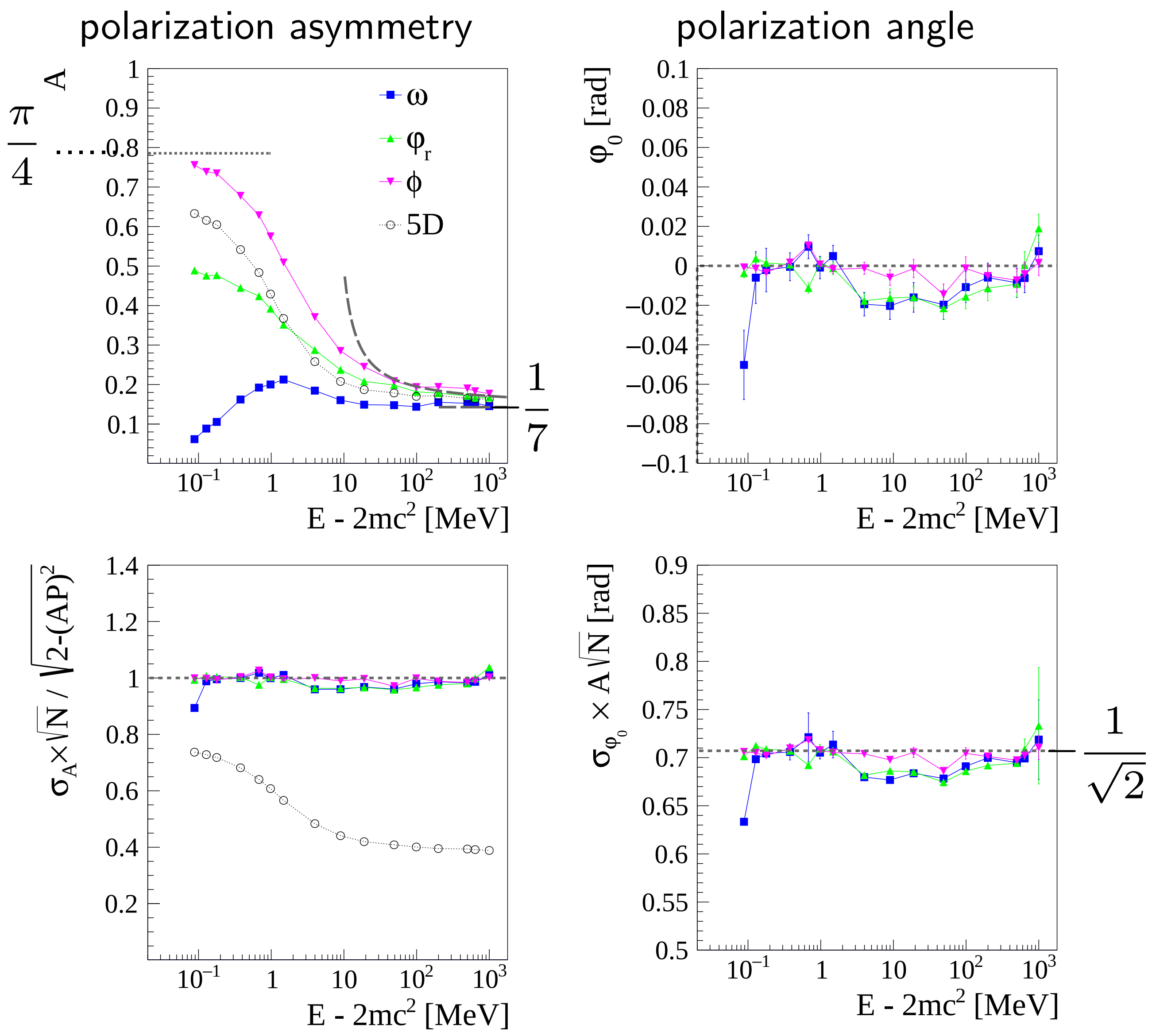
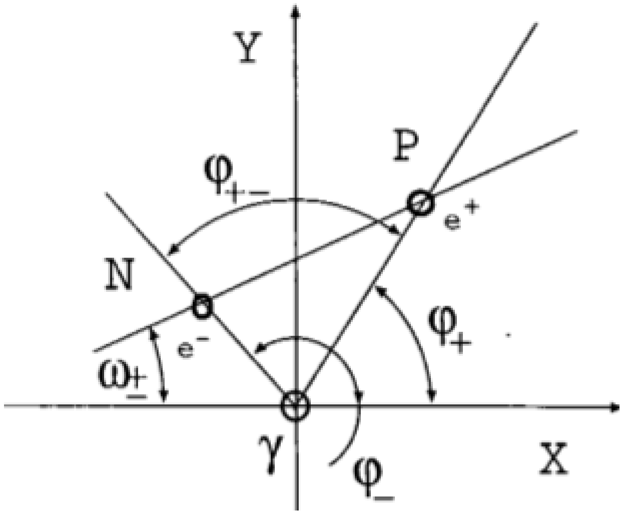
Polarimetry: Defining the Azimuthal Angle ?





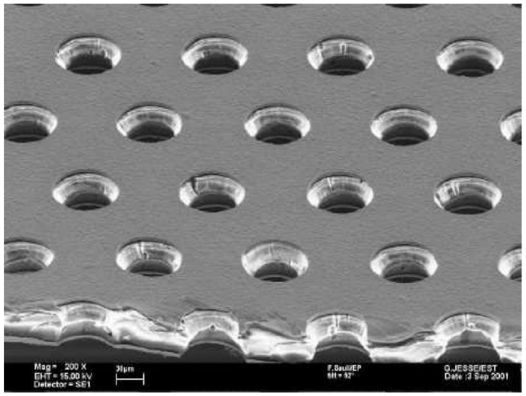
- ω
- φ_r recoil angle,

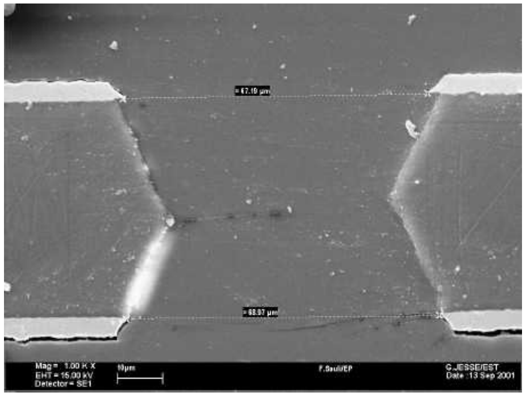
  $\varphi_r = \varphi_{\text{pair}} \pm \pi$
- $\phi = (\varphi_+ + \varphi_-)/2$, bisector of e^+ and e^- direction

Astropart. Phys. 88 (2017) 30

Gas amplification: micromegas + 2 GEM

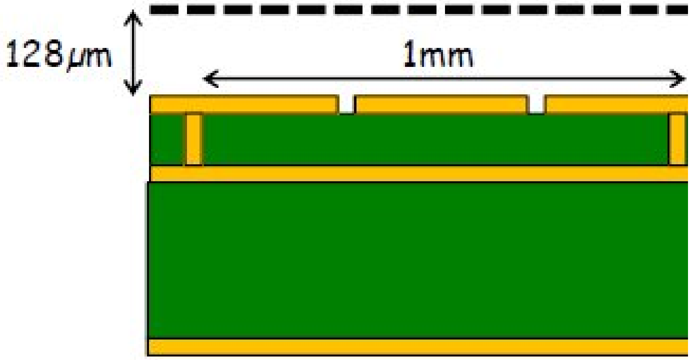
Gas Electron Multiplier
$50\,\mu\mathrm{m}$ Kapton, copper clad,
pitch $140\,\mu\mathrm{m}$, $\Phi 70\,\mu\mathrm{m}$

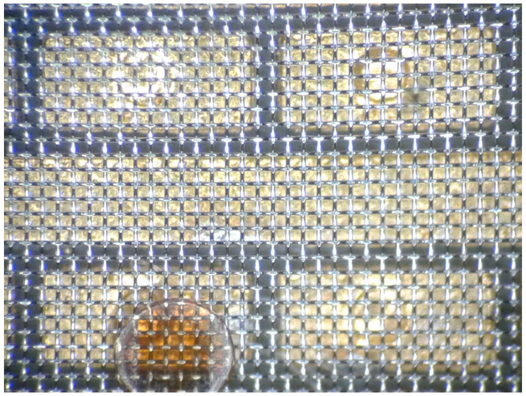




F. Sauli, NIM A 386, 531 (1997)

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

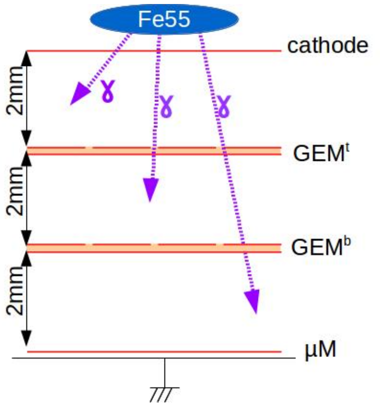


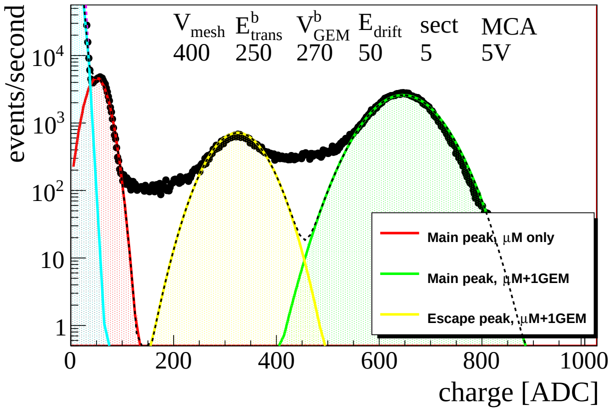


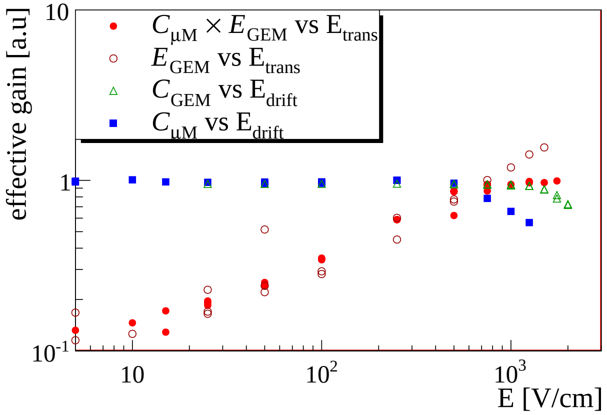
I. Giomataris et al., NIM A 560, 405 (2006)

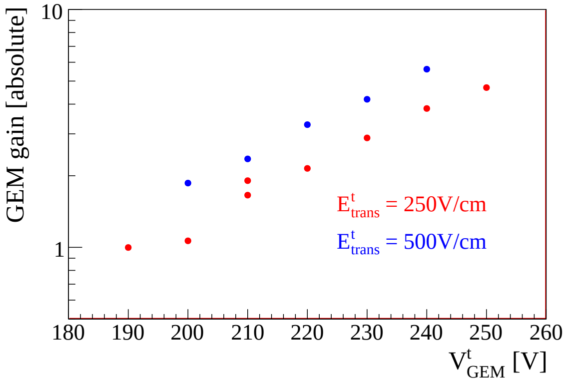
Micromegas + 2 GEM assemblies: characterization

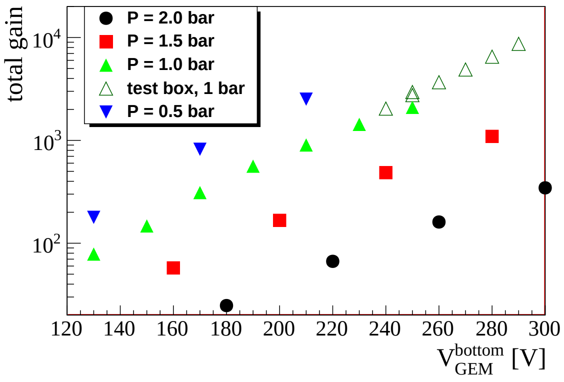
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)







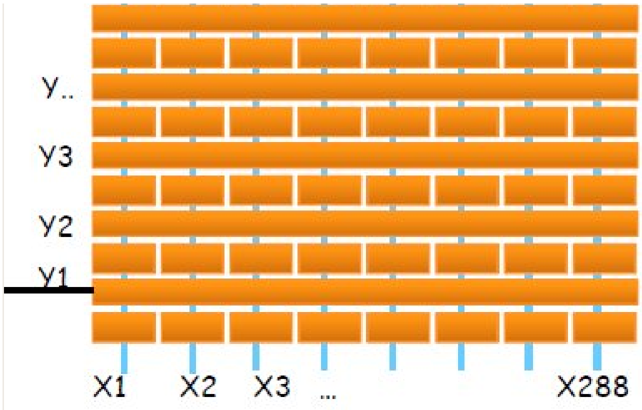


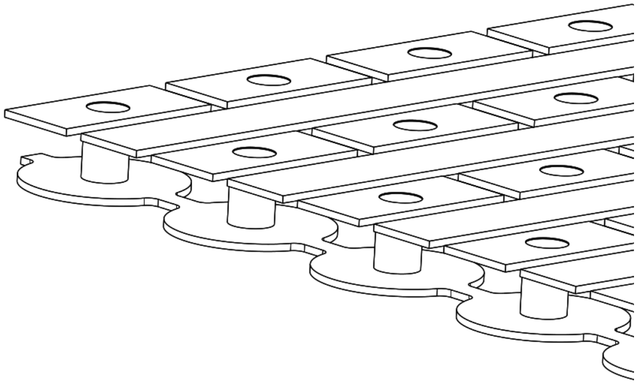


Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

Anode segmentation

- Avalanche electrons collected on a segmented anode.

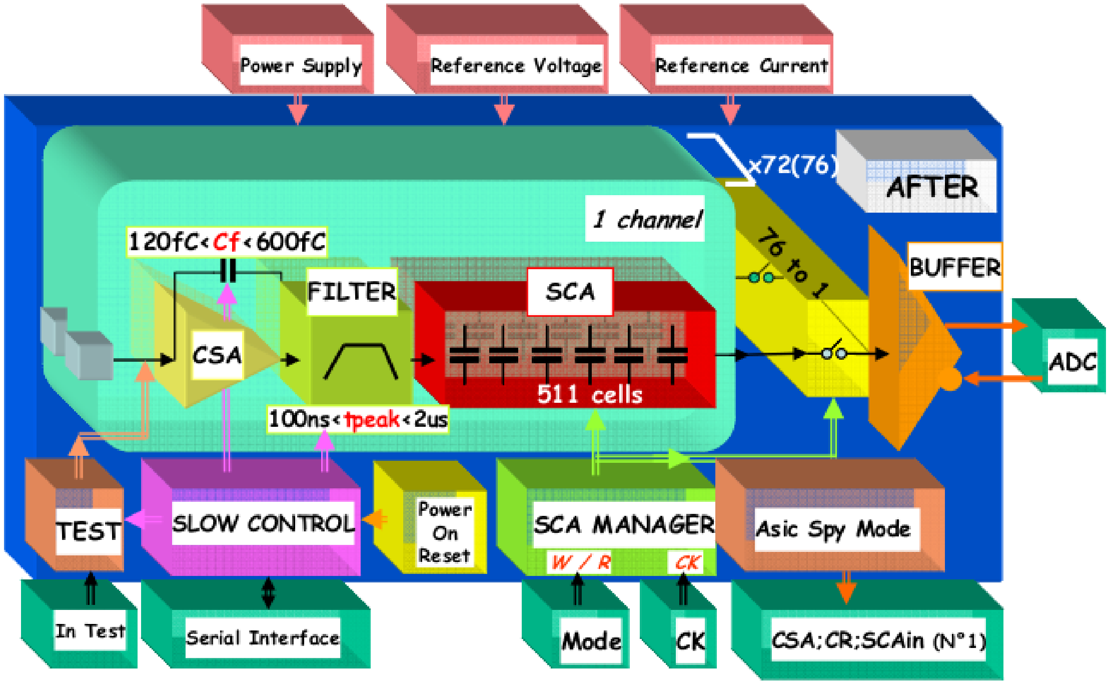




- Cu-clad PCB, strip pitch 1 mm, strip width ≈ $400\,\mu\mathrm{m}$

Signal digitization

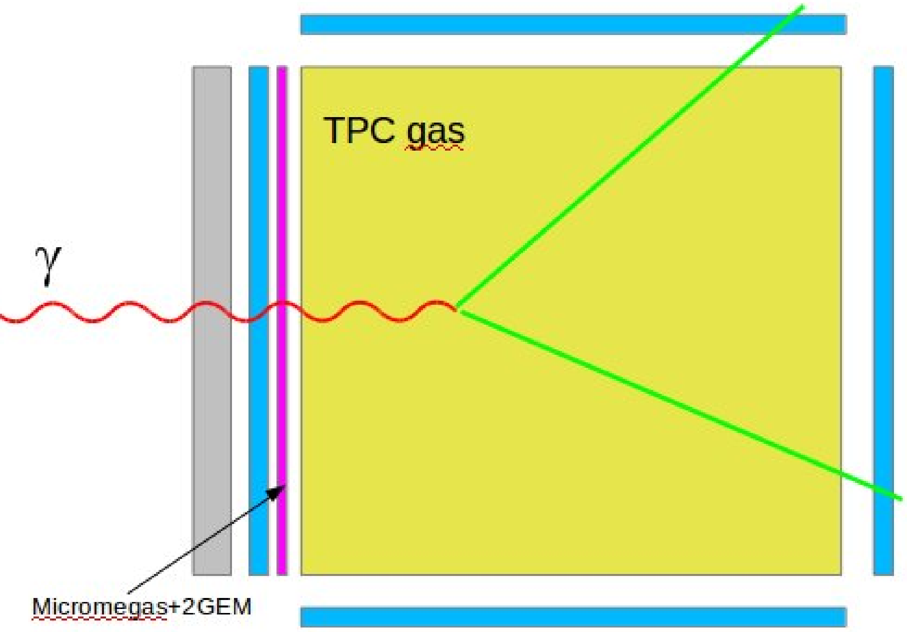
- 2 directions x, y, 288 strips (channels) / direction
- 72 channels /chip
- 4 chips / direction
- 511 time bins, “circular” SCA (Switched Capacitor Array)
- Input: 120 fC to 600 fC
- Up to 100 MHz sampling
- Shaping time 100 ns to 2 µs
- 12 bit ADC.

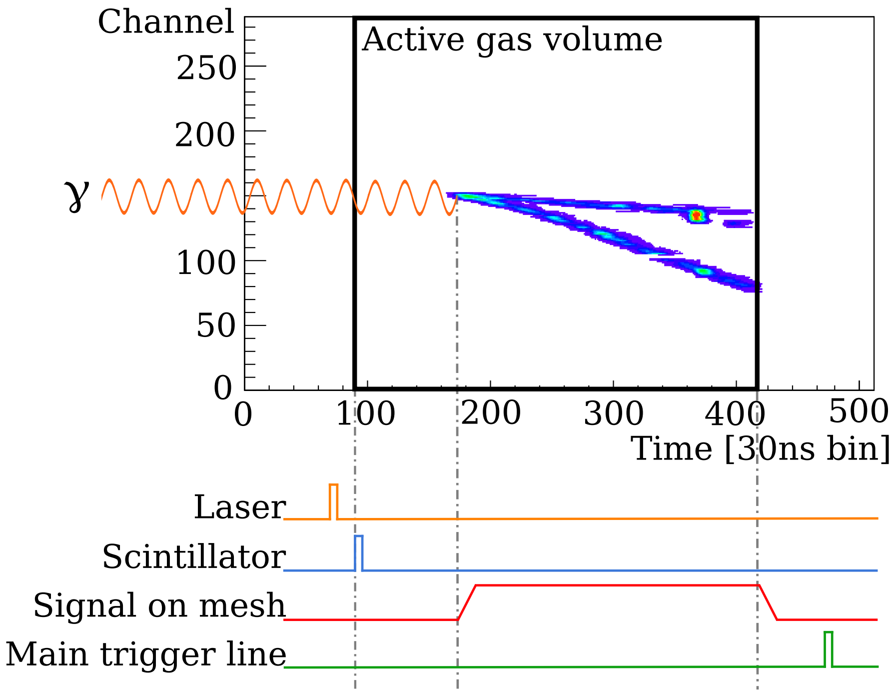


Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

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

"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

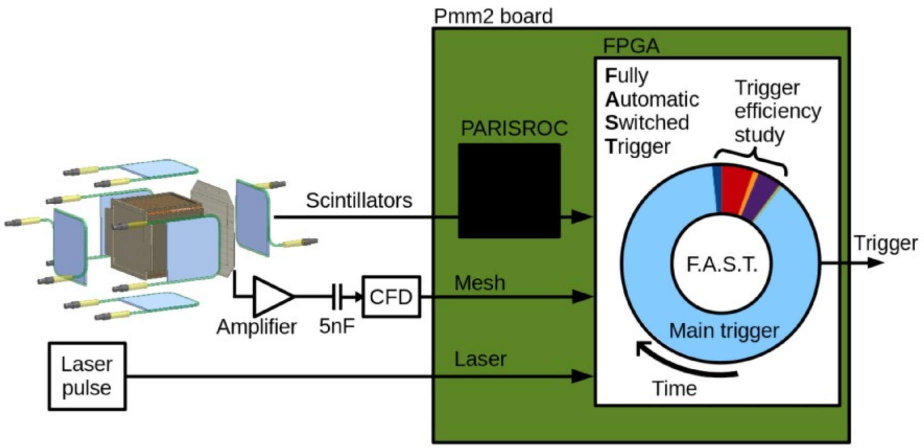
"Main line": $T_{\gamma,laser} = \overline{S}_{up} \cap O \cap M_{slow} \cap L$

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

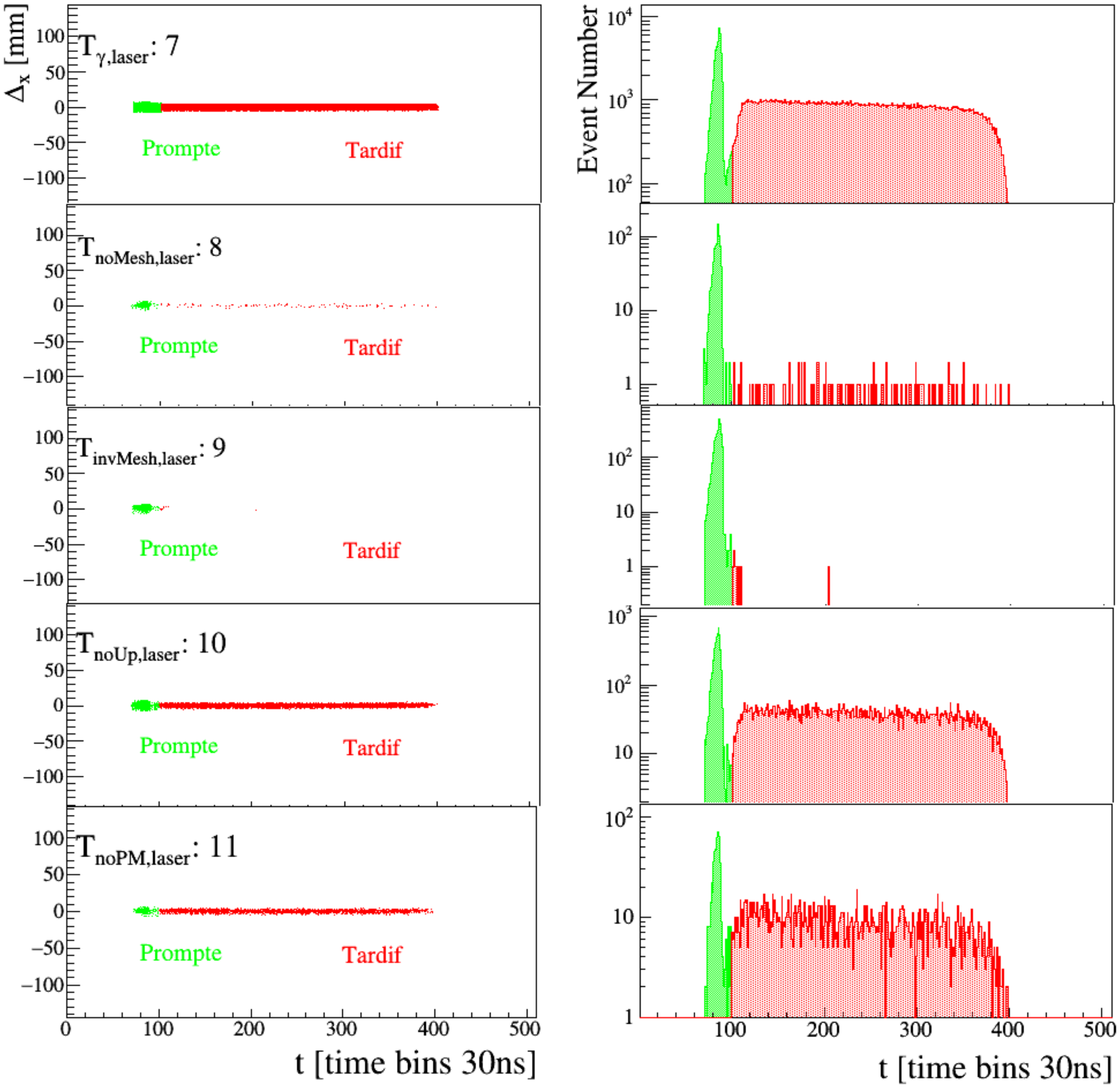


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

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

Towards a space detector: some elements

- Gas composition
- Gas pressure
- Temperature range
- Gas purity on the long term
- . . .

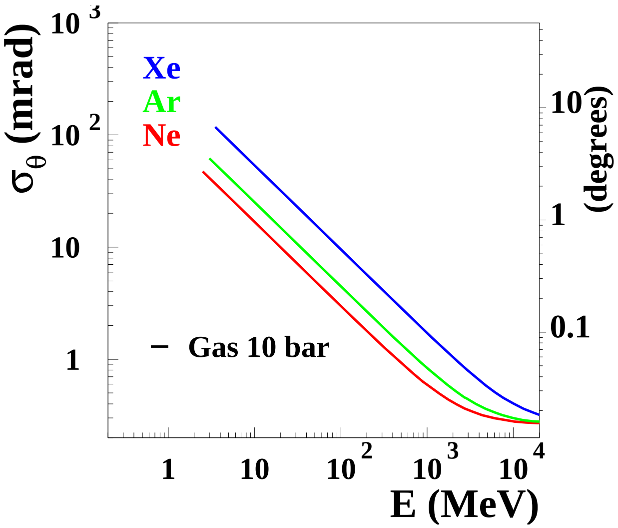
Towards a space detector: Gas composition: drifting species ?

- TPC's to some extent imune to pile-up
- $2 \times 1D$ orthogonal strips given the (small) available electronic powering (i.e., not pads)
- proton flux $20\mathrm{kHz/m^2}$ at Fermi/LAT orbit.
- need "fast gas":

drifting species	example	v_drift	t_drift	pile-up fraction	
electron	Ar:isoC_4H_{10}	$3.3\,\mathrm{cm/\mu s}$	$10\mathrm{\mu s}$	0.2 proton/m^2	manageable
negative ion	Ar:CS_2	$3.3\,\mathrm{cm/ms}$	$10\mathrm{ms}$	200 proton/m^2	nope

Gas composition: light / heavy Z ? Gas pressure ?

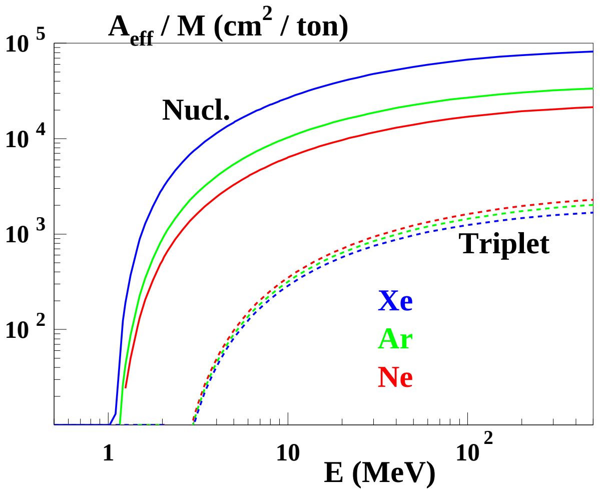
- $\rho \times X_0 = \frac{A}{Z^2} b, \quad \rho = aAP, \quad M = V\rho = VaAP, \quad X_0 = \frac{b}{aZ^2 P}$ $\quad a, b$ constants.



angular resolution degrades with Z

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

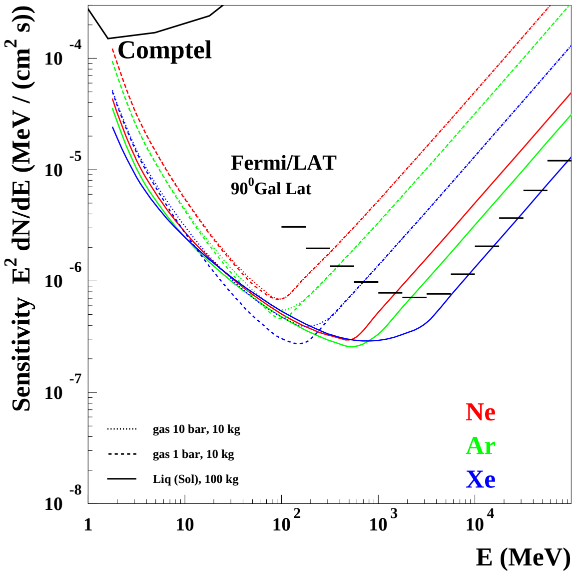
(multiple scattering)



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.

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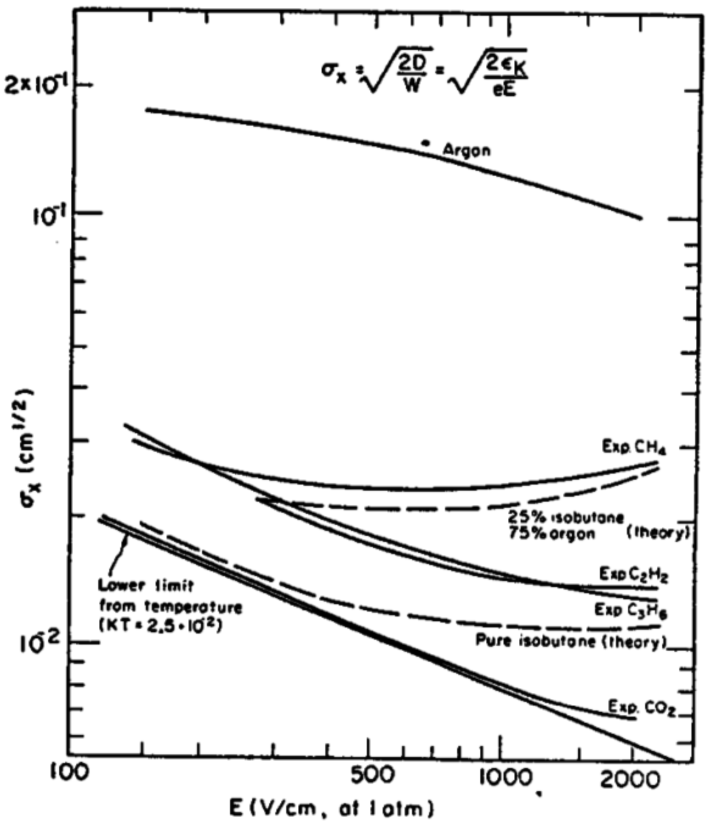
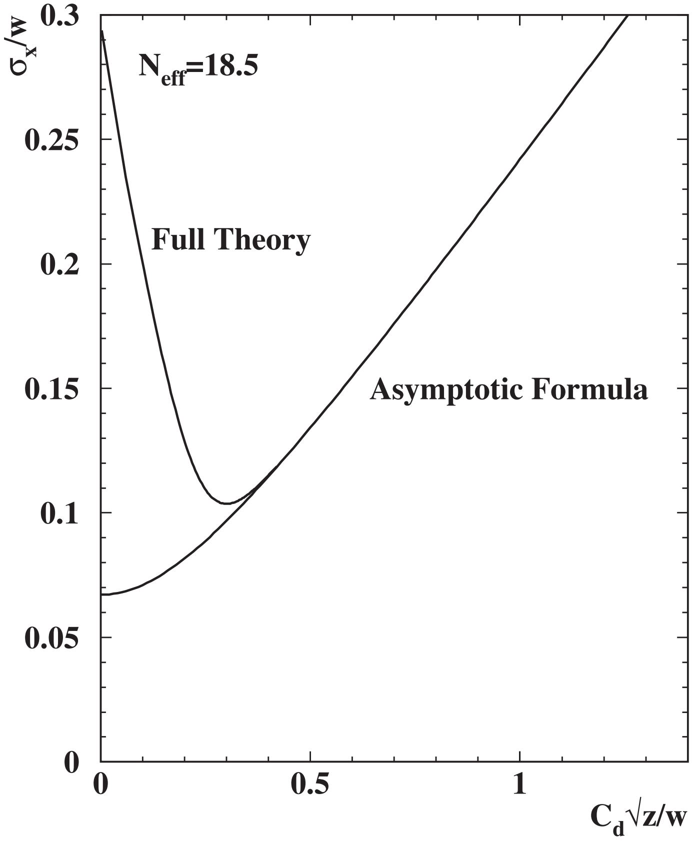
Gas composition, quencher





F. Sauli CERN-EP-83-103, 1983

D. C. Arogancia et al., NIM A 602, 403 (2009)

- Gas detectors need limitation of breakdown from UV photoelectric effect on the cathode: add poly($n > 2$)molecular “quencher” gas (alcanes, CO$_2$ ..)
- Mitigates diffusion $\sigma = \sigma_x/\sqrt{z}$, $\sigma_x = 200\,\mu\mathrm{m}/\sqrt{\mathrm{cm}}$, ($\sigma \approx 0.6\,\mathrm{mm}$ after $z = 9\,\mathrm{cm}$ drift)
- Diffusion is needed to minimize the TPC spatial resolution ! $C_D \equiv \sigma_x$, w strip pitch.

Pressure, Quencher fraction, e^- transport properties

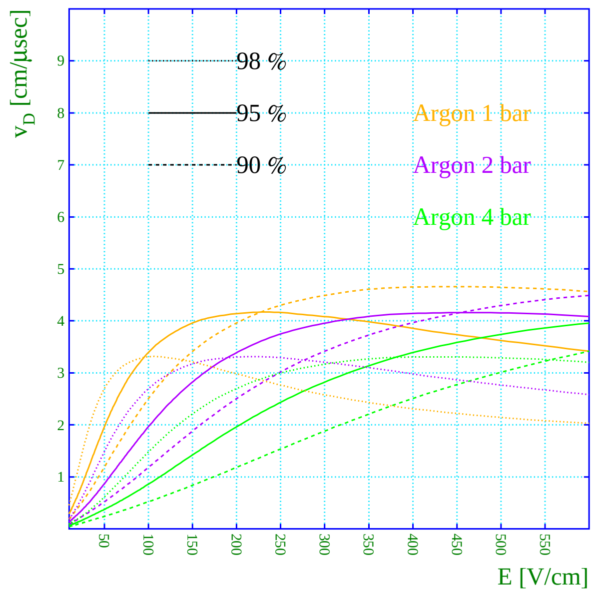
- Argon-iso-butane mixture with $(2, 5, 10)\%$ iso-butane and pressure $1, 2, 4\,\text{bar}$

Drift velocity

v_{drift}

$\text{cm}/\mu\text{s}$

Drift velocity in Ar/ISO mixtures

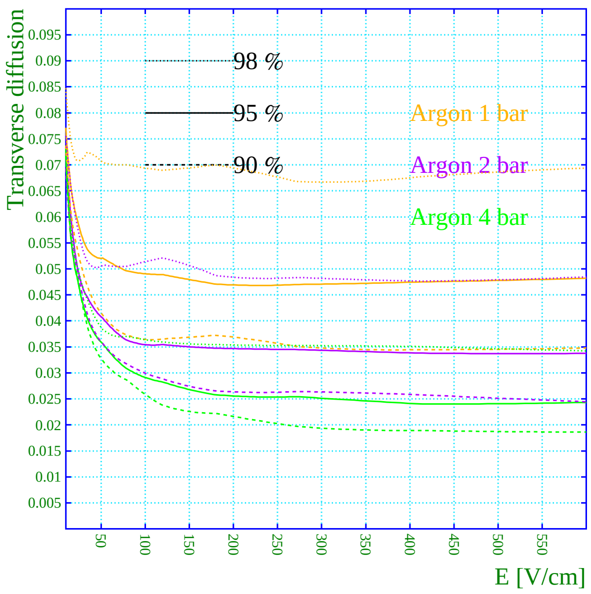


Transverse diffusion coefficient

$C_{D,T}$

$\text{cm}/\sqrt{\text{cm}}$

Transverse diffusion in Ar/ISO mixtures

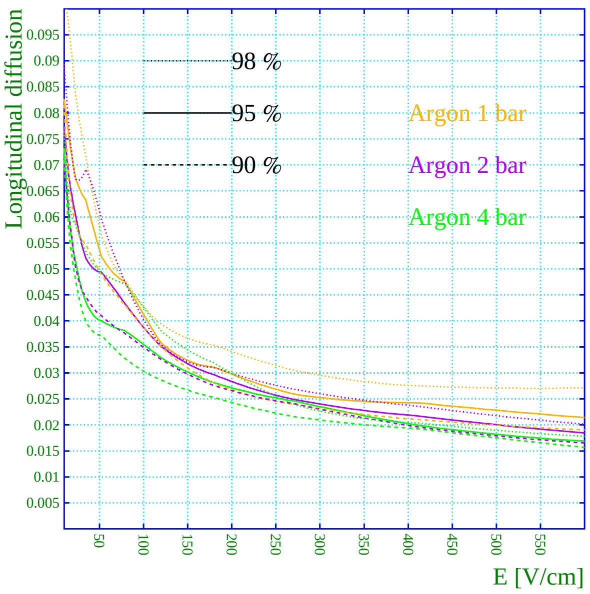


Longitudinal diffusion coefficient

$C_{D,L}$

$\text{cm}/\sqrt{\text{cm}}$

Longitudinal diffusion in Ar/ISO-95 mixtures



- v_{drift} max value does not depend on P; E value for v_{drift} maximum is $\propto P_{\text{C4H10}}$.
- $C_{D,T} \propto 1/\sqrt{P_{\text{C4H10}}}$, Transverse diffusion coefficient determined by quencher partial pressure
- $C_{D,L}$ fn of E, Longitudinal diffusion coefficient determined by drift field

garfield.web.cern.ch/

Temperature variation, Temperature range

- TPC parameters depend on gas density ρ, not on (pressure P, temperature T)
- Thermal vessel volume variations corrected by small (drift, amplification) voltages.

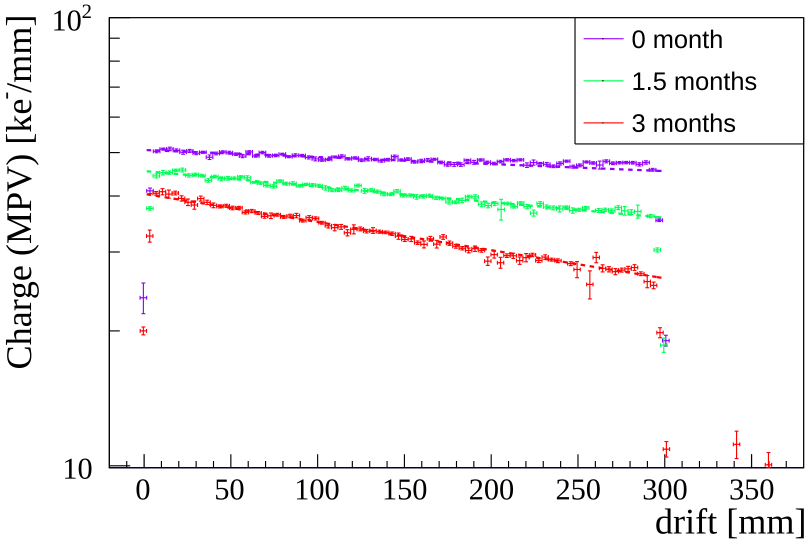
  (We operated the same set-up in the range 1-4 bar by simple voltage ajustments)
- Maximal temperature ?
  - check your electronics !
- Minimal temperature ?
  - avoid quencher partial liquefaction

gas	Ar	Xe	CH_4	C_2H_6	iso C_4H_{10}
boiling point at 1.013 bar ($^\circ\mathrm{C}$)	-185.8	-108.1	-161.5	-89	-11.7

  - alcanes have similar quencher properties.

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).

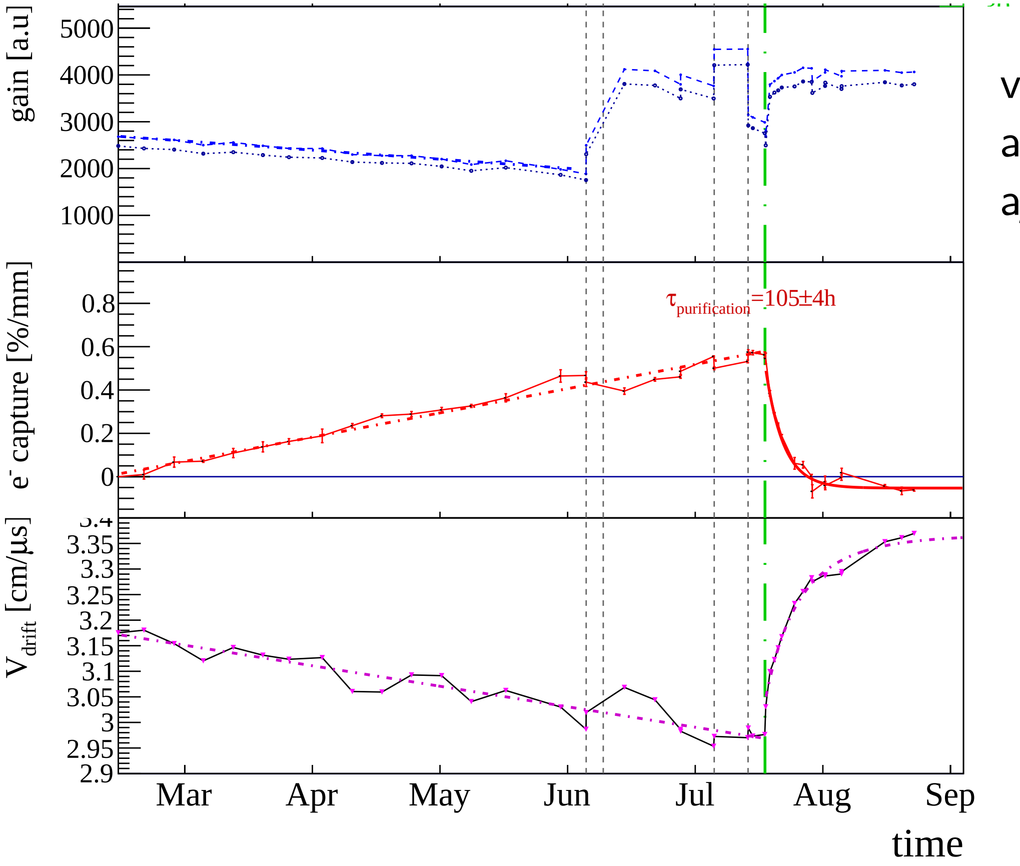


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- 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



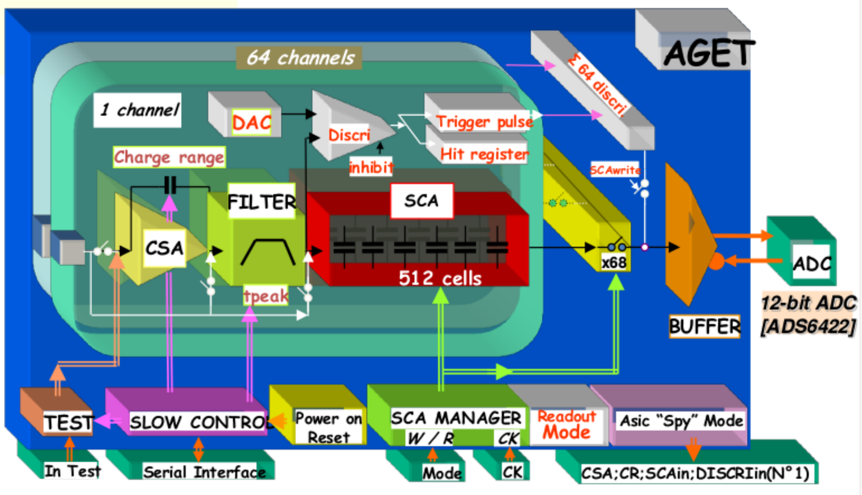
vertical lines:
amplification voltage
ajustments.

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 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:
    - 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 - 749.

- AGET → radhard ASTRE: "Asic with SCA & Trigger for detector Readout Electronics":

  Prototype series to foundry (2016). Tests in progress.