

HARPO: 1.7 - 74 MeV gamma-ray beam validation of a high-angular-resolution high-polarisation-dilution gas telescope and polarimeter

Denis Bernard,

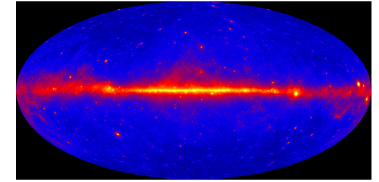
LLR, Ecole Polytechnique and CNRS/IN2P3, France

11th Workshop on Science with the New generation of High Energy Gamma-ray Experiments
18-21 October 2016, Pisa, Italy

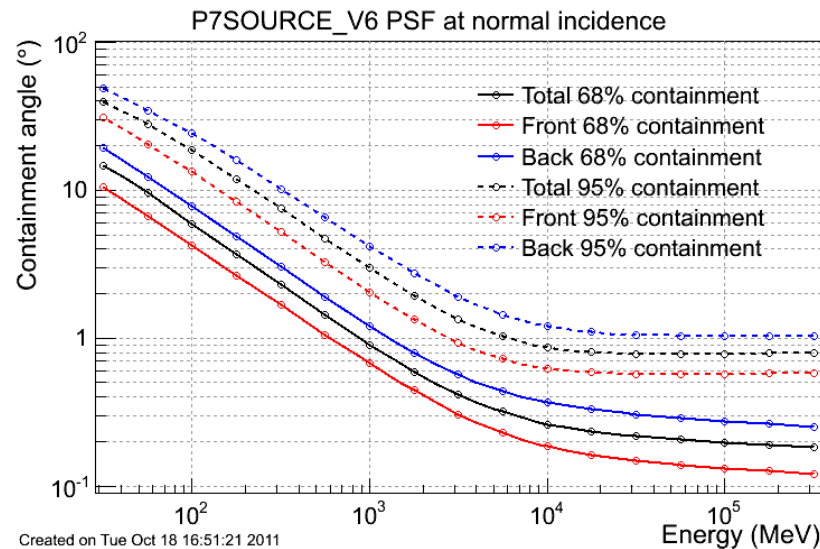
llr.in2p3.fr/~dbernard/polar/harpo-t-p.html



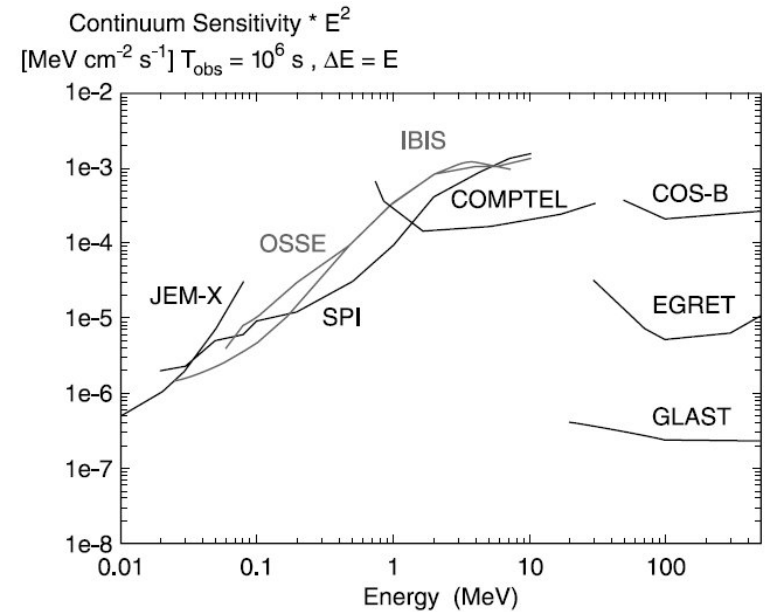
Non polarized astronomy



- Improve **angular resolution** – crowded sky regions



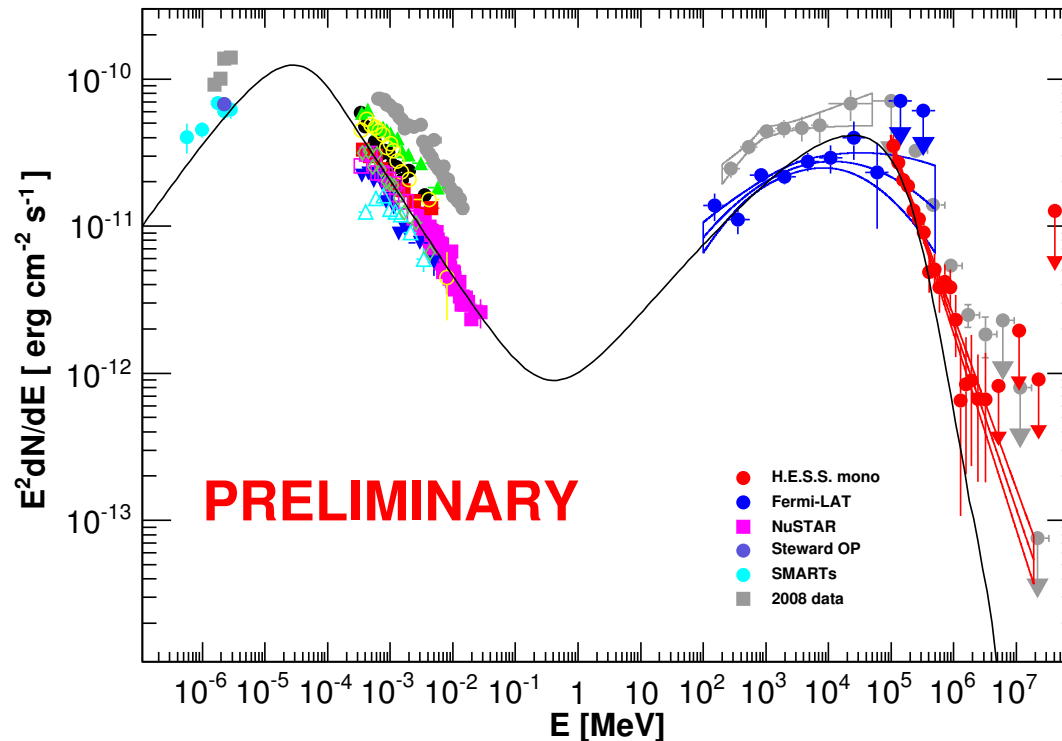
Fermi/LAT



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

- Solve **sensitivity** gap between Compton and pair telescopes
 - Actually Fermi is publishing mostly in the range 0.1 – 300 GeV
 - Improvement expected from PASS8

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

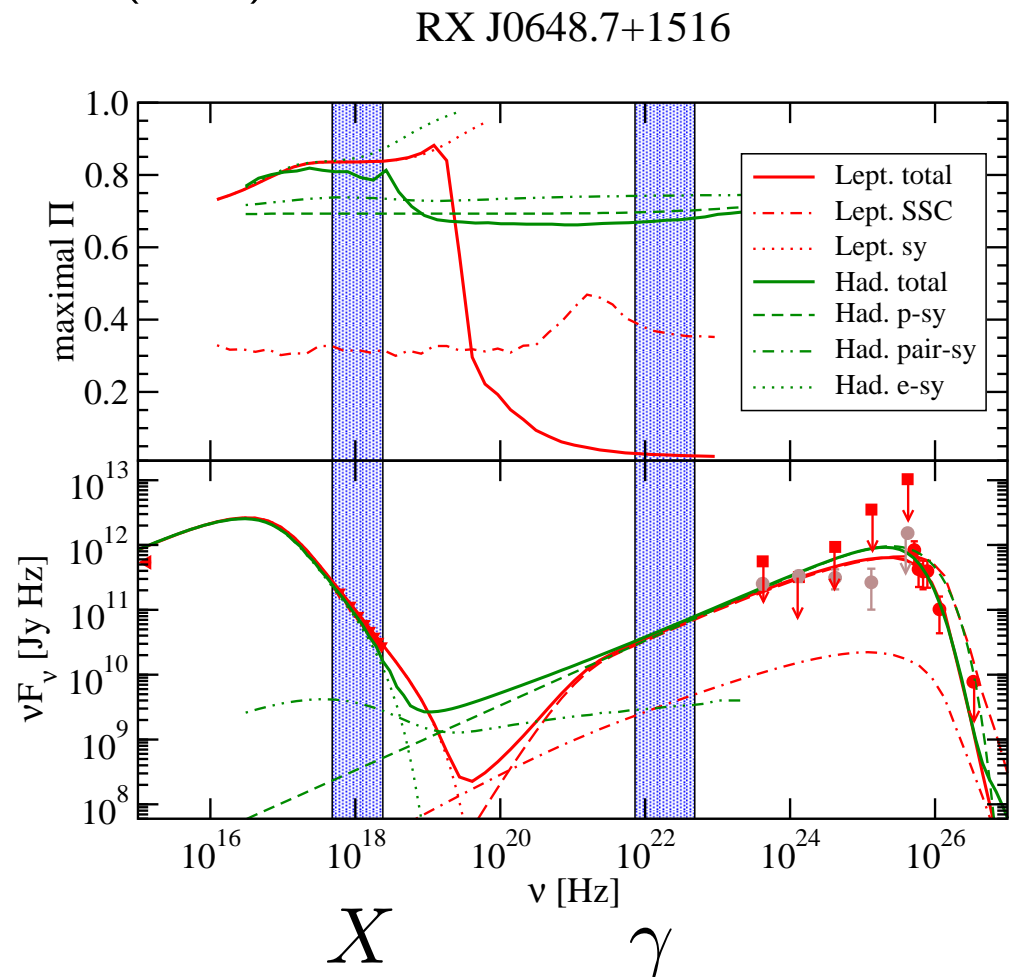
- Blazars: decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models
 - high-frequency-peaked BL Lac (HBL)
 - X band: 2 -10 keV
 - γ band: 30 - 200 MeV

● SED's indistinguishable, but

● X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$

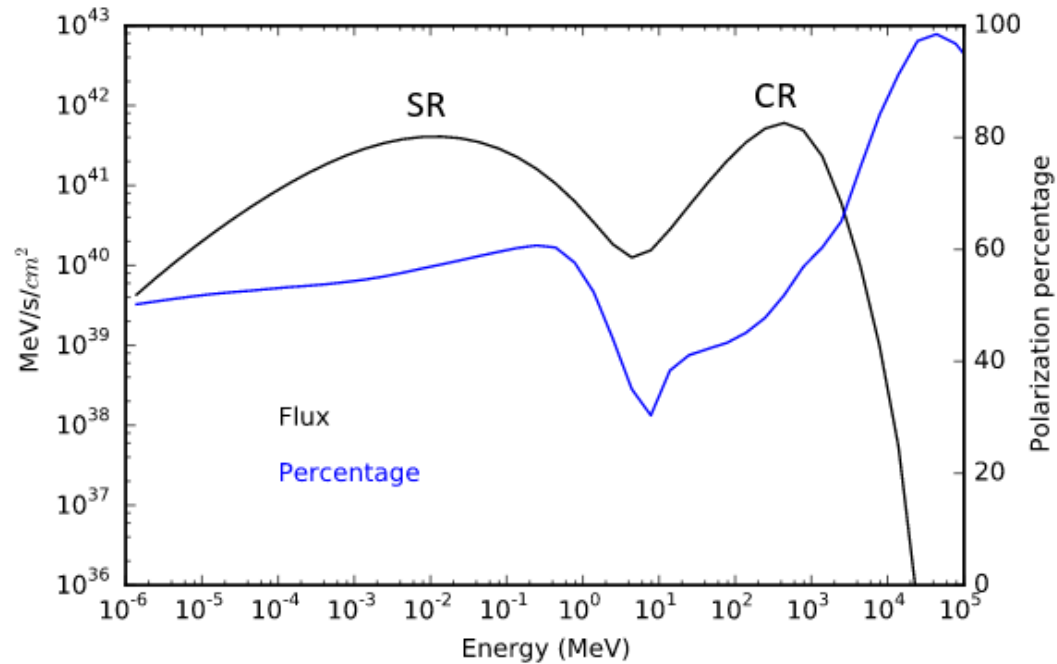
● γ -ray: $P_{\text{lept}} \ll P_{\text{hadr}}$

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



Pulsars : Phase-averaged polarization

- Transition between synchrotron and curvature radiation at 1 - 100 MeV in Crab-like pulsars
- Look for drop in polarization degree at transition



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

- **But** spin-flip curvature radiation important in (Crab like) young pulsars
- spin-flip curvature radiation becomes dominant in magnetars,
- contrary to classical radiation, spin-flip (QED) curvature radiation mostly **unpolarized**

G. Voisin, "gamma2016", 2016 Heidelberg Germany.

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 $\propto 1/k^2$!

Photon angular resolution

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

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

Contributions:

- Single-track angular resolution,
- Un-measured nucleus recoil momentum
- Single-track momentum resolution

See P. Gros' talk

See P. Gros' talk

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

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

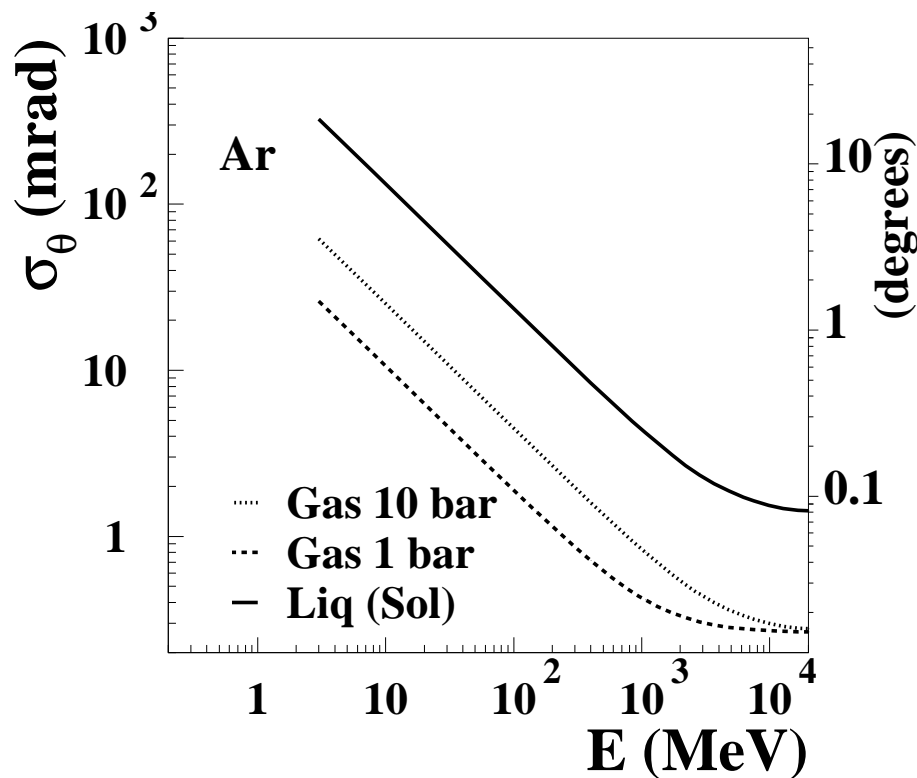
With:

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

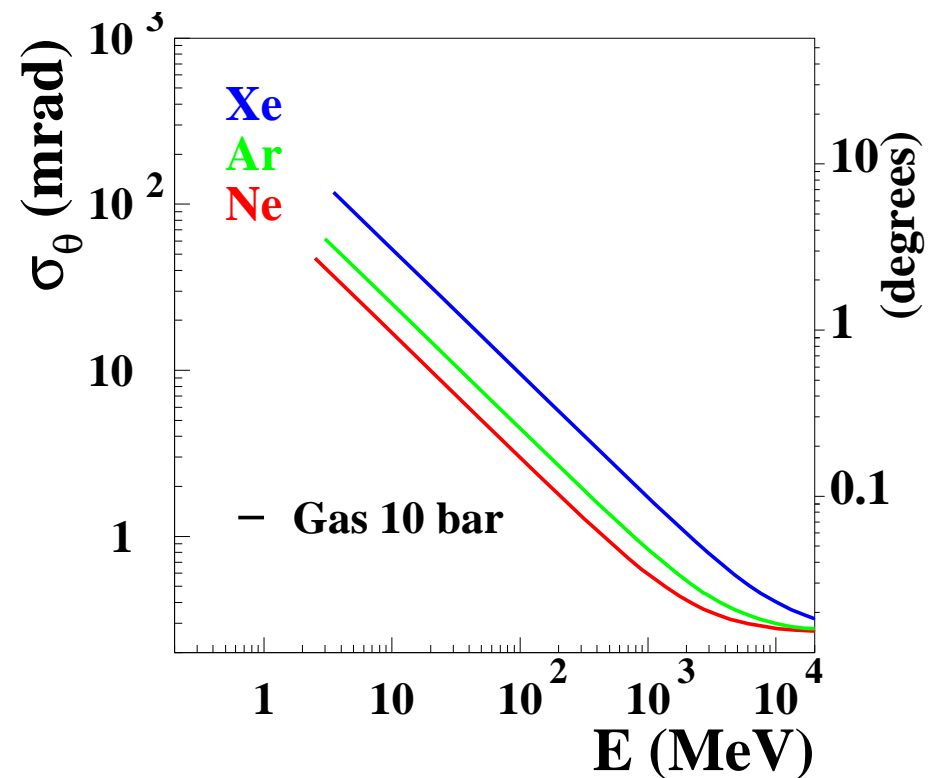
D.B., NIM A 701 (2013) 225, NIM A 729 (2013) 765

Single-track angular resolution

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



For various densities (argon)

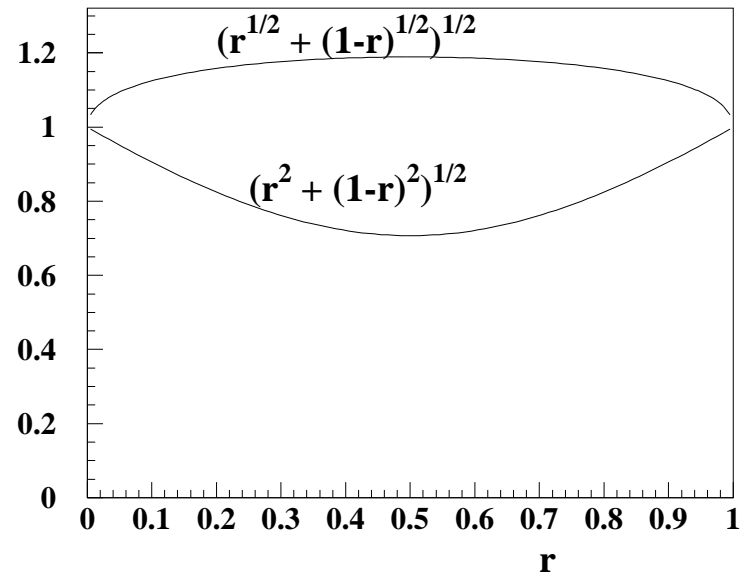


for various gases

D.B., NIM A 701 (2013) 225

Angular resolution: From Single-track to single photon

- Small angle approximation: $\theta_{x,\gamma} = r\theta_{x,+} + (1-r)\theta_{x,-}$,
- r fraction of energy carried away by the positron, $r = E_+/E$,



- multiple scattering dominated regime: $\sigma_{\theta\gamma} = \sigma_{\theta t} \sqrt{\sqrt{r} + \sqrt{1-r}}$
- high energy regime: $\sigma_{\theta\gamma} = \sigma_{\theta t} \sqrt{r^2 + (1-r)^2}$
- track to photon factor close to unity: neglected in the following.

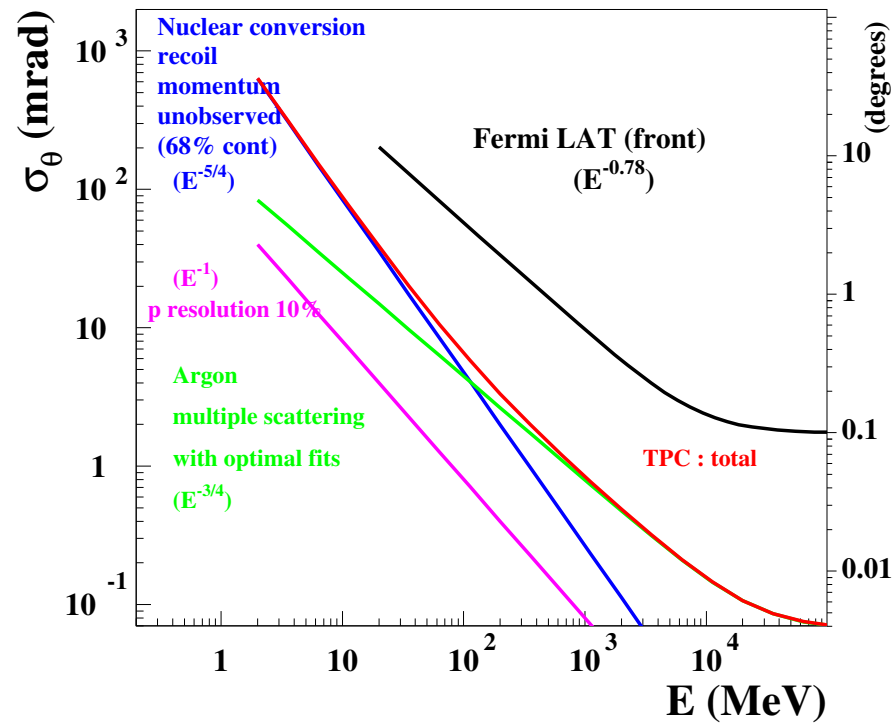
D.B., NIM A 701 (2013) 225

Angular resolution: Wrap up

- Argon-based gas, $P = 10$ bar

$X_0 = 1180$ cm

- Sampling pitch $l = 1$ mm, point resolution $\sigma = 0.1$ mm,

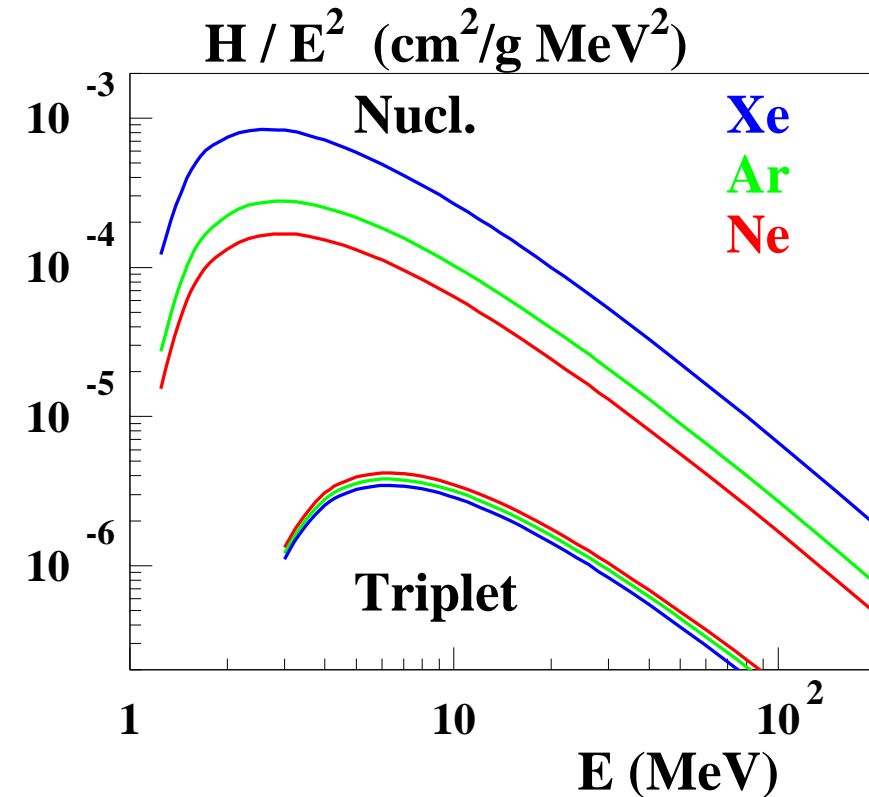
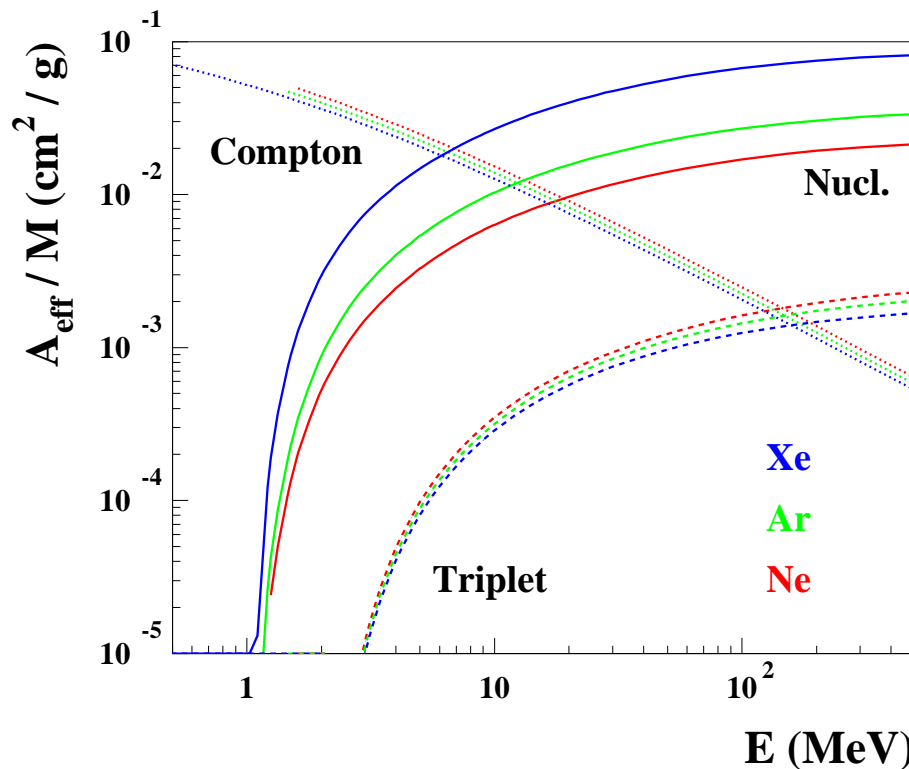


	multiple scattering	ion recoil momentum	total
	$\sigma_{\theta t} = (p/p_1)^{-3/4} \quad \text{with} \quad p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3} \right)^{1/6}$ $p_1 = 73 \text{ keV}/c$	$1.5 \text{ rad} \left(\frac{E}{1 \text{ MeV}} \right)^{-5/4}$	
$\sigma_\theta @ 100 \text{ MeV}$	0.26°	0.27°	0.37°

Thin detectors: Effective area

- $A_{\text{eff}} = H \times M,$

H photon attenuation



Argon, nucl.: $A_{\text{eff}}/M = 27 \text{ cm}^2/\text{kg} @ E = 100 \text{ MeV}$

National Institute of Standards and Technology (NIST)

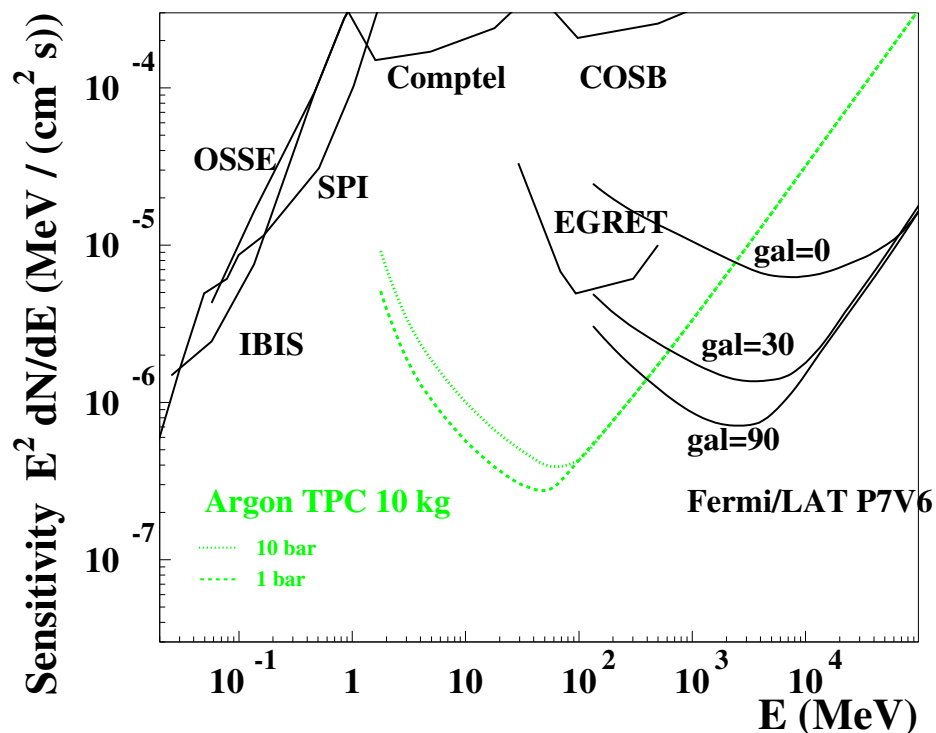
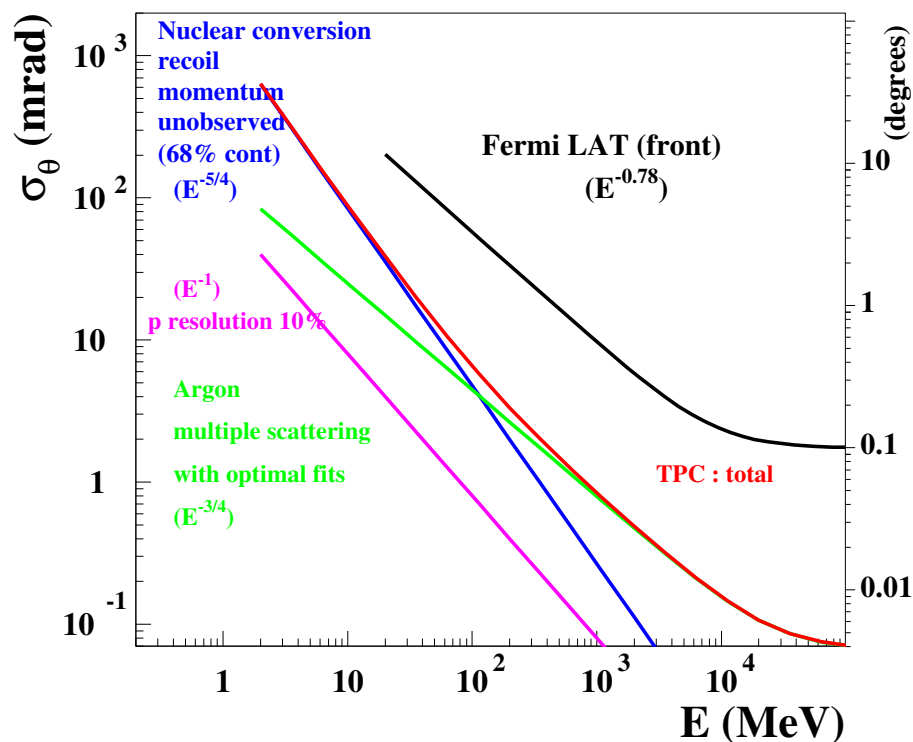
Performances with Thin Homogeneous Detector and Optimal Fits

Angular resolution

point-source differential sensitivity

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

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



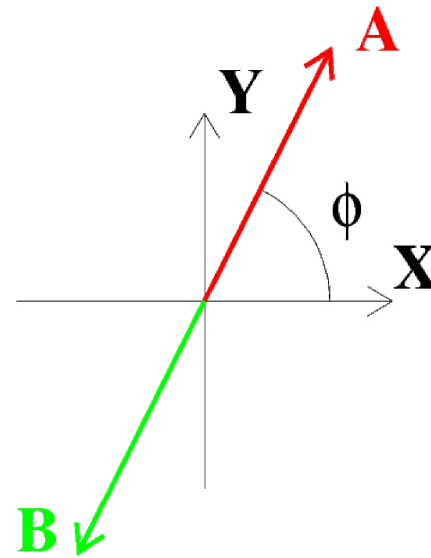
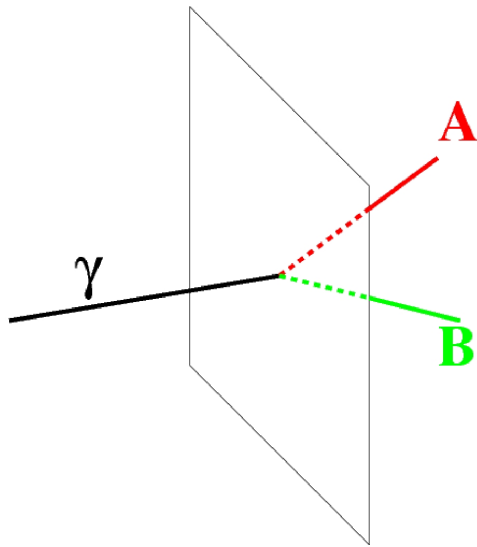
D.B., NIM A 701 (2013) 225

Polarimetry

- Photon has $J^{PC} = 1^{--}$: Modulation of azimuthal angle distribution

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

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

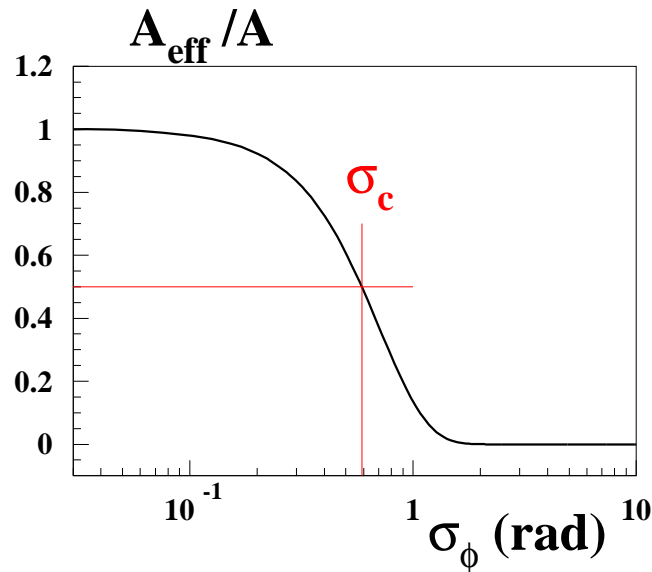


- P source linear polarisation fraction
- \mathcal{A} Polarization asymmetry
- ϕ azimuthal angle

Multiple Scattering: Dilution of the Asymmetry

Slabs

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



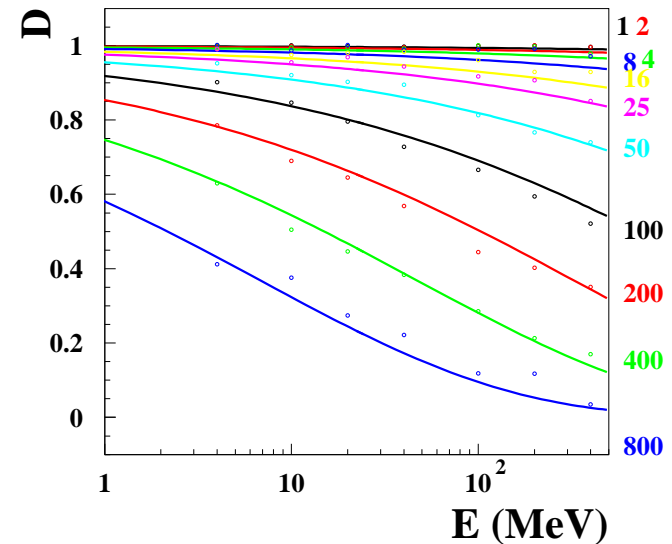
$$\sigma_{\phi} \approx 24 \text{ rad} \sqrt{x/X_0}$$

$\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2$ for 110 μm of Si, 4 μm of W

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

homogeneous detector
with optimal tracking

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



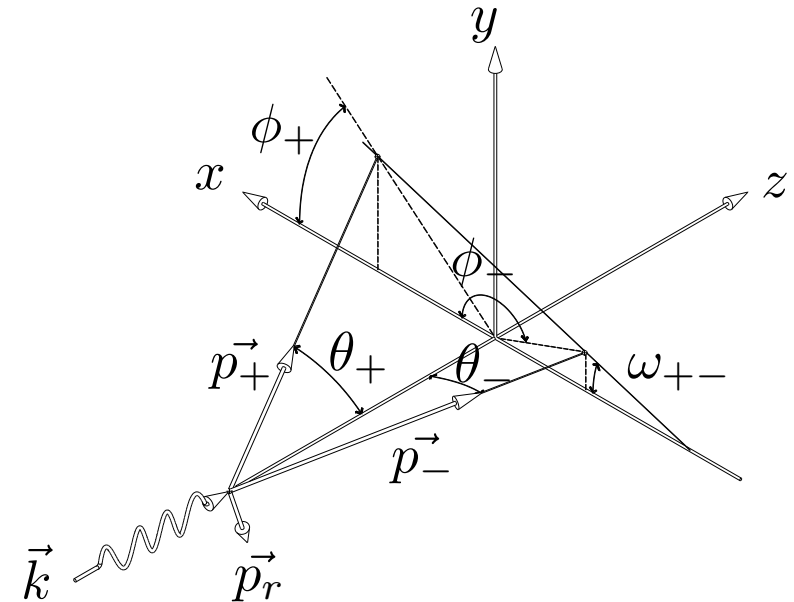
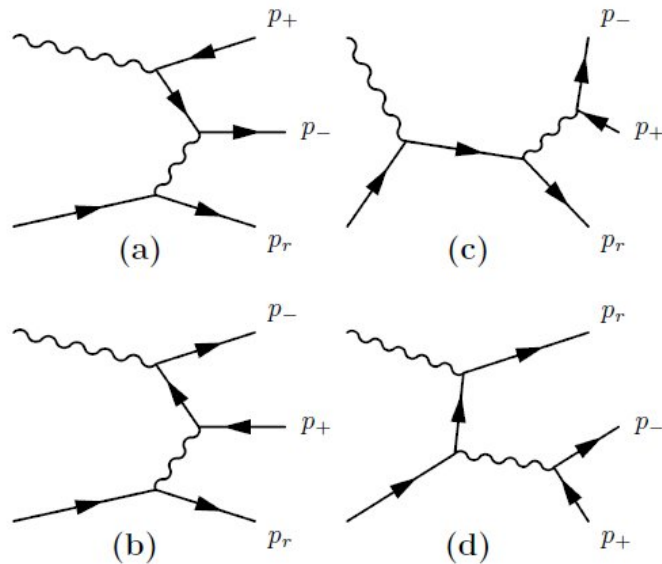
$$p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3} \right)^{1/6}$$

$p_1 = 50 \text{ keV}/c$ (1 bar argon) ,
 $p_1 = 1.5 \text{ MeV}/c$ (liquid argon).

D.B., 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 $x_+ \equiv E_+/E$



- Uses:

- HELAS amplitude computation
- SPRING event generator

H. Murayama, *et al.*, KEK-91-11.

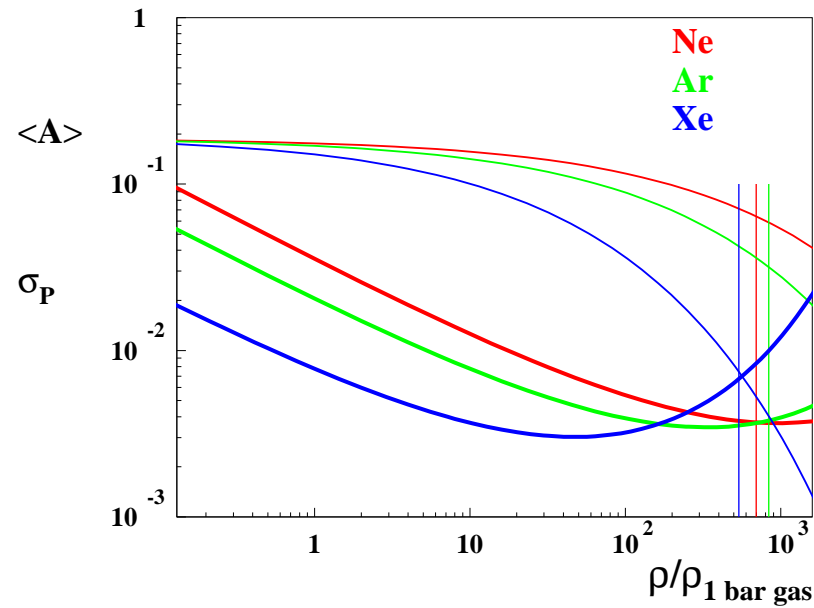
S. Kawabata, *Comput. Phys. Commun.* 88, 309 (1995).

D.B., *NIM A* 729 (2013) 765

Characterisation of available event generators : see P. Gros's talk

Polarimetry Performance

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



- Argon, 5 bar, $\mathcal{A}_{\text{eff}} \approx 15\%$, $\sigma_P \approx 1.0\%$,
- With experimental cuts applied $\Rightarrow \sigma_P \approx 1.4\%$,

D.B., 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, Patrick Poilleux, Igor Semeniouk, Shaobo Wang ^a
^aLLR, Ecole Polytechnique and CNRS/IN2P3, France

David Attié, Denis Calvet, Paul Colas, Alain Delbart, Patrick Sizun ^b
^bIRFU, CEA Saclay, France

Diego Götz ^{b,c}
^cAIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp, CEA Saclay, France

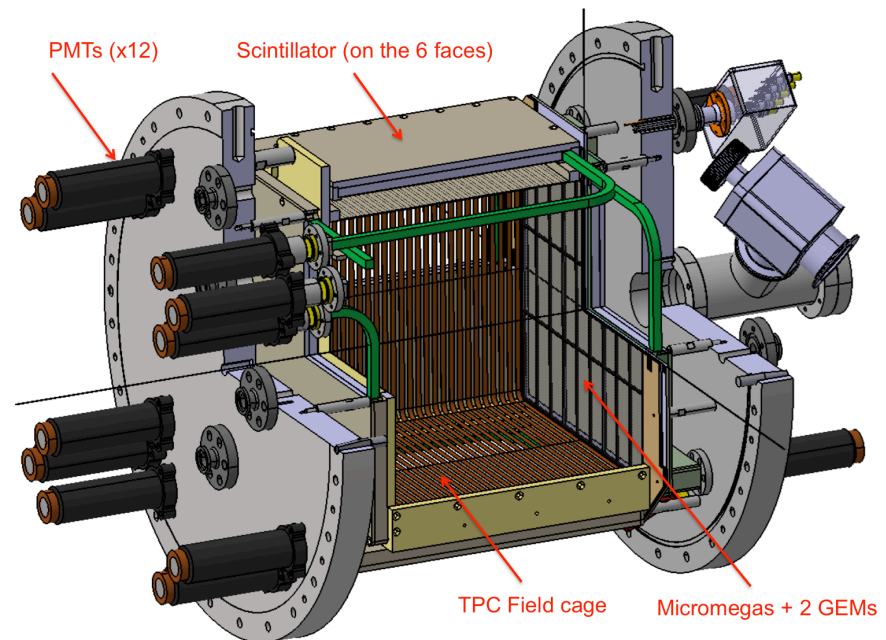
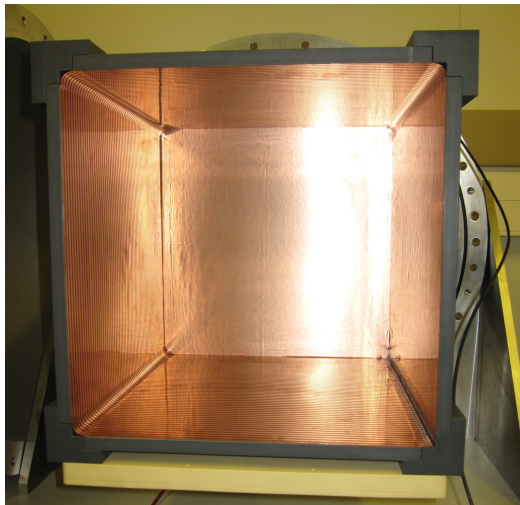
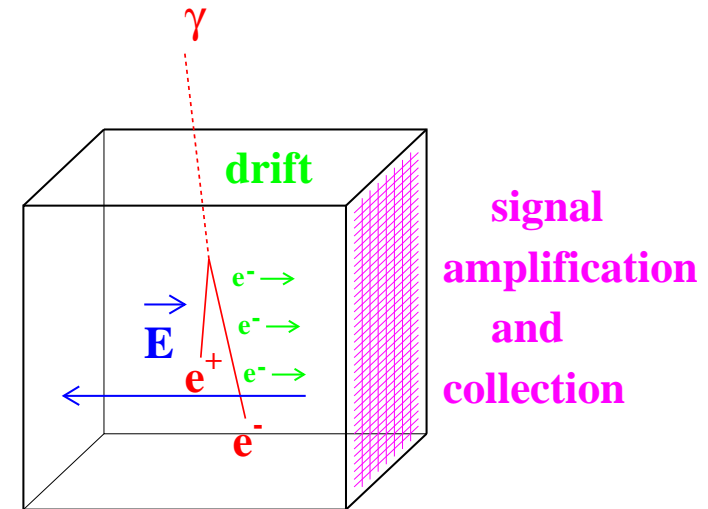
- Japan: the beam.

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

S. Daté, H. Ohkuma^f
^f JASRI/SPring8, Japan

HARPO: the Demonstrator

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

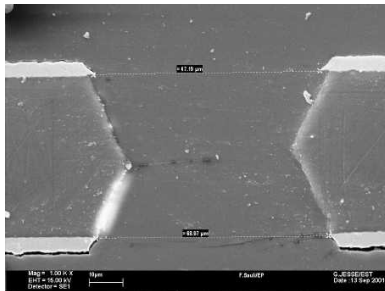
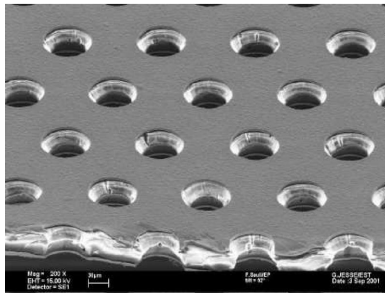


D.B., NIM A 695 (2012) 71,

NIM A 718 (2013) 395

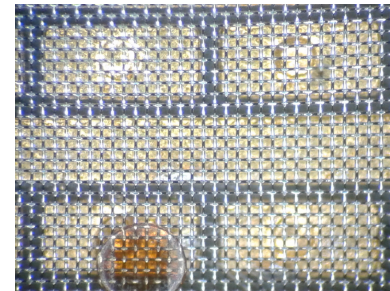
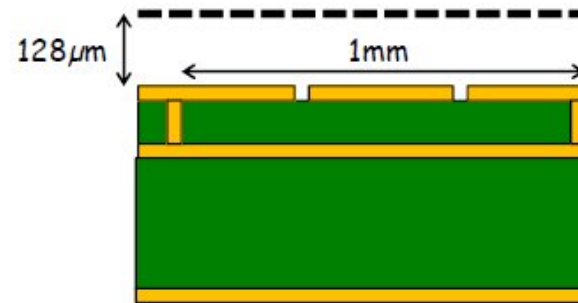
Gas amplification: micromegas + 2 GEM

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



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

“bulk” micromegas
gap 128 μm
(x, y) strips, pitch 1 mm, width 0.4 mm

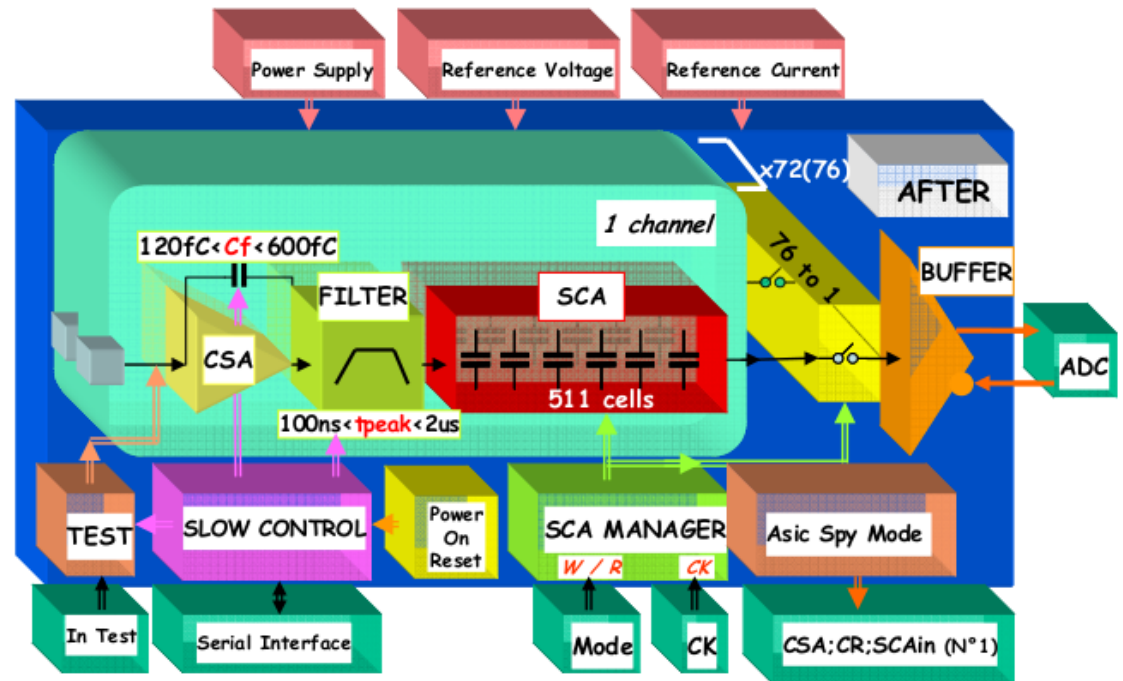


I. Giomataris *et al.*, NIM A 560, 405 (2006)

- Characterization of (Micromegas + 2 GEM) assemblies (^{55}Fe + cosmic rays)
Ph. Gros *et al.*, TIPP2014, PoS(TIPP2014)133

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 μ s
- 12 bit ADC.



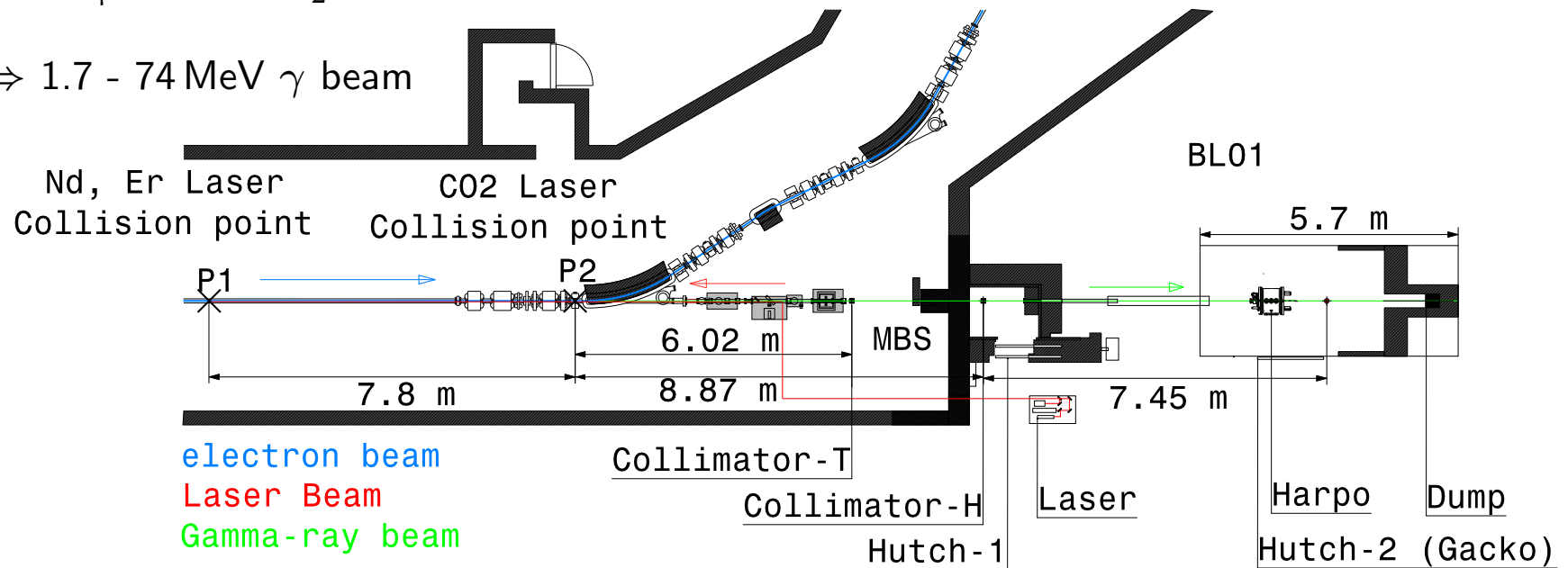
Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

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 μm and 1.064 μm 20 kHz pulsed Nd:YVO₄ (2ω and 1ω), 1.540 μm 200 kHz pulsed Er (fibre) and 10.55 μm CW CO₂ lasers

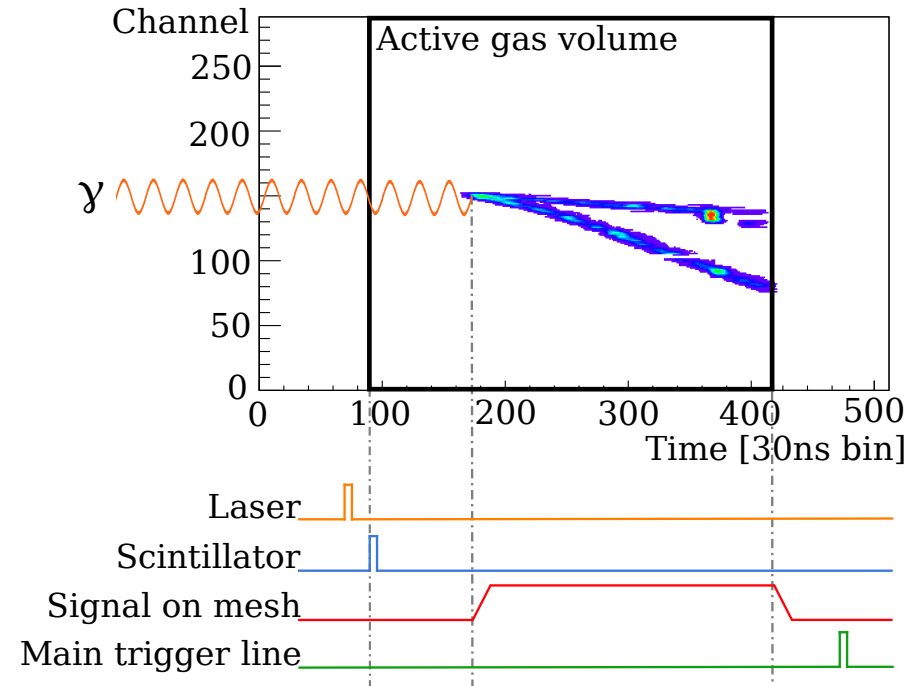
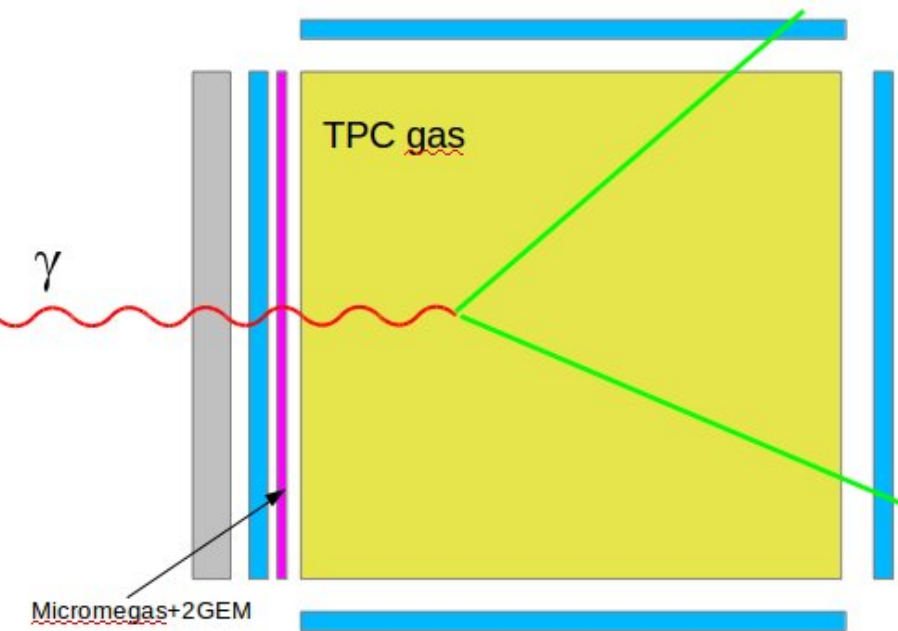
- \Rightarrow 1.7 - 74 MeV γ beam



- Monochromaticity by collimation on axis
- Fully polarized or random polarization beams ($P = 1$, $P = 0$)
- 2.1 bar Ar:isoC₄H₁₀ 95:5 (+ a 1.0 – 4.0 bar scan).

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

Beam trigger system



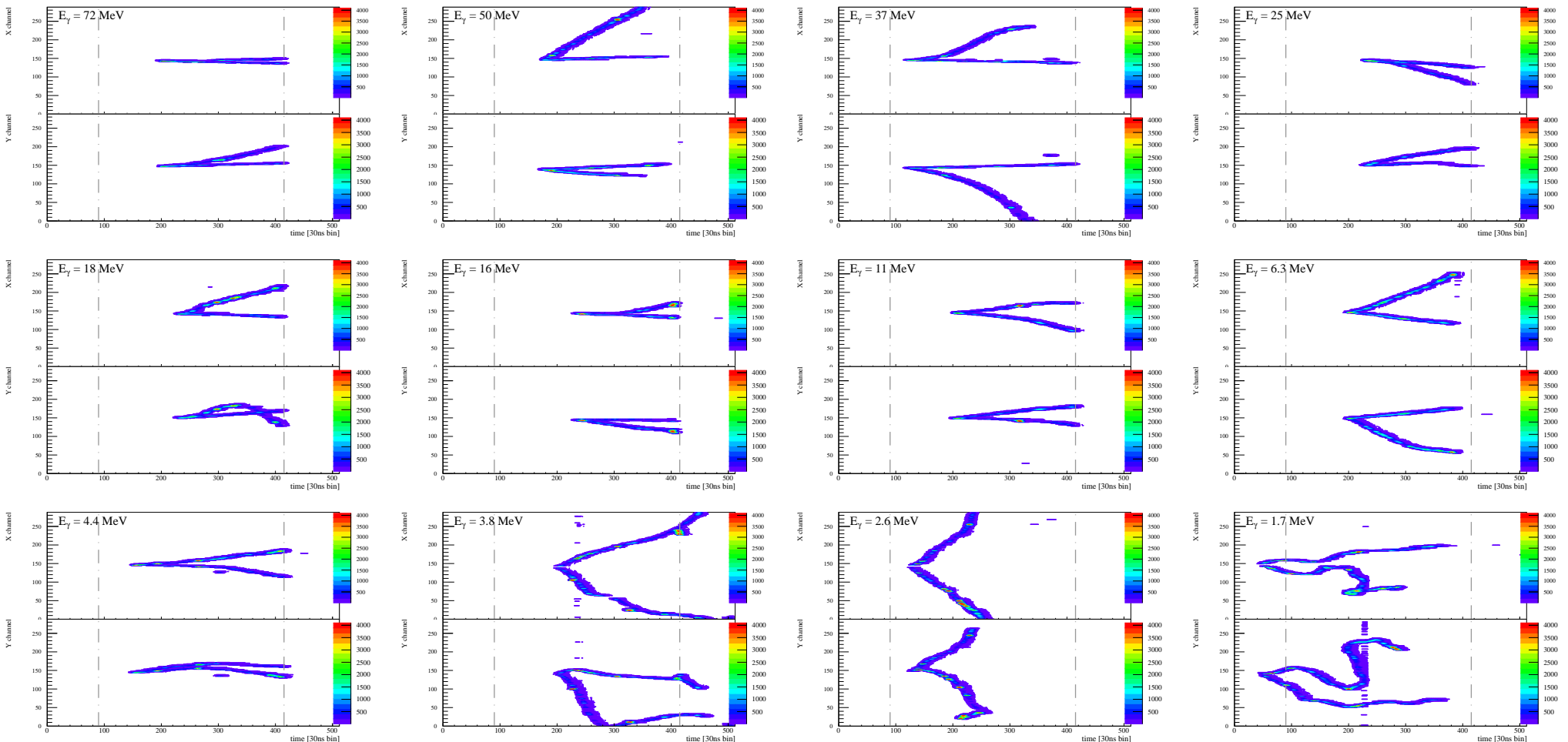
- S_{up} upstream scintillator
- O one of the 5 other scintillators
- M_{slow} : a delayed ($> 1\mu s$) signal on the μM mesh
- L laser trigger pulse

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

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

Y. Geerebaert, *et al.*, RT2016, 2016 IEEE-NPSS

Japan beam Data: gallery

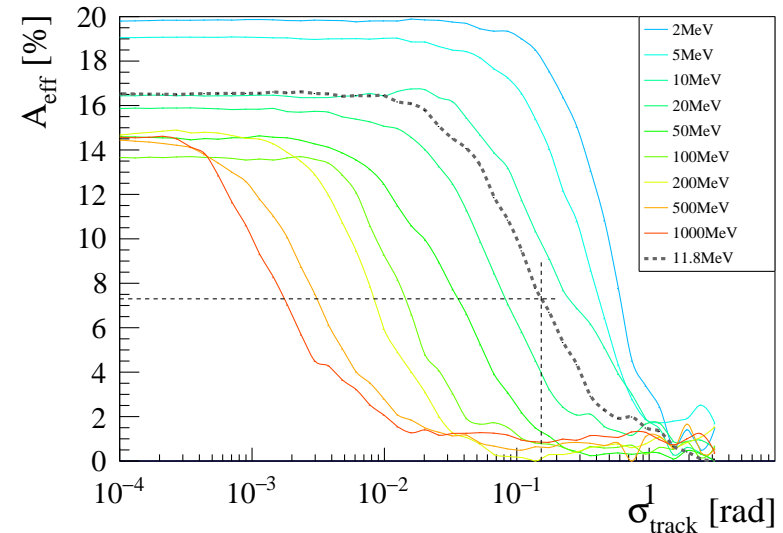
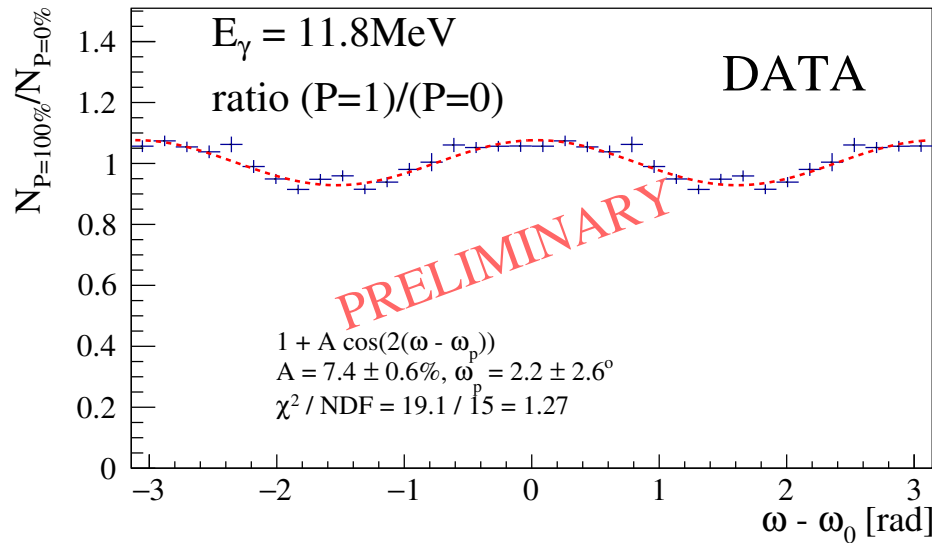


Sample of γ -rays from 74 to 1.7 MeV converting to e^+e^- in 2.1 bar Ar:isobutane 95:5 detected by the HARPO TPC
(pre-beam-calibration γ -ray energy on plots)

D. B. *et al.*, Future Space-based Gamma-ray Observatories Workshop , NASA GSFC 2016.

Polarization Asymmetry : beam results

- ICS of 1.55 μm photons from Er laser on 0.974 GeV $e^- \Rightarrow 11.8 \text{ MeV } \gamma\text{-rays}$



- Ratio of $P = 1$ to $P = 0$ azimuthal angle distributions for 11.8 MeV γ -ray photons converting to e^+e^- in 2.1 bar 95:5 argon-isobutane.
- First demonstration of the measurement of the linear polarisation of a γ -ray beam with pairs at low energy.

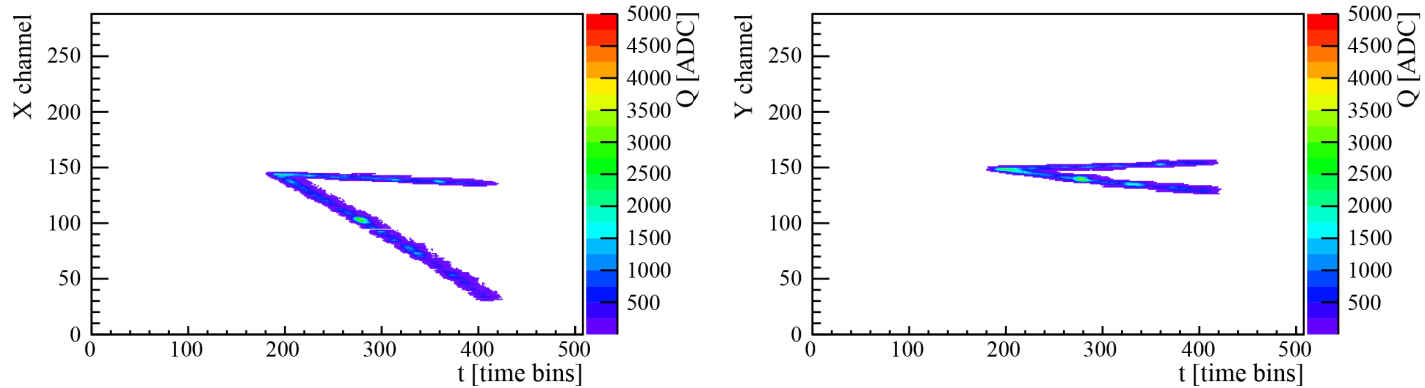
P. Gros *et al.*, SPIE2016 9905-95, arXiv:1606.09417

Conclusion

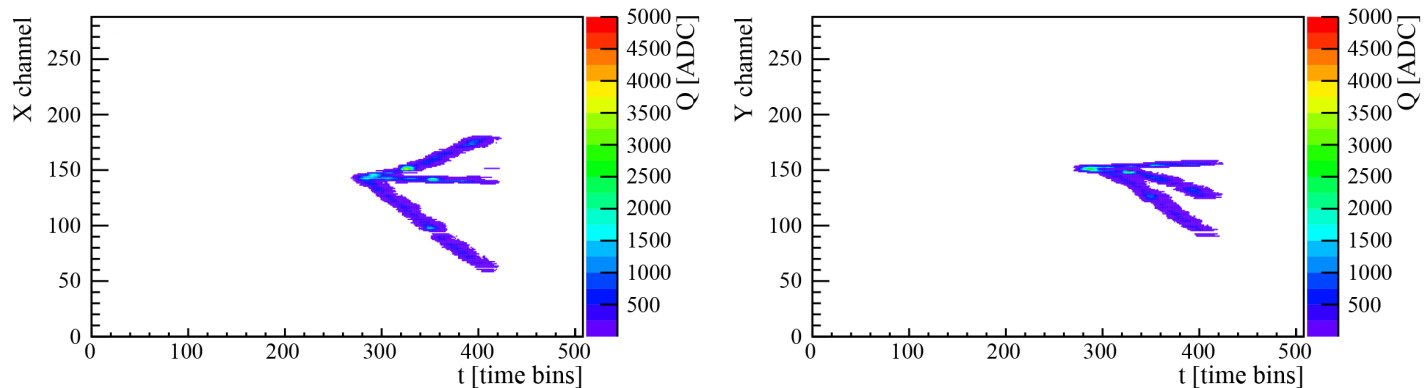
- Gas TPC is THE choice detector for ultimate angular resolution $\gamma \rightarrow e^+e^-$ astronomy and polarimetry in the MeV-GeV energy range
 - Robust detector used in HEP since the 1980's from sub-cm³ to multi-m³
 - From the lowest (eg. T2K) to the highest (eg. ALICE) rate, radiation, track multiplicity
 - Use of a low-diffusion, “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
 - Key issue is self-triggering: Self Triggered TPC as Gamma-ray Telescope “ST3G” scheme under study
 - radhard and upgraded version of digitizing chip : prototypes produced
 - balloon flight prototype under study.
 - Data taken:
 - with a (30cm)³ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
 - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, γ beam
- : analysis in progres.

“Nuclear” and “triplet” conversions

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



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



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

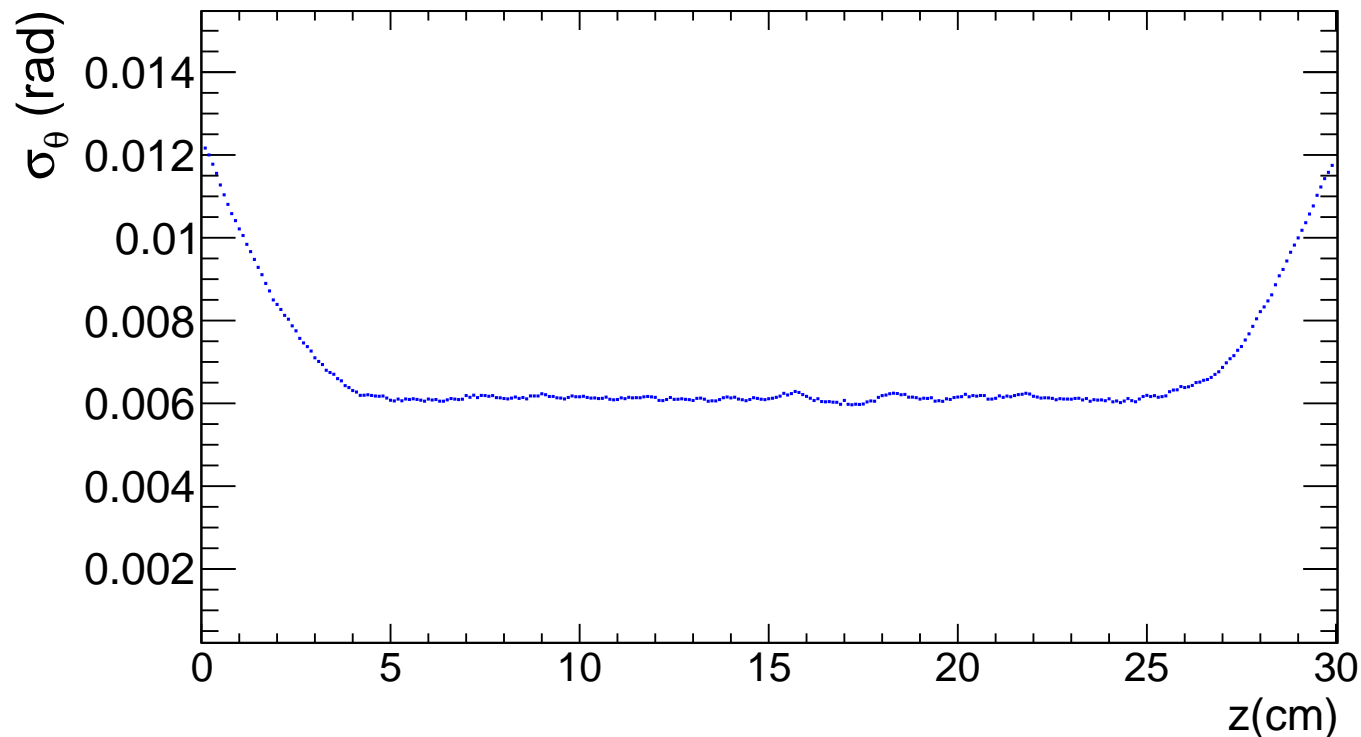
Back-up Slides

Single-track angular resolution with Optimal fits: Validation with a Kalman filter

- Validation with parameters: 5 bar argon, $\sigma = l = 0.1\text{cm}$;

$$p_1 = 13.6 \text{ MeV}/c \left(\frac{4\sigma^2 l}{X_0^3} \right)^{1/6} = 112 \text{ keV}/c$$

- 40 MeV/c electrons, $\sigma_{\theta t} = (p/p_1)^{-3/4} = 12.2 \text{ mrad}$



Angular resolution (residue RMS) as a function of the position along the track

NIM A 729 (2013) 765

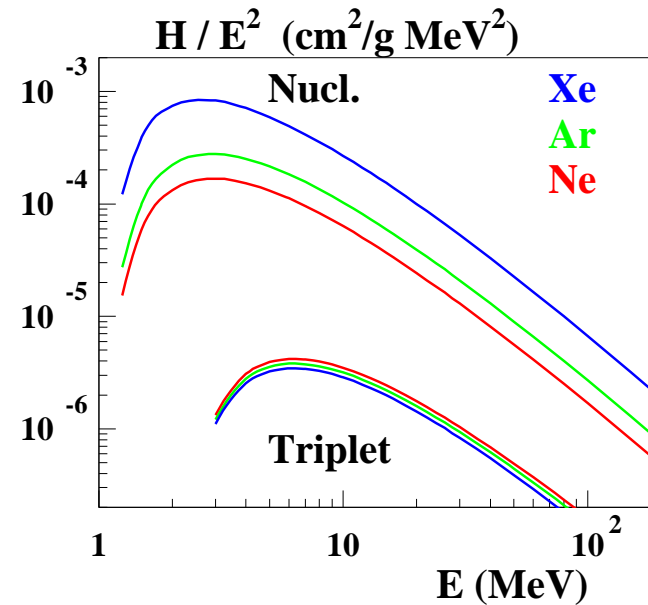
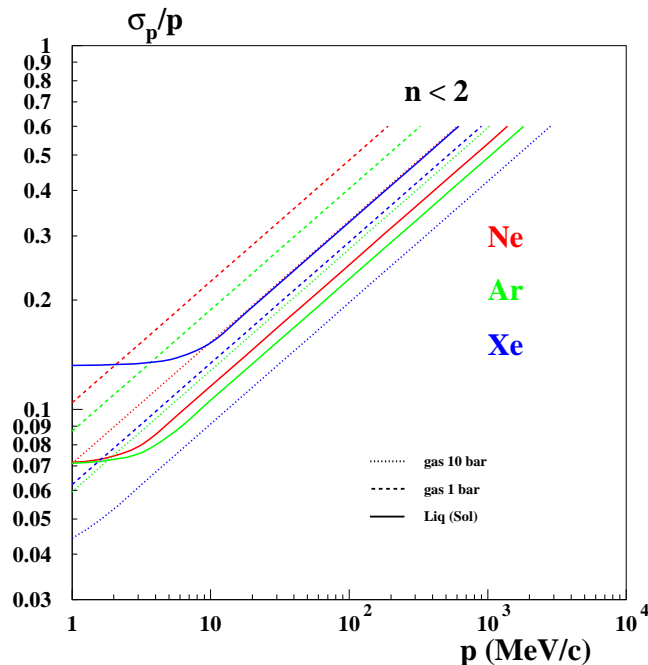
Track Momentum Measurement in TPC Alone from Multiple Estimations of Multiple Scattering

- multiple scattering $\theta_0 \propto 1/p \Rightarrow p \propto 1/\theta_0$ G. Molière, Zeit. Naturforschung A, 10 (1955) 177.

- optimization of track step size $\Rightarrow \frac{\sigma_p}{p} \propto \frac{1}{\sqrt{L}} \left[\frac{p \sigma \sqrt{X_0}}{13.6 \text{MeV}/c} \right]^{1/3}$

relative precision

E range of interest



A Kalman-filter based measurement should do a factor ≈ 2 better.

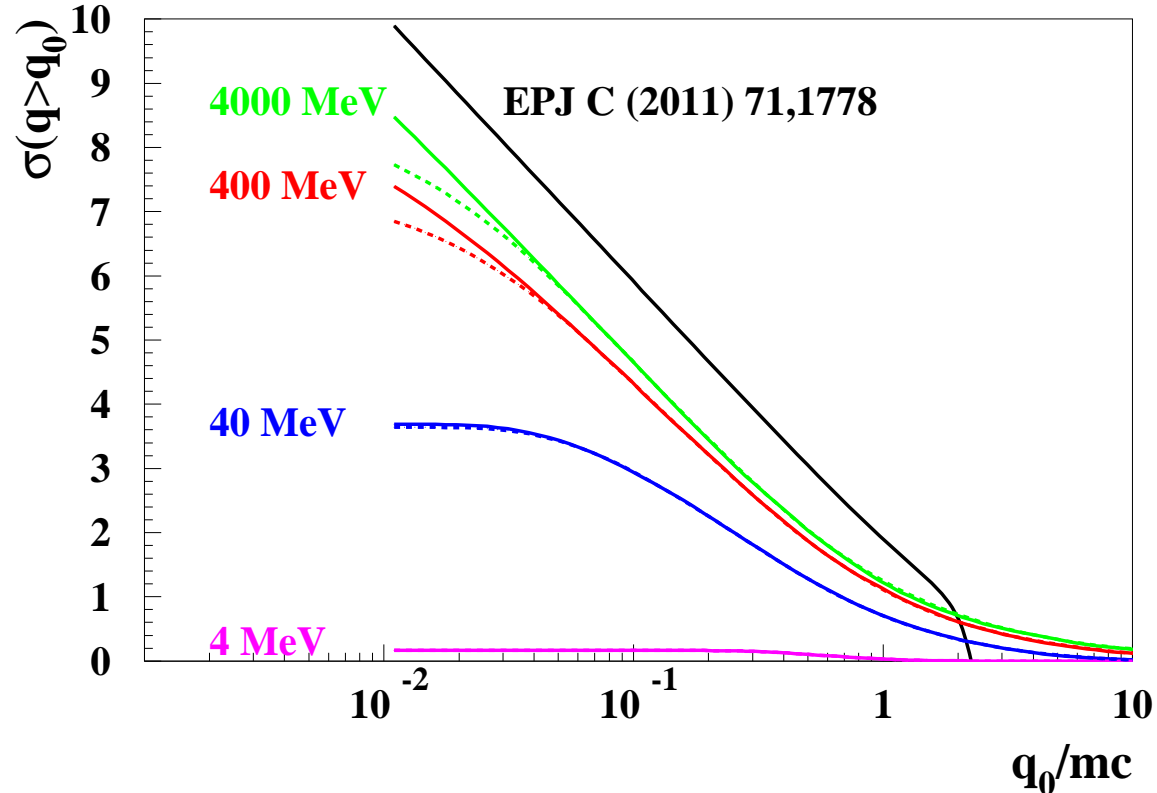
NIM A 701 (2013) 225

Evt Generator: One Example of Validation Plot

- Triplet conversion: 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:

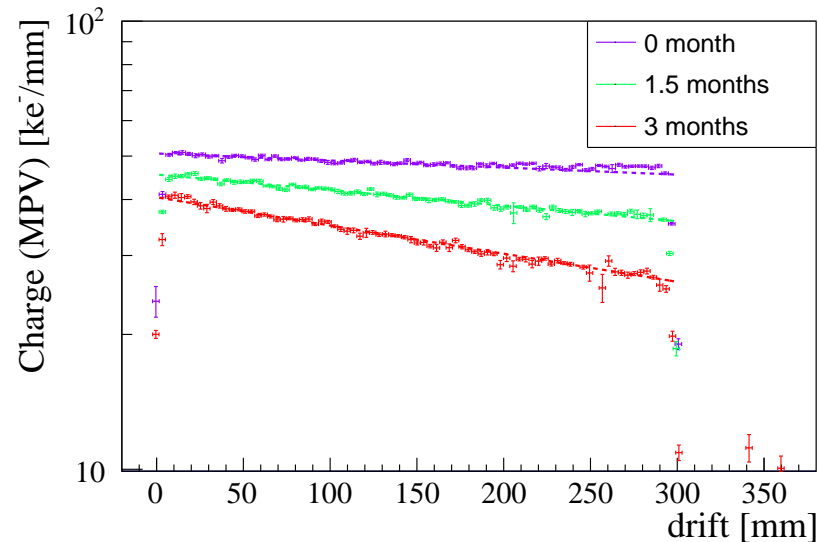
- High photon energy asymptotic expression by M. L. Iparraguirre and G. O. Depaola, *Eur. Phys. J. C* 71, 1778 (2011).



NIM A 729 (2013) 765

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).

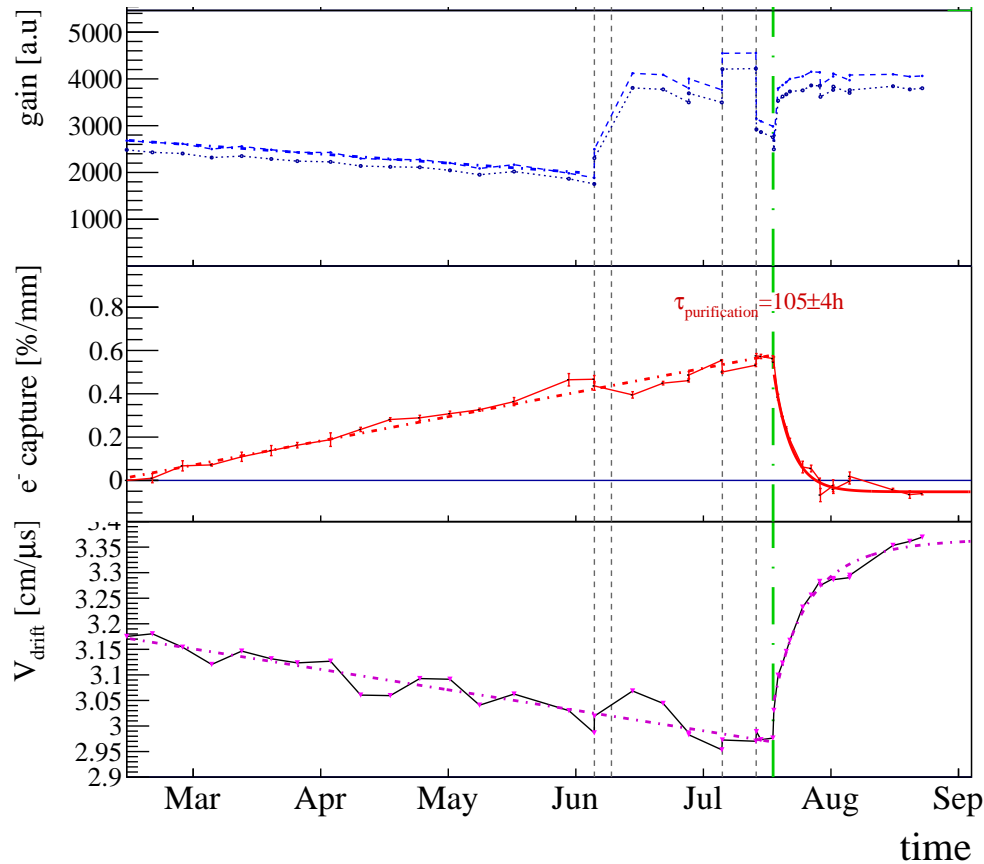


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- **O₂ 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. **O₂ fraction disappeared (< 20 ppm)**

M. Frodin *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](https://arxiv.org/abs/1512.03248) [physics.ins-det], MPGD2015, EPJ Web of Conferences

Search for Axions

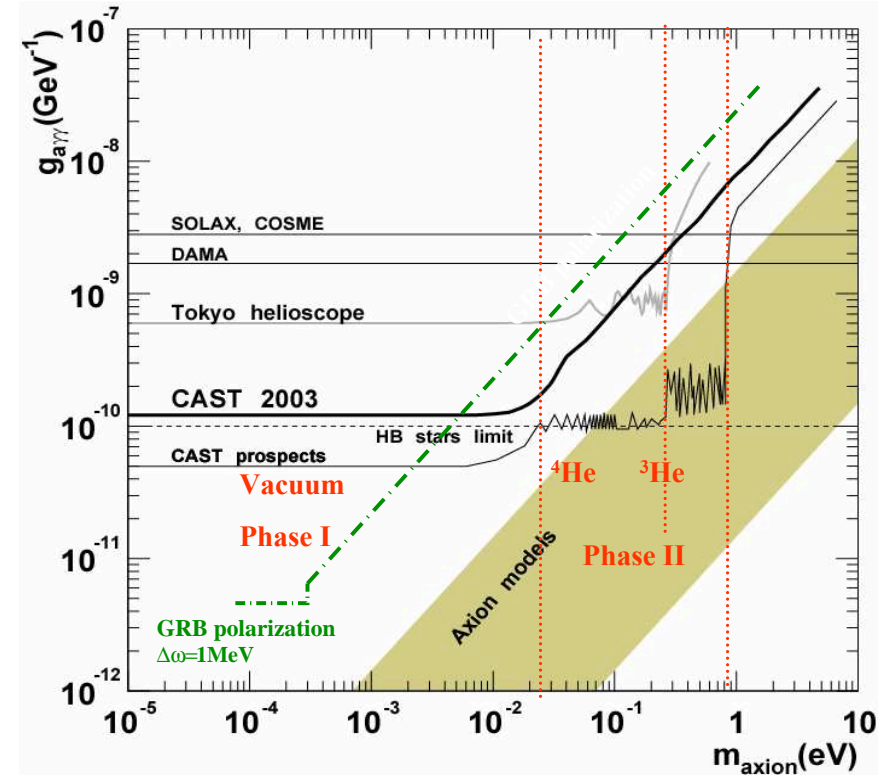
- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to 2 γ through triangle anomaly.
- γ propagation through $B \Rightarrow$ Dichroism $\Rightarrow E$ dependant rotation of linear polarization \Rightarrow linear polarization dilution.

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

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

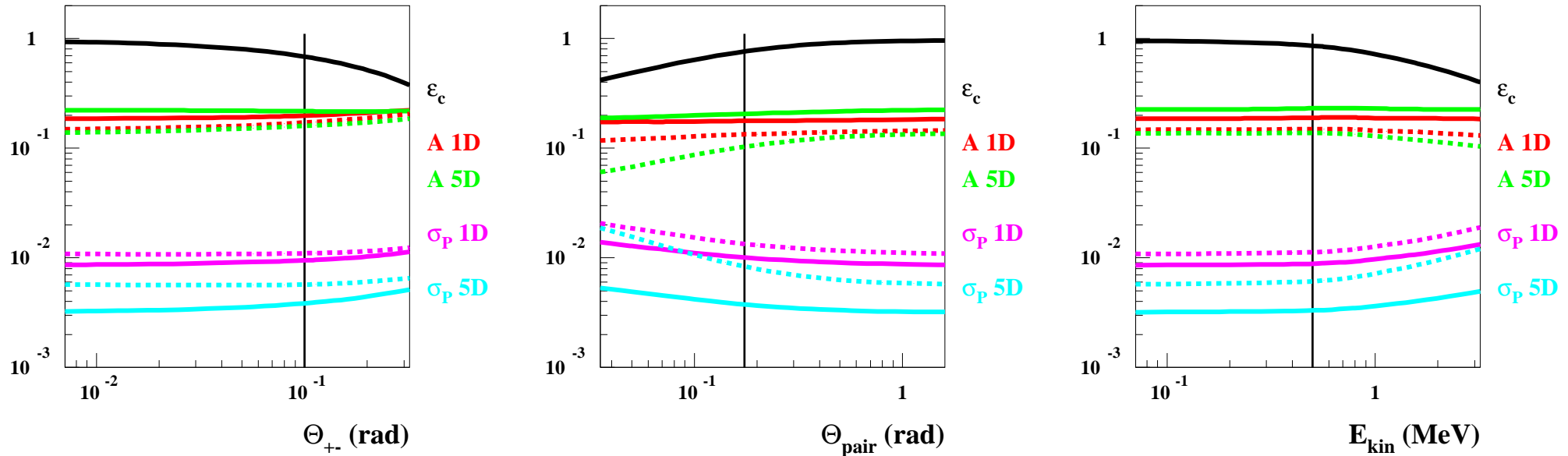
and the limit $g_{a\gamma\gamma}$ reaches a ω -independent constant.

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



Polarimetry: Effects of Experimental Cuts

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



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

D.B. NIM A 729 (2013) 765

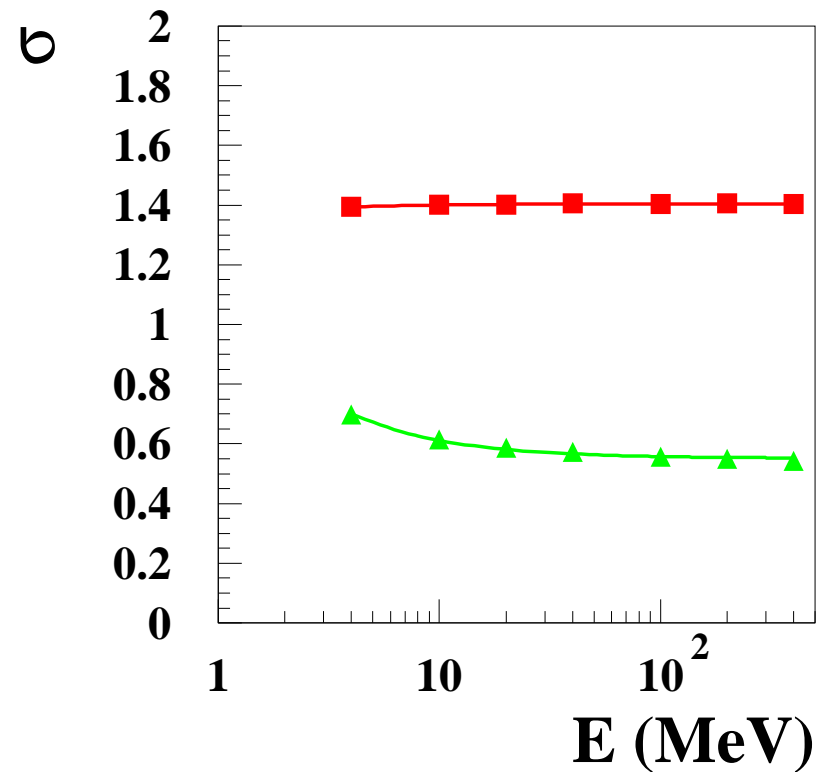
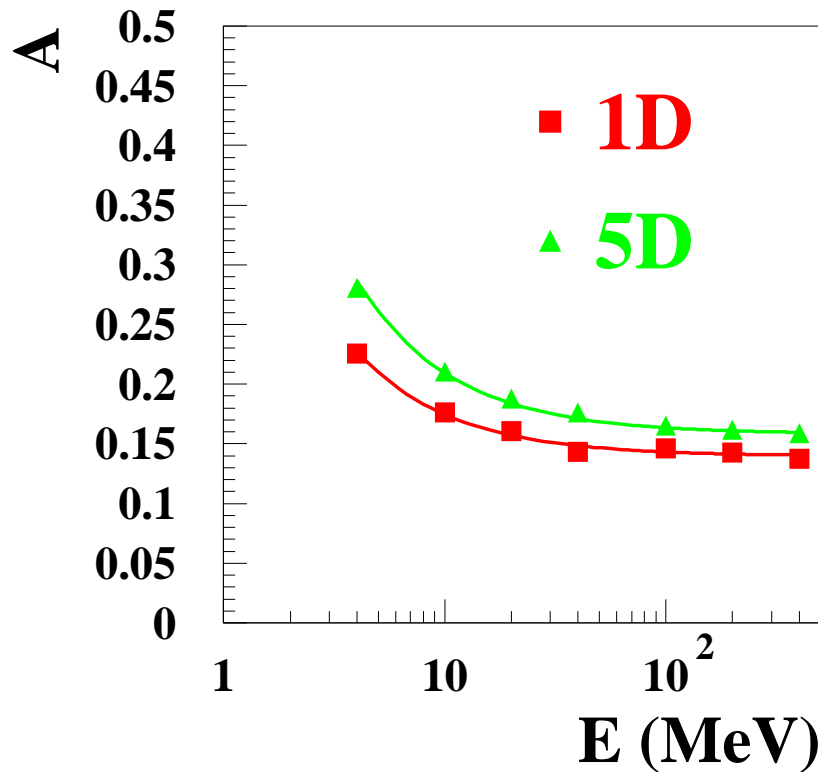
Polarimetry: Optimal Measurement

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

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

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Polarization asymmetry and measurement uncertainty



NIM A 729 (2013) 765

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

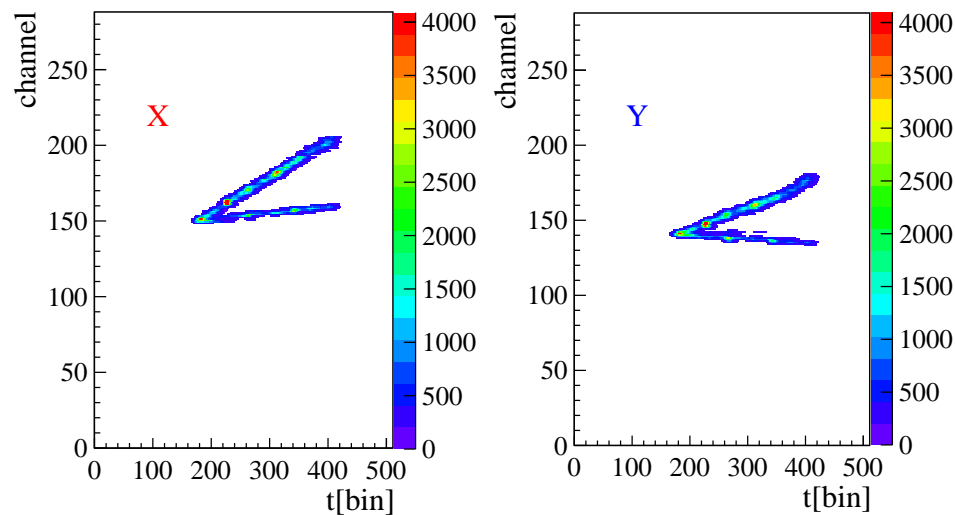
Boldyshev & Peresunko, *Yad. Fiz.* 14, 1027 (1971).

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

Polarimetry: Track matching issue

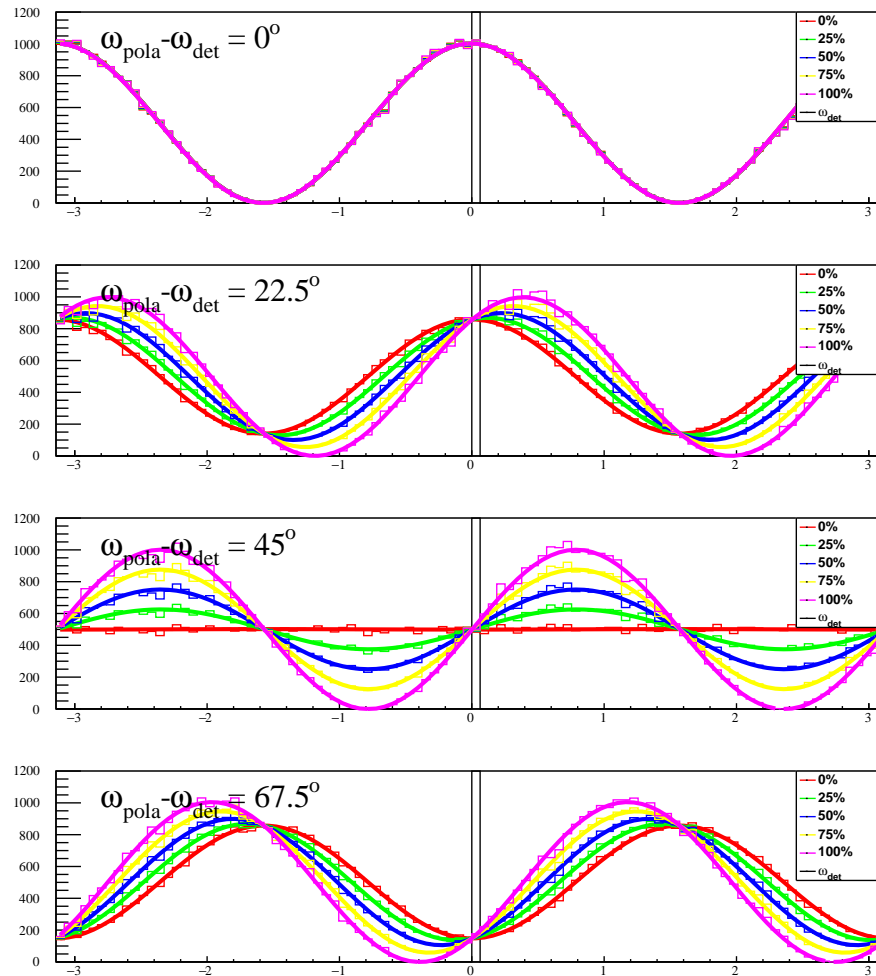
- Many foreseen project use 2×2 D projections, not true 3D imaging (gas TPC, silicon strip detectors)
- Ambiguity:

$$(\text{track}_{1,x}, \text{track}_{1,y})(\text{track}_{2,x}, \text{track}_{2,y}) \leftrightarrow (\text{track}_{1,x}, \text{track}_{2,y})(\text{track}_{1,y}, \text{track}_{2,x})$$



- Ruins the azimuthal angle information
- Assignment must be performed before multiple scattering blurs the picture

Track matching issue



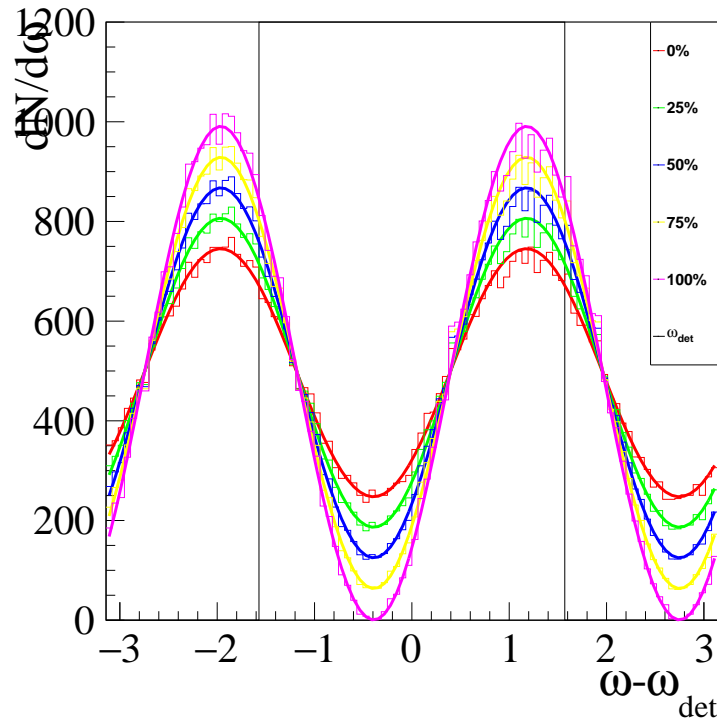
Observed angular distribution

- for fully polarised pairs ($P_{\text{eff}} = 1$),
- in a fixed direction wrt the detector ($\omega_{\text{pola}} - \omega_{\text{det}}$)
- for different values of the matching efficiency ε .

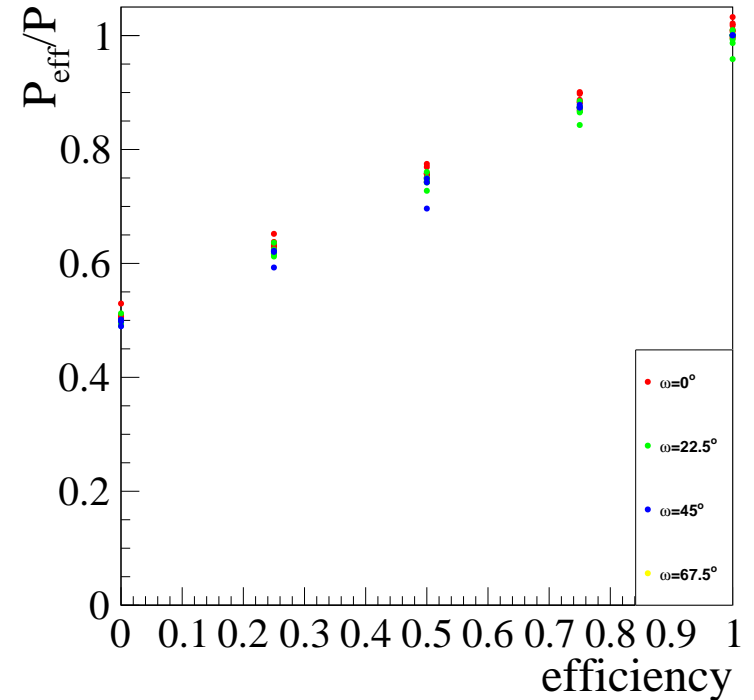
Philippe.Gros @ Ilr.in2p3.fr

Track matching issue: results

- Time (means $\omega_{\text{pola}} - \omega_{\text{det}}$) integrated distributions



Azimuthal distribution for different matching efficiencies



Dilution as a function of matching efficiency.

- A factor of 2 is at stake !

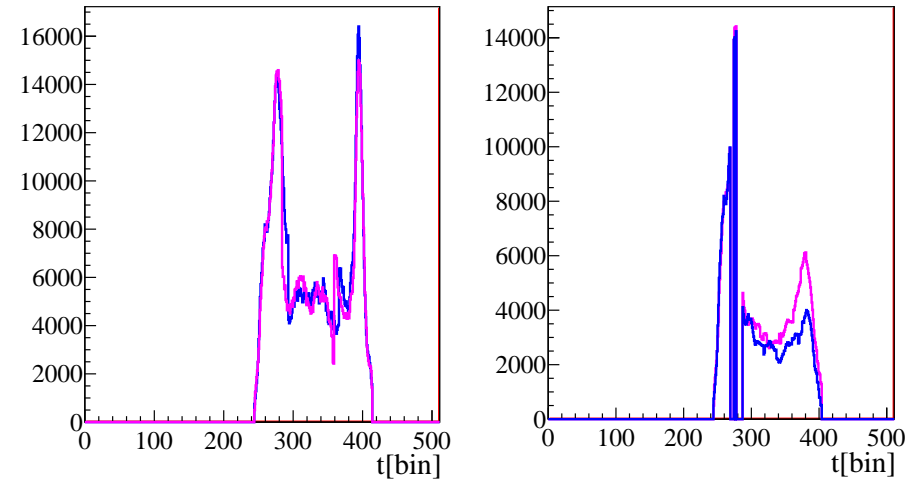
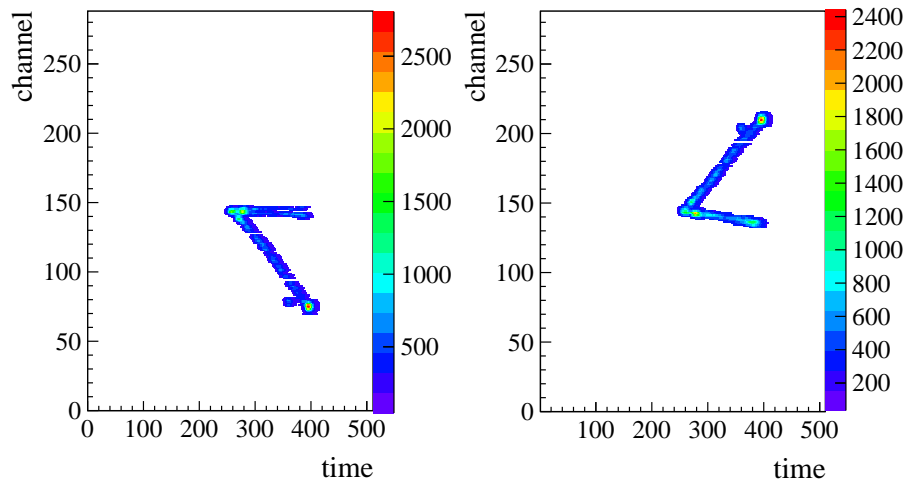
Philippe.Gros @ llr.in2p3.fr

x, y Matching

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

raw “maps”

track time spectra



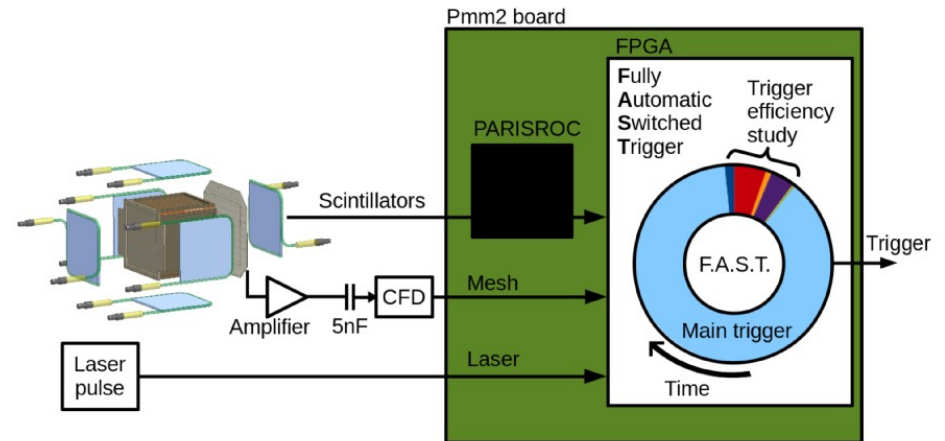
- x, y two-track ambiguity solved by track time spectra matching
- 1 channel = 1 mm.
- 1 time bin = 30 ns, $v_{\text{drift}} \approx 3.3 \text{ cm}/\mu\text{s} \Rightarrow 1 \text{ time bin} \propto 1 \text{ mm}$

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

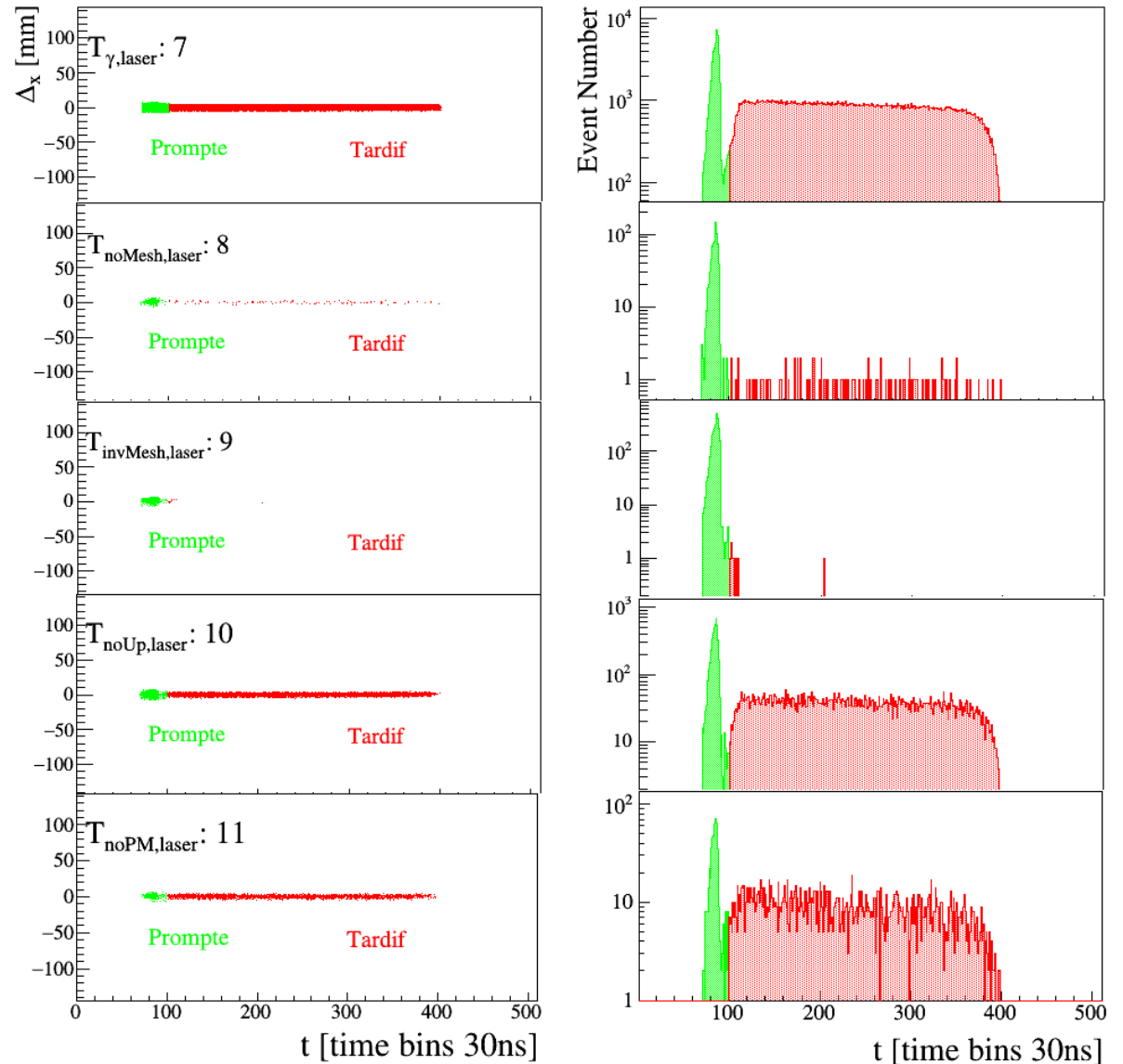


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

Y. Geerebaert & P. Gros *et al.*, VCI 2016, NIM A, arXiv:1603.06817

“Beam” trigger system: conversion point distributions

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



Y. Geerebaert, *et al.*, RT2016, 2016 IEEE-NPSS

Towards a space detector: some elements

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

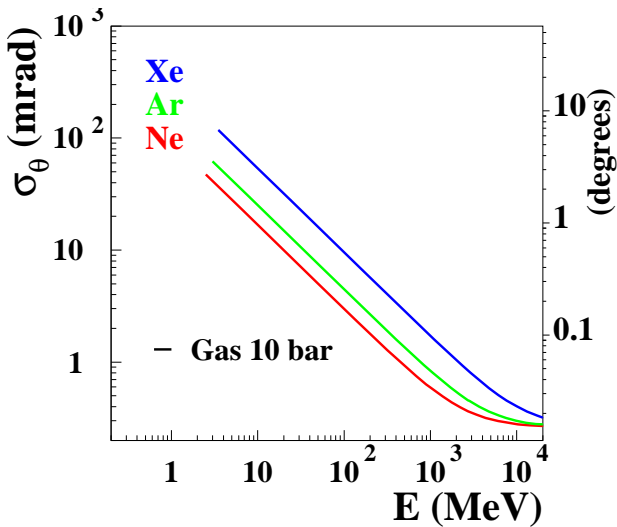
Towards a space detector: Gas composition: drifting species ?

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

drifting species	example	v_{drift}	t_{drift}	pile-up fraction	
electron	Ar:isoC ₄ H ₁₀	3.3 cm/ μs	10 μs	0.2 proton/ m^2	manageable
negative ion	Ar:CS ₂	3.3 cm/ms	10ms	200 proton/ m^2	nope

Gas composition: light / heavy Z ? Gas pressure ?

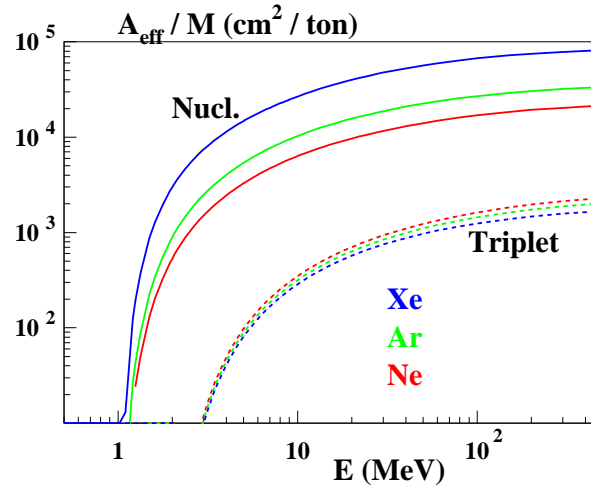
- $\rho \times X_0 = \frac{A}{Z^2}b$, $\rho = aAP$, $M = V\rho = VaAP$, $X_0 = \frac{b}{aZ^2P}$ a, b constants.



angular resolution degrades with Z

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

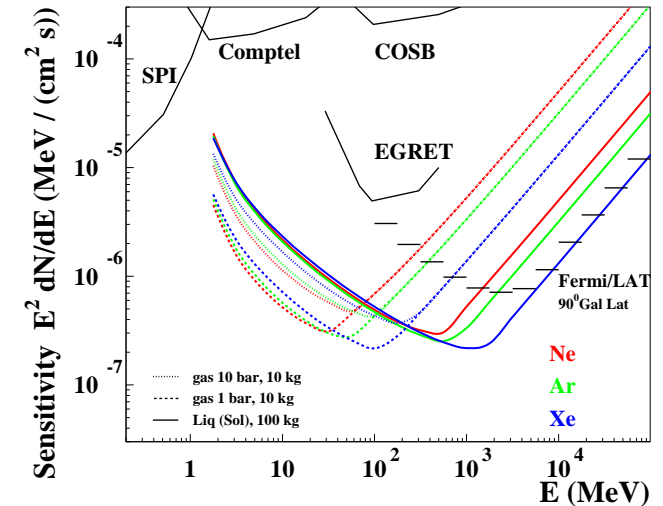
(multiple scattering)



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)

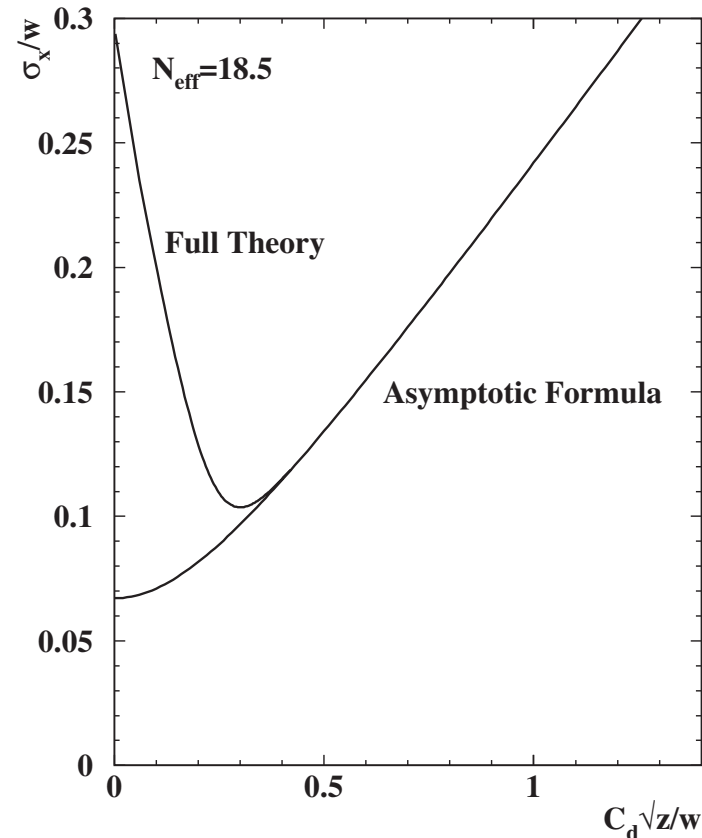
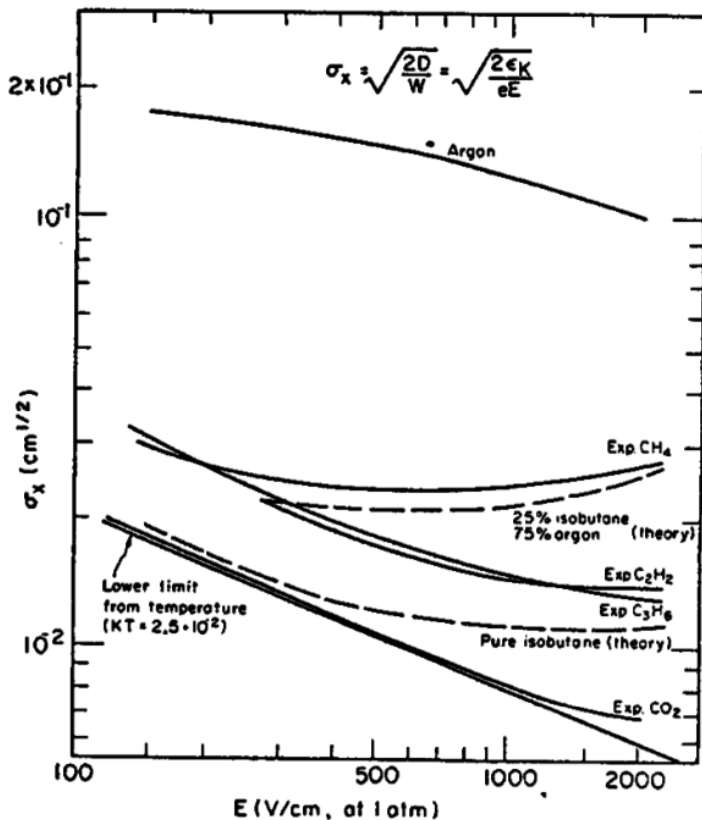
(assuming gaussian stats.)

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

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

NIM A 701 (2013) 225

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, CO₂ ..)
- Mitigates diffusion $\sigma = \sigma_x / \sqrt{z}$, $\sigma_x = 200 \mu\text{m} / \sqrt{\text{cm}}$, ($\sigma \approx 0.6 \text{ mm}$ after $z = 9 \text{ cm}$ drift)
- Diffusion is needed to minimize the TPC spatial resolution ! $C_D \equiv \sigma_x$, w strip pitch.

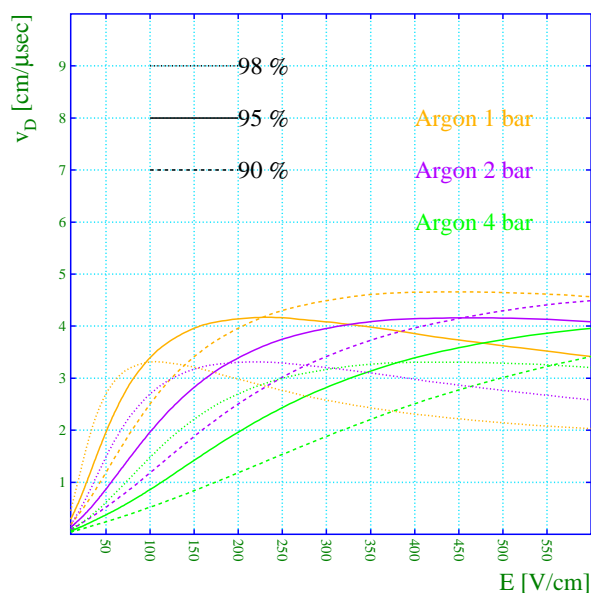
Pressure, Quencher fraction, e^- transport properties

- Argon-iso-butane mixture with (2, 5, 10)% iso-butane and pressure 1, 2, 4 bar

Drift velocity

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

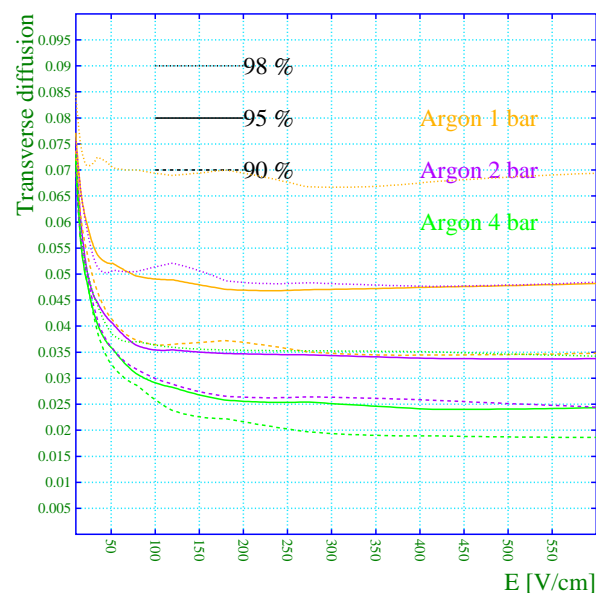
Drift velocity in Ar/ISO mixtures



Transverse diffusion coefficient

$$C_{D,T} \text{ cm}/\sqrt{\text{cm}}$$

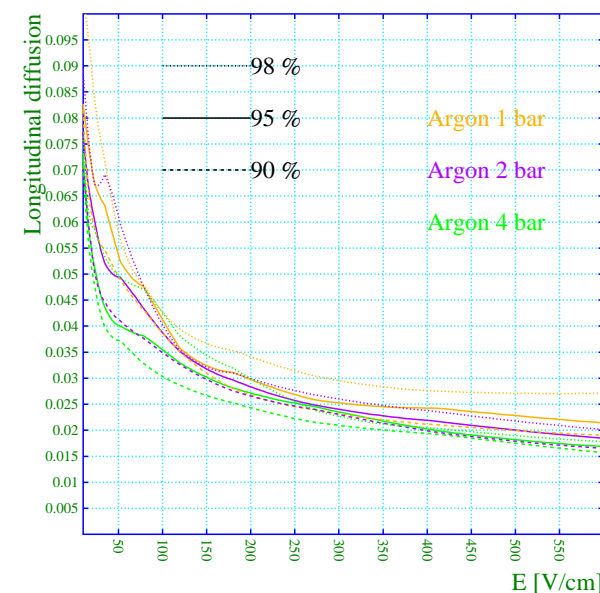
Transverse diffusion in Ar/ISO mixtures



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 adjustments)
- Maximal temperature ?
 - check your electronics !
 - plastic scintillator dome will soften at $\approx 80^\circ$
- Minimal temperature ?
 - avoid quencher partial liquefaction

gas	Ar	Xe	CH ₄	C ₂ H ₆	iso C ₄ H ₁₀
boiling point at 1.013 bar (°C)	-185.8	-108.1	-161.5	-89	-11.7

- alkanes have similar quencher properties.

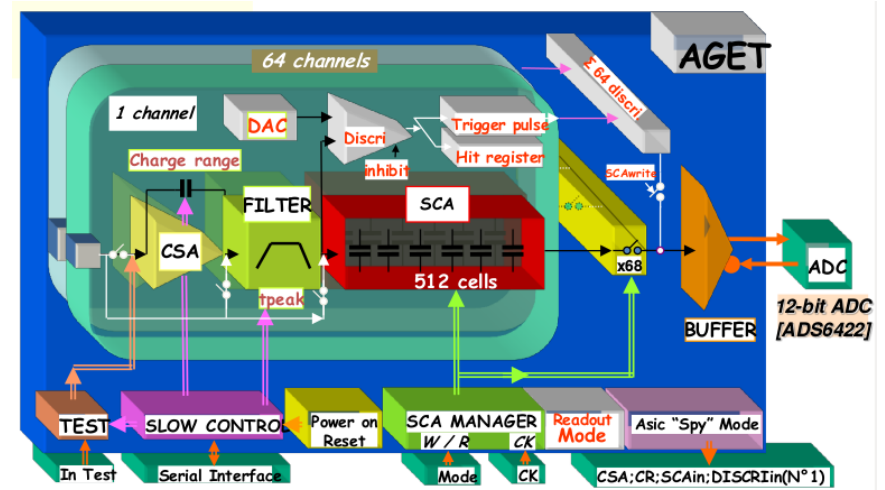
ST3G: Self Triggered TPC as Gamma-ray Telescope

- proton flux 20 kHz/m²
- drift duration 10 μs
- digitization duration 1.6 ms
- must use information as it arrives after drift in real time !
⇒ change digitizing chip AFTER → AGET

- ST3G trigger mechanism.
 - goal is to decipher one single through track (proton) from a pair that originates inside the gas volume ($\gamma \rightarrow e^+e^-$)
 - remember that entering tracks look like exiting tracks very much !

AGET: ASIC for Generic Electronics for TPC

- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- shaping: 16 peaking time values: 70 ns to 1 μ s
- 512 analog memory cells / channel
- F_{sampling}: 1 MHz to 100 MHz; F_{read}: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real time (25 MHz) Multiplicity signal: analog OR of the 64 discr Outputs
- Readout:

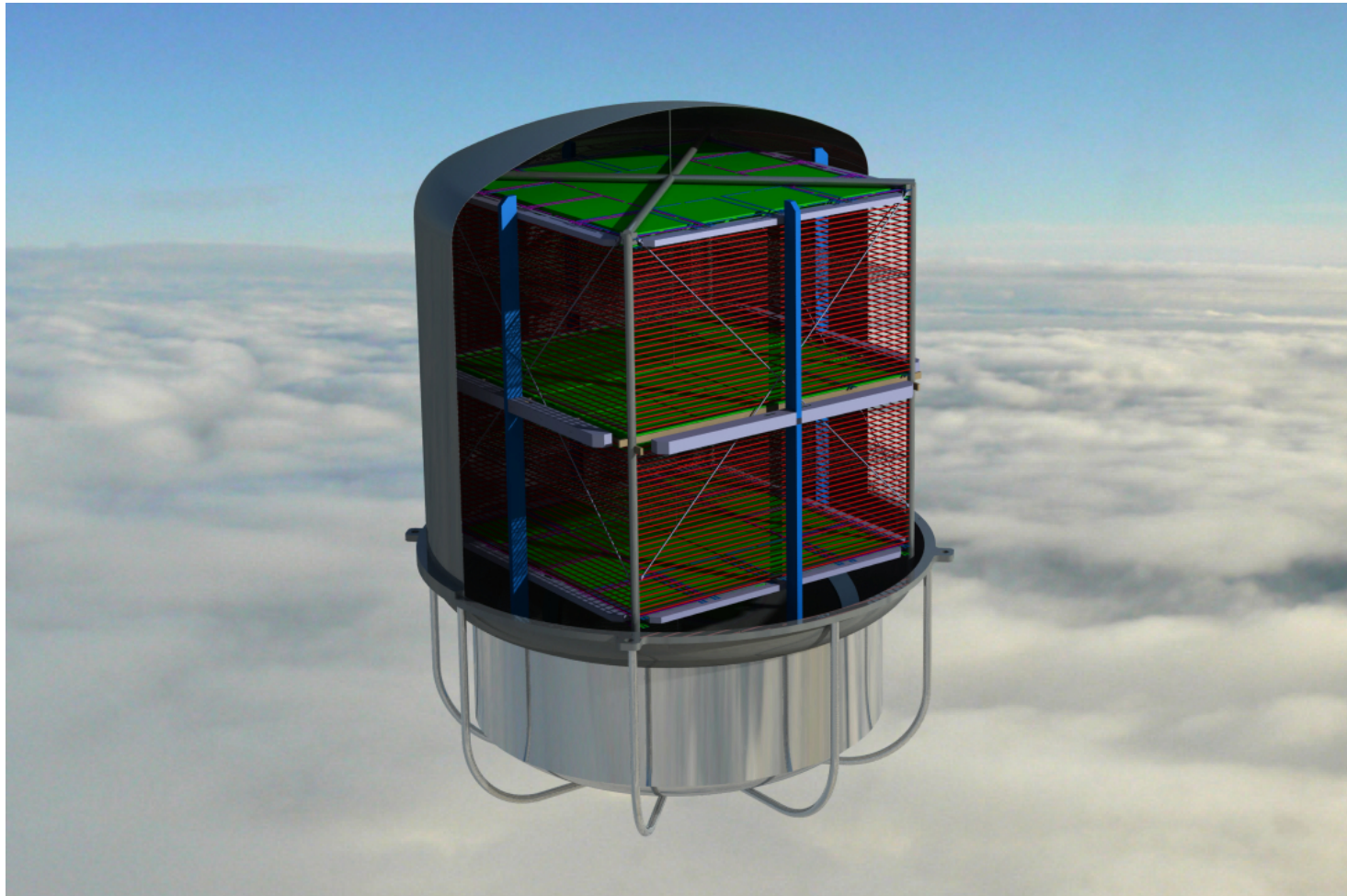


S. Anvar *et al.*, NSS/MIC, 2011 IEEE 745 - 749.

- Address of the hit channel(s)
- 3 readout modes: All, hit or specific channels
- Predefined number of analog cells / trigger (1 to 512)

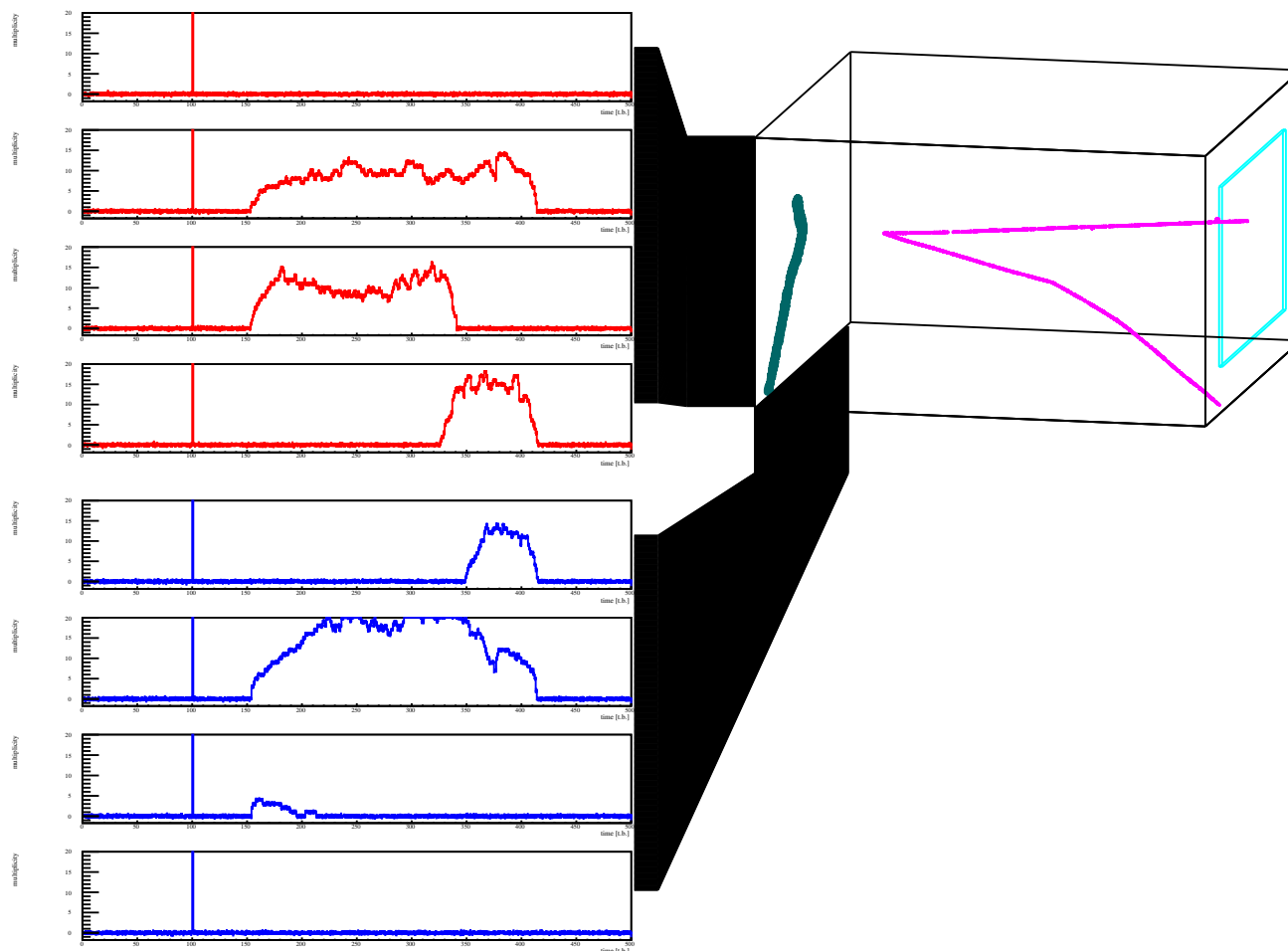
- AGET → **radhard** ASTRE: “Asic with SCA & Trigger for detector Readout Electronics”: presently being designed; submission to foundry hopefully end 2016.

ST3G scheme validation : prototype for a balloon test



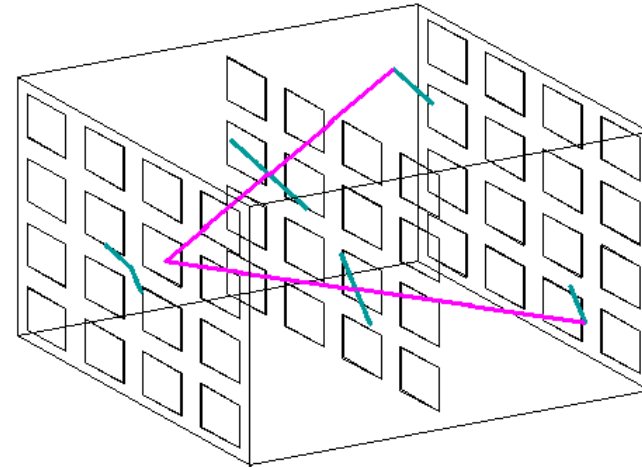
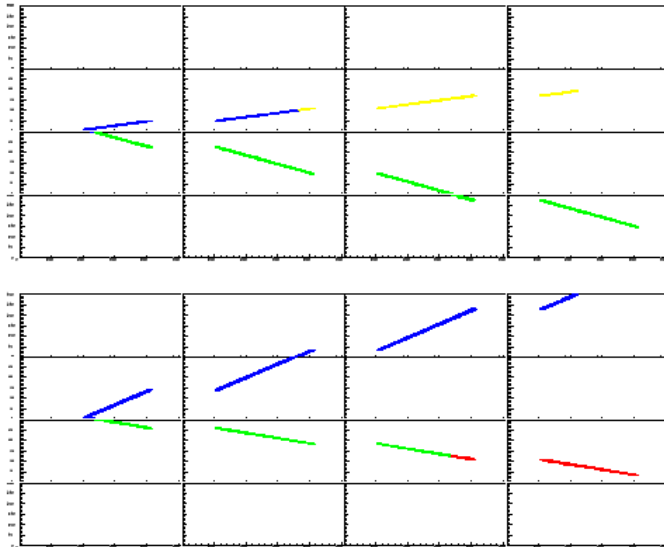
- A $4 \times 4 \times 4 = 64$ set of $(30 \text{ cm})^3$ modules.
- modules back-to-back 2-by-2 with common cathode.

ST3G trigger mechanism: signal from a single bloc



Simulation of the multiplicity signal for a γ -ray conversion in the present HARPO-prototype.

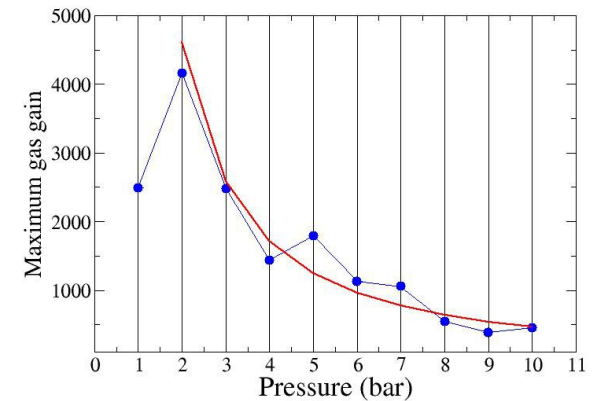
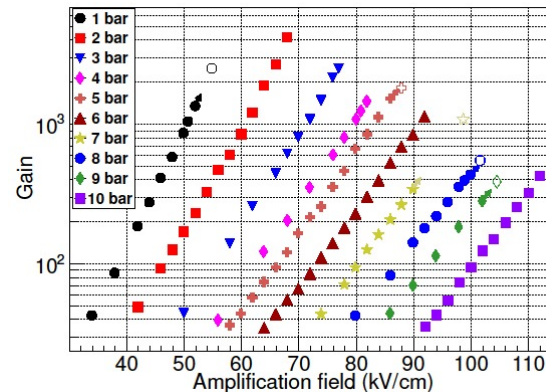
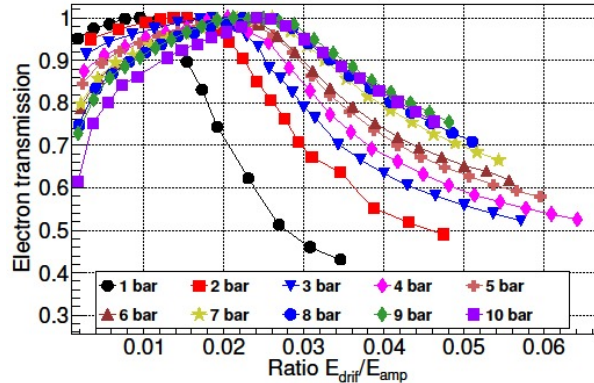
ST3G trigger: multi-bloc scheme



- $4 \times 4 \times 4 = 64$, $(30\text{cm})^3$, modules
- Sensitive volume $(1.2\text{m})^3$
- L0 trigger: coincidence of several modules (≥ 2) that see signal at the same time.
- Complete trigger mechanism to be designed and optimized
- geant4 simulation well advanced.

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 1st 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.