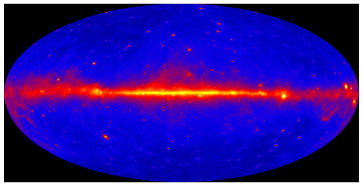
HARPO: 1.7 - 74 MeV gamma-ray beam validation of a high-angular-resolution high-polarisation-dilution gas telescope and polarimeter

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

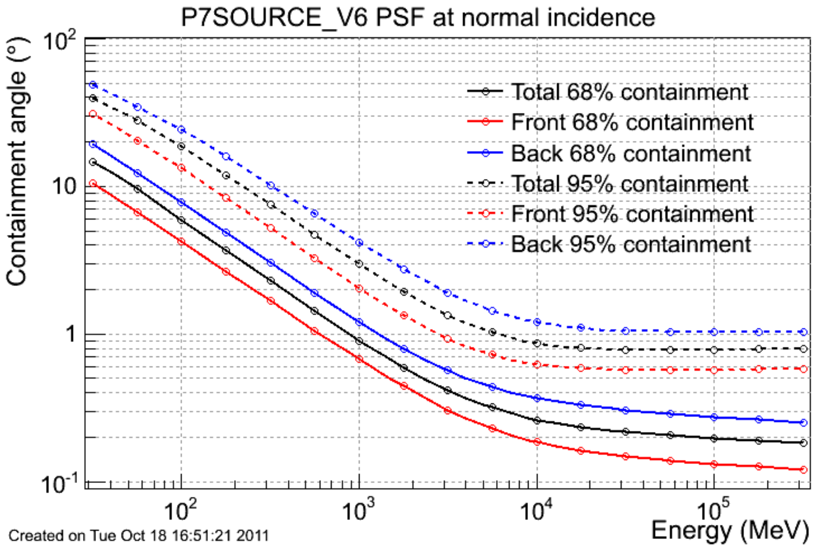
Japan-France ILC HARPO TPC meeting,
CEA Saclay, 24 October 2016

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

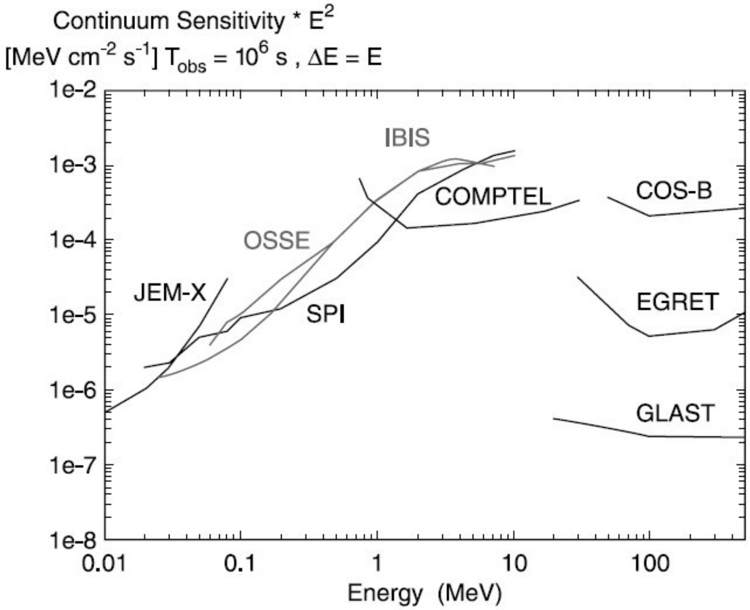
Non polarized astronomy



- Improve angular resolution – crowded sky regions



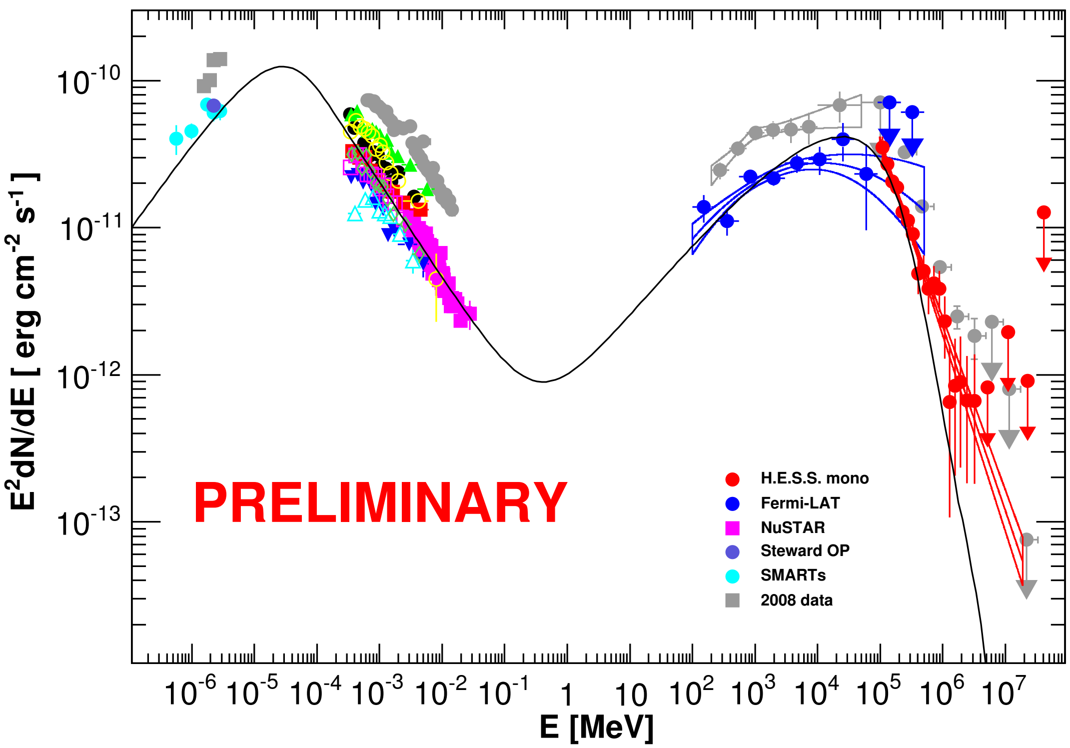
Fermi/LAT



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

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

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



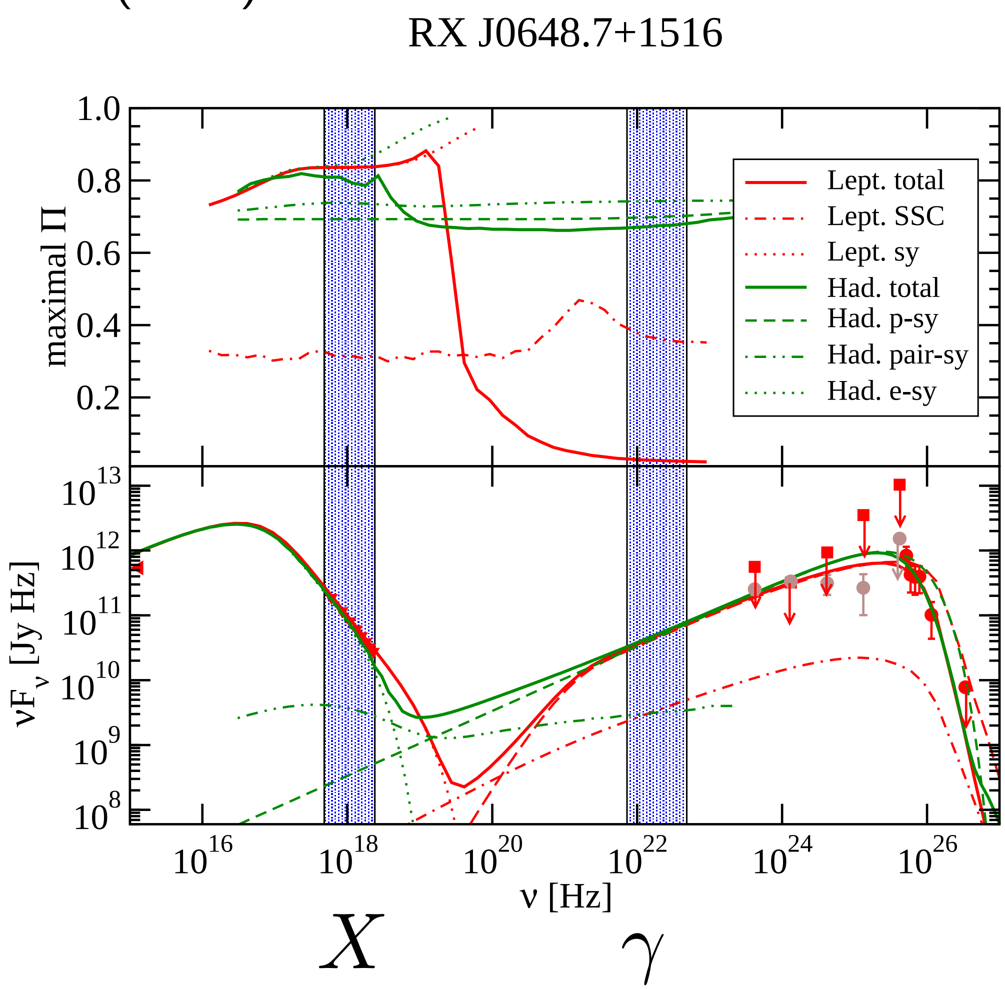
Grey points: dedicated Multiwavelength campaign 2013:

- 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

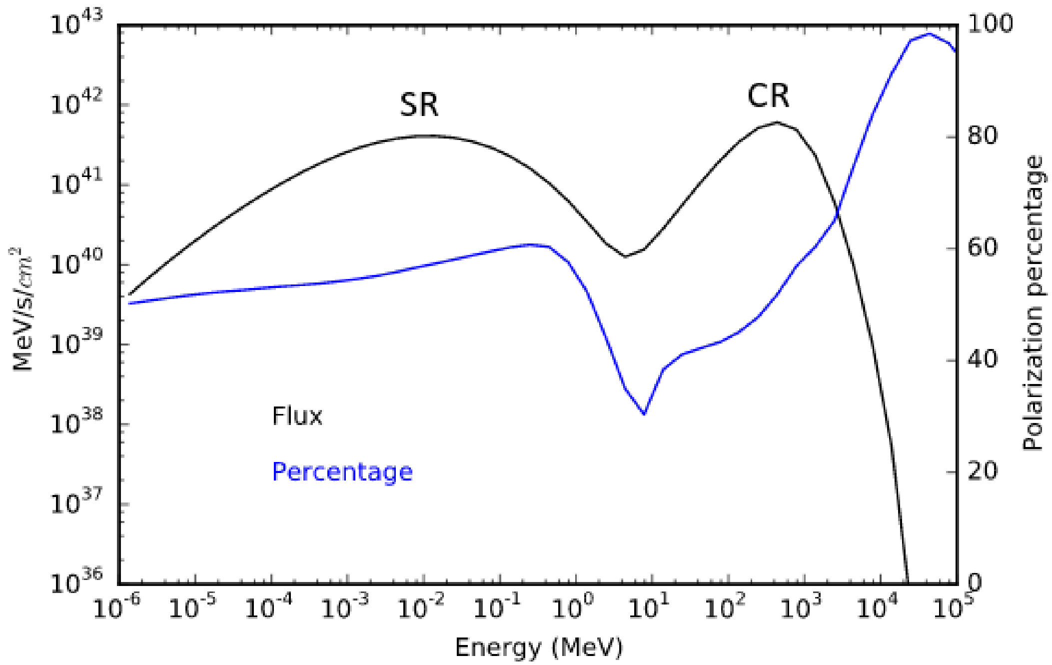


- SED's indistinguishable, but
- X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$
- γ-ray: $P_{\text{lept}} \ll P_{\text{hadr}}$

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

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

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

Contributions:

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

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

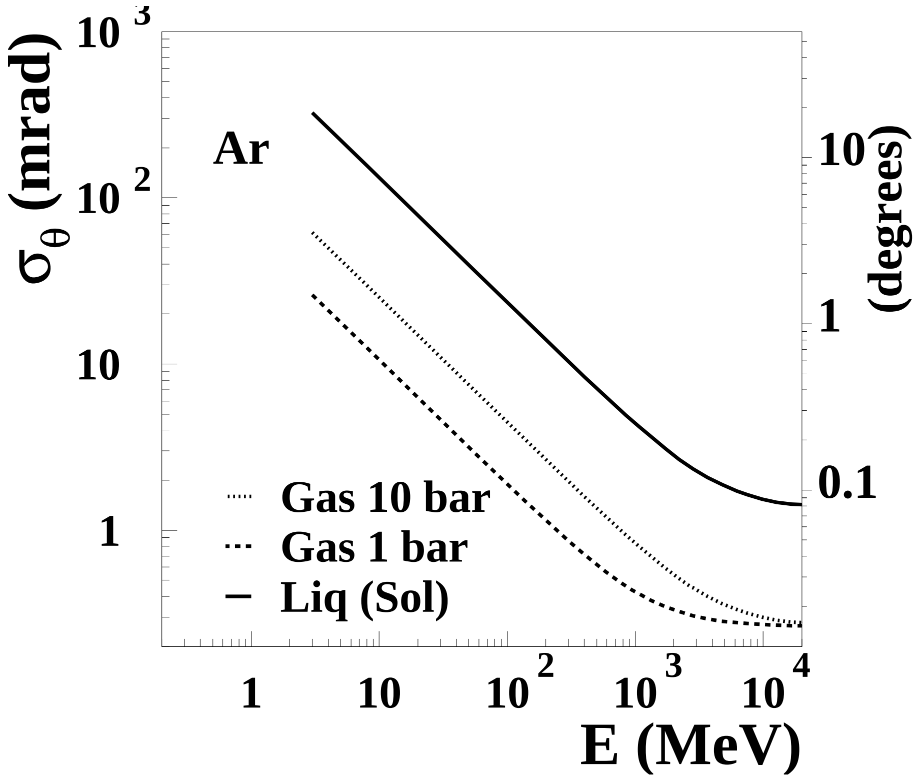
With:

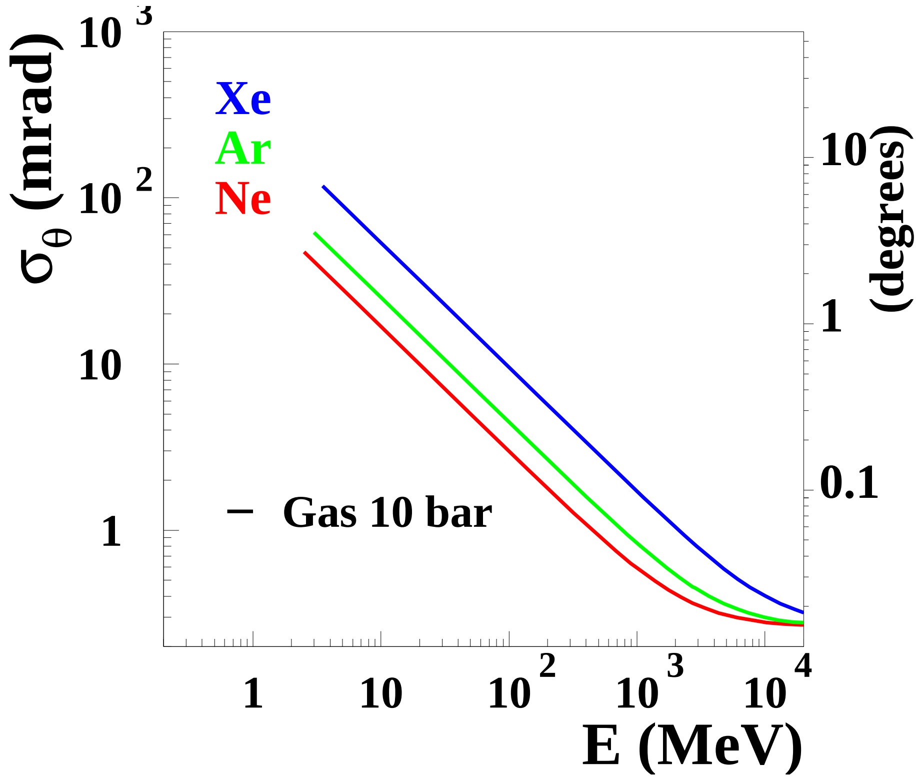
- p track momentum $[\mathrm{MeV}/c]$;
- $p_0 = 13.6\,\mathrm{MeV}/c$, multi-scattering constant;
- p_1 detector "multiple-scattering momentum" parameter $[\mathrm{MeV}/c]$;
- σ single measurement detector spatial resolution [cm];
- l track longitudinal sampling (pitch) [cm].

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 $l = 1\,\mathrm{mm}$, point resolution $\sigma = 0.1\,\mathrm{mm}$,



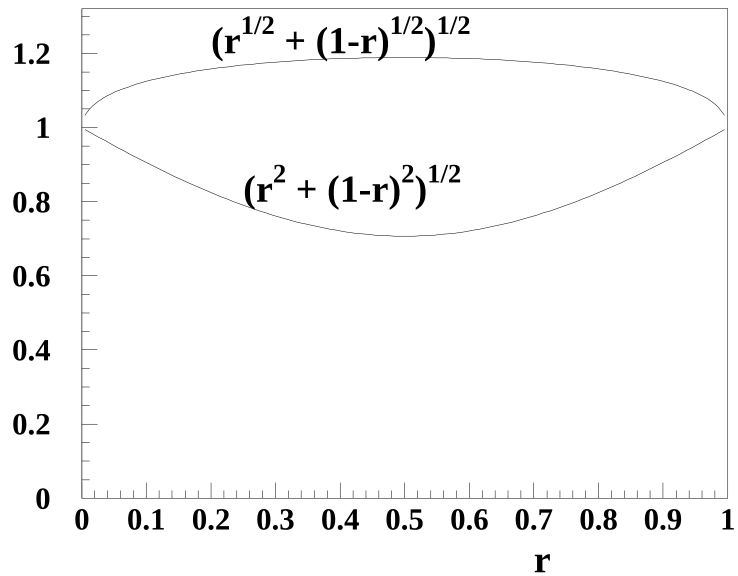


For various densities (argon) for various gases

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, $r = E_+/E$,

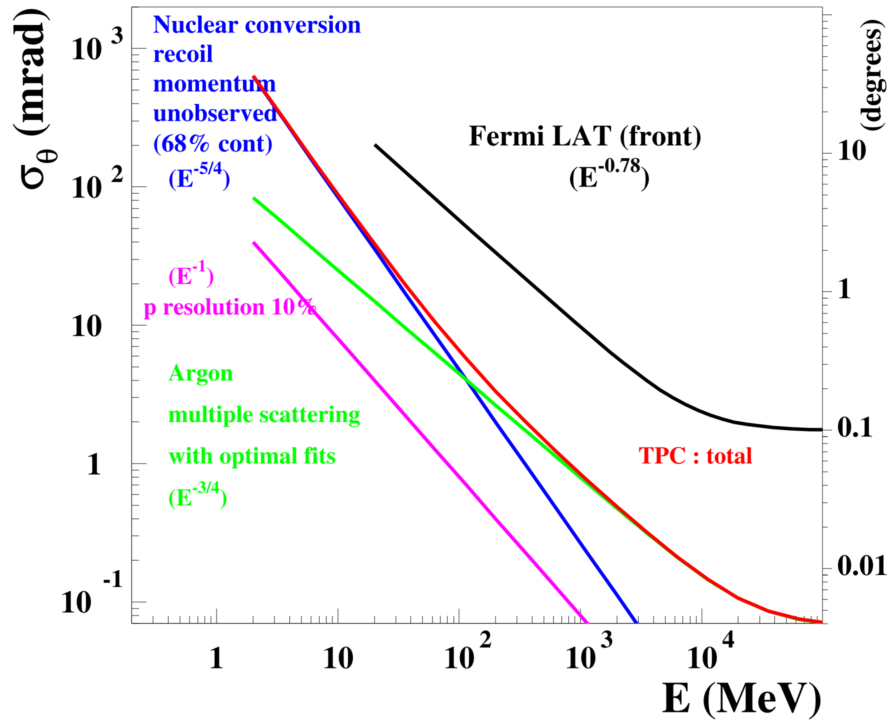


- multiple scattering dominated regime: $\sigma_{\theta\gamma} = \sigma_{\theta t}\sqrt{\sqrt{r} + \sqrt{1-r}}$
- high energy regime: $\sigma_{\theta\gamma} = \sigma_{\theta t}\sqrt{r^2 + (1-r)^2}$
- track to photon factor close to unity: neglected in the following.

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

Angular resolution: Wrap up

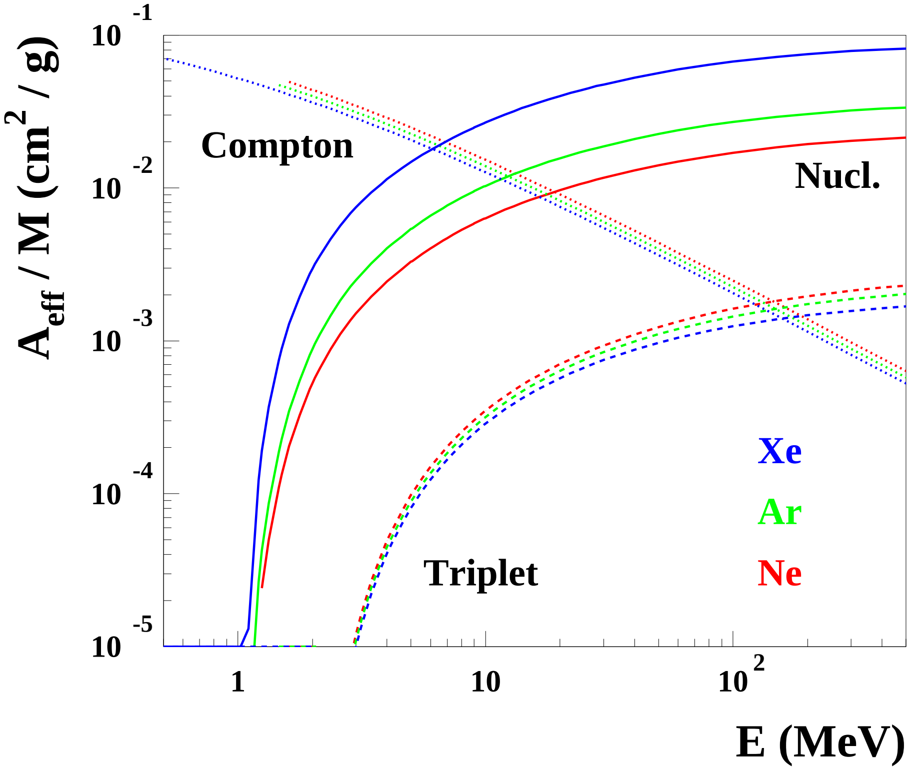
- Argon-based gas, $P = 10\,\mathrm{bar}$ $X_0 = 1180\,\mathrm{cm}$
- Sampling pitch $l = 1\,\mathrm{mm}$, point resolution $\sigma = 0.1\,\mathrm{mm}$,

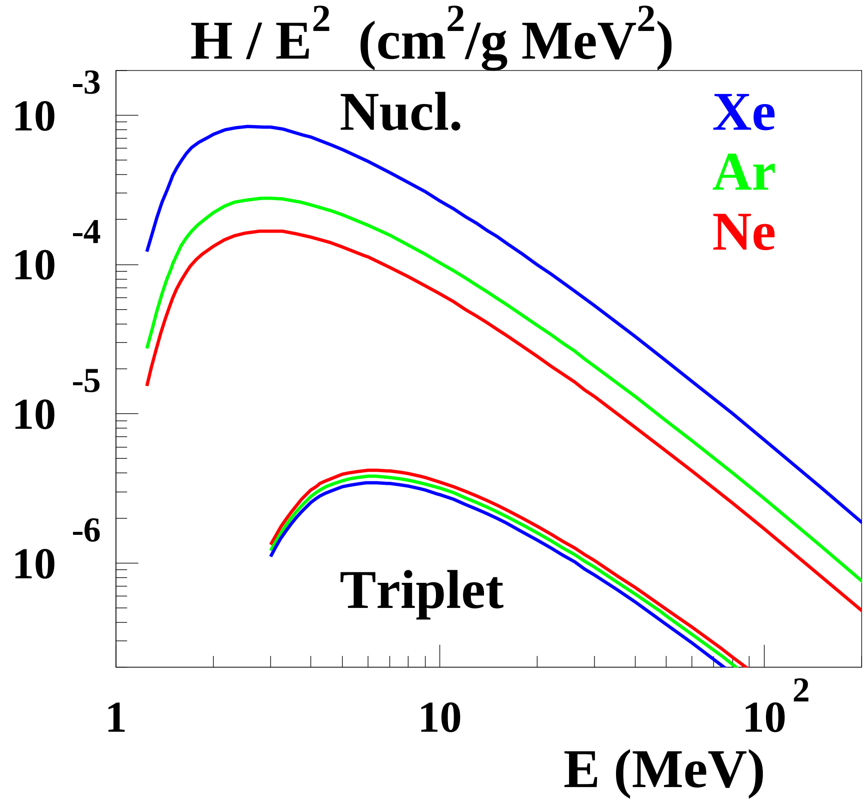


	multiple scattering	ion recoil momentum	total
	$\sigma_{\theta t} = (p/p_1)^{-3/4}$ with $p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$ $p_1 = 73\,\mathrm{keV}/c$	$1.5\,\mathrm{rad} \left(\frac{E}{1\,\mathrm{MeV}}\right)^{-5/4}$	
σ_θ @ 100 MeV	$0.26\,^\circ$	$0.27\,^\circ$	$0.37\,^\circ$

Thin detectors: Effective area

- $A_{\rm eff} = H \times M$, H photon attenuation





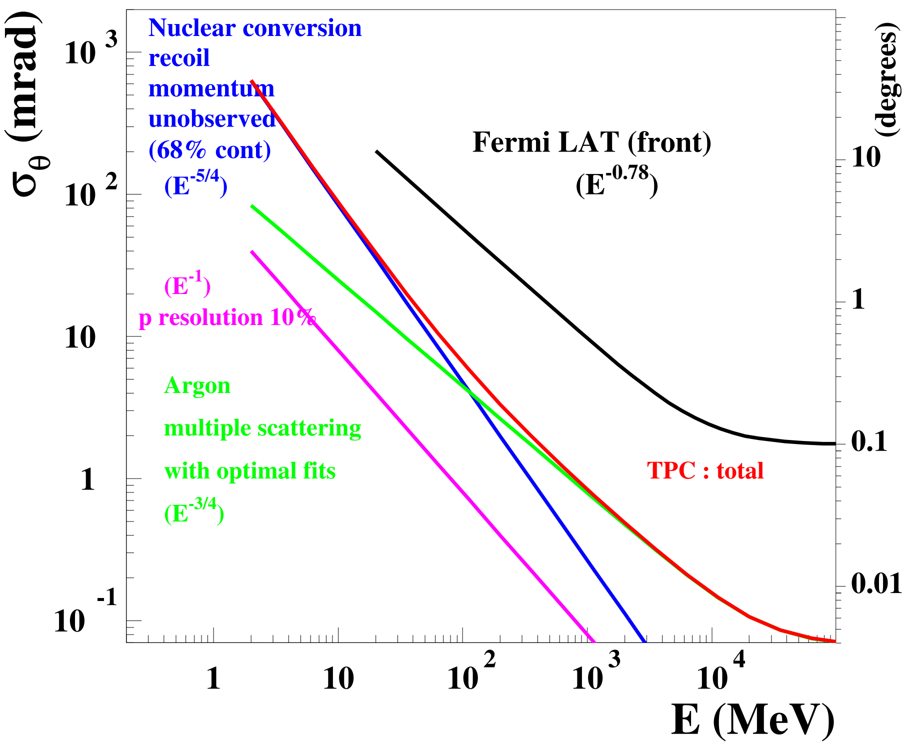
Argon, nucl.: $A_{\rm eff}/M = 27\,{\rm cm}^2/{\rm kg}$ @ $E = 100\,{\rm MeV}$

National Institute of Standards and Technology (NIST)

Performances with Thin Homogeneous Detector and Optimal Fits

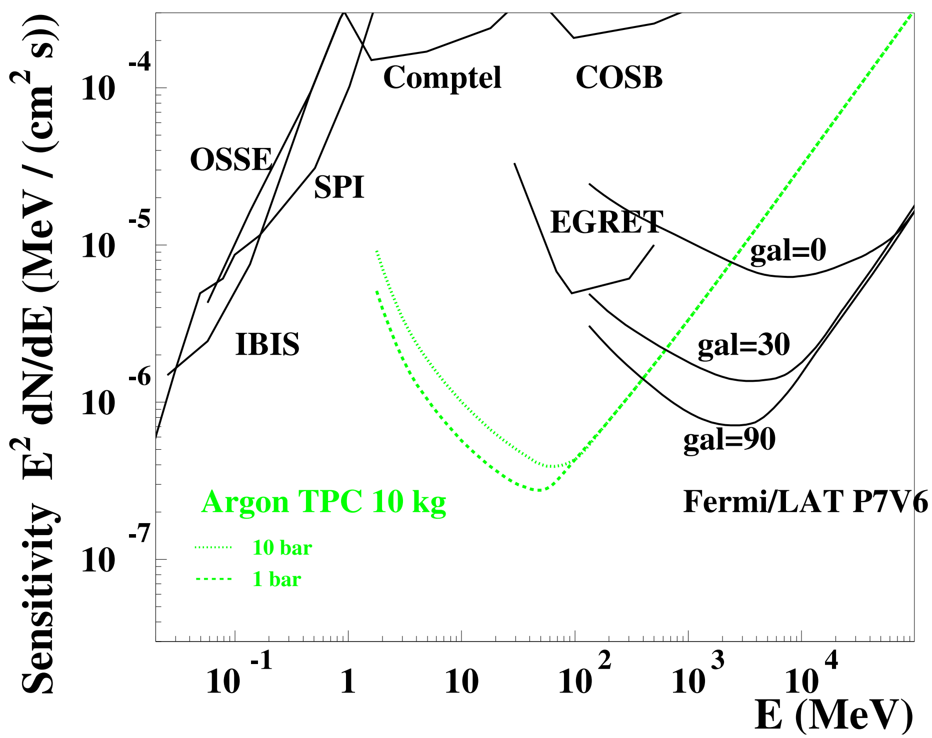
Angular resolution

- 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

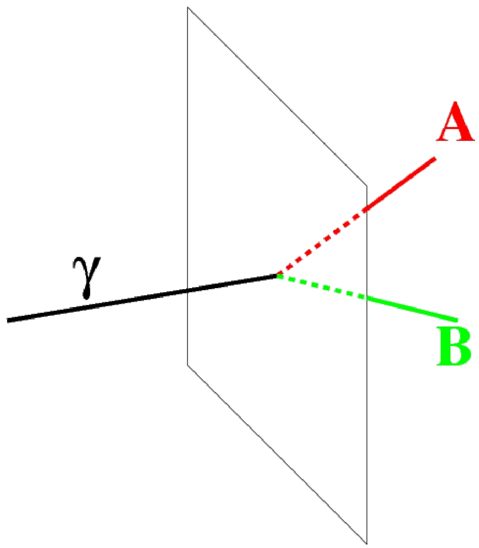


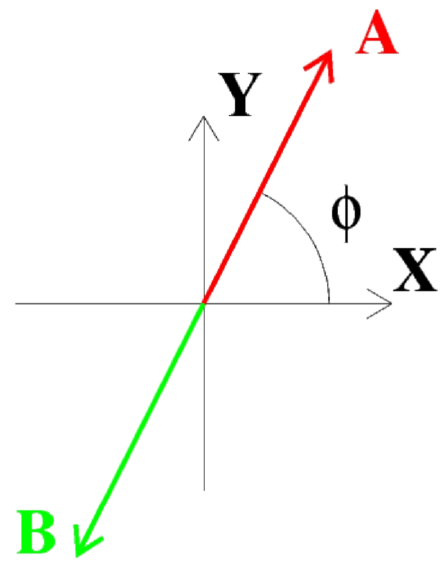
D.B., NIM A 701 (2013) 225

Polarimetry

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

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



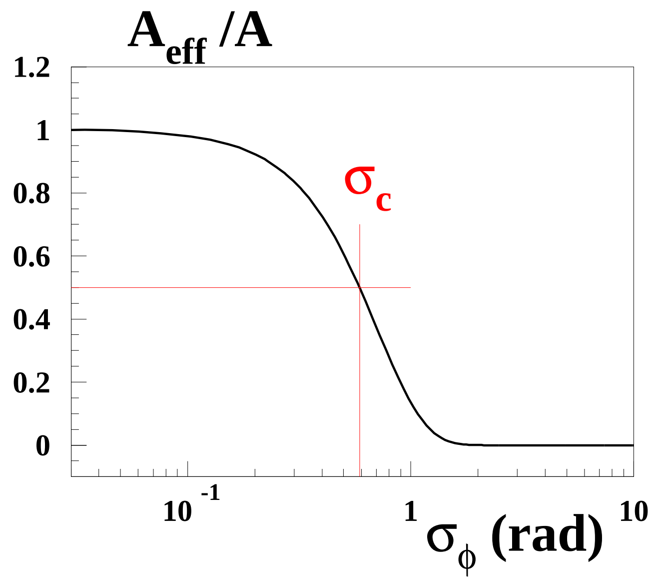


- P source linear polarisation fraction
- $\mathcal{A}$ Polarization asymmetry
- ϕ azimuthal angle

Multiple Scattering: Dilution of the Asymmetry

Slabs

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



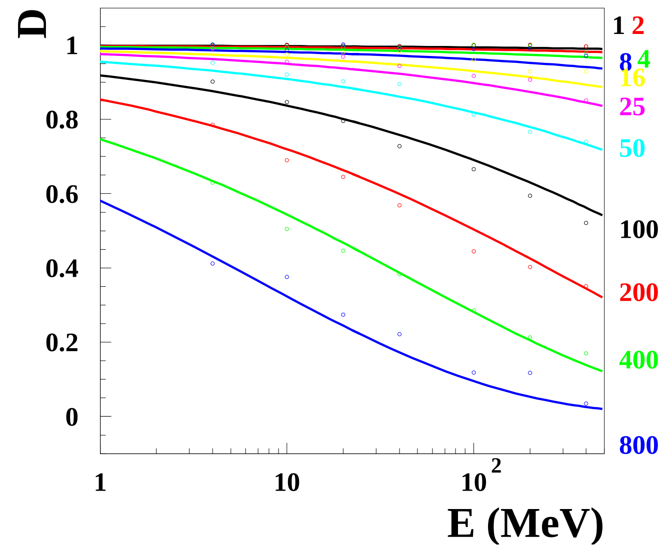
$$\sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$$

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

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

homogeneous detector with optimal tracking

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



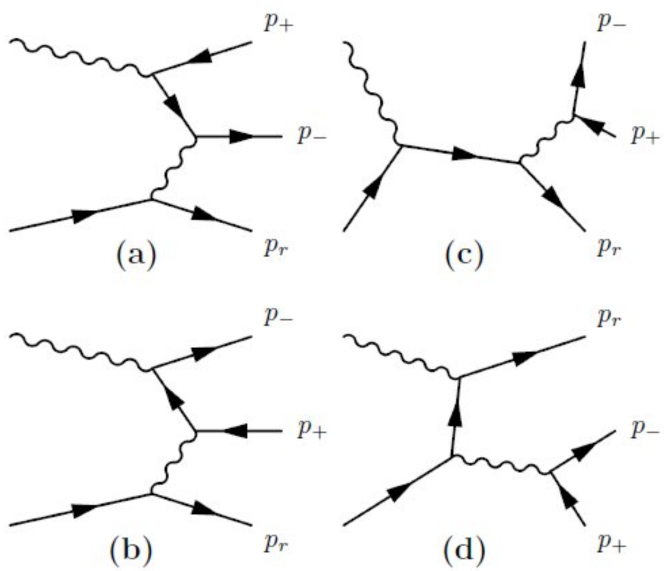
$$p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6},$$

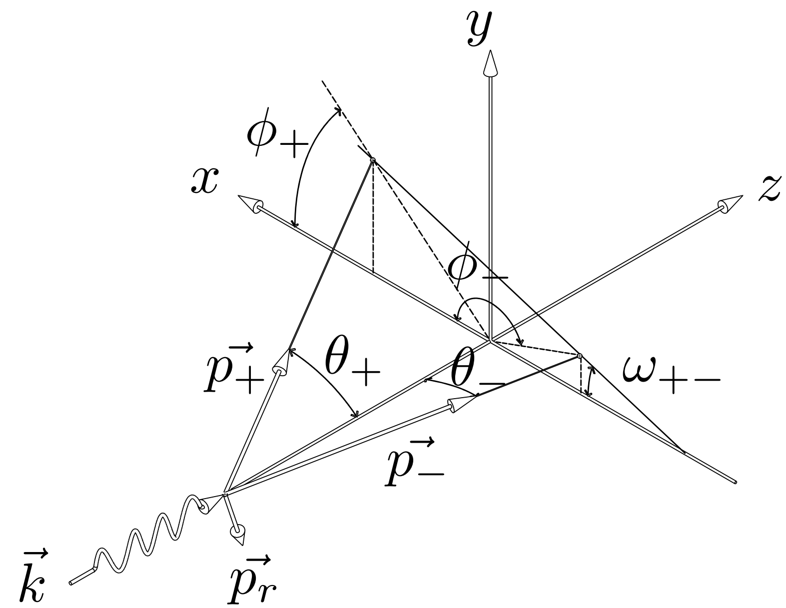
$p_1 = 50\,\text{keV}/c$ (1 bar argon) ,
$p_1 = 1.5\,\text{MeV}/c$ (liquid argon).

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 $x_+ \equiv E_+/E$





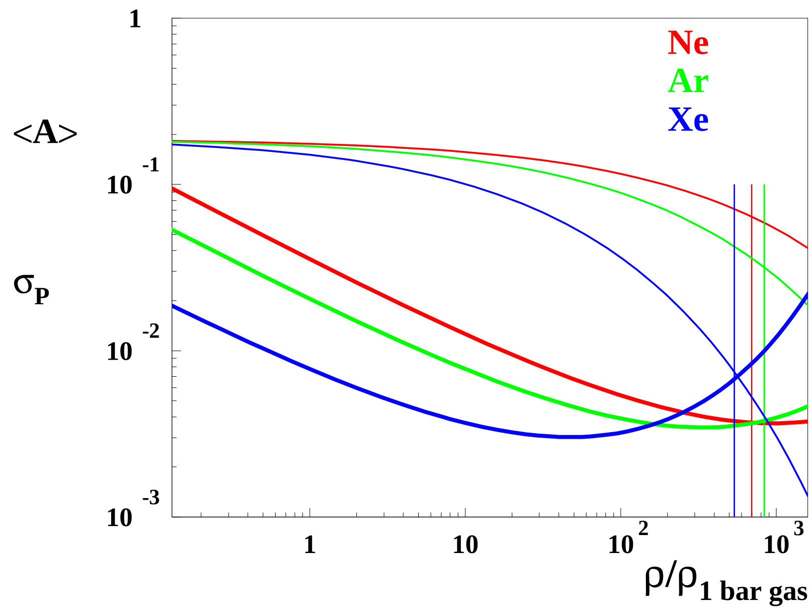
- Uses:
  - HELAS amplitude computation — H. Murayama, *et al.*, KEK-91-11.
  - SPRING event generator — S. Kawabata, Comput. Phys. Commun. 88, 309 (1995).

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



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

[a]LLR, Ecole Polytechnique and CNRS/IN2P3, France

David Attié, Denis Calvet, Paul Colas, Alain Delbart, Patrick Sizun [b]

[b]IRFU, CEA Saclay, France

Diego Götz [b,c]

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

- Japan: the beam.

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

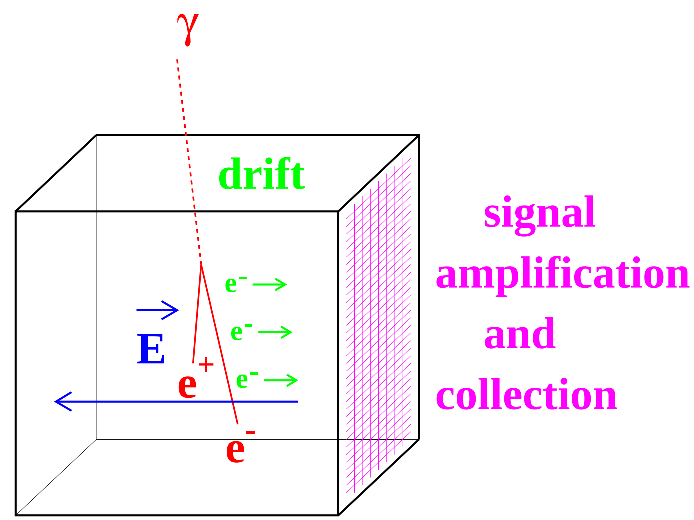
[e] LASTI, University of Hyôgo, Japan

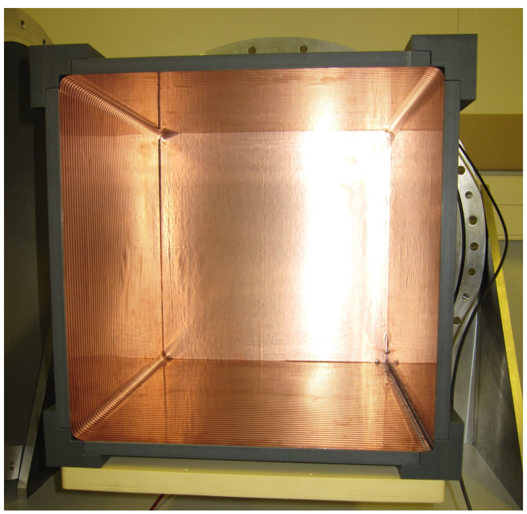
S. Daté, H. Ohkuma[f]

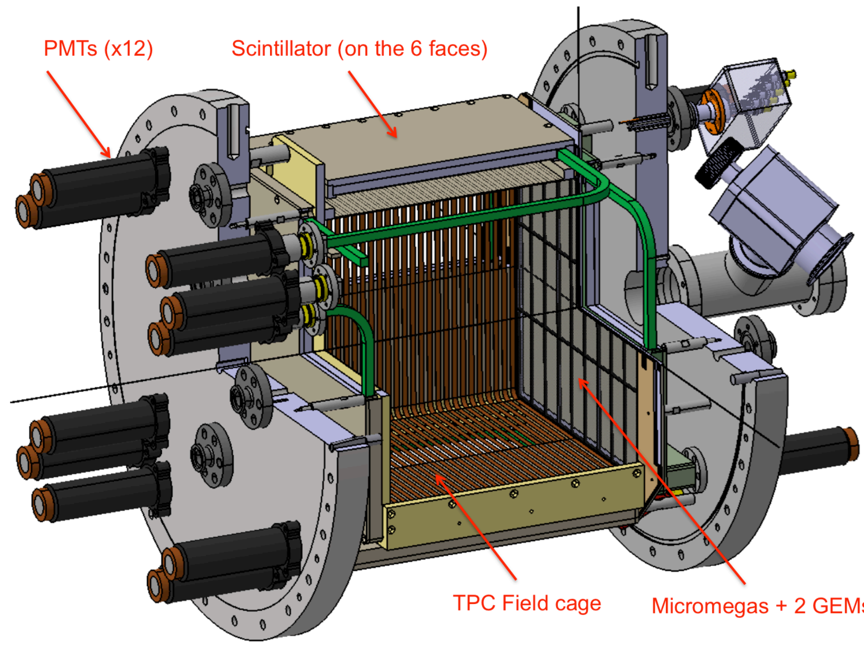
[f] JASRI/SPring8, Japan

HARPO: the Demonstrator

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



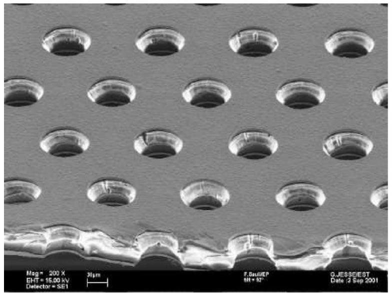


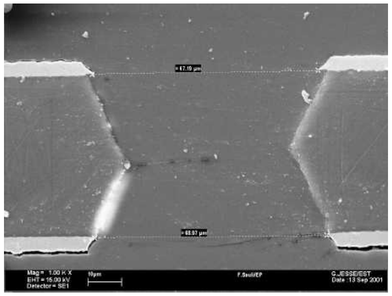


D.B., NIM A 695 (2012) 71, NIM A 718 (2013) 395

Gas amplification: micromegas + 2 GEM

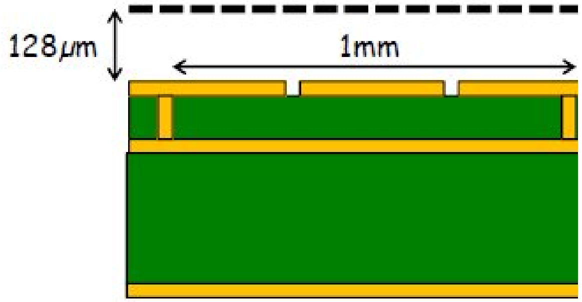
Gas Electron Multiplier
$50\,\mu m$ Kapton, copper clad,
pitch $140\,\mu m$, $\Phi 70\,\mu m$

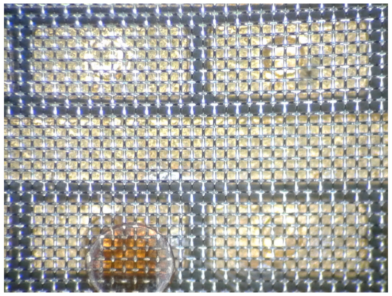




F. Sauli, NIM A 386, 531 (1997)

"bulk" micromegas
gap $128\,\mu m$
(x, y) strips, pitch 1 mm, width 0.4 mm

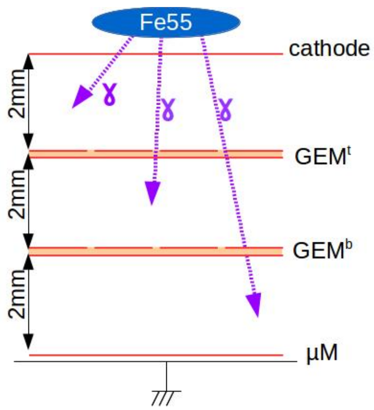


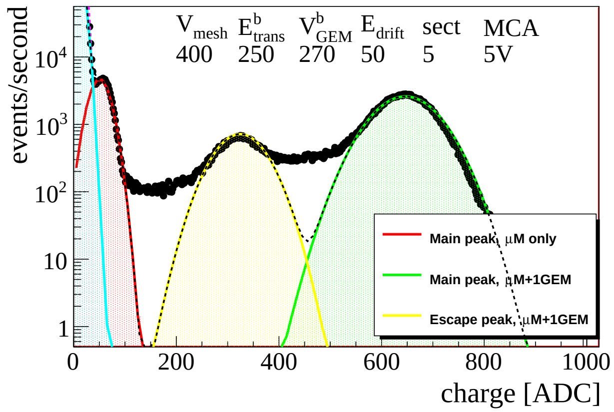


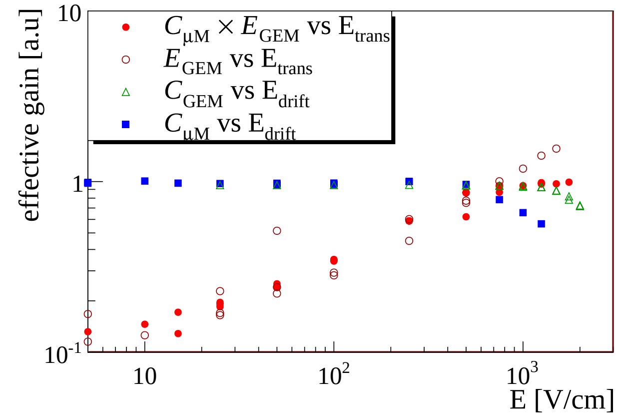
I. Giomataris *et al.*, NIM A 560, 405 (2006)

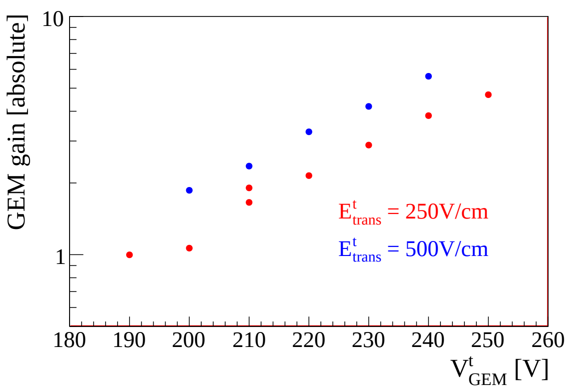
Micromegas + 2 GEM assemblies: characterization

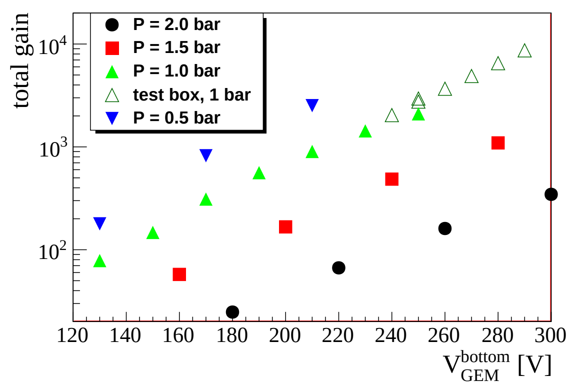
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)







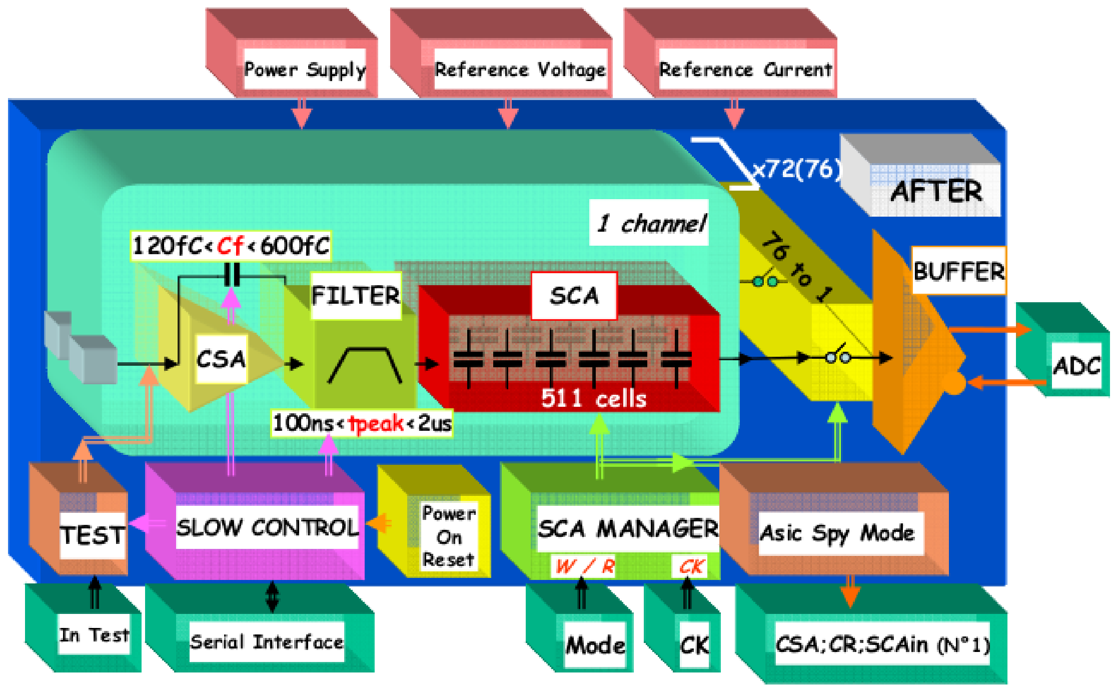




Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

Signal digitization

- 2 directions x, y, 288 strips (channels) / direction
- 72 channels / AFTER 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.

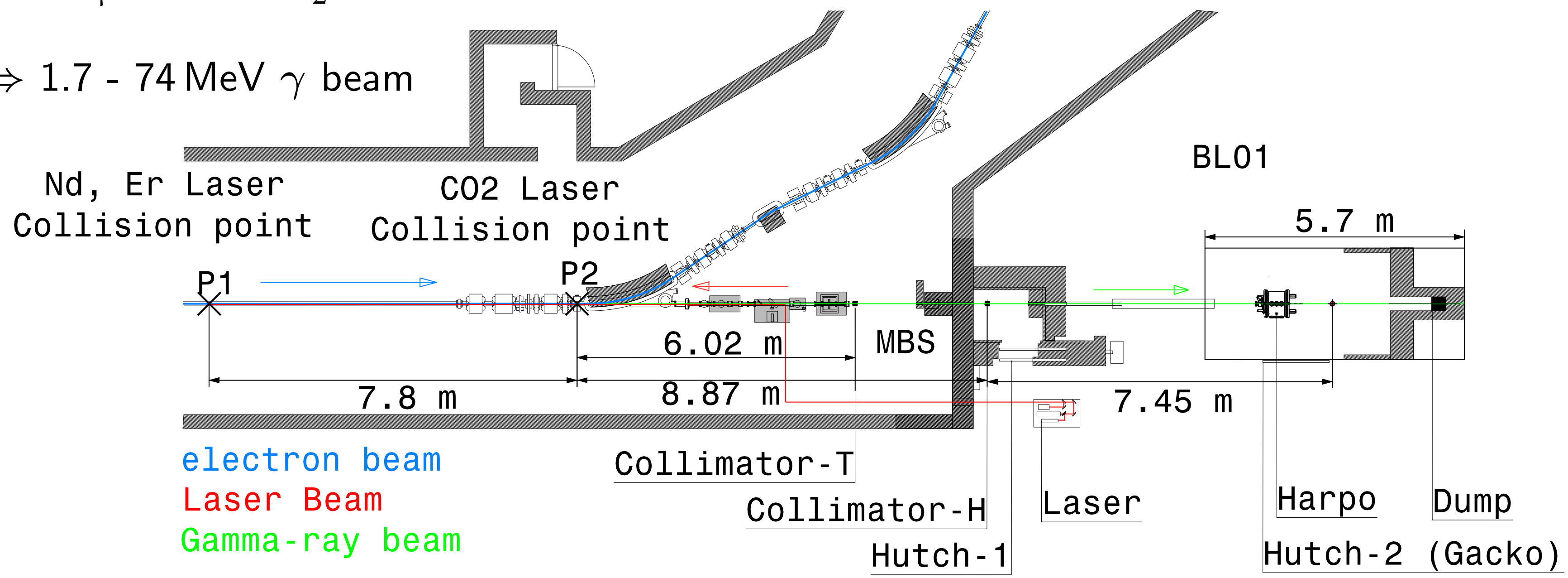


Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

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

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

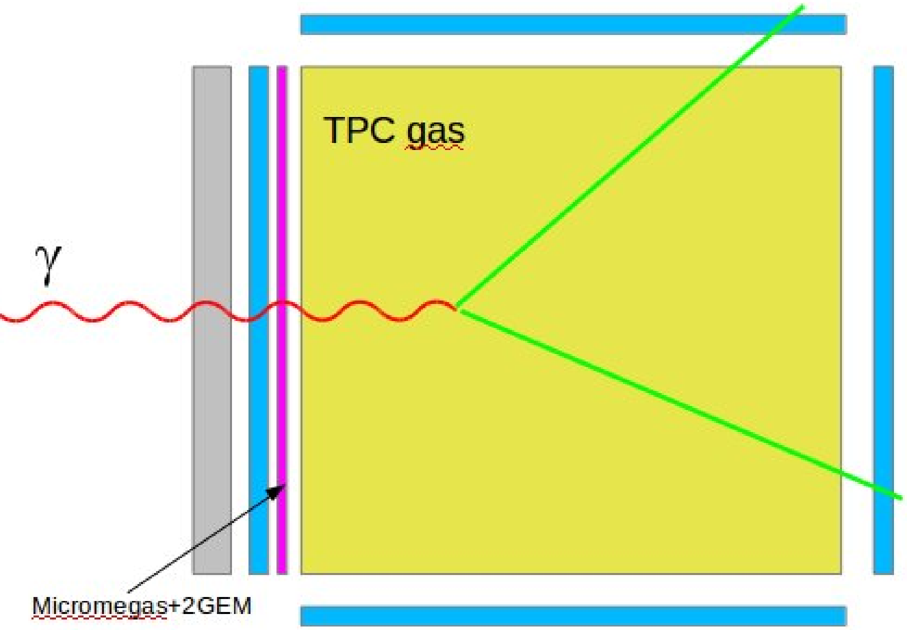
- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- $0.532\,\mu m$ and $1.064\,\mu m$ $20\,kHz$ pulsed Nd:YVO$_4$ (2ω and 1ω),
  $1.540\,\mu m$ $200\,kHz$ pulsed Er (fibre) and
  $10.55\,\mu m$ CW CO_2 lasers
- $\Rightarrow$ 1.7 - 74 MeV γ beam

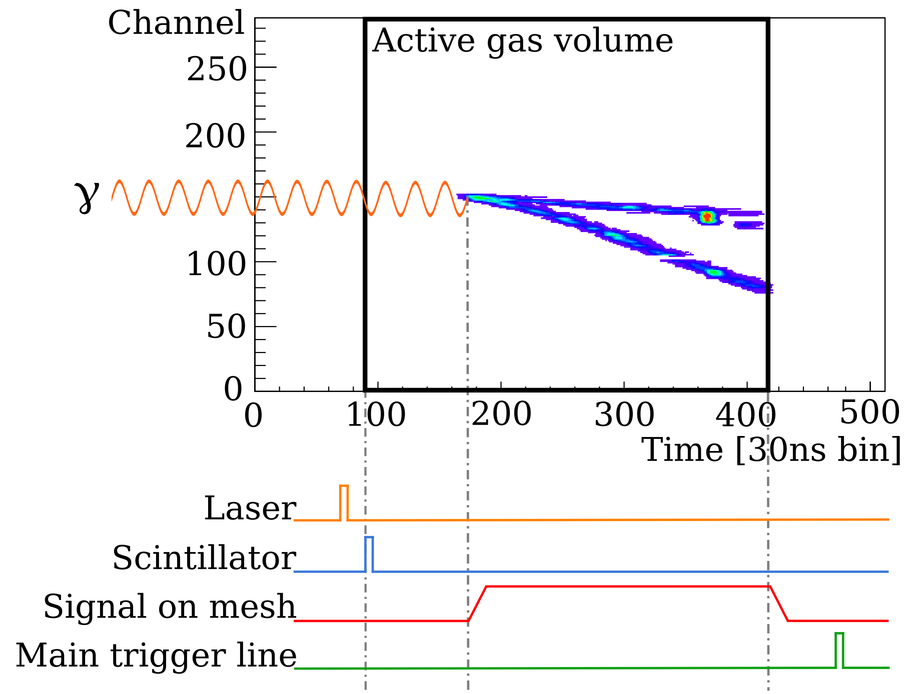


- Monochromaticity by collimation on axis
- Fully polarized or random polarization beams ($P = 1$, $P = 0$)
- 2.1 bar Ar:isoC_4H_{10} 95:5 (+ a 1.0 – 4.0 bar scan).

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

Beam trigger system





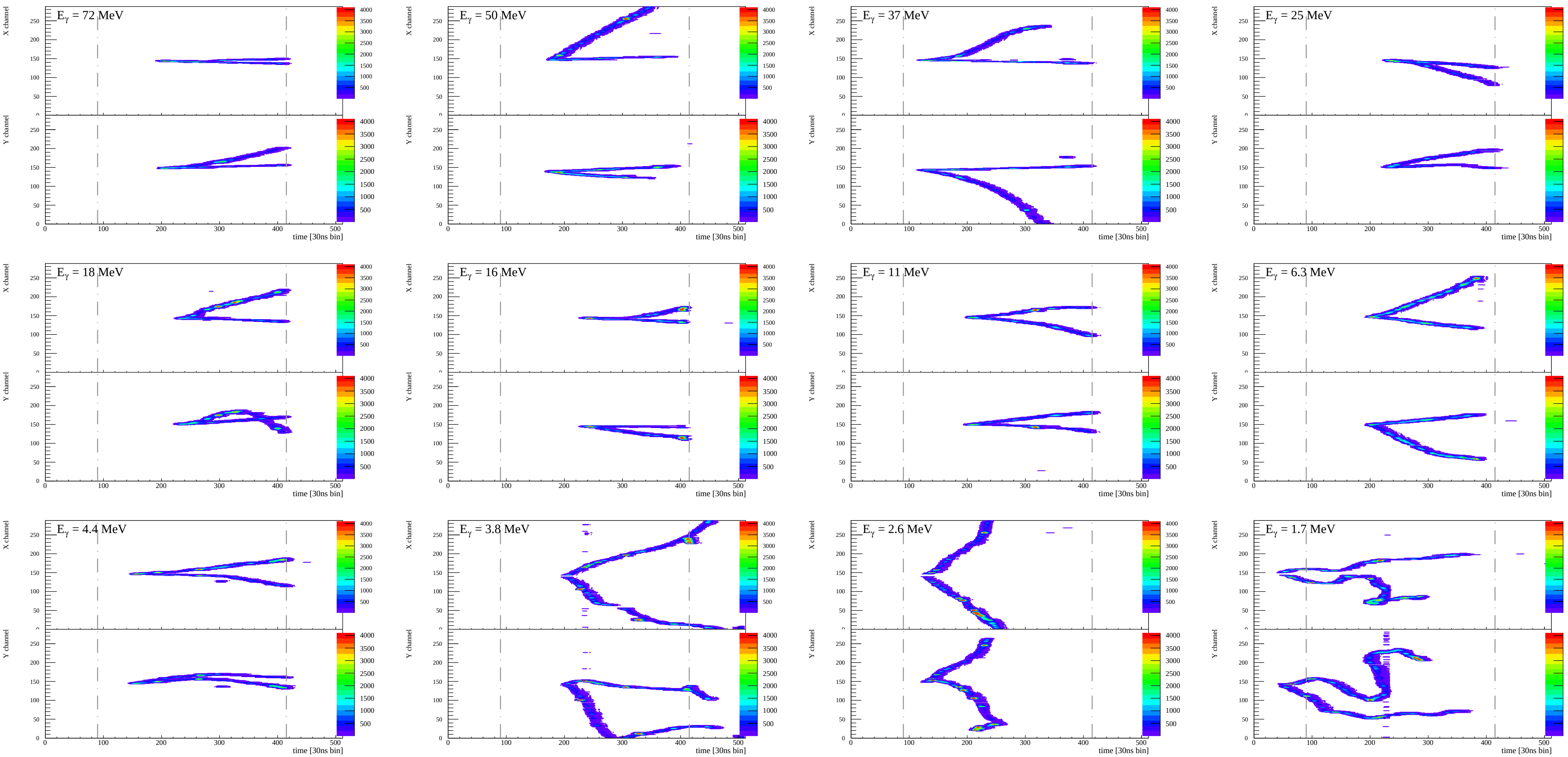
- S_{up} upstream scintillator
- O one of the 5 other scintillators
- M_{slow}: a delayed ($> 1\mu s$) signal on the μM mesh
- L laser trigger pulse

- 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

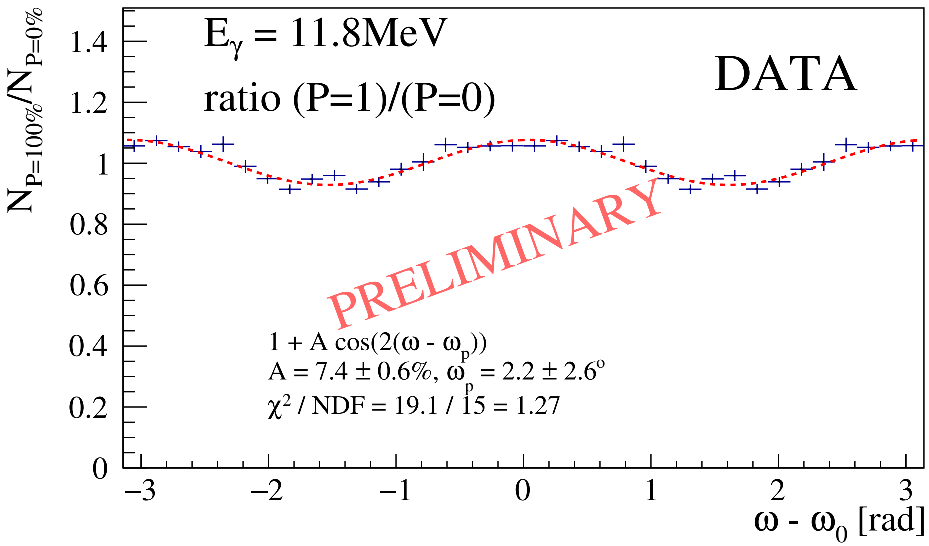


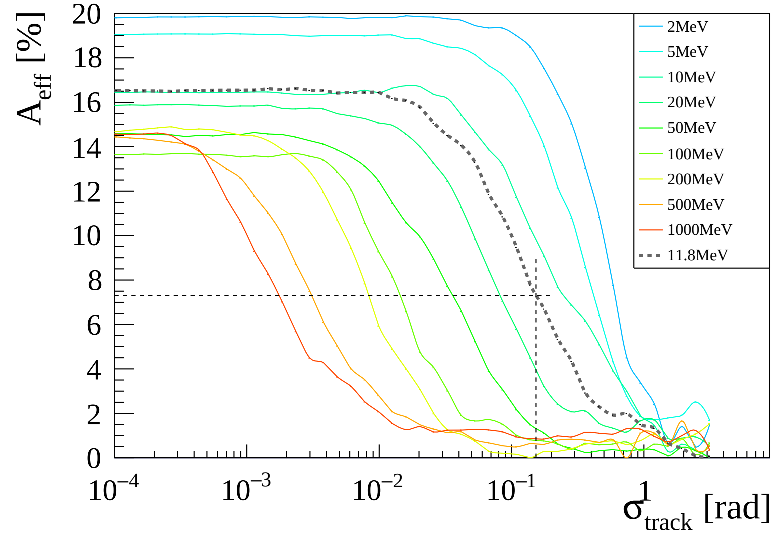
Sample of γ-rays from 74 to 1.7 MeV converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5 detected by the HARPO TPC
(pre-beam-calibration γ-ray energy on plots)

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

Polarization Asymmetry : beam results

- ICS of $1.55\,\mu\mathrm{m}$ photons from Er laser on 0.974 GeV e^- $\Rightarrow$ 11.8 MeV γ-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 $\gamma \to e^+e^-$ astronomy and polarimetry in the MeV-GeV energy range
- Robust detector used in HEP since the 1980's from sub-cm^3 to multi-m^3
- From the lowest (eg. T2K) to the highest (eg. ALICE) rate, radiation, track multiplicity
- Use of a low-diffusion, "fast" gas ($v_{\mathrm{drift}} \gg 1\,\mathrm{cm}/\mu\mathrm{s}$) mitigates background pile-up
- 4π acceptance, $\approx$ isotropic performances (x, y, z), $< 30\,\mathrm{ns}$ 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 $(30\mathrm{cm})^3$ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
  - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, γ beam

: analysis in progres.

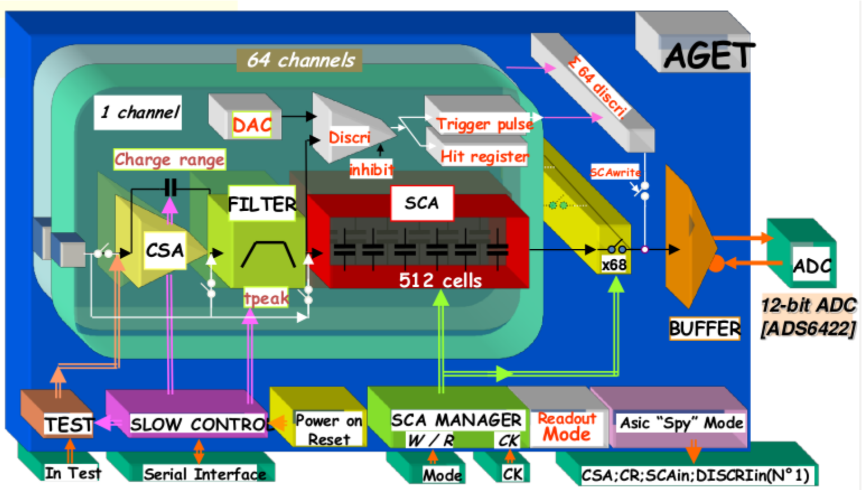
ST3G: Self Triggered TPC as Gamma-ray Telescope

- proton flux $20\,\mathrm{kHz/m^2}$
- drift duration $10\,\mu\mathrm{s}$
- digitization duration $1.6\,\mathrm{ms}$
- must use information as it arrives after drift in real time !

  $\Rightarrow$ change digitizing chip AFTER $\rightarrow$ 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



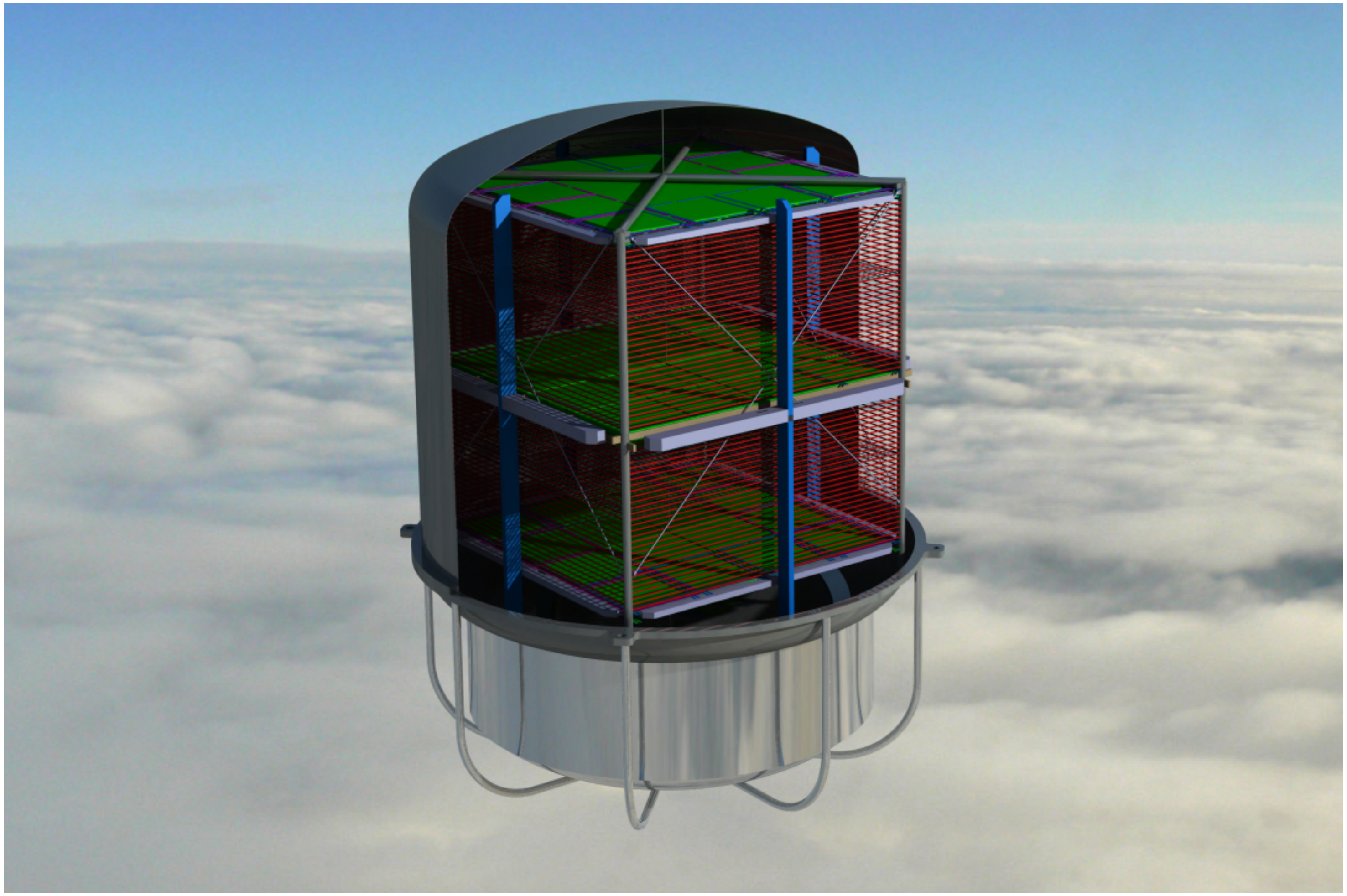
- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- shaping: 16 peaking time values: 70 ns to $1 \mu s$
- 512 analog memory cells / channel
- Fsampling: 1 MHz to 100 MHz; Fread: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real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

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

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

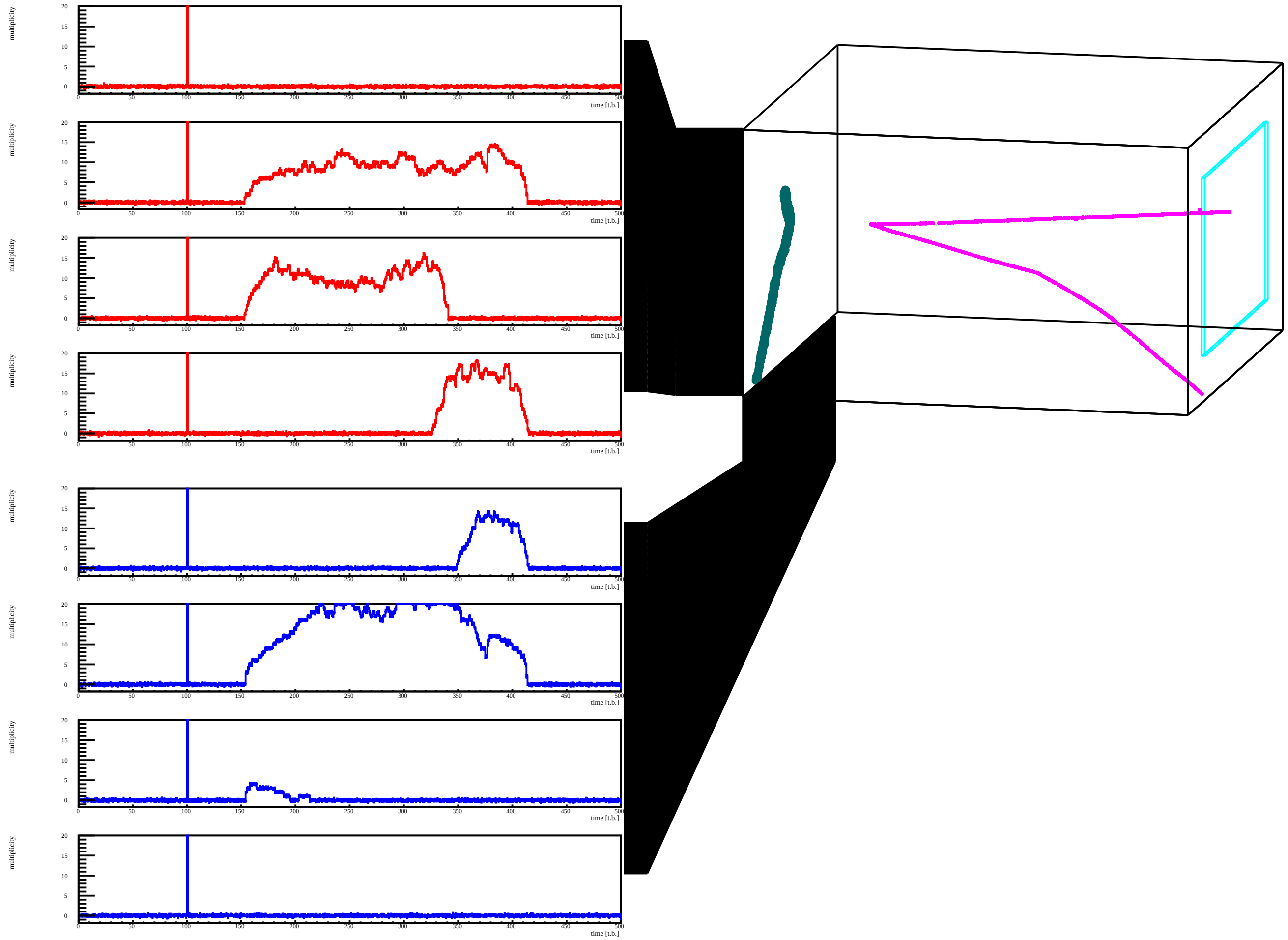
  presently being designed; submission to foundry hopefully end 2016.

ST3G scheme validation : prototype for a balloon test



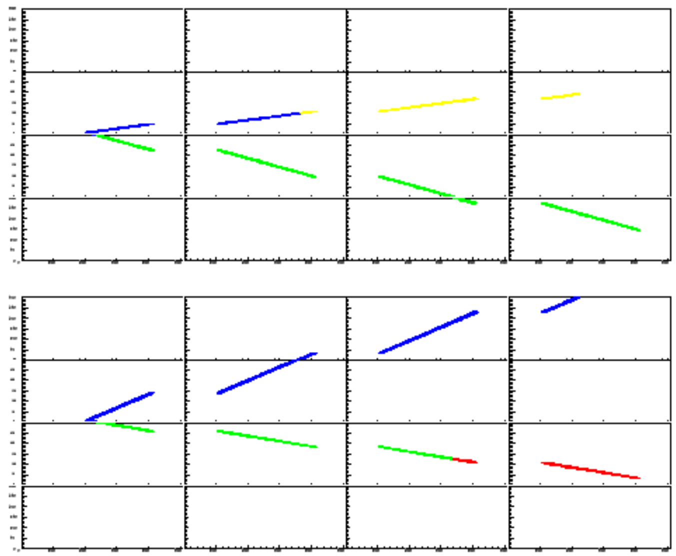
- A $4 \times 4 \times 4 = 64$ set of $(30\,\mathrm{cm})^3$ modules.
- modules back-to-back 2-by-2 with common cathode.

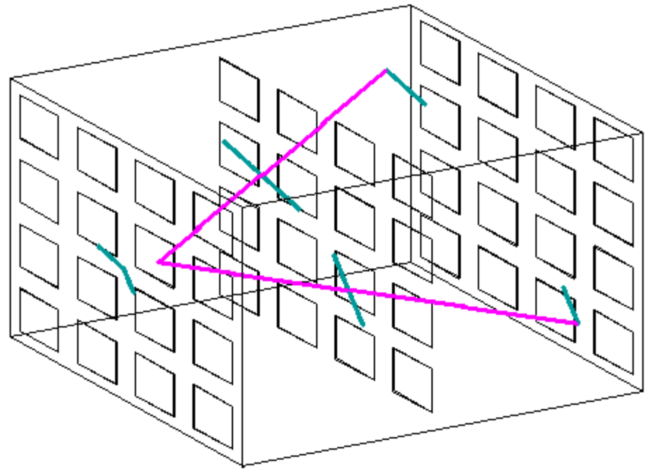
ST3G trigger mechanism: signal from a single bloc



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

ST3G trigger: multi-bloc scheme

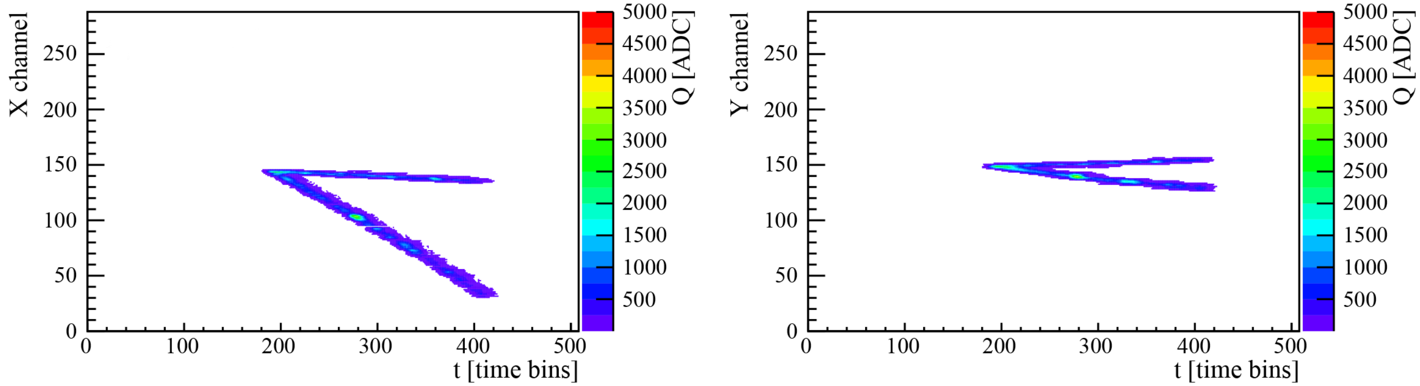




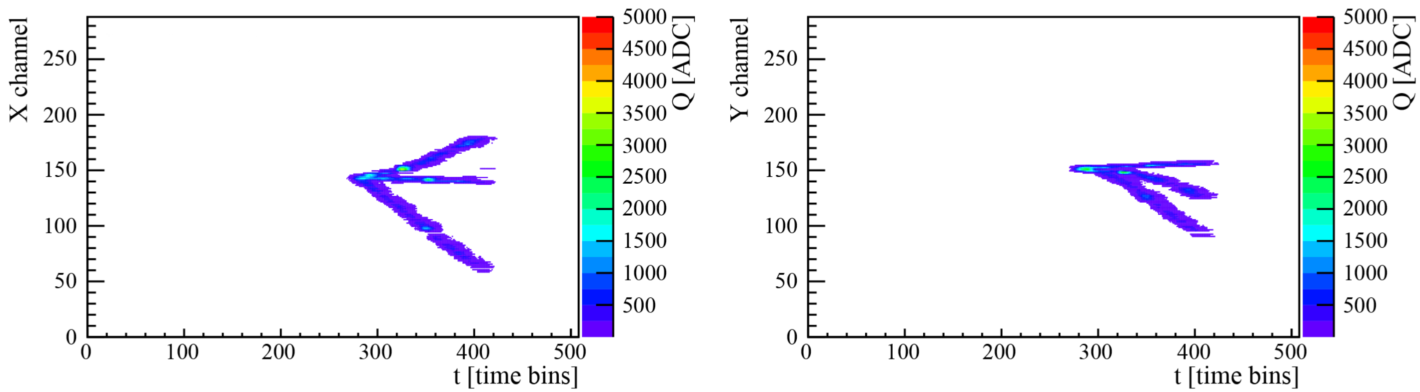
- $4 \times 4 \times 4 = 64$, $(30\text{cm})^3$, modules
- Sensitive volume $(1.2\text{m})^3$
- L0 trigger: coincidence of several modules (≥ 2) that see signal at the same time.
- Complete trigger mechanism to be designed and optimized
- geant4 simulation well advanced.

"Nuclear" and "triplet" conversions

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



$$\gamma e^- \to e^+ e^- e^-$$



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

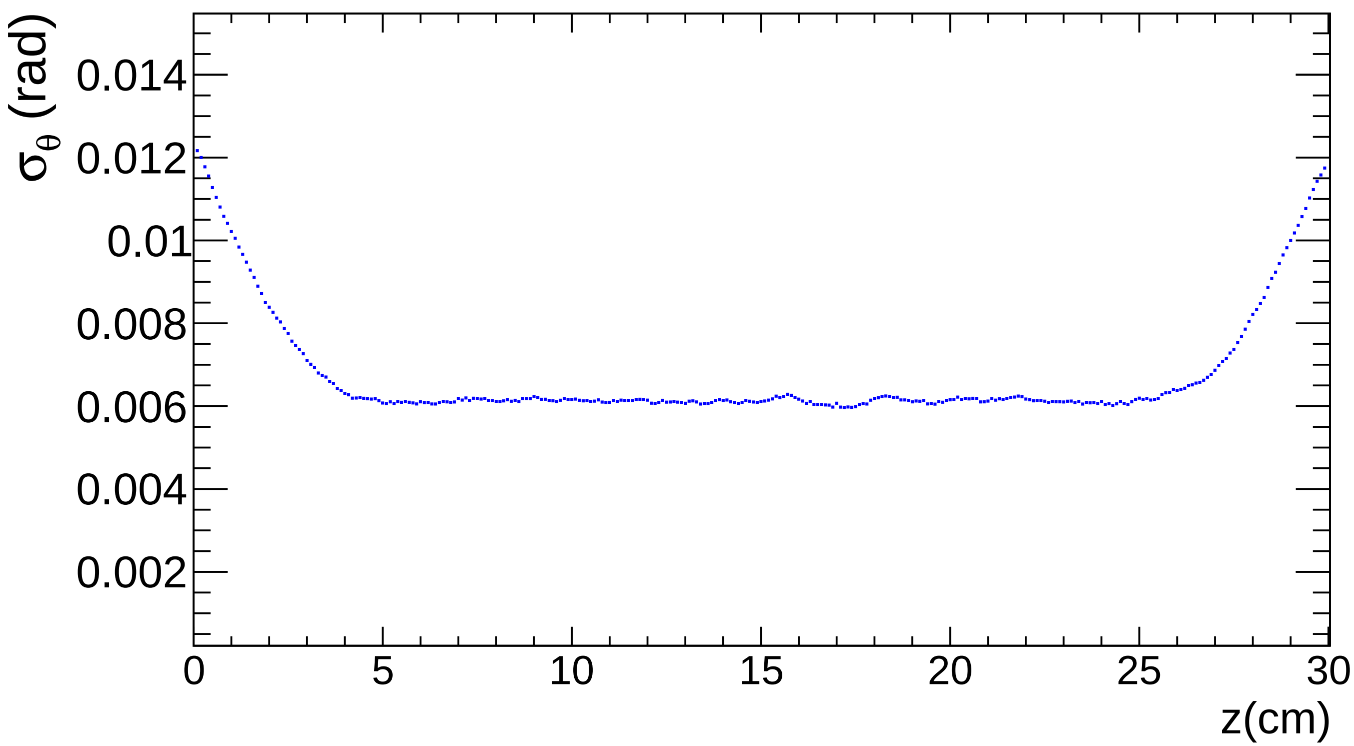
Back-up Slides

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

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

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

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



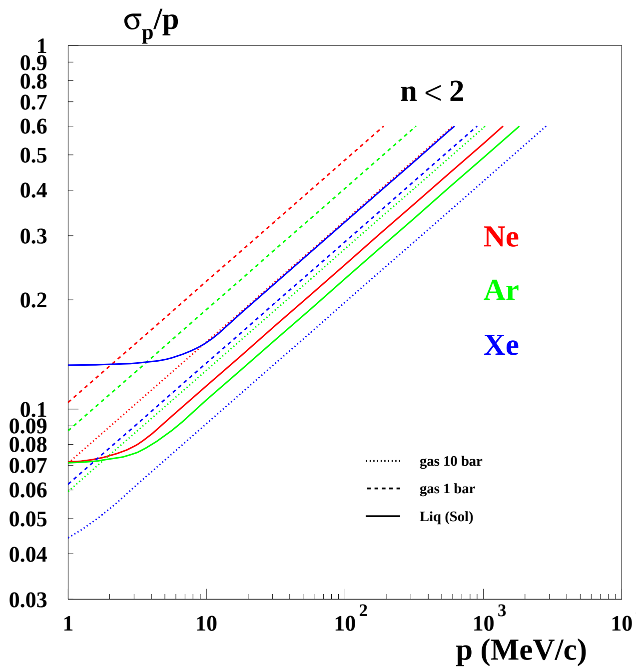
Angular resolution (residue RMS) as a function of the position along the track

NIM A 729 (2013) 765

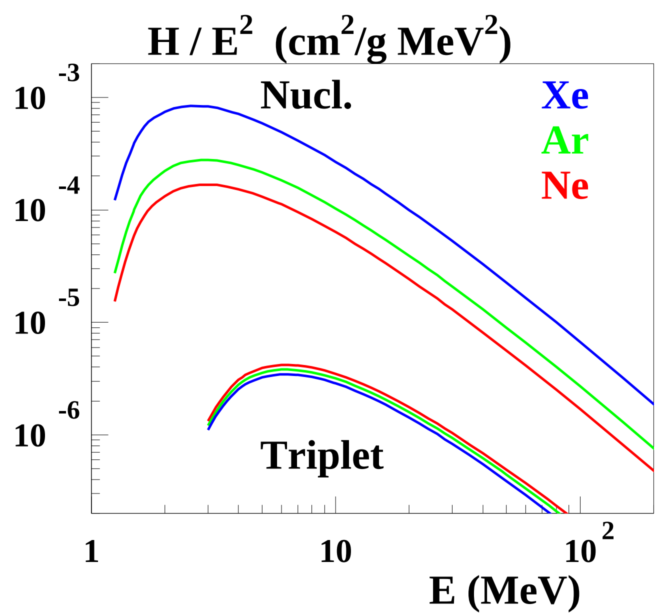
Track Momentum Measurement in TPC Alone from Multiple Estimations of Multiple Scattering

- 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 $\Rightarrow$ $$\frac{\sigma_p}{p} \propto \frac{1}{\sqrt{L}} \left[\frac{p\,\sigma\sqrt{X_0}}{13.6\mathrm{MeV}/c}\right]^{1/3}$$

relative precision



E range of interest



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

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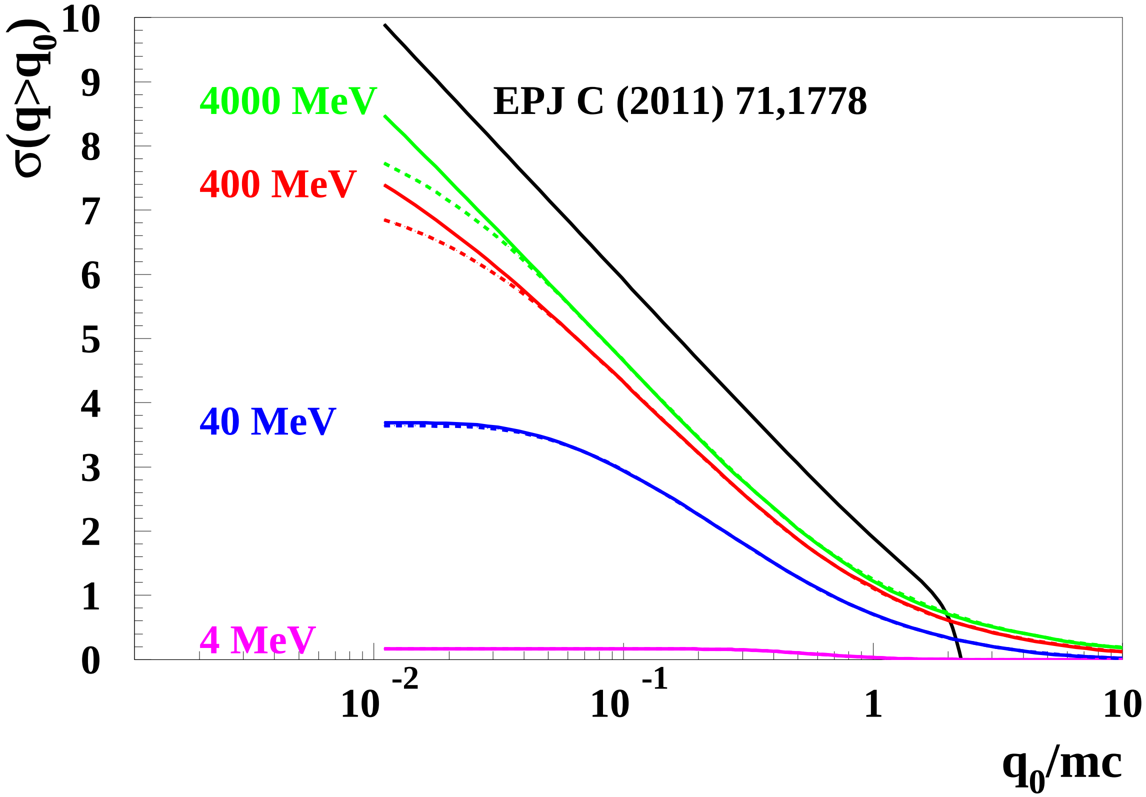
Evt Generator: One Example of Validation Plot

- 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).



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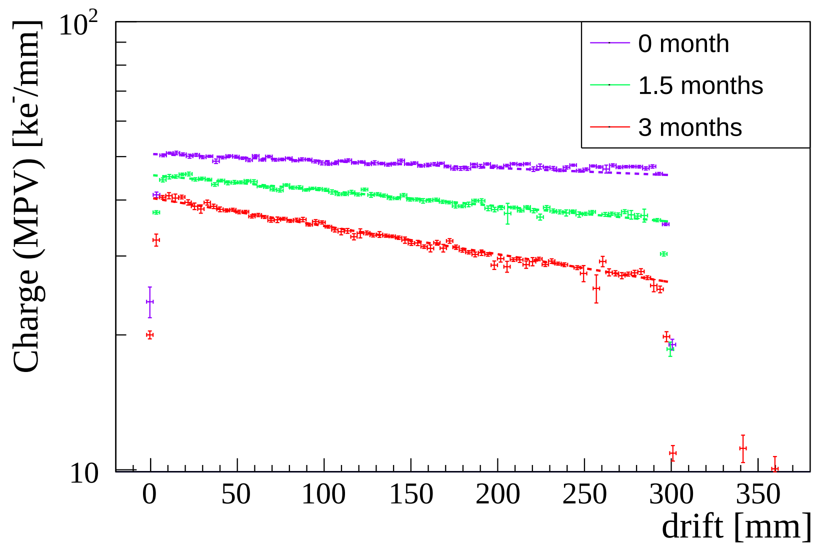
Gas purity on the long term

- 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).

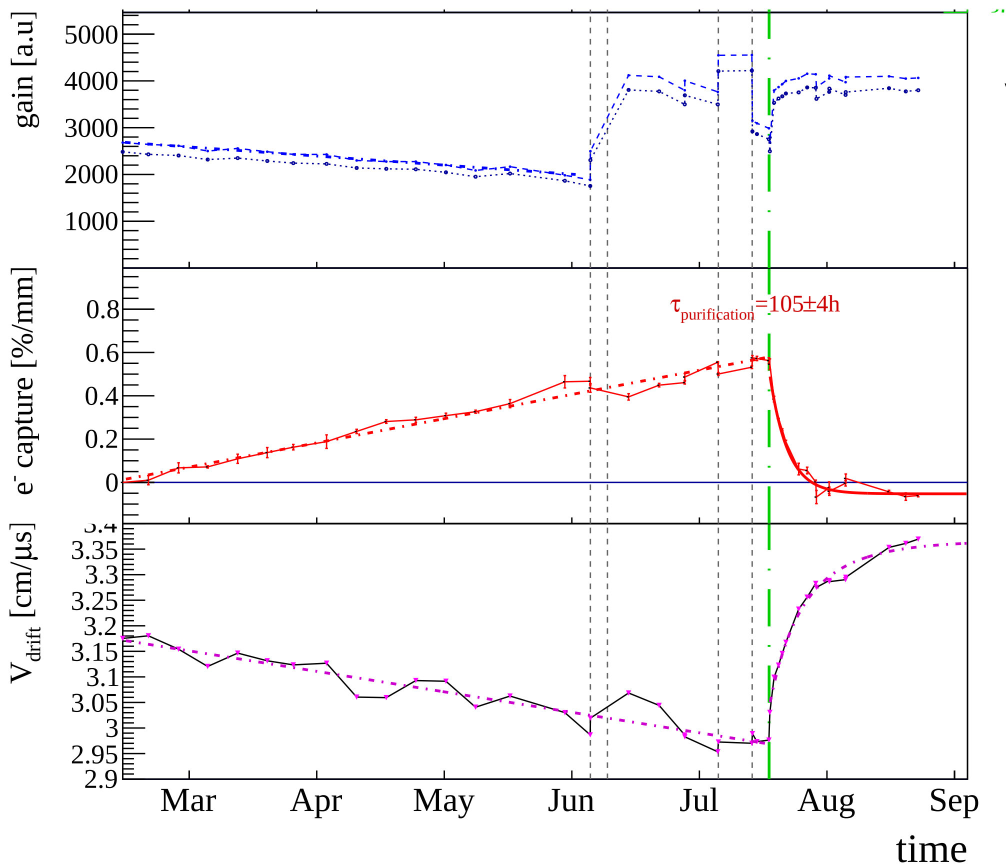


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- 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

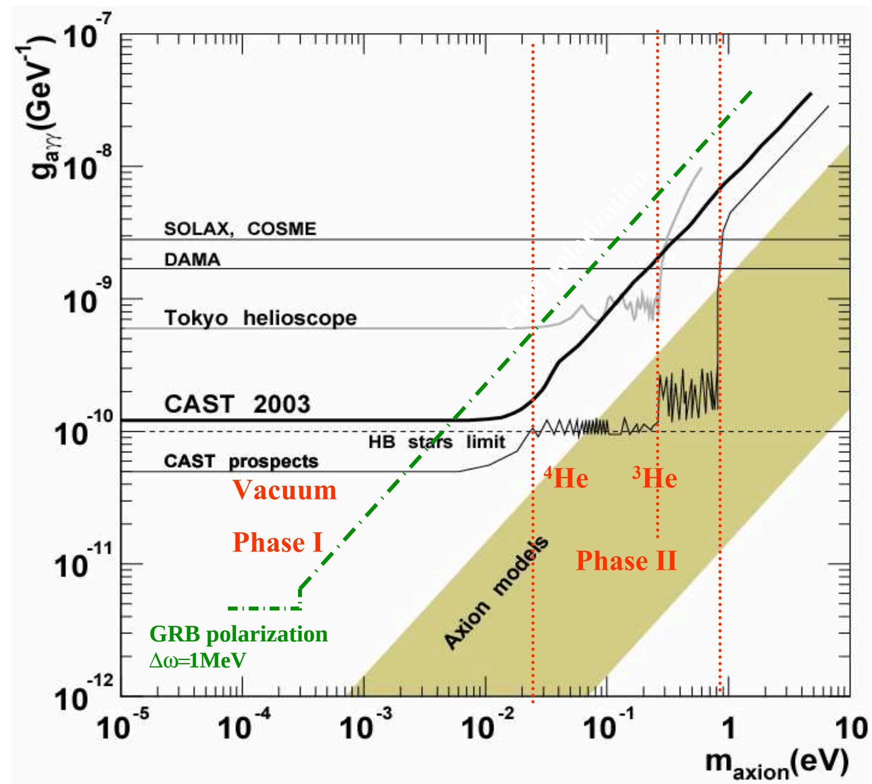
Search for Axions

- 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 $m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}}$

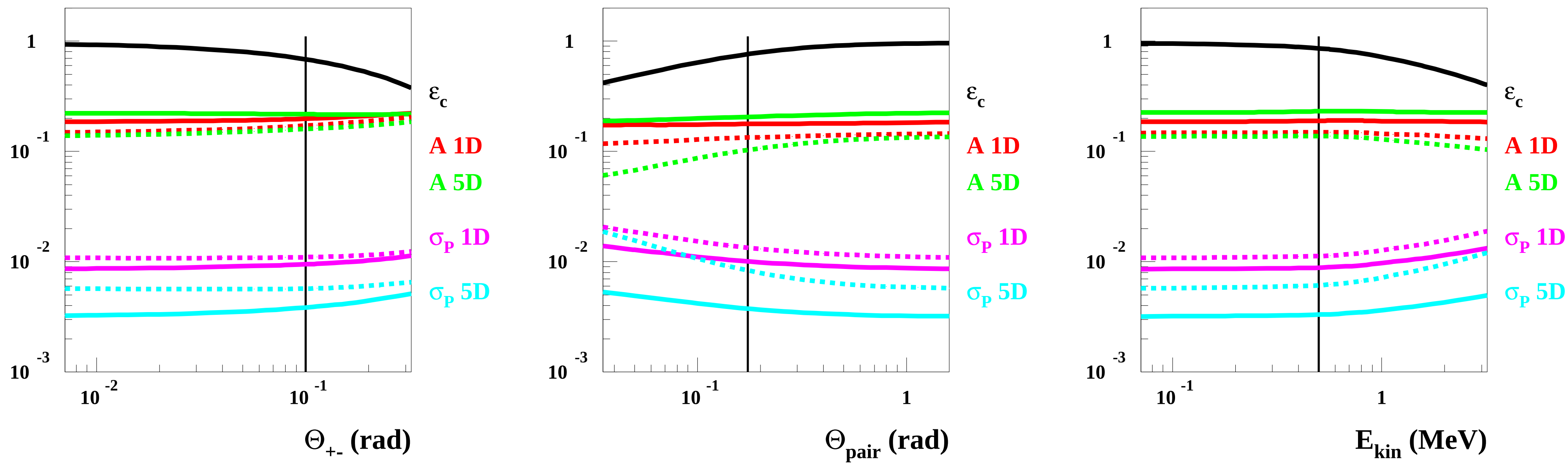
  and the limit $g_{a\gamma\gamma}$ reaches a ω-independent constant.



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

Polarimetry: Effects of Experimental Cuts

- opening angle, $\theta_{+-} > 0.1\,\mathrm{rad}$ (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. NIM 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" $p(\Omega) = (1 + \mathcal{A}P\cos[2(\phi)])$:

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

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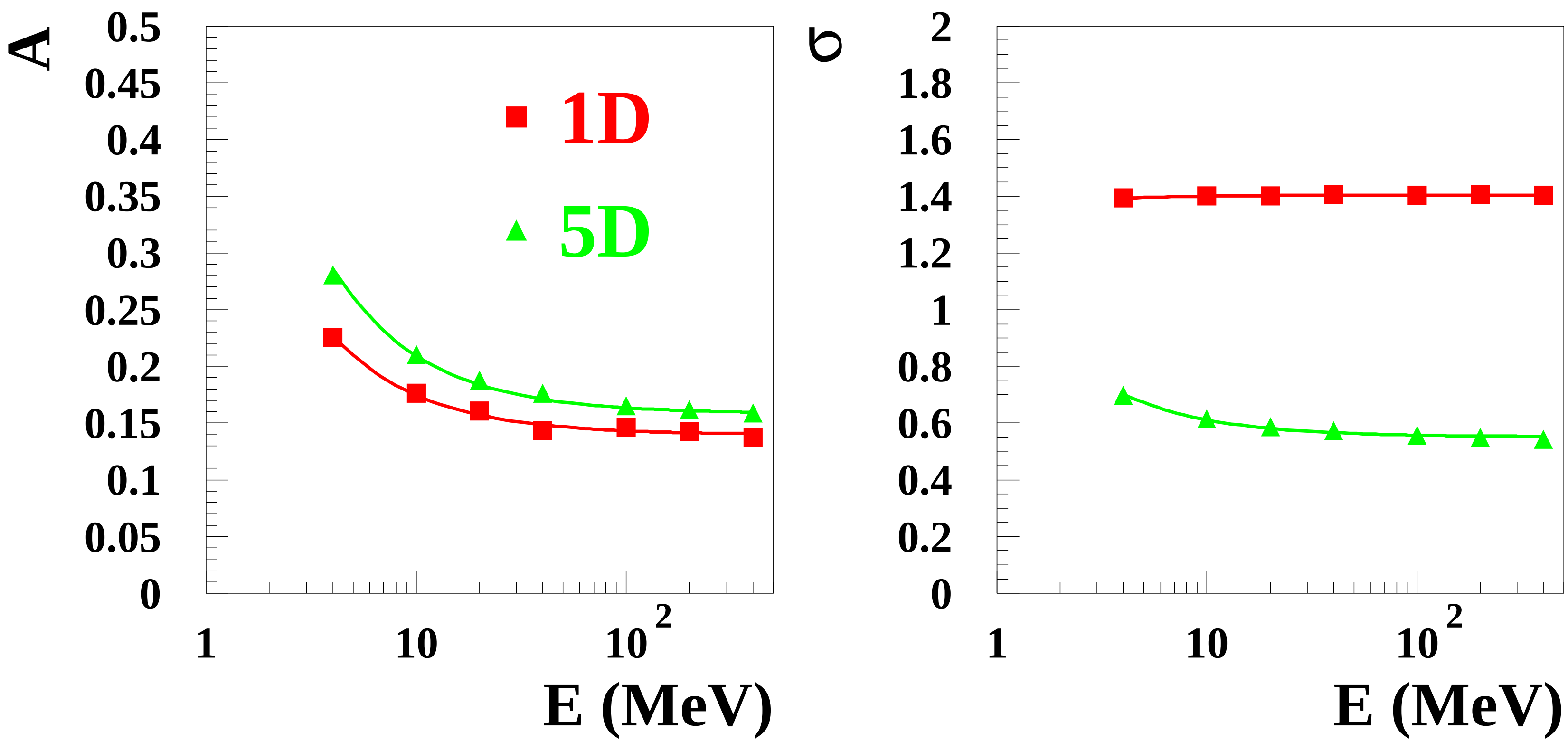
Polarization asymmetry and measurement uncertainty



NIM A 729 (2013) 765

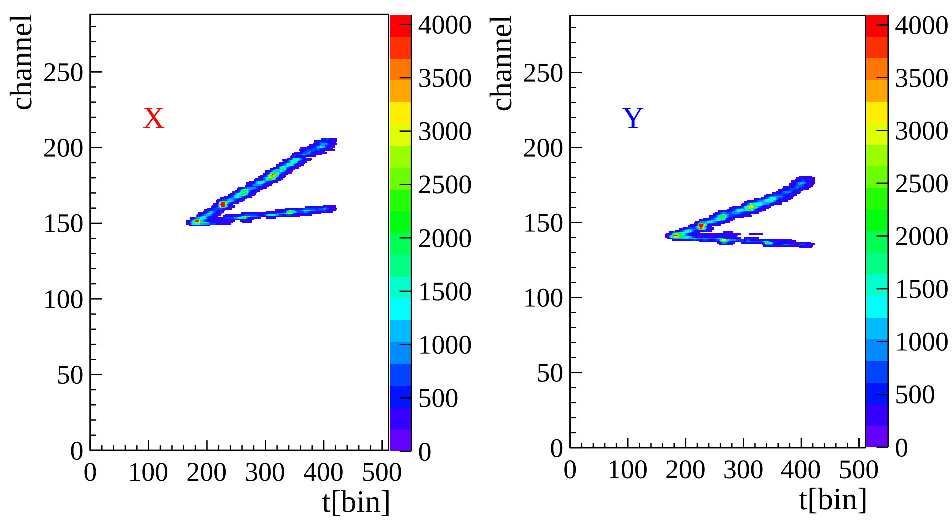
- Asymptotically $\mathcal{A} \approx 1/7 \approx \ 14\%$. Boldyshev & Peresunko, Yad. Fiz. 14, 1027 (1971).

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

Polarimetry: Track matching issue

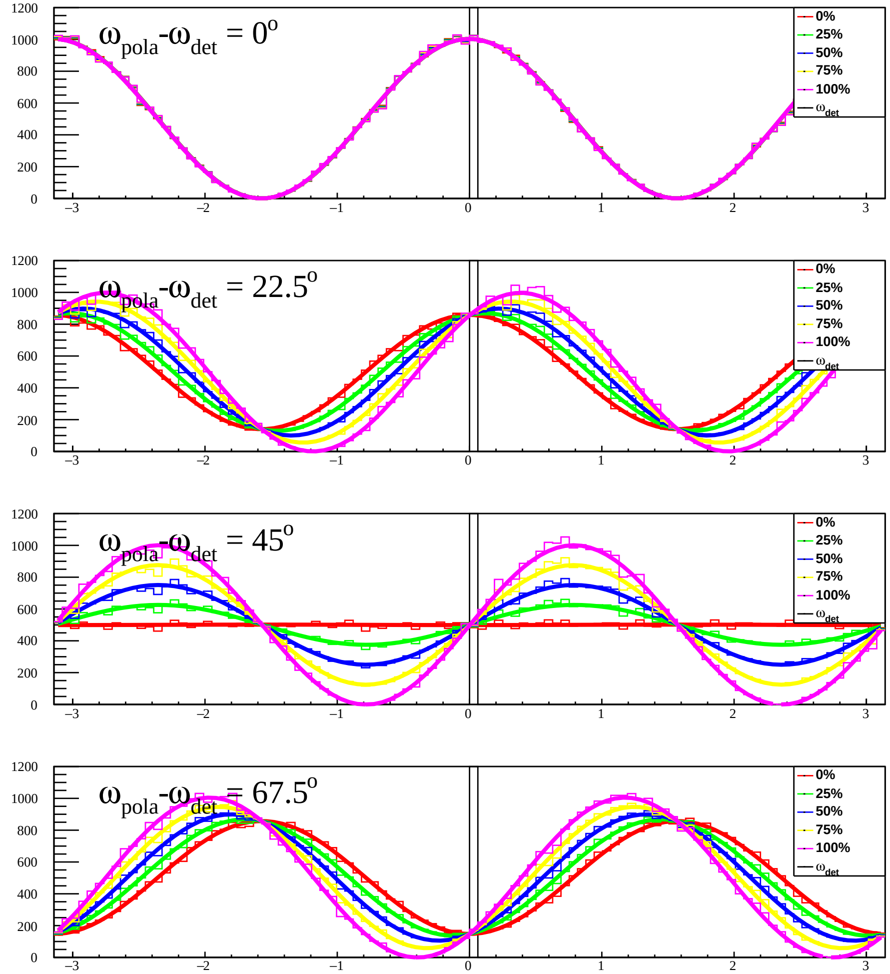
- Many foreseen project use 2×2D projections, not true 3D imaging (gas TPC, silicon strip detectors)
- Ambiguity:

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



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

Track matching issue



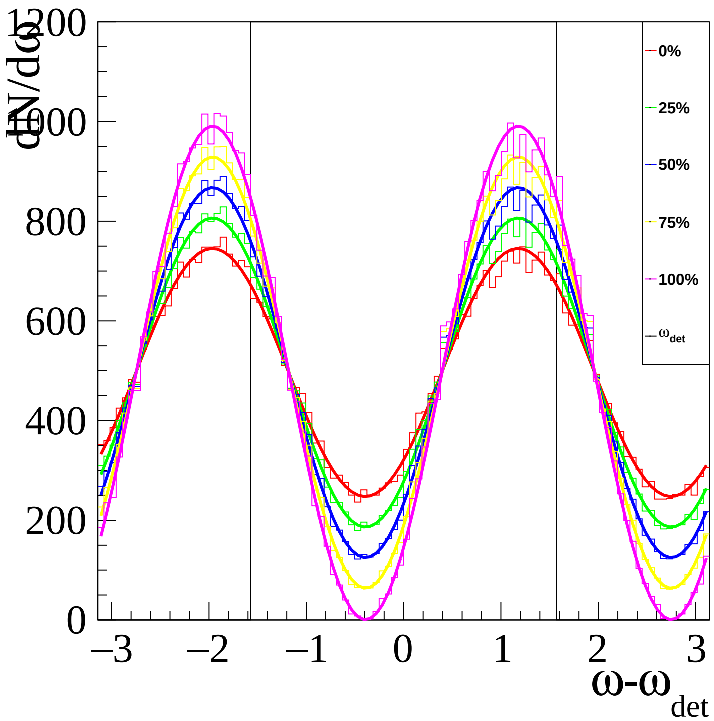
Observed angular distribution

Philippe.Gros @ llr.in2p3.fr

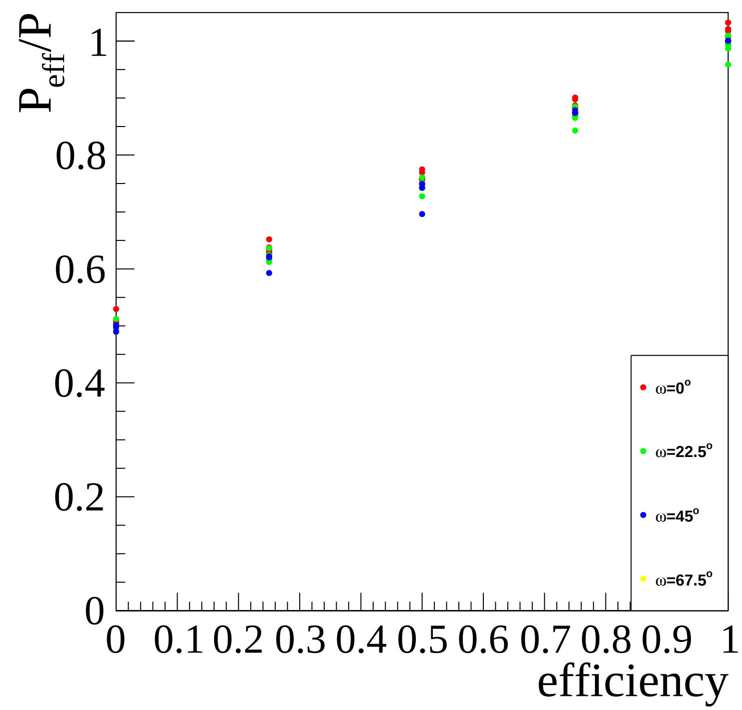
- for fully polarised pairs ($P_{\text{eff}} = 1$),
- in a fixed direction wrt the detector ($\omega_{\text{pola}} - \omega_{\text{det}}$)
- for different values of the matching efficiency ε.

Track matching issue: results

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



Azimutal distribution for different matching efficiencies



Dilution as a function of matching efficiency.

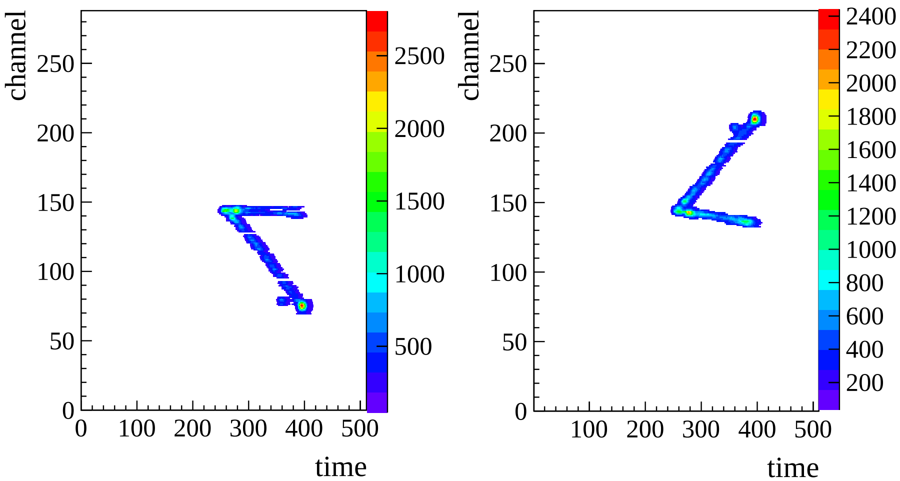
- A factor of 2 is at stake !

Philippe.Gros @ llr.in2p3.fr

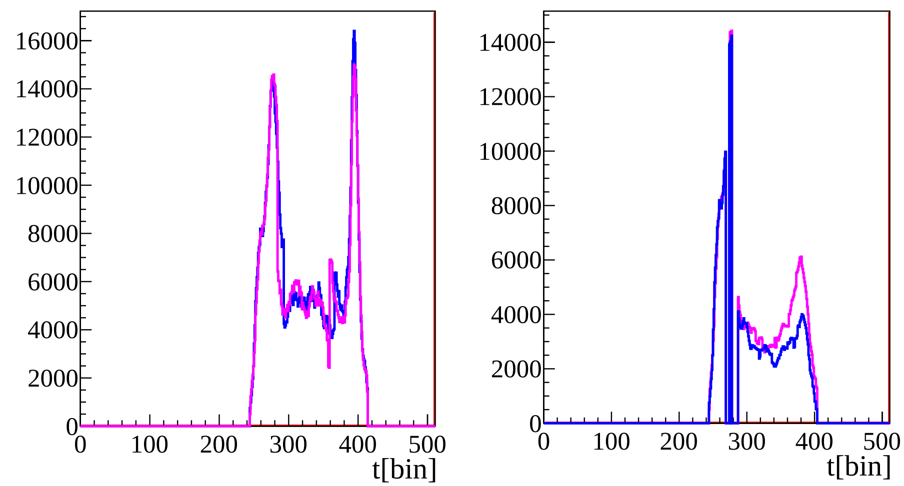
x, y *Matching*

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

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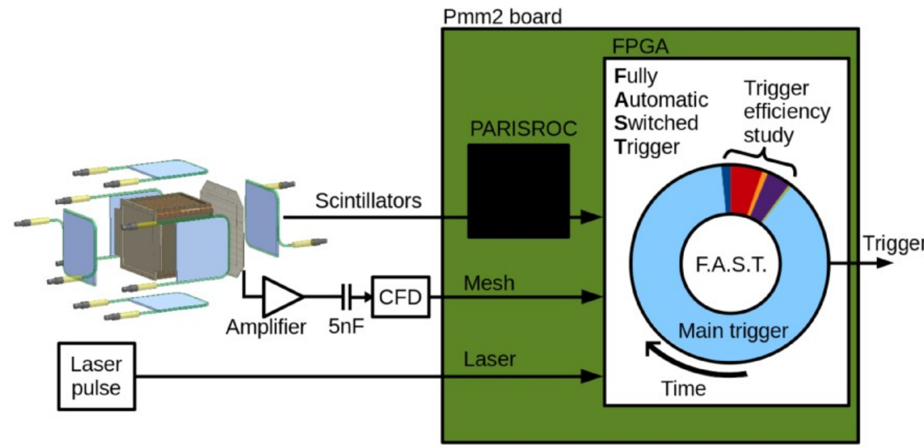
"Beam" trigger system: additional lines

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

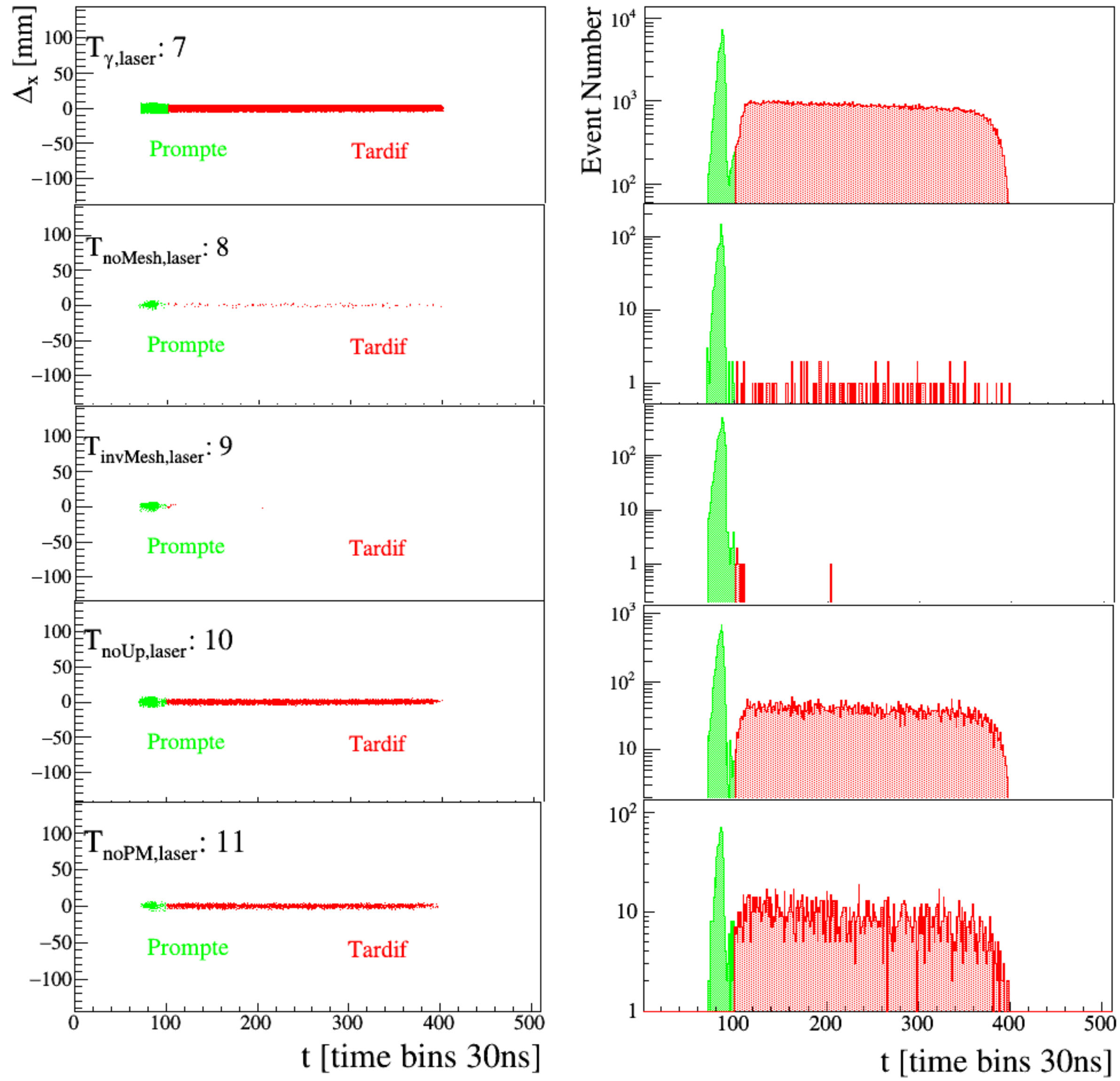


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

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
- . . .

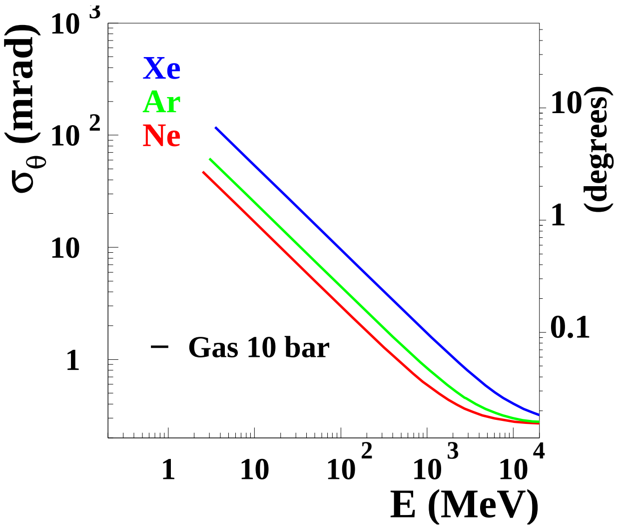
Towards a space detector: Gas composition: drifting species ?

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

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

Gas composition: light / heavy Z ? Gas pressure ?

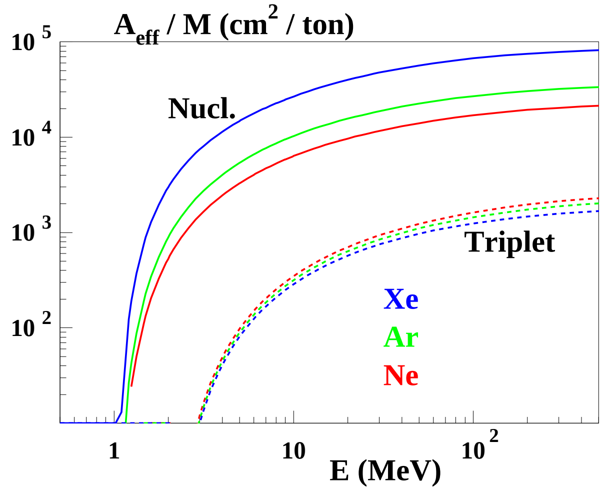
- $\rho \times X_0 = \frac{A}{Z^2} b, \quad \rho = aAP, \quad M = V\rho = VaAP, \quad X_0 = \frac{b}{aZ^2P} \quad a, b$ constants.



angular resolution degrades with Z

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

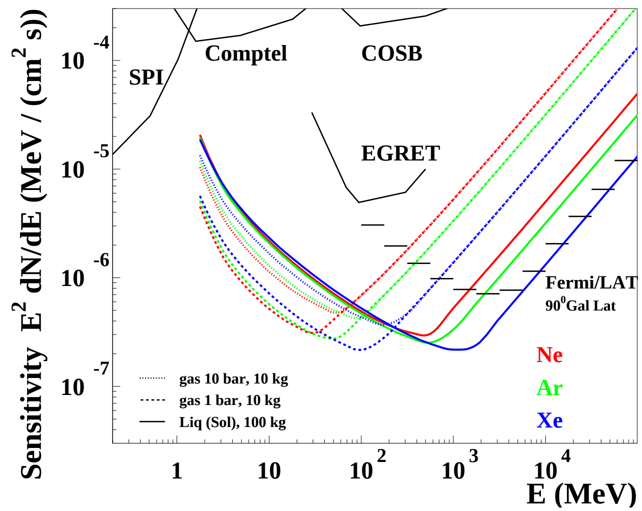
(multiple scattering)



effective area improves with Z

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

(asymptotically)



sensitivity mildly affected

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

(asymptotically)

(assuming gaussian stats.)

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

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

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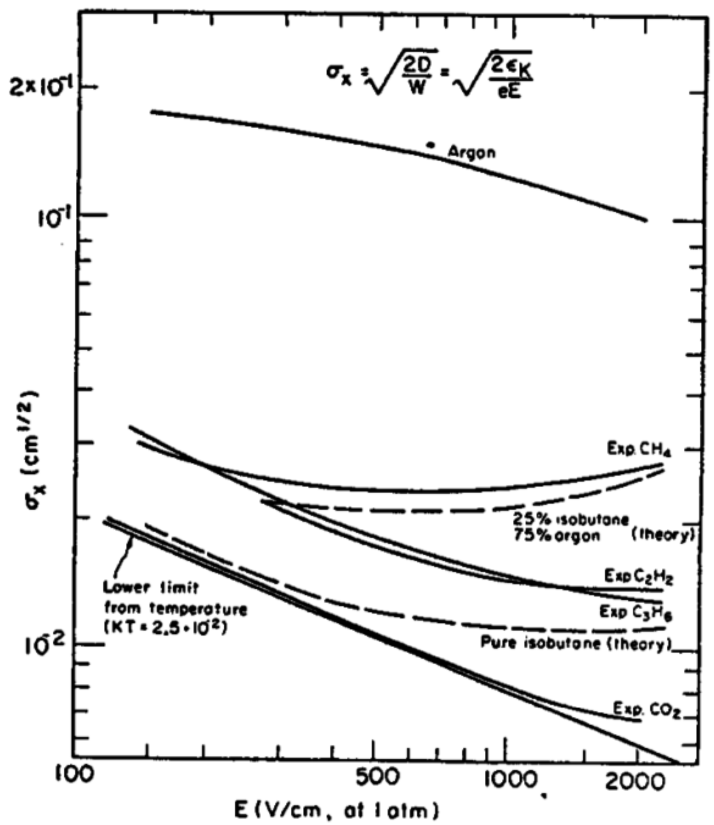
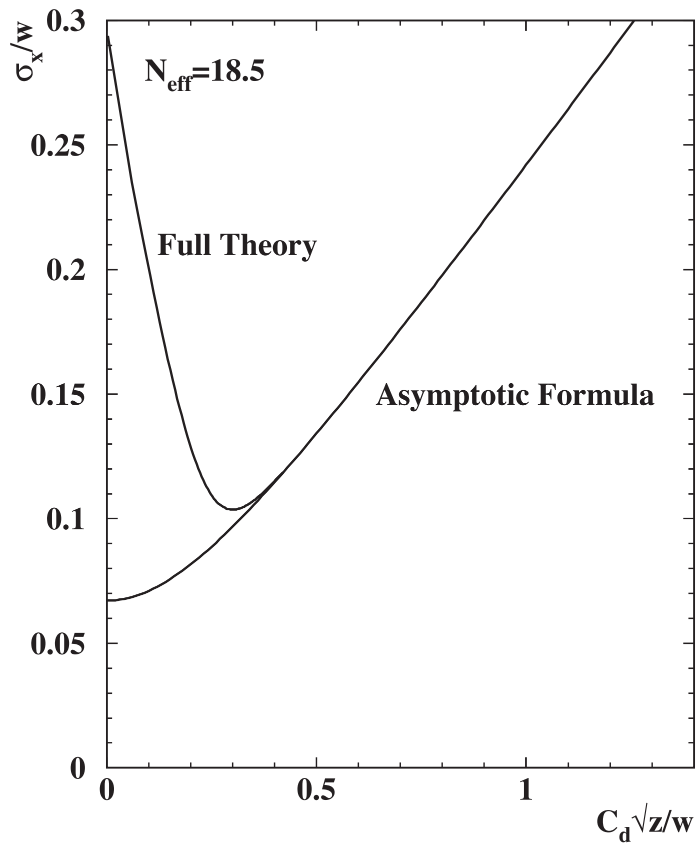
Gas composition, quencher





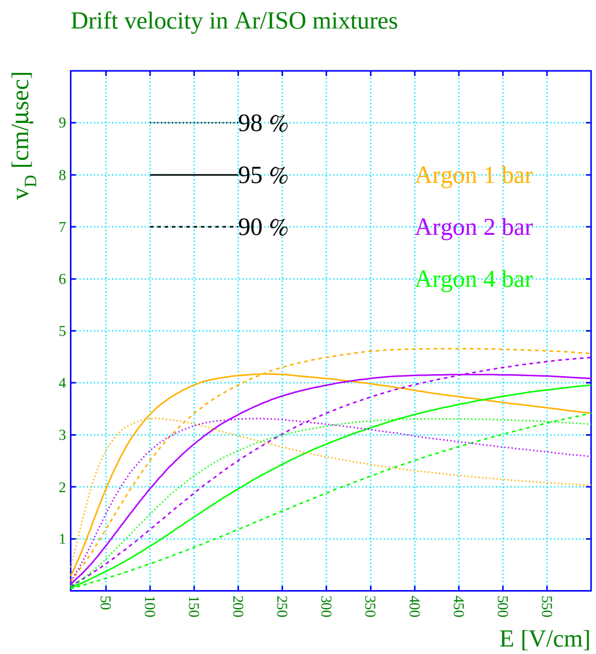
F. Sauli CERN-EP-83-103, 1983 D. C. Arogancia *et al.*, NIM A 602, 403 (2009)

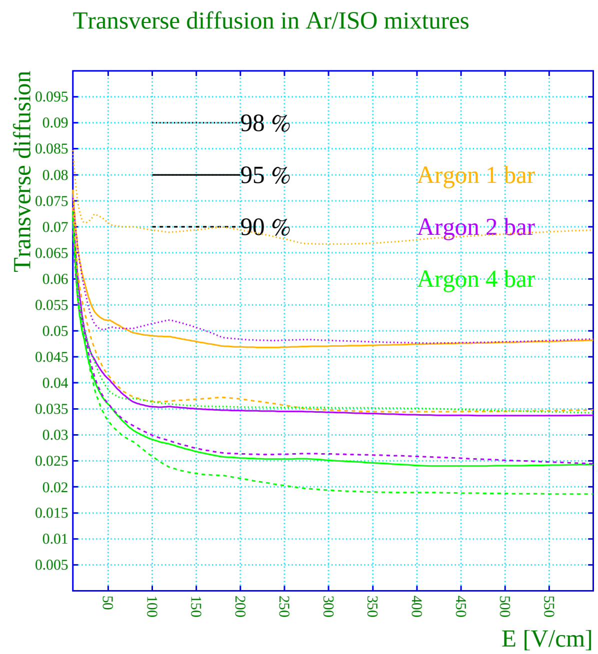
- Gas detectors need limitation of breakdown from UV photoelectric effect on the cathode: add poly($n > 2$)molecular "quencher" gas (alcanes, CO_2 ..)
- Mitigates diffusion $\sigma = \sigma_x/\sqrt{z}$, $\sigma_x = 200\,\mu\mathrm{m}/\sqrt{\mathrm{cm}}$, ($\sigma \approx 0.6\,\mathrm{mm}$ after $z = 9\,\mathrm{cm}$ drift)
- Diffusion is needed to minimize the TPC spatial resolution ! $C_D \equiv \sigma_x$, w strip pitch.

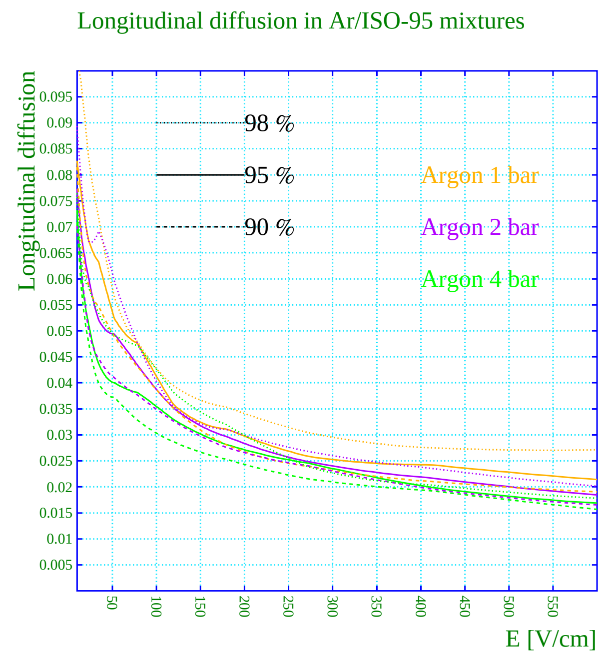
Pressure, Quencher fraction, e^- transport properties

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

Drift velocity	Transverse diffusion coefficient	Longitudinal diffusion coefficient
v_{drift}	$C_{D,T}$	$C_{D,L}$
$\text{cm}/\mu\text{s}$	$\text{cm}/\sqrt{\text{cm}}$	$\text{cm}/\sqrt{\text{cm}}$







- 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.

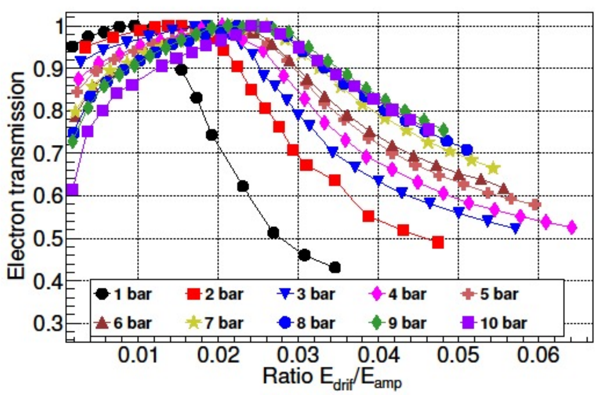
  (We operated the same set-up in the range 1-4 bar by simple voltage ajustments)
- Maximal temperature ?
  - check your electronics !
  - plastic scintillator dome will soften at $\approx 80^\circ$
- Minimal temperature ?
  - avoid quencher partial liquefaction

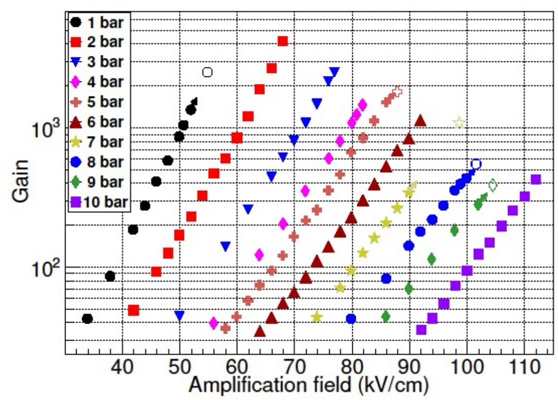
gas	Ar	Xe	CH_4	C_2H_6	iso C_4H_{10}
boiling point at 1.013 bar ($^\circ$C)	-185.8	-108.1	-161.5	-89	-11.7

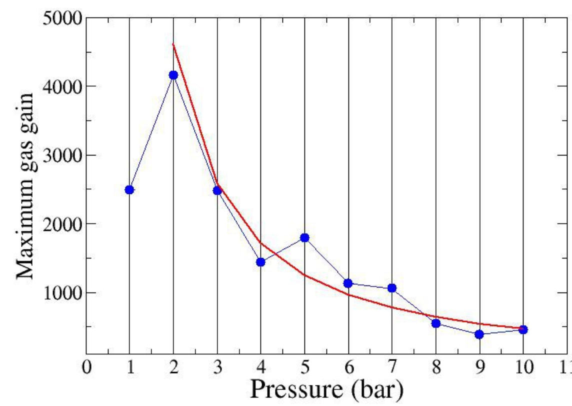
  - alcanes have similar quencher properties.

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.