HARPO : a TPC as a high-performance γ-ray telescope and a polarimeter in the MeV – GeV energy range

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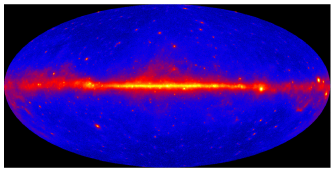
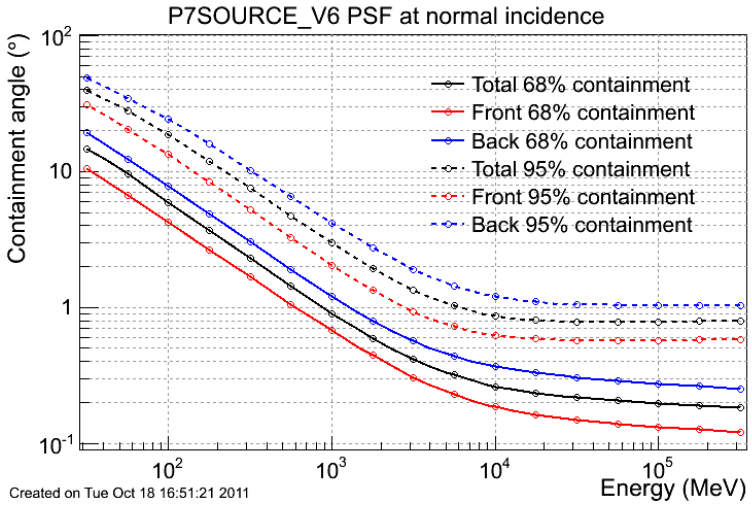
Conseil Scientifique du LabEx P2IO, 17 décembre 2014.

llr.in2p3.fr/∼dbernard/polar/HARPO.html

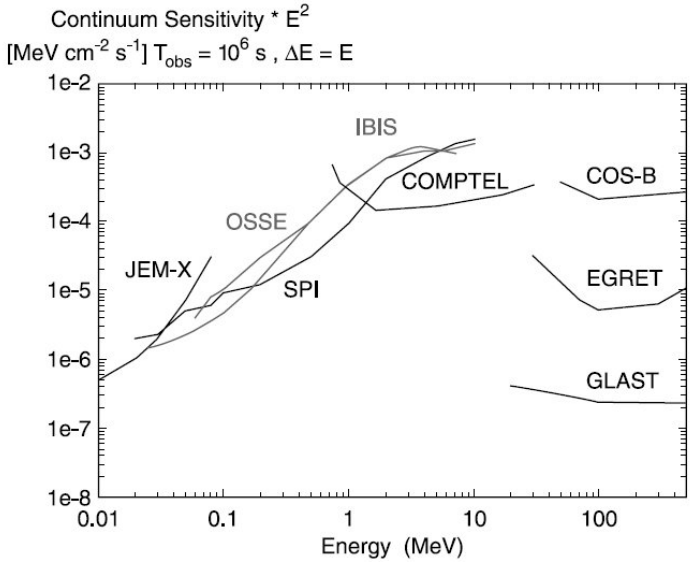
Science case



- **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,

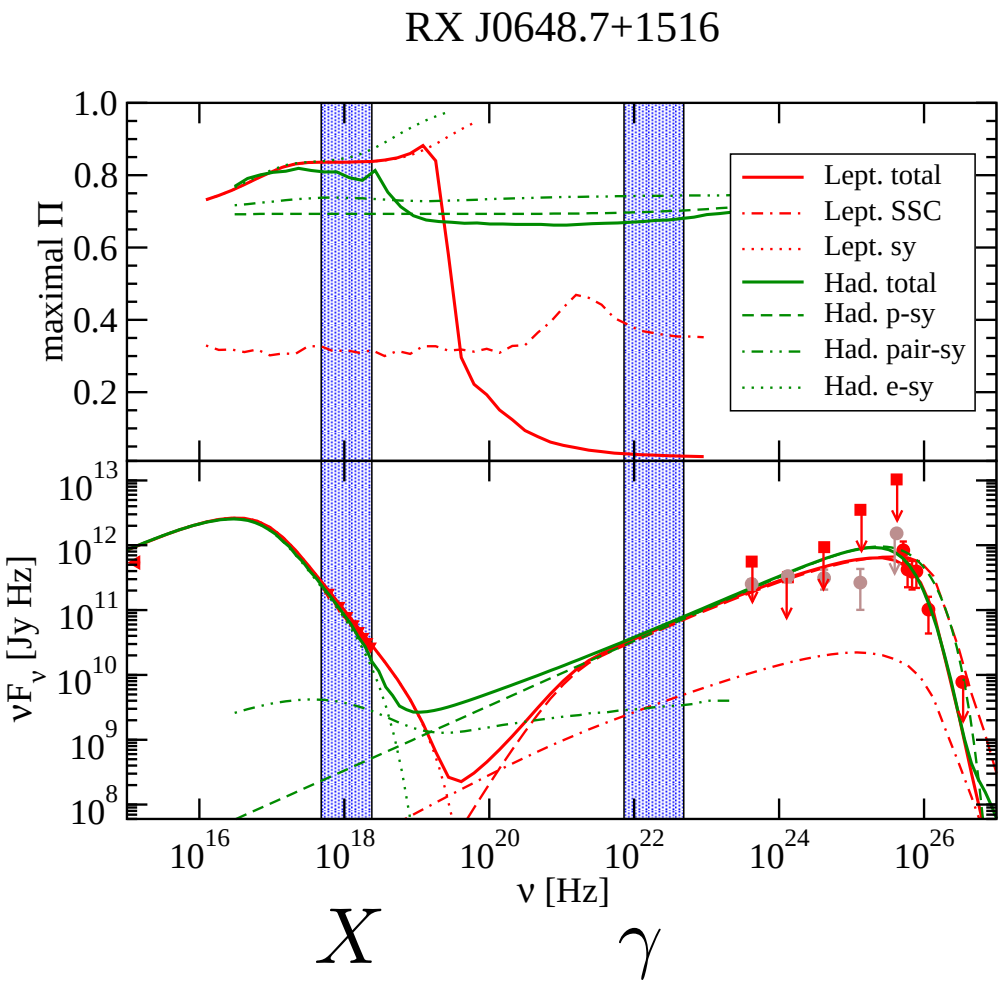
- **Polarimetry** : No γ polarimeter sensitive above 1 MeV in space ever
  - Cosmo / New Physics : LIV : Search for Lorentz Invariance Violation sensitivity $\propto E^2$,
  - Astrophysics : understand working mechanism(s) of γ cosmic sources

Polarimetry science case, astrophysics

- One example : 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. **7**74, 18 (2013)



HARPO : pre-P2IO

- LLR-only project ; powerful but "informal" contribution from Irfu.
- Performance studies well advanced
- μ-funding from
  - Particle-n-Universe (P-et-U) interdisciplinary CNRS program IN2P3-INSU (2010, 30 k€). Program was then cancelled
  - IN2P3 (2011, 11.7 k€).
- Built the "core" of a demonstrator,
  - and reconstruction program
  - (excellent) tracking performances characterized with cosmic-rays
  - but optimal amplification gain close to the limit of safe routine operation

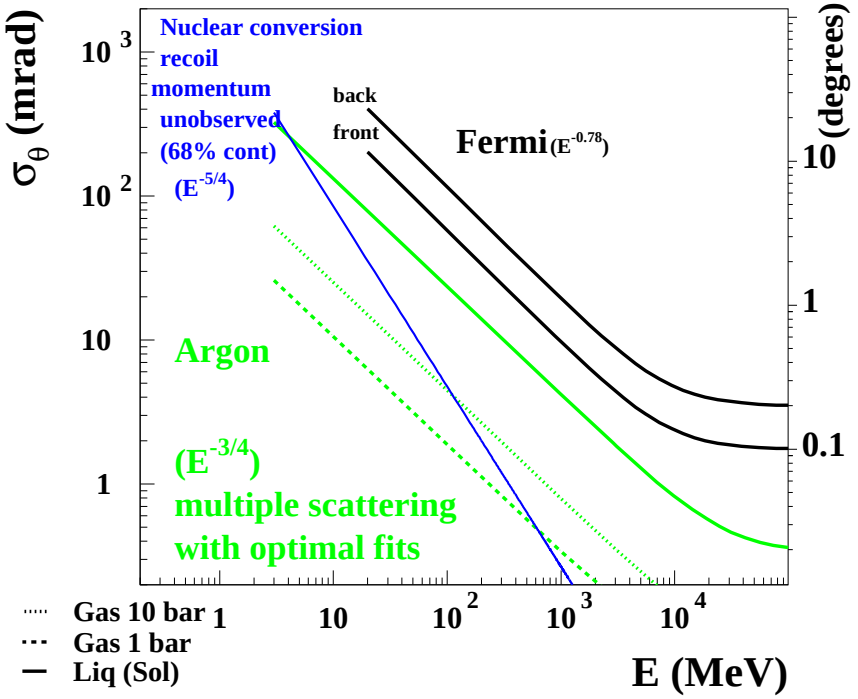
  12th Pisa Meeting on Advanced Detectors 2012, NIM A 718 (2013) 395 , arXiv :1210.4399 [astro-ph.IM]
- No simulation

End 2011 : HARPO was at the verge of death

Performances studies : $\gamma \to e^+e^-$ detection with a thin, homogeneous detector and optimal fits

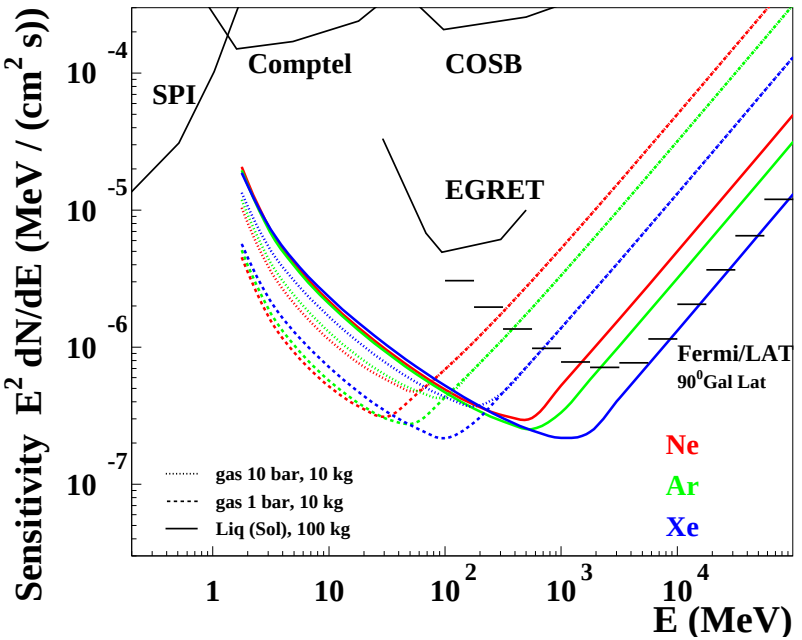
Angular resolution

- 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



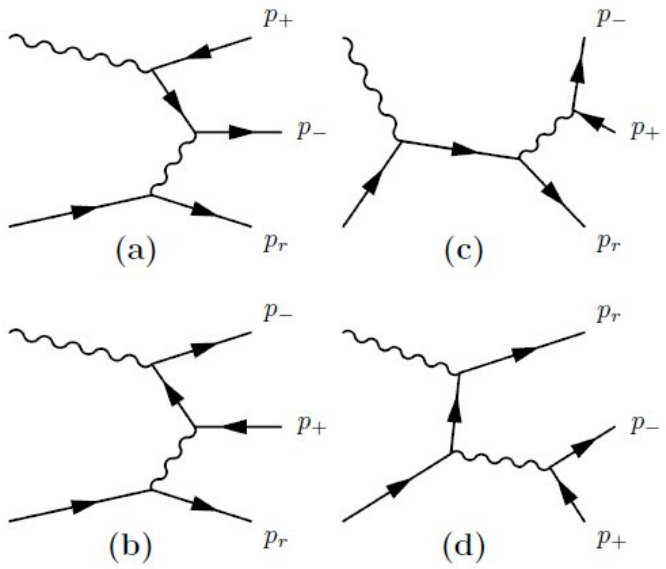
- Sampling pitch $l = 1\mathrm{mm}$, point resolution $\sigma = 0.1\mathrm{mm}$
- Validation of optimal fit performance with Kalman filter

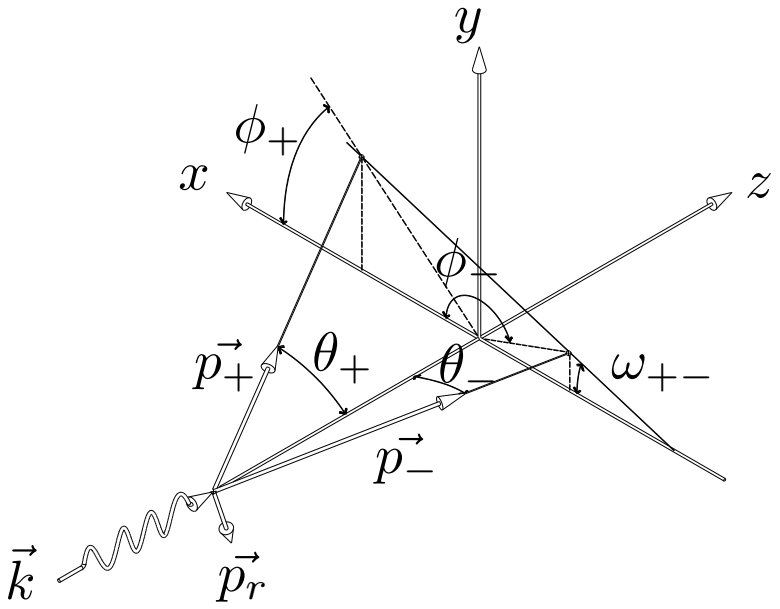
NIM A 701 (2013) 225

NIM A 729 (2013) 765

Developed, validated, an 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)

NIM A 729 (2013) 765

Dilution of polarization asymmetry due to multiple scattering : Optimal fits and full MC

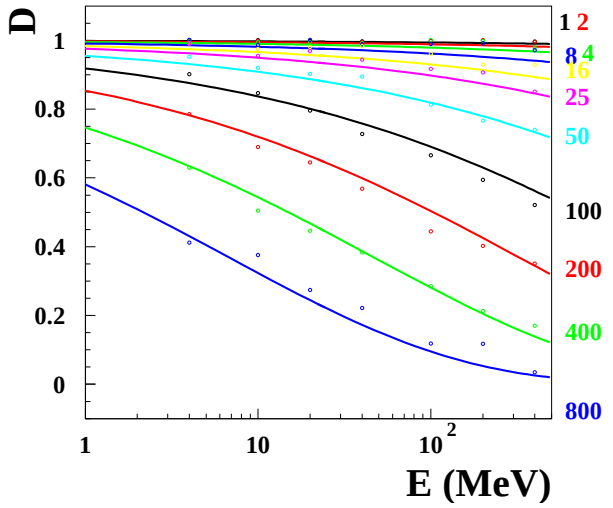
- Track angular resolution $(p/p_1)^{-3/4}$,

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

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

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

Points are from full MC.



Curves are $D(E, p_1) = \exp\left[-2(a\, p_1^b\, E^c)^2\right]$ parametrizations, a, b, c constants

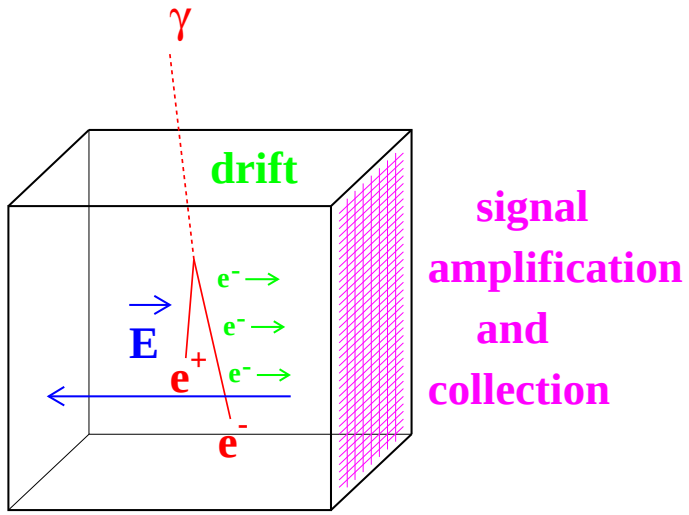
- Liquid : nope (Ar, $p_1 = 1.45\,\mathrm{MeV}/c$) ; gas : Possible ! (1 bar, $p_1 = 50\,\mathrm{keV}/c$)
- Crab-like source, $T = 1$ year, $V = 1\,\mathrm{m}^3$, $\sigma = l = 0.1\,\mathrm{cm}$, $\eta = \epsilon = 1$).

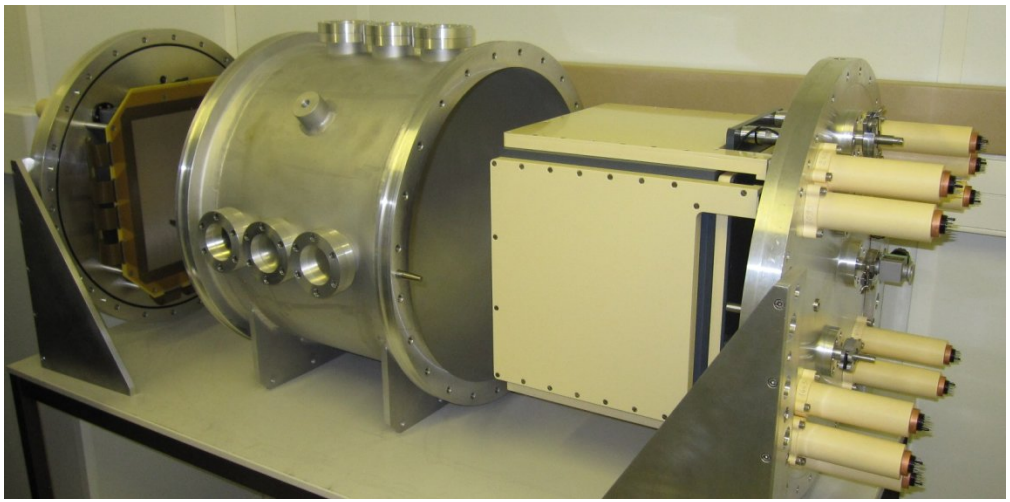
Argon, 5 bar, $\boxed{\sigma_P \approx 1.0\%}$, $\mathcal{A}_{\text{eff}} \approx 15\%$

NIM A 729 (2013) 765

HARPO : the Demonstrator

- $(30\mathrm{cm})^3$ cubic Time Projection Chamber (TPC)
- Ar :Iso 95 :5, up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on x, y strips, pitch 1 mm.
- AFTER chip digitization, up to 50 MHz.
  288×2 channels (x, y) FEC (Irfu - T2K TPC).
  2014 : FEMINOS (Irfu/Minos)
- Scintillator / WLS / PMT based trigger
  (PMm2 card, IPNO)



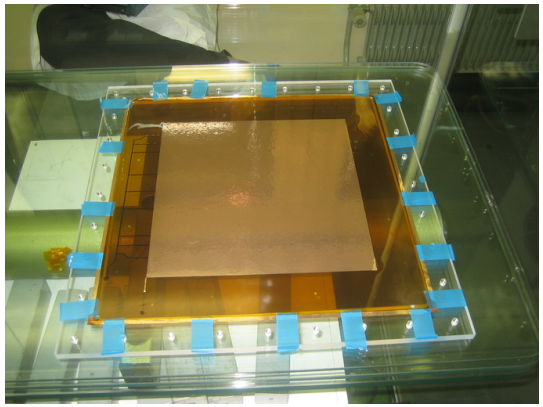


NIM A 695 (2012) 71, NIM A 718 (2013) 395

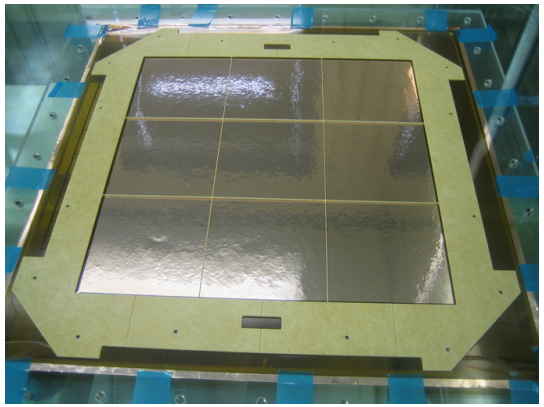
2013 : GEM

- GEM designed (LLR), produced (CERN), glued on frames (RD51/CERN)

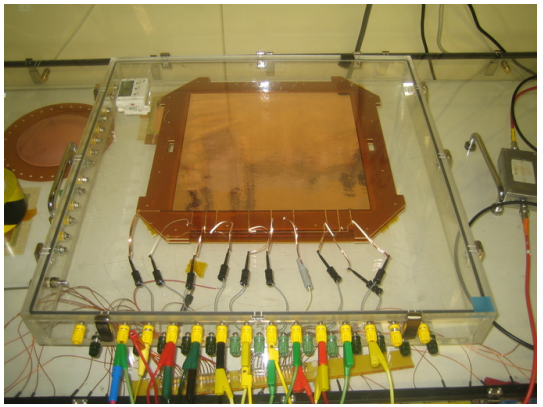
gluing preparation



glued on frame



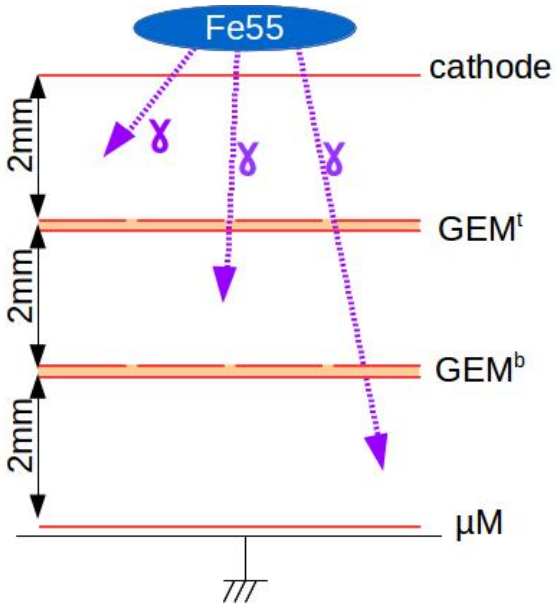
electrical tests

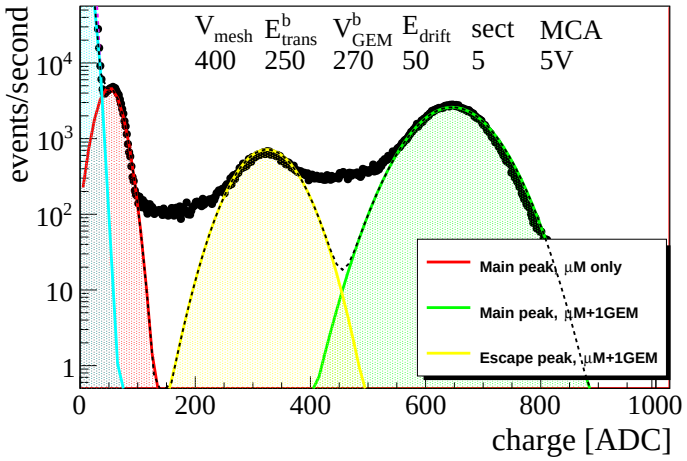


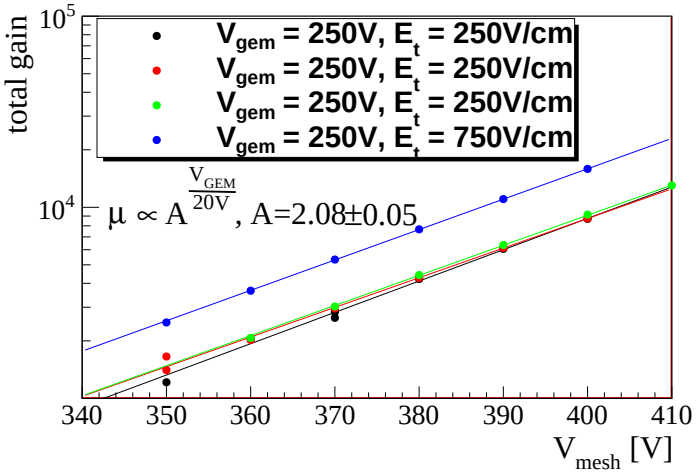
- "Regular" $50\mu m$ Kapton GEM
- 3 pieces (2 + 1 spare) produced.
- Characterized with ^{55}Fe source at 1 bar
- Integrated in detector

Ph. Gros, 13 th RD51 Collaboration Meeting, CERN 5 - 7 Feb 2014

Micromegas + (1 or 2) GEM ^{55}Fe cosmic-ray characterization



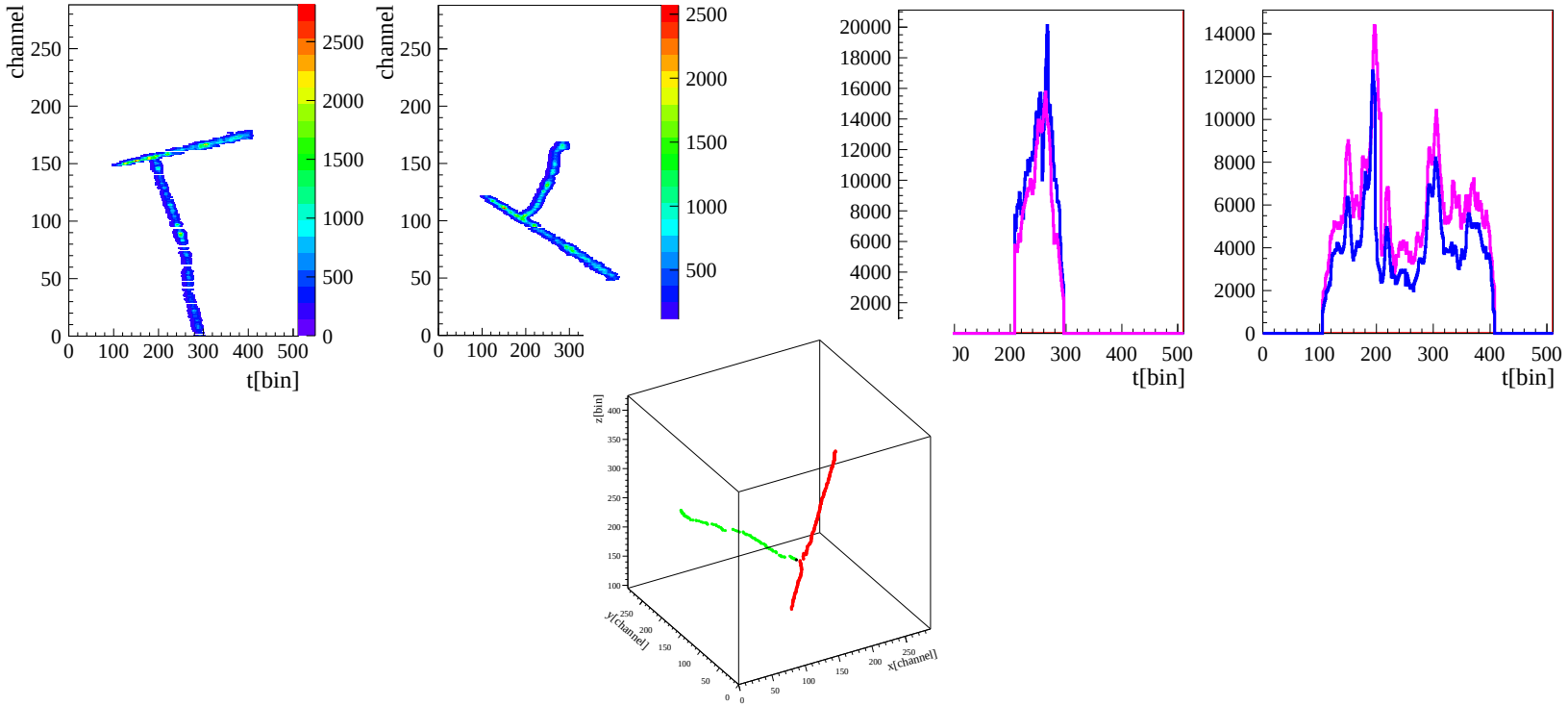




Ph. Gros, TIPP2014, to be published in Proceedings of Science

Event reconstruction

raw "maps" track time spectra (x, y matching)

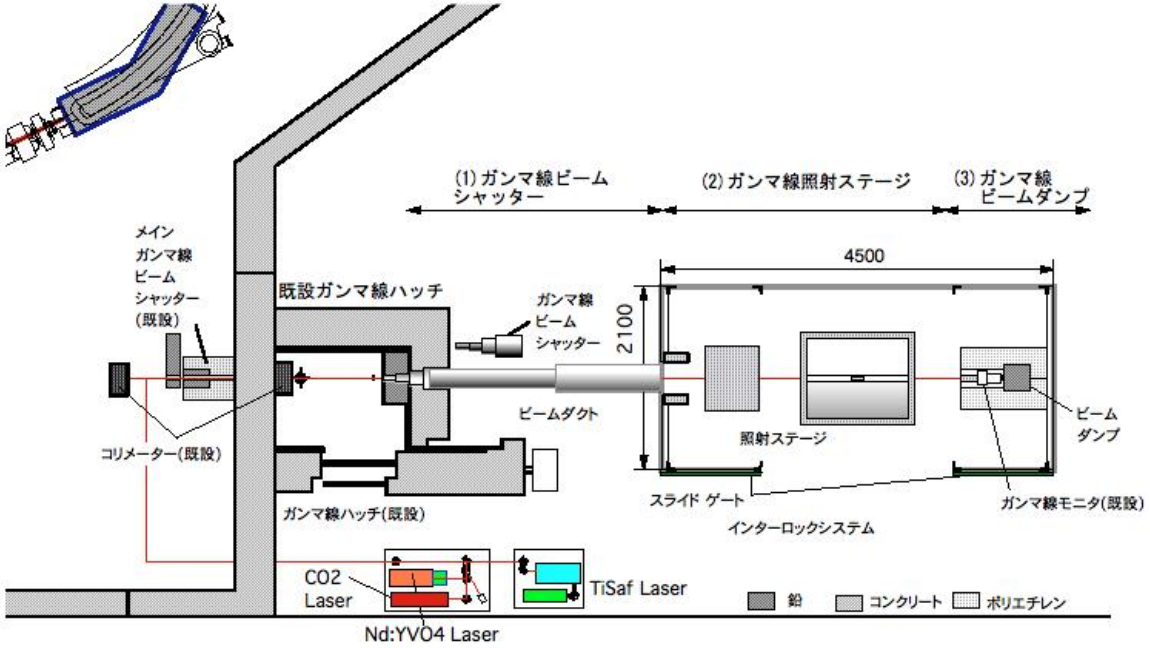


- 2 bar (Ar :95 Isobutane 5 %), shaping 100 ns.
- Evt reco of a cosmic ray traversing the TPC, emission of a δ ray
- Track pattern recognition by combinatorial Hough transform
- x, y two track ambiguity solved by track time spectra matching

Proc. SPIE 9144 Space Telescopes and Instrumentation : Ultraviolet to Gamma Ray, (2014) 91441M, arXiv :1406.4830 [astro-ph.IM]

Data taking at NewSUBARU, U. of Hyôgo, Japan, (20 Oct. – 22 Nov. 2014)

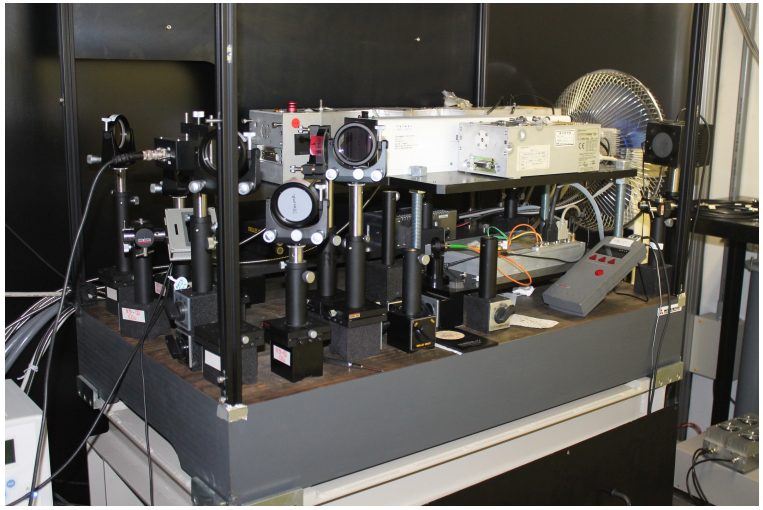
- $P \approx 1$ linearly polarized γ beam, from on-axis collision on (1.064, 0.532, 1.55, 10.64) μm (Nd $(1\omega, 2\omega)$, Er, CO2) laser pulses on 0.6 – 1.5 GeV e^-.
- 1.7 - 72 MeV γ energy range available.
- $P = 0$ beam available for detector-systematics studies.
- Monochromaticity achieved by γ collimation on axis. $\phi\,4\mathrm{mm}$ collimator.



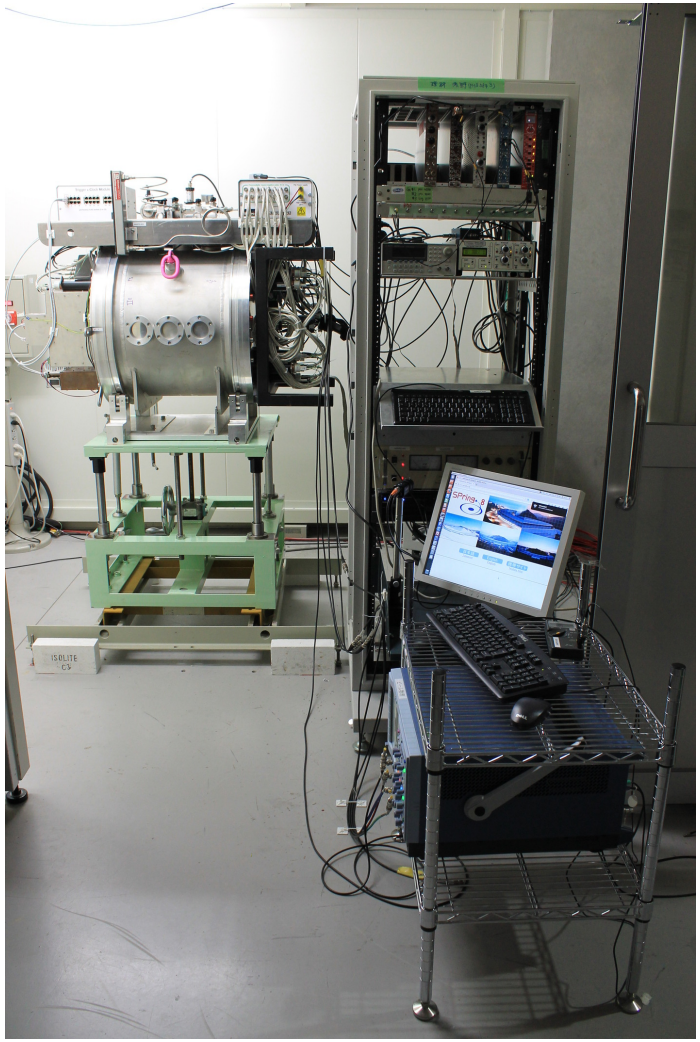
- Gamma-ray Collaboration Hutch of KOnan University (GACKO) Experimental zone finalized (2012) and validated (2013)

Pics

Shifters space

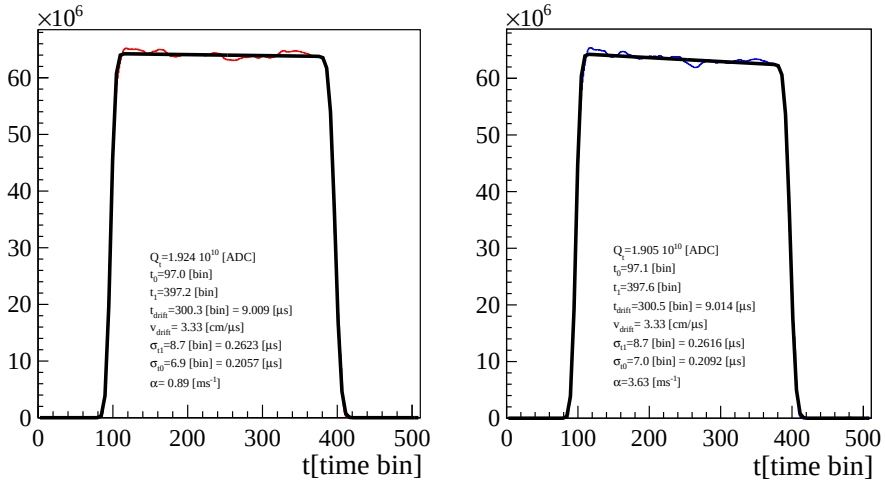


The laser corner.

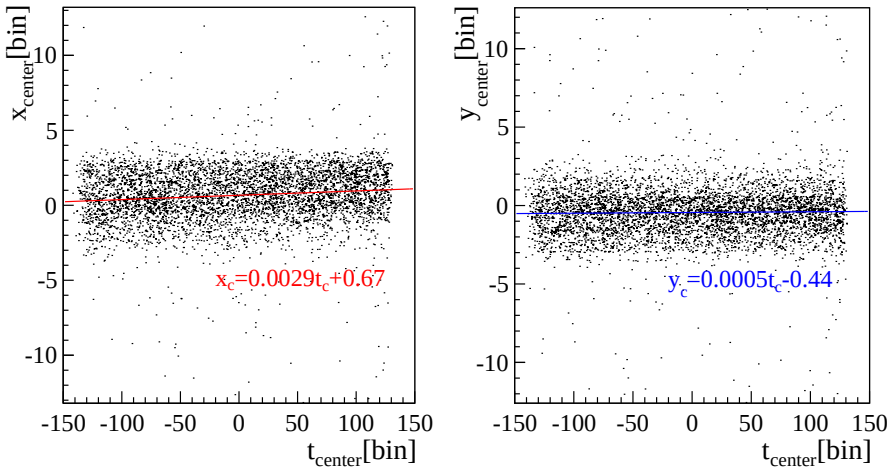


HARPO in Gacko

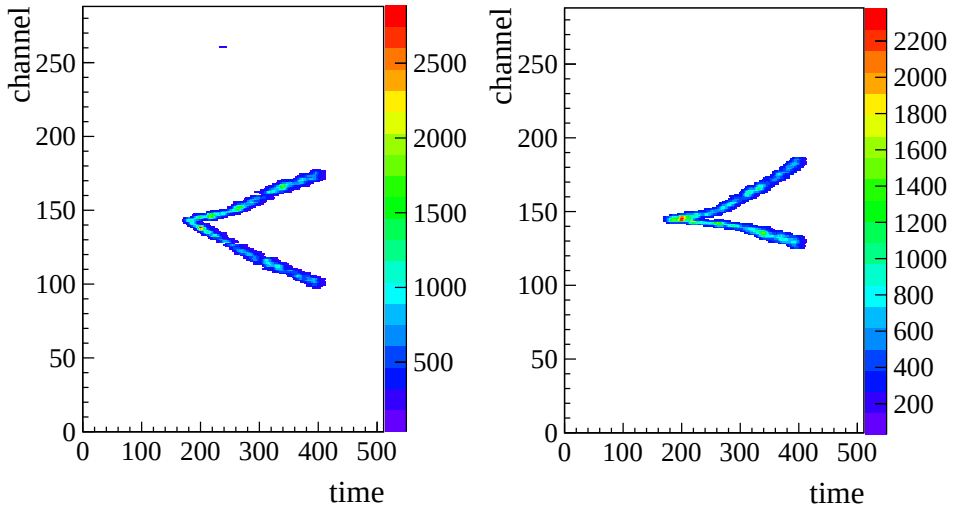
Data taking : a couple of monitoring plots



TPC calibration plot (x, y) (z traversing tracks).



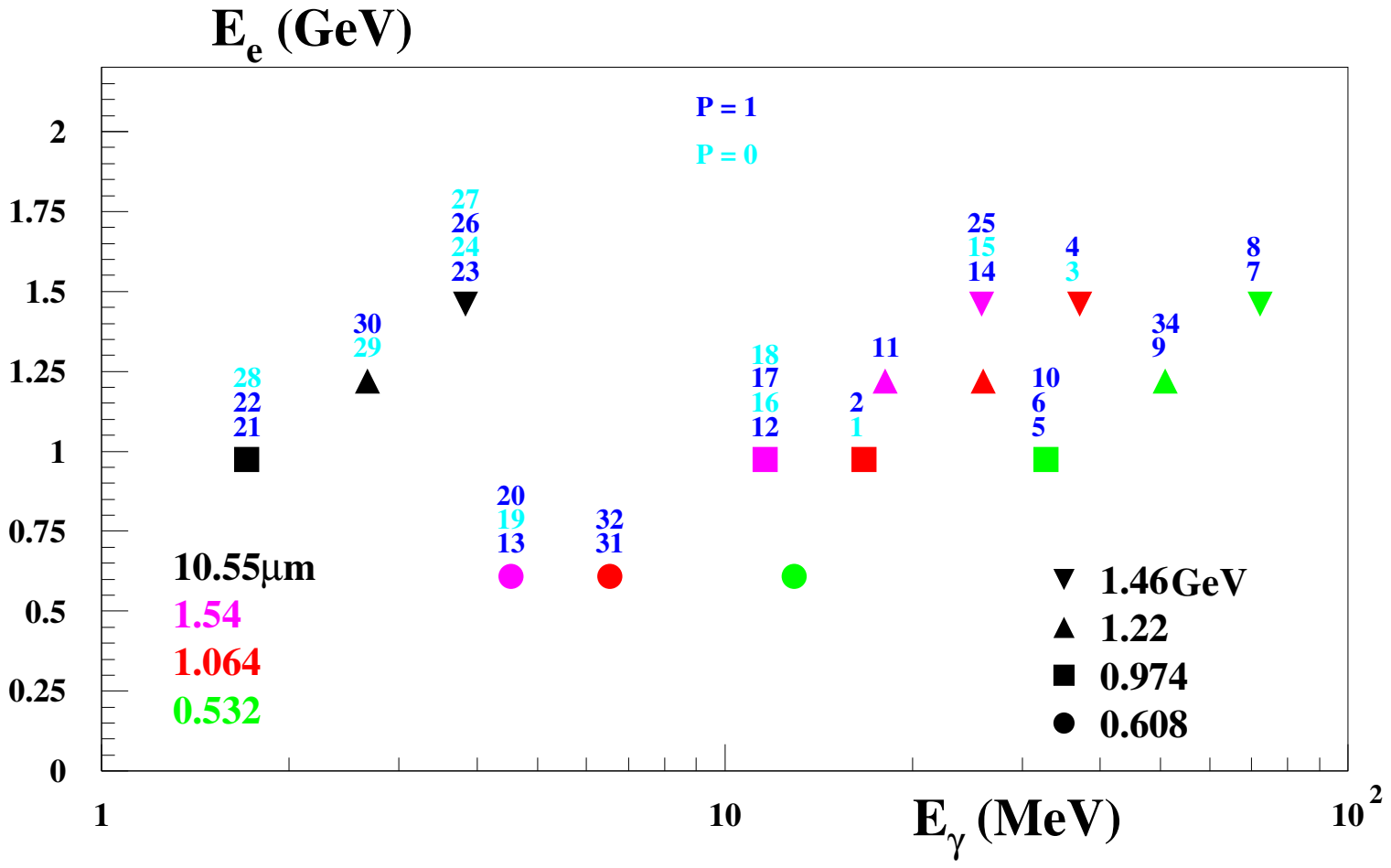
TPC alignment on collimated γ beam



One γ photon converts to an e^+e^- pair in the fiducial volume of the HARPO TPC.
Nd :YVO_4 (1ω) $1.064\mu\mathrm{m}$, $E_e = 1.0\mathrm{GeV}$, $E_\gamma = 17\mathrm{MeV}$, P= 2 bar

HARPO data taking : programme

- γ energy scan : ≈ 2 pt/day.
  Detector azimuthal rotation $\phi = -45, 0, +45, +90°$ and/or $P = 0, 1$



- 1 - 4 bar pressure scan

Data taking (preliminary) lessons and achievements

- Planned data taking programme completed.
- Smooth detector / beam (French / Japanese) groups interaction
- 3 week high-rate running in sealed mode with no visible gas degradation.
- Sophisticated trigger system worked perfectly

$$T_\gamma = \overline{S}_{up} \cap S_{other} \cap M \cap L \cap \overline{M}_{quick}$$

S scintillator, M micromegas mesh, L laser (when available).

$+$ dedicated downscaled lines for systematic studies

- $\approx$ 60 Mevts, of which $\approx 20\%$ are γ conversions to e^+e^- pair in the TPC gas.

- Analysis .. in preparation.
  - Measurement of the $\gamma \to e^+e^-$ polarization asymmetry $\mathcal{A}(E)$
  - Characterization of the detector performance,

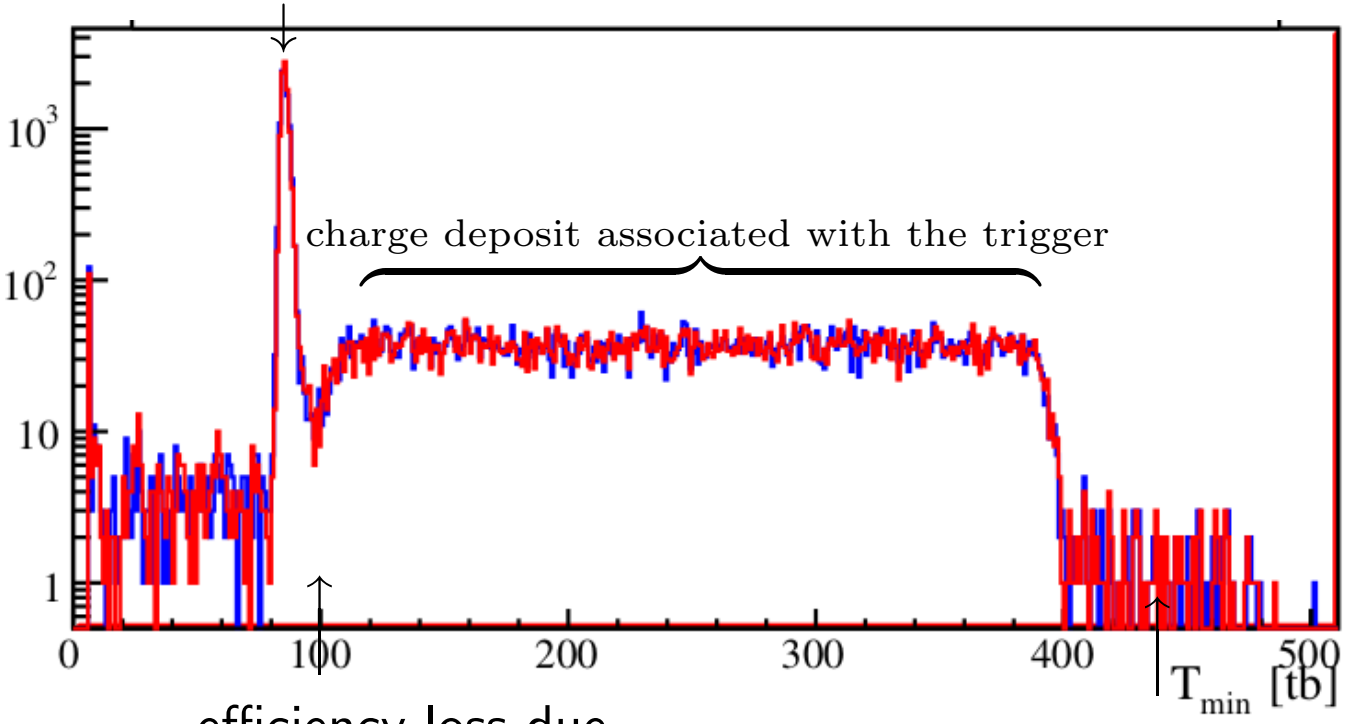
  .. in the γ energy range 1.7 - 72 MeV.

t_{min} distribution

- starting time of event, for T_γ trigger line.

$$T_\gamma = \overline{S}_{up} \cap S_{other} \cap M \cap L \cap \overline{M}_{quick}$$

residual
upstream tracks and
conversions in PCB



efficiency loss due
"quick" mesh veto

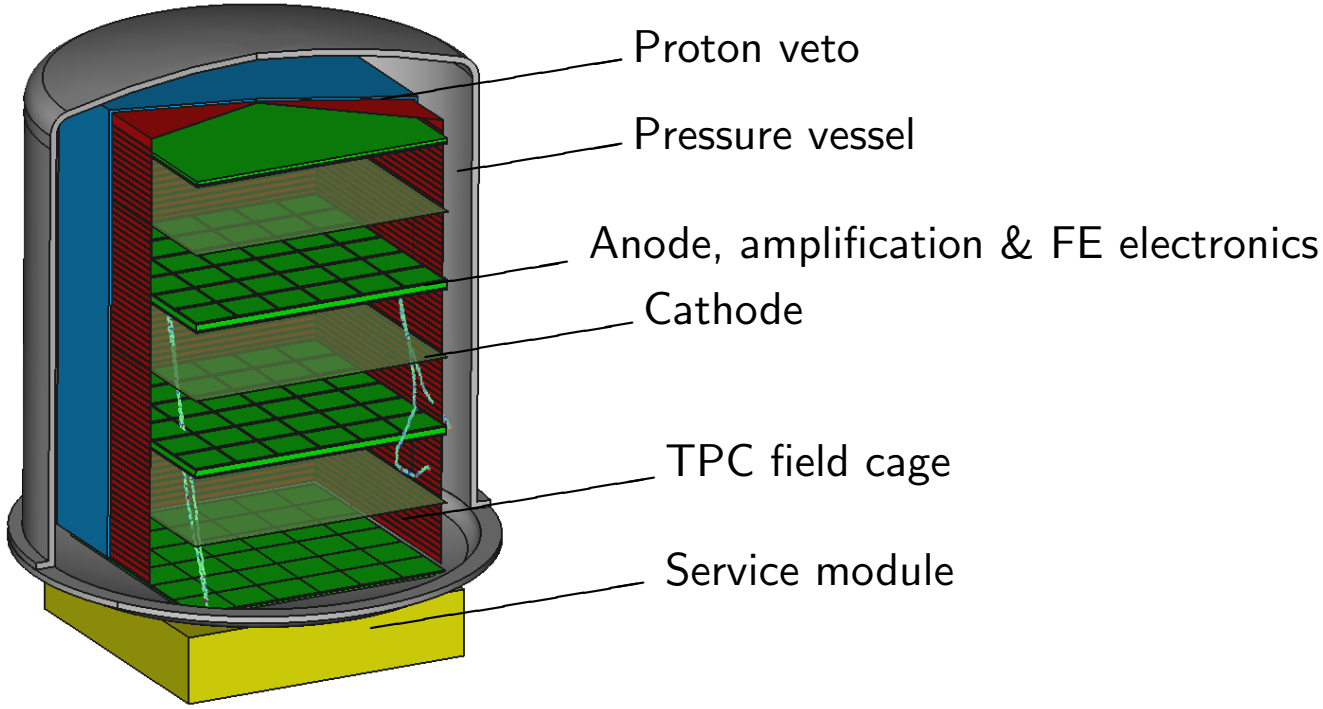
pile up of signal
not associated with the trigger

HARPO R&D P2IO [2012 – 2014] : a conclusion

- We are founding a new, high-resolution, high-sensitivity way to perform γ-ray astronomy, and for the first time, polarimetry, in the demanding energy range MeV-GeV.
- The presently ending P2IO contract has had the CNRS/IN2P3 – Irfu Collaboration take shape officially, and has been instrumental to **bringing HARPO from infancy to teenagehood**.
- The excellent results obtained so far and the data taking on beam would have never been possible without this P2IO support.
- Last but not least, this PI2O-funded success has been the base of the funding of the next phase of the project (ANR [2014-2017]), with in particular studies of several key aspects of the spatialization of the technique, and very specially, the design and the validation of an efficient trigger in space conditions.

I have a dream !

Exploded Schematic View of a Flight Telescope



3 layers, each layer of 2 back-to-back modules, each module a $(2\ \mathrm{m})^2 \times 0.5\ \mathrm{m}$ TPC with an endplate segmented into $(33\ \mathrm{cm})^2$ micromegas and charge collection blocks. 432 chips, $12\mathrm{m}^3$: 100 kg gas at 5 bar.

Conversions of a 100 MeV (left) and of a 10 MeV (right) photon in the TPC gas

Je vous remercie de votre attention.

Bibliographie [2012 – 2014]

- Publications :

  [1] "Polarimetry of cosmic gamma-ray sources above e^+e^- pair creation threshold," Nucl. Instrum. Meth. A 729 (2013) 765 [arXiv :1307.3892 [astro-ph.IM]].

  [2] "TPC in gamma-ray astronomy above pair-creation threshold," Nucl. Instrum. Meth. A 701 (2013) 225 [Erratum-ibid. A 713 (2013) 76] [arXiv :1211.1534 [astro-ph.IM]].

- Conferences : 12 oral presentations

- Theses in progress : 2

  links at `http://llr.in2p3.fr/~dbernard/polar/harpo-t-p.html`