

*HARPO - A Gaseous TPC for High Angular
Resolution Gamma-Ray Astronomy and Polarimetry
from the MeV to the TeV*

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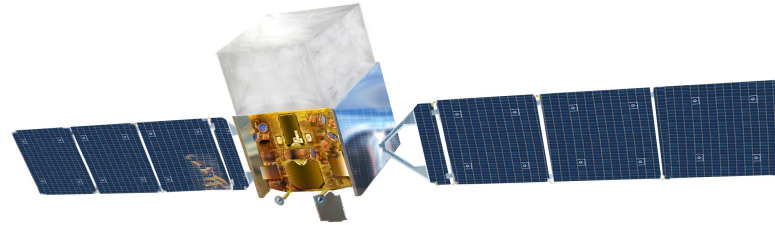
On behalf of the HARPO project

LLR @ Ecole Polytechnique, CNRS/IN2P3 & IRFU @ CEA Saclay

12th Pisa Meeting on Advanced Detectors

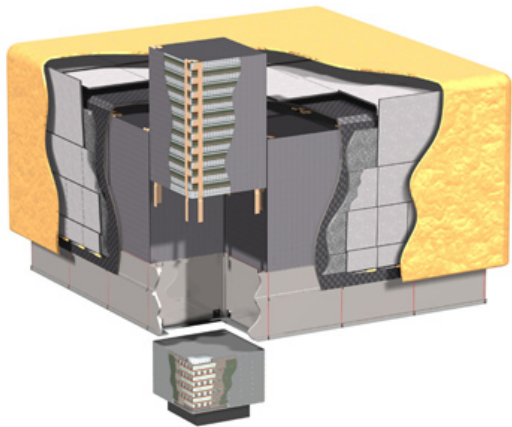
Elba 20 – 26 May 2012

Presently in space : *GLAST / Fermi*



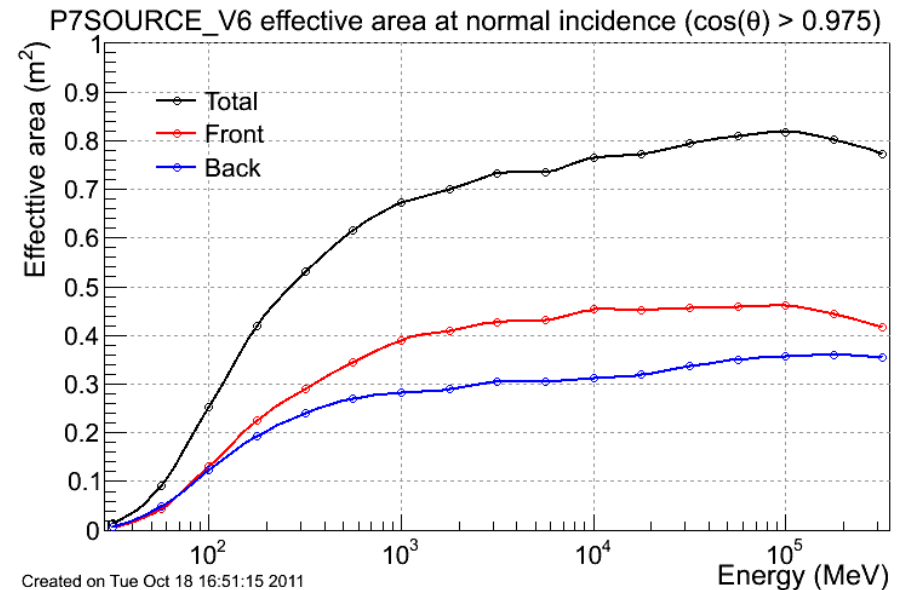
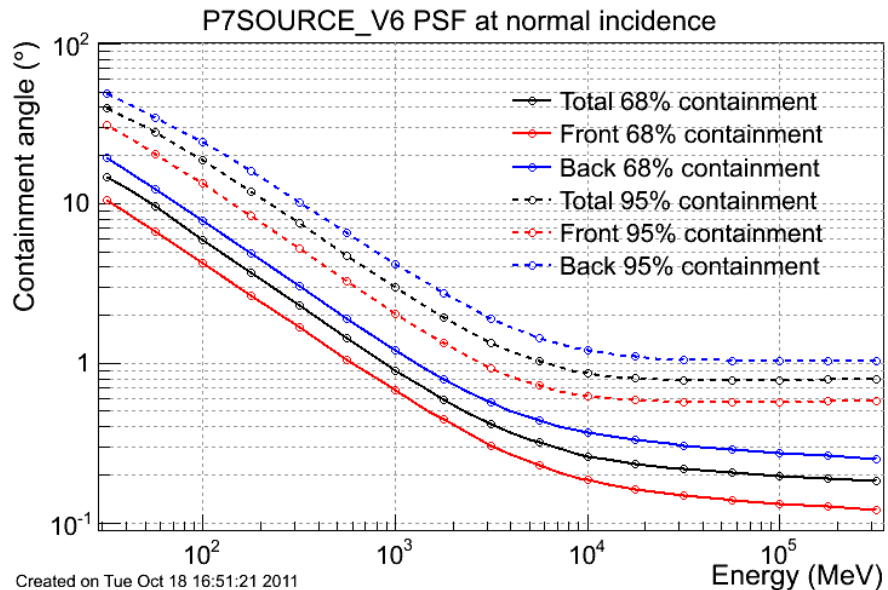
Fermi LAT : 2008 – 2013 → 2018 ?

- Impressive harvest on vast programme :
pulsars, active galactic nuclei (AGN), gamma-ray bursts (GRB), binary stars, supernova remnants
...
- E_γ range 20 MeV - 300 GeV
- 16-plane **Converter/Tracker W/Si** ($1.1X_0$)
- 8-layer **CsI :TI Calorimeter CsI :TI** ($8.6X_0$)
- Segmented scintillator cosmic-ray veto
- $1.8\text{m} \times 1.8\text{m} \times 0.7\text{m}$, 2.8 ton.



Fermi

- Actually Fermi is publishing mostly in the range 0.1 – 300 GeV
- Effective area $\approx 1 \text{ m}^2$ above 1 GeV



[Fermi LAT Performance page](#)

- Photon selection kills efficiency at low E
 - Due to huge background at low E
 - Due to larger angular resolution at low E
- No polarimetry

Directions for a future next-to-Fermi mission

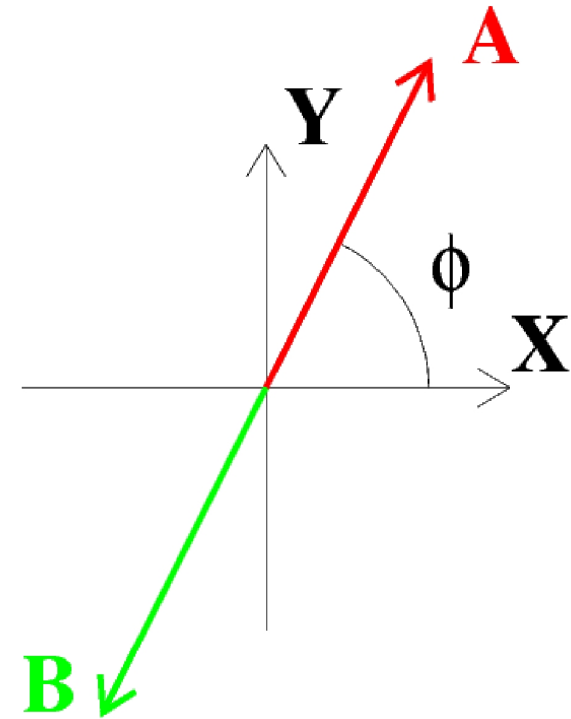
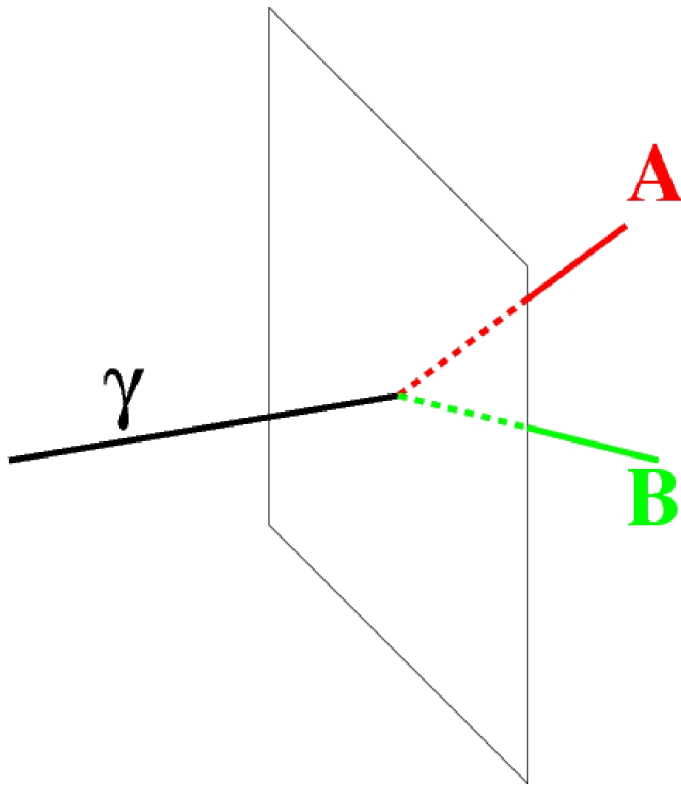
- Improve angular resolution
 - \Rightarrow Improve background rejection of pointlike sources
 - Improve A_{eff} at low E
- Enlarge A_{eff} — but watch mass budget !
- Have polarization sensibility

Cosmic γ -ray polarimetry : Why ?

- γ Rays produced in very violent events : (AGN, pulsars, GRB ..)
- γ polarization fraction key ingredient to understanding mechanism at work.
 - jets of relativistic matter impinging on intra galactic matter
 - hadronic interactions $\rightarrow \pi^0$'s $\rightarrow \gamma$'s : $P = 0$
 - Radiative processes (synchrotron, inv Compton) : P up to 70%
 - Synch : Turbulence of \vec{B} “dilutes” P : measurement of turbulence.

Linear Polarization !

Modulation of the azimuthal angle of the debris



– ϕ azimuthal angle

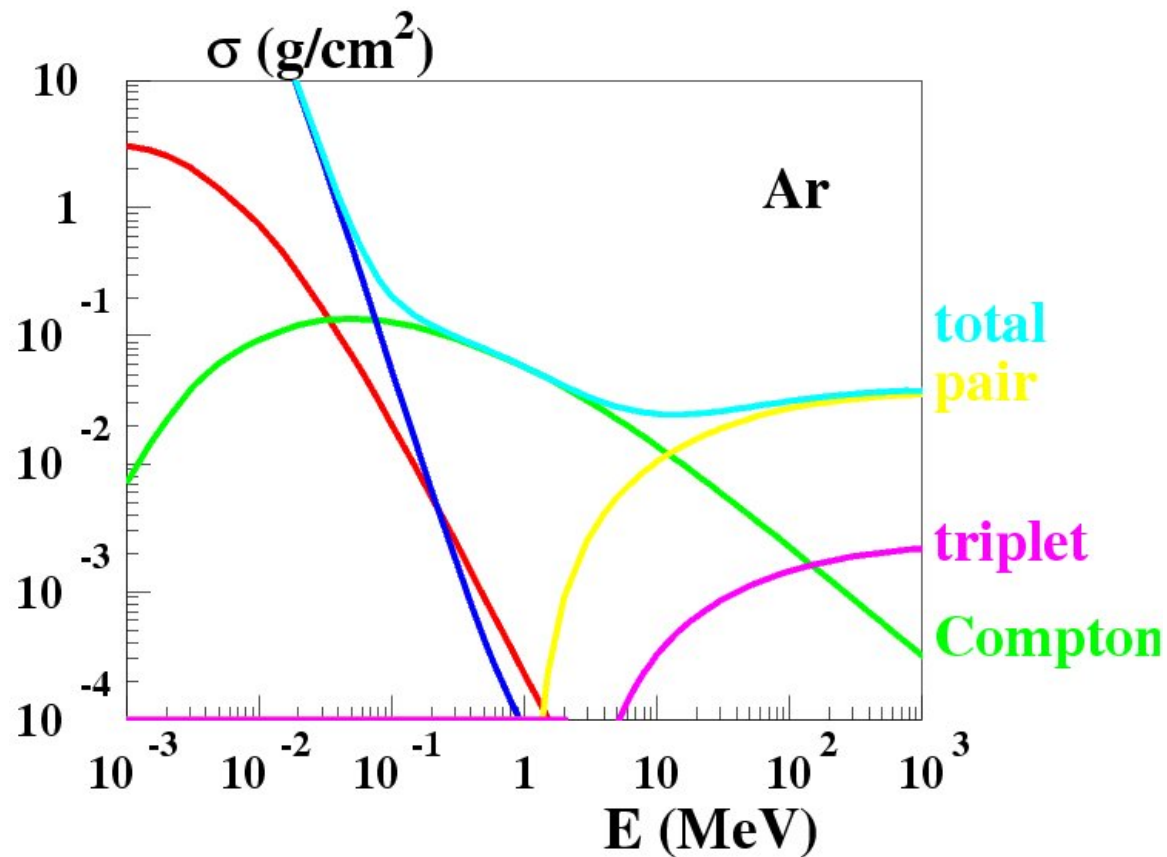
$$\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P \cos [2(\phi - \phi_0)])$$

Photon interaction with matter

Compton $\gamma e^- \rightarrow \gamma e^-$

“Nuclear” pair production : $\gamma Z \rightarrow Z e^+ e^-$

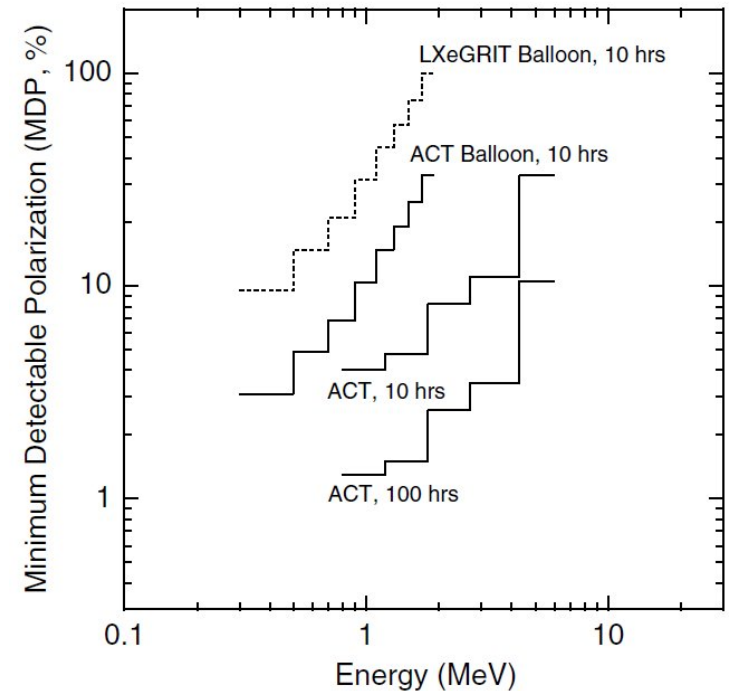
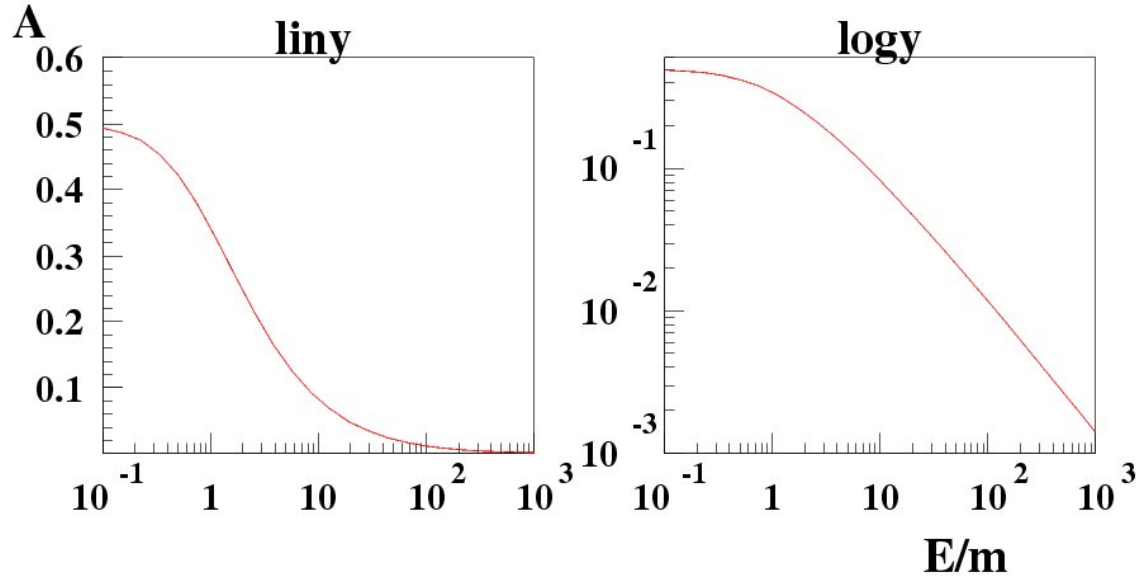
“Triplet” pair production : $\gamma e^- \rightarrow e^- e^+ e^-$



Compton

A number of hard X-Ray and soft- γ ray polarimeter projects , but

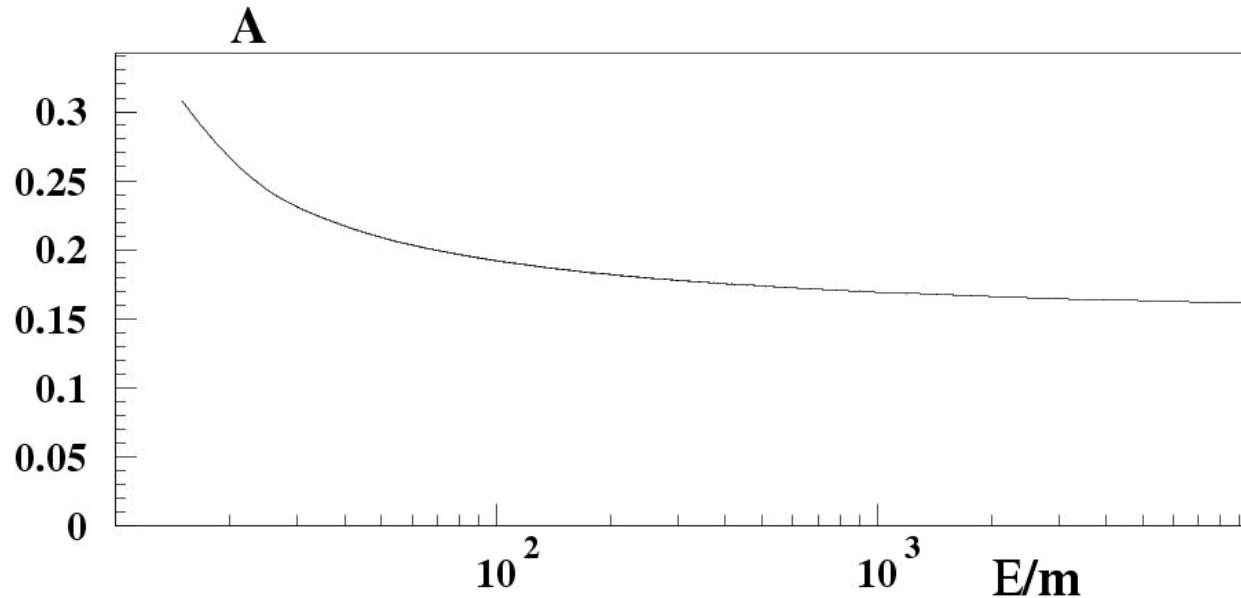
New Astr. Rev. 48 (2004) 215



Low sensitivity for $E > \text{few MeV}$

“Nuclear” pair production

In principle : very good



- Dominates cross section at high energy
- $A \approx 0.2$ at high energy

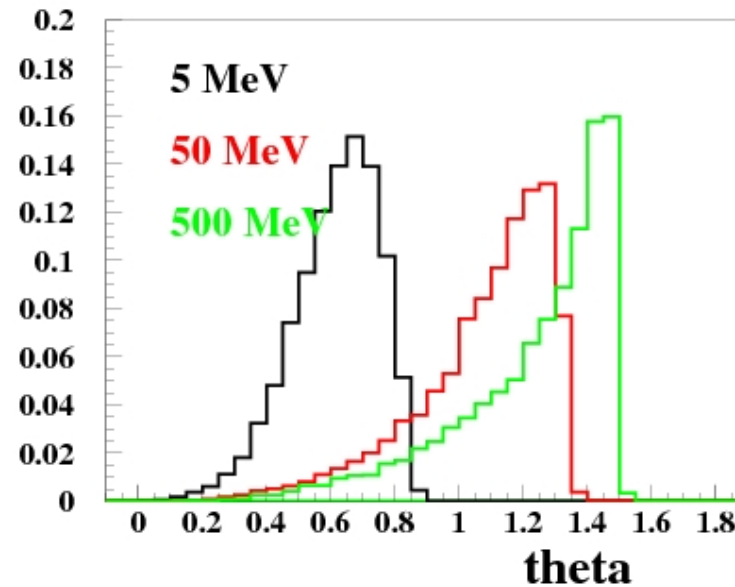
In practice :

- At low E_γ , a lot of multiple scattering $\Rightarrow \phi$ badly measured.
- At high E_γ , tight pair $\Rightarrow \phi$ badly measured.

“Nuclear” pair conversion used for non-polarized γ astronomy

$$\text{Triplet} : \gamma e^- \rightarrow e^- e^+ e^-$$

- The recoiling electron is emitted at a large angle



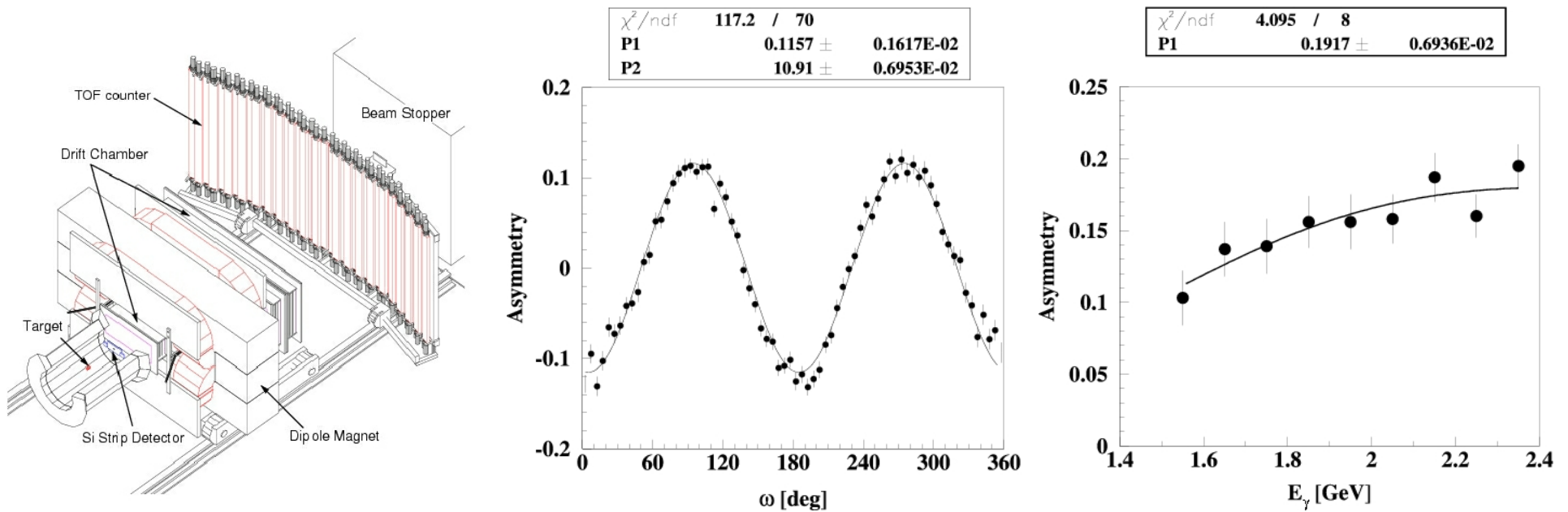
- 6 additional Feynman diagram (wrt “Nuclear” pair production)
 - Dominated by the same two at high energy.
- Triplet/pair $\sim 1/Z$ and same asymmetry $\mathcal{A} \approx 0.2$, asymptotically at high energy.
- Intricated computation at low energy (Born, other electrons ...)
 - To be validated experimentally

The only validation ..

Was performed :

- For nuclear pair production,
- and : at high Energy

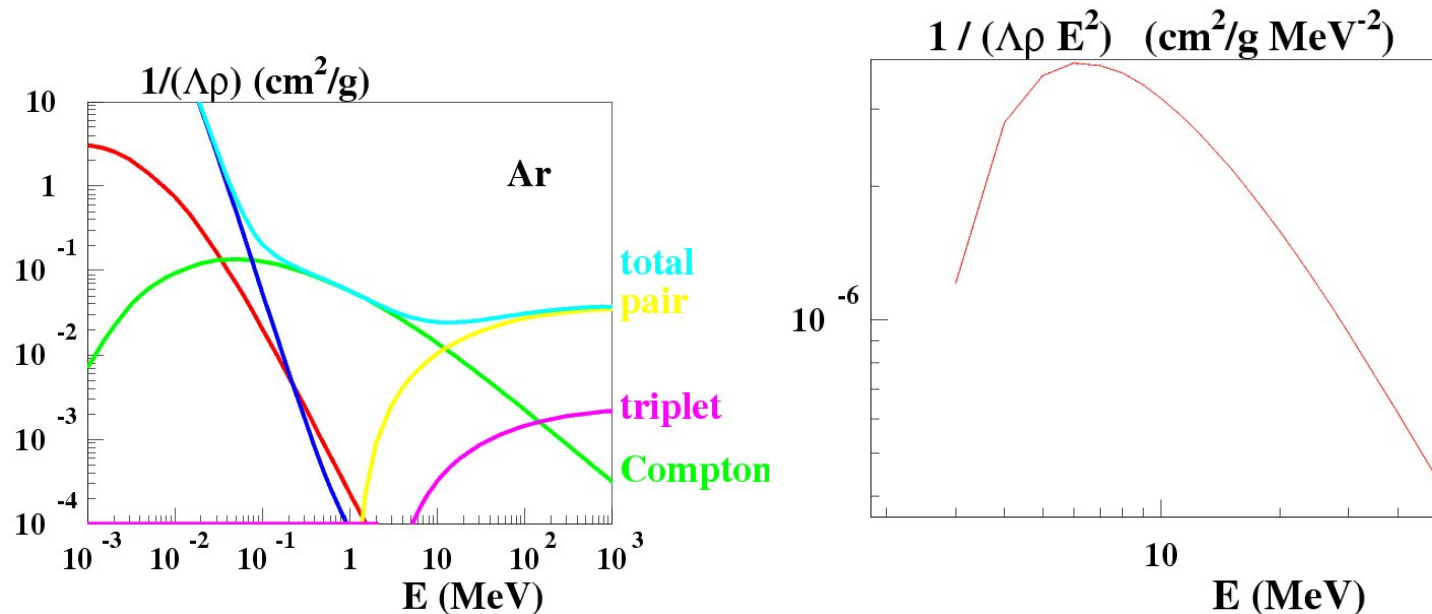
γ beam from Compton scattering of laser beam @ Spring-8



de Jager, et al., Eur.Phys.J.A19 :S275-S278,2004.

Satellite flight : Precision of P measurement

$$N_{int} = \int \frac{L}{\Lambda(E)} \frac{dF}{dE}(E) ST dE = M \times T \int \frac{1}{[\rho \Lambda(E)]} \frac{f}{E^2} dE$$



1 ton, 1 year, time fraction 50%, efficiency 100%, $\mathcal{A} \approx 0.2$

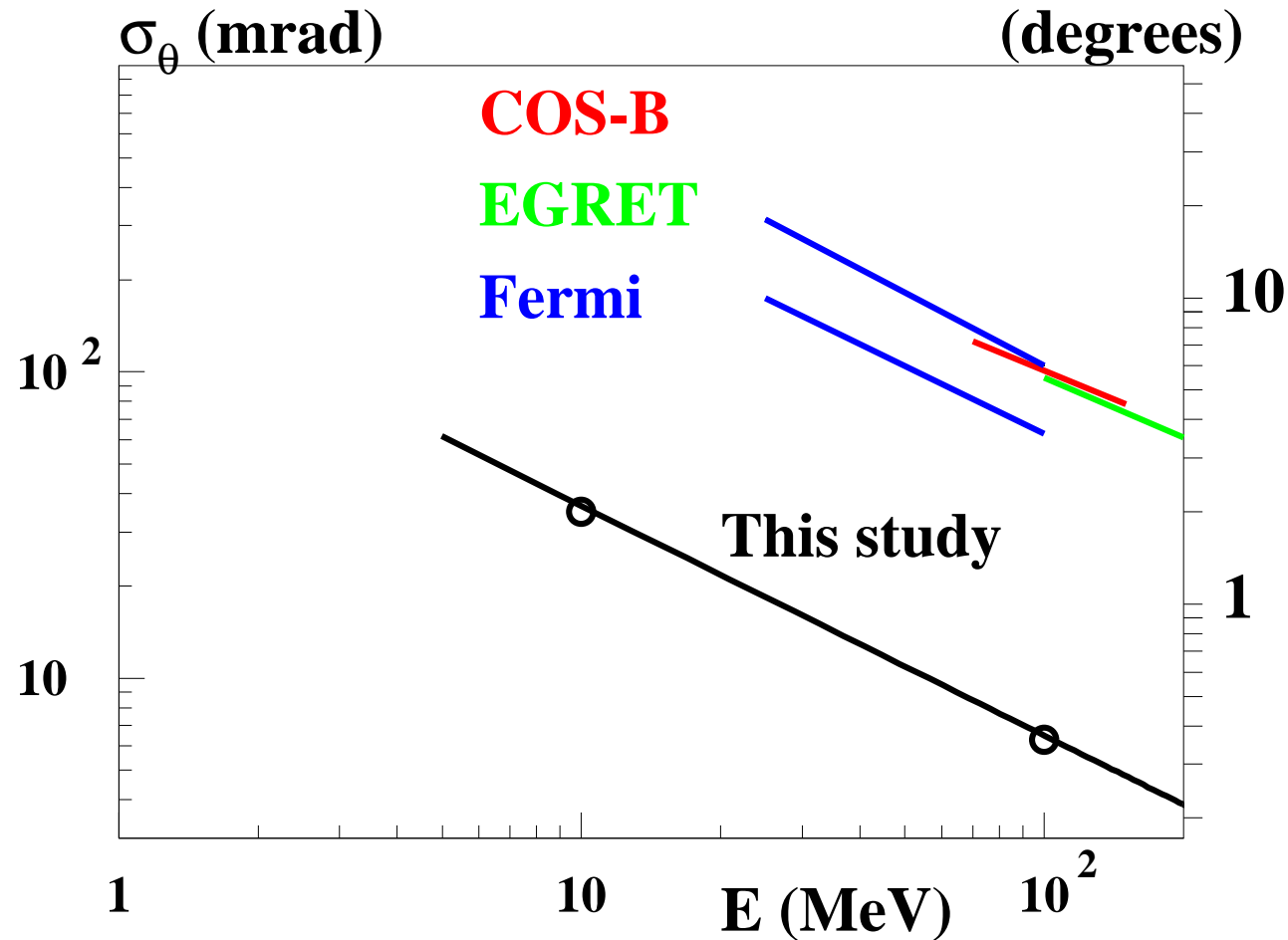
- $N_{int} = 1.5 \times 10^5$ on the Crab pulsar

- $2\% / \sqrt{\text{year} \cdot \text{ton}}$

$$\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}} \approx 0.0185$$

$\approx Z$ -independent.

Angular Resolution



- Black line is analytic prediction

Innes, NIM A 329, 238 (1993).

- Points are from Kalman-filter reconstruction

Frühwirth NIM A 262, 444 (1987).

Thin / Thick detectors

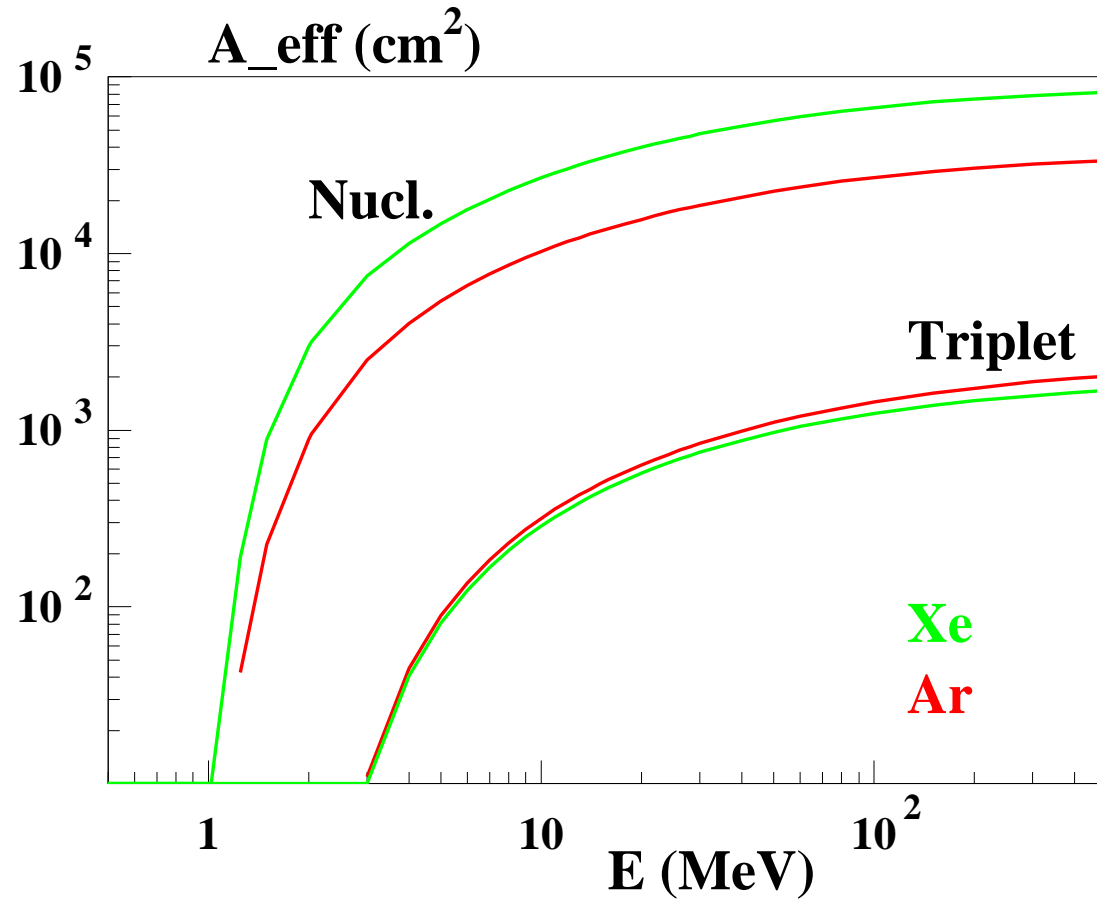
- Thick detector ($L \gg X_0$)
 - the 3 processes (pair, triplet, Compton) are competing
 - avoid low Z (Compton dominant)
 - avoid high Z (Pair dominant over triplet)
 - high conversion efficiency, $\epsilon \approx 1$, and $A_{eff} \approx S$
 - important to optimize geometry (thickness) at given mass.

- Thin detector ($L \ll X_0$) :
 - the 3 processes (pair, triplet, Compton) are not competing
 - low conversion efficiency, $\epsilon \ll 1$, and $A_{eff} \approx \sigma \times M$
 - details of geometry don't matter to first order.

Effective Area

In a thin detector, $A_{\text{eff}} \approx \sigma$

Ar :



@ 100 MeV : 3 m^2/ton (Ar), 7 m^2/ton (Xe);

Energy measurement

- Avoid calorimetry – kills mass budget
- At low energy (few MeV) : contained tracks : high precision E measurement.
- At higher energy (< few 10 MeV) : momentum measurement from multiple scattering
- At high energy :
 - magnetic spectrometry.
 - TRD up to $\Gamma_e \approx 10^5$ (100 GeV), both thin technologies.

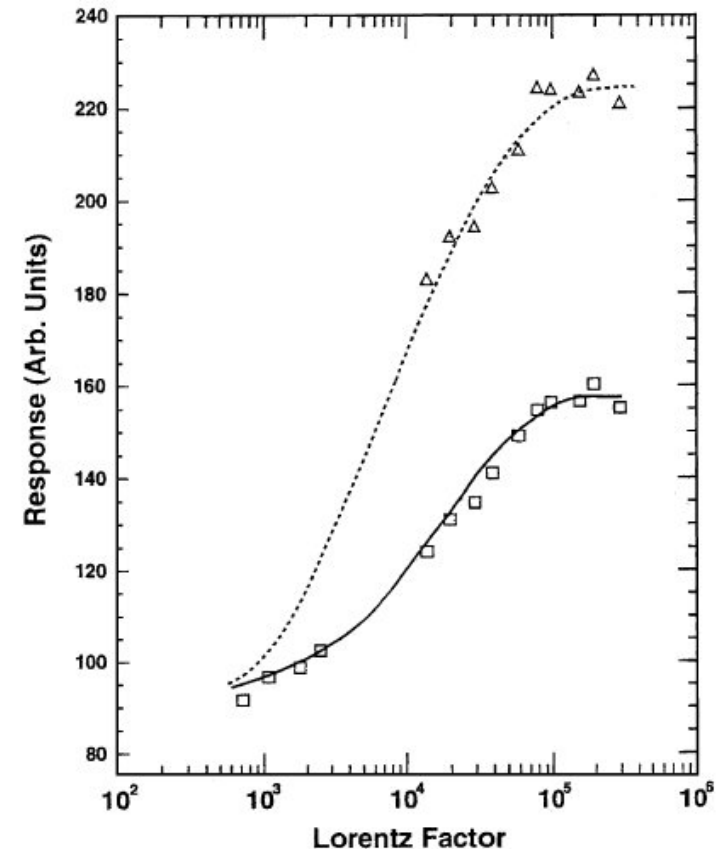


Fig. 8. Average signal versus Lorentz factor for a composite radiator/detector configuration consisting of plastic foils, foam, and fibers (triangles), and for a radiator of parallel Mylar foils of 76 μm thickness (squares). Note that the signal reaches saturation around $\gamma \approx 10^5$.

NIM A 531, 435 (2004).

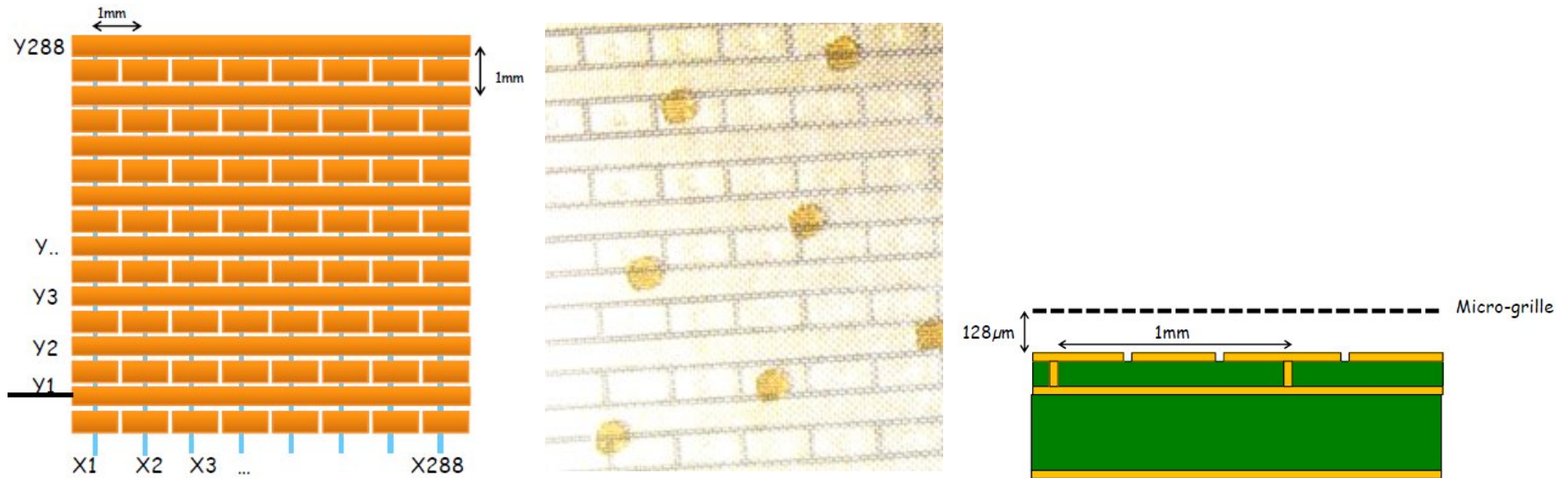
Our project : HARPO

- Ground Phase :
 - Characterize the TPC technology for γ astronomy and polarimetry
 - 1st measurement of \mathcal{A} at low energy.
- Demonstrator :
 - Need a homogeneous, finely, fully instrumented, 3D detector.
 - 30 cm cubic TPC, 5 bar, Argon-based mixture (à la T2K)
 - Pitch 1mm
 - Trigger : scintillator + WLS + PMT.
- A Collaboration of
 - LLR, Ecole Polytechnique, CNRS/IN2P3, Palaiseau, France
 - IRFU, CEA Saclay, Gif-sur-Yvette, France
 - Collaboration building with Japanese groups operating polarized γ -ray beam lines at SPring8 and NewSubaru (Hyôgo), in progress.

Amplification – collection – sampling

- Amplification by “bulk” micro-mesh micromegas

NIM A 608 (2009) 259

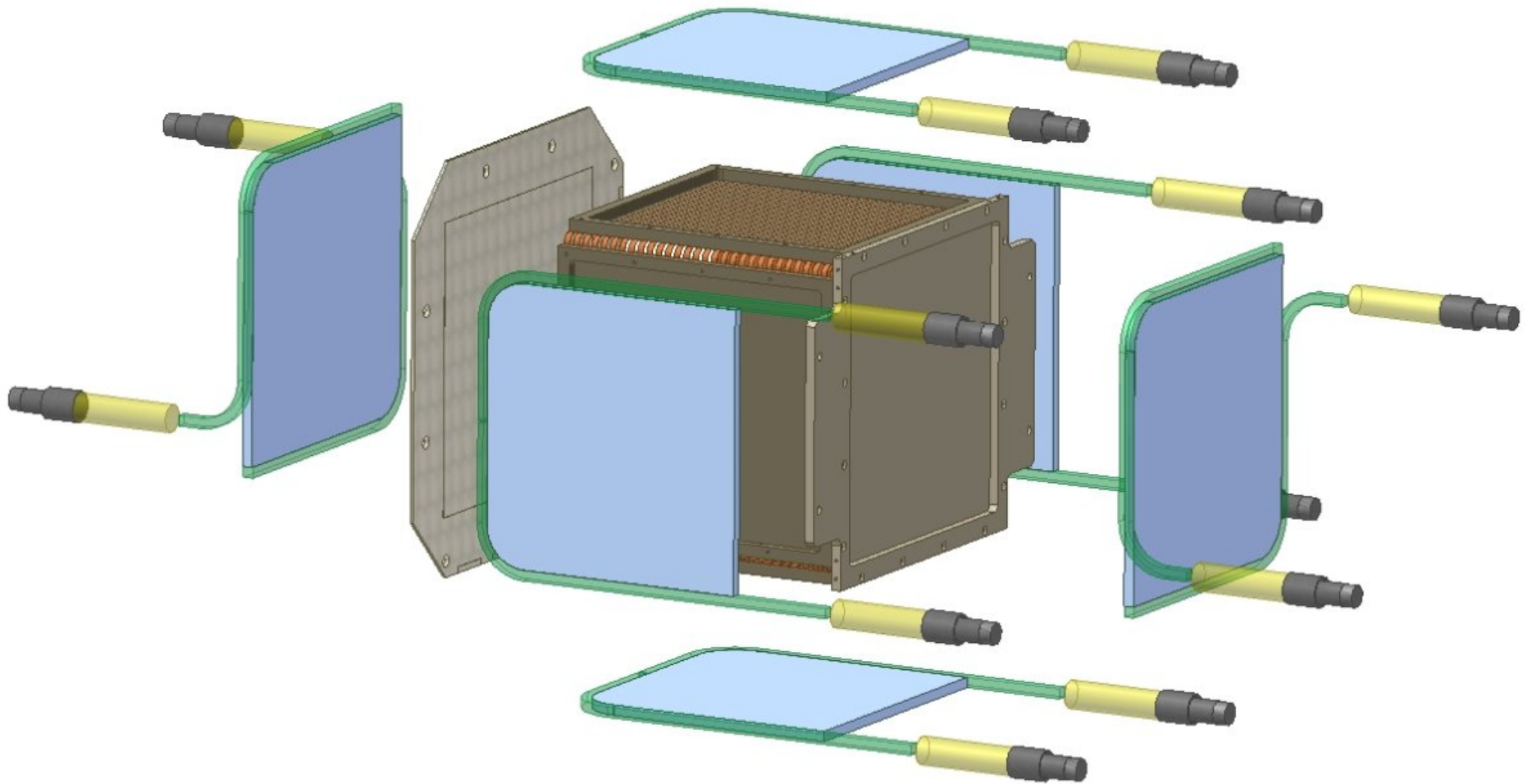


- Signal collection by strips on PCB, pitch = 1mm
- Sampling / acquisition performed by AFTER chip ; 50 MHz, 12 bits, shaping 100 ns

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

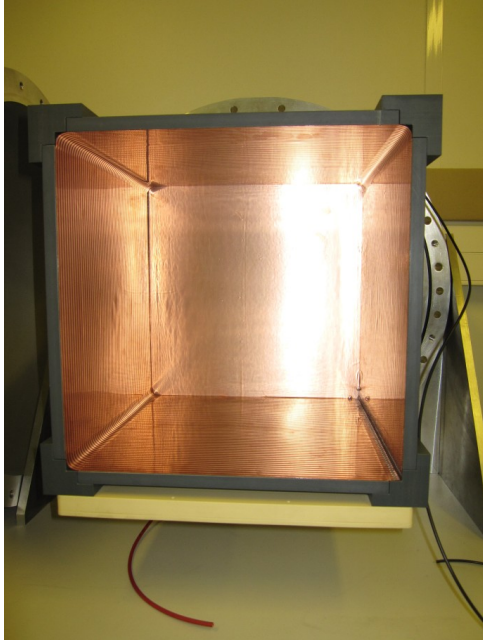
Micromegas and strip PCB from CERN workshop

The detector : being designed

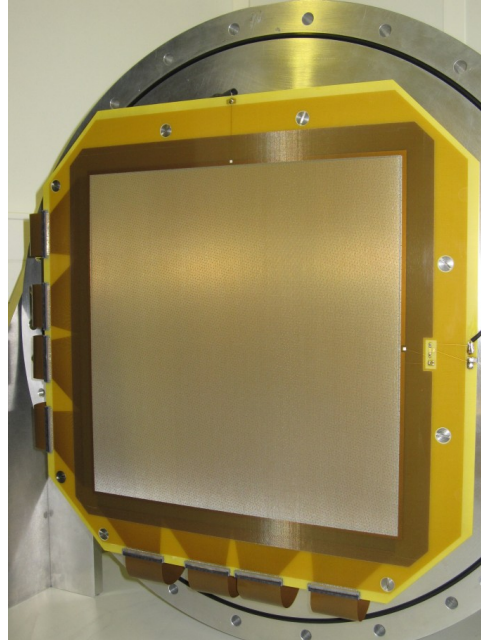


The detector : being assembled

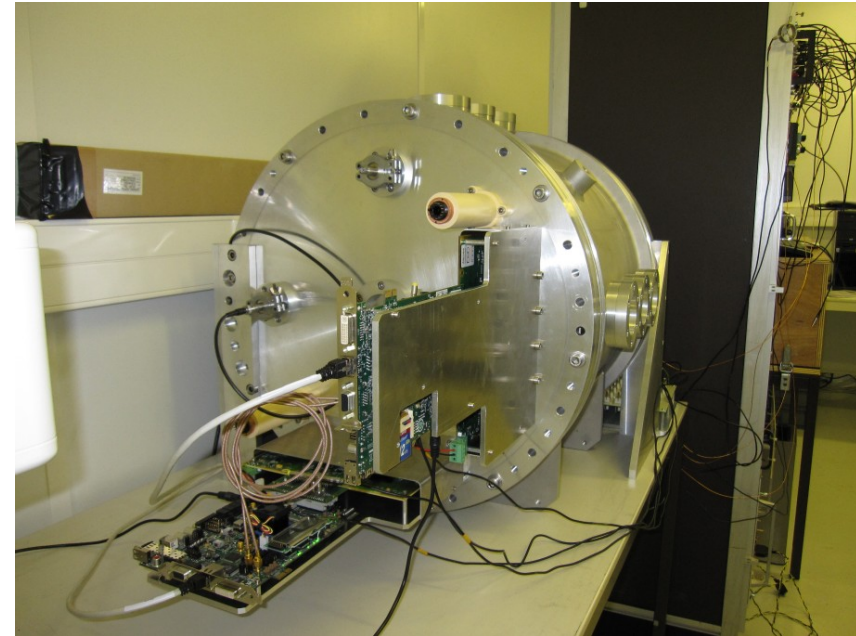
field cage



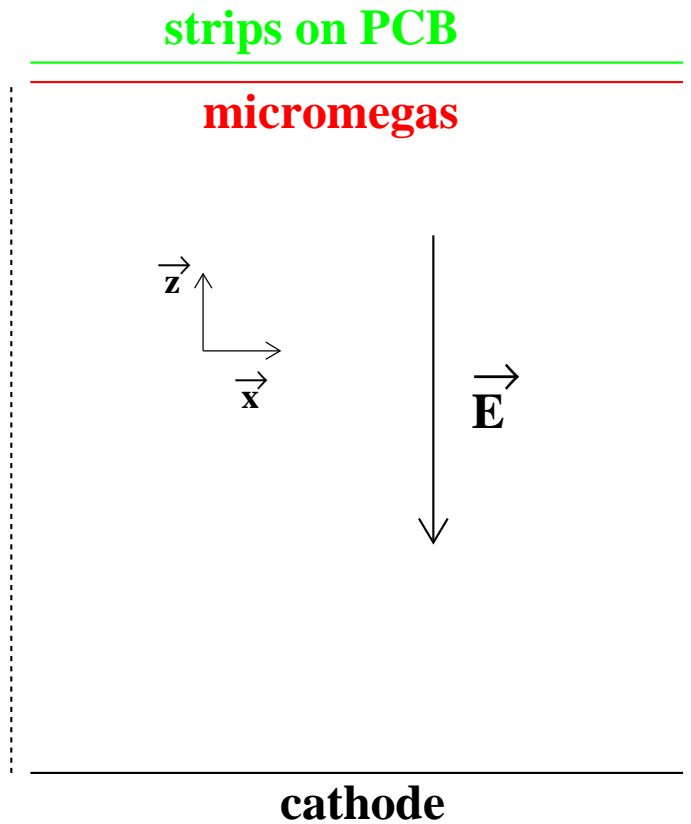
micromegas on PCB



electronics cards on vessel

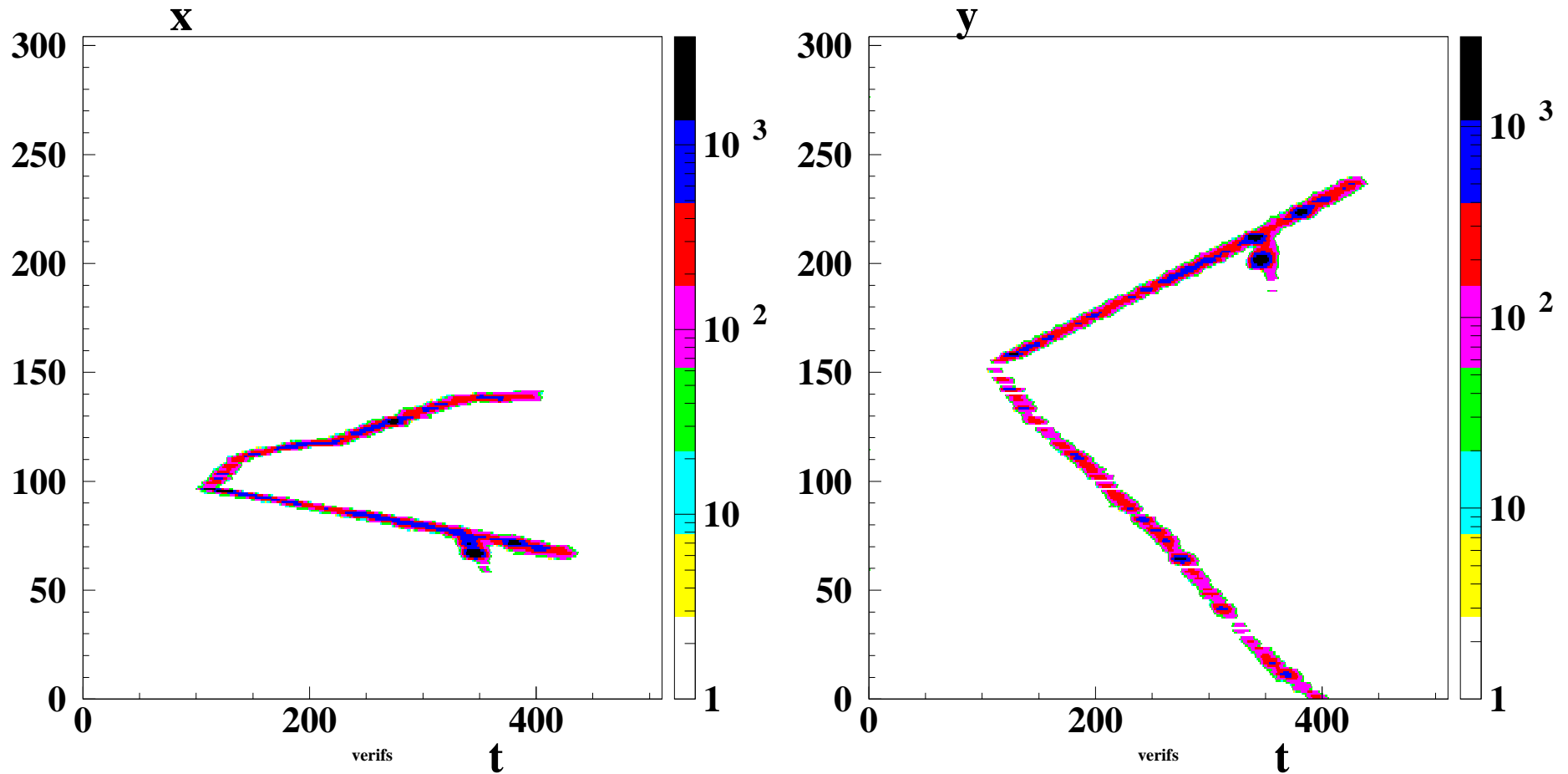


Cosmic rays tests in progress



- At the moment the detector in vertical position : TPC calibration with thru tracks

One event

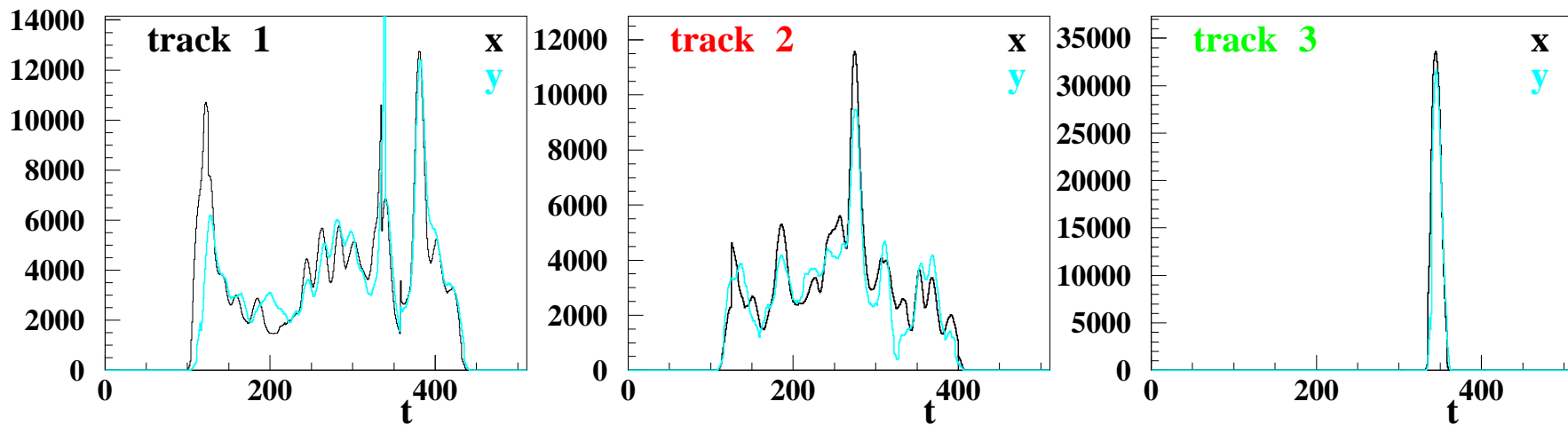
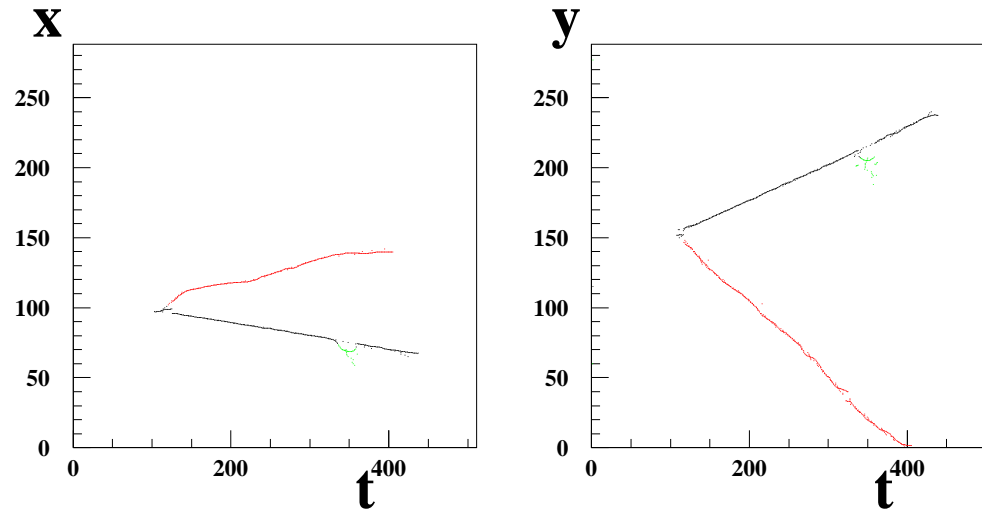


- $P = 2 \text{ bar}$, $V_{\mu M} = 480\text{V}$, $V_{drift} = 7560\text{V}$, (252V/cm)
- most likely a hard muon + a hard δ ray + a soft δ ray

Data acquisition / Reconstruction

- Two DAq modes :
 - “full” 608 kB / evt
 - “Zero suppress”, ≈ 15 kB / track (no optimization done yet)
- Reco (current status)
 - thresholding
 - clustering (row (channel), line(time bin))
 - track reconstruction (x , y , independantly) : combinatorial Hough method.
 - multi track events : x / y matching from t distributions

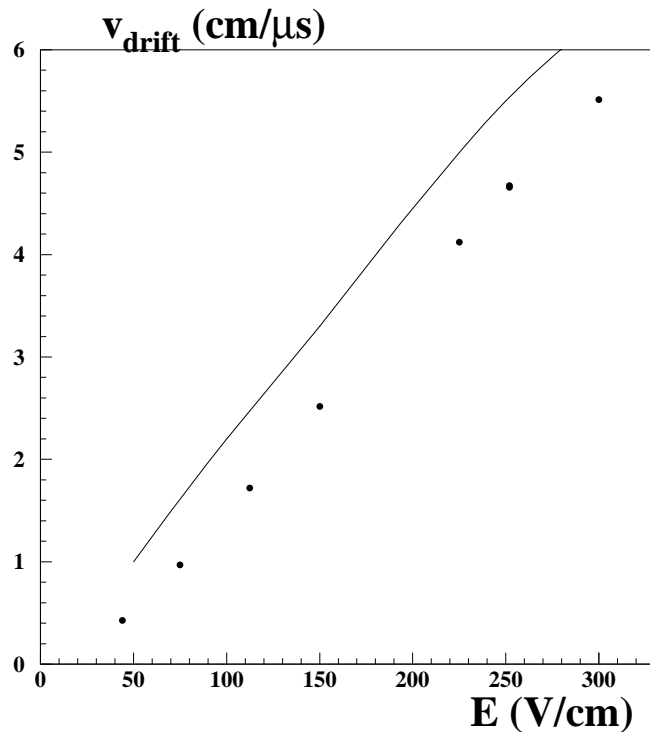
x / y matching : χ^2 from t distributions



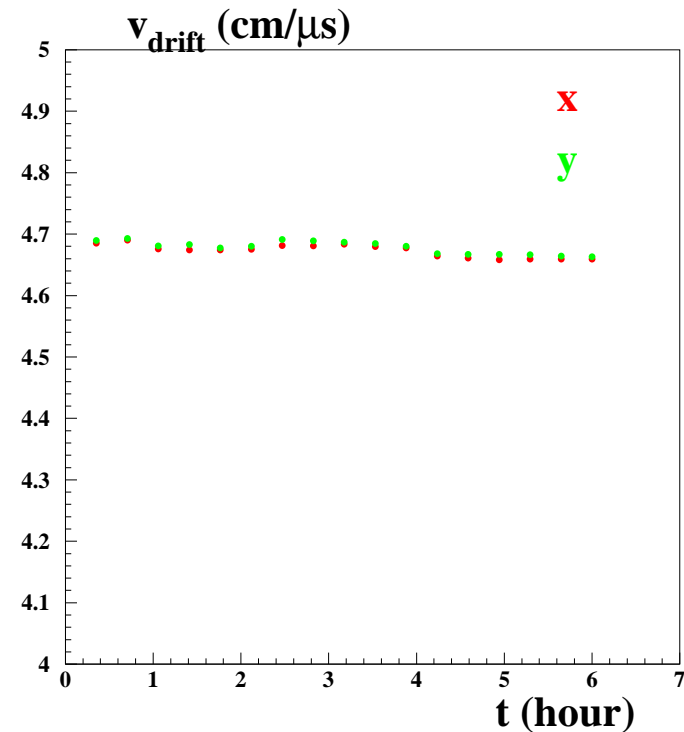
v_{drift} and t_0 calibration

- with thru tracks

variation of v_{drift} with E_{drift}



v_{drift} stability over a 6 hour run



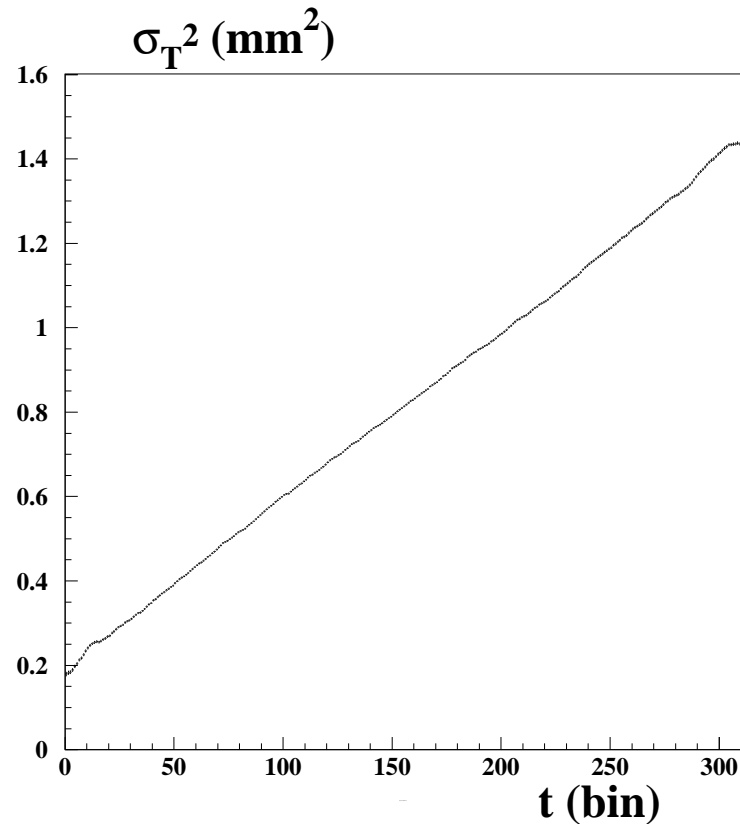
- v_{drift} somewhat lower than Garfield calculation
- stability better than a percent. (no P , T correction applied)

Preliminary

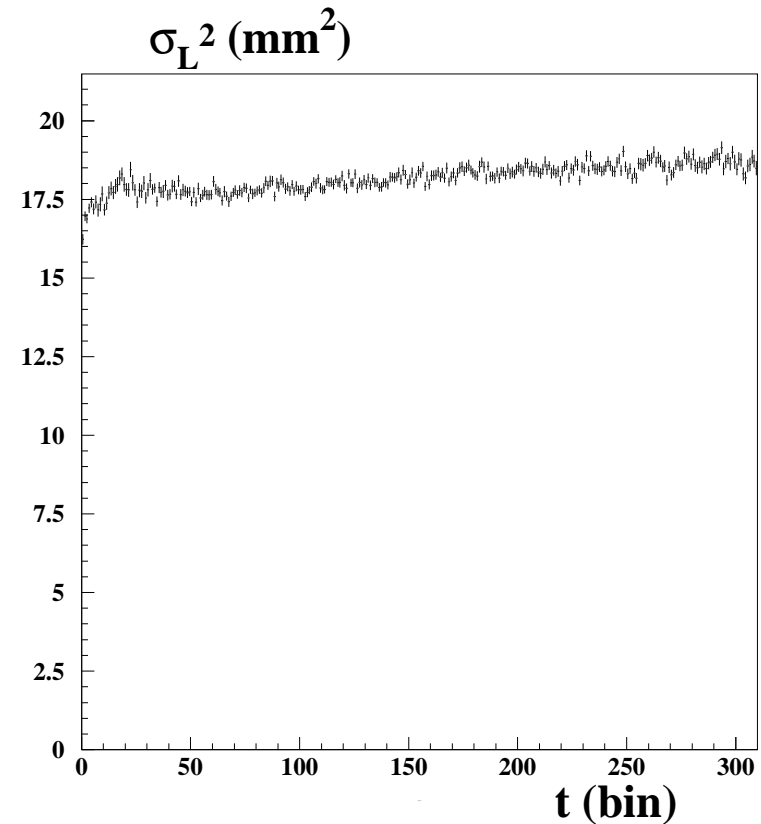
Diffusion :

Study of cluster size as a function of drift time.

transverse



longitudinal

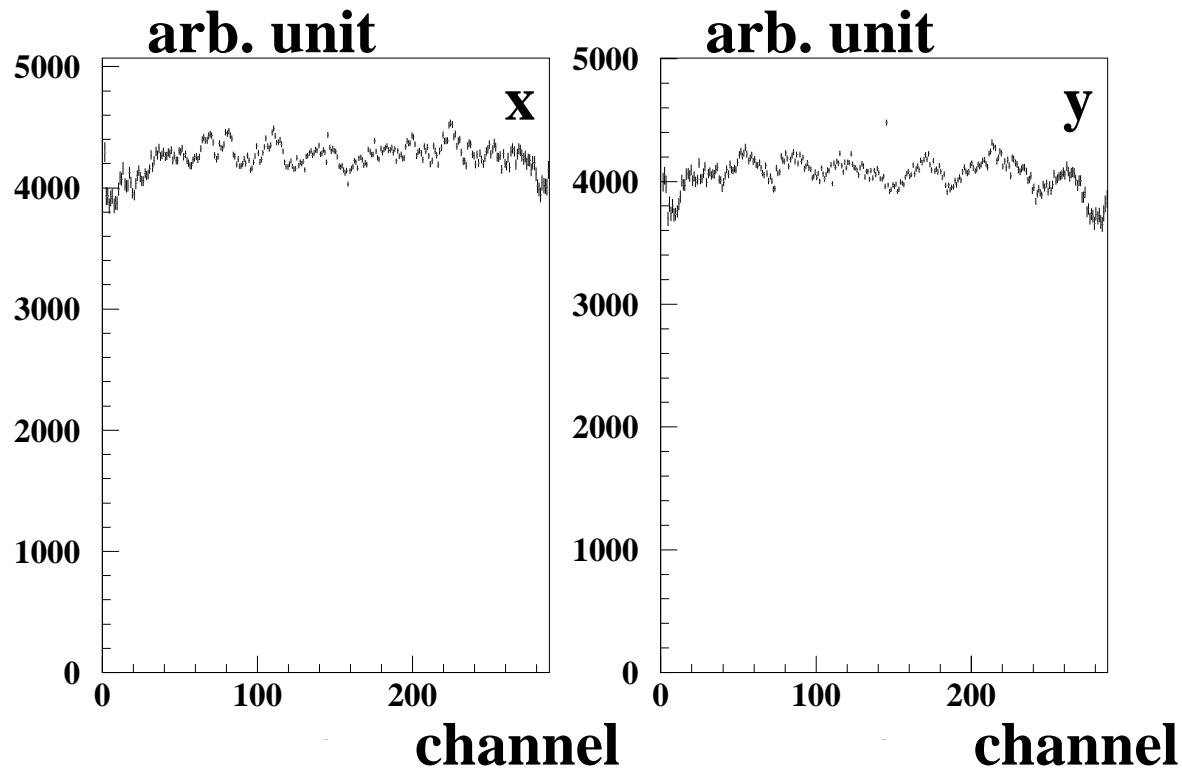


- long. : cluster time size dominated by shaping (100 ns @ 50 MHz : 5 bins)
- transverse : diffusion $224\mu\text{m}/\sqrt{\text{cm}}$ (Garfield : $225\mu\text{m}/\sqrt{\text{cm}}$)

Preliminary

Gain homogeneity

- decently straight, X/Y matched tracks,
- vertical tracks excluded ($\theta > 0.1$ rad).

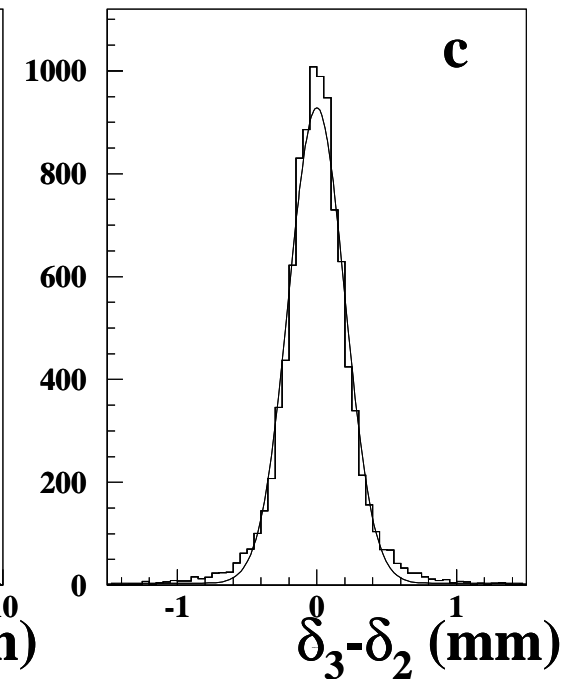
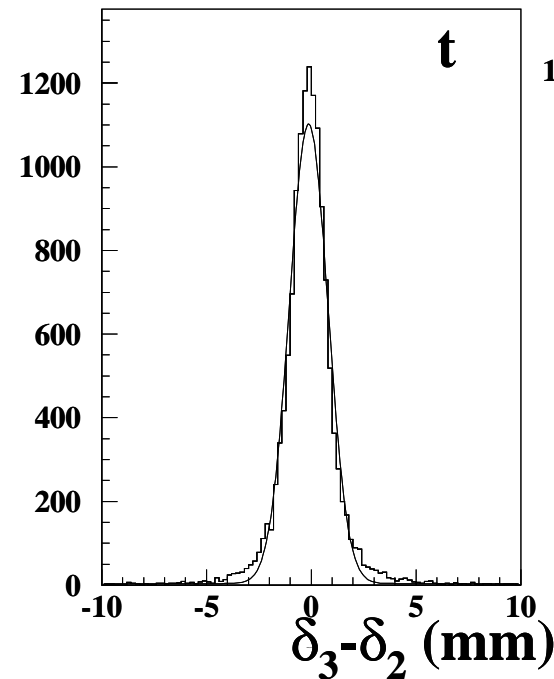
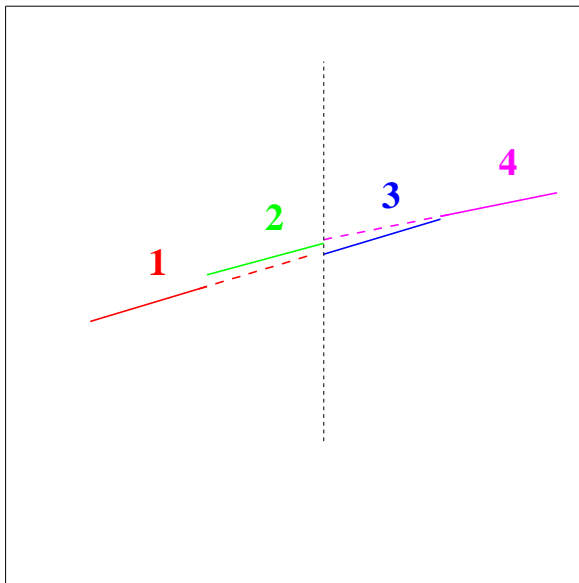


- same wiggles, same place, in all runs
- gain ratio $X/Y = 1.07$ (ie “continuous strips / linked pad strips”)

Preliminary

Spatial resolution

- decently straight, X/Y matched tracks preselected
- 4 segments method :
 - tight straight-track selection by $\text{seg}_1/\text{seg}_4$ matching
 - measurement of $\text{seg}_3\text{-seg}_2$ difference at center of track



- c axis (either x or y) : $\sigma = 192/\sqrt{2} = 136\mu\text{m}$
- t axis (z) : $\sigma = 850/\sqrt{2} = 600\mu\text{m}$

Preliminary

Schedule

- 2008-9 : Studies
- 2010 : Engineering design, 1st funding.
- 2011 : Construction, Integration
- 2012 :
 - Presently cosmic-ray characterisation (charged tracks)
 - Data taking, polarized γ rays, Hyôgo, Japan.
Compton scattering of a high energy e^- beam on linearly polarized laser
 - Spring-8, 8 GeV e^- storage ring
 - 1.5 – 2.4 GeV γ rays [Eur.Phys.J.A19 :S275-S278,2004](#)
 - New Subaru 1.5 GeV e^- storage ring
 - 2 - 40 MeV γ rays [Amano et al., NIM A 602 \(2009\) 337](#)

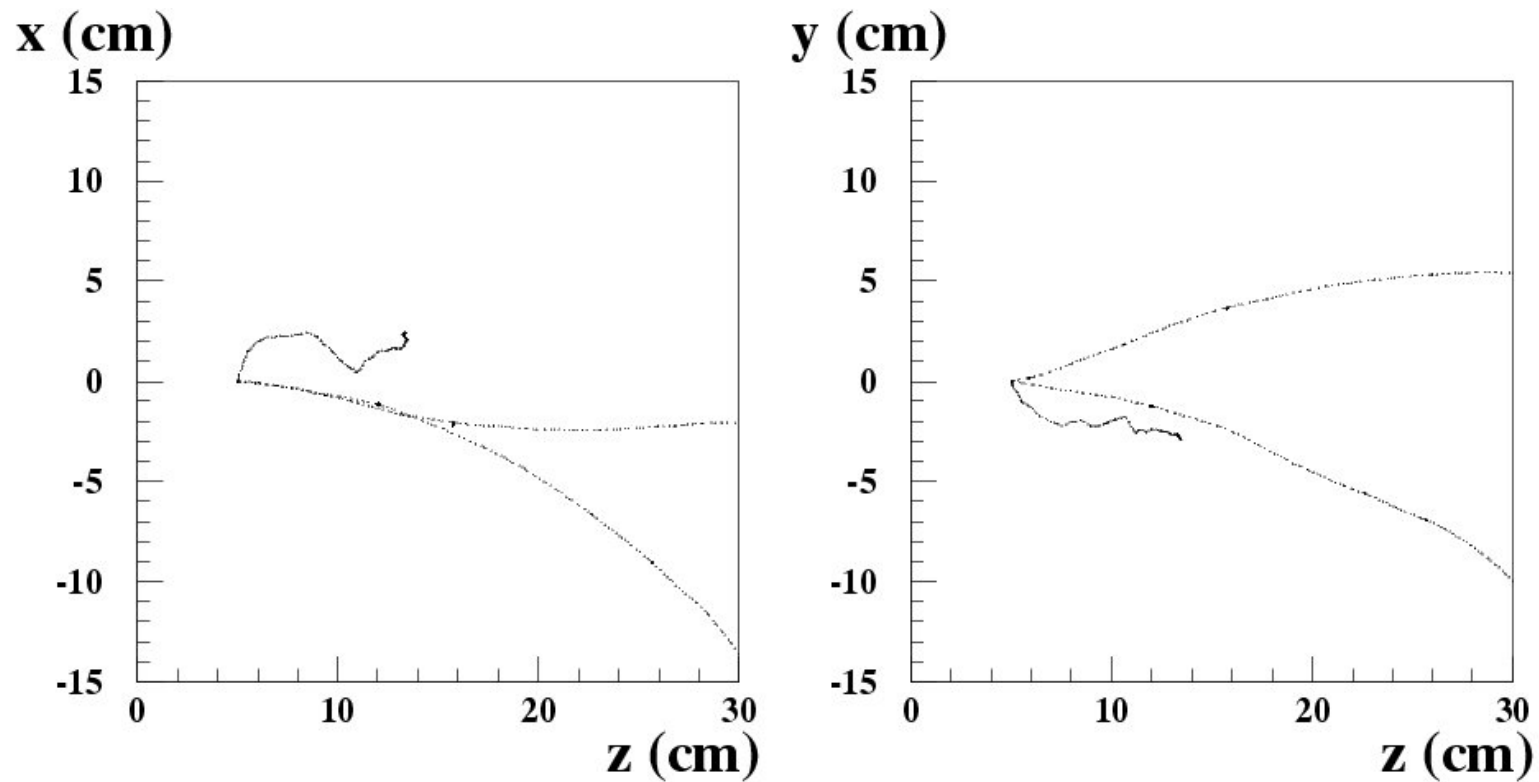
Conclusion : 1

- Characterization of detector with cosmic rays (charges tracks) in progress
- Excellent performances, appropriate for intended use.
- # of dead / noisy channels : 0 (zero).
- Good ageing properties : able to work with the same fill for 2 months (no recirculation / purification).
- reconstruction software to be further developed (vertexing ..)

Conclusion : 2

- A thin detector, a TPC, can be a telescope and a polarimeter :
 - With angular resolution 1/10 better than the W/Si technology,
 - That is, a background rejection factor lower by 2 order of magn.
 - An effective area A_{eff} of several m^2/ton .
 - eg. C2F6, 10 bar, $(2\text{m})^3$: 464 kg.
 - A 4π detector (2π if used in low orbit)
 - Rejection of the (huge at low energy) γ albedo is obvious from tracking
 - A dead-time free GRB detector (but watch electronics deadtime!)
- Fermi might be the last thick and polarization-blind γ mission ..
 - HARPO demonstrator commissioned
 - Expect going on beam at the end of the year !

Thanks for your kind attention



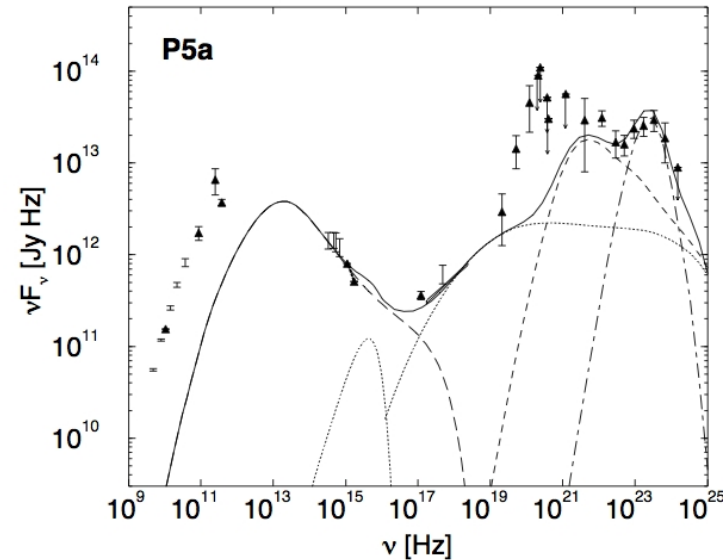
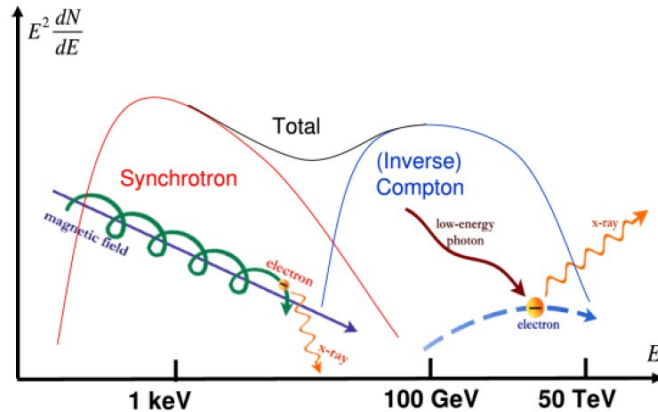
A 10 MeV γ photon undergoing triplet conversion in argon at 5 bar (EGS5 simulation).

Back-up slides

Cosmic γ -ray polarimetry : AGN's

Example : 3C279

Rept. Prog. Phys. 71, 116901 (2008)

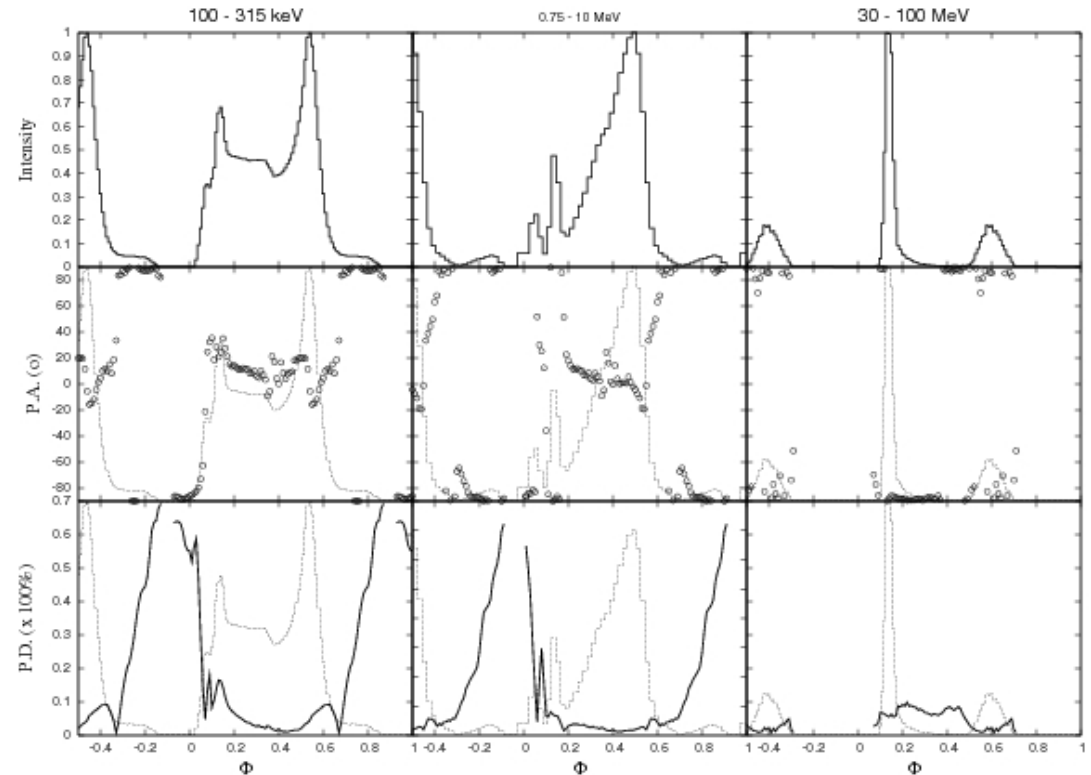
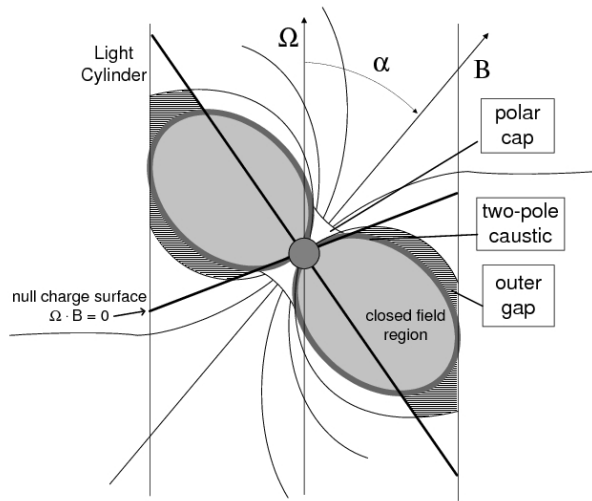


From left to right :

- synchrotron
- thermal from accretion disk
- SSC synchrotron-self Compton
- Compton on accretion disk photons
- Compton on photons from gas clouds
- ESC : P low (3 – 4 %)
- SSC : P 65 – 70 %
- [Mon. Not. R. Astron. Soc. 395, \(2009\) 1507.](#)

Cosmic gamma ray polarimetry : pulsars's

Fast-rotating neutron stars with huge magnetic field. eg : Crab



- Prediction for P model dependent. (Polar Cap 0, Outer gap medium, Slot Gap “caustic” high)
[Kaspi et al. arXiv :astro-ph/0402136.](#)
- Here : Outer gap model
[Takata et al. ApJ 670 \(2007\) 677](#)

Cosmic gamma ray polarimetry : GRB's

- Origin of γ -Ray bursts : unknown (supernovae ? mergers ?)
- Most models involve 2 relativistic jets.
- γ emission ?
 - Synchrotron Radiation : P low
(“efficient shock acceleration needs highly disordered magnetic fields”)
 - Inverse Compton Scattering : P high

Dado, Dar, De Rujula, arXiv :astro-ph/0403015.

Our 3 preferred sources

Are pulsars

		$F(E_\gamma > 100 \text{ MeV})$ $, \text{ph cm}^{-2} \text{s}^{-1}$	Γ	δ	Flux COMPTEL $\text{ph cm}^{-2} \text{s}^{-1}$
South :	Vela	$(834 \pm 11) \times 10^{-8}$	1.7	-45	$(1 - 30) \text{ MeV} : 8 \times 10^{-5}$.
North :	Geminga	$(353 \pm 6) \times 10^{-8}$	1.7	+17	$(2 - 10) \text{ MeV} : 6 \times 10^{-5}$.
	Crab	$(226 \pm 5) \times 10^{-8}$	2.2	+21	$(2 - 10) \text{ MeV} : 9 \times 10^{-5}$.

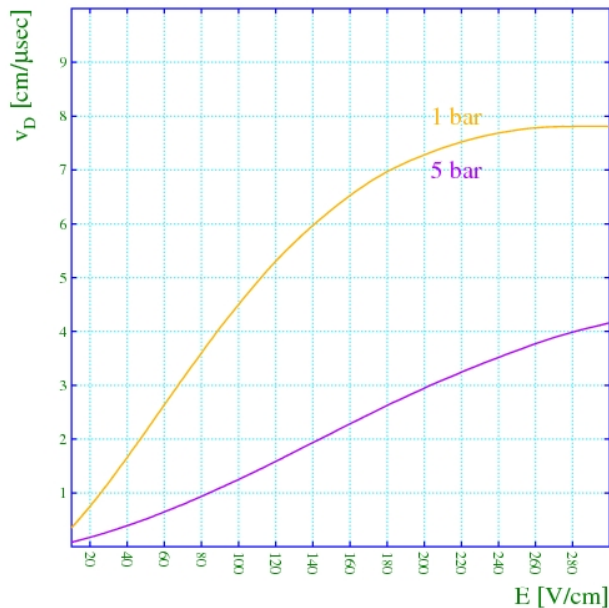
Typical target : $\Gamma = 2, f = 1 \text{ MeV} / \text{m}^2 \text{ s}$.

$$\frac{dF}{dE}(E) = f \frac{1}{E^2}$$

T2K-like Gas

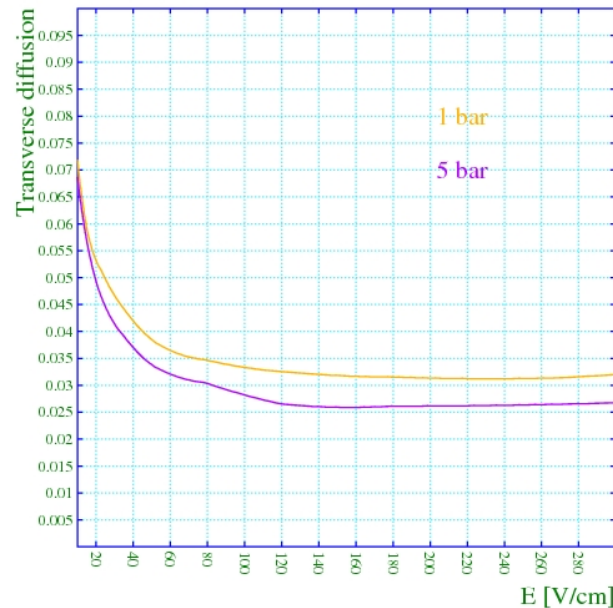
- Ar :95 ISO :2 CF4 :3 à 1 bar, D. Karlen NIM A (2010)
- Ar :99 ISO :0.4 CF4 :0.6 à 5 bar, Quencher partial pressure kept unchanged

Drift velocity



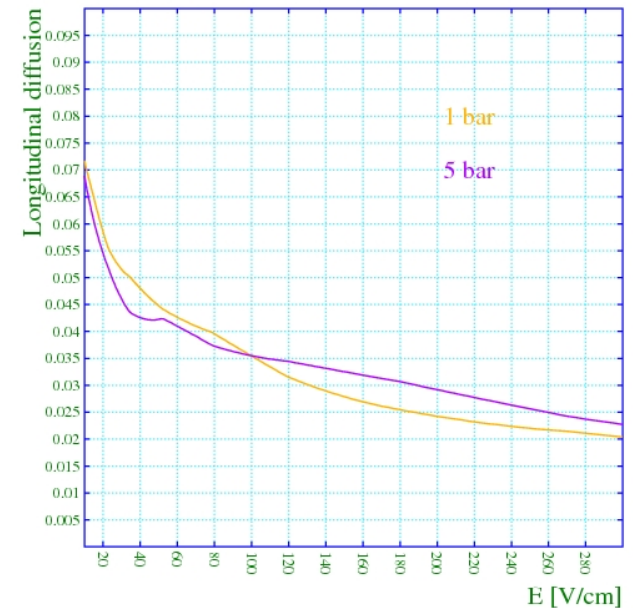
Plotfile of 21_2B8_14 on 27/09/10 with GasField version 7.30.

Transverse diffusion



Plotfile of 21_2B8_14 on 27/09/10 with GasField version 7.30.

Longitudinal diffusion



Plotfile of 21_2B8_14 on 27/09/10 with GasField version 7.30.

- matching of shaping (100 ns) resolution (1 mm) $\Rightarrow v_d \approx 1 \text{ cm}/\mu\text{s}$
- $P < 5 \text{ bar}$ for optimal high-gain operation of the micro-megas amplifier