HARPO

Characterization of a Gaseous TPC for High Angular Resolution Gamma-Ray Astronomy and Polarimetry from the MeV to the TeV

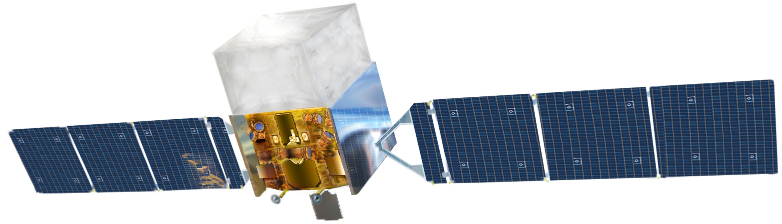
Denis Bernard
Laboratoire Leprince-Ringuet

On behalf of the HARPO project

- LLR @ Ecole Polytechnique, CNRS/IN2P3, FRANCE
- IRFU @ CEA Saclay, FRANCE
- NewSUBARU @ LASTI, University of Hyogo, JAPAN

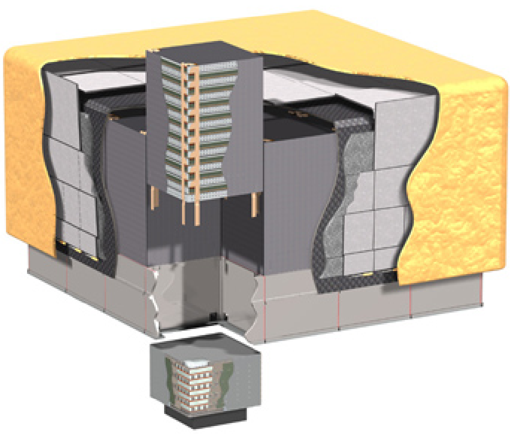
TYL-FKPPL Worskhop 28-30 May 2012 Université Blaise Pascal, France

Presently in space : GLAST / Fermi



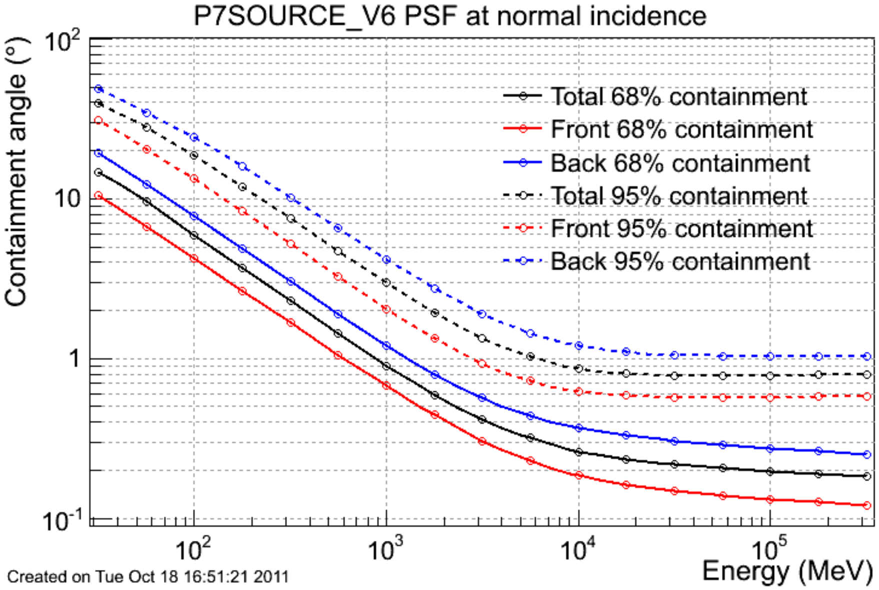
Fermi LAT : 2008 – 2013 $\rightarrow$ 2018 ?

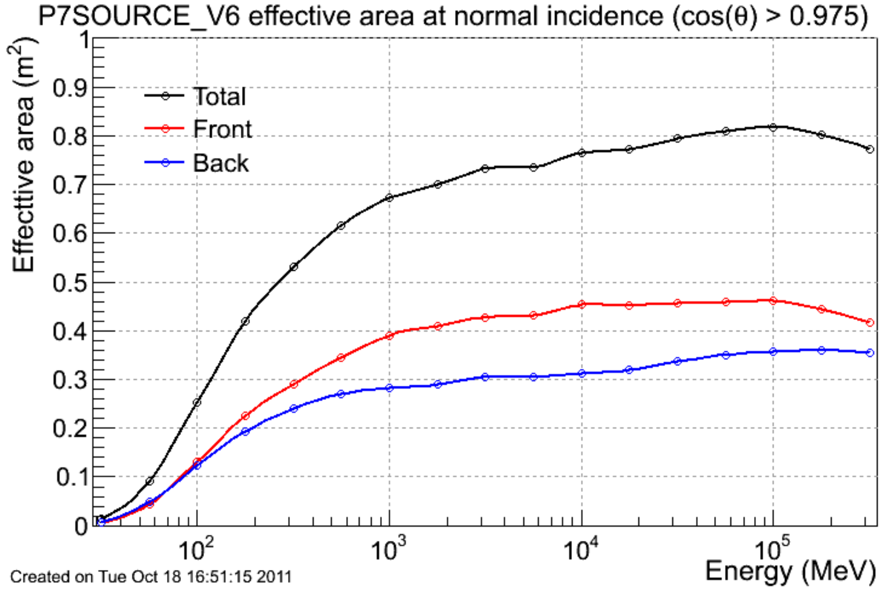
- Impressive harvest on vast programe :
  pulsars, active galactic nuclei (AGN), gamma-ray bursts (GRB), binary stars, supernova remnants
  ...
- E_γ range 20 MeV - 300 GeV
- 16-plane **Converter/Tracker W/Si** $(1.1 X_0)$
- 8-layer CsI :Tl **Calorimeter CsI :Tl** $(8.6 X_0)$
- Segmented scintillator 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 $0.1 - 300\,\mathrm{GeV}$
- Effective area ≈ 1 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 $A_{\rm eff}$ at low E

– Enlarge $A_{\rm eff}$ — but watch mass budget !

– Have polarization sensibility

Cosmic γ-ray polarimetry : Why ?

– γ Rays produced in very violent events : (AGN, pulsars, GRB ..)

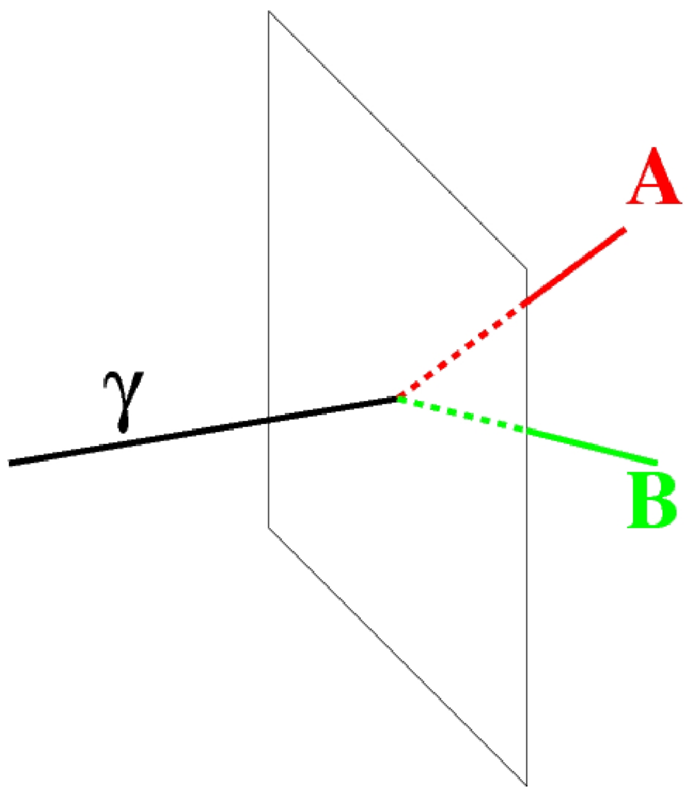
– γ polarization fraction key ingredient to understanding mechanism at work.

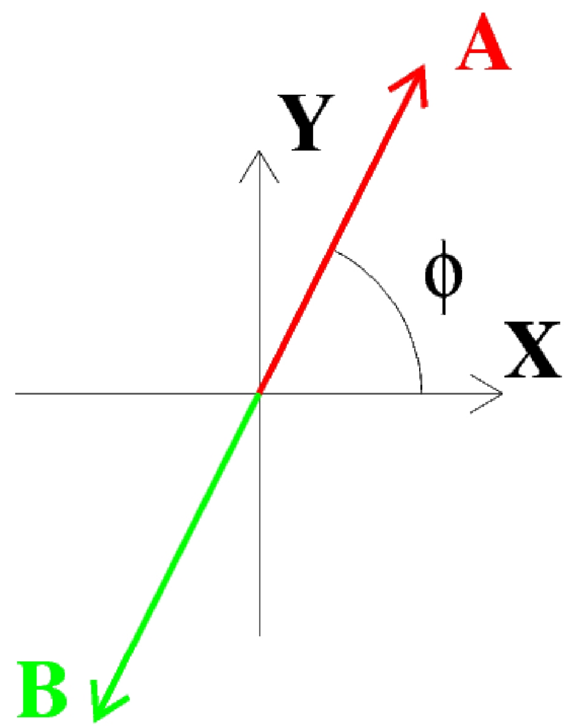
- jets of relativistic matter impinging on intra galactic matter
  - hadronic interactions $\rightarrow \pi^0$'s $\rightarrow \gamma$'s : $P = 0$

- Radiative processes (synchrotron, inv Compton) : P up to 70%
  - Synch : Turbulence of $\vec{B}$ "dilutes" P : measurement of turbulence.

Linear Polarization !

Modulation of the azimutal angle of the debris





– ϕ azimuthal angle

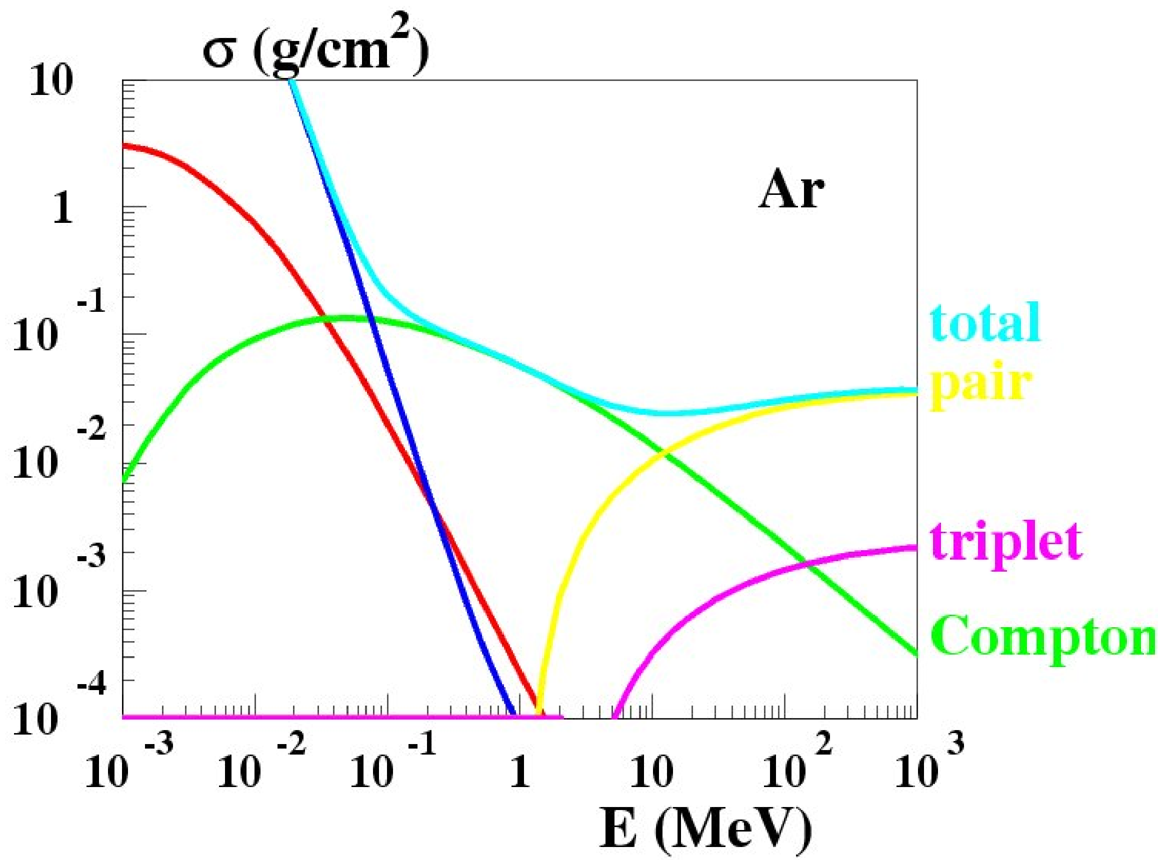
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P \cos[2(\phi - \phi_0)])$$

Photon interaction with matter

Compton $\gamma e^- \to \gamma e^-$

"Nuclear" pair production : $\gamma Z \to Z e^+ e^-$

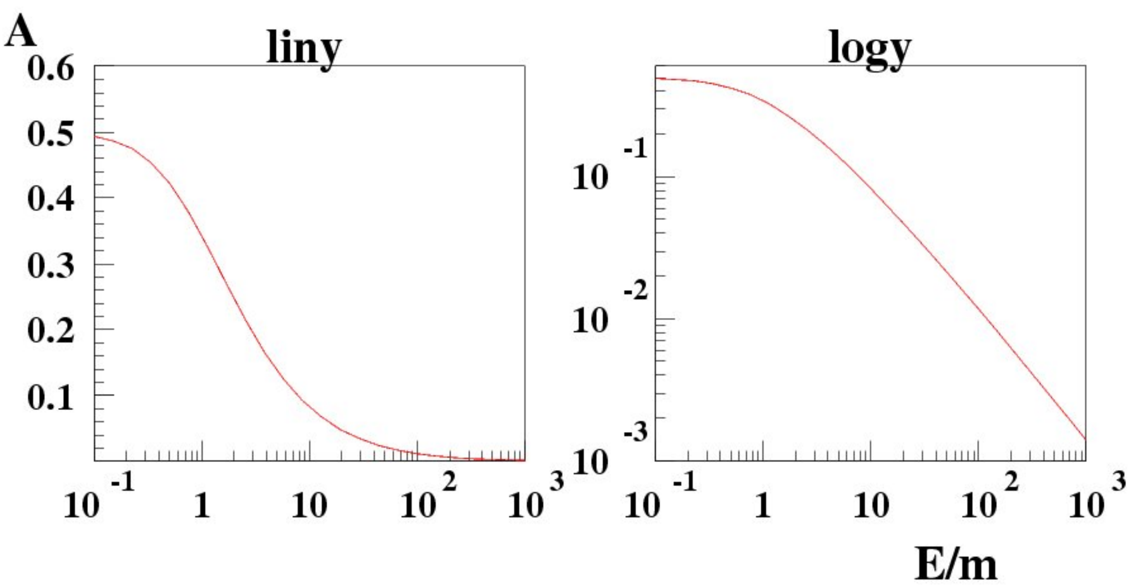
"Triplet" pair production : $\gamma e^- \to e^- e^+ e^-$

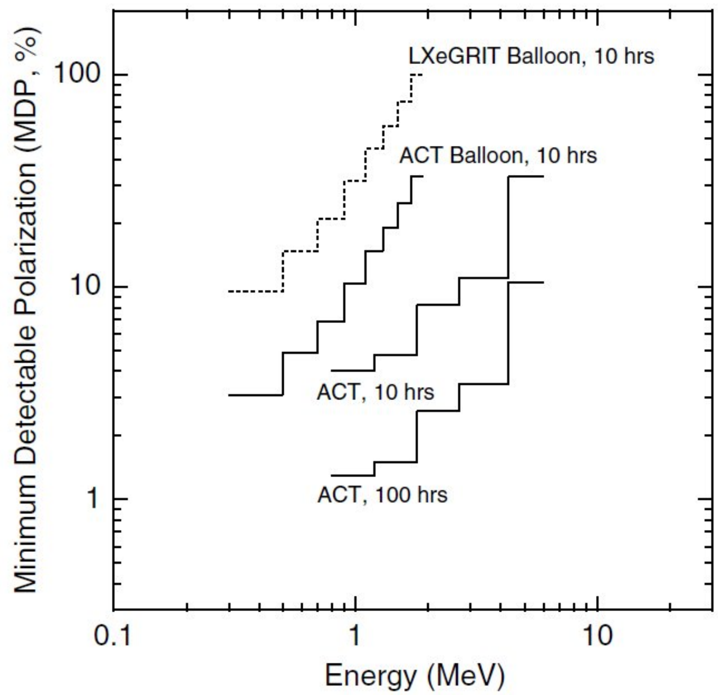


Compton

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

New Astr. Rev. 48 (2004) 215

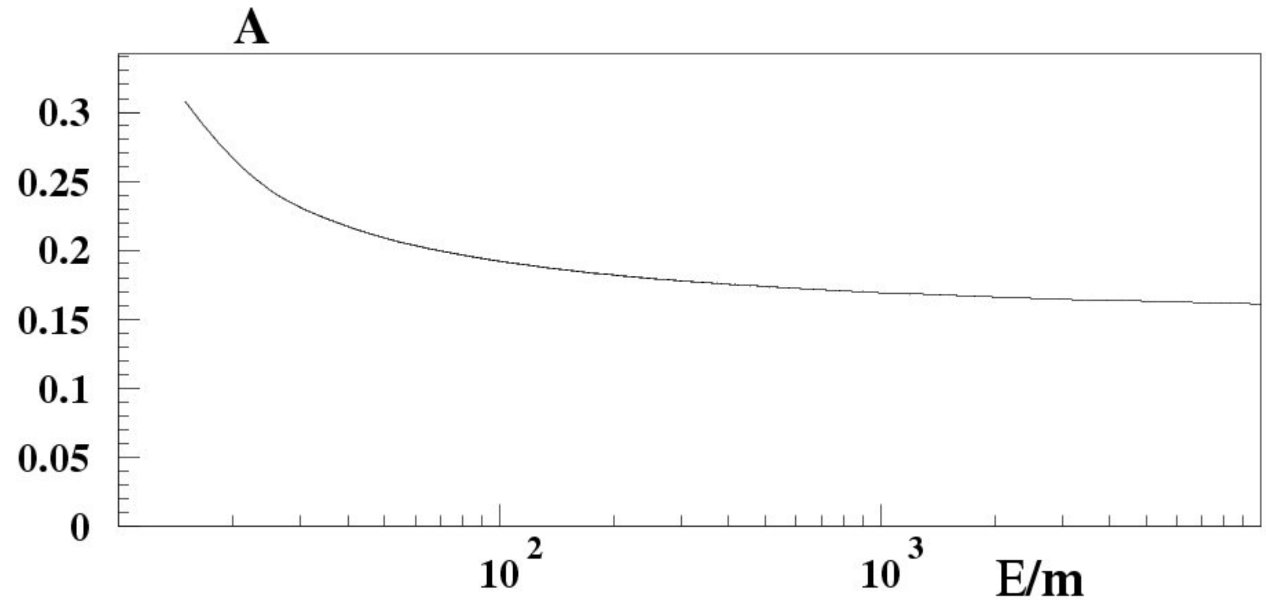




Low sensitivity for $E >$ few MeV

"Nuclear" pair production

In principle : very good



– Dominates cross section at high energy
– $\mathcal{A} \approx 0.2$ at high energy

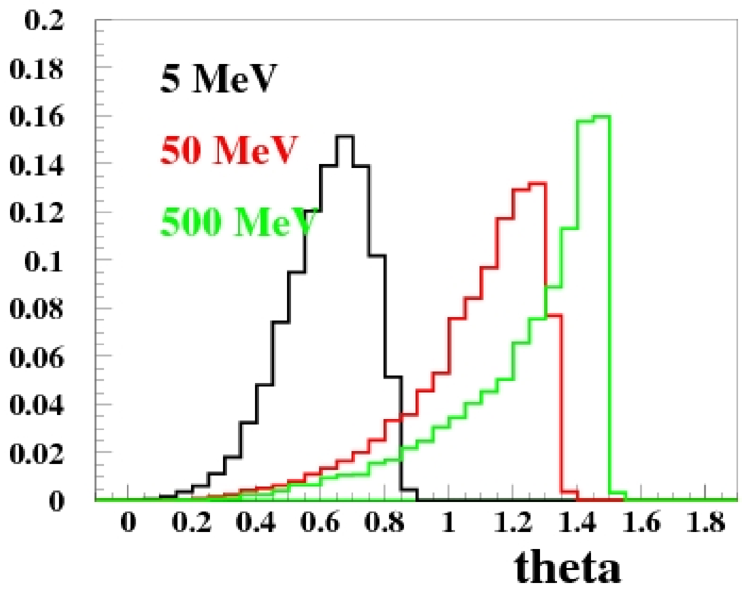
In practice :

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

"Nuclear" pair conversion used for non-polarized γ astronomy

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

– 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

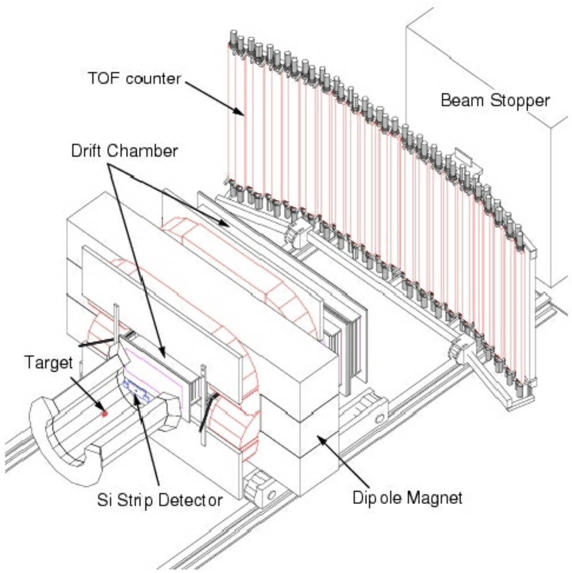
The only validation ..

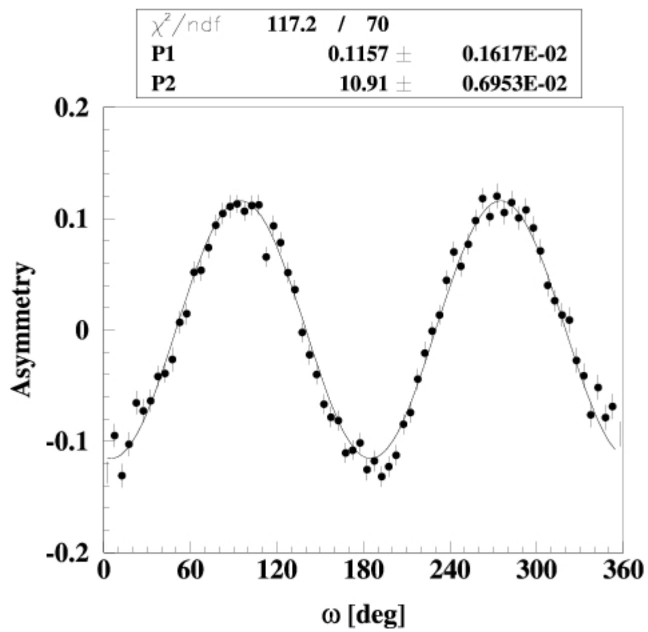
Was performed :

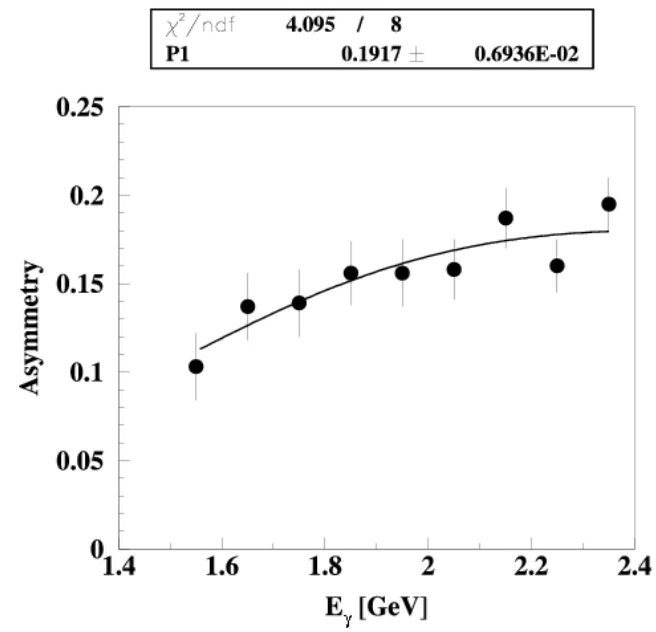
– For nuclear pair production,

– and : at high Energy

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



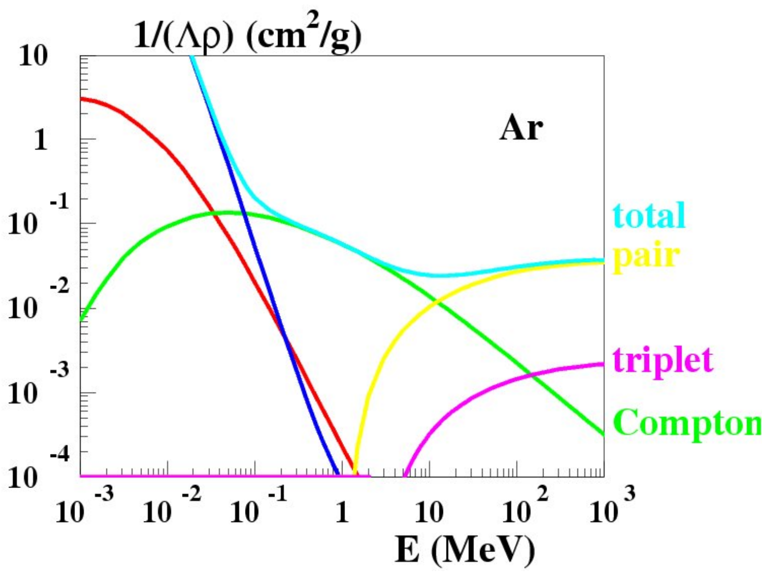


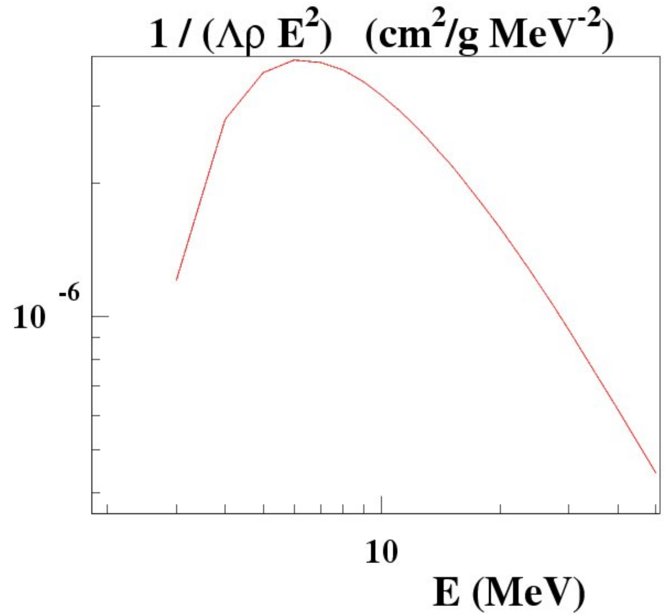


de Jager, et al., Eur.Phys.J.A19 :S275-S278,2004.

Satellite flight : Precision of P measurement

$$N_{int} = \int \frac{L}{\Lambda(E)} \frac{\mathrm{d}F}{\mathrm{d}E}(E) S T \mathrm{d}E = M \times T \int \frac{1}{[\rho \Lambda(E)]} \frac{f}{E^2} \mathrm{d}E$$

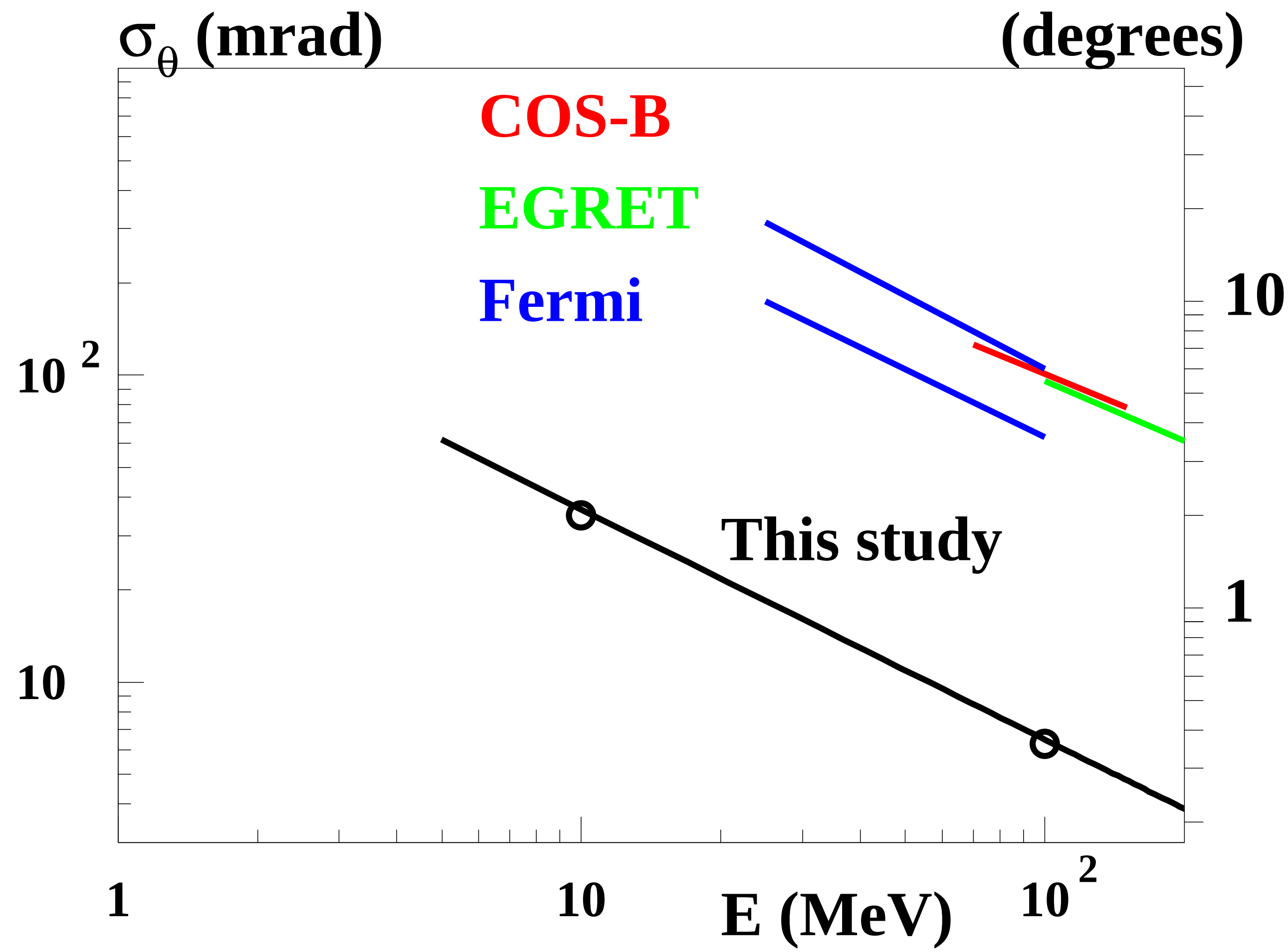




1 ton, 1 year, time fraction 50%, efficiency 100%, $\mathcal{A} \approx 0.2$

- $N_{int} = 1.5 \times 10^5$ on the Crab pulsar $\qquad \sigma_P \approx \frac{1}{\mathcal{A}}\sqrt{\frac{2}{N}} \approx 0.0185$
- $2\%/\sqrt{year.ton}$ $\qquad \approx Z$-independant.

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.

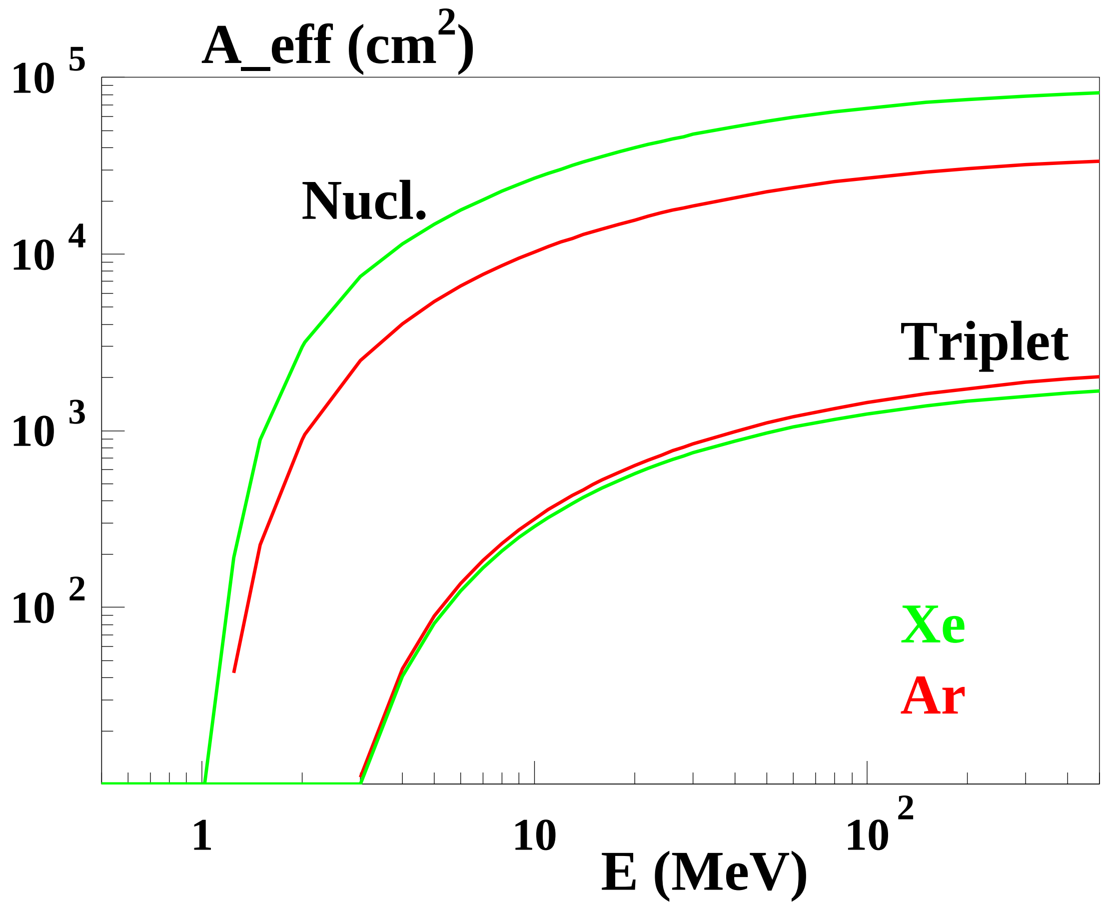
– Thin detector $(L \ll X_0)$:

- 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) ;

Our project : HARPO

– Ground Phase :

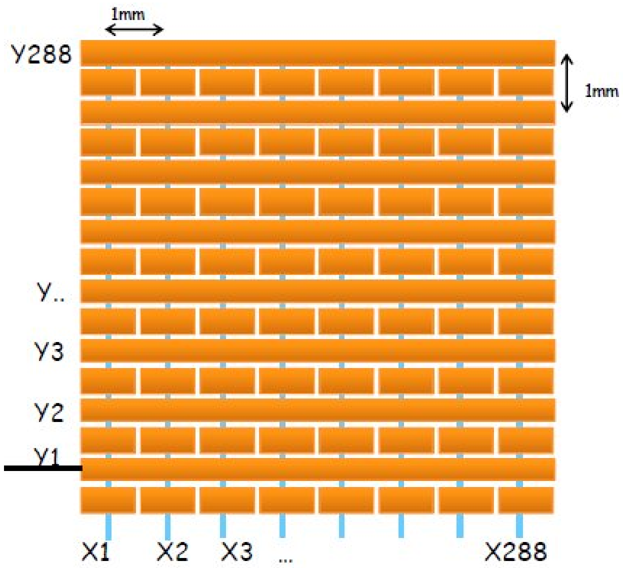
- Characterize the TPC technology for γ astronomy and polarimetry
- 1rst measurement of $\mathcal{A}$ at low energy.

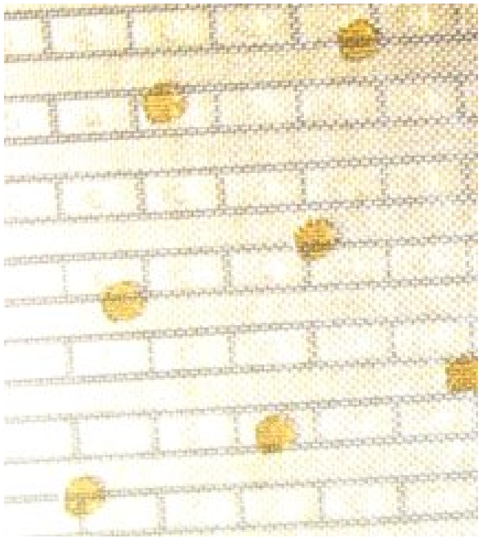
– Demonstrator :

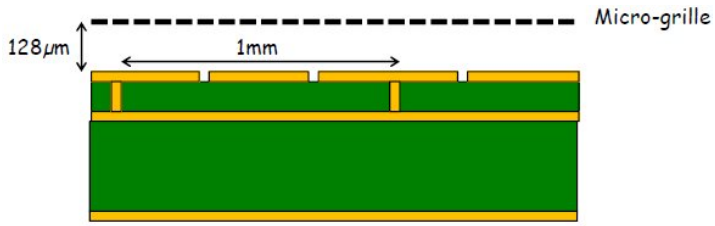
- Need a homogeneous, finely, fully instrumented, 3D detector.
- 30 cm cubic TPC, 5 bar, Argon-based mixture (à la T2K)
- Pitch 1mm
- Trigger : scintillator + WLS + PMT.

Amplication – collection – sampling

- Amplification by "bulk" micro-mesh micromegas NIM A 608 (2009) 259





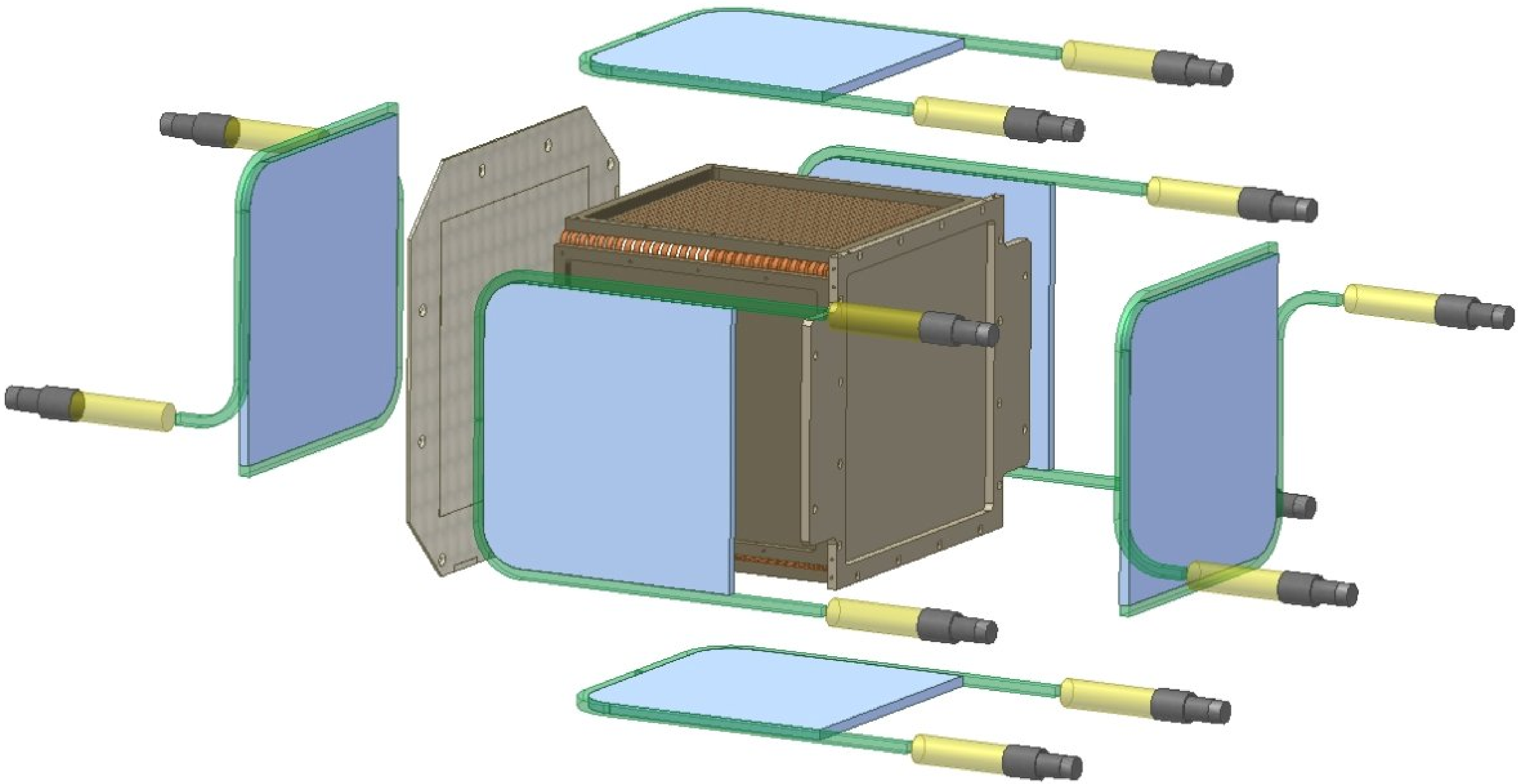


- Signal collection by strips on PCB, pitch = 1mm
- Sampling / acquisition performed by AFTER chip ; 50 MHz, 12 bits, shaping 100 ns

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

Micromegas and strip PCB from CERN workshop

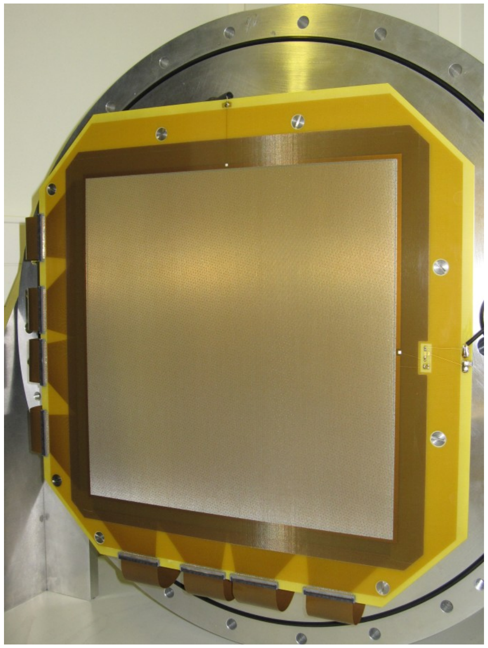
The detector : being designed



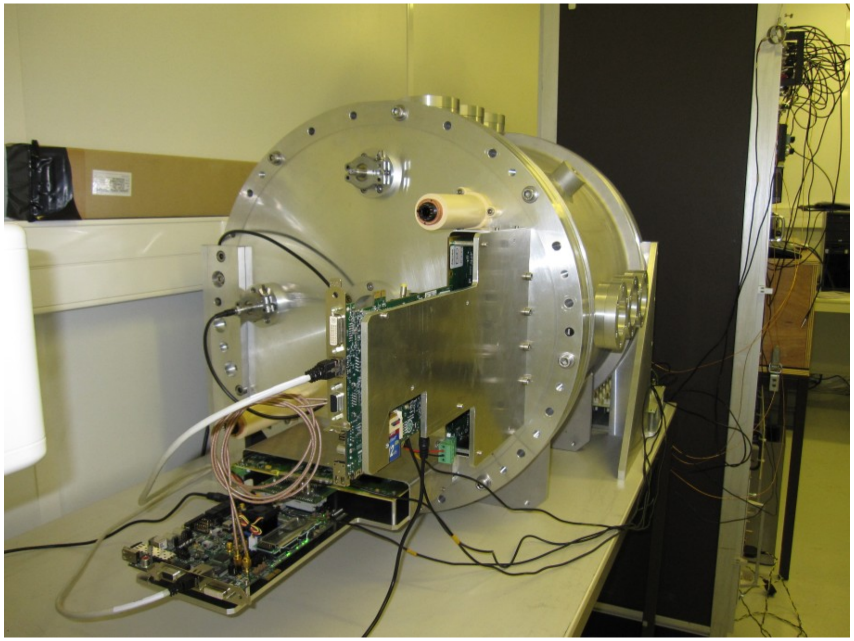
The detector : being assembled

field cage

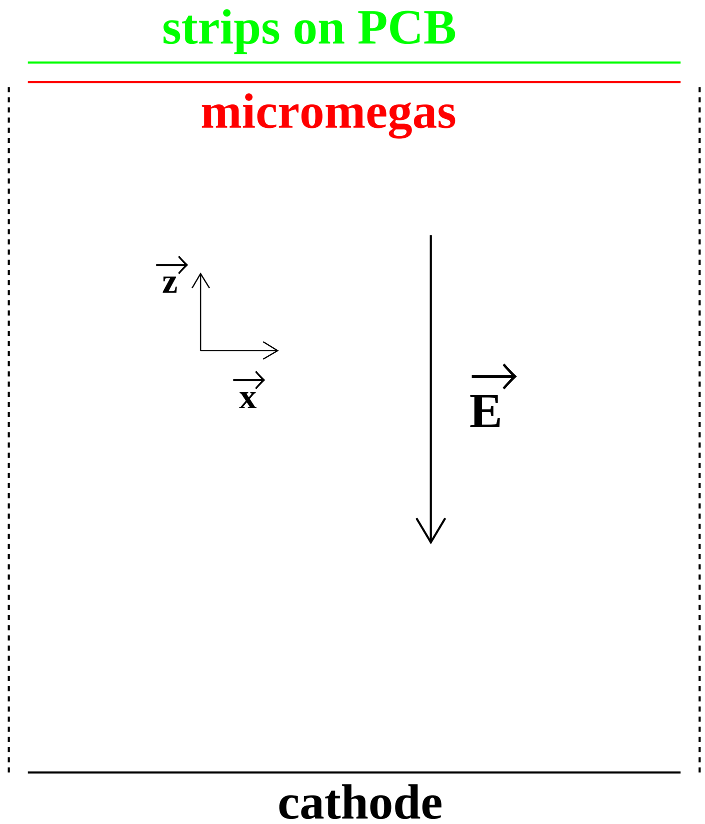
micromegas on PCB



electronics cards on vessel

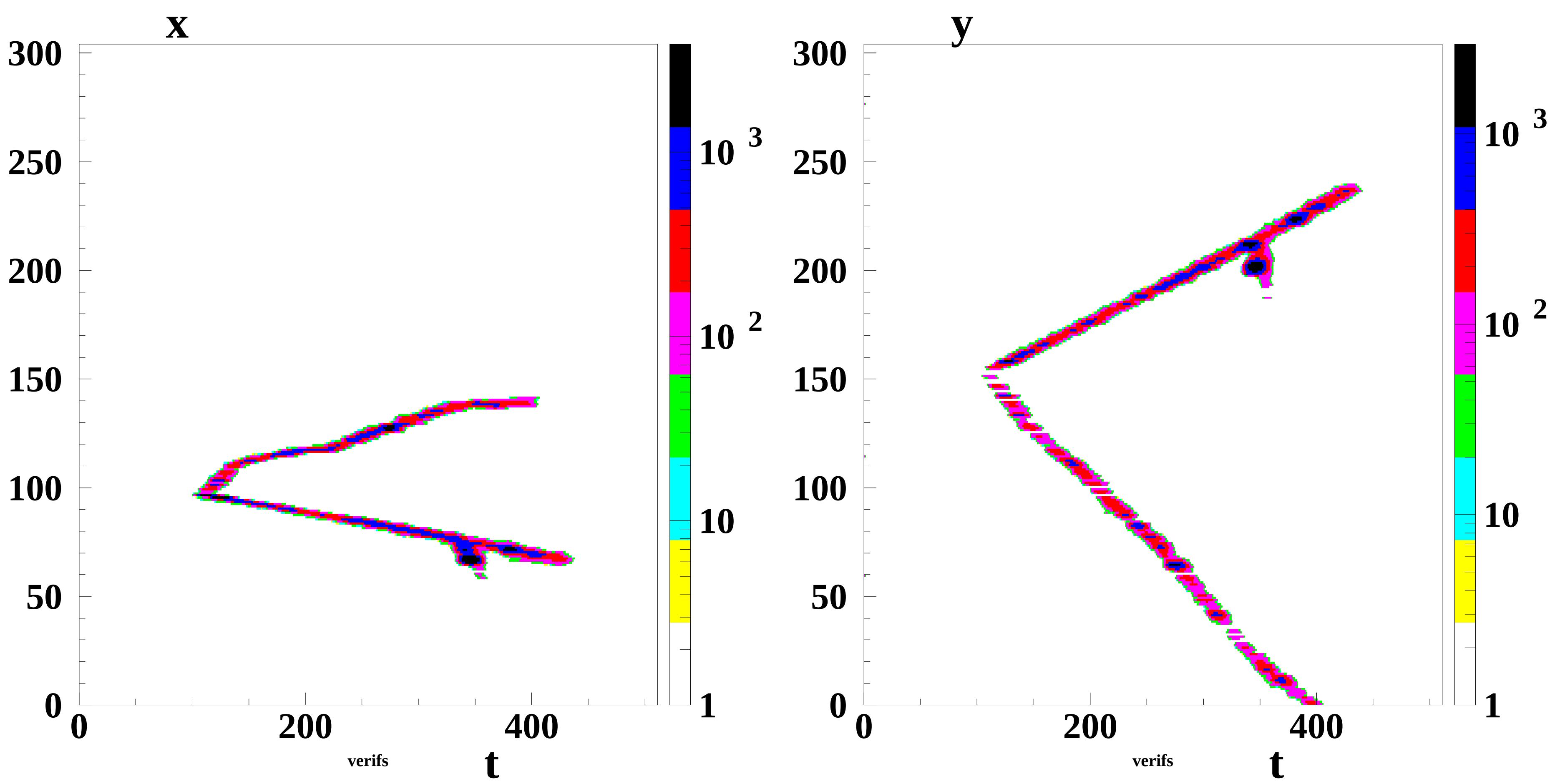


Cosmic rays tests in progress



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

One event



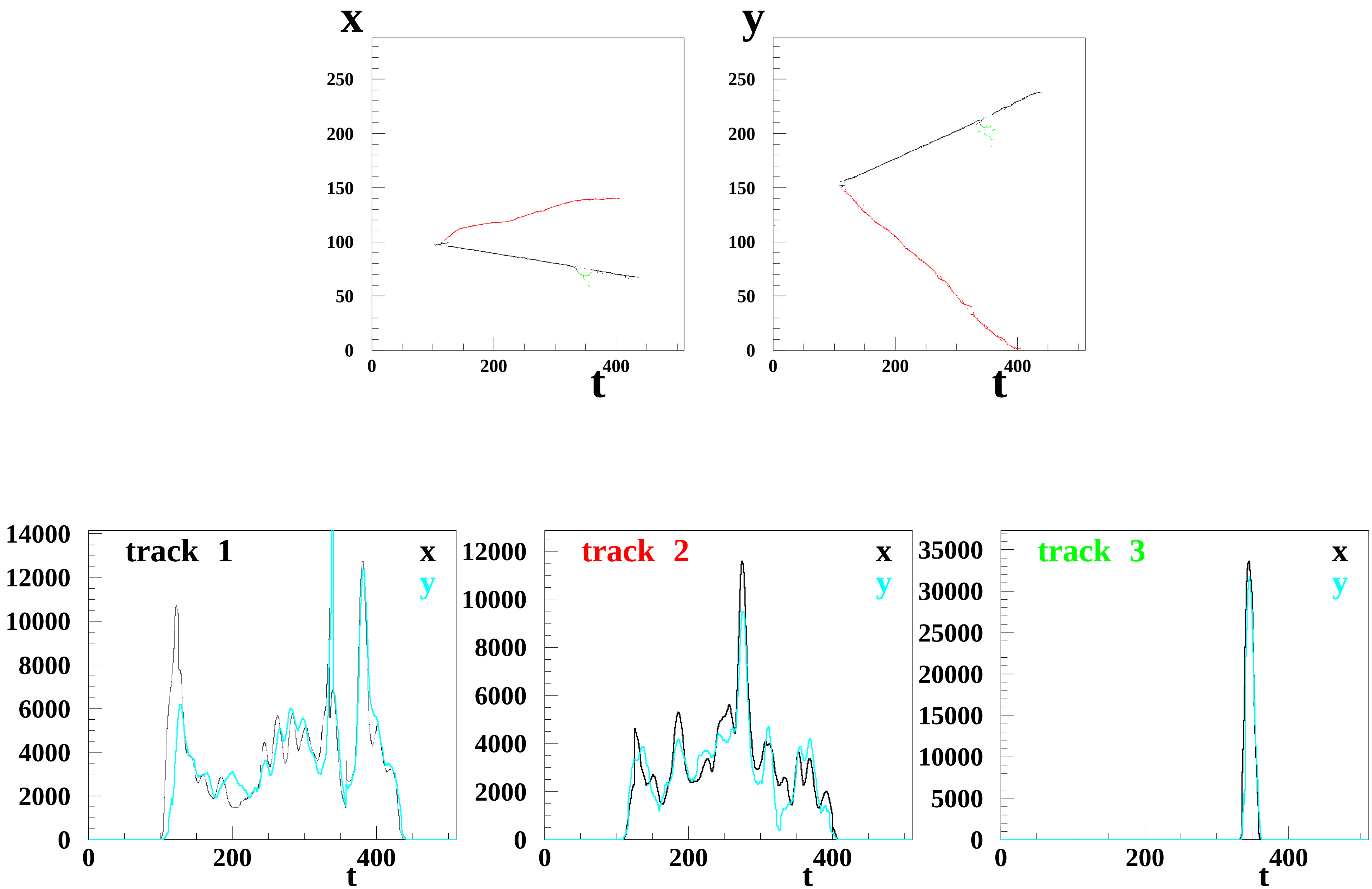
- $P = 2$ bar, $V_{\mu M} = 480\text{V}$, $V_{drift} = 7560\text{V}$, (252V/cm)
- most likely a hard muon + a hard δ ray + a soft δ ray

Data acquisition / Reconstruction

- Two DAq modes :
    - "full" 608 kB / evt
    - "Zero suppress", $\approx$ 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

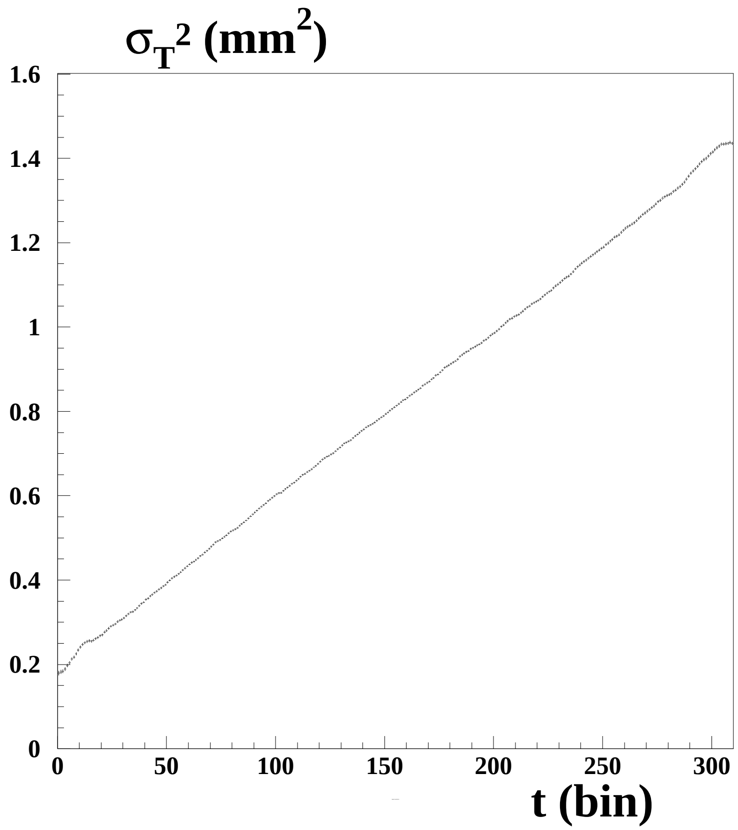
x / y matching : χ^2 from t distributions

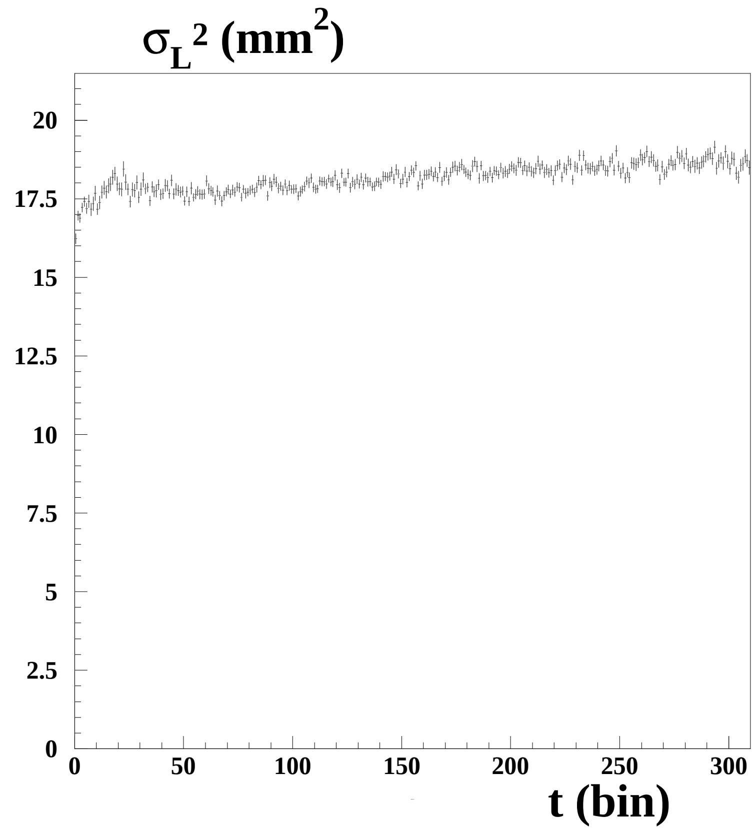


Diffusion :
Study of cluster size as a function of drift time.

transverse

longitudinal



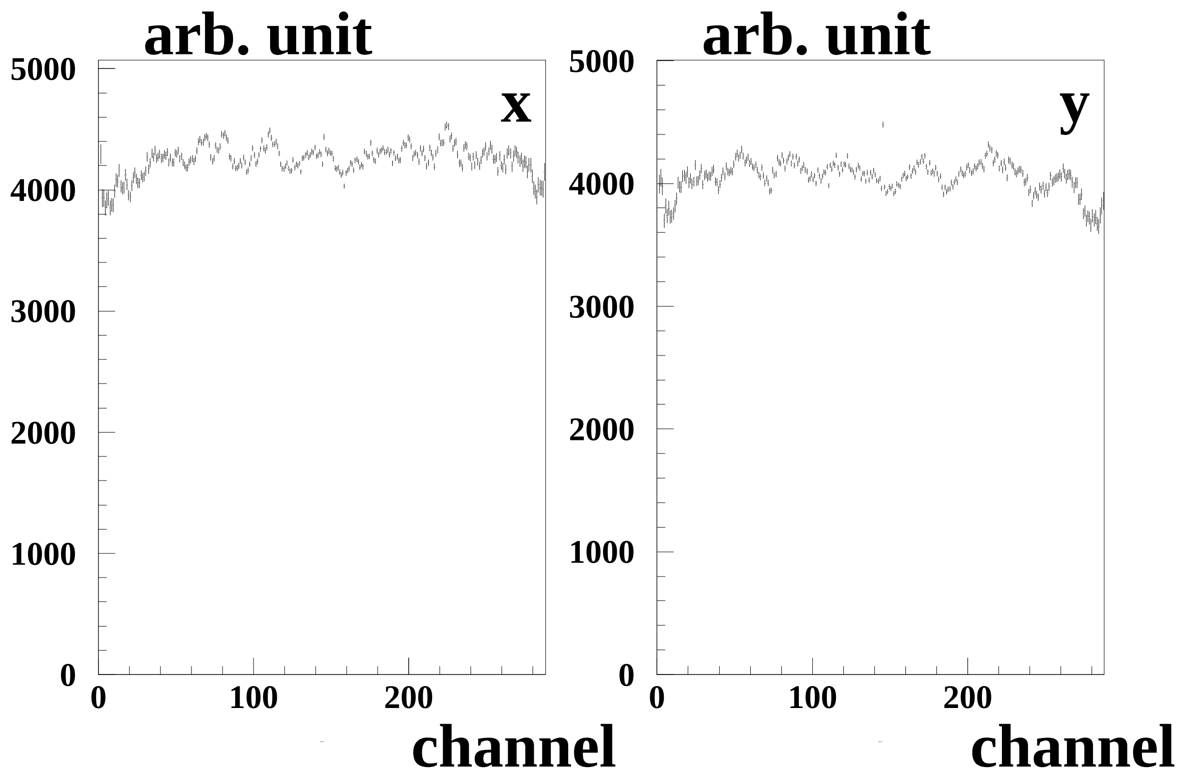


- long. : cluster time size dominated by shaping (100 ns @ 50 MHz : 5 bins)
- transverse : diffusion $224 \mu\mathrm{m}/\sqrt{\mathrm{cm}}$ (Garfield : $225 \mu\mathrm{m}/\sqrt{\mathrm{cm}}$)

Preliminary

Gain homogeneity

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

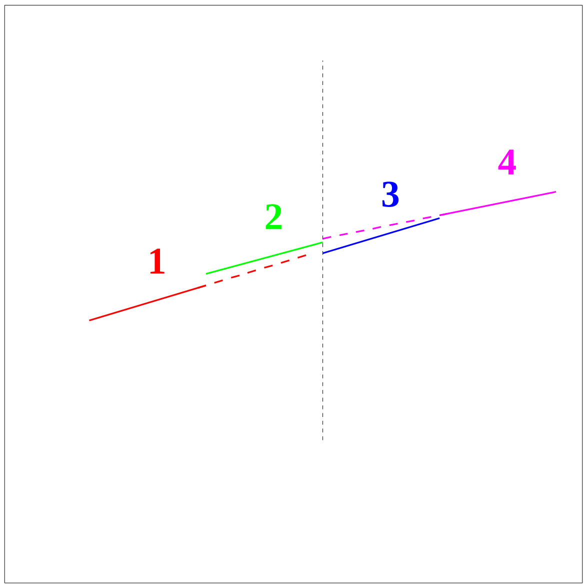


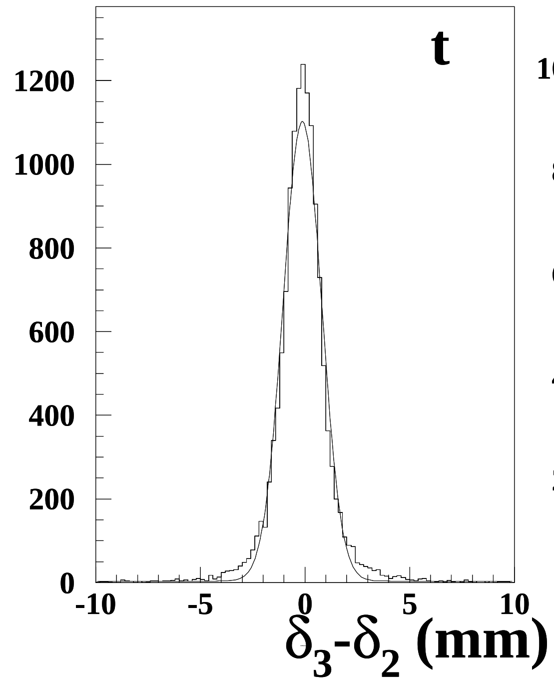
- same wiggles, same place, in all runs
- gain ratio X/Y = 1.07 (ie "continuous strips / linked pad strips")

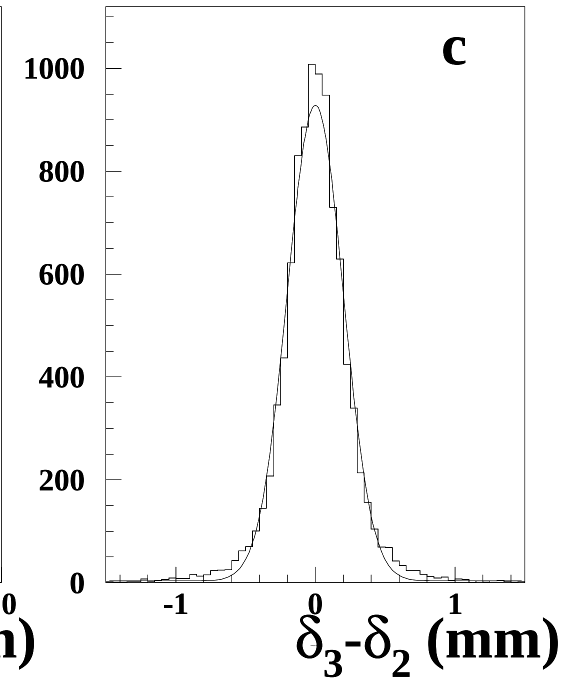
Preliminary

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 seg_3-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

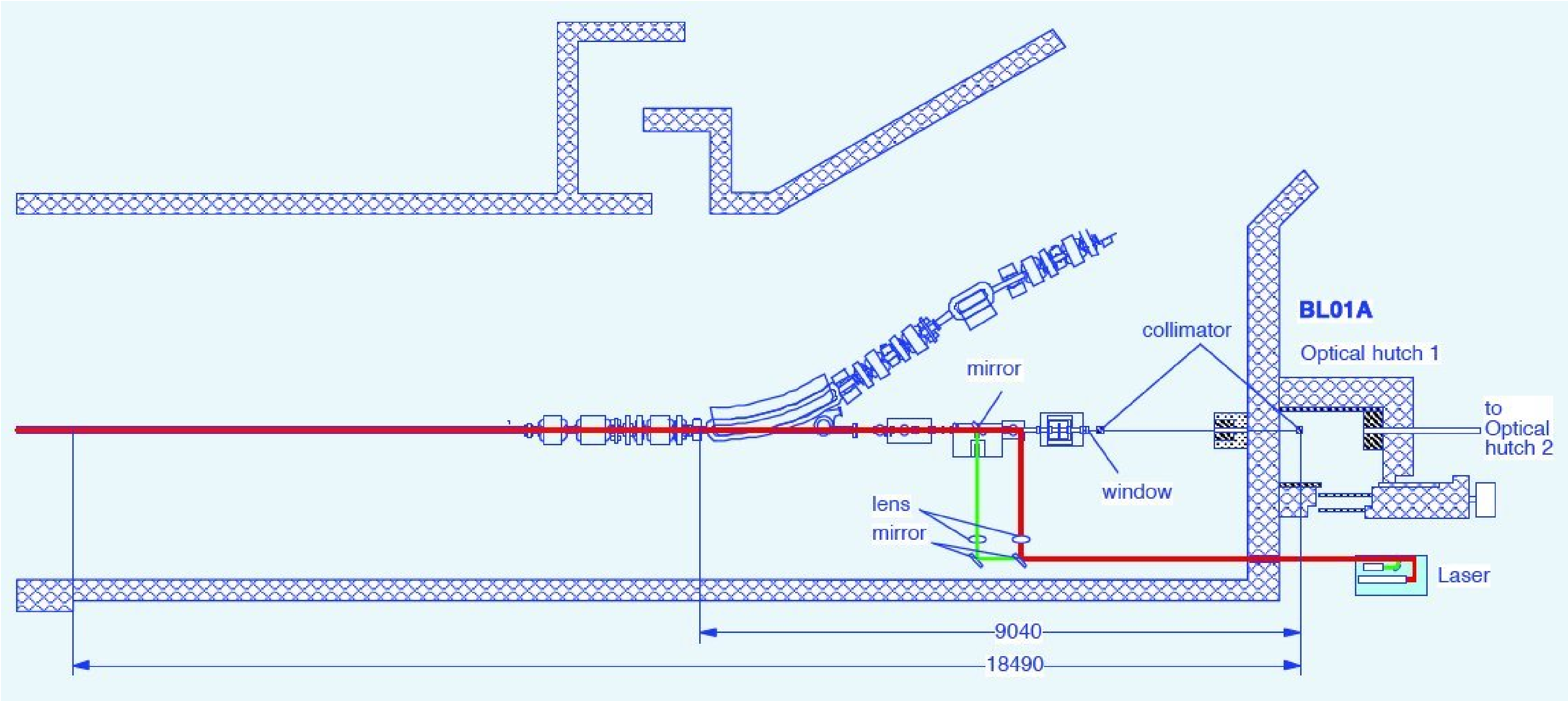
- 2008-9 : Studies
- 2010 : Engineering design, 1rst funding.
- 2011 : Construction, Integration
  - 25 - 27 Aug : 1rst Collaboration meeting
- 2012 :
  - Presenlty cosmic-ray characterisation (charged tracks)
  - Summer : 2nd Collaboration meeting
  - Data taking, polarized γ rays, Hyôgo, Japan.
    - NewSUBARU 1.5 GeV e^- storage ring
      - 2 - 40 MeV γ rays

Amano *et al.*, NIM A 602 (2009) 337

- 2013 Data analysis .. publication

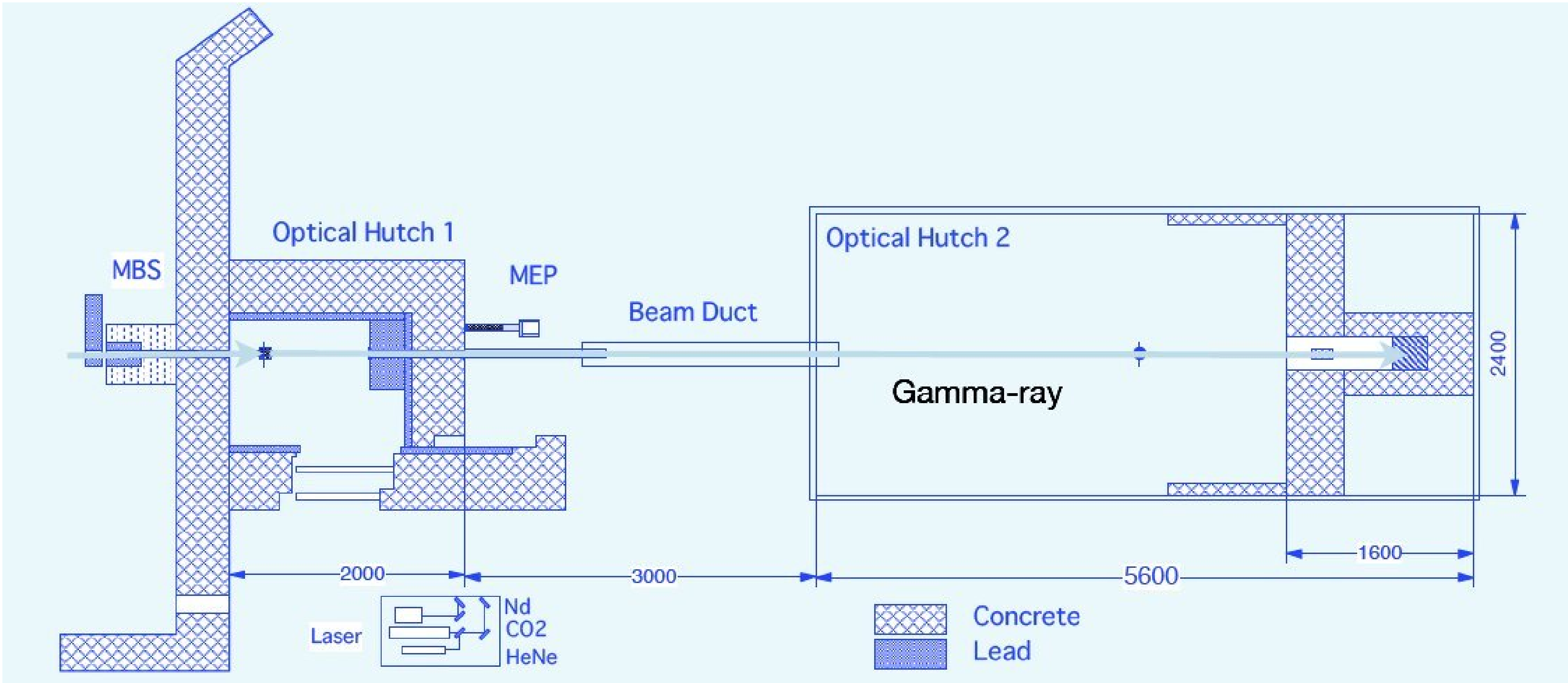
γ *beam line BL01 at NewSUBARU, U. of Hyogo*

- Compton scattering of a 1.0 - 1.5 GeV e^- beam on linearly polarized laser
- Monochromaticity by collimation of forward scattering
- Linear polarization $P \approx 100\%$



- Pr. Miyamoto, U. of Hyogo, et al.

New (larger) experimental Hutch



- The hutch was constructed under the collaboration between Konan University and University of Hyogo
- 5.6 (L) $\times$ 2.4 (W) $\times$ 2.6 (H) m
- Building completed (JFY2011)

Available γ ray energies (MeV)

Laser	λ (µm)	$E_{e^-} = 1\,\mathrm{GeV}$	$E_{e^-} = 1.5\,\mathrm{GeV}$
Nd :YVO_4 (ω)	1.064	17.6	39.1
Nd :YVO_4 (2ω)	0.532	34.5	76.3
CO_2	10.6	1.8	4.0
Er(fiber)	1.55	12.1	27.1
TiSaf	0.72	21.5	24.2

scan of the energy range of interest.

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 being further developped (vertexing ..)

– Beam line fits specs, Large hutch completed.

Conclusion : 2

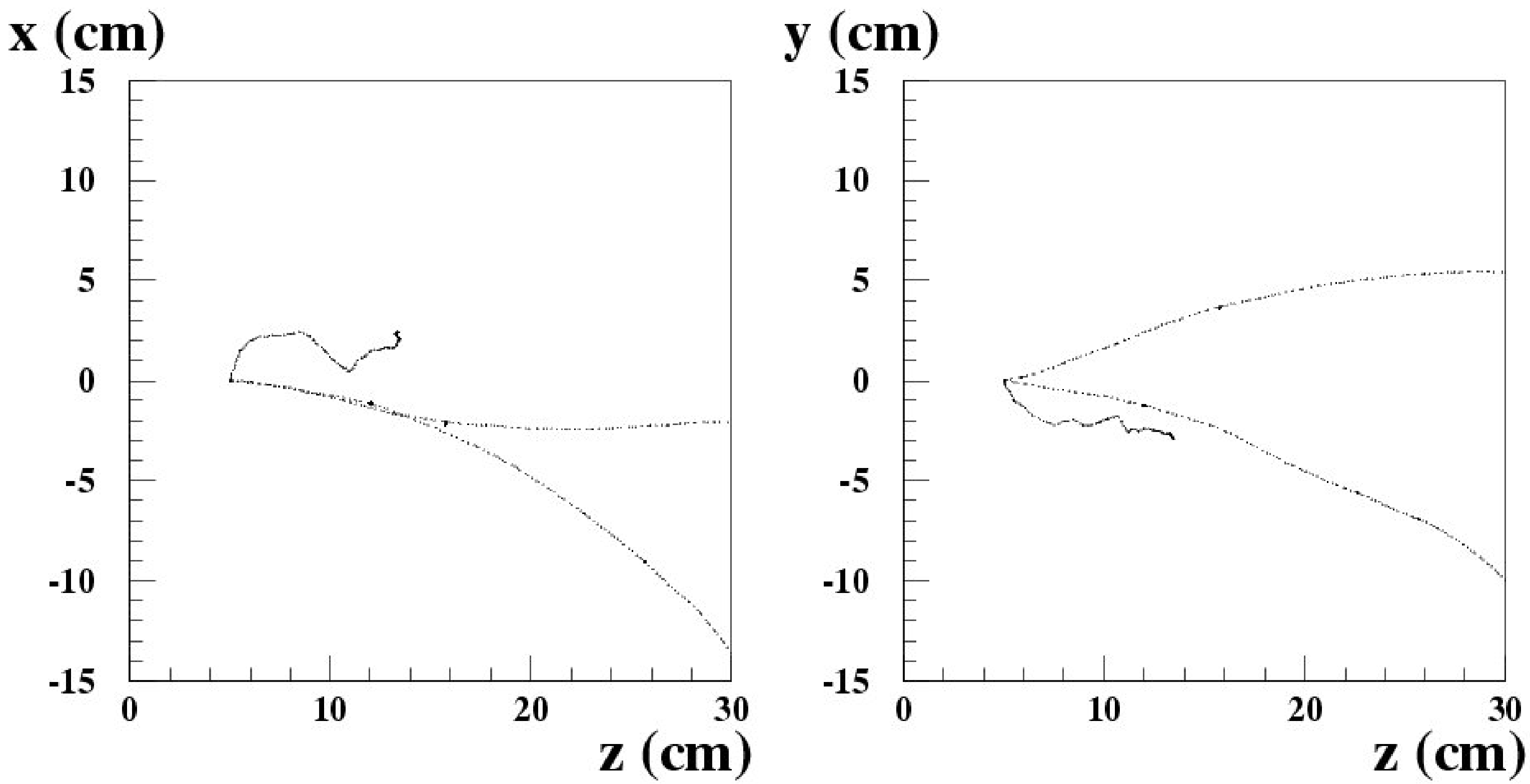
– A thin detector, a TPC, can be a telescope and a polarimeter :

- 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.
- 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 ..

– Expect going on beam at the end of the year !

Thanks for your kind attention



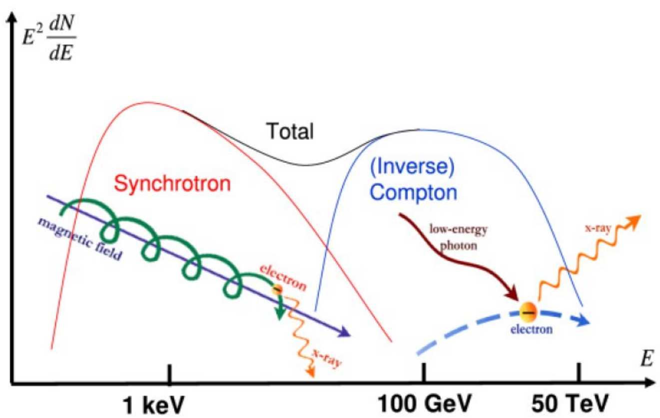
A 10 MeV γ photon undergoing triplet conversion in argon at 5 bar (EGS5 simulation).

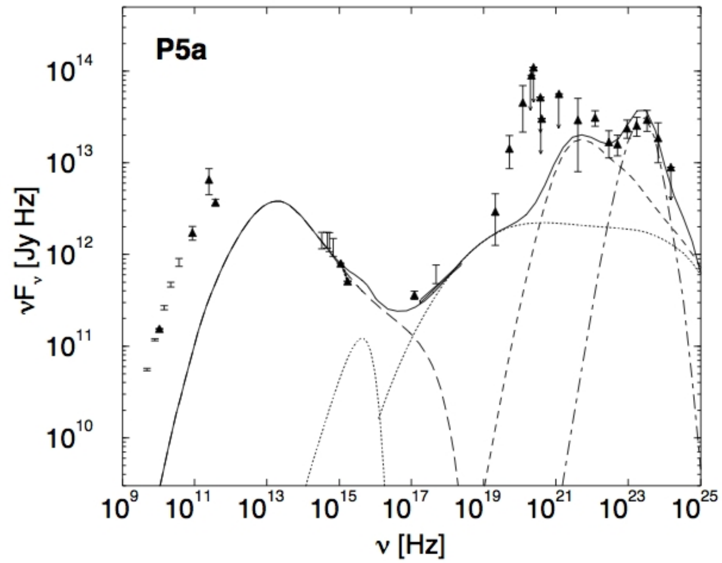
Back-up slides

Cosmic γ-ray polarimetry : AGN's

Example : 3C279

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





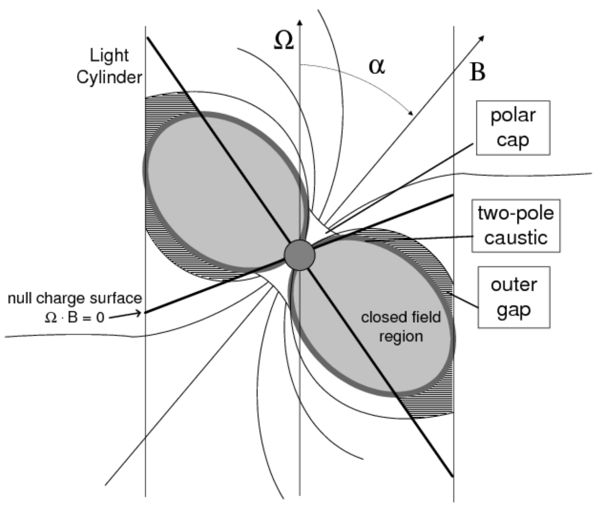
From left to right :

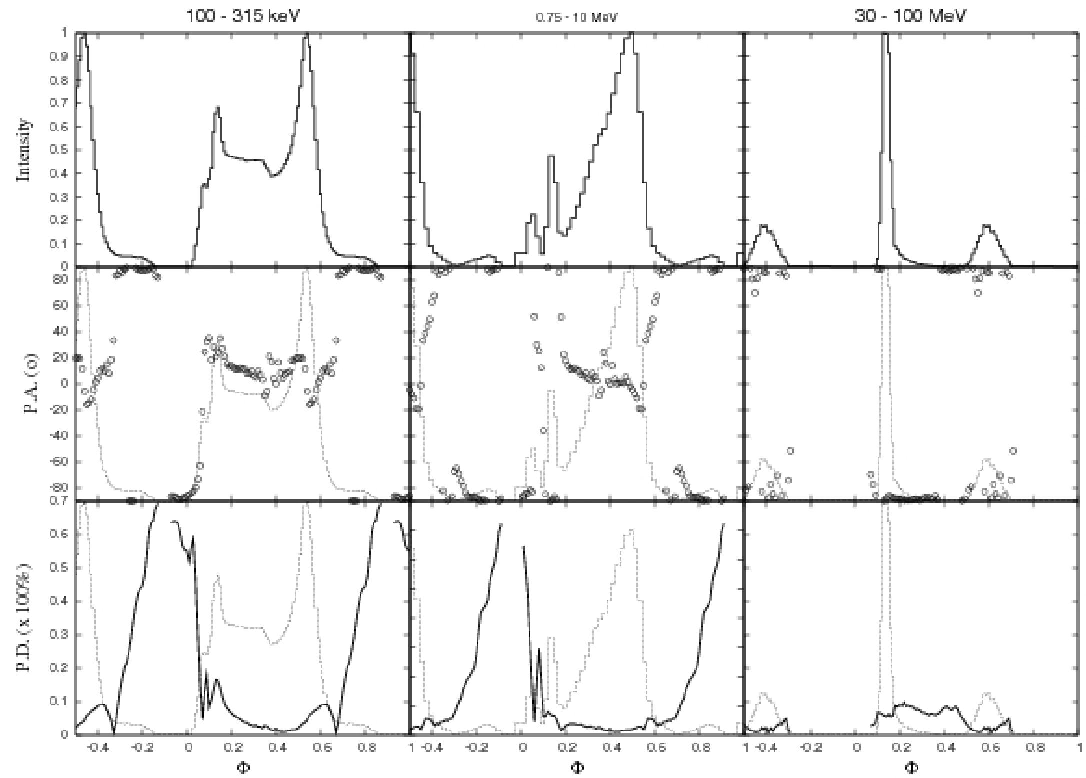
- synchrotron
- thermal from accretion disk
- SSC synchrotron-self Compton
- Compton on accreation disk photons
- Compton on photons from gas clouds

- 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

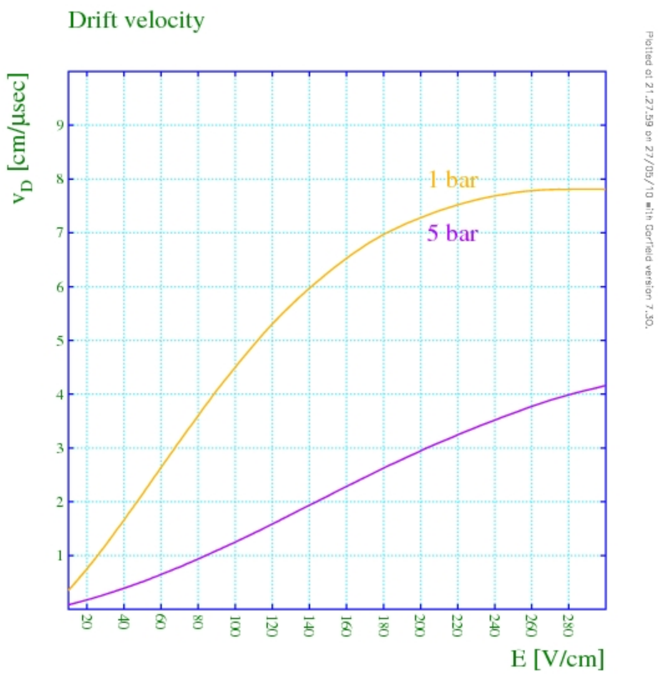
		$F(E_\gamma > 100\,MeV)$ $, ph\,cm^{-2}\,s^{-1}$	Γ	δ	Flux COMPTEL $ph\,cm^{-2}\,s^{-1}$
South :					
	Vela	$(834 \pm 11) \times 10^{-8}$	1.7	-45	$(1-30)\,MeV\;:\,8 \times 10^{-5}$.
North :					
	Geminga	$(353 \pm 6) \times 10^{-8}$	1.7	+17	$(2-10)\,MeV\;:\,6 \times 10^{-5}$.
	Crab	$(226 \pm 5) \times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

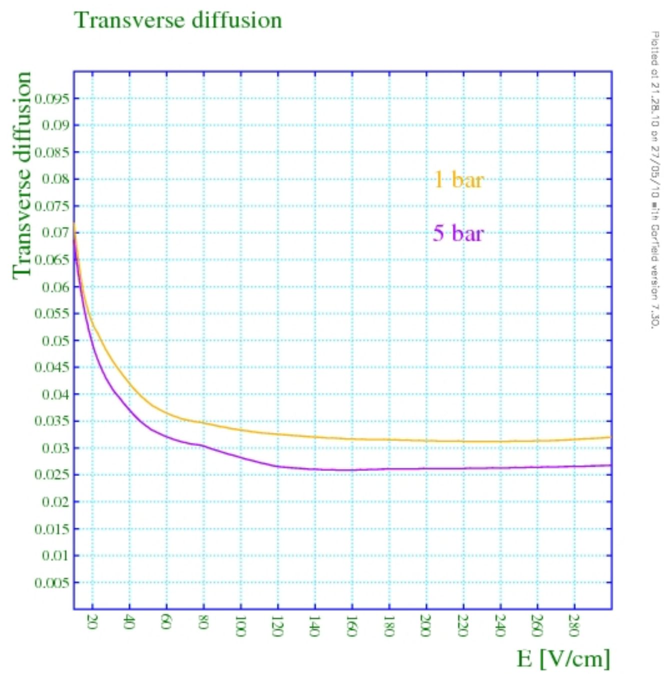
Typical target : $\Gamma = 2$, $f = 1\,\mathrm{MeV}/\,m^2\,s$.

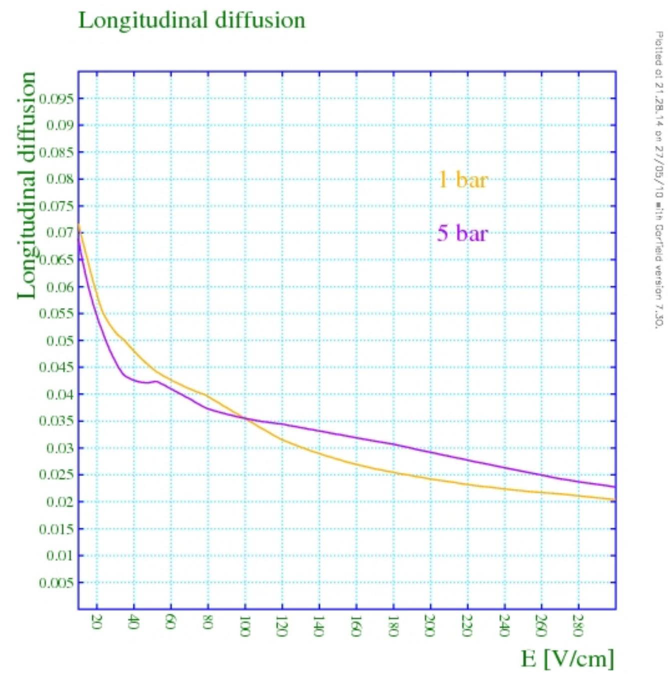
$$\frac{\mathrm{d}F}{\mathrm{d}E}(E) = f\frac{1}{E^2}$$

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







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

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.

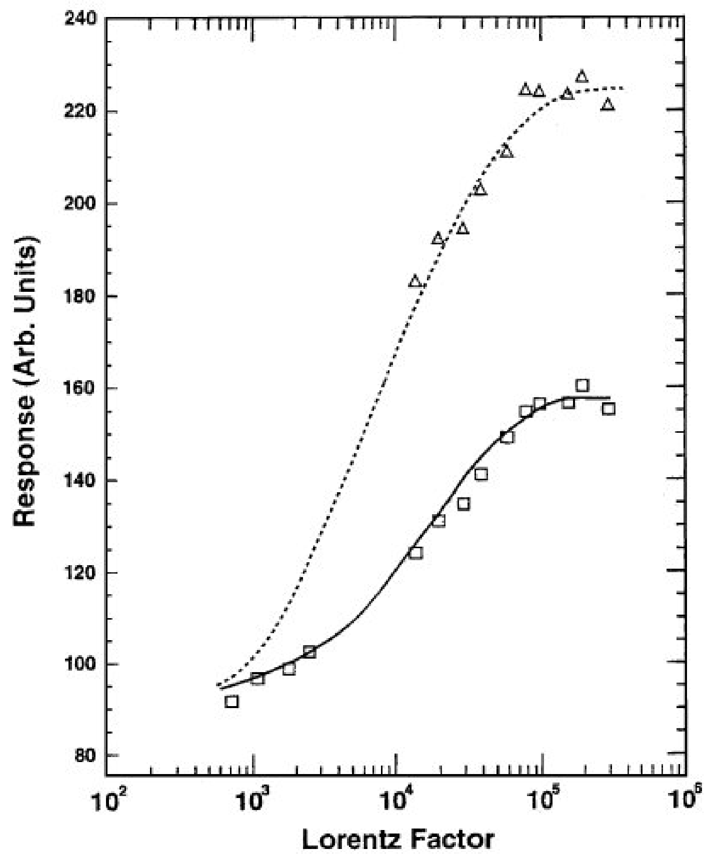


Fig. 8. Average signal versus Lorentz factor for a composite radiator/detector configuration consisting of plastic foils, foam, and fibers (triangles), and for a radiator of parallel Mylar foils of 76 µm thickness (squares). Note that the signal reaches saturation around $\gamma \approx 10^5$.

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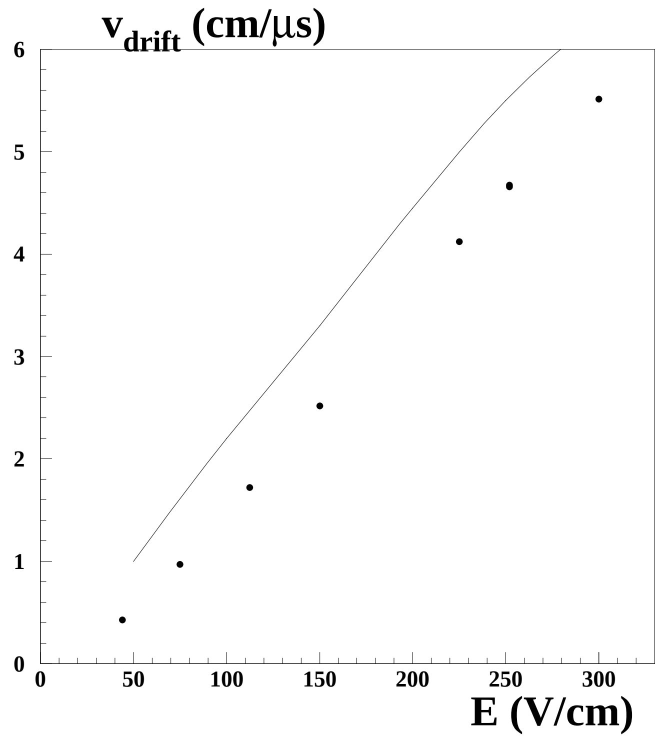
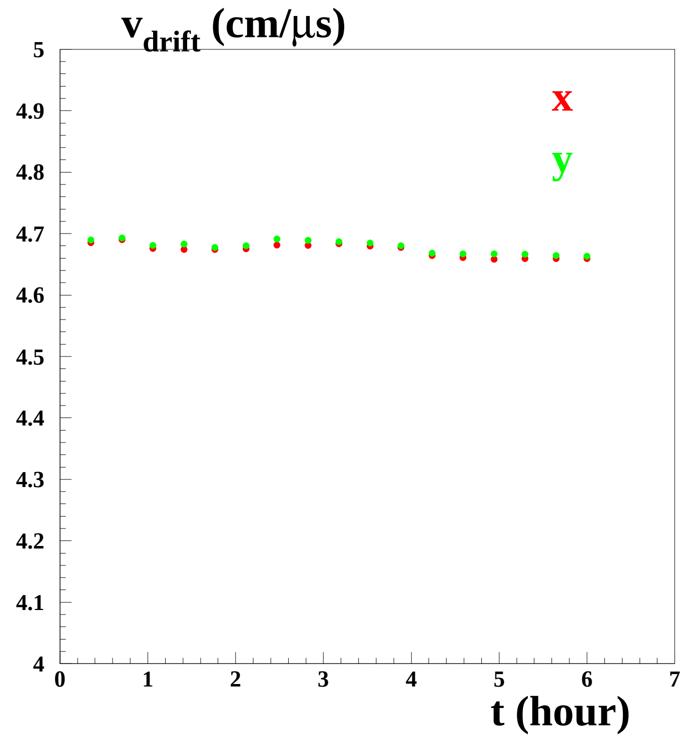
v_{drift} and t_0 calibration

- 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