High-angular-precision γ-ray astronomy and polarimetry.

From the MeV to the TeV

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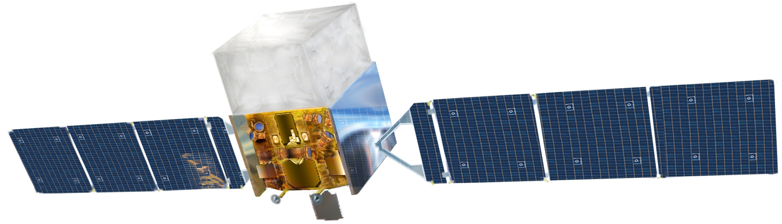
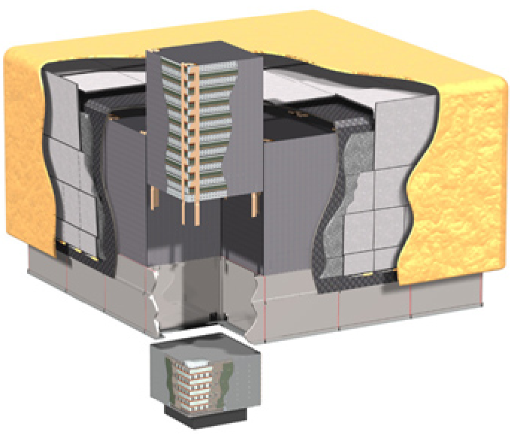
6th Int' Conference On New Developments In Photodetection
NDIP 2011, 4-8 Jul 2011, Lyon, France

GLAST / Fermi



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

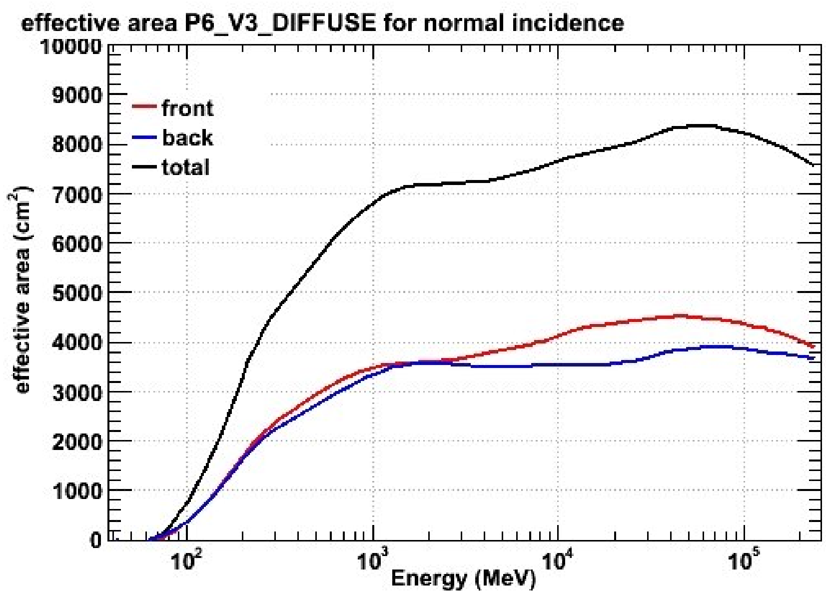
- Impressive harvest on vast programe :
  pulsars, active galactic nuclei (AGN), gamma-ray bursts (GRB), binary stars, supernova remnants ...
- E_γ range 20 MeV - 300 GeV
- 16-plane **Converter/Tracker W/Si** $(1.1 X_0)$
- 8-layer CsI :Tl **Calorimeter CsI :Tl** $(8.6 X_0)$
- Segmented scintillator cosmic-ray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

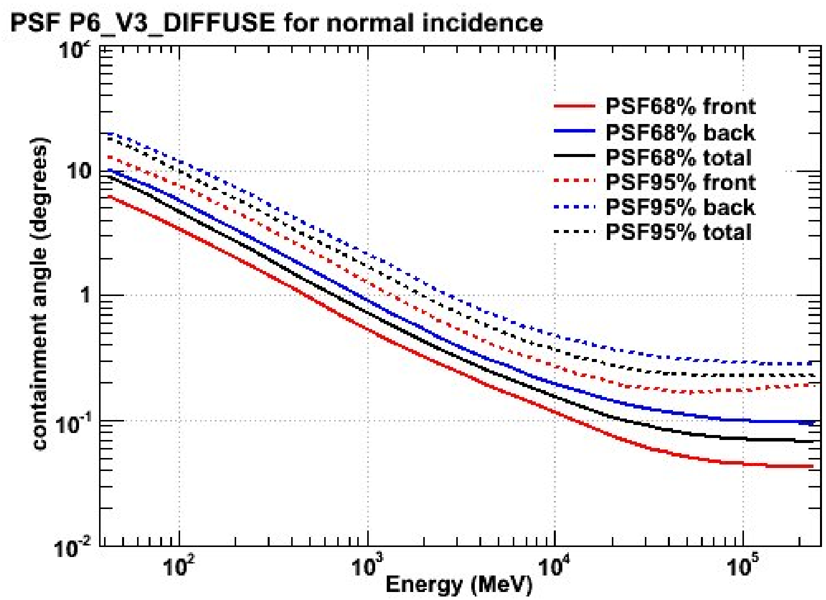


Fermi

– 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_{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's, pulsars, GRB's ..)

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

  – jets of relativistic matter impinging on intra galactic matter

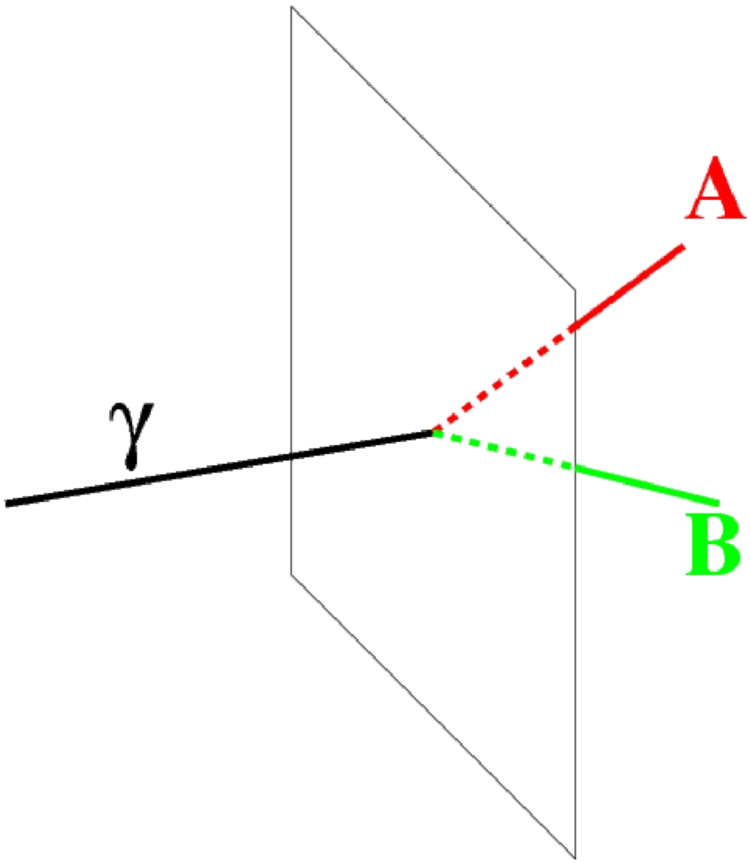
    - hadronic interactions $\rightarrow \pi^0$'s $\rightarrow \gamma$'s : $P = 0$

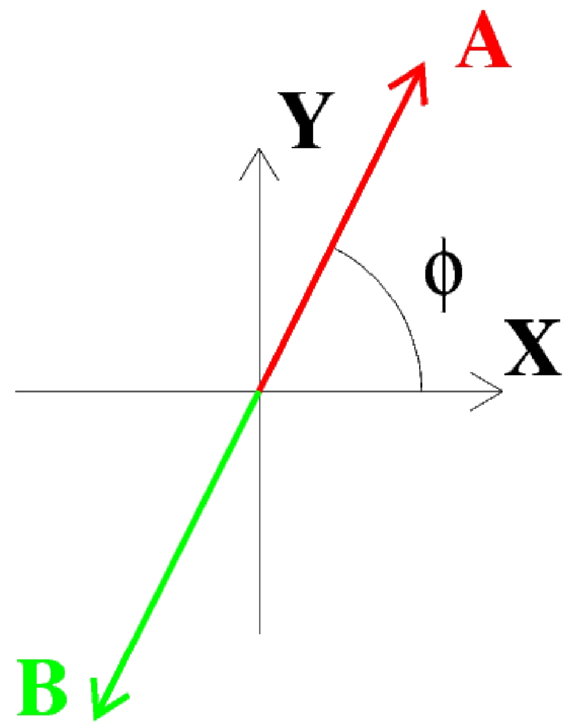
  – Radiative processes (synchrotron, inv Compton) : P up to 70%

    - Synch : Turbulence of $\vec{B}$ "dilutes" P : measurement of turbulence.

Linear Polarization !

Modulation of the azimutal angle of the debris





– ϕ azimuthal angle

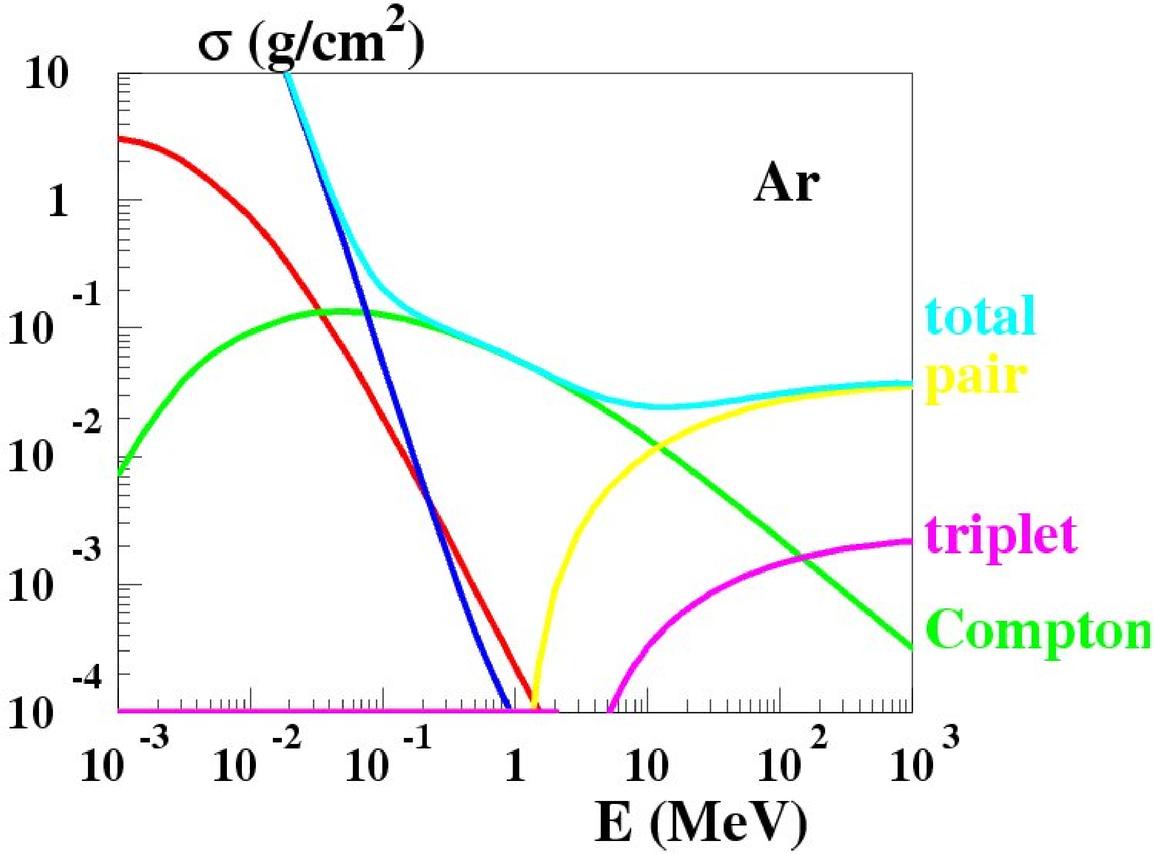
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P\cos[2(\phi - \phi_0)])$$

Photon interaction with matter

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

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

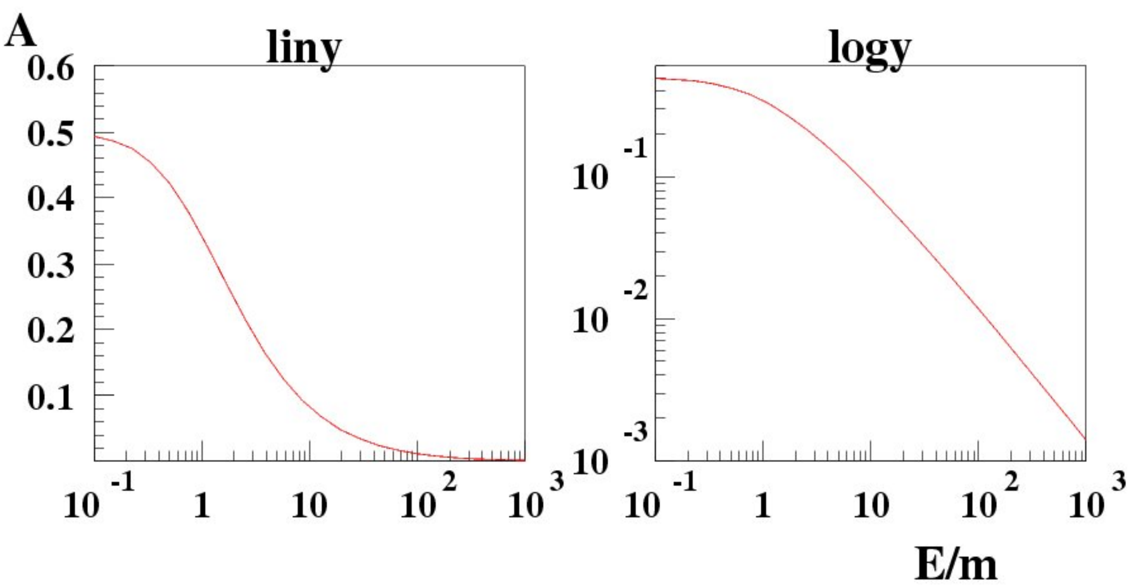
"Triplet" pair production : $\gamma e^- \rightarrow e^- e^+ e^-$

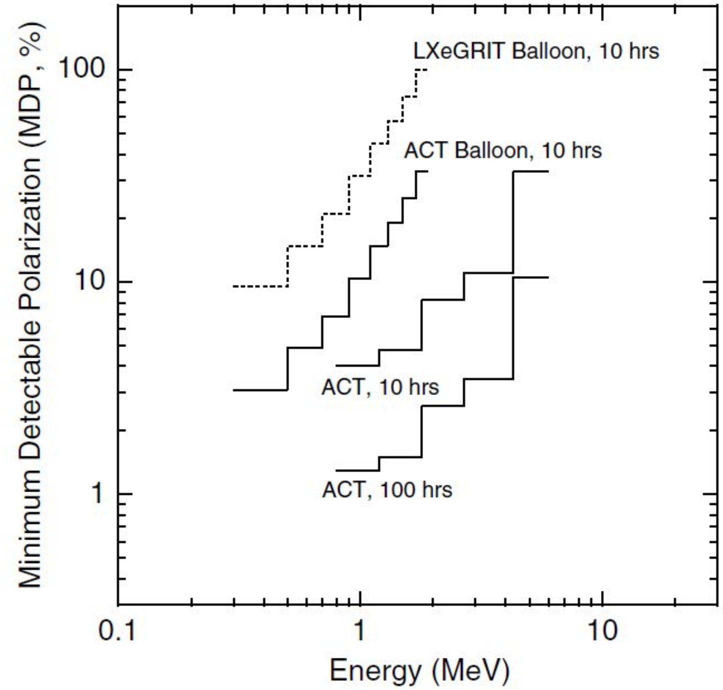


Compton

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

New Astr. Rev. 48 (2004) 215

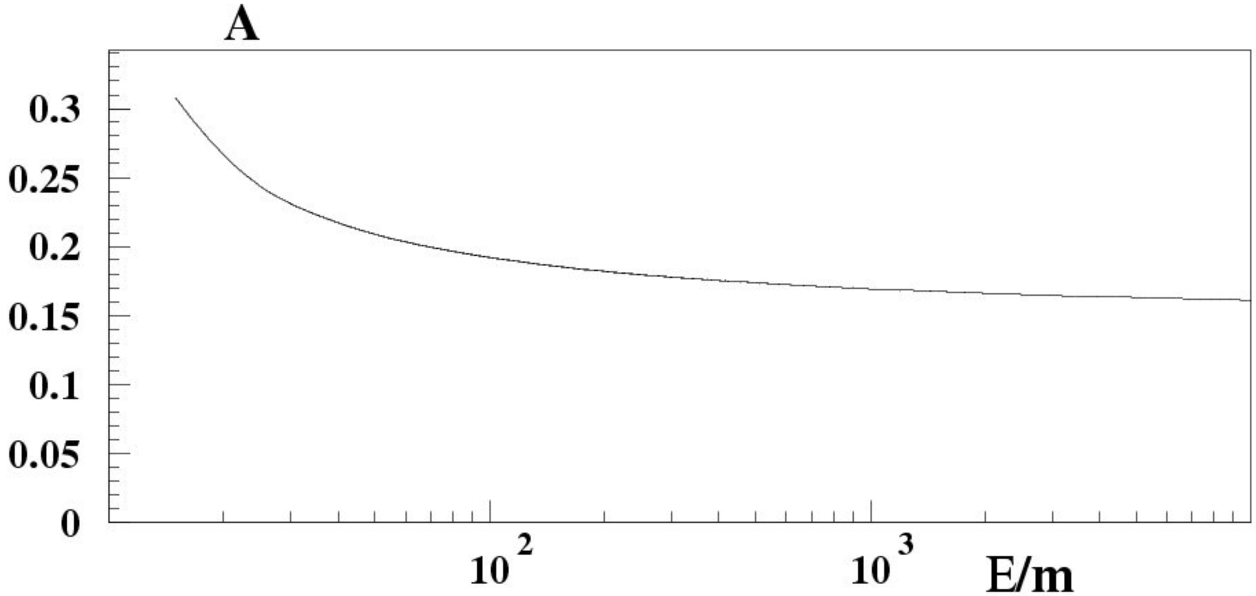




Low sensitivity for $E >$ few MeV

"Nuclear" pair production : in principle

In principle : very good



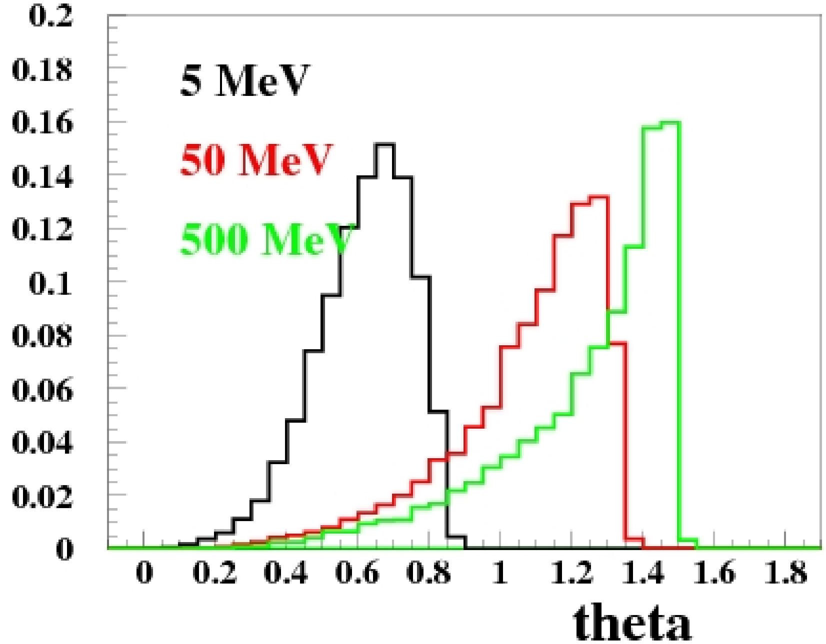
- Dominates cross section at high energy
- $\mathcal{A} \approx 0.2$ at high energy

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.

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

– The recoiling electron is emitted at a large angle



– Triplet / pair $\sim 1/Z$ at high energy.

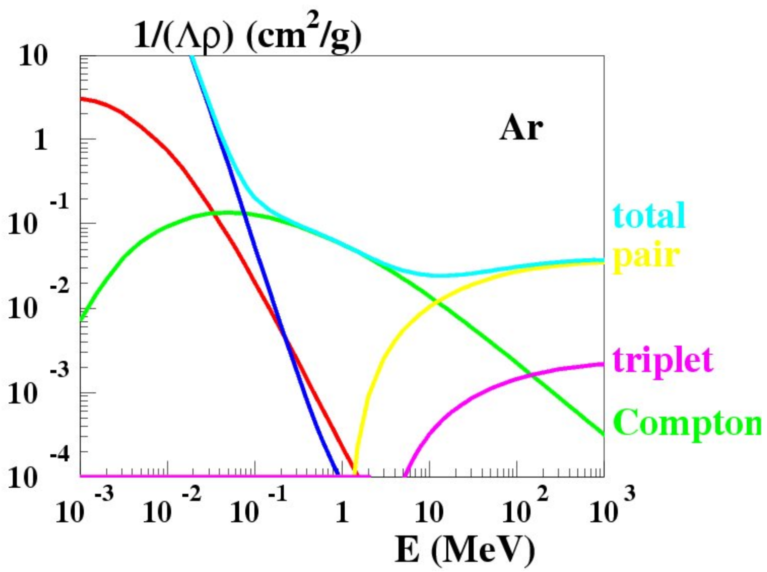
– Same asymmetry at high energy.

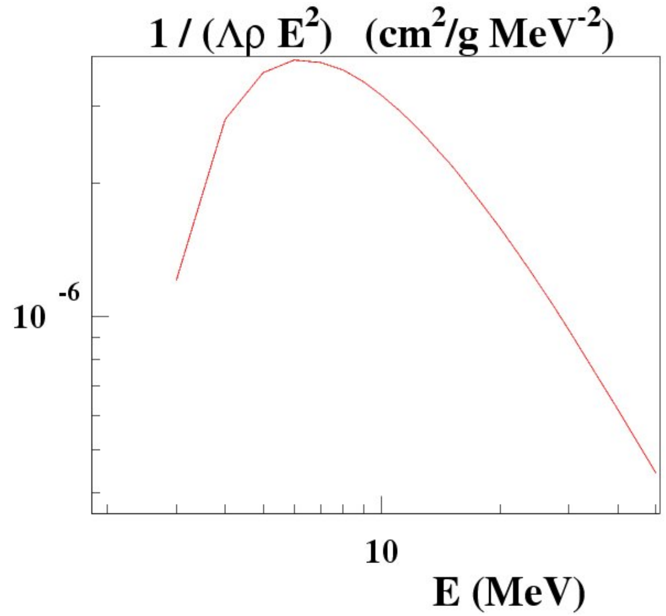
– 6 additional Feynman diagram (wrt "Nuclear" pair production)

- Dominated by the same two at high energy.

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

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

- $2\%/\sqrt{year.ton}$

$\approx Z$-independant.

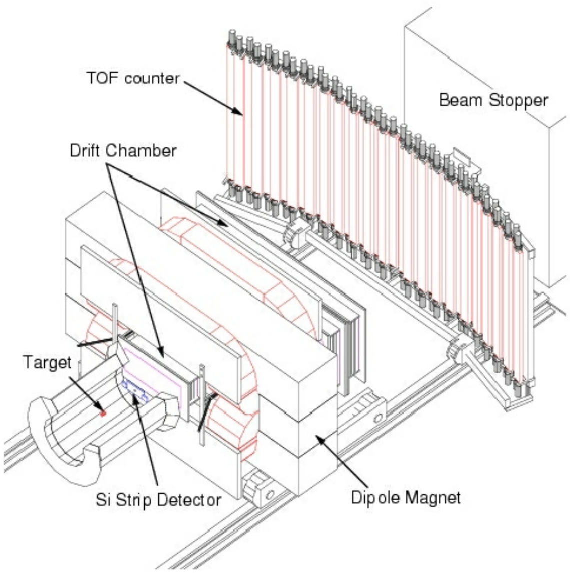
The only validation ..

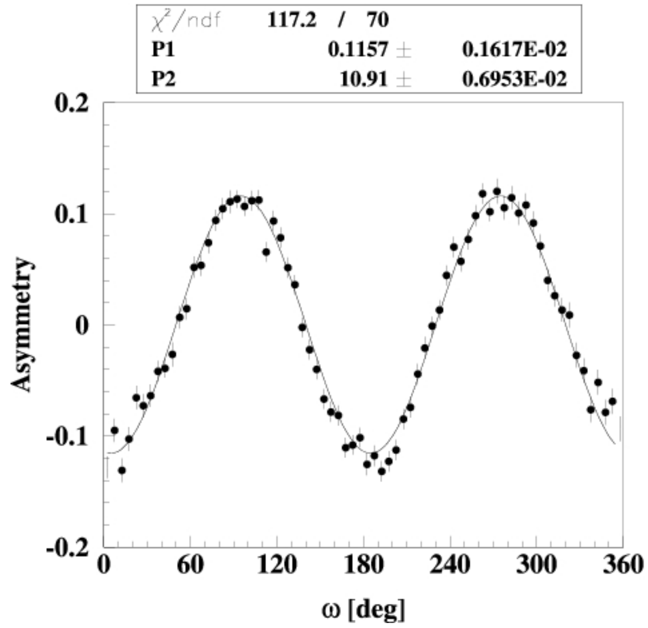
Was performed :

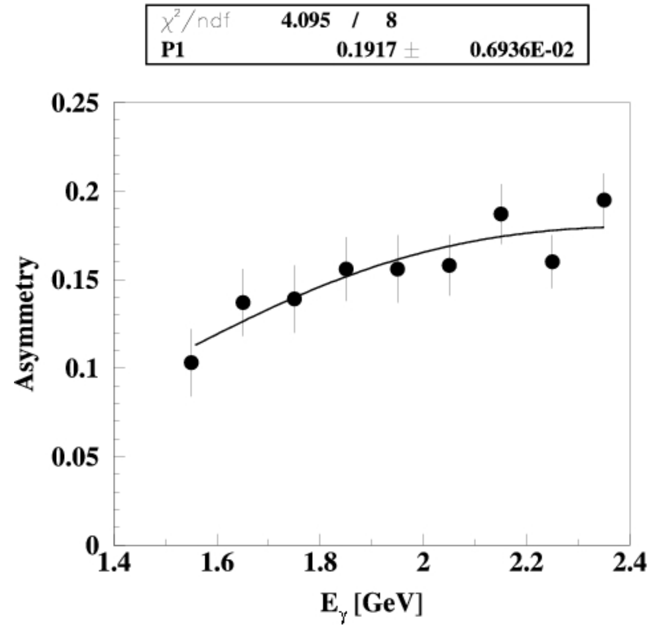
– For nuclear pair production,

– and : at high Energy

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



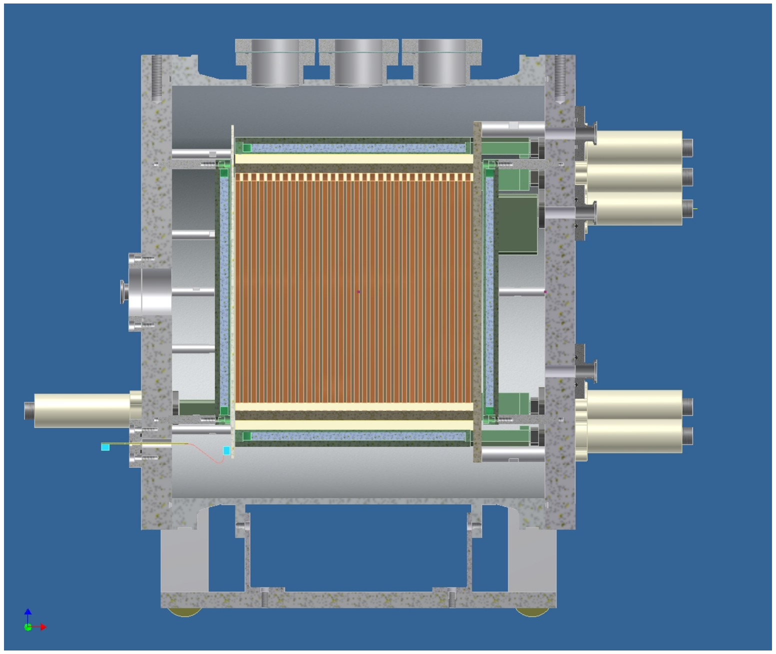




de Jager, et al., Eur.Phys.J.A19 :S275-S278,2004.

Our project

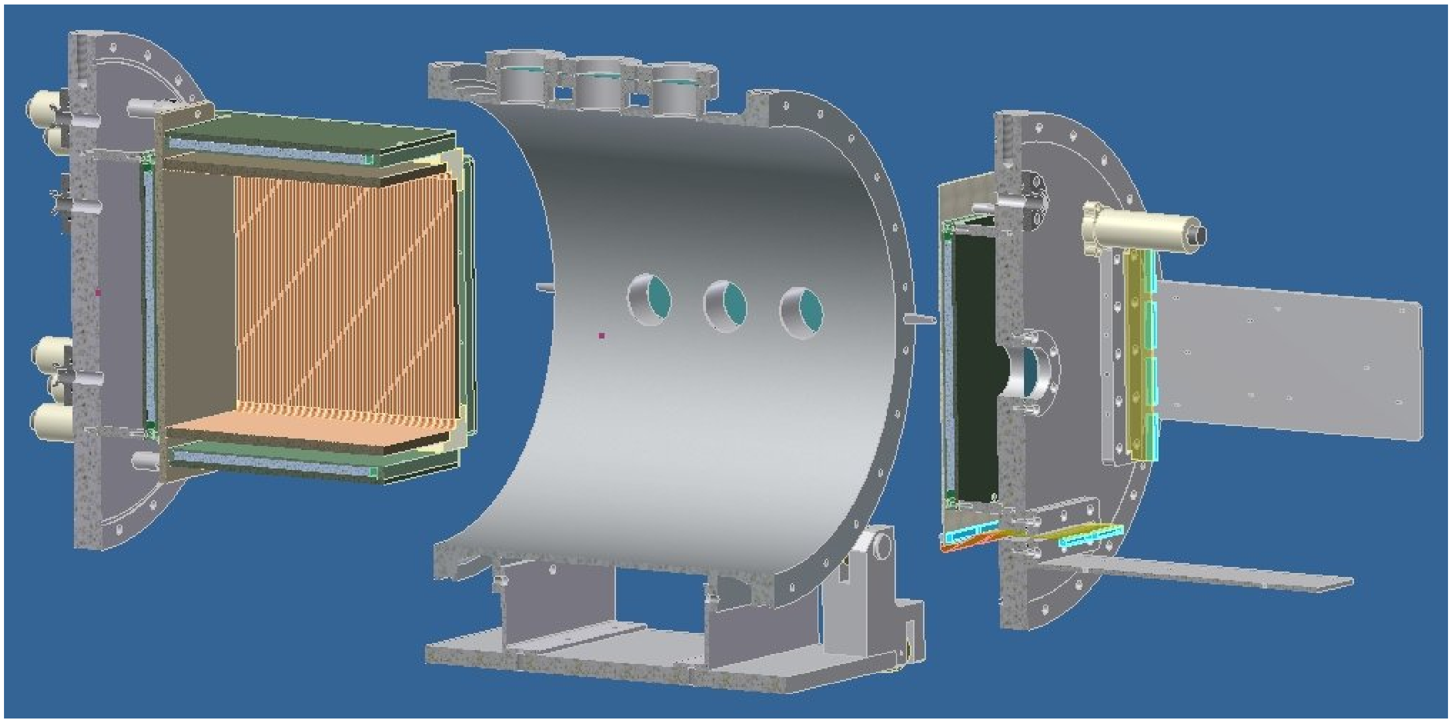
- Characterize the Time Projection Chmber (TPC) technology for γ astronomy and polarimetry
- 1rst measurement of $\mathcal{A}$ at low energy.



Demonstrator :

- 30 cm cubic TPC, 5 bar, Argon-based mixture (à la T2K)
- pitch 1mm, spatial resolution 1 mm
- trigger : scintillator + WLS + PMT.

Detector Layout : 2

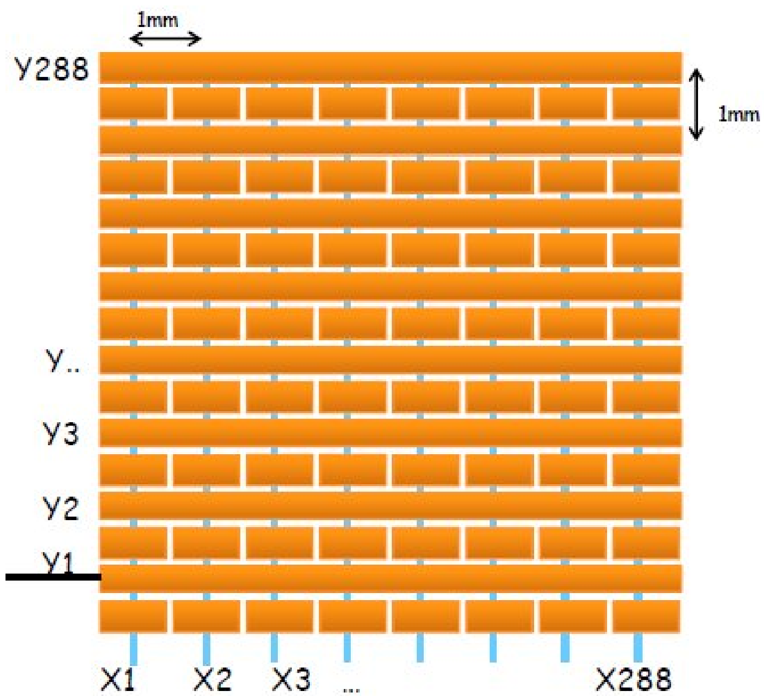


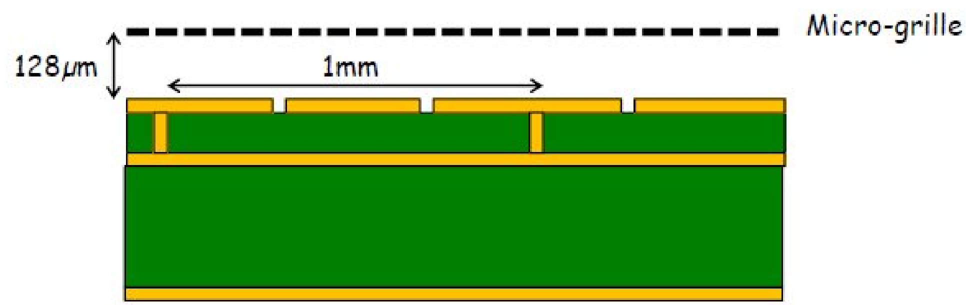
Al vessel, H =500 mm, Φ =500 mm

Amplication – collection – sampling

- Amplification by micro-mesh micromegas

NIM A 608 (2009) 259

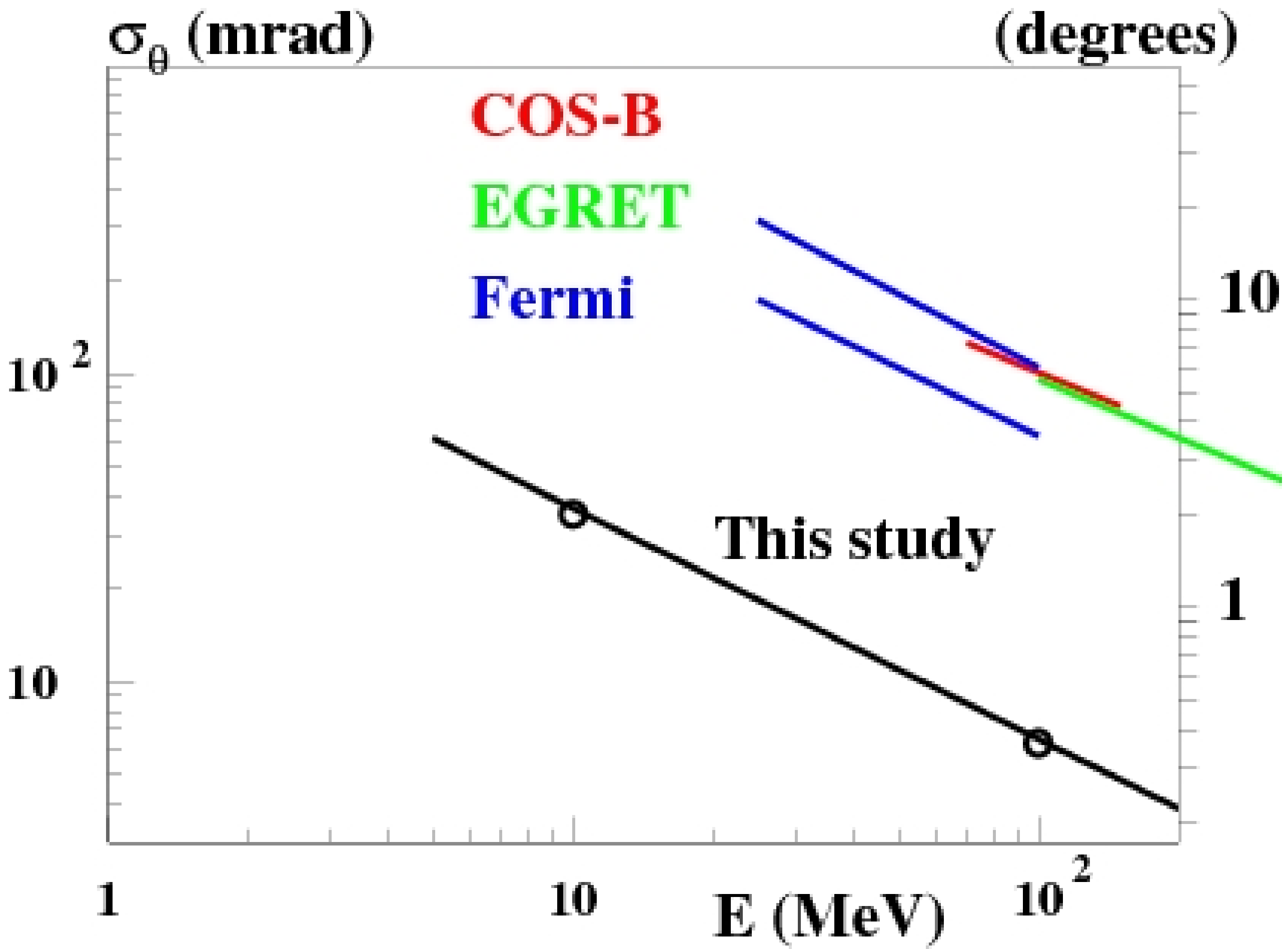




- Signal collection by strips on PCB, pitch = 1mm
- Sampling / acquisition performed by AFTER chip

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

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.

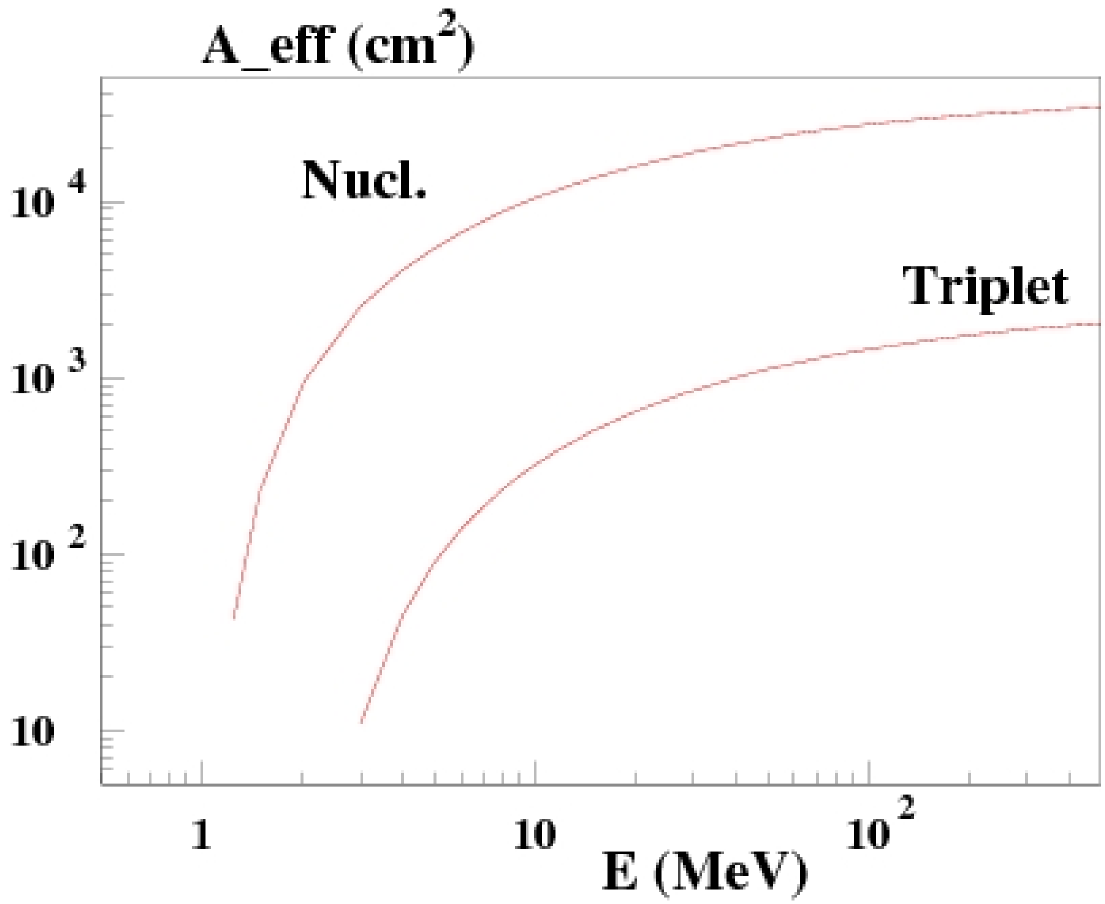
– Thin detector ($L \ll X_0$) :

- 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 thinh technologies.

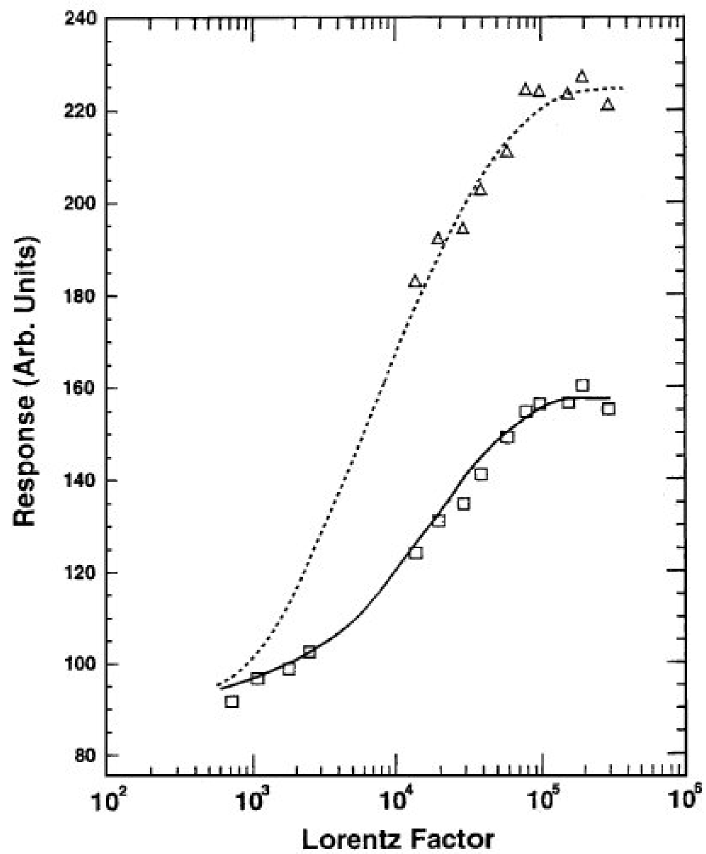


Fig. 8. Average signal versus Lorentz factor for a composite radiator/detector configuration consisting of plastic foils, foam, and fibers (triangles), and for a radiator of parallel Mylar foils of 76 μm thickness (squares). Note that the signal reaches saturation around $\gamma \approx 10^5$.

NIM A 531, 435 (2004).

General Schedule

- 2008-9 : Studies
- 2010 : Engineering design, 1rst funding.
- 2011 : Integration ; cosmic-ray characterisation of the tracker.
- 2012 : Data taking, polarized γ rays, Hyôgo, Japan.

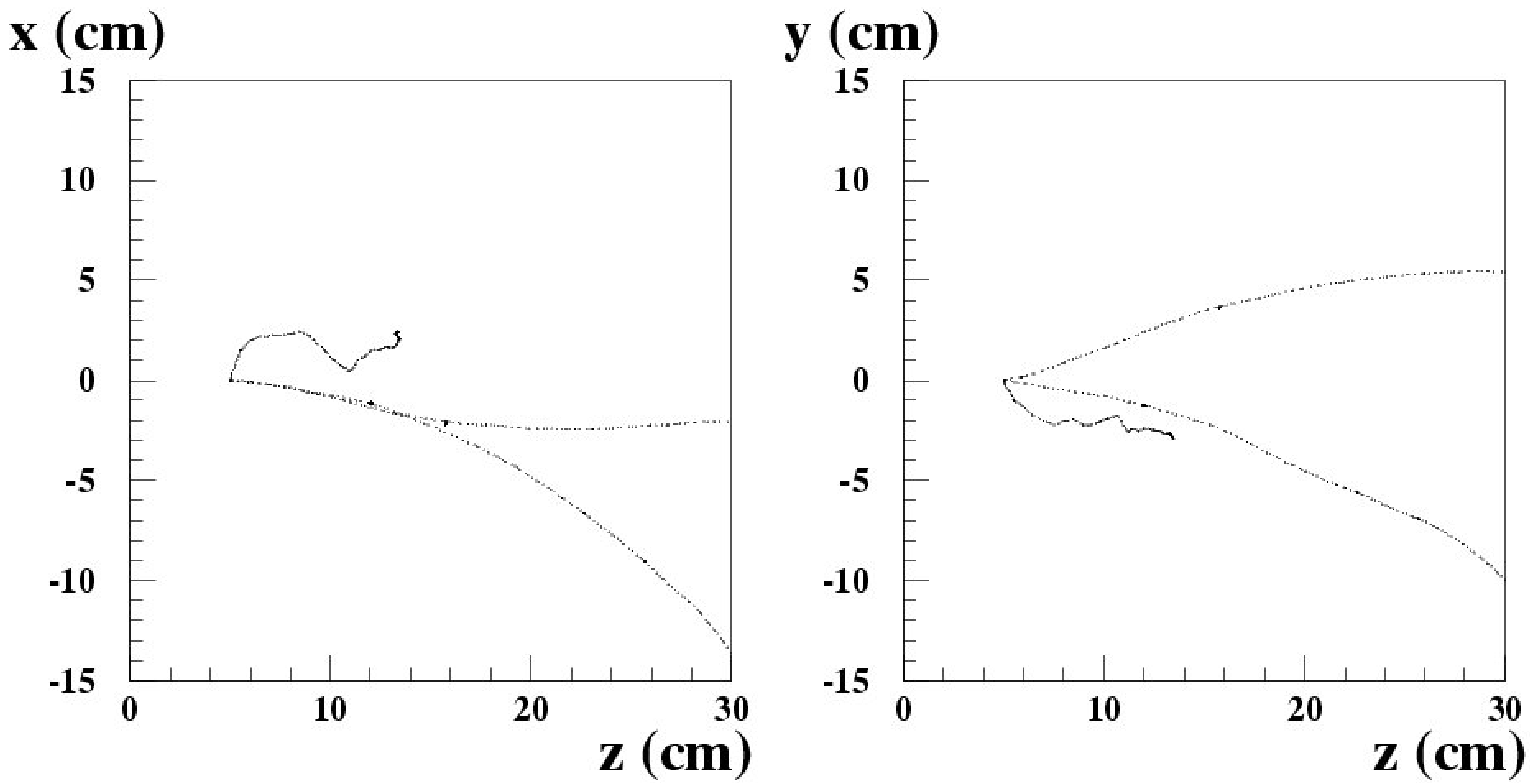
Conclusion

A thin detector, such as a TPC, can be a telescope and a polarimeter,

- With angular resolution 1/10 smaller 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
- Rejection of the (huge at low energy) γ albedo is obvious from tracking
- a TPC is a dead-time free GRB detector (but watch the deadtime of the electronics !)

Fermi might well be a the last thick and polarization insensitive γ mission ..

Thanks for your kind attention



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

Back-up slides

Measurements at SPring-8 / Subaru : 2012

Linearly polarized γ beams : Compton scattering, linearly polarized laser

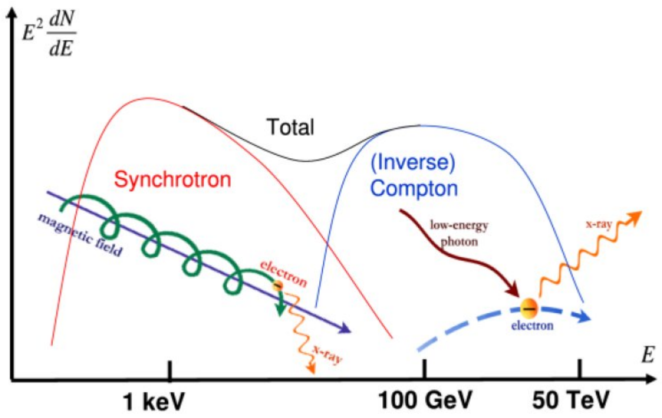
- Spring-8, 8 GeV e^- storage ring
  - 1.5 – 2.4 GeV γ rays Eur.Phys.J.A19 :S275-S278,2004
- New Subaru 1.5 GeV e^- storage ring
  - 2 - 70 MeV γ rays Aoki *et al.*, NIM A 516 (2004) 228

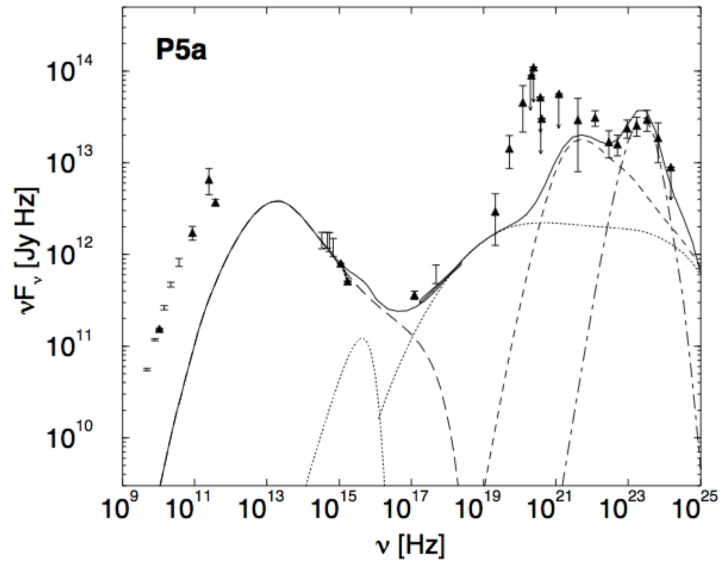
    Amano *et al.*, NIM A 602 (2009) 337

Cosmic γ-ray polarimetry : AGN's

Example : 3C279

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





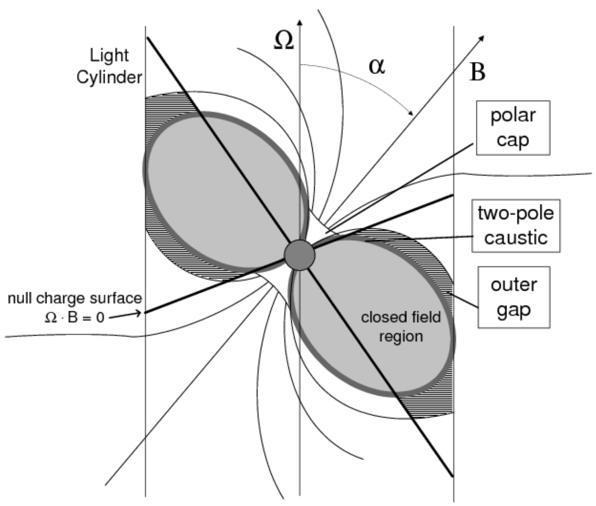
From left to right :

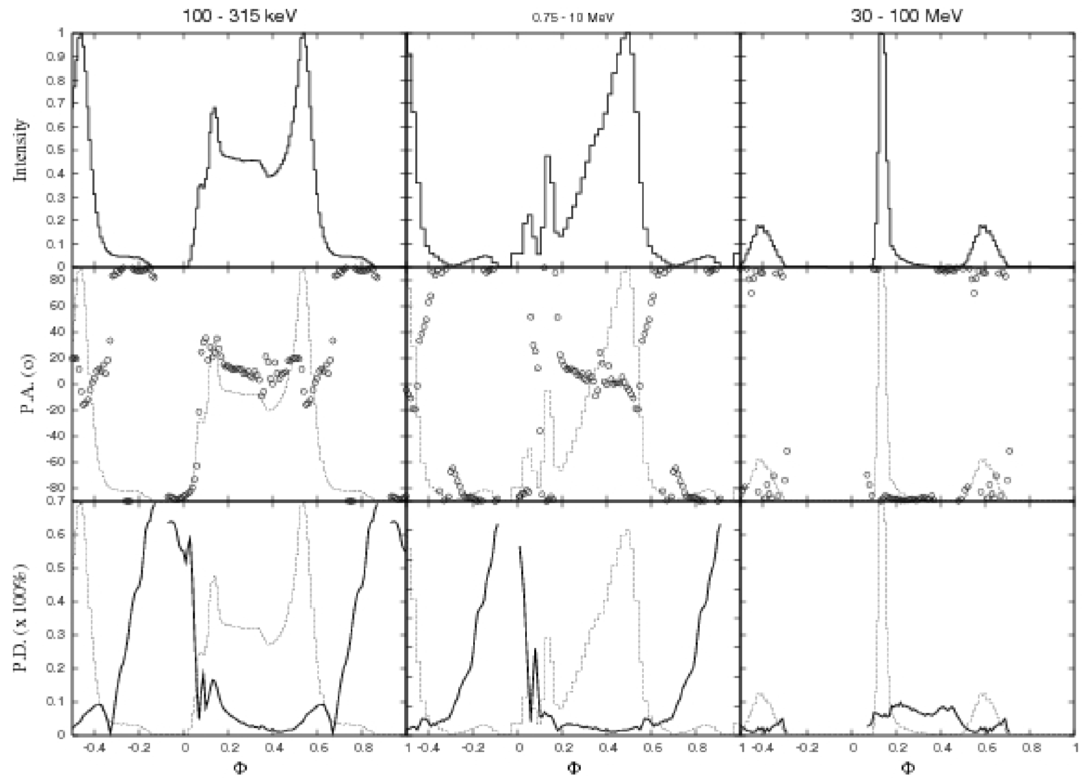
- synchrotron
- thermal from accretion disk
- SSC synchrotron-self Compton
- Compton on accreation disk photons
- Compton on photons from gas clouds

- 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

		$F(E_\gamma > 100\,MeV)$ $,ph\,cm^{-2}\,s^{-1}$	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 : $\Gamma = 2$, $f = 1\,\mathrm{MeV}/\,m^2\,s$.

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

Gain

- 5 bar, 1 mm, 1250 eV $\Rightarrow$ 62.5 mip electrons
- AFTER noise : 570 e^- @ 10 pF
- 10 $\times$ noise : 5700 e^-,
  $\Rightarrow$ gain $>$ 100 ..

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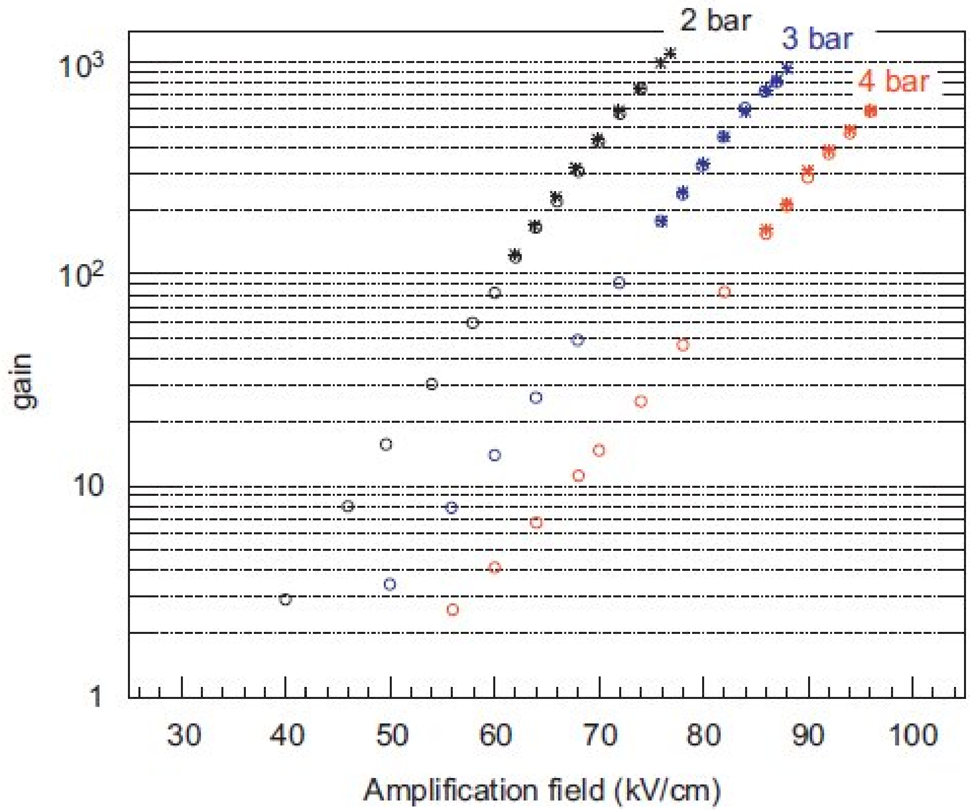
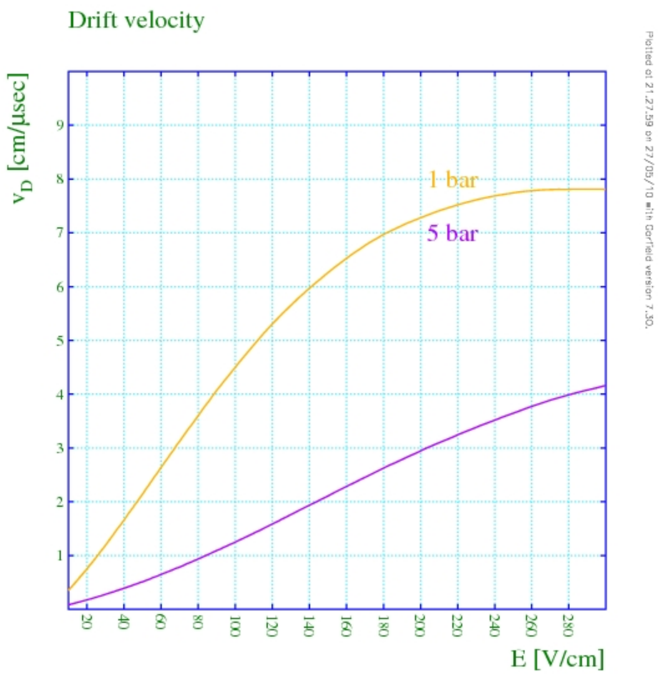
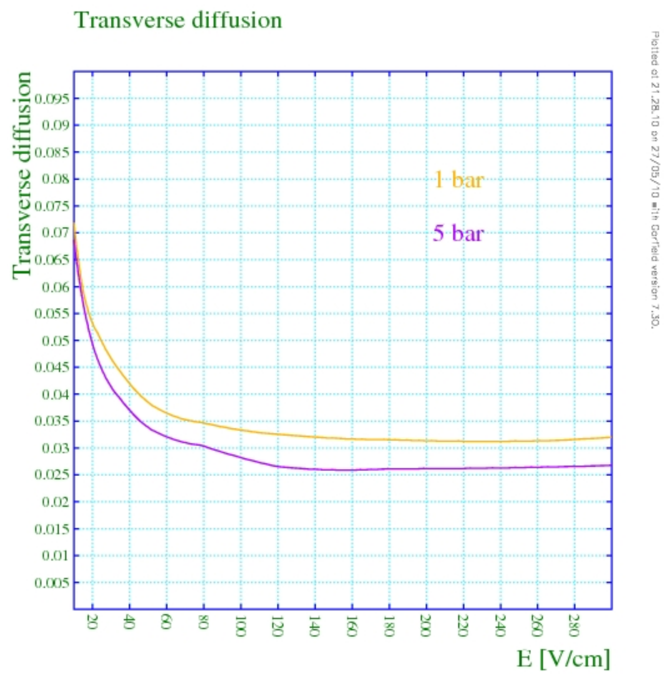


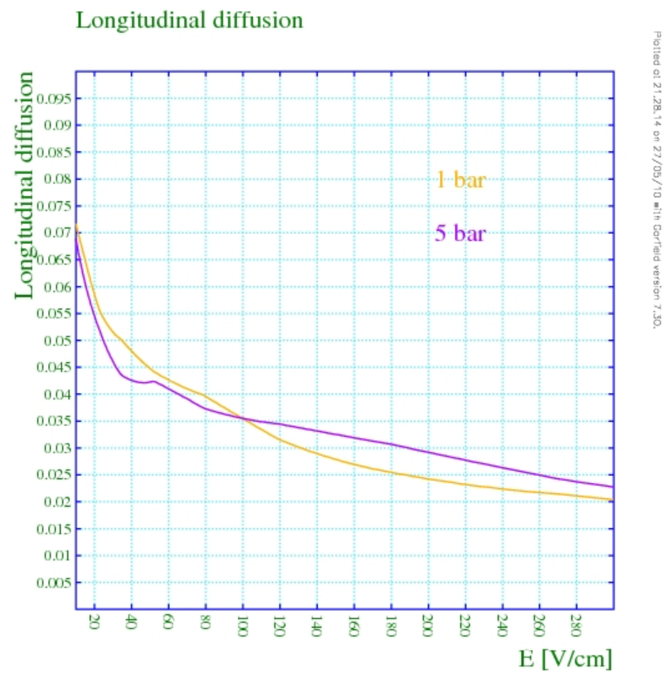
Fig. 5. Gain curves with both alpha (circles) and gamma (crosses) peaks, for Ar + 5% isobutane, at 2–4 bar.

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