HARPO
γ-ray polarimetry and high-angular-precision astronomy, above pair creation threshold

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RD51 Collaboration Meeting
Oct 2010, Bari

Layout

– Introduction
  - Why measure the (linear) polarization of γ-Ray sources ?
  - MeV γ-Ray astronomy : "filling the gap"

– One detector, two functions :
  - γ-Ray polarimetry in the MeV - GeV range
  - High-angular precision γ-Ray astronomy

– HARPO : 2008 – 2012 "ground" phase : One project, Two goals :
  - Experimental characterization of the technique.
  - High precision measurement of the polarization asymmetry

Cosmic gamma ray polarimetry : Why ?

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

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

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

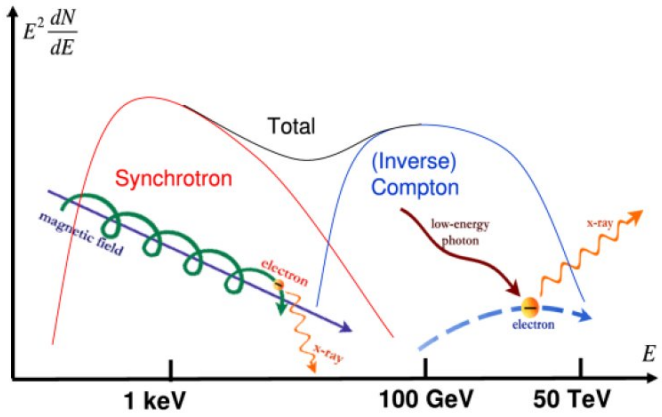
- Radiative processes (synchrotron, inv Compton) : P up to 70%

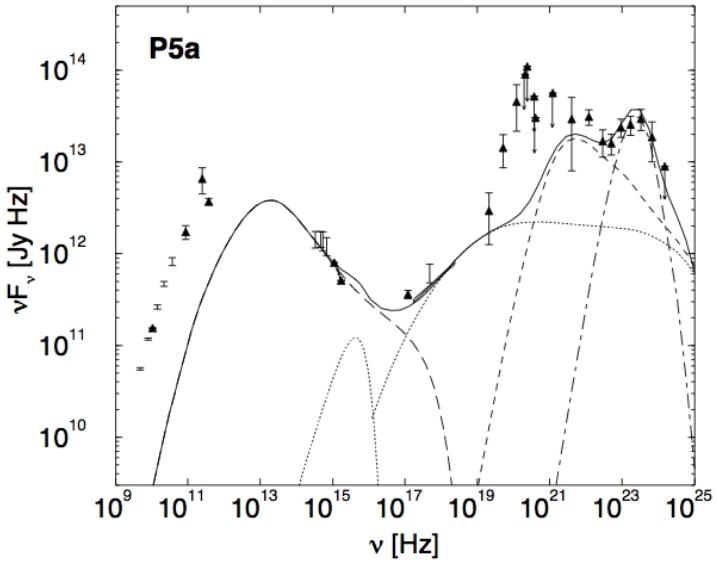
Linear Polarization !

Cosmic gamma ray polarimetry : AGN's

Example : 3C279

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





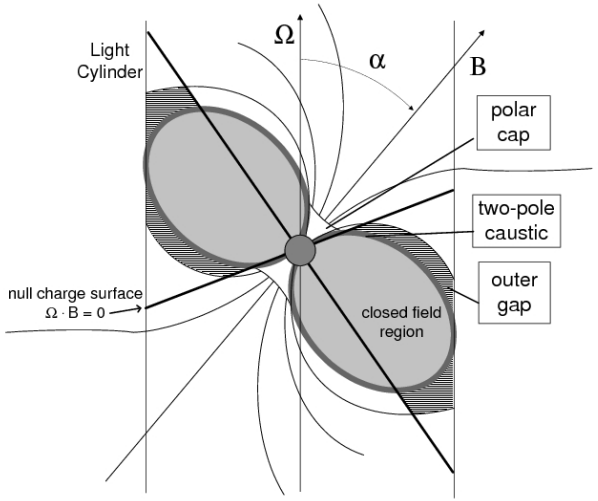
From left to right :

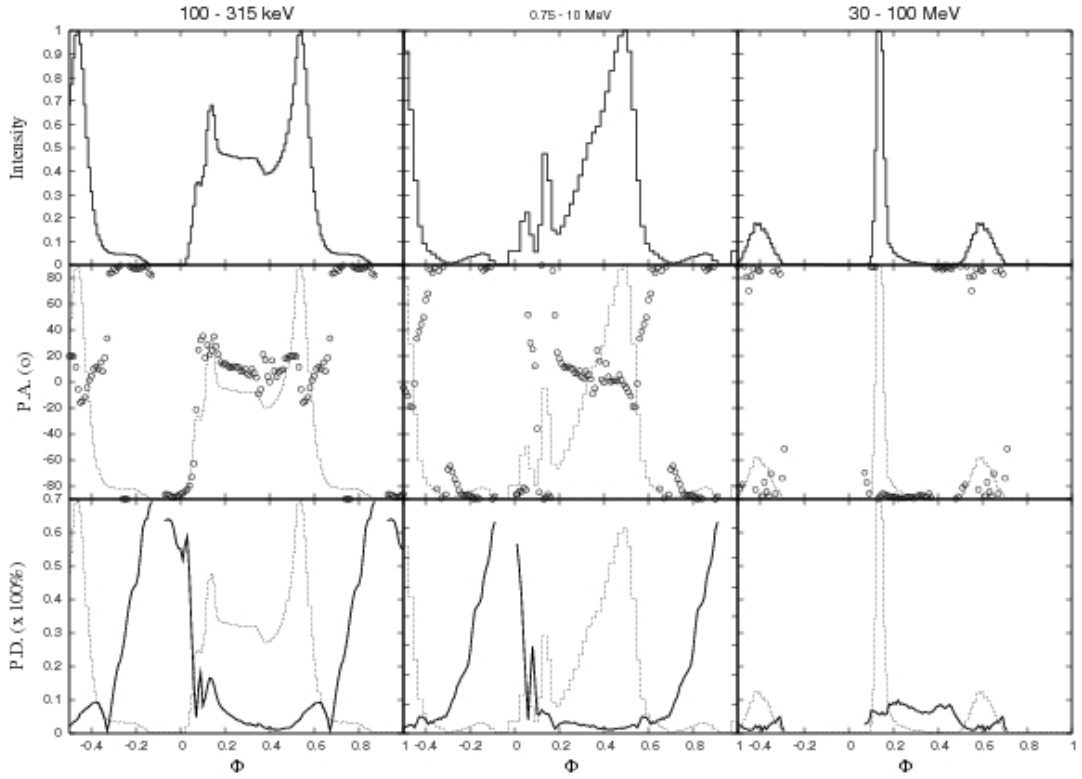
- synchrotron
- thermal from accretion disk
- SSC synchrotron-self Compton
- Compton on accreation disk photons
- Compton on photons from gas clouds

- 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 ?)

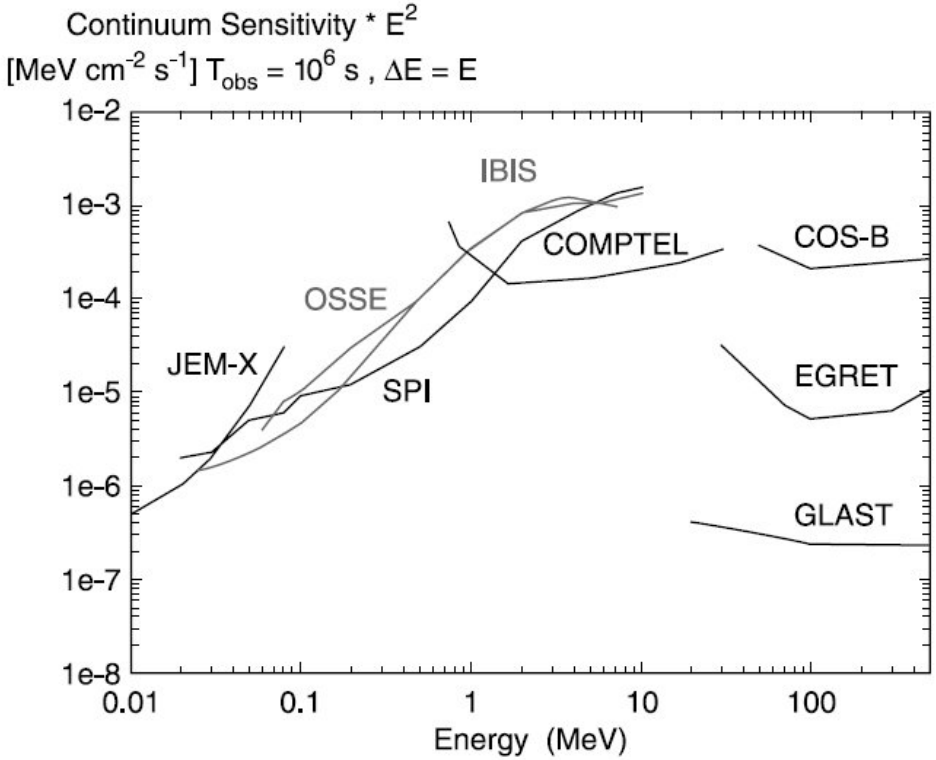
– Most models involve 2 relativistic jets.

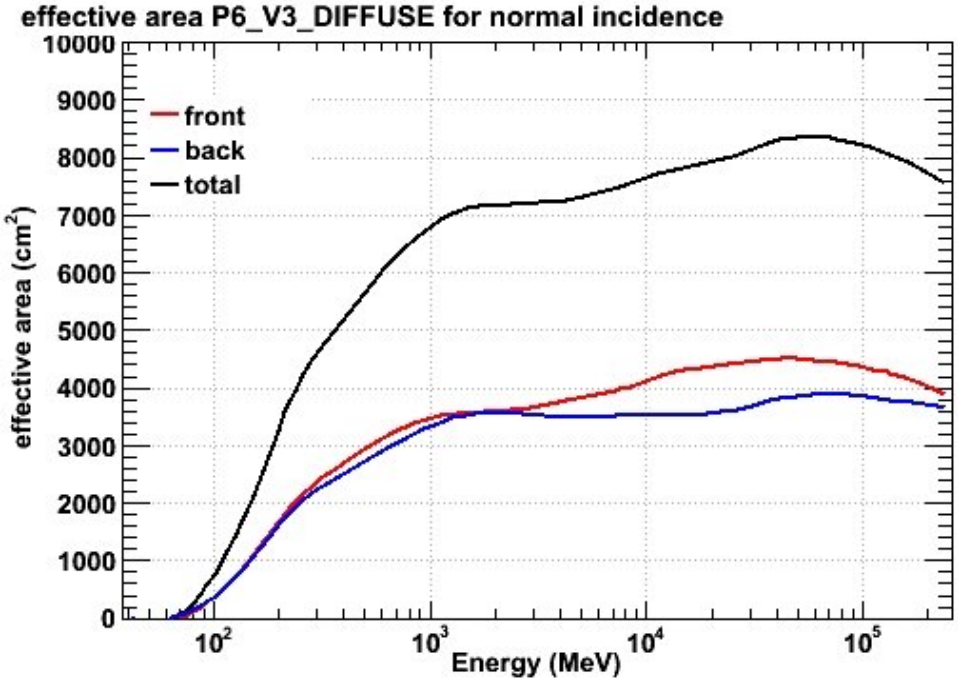
– γ emission ?

- 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.

γ Astronomy : filling the gap



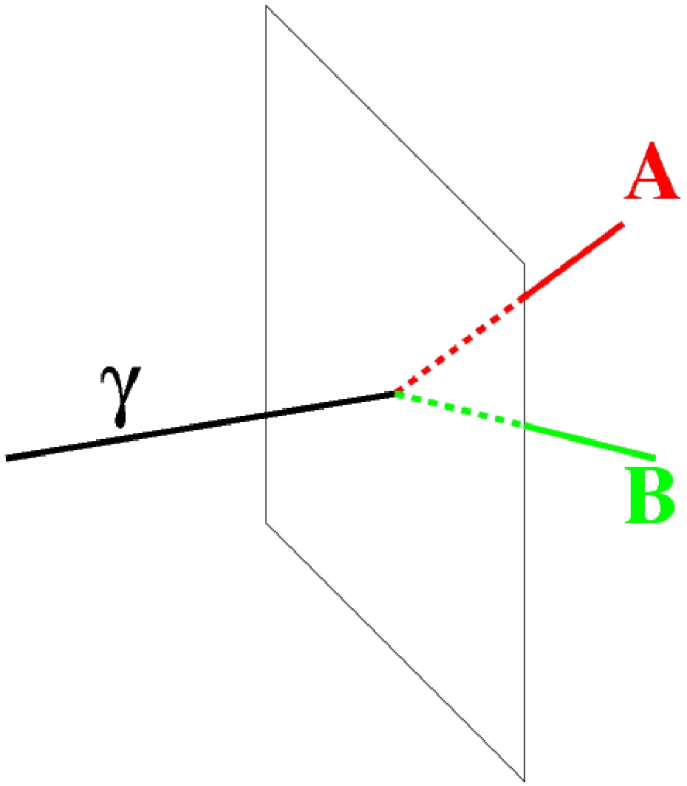


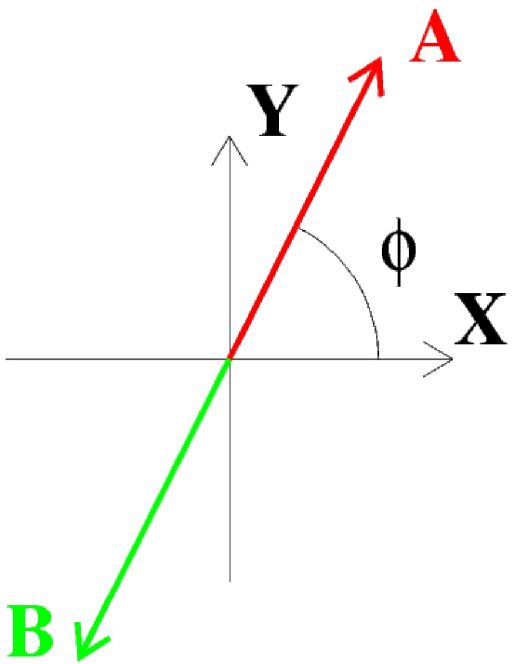
V. Schönfelder, New Astr. Rev. 48 (2004) 193

Fermi LAT Performance web page,

- Good angular resolution key factor in background rejection
- Angular Resolution @ 100 MeV :
  - EGRET 5.5° , Fermi/Glast 4.0°,

Polarimetry :
Modulation of the azimutal angle of the debris





– ϕ azimuthal angle

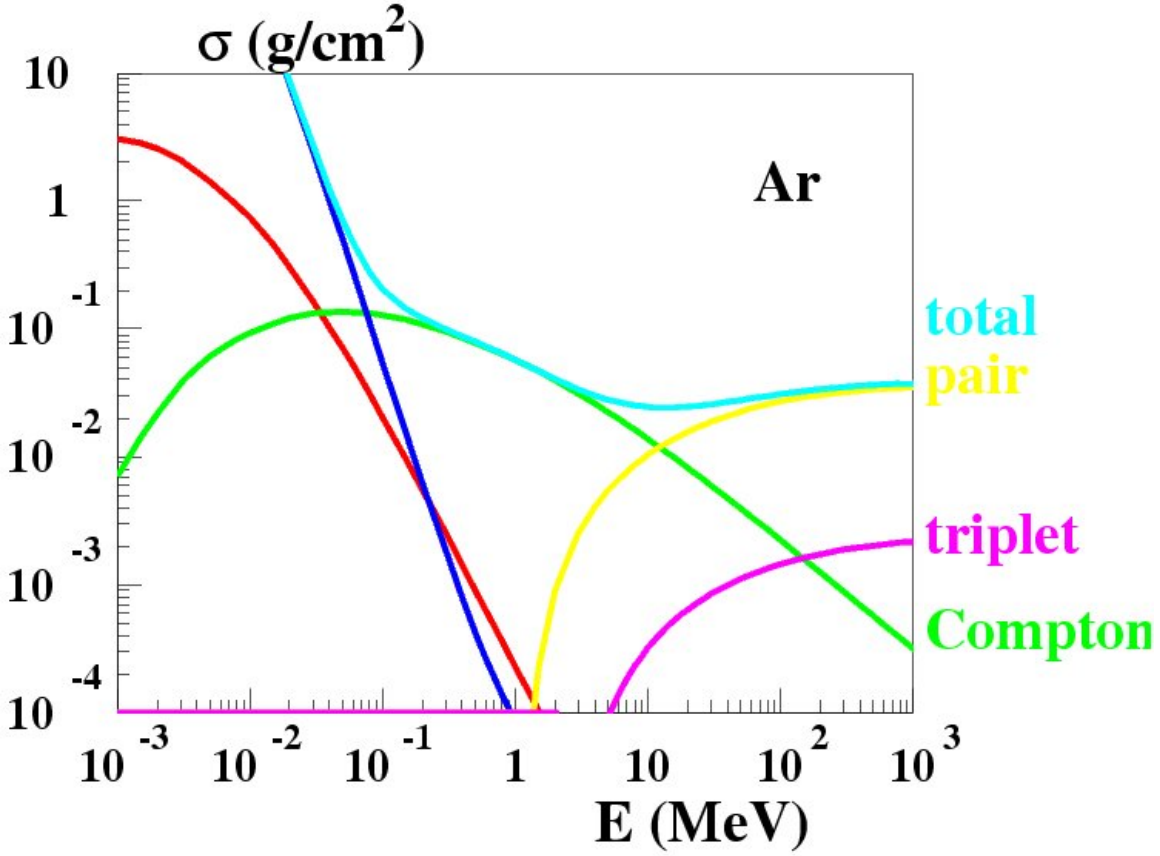
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P\cos\left[2(\phi - \phi_0)\right])$$

Photon interaction with matter

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

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

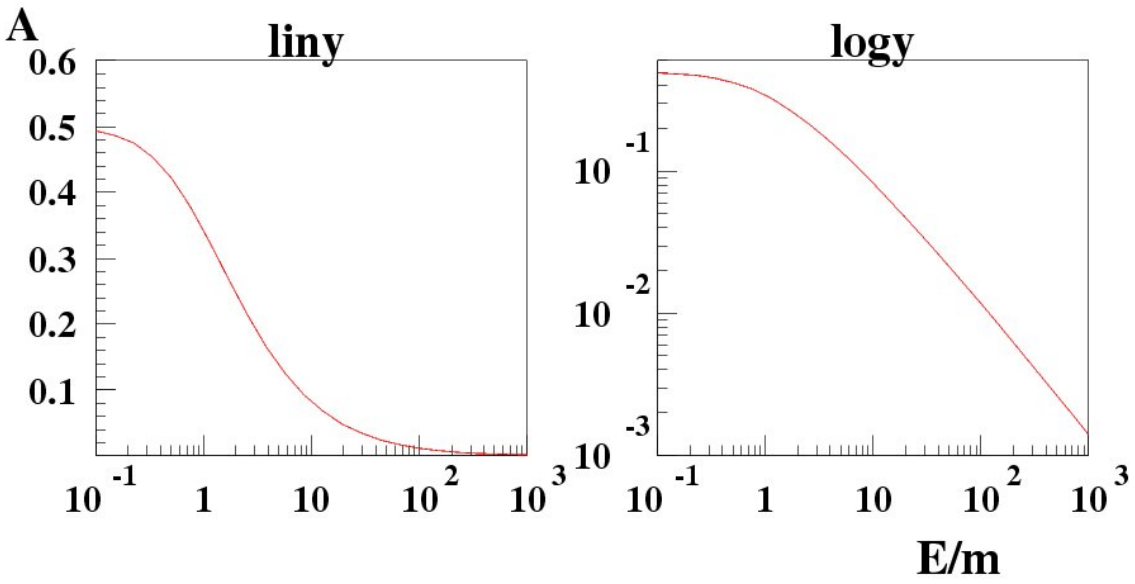
"Triplet" pair production : $\gamma e^- \rightarrow e^- e^+ e^-$

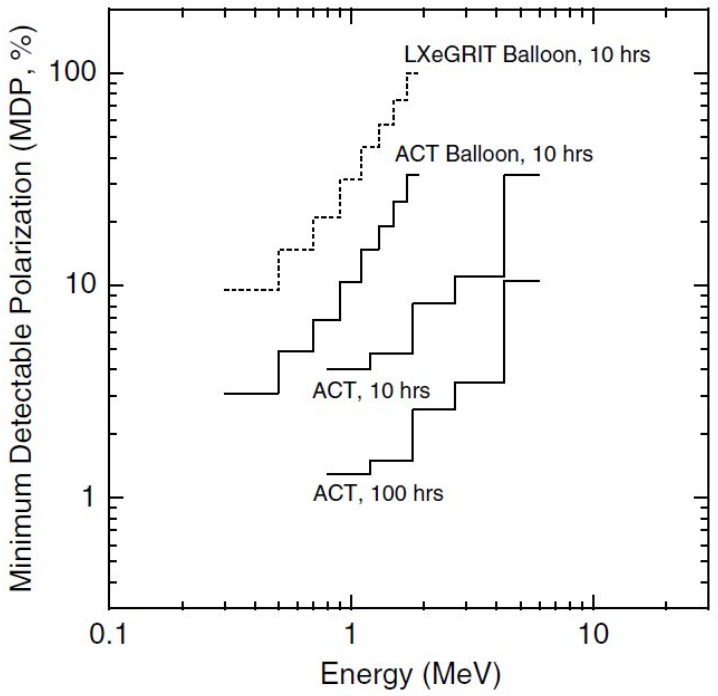


Compton

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

New Astr. Rev. 48 (2004) 215

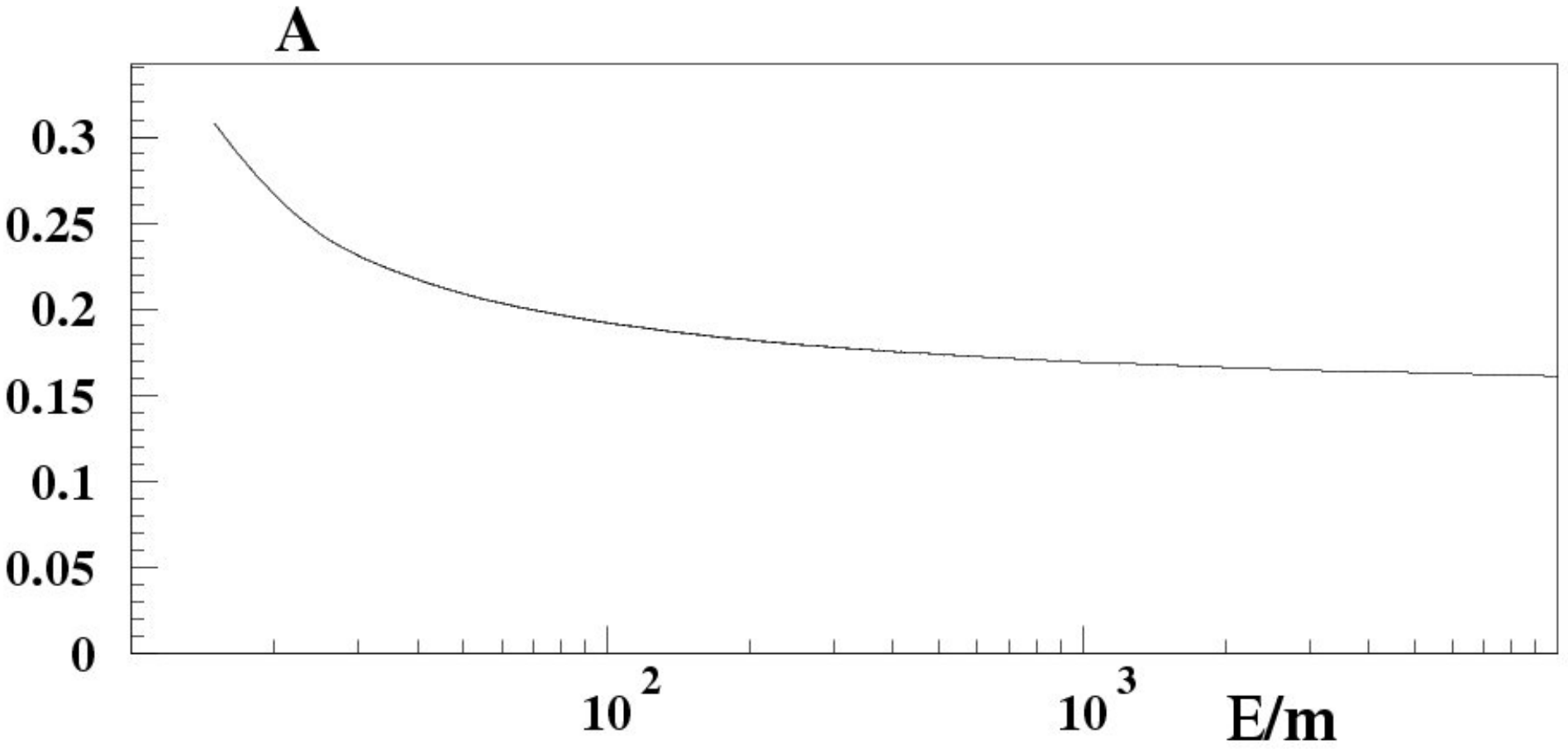




Low polarimetry sensitivity for γ energy range [1 MeV - 1 GeV]

"Nuclear" pair production : in principle

In principle : very good

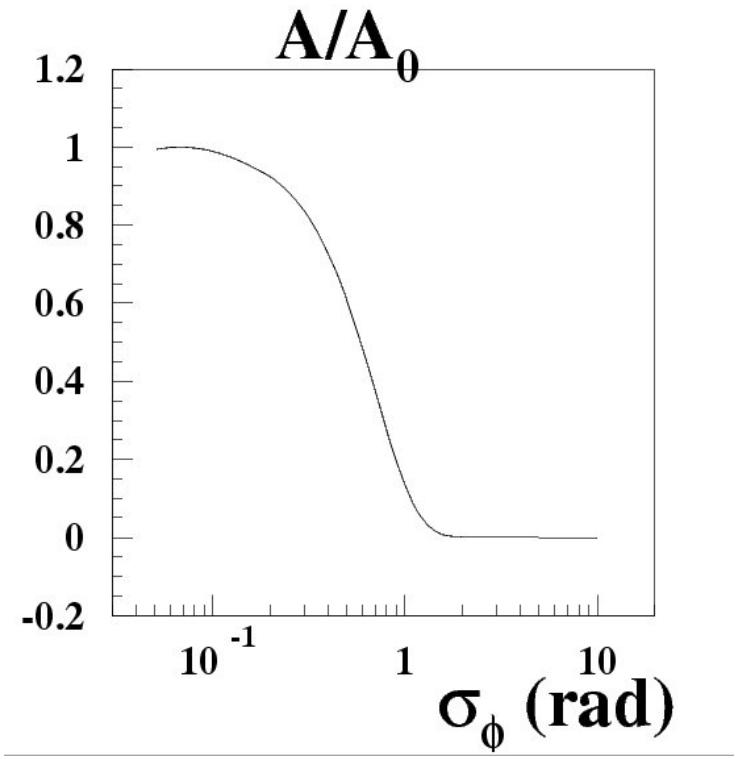


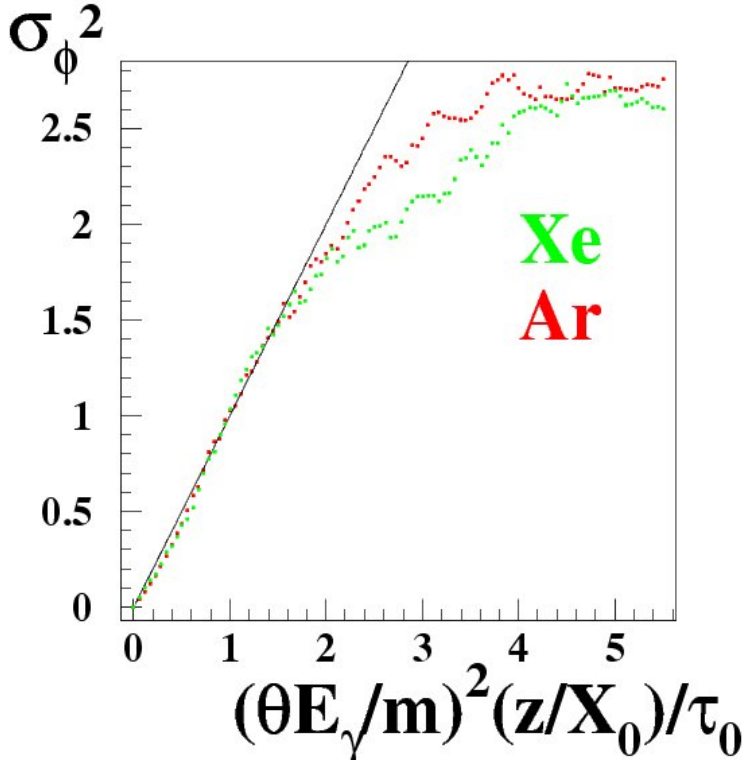
- Dominates cross section at high energy
- $\mathcal{A} \approx 0.2$ at high energy

"Nuclear" pair production : in practice

In practice : Problem

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



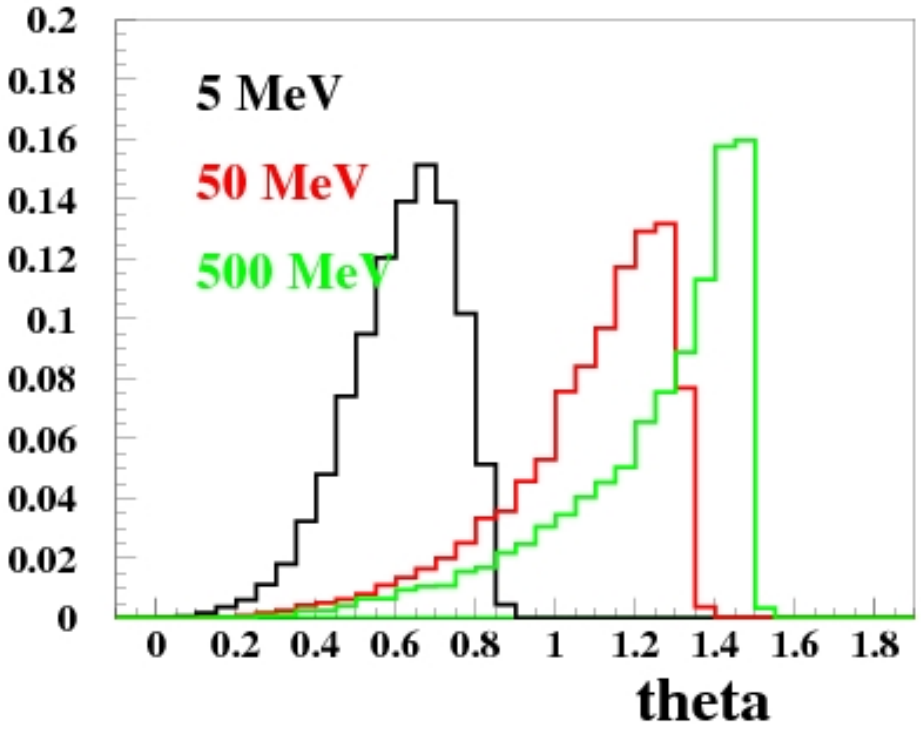


$\mathcal{A} = \mathcal{A}_0 e^{-2\sigma_\phi^2}$, $\sigma_\phi^2 \propto z$

After $3 \times 10^{-4} X_0$, $\sigma_\phi \approx 0.6$rad, $\mathcal{A} = \mathcal{A}_0/2$

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

– The recoiling electron is emitted at a large angle



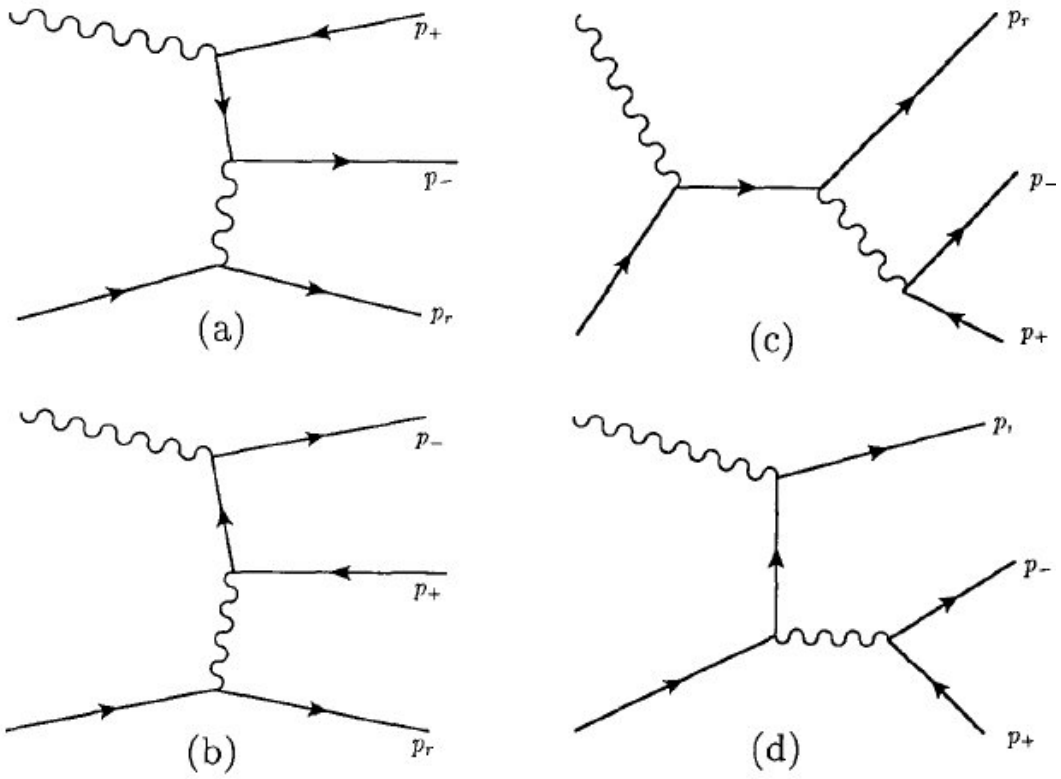
– Triplet / pair $\sim 1/Z$ at high energy.

– Same asymmetry at high energy.

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

- Dominated by the same two at high energy.

Triplet : High Energy Approximation



(and $e^- \leftrightarrow e^-$ exchange in final state for triplet)

- Nuclear pair production (a) and (b) dominate due to mass ratios
- Triplet : (a) and (b) dominate asymptotically at high energy

So keeping (a) and (b) is a high energy approximation for Triplet

Polarisation Asymmetries $\mathcal{A}$

– Theory : many approximations

- Born
- Screening from atomic electrons parametrized $F(q)$
- High energy.

– Experiment : very few measurements

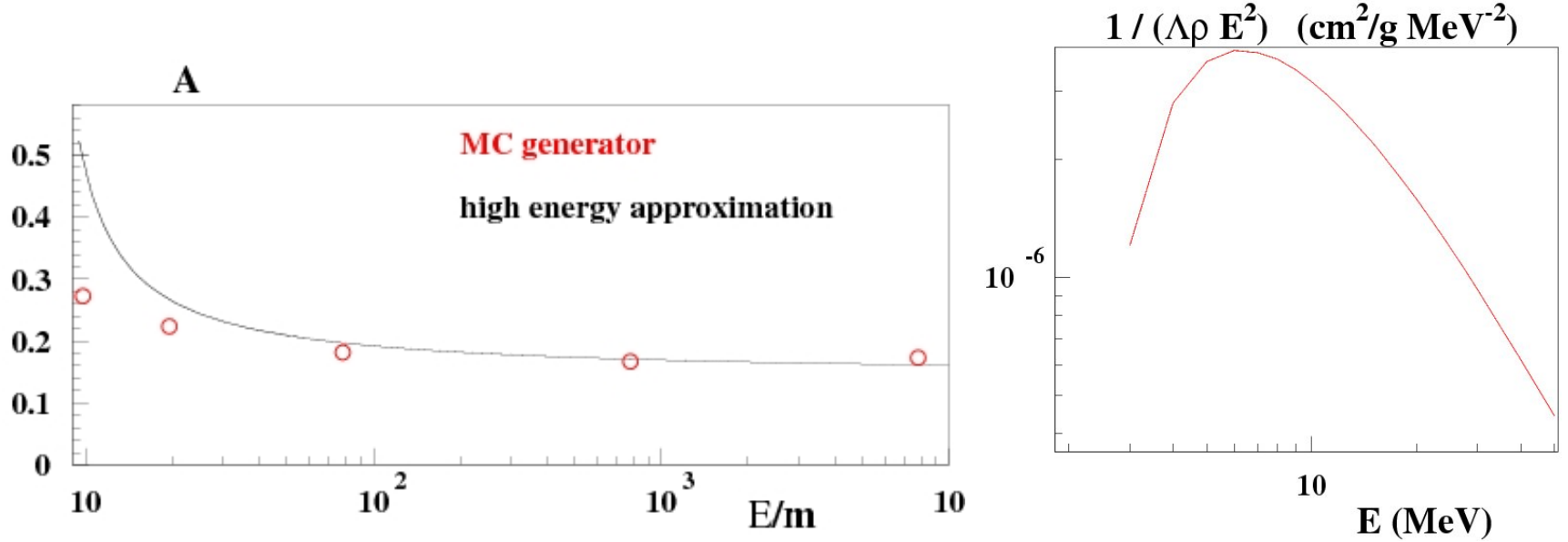
Reviews :

JW Motz, HA Olsen and HW Koch, Rev. Mod. Phys. 41, 581 - 639 (1969)

J. H. Hubbell, S. M. Seltzer, NIM B 213 (2004) 1

Relevant Energy Range 3 – 30 MeV

Triplet

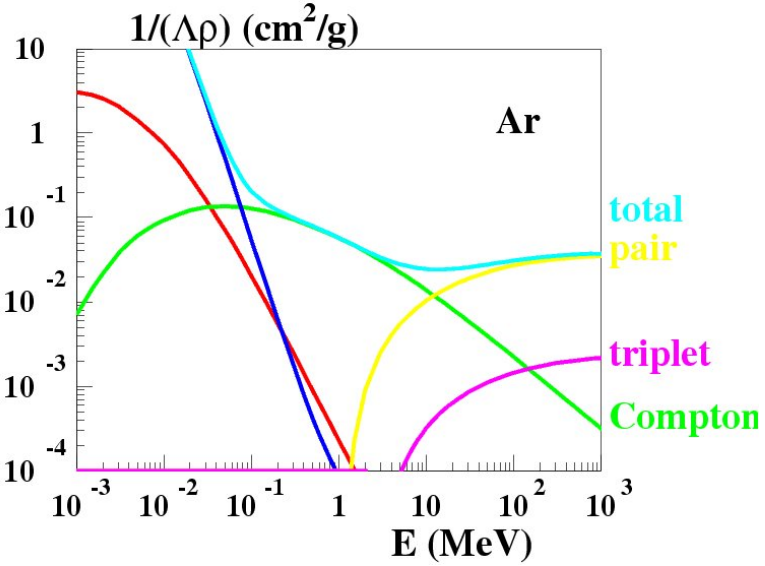


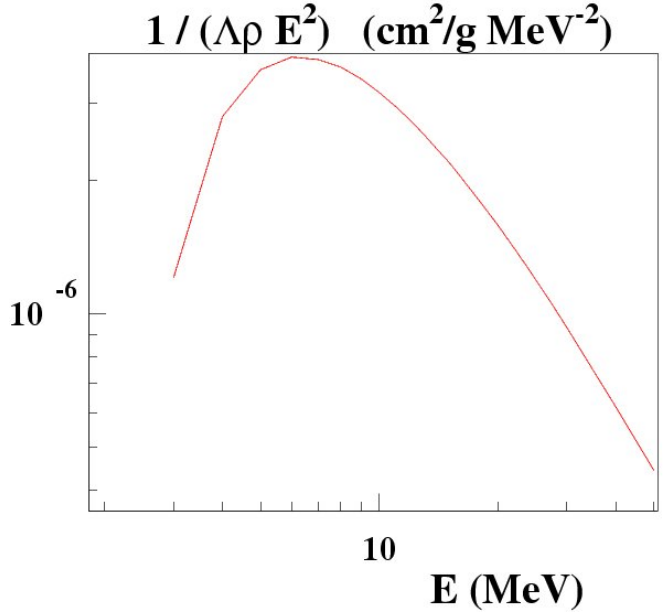
Approx : Baier *et al.* Sov. Phys. JETP 23, 104 (1966)

Generator : Endo, Kobayashi, Nucl. Instrum. Meth. A 328, 517 (1993).

Satellite flight : Precision of P measurement

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





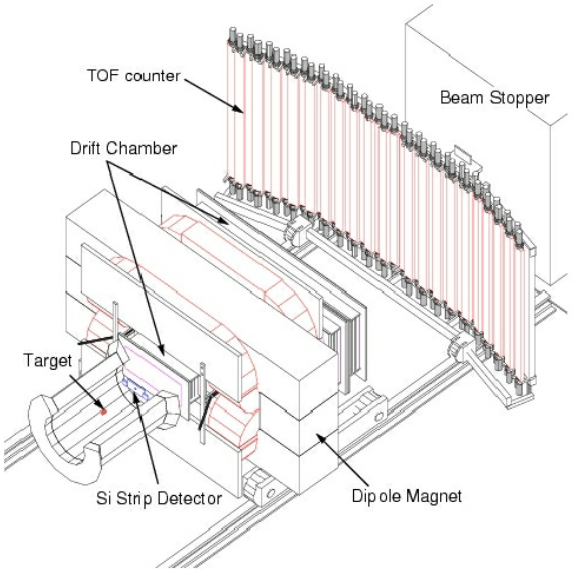
1 ton, 1 year, time fraction 50%, efficiency 100%, $\mathcal{A} \approx 0.2$

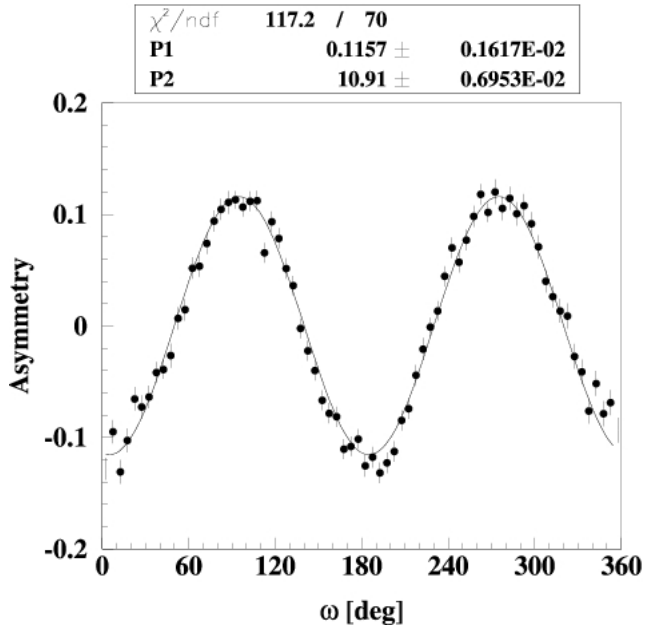
- $N_{int} = 1.5 \times 10^5$
- $2\%/\sqrt{year.ton}$ (Crab)

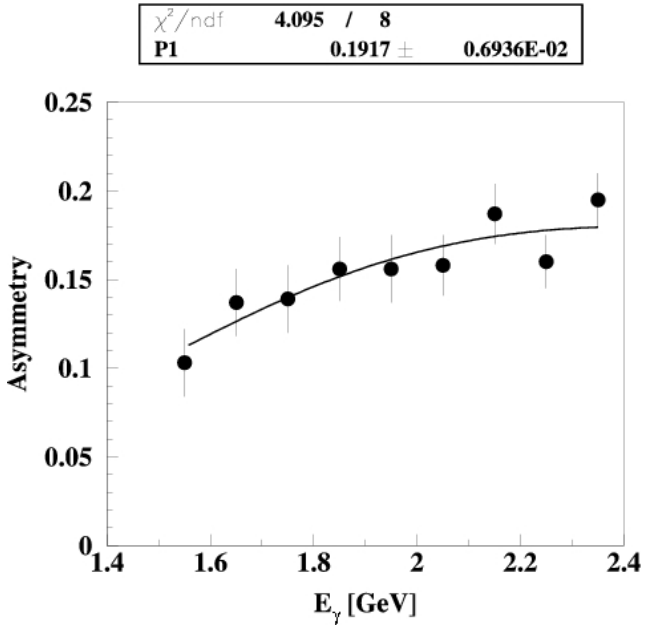
$$\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}} \approx 0.0185$$

Nuclear pair production : High Energy

Compton scattering of laser beam @ Spring-8







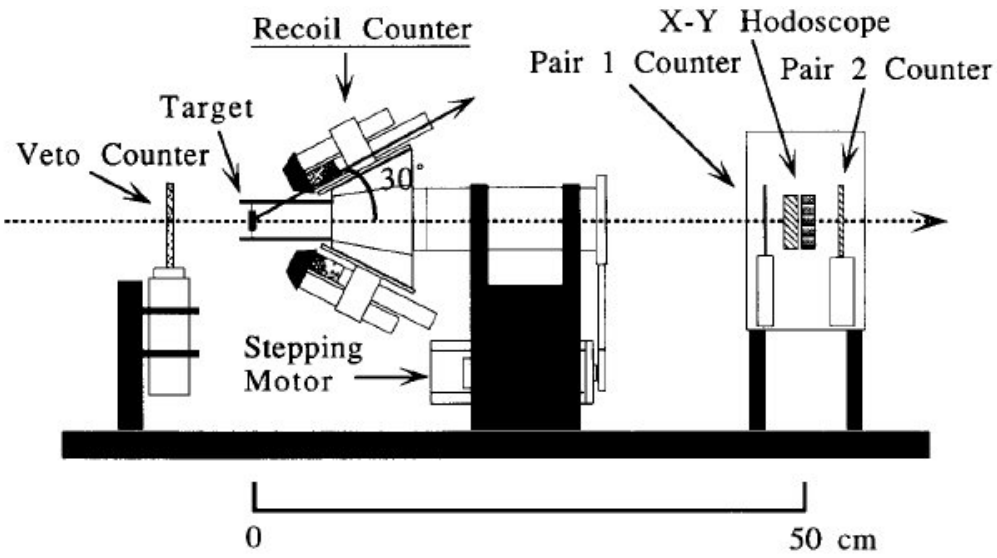
"Asymmetry" is here : $\mathcal{A} \times P$

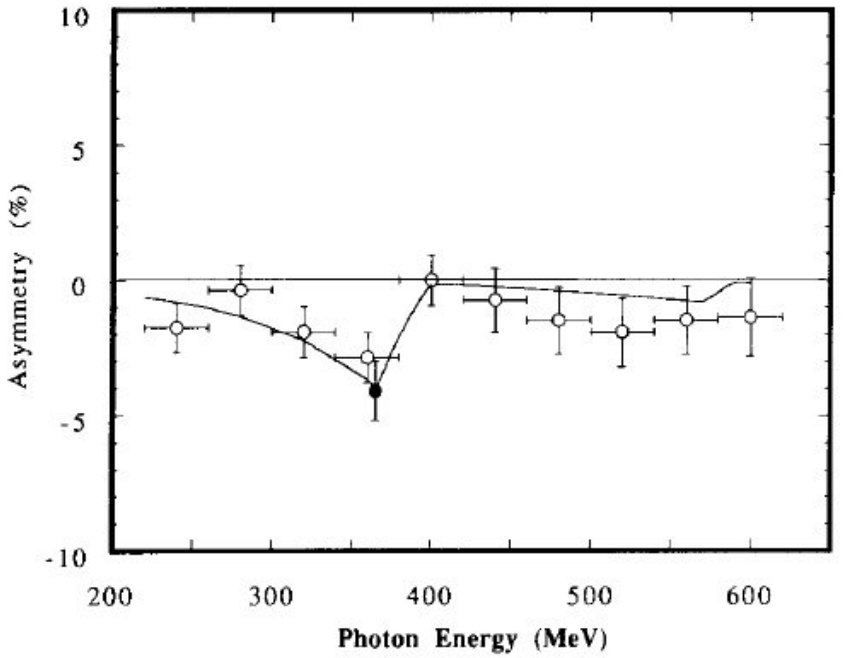
de Jager, et al., Eur.Phys.J.A19 :S275-S278,2004.

Triplet : High Energy

Coherent Bremsstrahlung on Si Crystal.

"Polarisation Max 50 % at 365 MeV". (◦ data, • MC)



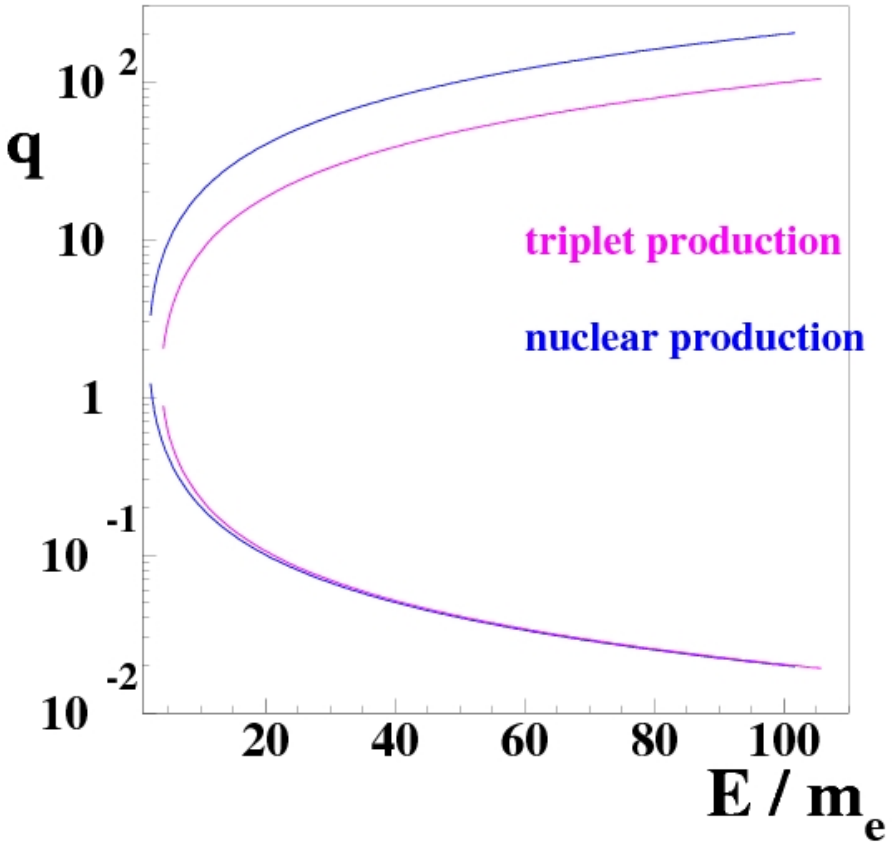


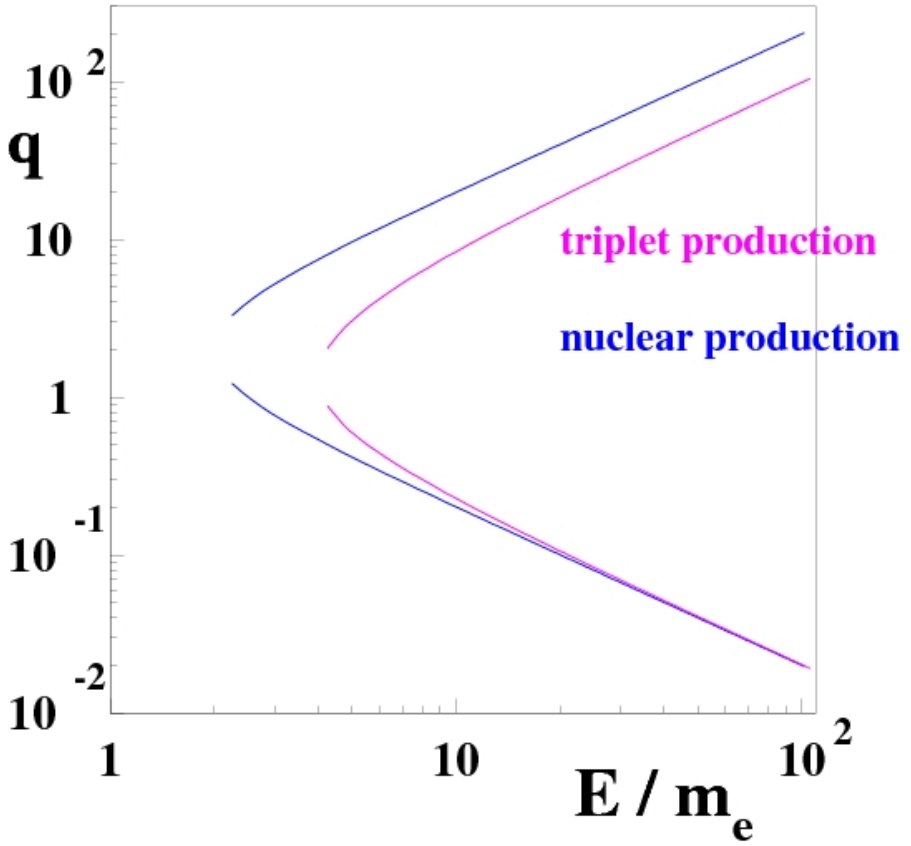
Y. Iwata *et al.*, NIM A336 (1993) 146

"Asymmetry" is here : $\mathcal{A} \times P$

q : kinematic limits

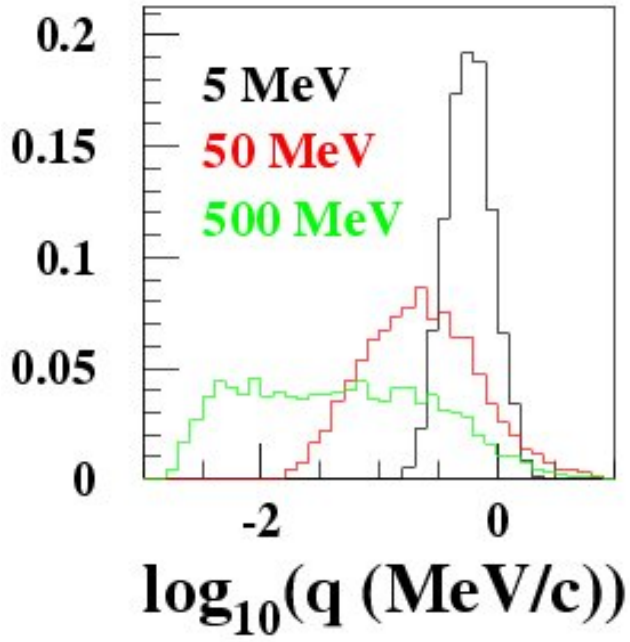
q transferred momentum

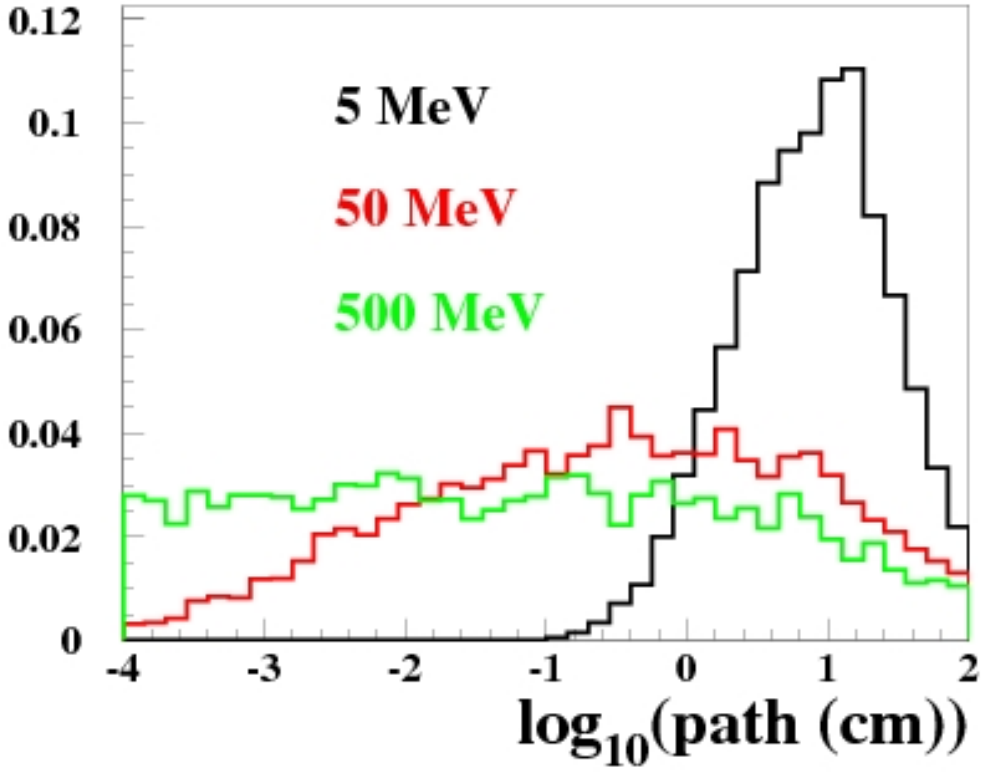




Sizing the detector

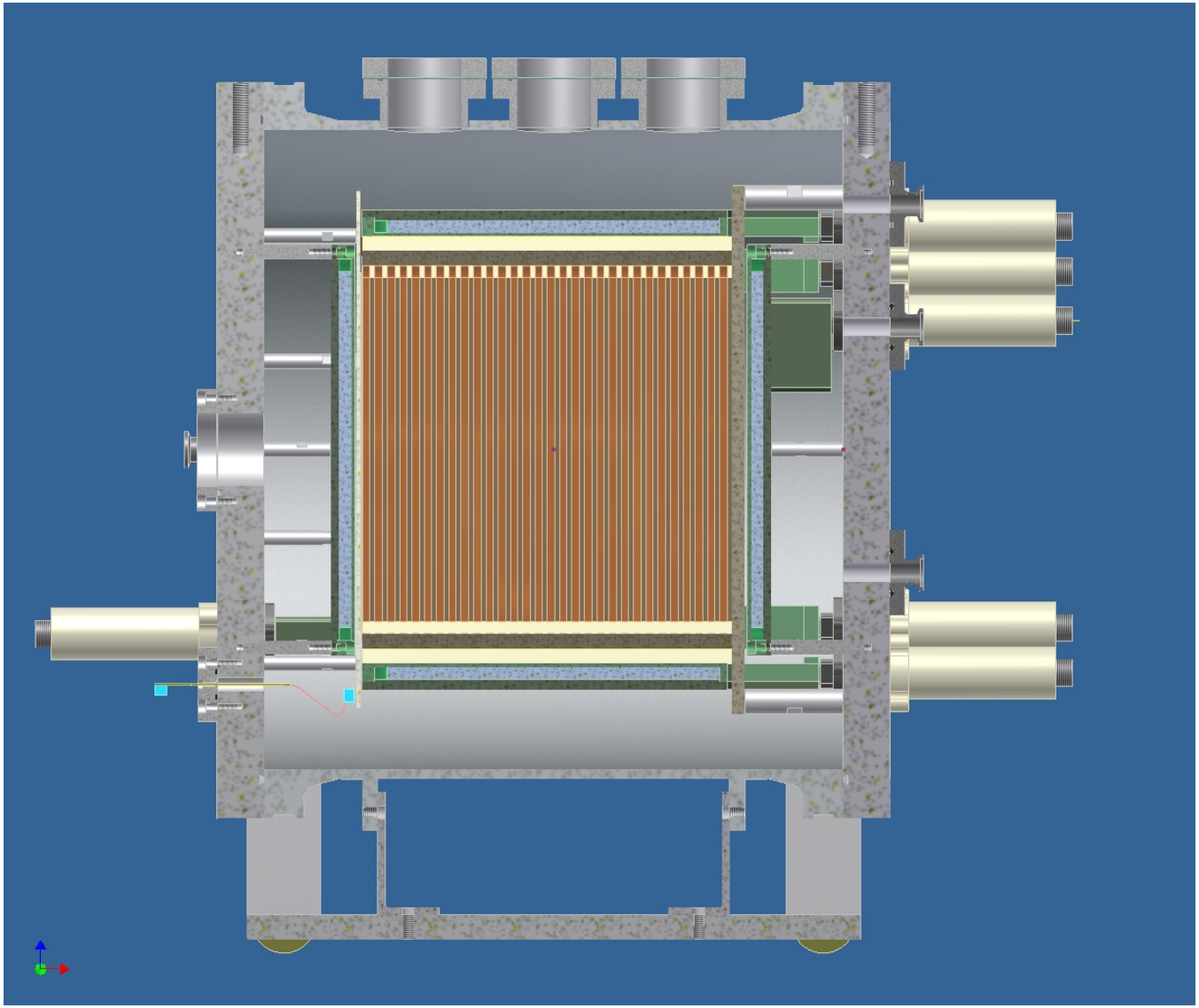
in 5 bar of Argon gas



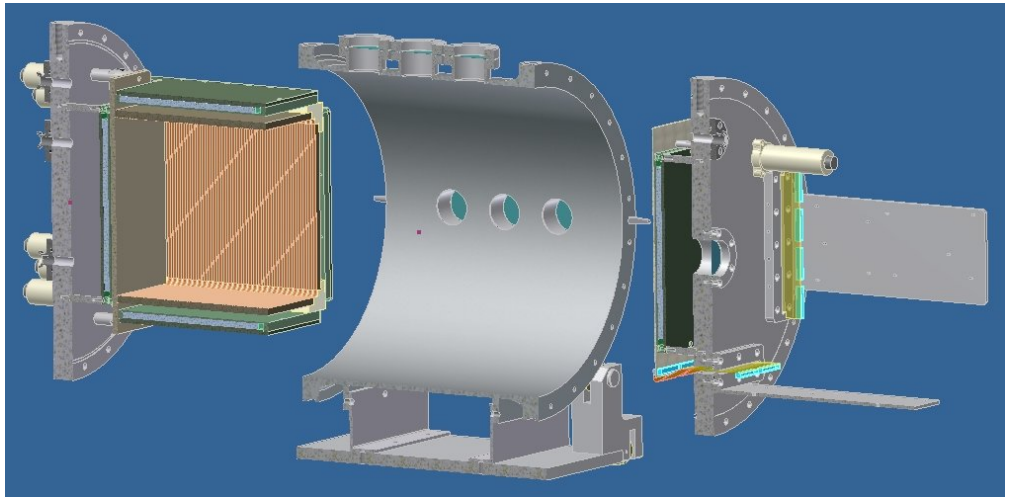


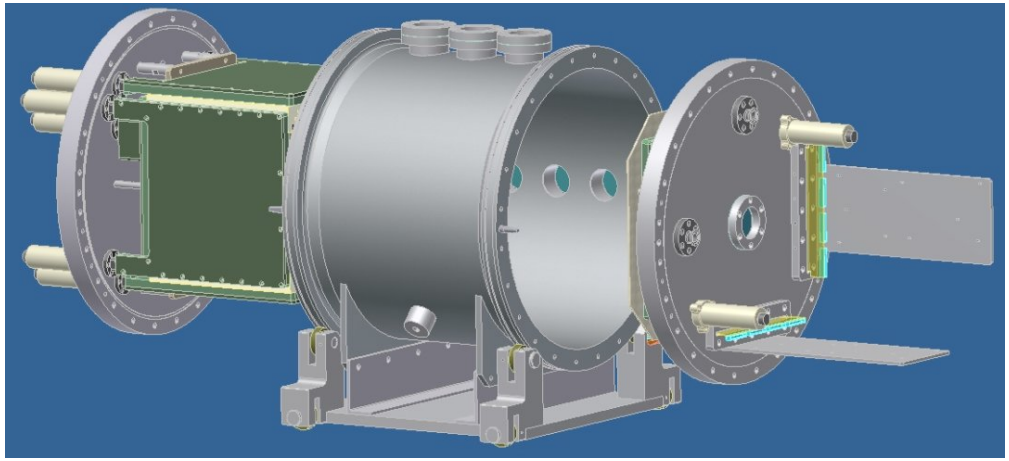
⇒ Cubic TPC, 30 cm, pitch 1mm, spatial resolution 1 mm ..

Detector Layout



Detector Layout : 2

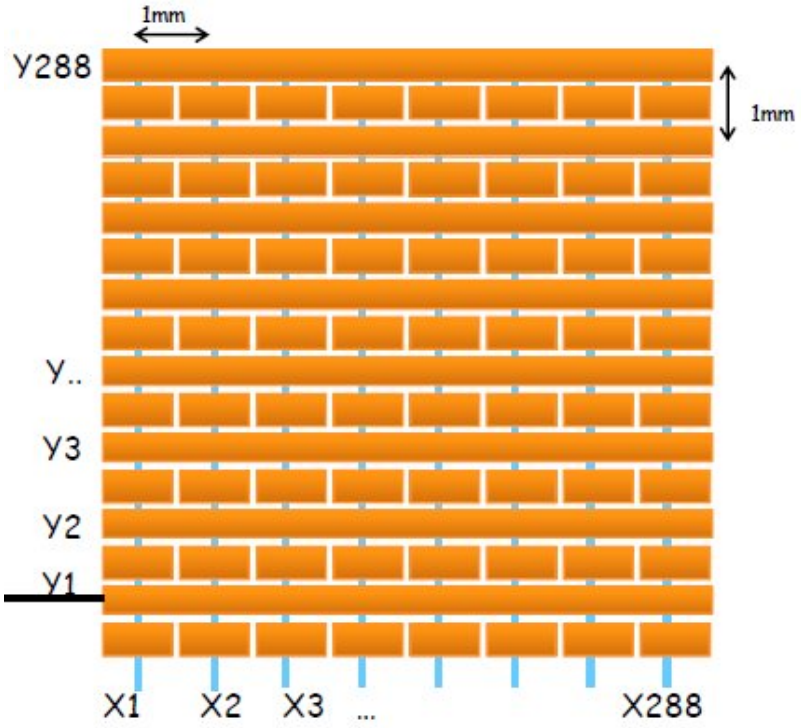


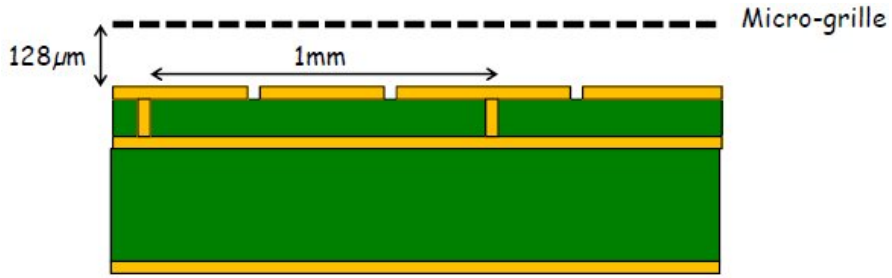


Al vessel, H =500 mm, Φ =500 mm

Amplification – Collection

- Amplification by micro-mesh micromegas



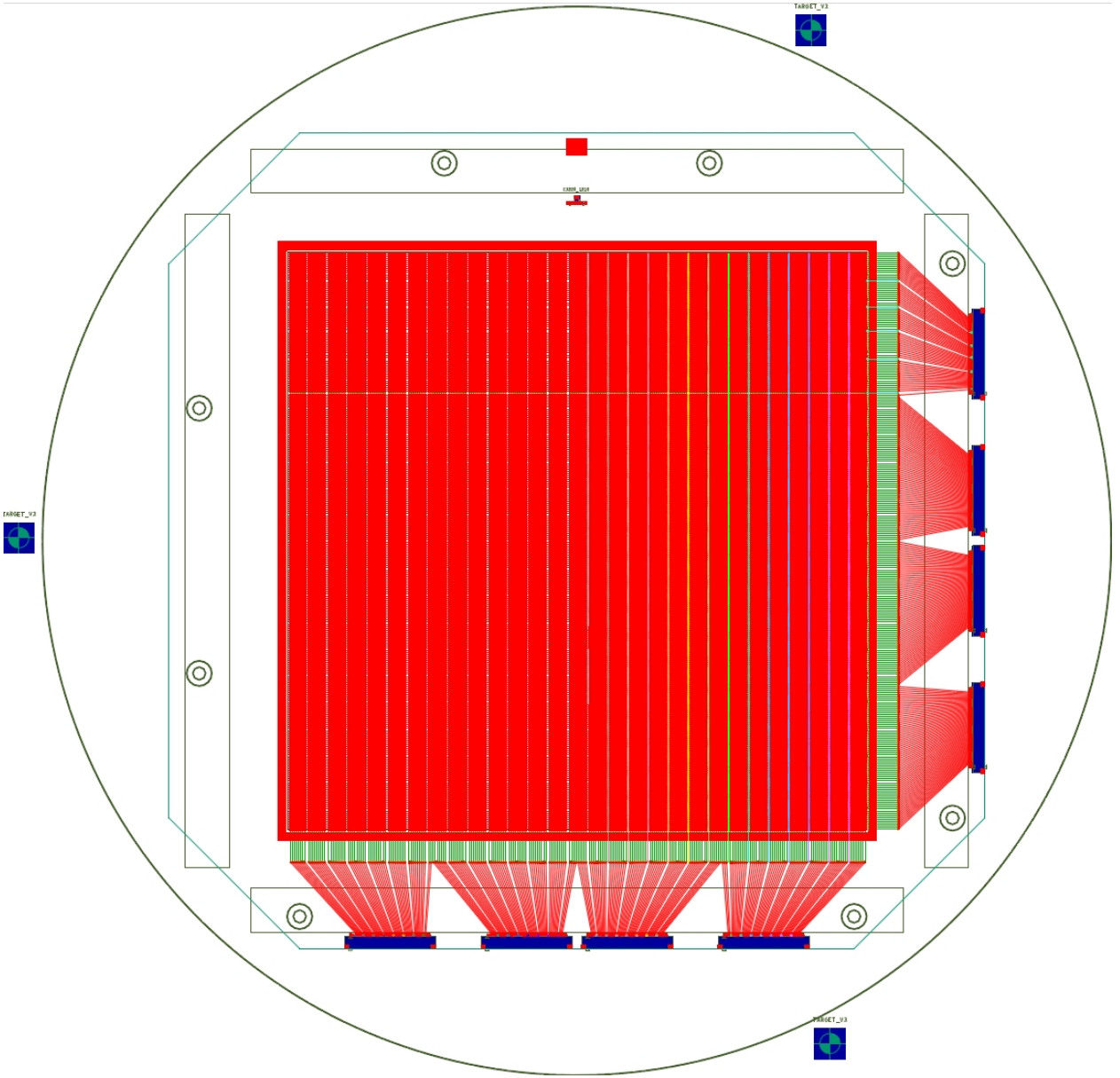


- Signal collection by strips on PCB, pitch = 1mm
- Sampling / acquisition performed by AFTER chip — IRFU

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

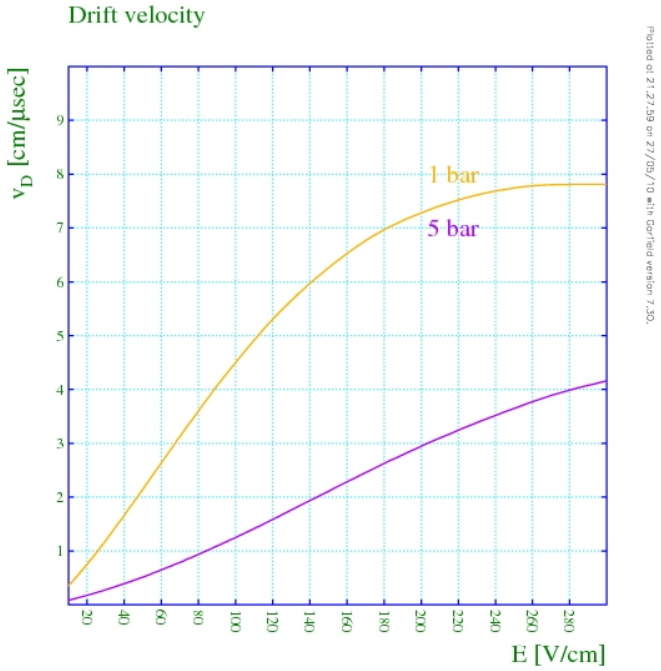
- To be made at CERN workshop

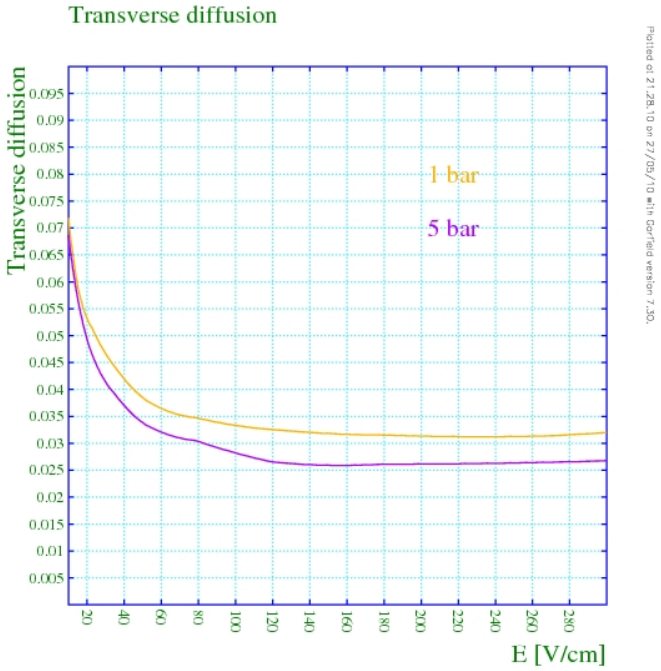
Le PCB à Strips

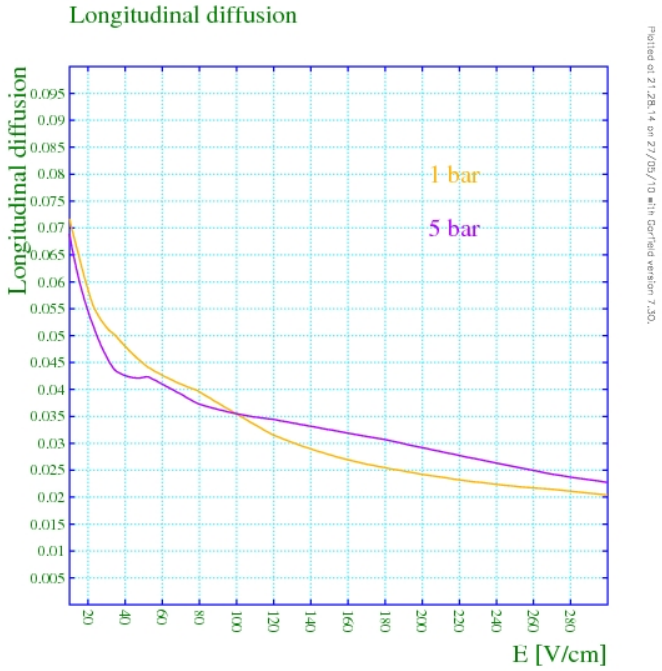


T2K-like Gas

- 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

Trigger

– Cosmic Rays
  - 2 scintillator coincidence
  - Rate 1 /(cm^2 min), 15 Hz.

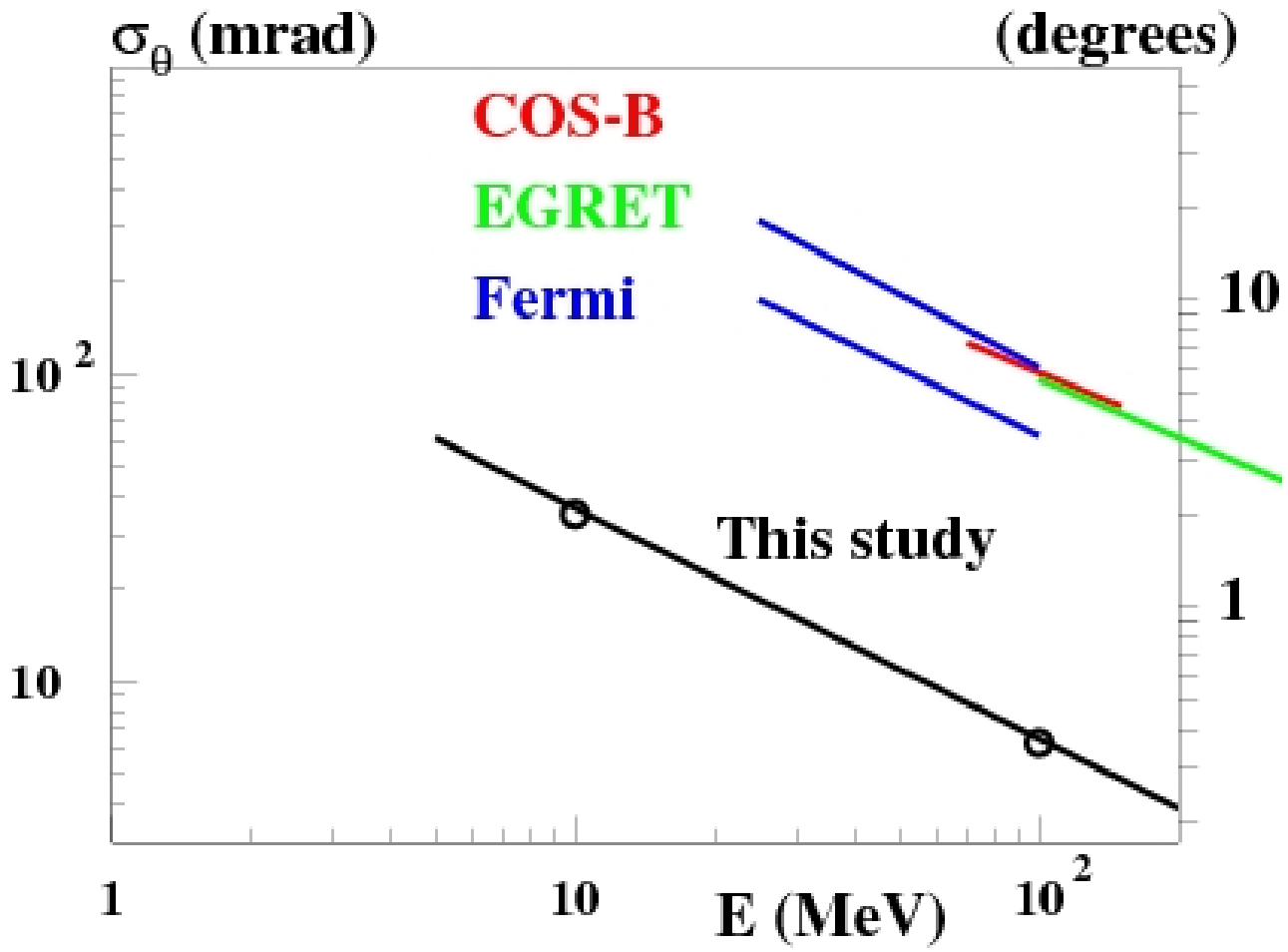
– γ-Ray beam
  - $\overline{U} \bigcap G \bigcap D$

The chip used can digitize data up to 1 kHz

$F \times \epsilon$	ϵ	Max flux F
1 kHz	1%	10^5 /s

– Scintillator, WaveLength shifter, PMT

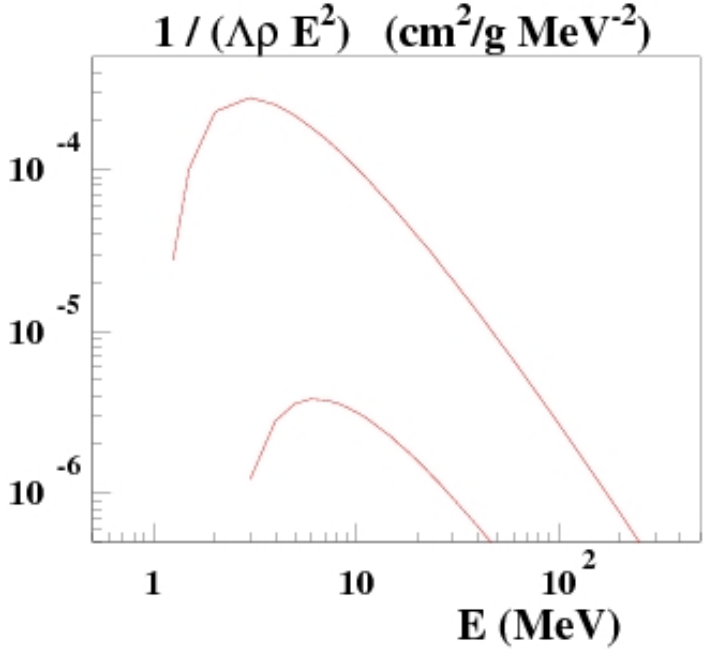
Angular Resolution

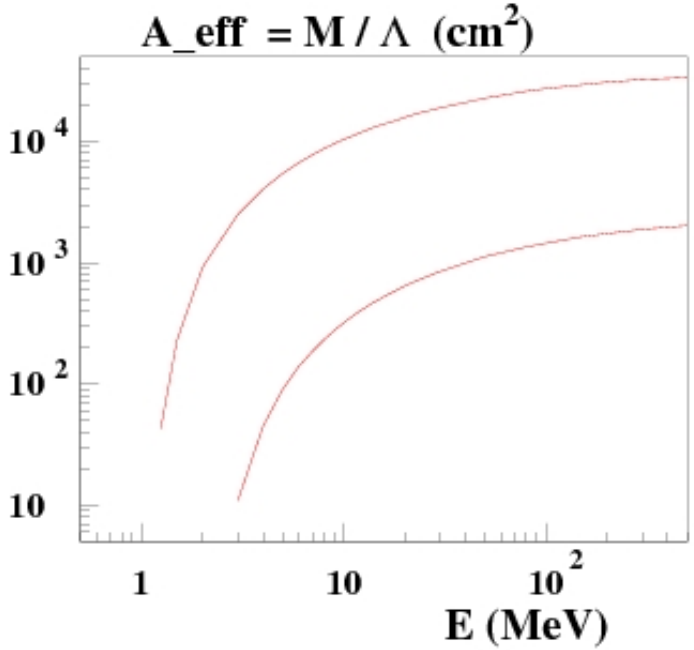


- Black line is analytic prediction
- Points are from Kalman-filter reconstruction

Frühwirth NIM A 262, 444 (1987).

Effective Area

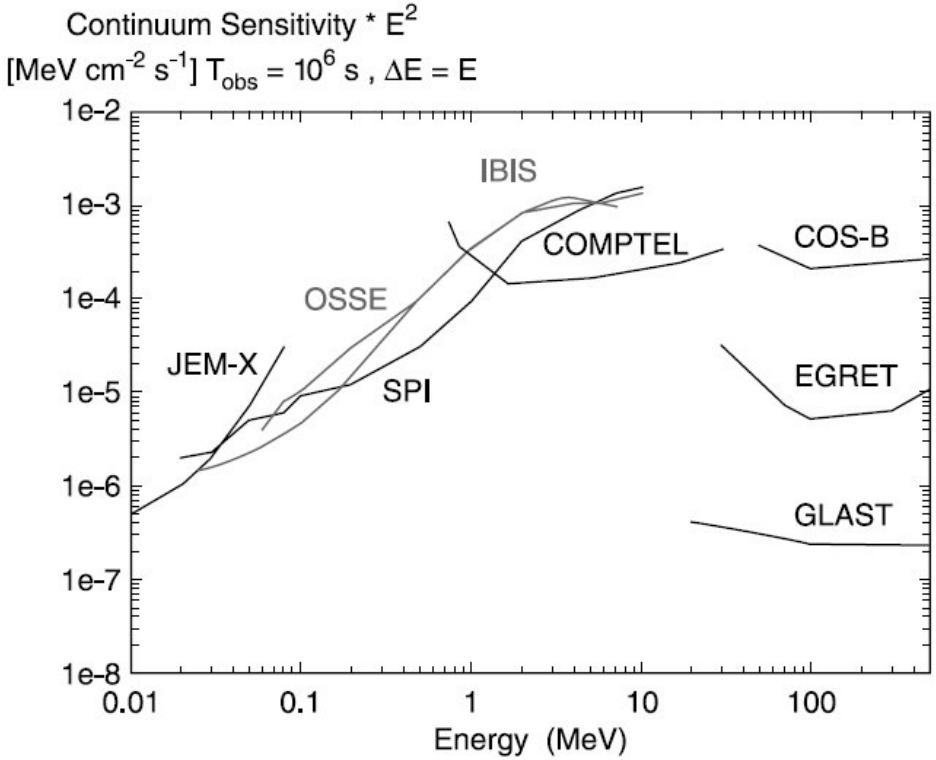


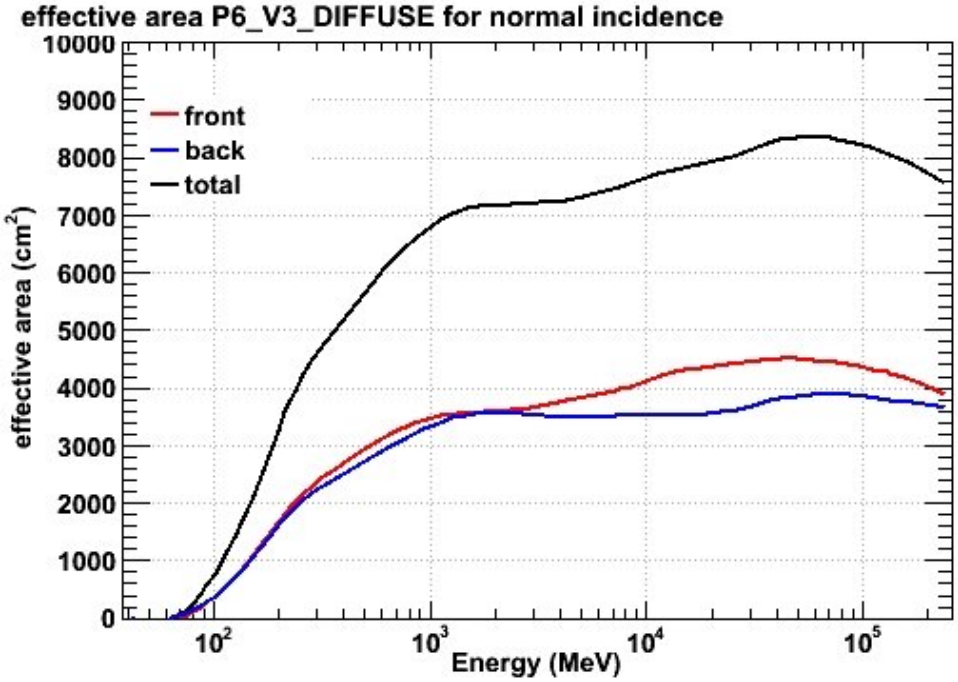


- Thin detector : Effective Area depends on Mass only
- 1 ton, efficiency 100%, fiducial volume 100%,

Effective Area asymptotically 3.7 m^2, (Fermi/Glast 1 m^2)

γ Astronomy : filling the gap





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

Fermi LAT Performance web page,

- Good angular resolution key factor in background rejection
- Angular Resolution @ 100 MeV :
  - EGRET 5.5° , Fermi/Glast 4.0°,
  - HARPO 0.4° "Hermetic ARgon POlarimeter"

Many Thanks

- IRFU / CEA
  - Ioannis Giomataris, Alain Delbart (micromegas / Strips PCB design)
  - Paul Colas (TPC)
  - Eric Delagnes (AFTER – FEC)
  - Denis Calvet (Firmware)
  - Georges Vasseurs (PM's)
- CERN
  - Rui De Oliveira (micromegas / Strips PCB design)

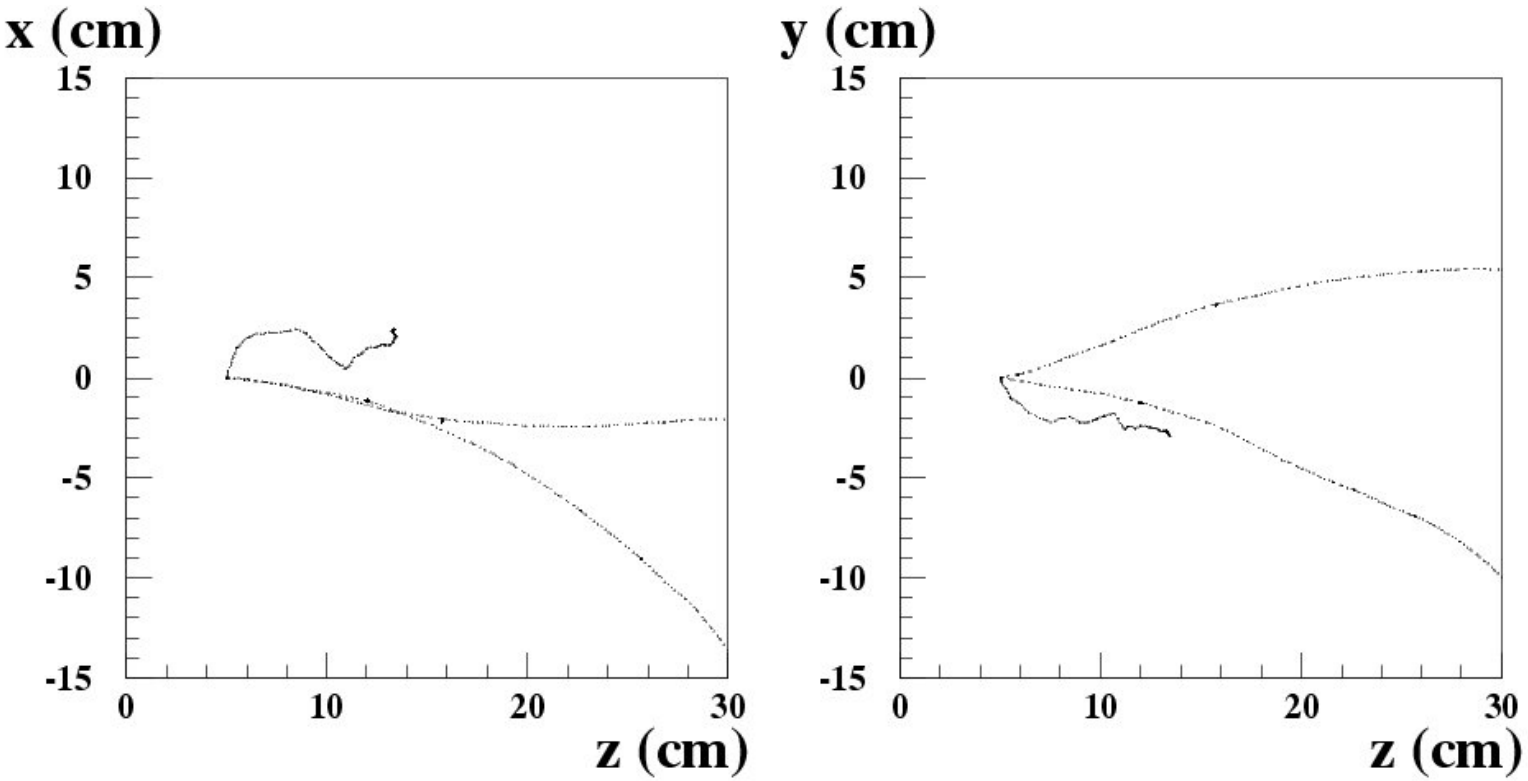
.. and their collaborators.

Conclusion

A 5 bar TPC for precision MeV – GeV γ- astronomy and polarimetry

- Astro γ : Angular Resolution 1/10 trackers with W converters
- MeV — GeV γPolarimetry
- High sensitivity :
  - High efficiency ; All sky detector : 4π acceptance
  - Evt imaging : Excellent non-γ (and upgoing γ) background rejection
  - No combinatoric background
- Deadtime-free GRB detector
- First precision validation of low energy (MeV) polarization asymmetry within reach.

Thanks for your kind attention



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

Back-up Slides

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 ..

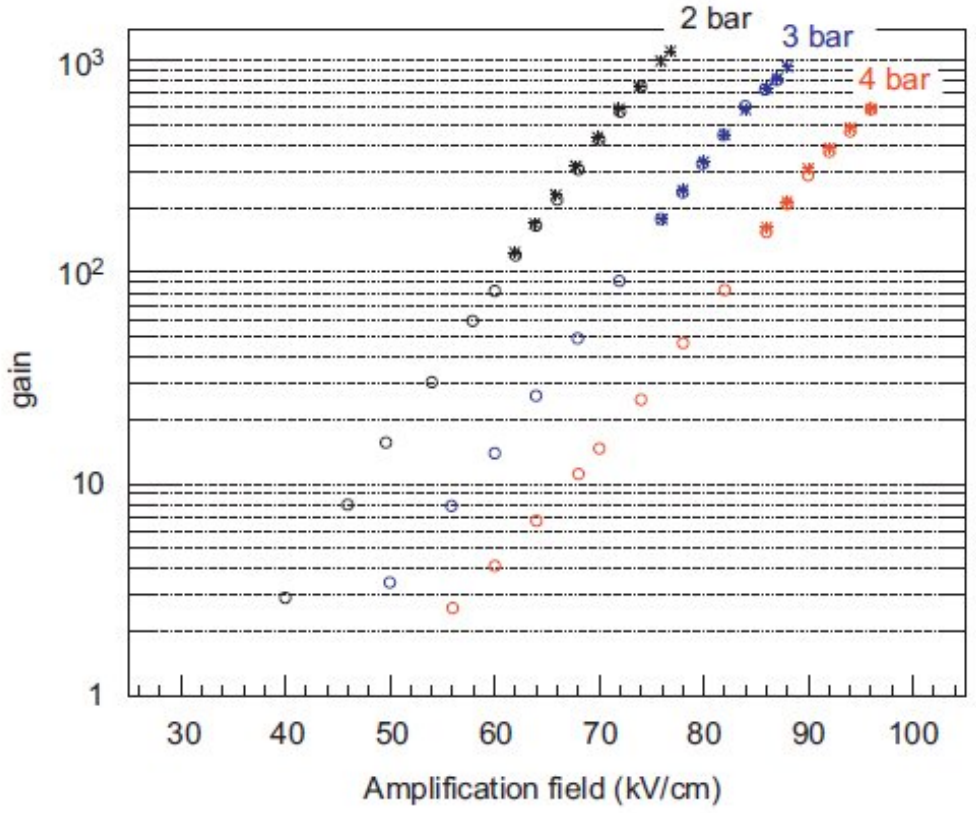


Fig. 5. Gain curves with both alpha (circles) and gamma (crosses) peaks, for Ar + 5% isobutane, at 2–4 bar.

NIM A 608 (2009) 259

Measurements at SPRing-8 / Subaru

Linearly polarized γ beams

- SPRing-8
  - High energy
    - BL33LEP 1.5 – 2.4 GeV, Eur.Phys.J.A19 :S275-S278,2004
  - Low energy Kawase *et al.*, NIM A 592 (2008) 154.
    - BL38B2 diagnosis beamline I, 10 MeV (taken down)
    - BL05SS diagnosis beamline II, 10 MeV (planned)

- New Subaru
  - YAG, 17.6 MeV Aoki *et al.*, NIM A 516 (2004) 228
  - CO2, 3.9 MeV Amano *et al.*, NIM A 602 (2009) 337

General Schedule

- 2008
  - MC studies
- 2009
  - Oct : Approved by LLR scientific Council
  - Group formation (engineers)
  - Budget request
- 2010
  - March : funding received for 2010 : detector
  - Design in progress
  - Start construction in the Fall.
- 2011
  - Mounting, tests
  - Cosmic rays runs $\Rightarrow$ NIM A.
  - γ Beam request
- 2012
  - γ beam runs, analysys, NIM A, PRL