HARPO : a TPC as a γ-Ray Telescope and Polarimeter
In the e^+e^- pair creation regime

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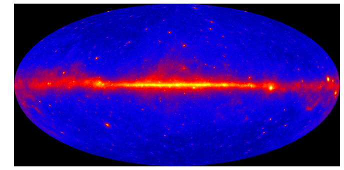
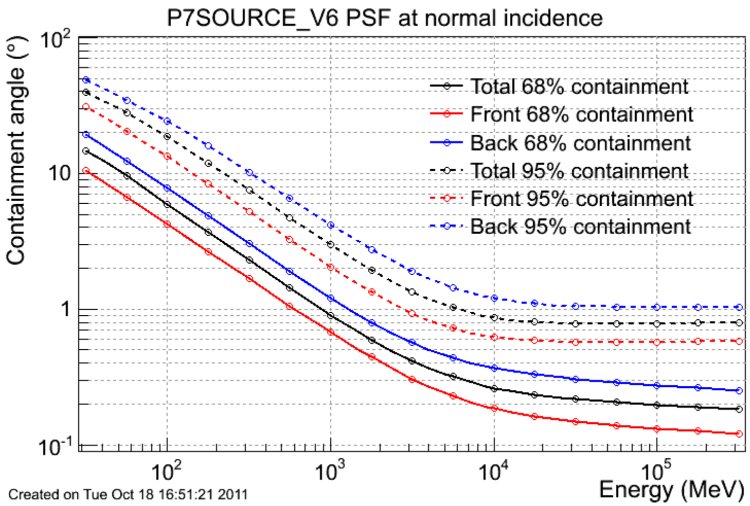
SPIE Astronomical Telescopes + Instrumentation,
Ultraviolet to gamma ray,
Palais des congrès de Montréal, Montréal, Québec, Canada ; 22 - 27 Juin 2014

llr.in2p3.fr/∼dbernard/polar/harpo-t-p.html

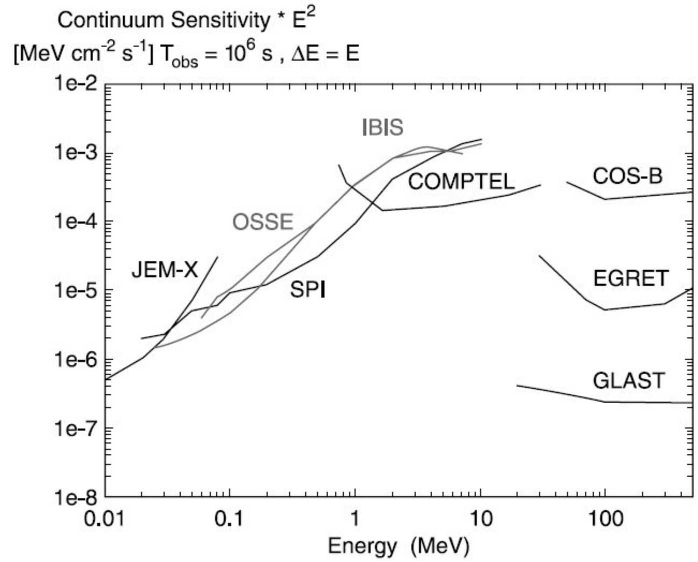
Science Case



- **Non polarized astronomy** :
  - Improve angular resolution – crowded sky regions



Fermi/LAT



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

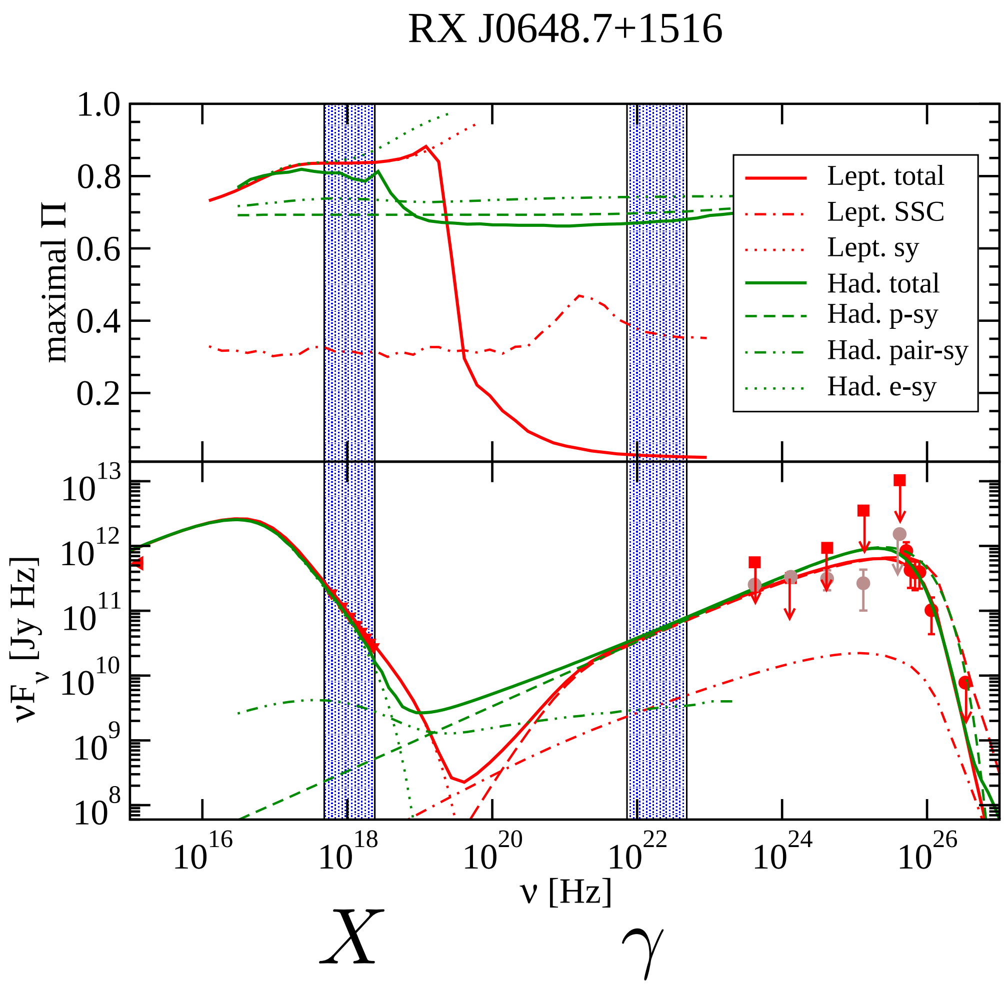
  - Solve sensitivity gap between Compton and pair telescopes
    - Actually Fermi is publishing mostly in the range $0.1 - 300\mathrm{GeV}$
    - Improvement expected from PASS8, **Poster [9144-131] Carmelo Sgrò**

- **Polarimetry** : No γ polarimeter above 1 MeV in space ever
  - Astrophysics : understand working mechanism(s) of γ cosmic sources
  - Cosmo / New Physics : LIV : Search for Lorentz Invariance Violation

Post-Fermi talk by Eric Charles on Sunday [9144-13]

Science Case : Polarimetry : Astrophysics

- One example : Blazar (AGN with jet pointing to us) : 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



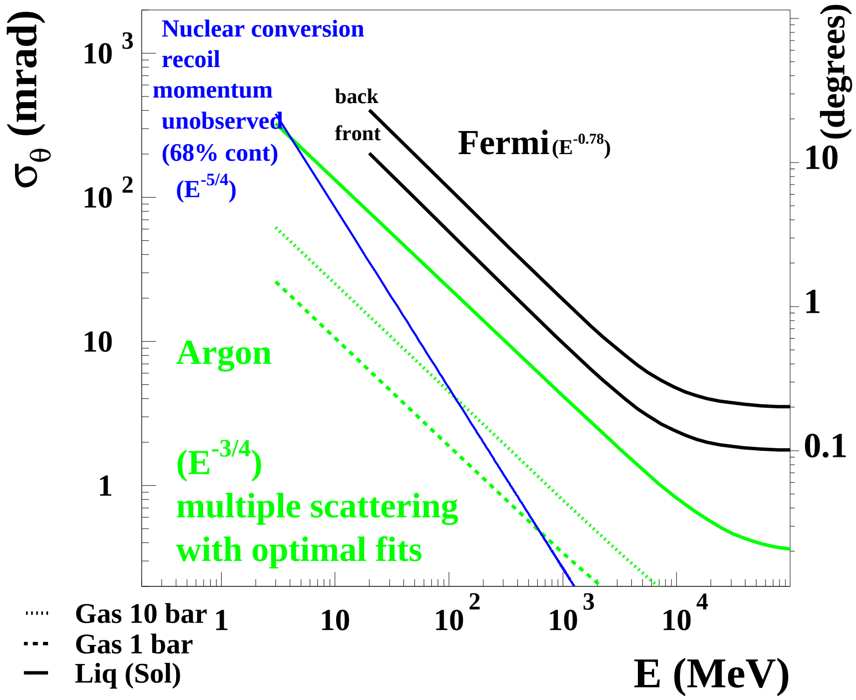
- SED's indistinguishable, but
- X-ray : $P_{\rm lept} \approx P_{\rm hadr}$
- γ-ray : $P_{\rm lept} \ll P_{\rm hadr}$

H. Zhang and M. Böttcher,
A.P. J. 774, 18 (2013)

Way Out : Use a Thin, Homogeneous Detector and Optimal Fits

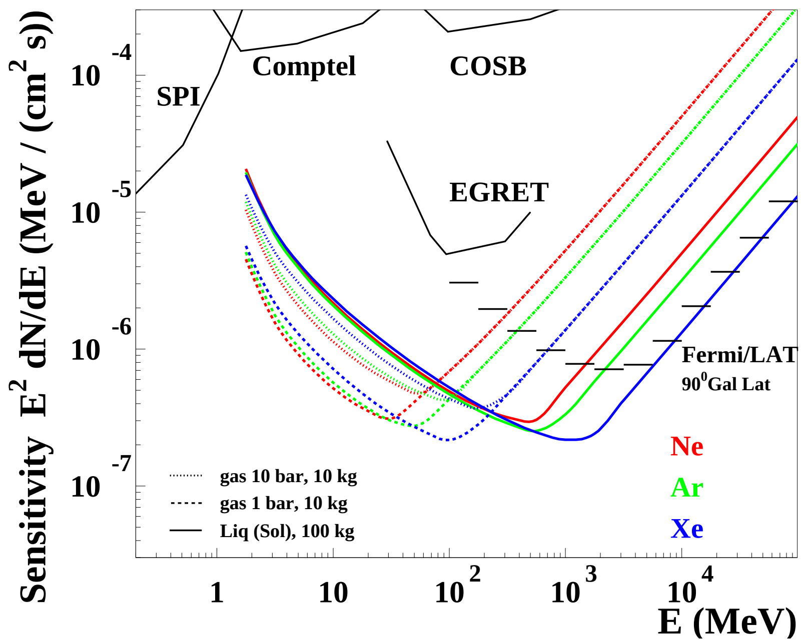
Angular resolution

- 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



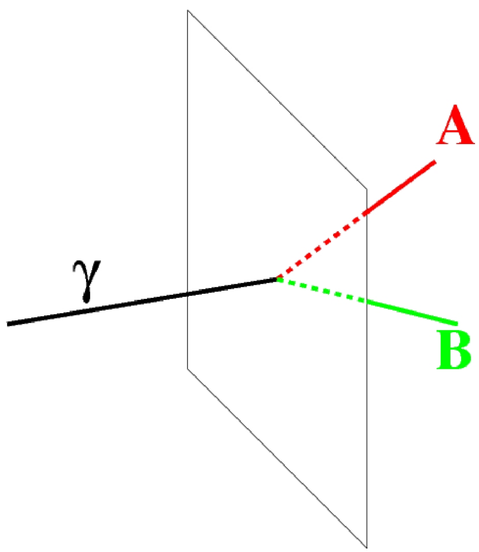
- Sampling pitch $l = 1\mathrm{mm}$, point resolution $\sigma = 0.1\mathrm{mm}$
- Validation of optimal fit performance with Kalman filter [D.B. NIM A 729 (2013) 765]

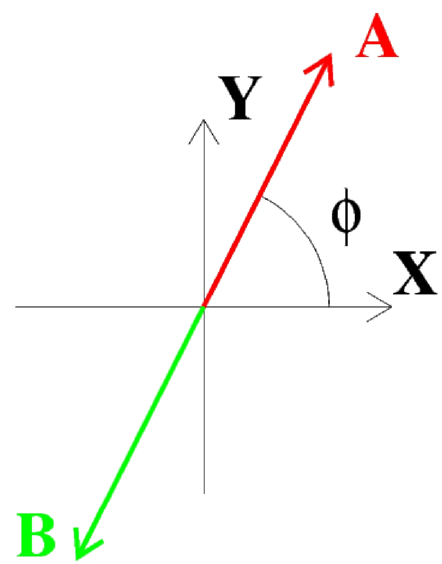
D.B. NIM A 701 (2013) 225

Polarimetry

- Modulation of azimuthal angle distribution

$$\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A} P \cos[2(\phi - \phi_0)]), \qquad \sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}},$$



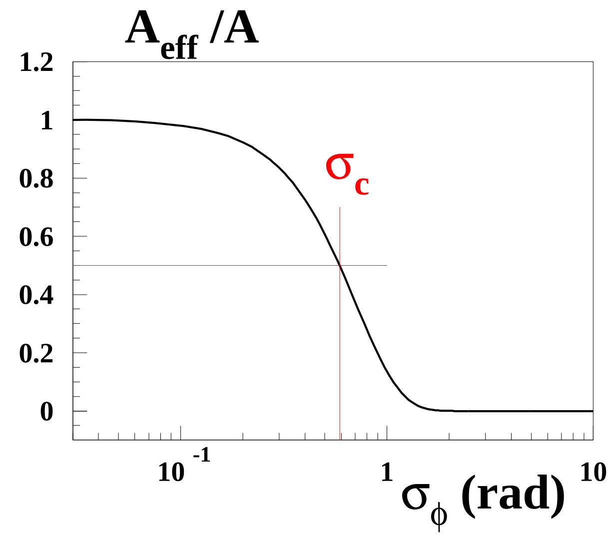


  - P source linear polarisation fraction
  - $\mathcal{A}$ Polarization asymmetry
  - ϕ azimuthal angle

Conversion in a Slab and Multiple Scattering : Dilution of the Polarisation Asymmetry

- $(1 + \mathcal{A}P\cos[2(\phi)]) \otimes e^{-\phi^2/2\sigma_\phi^2} = (1 + \mathcal{A}\ e^{-2\sigma_\phi^2}\ P\ \cos[2(\phi)])$

  $\Rightarrow \mathcal{A}_{\text{eff}} = \mathcal{A}\ e^{-2\sigma_\phi^2}$



- azimuthal angle RMS $\sigma_\phi = \dfrac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$,
  - $\theta_0 \approx \dfrac{13.6\,\text{MeV}/c}{\beta p}\sqrt{\dfrac{x}{X_0}}$,
  - most probable opening angle $\hat{\theta}_{+-} = 1.6\,\text{MeV}/E$ Olsen, PR. 131, 406 (1963).

  $\Rightarrow \sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$ (e.g. $\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2$ for $110\,\mu\text{m}$ of Si, $4\,\mu\text{m}$ of W)

- This dilution is energy-independent.

Conventional wisdom : γ polarimetry impossible with nuclear conversions $\gamma Z \rightarrow e^+e^-$

e.g. Mattox J. R.Astrophys. J. 363 (1990) 270, and refs therein

Very thin Si detectors are being considered though, e.g. PANGU talk by Meng Su on Sunday [9144-130].

But Harvard talk : Silicon : 2 single sided SSD of $150\ \mu\text{m}$ each ? And how solve the x, y two track ambiguity ?

γ *Polarimetry with a Homogeneous Detector and Optimal Fits*

- $\sigma_\phi = \dfrac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, azimuthal angle resolution
- $\sigma_{\theta,\text{track}} = (p/p_1)^{-3/4}$, angular resolution due to multiple scattering
  - $p_1 = 13.6\,\text{MeV}/c \left(\dfrac{4\sigma^2 l}{X_0^3}\right)^{1/6}$, Argon $(\sigma = l = 1\text{mm})$: $p_1 = 50\,\text{keV}/c$ (1 bar),

    $p_1 = 1.45\,\text{MeV}/c$ (liquid).
- $\hat{\theta}_{+-} = 1.6\,\text{MeV}/E$ most probable opening angle
- $\sigma_\phi = \left[x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}}\right] \dfrac{(p_1)^{\frac{3}{4}} E^{\frac{1}{4}}}{1.6\,\text{MeV}}$. azimuthal angle resolution
  - x_+ fraction of the energy carried away by the positron,

There is hope .. at low p_1 (gas) .. at low energy.

Also need study beyond the most probable opening angle $\theta_{+-} = \hat{\theta}_{+-}$ approximation

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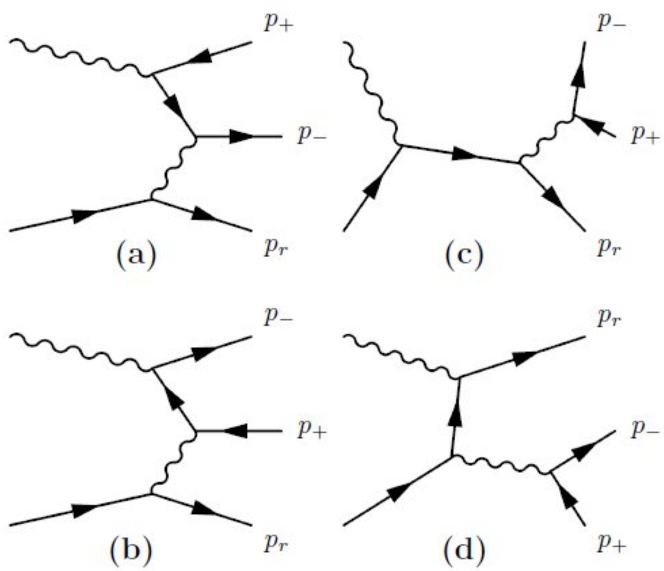
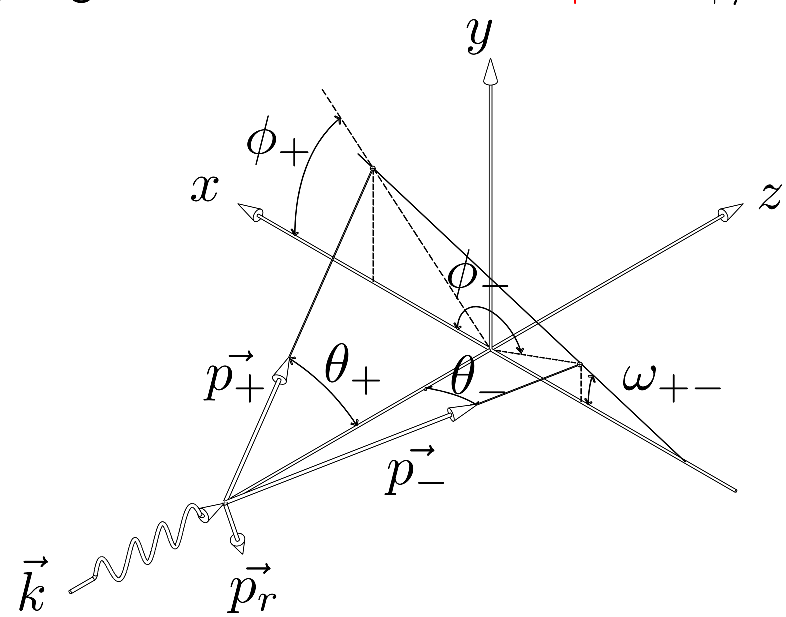
Developed, Validated, Event Generator

- 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)

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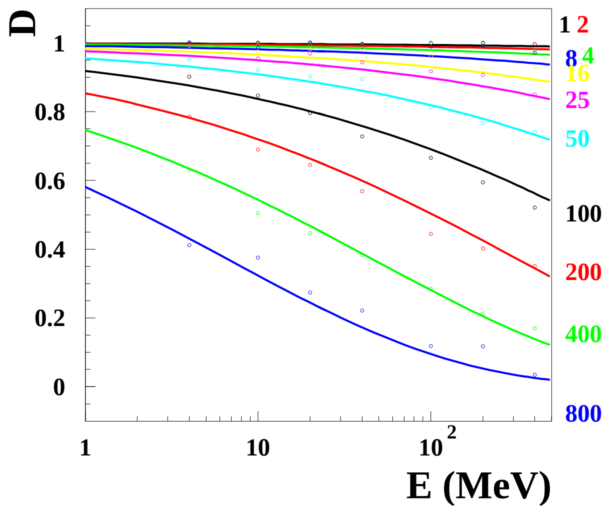
Dilution of Polarization Asymmetry due to Multiple Scattering : Optimal Fits and Full MC

- Remember : track angular resolution $(p/p_1)^{-3/4}$, $p_1 = 13.6\,\mathrm{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$
- $D \equiv \frac{\mathcal{A}_{\mathrm{eff}}(p_1)}{\mathcal{A}(p_1 = 0)}$



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

- 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, $p_1 = 50\,\mathrm{keV}/c$)

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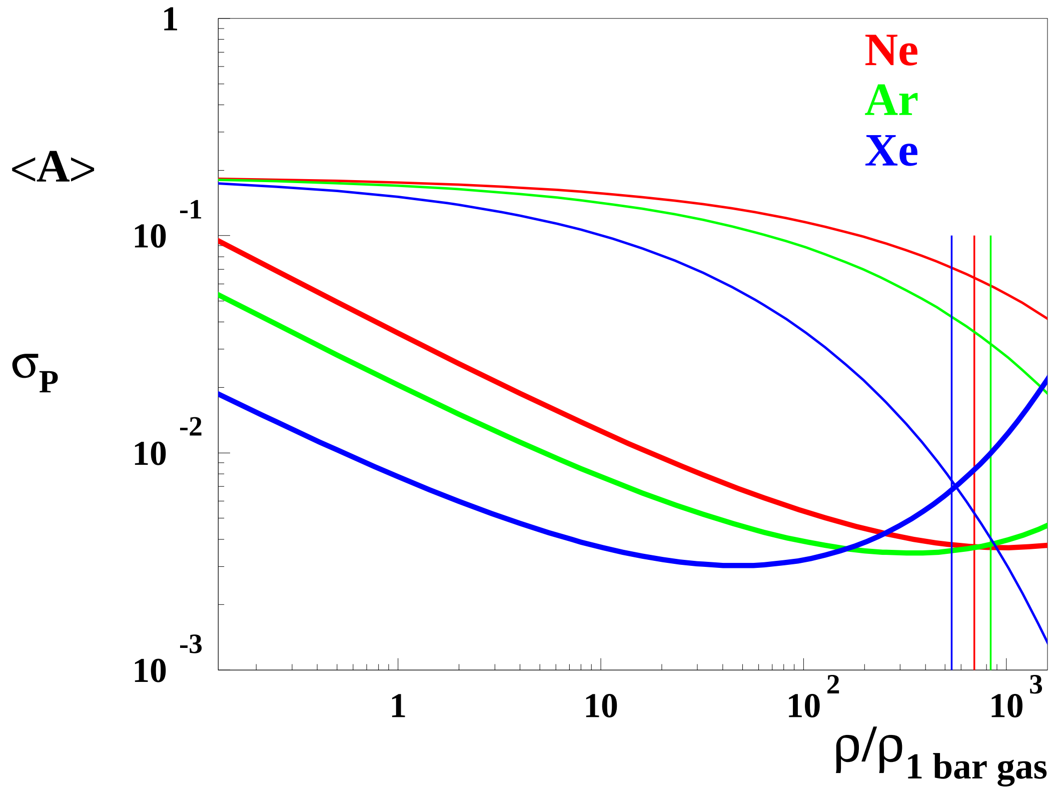
Polarimetry Performance : 1 : no Experimental Cuts

- Crab-like source, $T = 1$ year, $V = 1\,\mathrm{m}^3$, $\sigma = l = 0.1\,\mathrm{cm}$, $\eta = \epsilon = 1$).
- $\mathcal{A}_{\mathrm{eff}}$ (thin line), σ_P (thick line) ;



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

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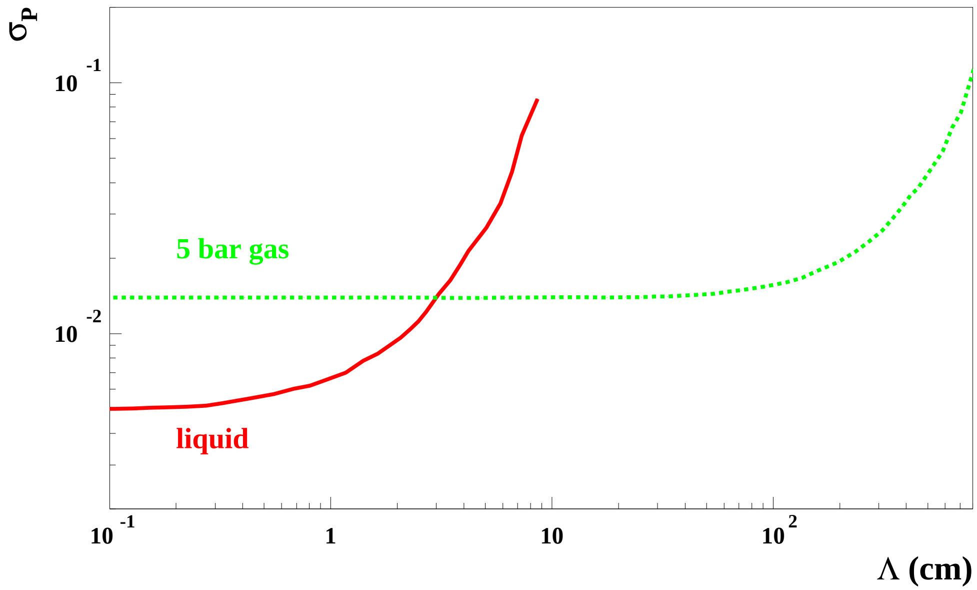
Polarimetry Performance : 2 : Experimental Cuts

- photon-source assignment selection $\theta_{pair} < 10\,^{\circ}$
- opening angle $\theta_{+-} > 0.1\,\mathrm{rad}$
- lepton (kinetic) energy cut (5 bar argon, $0.5\,\mathrm{MeV} \propto$ path length $\approx 30\,\mathrm{cm}$).
  $\sigma_P \approx 1.0\% \rightarrow 1.4\%$
- expressing the track E cut as a pathlength Λ cut (argon) :

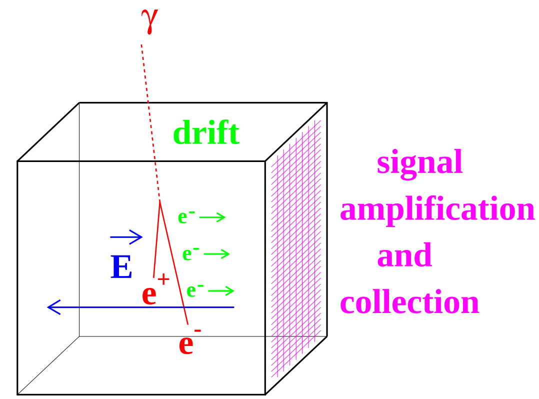


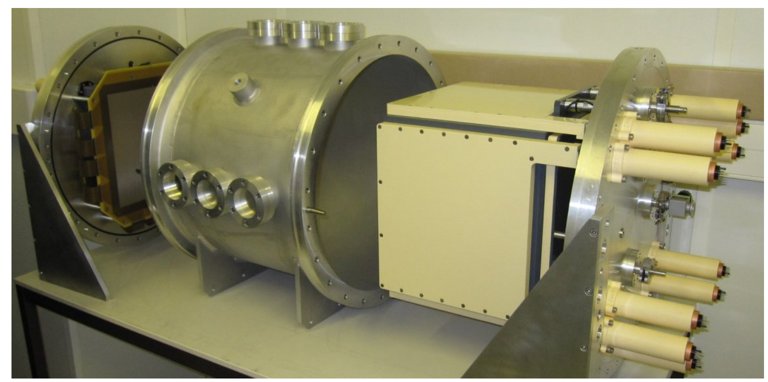
- polarimetry with a dense detector (liquid / solid TPC, scintillator cube) would imply efficient trigger / tracking / selection of cm long tracks.
- A stack of hyper-thin Si wafer could be considered homogeneous, and if spaced far enough .. low density .. enough ?

HARPO : the Demonstrator

- Time Projection Chamber (TPC)
- $(30\mathrm{cm})^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on x, y strips, pitch 1 mm.
- AFTER chip digitization, up to 50 MHz.
- Scintillator / WLS / PMT based trigger

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

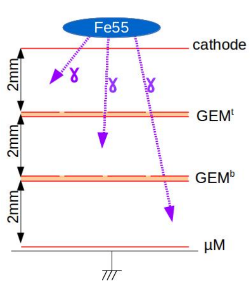


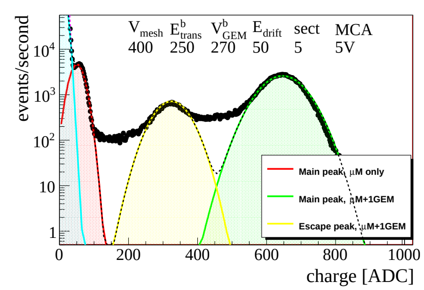


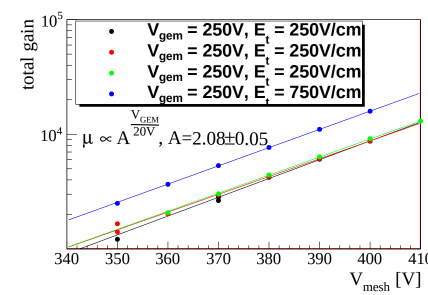
- micromegas + (1 or 2) GEM

  ^{55}Fe & cosmics caracterization

  Ph. Gros, TIPP2014

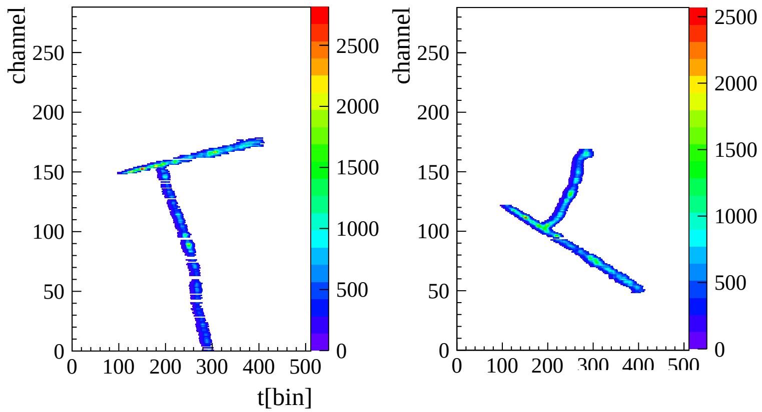




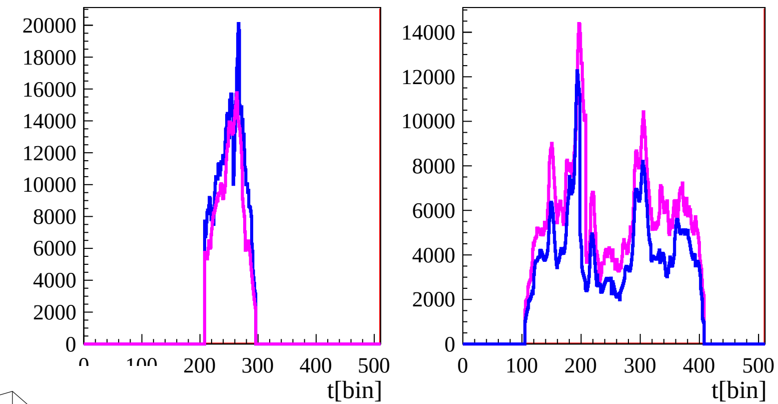


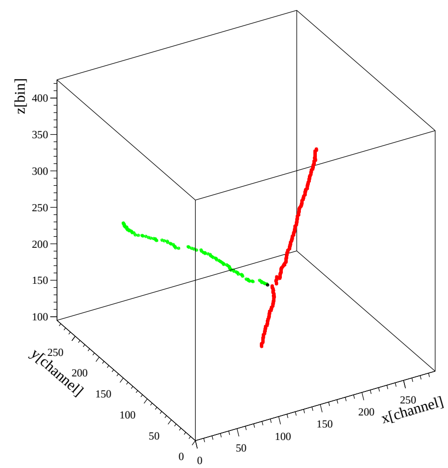
Event Reconstruction

raw “maps”



track time spectra (x, y matching)





- 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
- 2 bar (Ar :95 Isobutane 5 %), shaping 100 ns.

Conclusion

A thin active target such as a gas TPC is THE detector for γ astronomy in the e^+e^- with utmost performance in the [MeV - GeV] photon energy range,

- Angular resolution improvement by ≈ 1 order of magnitude w.r.t. the Fermi LAT within reach.
  @ 100 MeV, 5 bar argon, recoil $\approx$ MS, 0.4° in total

  Therefore, powerful Background rejection

  And rejection of atmospheric photons and of cosmic rays is straigthforward

- Full sky, 4π acceptance (.. if on a high orbit)

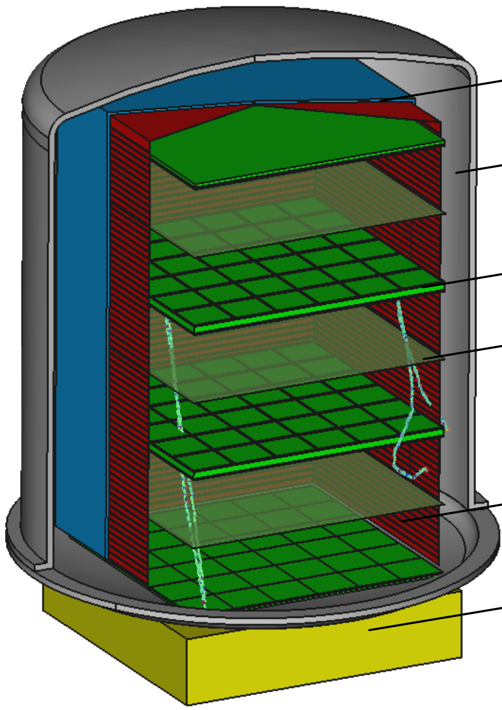
- Huge sensitivity improvement, closes the sensitivity gap between (Compton and W/Si pair) telescopes

- Provides, for the first time, polarimetry above 1 MeV !

- The HARPO demonstrator built and characterized with cosmic rays.

Preparation of data taking @ NewSUBARU Japan in Nov 2014 is in progress. ((almost) fully polarized γ beams 2 – 76 MeV)

Exploded Schematic View of a Flight Telescope



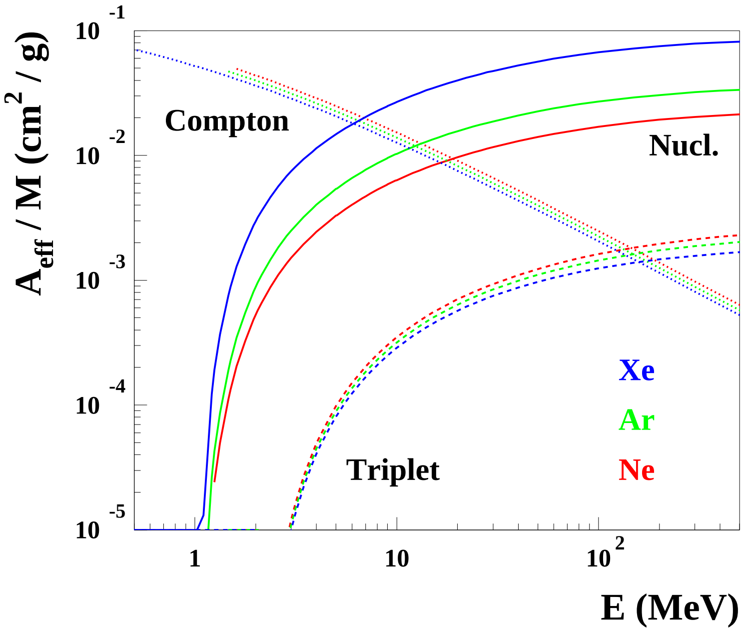
3 layers, each layer of 2 back-to-back modules, each module a $(2\ \mathrm{m})^2 \times 0.5\ \mathrm{m}$ TPC with an endplate segmented into $(33\ \mathrm{cm})^2$ micromegas and charge collection blocks. 432 chips, $(12\ \mathrm{m})^3$: 100 kg gas at 5 bar.

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

Je vous remercie de votre attention.

Back-up Slides

Thin / Thick Detectors, Effective Area



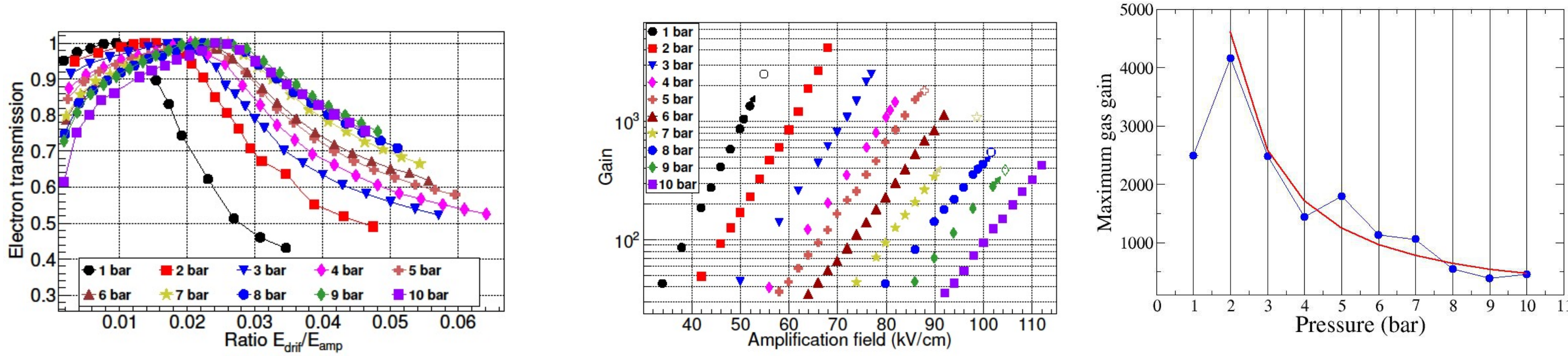
	Thick	Thin
Conversion probability	$p \approx 1$	$p \ll 1$
Effective area $A_{\rm eff}$	$\approx S \times \epsilon$	$\approx H \times M \times \epsilon$
Conversion processes (pair, triplet, Compton)	compete	don't compete with each other

- H photon attenuation, M detector mass, S surface, ϵ reconstruction efficiency
- Thin techno prevents γ loss due to Compton in low Z material at low E
- High E asymptote $A_{\rm eff} = 3.6 {\rm m}^2/{\rm ton}$ (Nuclear, Argon)

Which Pressure ?

- **Science**. Rising the pressure :
  - degrades the angular resolution and (mildly) point like source sensitivity
  - Increases the effective area improves the precision on the polarization

- Maximum **micropattern gas amplification gain** (micromegas, GEM) known to decrease with pressure .. but dE/dx increases ..



D. C. Herrera, *et al.*, "Micromegas-TPC operation at high pressure in Xenon-trimethylamine mixtures," J. Phys. Conf. Ser. 460, 012012 (2013).

micropattern gas amplification above 10 bar a concern, unless very small gap devices can be produced.

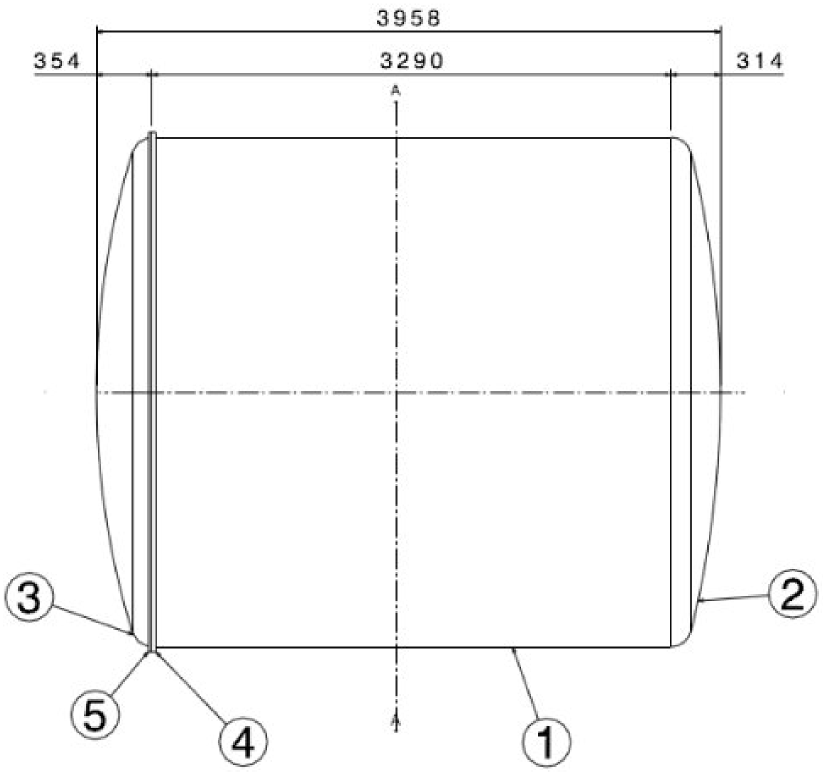
- **Vessel Mass** $\propto$ gas mass to 1rst order.
  - For a given mission : which limit will we touch first (volume, mass) ?

In this talk examples were given at 1, 5, 10 bar

Pressure Vessel : a Naive Static Study

P	Alloy Titanium	0.2% yield strength	@ T	safety factor	ϕ	t shell	t heads	M
5 bar	6Al-V4	750 MPa	$150^{\circ}\mathrm{C}$	1.6	3000 mm	4 mm	5.5 mm	1110 kg

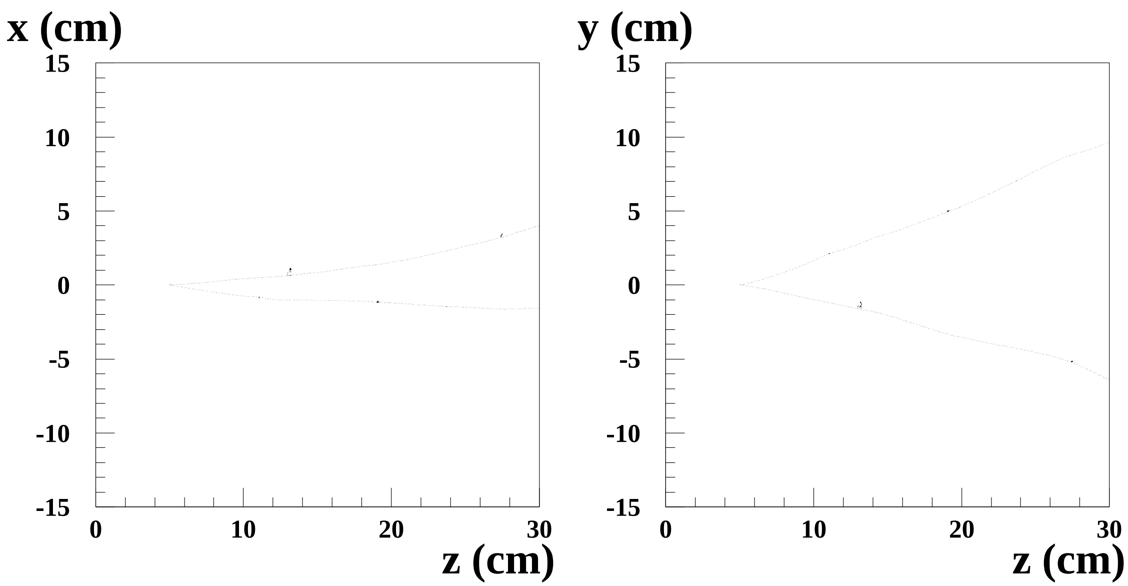
No re-inforcement of any kind at the moment.



TPC gas	100	kg
outside gas	150	
vessel	1110	
PCB	142	
Scintillator veto	300	?
electronics	?	
support	?	
gas system	?	
total	> 1800	kg

Behavior upon launch ?

A γ Nuclear Conversion in a 30 cm 5 bar Argon TPC



γ	Z	$\rightarrow$	e^+	e^-	Z
(10 MeV)			(4.3 MeV)	(5.7 MeV)	

(EGS5)

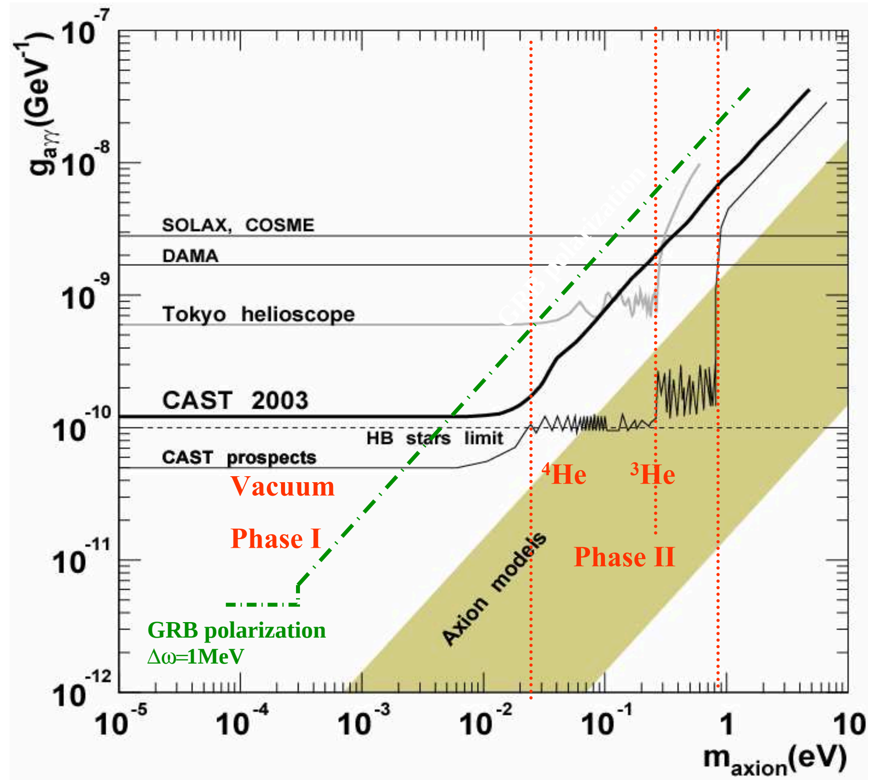
Search for Axions

- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to 2 γ through triangle anomaly.
- γ propagation through $B \Rightarrow$ Dichroism $\Rightarrow$ E dependant rotation of linear polarization $\Rightarrow$ linear polarization dilution.

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B\sqrt{\Delta\omega L_{GRB}}}$$

- Saturation over $L = 2\pi\omega/m_a^2 > L_{GRB}$ for $m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}}$

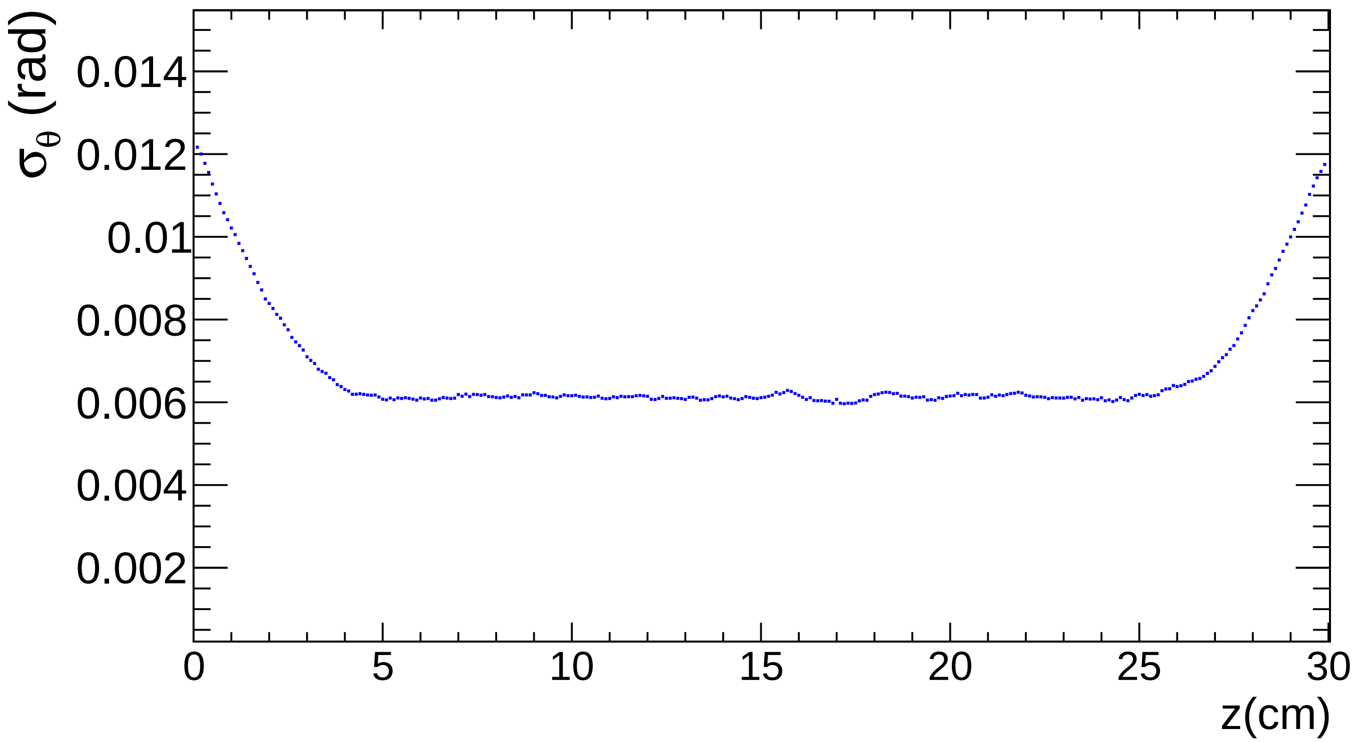
and the limit $g_{a\gamma\gamma}$ reaches a ω-independent constant.



A. Rubbia and A. S. Sakharov, Astropart. Phys. 29, 20 (2008)

Optimal Track Fit with Multiple Scattering
Cross Validation

- 5 bar argon, $\sigma = l = 0.1\text{cm}\,;$ $\qquad p_1 = 13.6\,\text{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6} = 112\,\text{keV}/c$
- $40\,\text{MeV}/c$ electrons, $\sigma_{\theta t} = (p/p_1)^{-3/4} = 12.2\,\text{mrad}$



Smoothed angle residues RMS for track fits with a Kalman filter.

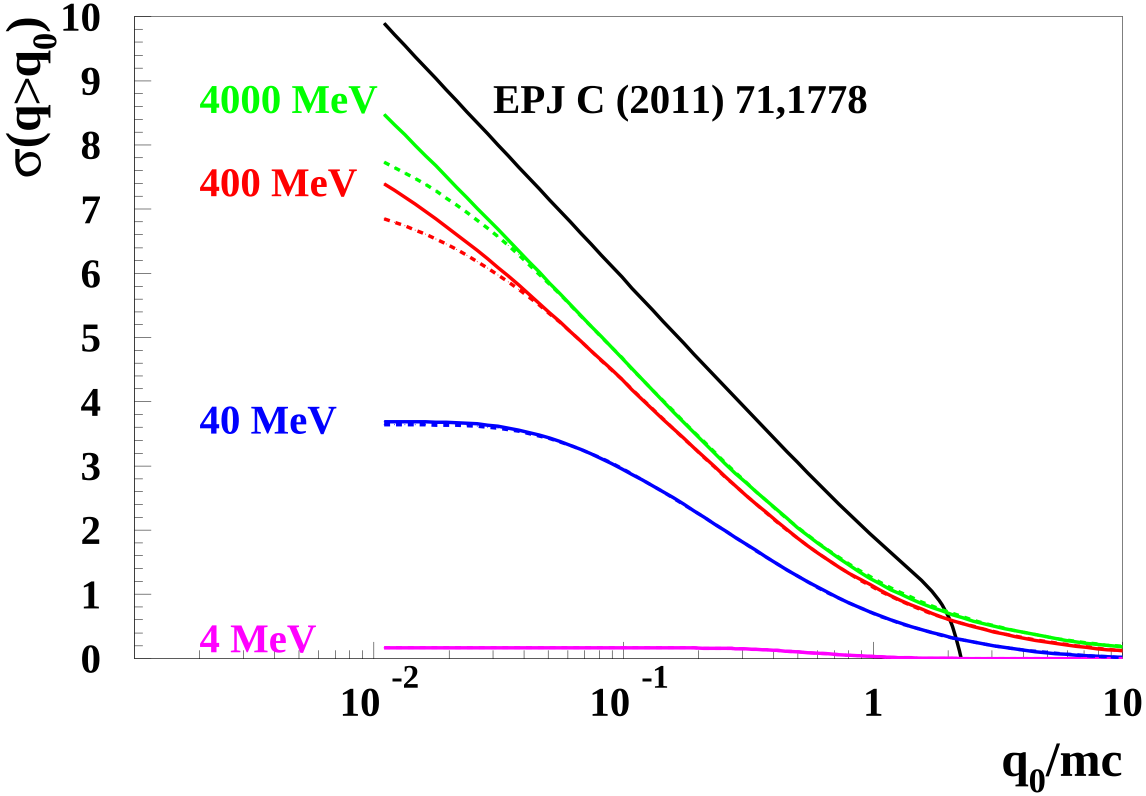
D.B. NIM A 729 (2013) 765

Evt Generator : One Example of Validation Plot

- Triplet conversion : cross section for recoil electron momentum larger than q_0, $\sigma(q > q_0)$, as a function of q_0/mc, for various photon energies E ;

Compared with :

- High photon energy asymptotic expression by M. L. Iparraguirre and G. O. Depaola, Eur. Phys. J. C 71, 1778 (2011).



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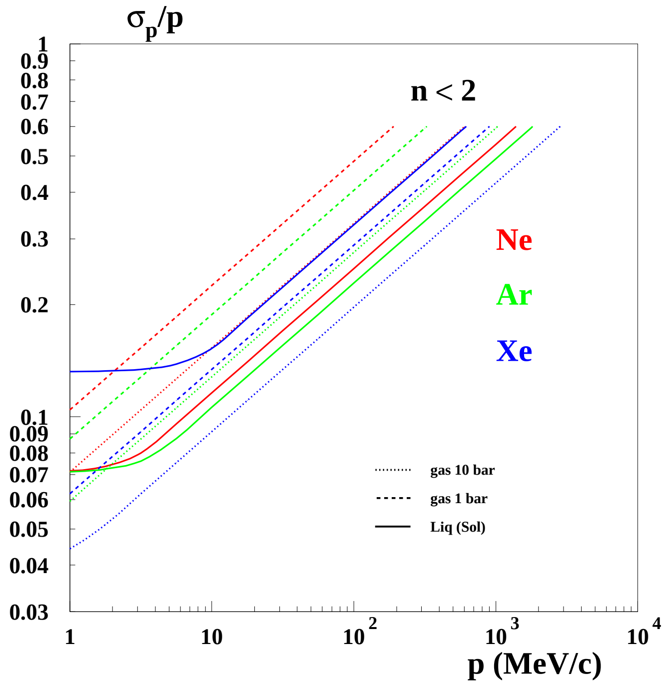
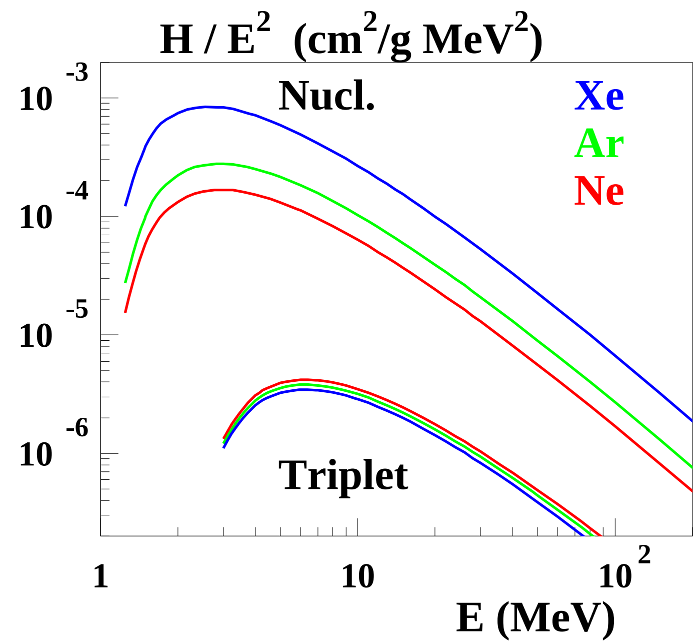
Track Momentum Measurement in TPC Alone from Multiple Estimations of Multiple Scattering

- multiple scattering $\theta_0 \propto 1/p \Rightarrow p \propto 1/\theta_0$ G. Molière, Zeit. Naturforschung A, 10 (1955) 177.
- optimization of track step size $\Rightarrow$ $$\frac{\sigma_p}{p} \propto \frac{1}{\sqrt{L}} \left[\frac{p\,\sigma\sqrt{X_0}}{13.6\mathrm{MeV}/c} \right]^{1/3}$$

relative precision



E range of interest



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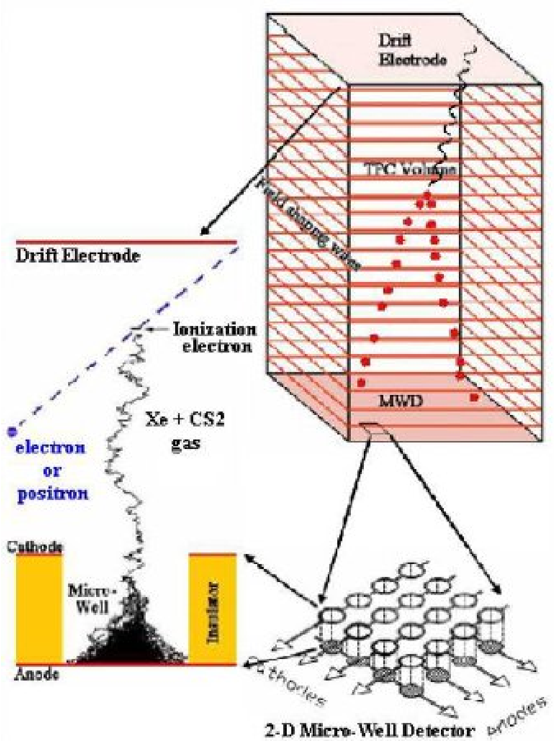
TPC-Based γ-Ray Telescope Projects

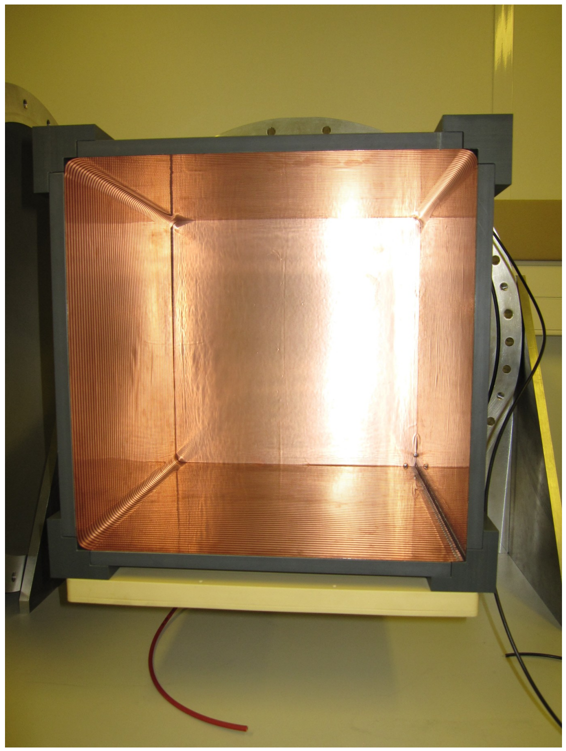
.. Most likely not exhaustive ..

AdEPT	HARPO	μ PIC
NASA	LLR & Irfu CEA/Saclay	Kyoto U.
et al.		*et al.*



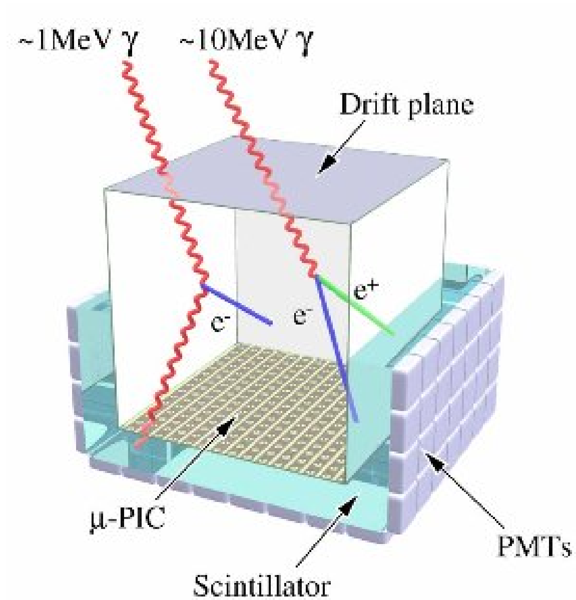
S. D. Hunter

Proc. of SPIE Vol. 7732 773221-7



D.B.

Pisa2012 & NIM A 718 (2013) 395



K. Ueno

Vienna 2010

Polarimetry : Optimal Measurement

- Remember, fit of $\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P\cos[2(\phi)])$ yields $\sigma_P \approx \frac{1}{\mathcal{A}}\sqrt{\frac{2}{N}}$,
- Optimal measurement ; Ω
  - let's define $p(\Omega)$ the pdf of set of (here 5) variables Ω
  - search for weight $w(\Omega)$, $\mathrm{E}(w)$ function of P, and variance σ_P^2 minimal ;
  - a solution is $w_{\mathrm{opt}} = \frac{\partial \ln p(\Omega)}{\partial P}$ e.g. : F. V. Tkachov, Part. Nucl. Lett. 111, 28 (2002)
  - polarimetry : $p(\Omega) \equiv f(\Omega) + P \times g(\Omega)$, $w_{\mathrm{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}$.
    - If $\mathcal{A} \ll 1$, $w_0 \equiv 2\frac{g(\Omega)}{f(\Omega)}$, and
    - for the 1D "projection" $p(\Omega) = (1 + \mathcal{A}P\cos[2(\phi)])$:

$$w_1 = 2\cos 2\phi, \qquad \mathrm{E}(w_1) = \mathcal{A}P, \qquad \sigma_P = \frac{1}{\mathcal{A}\sqrt{N}}\sqrt{2 - (\mathcal{A}P)^2},$$

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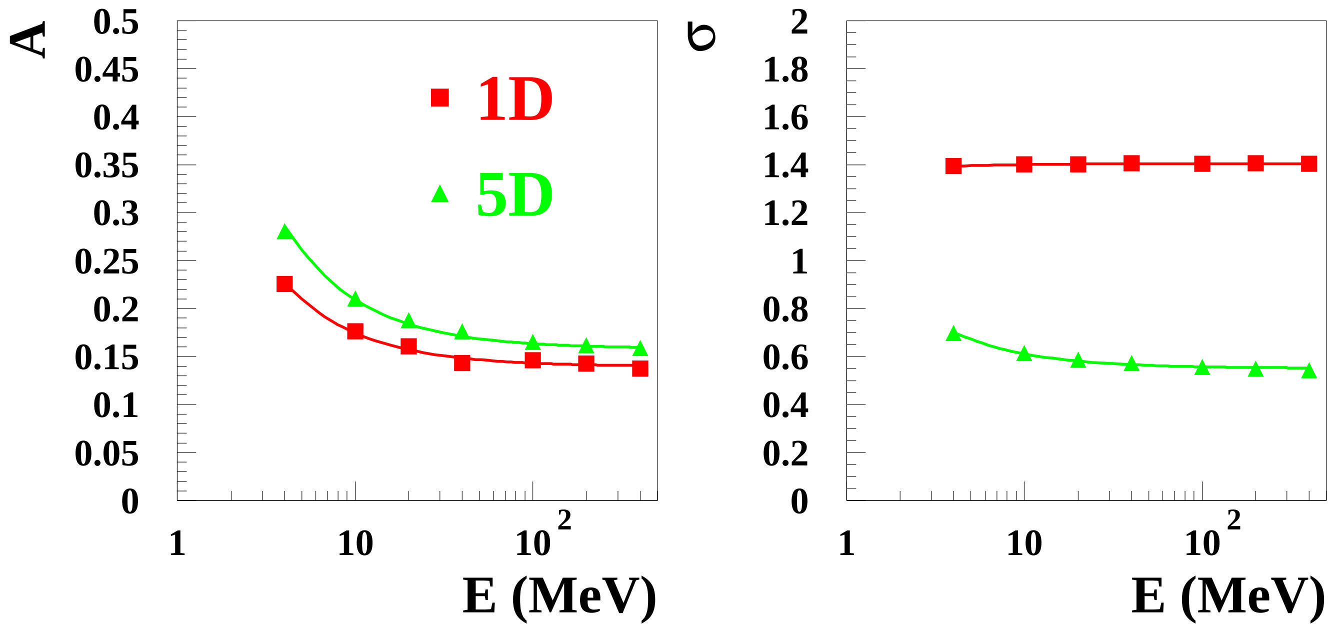
Polarimetry : Optimal Measurement

- Full MC, nuclear conversion



- 1D weight : validation $\sqrt{2}$
- 5D weight :
  - similar polarization asymmetry $\mathcal{A}$ ($\approx 15\%$ asymptotically at high E)
  - gain factor > 2 on precision σ_P w.r.t. 1D weight,
  - ability to measure precisely the 5D final state ?

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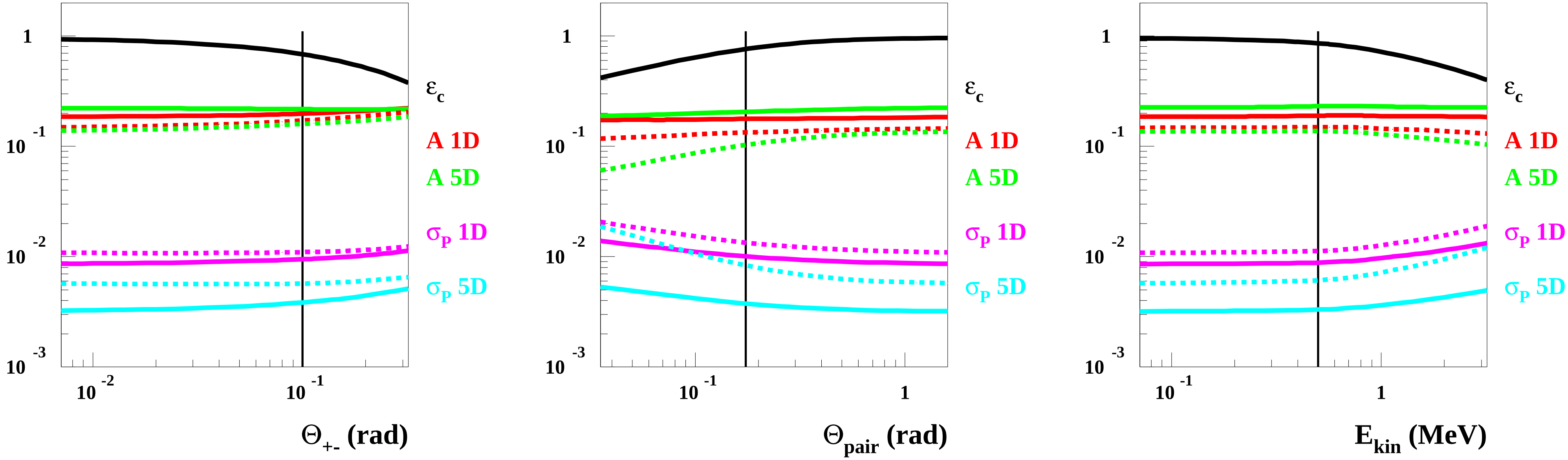
Polarimetry : Effects of Experimental Cuts

- opening angle, $\theta_{+-} > 0.1\,\mathrm{rad}$ (easy pattern recognition
- source selection $\theta_{pair} < 10\,^\circ$
- kinetic leptons energy $E_{kin} > 0.5\,\mathrm{MeV}$, (path length in 5 bar argon $\approx 30\,\mathrm{cm}$)



- All cuts : $\epsilon = 45\%$, (1D) $\mathcal{A}_{\mathrm{eff}} \approx 16.6\%$ $\sigma_P \approx 1.4\%$,

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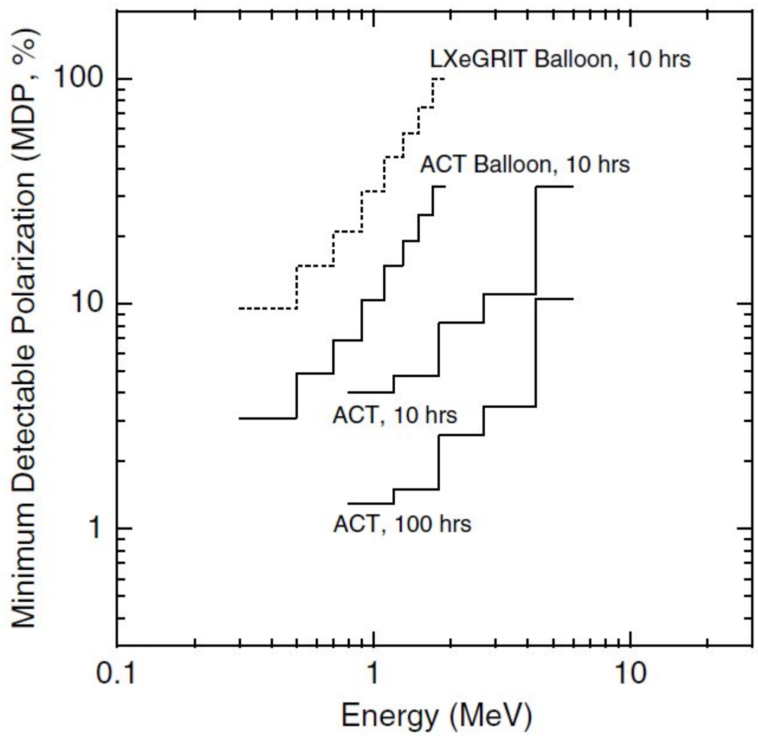
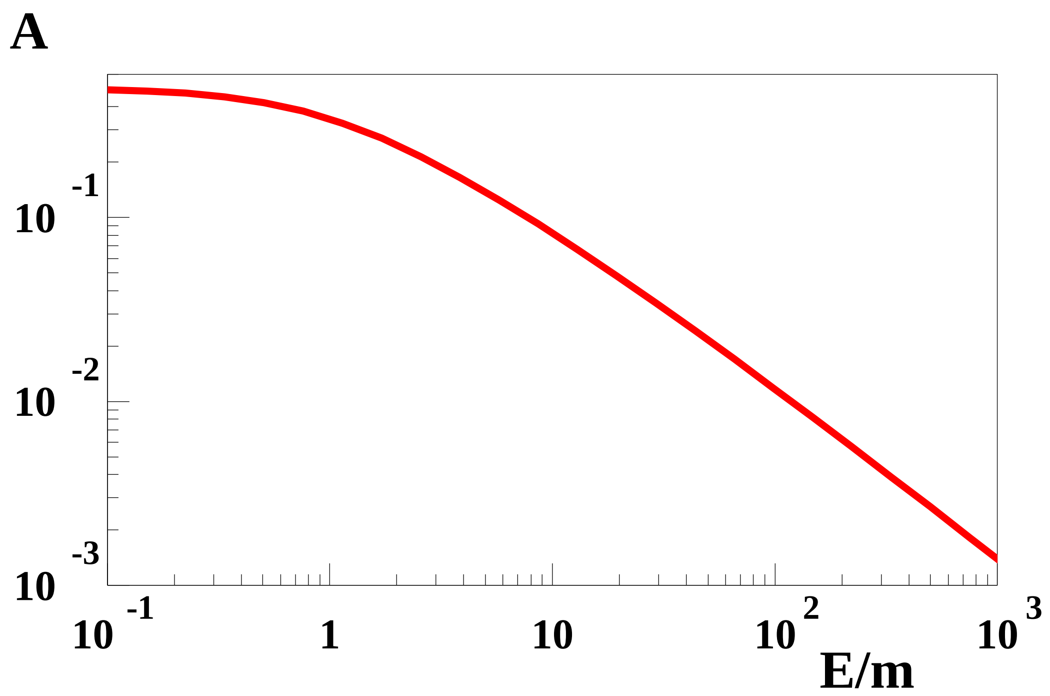
Polarimetry with Compton Scattering Events at High Energy

Minimum detectable polarization



Compton polarization asymmetry

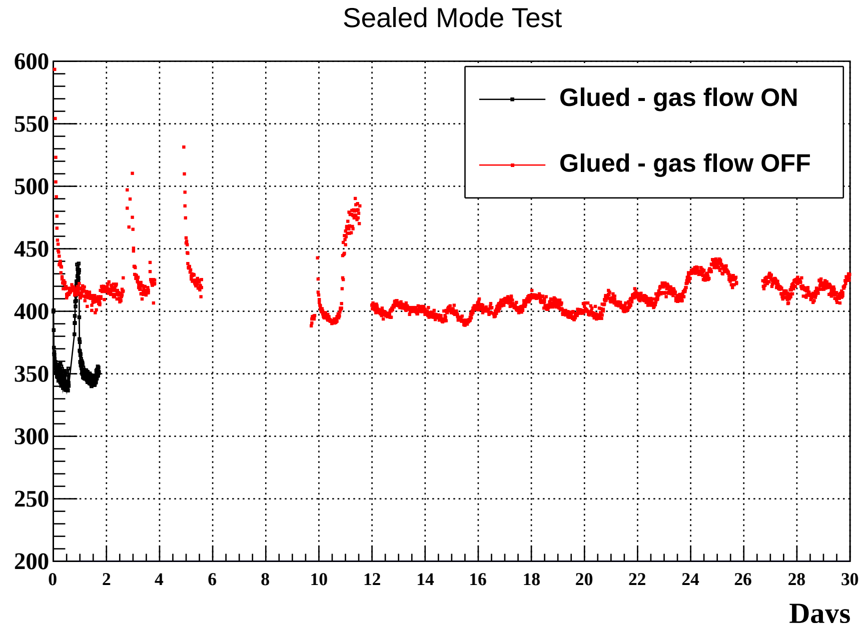


M. L. McConnell, J. M. Ryan

New Astronomy Reviews, 48 (2004) 215

Long Term Work with Gas Detector in Space

- Our present "ground" demonstrator is rather dirty (scintillator, WLS, PCB, glue ..)
- Sealed operation, no recirculation.
  $\Rightarrow$ After on month of working, it showed significant absorption over 30 cm drift length
- Obvious cure would be recirculating / purifying the gas.
- An other option is to separate "clean" and "dirty" volumes by a ceramic foil



D. Attié *et al.*, "Piggyback resistive Micromegas," JINST 8, C11007 (2013)

- Obviously the collecting board is on the "dirty" side
- The signal is then read through capacitive coupling