High performance MeV-GeV gamma-ray astronomy with a time projection chamber

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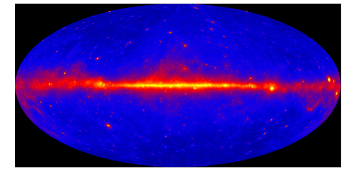
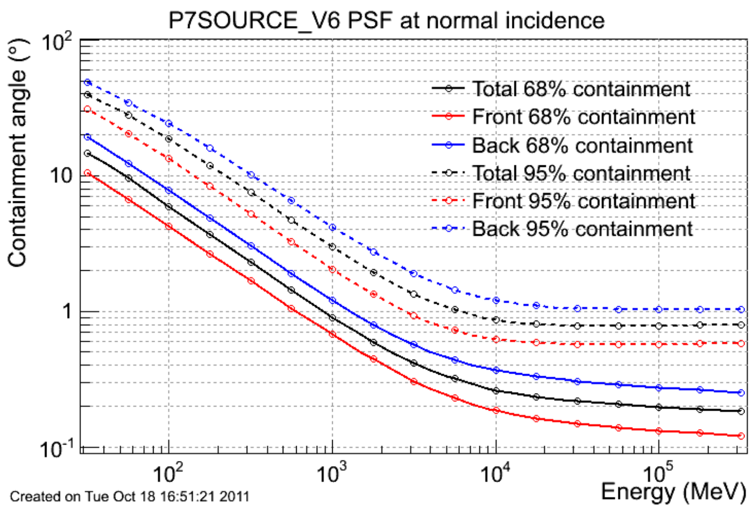
TeVPA2015, TeV Particle Astrophysics,
October 26-30 2015, Kashiwa Japan

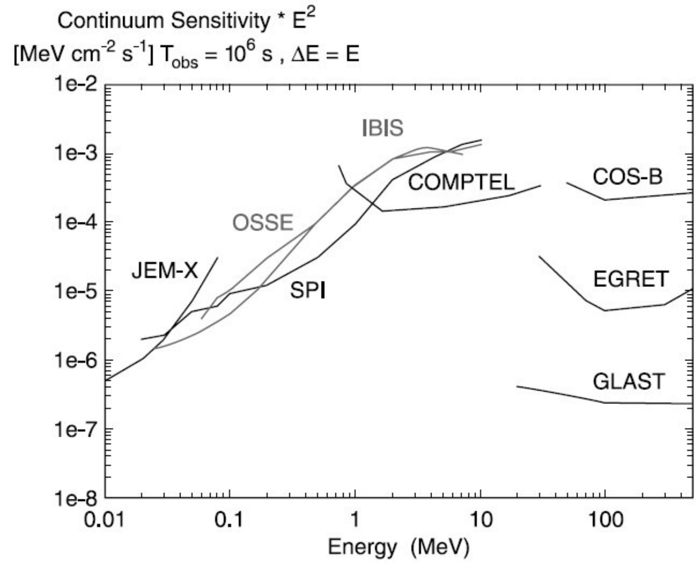
llr.in2p3.fr/∼dbernard/polar/harpo-t-p.html

Science Case



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





Fermi/LAT

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

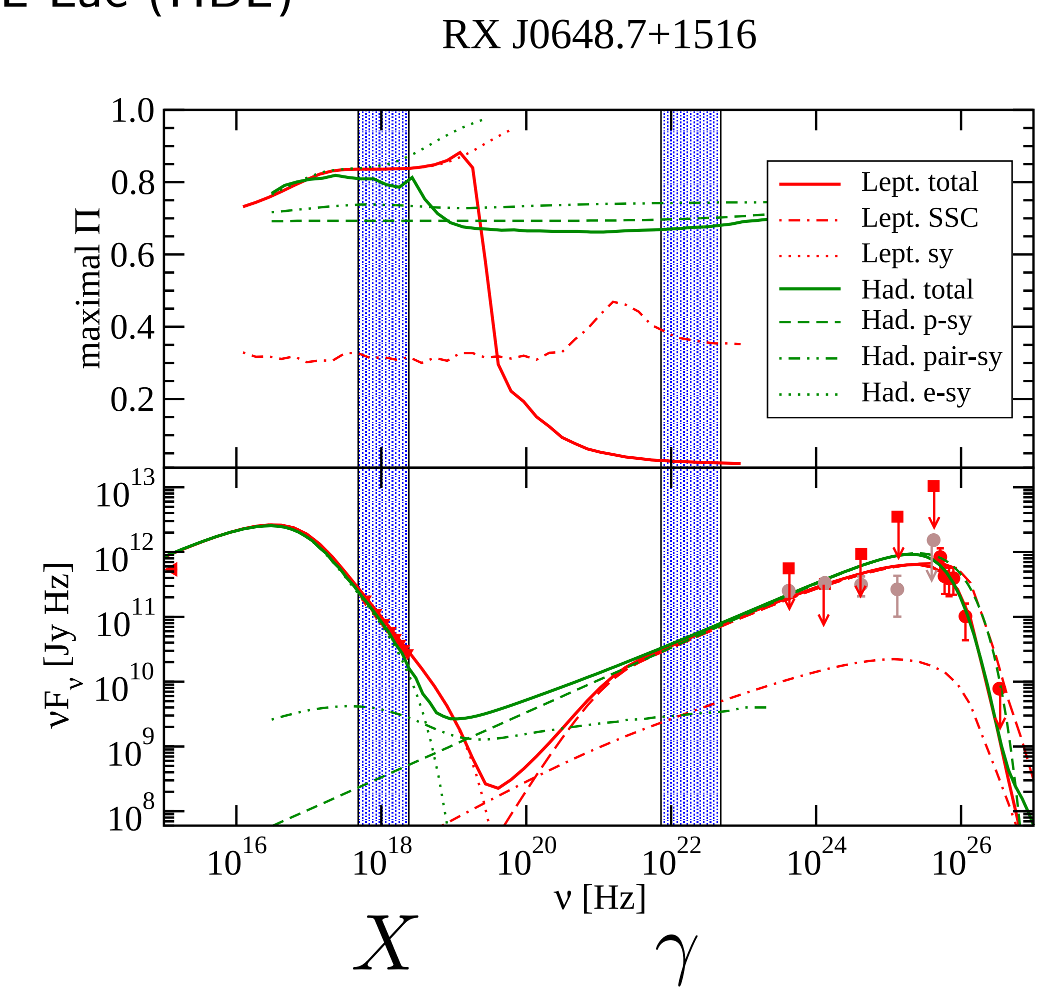
  - Solve sensitivity gap between Compton and pair telescopes
    - Actually Fermi is publishing mostly in the range $0.1 - 300\text{GeV}$
    - Improvement expected from PASS8

- **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 ($\Delta\theta \propto E^2$)

Science Case: Polarimetry: Astrophysics

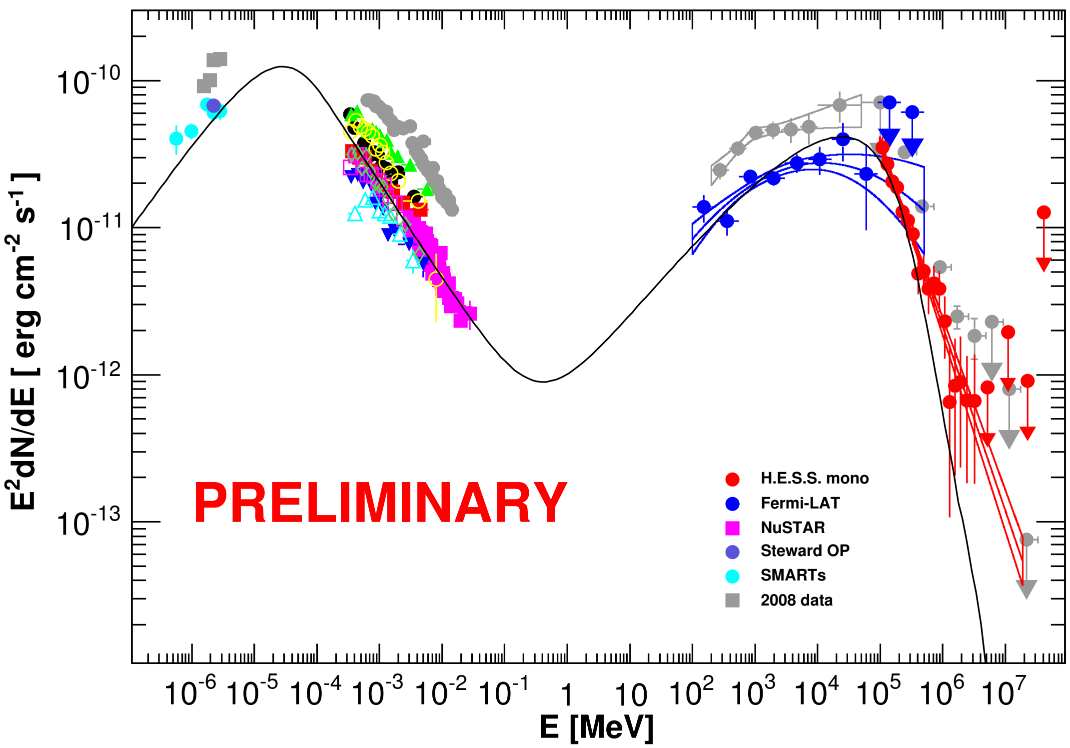
- One example: Blazar : decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models
  - high-frequency-peaked BL Lac (HBL)
  - X band: 2 -10 keV
  - γ band: 30 - 200 MeV
- SED's indistinguishable, but
- X-ray: $P_{\mathrm{lept}} \approx P_{\mathrm{hadr}}$
- γ-ray: $P_{\mathrm{lept}} \ll P_{\mathrm{hadr}}$

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



Nothing of polarimetry in this talk – See my SPIE2014 talk, arXiv:1406.4830 [astro-ph.IM]

γ-ray sensitivity gap: HBL PKS 2155-304 example



Grey points: dedicated Multiwavelength campaign 2013:

- NuSTAR satellite (3-79 keV),
- the Fermi Large Area Telescope (LAT, 100 MeV-300 GeV)
- (H.E.S.S.) array phase II

D. A. Sanchez *et al.*, 5th Fermi Symposium: Nagoya, Oct 2014 arXiv:1502.02915v2 [astro-ph.HE]

Photon angular resolution

$$\gamma \; Z \rightarrow e^+ \; e^- \; Z$$

$$\vec{k} = \vec{p_{e^+}} + \vec{p_{e^-}} + \vec{p_r}$$

Contributions:

- Single-track angular resolution,
- Un-measured nucleus recoil momentum for “nuclear” conversion
- Single-track momentum resolution

Single-track angular resolution

Hypotheses:

- Thin homogeneous detector;
- Tracking with optimal treatment of multiple-scattering-induced correlations (e.g., à la Kalman);
- Low energy, multiple-scattering-dominated, regime

$$\sigma_{\theta t} = (p/p_1)^{-3/4} \quad \text{with} \quad p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3} \right)^{1/6},$$

With:

- p track momentum $[\mathrm{MeV}/c]$;
- $p_0 = 13.6\,\mathrm{MeV}/c$, multi-scattering constant;
- p_1 detector "multiple-scattering momentum" parameter $[\mathrm{MeV}/c]$;
- σ single measurement detector spatial resolution [cm];
- l track sampling pitch [cm].

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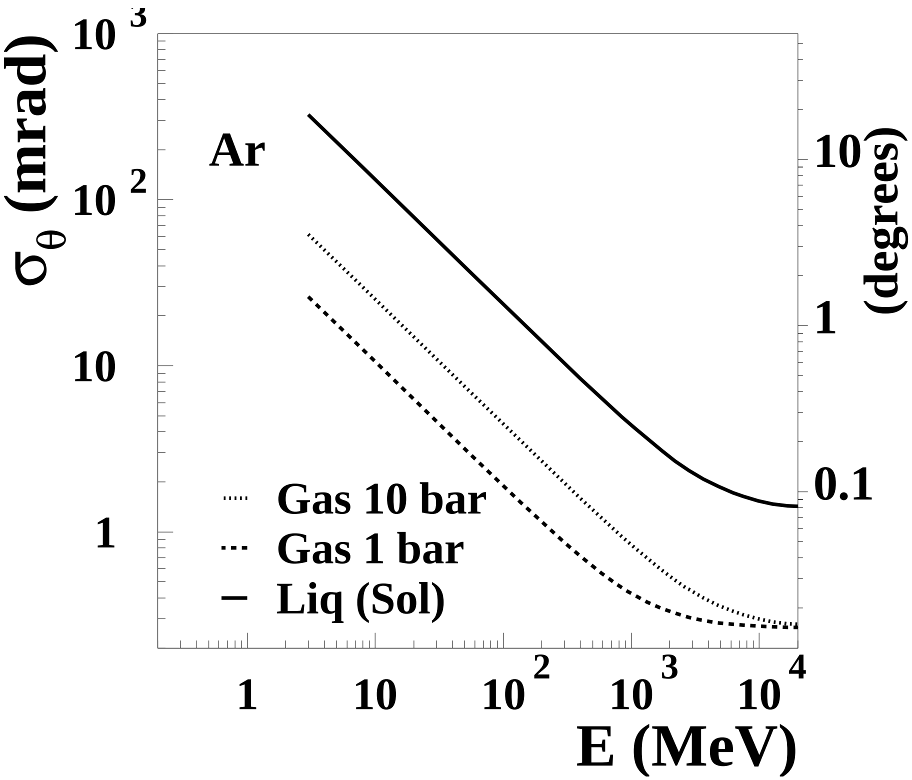
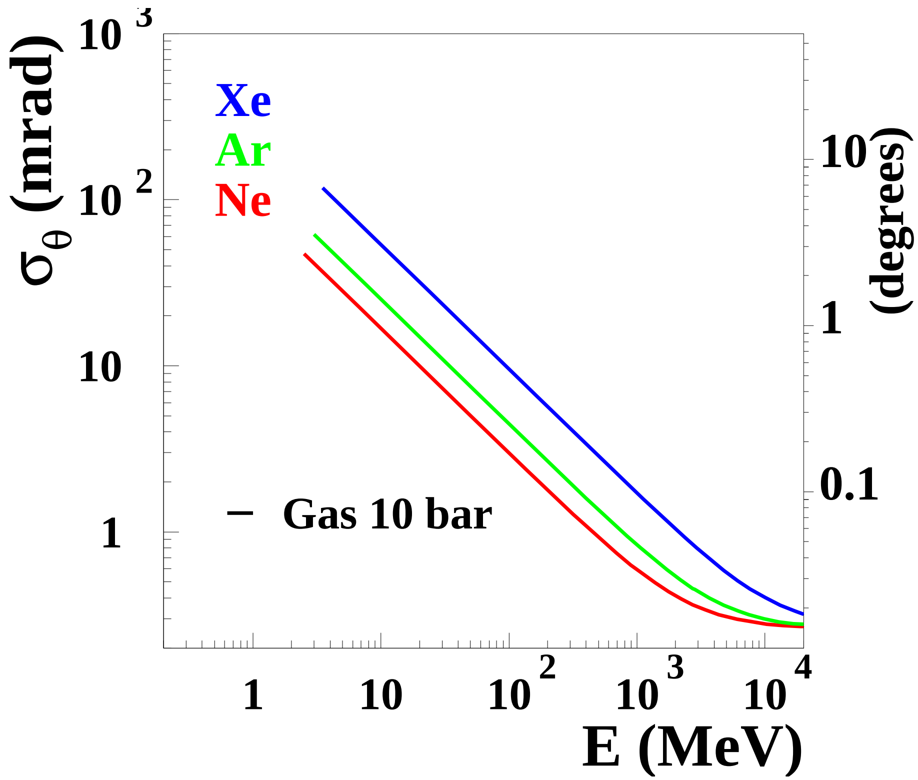
Single-track angular resolution

Dependence of the RMS photon angular resolution on photon energy





for various densities (argon)

in 10 bar gas for various gases

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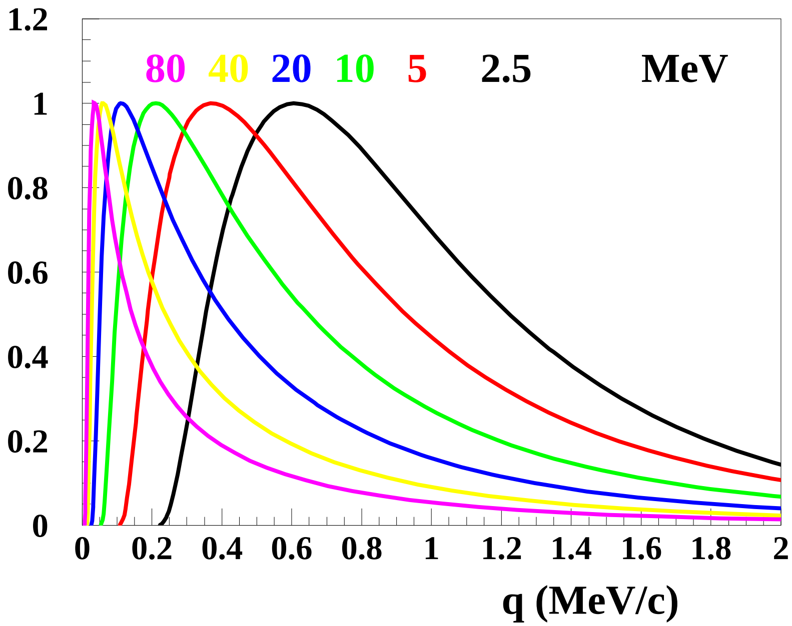
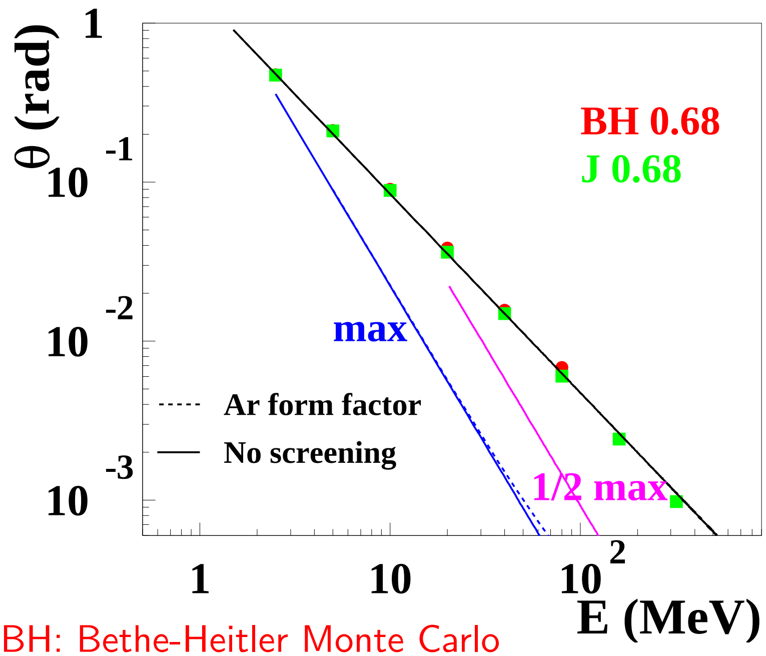
Angular resolution: Un-measured nucleus recoil momentum





BH: Bethe-Heitler Monte Carlo

R. Jost et al., Phys. Rev. 80, 189 (1950).

Recoil momentum distribution (no screening)

68 % "containment", most-probable and half-most-probable angles

68 % "containment" value $\theta = 1.5\,\mathrm{rad}\,\left(\frac{E}{1\,\mathrm{MeV}}\right)^{-5/4}$

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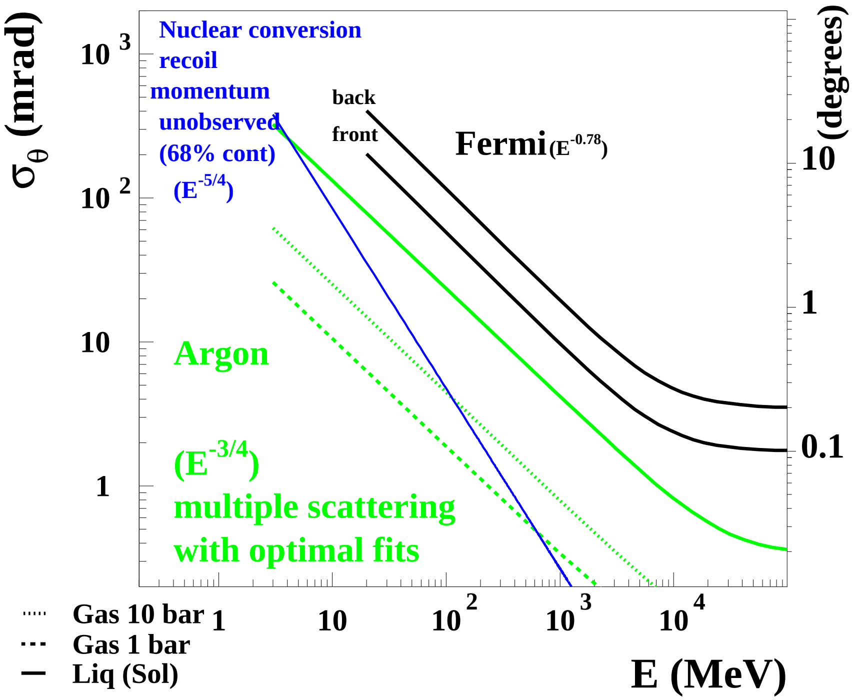
Way Out: Thin Homogeneous Detector and Optimal Fits

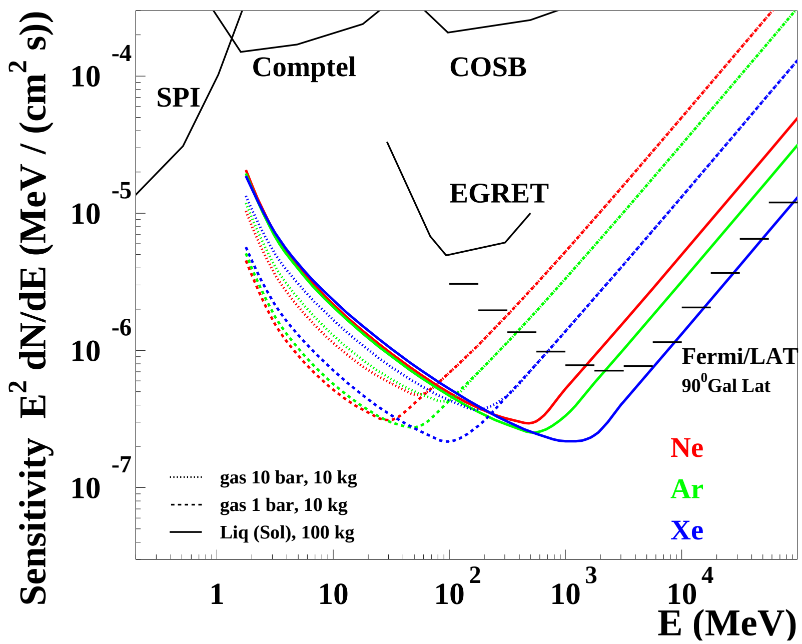
Angular resolution

- 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 [NIM A 729 (2013) 765]

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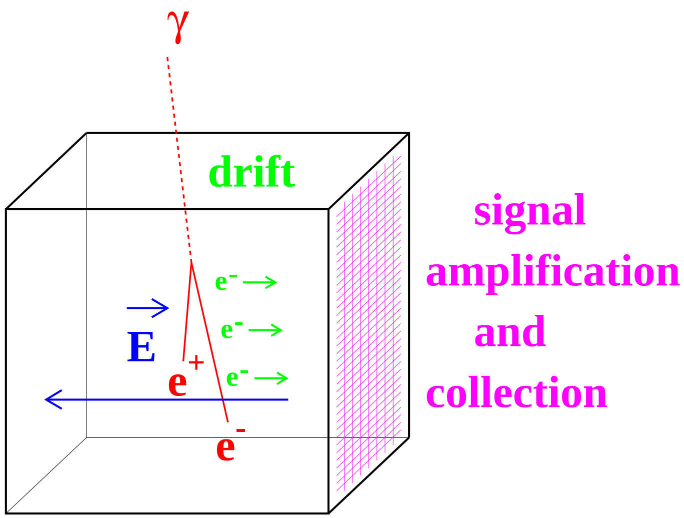
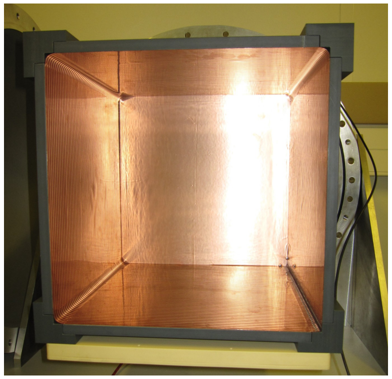
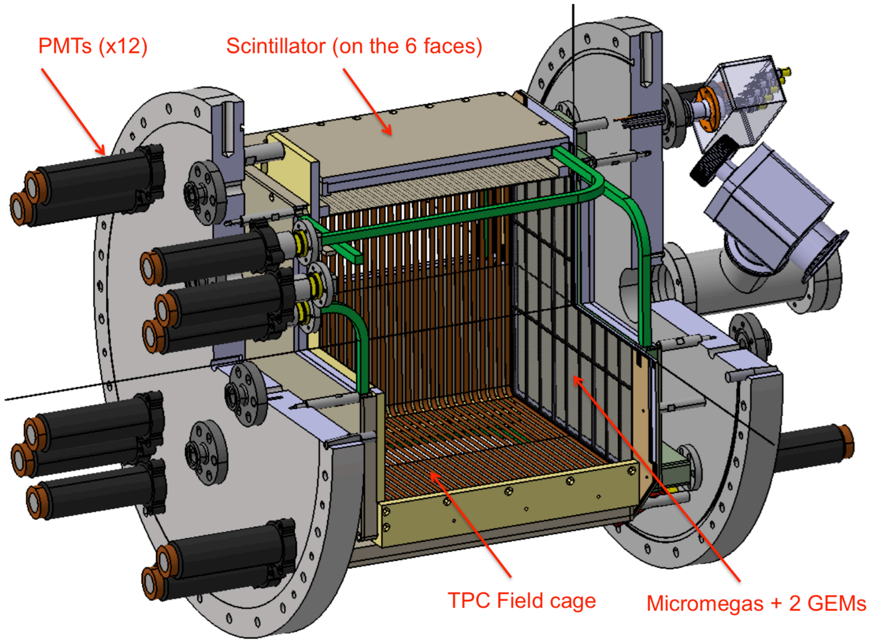
HARPO: the Demonstrator

- Time Projection Chamber (TPC)
- $(30\text{cm})^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification

  Ph. Gros, TIPP2014
- Collection on x, y strips, pitch 1 mm.
- AFTER chip digitization, up to 50 MHz.
- Scintillator / WLS / PMT based trigger



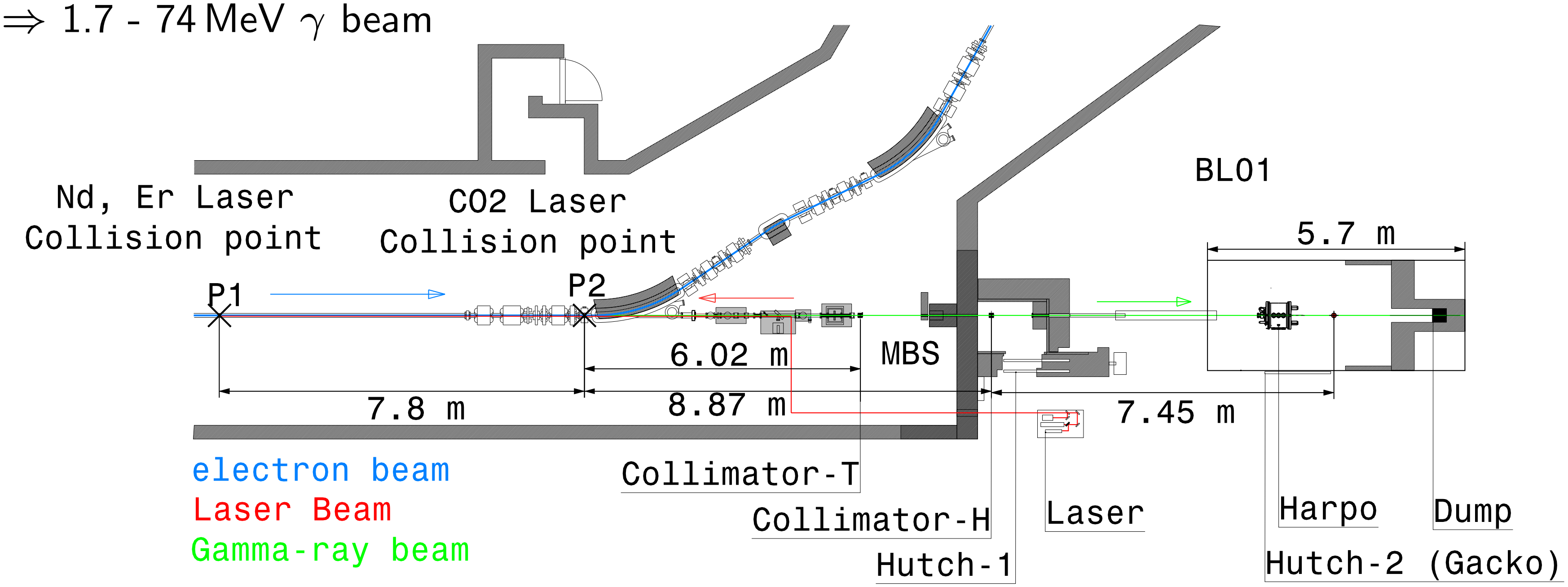




NIM A 695 (2012) 71, NIM A 718 (2013) 395

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- $0.532\,\mu\mathrm{m}$ and $1.064\,\mu\mathrm{m}$ $20\,\mathrm{kHz}$ pulsed Nd:YVO_4 (2ω and 1ω),
  $1.540\,\mu\mathrm{m}$ $200\,\mathrm{kHz}$ pulsed Er (fibre) and
  $10.55\,\mu\mathrm{m}$ CW CO_2 lasers
- $\Rightarrow$ 1.7 - 74 MeV γ beam

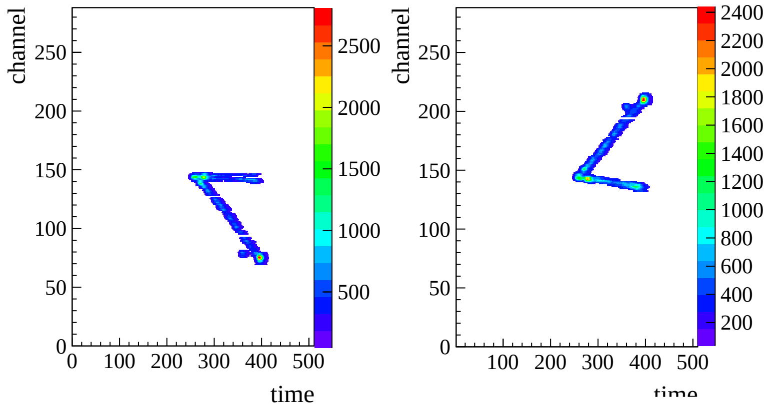


- Monochromaticity by collimation on axis

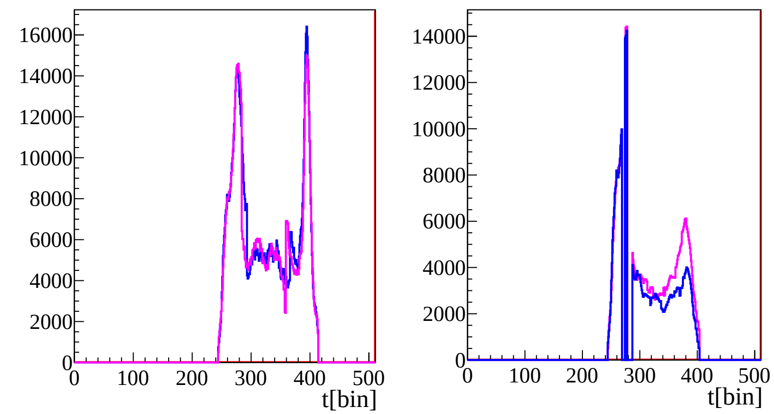
A. Delbart et al., ICRC2015, The Hague, The Netherlands, Aug. 2015

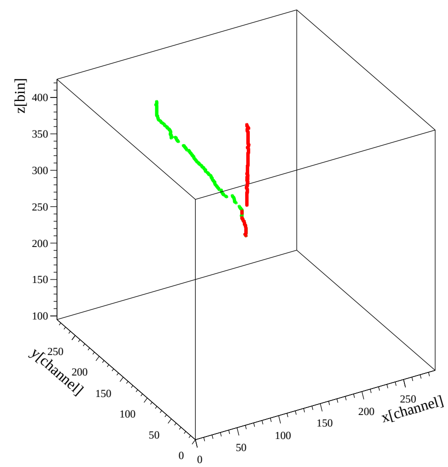
A 16.7 MeV gamma-ray converting to e^+e^-

raw "maps"



track time spectra (x, y matching)





- Track pattern recognition by combinatorial Hough transform
- x, y two track ambiguity solved by track time spectra matching
- 2.1 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

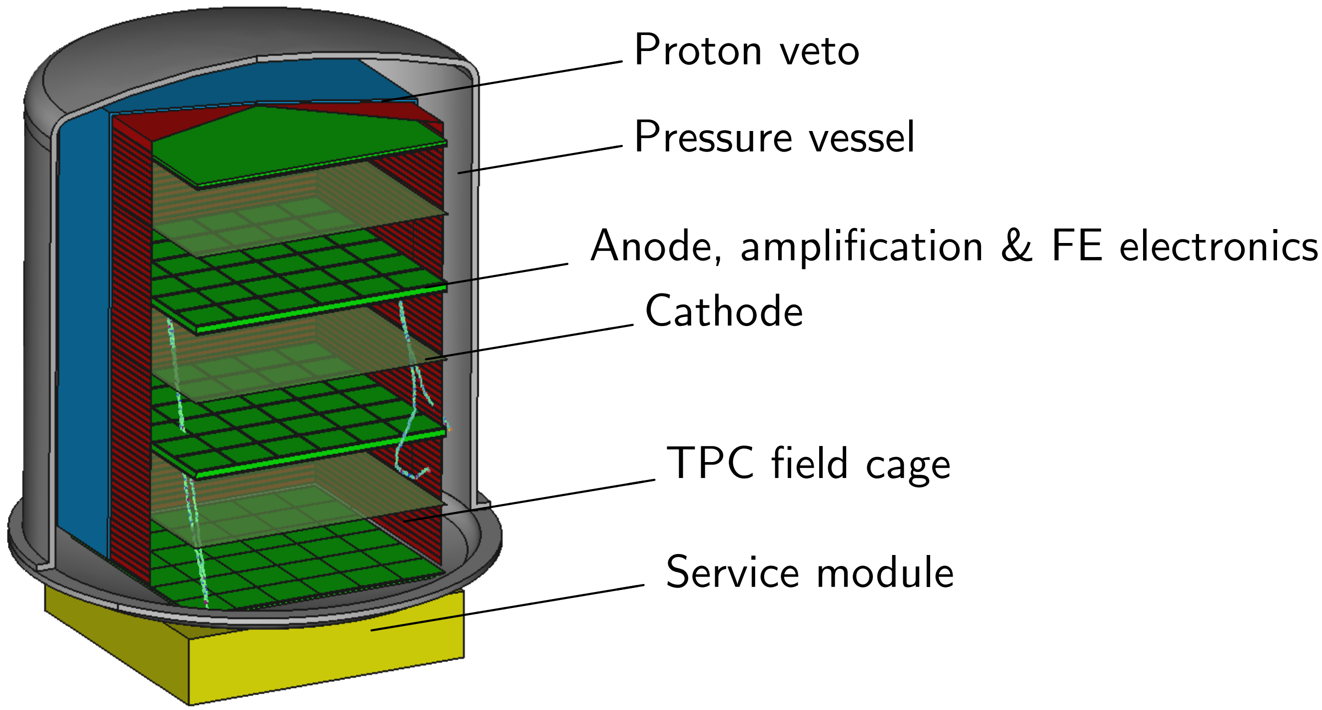
- Provides, for the first time, polarimetry above 1 MeV !

- Data taking @ NewSUBARU with fully- $(P \approx 1)$ and non- $(P \approx 0)$ polarized γ beam [1.7 - 74 MeV]

  Analysis in progress

Back-up Slides

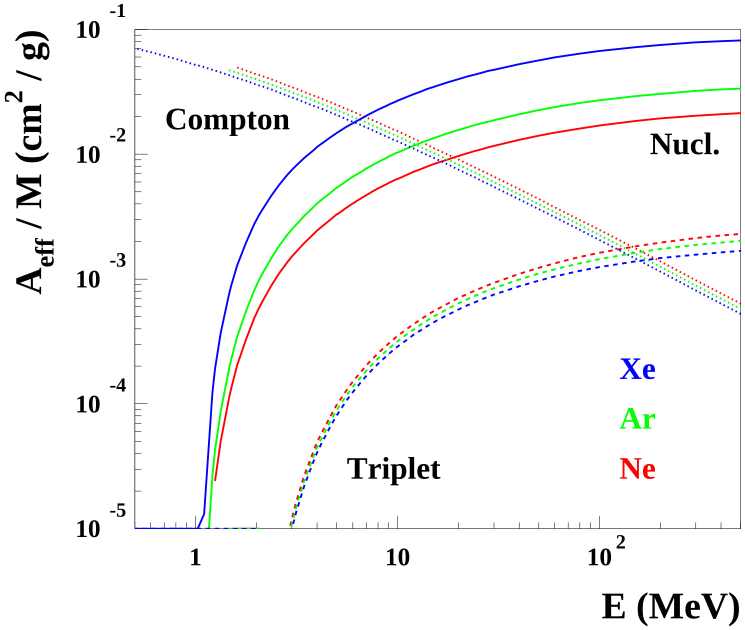
Exploded Schematic View of a Flight Telescope



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

Thin / Thick Detectors, Effective Area

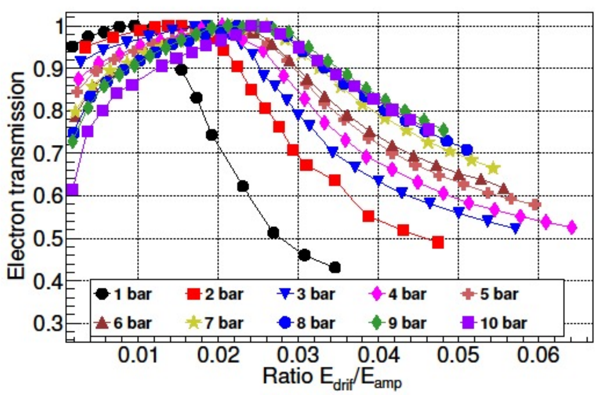


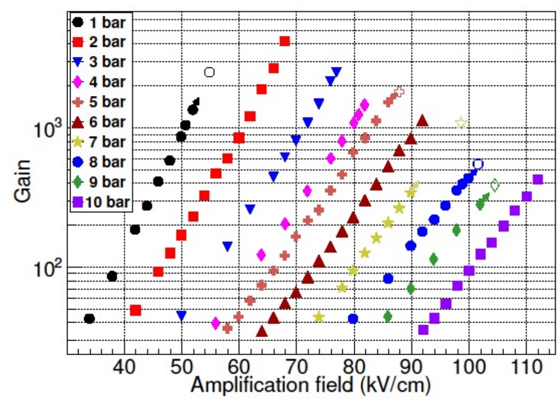
	Thick	Thin
Conversion probability	$p \approx 1$	$p \ll 1$
Effective area $A_{\rm eff}$	$\approx S \times \epsilon$	$\approx H \times M \times \epsilon$
Conversion processes (pair, triplet, Compton)	compete	don't compete with each other

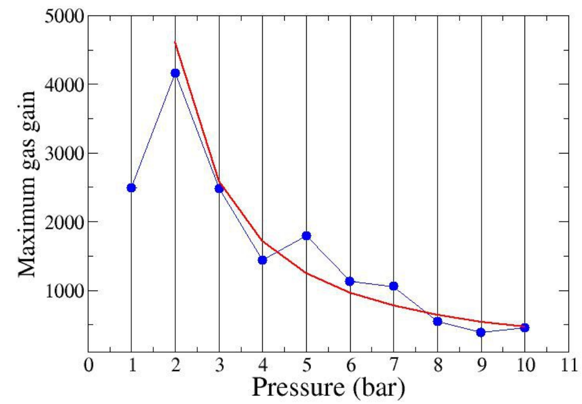
- H photon attenuation, M detector mass, S surface, ϵ reconstruction efficiency
- Thin techno prevents γ loss due to Compton in low Z material at low E
- High E asymptote $A_{\rm eff} = 3.6 {\rm m}^2/{\rm ton}$ (Nuclear, Argon)

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.

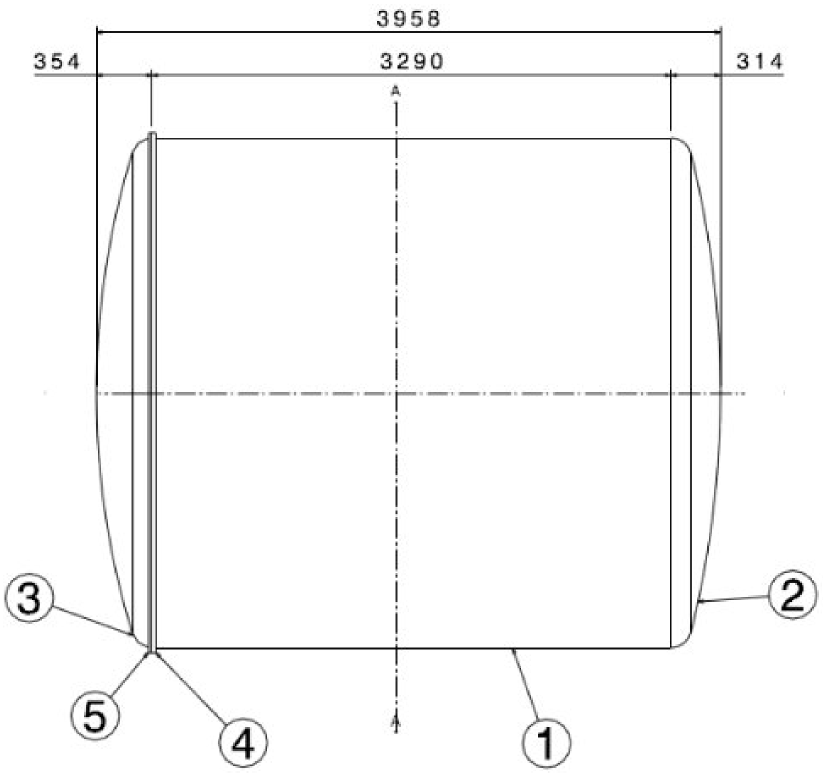
- **Vessel Mass** $\propto$ gas mass to 1rst order.
  - For a given mission: which limit will we touch first (volume, mass) ?

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	$150^{\circ}C$	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 ?

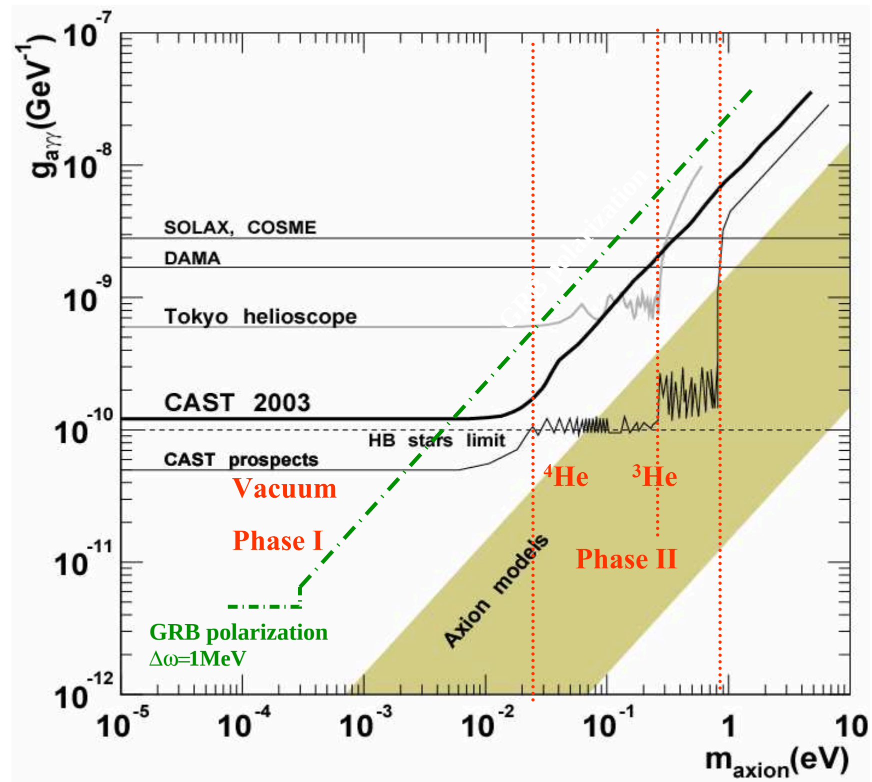
Search for Axions

- 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 $m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}}$

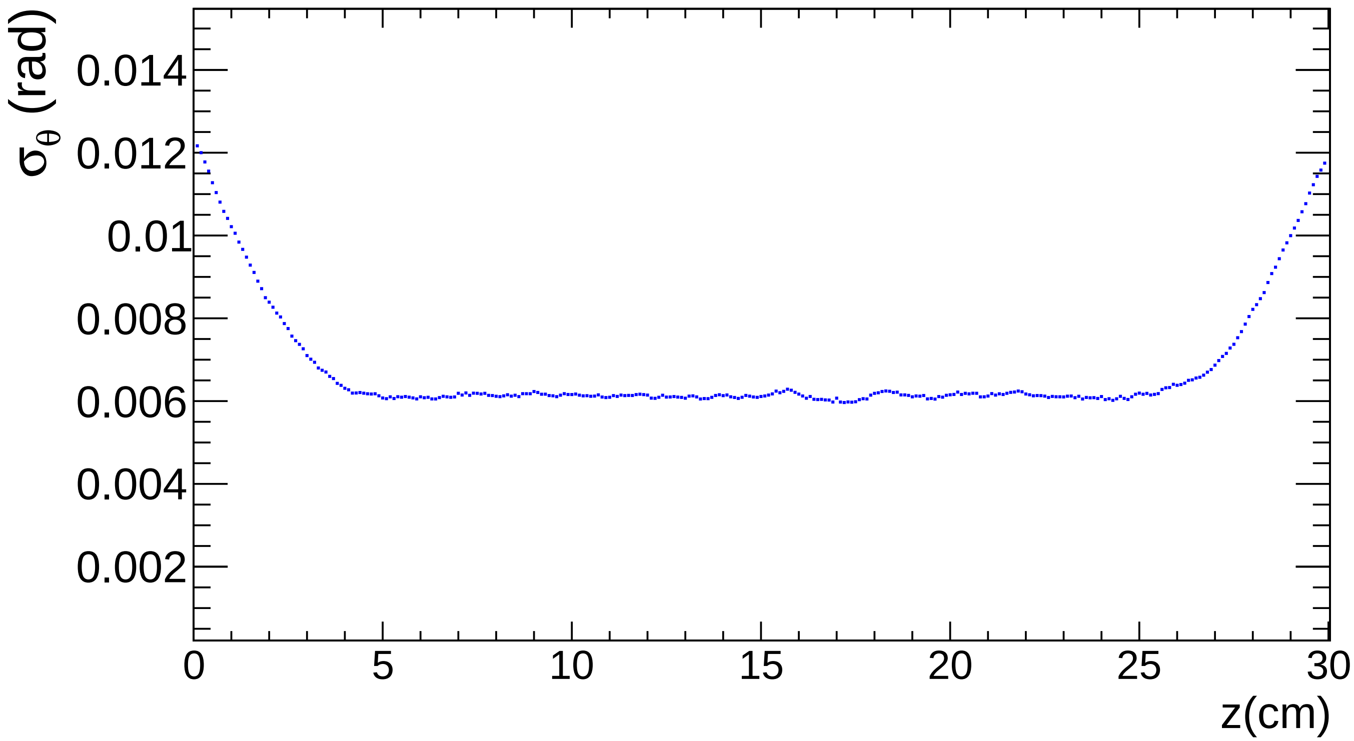
and the limit $g_{a\gamma\gamma}$ reaches a ω-independent constant.



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

Optimal Track Fit with Multiple Scattering
Cross Validation

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



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

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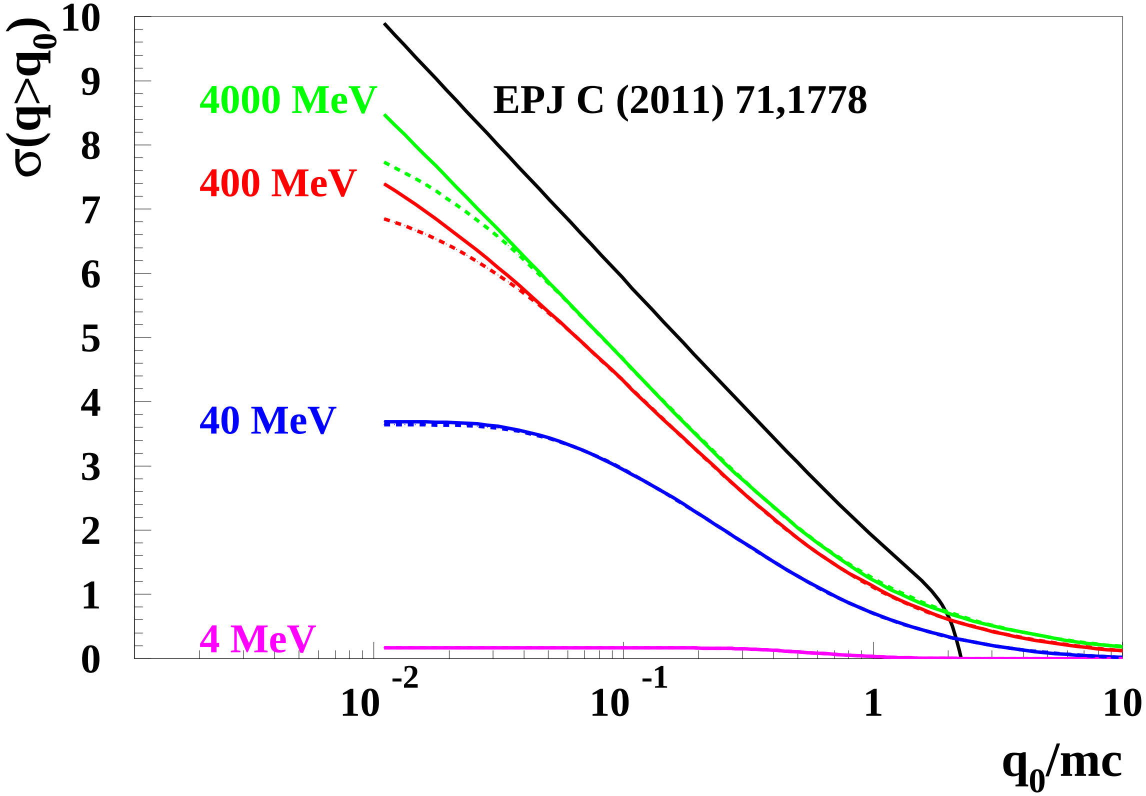
Evt Generator: One Example of Validation Plot

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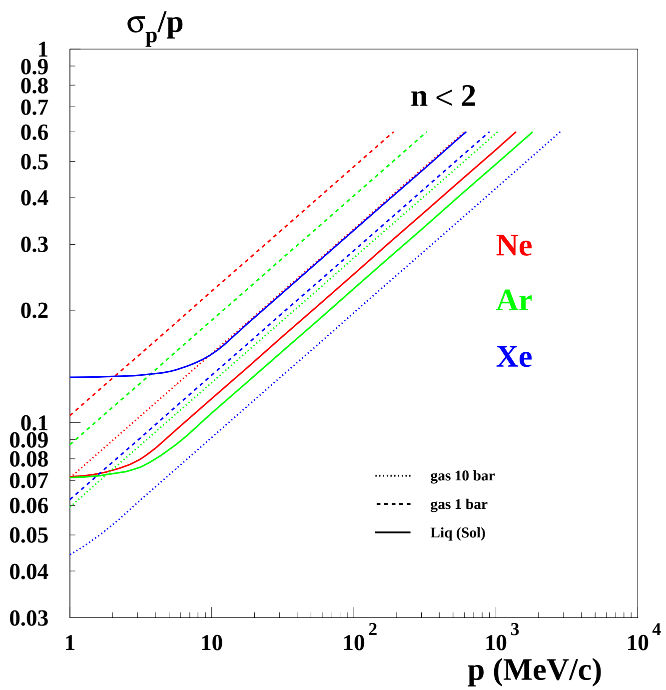
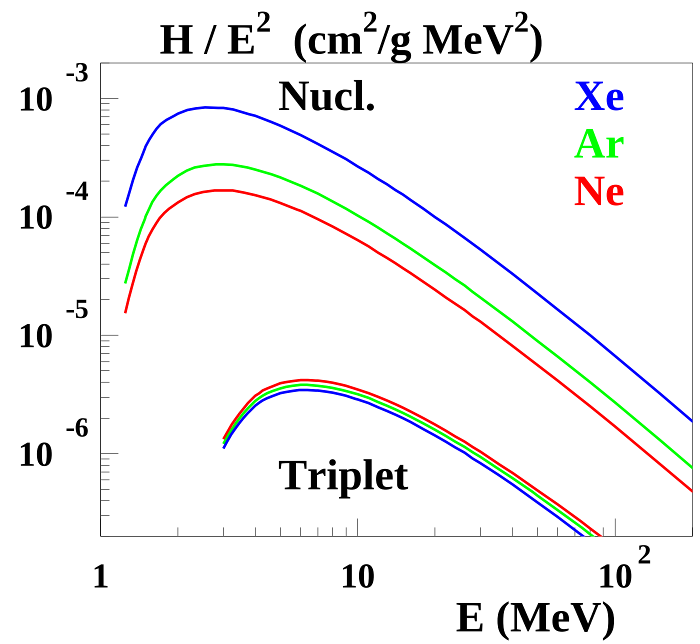
Track Momentum Measurement in TPC Alone from Multiple Estimations of Multiple Scattering

- 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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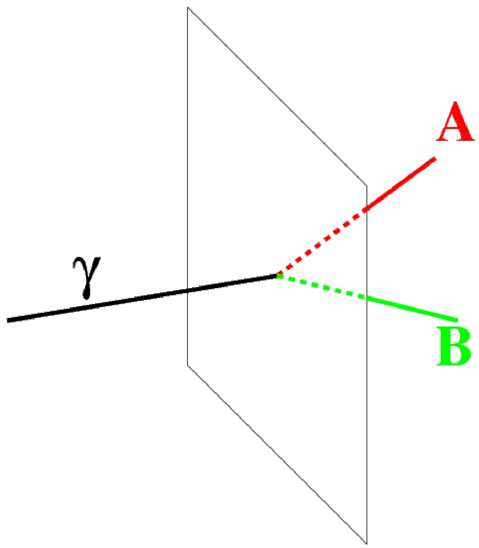
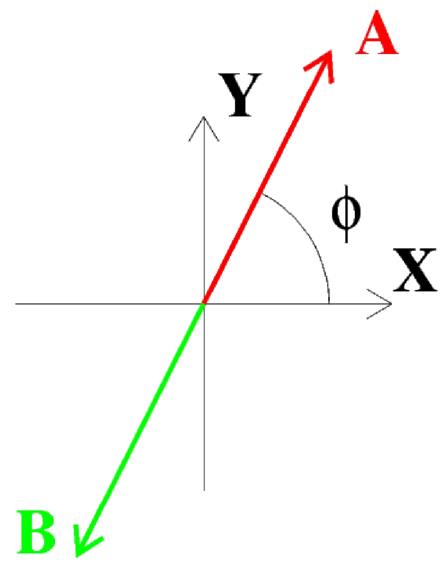
Polarimetry

- Modulation of azimuthal angle distribution

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



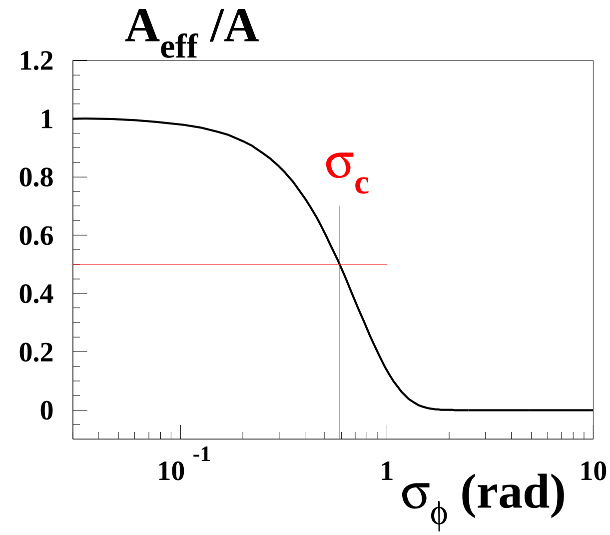


P source linear polarisation fraction
$\mathcal{A}$ Polarization asymmetry
ϕ azimuthal angle

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 $\gamma Z \rightarrow e^+e^-$

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

γ Polarimetry with a Homogeneous Detector and Optimal Fits

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

    $p_1 = 1.45\,\mathrm{MeV}/c$ (liquid).
- $\hat{\theta}_{+-} = 1.6\,\mathrm{MeV}/E$ most probable opening angle
- $\sigma_\phi = \left[x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}}\right] \frac{(p_1)^{\frac{3}{4}} E^{\frac{1}{4}}}{1.6\,\mathrm{MeV}}$. 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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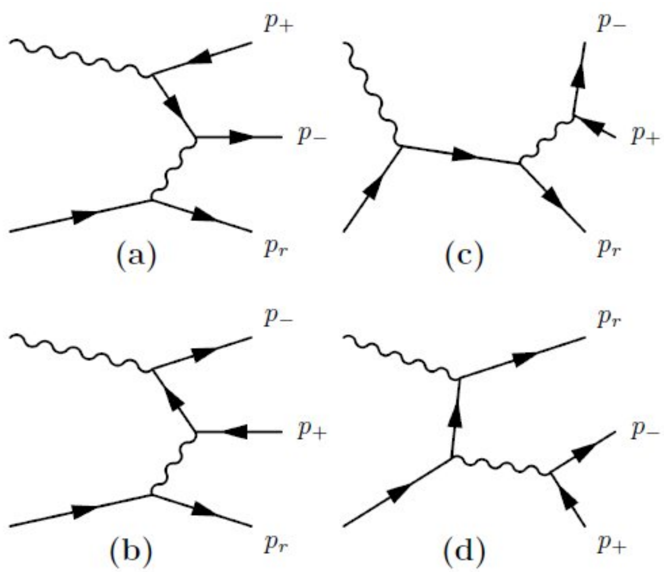
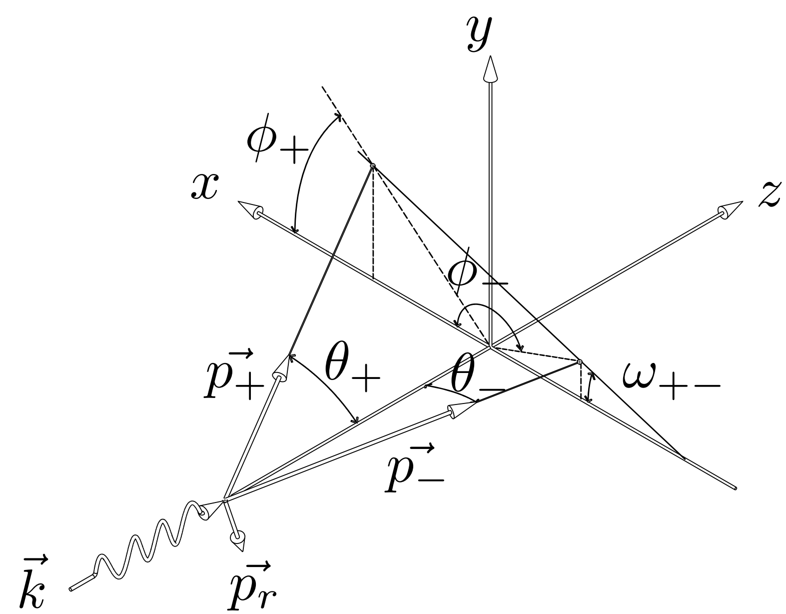
Developed, Validated, Event Generator

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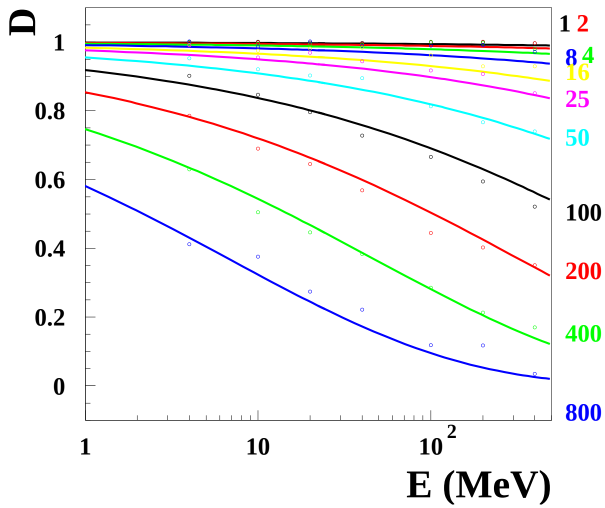
Dilution of Polarization Asymmetry due to Multiple Scattering : Optimal Fits and Full MC

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

- $D \equiv \frac{\mathcal{A}_{\text{eff}}(p_1)}{\mathcal{A}(p_1 = 0)}$



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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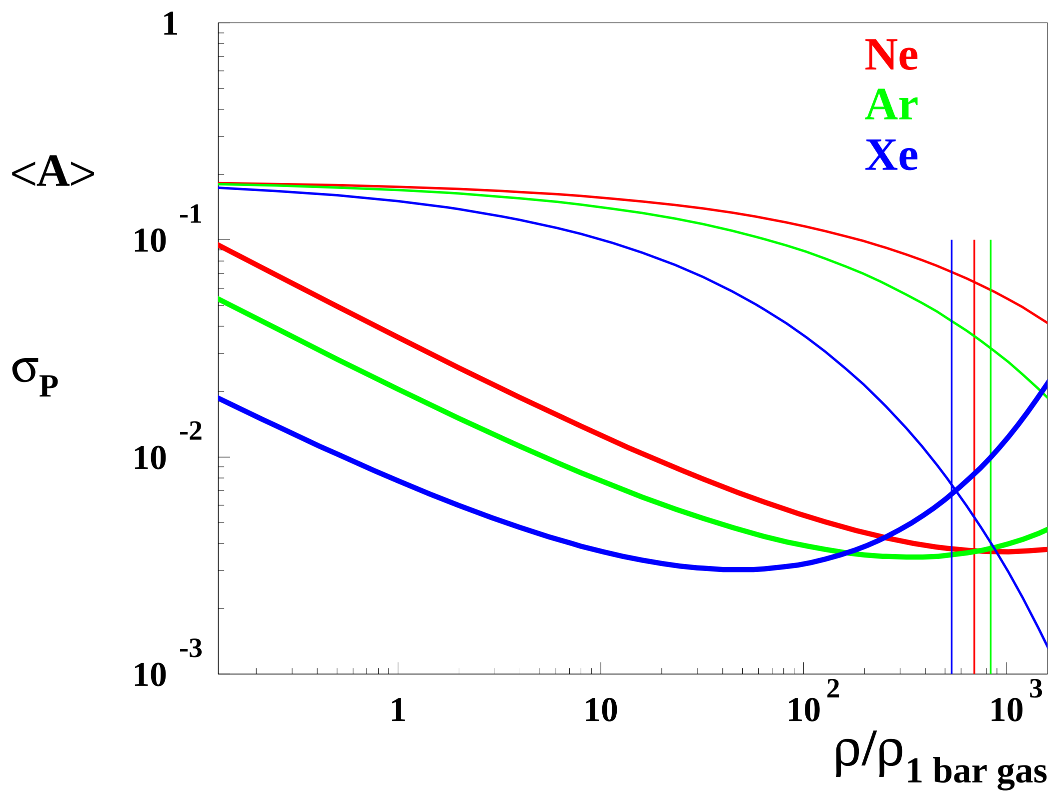
Polarimetry Performance (no Experimental Cuts)

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



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

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Polarimetry: Optimal Measurement

- Remember, fit of $\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P\cos[2(\phi)])$ 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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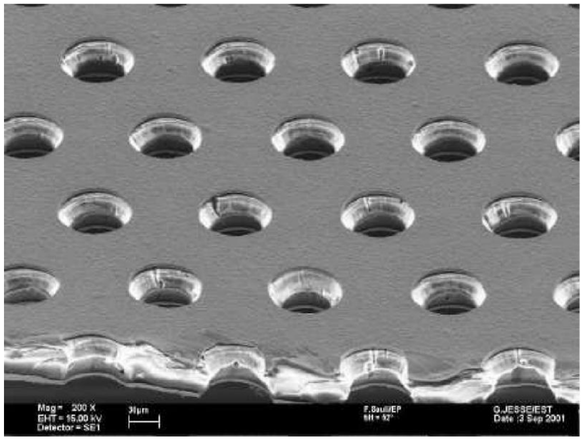
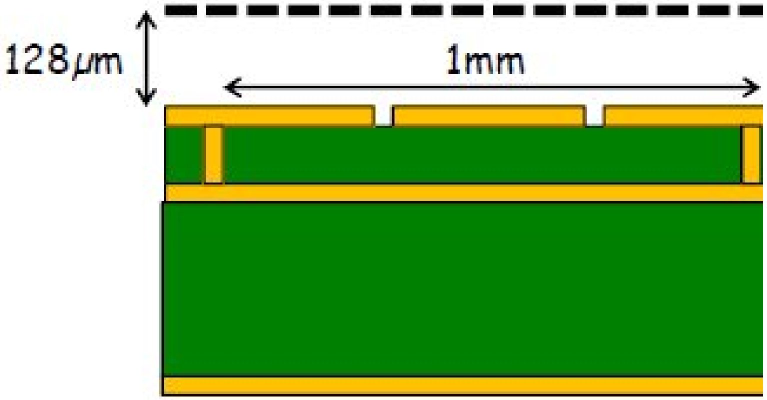
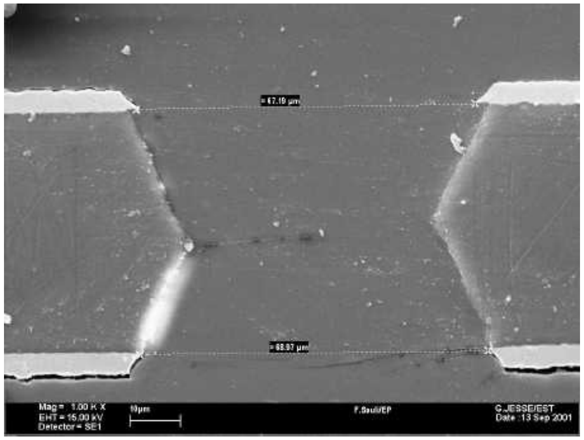
Gas amplification : micromegas + 2 GEM

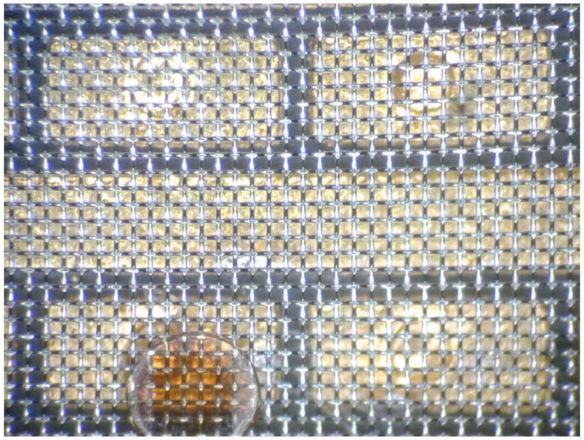
50µm Kapton, copper clad, pitch 140µm, Φ70µm

128µm "bulk" micromegas



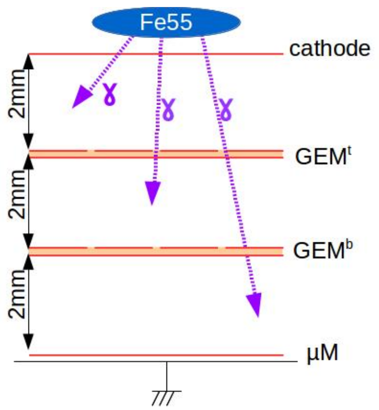


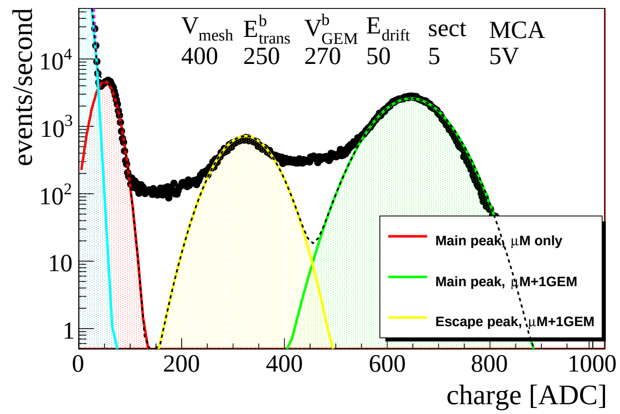


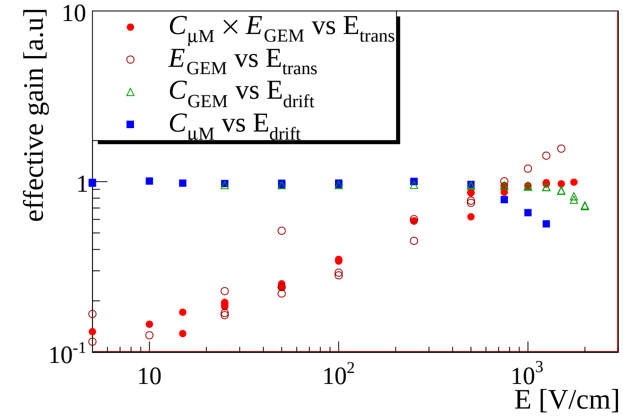


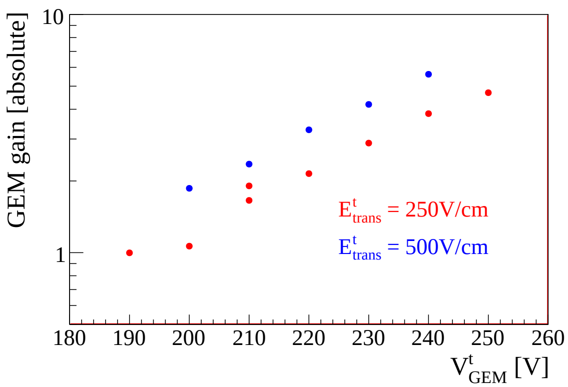
Micromegas + 2 GEM assemblies : characterization

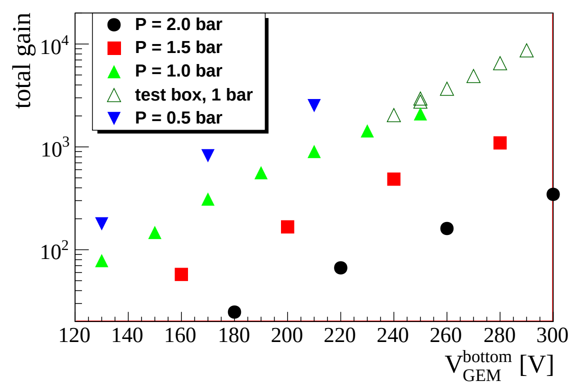
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)







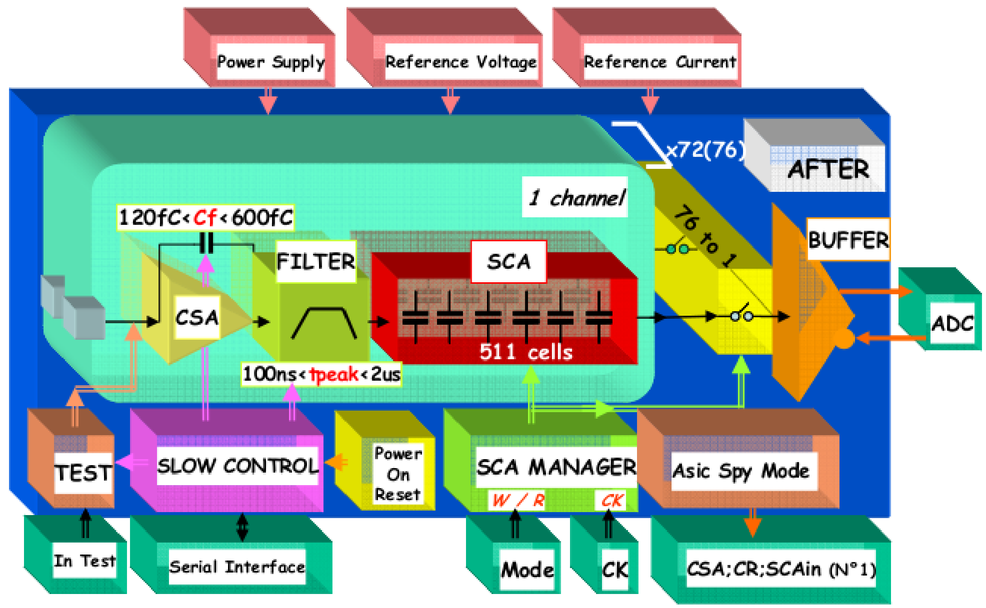




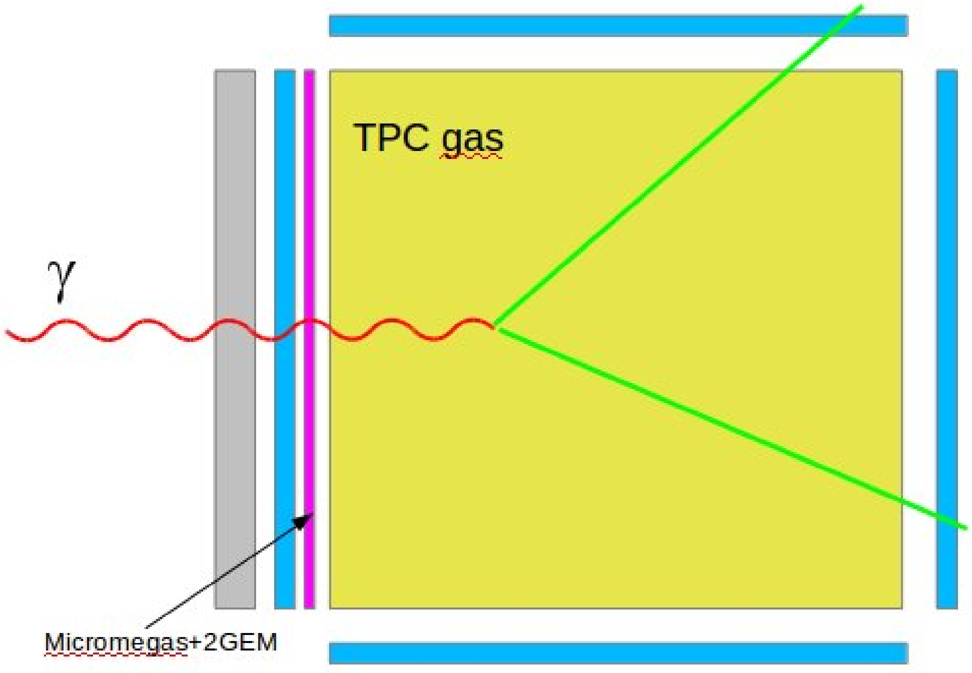
Ph. Gros, TIPP2014

Signal digitization

- 2 directions x, y
- 288 strips (channels) / direction
- 72 channels /chip
- 4 chips / direction
- 511 time bins ("circular" Switched Cap.
- Input: 120 fC to 600 fC
- Up to 50 MHz sampling
- Shaping time 100 ns to $2\mu s$
- 12 bit ADC.



"Beam" trigger system



- S_{up} upstream scintillator
- O one of the 5 other scintillators
- M_{slow} : a delayed ($> 1\mu s$) signal on the micromegas mesh
- L laser trigger pulse

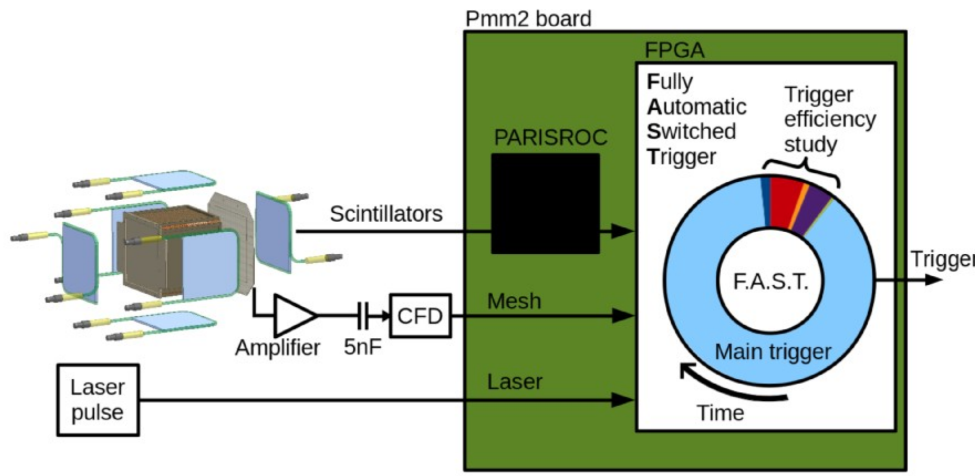
"Main line" : $T_{\gamma,laser} = \overline{S}_{up} \cap O \cap M_{slow} \cap L$

Wang et al. TPC2014, Paris, arXiv:1503.03772 [astro-ph.IM]

"Beam" trigger system : additional lines

Additional trigger lines :

7	$T_{\gamma,laser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap L$
8	$T_{noMesh,laser}$	$\overline{S}_{up} \cap O \cap L$
9	$T_{invMesh,laser}$	$\overline{S}_{up} \cap O \cap M_{quick} \cap L$
10	$T_{noUp,laser}$	$O \cap M_{slow} \cap L$
11	$T_{noPM,laser}$	$\overline{S}_{up} \cap M_{slow} \cap L$
12	$T_{noLaser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap \overline{L}$

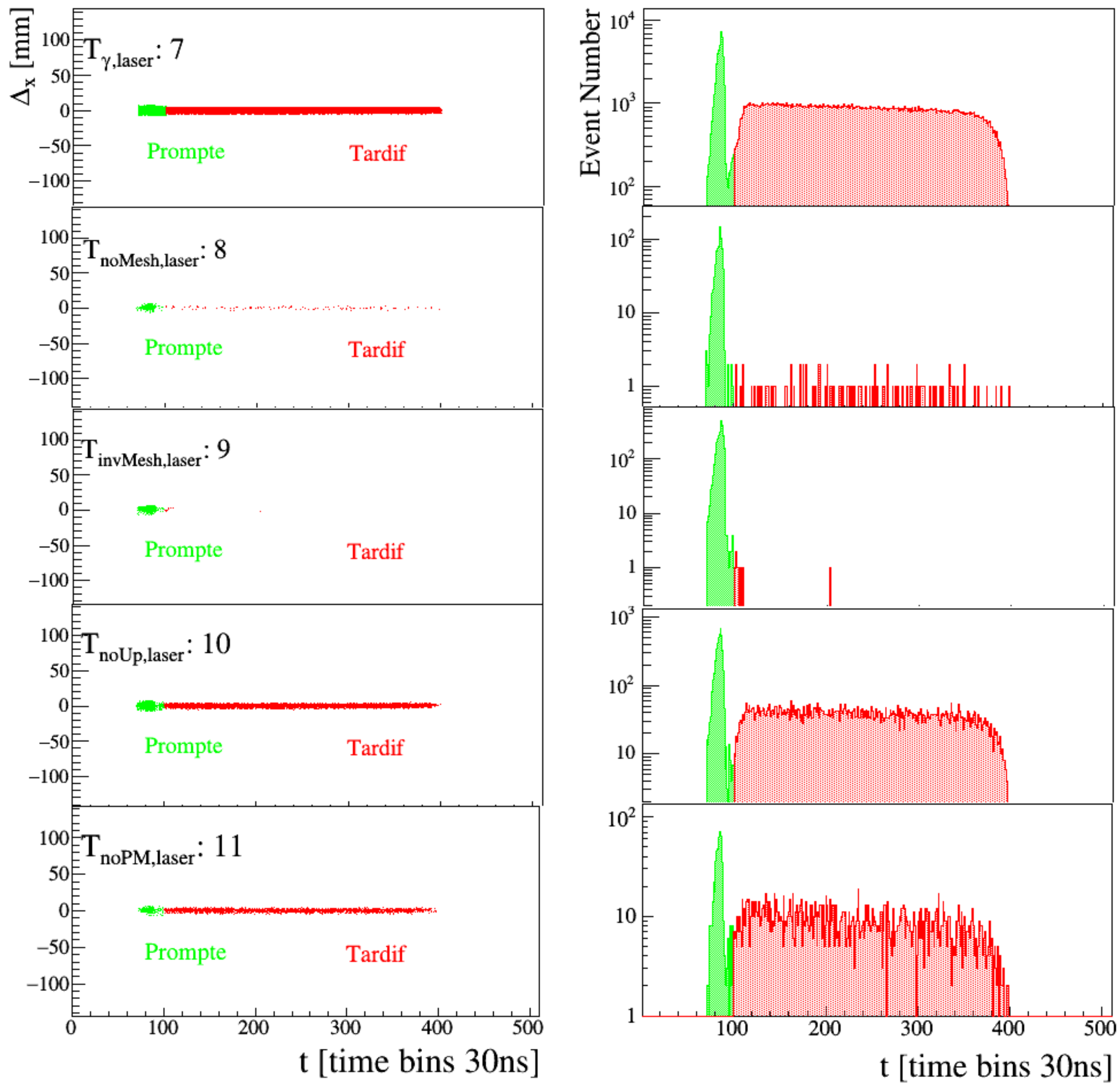


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015

"Beam" trigger system : conversion point distributions

- signal efficiency 51%
- background rejection 99.3%
- incident rate 2 kHz
- signal on disk 50 Hz



S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015