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

Denis Bernard, Philippe Bruel, Mickael Frotin, Yannick Geerebaert, Berrie Giebels, Philippe Gros, Deirdre Horan, Patrick Poilleux, Igor Semeniouk, Shaobo Wang \textsuperscript{a}
\textsuperscript{a}LLR, Ecole Polytechnique and CNRS/IN2P3, France

Shebli Anvar, David Attié, Paul Colas, Alain Delbart, Patrick Sizun \textsuperscript{b}
\textsuperscript{b}IRFU, CEA Saclay, France

Diego Götz \textsuperscript{b,c}
\textsuperscript{c}AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/Service d’Astrophysique, CEA Saclay, France

\textit{TeVPA2015, TeV Particle Astrophysics,}
October 26-30 2015, Kashiwa Japan

\texttt{llr.in2p3.fr/\sim dbernard/polar/harro-t-p.html}
**Science Case**

- **Non polarized astronomy:**
  - Improve **angular resolution** – crowded sky regions
  - 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 $\gamma$ polarimeter above 1 MeV in space ever**
  - Astrophysics: understand working mechanism(s) of $\gamma$ 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
  - $\gamma$ band: 30 - 200 MeV

- SED’s indistinguishable, but
  - X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$
  - $\gamma$-ray: $P_{\text{lept}} \ll P_{\text{hadr}}$

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


D. Bernard
High performance MeV-GeV $\gamma$-ray astronomy with a TPC
TeVPA, Oct 2015, Kashiwa
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

Photon angular resolution

\[ \gamma Z \rightarrow e^+ e^- Z \]

\[ \vec{k} = p_{e^+} + p_{e^-} + \vec{p}_r \]

Contributions:

- Single-track angular resolution,
- Un-measured nucleus recoil momentum for “nuclear” conversion
- Single-track momentum 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 [MeV/c];
- \( p_0 = 13.6 \text{ MeV/c} \), multi-scattering constant;
- \( p_1 \) detector “multiple-scattering momentum” parameter [MeV/c];
- \( \sigma \) single measurement detector spatial resolution [cm];
- \( l \) track sampling pitch [cm].

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

in 10 bar gas for various gases

NIM A 701 (2013) 225
Angular resolution: Un-measured nucleus recoil momentum

Recoil momentum distribution (no screening)

68 % “containment”, most-probable and half-most-probable angles

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

NIM A 701 (2013) 225
Angular resolution

- nucleus recoil $\propto E^{-5/4}$
- multiple scattering (optimal fits) $\propto E^{-3/4}$

limit detectable $E^2 dN/dE$, à la Fermi: 4 bins/decade, $5\sigma$ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. “against” extragalactic background

- Sampling pitch $l = 1\text{mm}$, point resolution $\sigma = 0.1\text{mm}$
**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

---

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

- Linearly polarized $\gamma$ beam from Laser inverse Compton scattering, $e^-$ beam 0.6 – 1.5 GeV.

- 0.532 $\mu$m and 1.064 $\mu$m 20 kHz pulsed Nd:YVO$_4$ (2$\omega$ and 1$\omega$), 1.540 $\mu$m 200 kHz pulsed Er (fibre) and 10.55 $\mu$m CW CO$_2$ lasers

- $\Rightarrow$ 1.7 - 74 MeV $\gamma$ beam

- Monochromaticity by collimation on axis

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

- 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 $\gamma$ astronomy in the $e^+e^-$ with utmost performance in the [MeV - GeV] photon energy range,

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

  Therefore, powerful **Background rejection**

- And rejection of atmospheric photons and of cosmic rays is straightforward

  - **Full sky, $4\pi$ 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 $\gamma$ 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 \((2 \text{ m})^2 \times 0.5 \text{ m}\) TPC with an endplate segmented into \((33 \text{ cm})^2\) micromegas and charge collection blocks. 432 chips, \((12 \text{ m})^3\): 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

<table>
<thead>
<tr>
<th>Conversion probability</th>
<th>Thick</th>
<th>Thin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p \approx 1$</td>
<td>$p \ll 1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effective area $A_{\text{eff}}$</th>
<th>Thick</th>
<th>Thin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\approx S \times \epsilon$</td>
<td>$\approx H \times M \times \epsilon$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conversion processes</th>
<th>Thick</th>
<th>Thin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pair, triplet, Compton)</td>
<td>compete</td>
<td>don't compete with each other</td>
</tr>
</tbody>
</table>

- $H$ photon attenuation, $M$ detector mass, $S$ surface, $\epsilon$ reconstruction efficiency
- Thin techno prevents $\gamma$ loss due to Compton in low $Z$ material at low $E$
- High $E$ asymptote $A_{\text{eff}} = 3.6m^2$/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 ..


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

- **Vessel Mass** $\propto$ gas mass to 1st 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

<table>
<thead>
<tr>
<th>$P$</th>
<th>Alloy</th>
<th>0.2% yield</th>
<th>@ T</th>
<th>safety factor</th>
<th>$\phi$</th>
<th>$t$</th>
<th>$t$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 bar</td>
<td>Titanium</td>
<td>strength</td>
<td>6Al-V4</td>
<td>750 MPa</td>
<td>150°C</td>
<td>1.6</td>
<td>3000 mm</td>
<td>4 mm</td>
</tr>
</tbody>
</table>

No re-inforcement of any kind at the moment.

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

| 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 $\gamma$ through triangle anomaly.

- $\gamma$ 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 $\omega$-independent constant.

Optimal Track Fit with Multiple Scattering Cross Validation

- 5 bar argon, $\sigma = l = 0.1 \text{cm}$; $p_1 = 13.6 \text{MeV}/c \left( \frac{4\sigma^2 l}{X^3_0} \right)^{1/6} = 112 \text{keV}/c$

- 40 MeV/$c$ electrons, $\sigma_{\theta t} = \left( \frac{p}{p_1} \right)^{-3/4} = 12.2 \text{mrad}$

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

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:

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

- multiple scattering $\theta_0 \propto 1/p \Rightarrow p \propto 1/\theta_0$  

- optimization of track step size $\Rightarrow \frac{\sigma_p}{p} \propto \frac{1}{\sqrt{L}} \left[ \frac{p \sigma \sqrt{X_0}}{13.6\text{MeV}/c} \right]^{1/3}$

Relative precision

$E$ range of interest

NIM A 701 (2013) 225
Polarimetry

- Modulation of azimuthal angle distribution

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

\[ \sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}}, \]

\( P \) source linear polarisation fraction

\( \mathcal{A} \) Polarization asymmetry

\( \phi \) azimuthal angle
Conversion in a Slab and Multiple Scattering:

Dilution of the Polarisation Asymmetry

(1 + AP cos [2(φ)]) ⊗ e^{−φ^2/2\sigma^2_φ} = (1 + A e^{−2\sigma^2_φ} P cos [2(φ)])

⇒ \text{A}_{\text{eff}} = A e^{−2\sigma^2_φ}

azimuthal angle RMS \( \sigma_φ = \frac{\theta_{0,e+} \oplus \theta_{0,e−}}{\hat{\theta}_{+-}} \),

\( \theta_0 \approx \frac{13.6 \text{ MeV}/c}{β_p} \sqrt{\frac{x}{X_0}} \),

most probable opening angle \( \hat{\theta}_{+-} = 1.6 \text{ MeV}/E \)

⇒ \( \sigma_φ \approx 24 \text{ rad} \sqrt{x/X_0} \) (e.g. \( \text{A}_{\text{eff}}/A = 1/2 \) 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 \( γZ \rightarrow e^+ e^- \)

γ Polarimetry with a Homogeneous Detector and Optimal Fits

- $\sigma_\phi = \frac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, azimuthal angle resolution
- $\sigma_{\theta,\text{track}} = \left( \frac{p}{p_1} \right)^{-3/4}$, angular resolution due to multiple scattering

- $p_1 = 13.6 \text{ MeV}/c \left( \frac{4\sigma^2 l}{X^3_0} \right)^{1/6}$, Argon ($\sigma = l = 1 \text{ mm}$): $p_1 = 50 \text{ keV}/c$ (1 bar), $p_1 = 1.45 \text{ MeV}/c$ (liquid). most probable opening angle

- $\hat{\theta}_{+-} = 1.6 \text{ MeV}/E$

- $\sigma_\phi = \left[ x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}} \right] \left( \frac{p_1}{1.6 \text{ MeV}} \right)^{3/4} E^{1/4}$, 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

NIM A 729 (2013) 765
**Developed, Validated, Event Generator**

- Development of a full (5D) exact (down to threshold) polarized evt generator
- Variables: azimuthal ($\phi_+$, $\phi_-$) and polar ($\theta_+$, $\theta_-$) angles of $e^+$ and $e^-$, and $x_+ \equiv E_+/E$

![Diagram of particle interactions and angles]

- Uses:
  - HELAS amplitude computation
  - SPRING event generator
- Validation against published 1D distributions (nuclear and triplet conversions)

NIM A 729 (2013) 765

D. Bernard
High performance MeV-GeV $\gamma$-ray astronomy with a TPC
TeVPA, Oct 2015, Kashiwa
Dilution of Polarization Asymmetry due to Multiple Scattering: Optimal Fits and Full MC

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

- \(D \equiv \frac{A_{\text{eff}}(p_1)}{A(p_1 = 0)}\)

Energy variation of \(D\) for various values of \(p_1\) (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, \(p_1 = 1.45\) MeV/c); gas: Possible! (1 bar, \(p_1 = 50\) keV/c)

NIM A 729 (2013) 765
Polarimetry Performance (no Experimental Cuts)

- Crab-like source, $T = 1$ year, $V = 1 \text{ m}^3$, $\sigma = l = 0.1 \text{ cm}$, $\eta = \epsilon = 1$.

- $A_{\text{eff}}$ (thin line), $\sigma_P$ (thick line);

- Argon, 5 bar, $\sigma_P \approx 1.0\%$, $A_{\text{eff}} \approx 15\%$
Polarimetry: Optimal Measurement

- Remember, fit of $\frac{d\Gamma}{d\phi} \propto (1 + AP \cos [2(\phi)])$ yields $\sigma_P \approx \frac{1}{A} \sqrt{\frac{2}{N}}$.

- Optimal measurement; $\Omega$
  - let’s define $p(\Omega)$ the pdf of set of (here 5) variables $\Omega$
  - search for weight $w(\Omega)$, $E(w)$ function of $P$, and variance $\sigma_P^2$ minimal;
  - a solution is $w_{\text{opt}} = \frac{\partial \ln p(\Omega)}{\partial P}$
  - polarimetry: $p(\Omega) \equiv f(\Omega) + P \times g(\Omega)$, $w_{\text{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}$.
  - If $A \ll 1$, $w_0 = \frac{2g(\Omega)}{f(\Omega)}$, and
  - for the 1D “projection” $p(\Omega) = (1 + AP \cos [2(\phi)])$: $w_1 = 2 \cos 2\phi$, $E(w_1) = AP$, $\sigma_P = \frac{1}{A\sqrt{N}} \sqrt{2 - (AP)^2}$.

NIM A 729 (2013) 765
Gas amplification: micromegas + 2 GEM

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

128µm “bulk” micromegas
Micromegas + 2 GEM assemblies: characterization

55Fe (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 Capacitor Array)
- Input: 120 fC to 600 fC
- Up to 50 MHz sampling
- Shaping time 100 ns to 2μs
- 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” : $T_{\gamma,laser} = S_{up} \cap O \cap M_{slow} \cap L$

“Beam” trigger system: additional lines

Additional trigger lines:

7 $T_{\gamma,\text{laser}}$: $\overline{S}_{\text{up}} \cap O \cap M_{\text{slow}} \cap L$

8 $T_{\text{noMesh, laser}}$: $\overline{S}_{\text{up}} \cap O \cap L$

9 $T_{\text{invMesh, laser}}$: $\overline{S}_{\text{up}} \cap O \cap M_{\text{quick}} \cap L$

10 $T_{\text{noUp, laser}}$: $O \cap M_{\text{slow}} \cap L$

11 $T_{\text{noPM, laser}}$: $\overline{S}_{\text{up}} \cap M_{\text{slow}} \cap L$

12 $T_{\text{noLaser}}$: $\overline{S}_{\text{up}} \cap O \cap M_{\text{slow}} \cap \overline{L}$

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

“Beam” trigger system: conversion point distributions

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