Gas TPCs for High-angular-resolution and Sensitivity
\[ \gamma \rightarrow e^+e^- \] Astronomy and Polarimetry

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

- Thursday
  - $\mu$-introduction on the science case
  - Gas TPCs for high-angular-resolution and sensitivity $\gamma \rightarrow e^+e^-$ astronomy and polarimetry

- Friday:
  - The CNRS-CEA “HARPO” (Hermetic ARgon POlarimeter) instrument project
Non polarized astronomy

- Improve **angular resolution** – crowded sky regions

  ![Graph of P7SOURCE_V6 PSF at normal incidence](image1)

  Fermi/LAT  

- 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

  ![Graph of Continuum Sensitivity](image2)
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
**Science Case: Polarimetry: Astrophysics**

- Blazars: 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: \( P_{\text{lept}} \approx P_{\text{hadr}} \)
  - γ-ray: \( P_{\text{lept}} \ll P_{\text{hadr}} \)

H. Zhang and M. Böttcher, A.P. J. 774, 18 (2013)
LIV: Search for Lorentz Invariance Violation

- Particle (photon) dispersion relations modified in LIV effective field theories (EFT)

- Additional term to the QED Lagrangian parametrized by $\xi/M$, $M$ Planck mass.

- $\xi$ bounds:
  - time of flight from the Crab: $\Delta t = \xi(k_2 - k_1)D/M$, $\xi \leq \mathcal{O}(100)$.
  - birefringence $\Delta \theta = \xi(k_2^2 - k_1^2)D/2M$

  LIV induced birefringence would blurr the linear polarization of GRB emission.

  $\xi \leq 3.4 \times 10^{-16}$ with IBIS on Integral (250 – 800 keV)


- Bound $\propto 1/k^2$!
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
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

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

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 longitudinal sampling (pitch) [cm].

**Single-track angular resolution**

- Dependence of the RMS photon angular resolution on photon energy

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

For various densities (argon) for various gases

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Single-track angular resolution with Optimal fits: Validation with a Kalman filter

- Validation with parameters: 5 bar argon, $\sigma = l = 0.1\text{cm}$;
  
  $$p_1 = 13.6\text{ MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6} = 112\text{ keV}/c$$

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

Angular resolution (residue RMS) as a function of the position along the track

NIM A 729 (2013) 765
Angular resolution: From Single-track to single photon

- Small angle approximation: \( \theta_{x,\gamma} = r \theta_{x,+} + (1 - r) \theta_{x,-} \)

- \( r \) fraction of energy carried away by the positron, \( r = \frac{E_+}{E} \)

- multiple scattering dominated regime: \( \sigma_{\theta\gamma} = \sigma_{\theta \tau} \sqrt{\sqrt{r} + \sqrt{1 - r}} \)

- high energy regime: \( \sigma_{\theta\gamma} = \sigma_{\theta \tau} \sqrt{r^2 + (1 - r)^2} \)

- track to photon factor close to unity: neglected in the following.

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Angular resolution: Un-measured nucleus recoil momentum

Recoil momentum distribution (no screening)

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

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

BH: Bethe-Heitler Monte Carlo

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Angular resolution: Wrap up

- Argon-based gas, $P = 10$ bar
  \[ X_0 = 1180 \text{ cm} \]

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

\[
\sigma_{\theta t} = \left( \frac{p}{p_1} \right)^{-3/4} \quad \text{with} \quad p_1 = p_0 \left( \frac{4\sigma^2 l}{X_0^3} \right)^{1/6} \quad \text{1.5 rad} \left( \frac{E}{1 \text{ MeV}} \right)^{-5/4}
\]

\[
p_1 = 73 \text{ keV} / c
\]

\[
\begin{array}{ccc}
\text{multiple scattering} & \text{ion recoil momentum} & \text{total} \\
\sigma_{\theta} @ 100 \text{ MeV} & 0.26^\circ & 0.27^\circ & 0.37^\circ
\end{array}
\]
Thin detectors: Effective area

- \( A_{\text{eff}} = H \times M \),

- \( H \) photon attenuation

- \( H / E^2 \) (cm\(^2\)/g MeV\(^2\))

Argon, nucl.: \( A_{\text{eff}}/M = 27 \text{ cm}^2/\text{kg} @ E = 100 \text{ MeV} \)

National Institute of Standards and Technology (NIST)
Performances with 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 $E^2 dN/dE$, à la Fermi: 4 bins/decade, $5\sigma$ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. “against” extragalactic background
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 \( \Rightarrow \sigma_p/p \propto \frac{1}{\sqrt{L}} \left[ \frac{p \sigma \sqrt{X_0}}{13.6 \text{MeV}/c} \right]^{1/3} \)

\( E \) range of interest

A Kalman-filter based measurement should do a factor \( \approx 2 \) better.

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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

- \((1 + AP \cos [2(\phi)]) \otimes e^{-\phi^2/2\sigma^2_{\phi}} = (1 + A e^{-2\sigma^2_{\phi}} P \cos [2(\phi)])\)

\[\Rightarrow A_{\text{eff}} = A e^{-2\sigma^2_{\phi}}\]

- Azimuthal angle RMS \(\sigma_{\phi} = \frac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}\),

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

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

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

- This dilution is energy-independent.

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

Yu. D. Kotov, Space Science Reviews 49 (1988) 185,

\( \gamma \) Polarimetry with a Homogeneous Detector and Optimal Fits

- \( \sigma_\phi = \frac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}} \), azimuthal angle resolution
- \( \sigma_{\theta,\text{track}} = (p/p_1)^{-3/4} \), angular resolution due to multiple scattering
- \( p_1 = 13.6 \text{ MeV/c} \left( \frac{4\sigma^2 l}{X_0^3} \right)^{1/6} \), 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
- \( \sigma_\phi = \left[ x_+^{-3/4} \oplus (1 - x_+)^{-3/4} \right] \frac{(p_1)^{3/4}E^{1/4}}{1.6 \text{ MeV}} \), 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 ($\phi_+, \phi_-)$ and polar ($\theta_+, \theta_-)$ angles of $e^+$ and $e^-$, and $x_+ \equiv E_+ / E$

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

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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:

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

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

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

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)

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**Polarimetry Performance (no Experimental Cuts)**

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

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

- Argon, 5 bar, \( A_{\text{eff}} \approx 15\%, \ \sigma_P \approx 1.0\% \),

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Polarimetry : Effects of Experimental Cuts

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

- All cuts : $\epsilon = 45\%$, (1D) $A_{\text{eff}} \approx 16.6\% \, \sigma_P \approx 1.4\%$

D.B. NIM A 729 (2013) 765
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 \( \sigma^2_P \) minimal;
  - a solution is \( w_{\text{opt}} = \frac{\partial \ln p(\Omega)}{\partial P} \)
    e.g.: F. V. Tkachov, Part. Nucl. Lett. 111, 28 (2002)

  - polarimetry: \( p(\Omega) \equiv f(\Omega) + P \times g(\Omega) \), \( w_{\text{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)} \).

    - If \( A \ll 1 \), \( w_0 \equiv \frac{2g(\Omega)}{f(\Omega)} \), and
    - for the 1D “projection” \( p(\Omega) = (1 + AP \cos [2(\phi)]) \):
      \( w_1 = 2 \cos 2\phi, \quad E(w_1) = AP, \quad \sigma_P = \frac{1}{A\sqrt{N}} \sqrt{2 - (AP)^2} \).
Polarization asymmetry and measurement uncertainty

- Asymptotically $A \approx 1/7 \approx 14\%$.

$$\frac{d\sigma}{d\phi} \propto \alpha r_0^2 \left( \left[ \frac{28}{9} \ln 2(E/m) - \frac{218}{27} \right] - P \cos [2(\phi - \phi_0)] \left[ \frac{4}{9} \ln (2E/m) - \frac{20}{27} \right] \right)$$

[NIM A 729 (2013) 765]

Polarimetry: Track matching issue

- Many foreseen project use $2 \times 2$D projections, not true 3D imaging (gas TPC, silicon strip detectors)

- Ambiguity:
  \[(\text{track}_1, x, \text{track}_1, y)(\text{track}_2, x, \text{track}_2, y) \leftrightarrow (\text{track}_1, x, \text{track}_2, y)(\text{track}_1, x, \text{track}_2, y)\]

- Ruins the azimuthal angle information

- Assignment must be performed before multiple scattering blurs the picture
Observed angular distribution

- for fully polarised pairs ($P_{\text{eff}} = 1$),
- in a fixed direction wrt the detector ($\omega_{\text{pola}} - \omega_{\text{det}}$)
- for different values of the matching efficiency $\varepsilon$. 

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**Track matching issue: results**

- Time (means $\omega_{\text{pola}} - \omega_{\text{det}}$) integrated distributions

Azimuthal distribution for different matching efficiencies

Dilution as a function of matching efficiency.

- A factor of 2 is at stake!

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Conclusion

• The MeV sensitivity gap is an angular resolution issue

• Thin detectors provide ultimate angular resolution
  • but still recoil-dominated at lowest energy)
  • Triplet conversion : nope.

• Argon-based TPC : 0.4° @ 100 MeV, (50/50 multiple scattering/recoil)

• Polarimetry a new window to be opened on the high-energy sky

• Demanding in terms of statistics, \( \sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}} \), \( \mathcal{A} \approx 1/7 \) asymptotically

• Demanding in terms of detection
  • multiple scattering – solved by the use of a “thin detector”
  • watch your track matching !
  • \( \eta \epsilon T = 1 \) year, \( V = 1 \text{ m}^3 \), 5 bar argon, \( \mathcal{A}_{\text{eff}} \approx 16.6\% \), \( \sigma_P = 1.4\% \) on the Crab, a 5\( \sigma \) MDP of 7%/\( \sqrt{\text{Flux/ Crab}} \)

Je vous remercie de votre attention distinguée !