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

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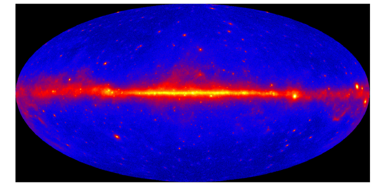
llr.in2p3.fr/∼dbernard/polar/harpo-t-p.html

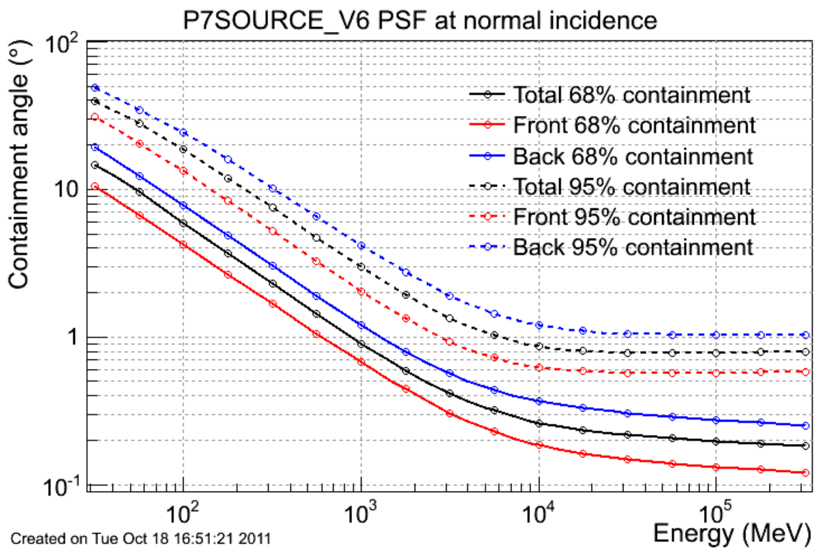
Talks Lay-out

- Thursday
  - μ-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

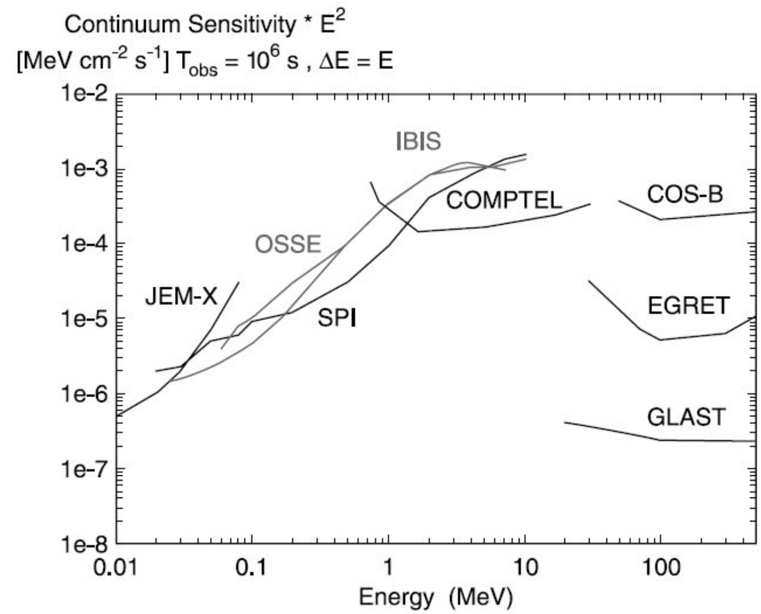
Non polarized astronomy



- Improve angular resolution – crowded sky regions



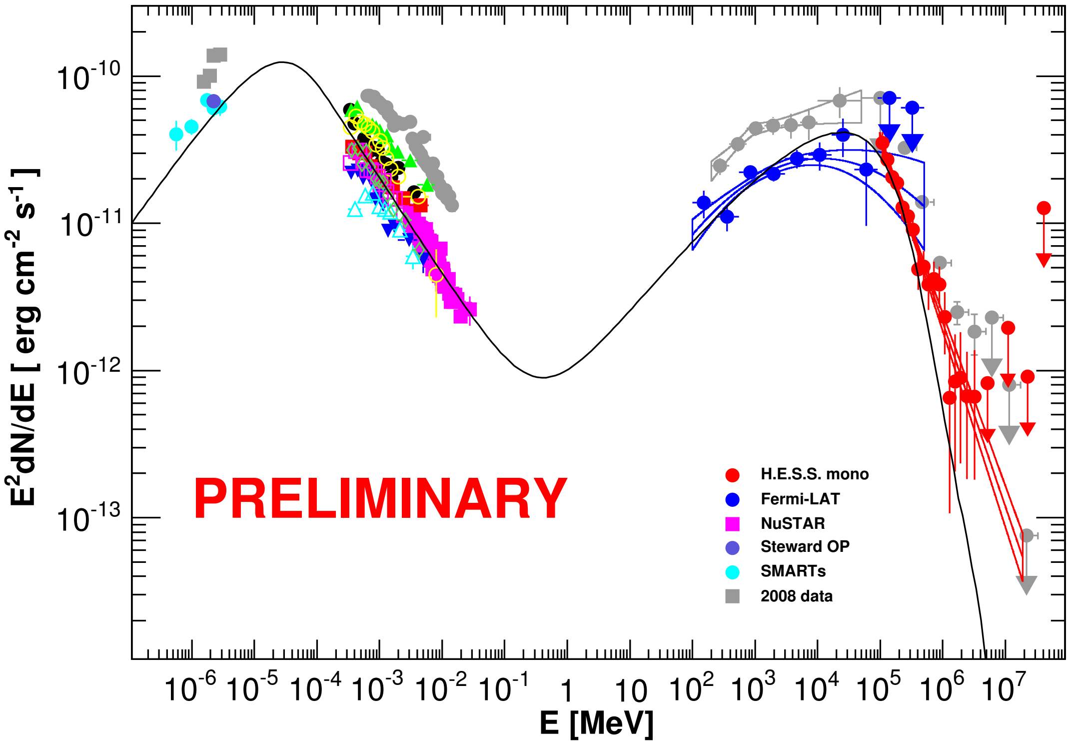
Fermi/LAT



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

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



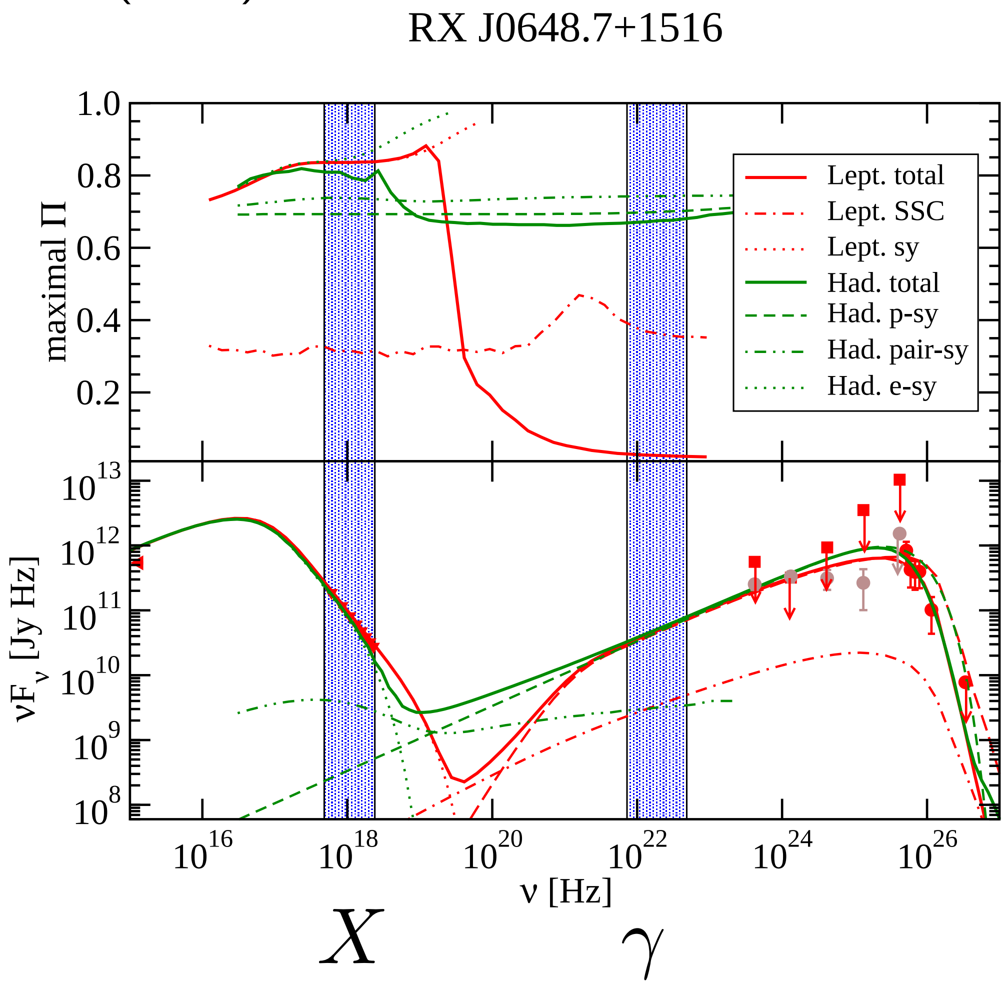
Grey points: dedicated Multiwavelength campaign 2013:

- 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]

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: $P_{\rm lept} \approx P_{\rm hadr}$
- γ-ray: $P_{\rm lept} \ll P_{\rm hadr}$

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

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 ξ/M,
  M Planck mass.
- ξ 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)
    D. Götz, *et al.*, MNRAS 431 (2013) 3550
- Bound $\propto 1/k^2$!

Photon angular resolution

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

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

<u>Contributions:</u>

- 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 longitudinal sampling (pitch) [cm].

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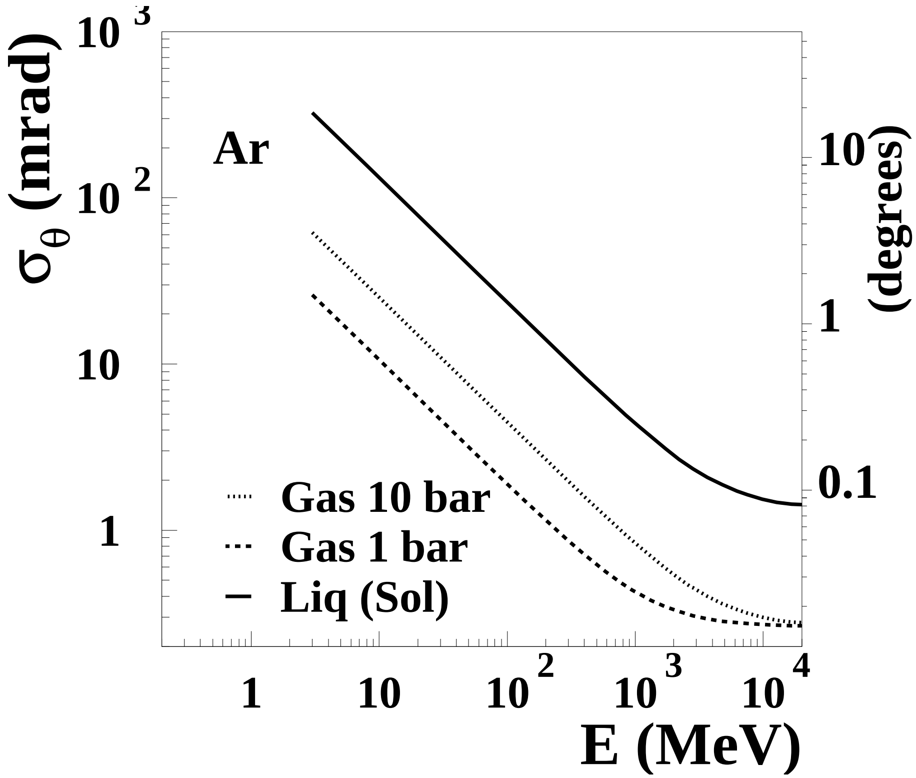
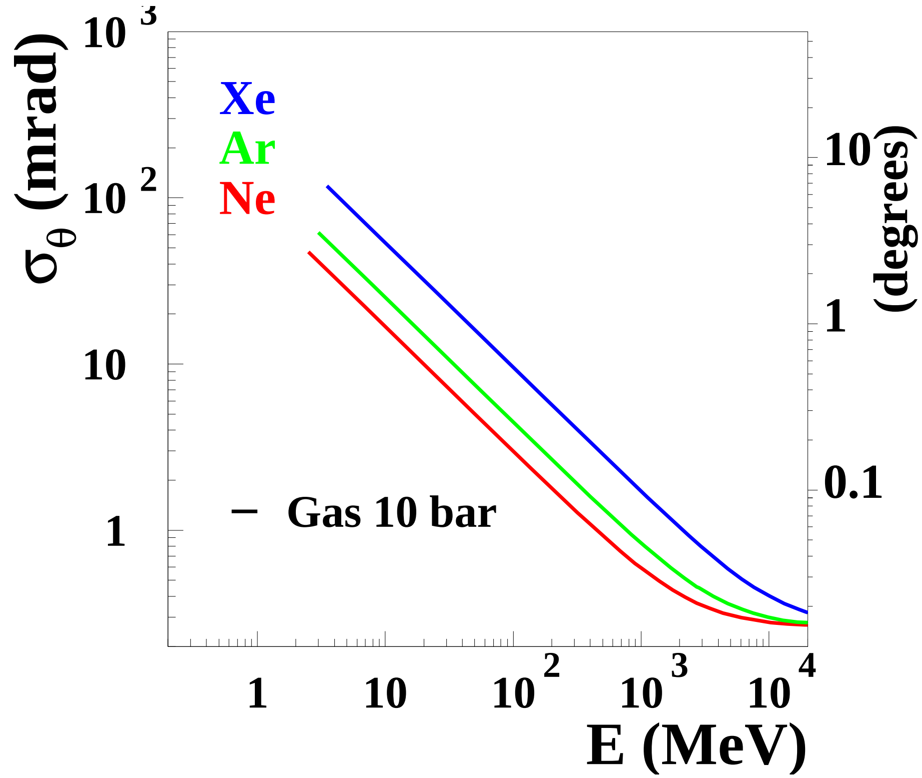
Single-track angular resolution

- Dependence of the RMS photon angular resolution on photon energy
- Sampling pitch $l = 1\,\mathrm{mm}$, point resolution $\sigma = 0.1\,\mathrm{mm}$,





For various densities (argon) for various gases

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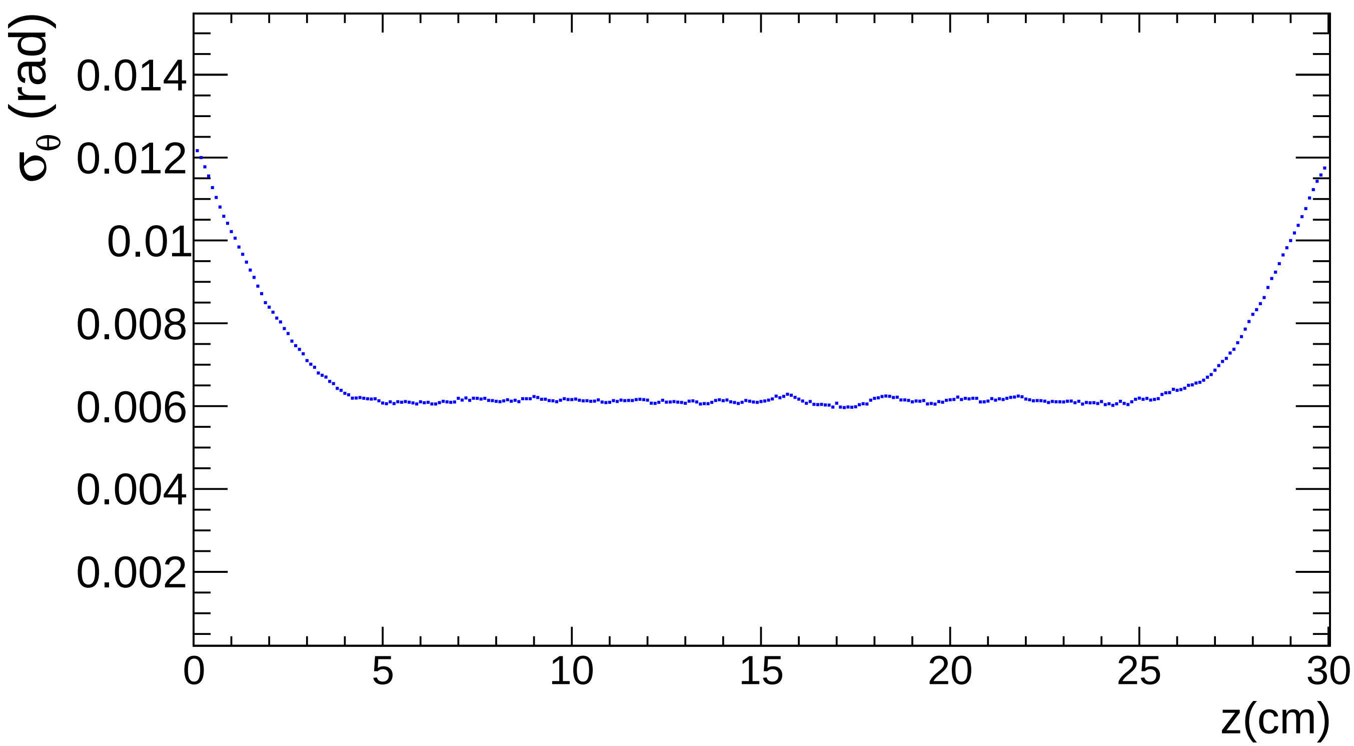
Single-track angular resolution with Optimal fits: Validation with a Kalman filter

- Validation with parameters : 5 bar argon, $\sigma = l = 0.1\text{cm}$;

$$p_1 = 13.6\,\text{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6} = 112\,\text{keV}/c$$

- $40\,\text{MeV}/c$ 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

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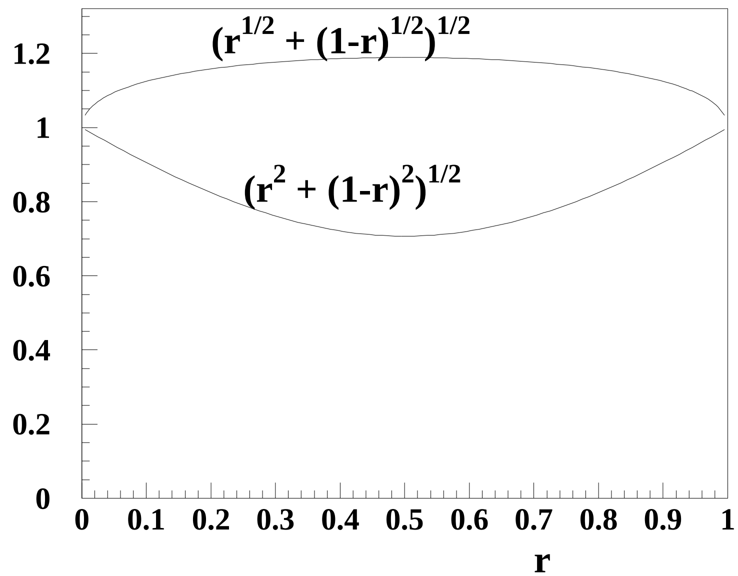
Angular resolution: From Single-track to single photon

- Small angle approximation: $\theta_{x,\gamma} = r\theta_{x,+} + (1-r)\theta_{x,-}$,
- r fraction of energy carried away by the positron, $r = E_+/E$,



- multiple scattering dominated regime: $\sigma_{\theta\gamma} = \sigma_{\theta t}\sqrt{\sqrt{r} + \sqrt{1-r}}$
- high energy regime: $\sigma_{\theta\gamma} = \sigma_{\theta t}\sqrt{r^2 + (1-r)^2}$
- track to photon factor close to unity: neglected in the following.

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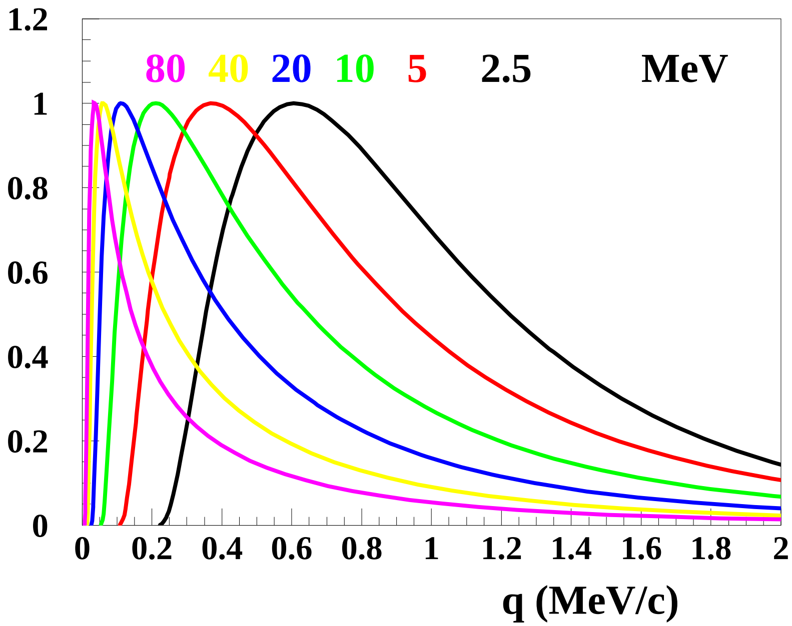
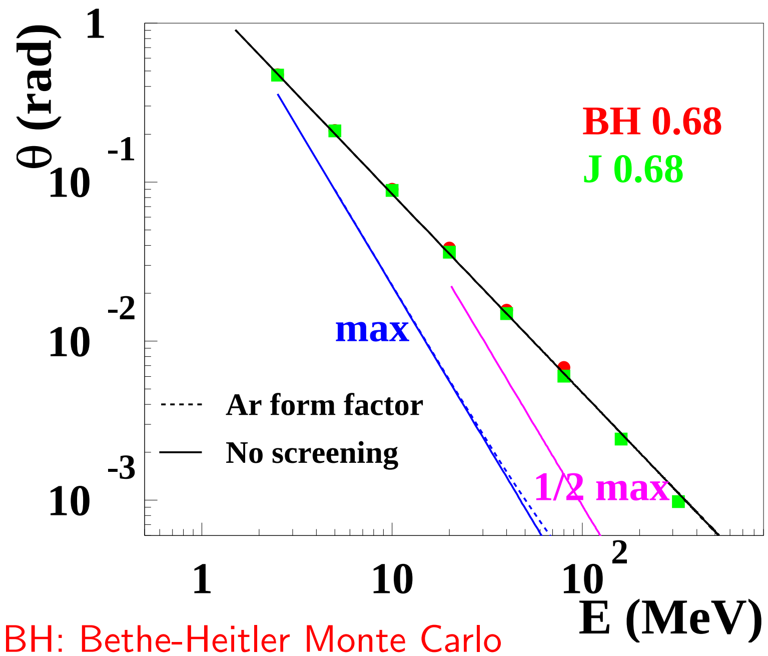
Angular resolution: Un-measured nucleus recoil momentum





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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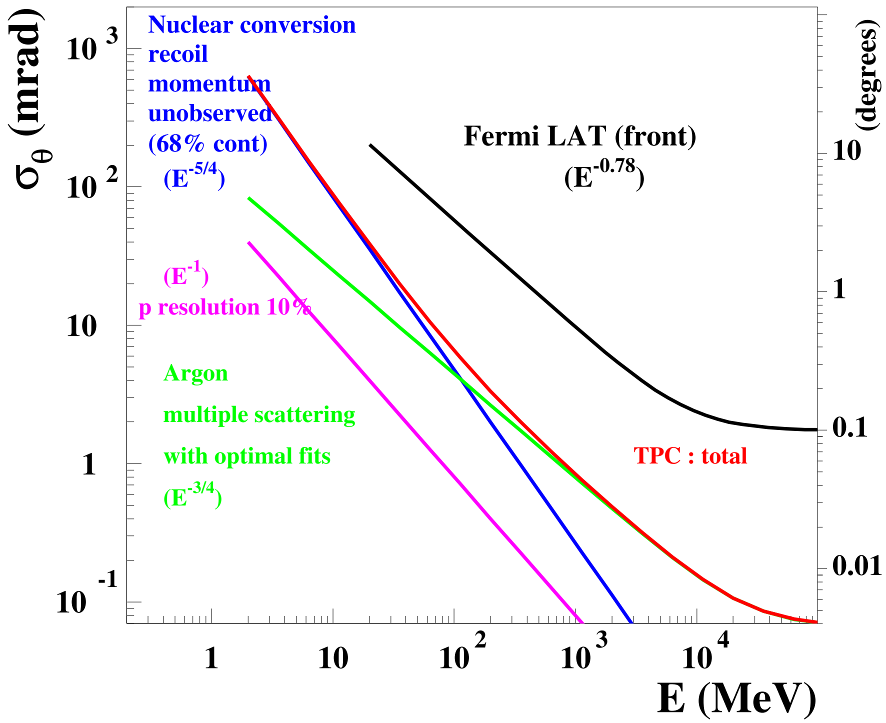
Angular resolution: Wrap up

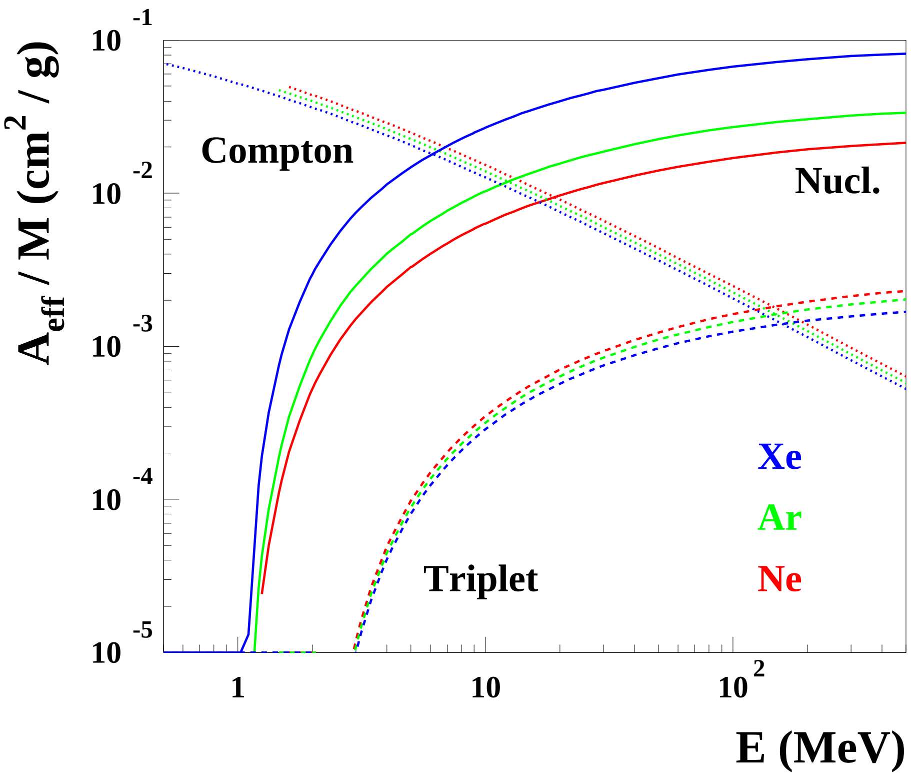
- Argon-based gas, $P = 10\,\mathrm{bar}$ $\qquad X_0 = 1180\,\mathrm{cm}$
- Sampling pitch $l = 1\,\mathrm{mm}$, point resolution $\sigma = 0.1\,\mathrm{mm}$,

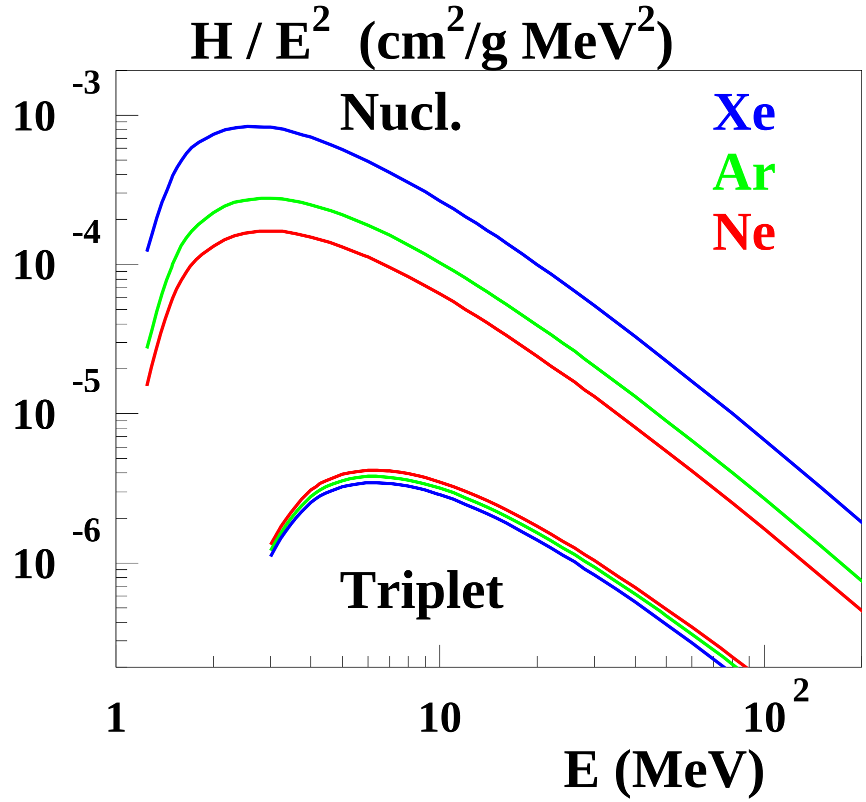


	multiple scattering	ion recoil momentum	total
	$\sigma_{\theta t} = (p/p_1)^{-3/4}$ with $p_1 = p_0 \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$ $p_1 = 73\,\mathrm{keV}/c$	$1.5\,\mathrm{rad}\left(\frac{E}{1\,\mathrm{MeV}}\right)^{-5/4}$	
σ_θ @ 100 MeV	0.26°	0.27°	0.37°

Thin detectors: Effective area

- $A_{\rm eff} = H \times M$, H photon attenuation





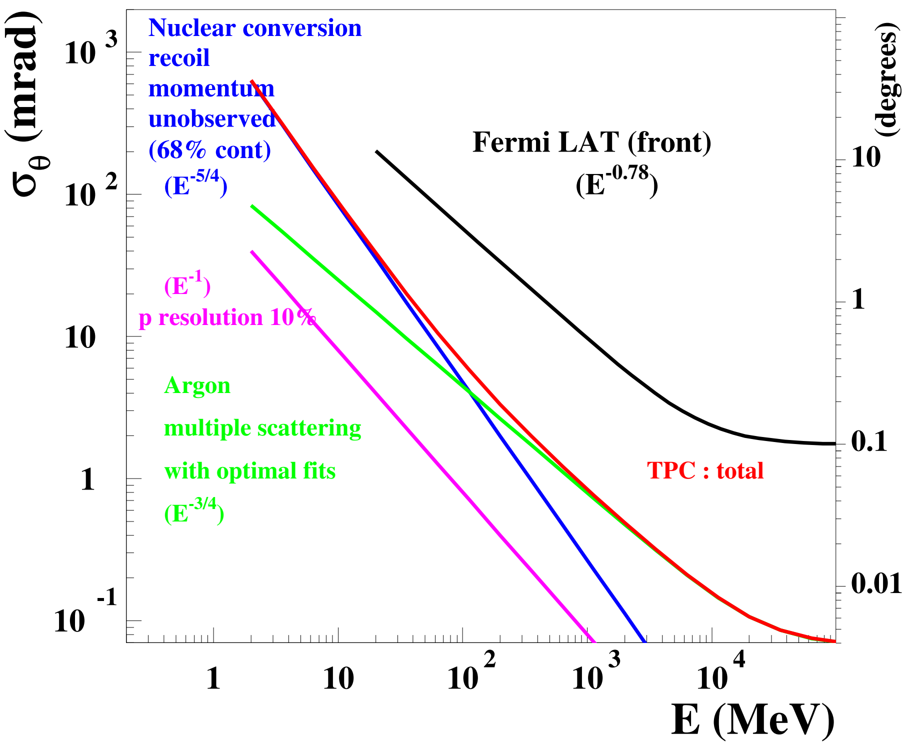
Argon, nucl.: $A_{\rm eff}/M = 27\,{\rm cm}^2/{\rm kg}$ @ $E = 100\,{\rm MeV}$

National Institute of Standards and Technology (NIST)

Performances with Thin Homogeneous Detector and Optimal Fits

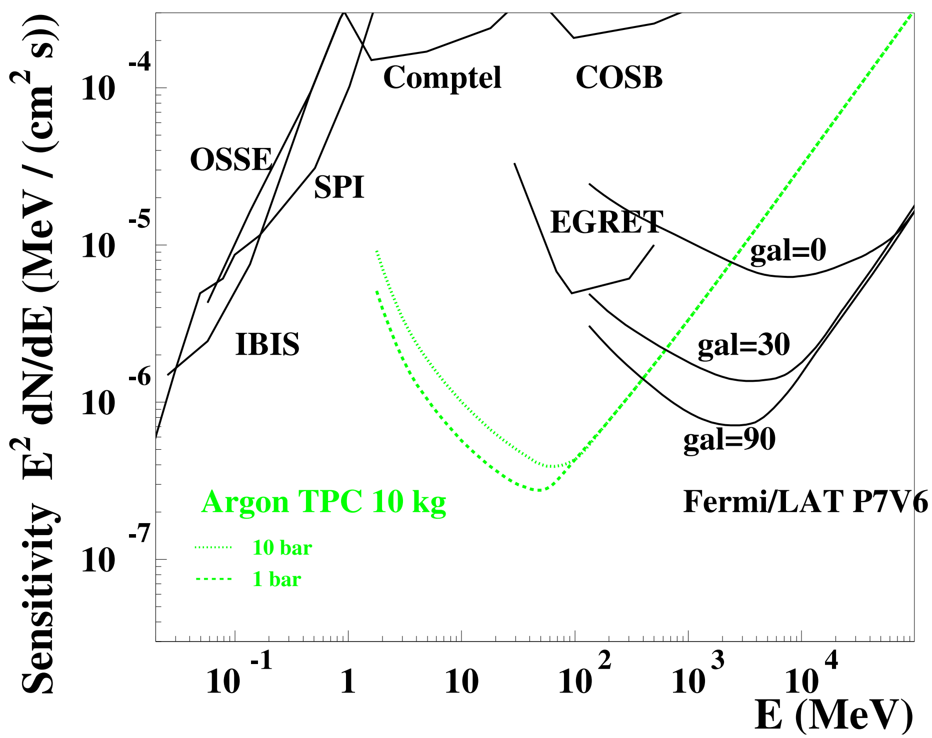
Angular resolution

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



point-source differential sensitivity

limit detectable $E^2 \mathrm{d}N/\mathrm{d}E$, à la Fermi: 4 bins/decade, 5σ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. "against" extragalactic background



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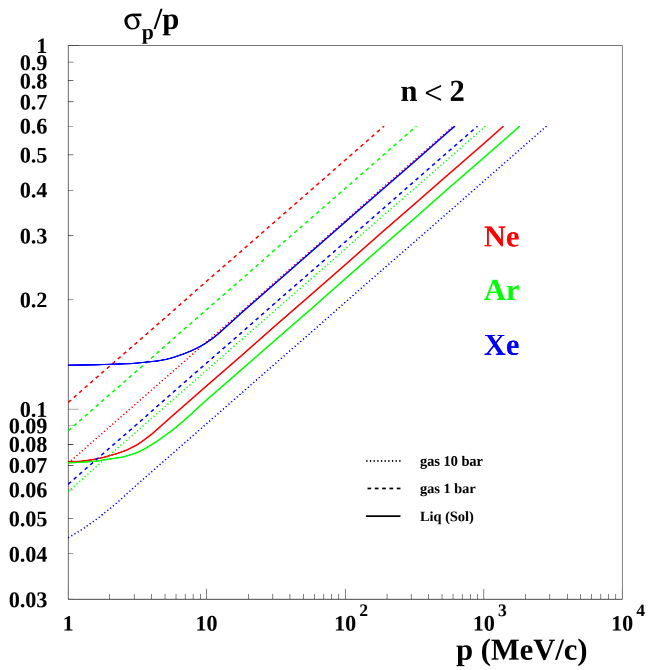
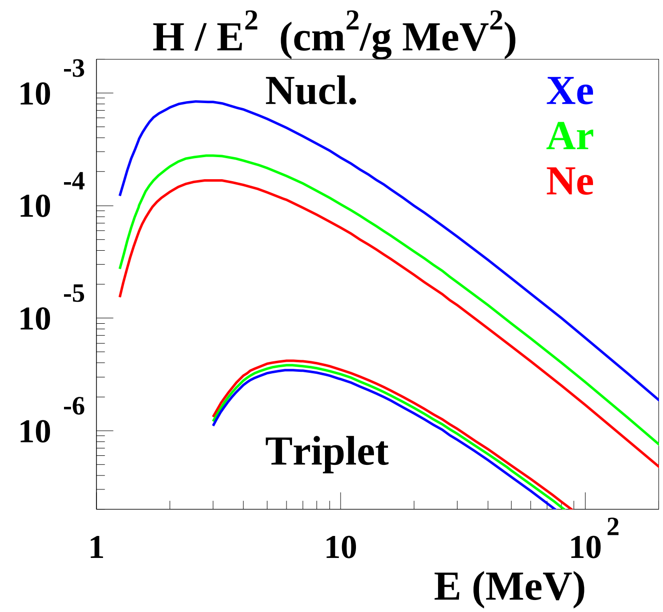
Track Momentum Measurement in TPC Alone from Multiple Estimations of Multiple Scattering

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

relative precision



E range of interest



A Kalman-filter based measurement should do a factor ≈ 2 better.

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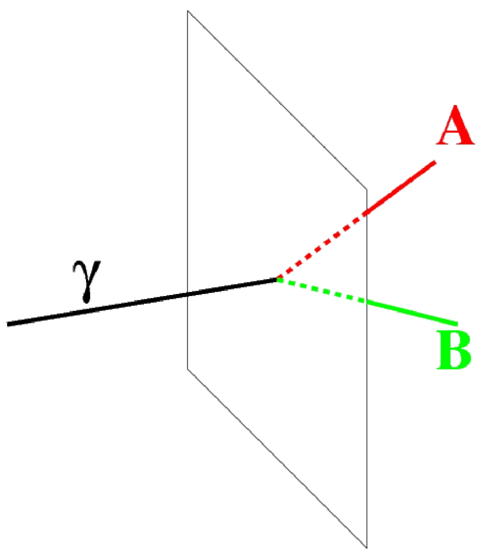
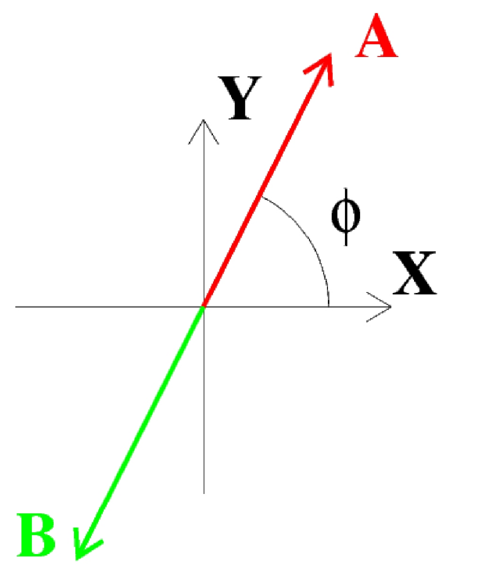
Polarimetry

- Modulation of azimuthal angle distribution

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



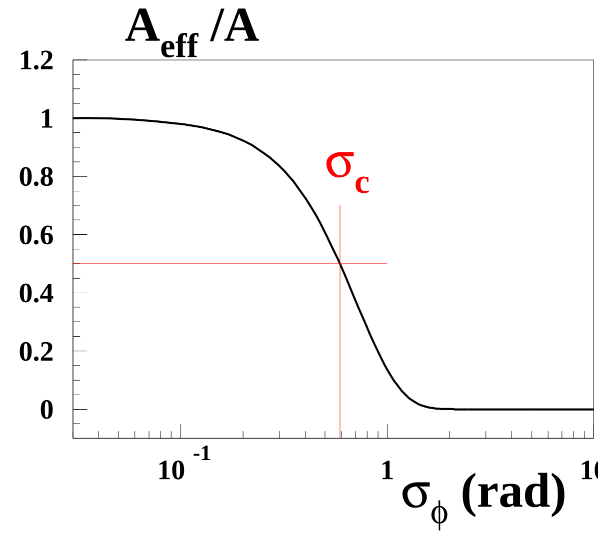


- P source linear polarisation fraction
- $\mathcal{A}$ Polarization asymmetry
- ϕ azimuthal angle

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

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

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

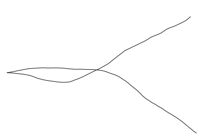


- azimuthal angle RMS $\sigma_\phi = \dfrac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$,
  - $\theta_0 \approx \dfrac{13.6\,\text{MeV}/c}{\beta p}\sqrt{\dfrac{x}{X_0}}$,
  - most probable opening angle $\hat{\theta}_{+-} = 1.6\,\text{MeV}/E$ — Olsen, PR. 131, 406 (1963).

$\Rightarrow \sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$ (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 $\gamma Z \rightarrow e^+e^-$



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

Mattox J. R. Astrophys. J. 363 (1990) 270

γ *Polarimetry with a Homogeneous Detector and Optimal Fits*

- $\sigma_\phi = \frac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, azimuthal angle resolution
- $\sigma_{\theta,\text{track}} = (p/p_1)^{-3/4}$, 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
- $\sigma_\phi = \left[x_+^{-\frac{3}{4}} \oplus (1 - x_+)^{-\frac{3}{4}}\right] \frac{(p_1)^{\frac{3}{4}} E^{\frac{1}{4}}}{1.6\,\text{MeV}}$. 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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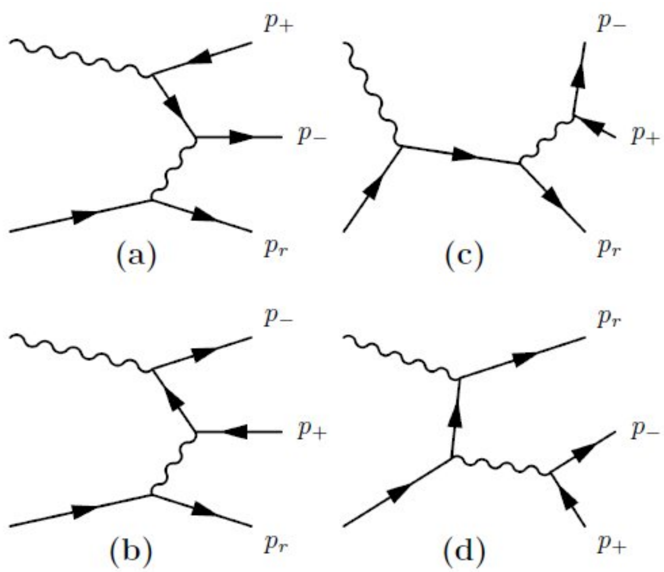
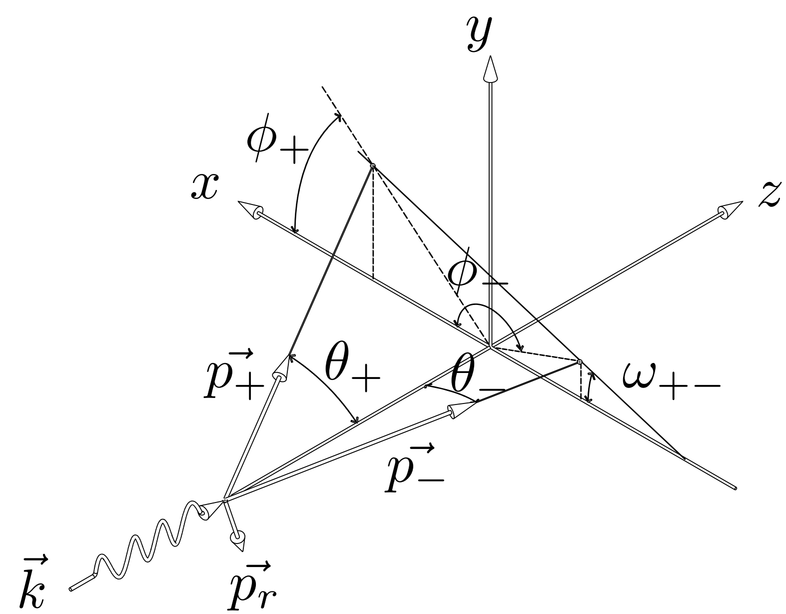
Developed, Validated, Event Generator

- 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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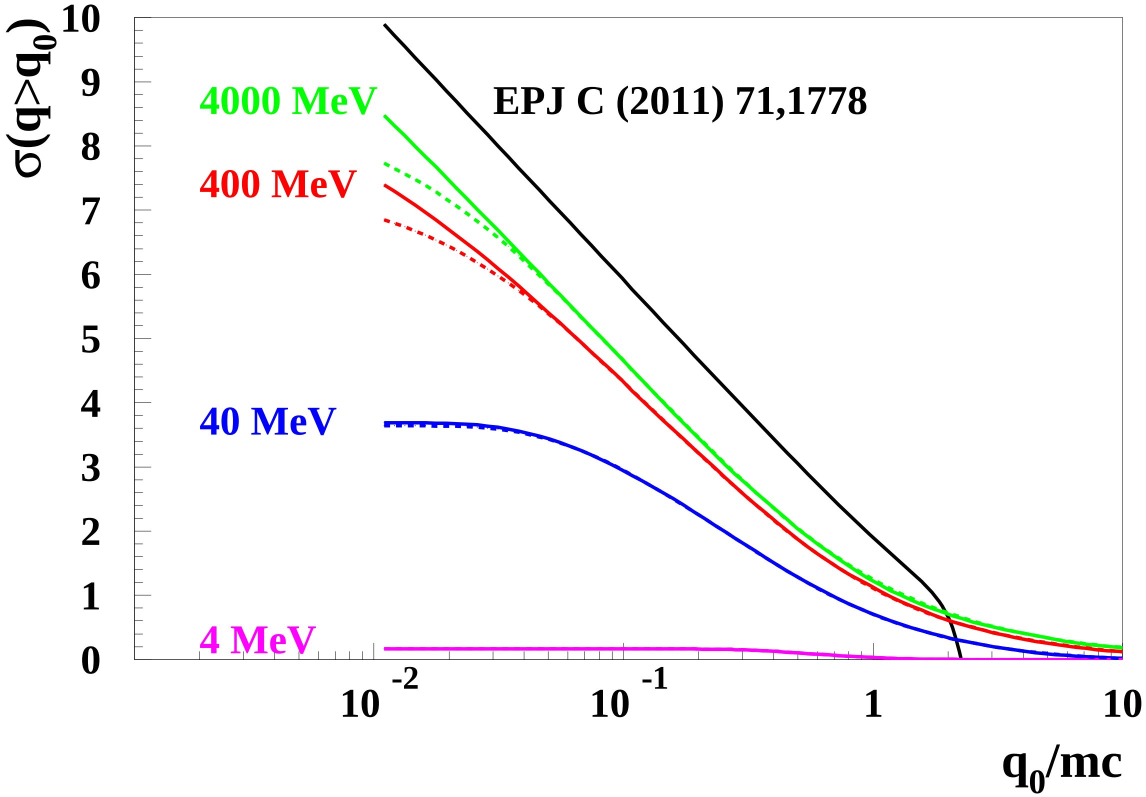
Evt Generator: One Example of Validation Plot

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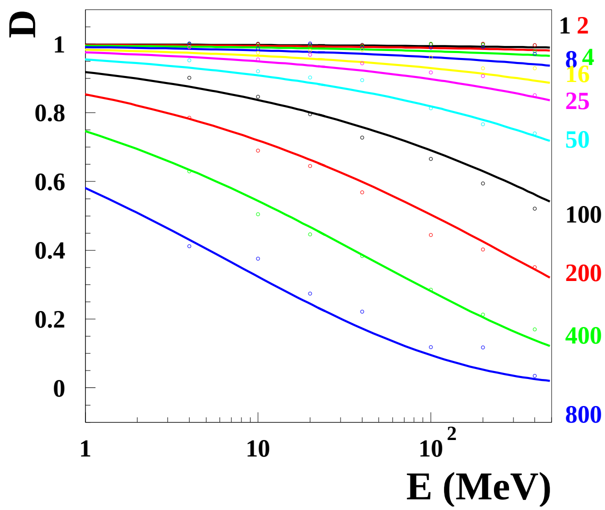
Dilution of Polarization Asymmetry due to Multiple Scattering: Optimal Fits and Full MC

- 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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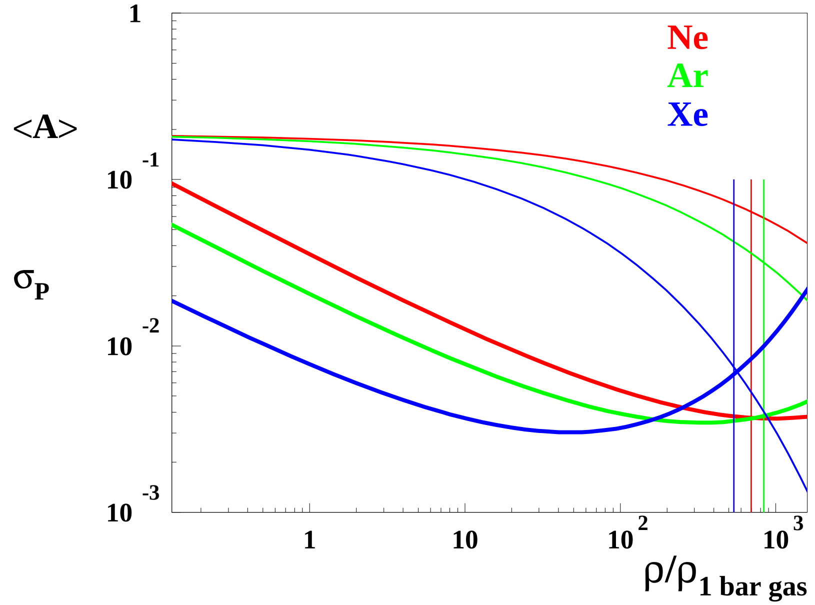
Polarimetry Performance (no Experimental Cuts)

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

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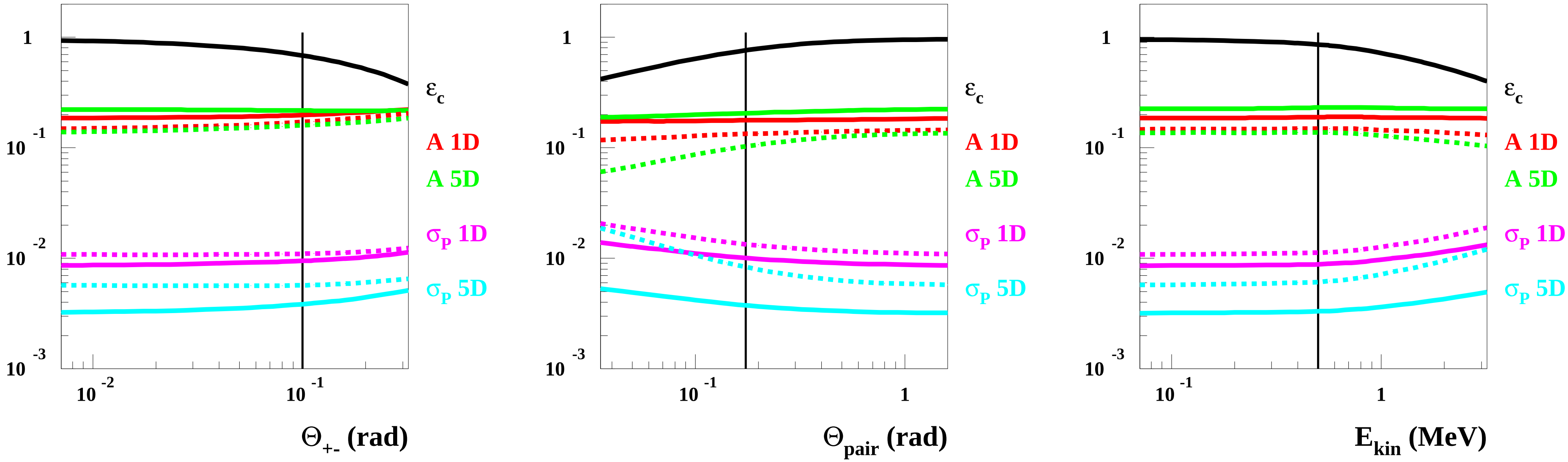
Polarimetry : Effects of Experimental Cuts

- 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: 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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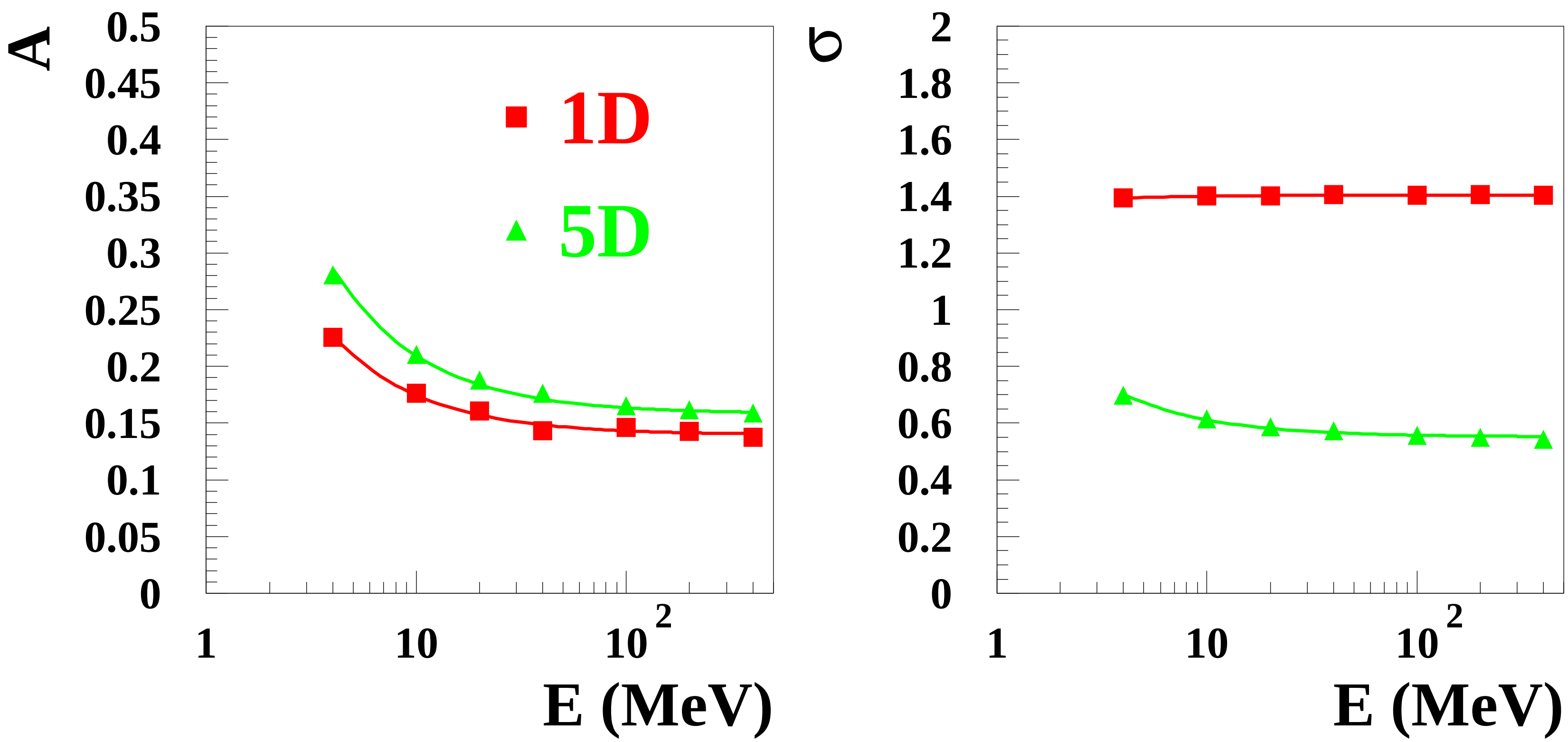
Polarization asymmetry and measurement uncertainty



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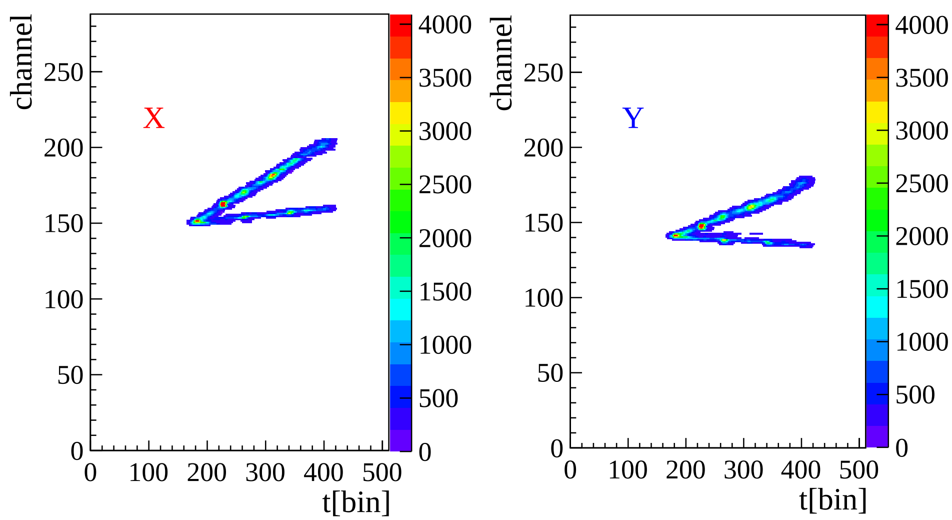
- Asymptotically $\mathcal{A} \approx 1/7 \approx \ 14\%$. Boldyshev & Peresunko, Yad. Fiz. 14, 1027 (1971).

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

Polarimetry : Track matching issue

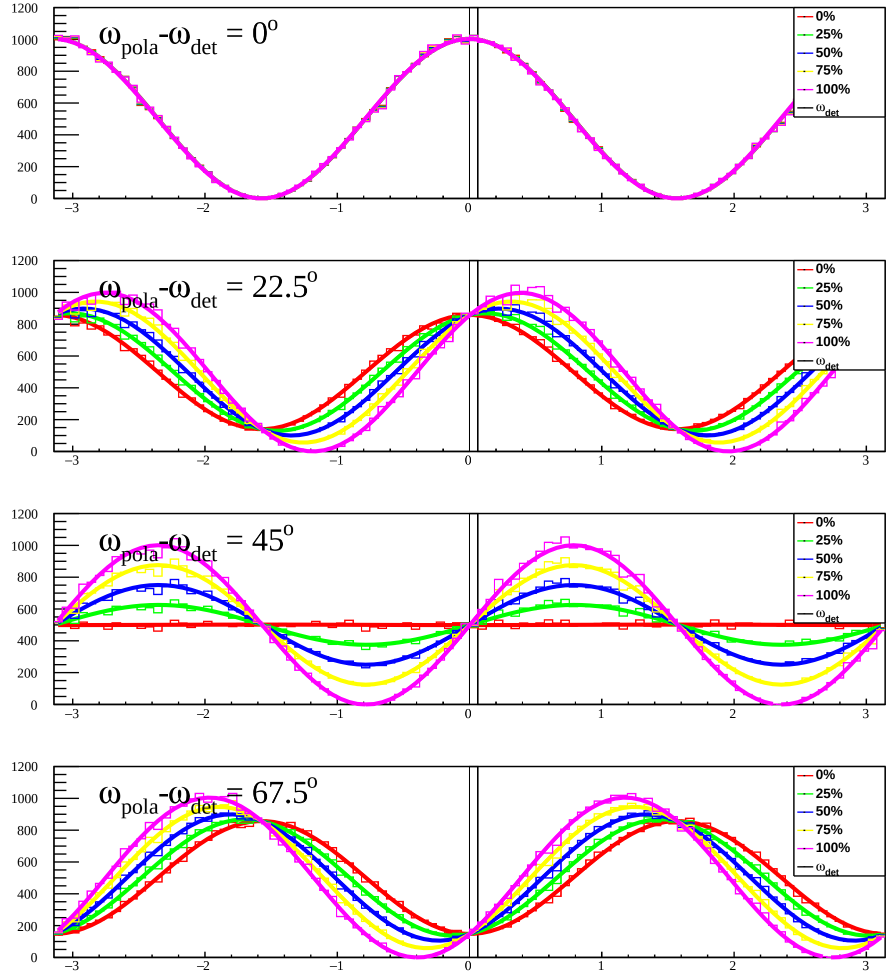
- Many foreseen project use 2×2D projections, not true 3D imaging (gas TPC, silicon strip detectors)
- Ambiguity :

  $(\text{track}_{1,x}, \text{track}_{1,y})(\text{track}_{2,x}, \text{track}_{2,y}) \leftrightarrow (\text{track}_{1,x}, \text{track}_{2,y})(\text{track}_{1,x}, \text{track}_{2,y})$



- Ruins the azimutal angle information
- Assignment must be performed before multiple scattering blurs the picture

Track matching issue



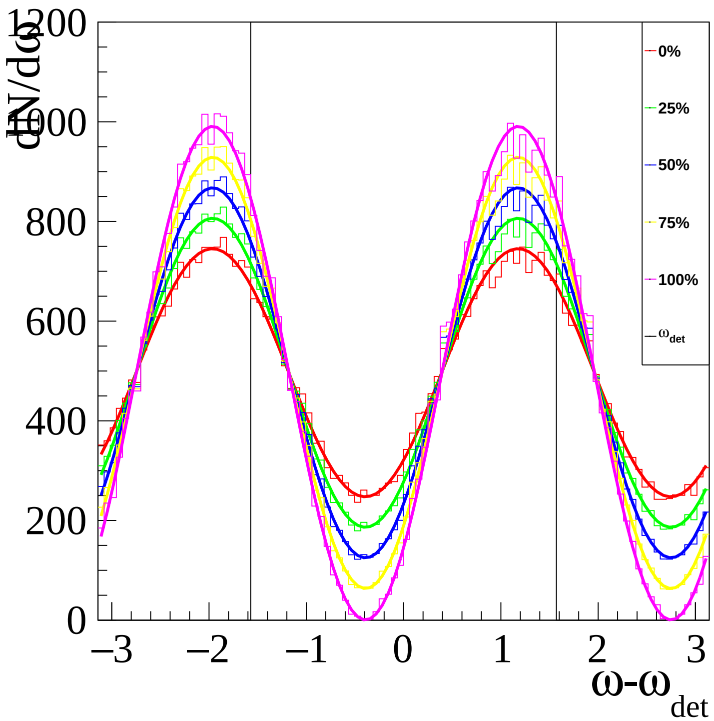
Observed angular distribution

Philippe.Gros @ llr.in2p3.fr

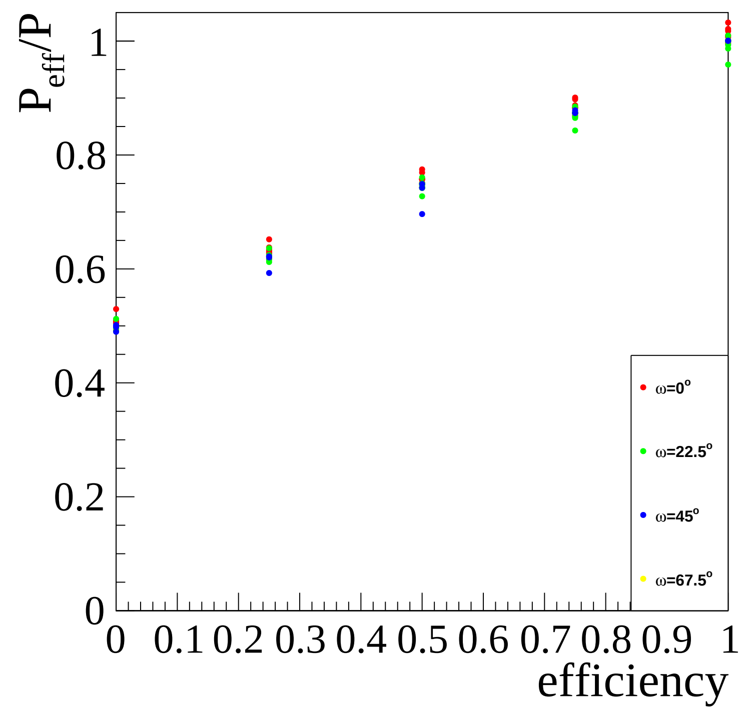
- for fully polarised pairs ($P_{\text{eff}} = 1$),
- in a fixed direction wrt the detector ($\omega_{\text{pola}} - \omega_{\text{det}}$)
- for different values of the matching efficiency ε.

Track matching issue: results

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



Azimutal 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)

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- Polarimetry a new window to be opened on the high-energy sky
- Demanding in terms of statistics, $\sigma_P \approx \dfrac{1}{\mathcal{A}}\sqrt{\dfrac{2}{N}}$, $\mathcal{A} \approx 1/7$ asymptotically
- Demanding in terms of detection
  - multiple scattering – solved by the use of a "thin detetector"
  - watch your track matching !
  - $\eta\epsilon T = 1\,\text{year}$, $V = 1\,\mathrm{m}^3$, 5 bar argon, $\mathcal{A}_{\text{eff}} \approx 16.6\%$, $\sigma_P = 1.4\%$ on the Crab, a 5σ MDP of $7\%/\sqrt{\text{Flux/Crab}}$

Je vous remercie de votre attention distinguée !