HARPO:A TPC as high performance gamma ray telescope and polarimeter

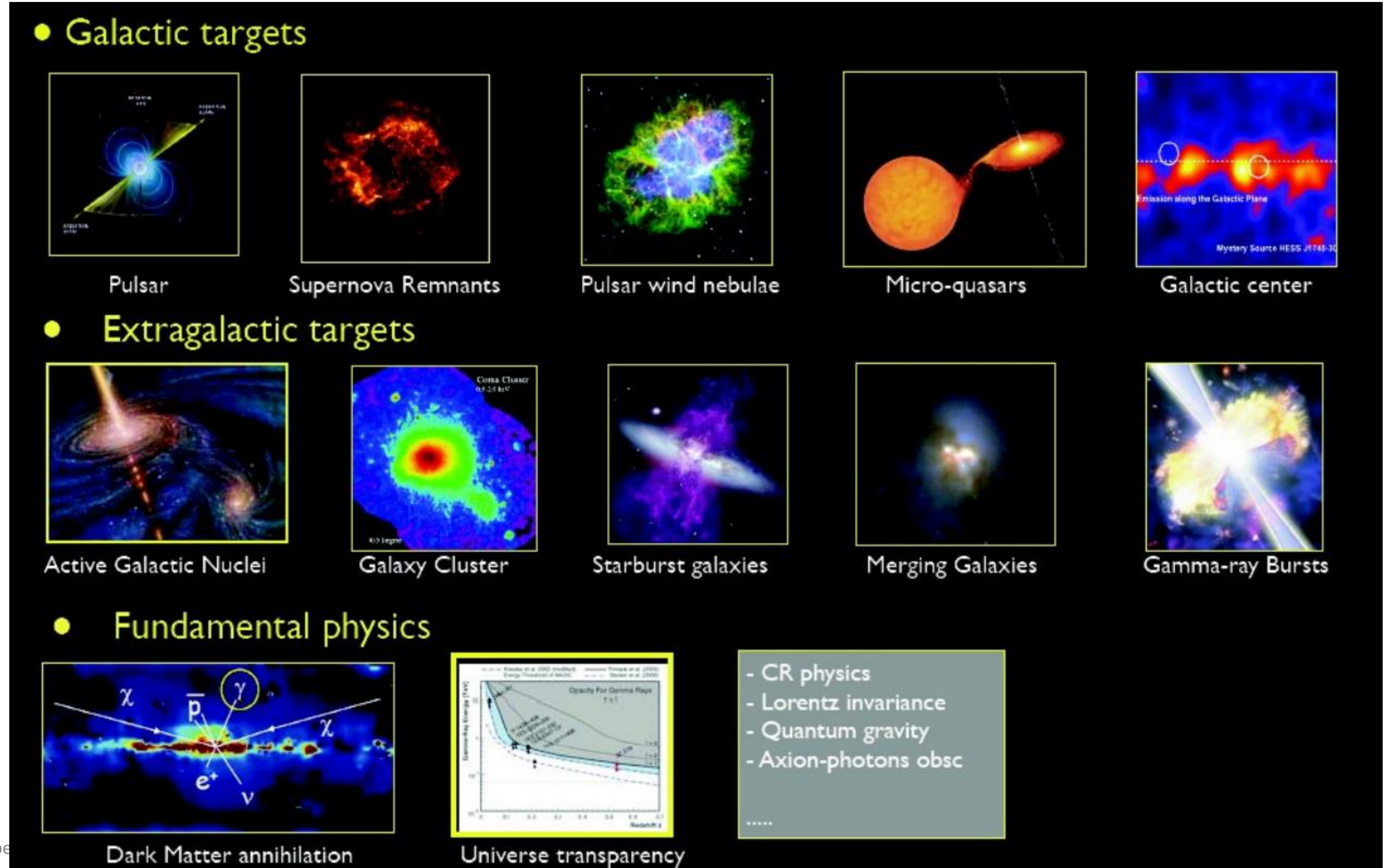
Shaobo Wang (王少博)

On behalf of HARPO Collaboration

2022-08-19

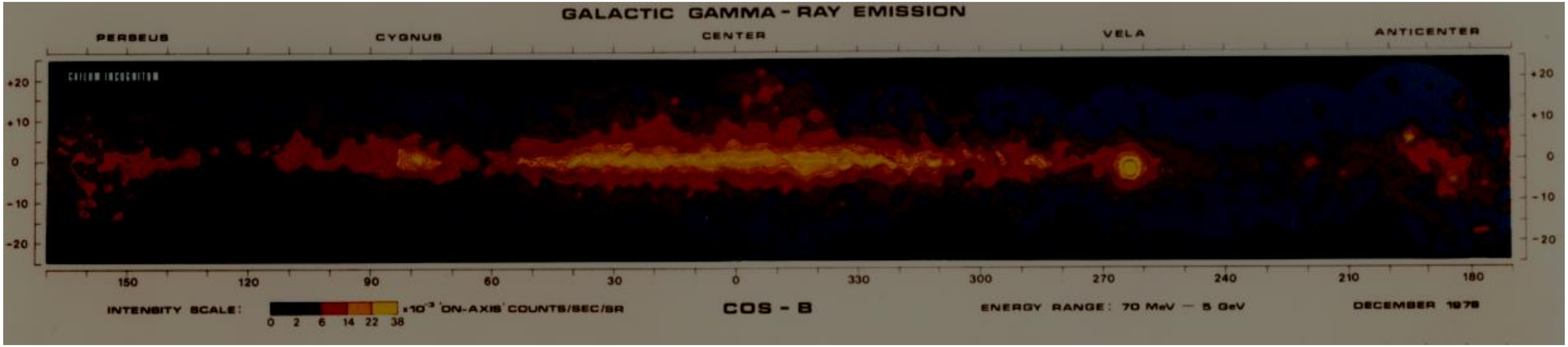
@USTC

Science Case : Gamma astronomy

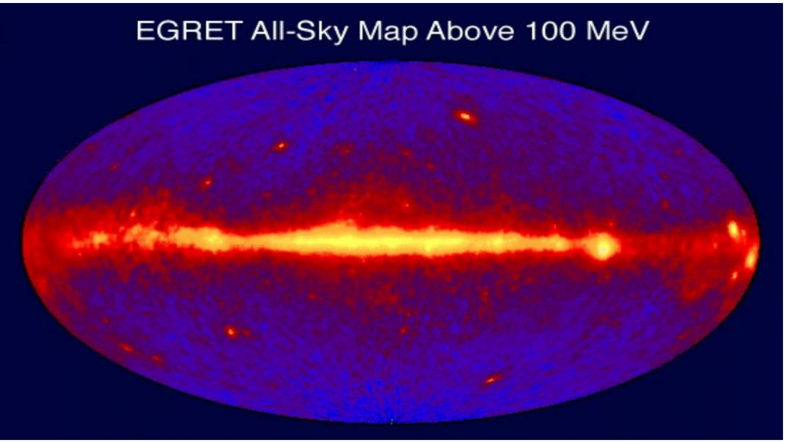


Gamma telescopes performance

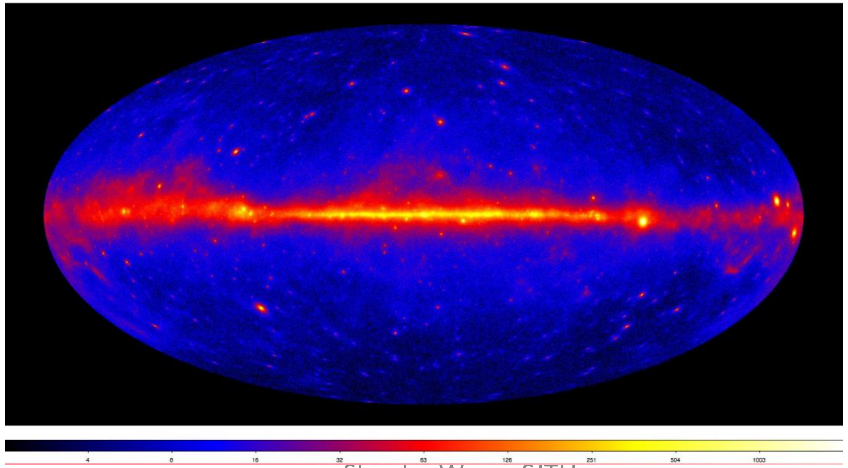
COS-B (1975-1982) 70MeV - 5GeV



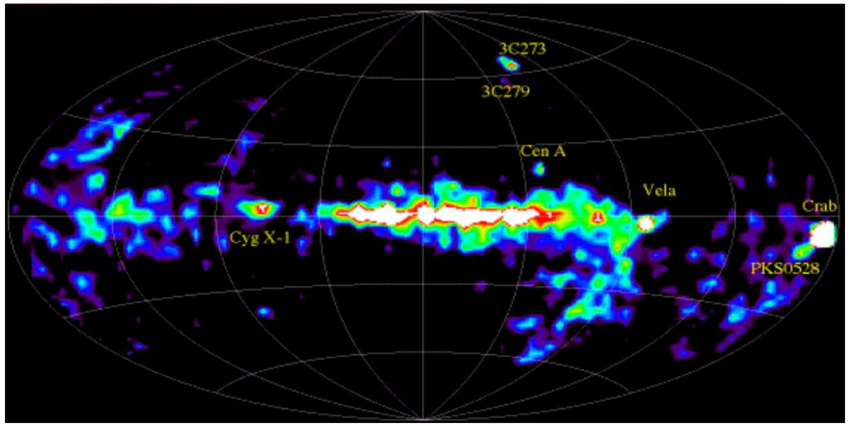
EGRET (1991-2000)
271 sources>100MeV



Fermi (2008-)
1873 sources>100MeV

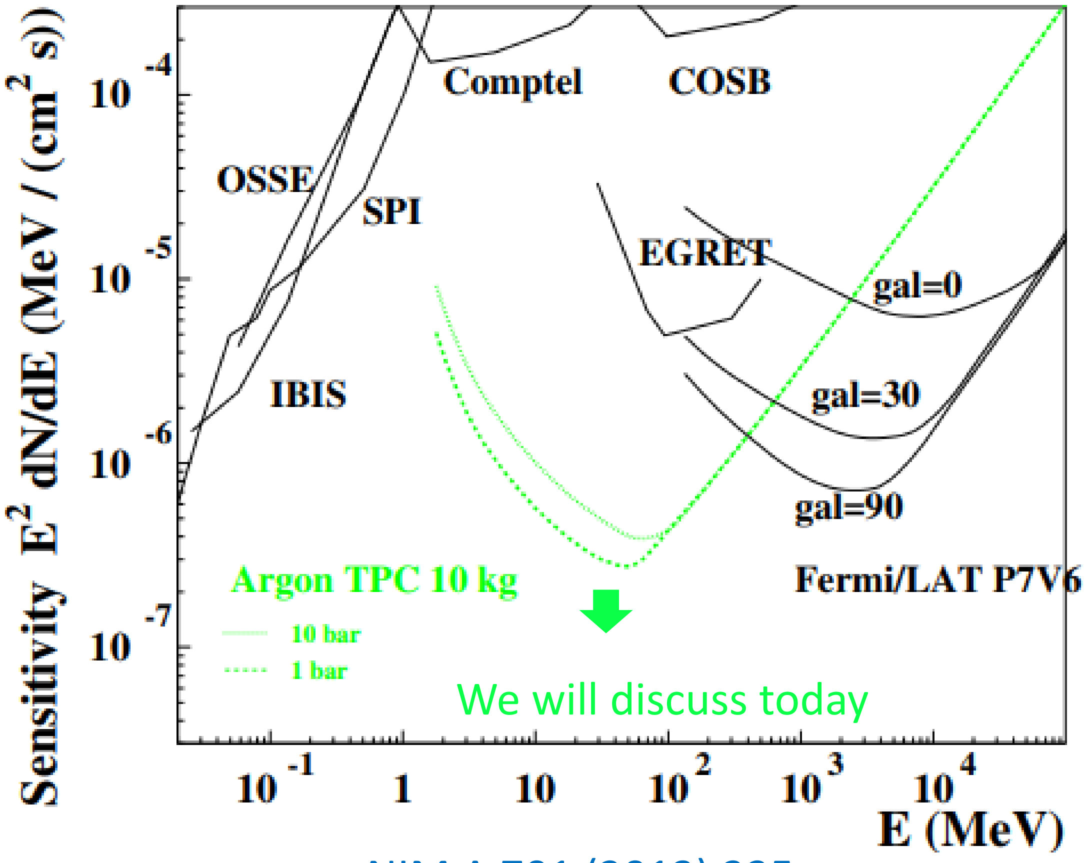


Comptel (1991-2000)
63 sources <u>1-30MeV</u>



Gamma telescopes performance

- There is important progress in gamma ray telescope at high energy (>100MeV)
- Still a big performance gap at lower energy



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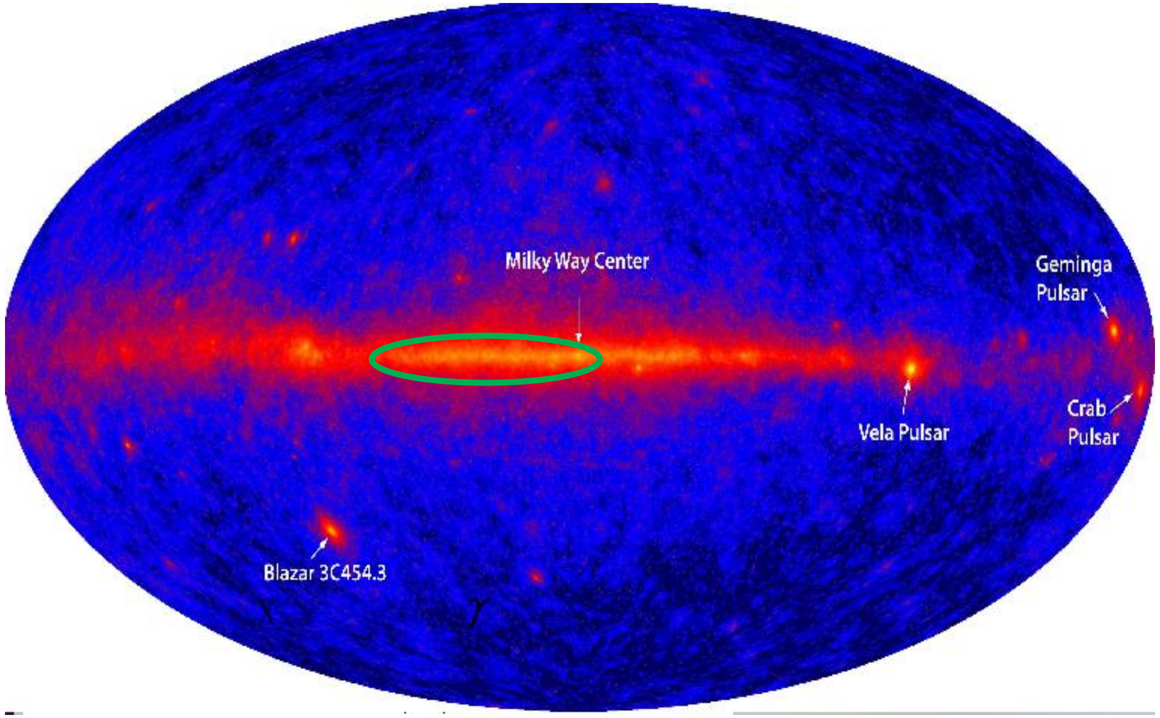
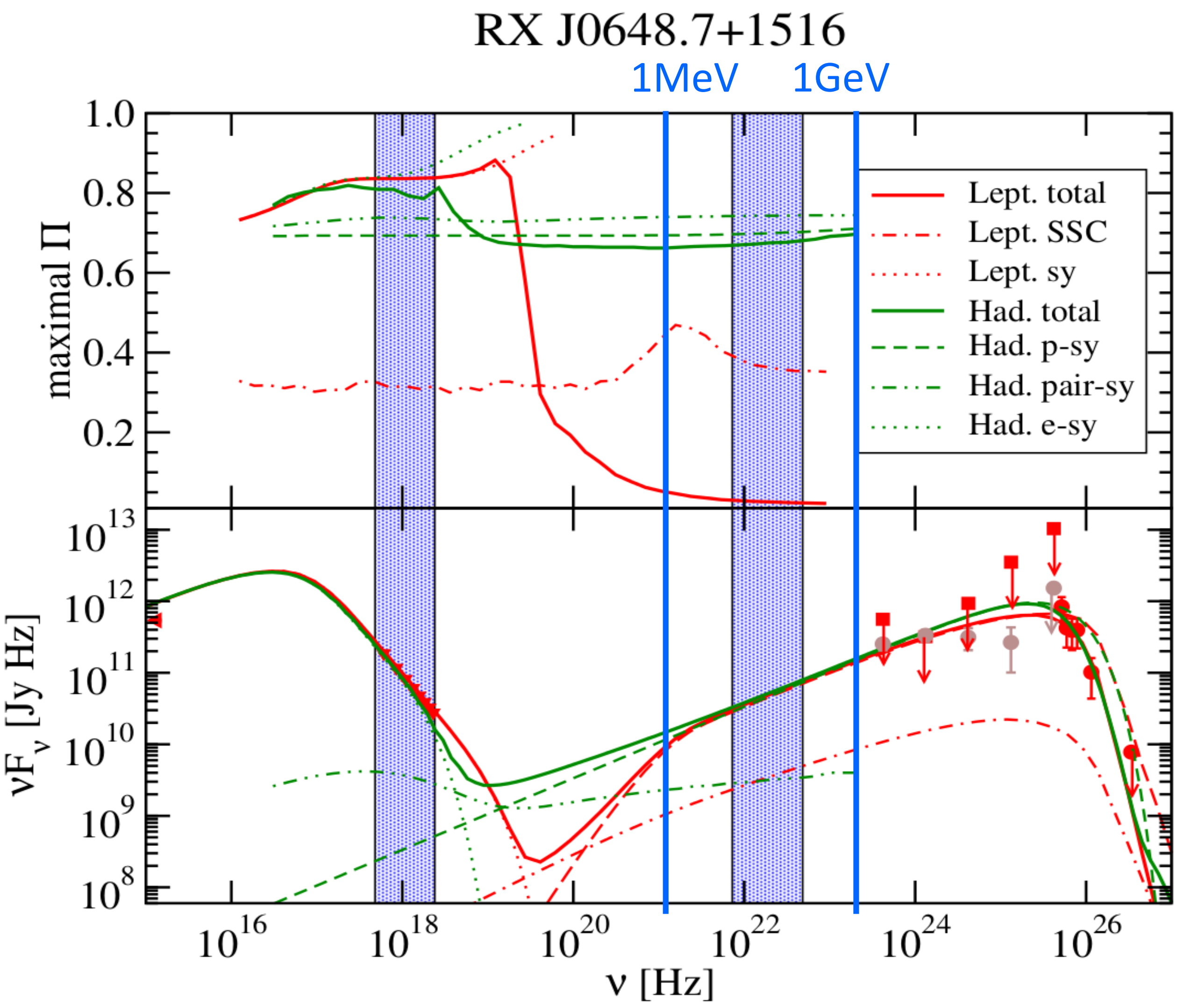


Polarimetry

- Blazars: decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models

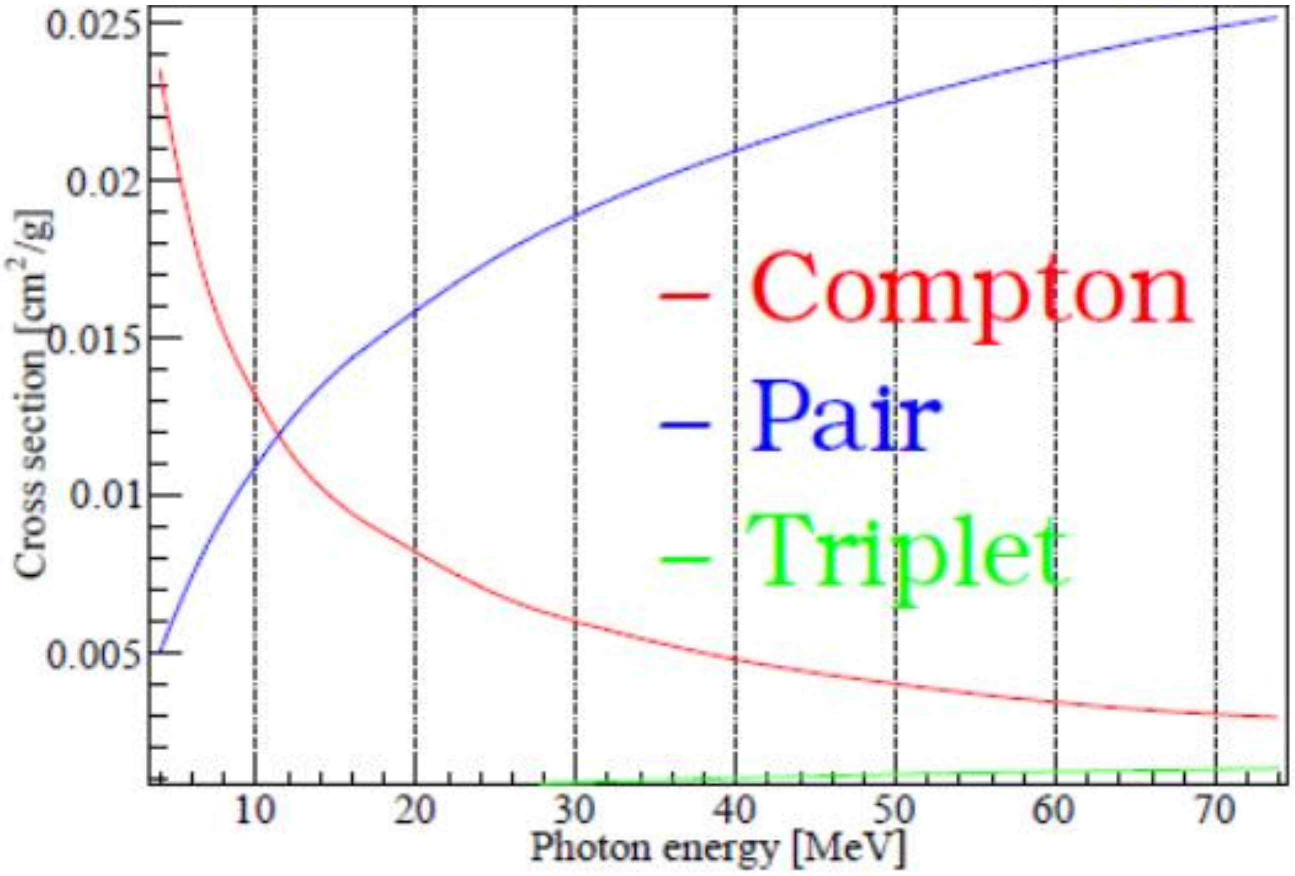
- Polarization can give the answer
  - no difference in X
  - visible in gamma



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

Astrophysics at MeV energies

- In the 1-100 MeV range, the Compton cross-section becomes small.
- The pair creation keeps the memory of the photon direction and the decay plane gives the polarization direction.



Differential sensitivity

- The angular resolution is an important factor for sensitivity
- Compute the sensitivity to the detection of a faint high-latitude point-like source
- Gaussian statistics, the significance: $S = n\sqrt{B}$
  - Signal counts:

$$S = T \times \eta \times A_{\text{eff}}(E) \times I_0(E) \times \epsilon \times \Delta E$$

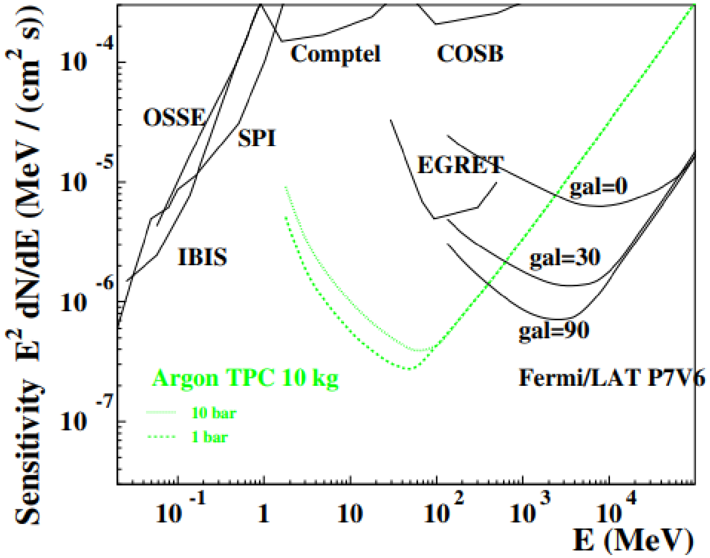
  - Background counts:

$$B = T \times \eta \times A_{\text{eff}}(E) \times \pi\sigma_\theta^2 \int F_B(E) dE$$

- The sensitivity s expressed as the minimum detectable signal intensity, multiplied by E^2

$$s \approx \frac{n\ \sigma_\theta\ E^2}{\Delta E}\sqrt{\frac{\pi \int B(E)\ \mathrm{d}E}{T\ \eta\ A_{\text{eff}}}}$$

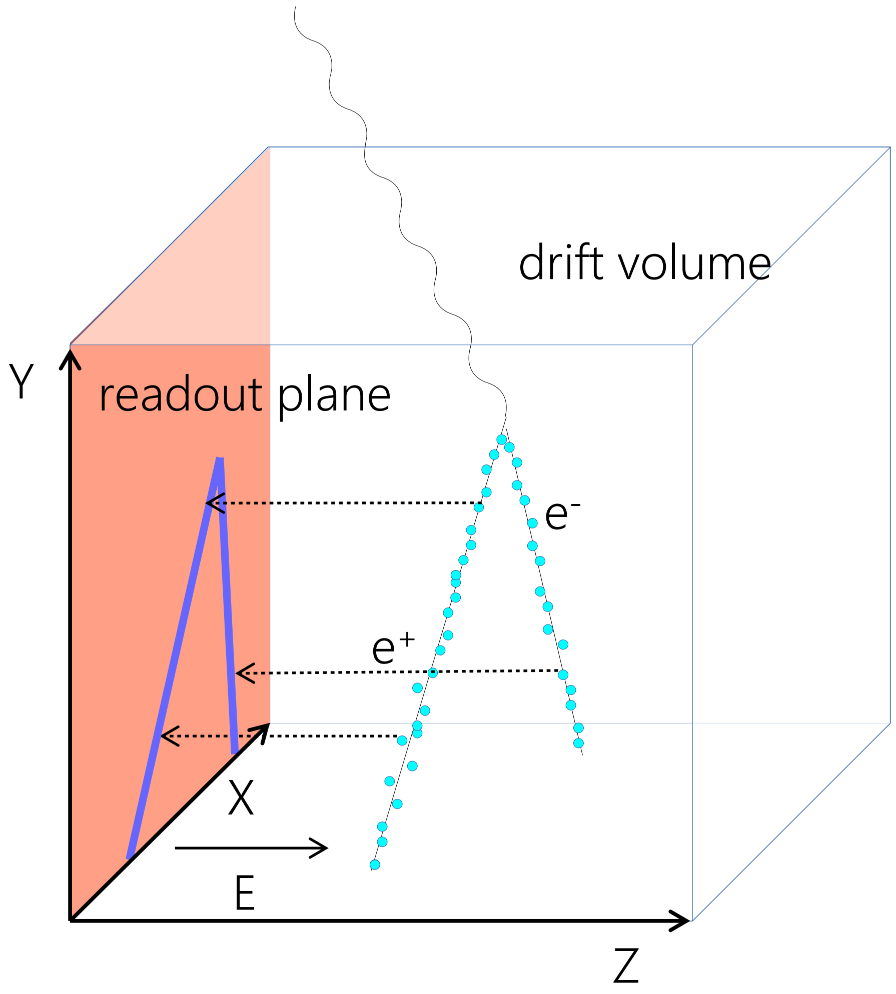
compare to Fermi's differential sensitivity at 90◦ galactic latitude



T: observation time
η: exposure fraction
I_0: signal intensity
F_B: background flux
E: energy
A_{eff}: effective area per unit mass

Time Projection Chamber (TPC)

- photons are converted in the gas
- produced electrons ionize the gas
- ionization electrons drift along E field
- electrons are amplified and measured on the x&y readout plane
- time gives a measure of the z coordinate
  - t0 from external trigger
  - drift velocity

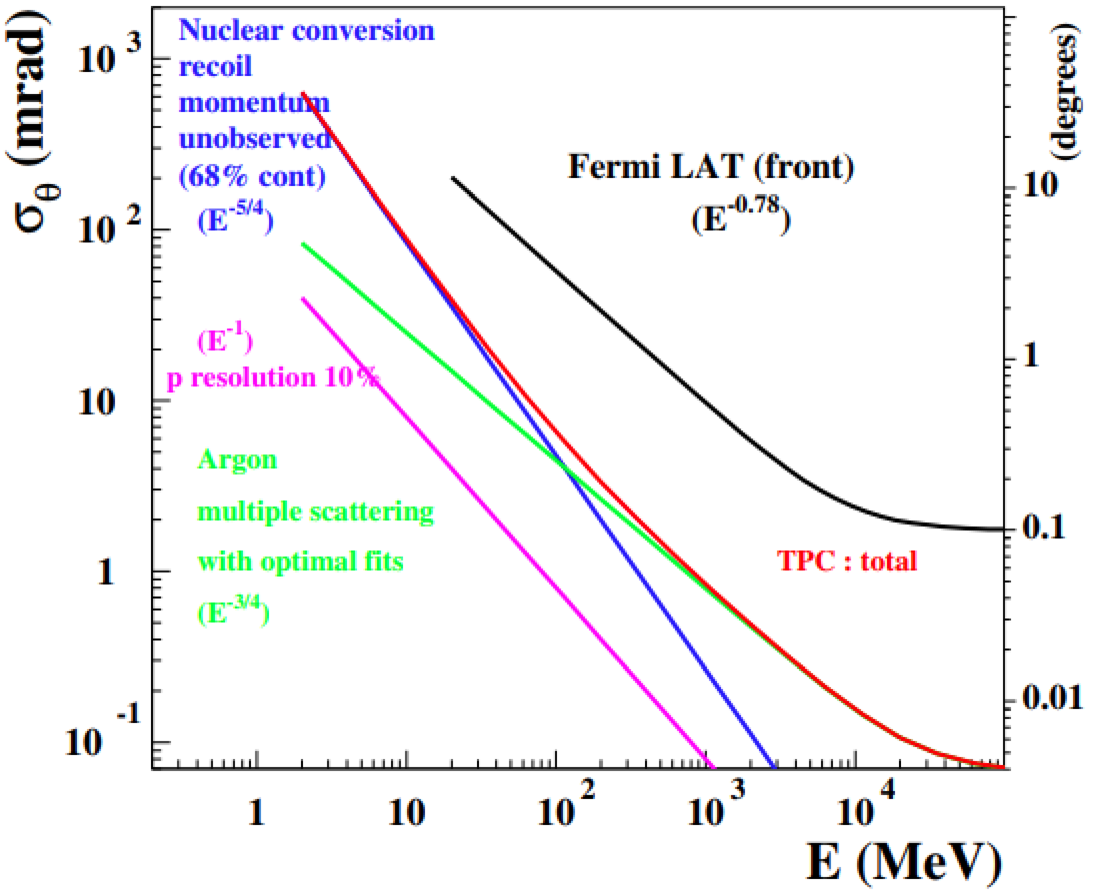


TPC Characteristics

- A gaseous 3D tracking detector
  - Often used in particle physics
  - High spatial resolution (<1mm), excellent tracking
  - Low multiple scattering => tracking even for low momentum tracks
- "Thin" active target
  - Sensitivity proportional to mass, not surface
  - Polarization information accessible

Expected Performance

- Angular resolution
  - limited by multiple scattering above 100MeV
  - limited by the unknown recoil nucleus momentum below 100MeV
  - only multiple scattering for triplet conversion, but very low efficiency
- Up to 1 order of magnitude better than Fermi!



D.B., NIM A 701 (2013) 225

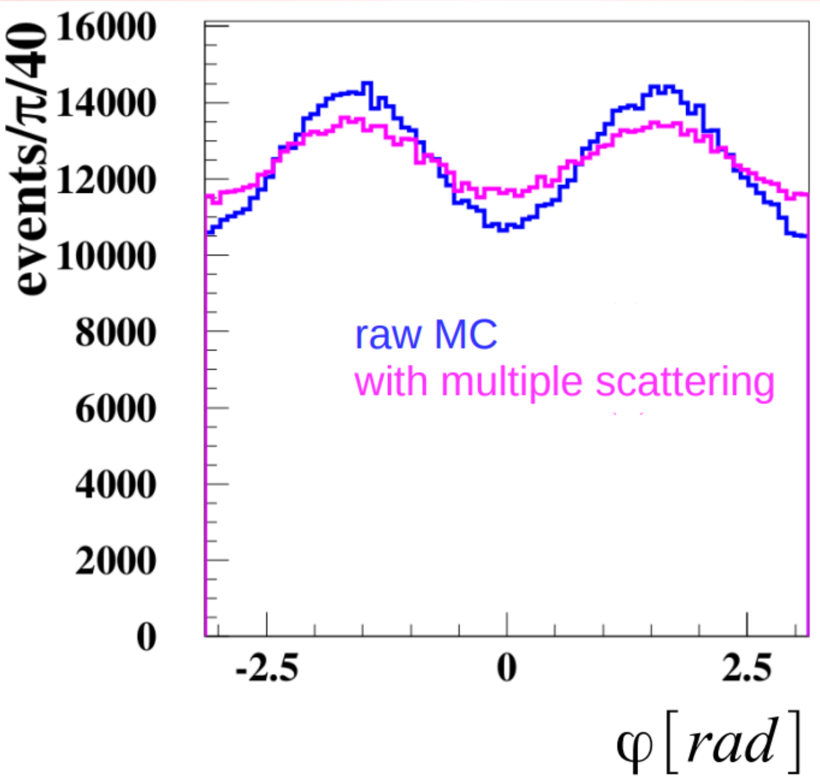
Polarimetry

- Polarimetry capabilities depend on many parameters:
  energy, exposure, detector size, gas pressure...
- Multiple scattering dilutes the polarization modulation
- In converters, it is very quickly lost
- In Argon at 5 bar:
  (resolution 1mm, $1m^3$,
  Crab-like, 1 year exposure, efficiency=1)
- Polarization asymmetry A~15%
- Polarization resolution ~ 1%

Differential conversion interaction rate in detector:

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

A: polarization asymmetry
P: polarization fraction



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The HARPO Project

- HARPO (Hermetic ARgon POlarimeter)
- Instrument in France

Denis Bernard, Philippe Bruel, Mickael Frotin, Yannick Geerebaert, Berrie Giebels, Philippe Gros, Deirdre Horan, Marc Louzir, Frédéric Magniette, Patrick Poilleux, Igor Semeniouk, Shaobo Wang [a]
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[b]IRFU, CEA Saclay, France

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- Beam test in Japan

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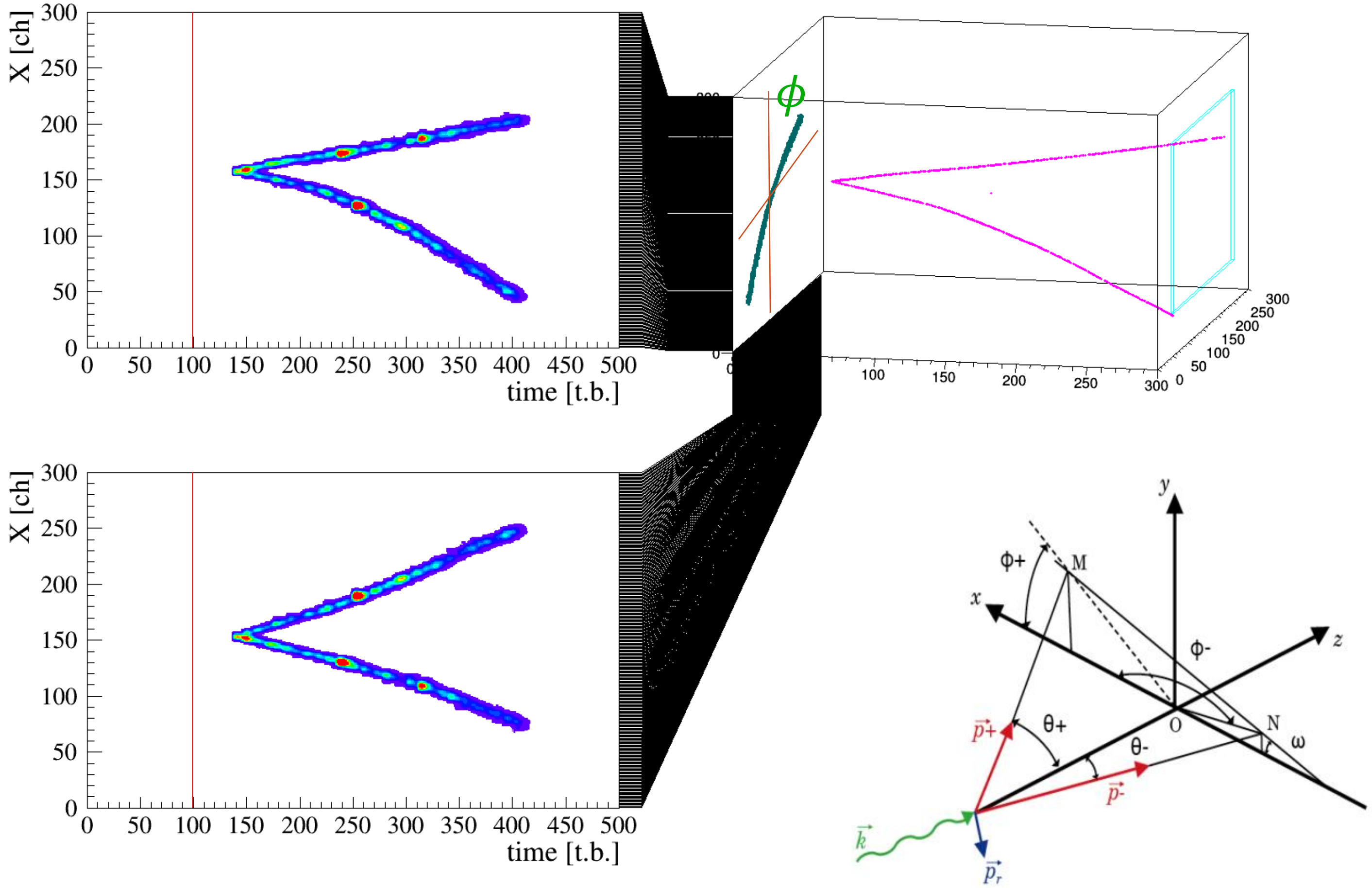
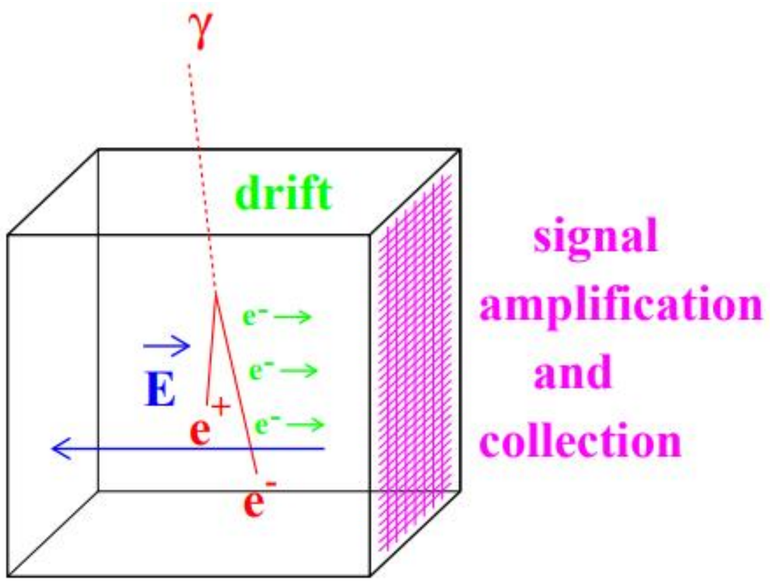
The HARPO Project

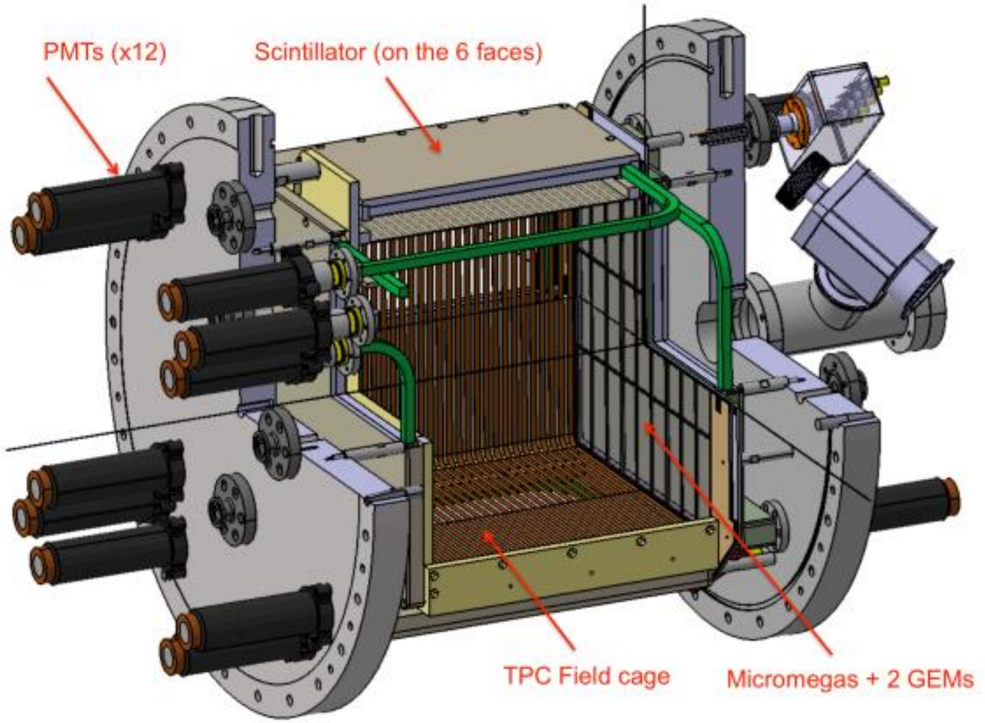
- High angle resolution and sensitivity telescope
- Polarimeter for studying cosmic gamma ray sources above MeV



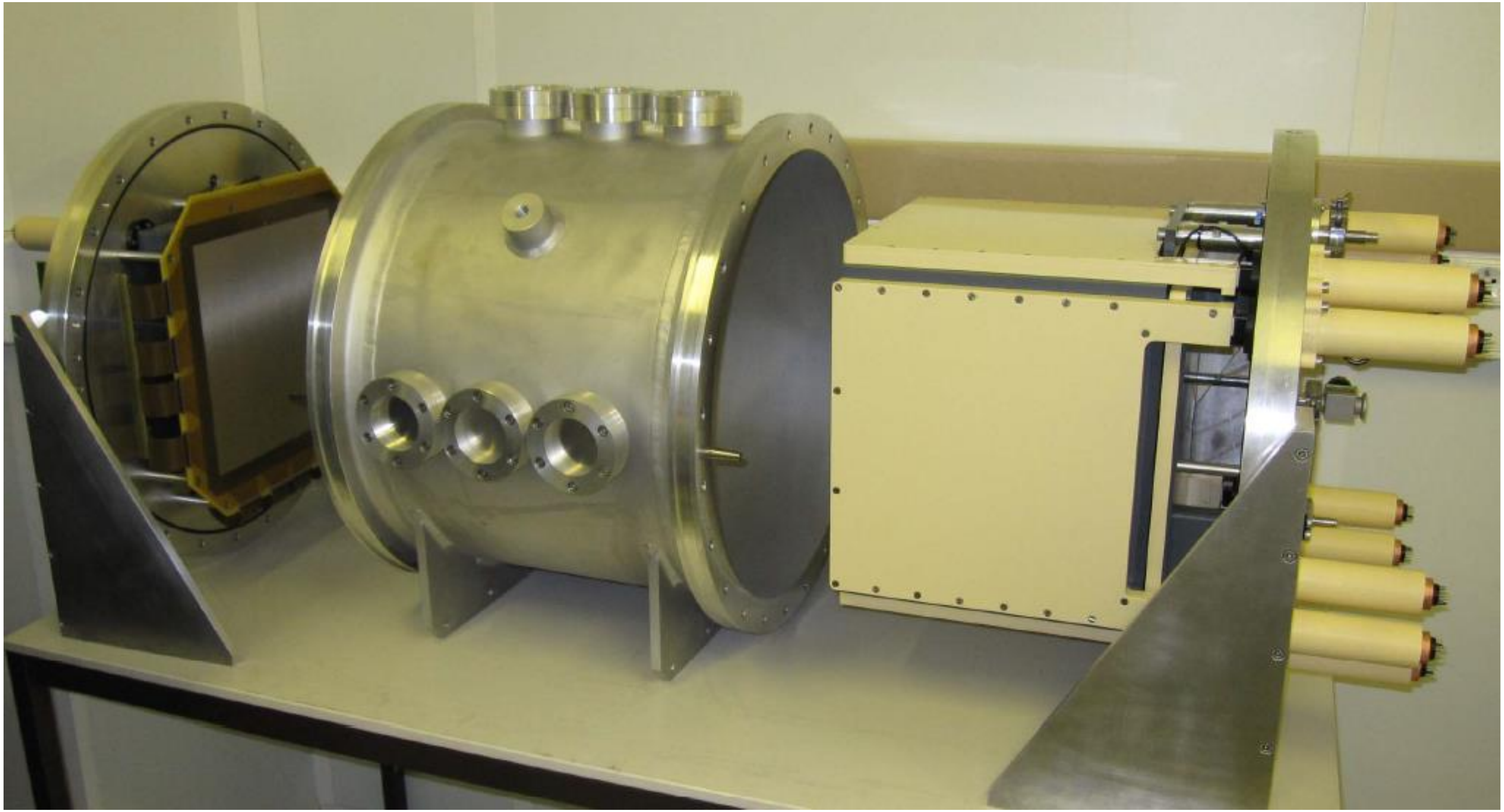
The HARPO Demonstrator

- Purpose: Assess challenges and demonstrate performance in test beam
- $(30cm)^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on x, y strips, pitch 1 mm.
- AFTER chip digitization, up to 100 MHz.
- Scintillator / WLS / PMT based trigger



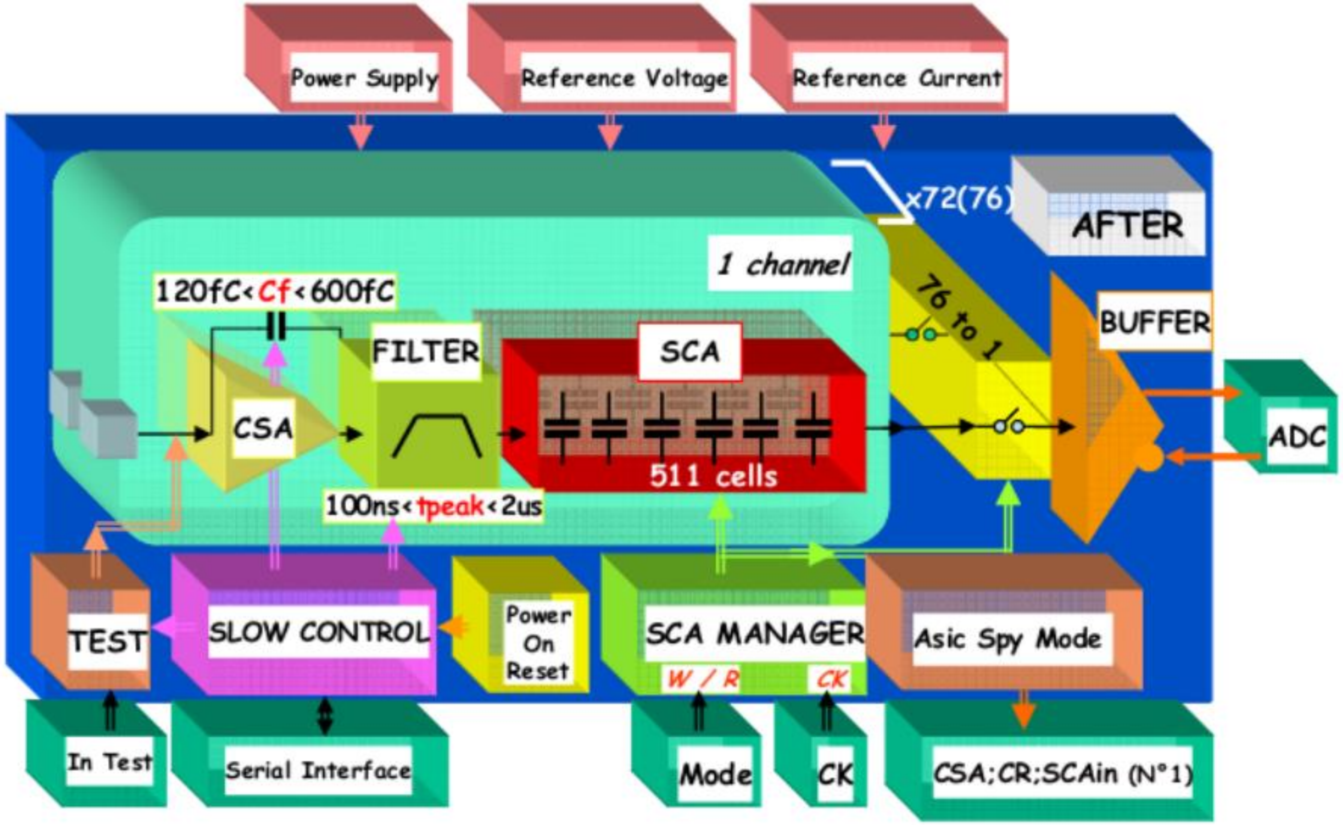


The HARPO Demonstrator

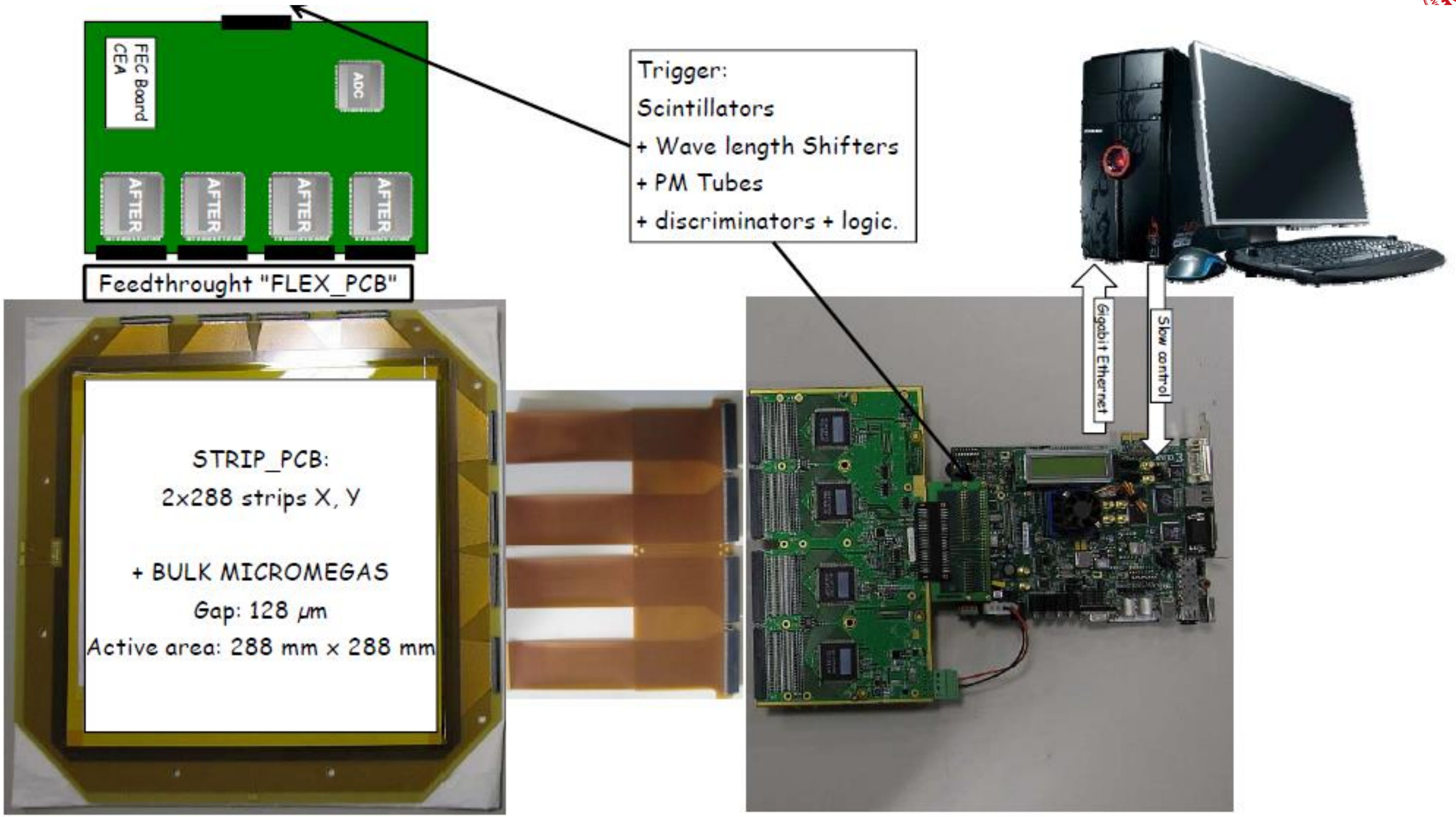


Readout electronics

- Based on T2K front – end (AFTER chip) and ML507：
  - 2 directions x, y, 288 strips (channels) / direction
  - 72 channels /chip
  - 4 chips / direction
  - 511 time bins, “circular” SCA (Switched Capacitor Array)
  - Input: 120 fC to 600 fC
  - Up to 100 MHz sampling
  - Shaping time 100 ns to 2 µs
  - 12 bit ADC.



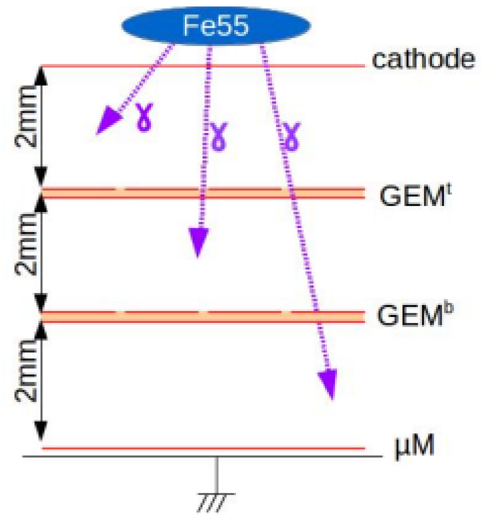
Signal readout

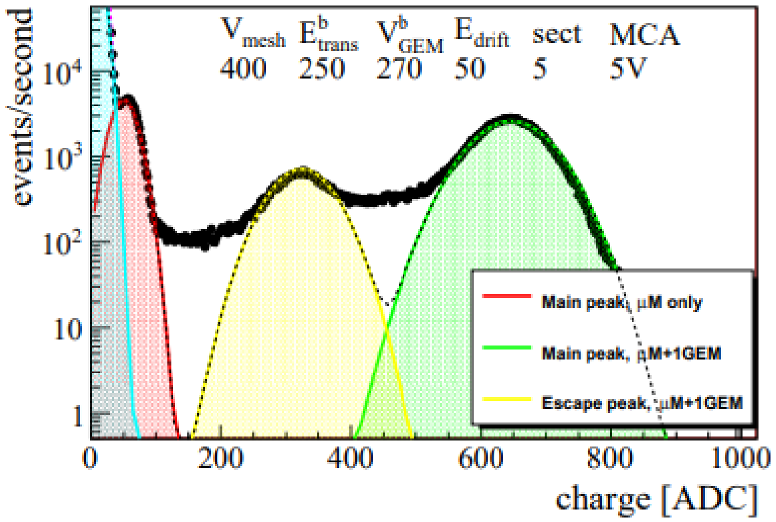


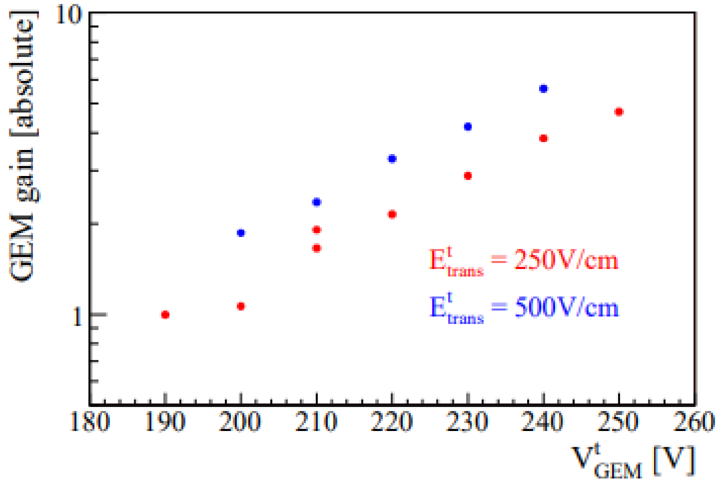
Yannick Geerebaert LLR, École Polytechnique, CNRS, IN2P3 Palaiseau France

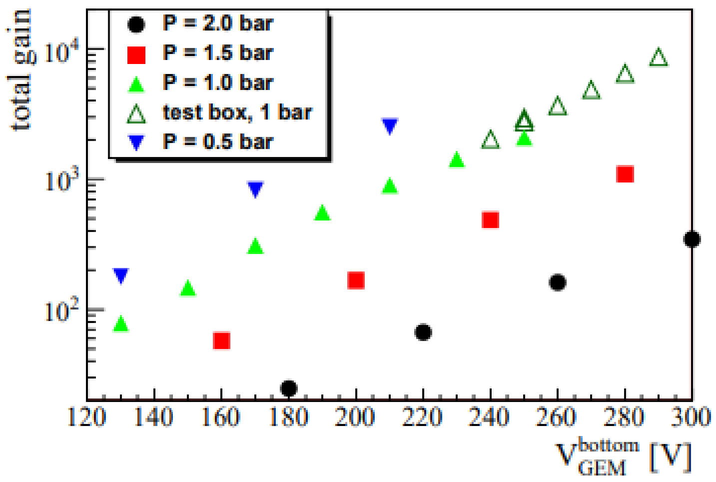
Gas amplification: micromegas + 2 GEM

- Decision was made to add a GEM stage on top of the Micromegas, to obtain a comfortable gain (x7) while keeping good stability
- ^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)







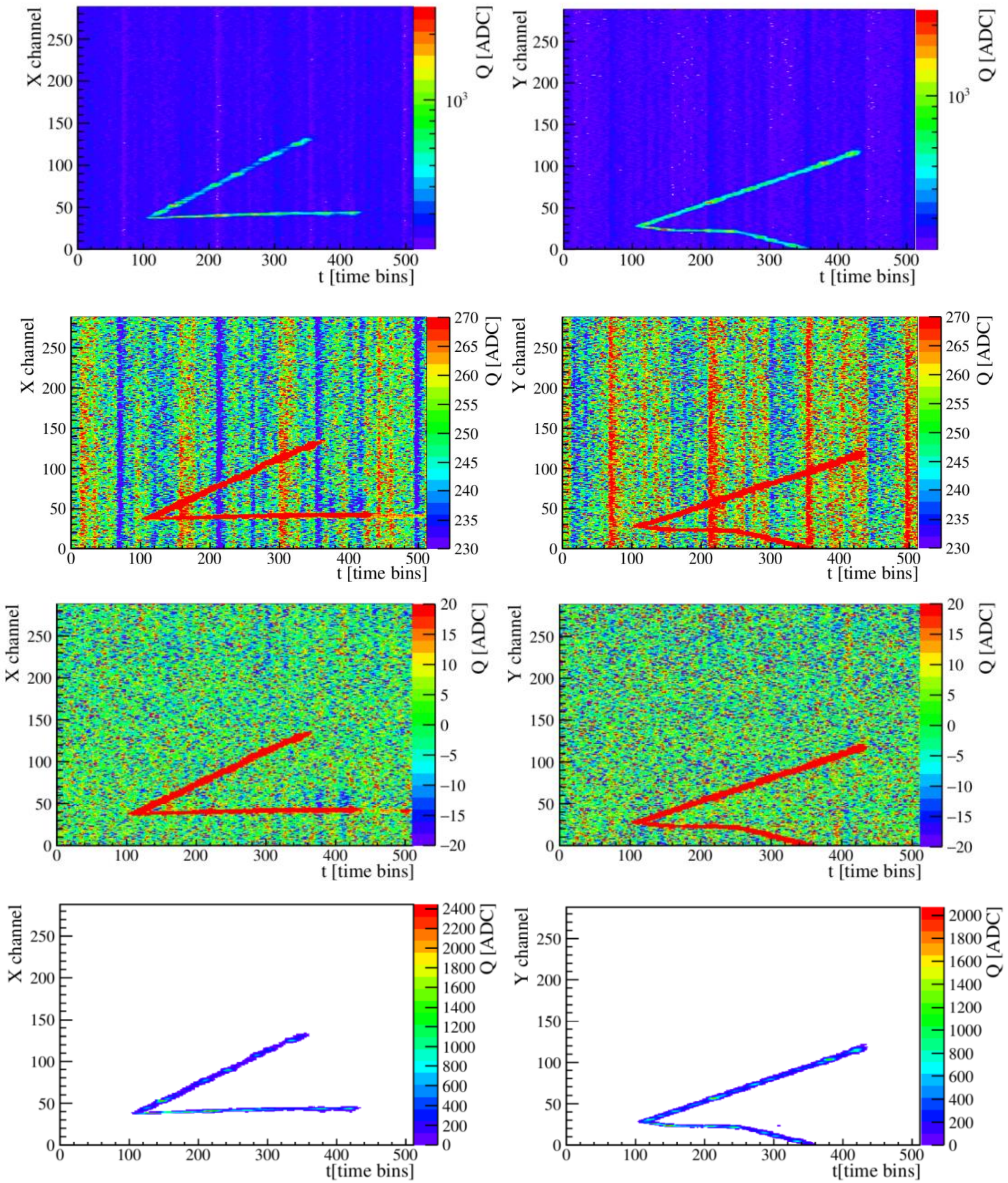


PoS(TIPP2014)133

Cosmic Ray Test

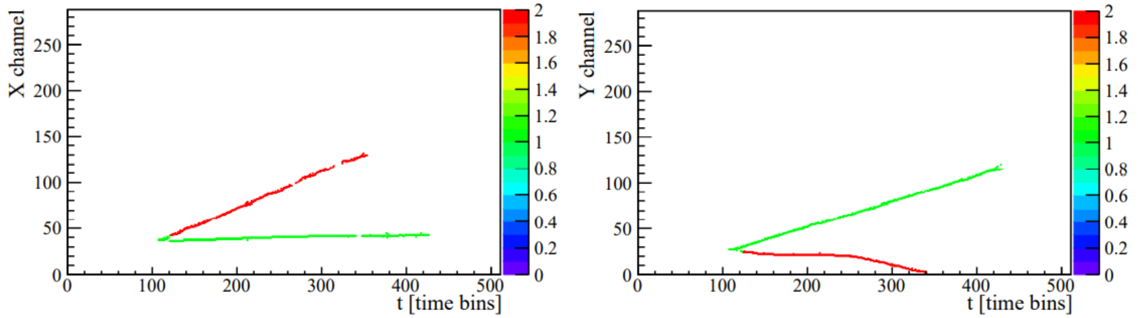
- Simple scintillator coincidence trigger
  - top/bottom coincidence
- Pressure from 0.5 to 2 bar Ar-5%Iso
- Two planes readout
  - X and Time (Z)
  - Y and Time (Z)
- Track reconstruction and matching

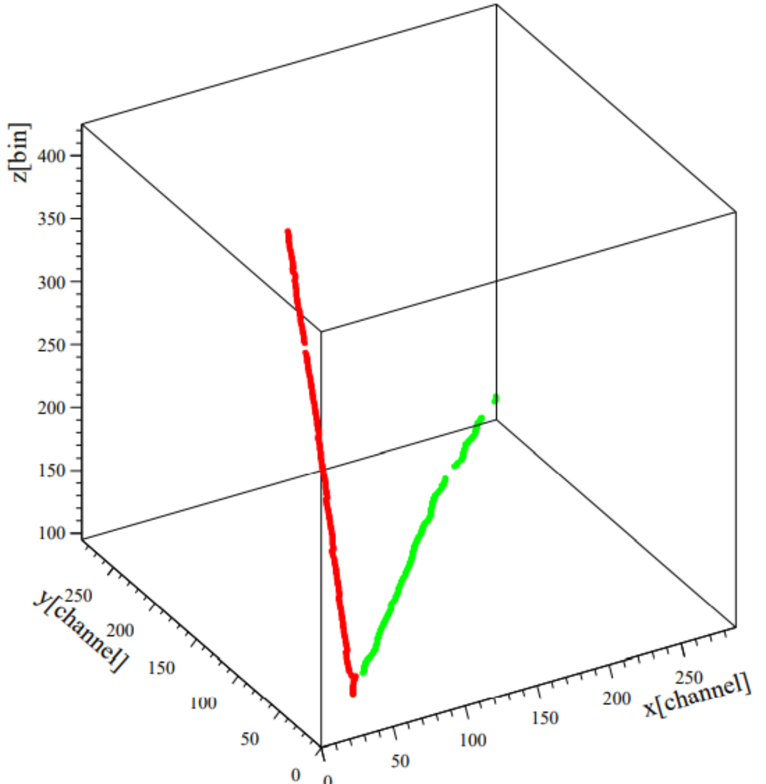
Data taking and Track Reconstruction



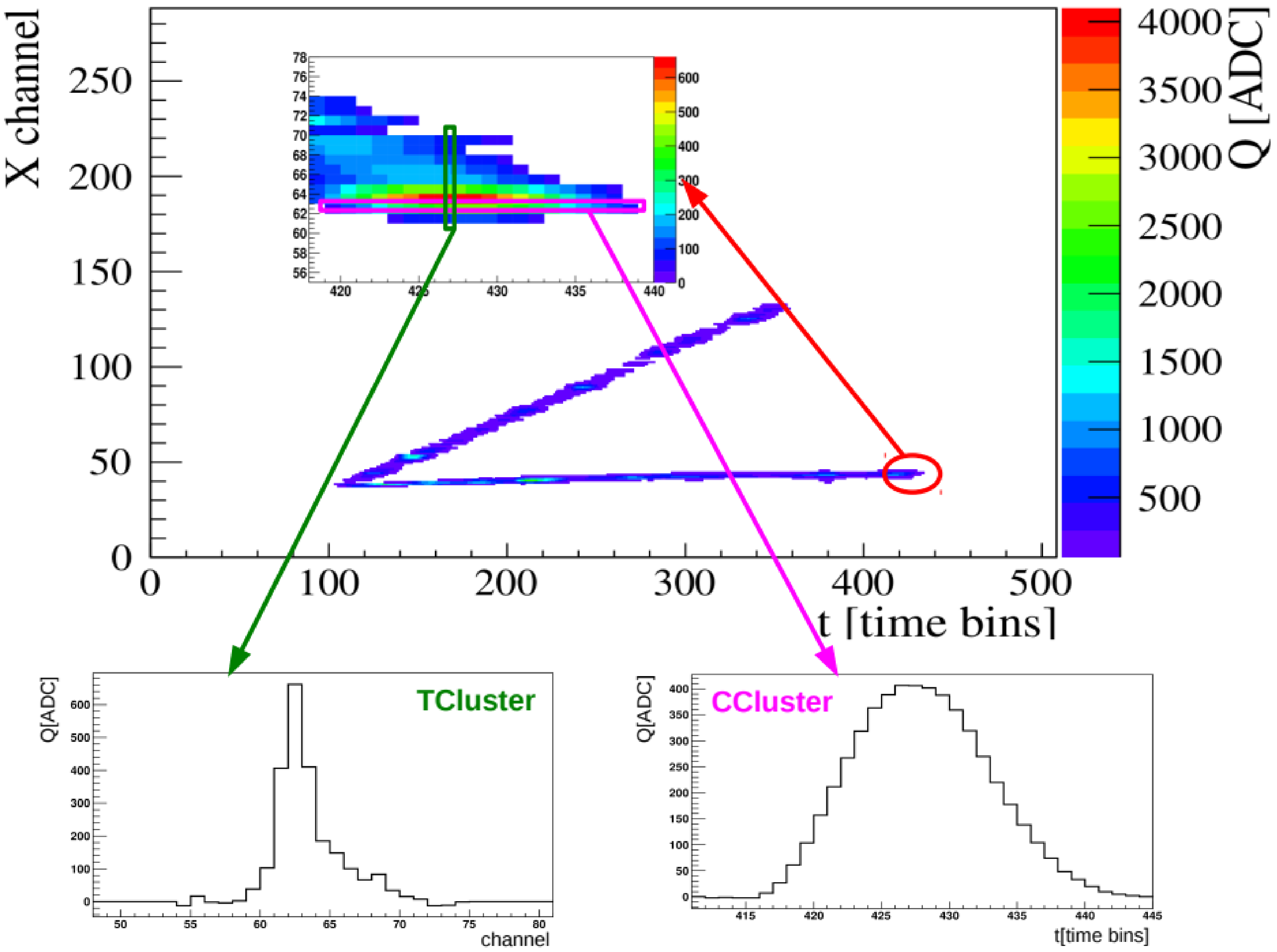
Signal selection

3D track reconstruction

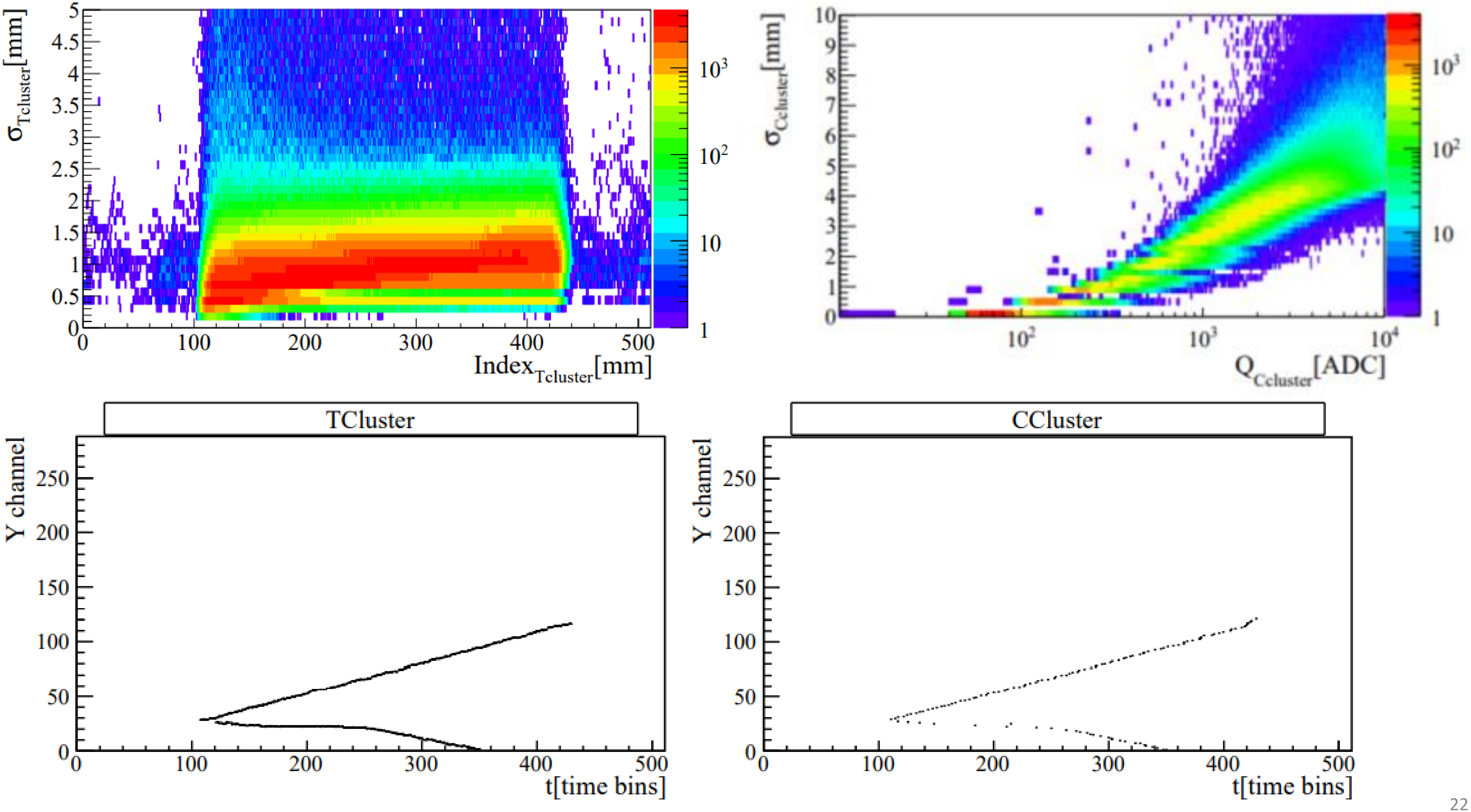




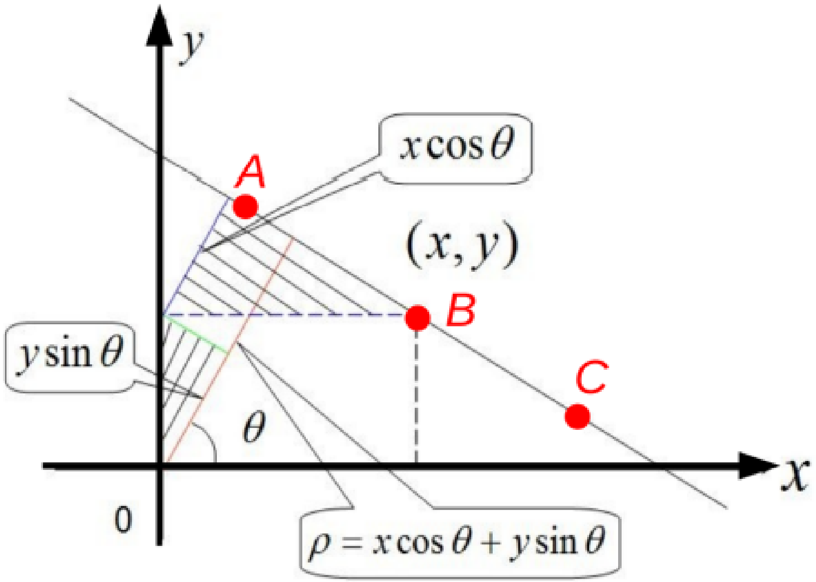
Track reconstruction： Clustering

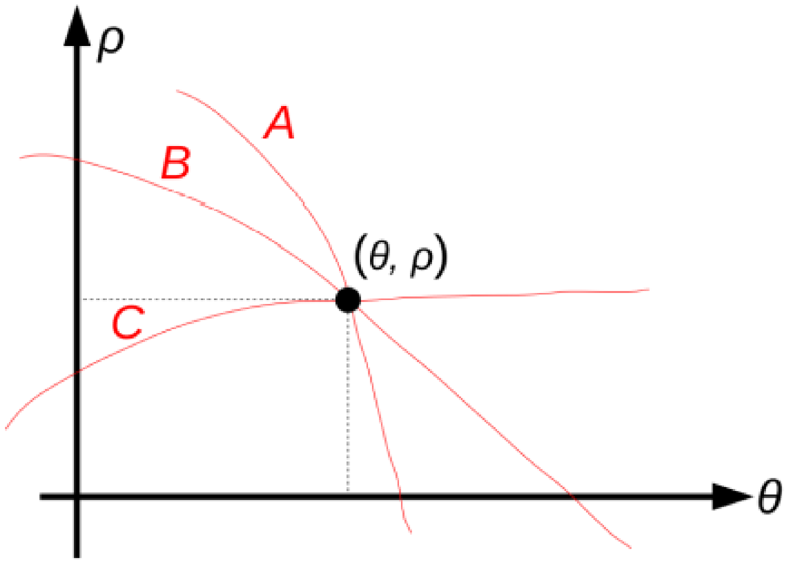


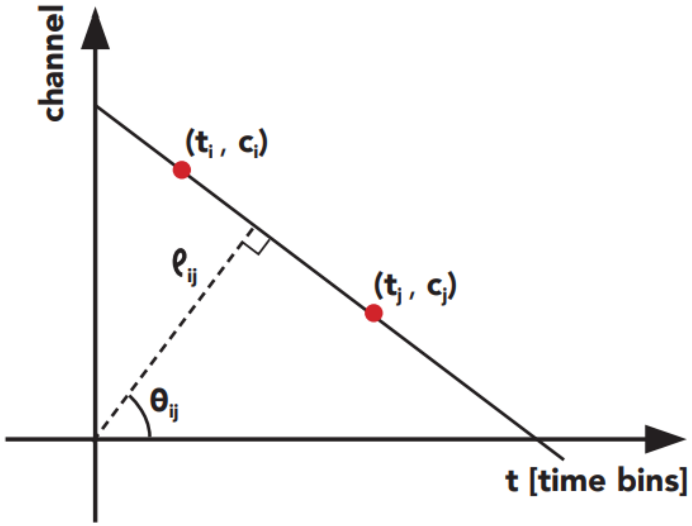
Track reconstruction： Clustering



Hough track finding in 2D





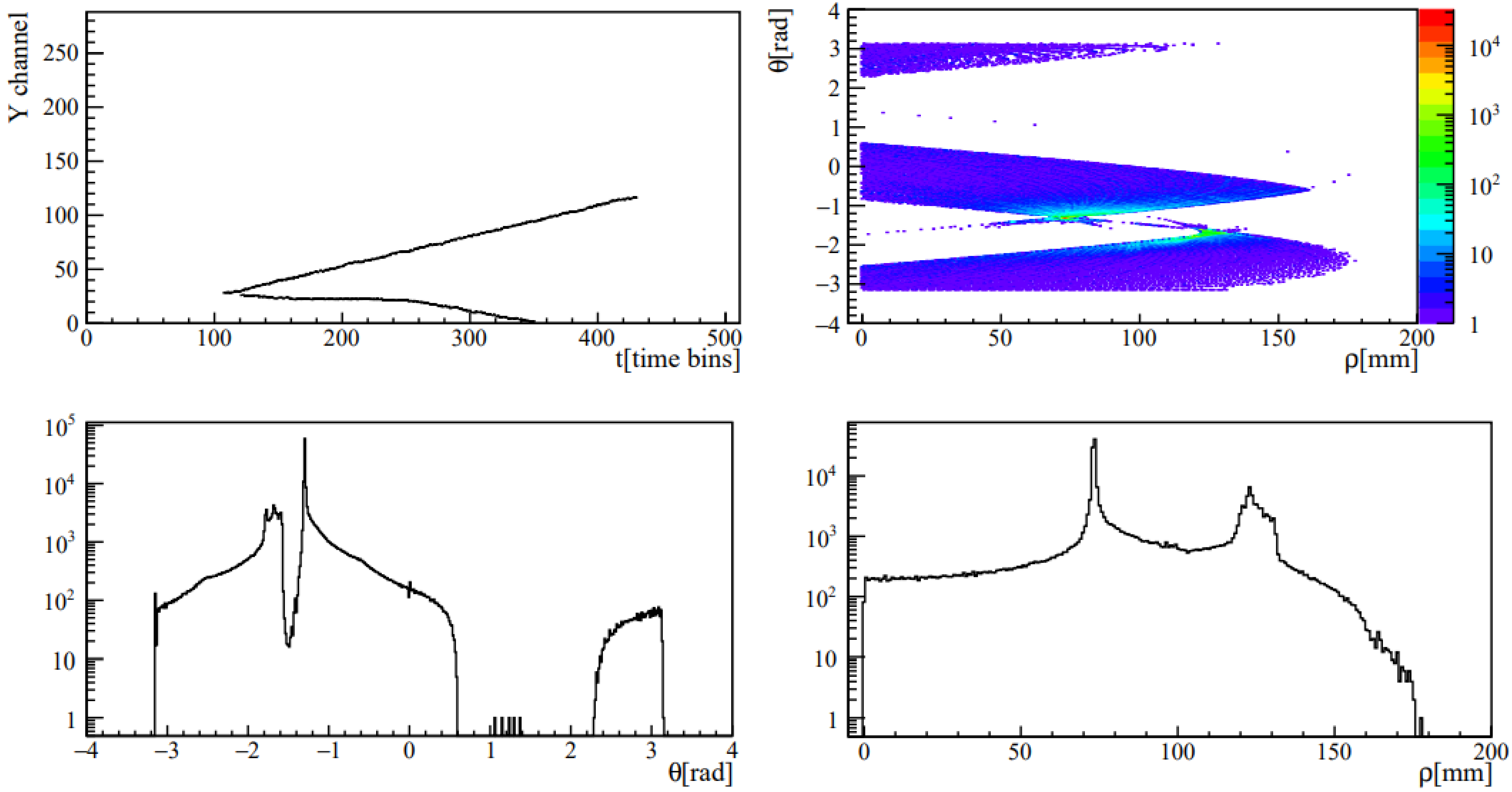


$$d_{ij} = \sqrt{(c_i - c_j)^2 + (t_i - t_j)^2}$$

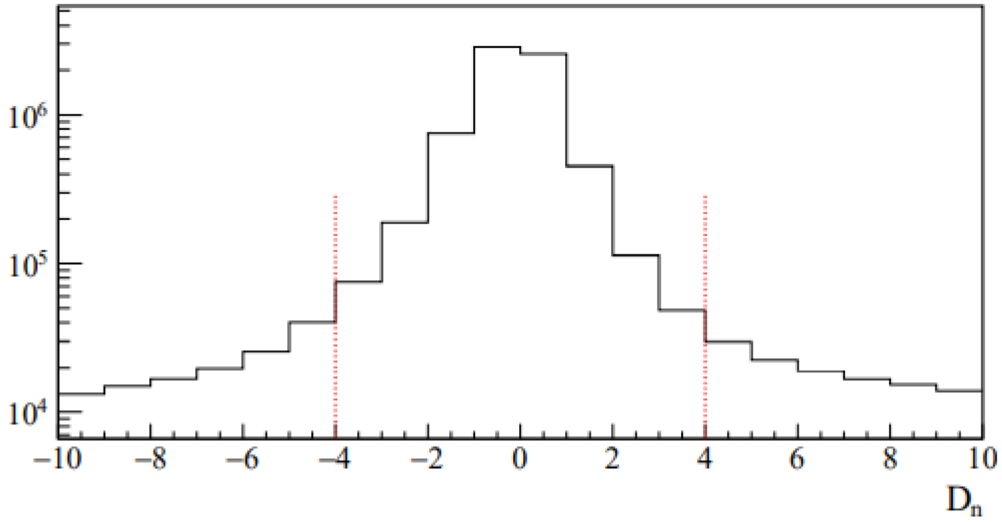
$$\rho_{ij} = \frac{c_i \times t_j - c_j \times t_i}{d_{ij}}$$

$$\theta_{ij} = \mathrm{atan2}(t_j - t_i, c_j - c_i)$$

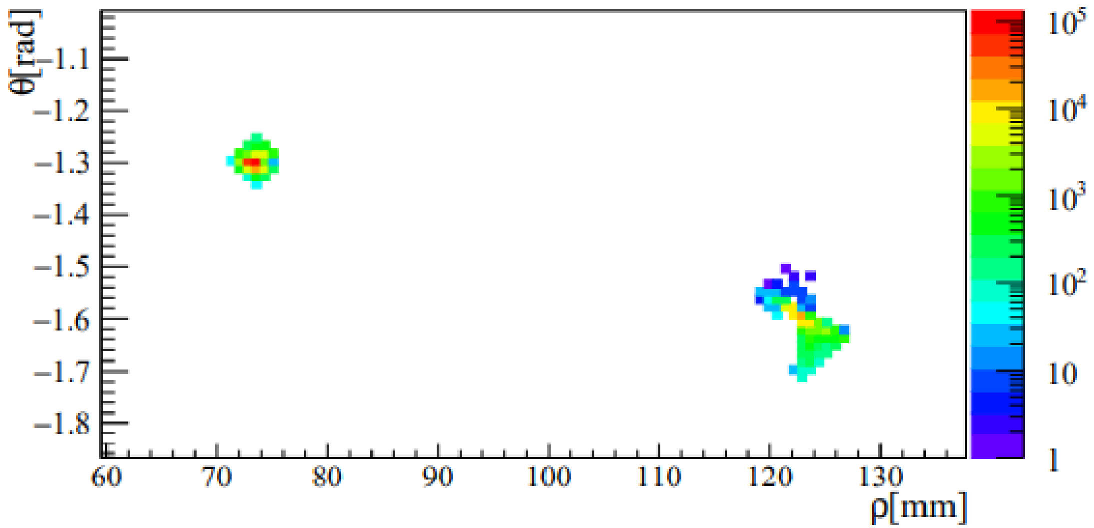
Hough track finding in 2D

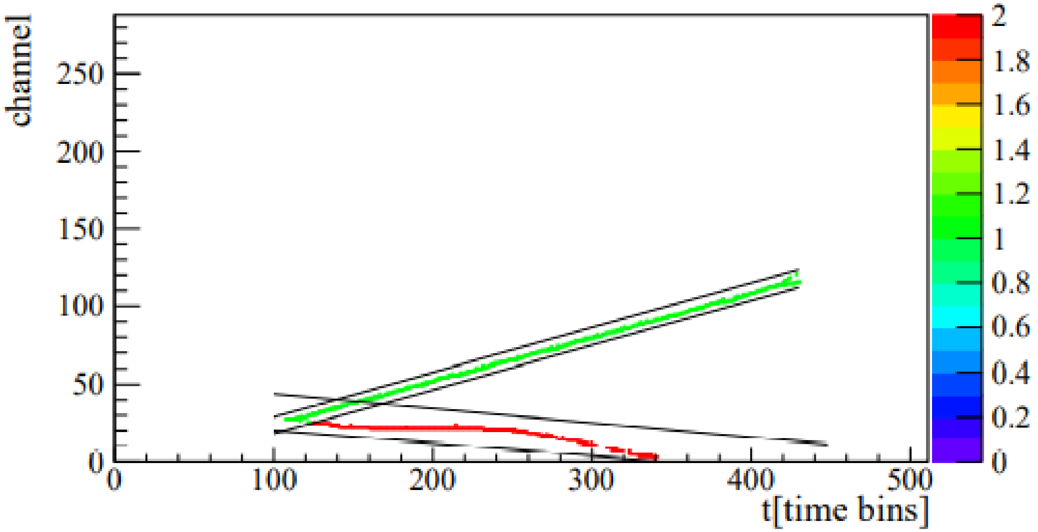


Hough track finding in 2D

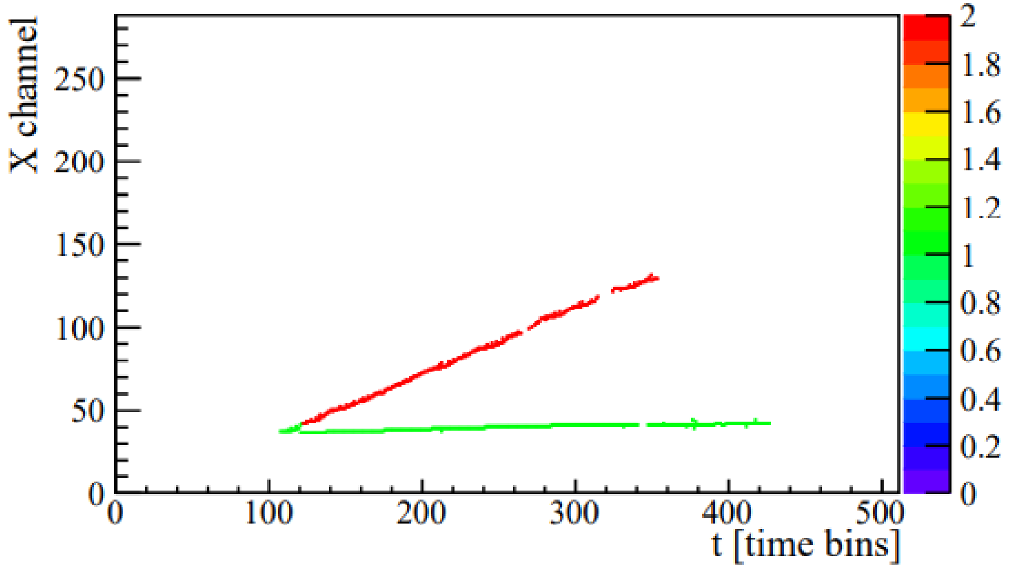


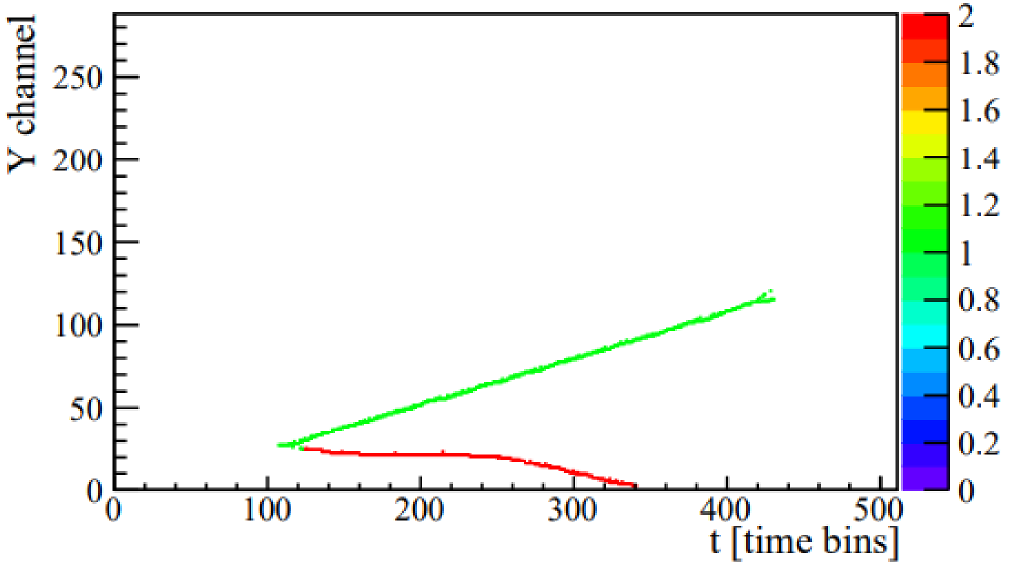
- A Dn is needed to select (θ, ρ)
- All the clusters within the “road” are classified in the track
- The rest clusters are used to find the 2nd track

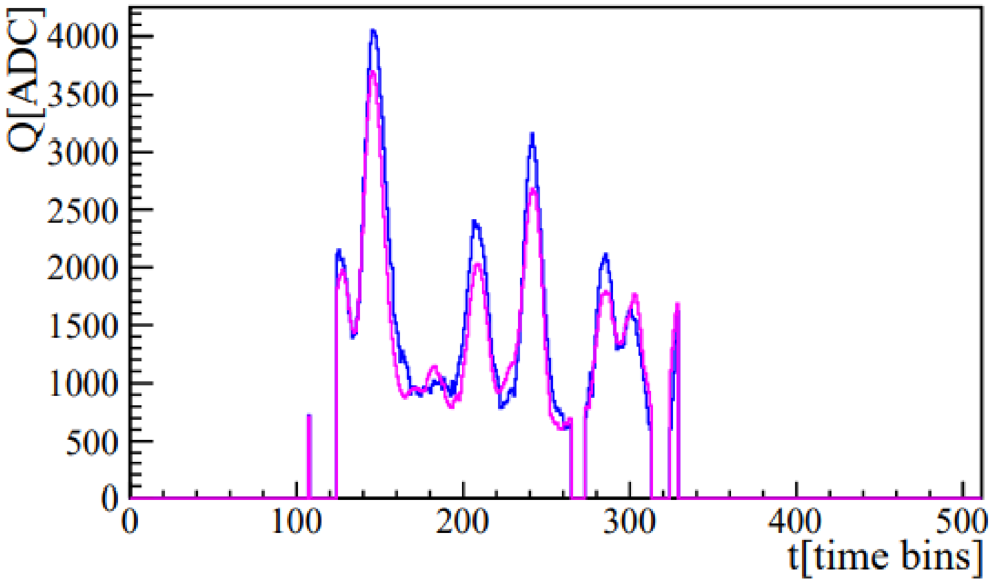


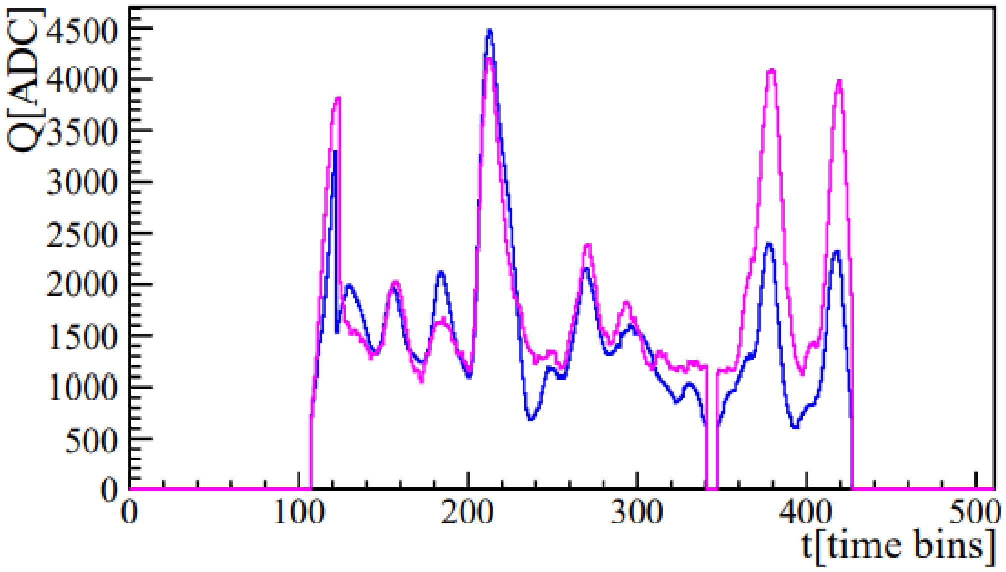


XZ&YZ track marching

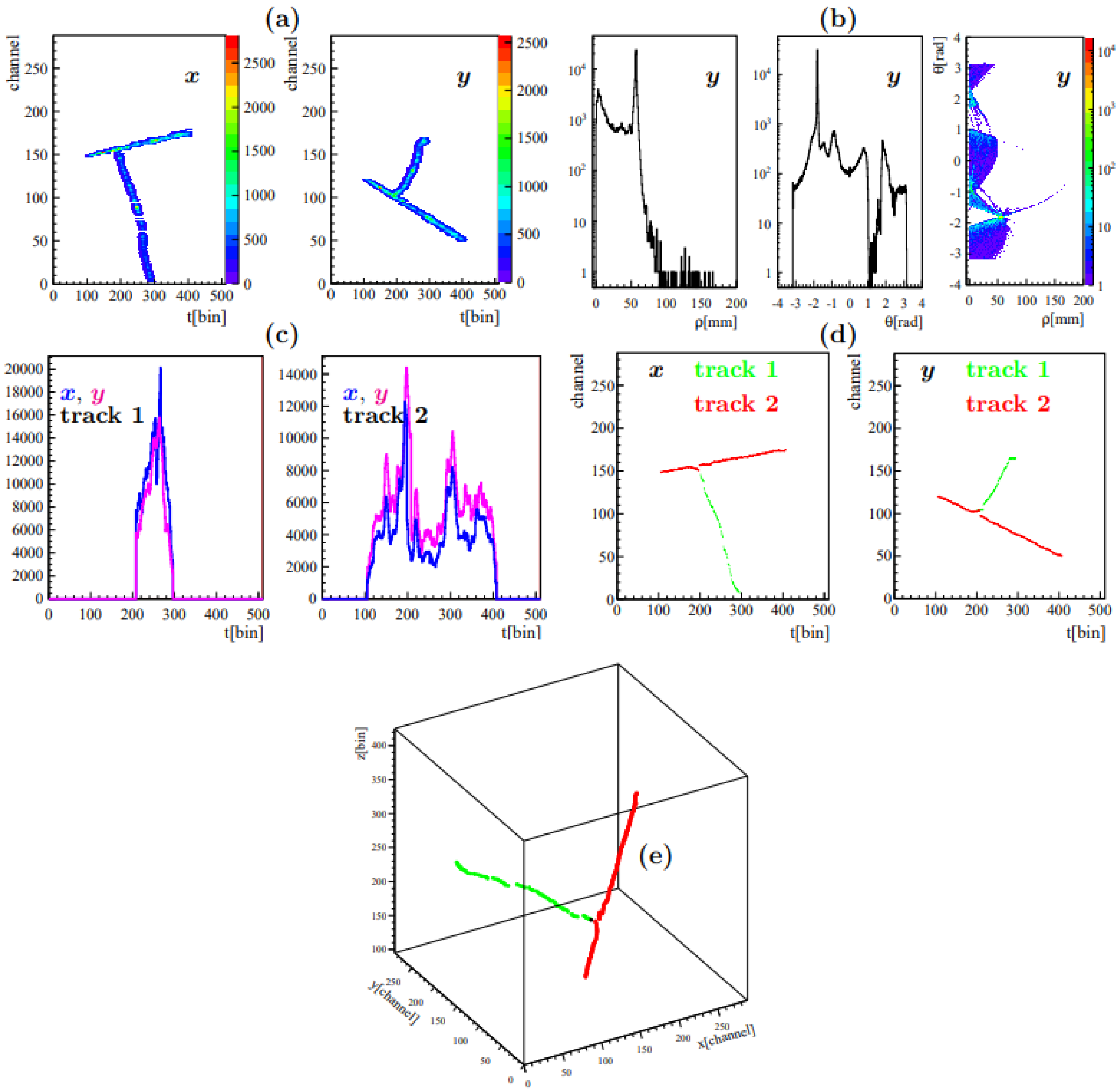


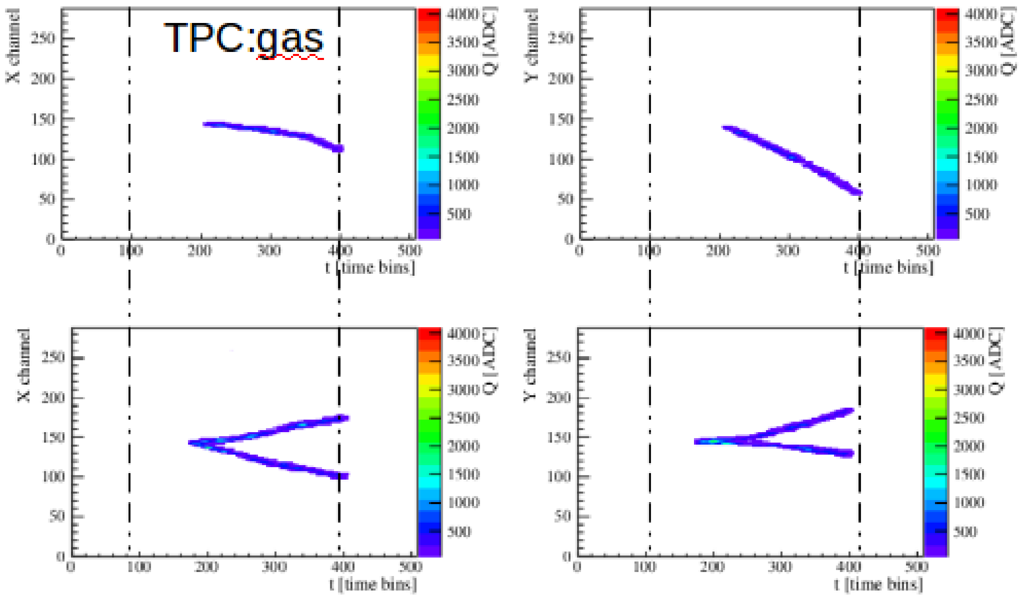


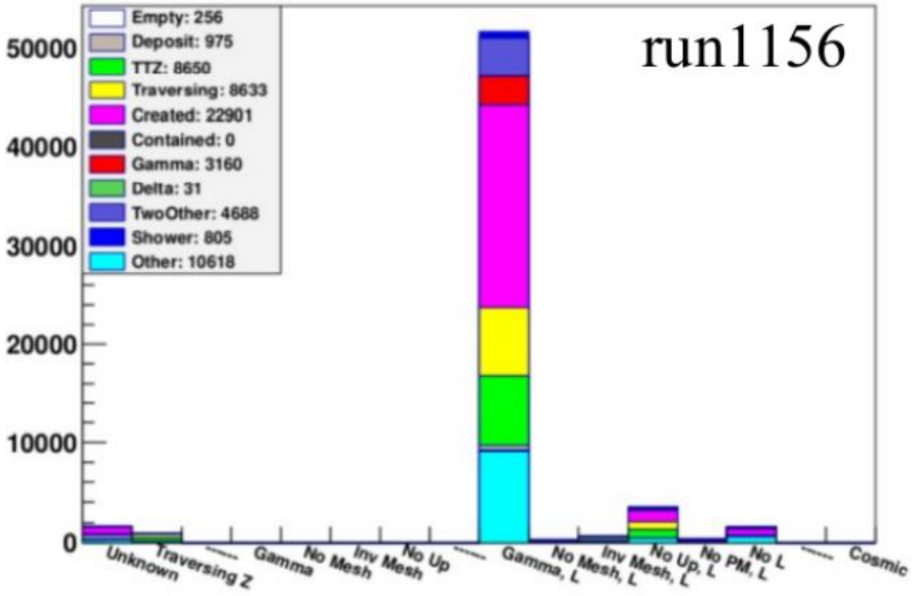




Track reconstruction

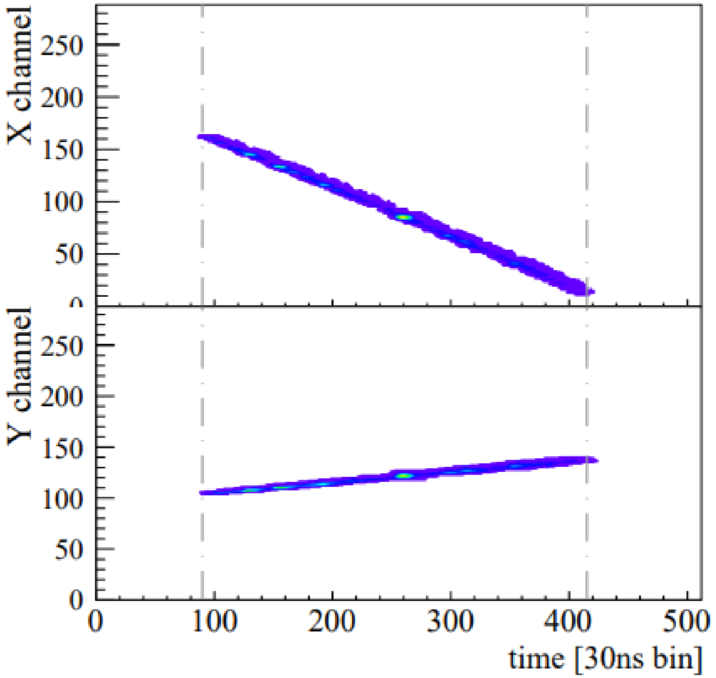


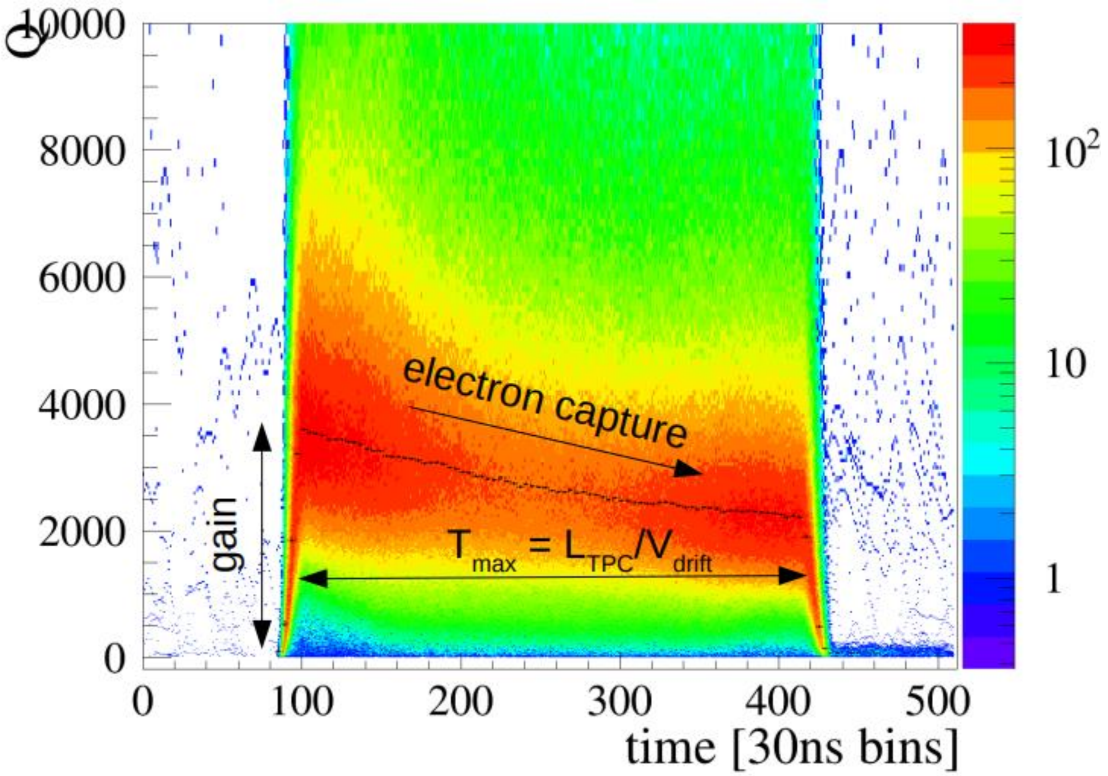




Diagnostics: Q vs T_{drift} with muon track

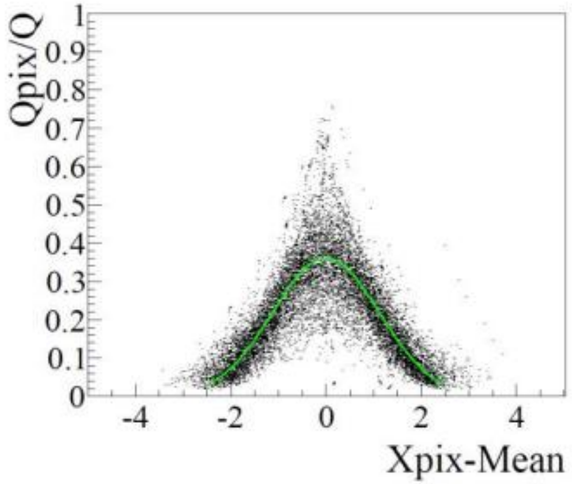
- The charge is normalized with regard to the track angle
- Normalized charge as a function of the drift time for a 6000 s cosmic-ray run
- V_{drift} is also easily extracted from this plot

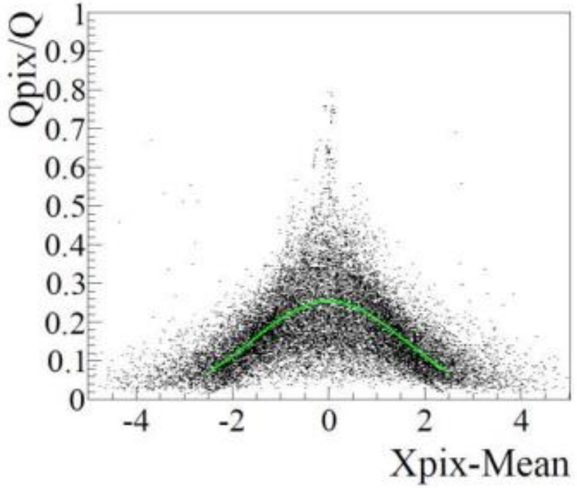


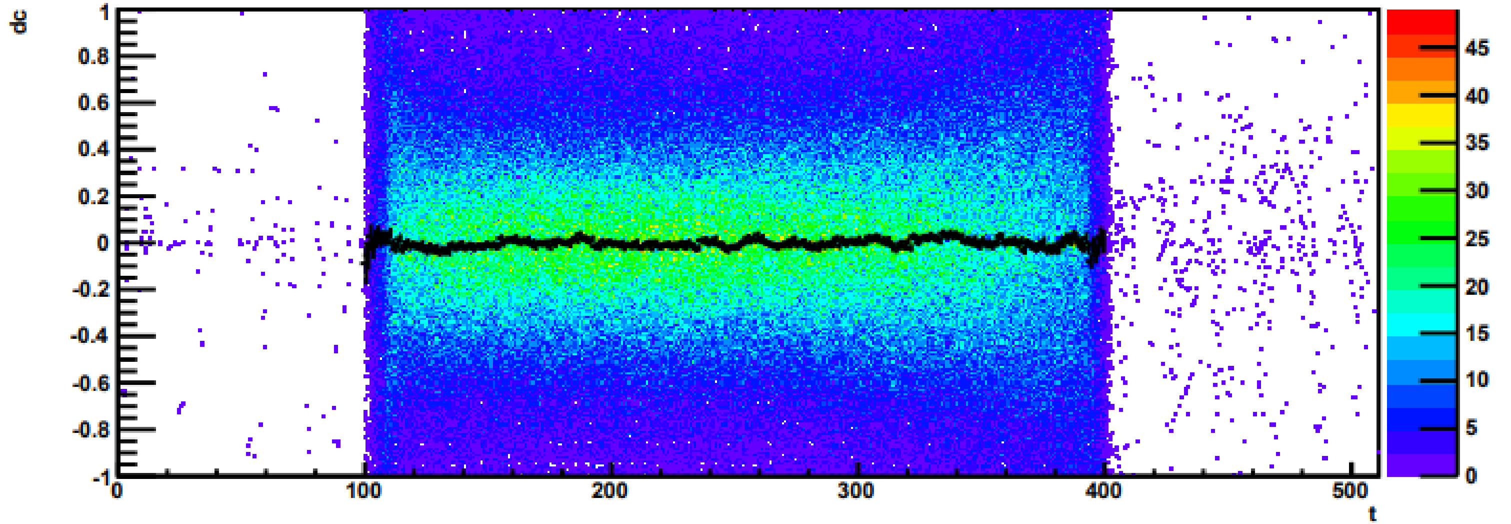


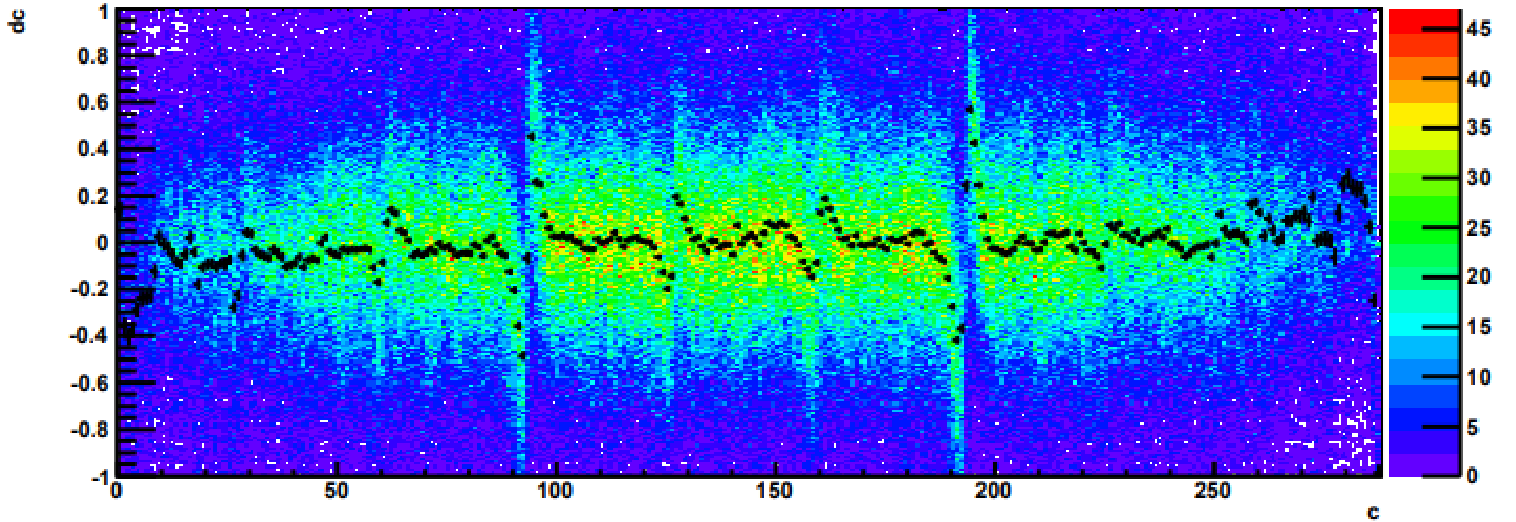
Characterization with traversing cosmic rays

- Electric field distortion in the TPC
- Diffusion effect study



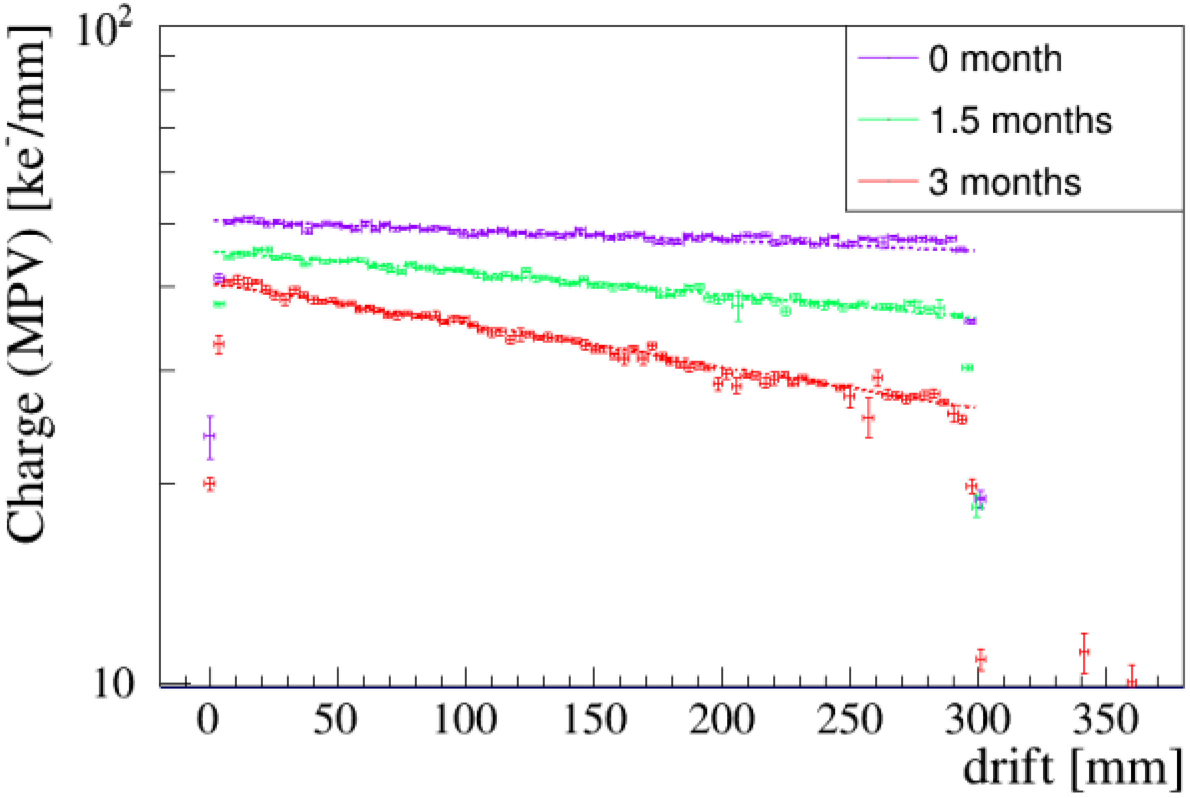






Cosmic runs @LLR

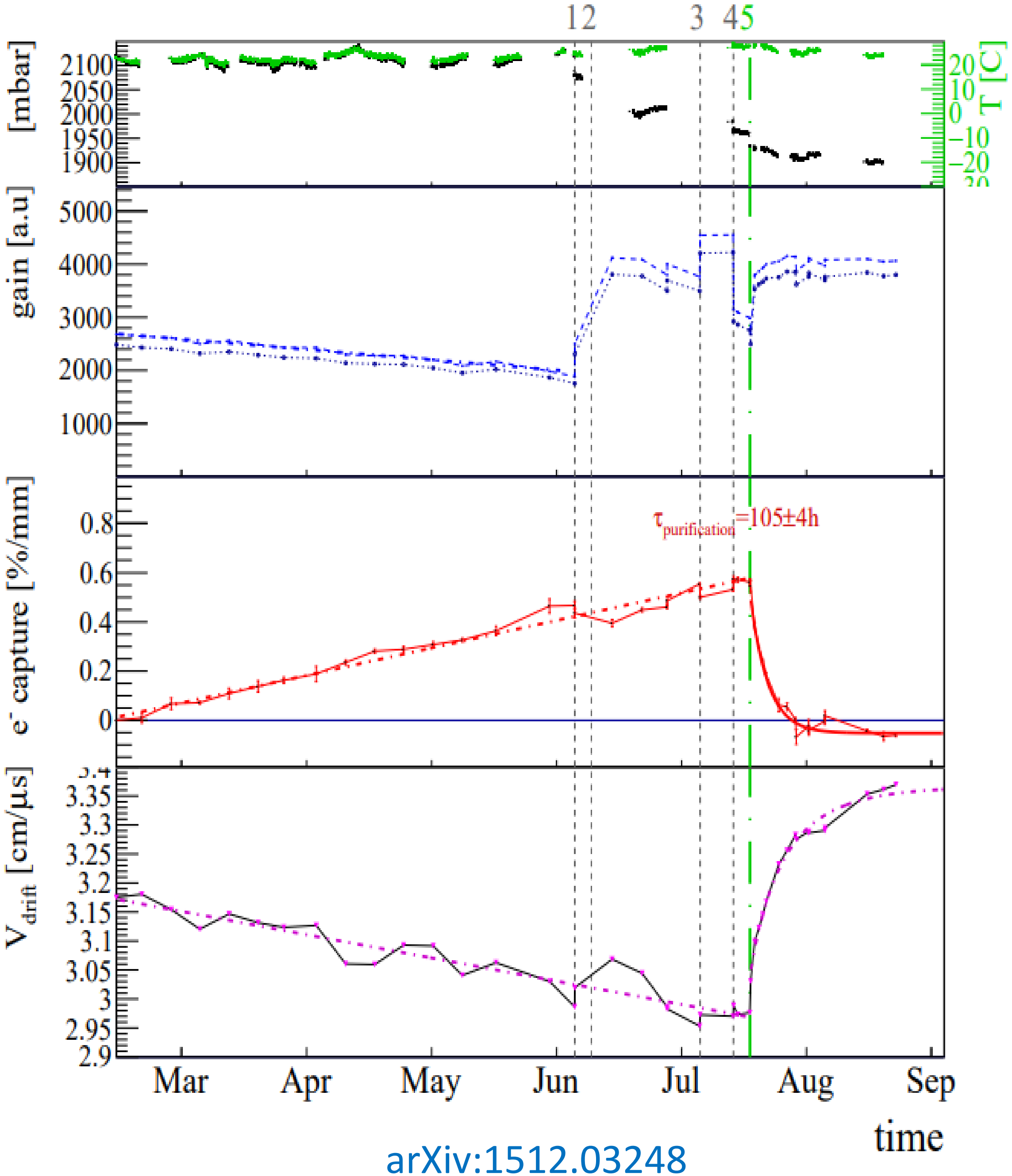
- Relative measurements – First run as reference ("clean gas")
- HV on all the time, data taking at regular interval , weekly data taking of ~1.5h, for 6 months
- Clear degradation of gain and e- capture



Gas stability

- Recovery of full performance after 6 month sealed
- Detector not optimized for outgassing

Sample # Compound		1 July 08	2 Aug. 27	3 Sept. 17
iC_4H_{10}	%	5.10	4.42	4.49
O_2	ppm	180	<20	<20
CO	ppm	190	250	130
CO_2	ppm	120	160	130
N_2	ppm	620	890	850



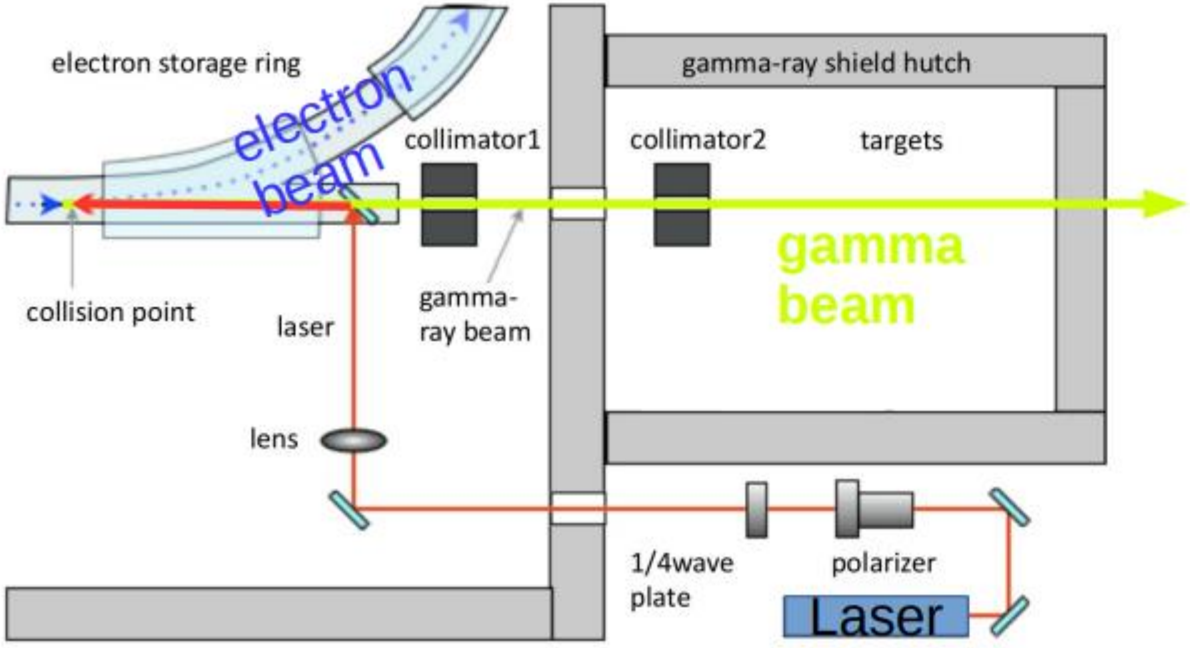
arXiv:1512.03248

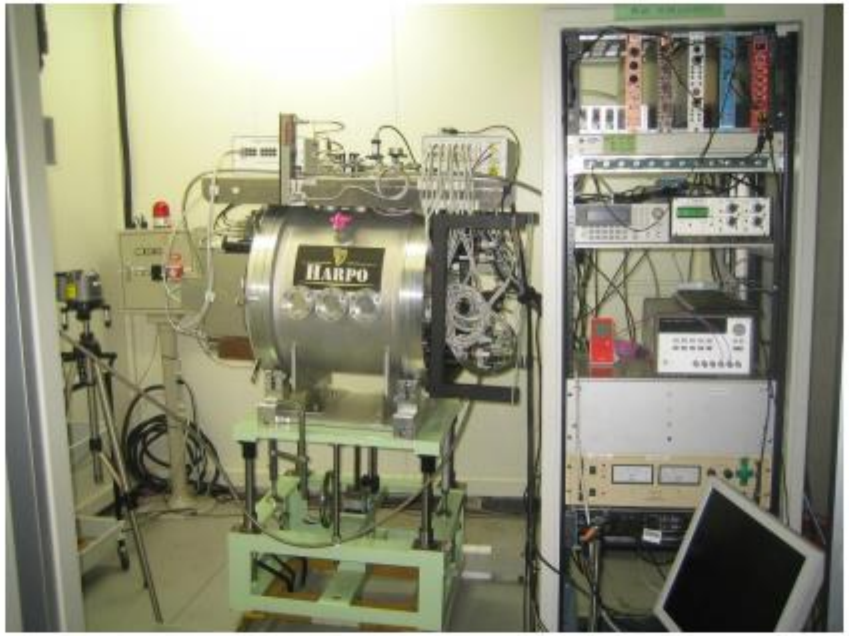
Photon beam test in NewSUBARU

- Polarized gamma ray beam
  - Inverse Compton
  - electron beam 0.6, 1., 1.2 or 1.5 GeV
  - laser Nd (1ω or 2ω), Er or CO_2 →polarized photons 1.71 to 74 MeV
- Pulsed mode
  - Nd: 20kHz, Er:200kHz, CO_2: not

Measurement in polarized photon beam

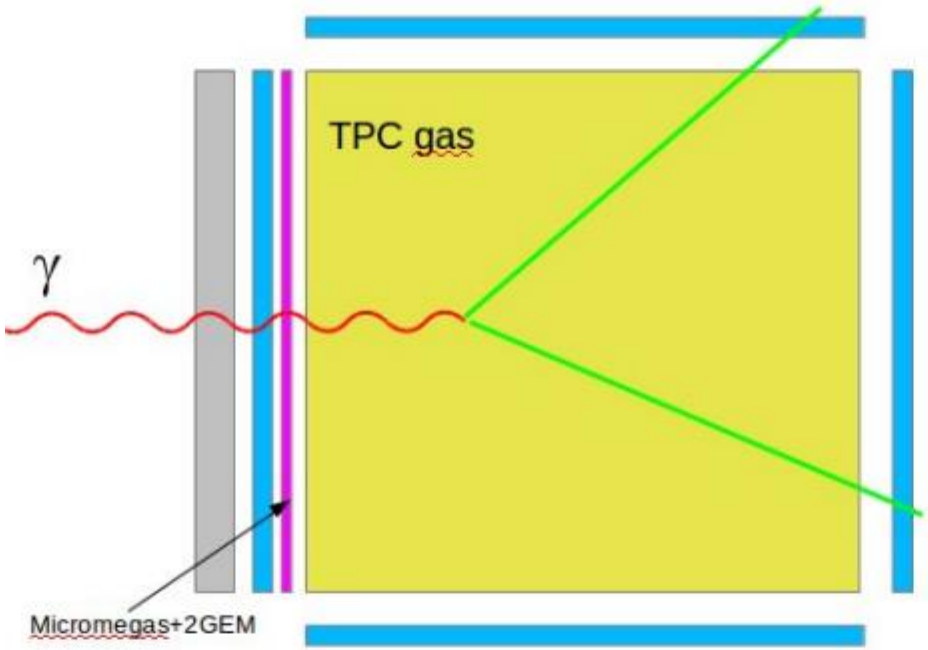
- 13 Energy points, 1.7 to 74MeV, ~60Mevents
- Monochromaticity by collimation on axis
- Fully polarized or random polarization beams (P = 0, P = 1)
- 2.1 bar Ar:isoC4H10 95:5 (1-4 bar scan)



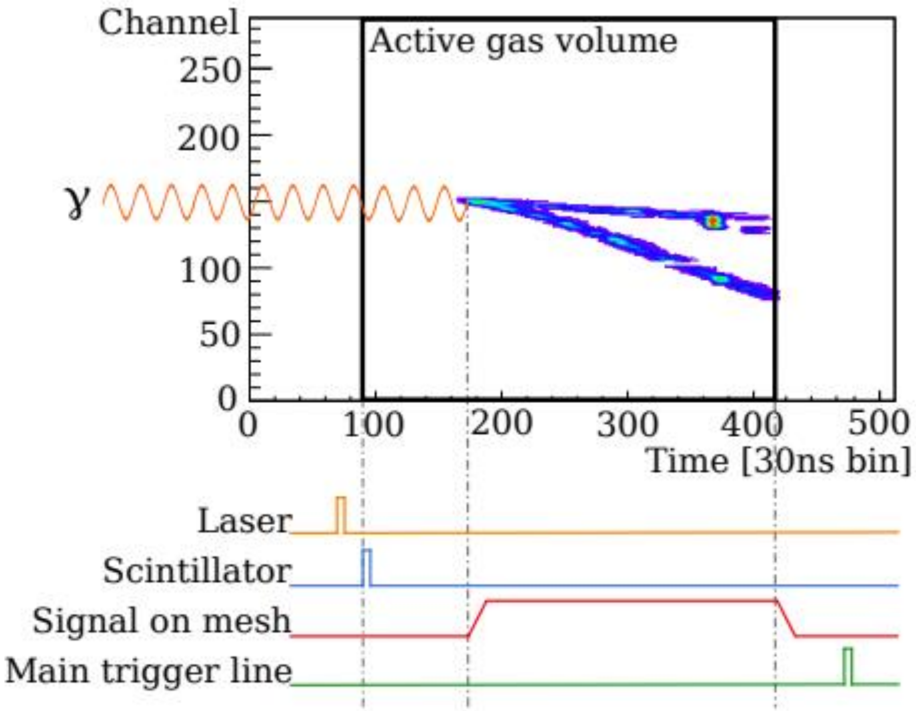


Beam trigger system

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

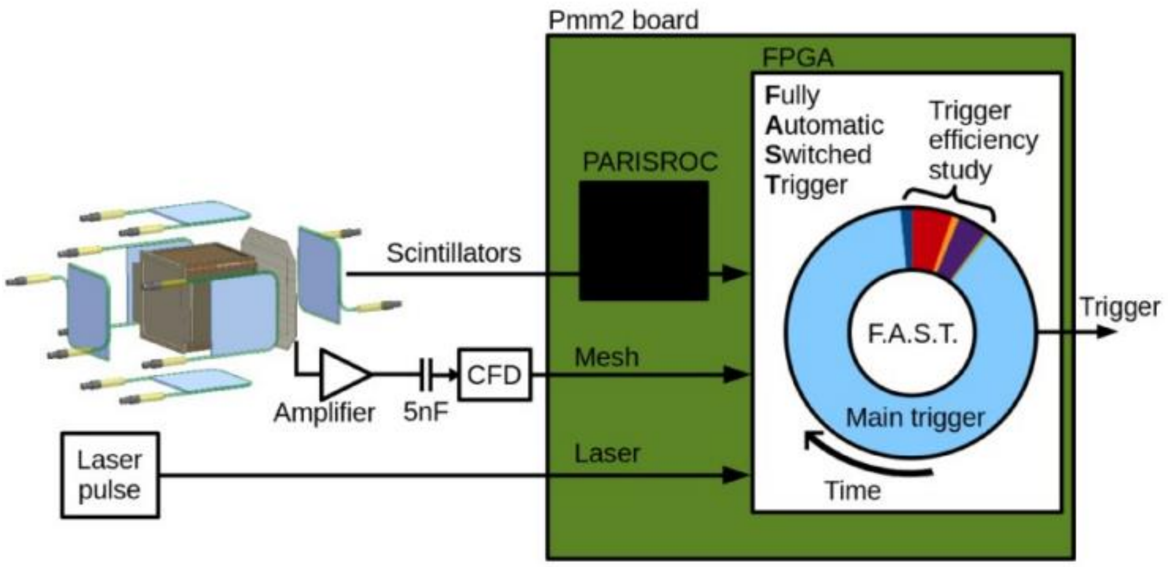


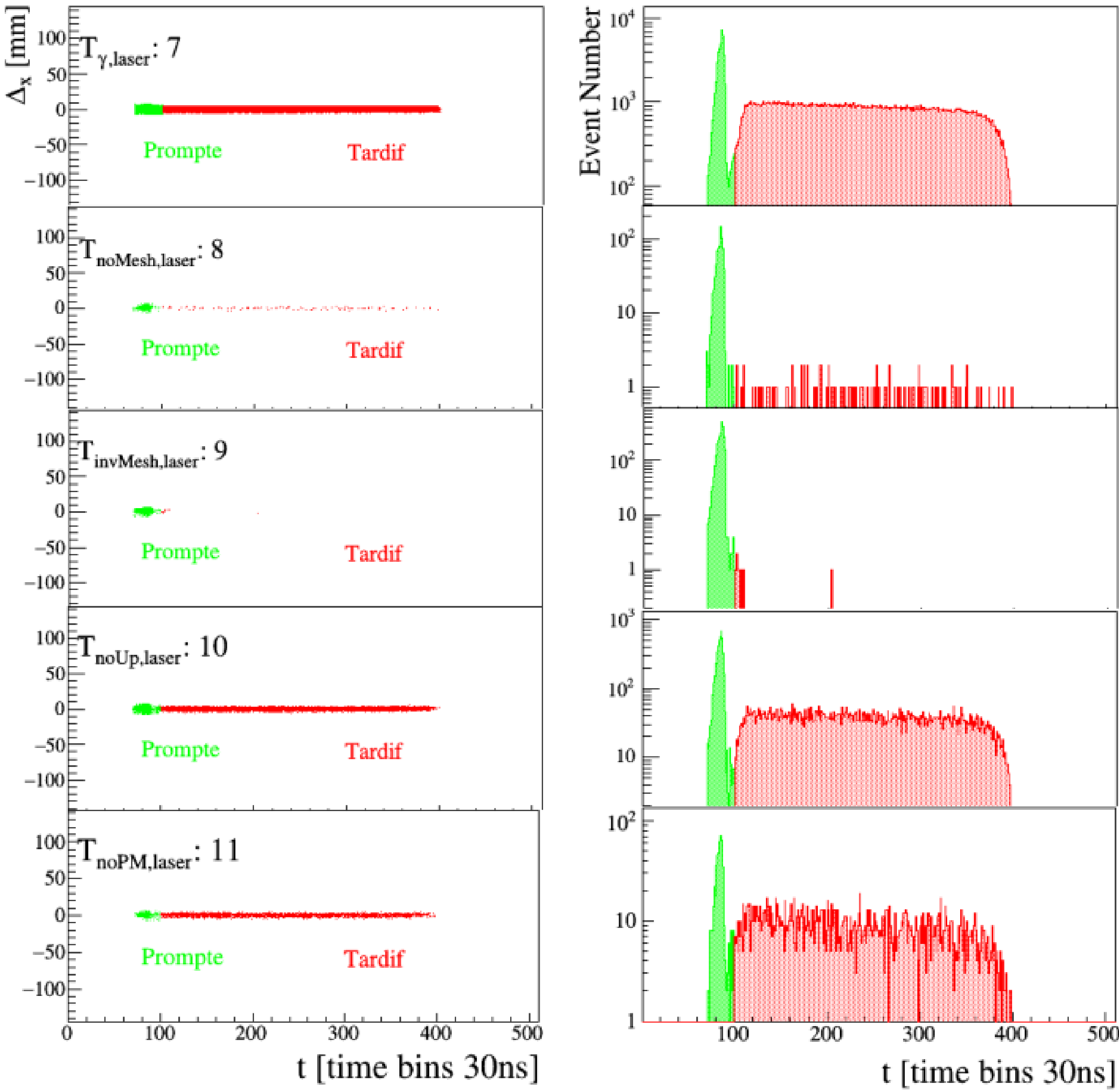
"Main line": $T_{\gamma,laser} = S_{up} \cap O \cap M_{slow} \cap L$



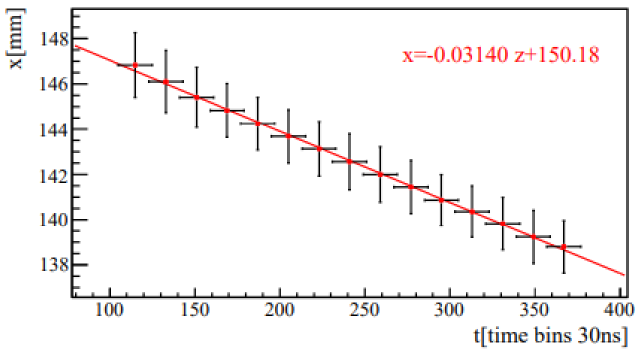
Beam trigger system

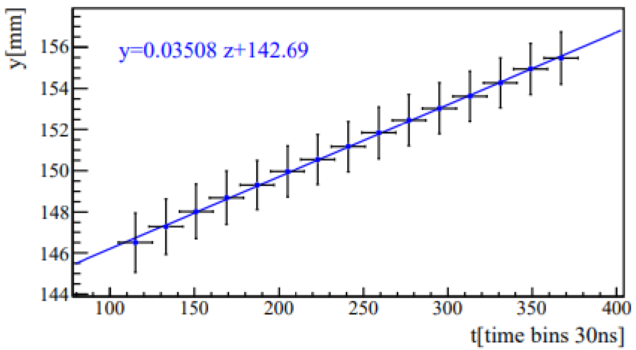
- signal efficiency 51 %
- background rejection 99.3 %
- incident rate 2 kHz
- signal on disk 50 Hz

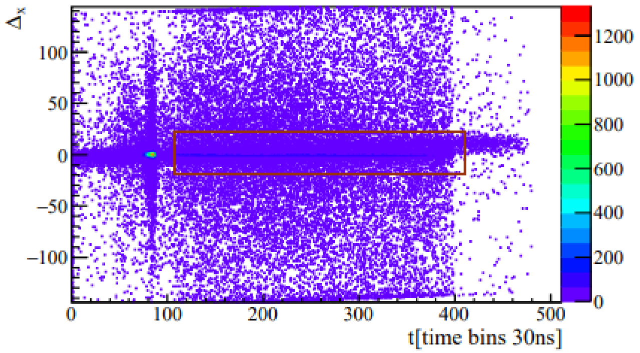


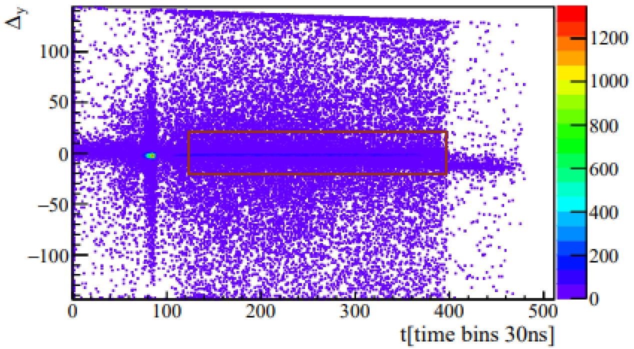


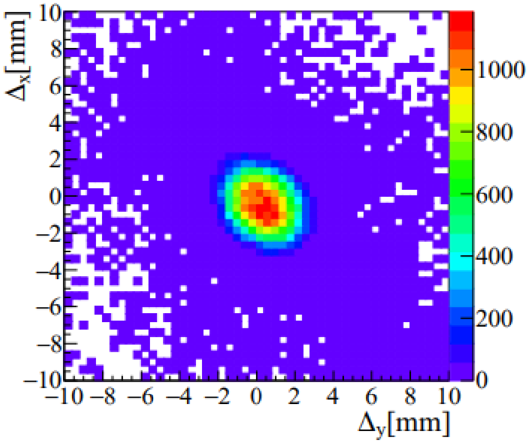
Event pre-selection

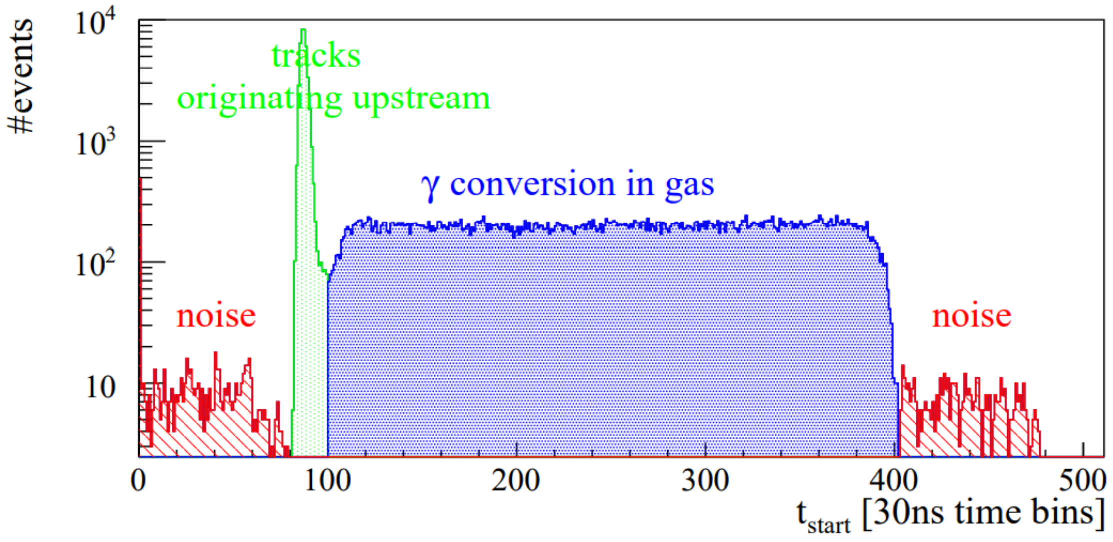


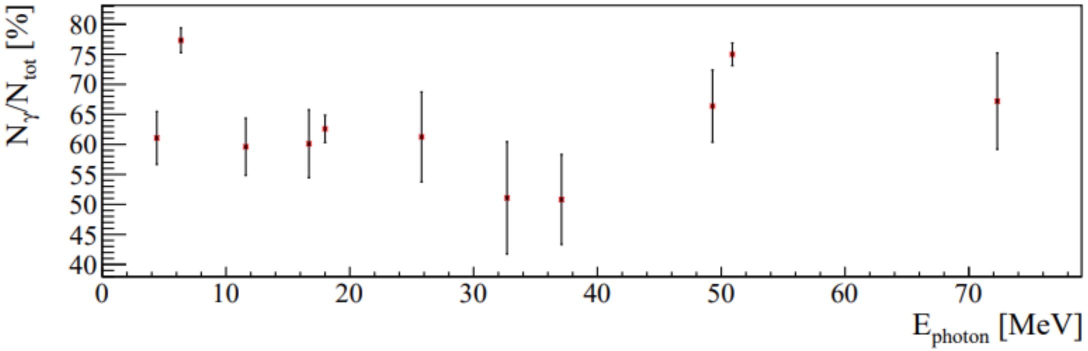


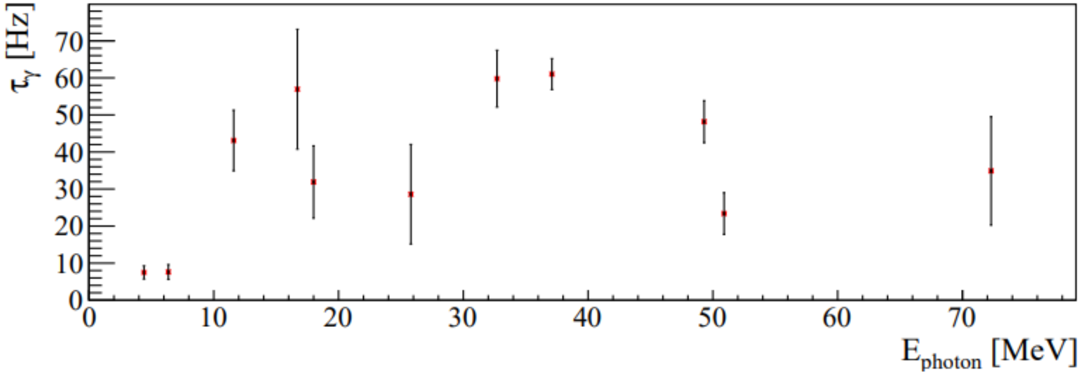








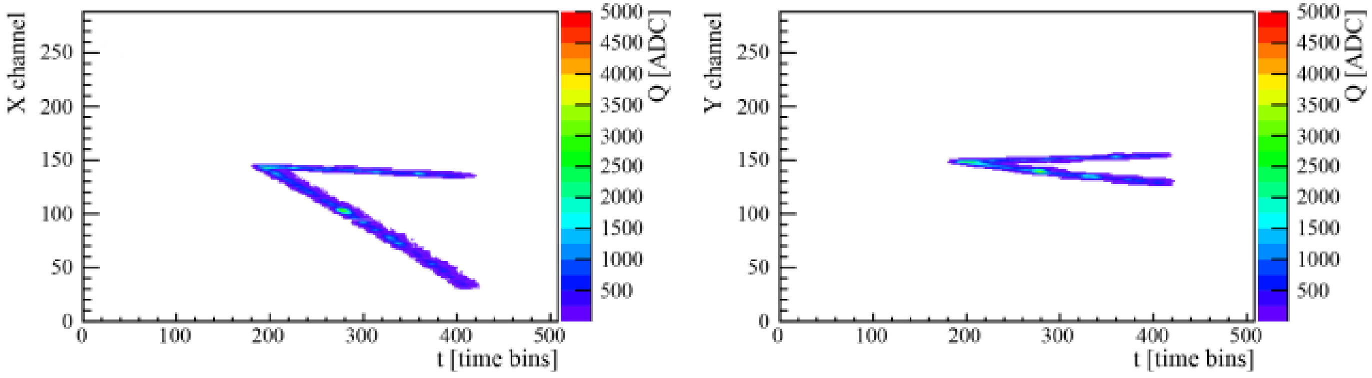




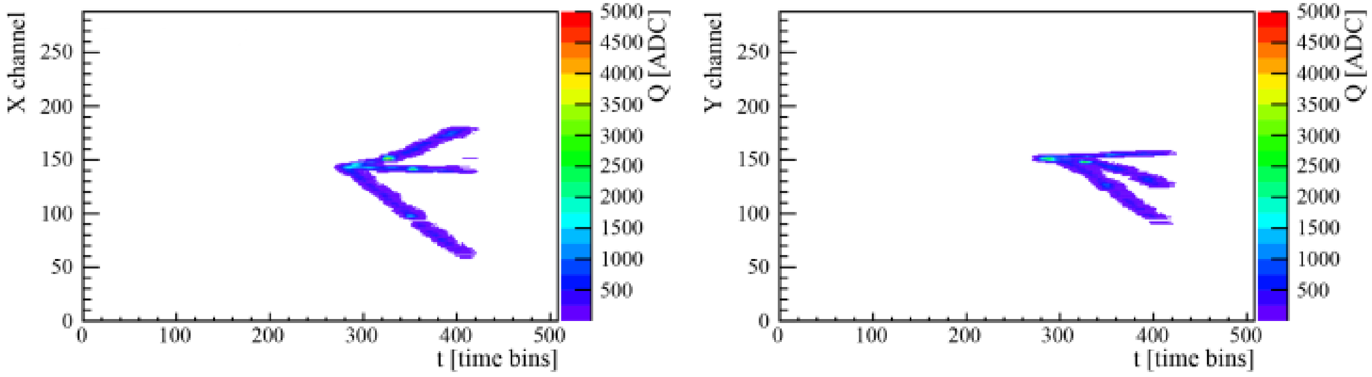
“Nuclear” and “triplet” pair conversion

- 74 MeV γ-rays from NewSUBARU conversions in 2.1 bar Ar:Isobutane 95:5

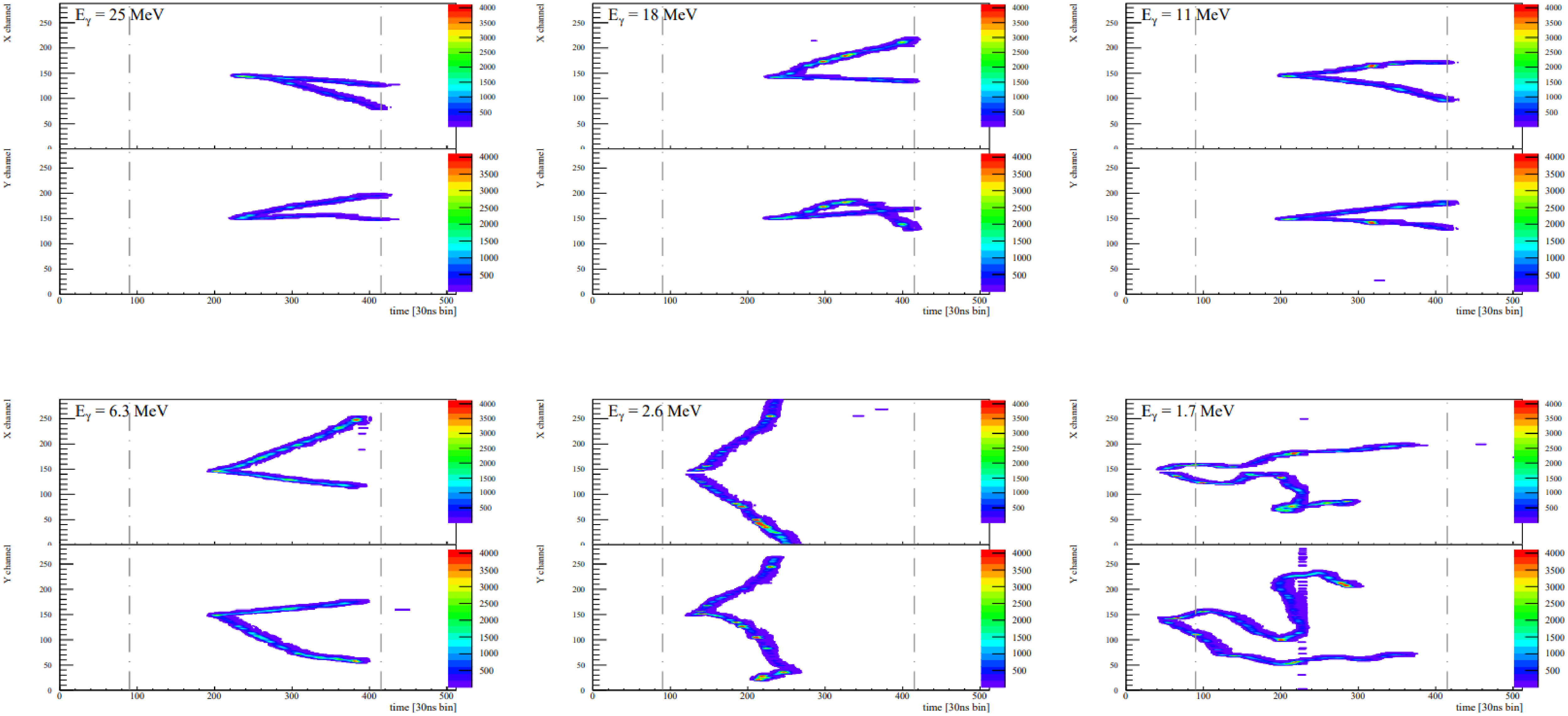
$$\gamma Z \rightarrow e^+ e^- Z$$



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

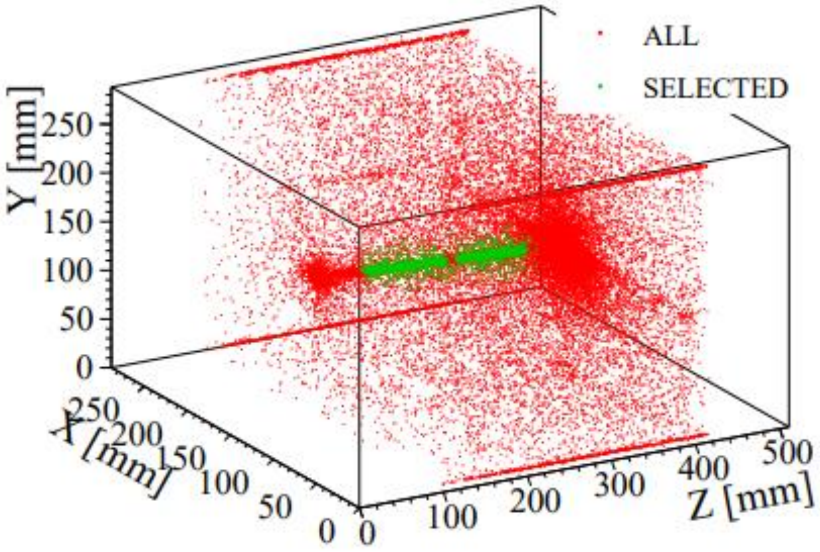


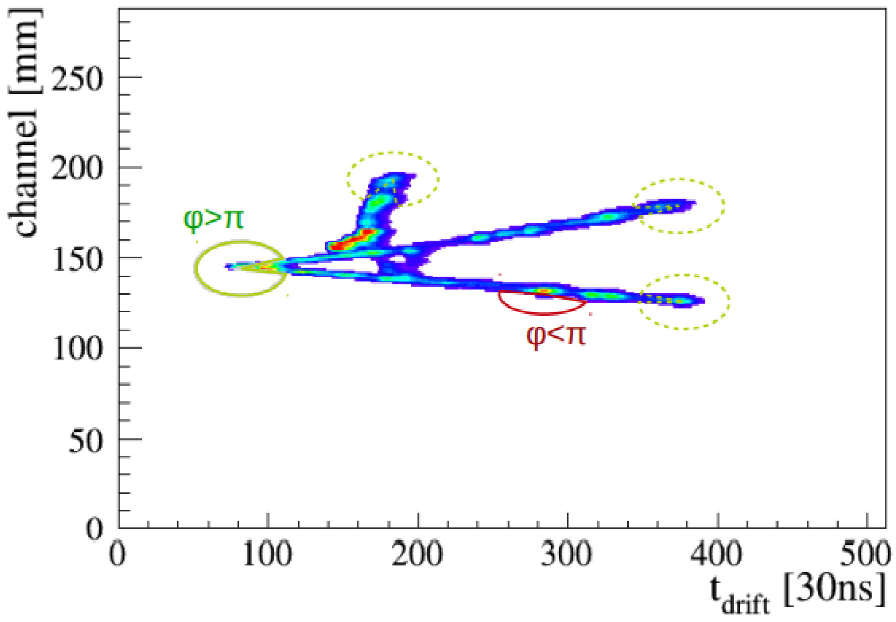
Pair conversion events

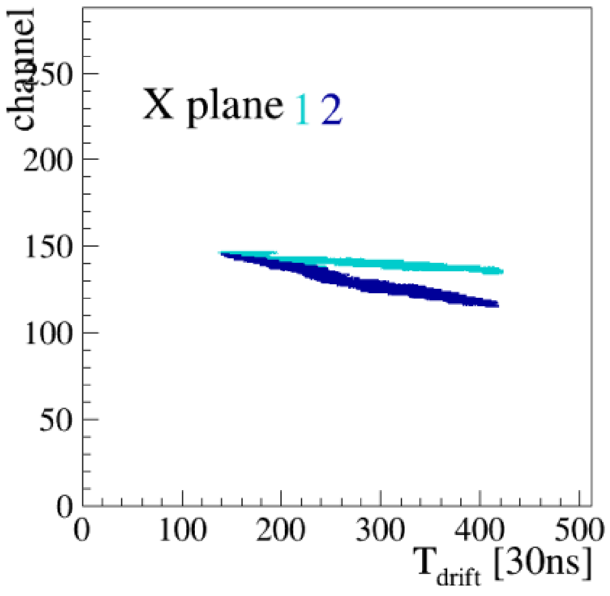


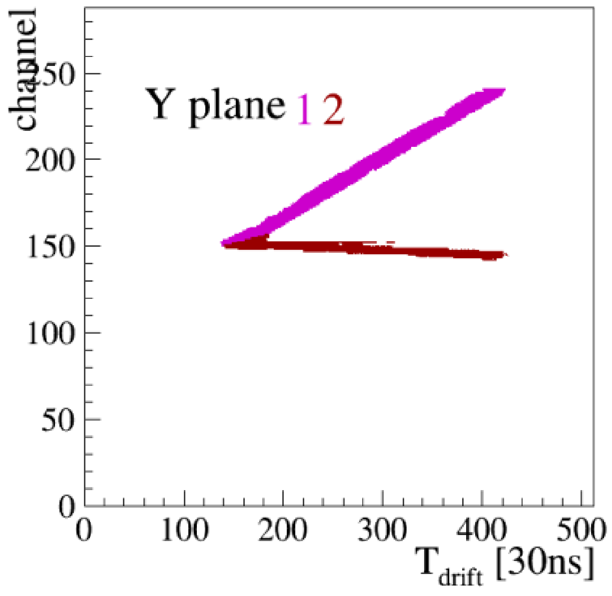
Event selection

- Hough track finding for track reconstruction
- Keep only straight lines to cut off the delta electron
- Vertex Matching



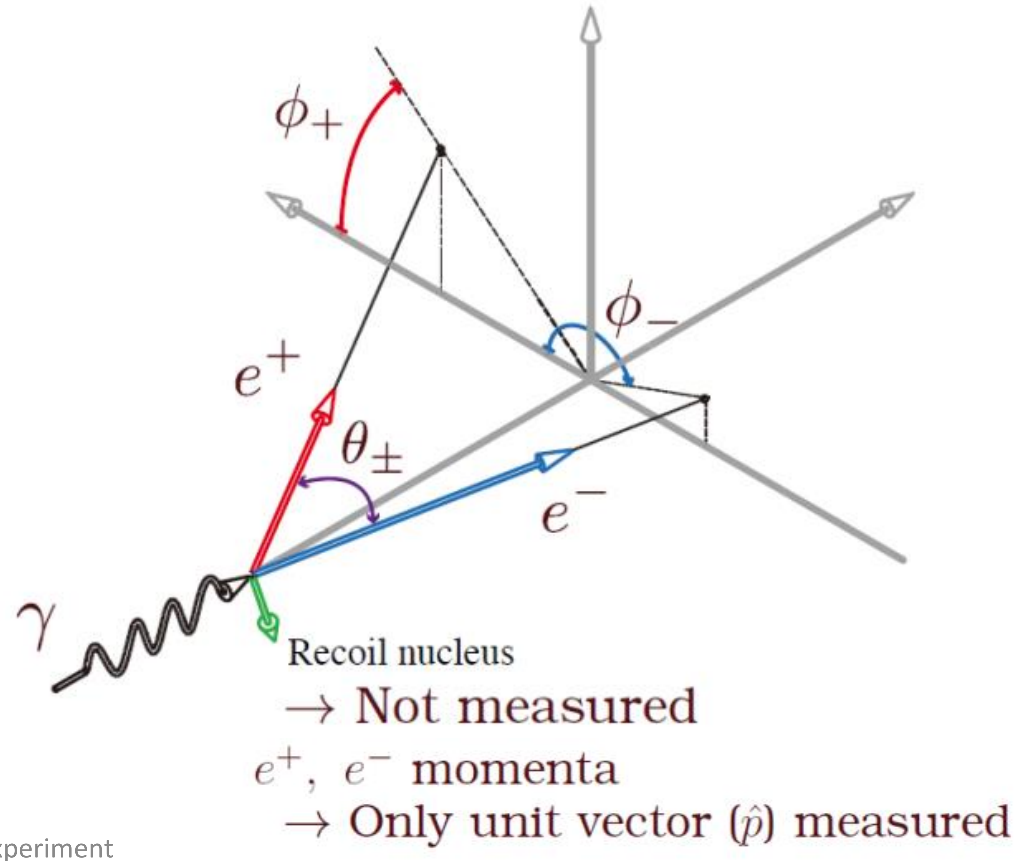






Measurement method

- 5 necessary variables to descript this interation: $\theta_+, \theta_-, \phi_+, \phi_-, E_+/E$
- Event generator: G4BetheHeitler5DModel
  - Samples the full five-dimensional, 1rst order Born, "Bethe-Heitler" differential cross section
  - Generates recoil momentum out of photon-pair plane



- Azimuthal angle:

$$\phi := \frac{\phi_+ + \phi_-}{2} - \phi_0$$

- Opening angle:

$$\theta_\pm := \arccos(\hat{p}_{e^+} \cdot \hat{p}_{e^-})$$

- Pesudo Gamma direction:

$$\hat{p}_\gamma \sim \frac{\hat{p}_{e^+} + \hat{p}_{e^-}}{|\hat{p}_{e^+} + \hat{p}_{e^-}|}$$

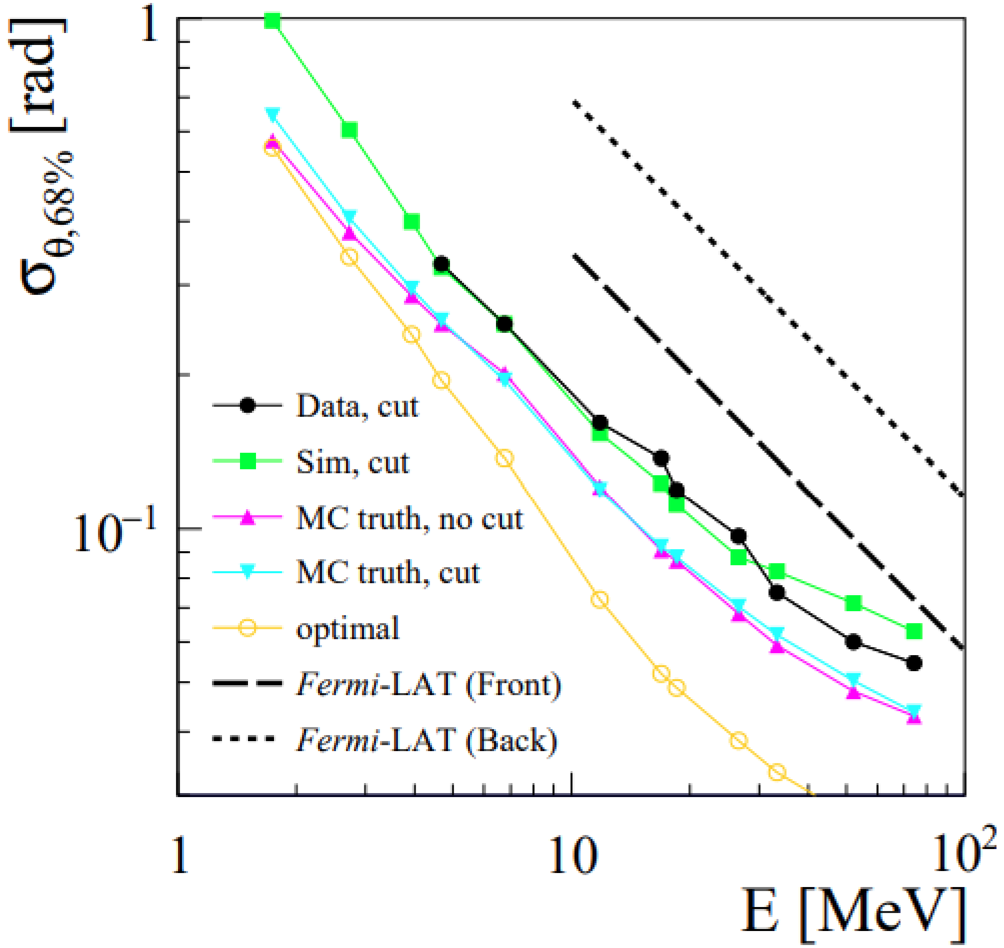
- Differential cross section

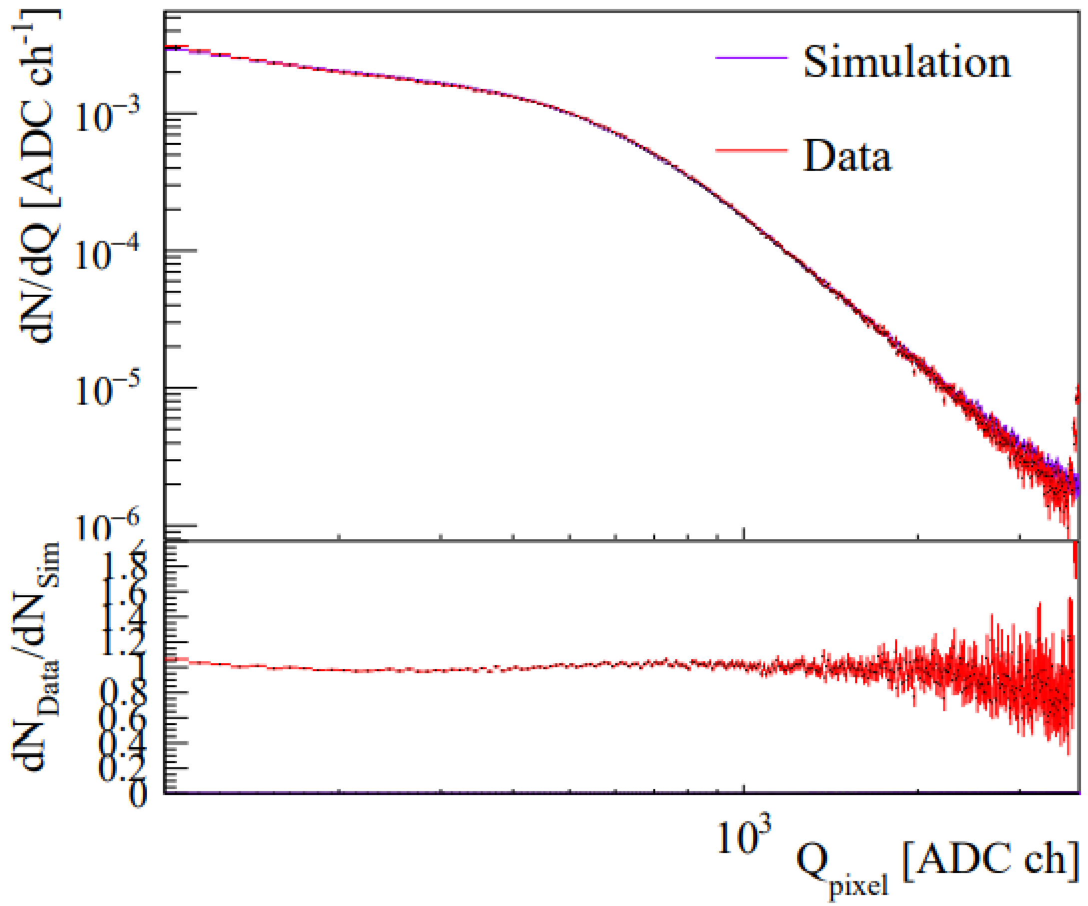
$$\frac{d\sigma}{d\phi} \propto 1 + AP\cos(2\phi)$$

Fraction of polarized phton [0:1] (P)

Polarization asymmetry (A)

Angular resolution

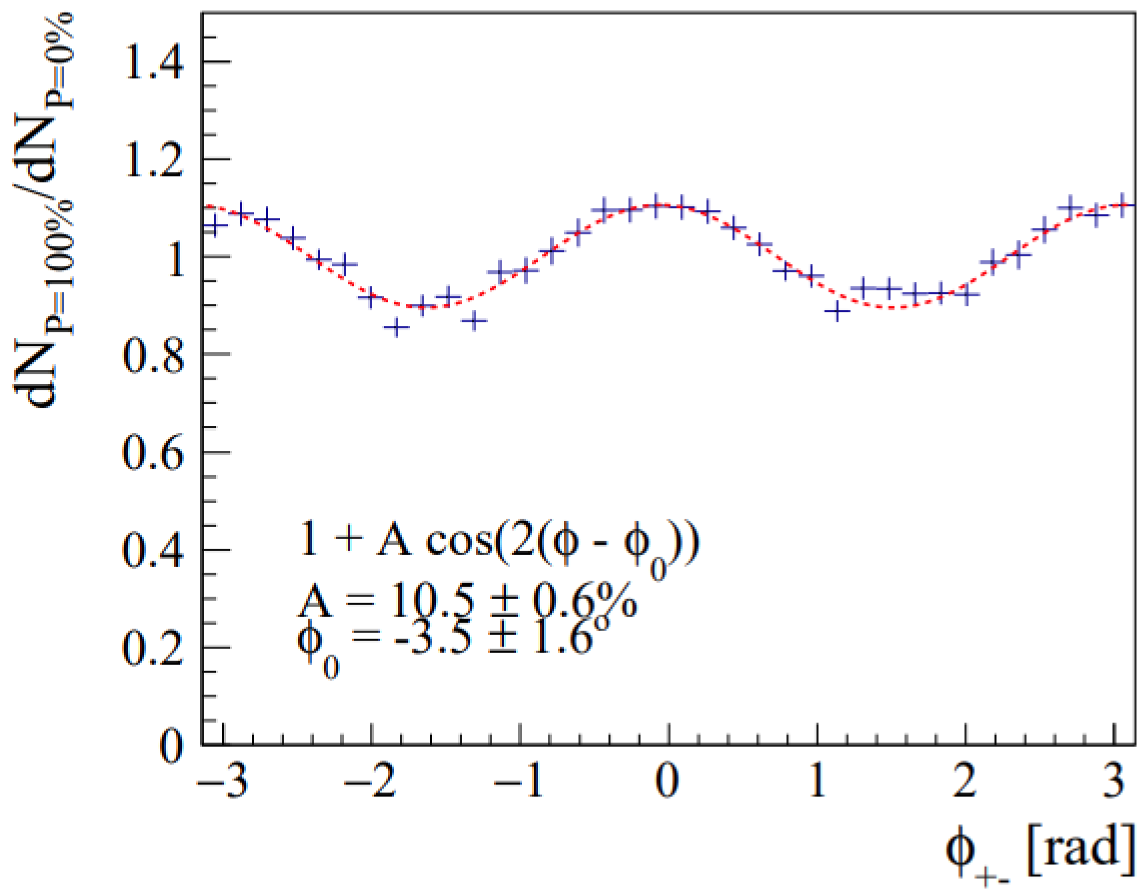




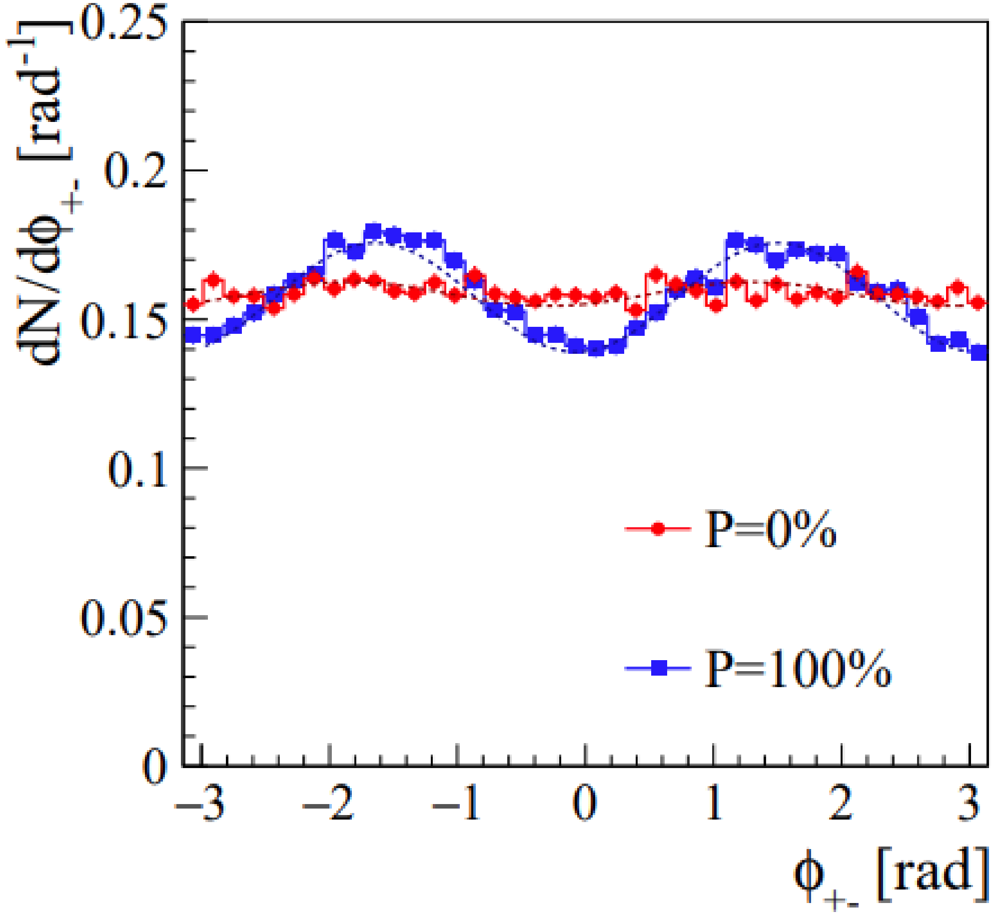
P. Gros et al. Astroparticle Physics 97 (2018) 10

Polarimetry: (P = 1)/(P = 0) ratios

11.8 MeV γ rays in 2.1 bar argon



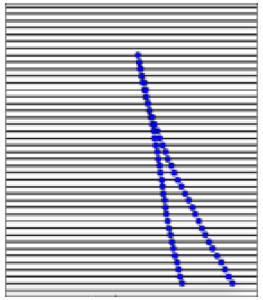
Simulated distributions for 11.8 MeV photons (isotropic photons)



P. Gros et al. Astroparticle Physics 97 (2018) 10

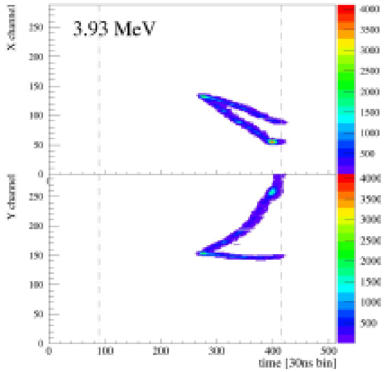
Polarimetry with High-Angular Resolution

W-less, Si-stack detectors
AMEGO, e-ASTROGAM
1.3°@ 100 MeV
A. De Angelis *et al.*, Exp. Astr. **44** (2017) 25



Emulsions
GRAINE
1°@ 100 MeV
S. Takahashi *et al.*, PTEP **2015** (2015) 043H01

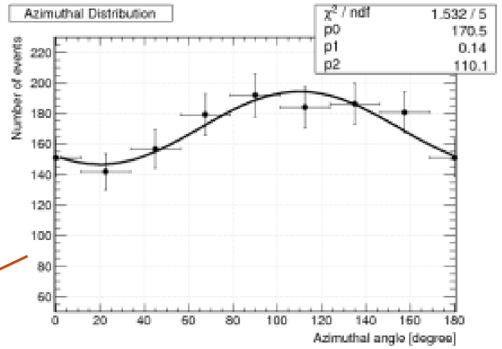
Gas TPC
HARPO
0.4°@ 100 MeV → ~1.5@74 MeV?
D. Bernard, NIM A 701 (2013) 225



Polarimetry with $\gamma \to e^+e^-$:

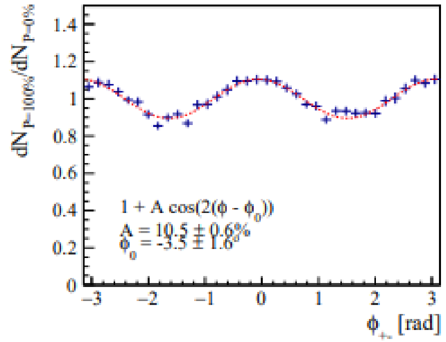
?

K. Ozaki *et al.*, NIM A **833** (2016)165



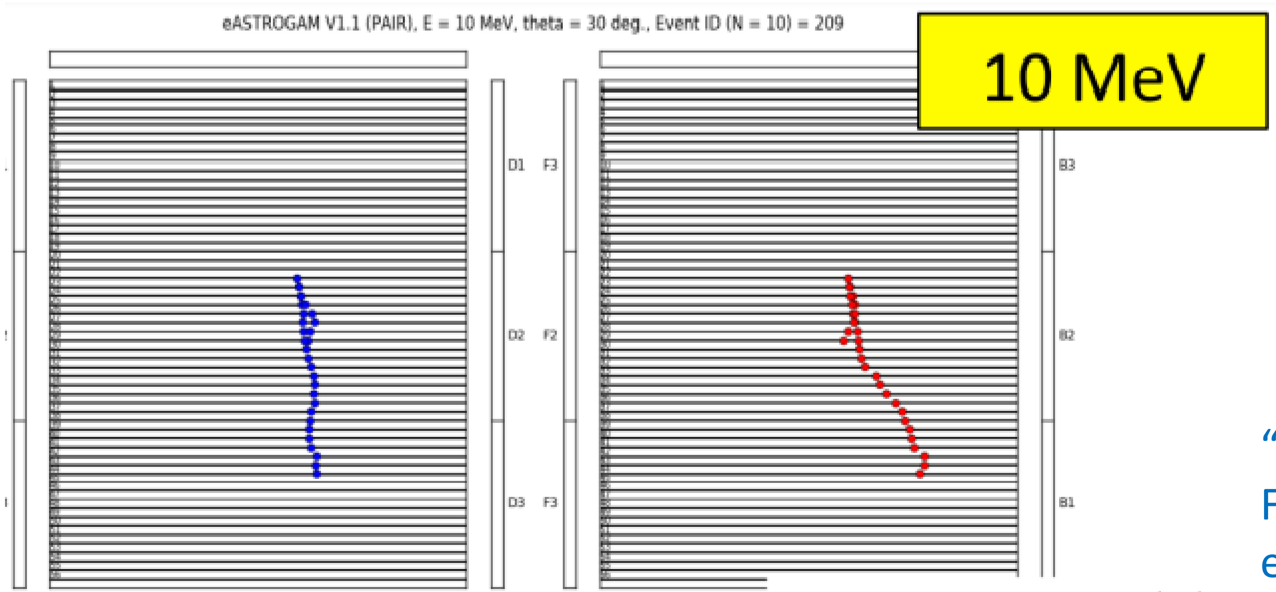
2.4 GeV (50 MeV threshold ?)

P. Gros *et al.*, Astroparticle Physics 97 (2018) 10

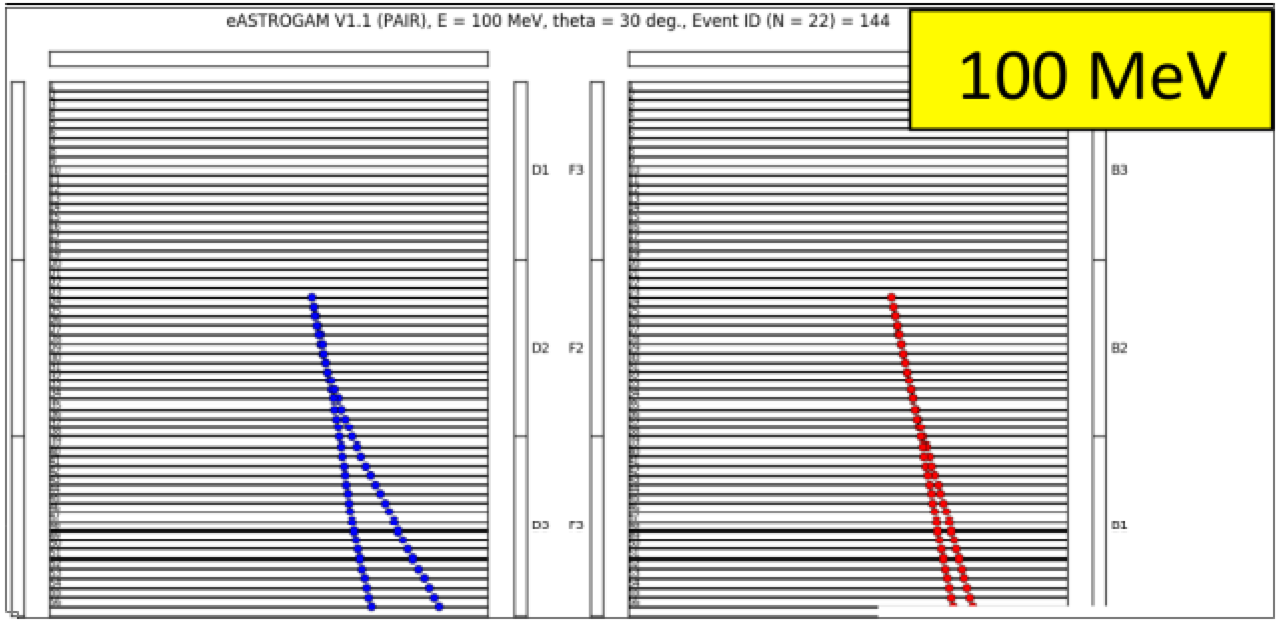


11.8 MeV

Main issue, the ability to collect data at low energy

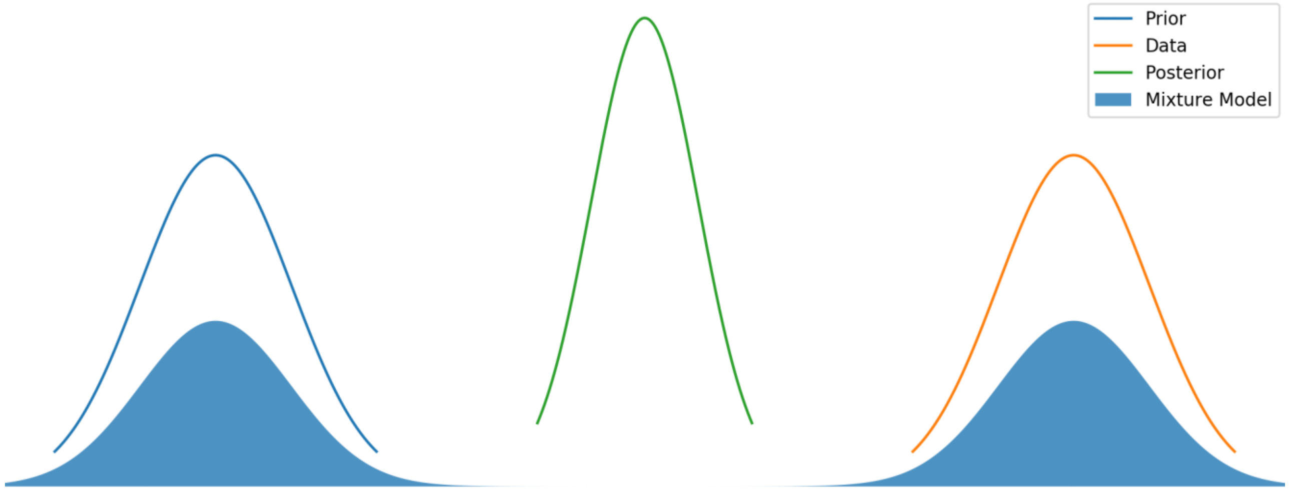


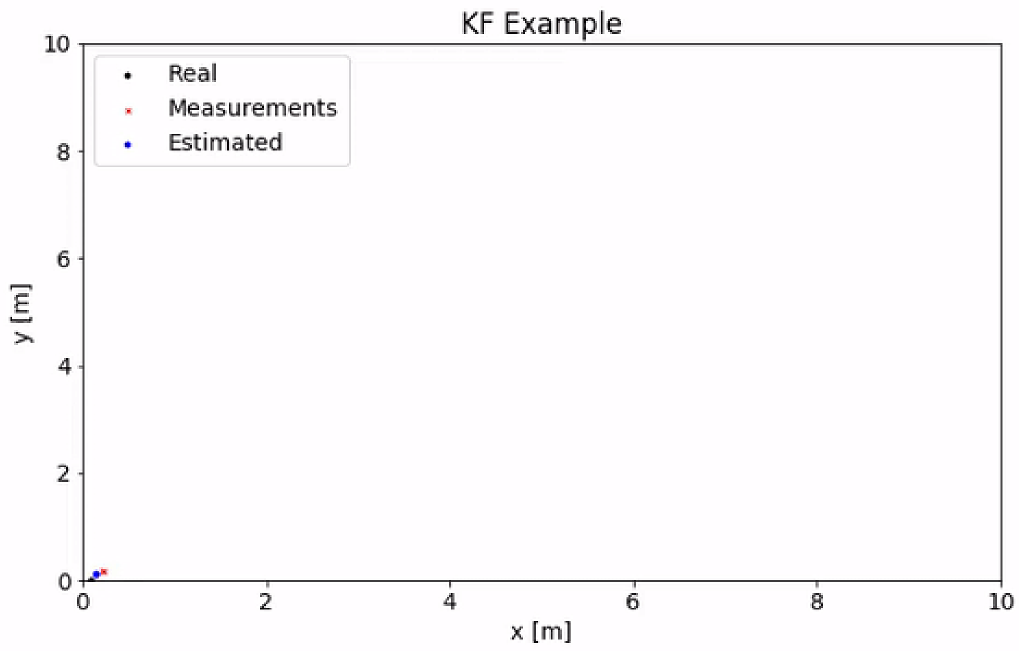
“Simulation of e-ASTROGAM”, V. Fioretti, eASTROGAM Workshop: the extreme Universe, 28/02 - 02/03/2017 Padova



粒子径迹重建上可能的优化

- 卡尔曼滤波：是一种利用<u>线性系统</u>状态方程，通过系统输入输出观测数据，对<u>系统状态</u>进行最优估计的算法。
- 现在卡尔曼滤波被广泛应用于粒子物理径迹重建和顶点重建，卫星导航，工业降噪，心电监测……

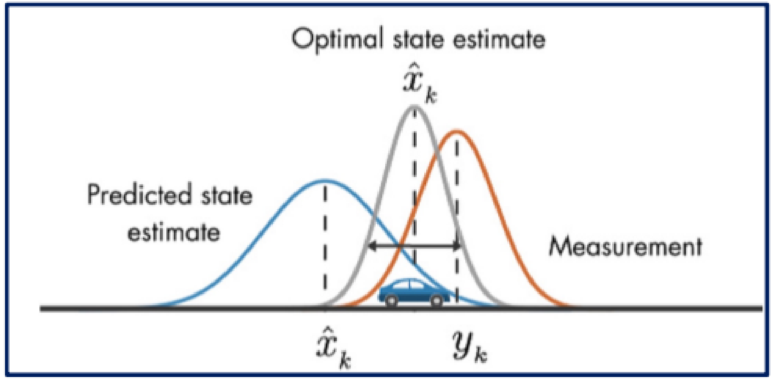




Kalman Filter in PandaX-III

➢卡尔曼滤波

最优线性估计器



多次散射 莫里哀公式：

$$\theta^{rms}_{\text{space}} = \frac{19.2\,\text{MeV}}{pv}\sqrt{\lambda_0}[1 + 0.038\ln\lambda_0]$$

过程噪声

状态方程：

$$s_k = F s_{k-1} + \omega_k$$

状态向量

$$\begin{bmatrix} [x]_k \\ [y]_k \\ [z]_k \\ [u_x]_k \\ [u_y]_k \\ [u_z]_k \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \lambda & 0 & 0 \\ 0 & 1 & 0 & 0 & \lambda & 0 \\ 0 & 0 & 1 & 0 & 0 & \lambda \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} [x]_{k-1} \\ [y]_{k-1} \\ [z]_{k-1} \\ [u_x]_{k-1} \\ [u_y]_{k-1} \\ [u_z]_{k-1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ G(0,[\theta_x]_k) \\ G(0,[\theta_y]_k) \\ G(0,[\theta_z]_k) \end{bmatrix},$$

测量方程：

$$m_k = H x_k + \delta_k$$

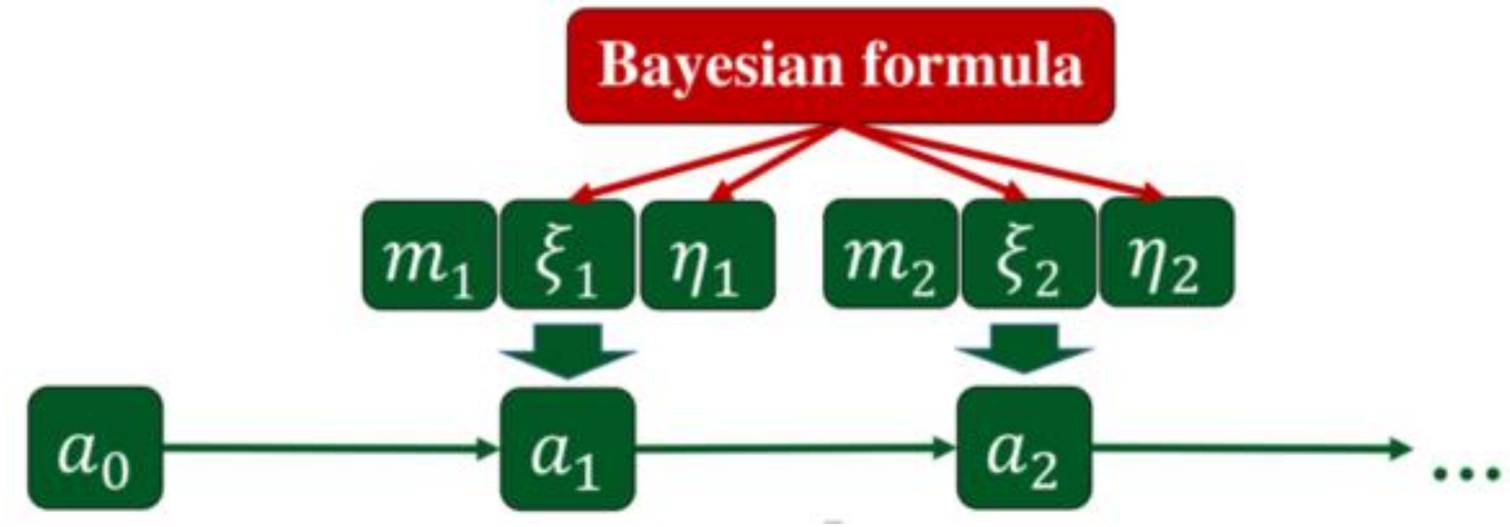
测量向量　　测量噪声　　贝叶斯公式确定

$$\begin{bmatrix} [x^m]_k \\ [y^m]_k \\ [z^m]_k \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} [x]_k \\ [y]_k \\ [z]_k \end{bmatrix} + \begin{bmatrix} G(0,[\sigma_x]_k) \\ G(0,[\sigma_y]_k) \\ G(0,[\sigma_z]_k) \end{bmatrix},$$

12

Kalman Filter in PandaX-III

- Kalman Filter in Bayssian Formalism (KFBF)



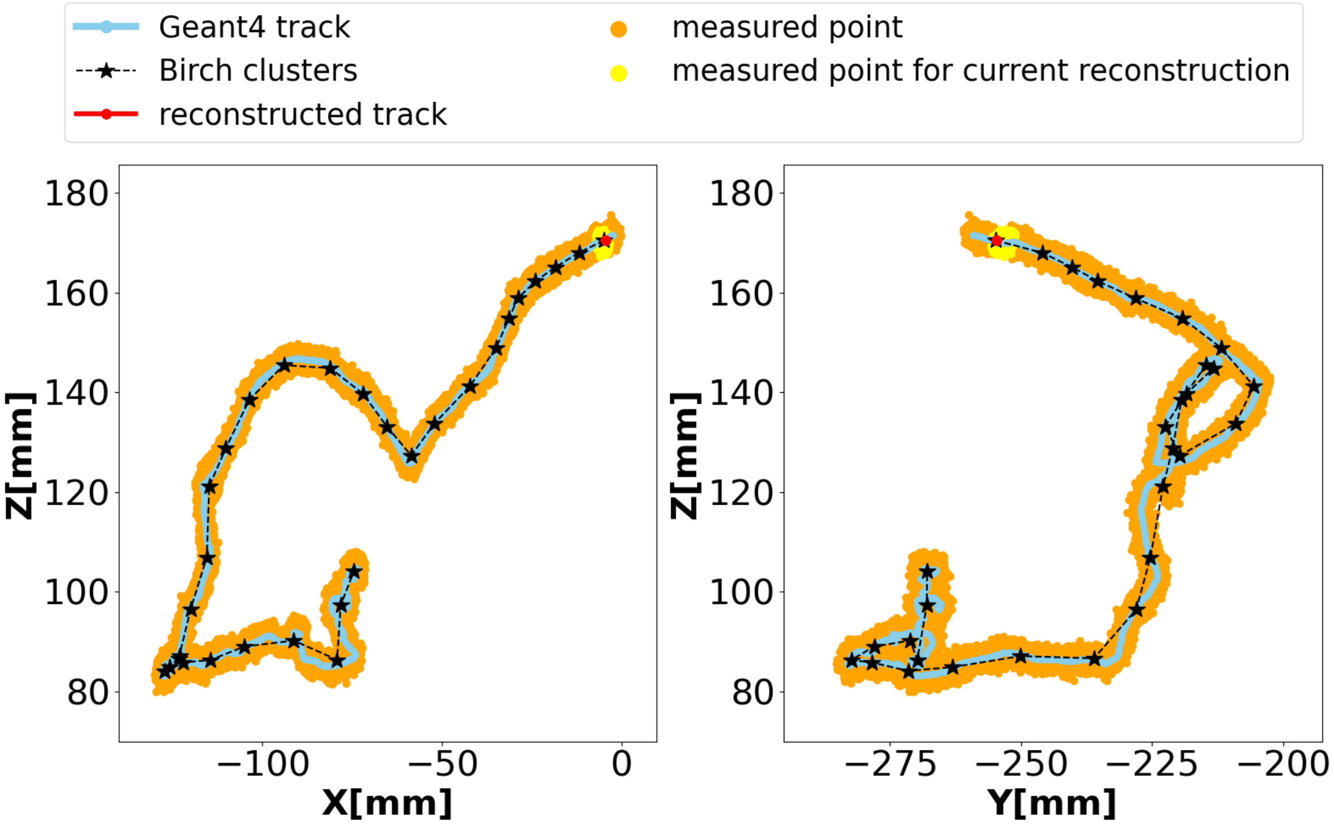
Radiat. Detect. Technol. Methods 4 (2019) 1, 70-77

Nucl. Instrum. Meth. A 867 (2017)

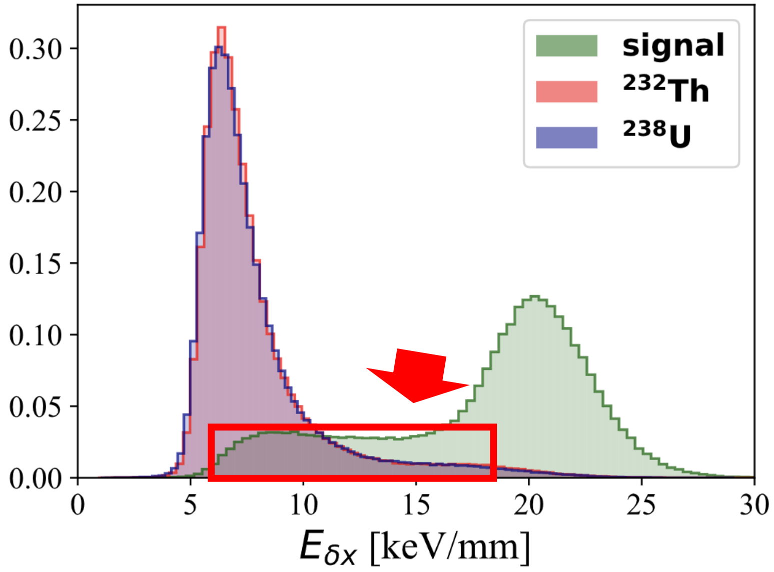
JHEP 06 (2021) 106

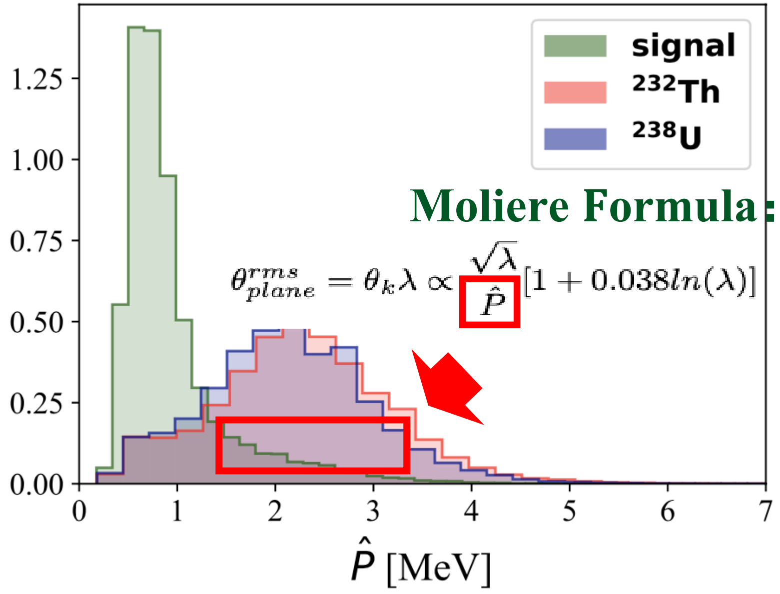
Track reconstruction with KFBF

- KFBF parameters reconstructed : (x,y,z, ux, uy, uz)



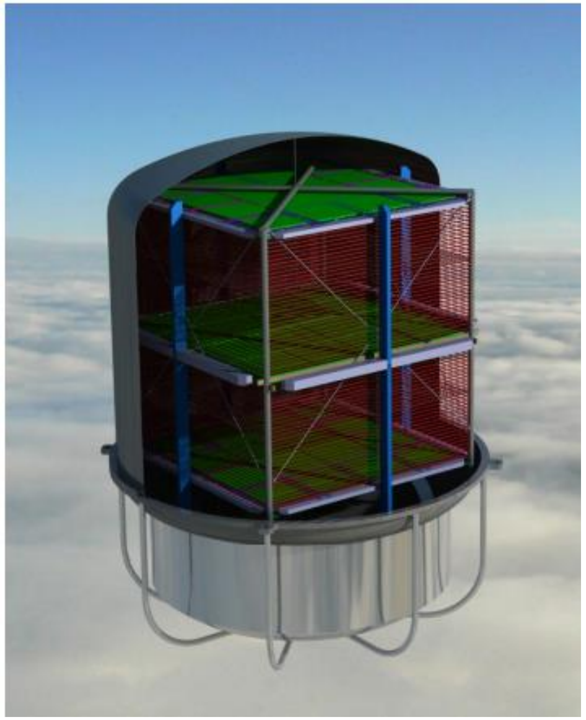
JHEP 06 (2021) 106

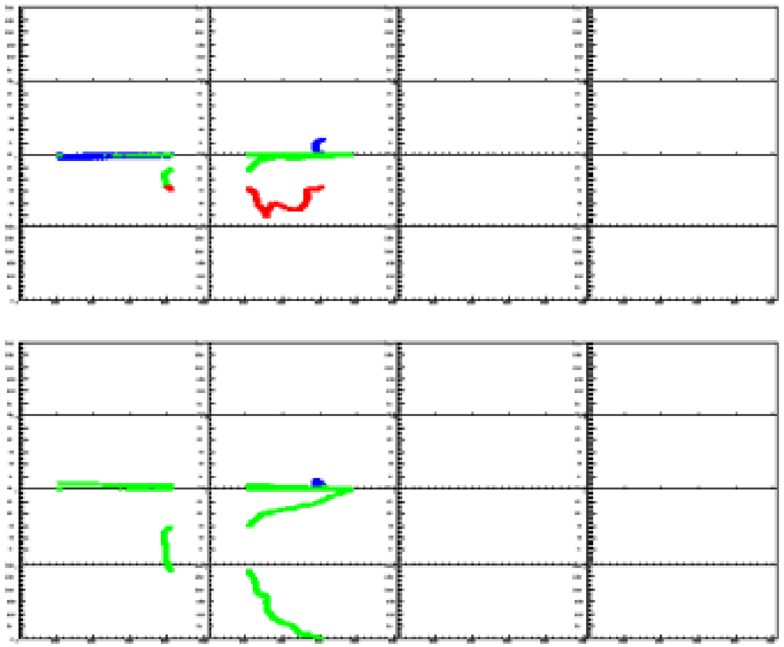


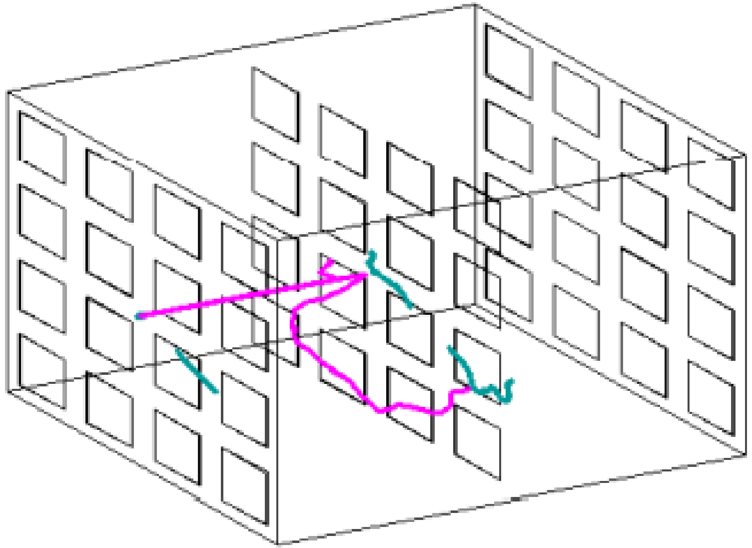


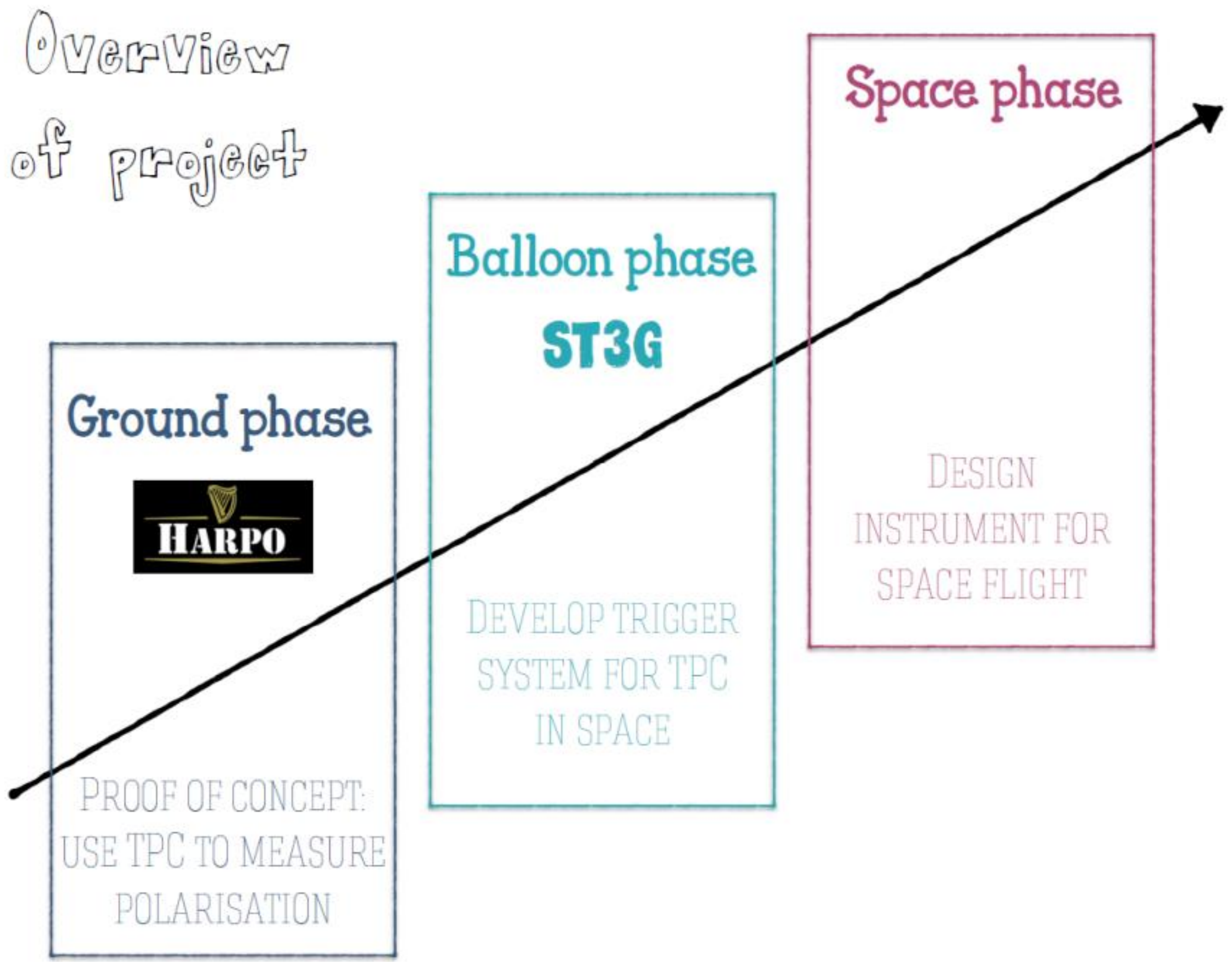
Balloon borne TPC: ST3G

- Self Triggered Tpc Gamma-ray Telescope
- Validation of a trigger using TPC signal only – AGET/ASTRE self-trigger readout
- Stratospheric balloon
- 4x4x4=64xHARPO = $(1.2m)^3$

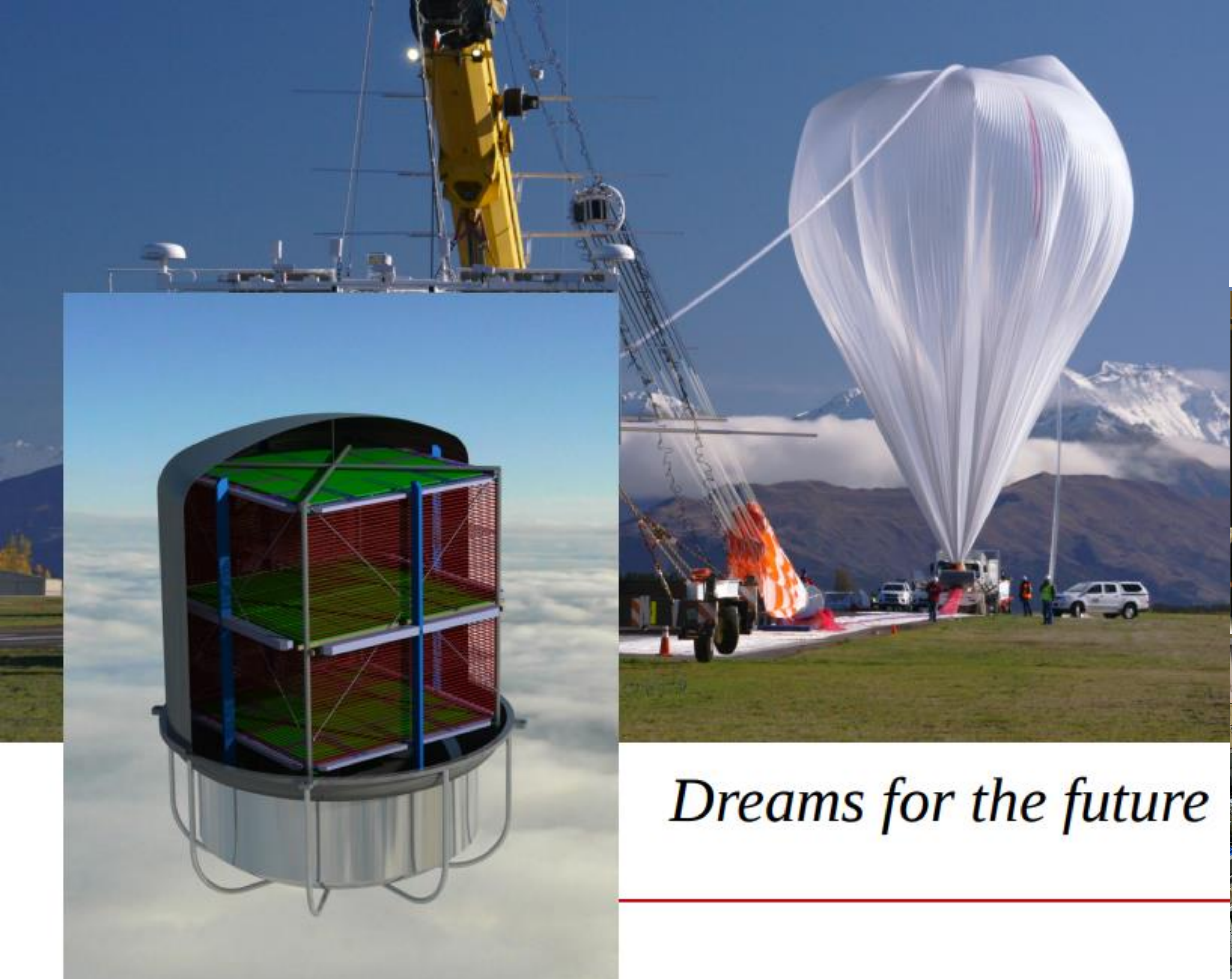


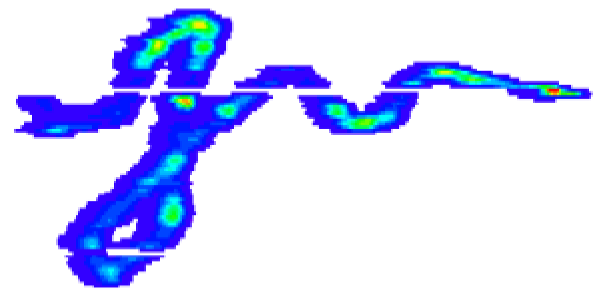






Max trigger rate ~600 Hz
γ conversion rate 400 Hz
Compton scatt : 7 kHz
Charged tracks 33 kHz/m²





Dreams for the future

Spin-offs:

- A C++ version of our event generator has been deployed as the G4BetheHeitler5DModel physics model with Geant4 (*Nucl. Instrum. Meth. A* ***899*** *(2018) 85*)
- An analytical analysis of the single-track angular resolution with an optimal tracking
  - an optimal method to measure the momentum of a track in a non-magnetic tracker from the analysis of the deflections due to multiple scattering (Bayes and Kalman giving hand to Molière)
  - It is of particular interest to silicon-detector based telescopes (Fermi-LAT, AGILE, e-ASTROGAM, AMEGO) and for large liquid argon TPC active targets that are developed for long-base neutrino studies
- A 3rd generation “ASTRE” (Asic with SCA and Trigger for detector Readout Electronics) readout chip for TPC
  - a modified version of the self-triggerable AGET chip (*Nucl. Instrum. Meth. A* ***2017.10.043***),
  - in particular for its ionizing-radiation hardness (characterization on beam has shown a LET threshold extended from 3 to 20 MeV / (mg · cm^2))

Thanks！

Angular resolution and gas choice

- Single track angular resolution
  - multiple scattering angle:

$$\theta_0 = \frac{p_0}{\beta c p}\sqrt{\frac{x}{X_0}}$$

  - At high momentum, multiple scattering can be neglected and the detector resolution dominates:

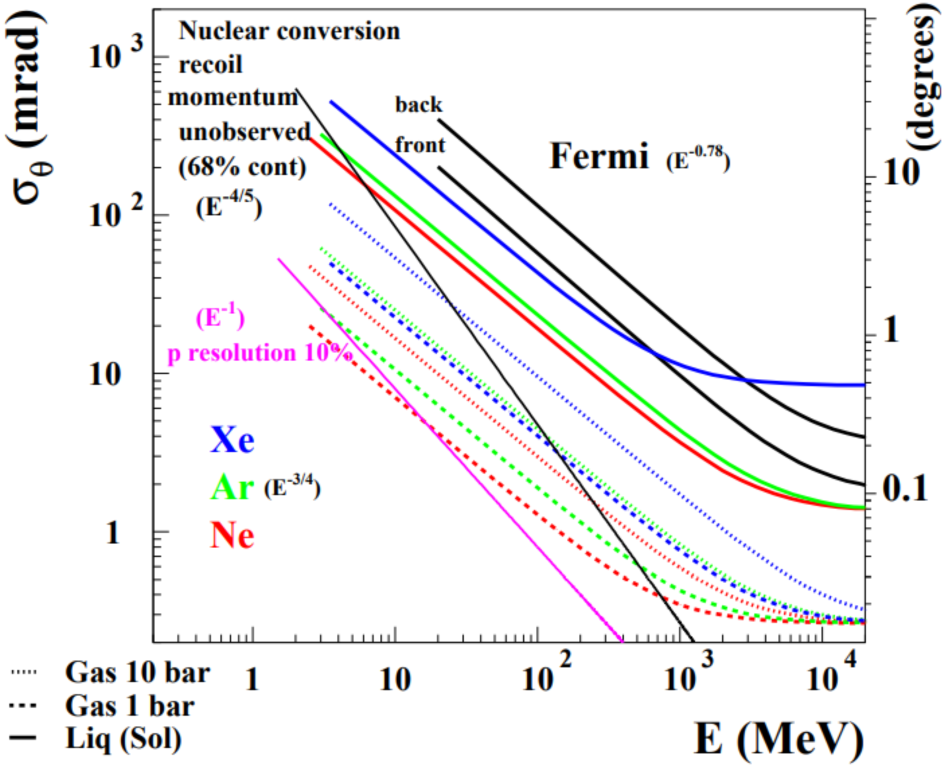
$$\sigma_{\theta t H} \approx \frac{8\sigma}{L}\sqrt{3/(N+5)}$$

  - At low momentum, multiple scattering dominates:

$$\sigma_{\theta t L} \approx (2\sigma)^{1/4} l^{1/8} X_0^{-3/8} (p/p_0)^{-3/4}$$

- From tracks to photon:

$$\vec{p_\gamma} = \vec{p_{e^+}} + \vec{p_{e^-}} + \vec{q}$$



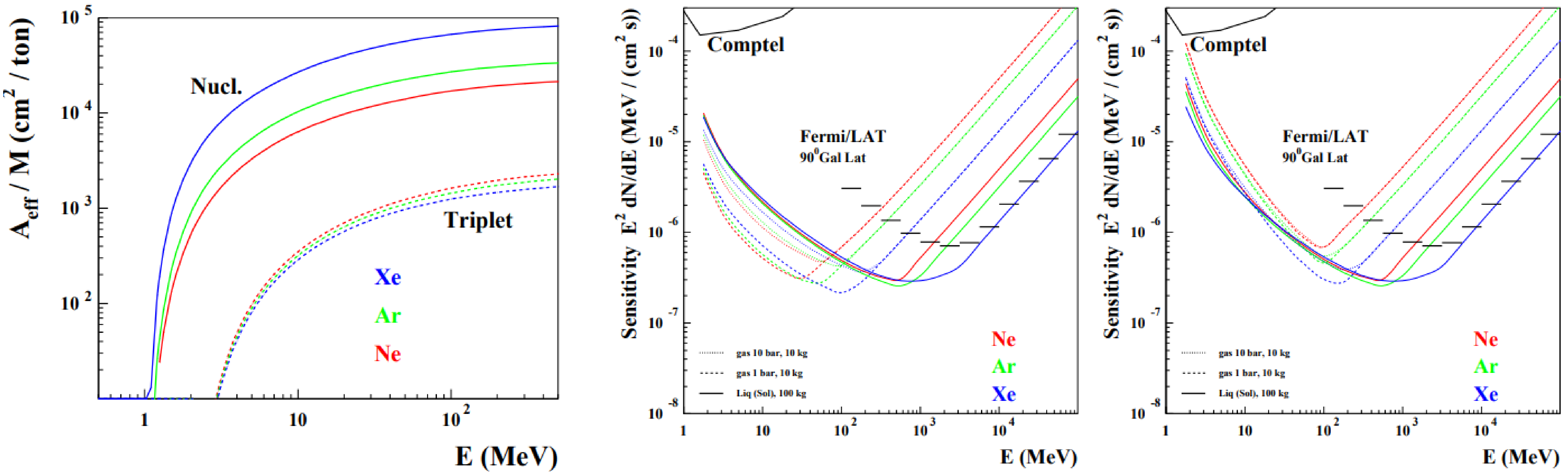
Sensitivity and gas choice

- Dependence on energy of the effective area per unit mass
- Compute the sensitivity to the detection of a faint high-latitude point-like source

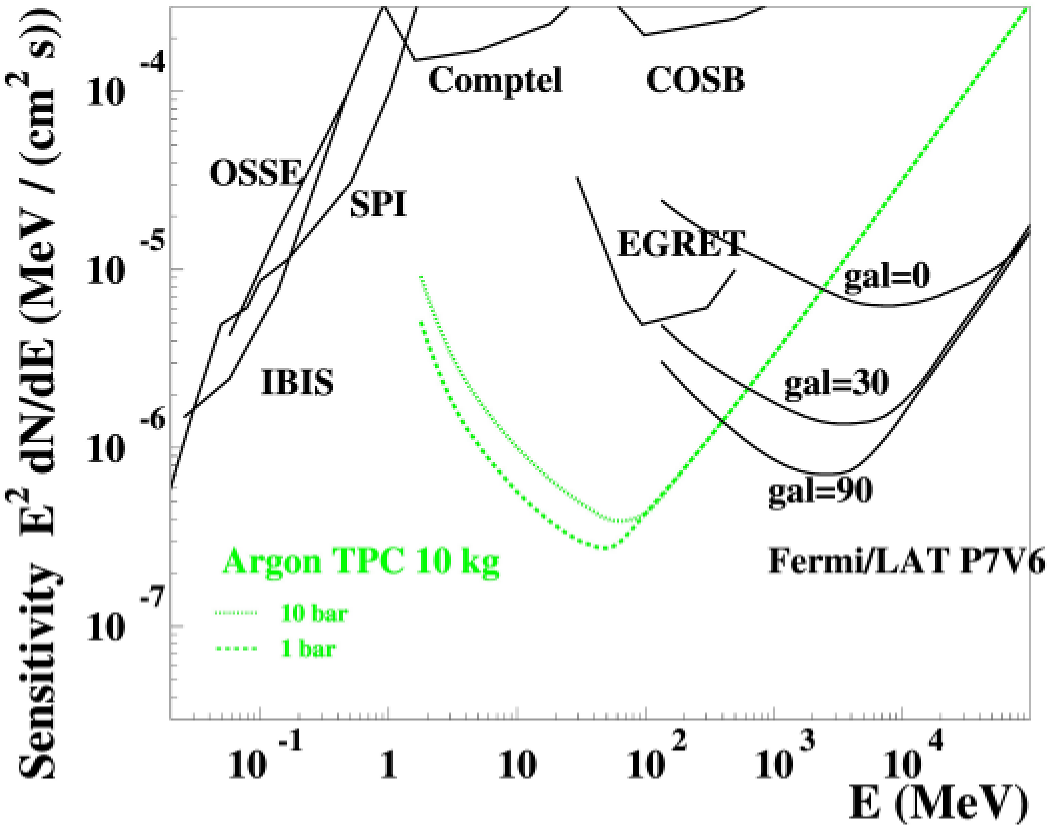
$$S = T \times \eta \times A_{\text{eff}}(E) \times I_0(E) \times \epsilon \times \Delta E$$

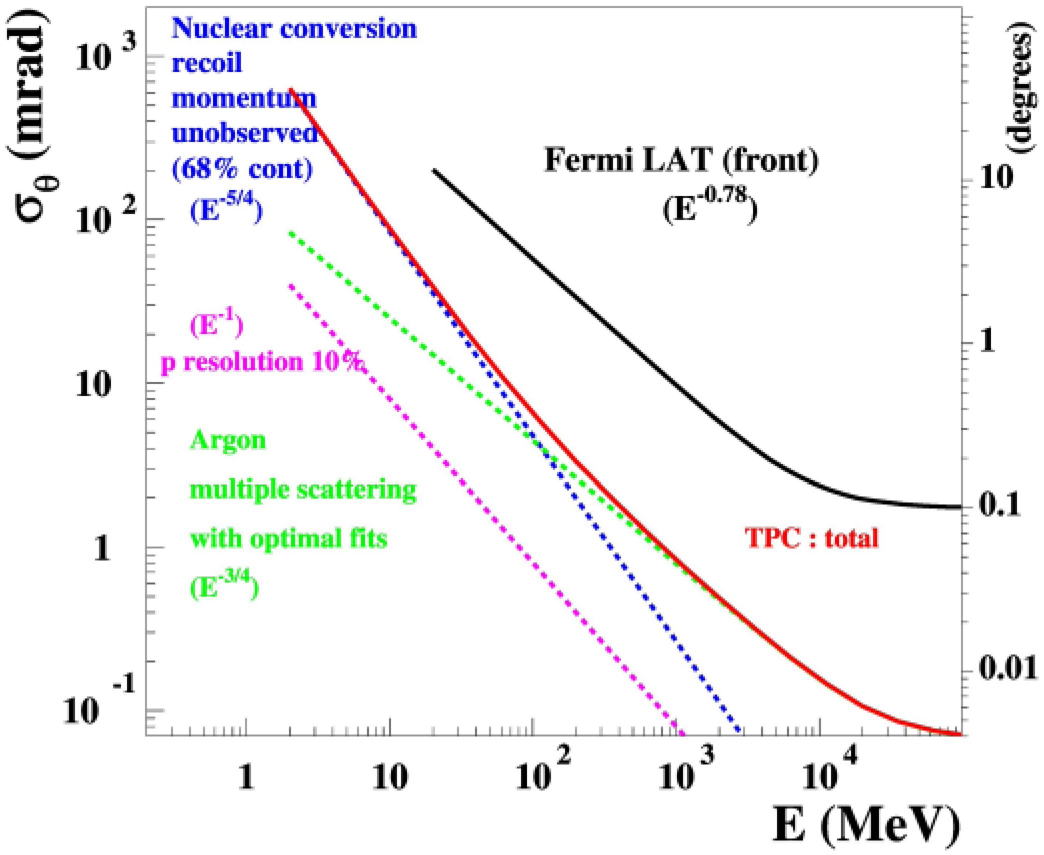
$$B = T \times \eta \times A_{\text{eff}}(E) \times \pi\sigma_\theta^2 \int F_B(E)dE$$

$$S = n\sqrt{B} \longrightarrow s \approx \frac{n\ \sigma_\theta\ E^2}{\Delta E}\sqrt{\frac{\pi \int B(E)\,\mathrm{d}E}{T\ \eta\ A_{\text{eff}}}}$$



Expected performance of HARPO





D. Bernard,
NIM A 701 (2013) 225

Instrument	FOV	Energy range	Effective Area	Technology	Angular Resolution	Type	Science	Status
SPR-N	Full Sun disk	20 – 100 keV	50 cm^2	Be scatterer and scintillators	Non imaging	Satellite	Solar flares	2001-2005
MEGA	2π sr	$300 – 5 \times 10^4$ keV	324 cm^2	Silicon strips and CsI	Some degree	Balloon 3D	GRB Point sources	Prototype
PHENEX	4.8°	40 – 200 keV	44 cm^2	Plastic scintillator and CsI	Non imaging	Balloon Collimated	Point source	2006 and 2009
TIGRE	$45° \times 45°$	$400 – 10^5$ keV	80 cm^2 at1 MeV	Silicon strips and CsI	2° ARM at 1 MeV	Balloon 3D	GRB Point sources	2010
PENGUIN-M	$45° \times 45°$	20 – 150 keV	78 cm^2	Plastic scintillator and NaI	Non imaging	Satellite	Solar flares	2009-2010
GAP	$30° \times 30°$	50 – 300 keV	176 cm^2	Plastic scintillator and CsI	Non imaging	Satellite Wide-field	GRB	2010-2011
GRAPE	2π sr	50 – 500 keV	144 cm^2	Plastic scintillator and CsI	Non imaging	Balloon Wide-field	GRB	2011 and 2014
POGO+	2°	20 – 180 keV	1400 cm^2	Plastic scintillator and CsI	2°	Balloon Collimated	Point sources	2016
COSI (Balloon)	π sr	200 – 2000 keV	256 cm^2	Segmented Ge	3.2°	Balloon 3D	GRB Point sources	2016
SGD	$0.6° \times 0.6°$	50 – 200 keV	210 cm^2	Si pixels and CdTe	30°	Satellite Collimated	Point sources	2016
X-Calibur / XL-Calibur	6′	20 – 60 keV 20 – 80 keV	10 cm^2 at 50 keV 100 cm^2 at 50 keV	Be scatterer and CZT	Non imaging	Balloon Focal plane	Point sources	2016, 2019, 2022
INTEGRAL IBIS	$9° \times 9°$	$15 – 10^4$ keV	2600 cm^2	CdTe, CsI	12″	Satellite Coded mask	Point sources GRB	Flying since Oct 2002
INTEGRAL SPI	$9° \times 9°$	$15 – 10^4$ keV	500 cm^2	Ge	1°	Satellite Coded mask	Point source	Flying since Oct 2002
AstroSat	$4.6° \times 4.6°$	100 – 350 keV	924 cm^2 above 100 keV	CZT	Non imaging	Satellite Coded mask	GRB, Point sources	Flying since 2015
POLAR	2π sr	50 – 500 keV	300 cm^2 at 300 keV	Plastic scintillator	10° bright GRB	Space station Wide-field	GRB	2016-2107
POLAR-2	2π sr	10 – 500 keV	1250 cm^2 at 300 keV	Plastic scintillator	5° bright GRB	Space station Wide-field	GRB	Manifested 2024
PING-P	$45° \times 45°$	20 – 150 keV	30 cm^2	Plastic scintillator and CsI	Non imaging	Satellite	Solar flares	2025
PolariS	$10'' \times 10''$	10 – 80 keV	3.2 cm^2	Plastic scintillator and GSO	1°	Satellite Focal plane	Point sources	Under development Launch TBD
COSI (SMEX)	π sr	200 – 2000 keV	256 cm^2	Segmented Ge	3.2°	Satellite 3D	GRB, Galactic sources	Selected 2025
LEAP	1.5π sr	50 – 500 keV	1000 cm^2	Plastic scintillator and CsI	1 − −5°	ISS Wide-field	GRB	Proposed
AMEGO	2.5 sr	$200 – 10^6$ keV	608 cm^2	Silicon strips CZT and CsI	2.5° at 1 MeV	Satellite 3D	Point sources GRB	Proposed
e-ASTROGAM ASTROMEV	2.5 sr	$300 – 3 \times 10^6$ keV	10 000 cm^2	Silicon strips and CsI	0.15° at 1 GeV	Satellite 3D	Point sources GRB	Proposed

References: SPR-N (Bogomolov et al., 2003), MEGA (Bloser et al., 2006), PHENEX (Gunji et al., 2008), TIGRE (Bhattacharya et al., 2004; O'Neill et al., 1996), PENGUIN-M (Dergachev et al., 2009), GAP (Yonetoku et al., 2006), GRAPE (Bloser et al., 2009), POGO+ (Friis et al., 2018), COSI (Balloon) (Yang et al., 2018), SGD (Aharonian et al., 2018), X-Calibur (Kislat et al., 2018), XL-Calibur (Abarr et al., 2021), IBIS (Ubertini et al., 2003), SPI (Vedrenne et al., 2003), AstroSat (Vadawale et al., 2015), POLAR (Produit et al., 2018), POLAR-2 (Kole, 2019), PING-P (Kotov et al., 2016), PolariS (Hayashida et al., 2014), COSI (SMEX) (Tomsick et al., 2019), LEAP (McConnell et al., 2021), AMEGO (McEnery et al., 2019), e-ASTROGAM (De Angelis et al., 2018)