A comprehensive analysis of polarized  -ray beam data with HARPO demonstrator

on behalf of
the HARPO collaboration

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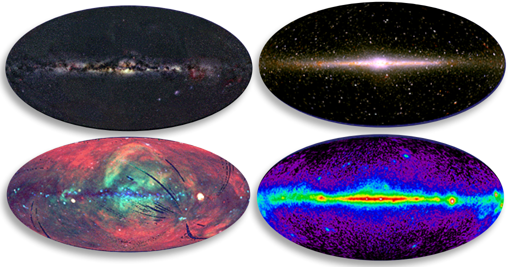
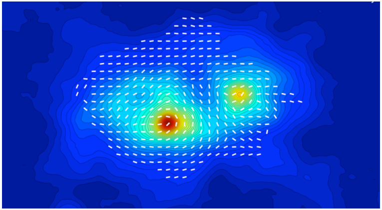
Probing the universe with EM spectrum



▸Observable quantities :

- Direction
- Intensity
- Polarization

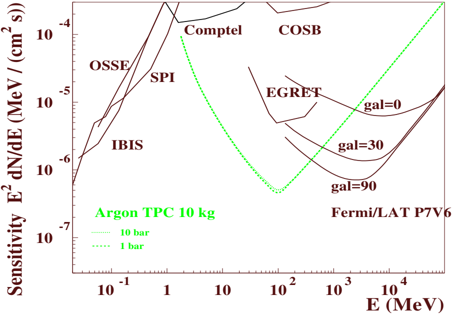
for all energy range !



(NASA:https://www.nasa.gov/)

▸Several models of gamma-ray emission mechanism have very different polarisation signatures.

Our main target (1-100 MeV)

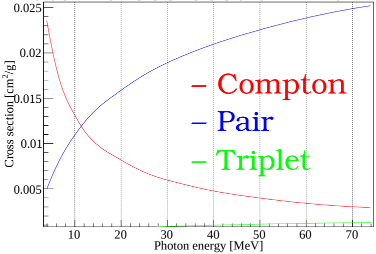


▶Sensitivity gap (1∼100 MeV).

▶No polarization measurement over 1 MeV.

▶Very attractive (Flux $\sim 1/E^2$).

Photon cross section with Ar

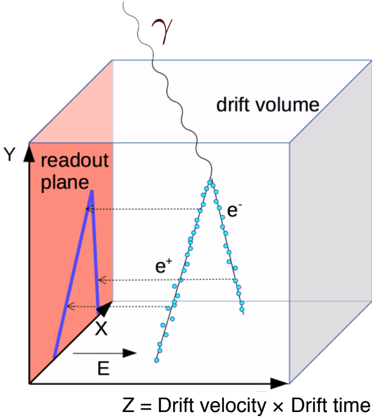


▶Difficulties in this region:
- Feeble Compton scattering,
- Multiple scattering,

→ pair production & thin detector!

TPC as an active target

T ime P rojection C hamber



▶Working principle :

1.) Photon conversion in TPC
$\gamma \rightarrow e^+e^-$,

2.) e^+,e^- ionize gas molecules,

3.) Electrons created along the tracks drift toward end plane,

4.) Read X, Y position and arrival timing,

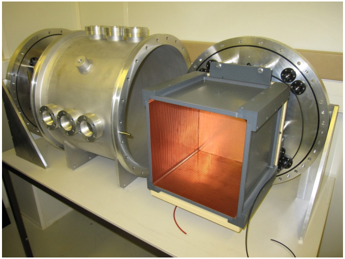
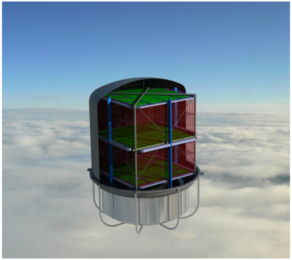
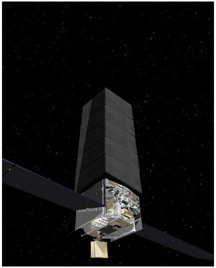
5.) Construct 3D tracks.

Project overview

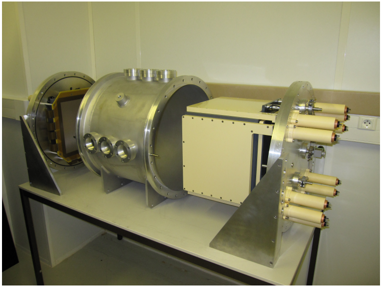
▶Ground phase (=Harpo) ← WE ARE HERE
- Proof of design concept.

▶Balloon phase (∼35 km high), size: 1.2 m×1.2 m×1.2 m
- Feasibility study of self-trigger system.

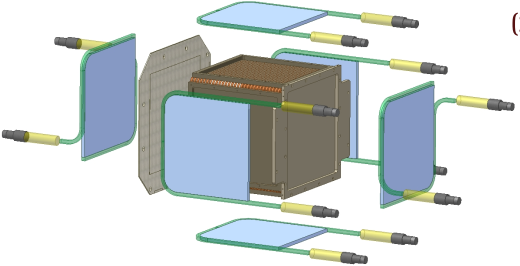
▶Space phase (∼100 km high), size: 2 m×2 m×1 m
- Extending our knowledge of the universe!

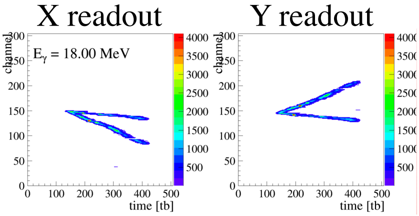




Demonstrator : HARPO



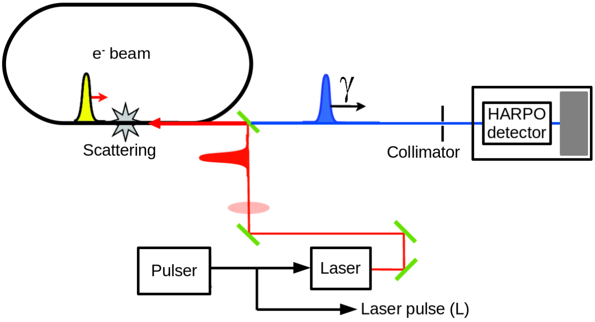
- 30 cm^3 size
- 6 Scintillators for event selection
- Micromegas + GEM
  (GEM was needed for high pressure condition (>3 bar).)
- 2×2D readout (X,Y),
  (288ch×1 mm pitch)

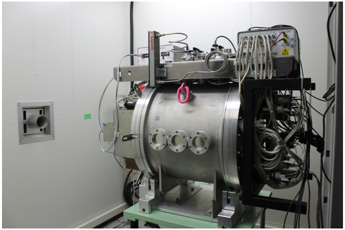




Beam test campaign

NewSUBARU in the Spring-8 site (Japan)



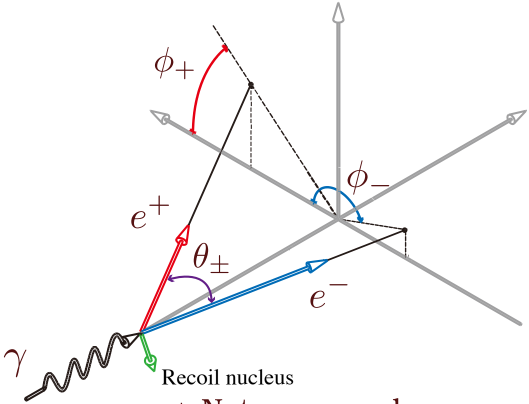


Taken data : Photon beams, E = 1.71 to 72.3 MeV, P=0,∼1.

Main target in this talk : 4 ∼ 20 MeV

- 1.71 ∼ 4 MeV → event pileups due to pseudo continuous laser.
- 20 ∼ 72.3 MeV → saturation, need larger detector.

Measurement strategy



$\rightarrow$ Not measured

e^+, e^- momenta
$\rightarrow$ Only unit vector ($\hat{p}$) measured

- **Azimuthal angle** :

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

- **Opening angle** :

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

(Pseudo) Gamma direction :

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

Differential cross section :

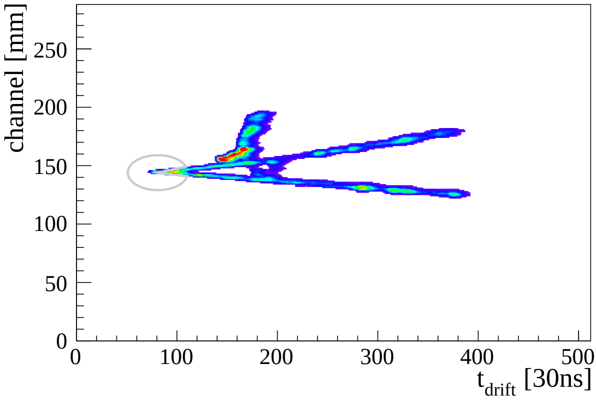
Fraction of polarized phton [0:1]

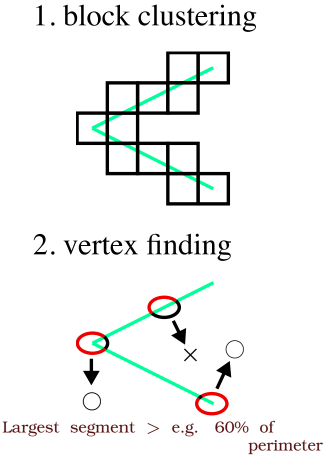
$$\frac{d\sigma}{d\phi} \propto 1 + AP\cos(2\phi)$$

Polarization asymmetry

Event reconstruction

▸ Vertex finding in 2D (XZ and YZ)

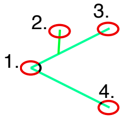


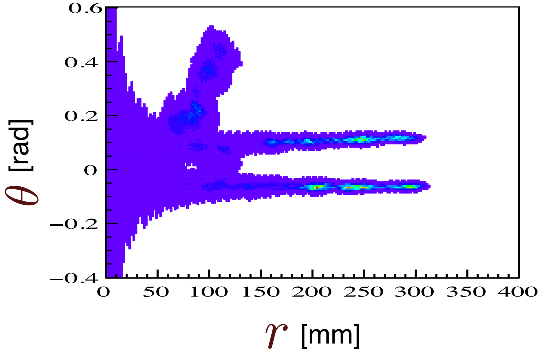


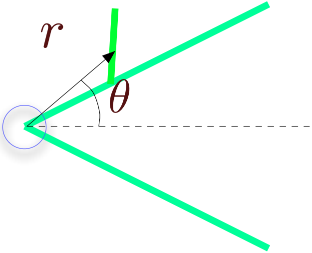
Event reconstruction

▶Track-direction estimation in 2D (Unit vector of e^+/e^- momentum)

3. plotting $r\theta$ to the other clusters from each vertex candidate.



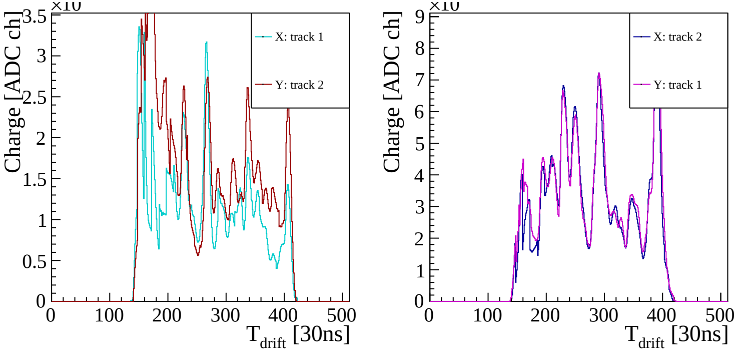




Event reconstruction

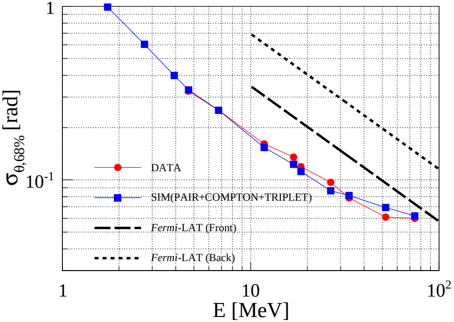
▶$2\times2D \rightarrow 3D$ reconstruction (XZ, YZ $\rightarrow$ XYZ)

2D-track matching based on charge/time information



Telescope performance

Angular resolution



- ▶ Simulation works very well,
- ▶ Good angular resolution,
- ▶20∼100 MeV energy range will be improved with larger detector,
- ▶Momentum measurement for e^+,e^- improves the peformance.

Polarimetry performance

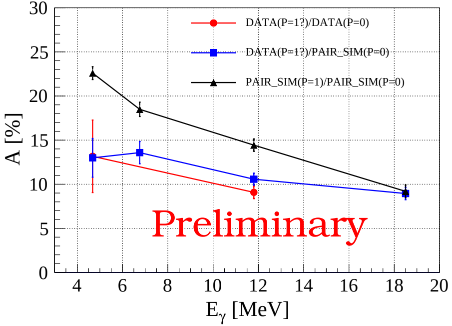
Minimizing systematics by taking ratio of P=1 and P=0.

Fraction of polarized phton [0:1]

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

Polarization asymmetry

Polarization asymmetry



▶Simulation includes only pair process for now.
→ being updated.

▶Good agreement between data and simulation for P=0.

▶Discrepancy between data and simulation for P=1.
→ $P \neq 1$?? No clue.

▶ Polarimetry is feasible!

Conclusion

▶ Gaseous detector can be a good candidate for low energy (1 MeV $\sim$ a few hundreds MeV) gamma-ray astronomy.

▶Ground phase (HARPO) has been completed in good shape.

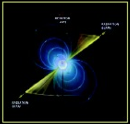
- TPC with Micromegas (+GEM),
- A beam test champaign was successfully done,
- Simulation works very well ,
- There is room for improvement on reconstruction-algorithm, but the results are already promising.

▶We are looking for funding (CNES etc.) for a balloon flight phase (ST3G).

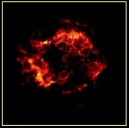
Backup

Science case

- Galactic targets

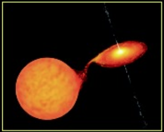


Pulsar

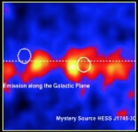


Supernova Remnants

Pulsar wind nebulae



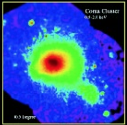
Micro-quasars



Galactic center

- Extragalactic targets

Active Galactic Nuclei



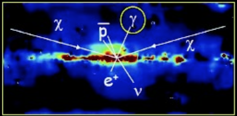
Galaxy Cluster

Starburst galaxies

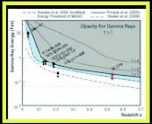
Merging Galaxies

Gamma-ray Bursts

- Fundamental physics



Dark Matter annihilation



Universe transparency

- CR physics
- Lorentz invariance
- Quantum gravity
- Axion-photons obsc

.....

Space challenges

▶Trigger

- Heavy cosmic ray background,

$\rightarrow$ Self-trigger concept,

- Non directional signal,

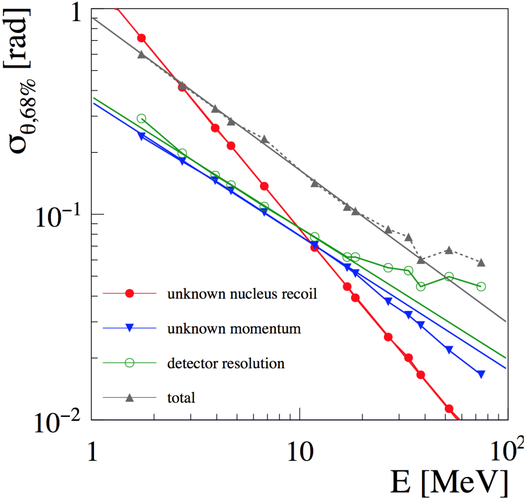
▶Gas stability

- Keep purity over several months/years,

$\rightarrow$ Purification circuit,

▶Radiation hard electronics.

Contribution to angular resolution



Polarization asymmetry

- Coefficient of the angle term for P=1,
- Related to sensitivity of polarization,
- Depending on QED process but also detector effect, (track angular resolution including multiple scattering effect)

$\rightarrow$

Must be measured with known P in advance.

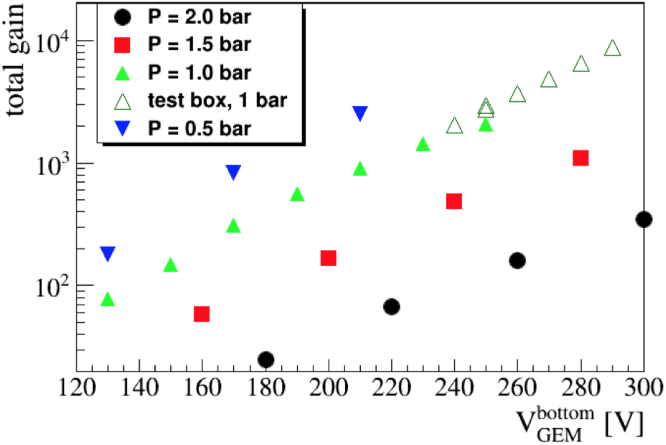
Polarization performance

Ref. : D. Bernard, NIM A 701 (2013) 225.
- Argon at 1 m^3, 5 bar,
- 1 mm point resolution,
- Crab-like source,
- 1 year exposure,
- efficiency ~ 1

$\rightarrow$

Polarization asymmetry $\sim$ 15%,
Polarization resolution $\sim$ 1%.

Gain-Pressure



Beam test information

Gas : Ar/iC_4H_10 95/5, closed,
Pressure : 1, 1.5, 2, 3, 4 bar, mainly 2 bar.
Electronics : AFTER readout electronics, 511 time bins,
33.3 MHz, 100 ns shaping time, digitization 1.67 ms.
$\sim$20% of photons were converted in the detector.

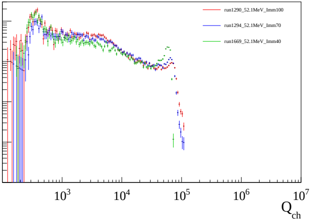
Trigger rate :

7	$T_{\gamma,laser}$	$N_{\overline{S}_{up}\cap O\cap M_{slow}\cap L,p}$	197 822	$\tau_{\overline{S}_{up}\cap O\cap M_{slow}\cap L,p}$	13 (1 ± 0.002) Hz
Main trigger		$N_{\overline{S}_{up}\cap O\cap M_{slow}\cap L,t}$	785 837	$\tau_{\overline{S}_{up}\cap O\cap M_{slow}\cap L,t}$	52 (1 ± 0.001) Hz
8	$T_{noMesh,laser}$	$N_{\overline{S}_{up}\cap O\cap L,p}$	2 698	$\tau_{\overline{S}_{up}\cap O\cap L,p}$	589 (1 ± 0.019) Hz
		$N_{\overline{S}_{up}\cap O\cap L,t}$	321	$\tau_{\overline{S}_{up}\cap O\cap L,t}$	70 (1 ± 0.056) Hz
9	$T_{invMesh,laser}$	$N_{\overline{S}_{up}\cap O\cap M_{quick}\cap L,p}$	9 958	$\tau_{\overline{S}_{up}\cap O\cap M_{quick}\cap L,p}$	506 (1 ± 0.010) Hz
		$N_{\overline{S}_{up}\cap O\cap M_{quick}\cap L,t}$	25	$\tau_{\overline{S}_{up}\cap O\cap M_{quick}\cap L,t}$	1.3 (1 ± 0.020) Hz
10	$T_{noUp,laser}$	$N_{O\cap M_{slow}\cap L,p}$	18 427	$\tau_{O\cap M_{slow}\cap L,p}$	29 (1 ± 0.007) Hz
		$N_{O\cap M_{slow}\cap L,t}$	34 311	$\tau_{O\cap M_{slow}\cap L,t}$	54 (1 ± 0.005) Hz
11	$T_{noPM,laser}$	$N_{\overline{S}_{up}\cap M_{slow}\cap L,p}$	2 136	$\tau_{\overline{S}_{up}\cap M_{slow}\cap L,p}$	18 (1 ± 0.022) Hz
		$N_{\overline{S}_{up}\cap M_{slow}\cap L,t}$	8 862	$\tau_{\overline{S}_{up}\cap M_{slow}\cap L,t}$	73 (1 ± 0.011) Hz

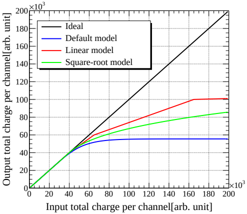
Beam test campaign (2)

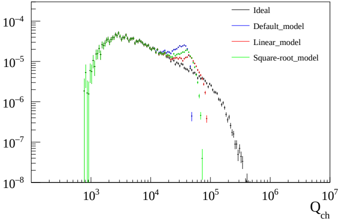
▸Preamplifier saturation

- Charge distribution (Data)



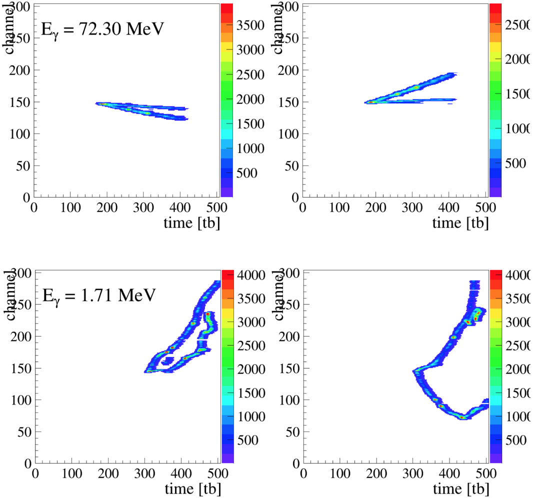
- Simulation



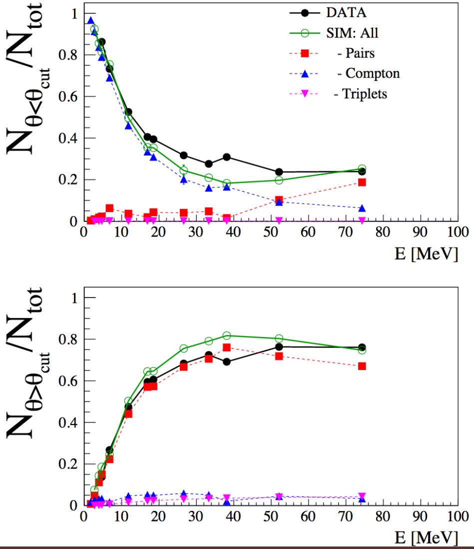


- Saturation point varies.
- Never happens in simulation.
- Found that it was caused by previous saturated events.
- Visible at higher energies because of smaller opening angle.
- Not a big issue for lower energy range ($<$ 20MeV).
- **Avoidable by lowering gain.**

Event display



Event selection performance



Reconstruction information

▶Block clustering : 6 strips, 12 time-bins

▶Possible improvements:
- Vertexing algorithm using better peak-finding,
- Tracking algorithm,
- Momentum estimation using multiple scattering, ...

Gas purification test