

Talks Lay-out

- Wednesday 12 April
 - ST3G - Self-triggered TPC for Space gamma-ray Telescope - A prototype balloon detector,
Deirdre Horan
 - HARPO : development of a prototype gas TPC as a gamma-ray active target, for ground validation
Denis Bernard
- Thursday 13 April
 - High performance gamma-ray astronomy and polarimetry with gas active-target telescopes
Denis Bernard
 - Angular resolution and polarimetry measurement in a 1.7-74MeV photon beam with HARPO
Philippe Gros

The HARPO (Hermetic ARgon POLarimeter) instrument project

- France: the detector

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
^aLLR, Ecole Polytechnique and CNRS/IN2P3, France

David Attié, Pascal Baron, David Baudin, Denis Calvet, Paul Colas, Alain Delbart, Patrick Sizun, Ryo Yonamine ^b
^bIRFU, CEA Saclay, France

Diego Götz ^{b,c}
^cAIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp, CEA Saclay, France

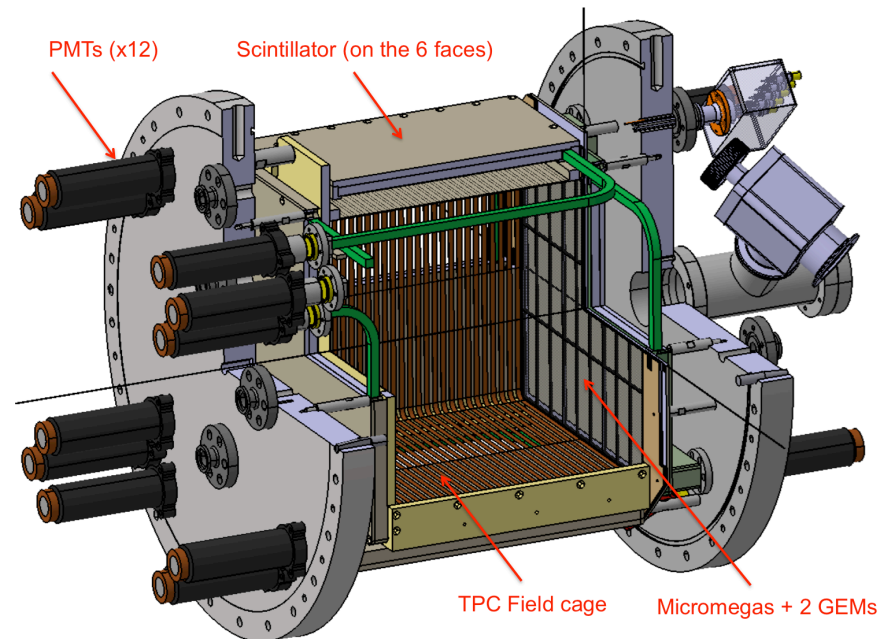
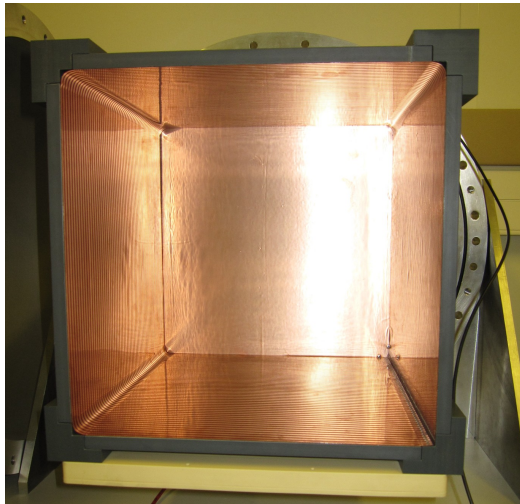
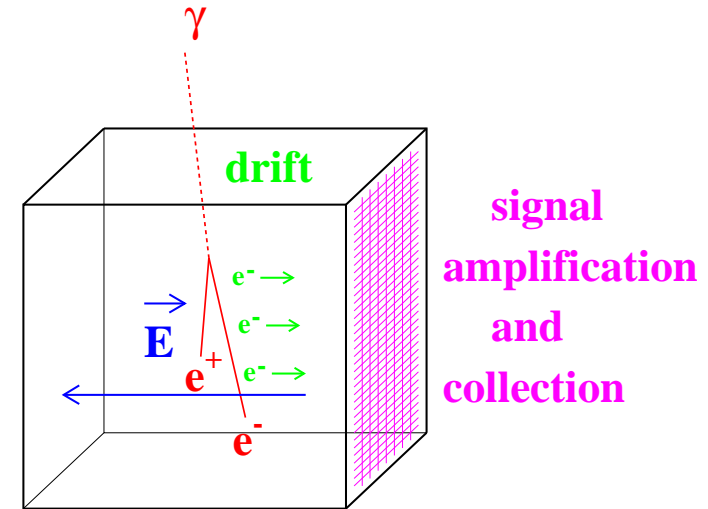
- Japan: the beam.

S. Amano, T. Kotaka, S. Hashimoto, Y. Minamiyama, A. Takemoto, M. Yamaguchi, S. Miyamoto^e
^e LASTI, University of Hyôgo, Japan

S. Daté, H. Ohkuma^f
^f JASRI/SPring8, Japan

HARPO: the Demonstrator

- Time Projection Chamber (TPC)
- $(30\text{cm})^3$ 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

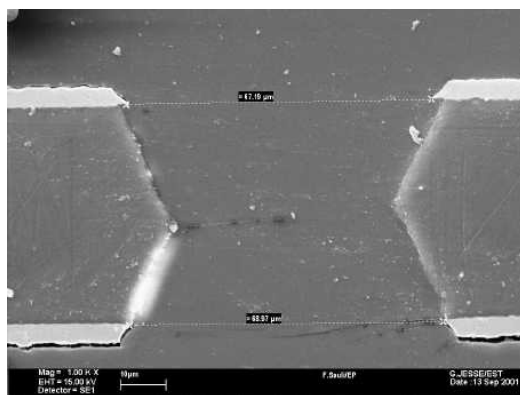
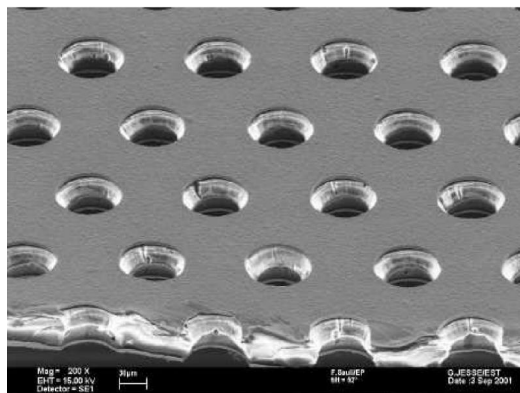


NIM A 695 (2012) 71,

NIM A 718 (2013) 395

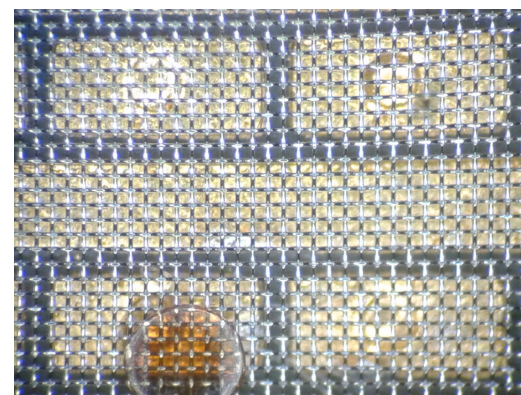
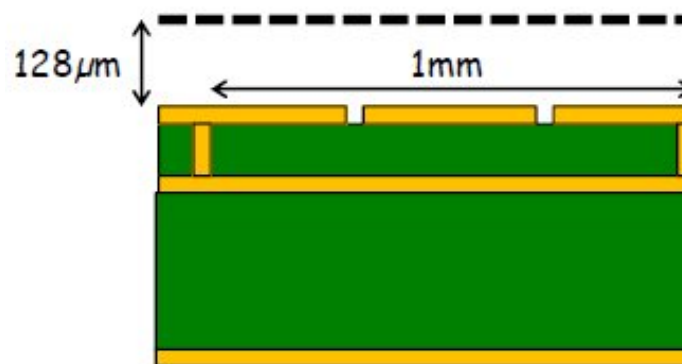
Gas amplification: micromegas + 2 GEM

Gas Electron Multiplier
50 μm Kapton, copper clad,
pitch 140 μm , $\Phi 70 \mu\text{m}$



F. Sauli, NIM A 386, 531 (1997)

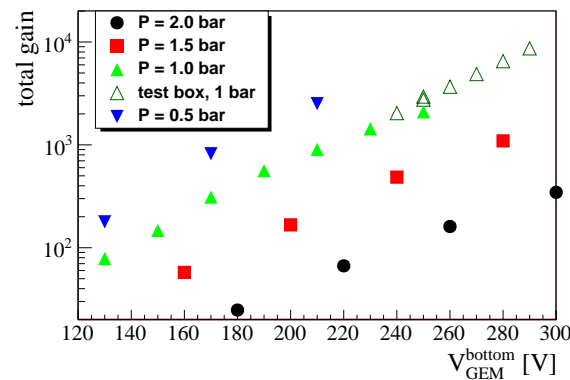
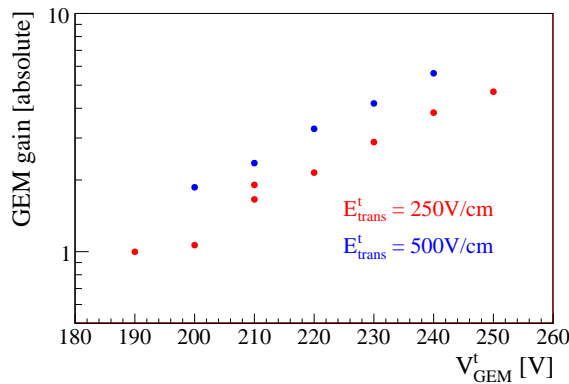
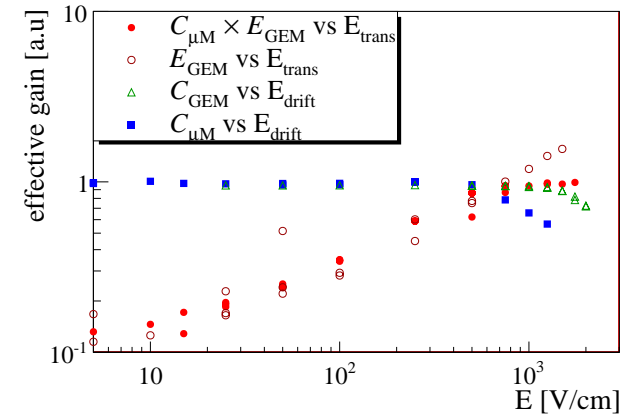
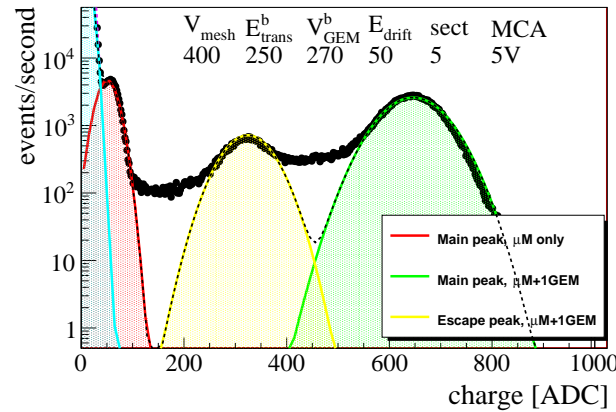
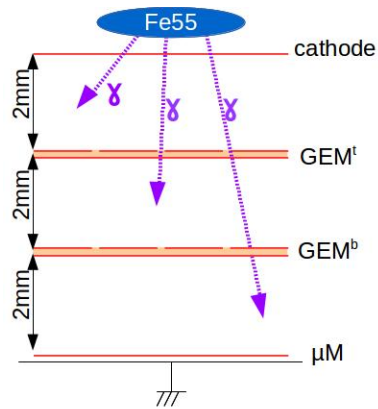
“bulk” micromegas
gap 128 μm



I. Giomataris et al., NIM A 560, 405 (2006)

Micromegas + 2 GEM assemblies: characterization

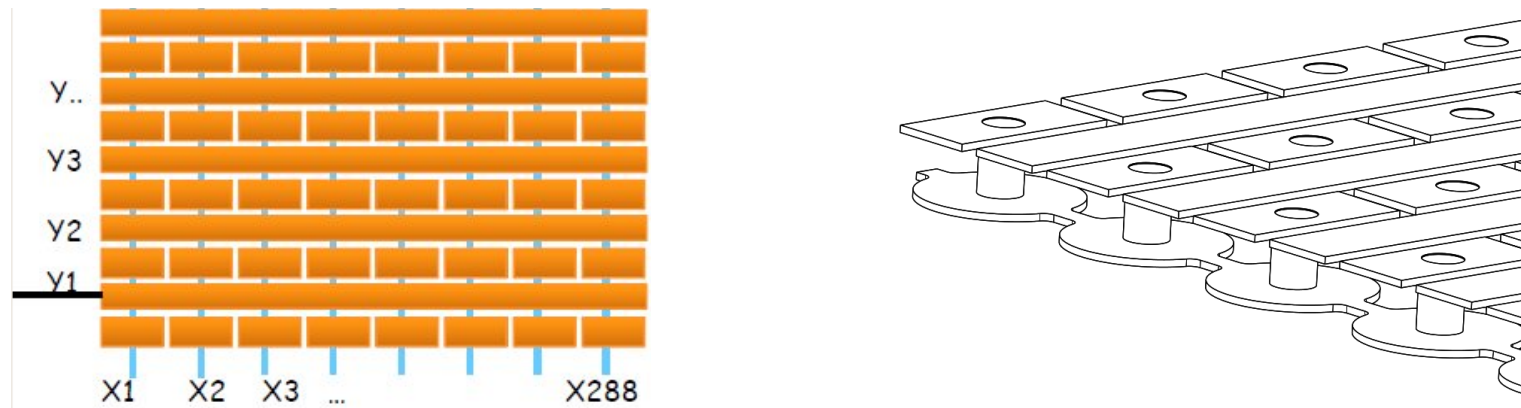
^{55}Fe (dedicated test bench) and cosmic-rays (in TPC)



Ph. Gros et al., TIPP2014, PoS(TIPP2014)133

Anode segmentation

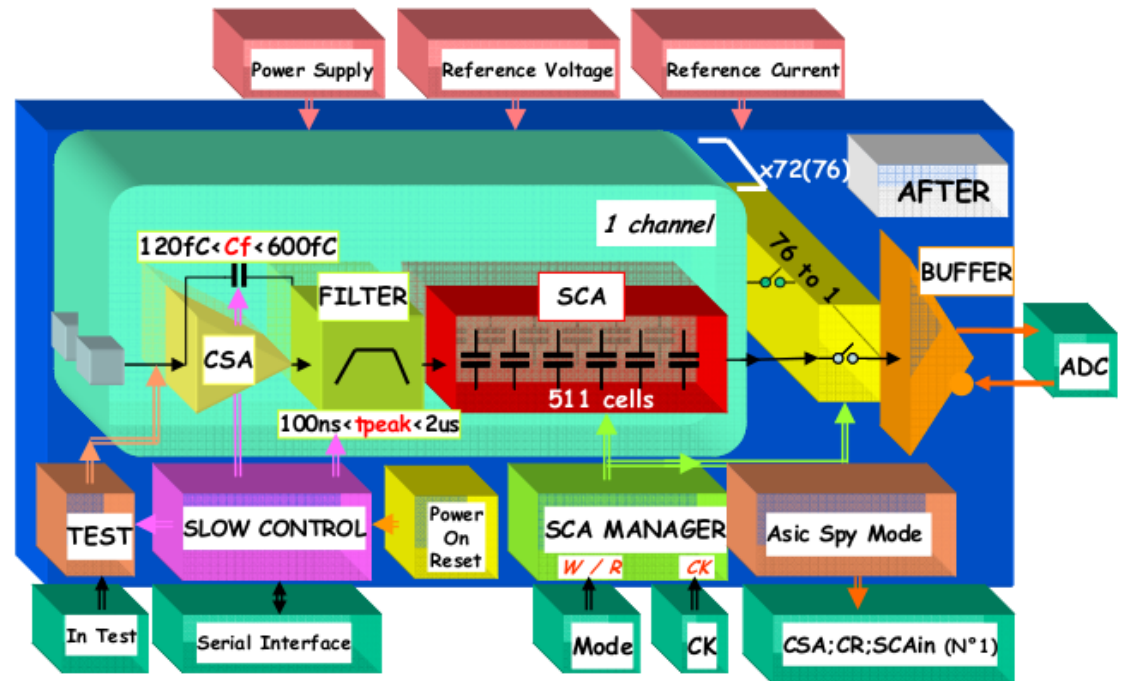
- Avalanche electrons collected on a segmented anode.



- Cu-clad PCB, strip pitch 1 mm, strip width $\approx 400 \mu\text{m}$

Signal digitization

- 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 μ s
- 12 bit ADC.



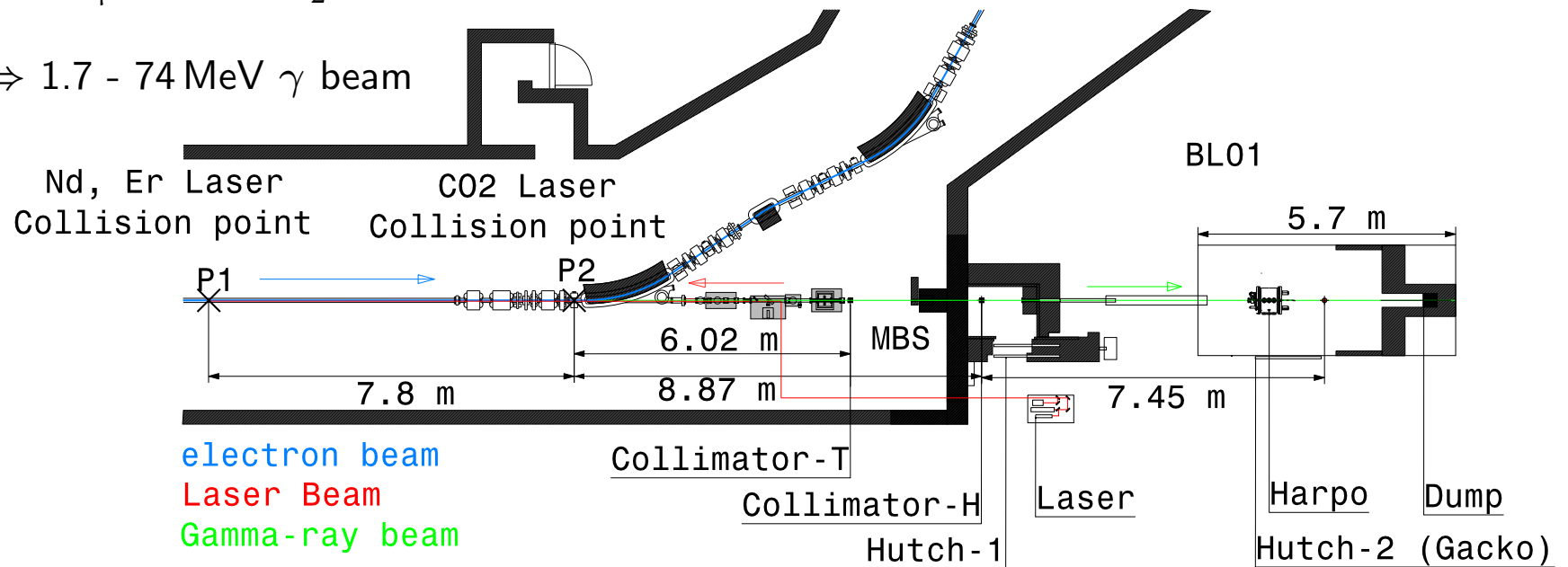
Our set-up: 1/(30 ns) sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

P. Baron et al., IEEE Trans. Nucl. Sci. 55, 1744 (2008).

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

- Linearly polarized γ beam from Laser inverse Compton scattering, e^- beam 0.6 – 1.5 GeV.
- 0.532 μm and 1.064 μm 20 kHz pulsed Nd:YVO₄ (2ω and 1ω), 1.540 μm 200 kHz pulsed Er (fibre) and 10.55 μm CW CO₂ lasers

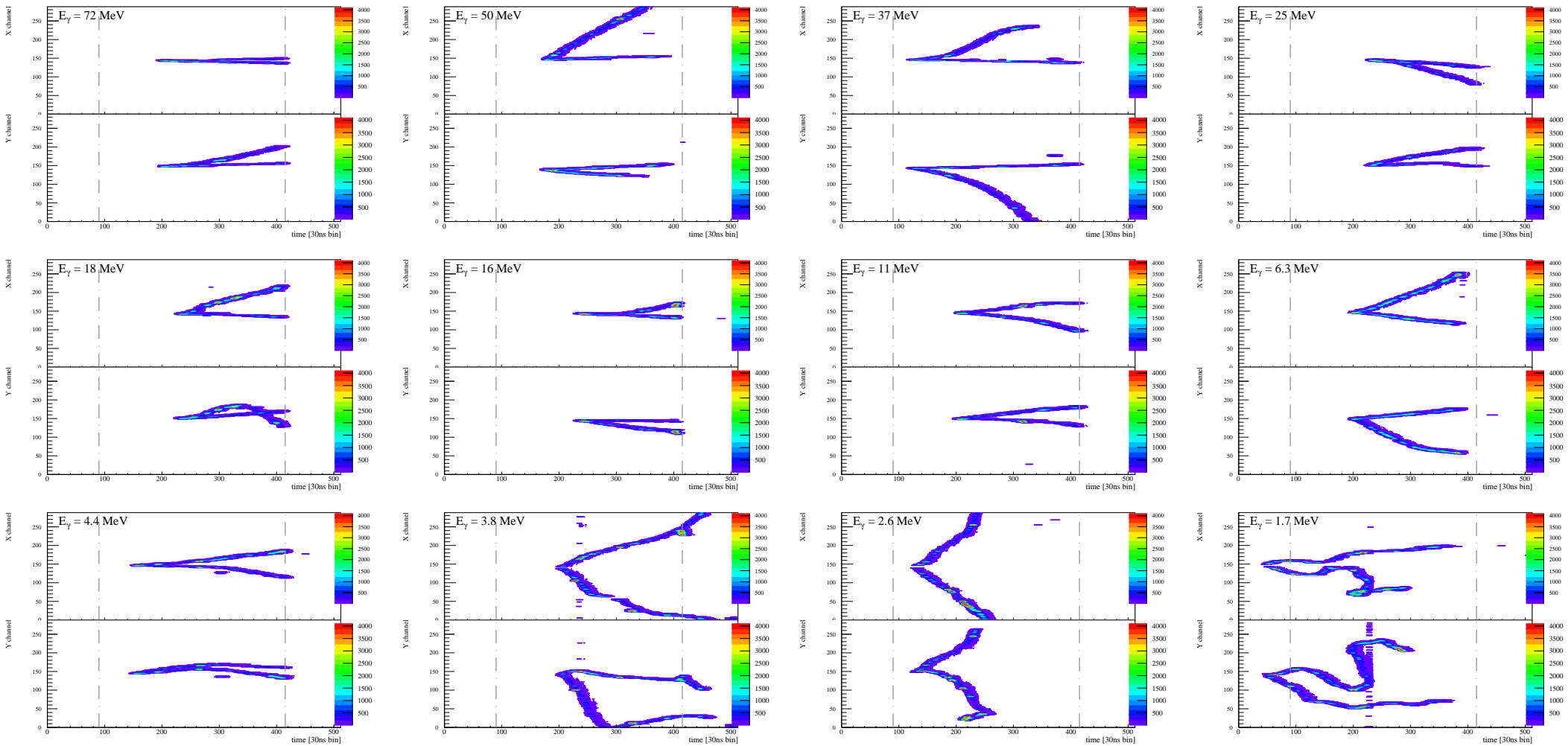
- \Rightarrow 1.7 - 74 MeV γ beam



- Monochromaticity by collimation on axis
- Fully polarized or random polarization beams ($P = 0$, $P = 1$)
- 2.1 bar Ar:isoC₄H₁₀ 95:5 (+ a 1-4 bar scan).

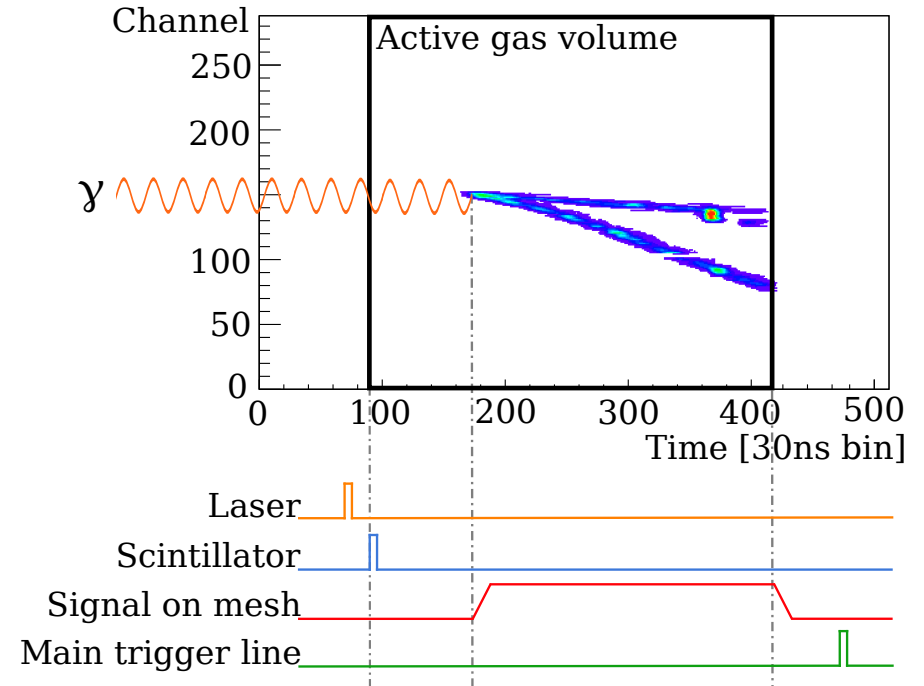
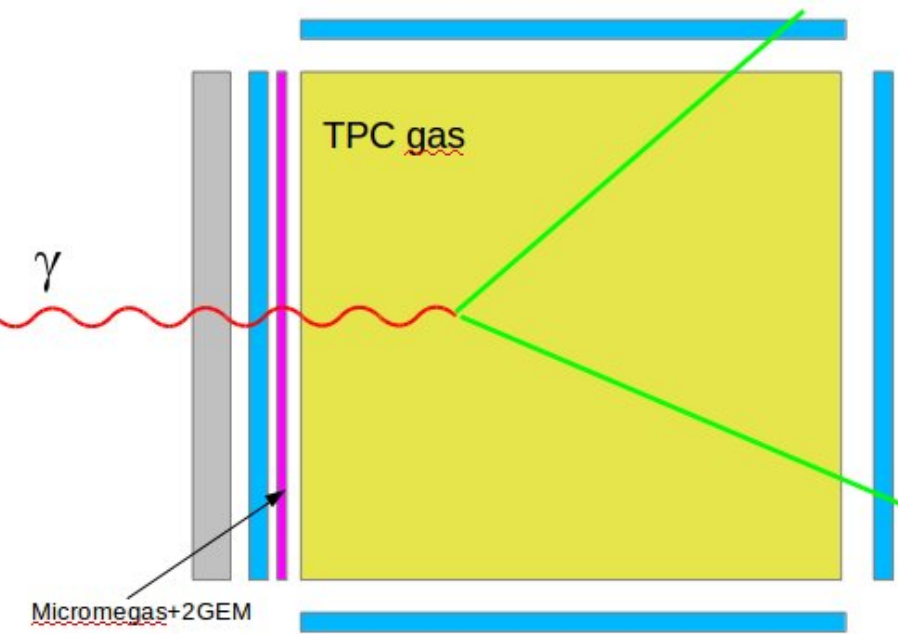
A. Delbart et al., ICRC2015, The Hague, 2015

Japan beam Data: gallery



Sample of γ -rays from 74 to 1.7 MeV converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5
detected by the HARPO TPC
(pre-beam-calibration γ -ray energy on plots)

“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

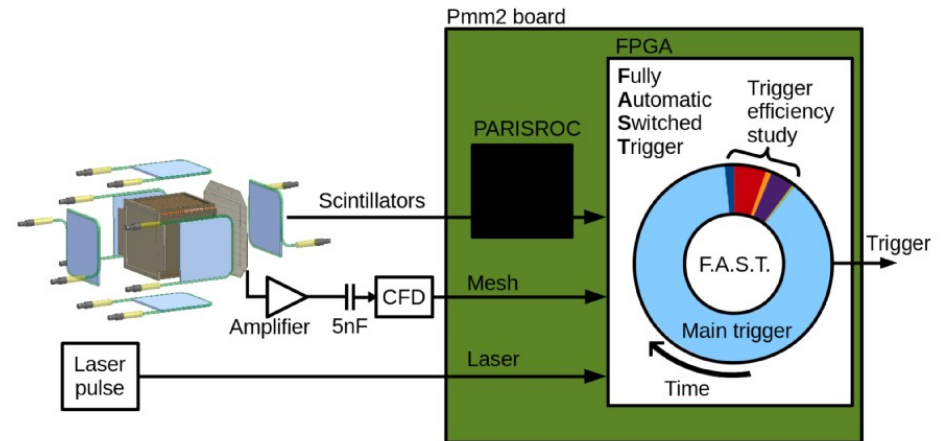
“Main line”: $T_{\gamma,laser} = \bar{S}_{up} \cap O \cap M_{slow} \cap L$

Wang et al., TPC2014, Paris, [J. Phys. Conf. Ser. 650 \(2015\) 012016](#), [arXiv:1503.03772 \[astro-ph.IM\]](#)

“Beam” trigger system: additional lines

- Additional trigger lines:

7	$T_{\gamma,laser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap L$
8	$T_{noMesh,laser}$	$\overline{S}_{up} \cap O \cap L$
9	$T_{invMesh,laser}$	$\overline{S}_{up} \cap O \cap M_{quick} \cap L$
10	$T_{noUp,laser}$	$O \cap M_{slow} \cap L$
11	$T_{noPM,laser}$	$\overline{S}_{up} \cap M_{slow} \cap L$
12	$T_{noLaser}$	$\overline{S}_{up} \cap O \cap M_{slow} \cap \overline{L}$

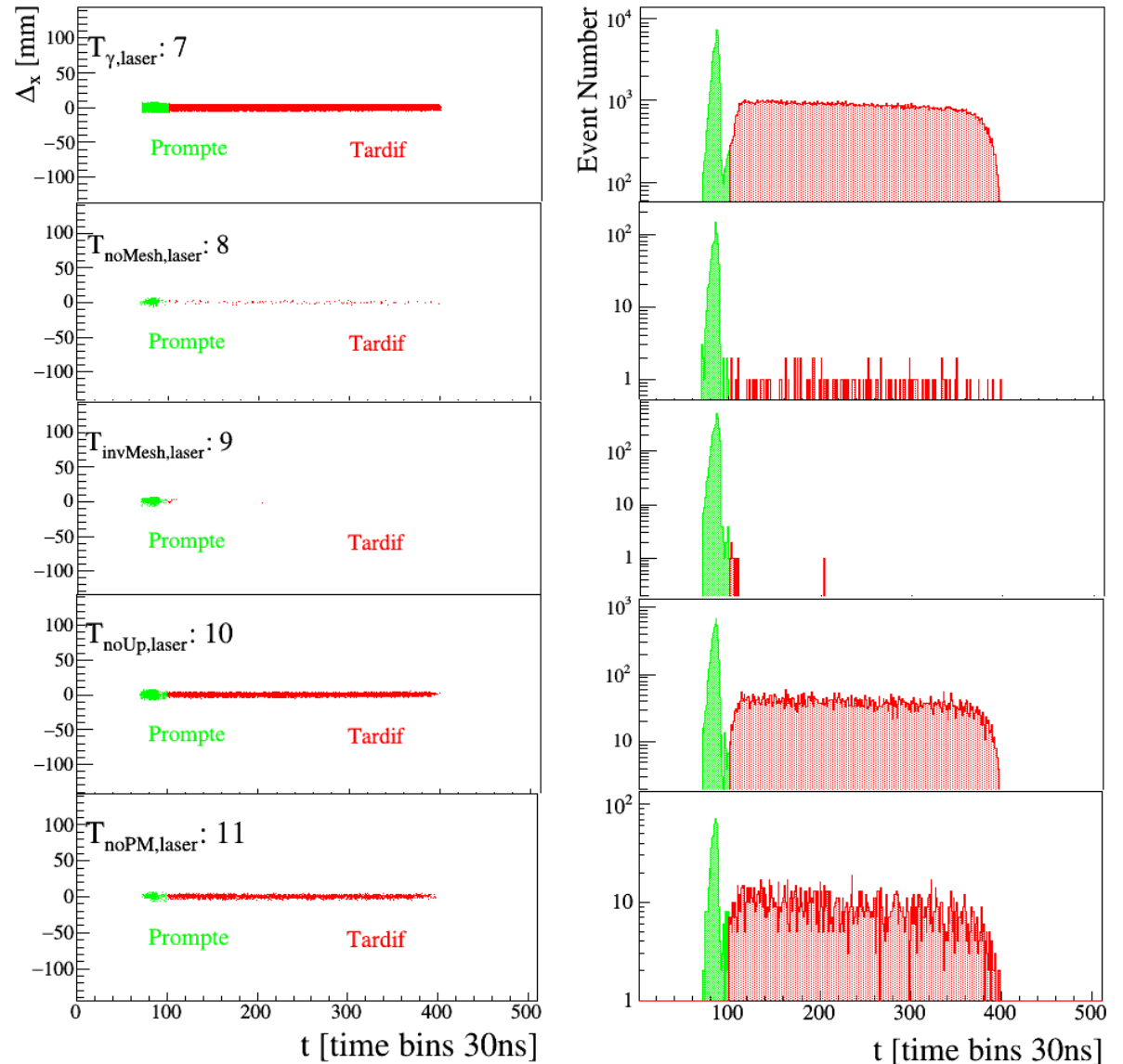


Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

Y. Geerebaert, P. Gros, et al., Vienna Conference on Instrumentation 2016

“Beam” trigger system: conversion point distributions

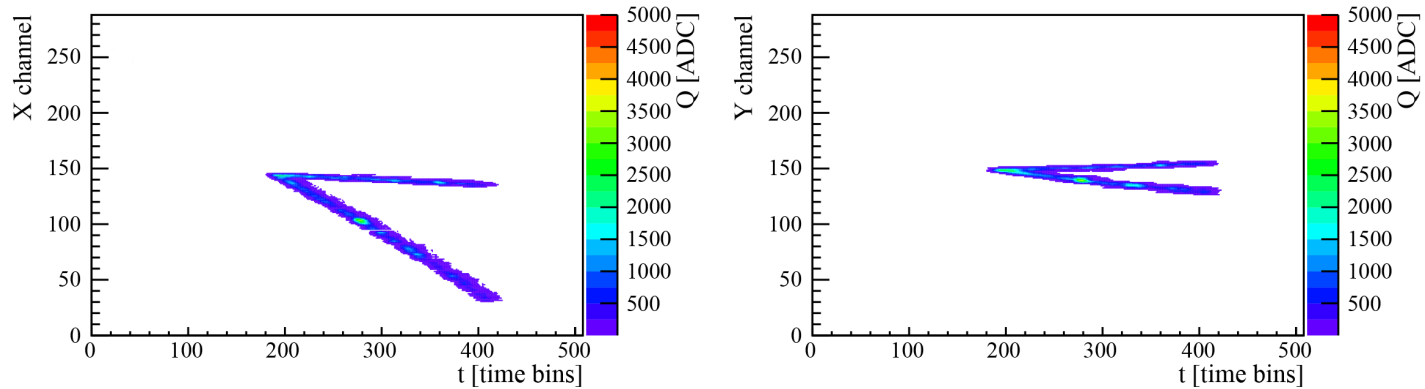
- signal efficiency 51 %
- background rejection 99.3 %
- incident rate 2 kHz
- signal on disk 50 Hz



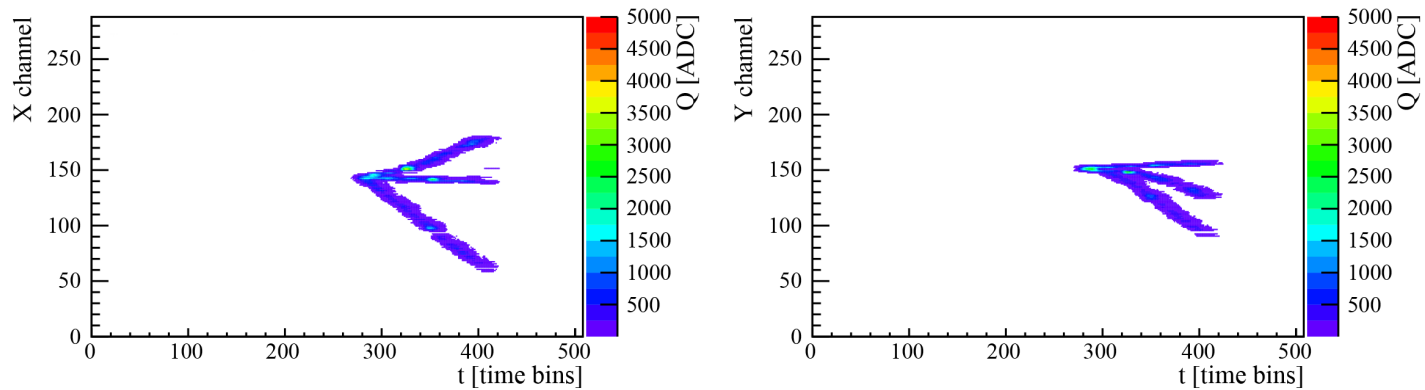
S. Wang, Ph D Thesis, Ecole Polytechnique, 24 septembre 2015, in French

End of “ground” prototype validation section

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



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



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

Towards a space detector: some elements

- Gas composition
- Gas pressure
- Temperature range
- Gas purity on the long term
- . . .

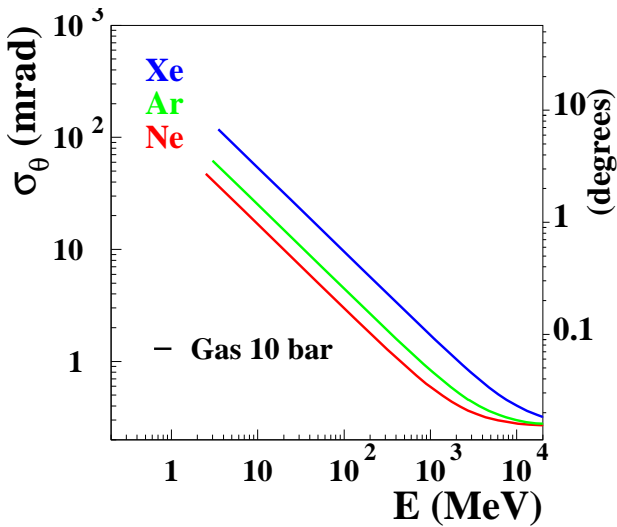
Towards a space detector: Gas composition: drifting species ?

- TPC's to some extent immune to pile-up
- $2 \times 1D$ orthogonal strips given the (small) available electronic powering (i.e., not pads)
- proton flux $20\text{kHz}/\text{m}^2$ at Fermi/LAT orbit.
- need "fast gas":

drifting species	example	v_{drift}	t_{drift}	pile-up fraction	
electron	Ar:isoC ₄ H ₁₀	3.3 cm/ μs	10 μs	0.2 proton/ m^2	manageable
negative ion	Ar:CS ₂	3.3 cm/ms	10ms	200 proton/ m^2	nope

Gas composition: light / heavy Z ? Gas pressure ?

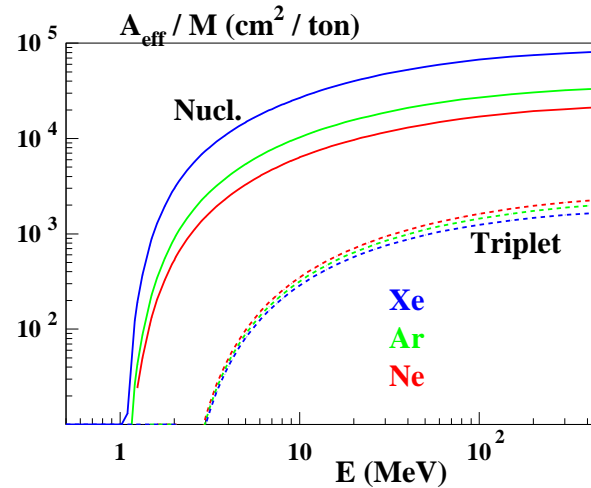
- $\rho \times X_0 = \frac{A}{Z^2} b$, $\rho = aAP$, $M = V\rho = VaAP$, $X_0 = \frac{b}{aZ^2P}$ a, b constants.



angular resolution degrades with Z

$$\sigma_\theta \propto X_0^{-3/8} \propto Z^{3/4} P^{3/8}$$

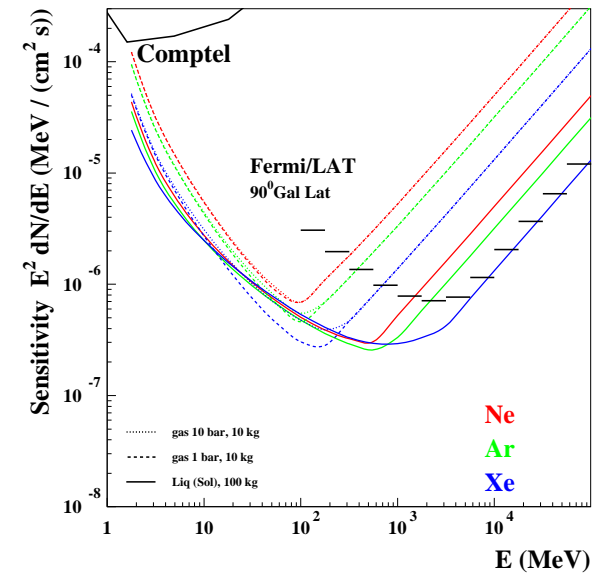
(multiple scattering)



effective area improves with Z

$$A_{\text{eff}} \propto \frac{V}{X_0} \propto VPZ^2$$

(asymptotically)



sensitivity mildly affected

$$s \propto \frac{\sigma_\theta}{\sqrt{A_{\text{eff}}}} \propto \frac{X_0^{1/8}}{\sqrt{V}} \propto \frac{1}{V^{1/2} Z^{1/4} P^{1/8}}$$

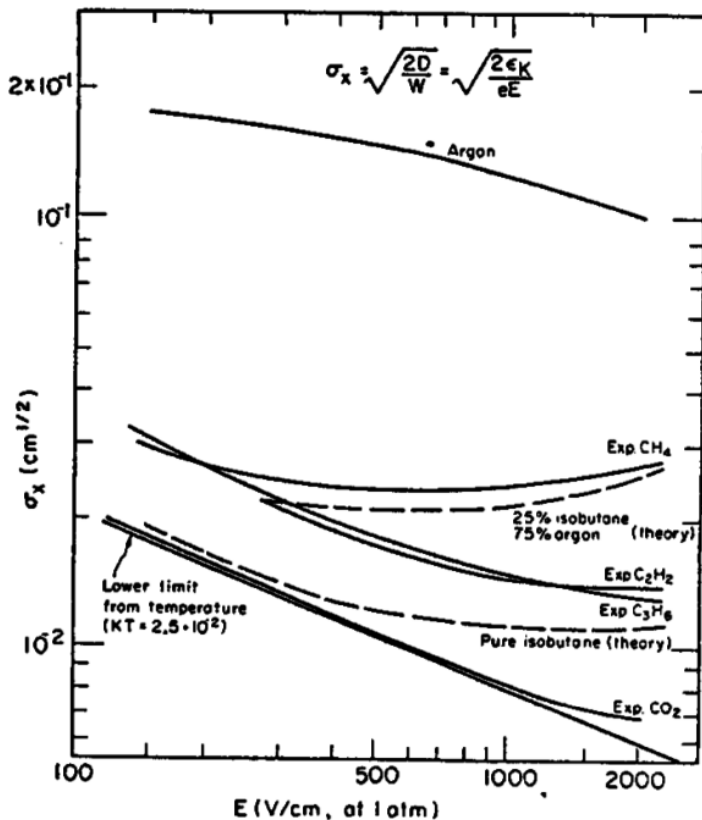
(assuming gaussian stats.)

- Note that $M_{\text{vessel}} \propto P$ and $M_{\text{gas}} \propto P$ so $M_{\text{vessel}} \propto M_{\text{gas}}$

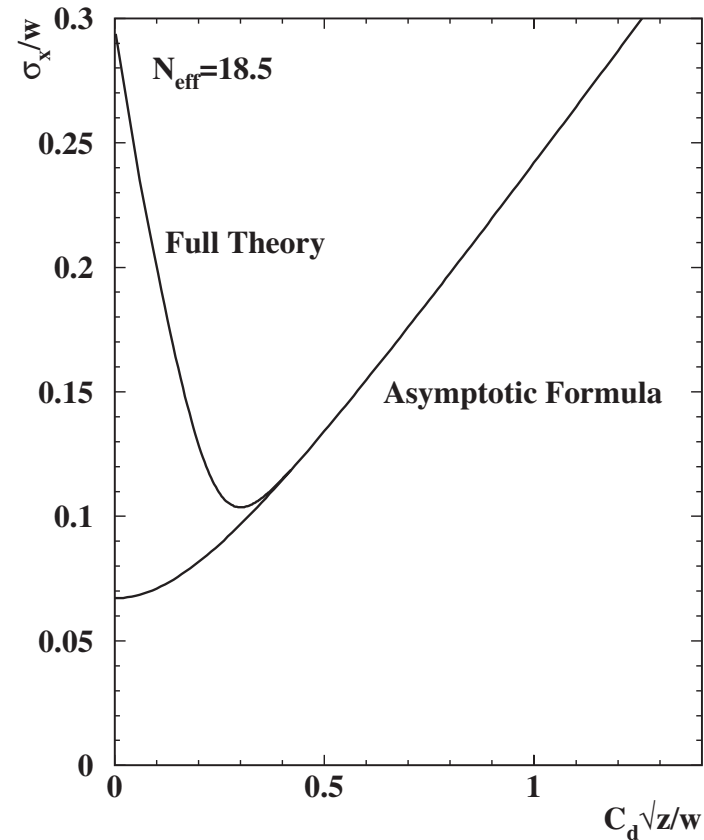
$M_{\text{vessel}} / M_{\text{gas}} \approx 0.36$ for Ti alloy sphere at elastic limit / Argon.

NIM A 701 (2013) 225

Gas composition, quencher



F. Sauli CERN-EP-83-103, 1983



D. C. Arogancia et al., NIM A 602, 403 (2009)

- Gas detectors need limitation of breakdown from UV photoelectric effect on the cathode: add poly($n > 2$)molecular “quencher” gas (alcanes, CO_2 ..)
- Mitigates diffusion $\sigma = \sigma_x / \sqrt{z}$, $\sigma_x = 200 \mu\text{m} / \sqrt{\text{cm}}$, ($\sigma \approx 0.6 \text{ mm}$ after $z = 9 \text{ cm}$ drift)
- Diffusion is needed to minimize the TPC spatial resolution ! $C_D \equiv \sigma_x$, w strip pitch.

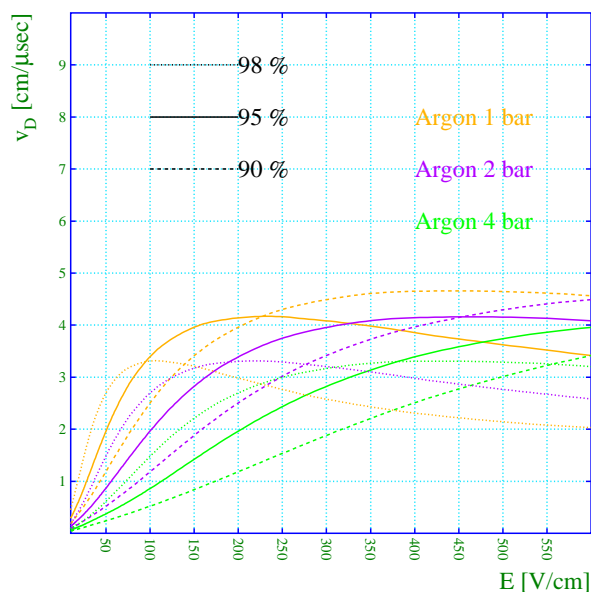
Pressure, Quencher fraction, e^- transport properties

- Argon-iso-butane mixture with (2, 5, 10)% iso-butane and pressure 1, 2, 4 bar

Drift velocity

$$v_{\text{drift}} \text{ cm}/\mu\text{s}$$

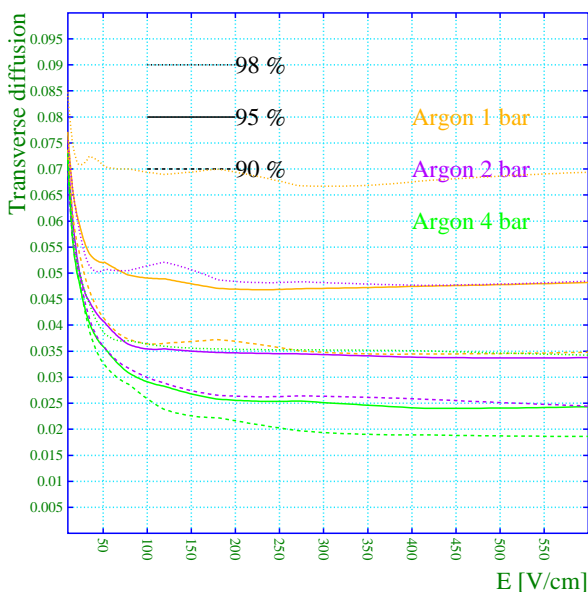
Drift velocity in Ar/ISO mixtures



Transverse diffusion coefficient

$$C_{D,T} \text{ cm}/\sqrt{\text{cm}}$$

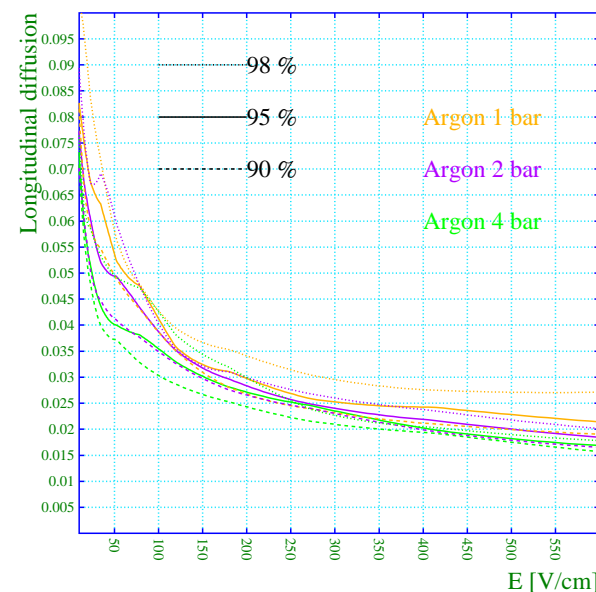
Transverse diffusion in Ar/ISO mixtures



Longitudinal diffusion coefficient

$$C_{D,L} \text{ cm}/\sqrt{\text{cm}}$$

Longitudinal diffusion in Ar/ISO-95 mixtures



- v_{drift} max value does not depend on P ; E value for v_{drift} maximum is $\propto P_{\text{C4H10}}$.
- $C_{D,T} \propto 1/\sqrt{P_{\text{C4H10}}}$, Transverse diffusion coefficient determined by quencher partial pressure
- $C_{D,L}$ fn of E , Longitudinal diffusion coefficient determined by drift field

garfield.web.cern.ch/

Temperature variation, Temperature range

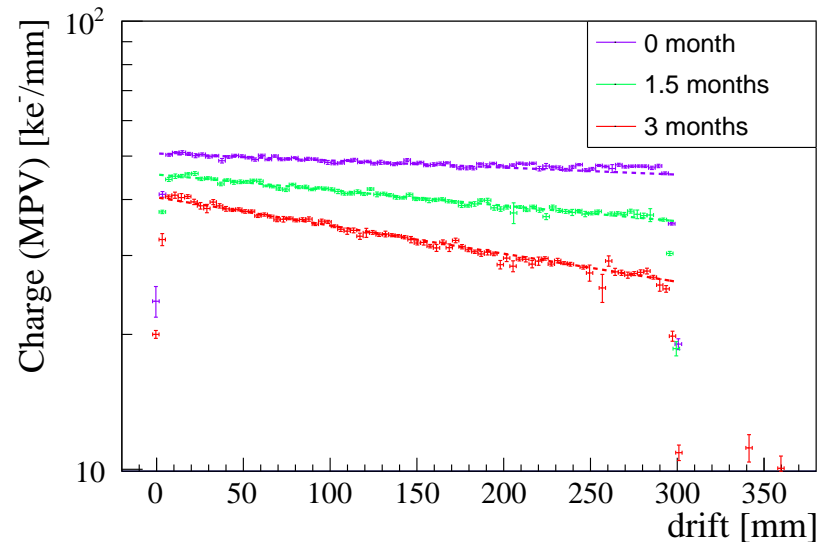
- TPC parameters depend on gas density ρ , not on (pressure P , temperature T)
- Thermal vessel volume variations corrected by small (drift, amplification) voltages.
(We operated the same set-up in the range 1-4 bar by simple voltage adjustments)
- Maximal temperature ?
 - check your electronics !
- Minimal temperature ?
 - avoid quencher partial liquefaction

gas	Ar	Xe	CH ₄	C ₂ H ₆	iso C ₄ H ₁₀
boiling point at 1.013 bar (°C)	-185.8	-108.1	-161.5	-89	-11.7

- alkanes have similar quencher properties.

Gas purity on the long term

- HARPO pressure vessel extremely dirty: scintillator, WLS, PVC box, PCB, epoxy, O-rings ..
- We have observed the evolution of the gaz quality in sealed mode [Fev. - Jun.] 2015 (2.1 bar).

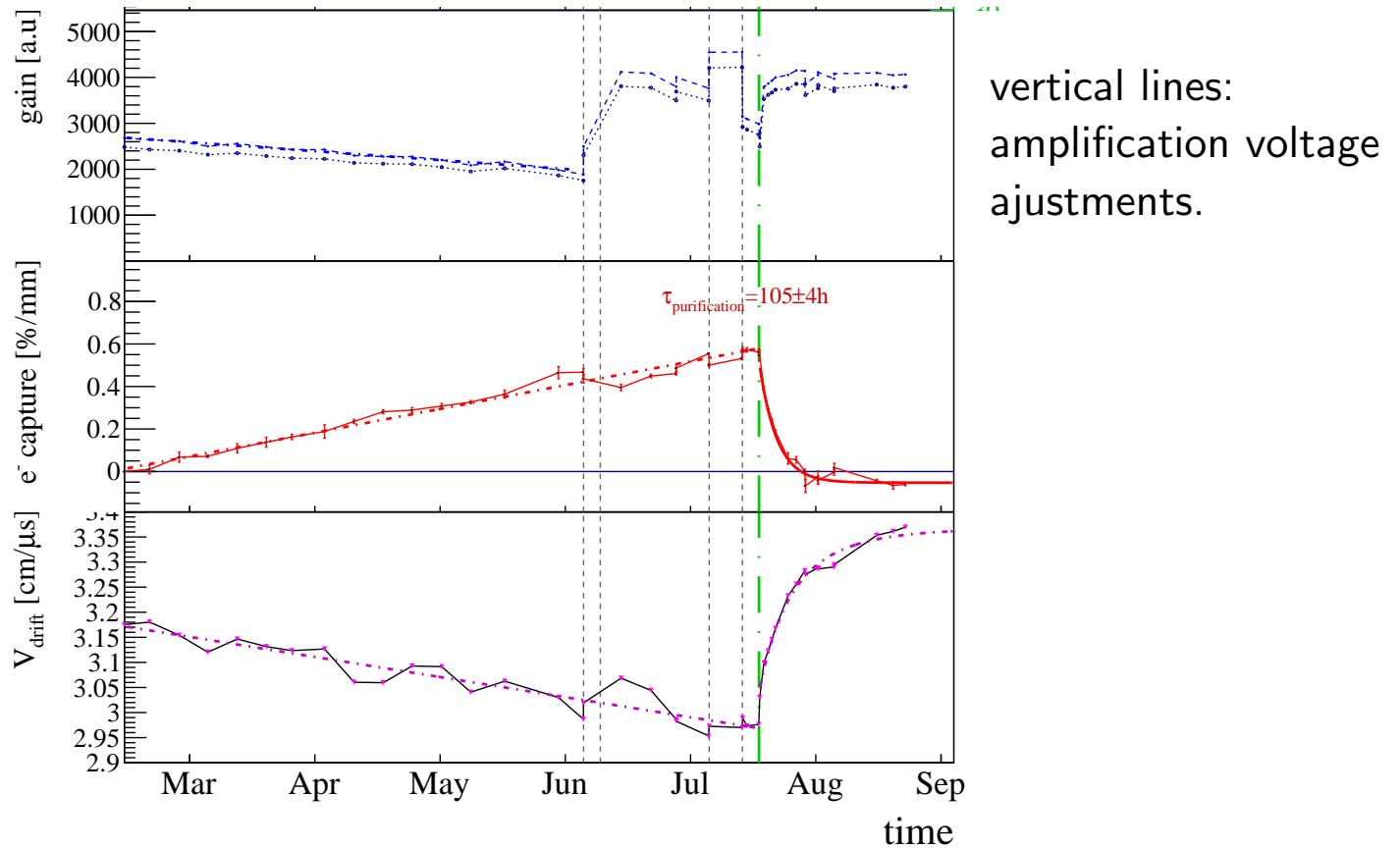


Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- **O₂ fraction peaked at 180 ppm** on Jul. 08. $O_2/(O_2 + N_2) = 0.225$, compatible with air.
- Then we switched an oxisorb recirculation to operation. **O₂ fraction disappeared (< 20 ppm)**

M. Frotin et al., [arXiv:1512.03248](https://arxiv.org/abs/1512.03248) [physics.ins-det], MPGD2015, EPJ Web of Conferences

Gas purity on the long term: results



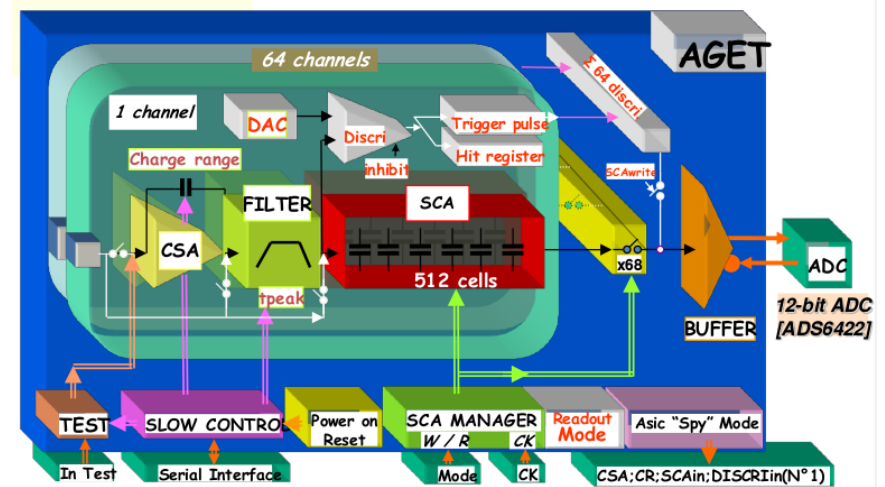
Time evolution of the amplification gain, of the electron capture and of the drift velocity as measured with cosmic-rays through [Fev. - Sept.] 2015.

- Interpreted as air leak or air outgassing, with complete gas cleaning upon purification
- Good prospects to run a TPC for years with a simple oxisorb cleaning

M. Frotin et al., [arXiv:1512.03248](https://arxiv.org/abs/1512.03248) [physics.ins-det], MPGD2015, EPJ Web of Conferences

AGET: ASIC for Generic Electronics for TPC

- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- shaping: 16 peaking time values: 70 ns to 1 μ s
- 512 analog memory cells / channel
- F_{sampling}: 1 MHz to 100 MHz; F_{read}: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real time (25 MHz) Multiplicity signal: analog OR of the 64 discr Outputs
- Readout:



S. Anvar *et al.*, NSS/MIC, 2011 IEEE 745 - 749.

- Address of the hit channel(s)
 - 3 readout modes: All, hit or specific channels
 - Predefined number of analog cells / trigger (1 to 512)
-
- AGET → **radhard** ASTRE: “Asic with SCA & Trigger for detector Readout Electronics”:
Prototype series to foundry (2016). Tests in progress.

Conclusion

- Gas TPC is THE choice detector for ultimate angular resolution $\gamma \rightarrow e^+e^-$ astronomy and polarimetry
- Robust detector used in HEP since the 1980's from sub-cm³ to multi-m³
- From the lowest (eg. T2K) to the highest (eg. ALICE) rate, radiation, track multiplicity
- Use of a “Fast” gas ($v_{\text{drift}} \gg 1 \text{ cm}/\mu\text{s}$) mitigates background pile-up
- 4π acceptance, \approx isotropic performances (x, y, z), $< 30 \text{ ns}$ event time resolution
- Low number of electronics modules by use of projections – strips.
 - induced track matching issue easily solved.
- Ability to cope with intense GRB – dedicated buffer needed
- Key issue is self-triggering: ST3G scheme under study
 - radhard and upgraded version of digitizing chip realized
 - balloon flight prototype under study.
- Data taken:
 - with a (30cm)³ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
 - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, γ beam

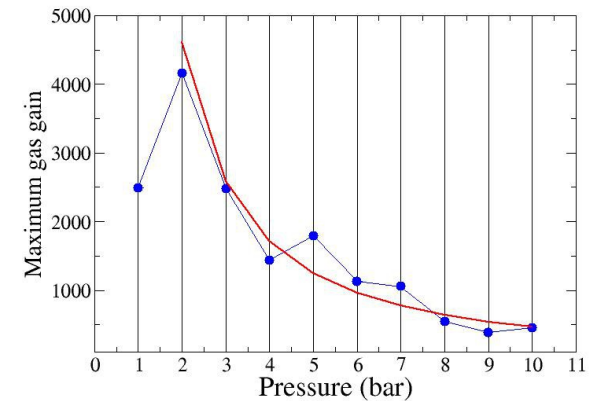
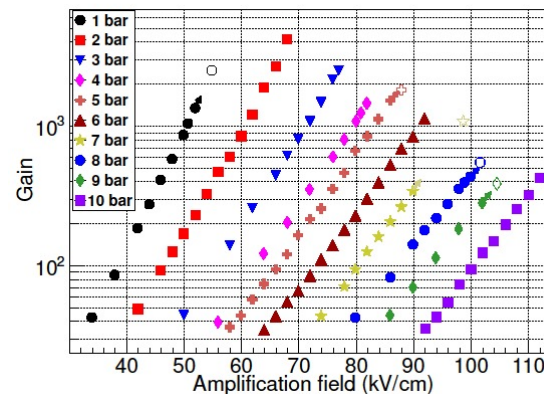
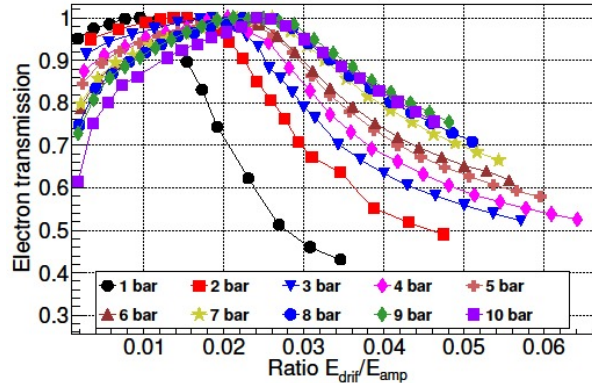
Analysis: Philippe's talk !

Je vous remercie de votre attention distinguée !

Back-up Slides

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** ..



D. C. Herrera, *et al.*, "Micromegas-TPC operation at high pressure in Xenon-trimethylamine mixtures," J. Phys. Conf. Ser. 460, 012012 (2013).

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 given at 1, 5, 10 bar.

Data taken mostly at 2.1 bar, + a 1-4 bar scan.

Search for Axions

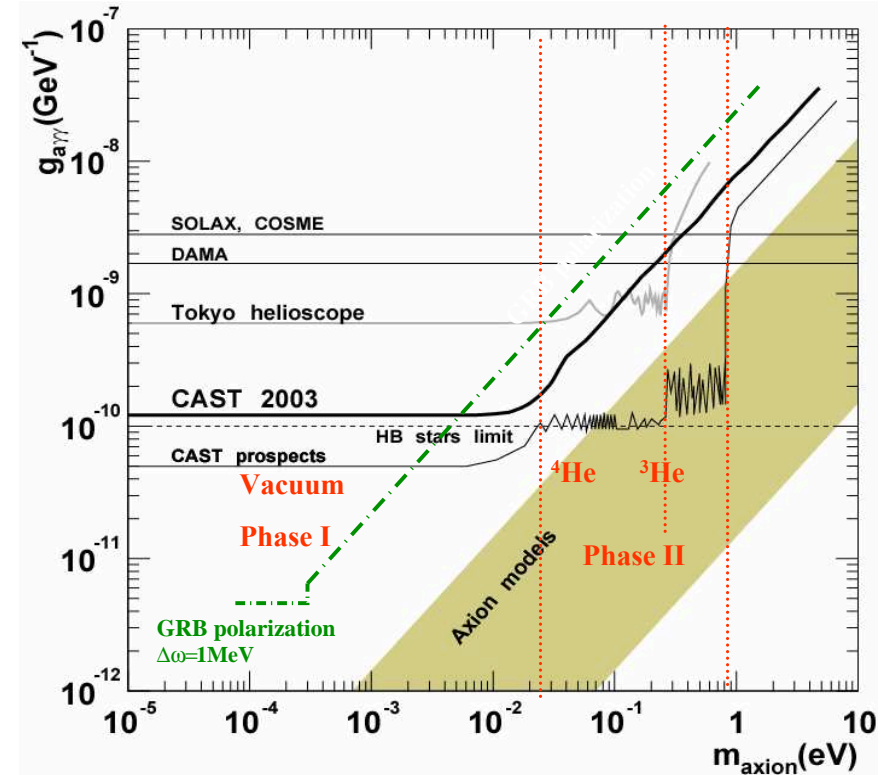
- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to 2 γ through triangle anomaly.
- γ propagation through $B \Rightarrow$ Dichroism $\Rightarrow E$ dependant rotation of linear polarization \Rightarrow linear polarization dilution.

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B \sqrt{\Delta\omega L_{GRB}}}$$

- 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 ω -independent constant.

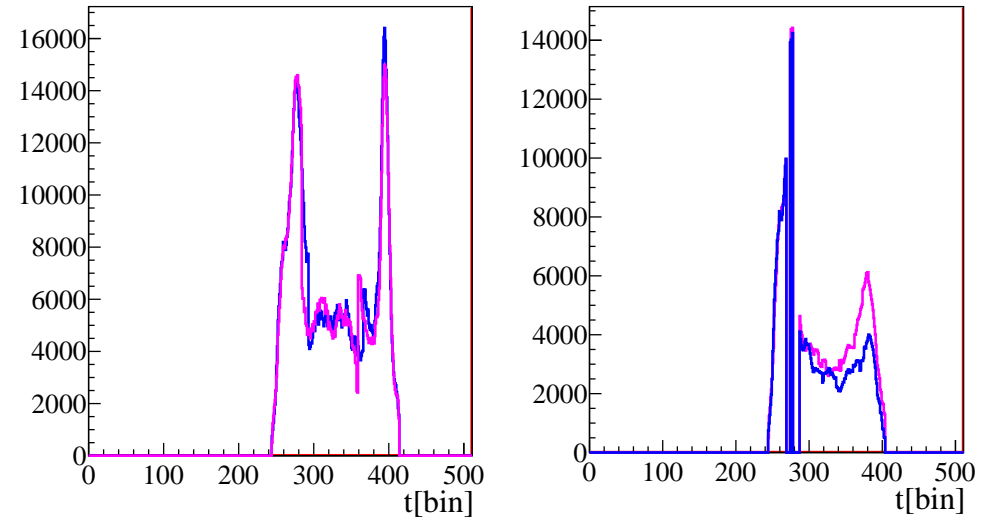
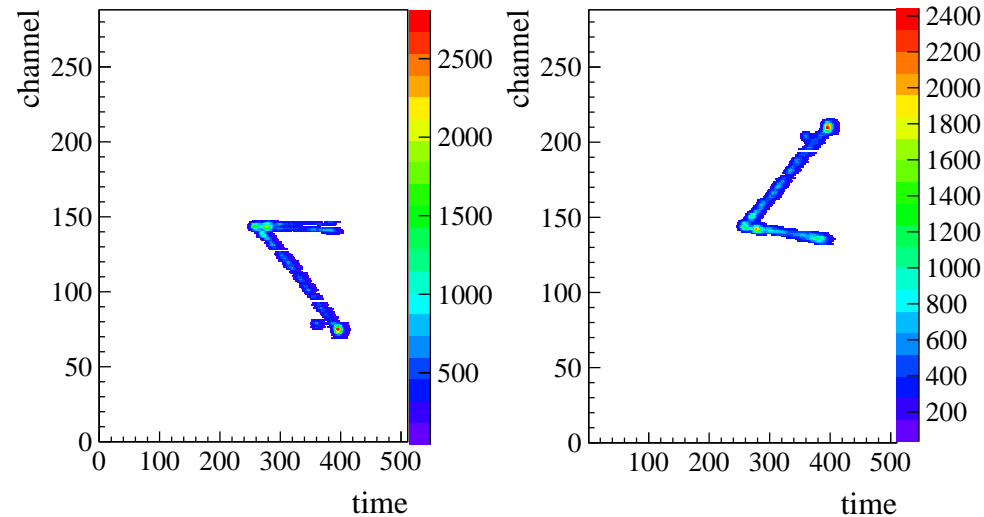
A. Rubbia and A. S. Sakharov, *Astropart. Phys.* 29, 20 (2008)



A 16.7 MeV γ -ray converting to e^+e^- in 2.1 bar Ar:Isobutane 95:5

raw “maps”

track time spectra



- x, y two-track ambiguity solved by track time spectra matching
- 1 channel = 1 mm.
- 1 time bin = 30 ns, $v_{\text{drift}} \approx 3.3 \text{ cm}/\mu\text{s} \Rightarrow 1 \text{ time bin} \propto 1 \text{ mm}$