ATMOSPHERIC MUON FLUX MEASUREMENTS WITH A GEM-BASED HODOSCOPE

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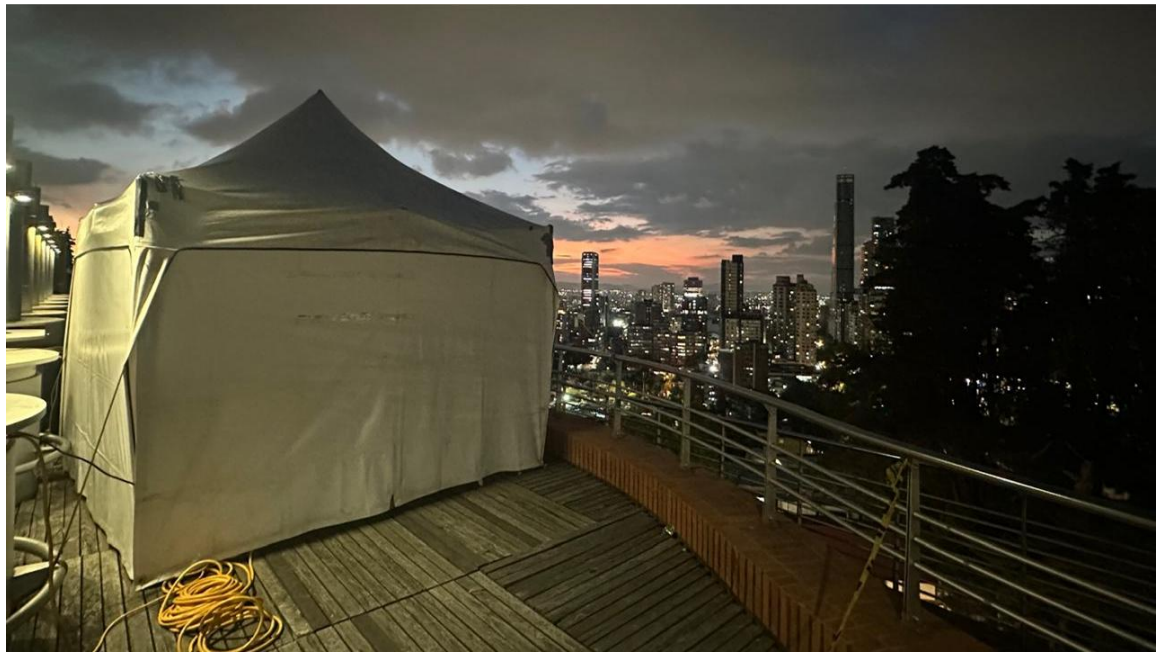
Taller: APLICACIONES INTERDISCIPLINARIAS DE DETECTORES DE PARTÍCULAS

June 10, 2012



Universidad de los Andes | Grupo de Investigación Altas Energías

FIGURES AND RESULTS TAKEN FROM FOLLOWING MATERIAL:

- CERN thesis: Scharenberg, L. (2022).Next-Generation Electronics for the Read-Out of Micro-Pattern Gaseous Detectors. PhD thesis, Bonn U.
- Thanks to Hans Muller for material available in https://srs-e.web.cern.ch/.
- DRD1 Gaseous Detectors School 2025.
- Meléndez Zamora, S. (2026). Atmospheric Muon flux study with GEM detectors. Universidad de los Andes.

OUTLINE

1. ATMOSPHERIC MUON FLUX
2. HODOSCOPES AND MUOGRAPHY
3. GEM DETECTOR
4. THE RD51 SRS READOUT SYSTEM
5. TRACKER
6. OPEN SKY MEASUREMENTS
7. REMARKS AND FUTURE WORK

1. ATMOSPHERIC MUON FLUX

- electromagnetic showers,
- hadronic showers,
- muons from meson weak decays.

Muon production processes:

- $\pi^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu}$ branching ratio of 99.99%
- $K^{\pm} \longrightarrow \mu^{\pm}\nu_{\mu}$ branching ratio of 63.56%

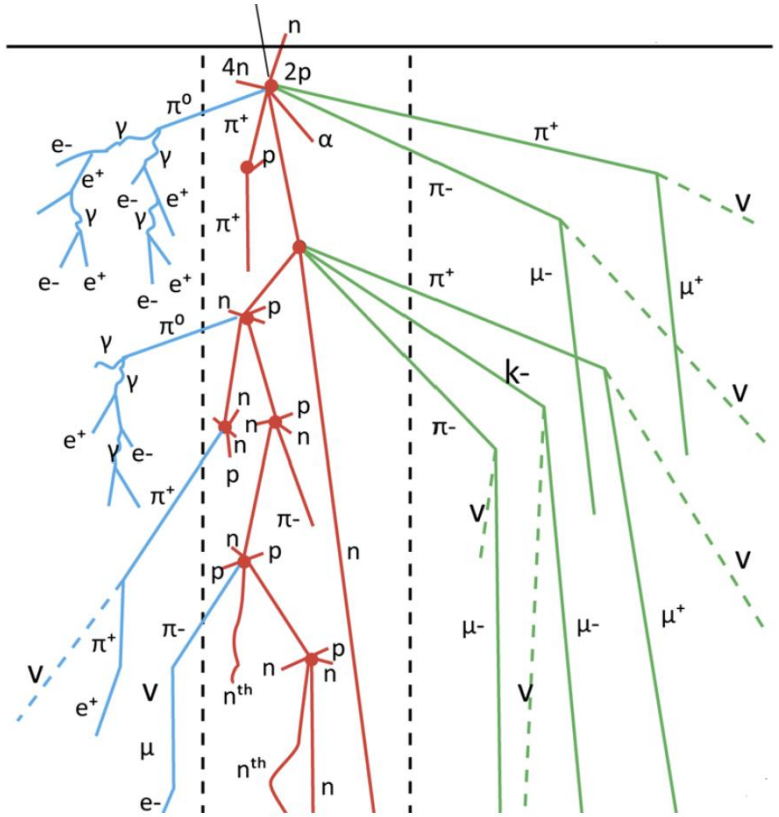
$$\mathcal{P}_{\mu}(E_{\mu}, X) = \mathcal{P}_{\mu}^{\pi} + \mathcal{P}_{\mu}^{K} \quad \propto \frac{1}{X \cos\theta} \int \frac{\Phi(E, X)}{E^2}\, dE$$

It leads to the Gaisser formula

γ

$$\frac{dN_{\mu}}{dE_{\mu}} \approx 0.14\, E_{\mu}^{-2.7} \left(\frac{1}{1 + \frac{1.1\, E_{\mu} \cos\theta}{115}} + \frac{0.054}{1 + \frac{1.1\, E_{\mu} \cos\theta}{850}} \right) \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}.$$

Predicts $I_{\mu}(\theta) \propto (\cos\theta)^2$.

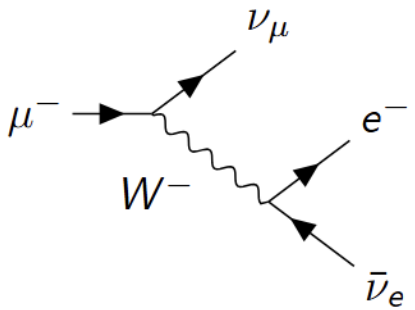


[Gosse and Phillips, 2001]

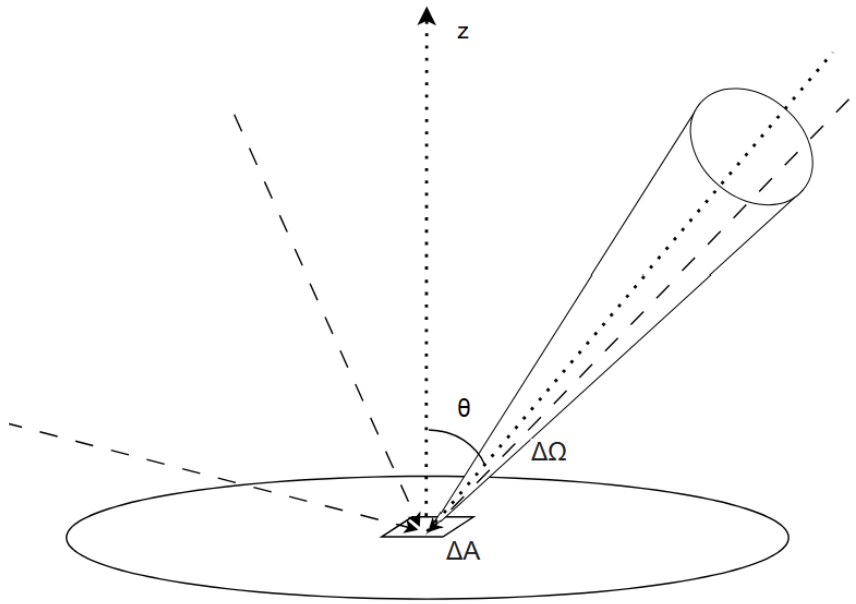
1. ATMOSPHERIC MUON FLUX

Muons:

- Mass: $M_\mu \sim 200 \times M_e = 105.7\ MeV/c^2$
- Lifetime $\sim 2.2\ \mu s$
- No hadronic interactions, no Bremsstrahlung.
  - Decay: $\mu^\pm \rightarrow e^\pm \nu_\mu \nu_e$
  - Capture: $\mu^- + p^+ \rightarrow n + \nu_\mu$



$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$



Muon Flux at earth's surface:

- Flux: $\sim 150/m^2/s \propto \cos^2\theta$
- Mean Energy: $4\ GeV$.
- Azimuthally isotropic.

$$\frac{dN}{dA\,dt\,d\Omega} \equiv \frac{d\Phi}{d\Omega} = I_0 \cos^n \theta$$

Vertical Intensity in Bogotá:

$$I_0 = (127.7 \pm 2.2)\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$n = 2.145 \pm 0.046$$

[Borja et al., 2022]

2. HODOSCOPES AND MUOGRAPHY

Muography

- Scattering-based muography: $\sigma_\theta = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{L_{\text{rad}}}} \left[1 + \frac{1}{9}\log\left(\frac{x}{L_{\text{rad}}}\right)\right]$
- Muon metrology: No object, compare tracklets in two trackers: Determine relative position.
- Absorption-based (transmission) muography:

D. Attié et al., ScanPyramids Symposium (2016).

Ratio between initial and final fluxes is directly related with Opacity:

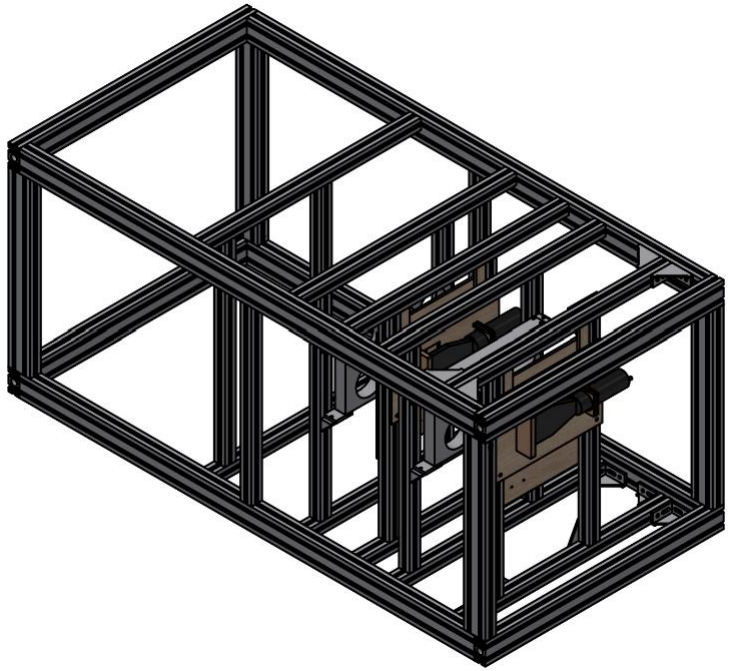
$$\delta = \rho \times d$$

Differences in final flux (after normalization) for different directions also points to Opacity differences.

Precise knowledge of the atmospheric muons flux is appropriate.

2. HODOSCOPES AND MUOGRAPHY

Hodoscope: "hodos“ path - "skopos“ observer
Reconstruct muon track direction.



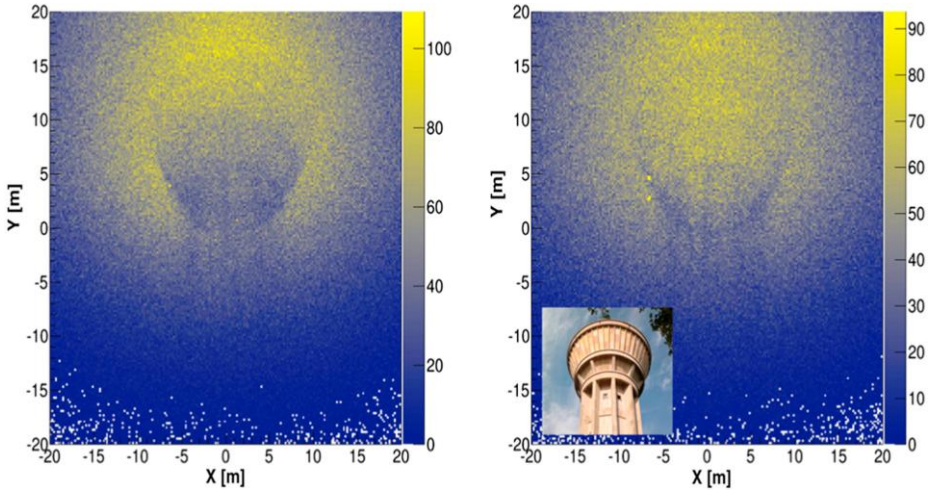
Hodoscope requirements

- Robust mechanics and DAQ
- Reliable and portable
- High efficiency
- Climate stability
- Environmental resistance
- High resolution / low noise
- Long-term continuous operation (~months)

2. HODOSCOPES AND MUOGRAPHY

WatTo experiment: MPGD beyond fundamental research

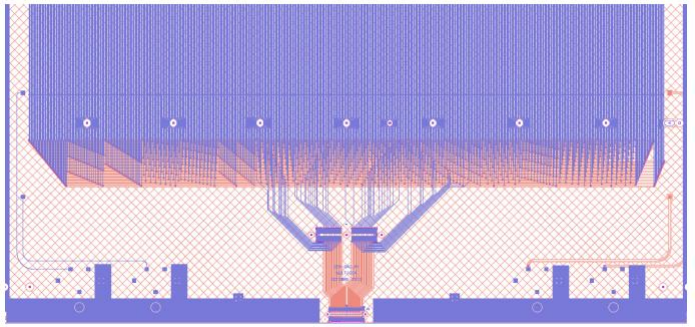
- Use of 4 Genetic Multiplexed Resistive Bulk Micromegas. (50x50 cm^2)
- 4 weeks of data taking (Water tower).
- The most precise muon telescope in the world!



Bouteille et al. (2016).

Setup

Multiplexed Readout:



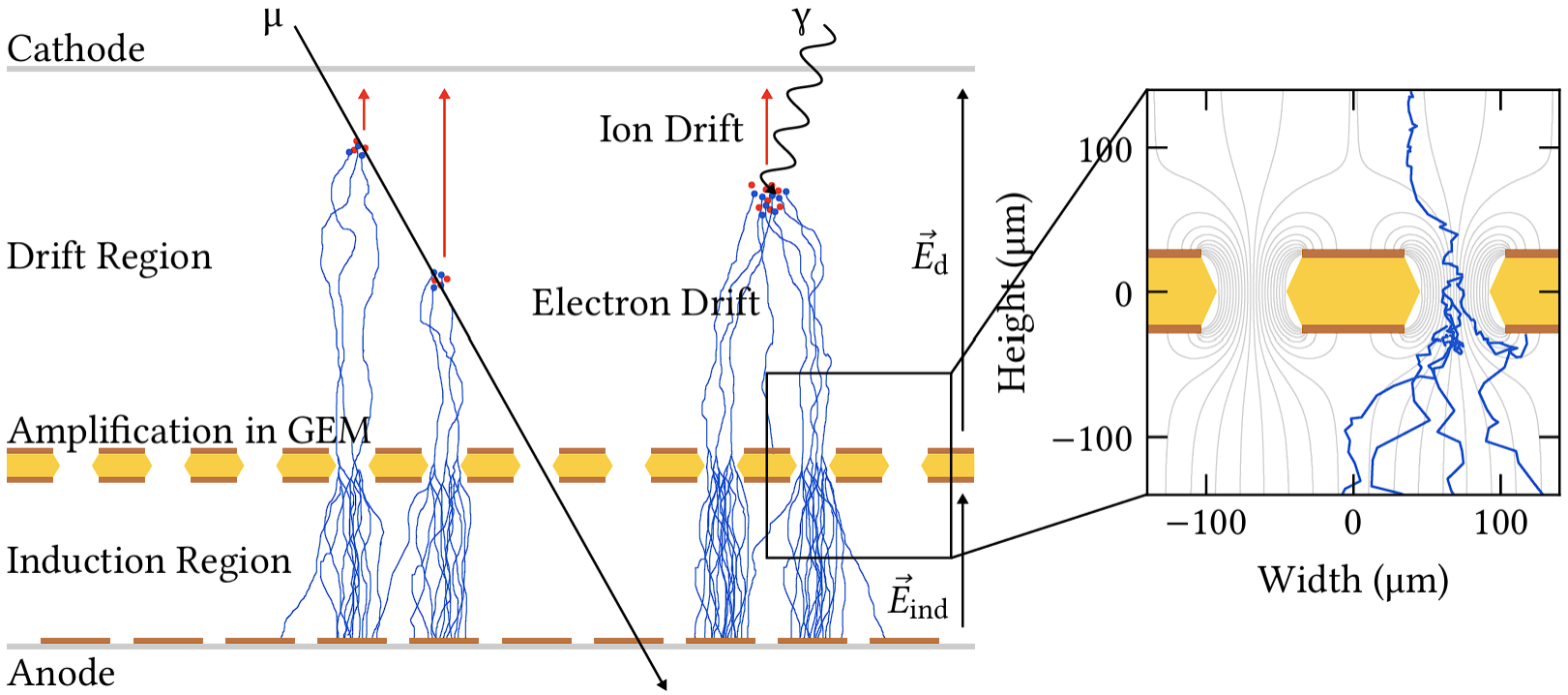
Nucl. Instrum. Meth. A 729 (2013) 888

From 1037 to 61 channels both X and Y → 1/34 lines reduction → Simpler DAQ!!

3. GEM DETECTOR

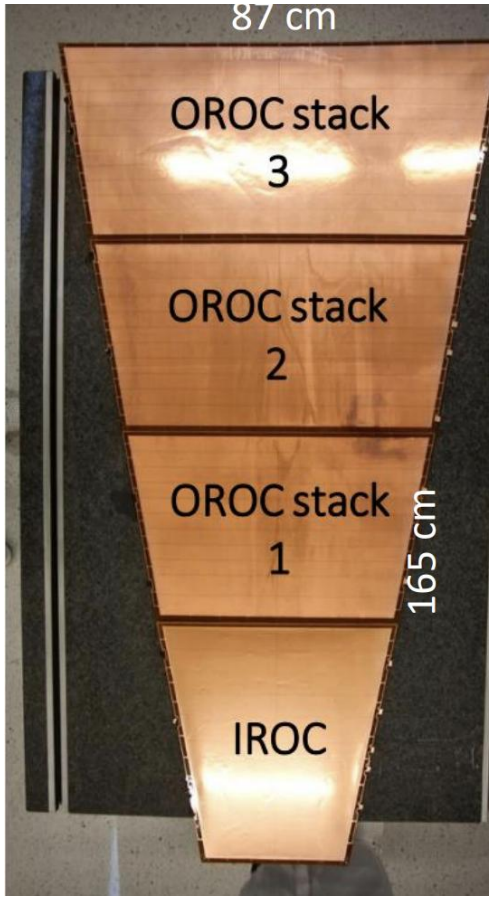
- MPGD family.
- 2D-Detector.
- Spatial Resolution (50-100 μm)
- Energy Resolution:
  18% FWM a 5.9 keV
- Rate capability $\mathcal{O}$(MHz/cm^2)
- Gain 10^3@400 V (90/10 ArCO2)

F. Sauli, Nucl. Instr. Meth. A386(1997)531



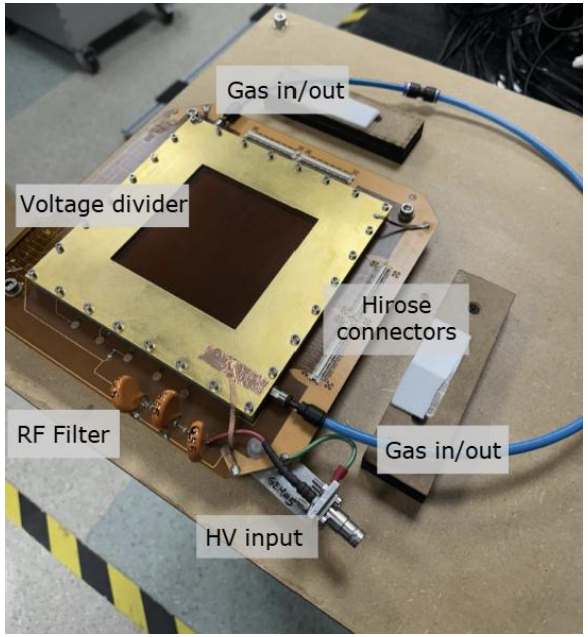
Scharenberg (2022)

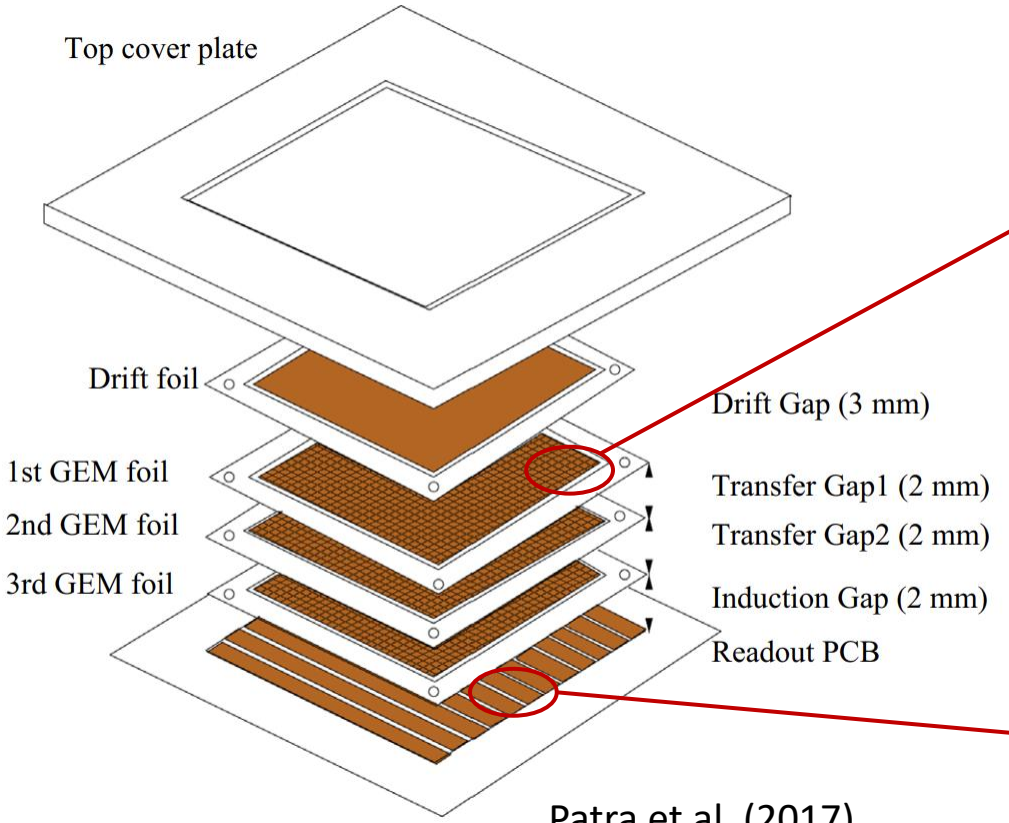
3. GEM DETECTOR



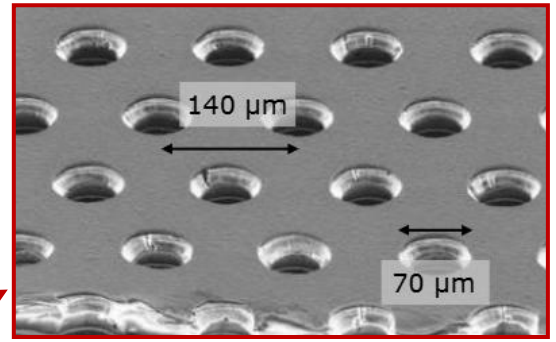
J. Adolfsson et al, JINST16 (20210)P03021

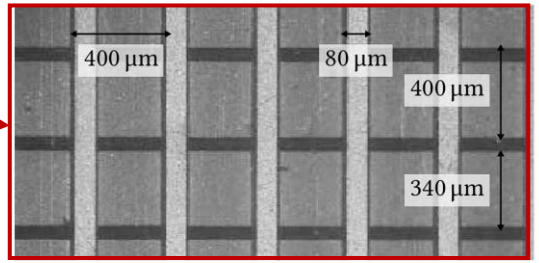
3. COMPASS LIKE TRIPLE GEM





Patra et al. (2017)





THE RD51 SRS READOUT SYSTEM

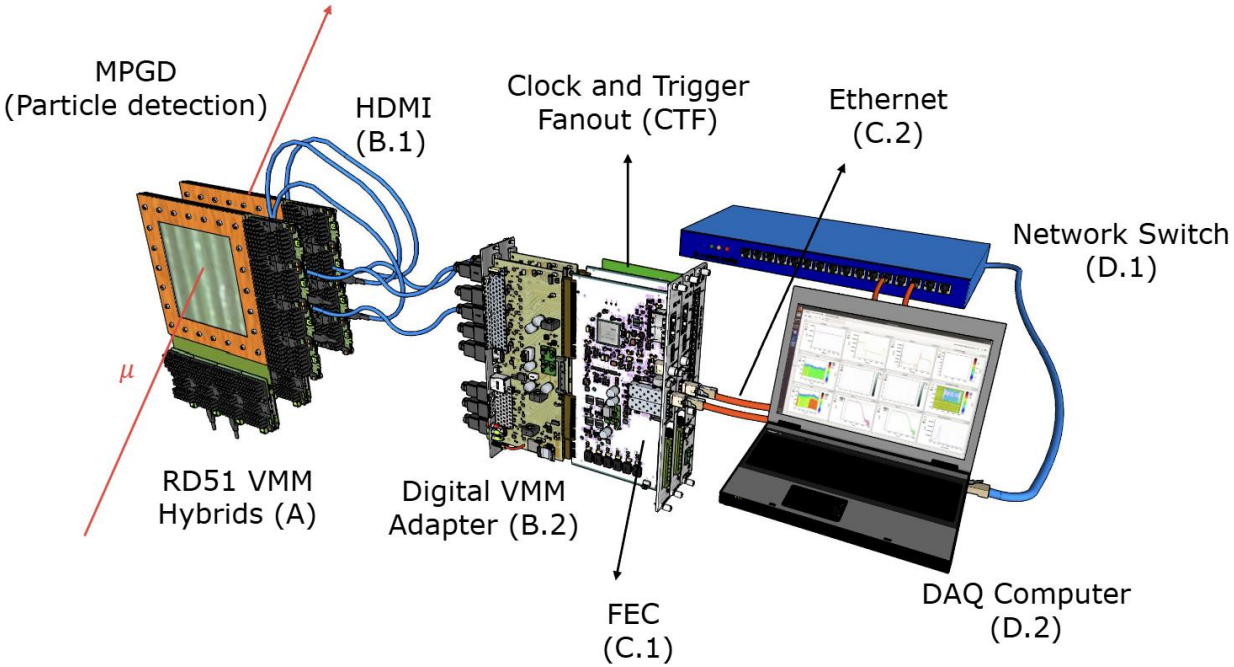
Small systems flavour

Large systems flavour

- RD51 Scalable Readout System (SRS): Modular and flexible electronic architecture.
- Readout of MPGD gaseous detectors and other particle detection devices.
- Developed in 2009 as a prototype within the ALICE and RD51 collaborations.
- Continuos and Self-triggered Mode.
- Bonn FW, 40 MHz Base clock.

4. THE RD51 SRS READOUT SYSTEM

- **Stage A — Front-end**: Signal amplification and digitization in the hybrid electronics.
- **Stage B — Data transmission**:
  - **B.1**: HDMI link transmits hit data and returns clock and configuration.
  - **B.2**: DVMM interfaces hybrids with the FEC.

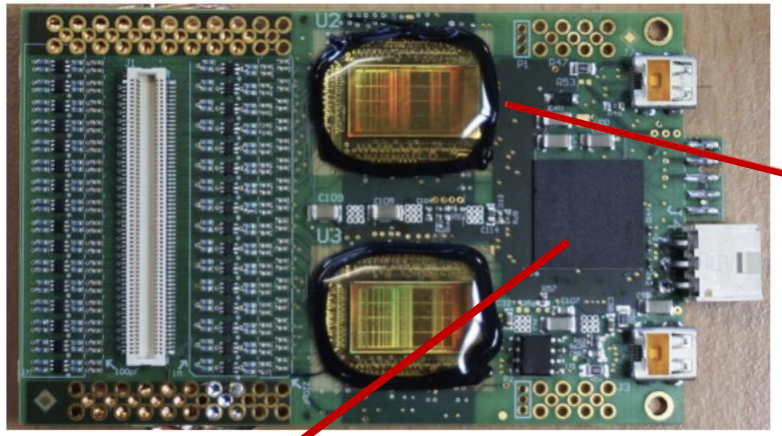


- **Stage C — Data concentration**:
  - **C.1**: Front-End Concentrator (FEC).
  - **C.2**: Ethernet data transmission.
- **Stage D — DAQ**: Network switch aggregates multiple FECs and forwards data to the DAQ PC.

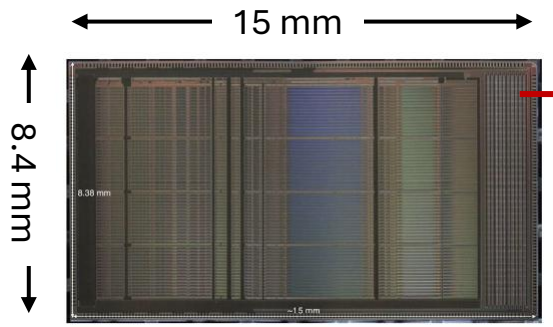
A common clock is distributed by the **CTF card** to ensure synchronization.

4. THE RD51 SRS READOUT SYSTEM: FRONT-END ELECTRONICS

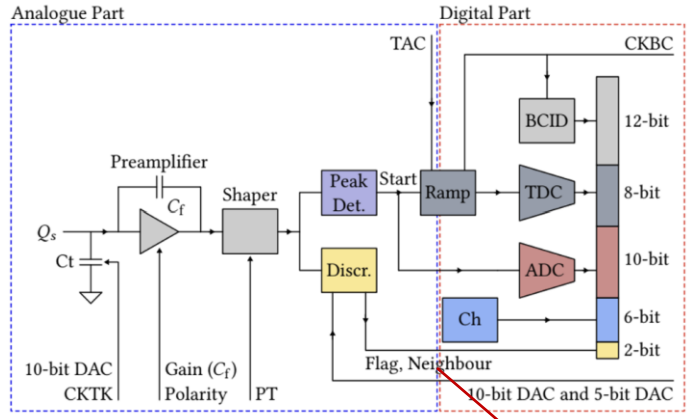
PCB Hybrid



VMM 3a

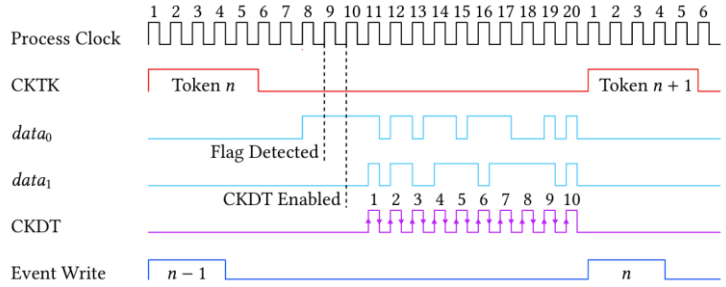


1 ch. electronic chain

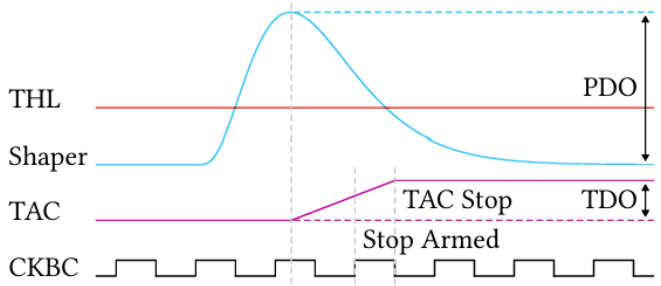


Scharenberg (2022)

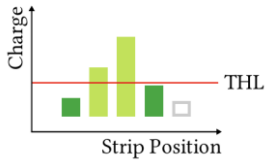
FPGA



Scharenberg (2022)



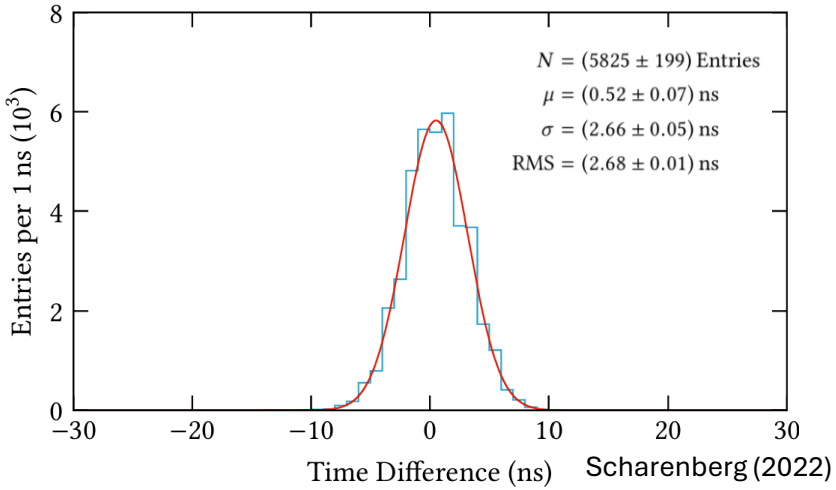
$$t_c = \text{BCID}\ T_{CKBC} + \left(1.5\ T_{CKBC} - \text{TDO}\ \frac{\text{TAC slope}}{255}\right)$$



4. THE RD51 SRS READOUT SYSTEM: GENERAL PERFORMANCE

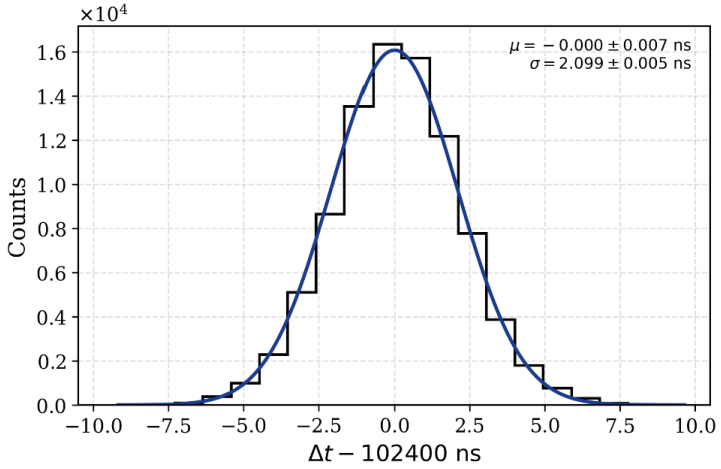
Time measurements: Resolution: **2 ns** at 200ns peaking time. **0.5ns** at 25ns peaking time.

Two VMM Channels

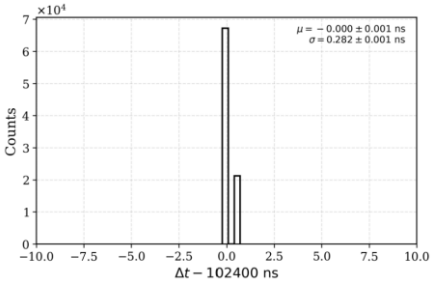


Scharenberg (2022)

Single Channel



Latency calibration



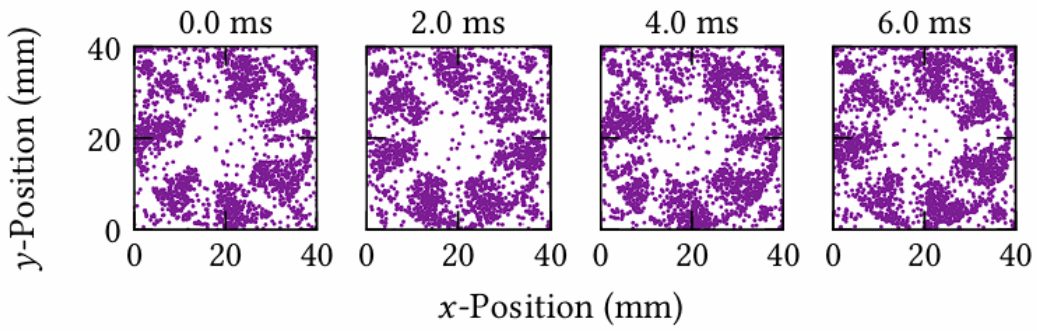
Rate capability

	Readout stage	Quantity unit Rate per	Maximum rate (Mhits/s)	(Mbps)	Limiting factor
A.1	VMM3a channel	Channel	3.6	144	ADC conversion time
A.2	VMM3a to Spartan-6	VMM3a	$8.\bar{8}$	$355.\bar{5}$	CKTK frequency

Scharenberg (2022)

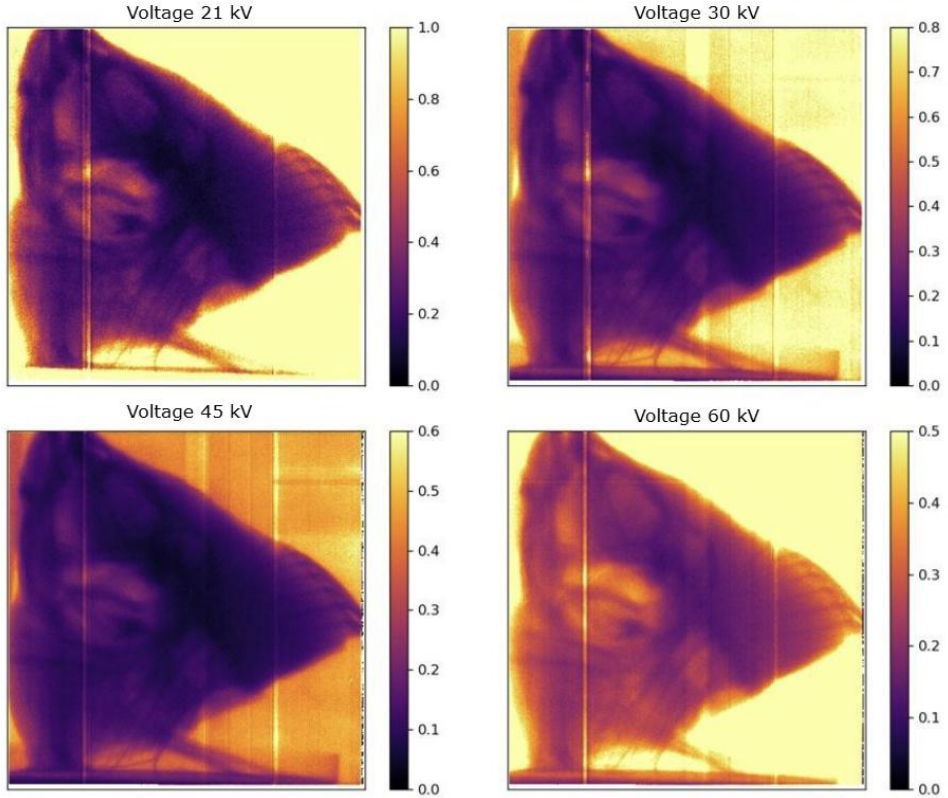
4. THE RD51 SRS READOUT SYSTEM: X-RAY PERFORMANCE

Rotating Fan



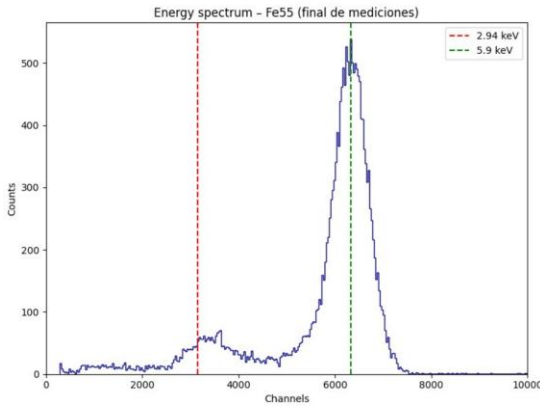
Scharenberg (2022)

X-ray image of a fish head

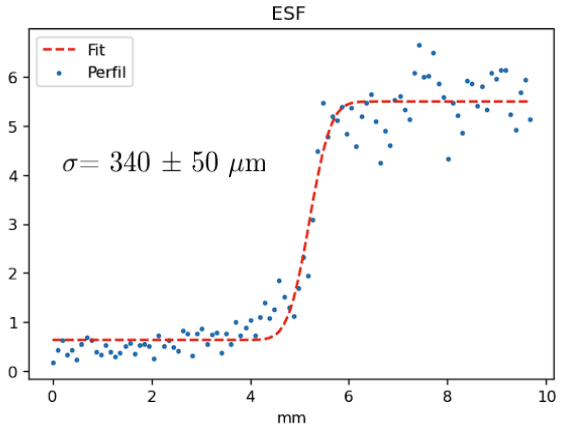


García Vargas, B. (2024)

Fe55*



Spatial resolution



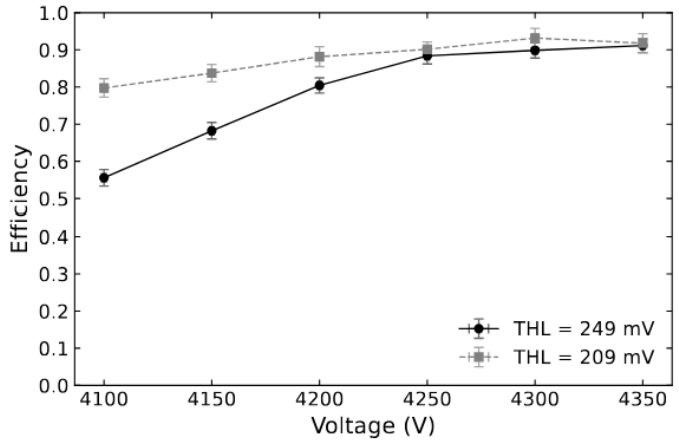
García Vargas, B. (2024)

*Figure courtesy of Mateo Mosquera

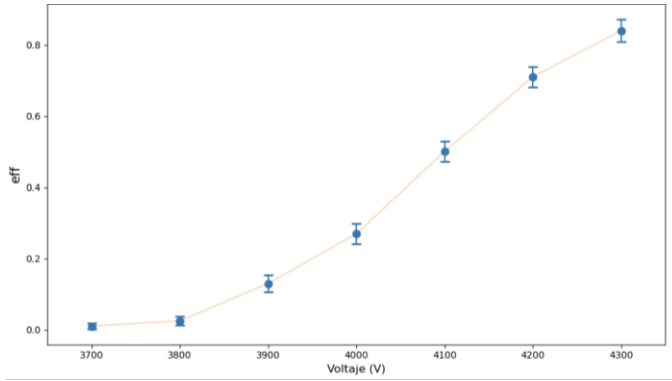
4. THE RD51 SRS READOUT SYSTEM: ATMOSPHERIC MUONS PERFORMANCE

GEM detector Efficiency:

Using PBX

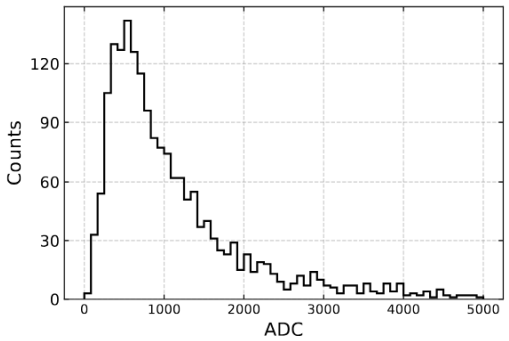


Using PMX

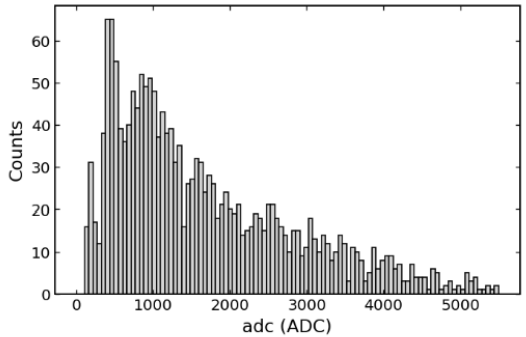


Deposited charge

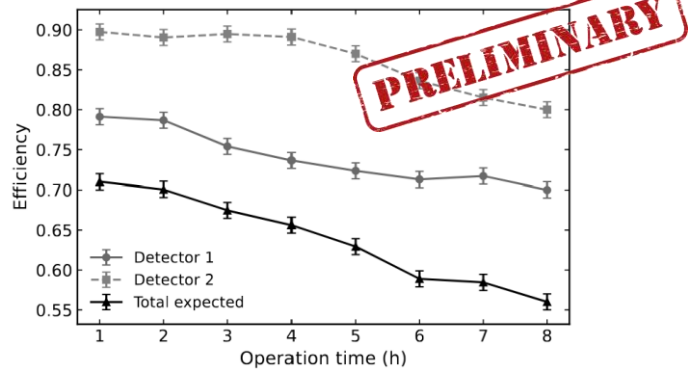
Single GEM detector



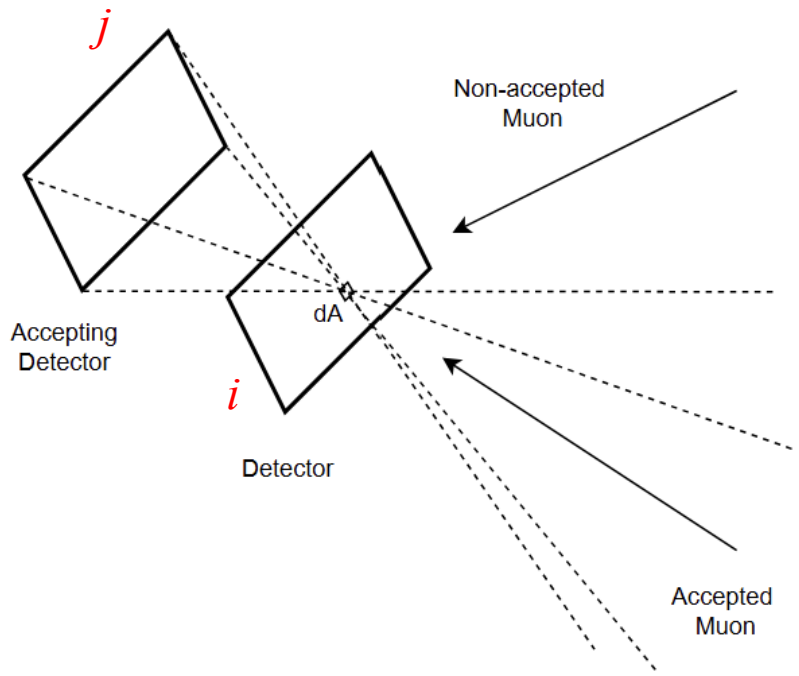
Track process.



Efficiency in Time performance



5. TRACKER: GEOMETRICAL ACCEPTANCE



Fraction of measured muon flux with a tracker of identity detectors with active area S:

$$\frac{(n+1)\, d\Omega\, \cos^n\theta \left[\frac{1}{S} \int_{y_a}^{y_b} \int_{x_a}^{x_b} f(\theta, x, y)\, dx\, dy \right]}{2\pi}$$

Bracket quantity is called geometrical acceptance $W_\theta(\theta, \lambda)$ for azimuthal independent flux.

The f function is the fraction of muon flux which is accepted in region (x, y) at angle θ in area element dx dy

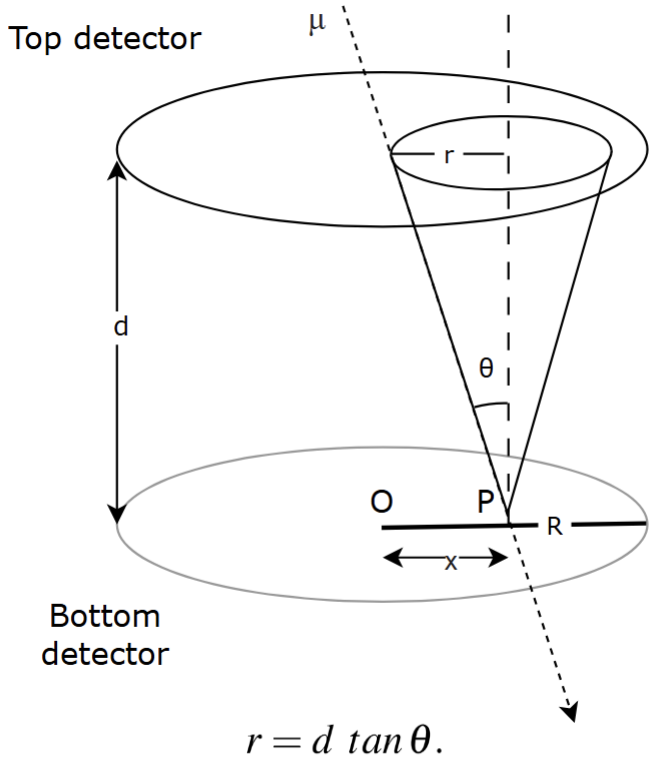
$$0 \leq f(\theta, x, y) \leq 1$$

Upward-pointing detectors for atmospheric muon flux measurements

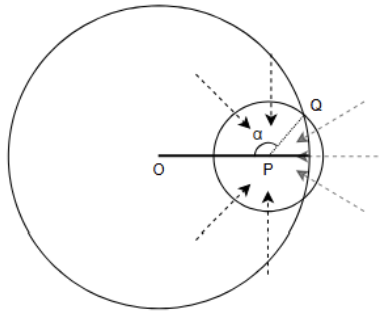
$$W(0, \lambda) = 1, \quad W(\theta_{\max}, \lambda) = 0,$$

5. TRACKER: GEOMETRICAL ACCEPTANCE

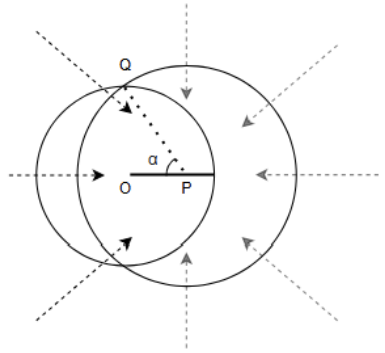
Parallel circular plane detectors:



$$r = d\ tan\,\theta.$$



(a) $0 < r < R$ case. The observation point moves along the path $0 \le x \le R$.



(b) $R < r < 2R$ case. The observation point moves along the path $r \le x \le R$.

$$W_\theta(\theta,\lambda) = \begin{cases} \frac{2}{\pi}\left(\cos^{-1}(\lambda\ \tan\theta) - (\lambda\ \tan\theta)\sqrt{1-(\lambda\ \tan\theta)^2}\right), & \text{if } 0 \le \theta \le \theta_{\max}, \\ 0, & \text{otherwise.} \end{cases}$$

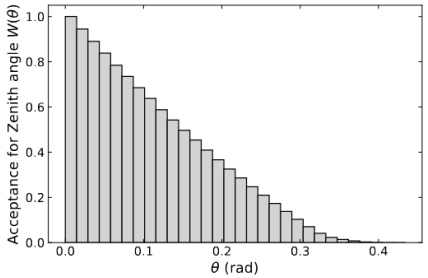
$$W_\phi = 1 - \frac{4}{\pi}\int_0^{\pi/2} \frac{\cos^2\alpha}{\sqrt{1+4\lambda^2\cos^2\alpha}}\,d\alpha.$$

5. TRACKER: GEOMETRICAL ACCEPTANCE

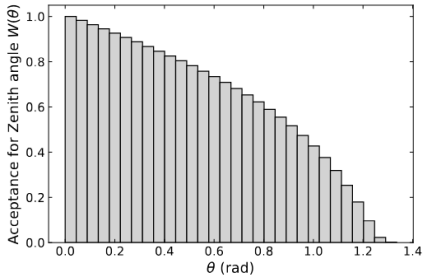
Parallel square plane detectors:

Simulated acceptance:

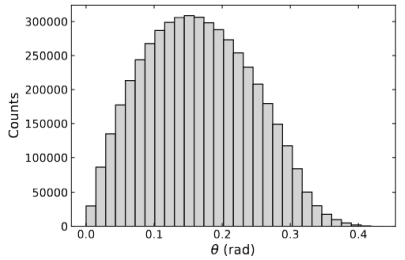
$$\frac{\Phi_\theta(\theta)_{ij}}{\Phi_\theta(\theta)_i} = \frac{A_\theta \sin\theta\cos^2\theta\, W_\theta(\theta,\lambda)}{A_\theta \sin\theta\cos^2\theta} = W_\theta(\theta,\lambda),$$



(a) Acceptance function $W(\theta)$ (30 cm separation).

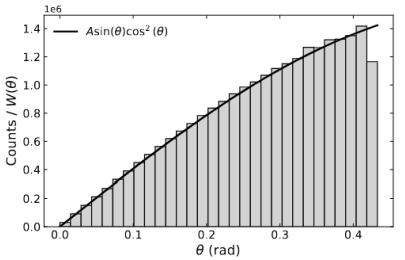


(b) Acceptance function $W(\theta)$ (10/3 cm separation).



Simulated zenith angle distribution for a $\cos^2\theta$ muon flux ($d > l$ configuration)

Dividing by $W(\theta,\lambda)$



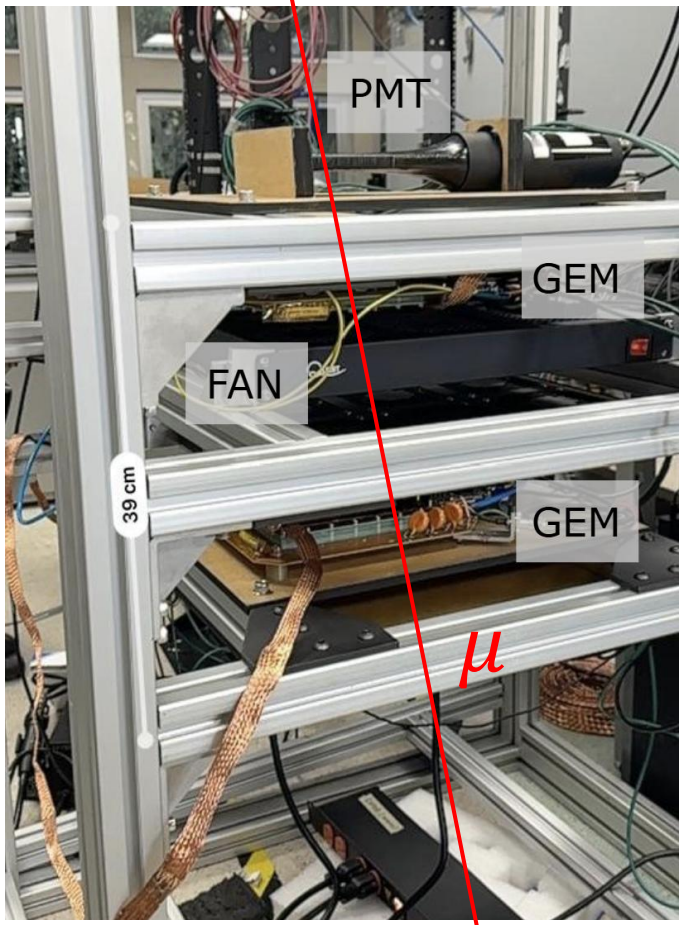
Corrected distribution: $A \sin\theta \cos^2\theta$

$$N_\theta = A_\theta \cos^2\theta \sin\theta\, W_\theta(\theta,\lambda)\,\Delta\theta$$

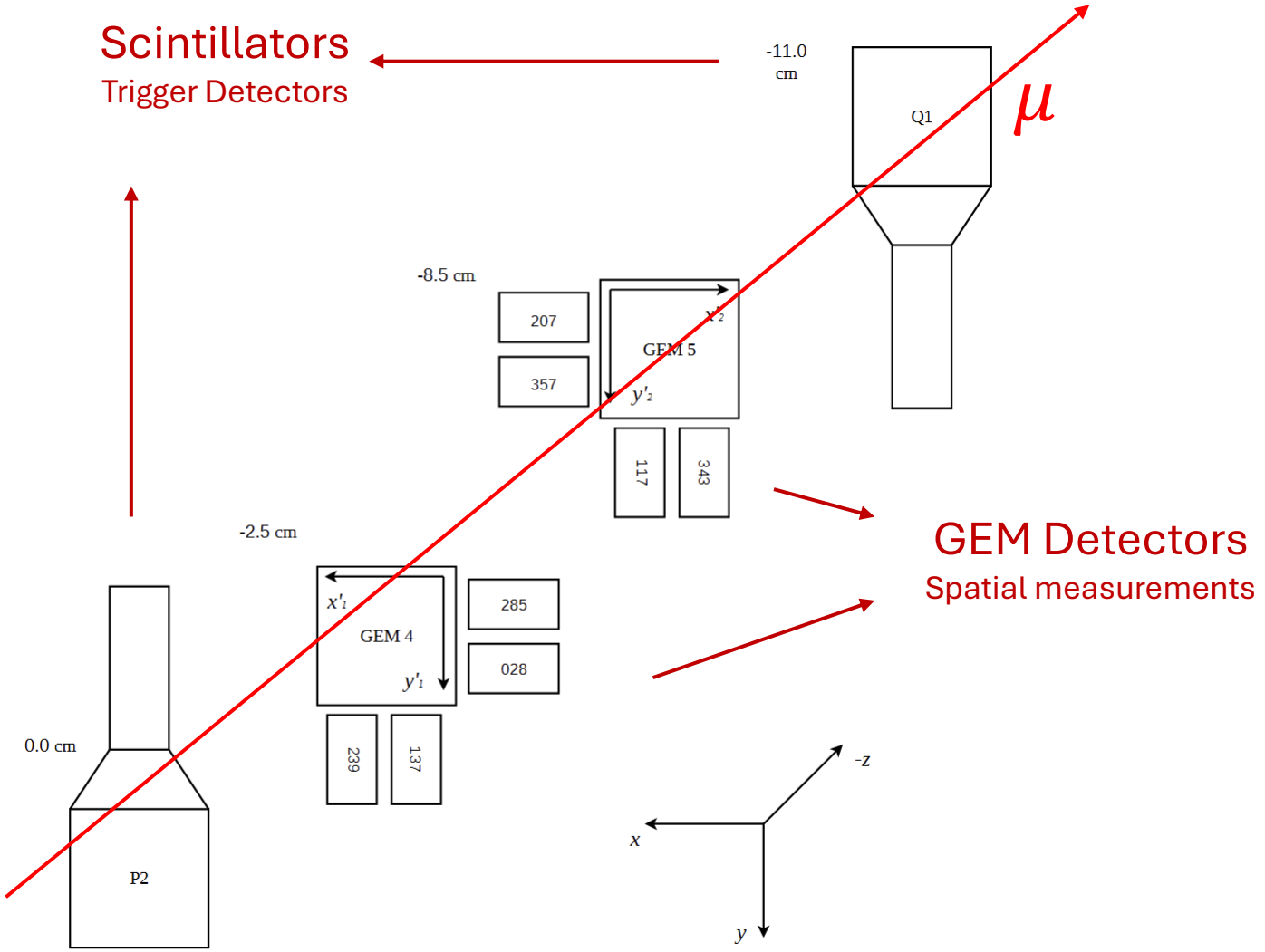
Muon flux determination:

$$\frac{\Delta N}{\Delta\Omega\Delta t\Delta A} = \frac{N_\theta}{\epsilon_1\epsilon_2\epsilon_3\epsilon_4\epsilon_{\mathrm{DAQ}}\,\Delta\theta\,W(\theta)\,\Delta t\,A_{\mathrm{Det.\,eff.}}}.$$

5. TRACKER GEOMETRY



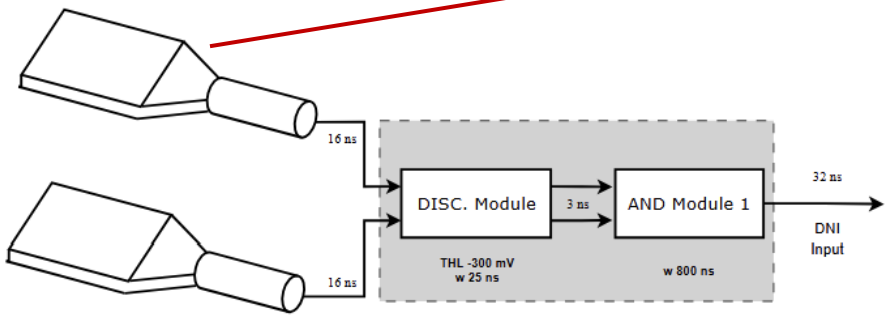
Scintillators
Trigger Detectors

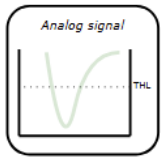


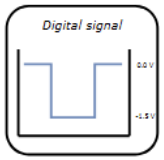
GEM Detectors
Spatial measurements

5. TRACKER: TRIGGER

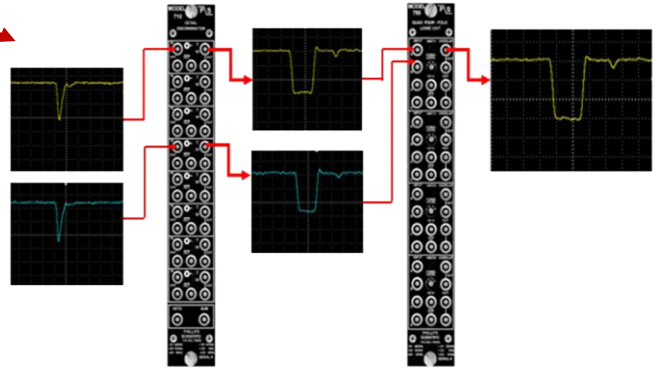
Offline Trigger: An external trigger signal injected to define a time reference.





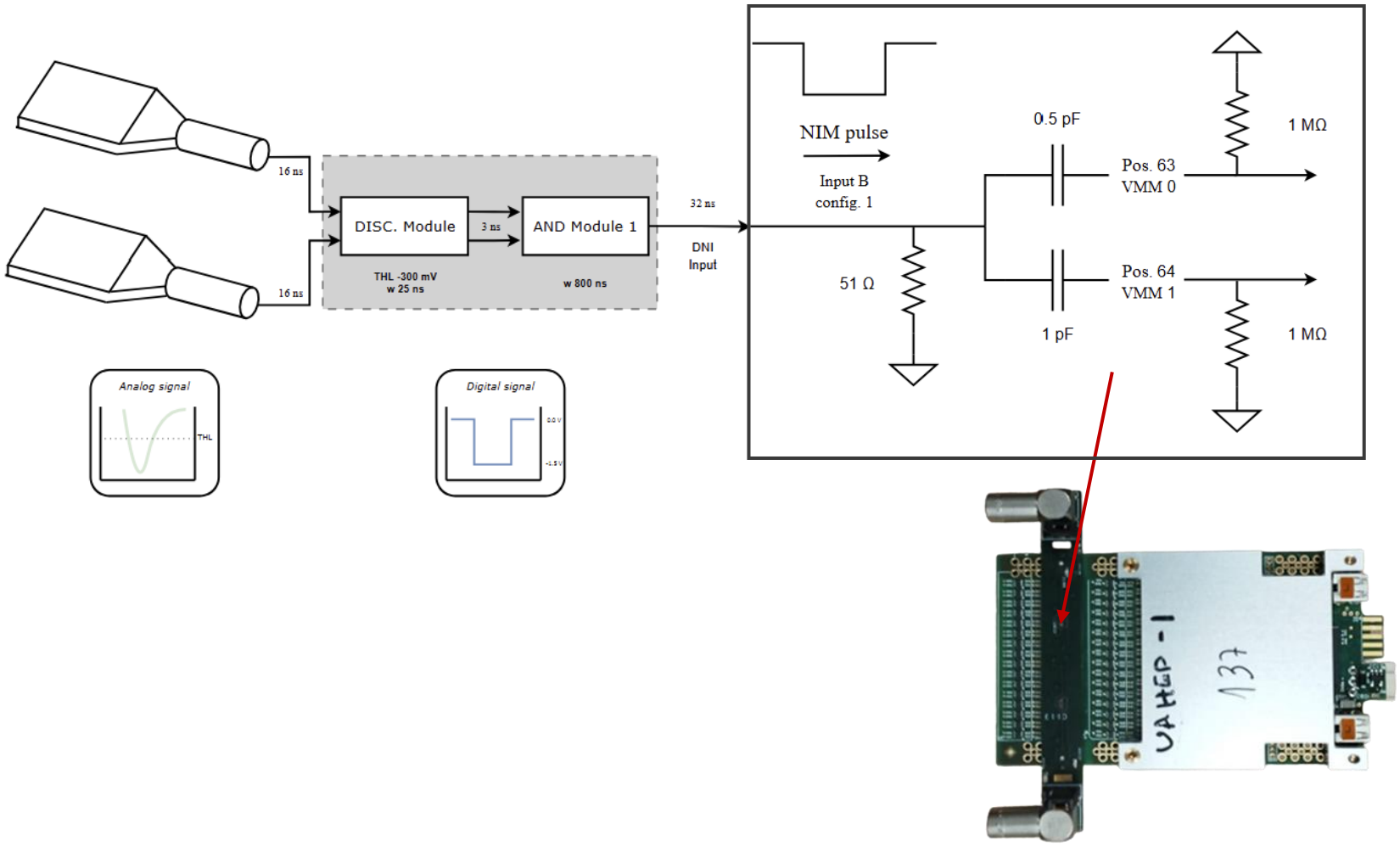


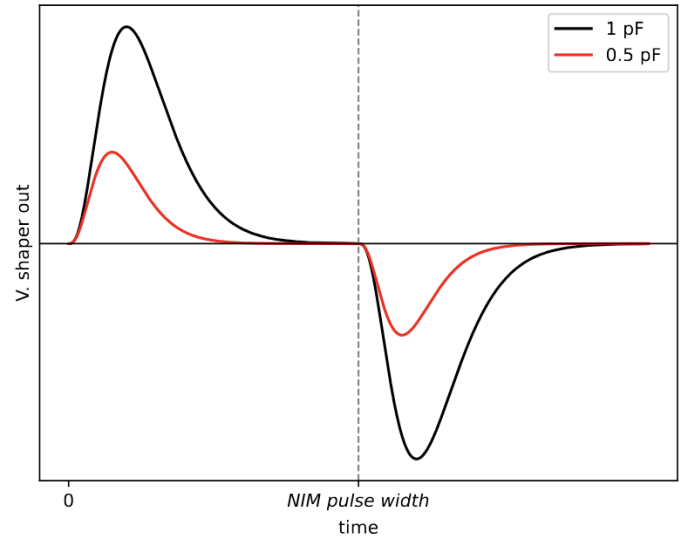
NIM electronics:



5. TRACKER: TRIGGER

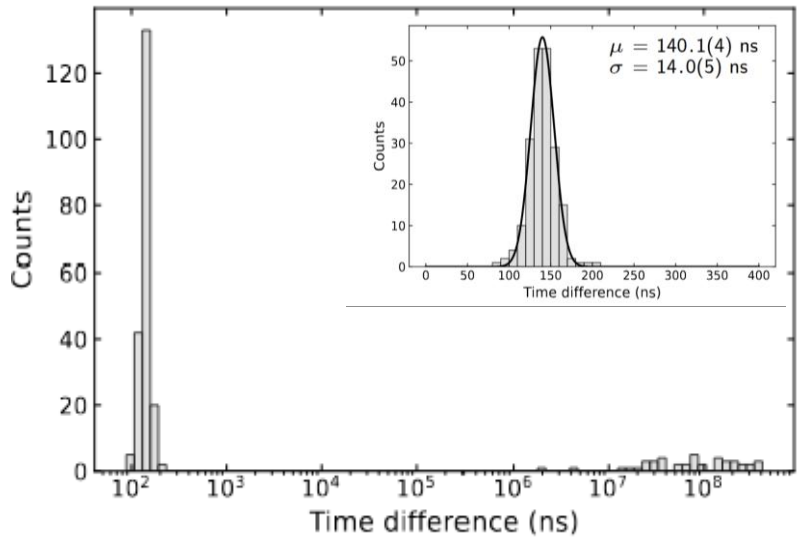
Offline Trigger: An external trigger signal injected to define a time reference.



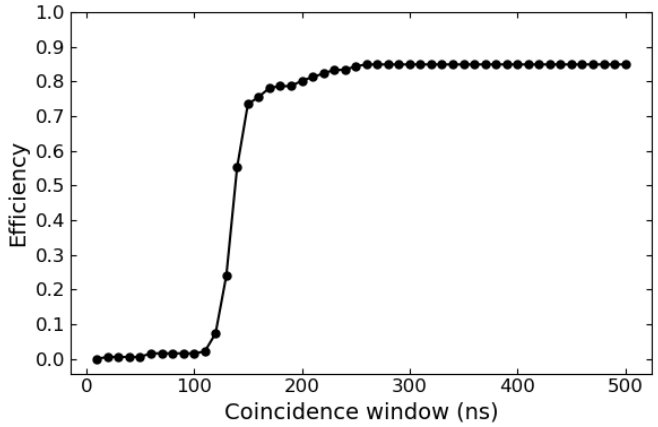


5. TRACKER: TRIGGER

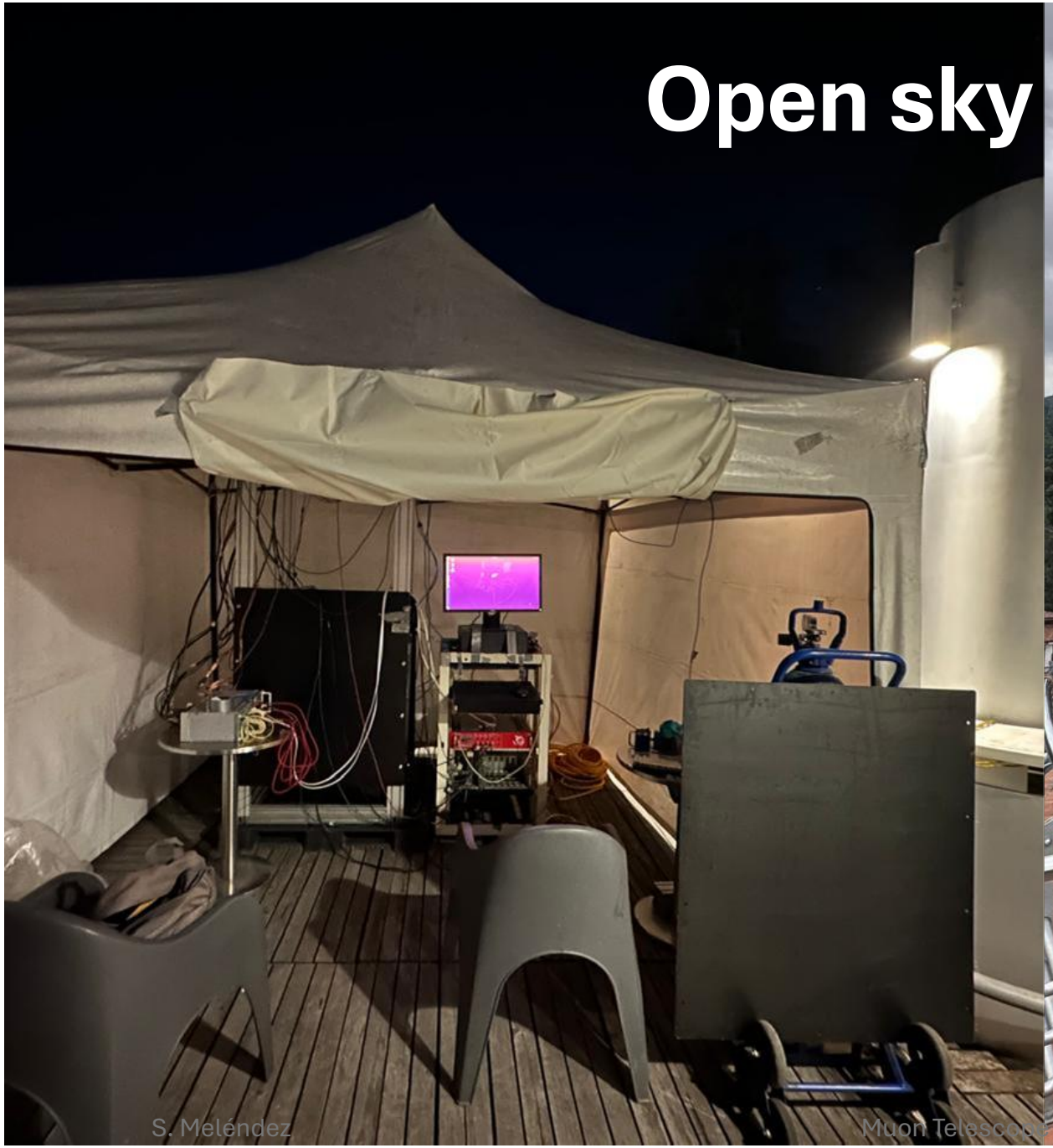
Offline Trigger: An external trigger signal injected to define a time reference.

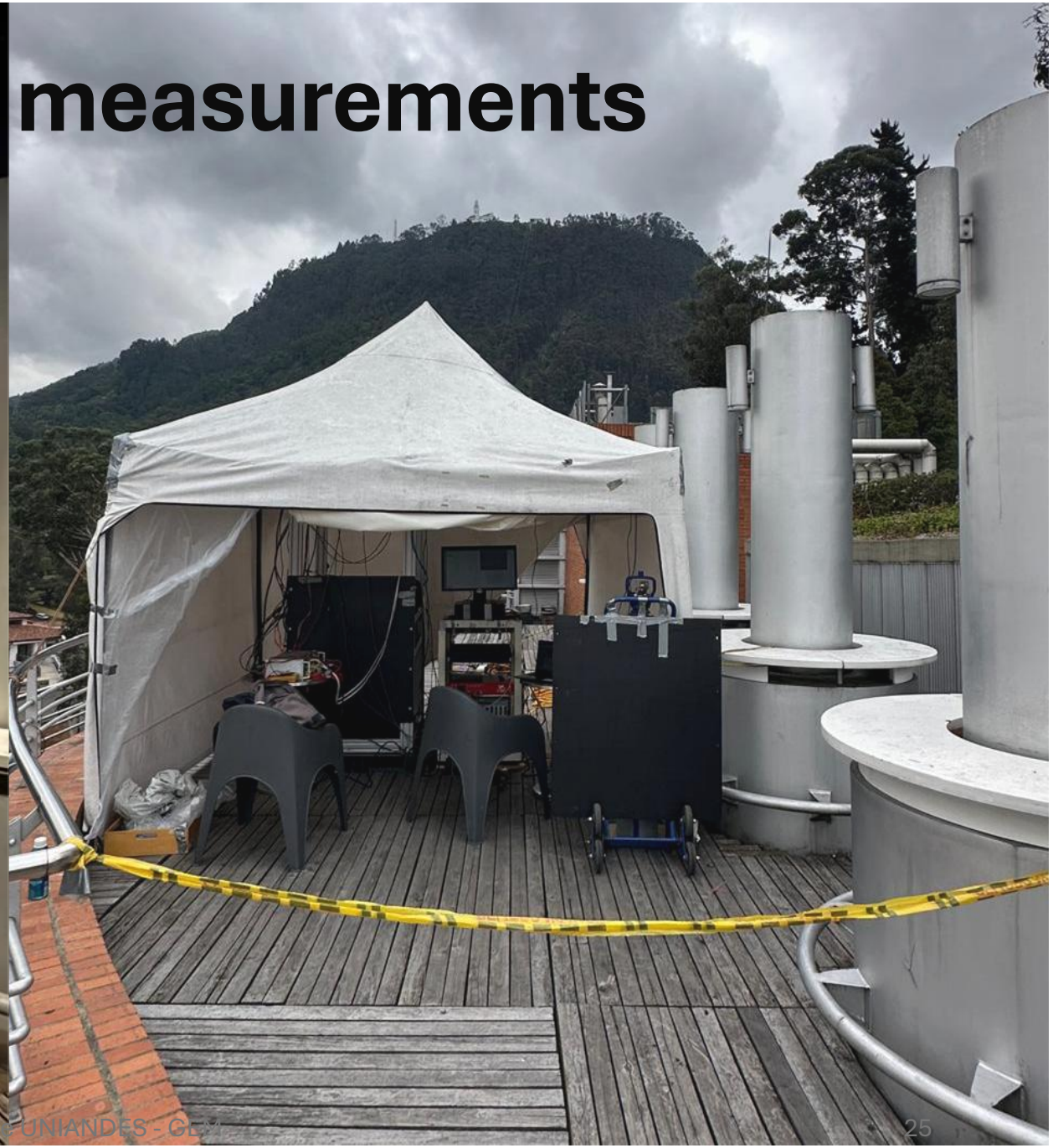


Time window for matched events:

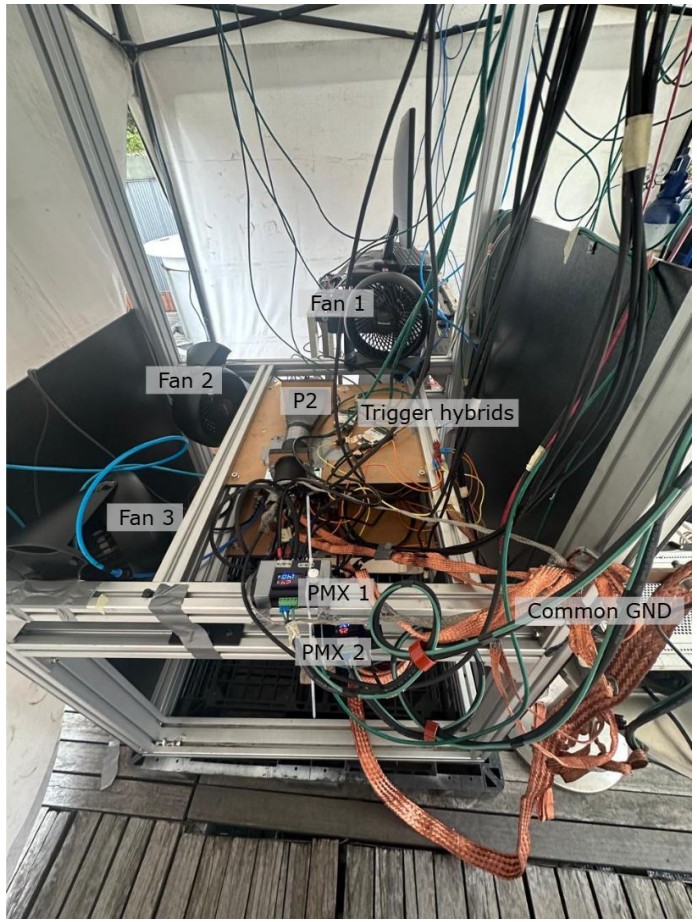


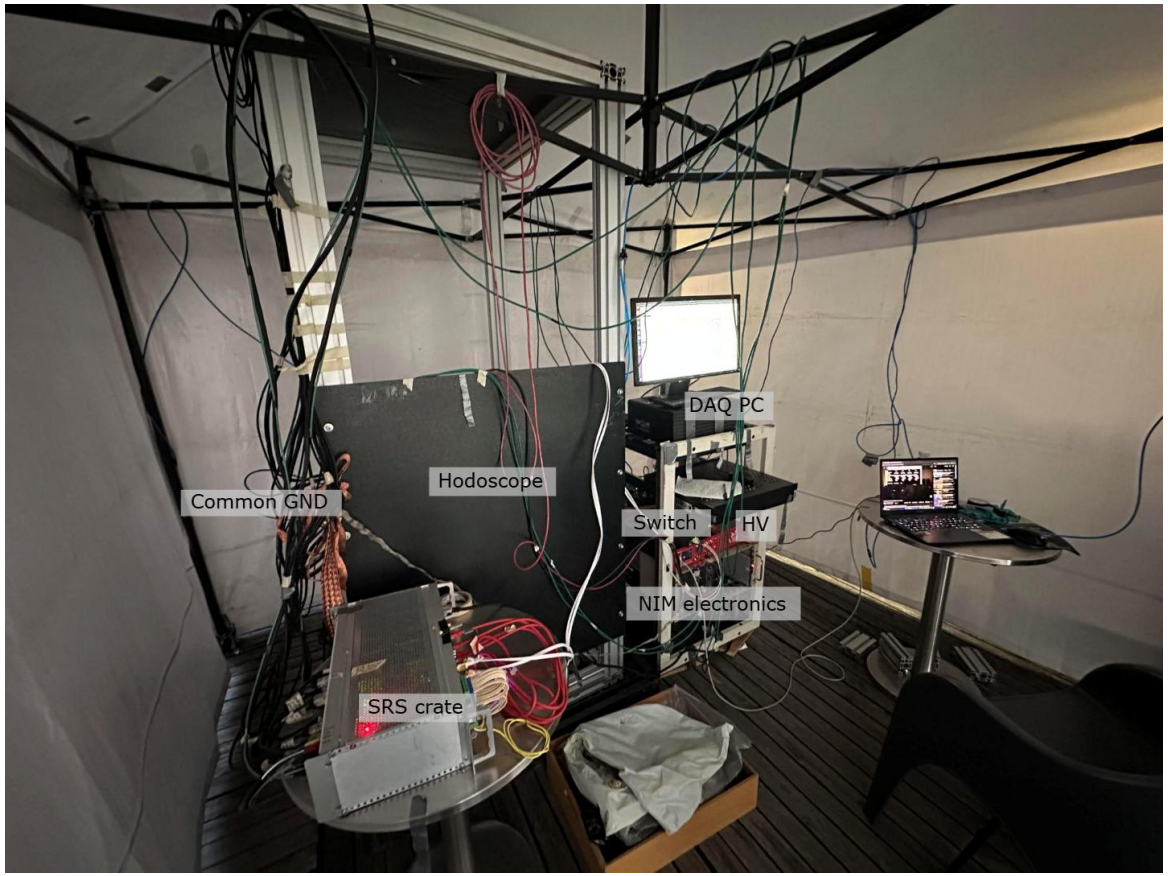
Open sky measurements





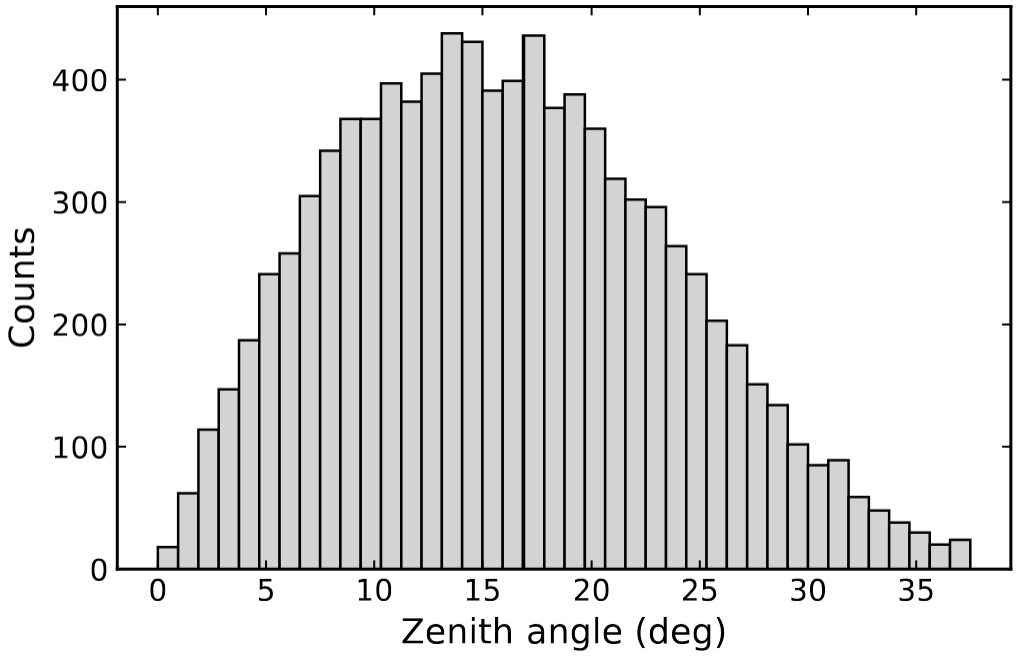
5. TRACKER


Fan 1
Fan 2
P2
Trigger hybrids
Fan 3
PMX 1
Common GND
PMX 2


DAQ PC
Hodoscope
Common GND
Switch
HV
NIM electronics
SRS crate

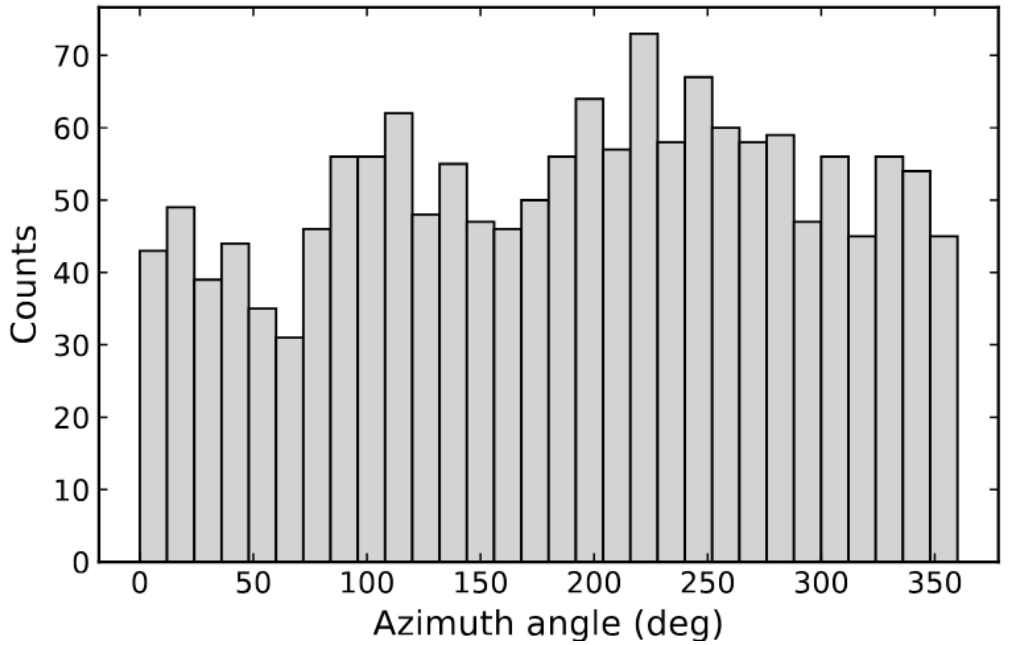
6. RESULTS: ANGULAR DISTRIBUTIONS

Zenith angle



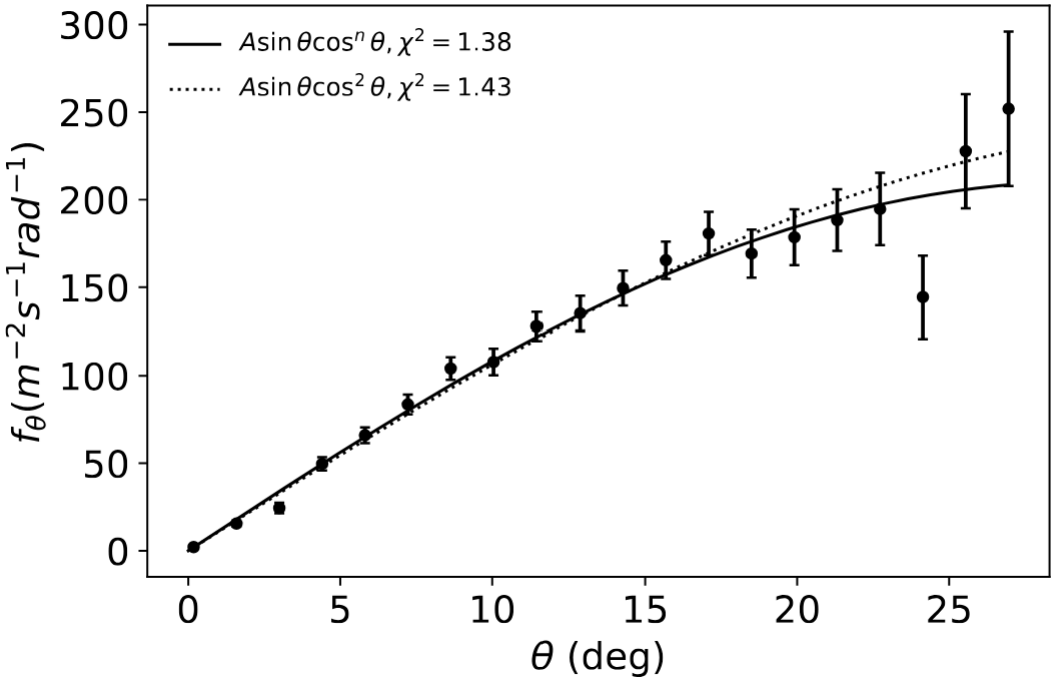
13 hours data take

Azimuth angle



4 hours data take

6. RESULTS: MEASURED ATMOSPHERIC MUON FLUX



$$I_V = \int_0^{2\pi}\int_0^{\pi/2} \frac{A}{2\pi}\cos^2\theta\,\sin\theta\,d\theta\,d\phi = 217(7)\,\mathrm{m}^{-2}\mathrm{s}^{-1}$$

Parameters:

Exponent: $n = 3.0(7),$

Vertical muon flux intensity: $104(3)\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}.$

1.3 muons per cm² per minute.

7. REMARKS AND FUTURE WORK

- New measurements with improved detector alignment, larger solid-angle coverage, and reduced noise levels (currently working).
- Further characterization of the SRS DAQ remains to be explored, including neighbor logic, DDR, peak-time and gain optimization…
- Software and firmware upgrades aimed at improving system stability.
- PBX system upgrade.
- Application of muon tomography to geological structures.
- Exploration of graphene-boron coatings for GEM-based neutron detection.
- Investigation of multiplexing schemes and system miniaturization.

Thank you for your attention!