Study of the mass composition of cosmic rays with the Underground Muon Detector of AMIGA

Joaquín de Jesús

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HIRSAP Meeting
22/11/2023

Outline

- Detector characterization
  - Fiber attenuation
  - Single-muon ADC charge
- Long-term performance
- Binary reconstruction optimization

PROCEEDINGS OF SCIENCE

Status and Performance of the Underground Muon Detector of the Pierre Auger Observatory

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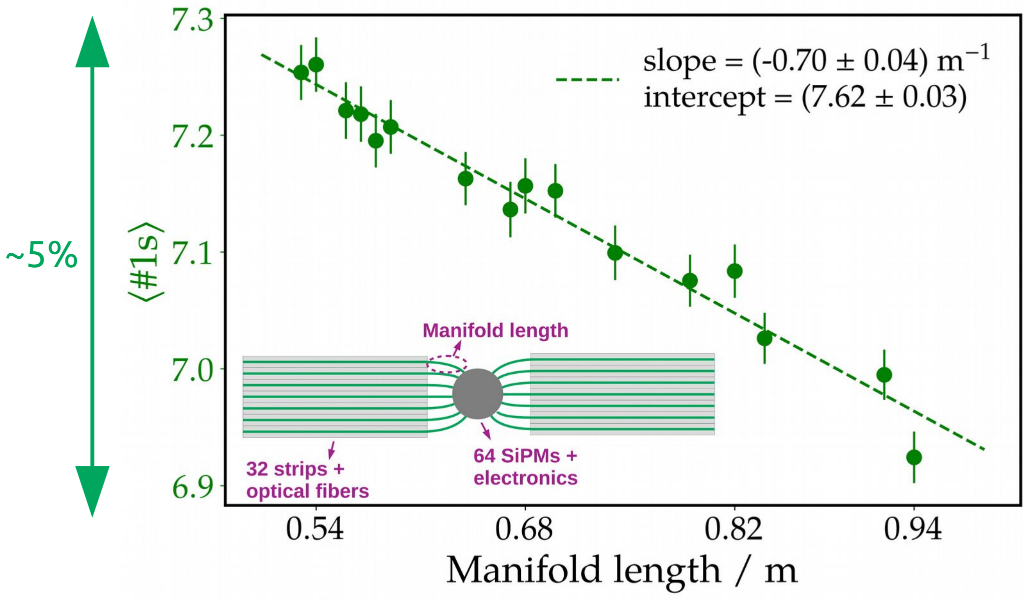
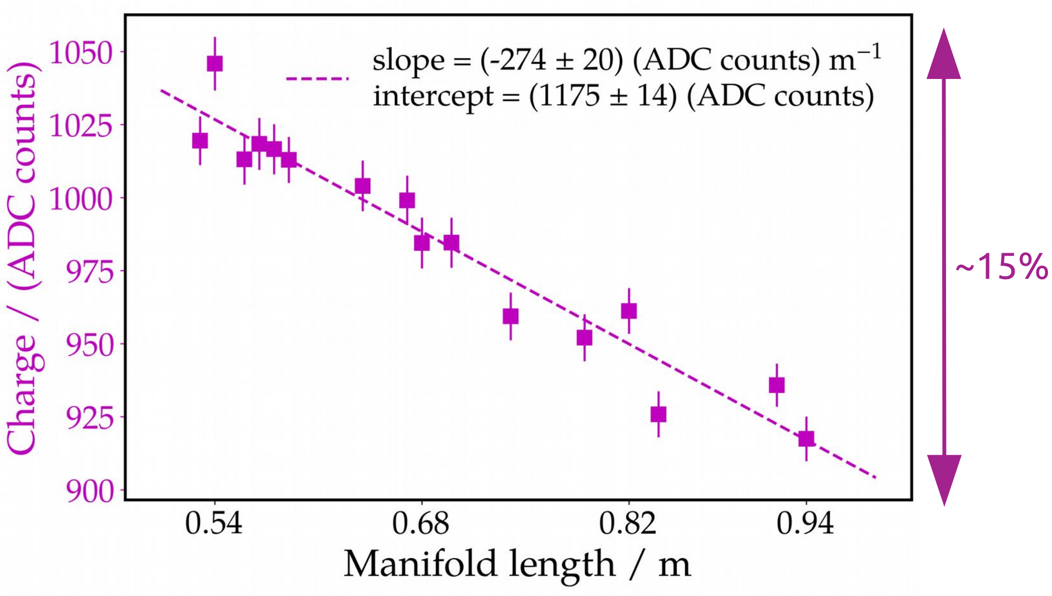
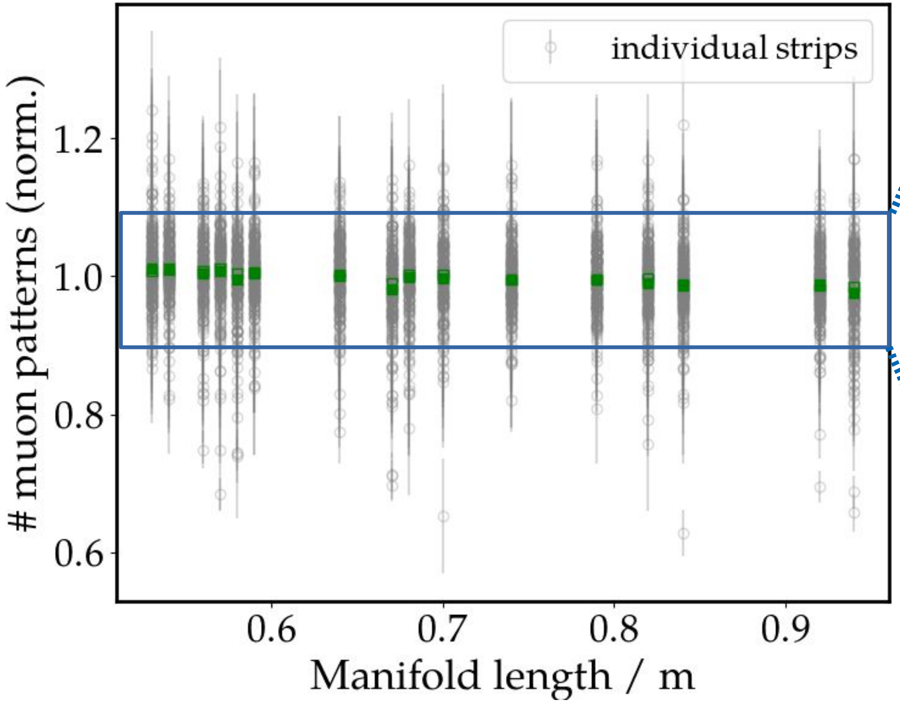
Fiber attenuation

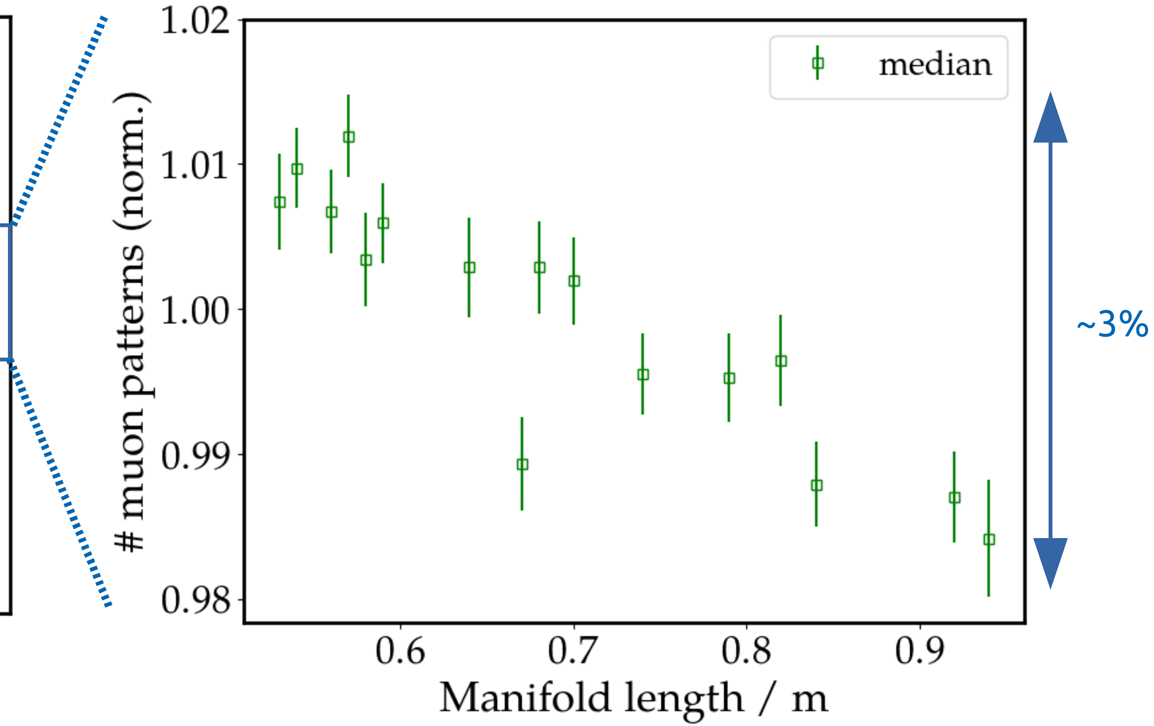




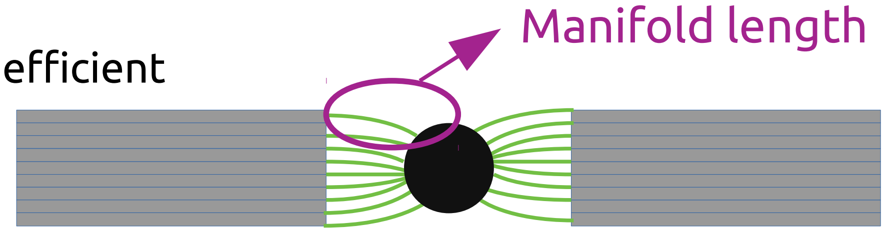
- Binary and ADC signals decrease with fiber length

Fiber attenuation



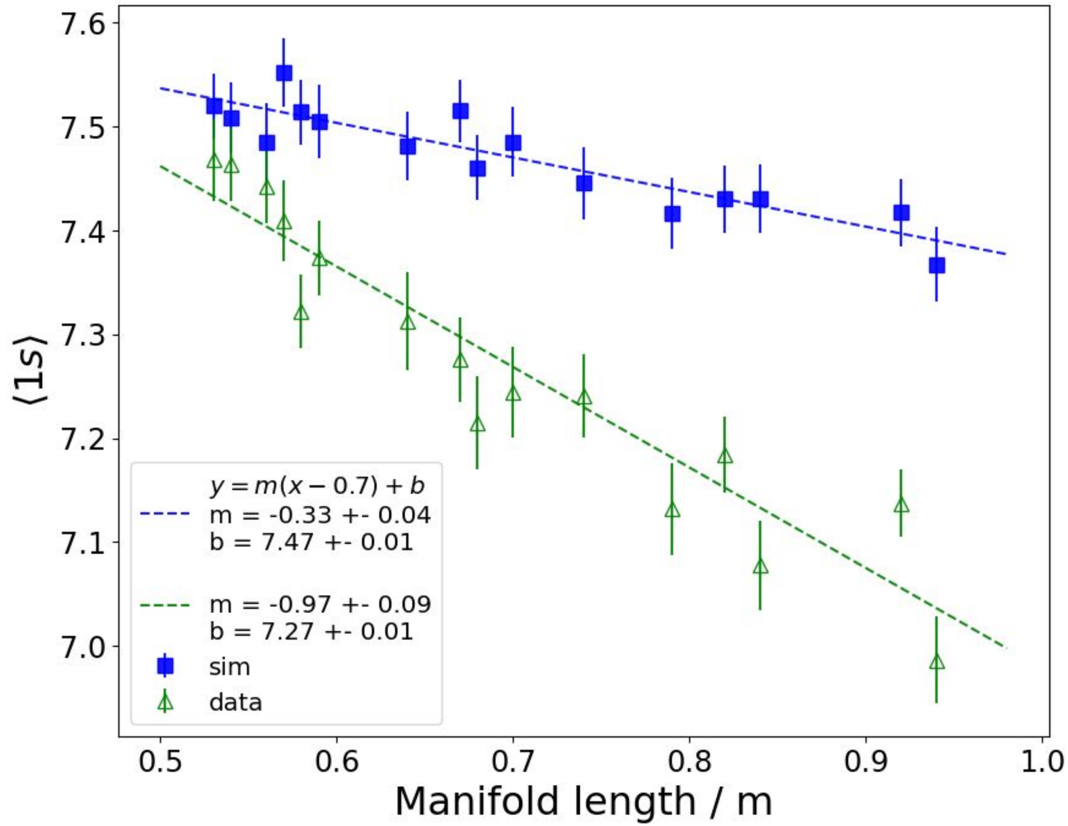


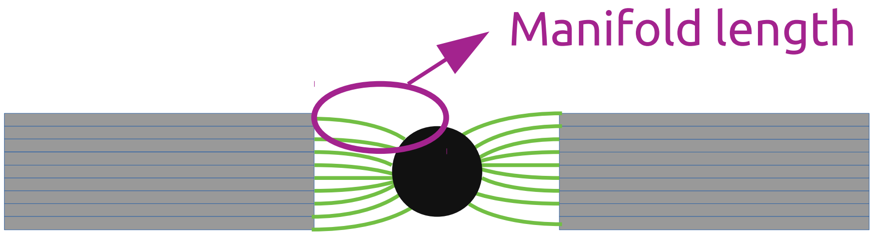
- Muon pattern = 1111x
- Strips with longer fibers are slightly more inefficient



Not shown in the proceeding

Fiber attenuation: data & simulations

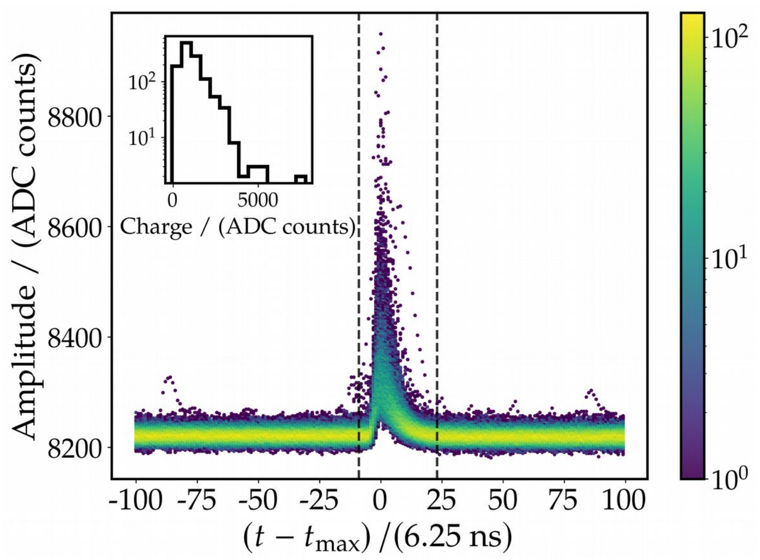




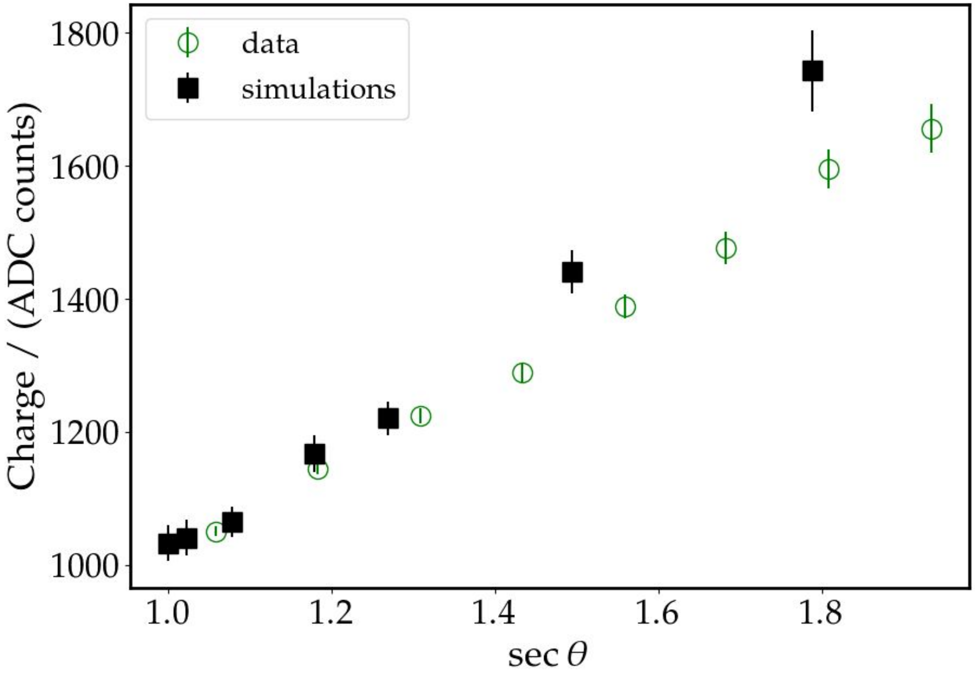
- Stronger attenuation in data than simulations
- Simple and straightforward observable to tune simulations
- Impact on efficiency and corner-clipping?

Not shown in the proceeding

Single-muon ADC charge



- Single-muon ADC traces
  (modules with only 1 bar activated)



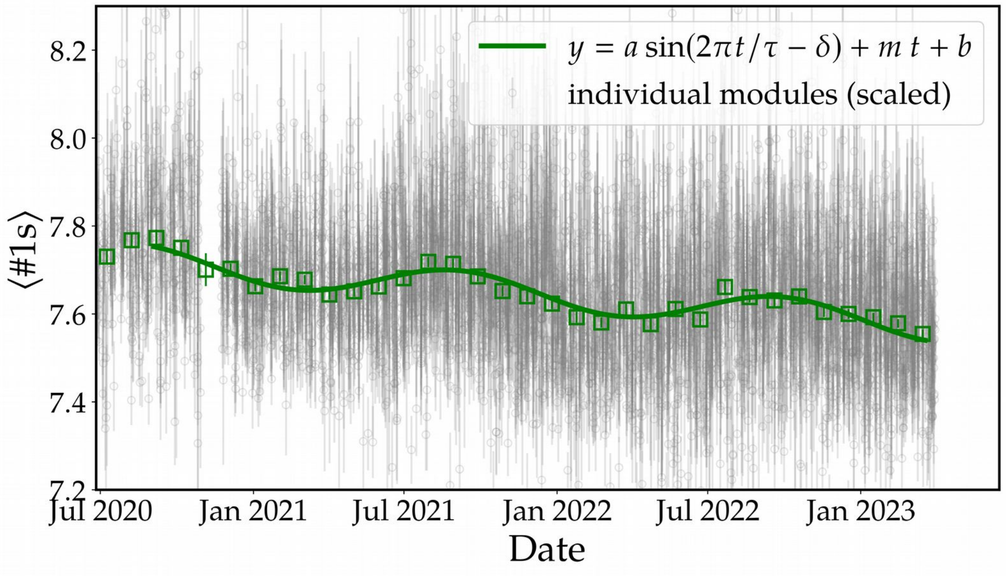
- Why is charge not increasing fast enough with θ in data?
  - Angular and energy distribution of muons discarded
  - Selection bias (efficiency)?
  - To be understood

Outline

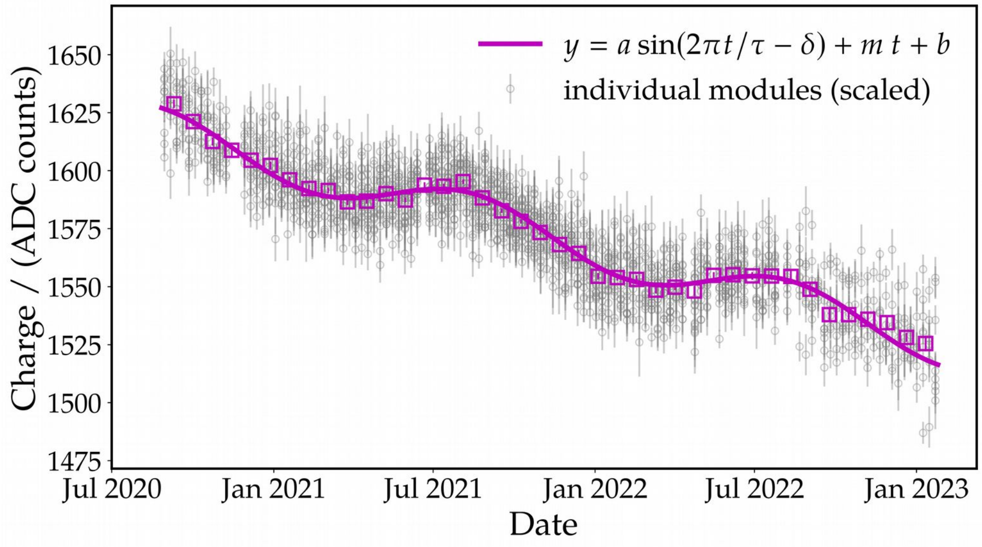
- Detector characterization
  - Fiber attenuation
  - Single-muon ADC charge
- Long-term performance
- Binary reconstruction optimization

Long-term behaviour

Binary (air-shower events)



ADC (online charge)



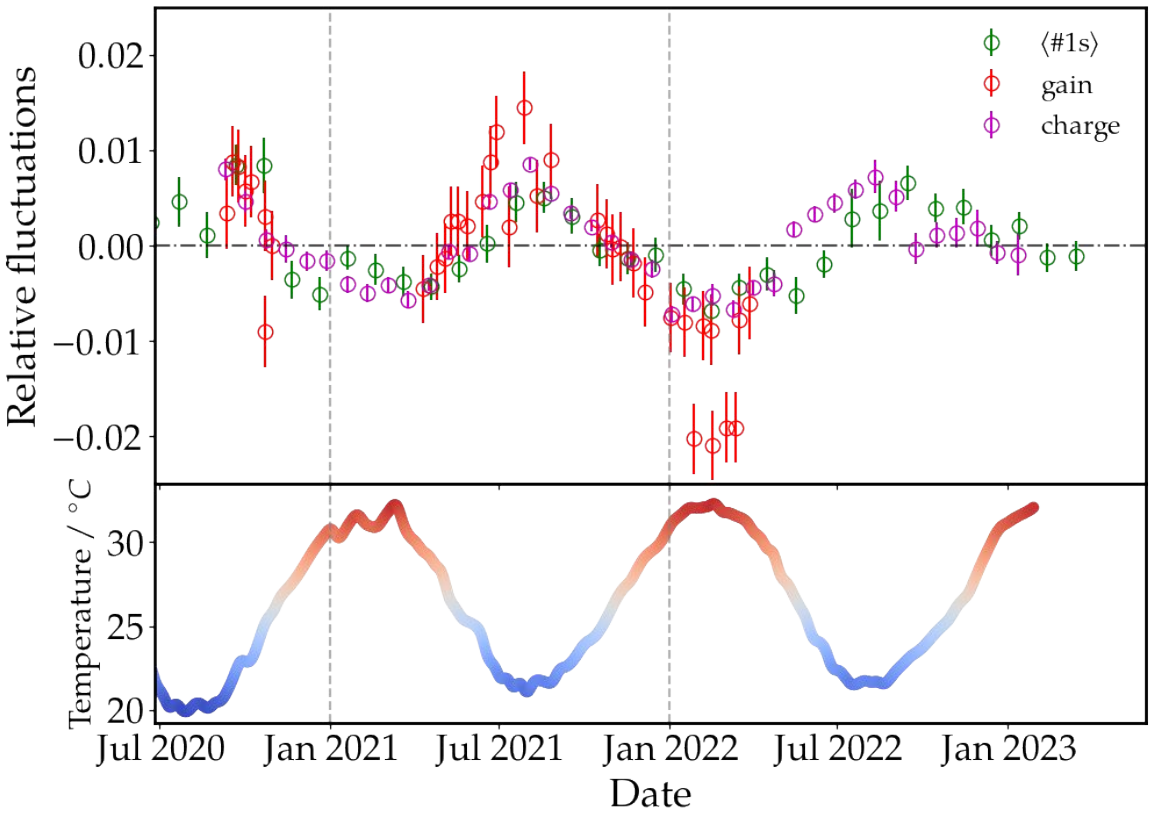
- Seasonal fluctuations + aging

$$y = \boxed{a \sin(2\pi t/\tau - \delta)} + \boxed{m\,t + b}$$

±1%

-0.7% / yr (binary)
-2.5% / yr (ADC)

Long-term behaviour

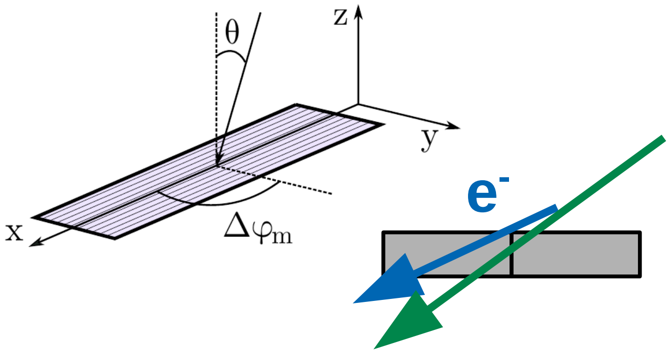


- Linear term (aging) substracted from #1s and charge
- Periodic measurement of gain in a single module (F. Gollan)
- Fluctuations in signals is consistent with gain

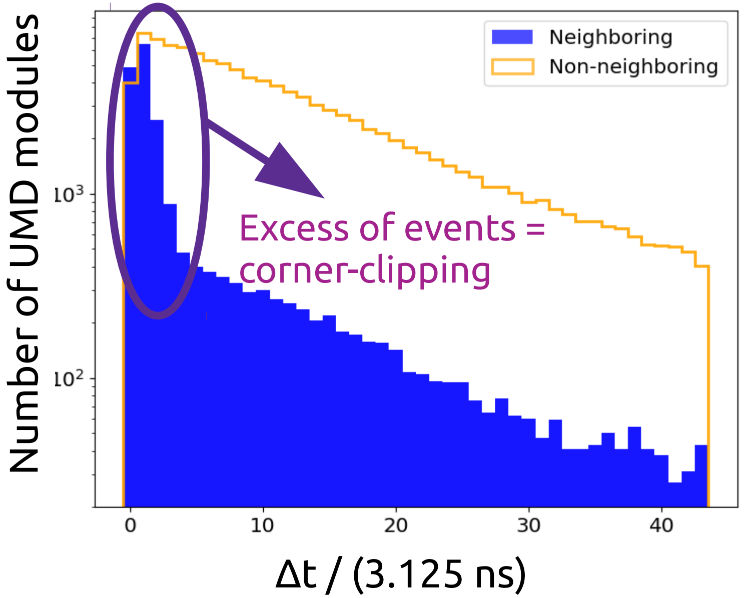
Outline

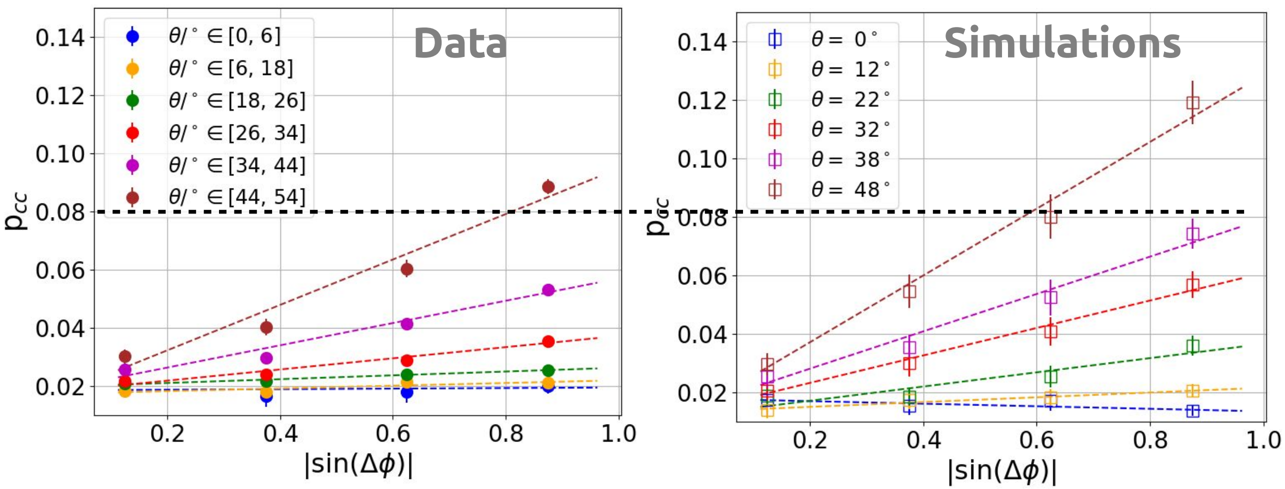
- Detector characterization
  - Fiber attenuation
  - Single-muon ADC charge
- Long-term performance
- Binary reconstruction optimization

Corner-clipping correction



- Inclined muons (or e-) that activate two neighboring bars
- Geometry-dependent source of overcounting
- Timing between neighboring and non-neighboring bars → single-muon corner-clipping probability $p_{cc}(\theta, \Delta\varphi)$ → Data-driven corner-clipping correction
- Potential to extend analysis to higher multiplicities (see backup)

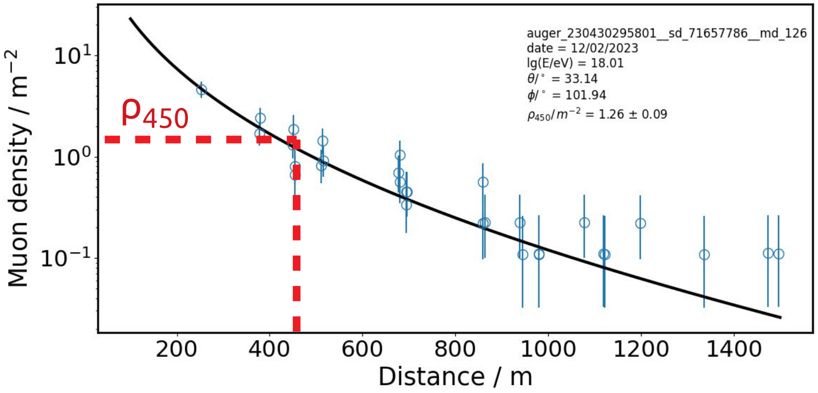




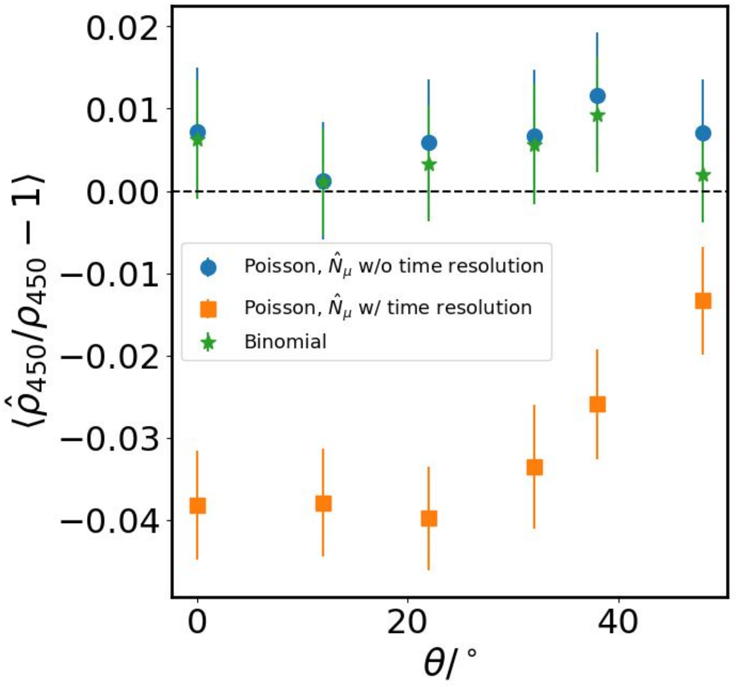
- Larger p_{cc} values for simulations (simulations are too efficient?)

UMD LDF fit

- Final goal of the reconstruction is to fit a LDF → Muon density at 450 m as a **measure of the muon content**

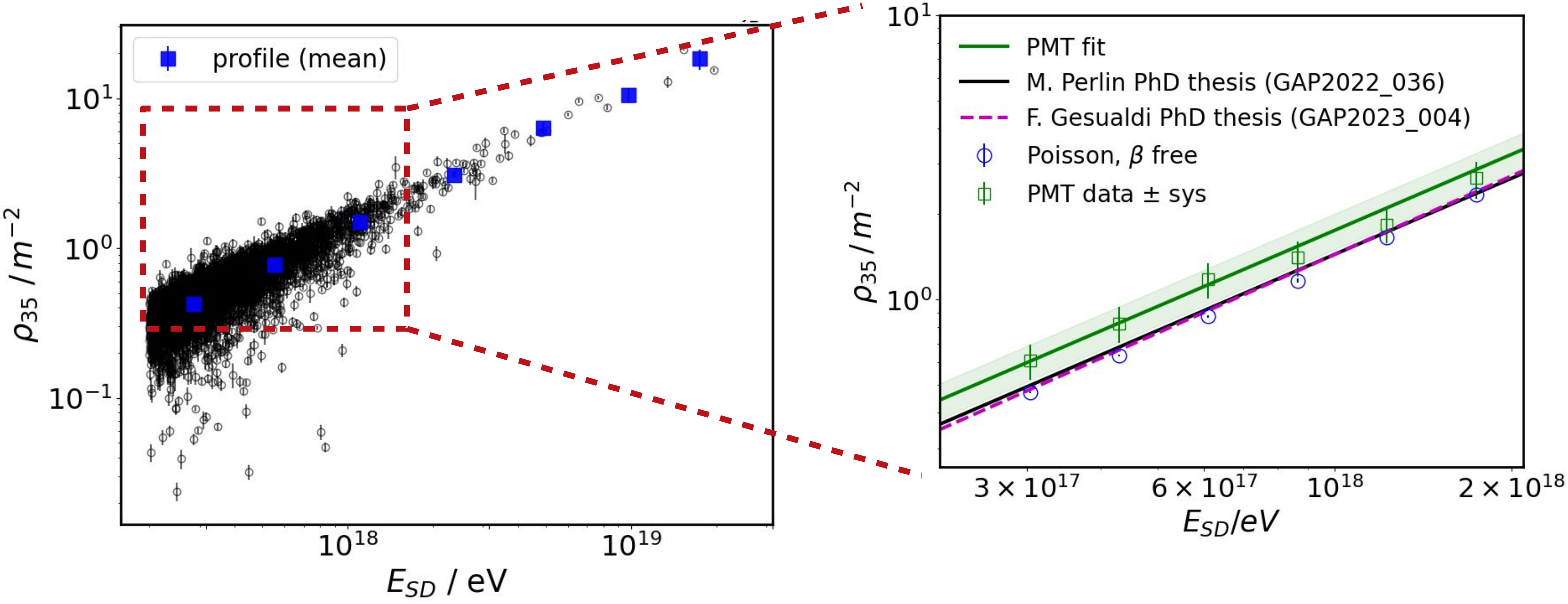


Fe, lg(E/eV) = 18.5



- Different reconstructions methods were tested with simulations (different likelihoods; timing of traces)
- Bias is flat with zenith (corner-clipping correction works)
- Two optimal methods applied to data

Muon content vs energy (preliminary)



- Muon content in this work in **agreement with other SiPMs** measurements
- ~ 18% **less muons** wrt PMT data (to be understood)
- Caveats: no efficiency correction/systematics

Summary & Outlook

Detector characterization

- Fiber attenuation characterized in ADC and binary modes
- Charge vs θ → not increasing as secθ (still open)

Long-term performance

- Aging -2.5% / year in charge and -0.7% / year in #1s
- ± 1% seasonal modulation in charge and #1s → consistent with gain fluctuations

Reconstruction optimization

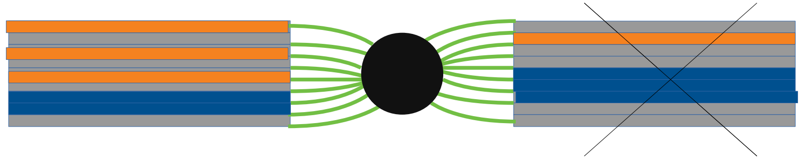
- Data-driven corner-clipping correction
- Preliminary results in data show **very good agreement** with previous SiPM results (different methods/reconstructions)
- There is a **tension** between SiPM and PMT data (~-18%)

Outlook

- Fine tune simulations (fiber attenuation)
- Compare LDF with previous experiments
- Mass composition analysis

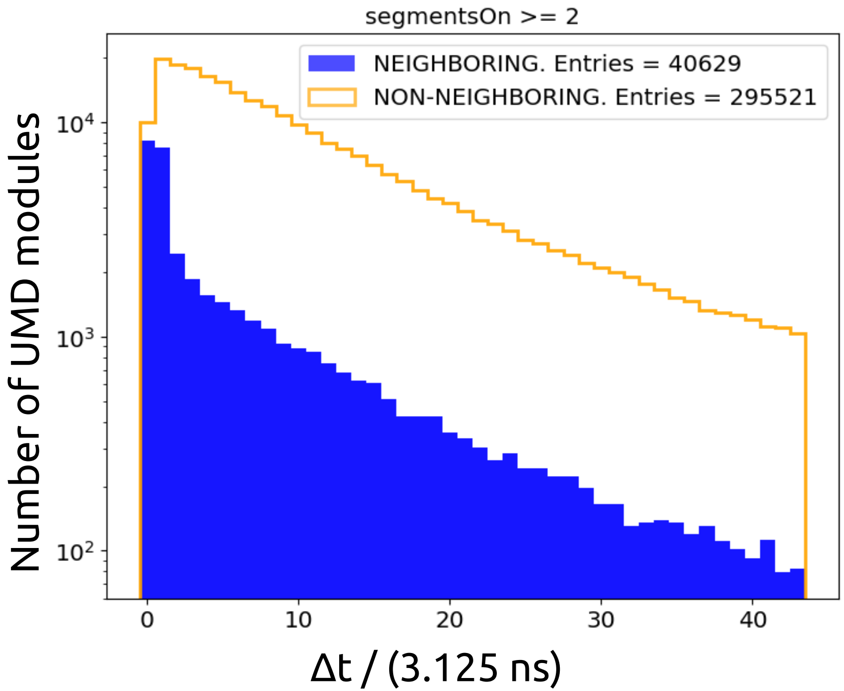
Backup

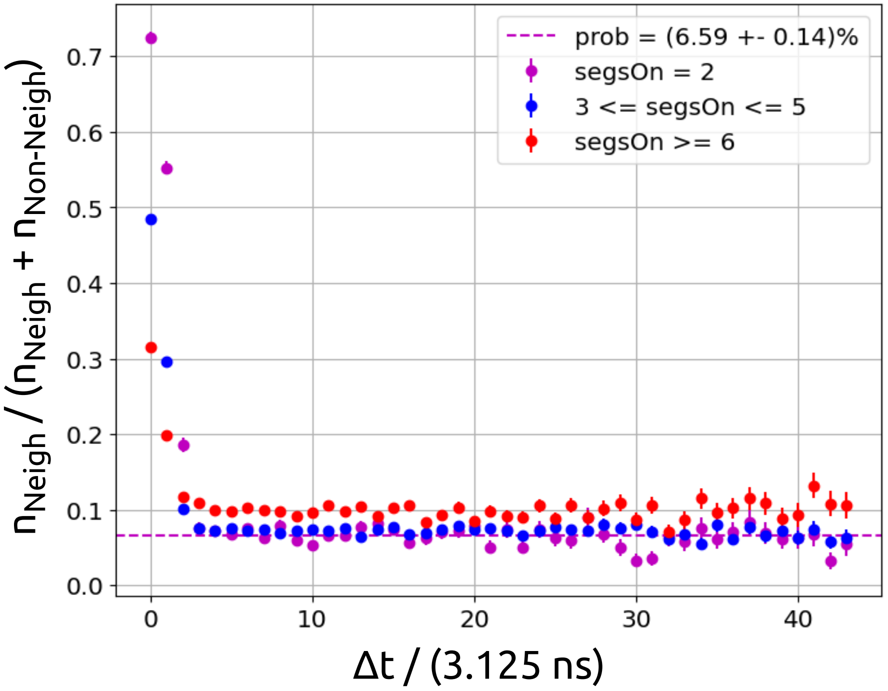
Corner-clipping for higher multiplicities



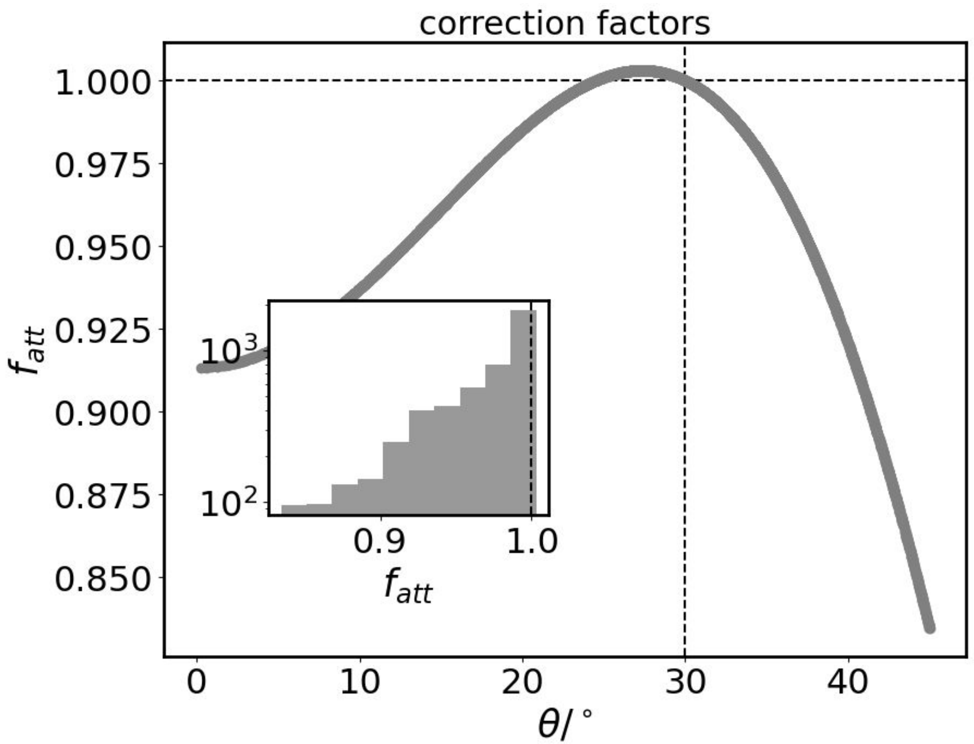
- Potential to extend the analysis closer to the core
- Increase statistics (module-by-module analysis?)
- To study: selection bias? Definition of pcc?

- Δt for isolated neighboring pairs & non-neighboring pairs combinations

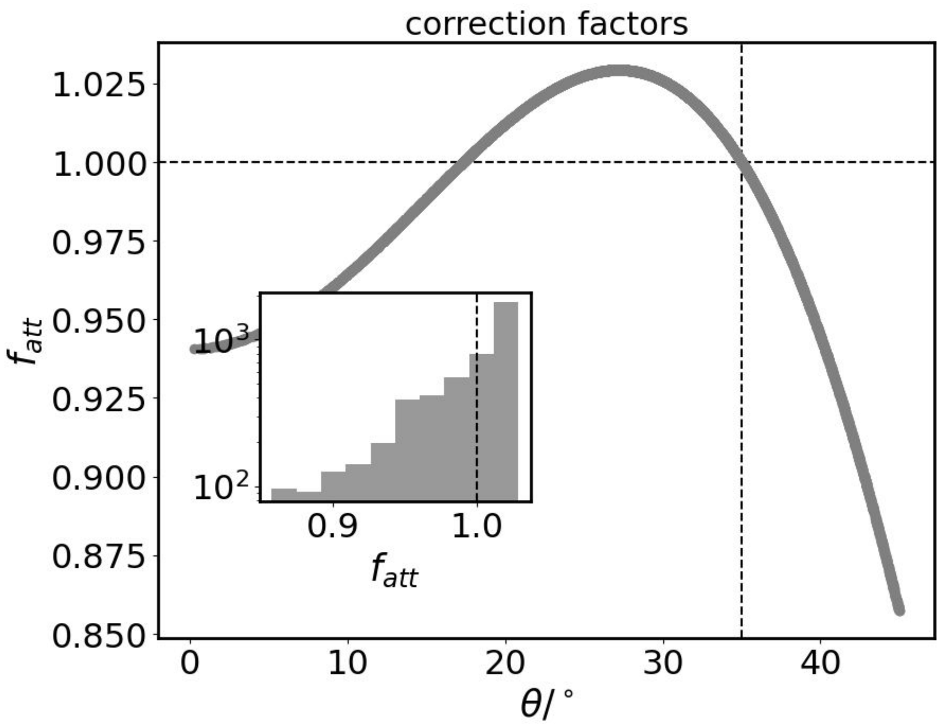




Attenuation correction: impact of θ_{ref}

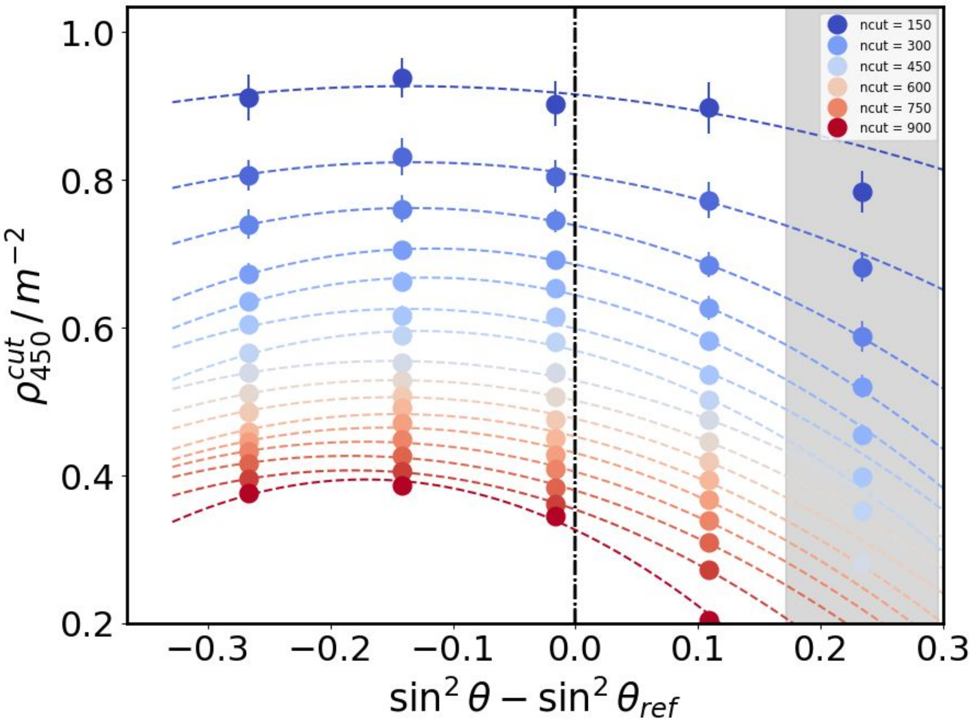


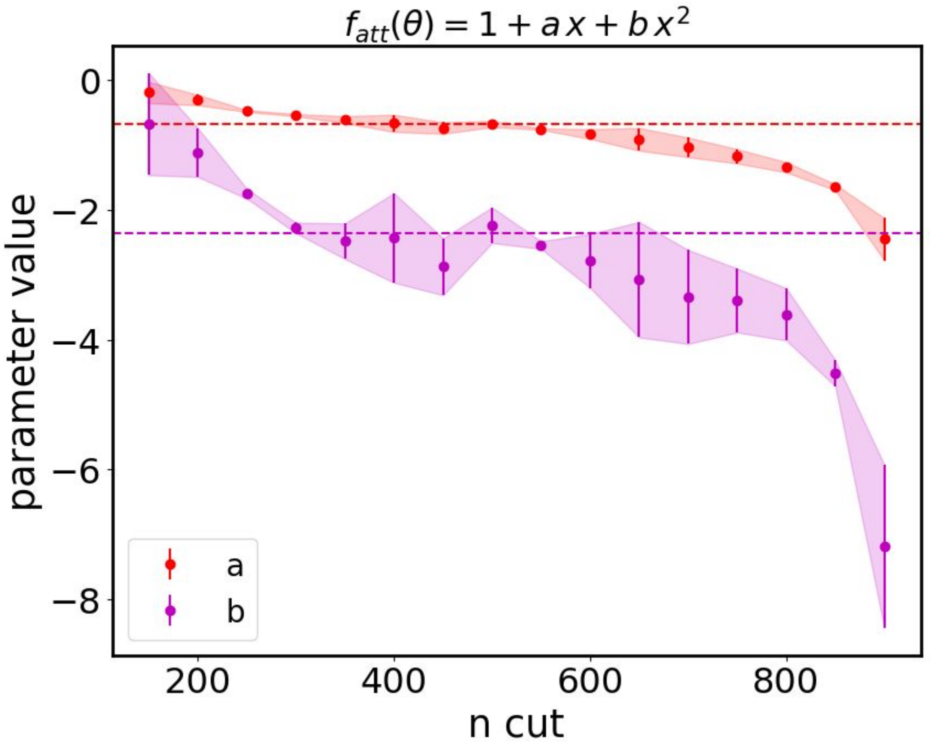
Θ_{ref} = 30°
Most of the factors are close to 1 (good)



Θ_{ref} = 35°
Most of the factors are larger than 1 (not so good)

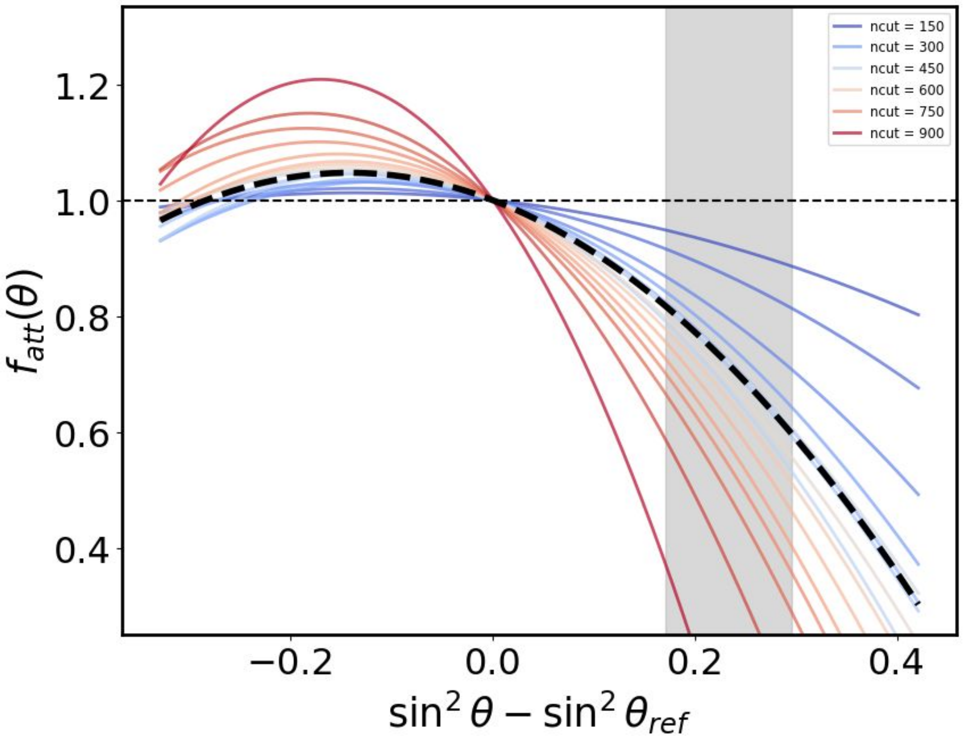
Attenuation correction

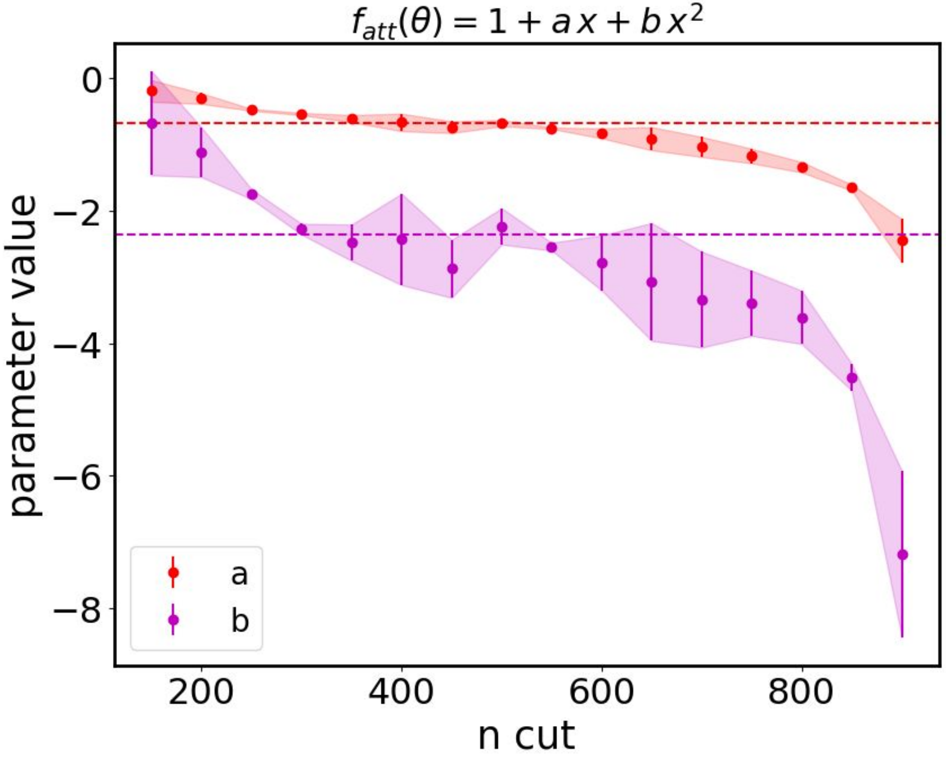




- CIC countdown method, $\theta_{ref} = 35°$

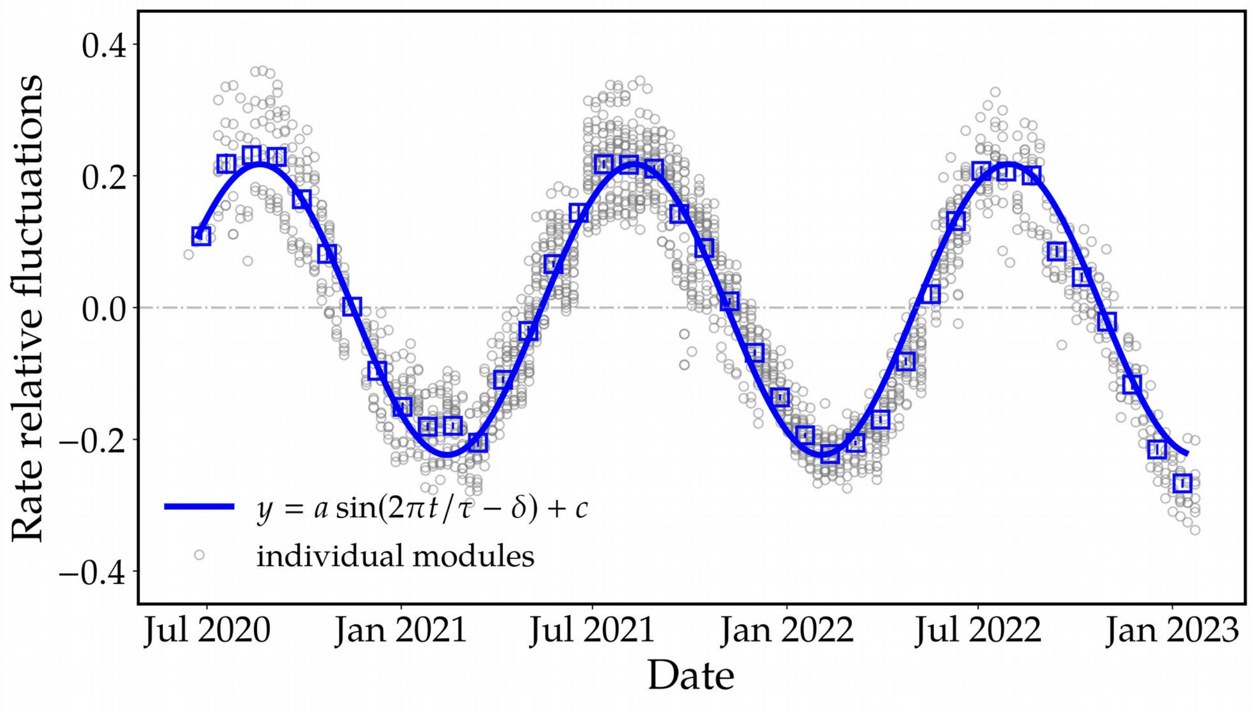
Attenuation correction





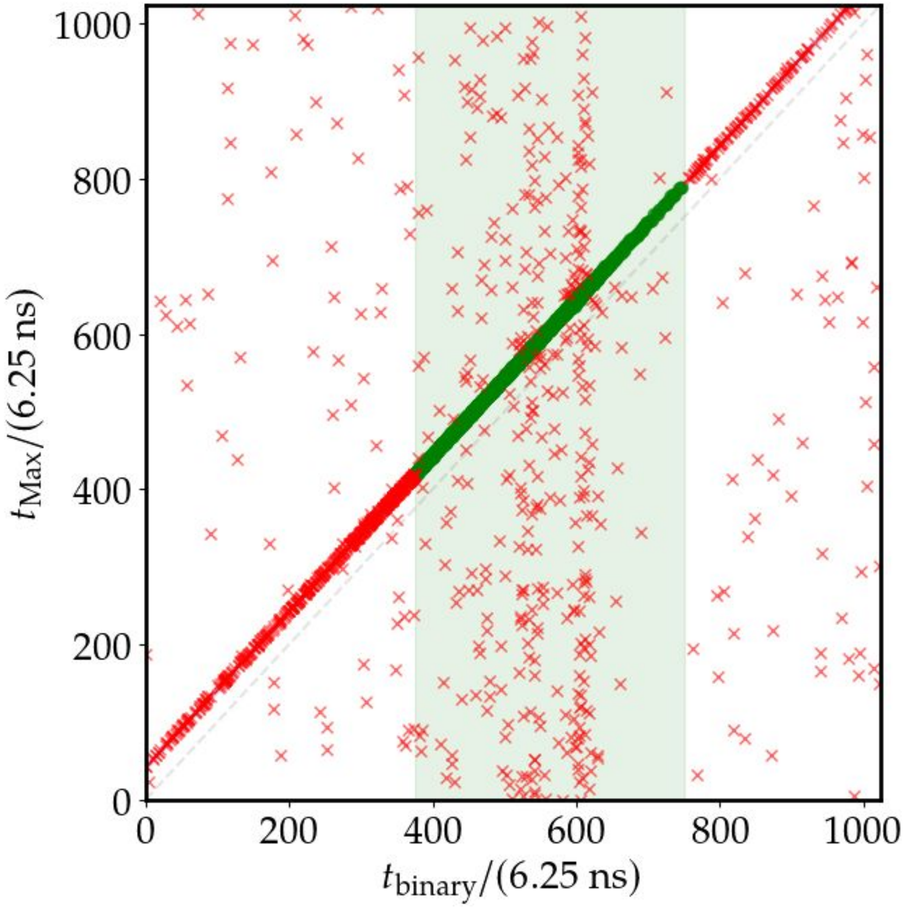
- CIC countdown method, $\theta_{ref} = 35°$
- Weighted mean of parameters a and b
- $\rho_{35} = \rho_{450} / f_{att}(\theta)$

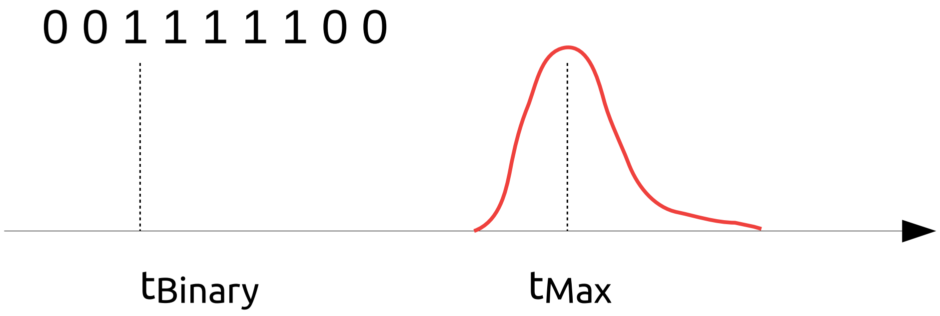
Long-term performance: rate of online charge



- Rate of T1 + single-muon pattern
- ± 20% fluctuation → To be investigated

Single-muon ADC traces





Previous work

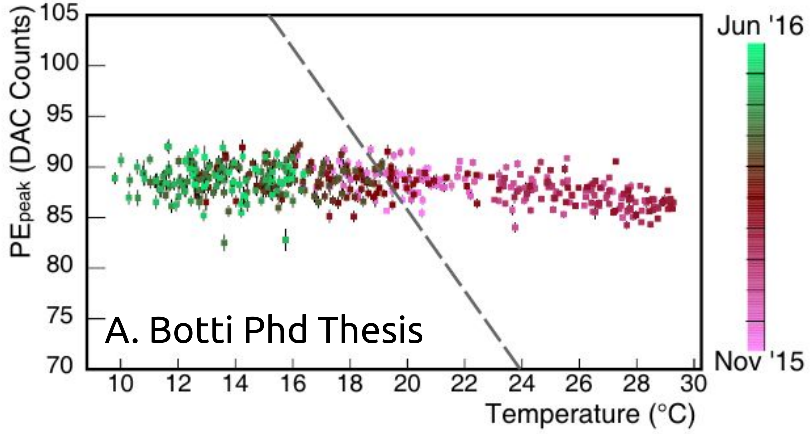
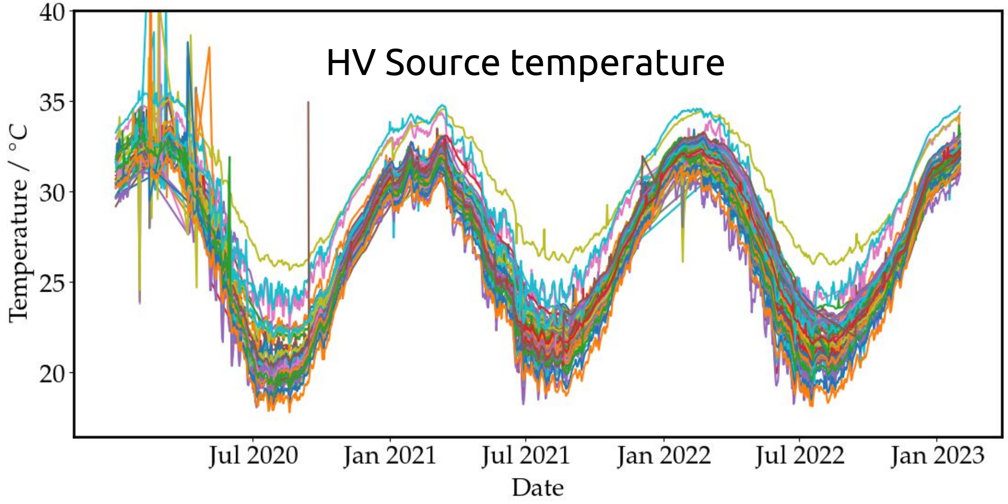
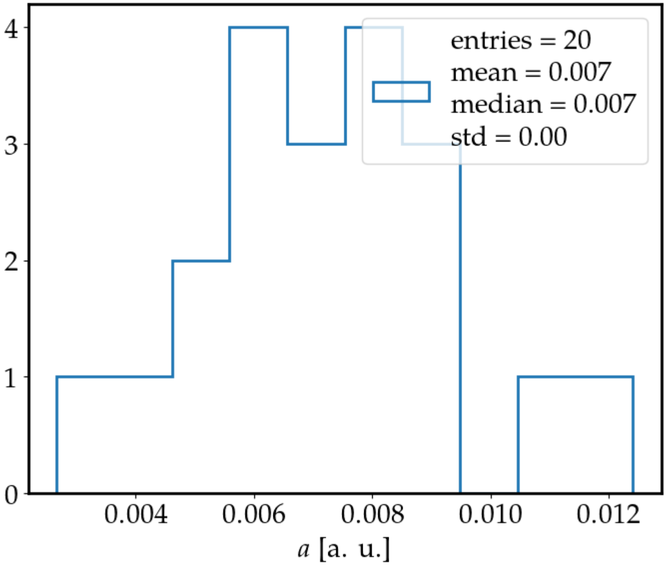


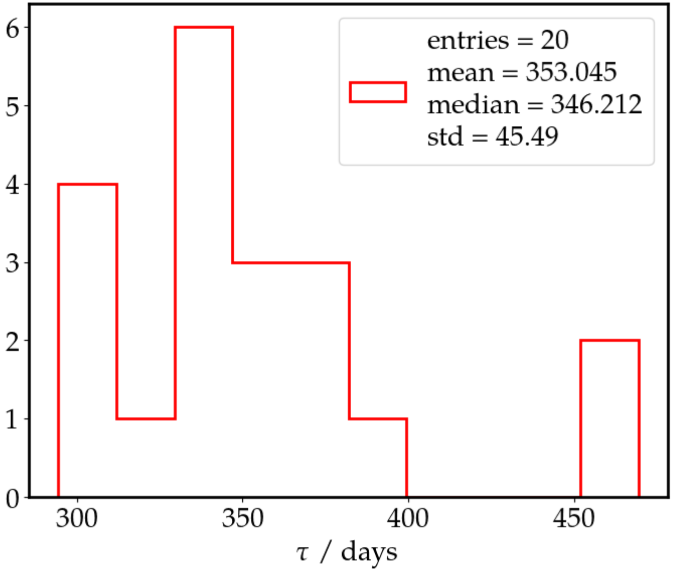
Figure 4.10: 1 PE amplitude as a function of the SiPM temperature over an eight-month period with a temperature range of $\sim 10-30$°C. The colors indicate the months: greenish for the coldest season and reddish to the warmest. The dotted-gray line shows 1 PE amplitude temperature dependence had there not been any temperature compensation in the front-end electronics. The almost constant 1 PE amplitude shows that the gain stabilization works at the level of 0.2%/°C.

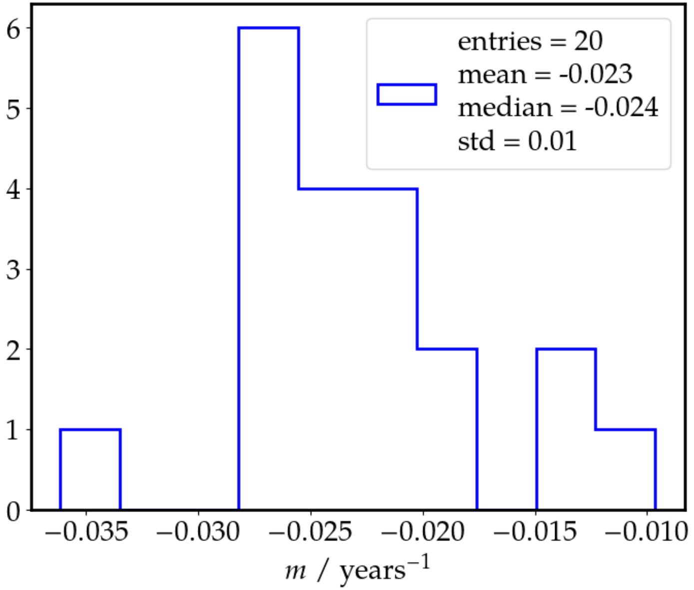


ΔT = 15 C → ΔGain = 3% (consistent with what we see)

ADC T1 - Charge – Module by module analysis





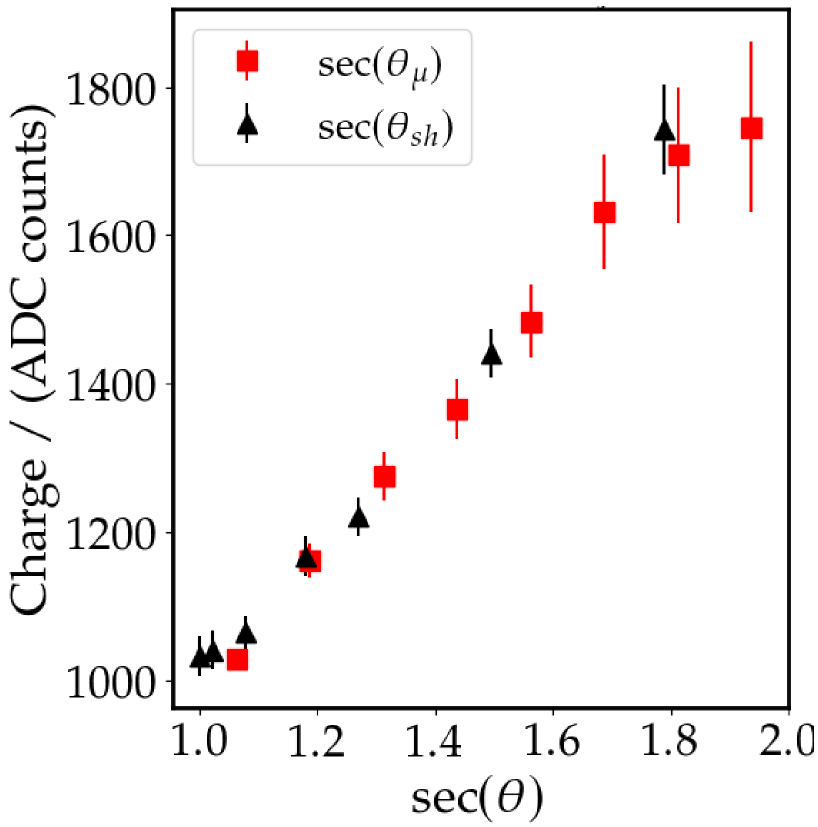


$$y = a \sin(2\pi t/\tau - \delta) + mx + b$$

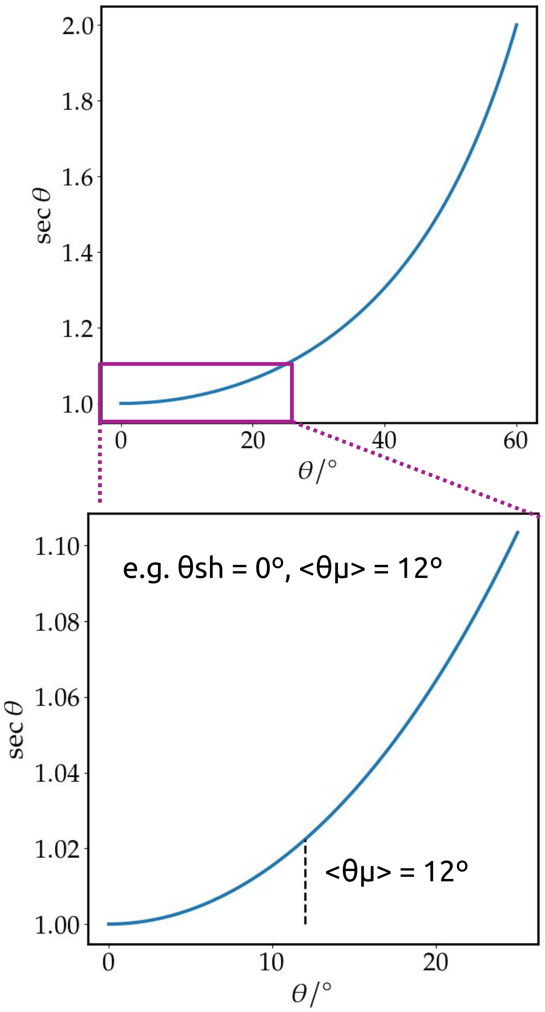
Aging: m = -2.5 % / year

Consistent with the 'global' analysis

Single-muon charge vs θ: angular distribution of muons

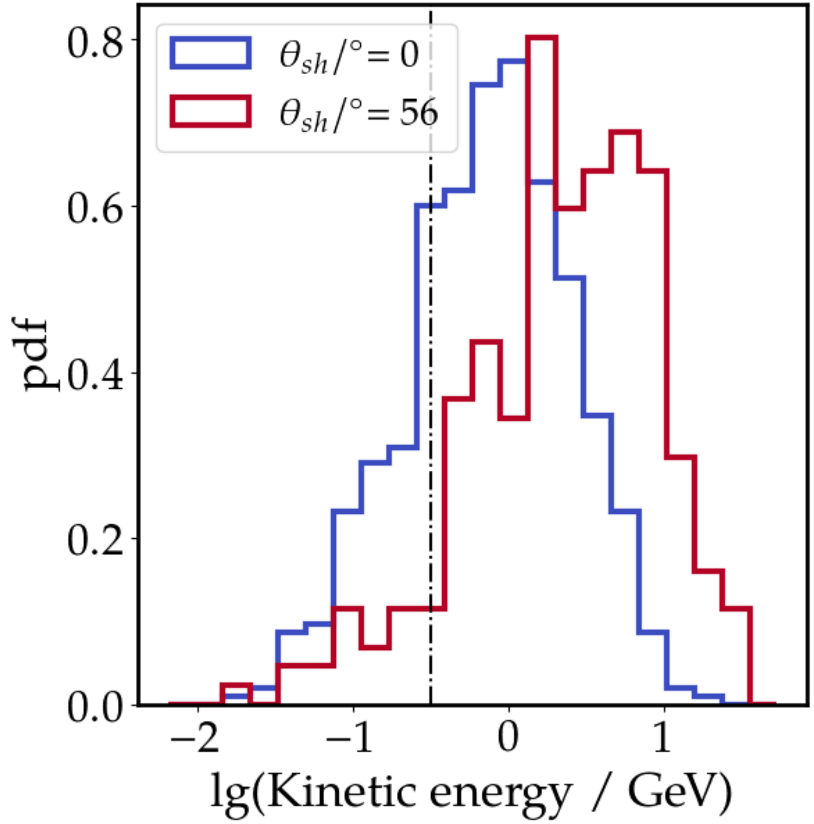


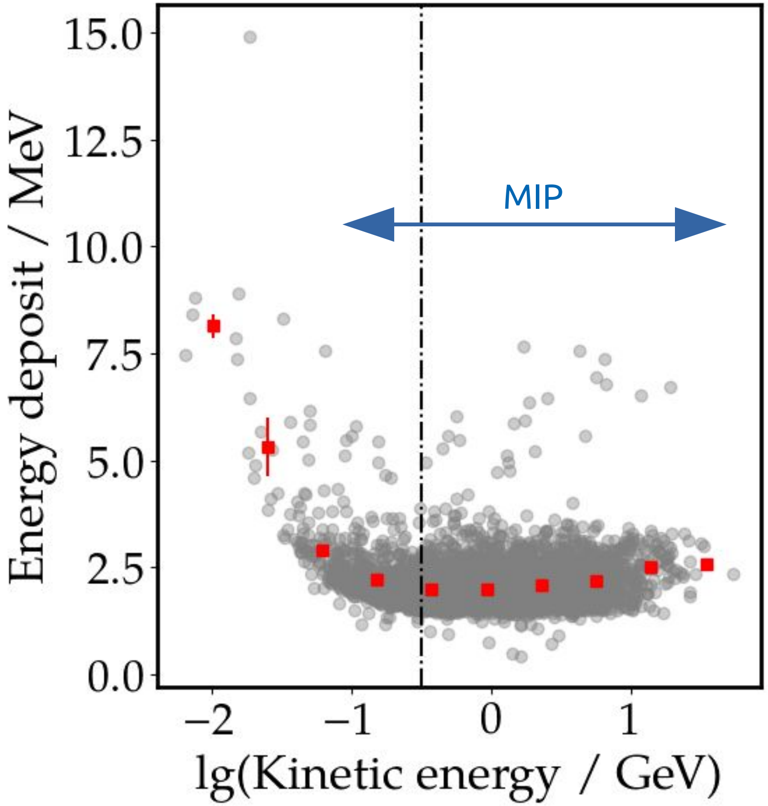
- Using θμ or θsh yields the same slope
- **Angular distribution of muons discarded**



- Secant varies slowly for small θ → it still holds that secθμ ~ secθsh

Single-muon charge vs θ: energy spectrum of muons

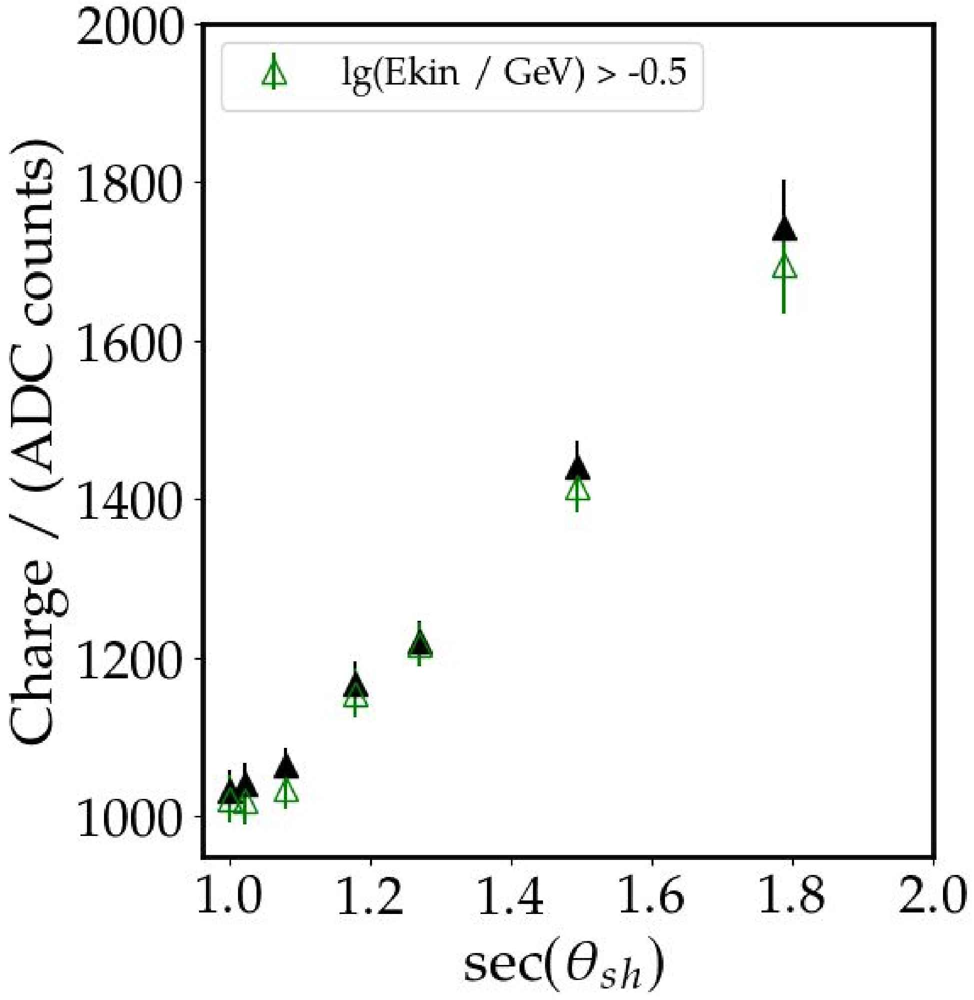




<u>Hypothesis</u>

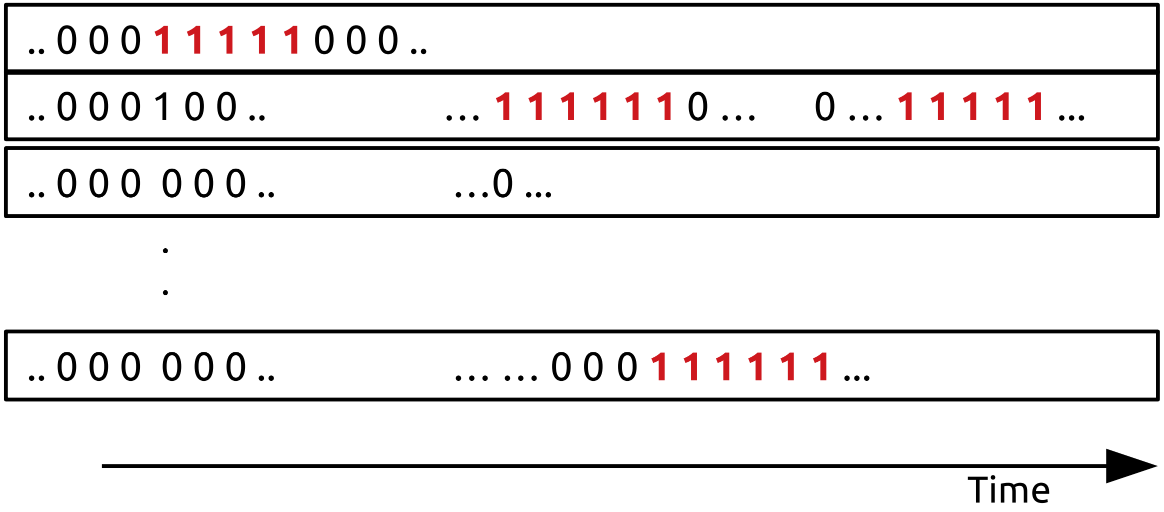
- Vertical events have lower energy muons → more influence of below-MIP muons
  → If I do cut in kinetic energy lg(Kinetic energy / GeV) > -0.5 I should see a difference in charge vs secθ

Single-muon charge vs θ: energy spectrum of muons



- Applying energy cut has no effect on the slope
- **Energy spectrum of muons discarded**

Estimating Nμ without time resolution



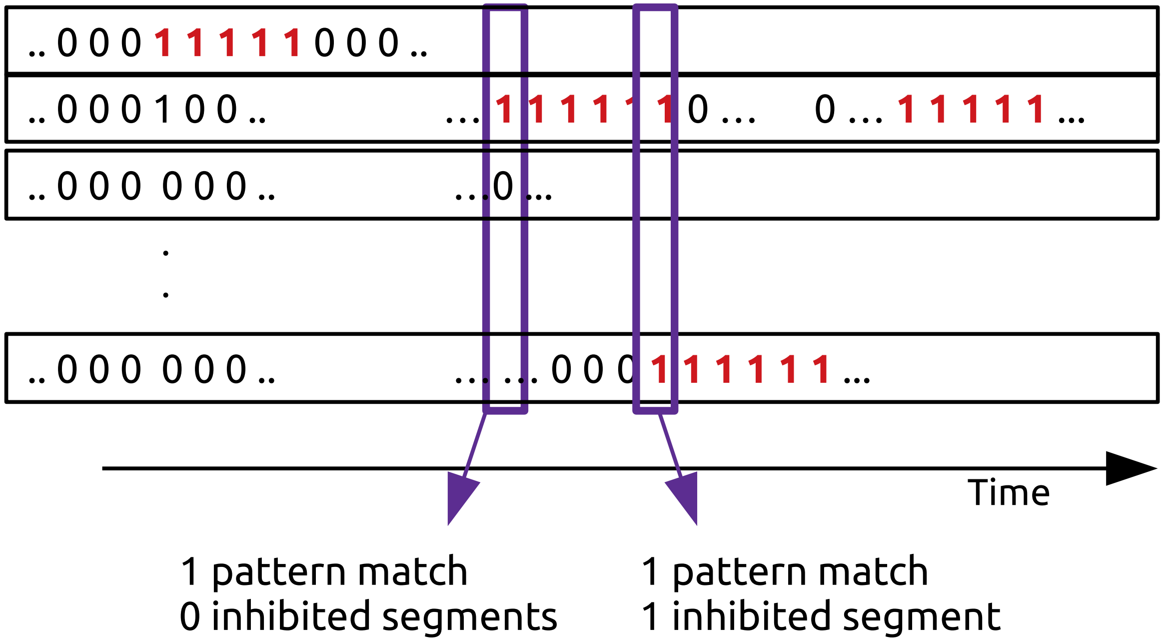
- k = # bars with **at least one** muon pattern (k = 3 in the example)
- It can be shown

$$\hat{N}_\mu = \frac{\ln(1 - k/64)}{\ln(1 - 1/64)}$$

- Statistically simple model and straightforward
- Independent of the time distribution of muons

D. Ravignani, A. D. Supanitsky, Astropar. Phys. (2015), 65, 1-10

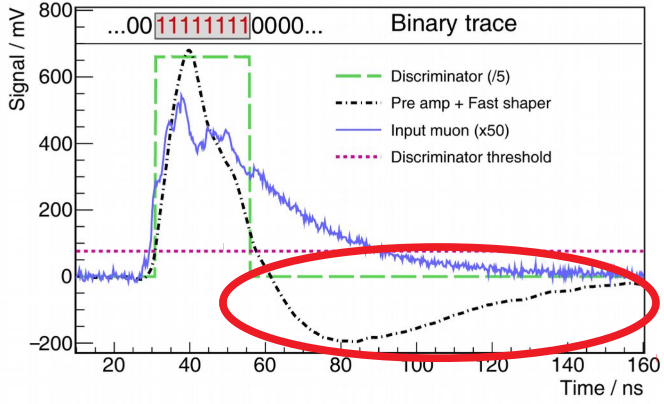
Estimating Nμ with time resolution



- For each time bin i:
  - # of muon patterns starting in bin k_i
  - # of inhibited segments (earlier muon pattern matchs + dead time) n_i^{inh}

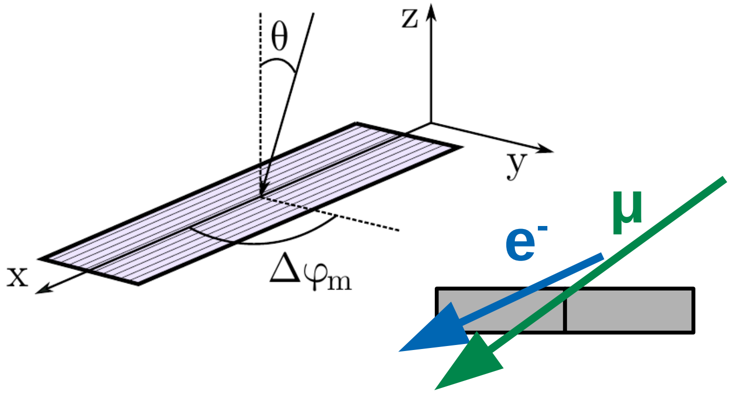
$$\hat{N}_\mu = \sum_{i \in \text{time bins}} \frac{64}{64 - n_i^{\text{inh}}} \frac{\ln(1 - k_i/(64 - n_i^{\text{inh}}))}{\ln(1 - 1/(64 - n_i^{\text{inh}}))}$$

- Subject to electronic undershoot bias



F. Gesualdi, A. D. Supanitsky, Eur. Phys. J.C. (2022), 82, 925

Corner-clipping muons



- Inclined muons (or e-) that activate two neighboring bars
- Geometry-dependent source of overcounting
- Data-driven correction with single-muon corner-clipping probability $p_{cc}(\theta, \Delta\varphi)$*

$$\hat{N}_\mu = \frac{1}{(1 + p_{\rm cc}(\theta, \Delta\phi))} \frac{\ln(1 - k/64)}{\ln(1 - 1/64)}$$

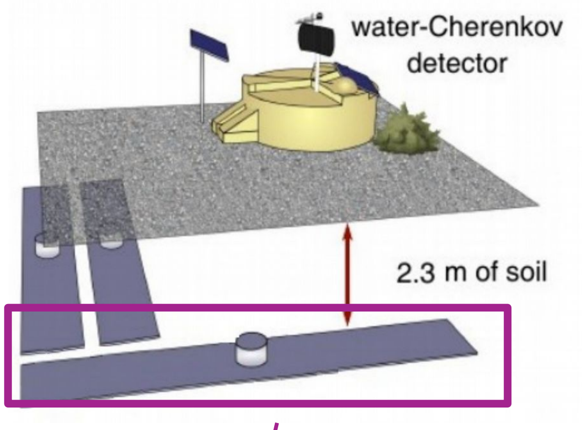
w/o time resolution

$$\hat{N}_\mu = \frac{1}{(1 + p_{\rm cc}(\theta, \Delta\phi))} \sum_{i \in \text{time bins}} \frac{64}{64 - n_i^{\rm inh}} \frac{\ln(1 - k_i/(64 - n_i^{\rm inh}))}{\ln(1 - 1/(64 - n_i^{\rm inh}))}$$

w/ time resolution

*See presentation in Foundations March Collaboration Meeting 2023

Muon LDF fit – Poisson Likelihood



Detector j

measurement $\hat{N}_{\mu_j}$

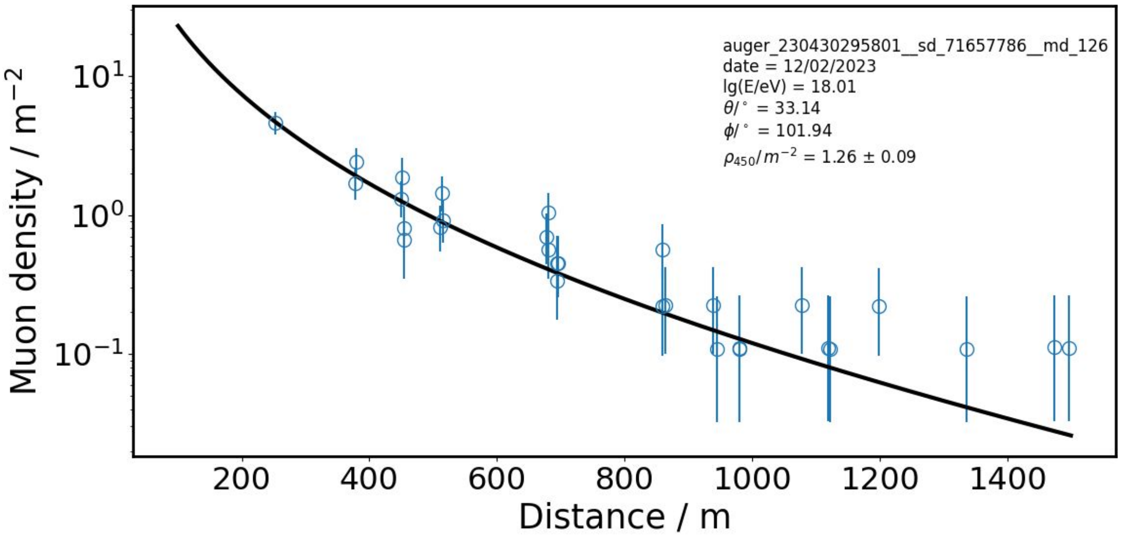
expected value $\mu_j = \rho_{\mathrm{LDF}}(r_j)\, A \cos\theta$

likelihood $\mathrm{Poisson}_{\hat{N}_{\mu_j}}(\mu_j)$

Event likelihood

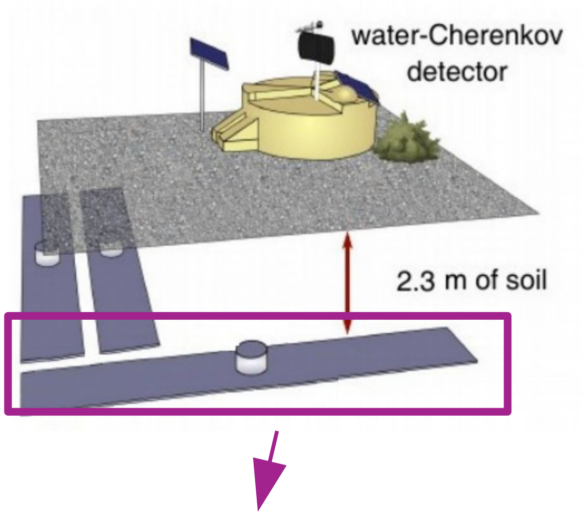
$$L_{\mathrm{event}} = \prod_j \mathrm{Poisson}_{\hat{N}_{\mu_j}}(\mu_j)$$

Maximize to obtain $\hat{\rho}_{450}$



A. D. Supanitsky et al, Astropar. Phys. (2008), 29, 461

Muon LDF fit – Binomial Likelihood



Detector j

measurement k_j = # bars with at least one pattern

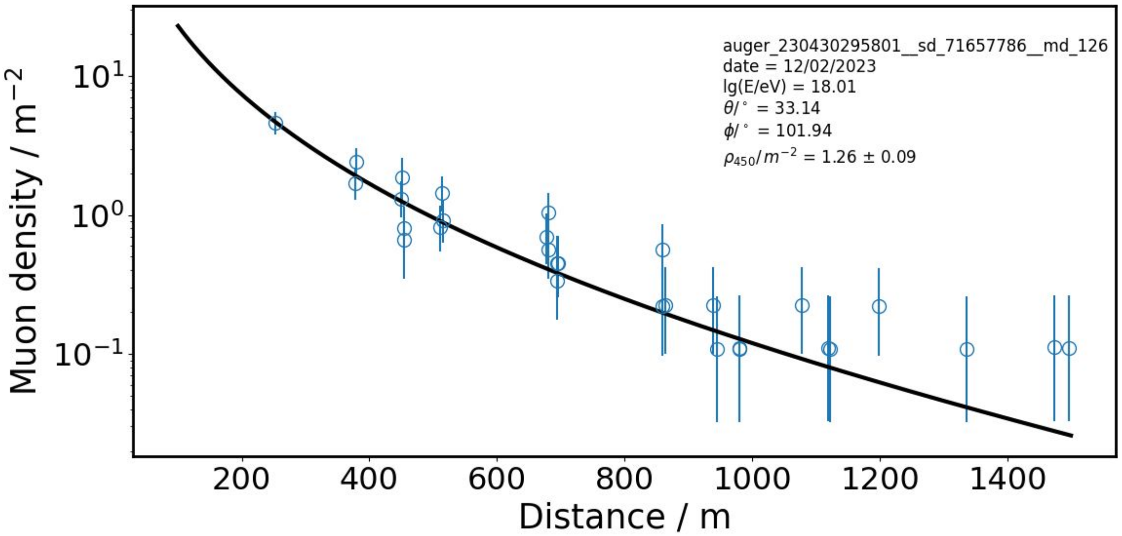
expected value $\mu_j = \rho_{\mathrm{LDF}}(r_j)\, A\, \cos\theta$

likelihood $\mathrm{Binom}_{k_j}(n = 64\,,\, p = 1 - e^{-\mu_j/64})$

Event likelihood

$$L_{\mathrm{event}} = \prod_j \mathrm{Binom}_{k_j}(n = 64\,,\, p = 1 - e^{-\mu_j/64})$$

Maximize to obtain $\hat{\rho}_{450}$



D. Ravignani, A. D. Supanitsky, Astropar. Phys. (2015), 65, 1-10

Available reconstructions

Likelihood

k = # bars with at least one pattern → $\hat{N}_\mu$ → Poisson

k = # bars with at least one pattern → Binomial

Poisson, Binomial: w/o time resolution

k_i and n_i^{inh} for each time bin i → $\hat{N}_\mu$ → Poisson

Poisson: w/ time resolution

1) Now included in a consistent way in Offline (see backup)

2) Test performance of each reconstruction (discrete CORSIKA library + Offline)

- Each shower reconstructed once with each method
- Bias and resolution in ρ_{450} with dense ring