The role of direct muon measurements in Auger

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Institute for Astroparticle Physics

PIERRE AUGER OBSERVATORY

Karlsruher Institut für Technologie

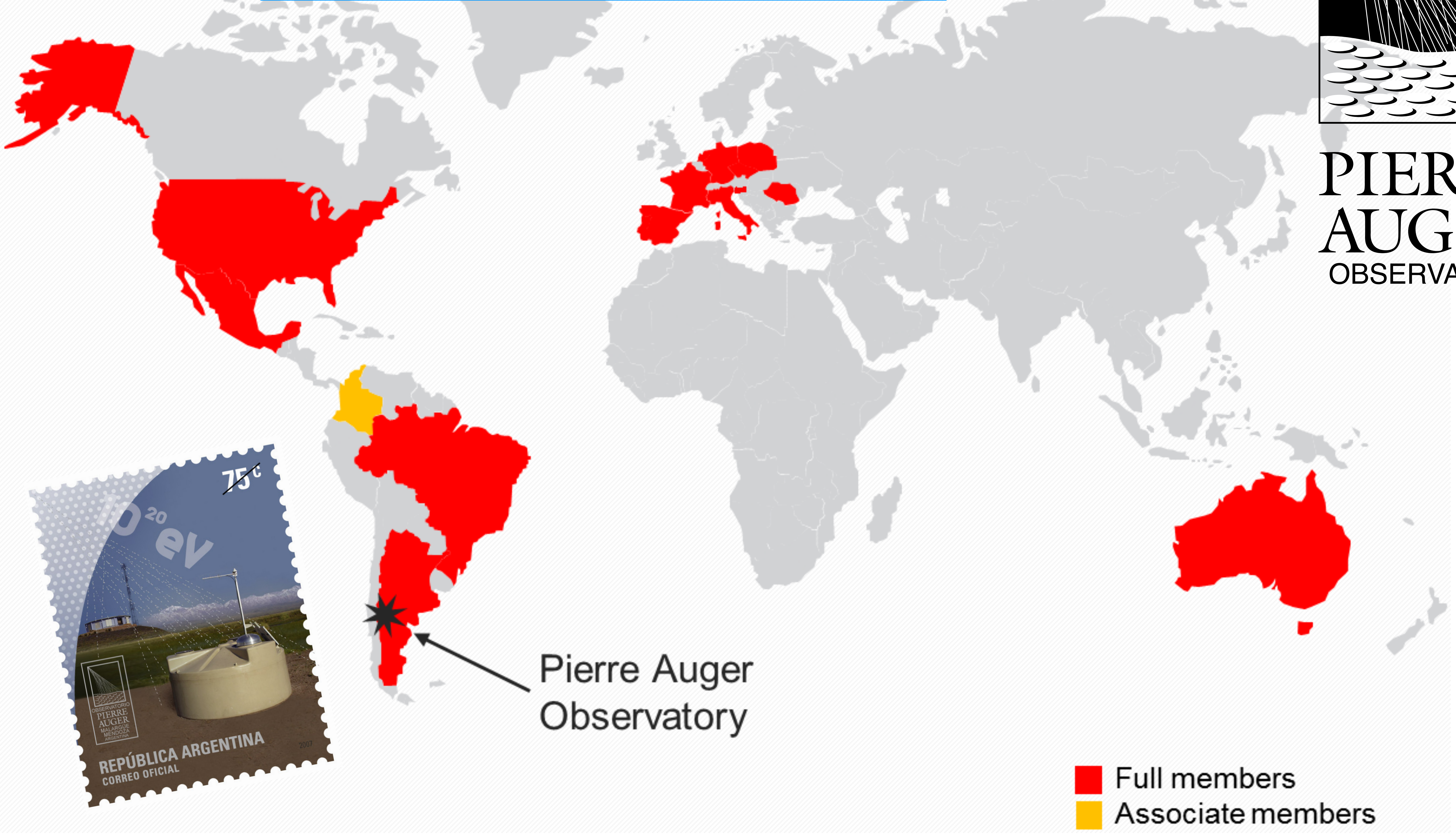
Workshop on tuning of hadronic interaction models
22-25 January 2024

The Pierre Auger collaboration

17 countries, ~90 institutions, ~400 authors

Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

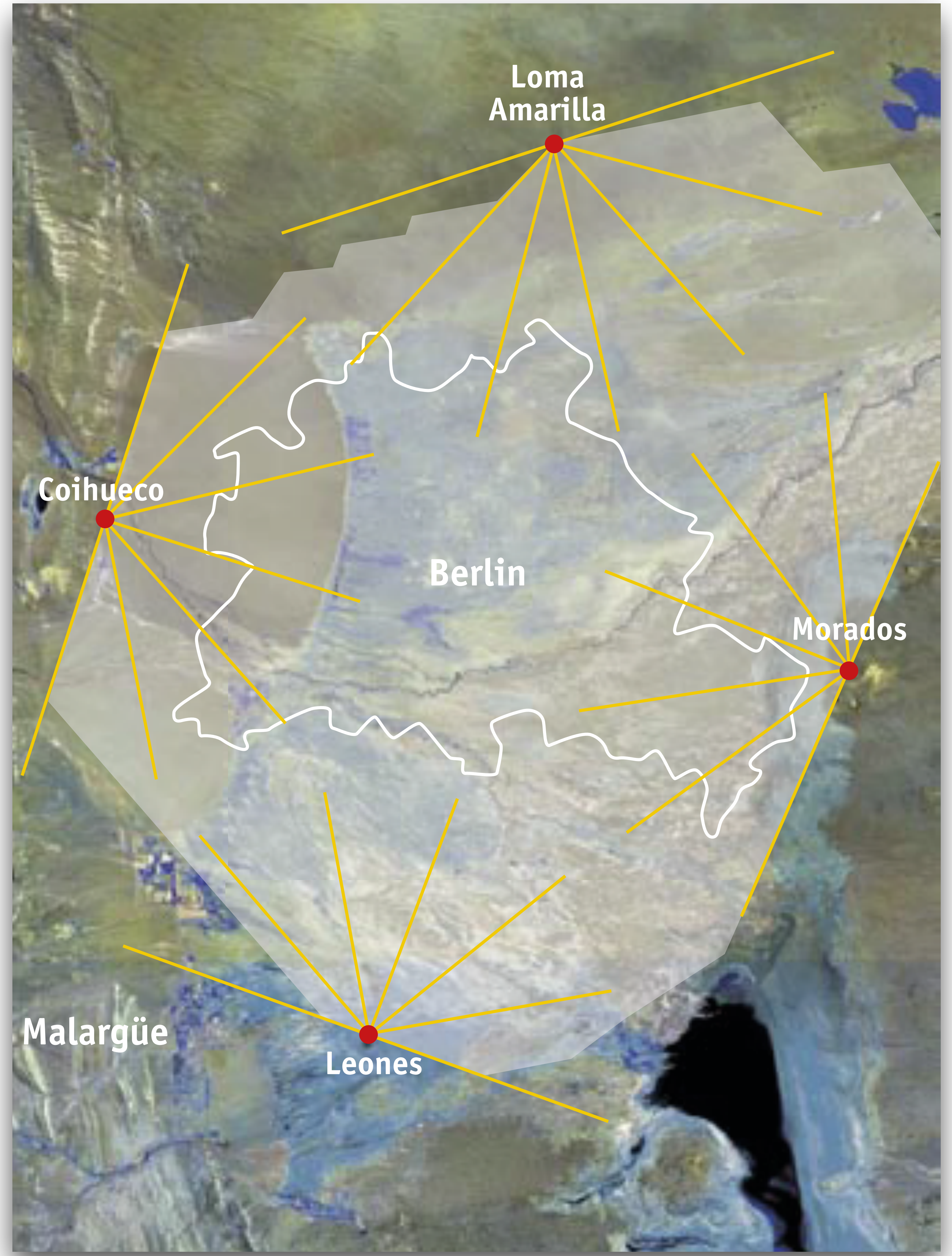
associated



PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory

- East of Andes
- Province of Mendoza, Argentina
- Area 3000 km² (4x Berlin)
- 2000: Engineering Array
- 2004: start...
- 2008: ...end of construction of Auger
- 2024: end of construction of AugerPrime

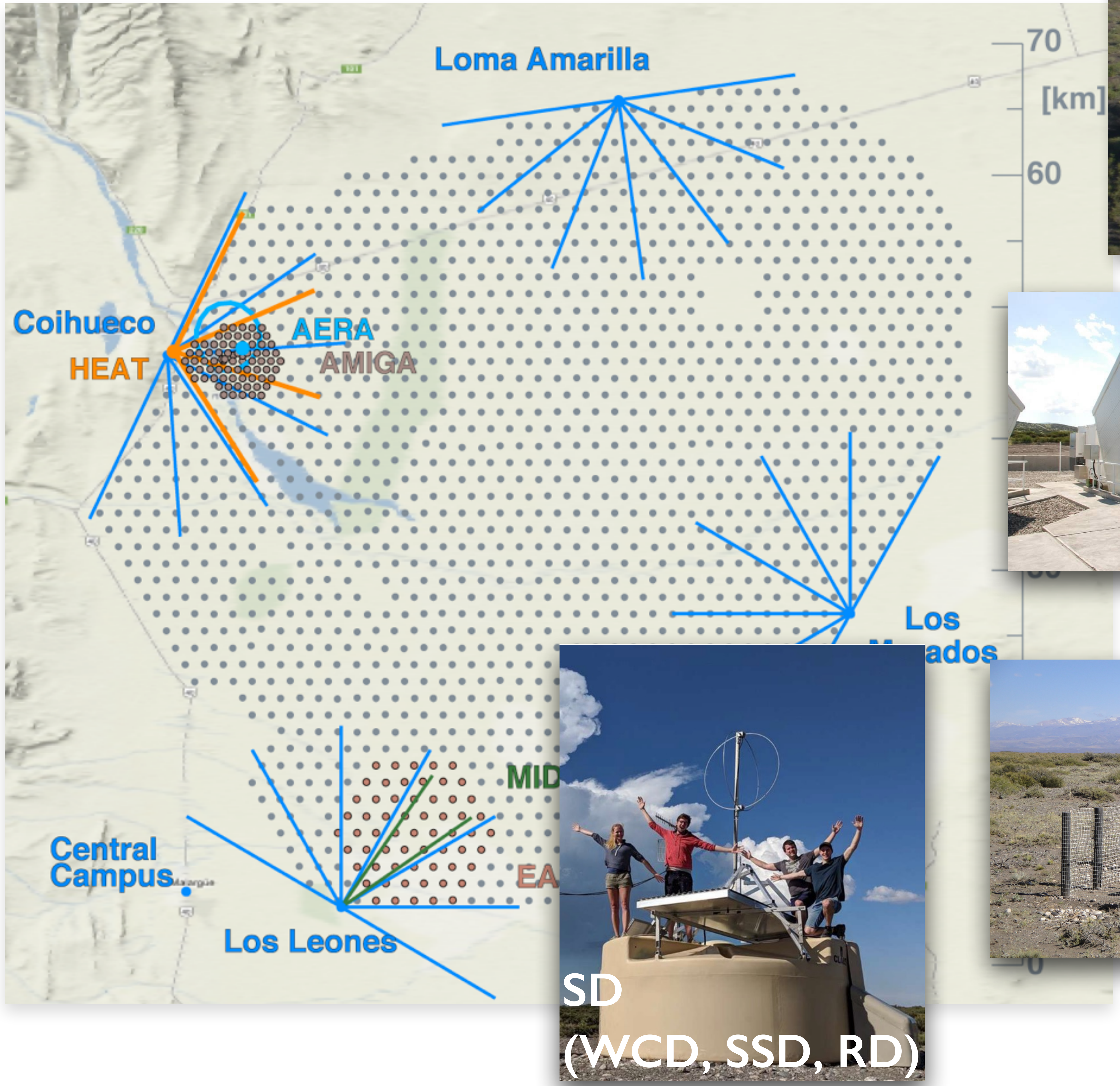


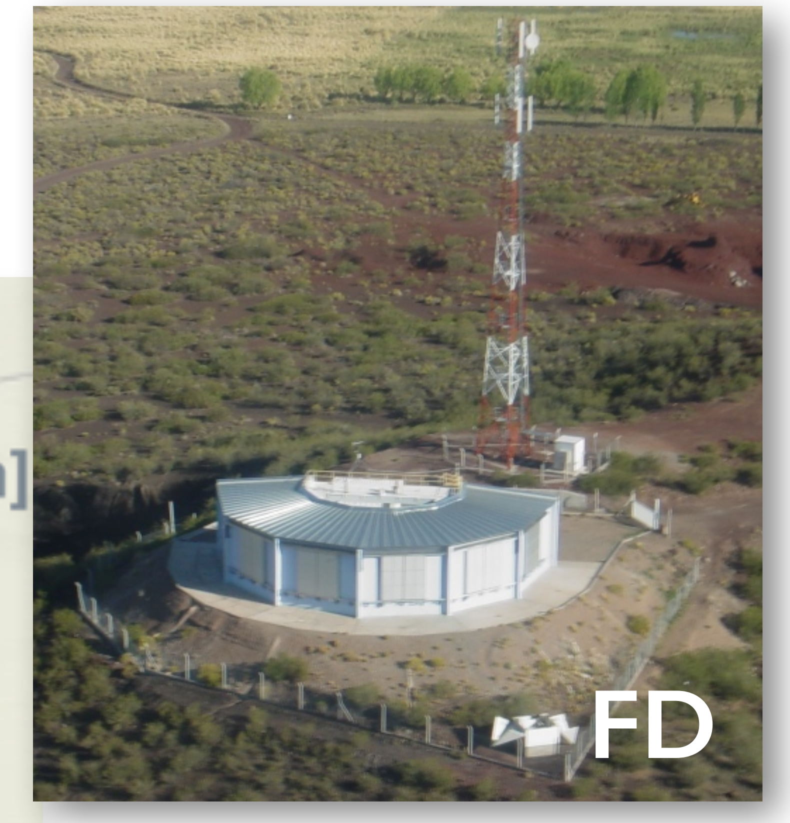
The Pierre Auger Observatory

Fluorescence detector (FD)
- 4 sites
  - 0-30°
  - E>10^{18} eV
- HEAT
  - 30°-60°
  - E>10^{17} eV

Surface detector array (SD)
- Grid of 1500 m / 750 m / 433 m
  - 3000 km² / 24 km²
  - 1660 stations / 61 / 12
  - Water Cherenkov Tanks (WCD)
  - Scintillation Detectors (SSD)
  - Radio Antennae (RD)
  - E>$10^{18.5}$ eV
- Grid of 750 m and 433 m
  - ***Incl. UMD muon counters***
  - E>$10^{17.5}$ eV

Radio array (AERA)
- 153 stations
- 17 km²





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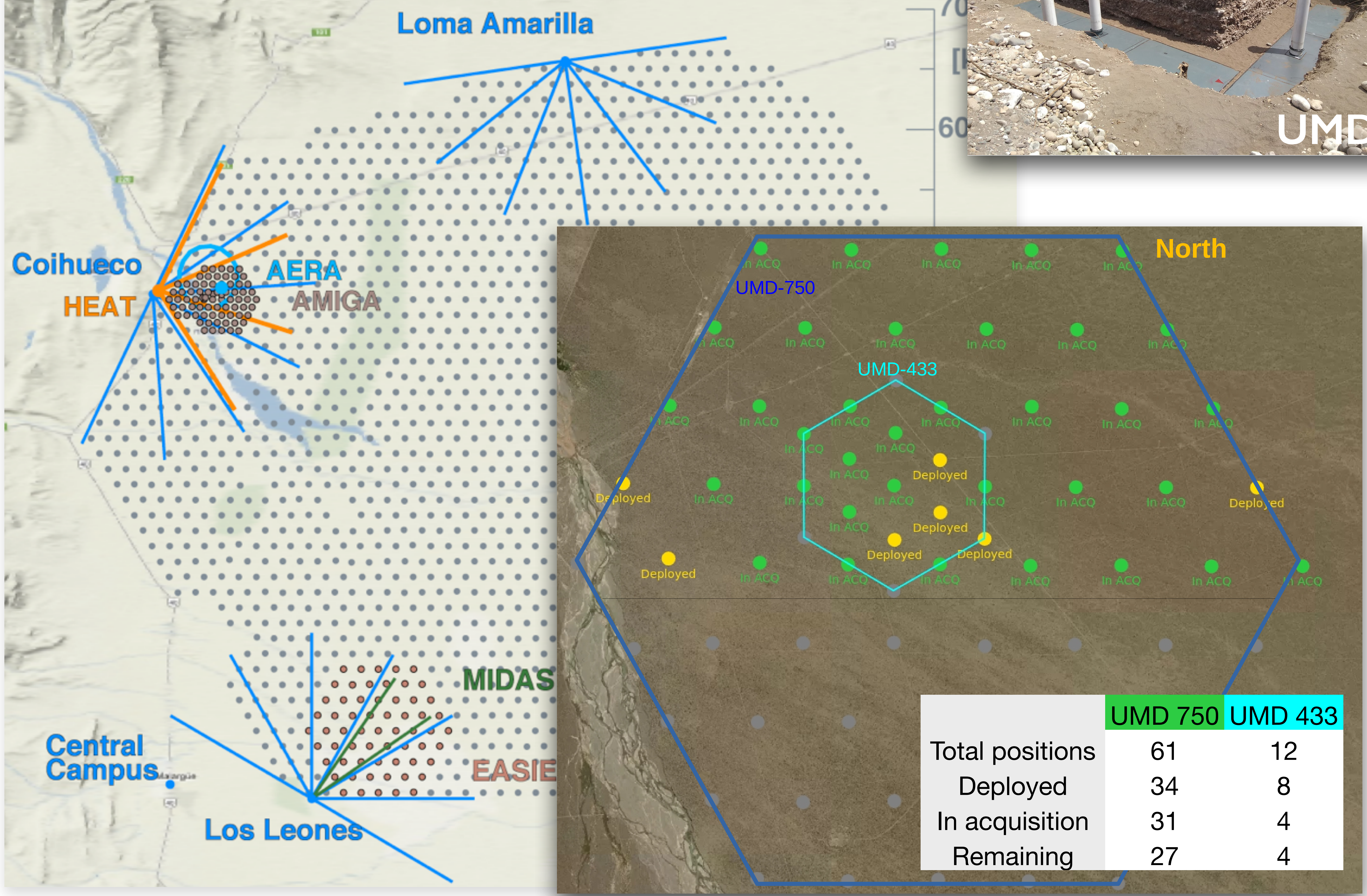
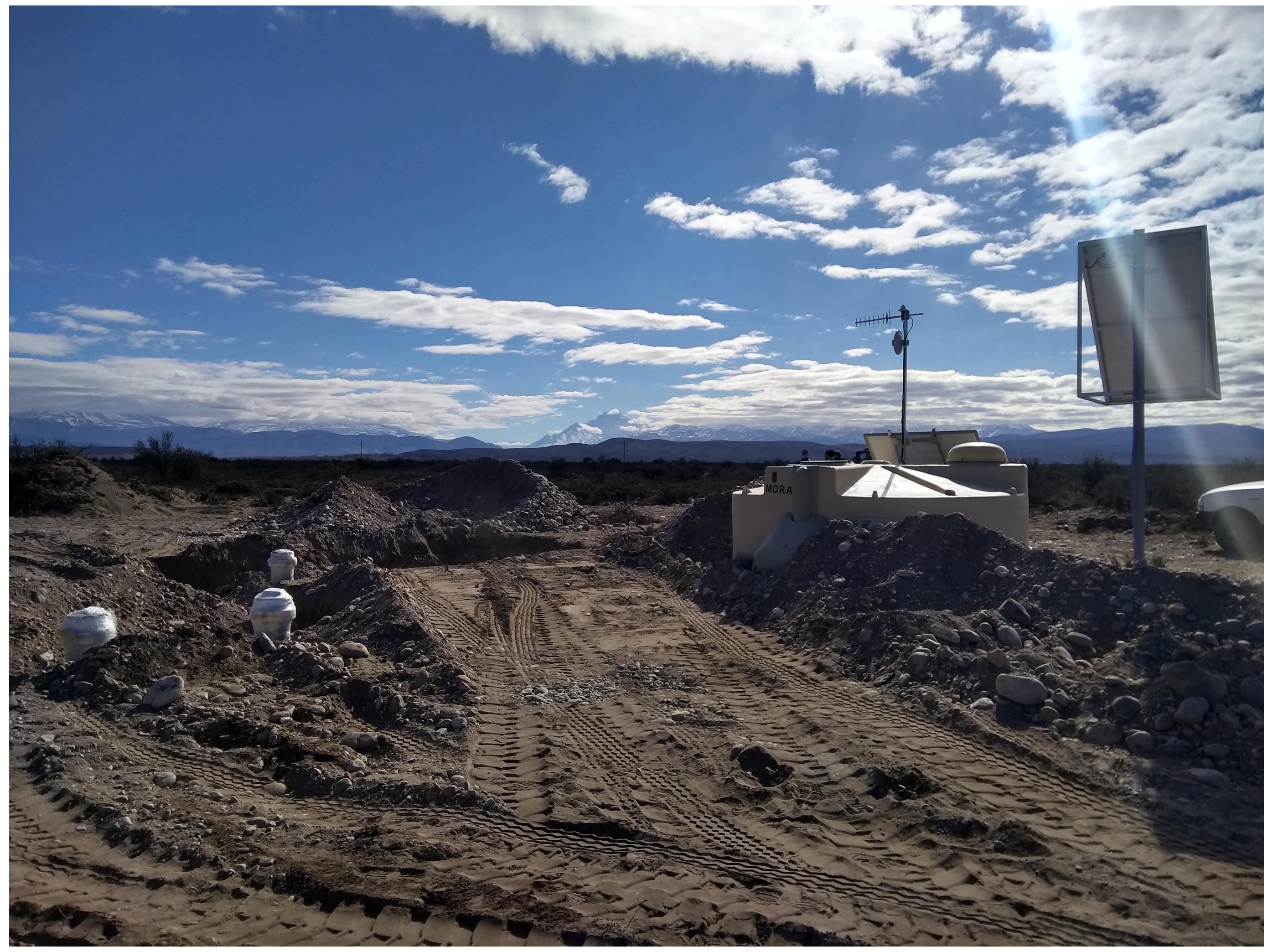


	UMD 750	UMD 433
Total positions	61	12
Deployed	34	8
In acquisition	31	4
Remaining	27	4

Deployment (4 positions/month)



Hybrid detection

Fluorescence Detector (FD):

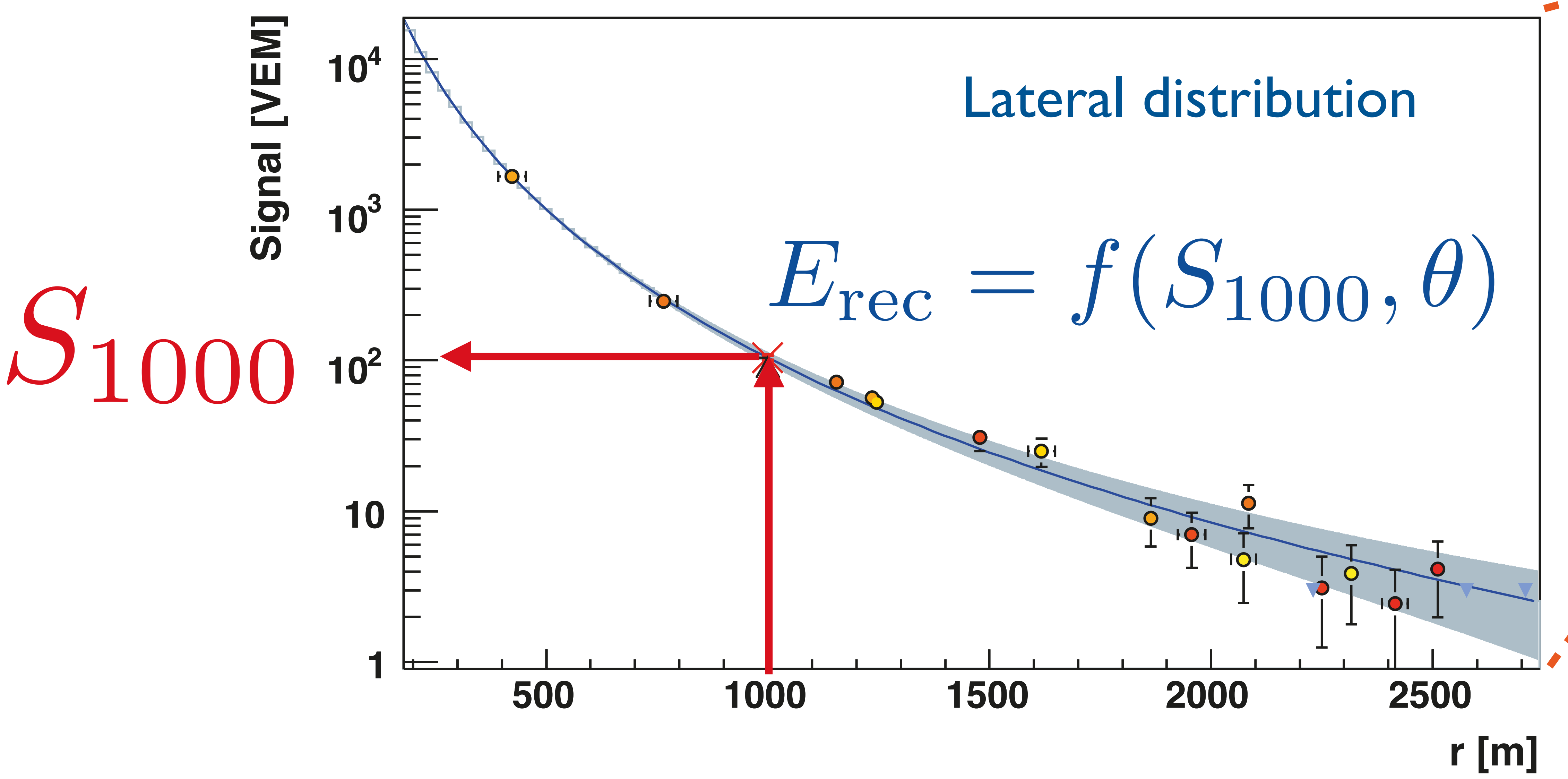
- calorimetric measurement of energy
- ca.15% duty cycle

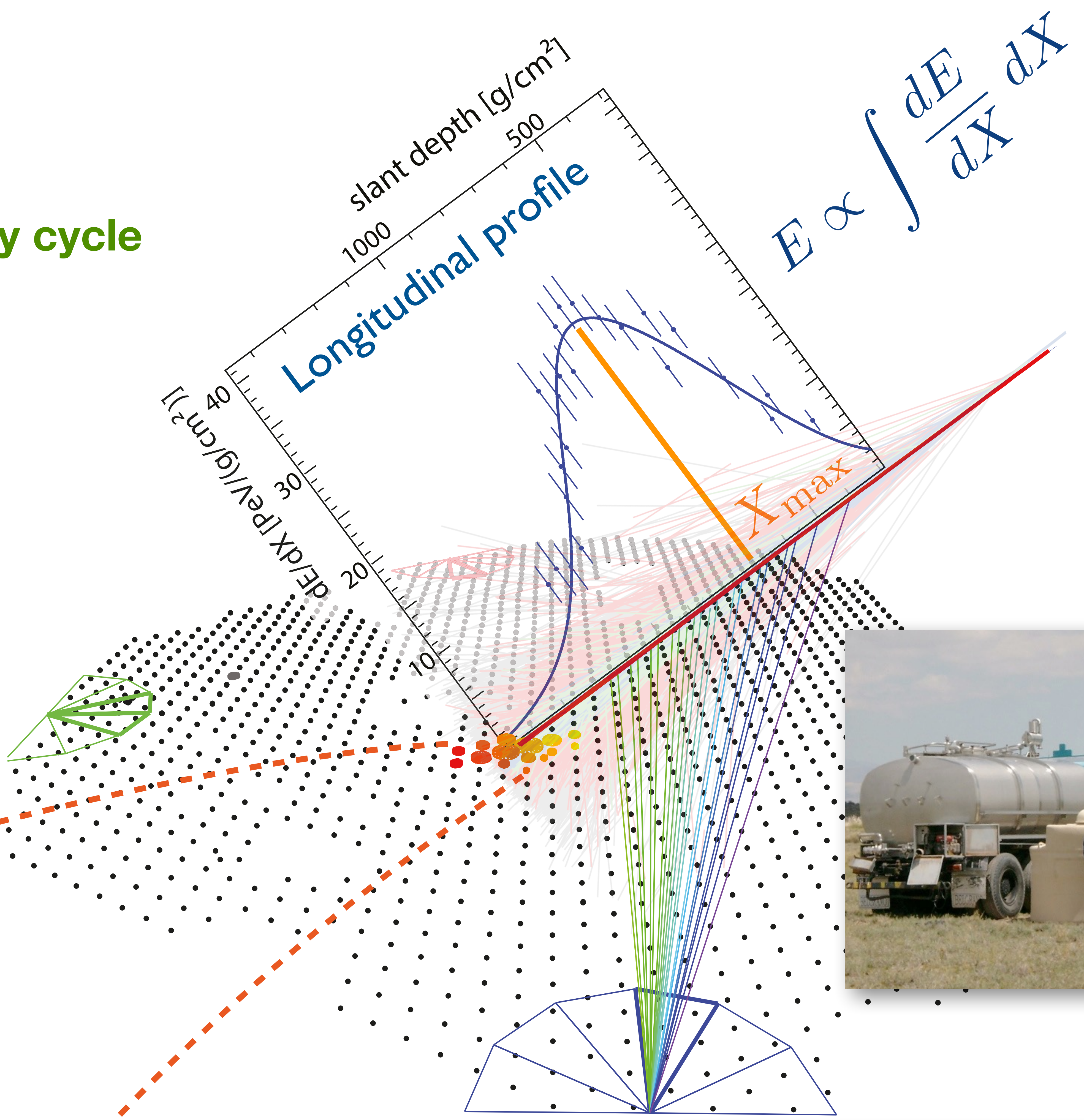
Surface Detector (SD):

- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle

13% duty cycle

100% duty cycle





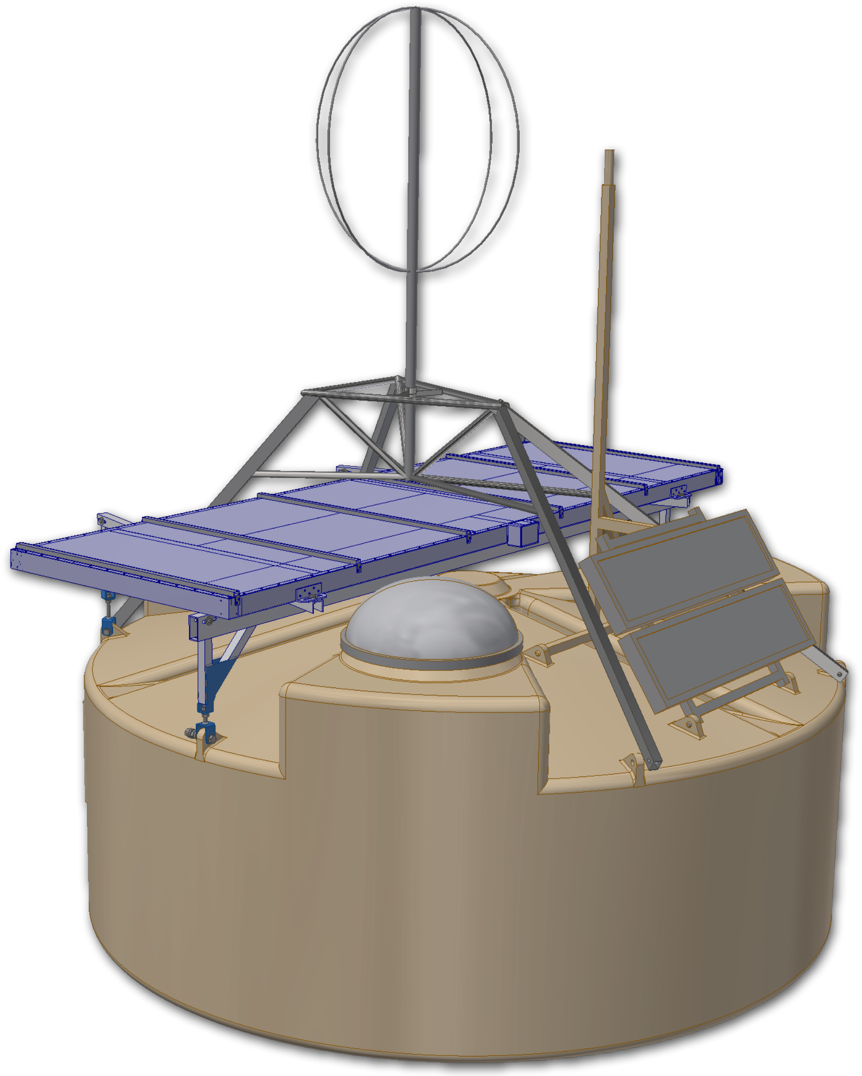
Event observed with
Auger Observatory

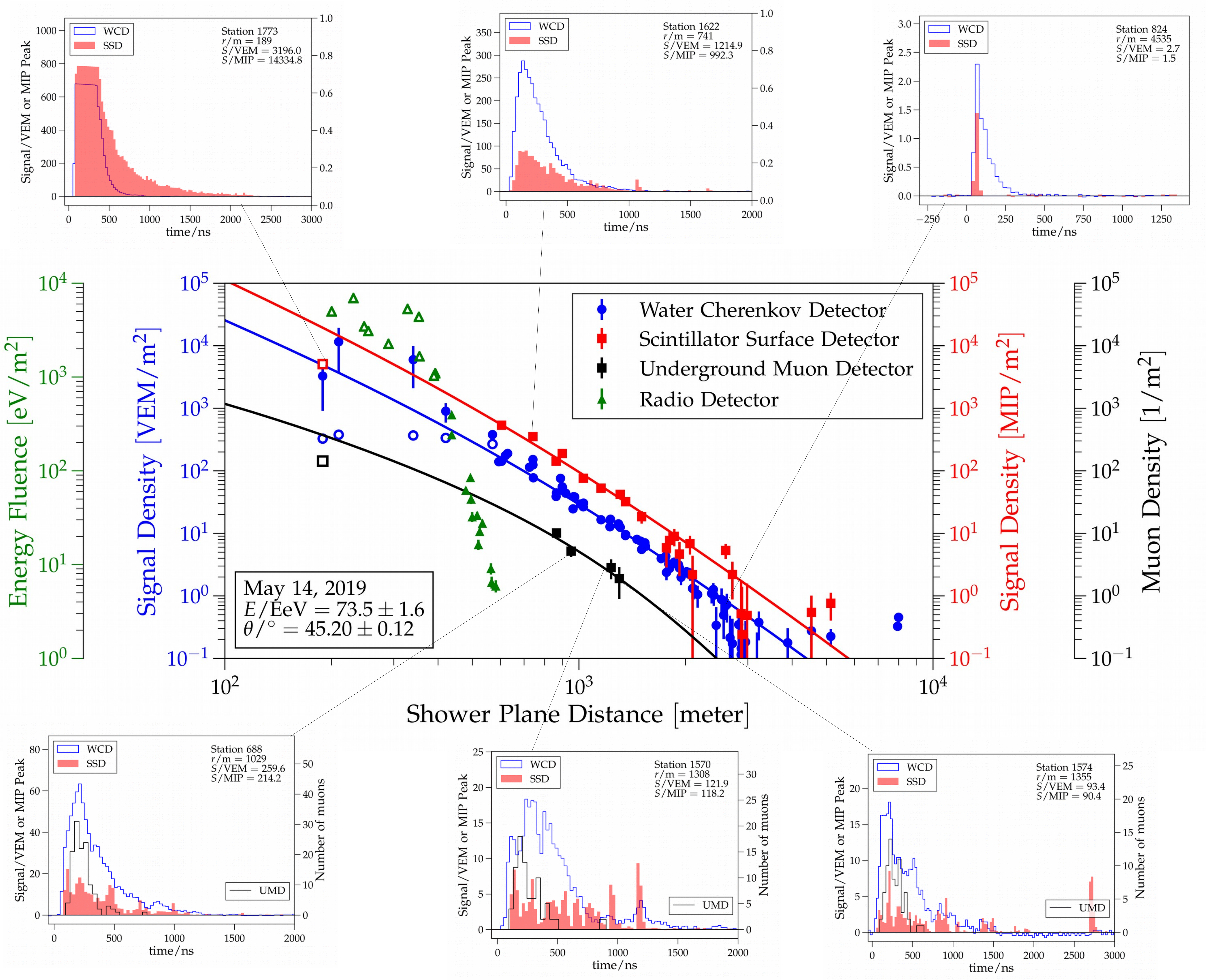
AugerPrime data

WCD, SSD, UMD, AERA

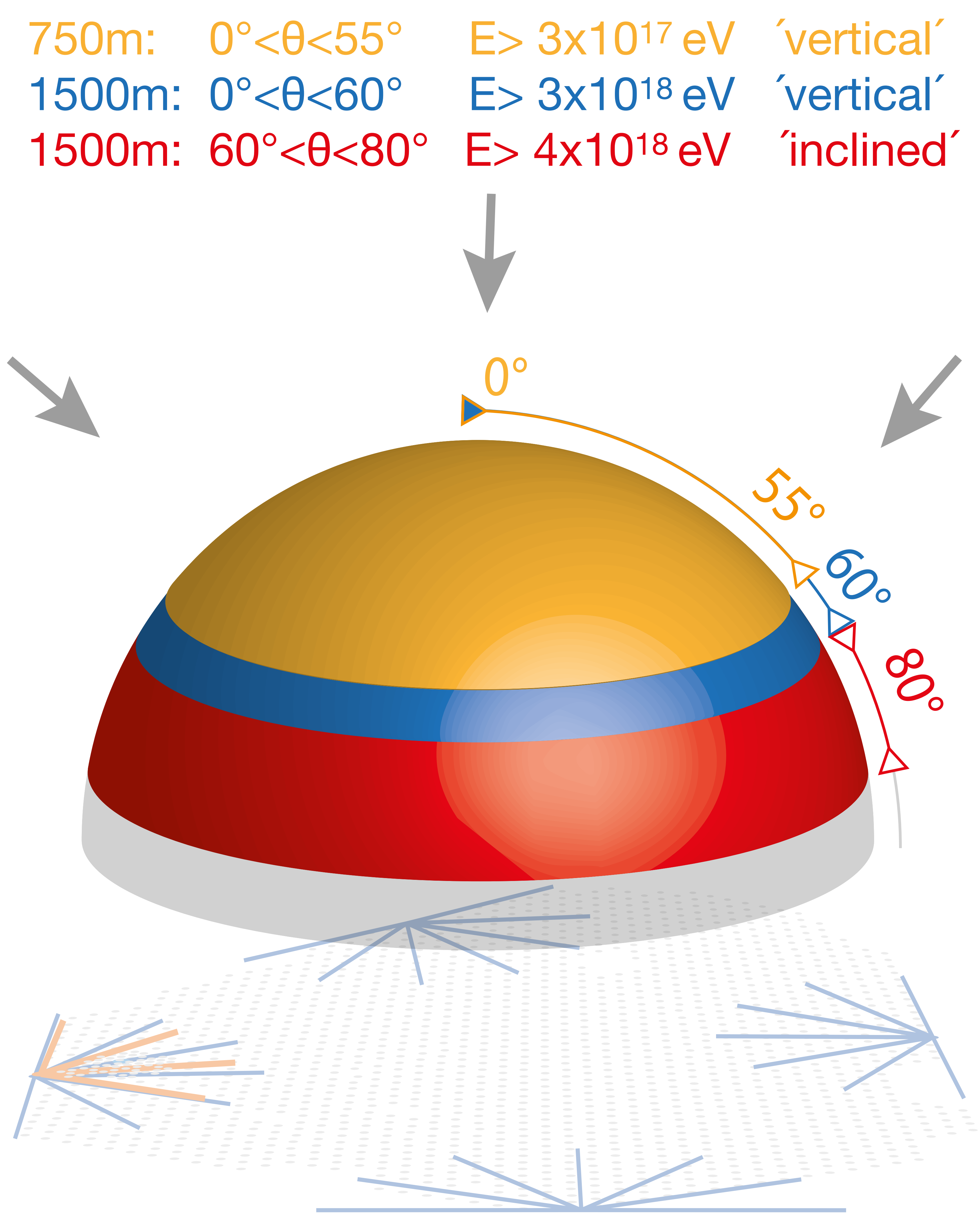
- Water Cherenkov Detector (WCD)
- Scintillation Surface Detector (SSD)
- Underground Muon Detector (UMD)
- Radio Detector (AERA)
- New electronics: 40 MHz → 120 MHz

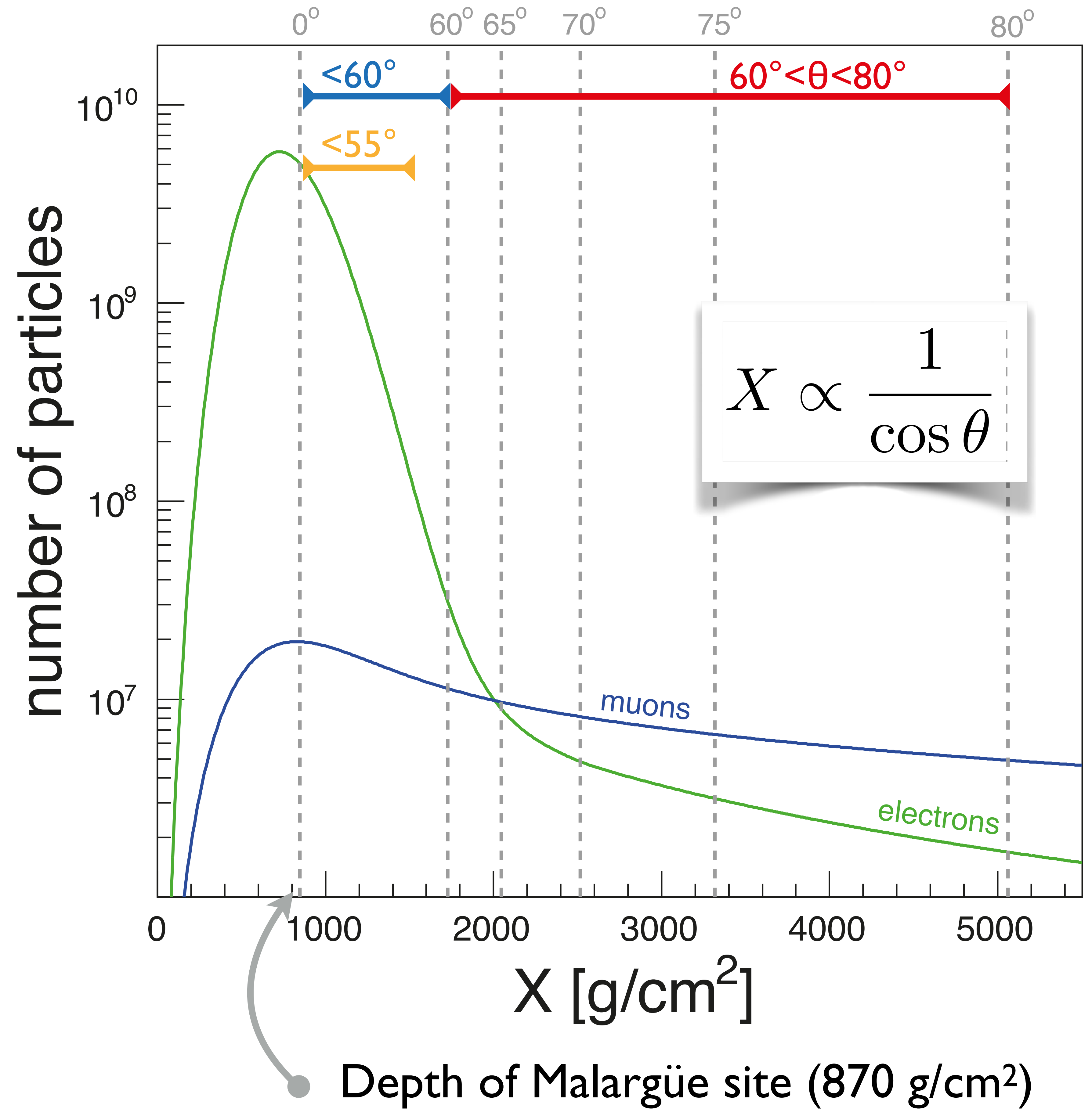
- Additional data AND correlations available
- Detailed timing information of signals available (time traces)
- No small PMT in WCD in place
- Not all SSDs in place at time of the event





Different zenith ranges probe different stages of shower evolution



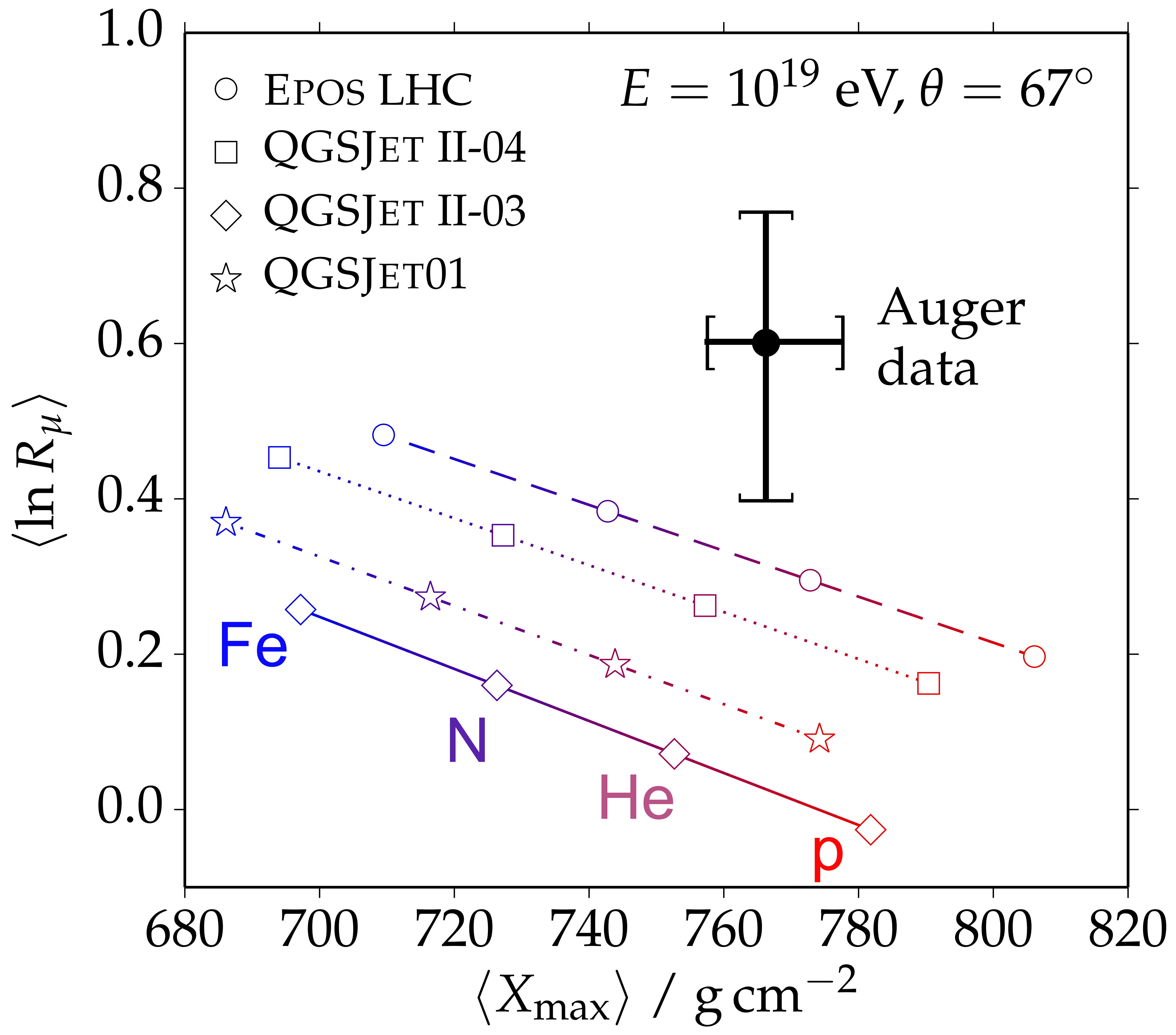


$$X \propto \frac{1}{\cos\theta}$$

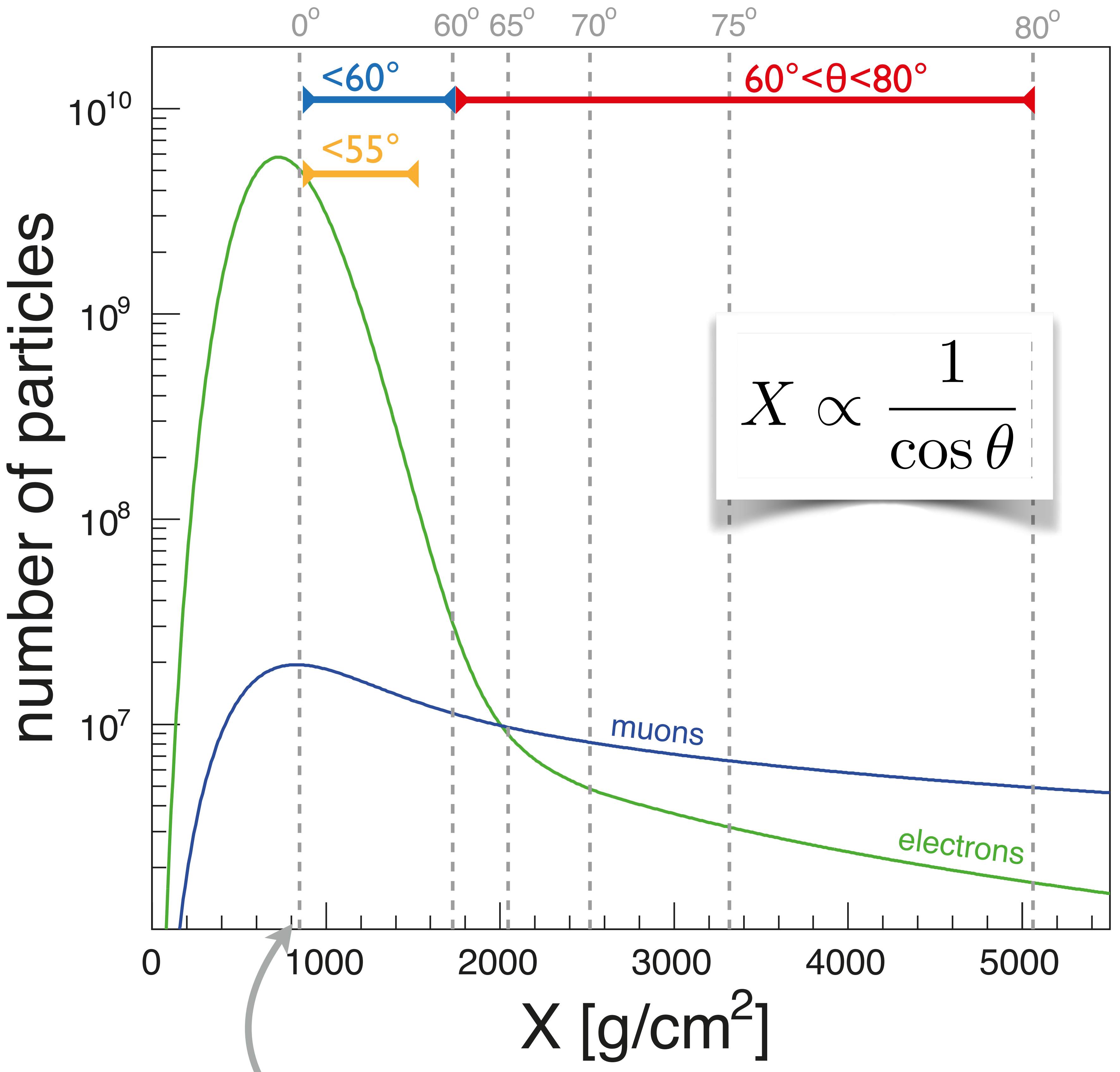
Showers with large zenith
⇒ muon dominated

Hadronic interactions: Muon deficit in simulations

Air shower modelling: CORSIKA



30-70% deficit



Depth of Malargüe site (870 g/cm²)

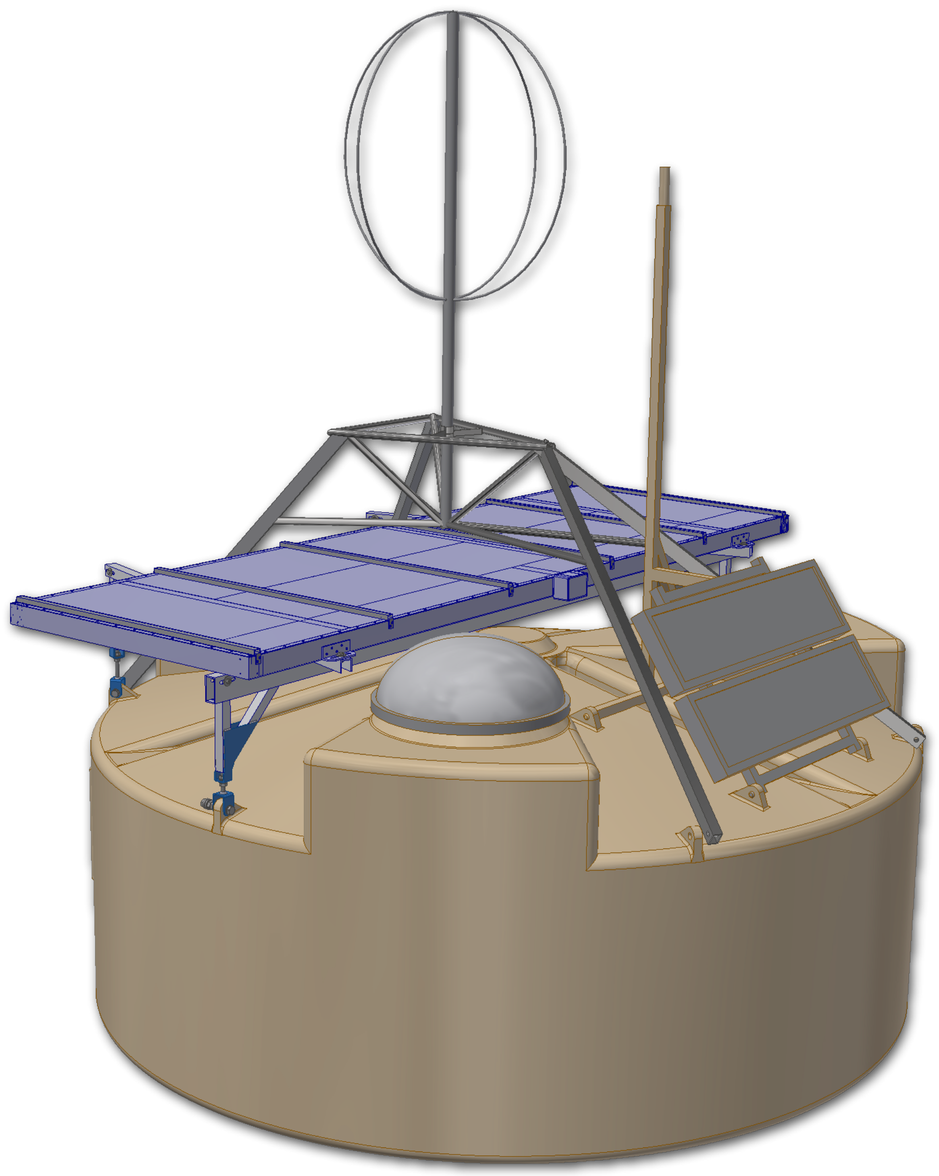
Showers with large zenith
⇒ muon dominated

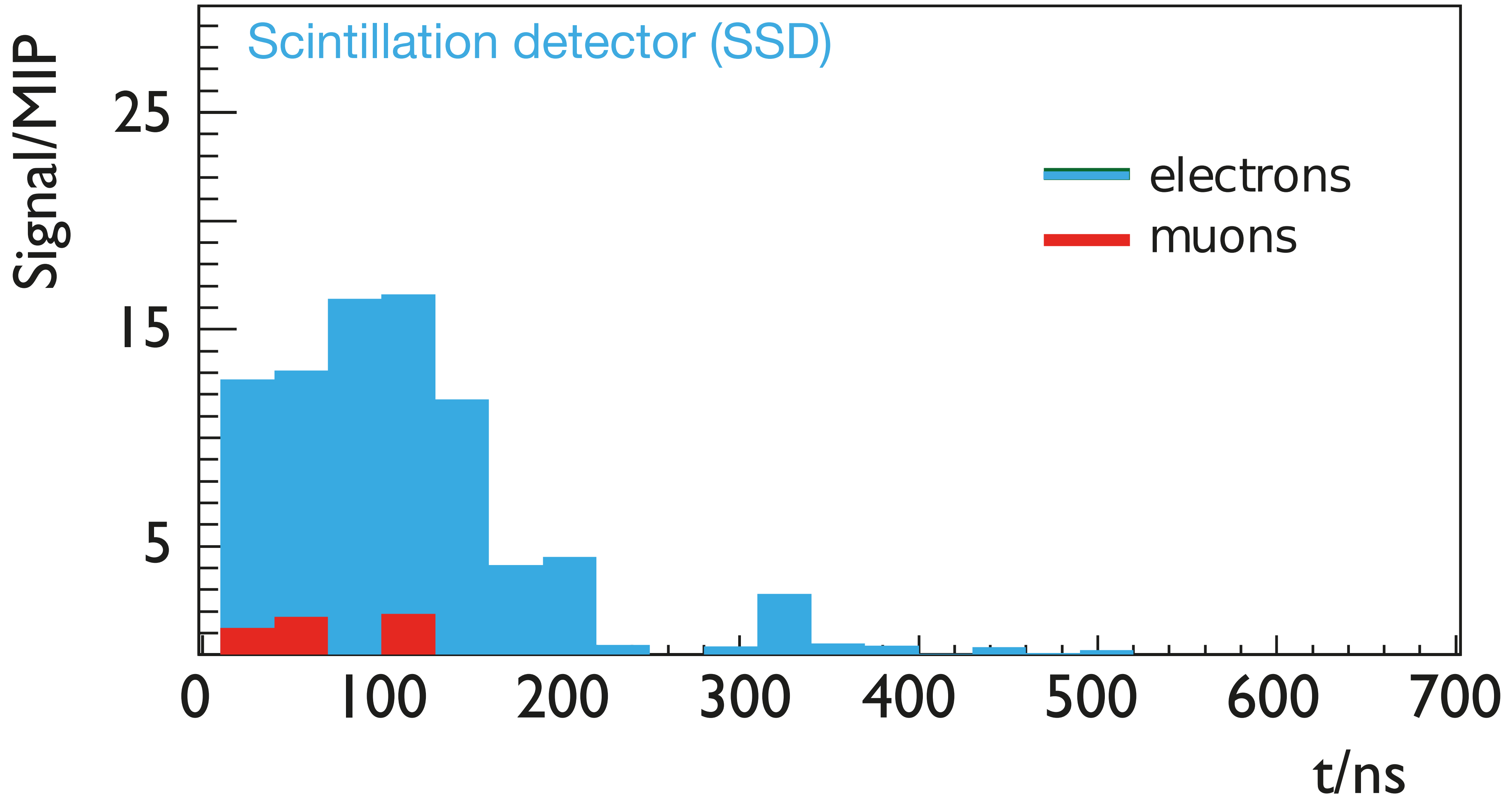
Indirect muon determination for the whole array: Matrix inversion method

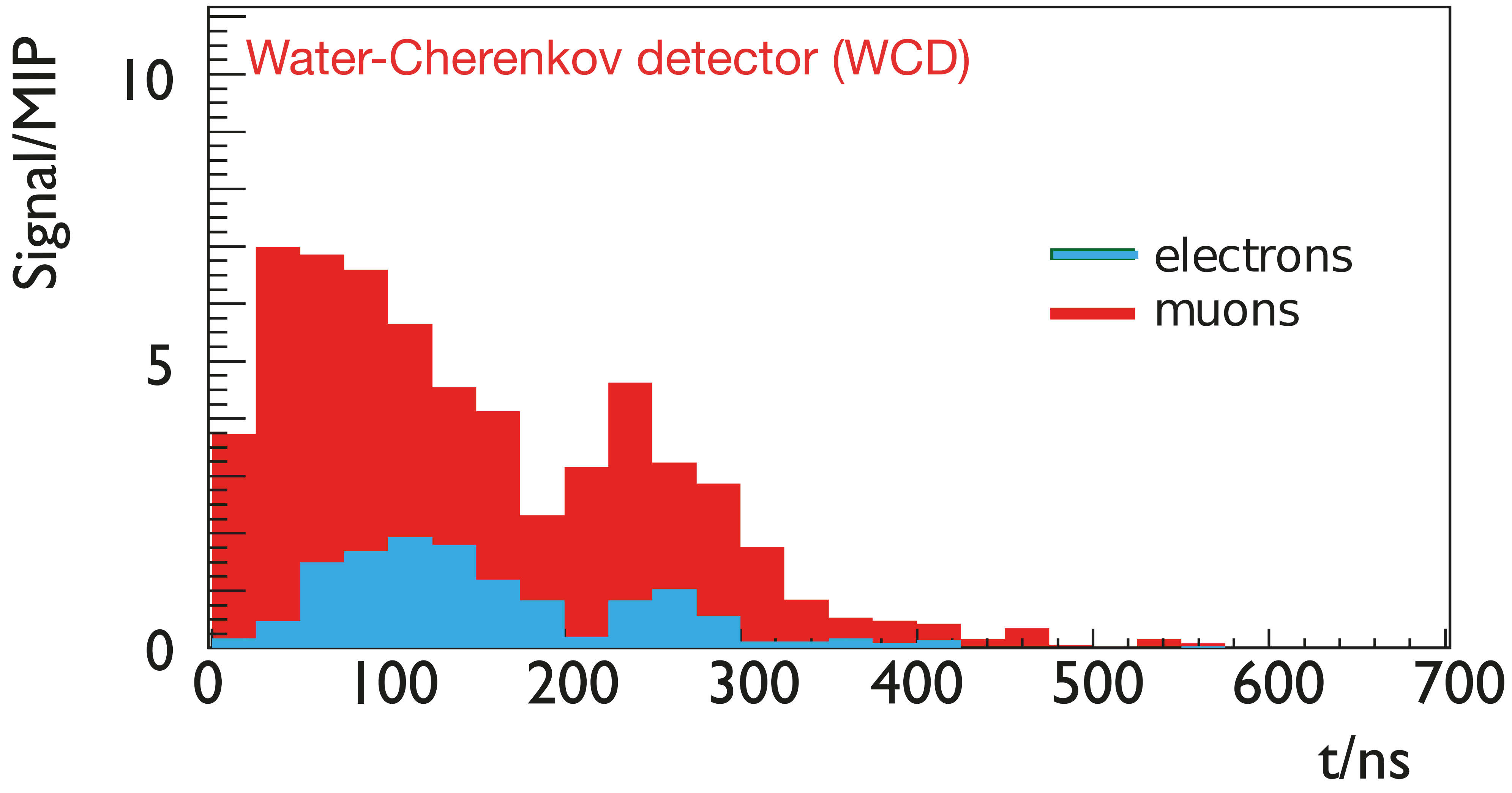
SSD and WCD signal data

- Available for the whole 1500m array
- Based in total signals the muon content can be extracted by matrix inversion

$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em,WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

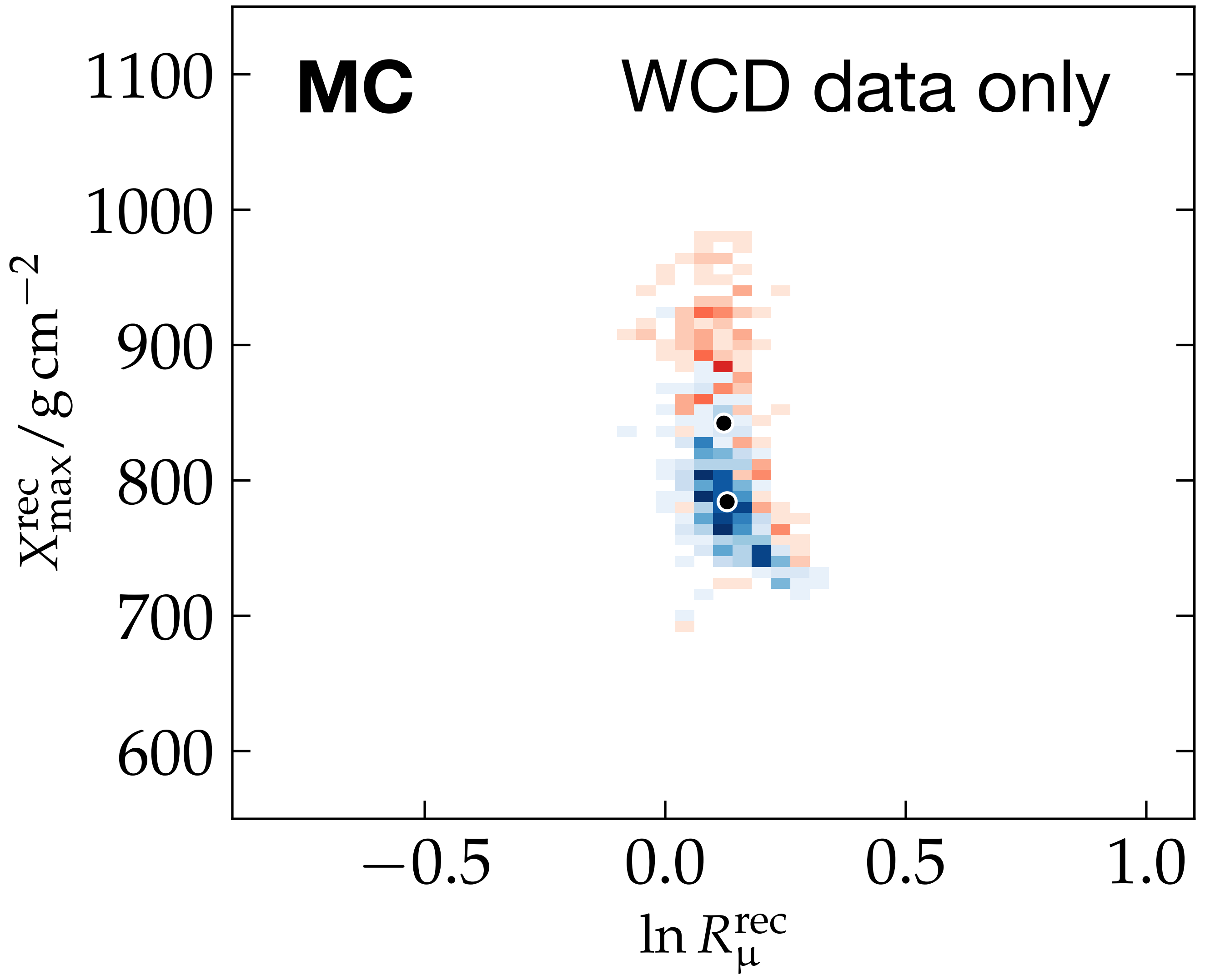


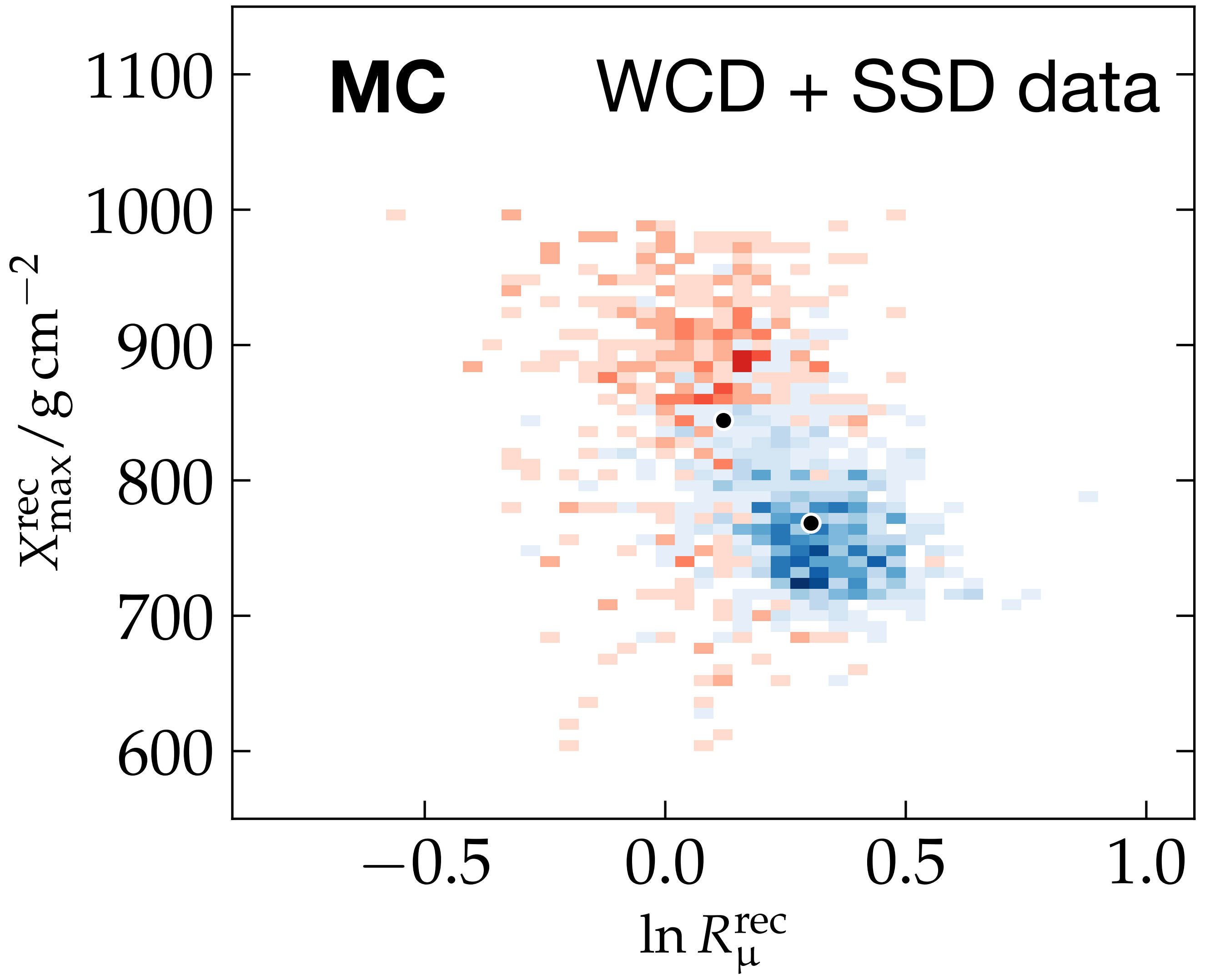




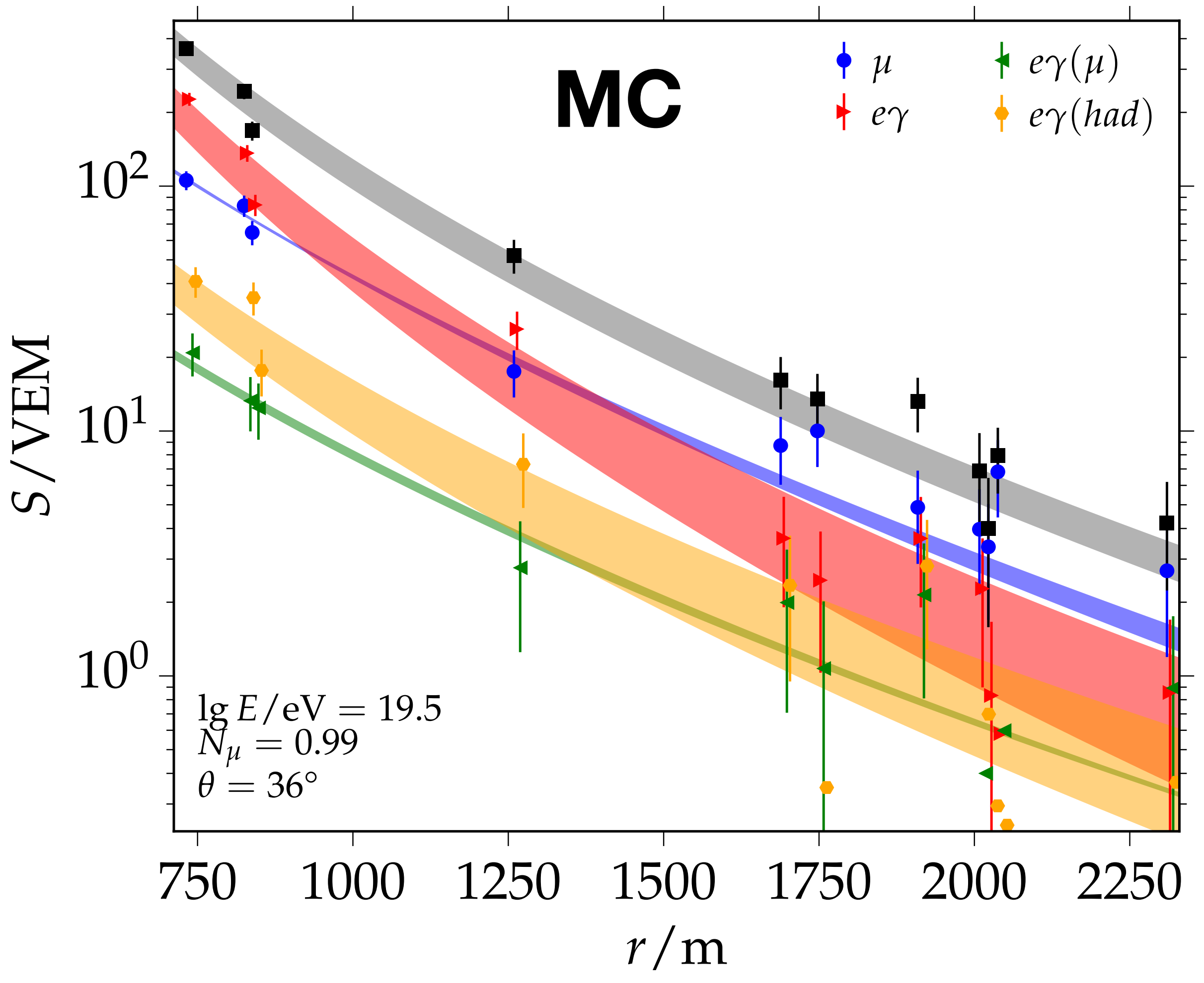
Indirect muon determination for the whole array: Universality

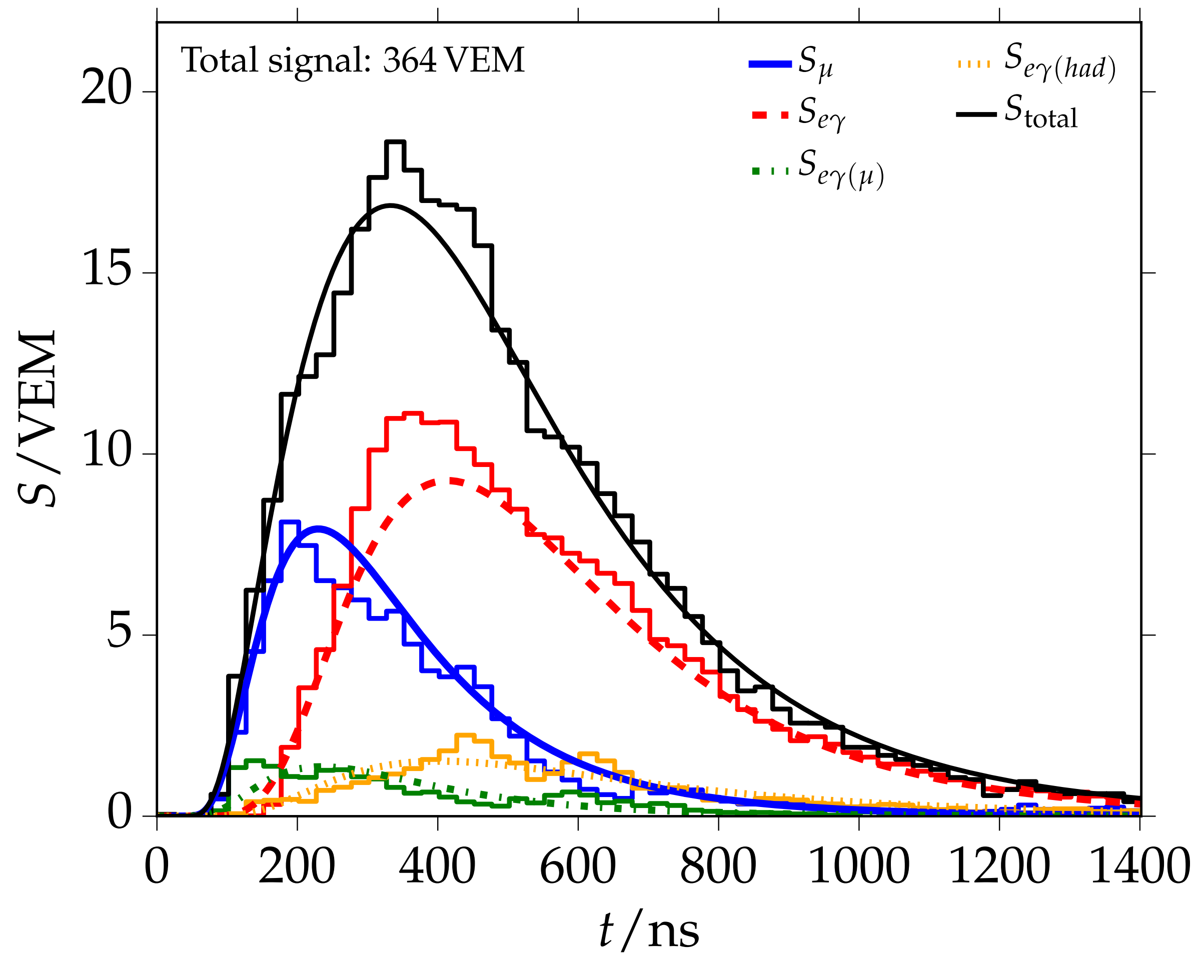
- Extraction of physics observables like E, X_{max} and R_μ from underlying universal shower properties
- WCD data only hardly allow extraction of more than 1 observable due to strong correlations (left plot; MC data)
- WCD + SSD provide *independent* (less dependent) information of shower evolution (right plot; MC data)

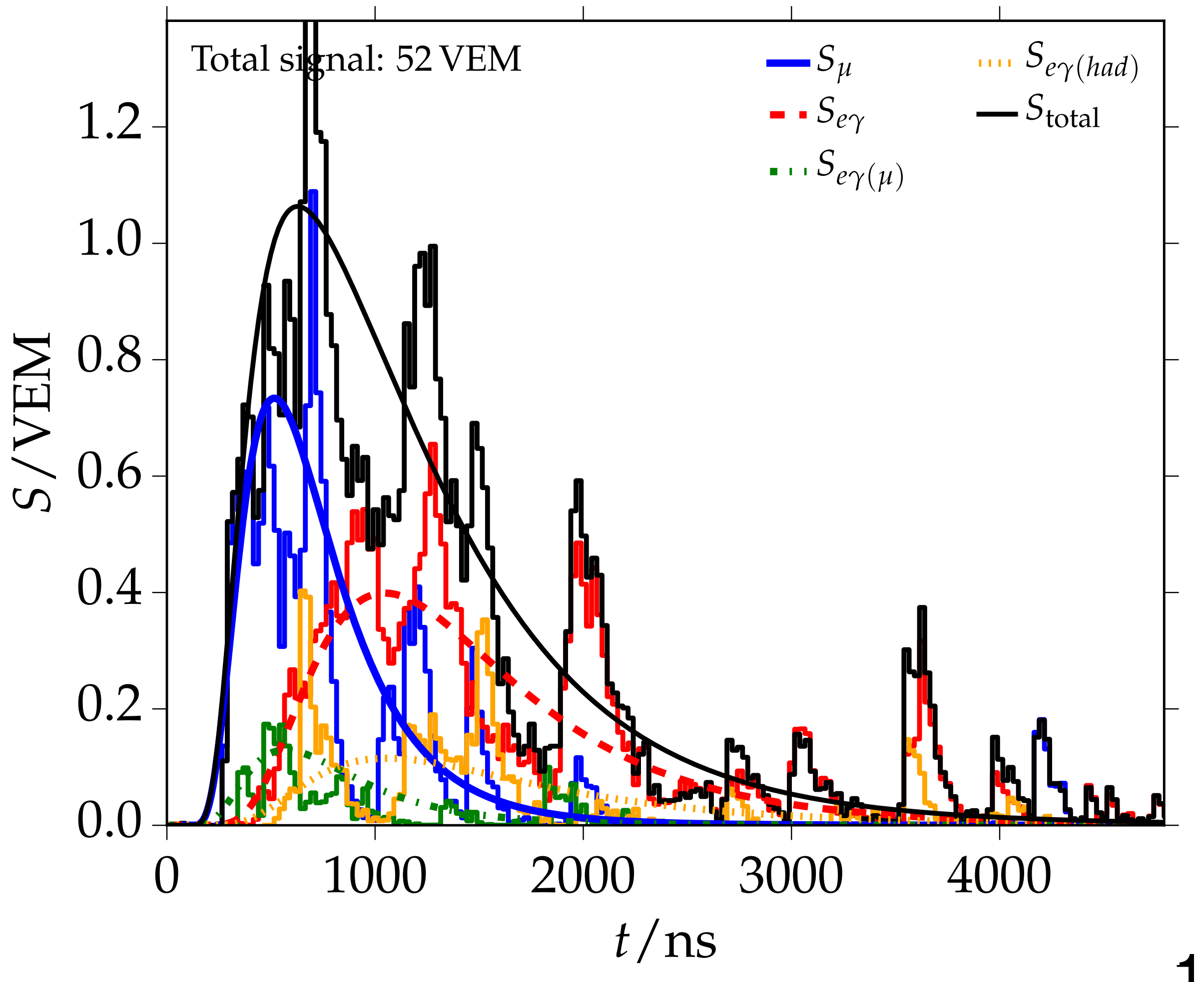




For sake of simplicity:
- Showing WCD data only (MC data)
- Single event @ $10^{19.5}$ eV
- Zenith 36°

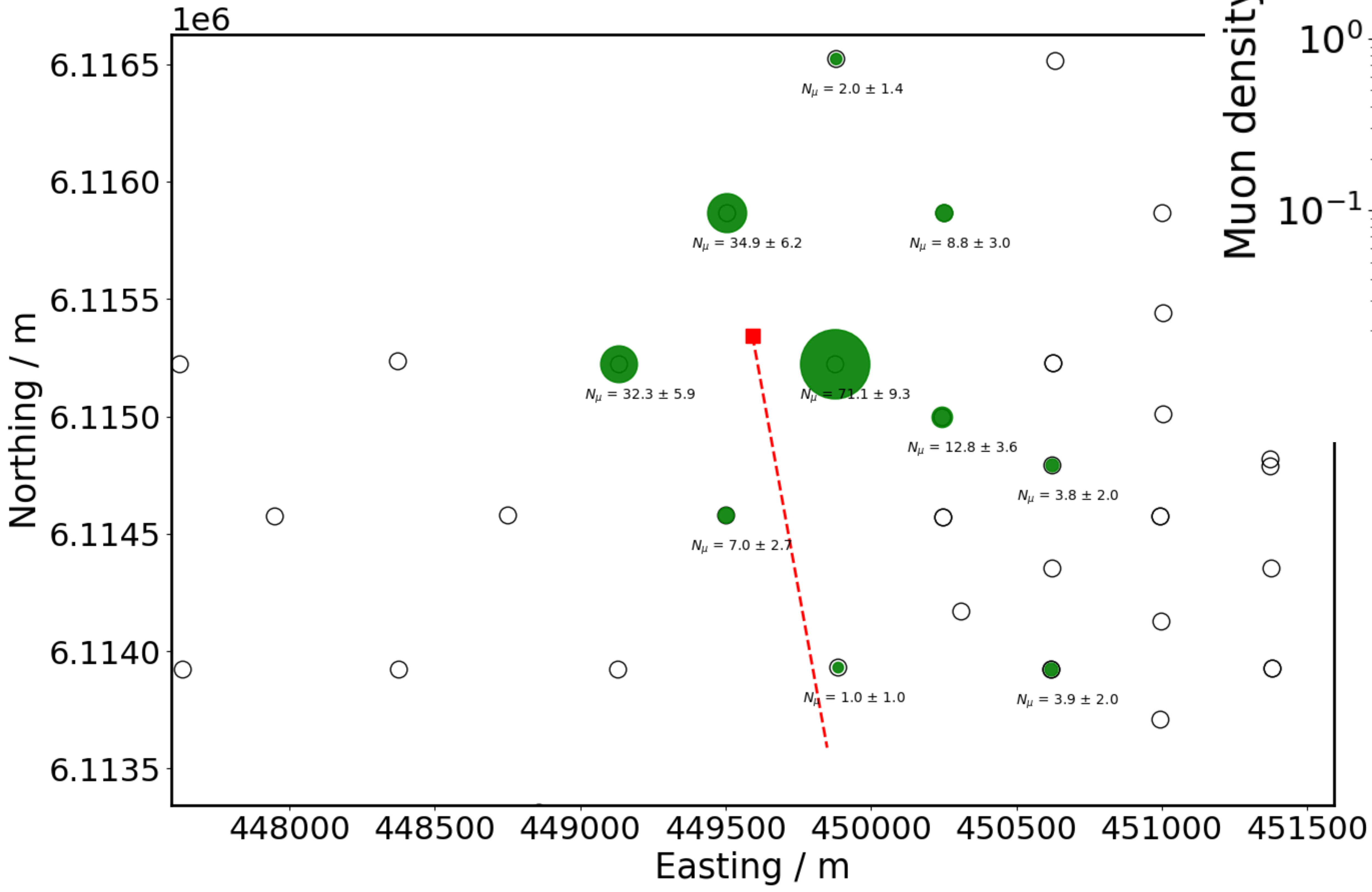


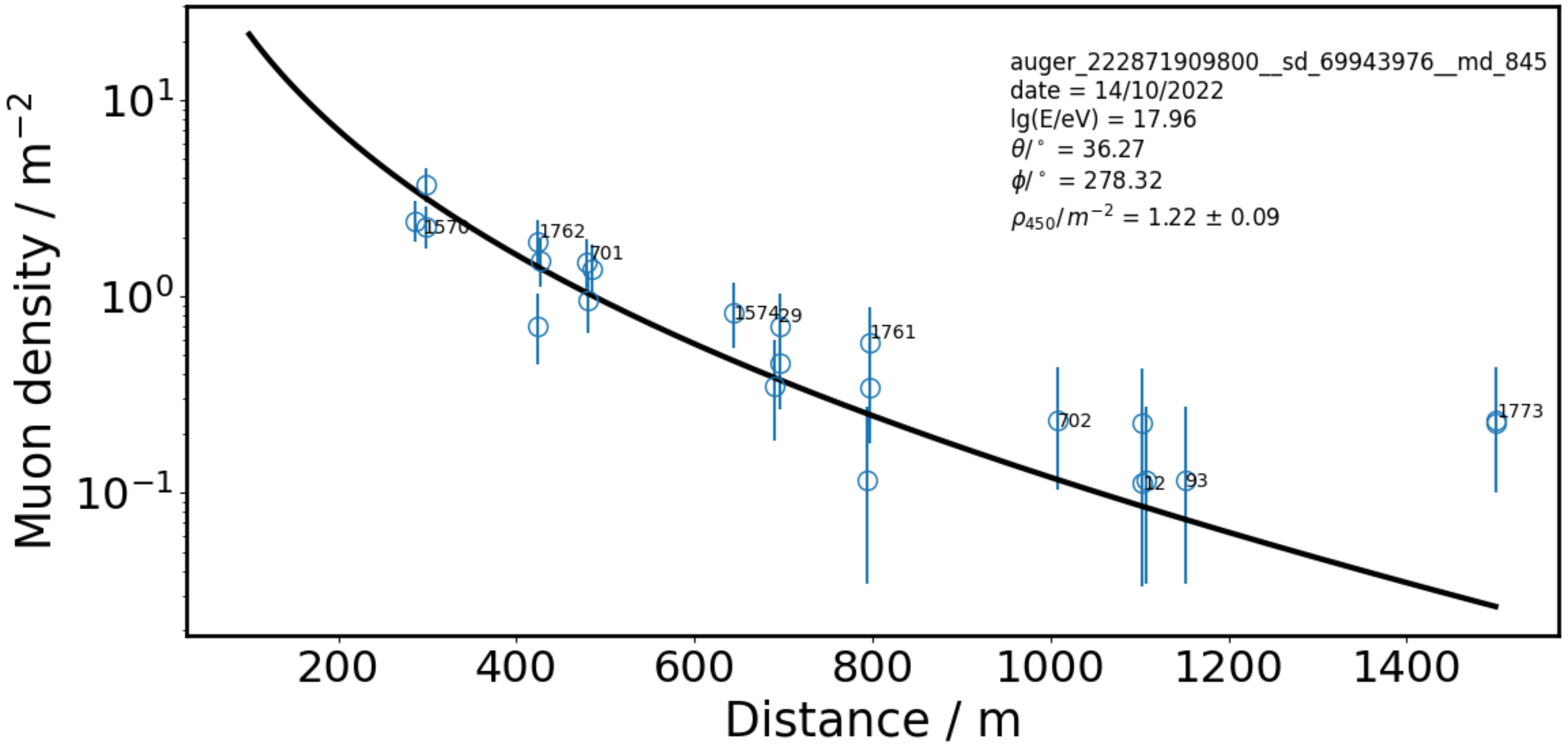




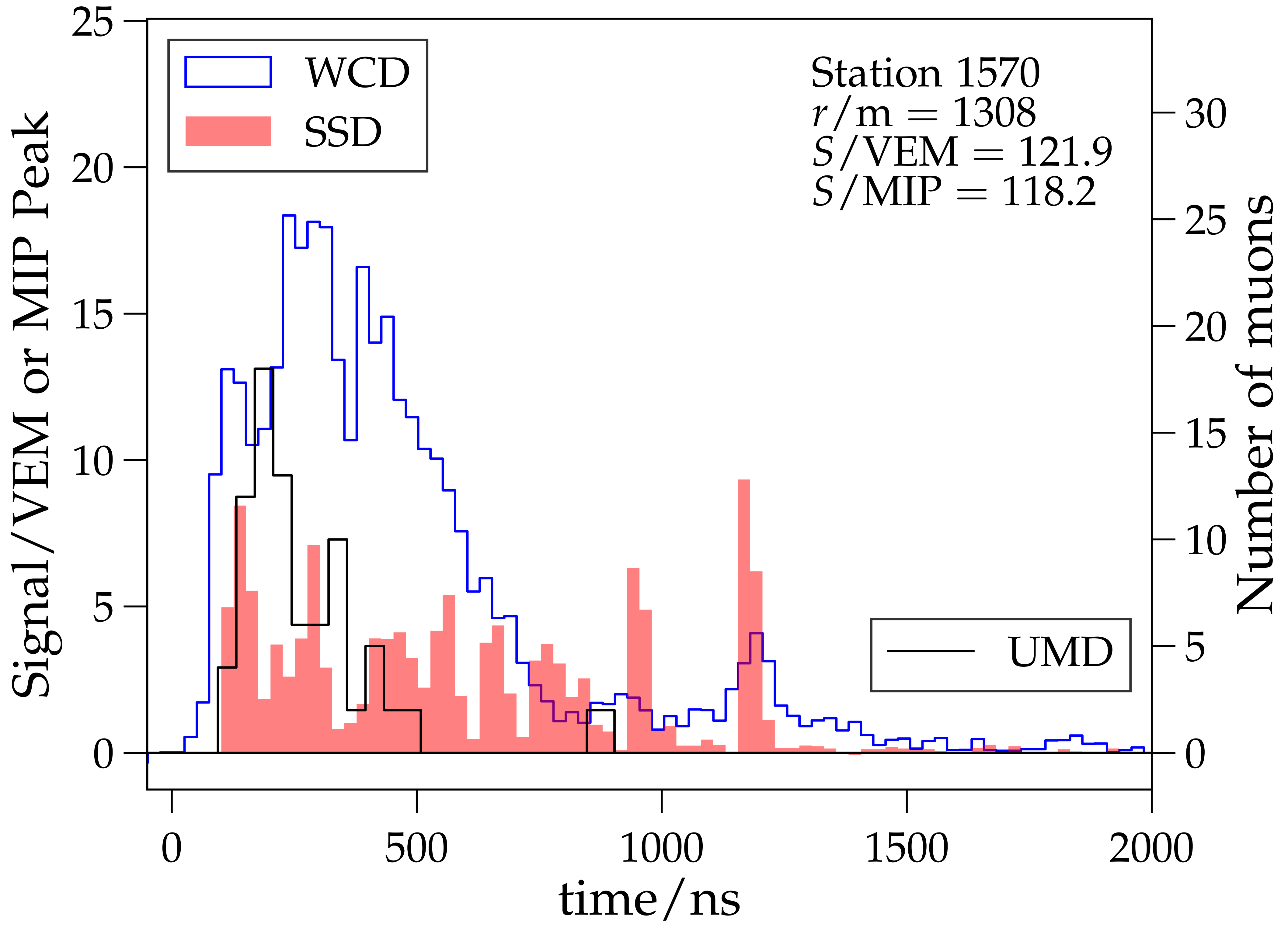
Direct measurement:
Underground Muon Detector event

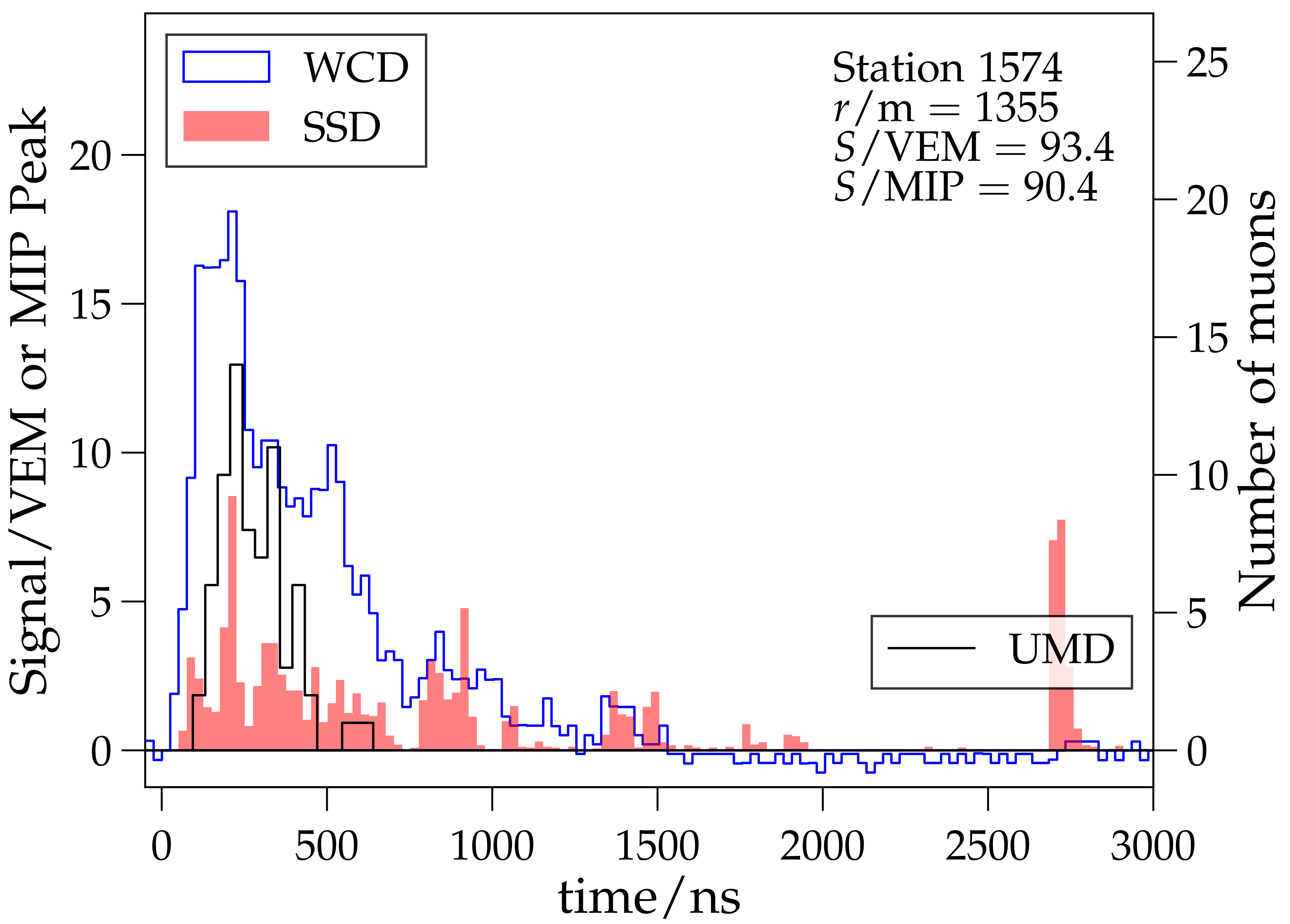
- Recored in 10/2023
- Energy ~ 10^{18} EeV
- θ ~36°





Timing information of all 3 detectors: WCD, SSD and **UMD**





Combined information contains correlations to be used

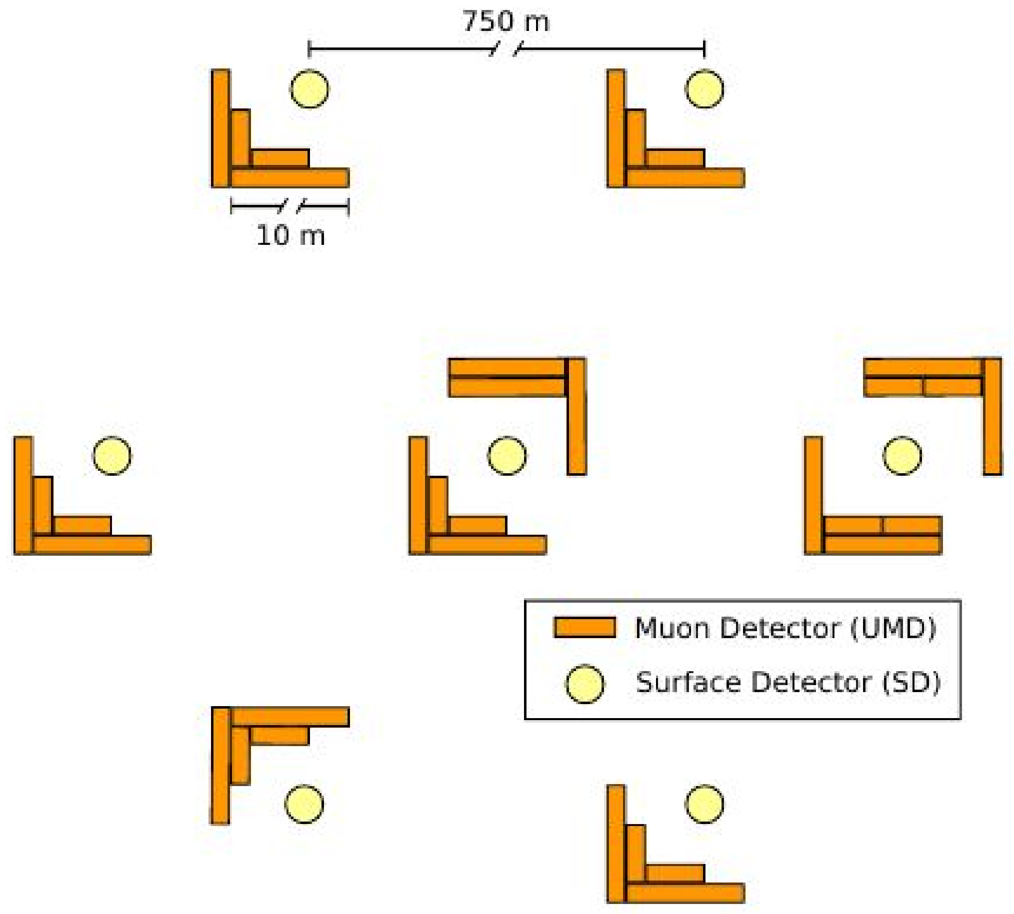
Allows to transfer the ***direct*** muon measurement to the ***indirect*** determined N_{μ}

Underground Muon Detector (UMD)

The Engineering Array up to 2017 vs now

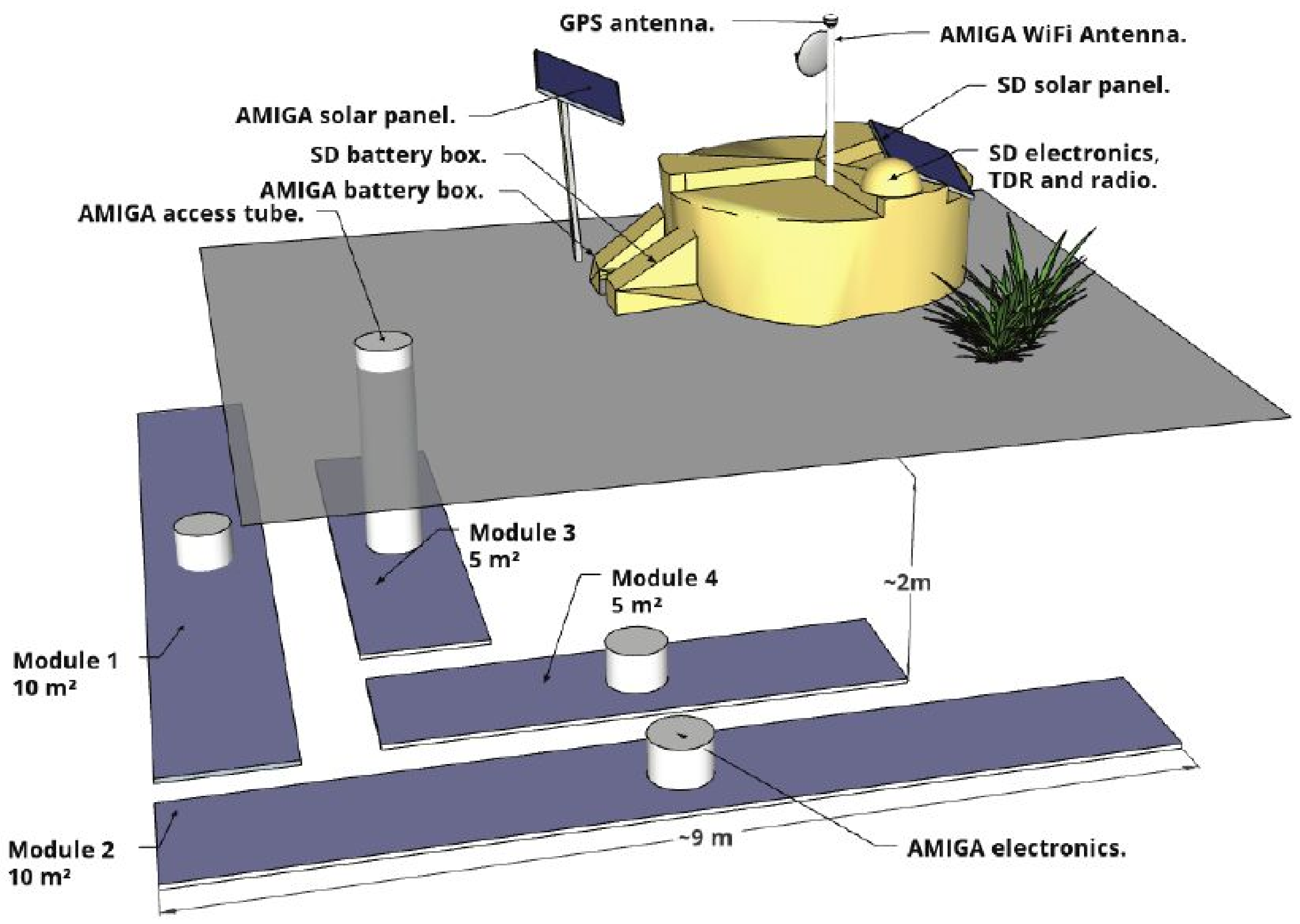
Aim:

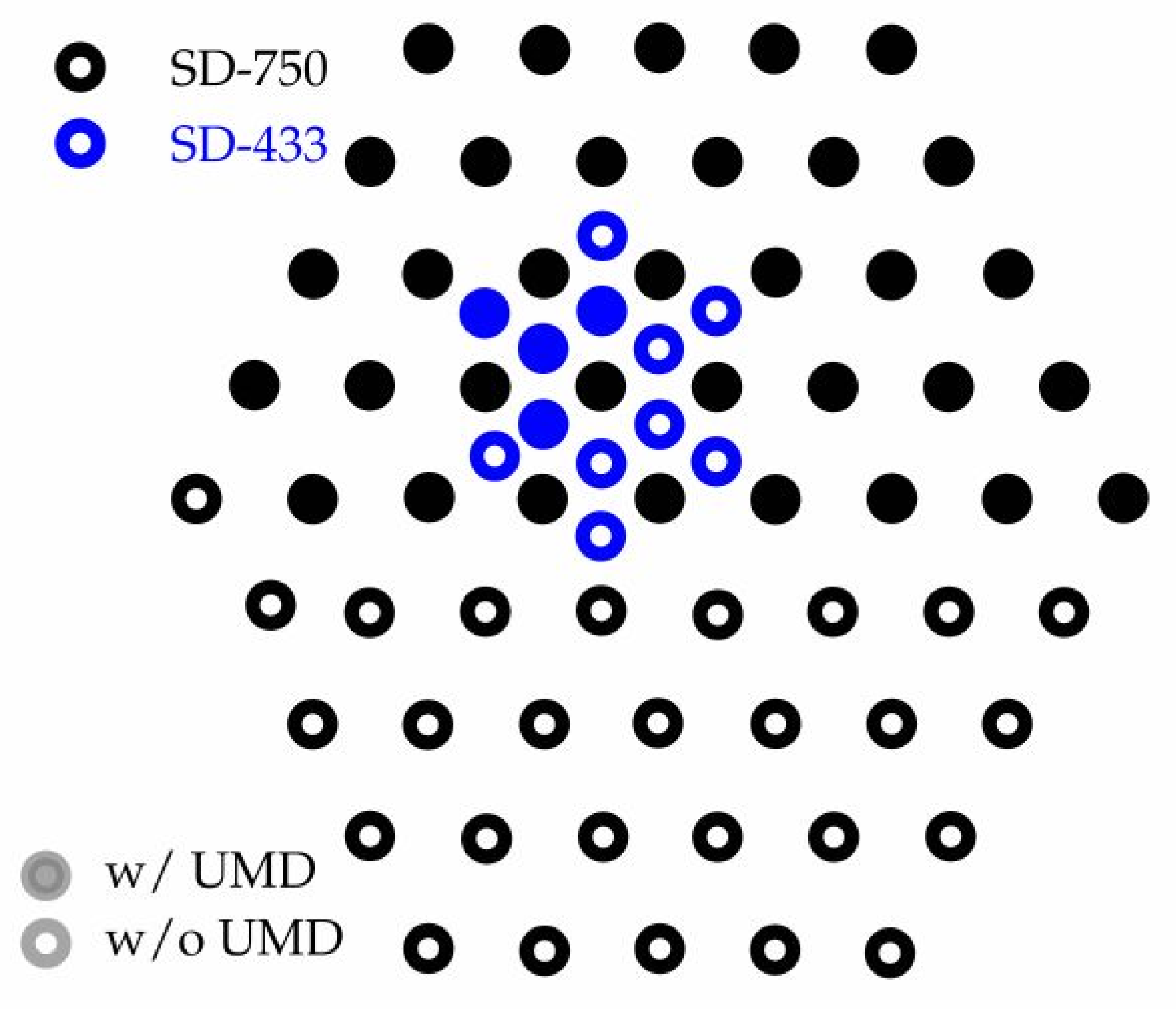
- Muon discrepancy in simulations
- Validation of AugerPrime
- Model tests with direct muon measurement



***PMT* readout:**

- til 2017
- 64 pixel PMT (Hamamatsu)
- 7 positions





***SiPM* readout:**

- Starting in 2017
- Deployed by end of 2024
- 64 pixel SiPM
- 61 positions

Muon estimation

64 **SiPMs** signals

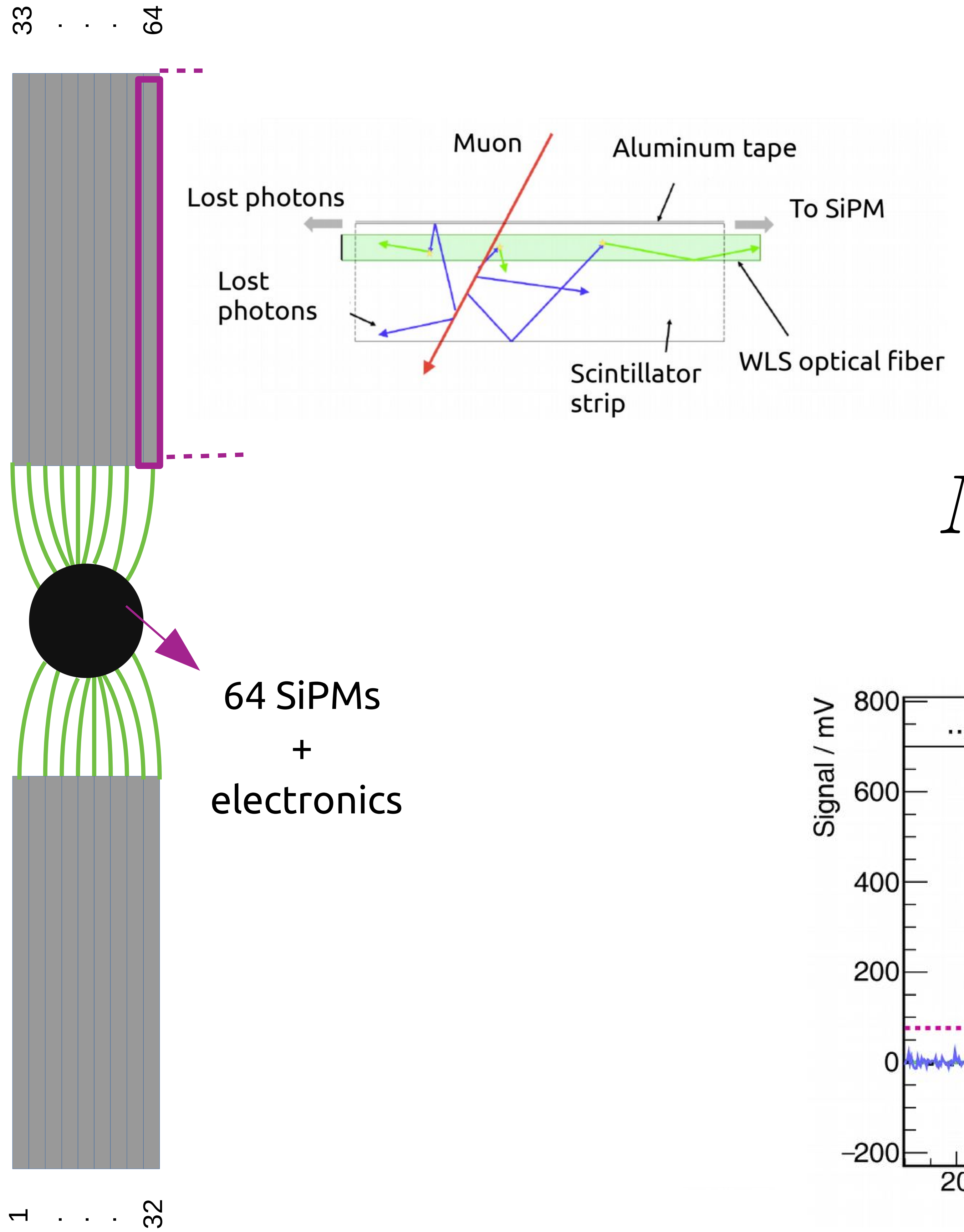
Counter channel	ADC channel
Pre amplifier (ASIC)	Adders
Fast shaper (ASIC)	Amplification
Discriminator (ASIC)	**HG** / **LG**
FPGA	**ADC** / **ADC**
64x 2048 bit @ 3.125ns	2x 1024 samples @ 6.25ns

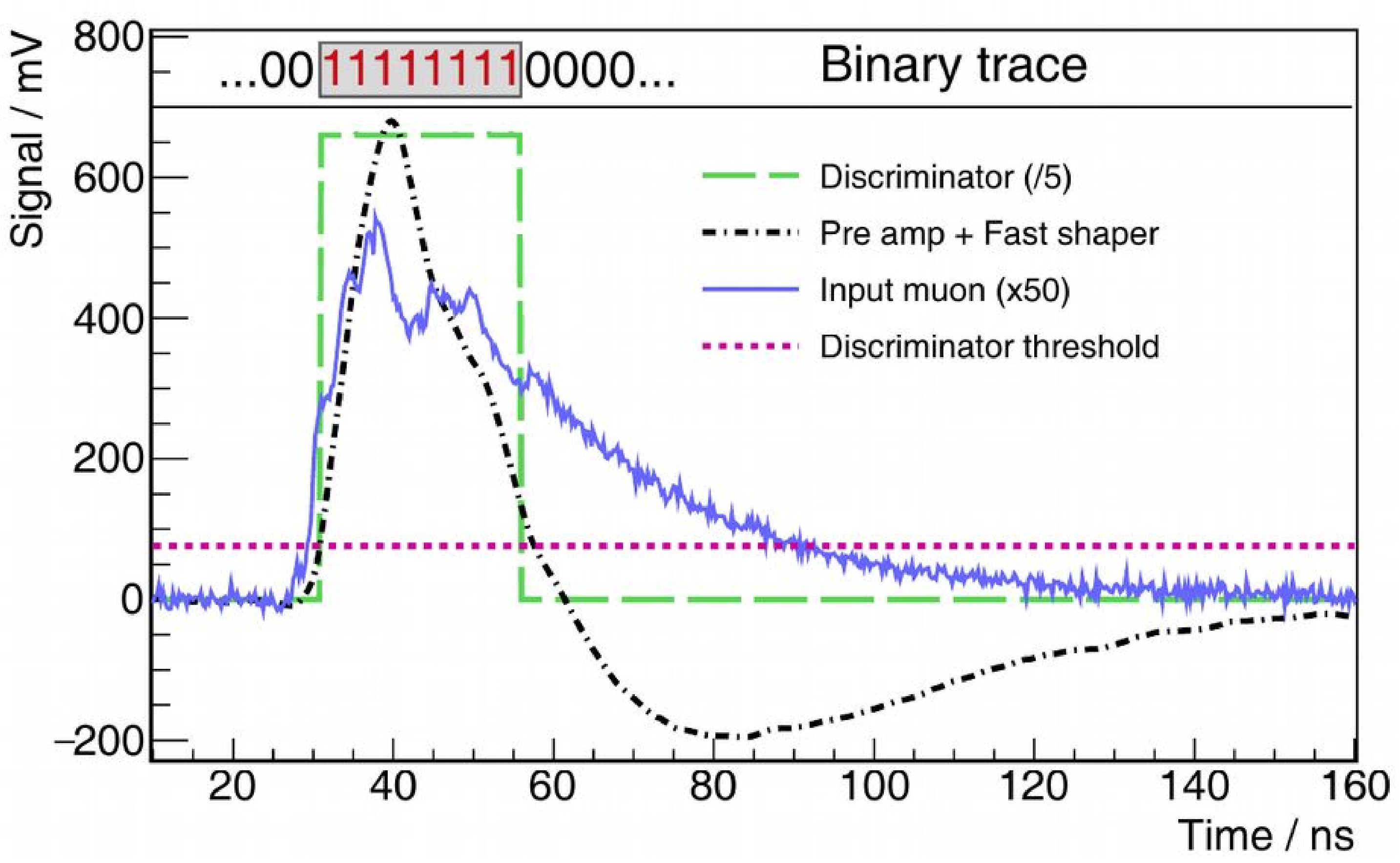
$\hat{N}_\mu \rightarrow$ # strips with signal

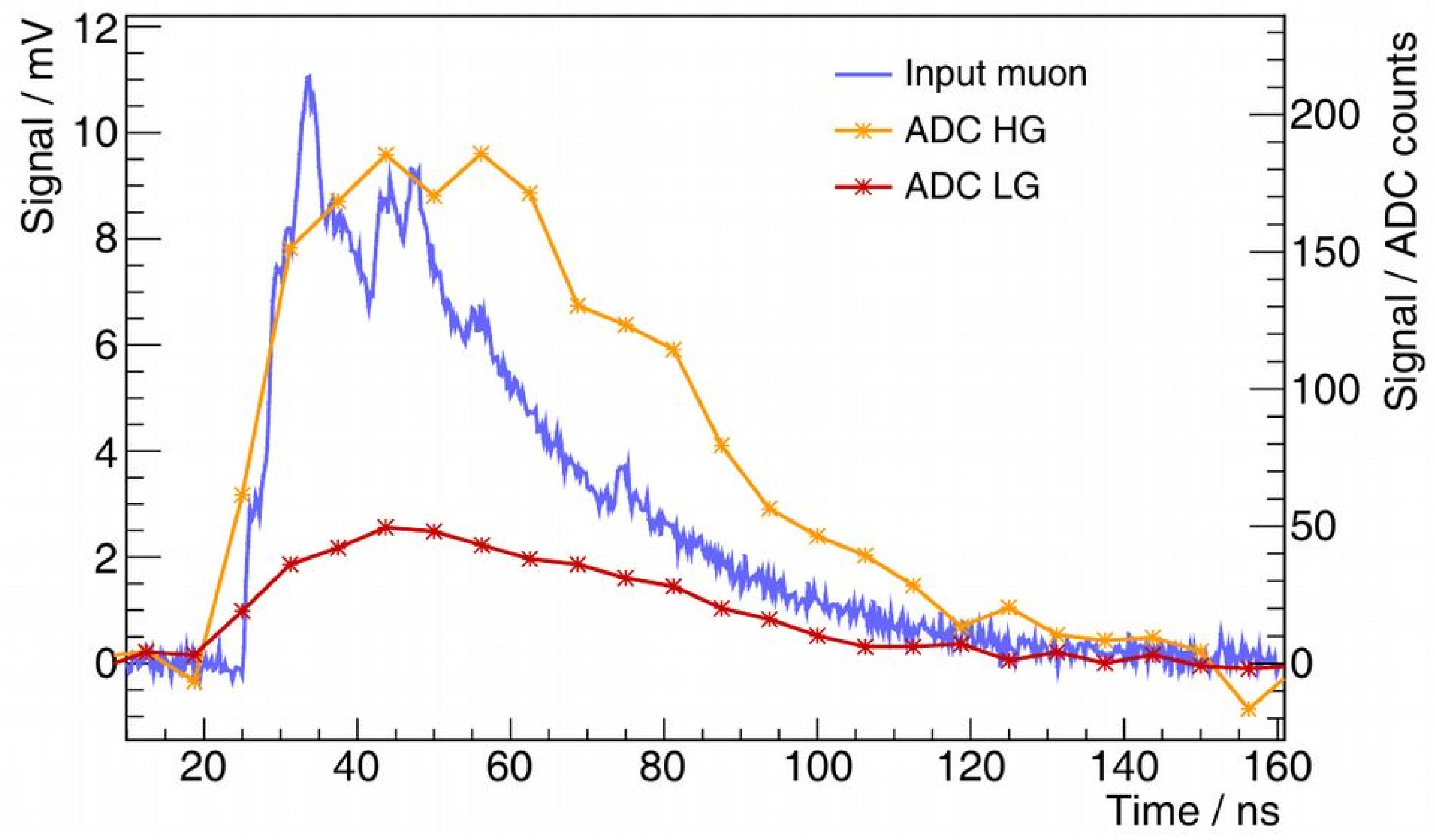
$\hat{N}_\mu \rightarrow Q_{signal} / \langle Q_\mu \rangle$

PMT: 64 counters (111XXXXX)

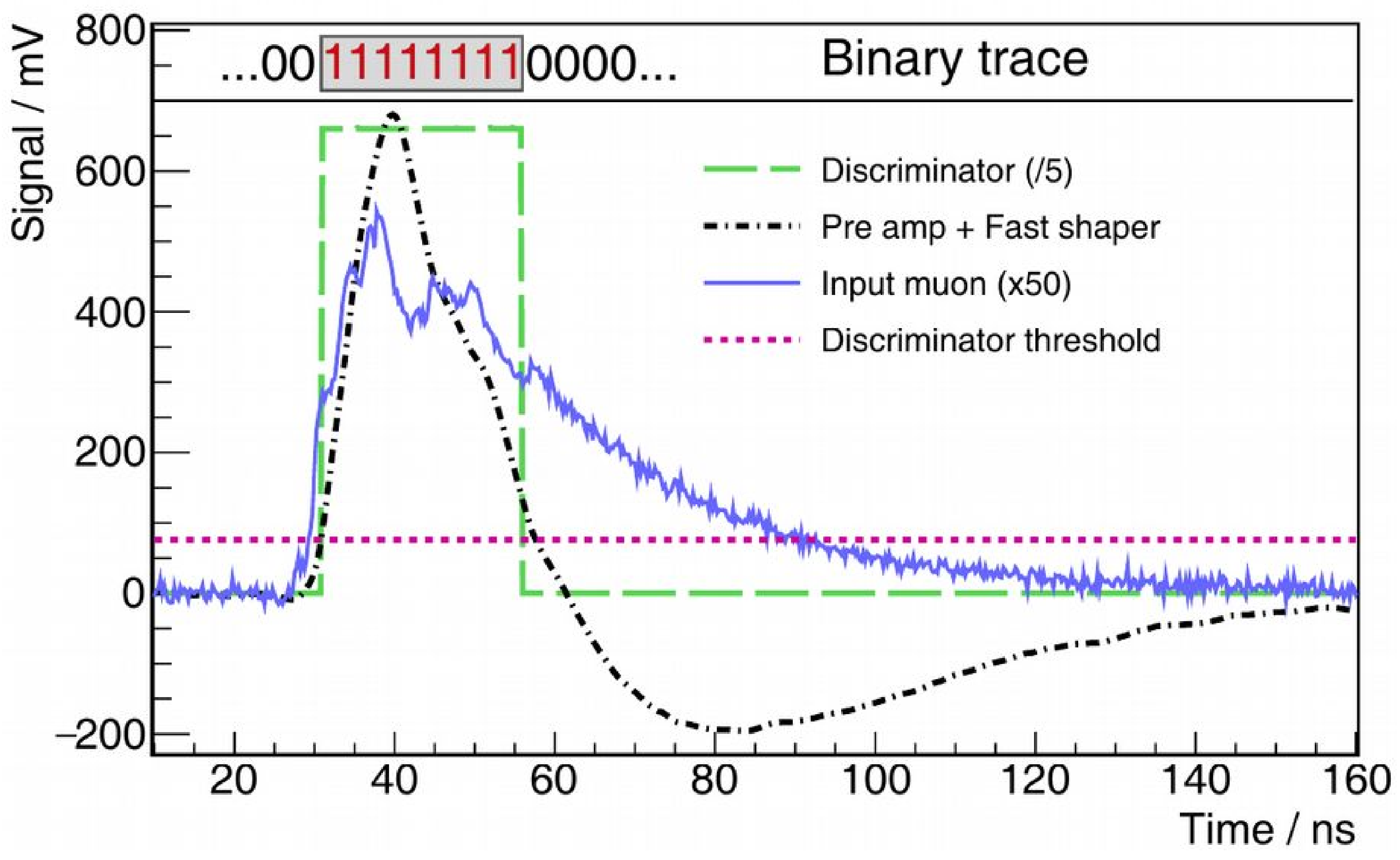
SiPM: 64 counters (1111XXXX) + Integrator

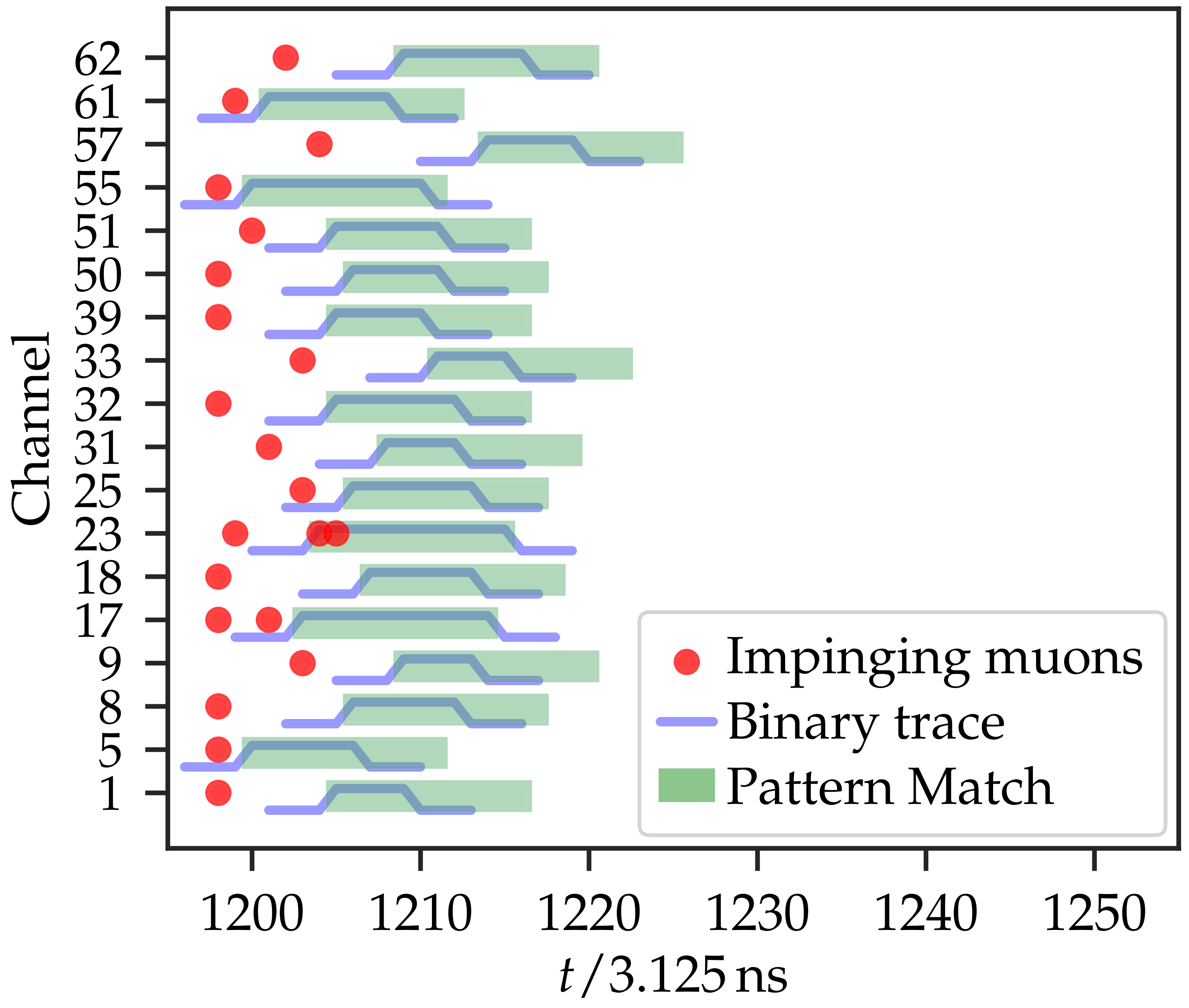






Counting strategies





PMT data (Infinite, N-bin, N-bin centered)

SiPM data (1-bin)

Strategy	$\widehat{\mu}$	$\widehat{N}_\mu$	n_w	Centered
Infinite	$-n_s \ln\left(1-\frac{k}{n_s}\right)$	$\frac{\ln\left(1-\frac{k}{n_s}\right)}{\ln\left(1-\frac{1}{n_s}\right)}$	1	–
N-bin	$-\sum_{j=1}^{n_w} n_s \ln\left(1-\frac{k_j}{n_s}\right)$	$\sum_{j=1}^{n_w} \frac{\ln\left(1-\frac{k_j}{n_s}\right)}{\ln\left(1-\frac{1}{n_s}\right)}$	171	No
N-bin centered	$-\sum_{1}^{j=n_w} n_s \ln\left(1-\frac{k_j}{n_s}\right)$	$\sum_{j=1}^{n_w} \frac{\ln\left(1-\frac{k_j}{n_s}\right)}{\ln\left(1-\frac{1}{n_s}\right)}$	170-171	Yes
1-bin	$-\sum_{j=1}^{n_w} n_s \ln\left(1-\frac{k_j}{n_s-n_{\mathrm{inhib},j}}\right)$	$\sum_{j=1}^{n_w} \frac{n_s}{n_s-n_{\mathrm{inhib},j}} \frac{\ln\left(1-\frac{k_j}{n_s-n_{\mathrm{inhib},j}}\right)}{\ln\left(1-\frac{1}{n_s-n_{\mathrm{inhib},j}}\right)}$	2048	–

μ: average number of muons expected from EASs

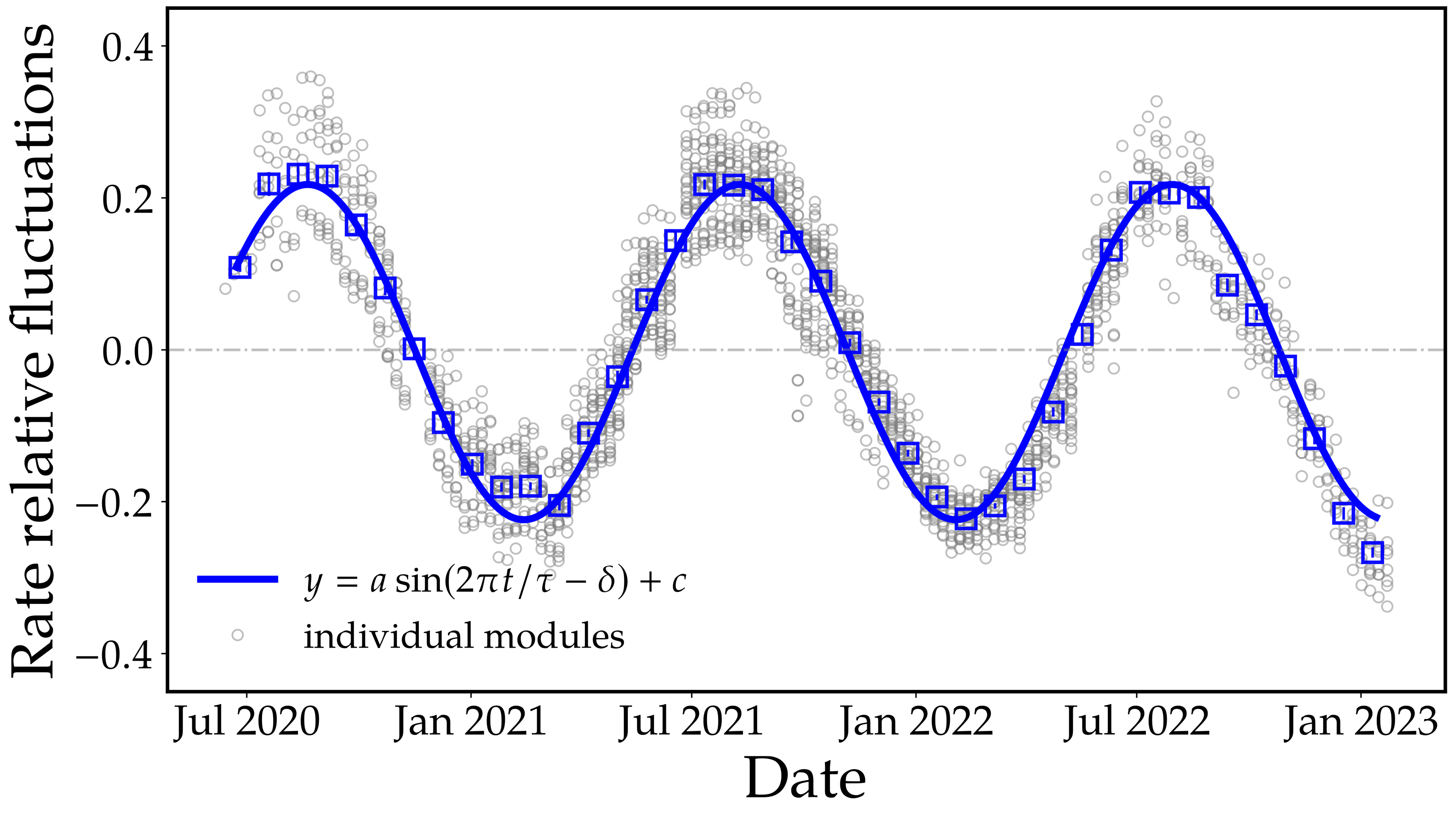
N_μ: number of impinging muons

n_w: number of windows

k: Occupancy

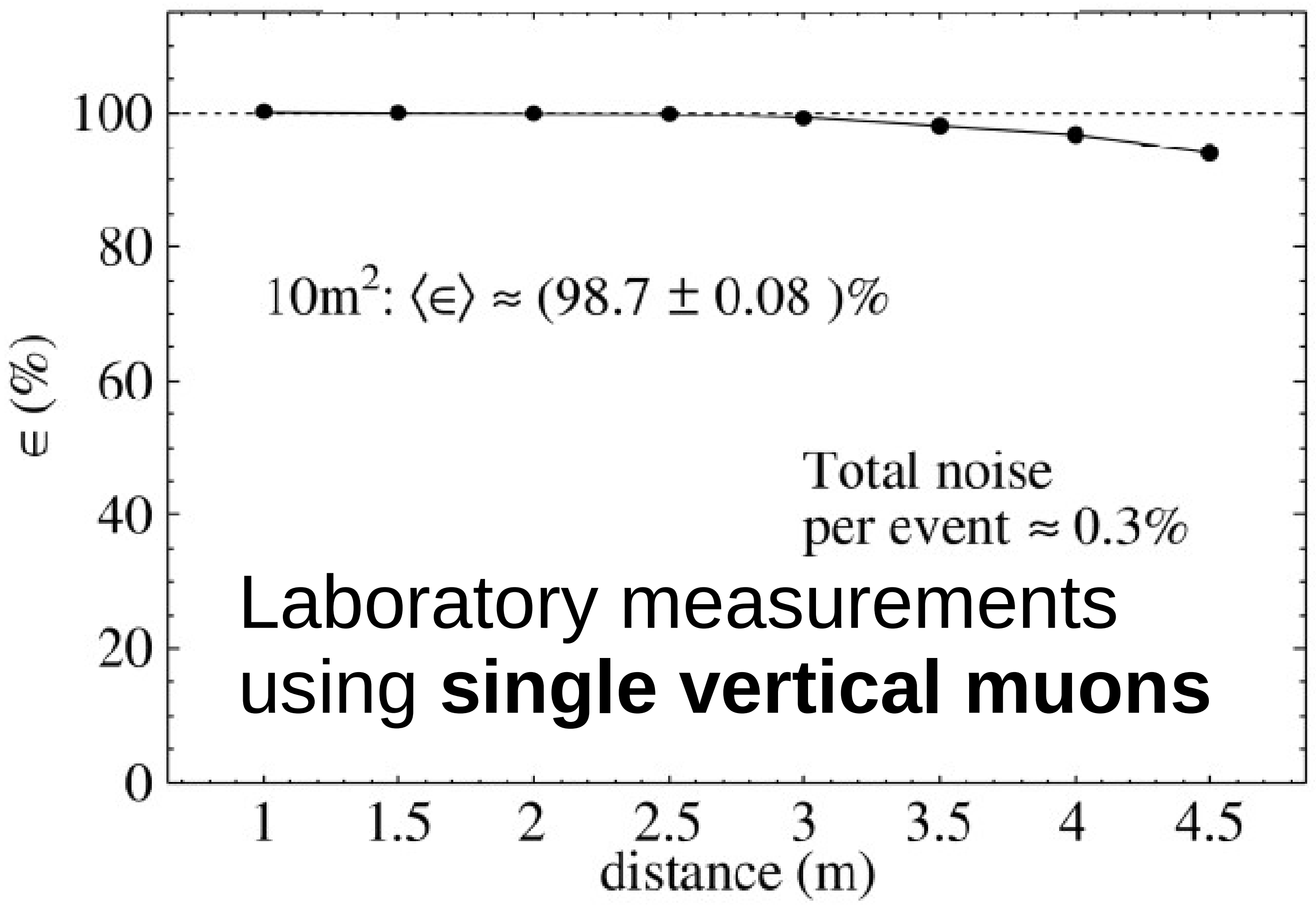
Further levels of complexity in determining N_{μ}

Random WCD trigger → single muons

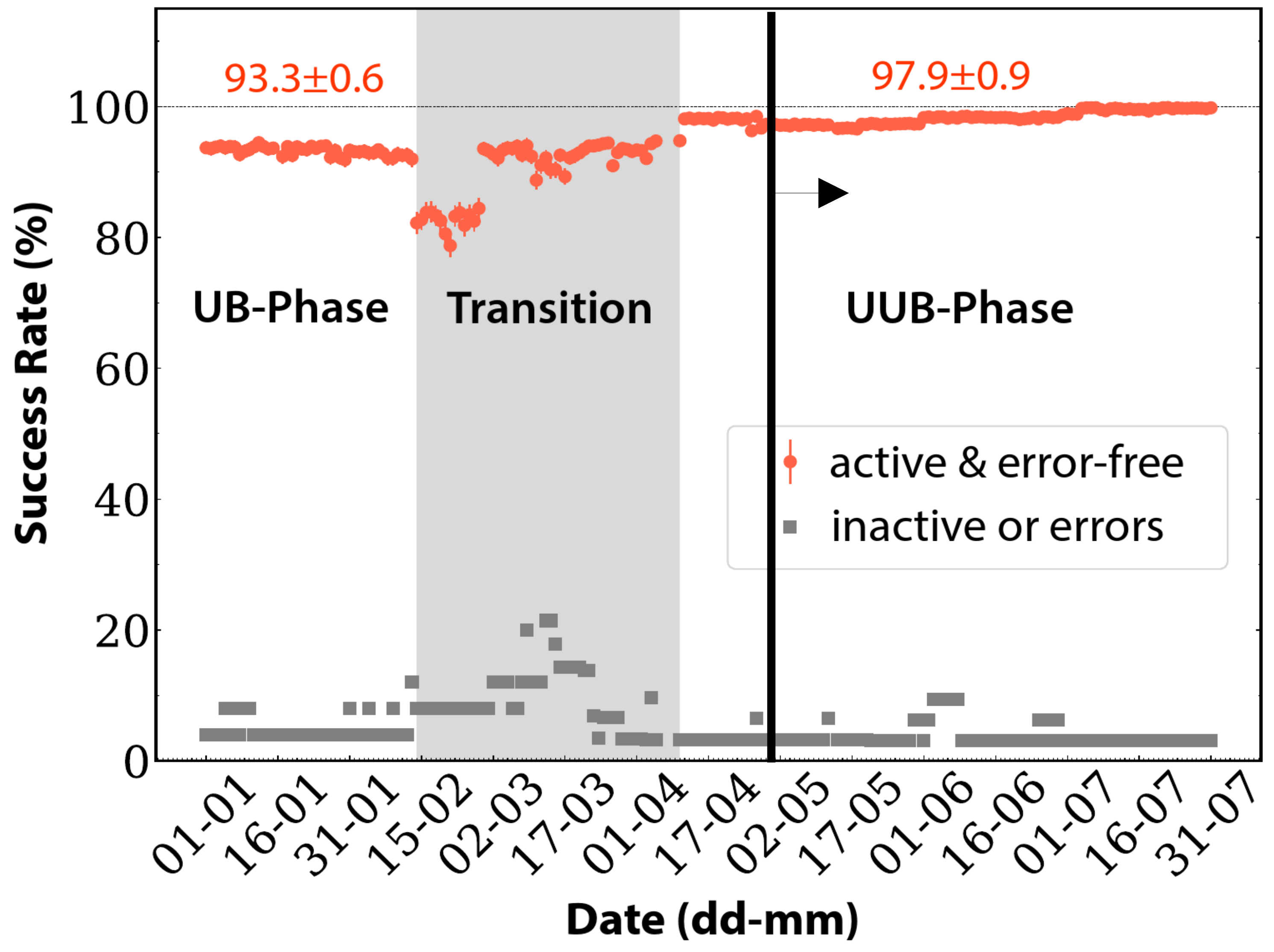


Efficiency of binary channels

"...**1111**xx..." pattern

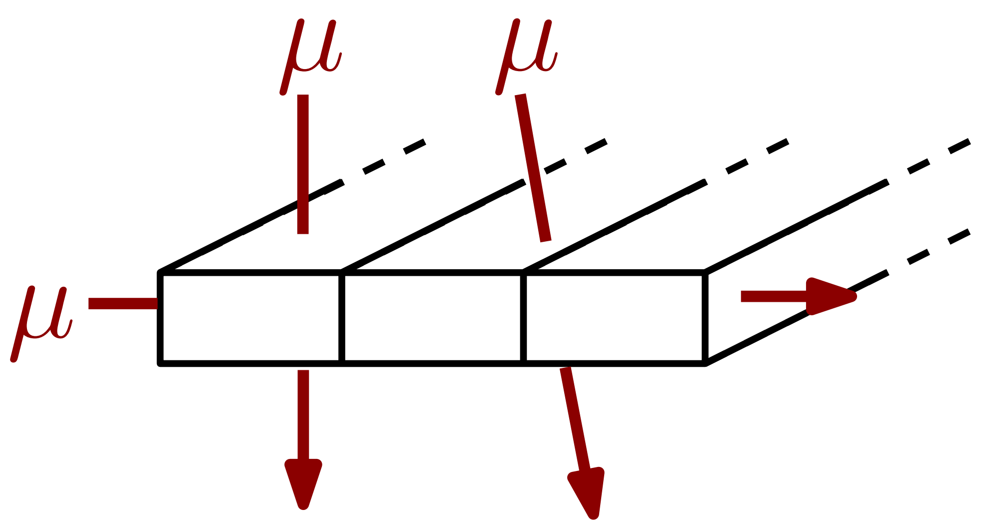


New electronics
→ Improved transfer rate

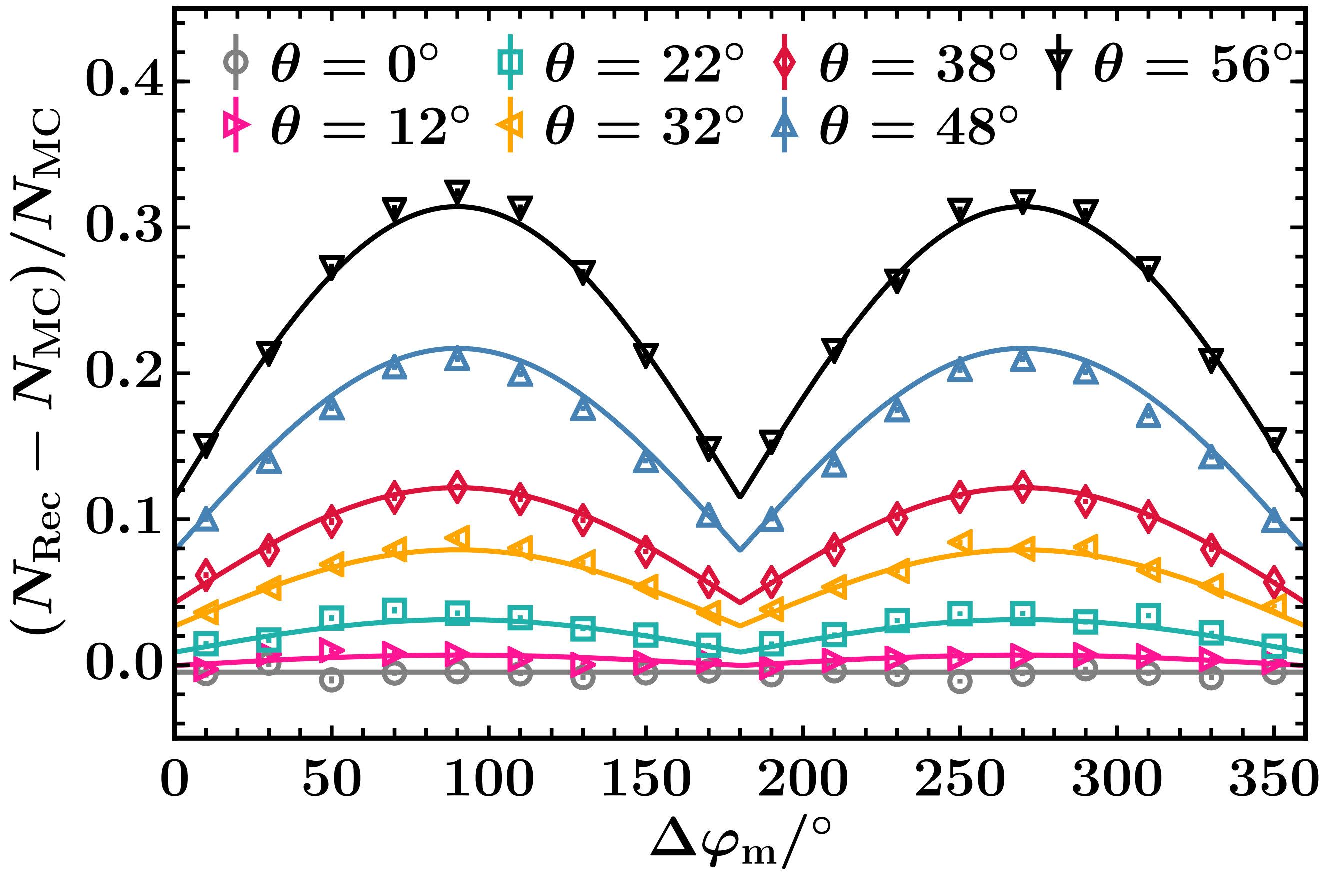


Further levels of complexity in determining N_μ

Inclined muons going through multiple scintillator bars cause overcounting

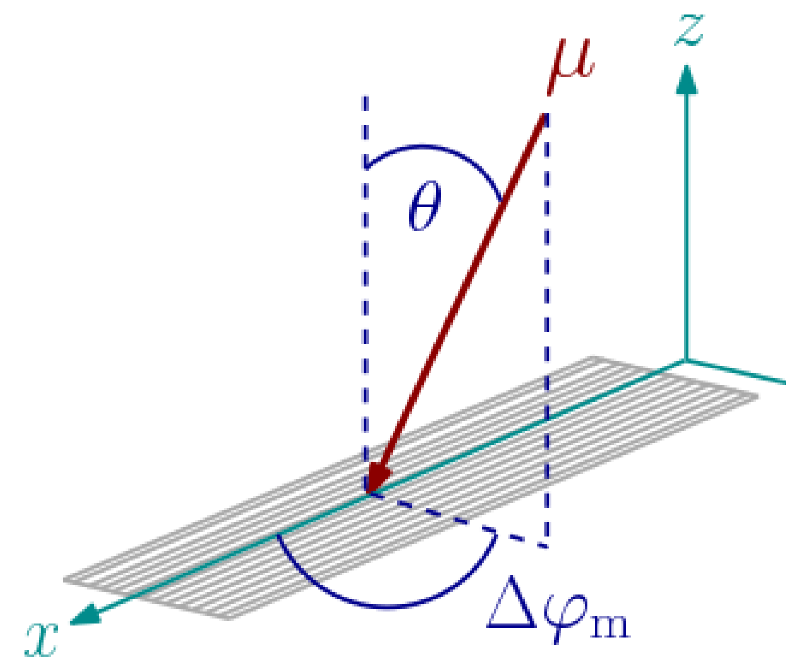


Parametrized relative over-counting as fct. of $\Delta\phi_m$ with simulations

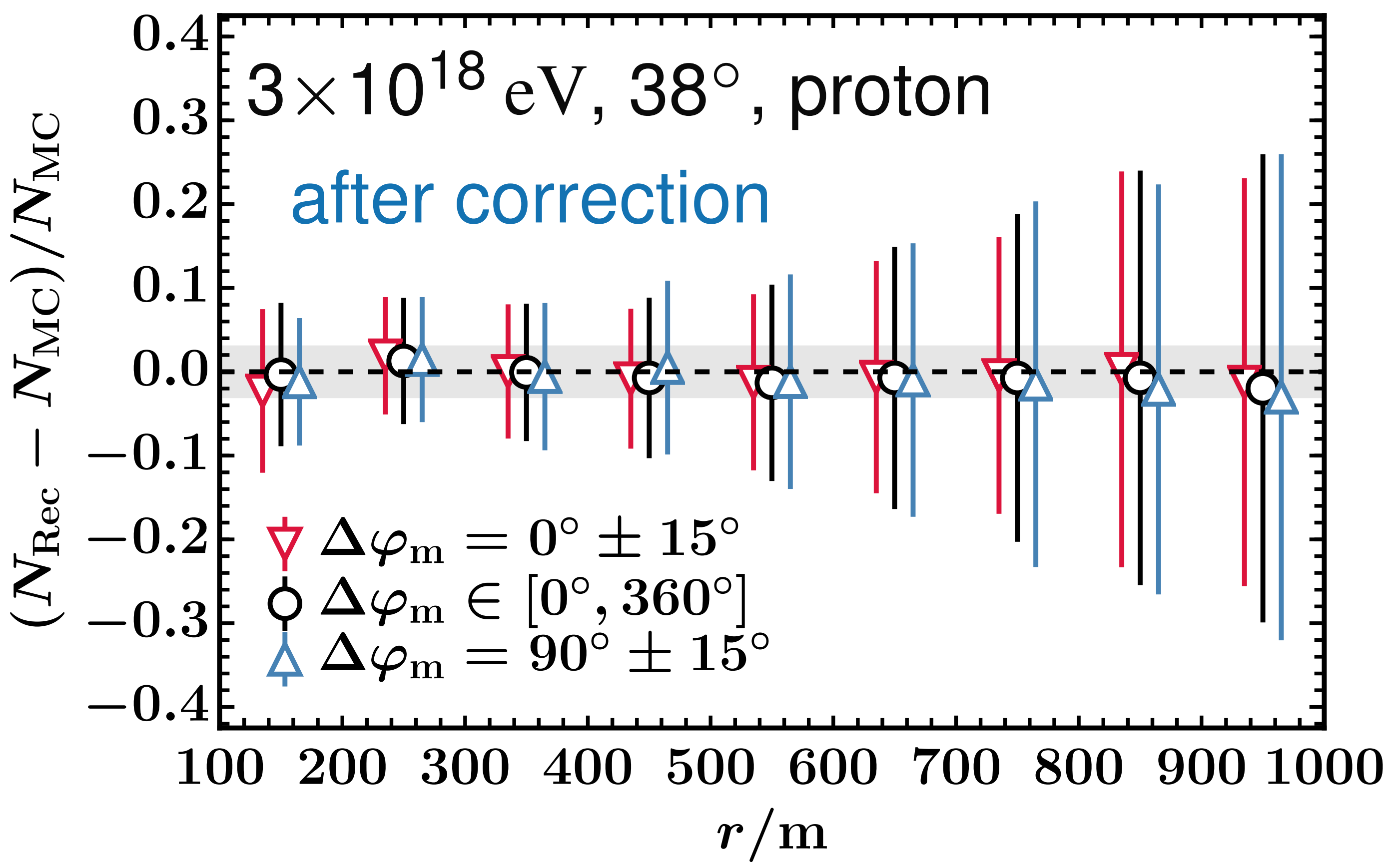


$$f_{\text{clip}}(\theta, \Delta\varphi_{\text{m}}) = a(\theta) + b(\theta) \cdot |\sin \Delta\varphi_{\text{m}}|$$

Inclined muons going through multiple scintillator bars cause overcounting



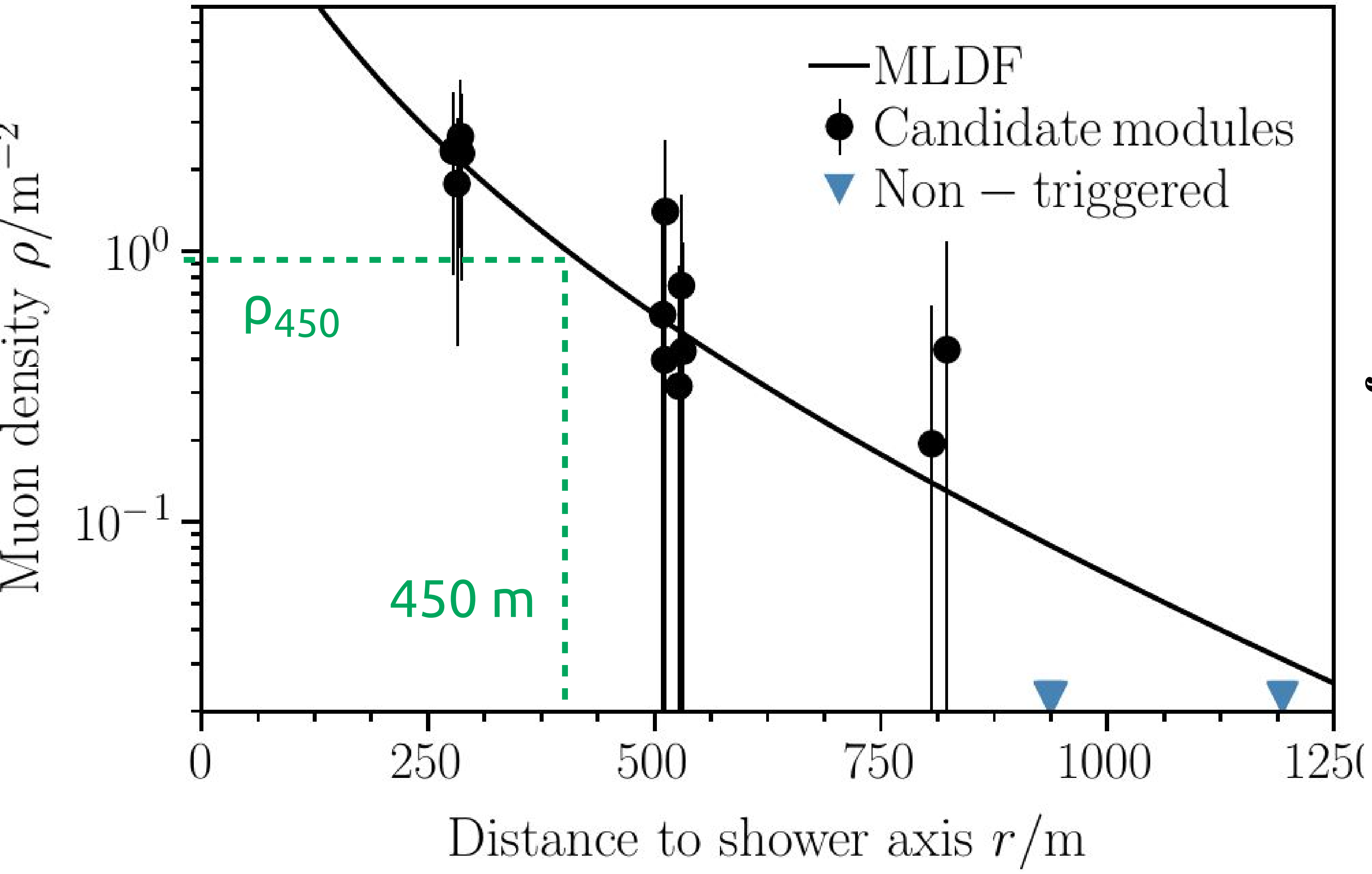
Corrected over-counting as fct. of distance

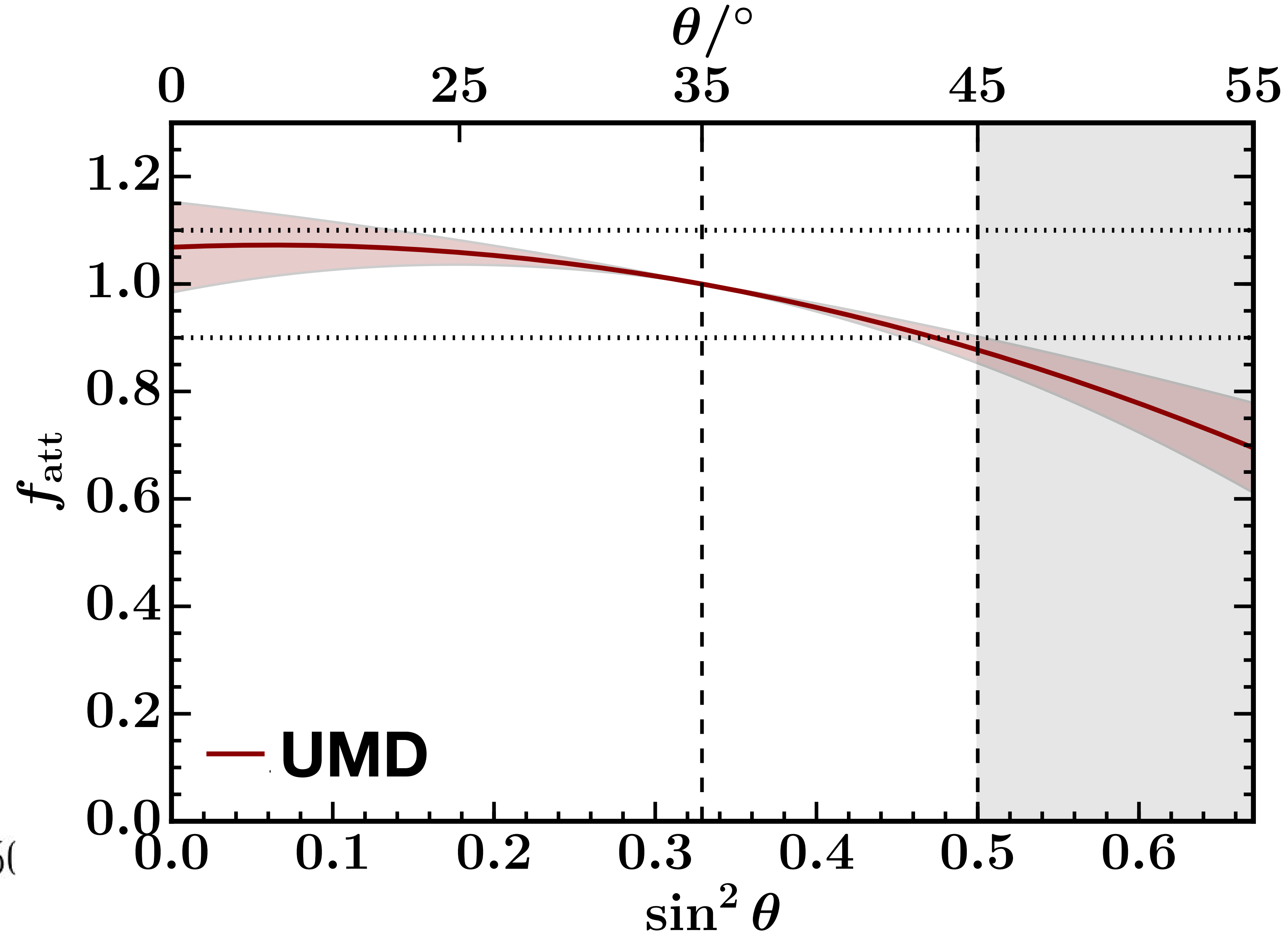


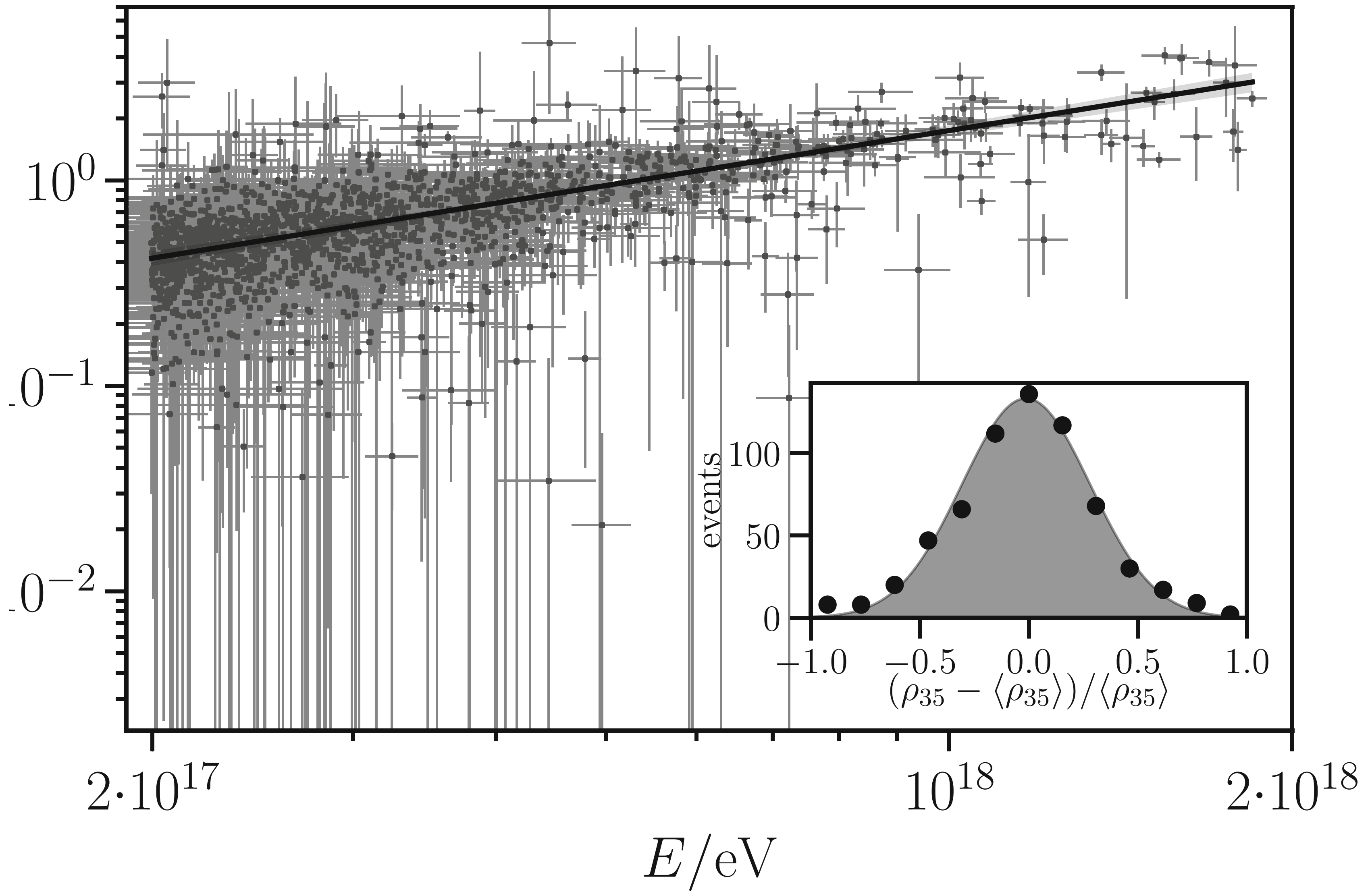
Results from engineering array

- Lateral Distribution Function (LDF) fitted
- ρ_{35}: Estimator of muon density at 450 m corrected for atmospheric attenuation (CIC)
- 1 year of data acquisition

Uncertainty Source	Relative Syst. Unc.	Percentage
Module efficiency corr.	$\sigma_{\mathrm{sys,eff}}/\rho_{450}$	9.9%
MLDF parametrization	$\sigma_{\mathrm{sys,MLDF}}/\rho_{450}$	8.8%
Electronics calibration	$\sigma_{\mathrm{sys,cal}}/\rho_{450}$	3.9%
Soil density	$\sigma_{\mathrm{sys,soil}}/\rho_{450}$	2.8%
Attenuation correction	$\sigma_{\mathrm{sys},f_{\mathrm{att}}}/f_{\mathrm{att}}$	2.3%
Total	$\sigma_{\mathrm{sys},\rho_{35}}/\rho_{35}$	**14.3%**

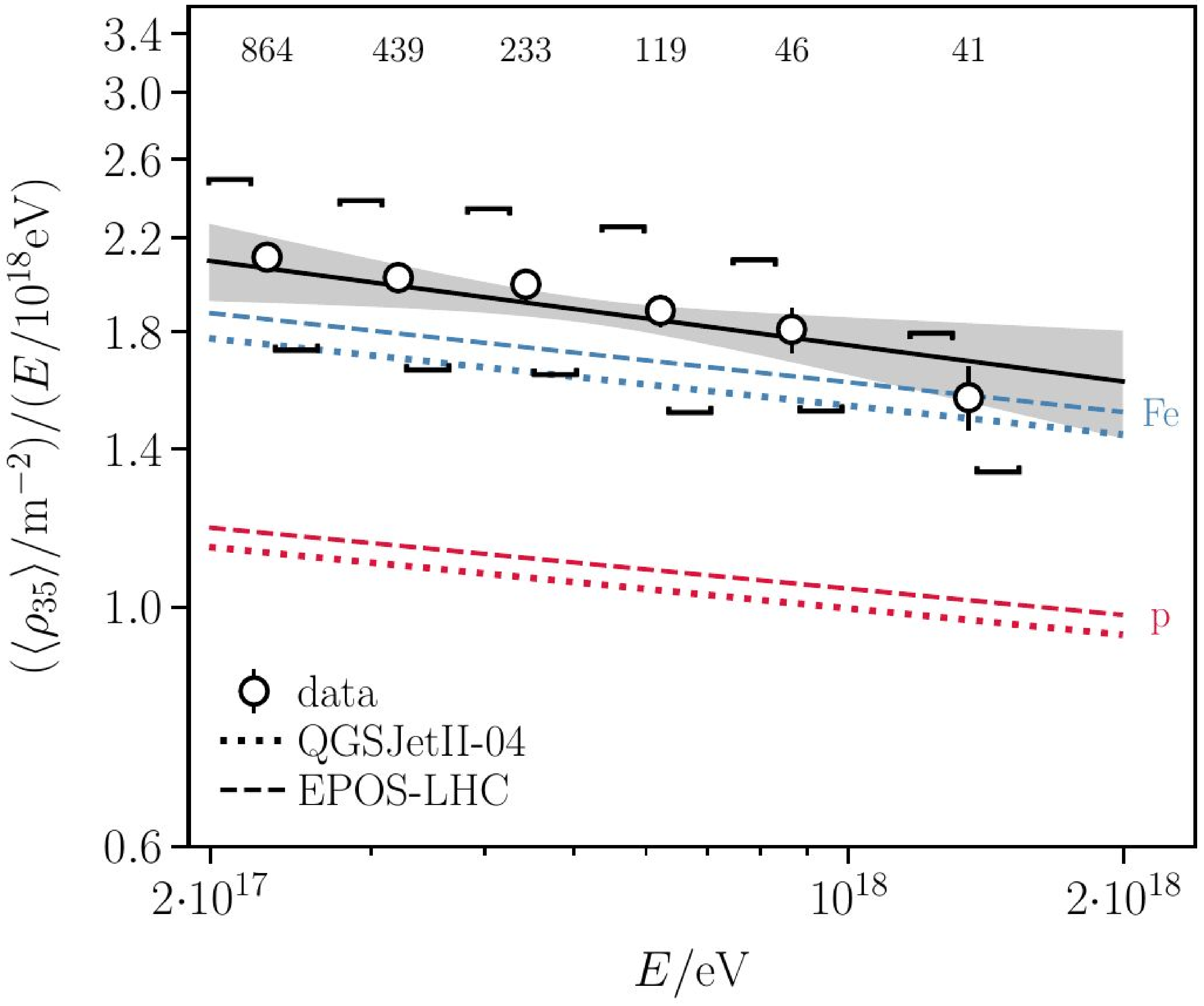


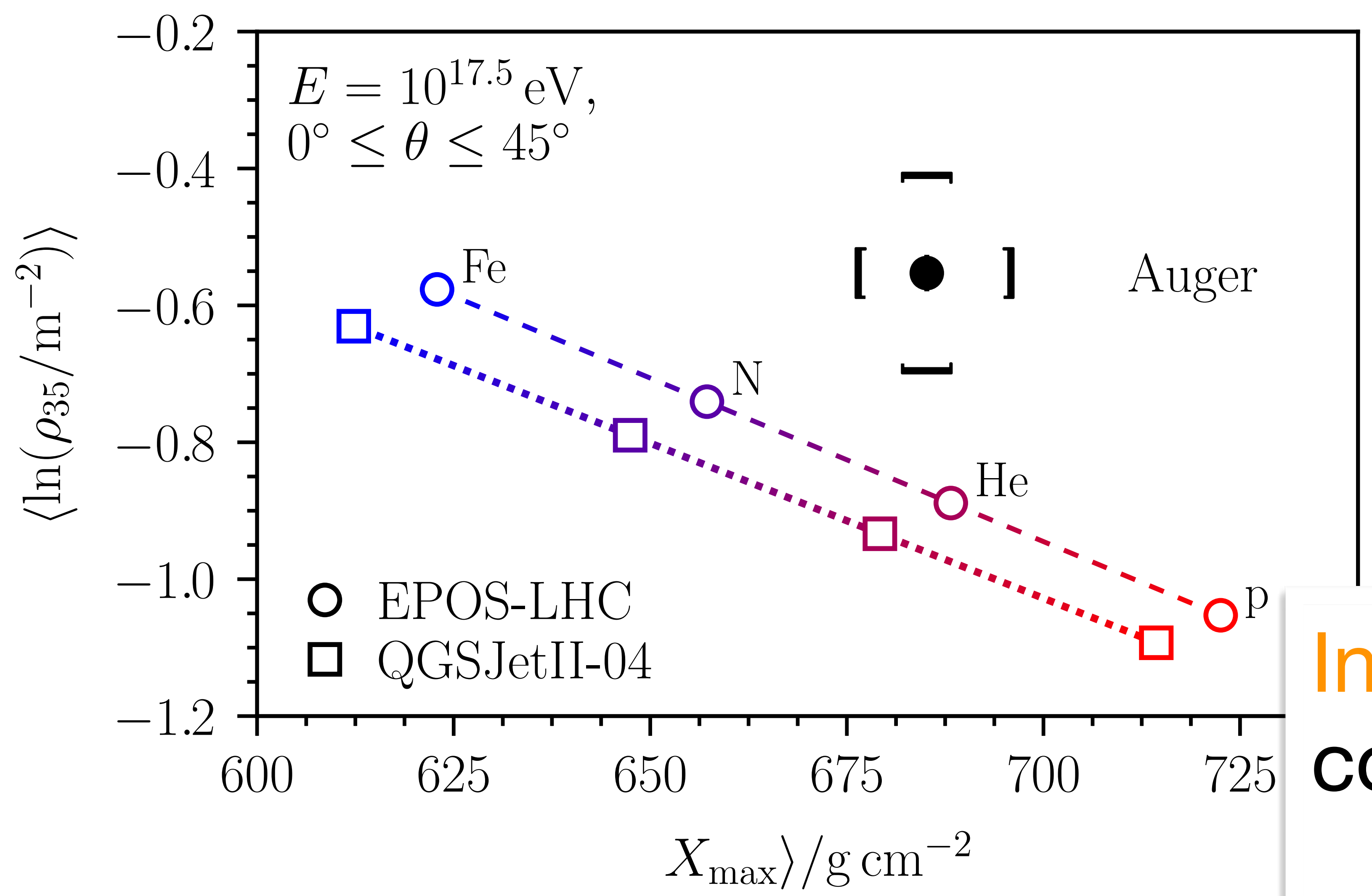


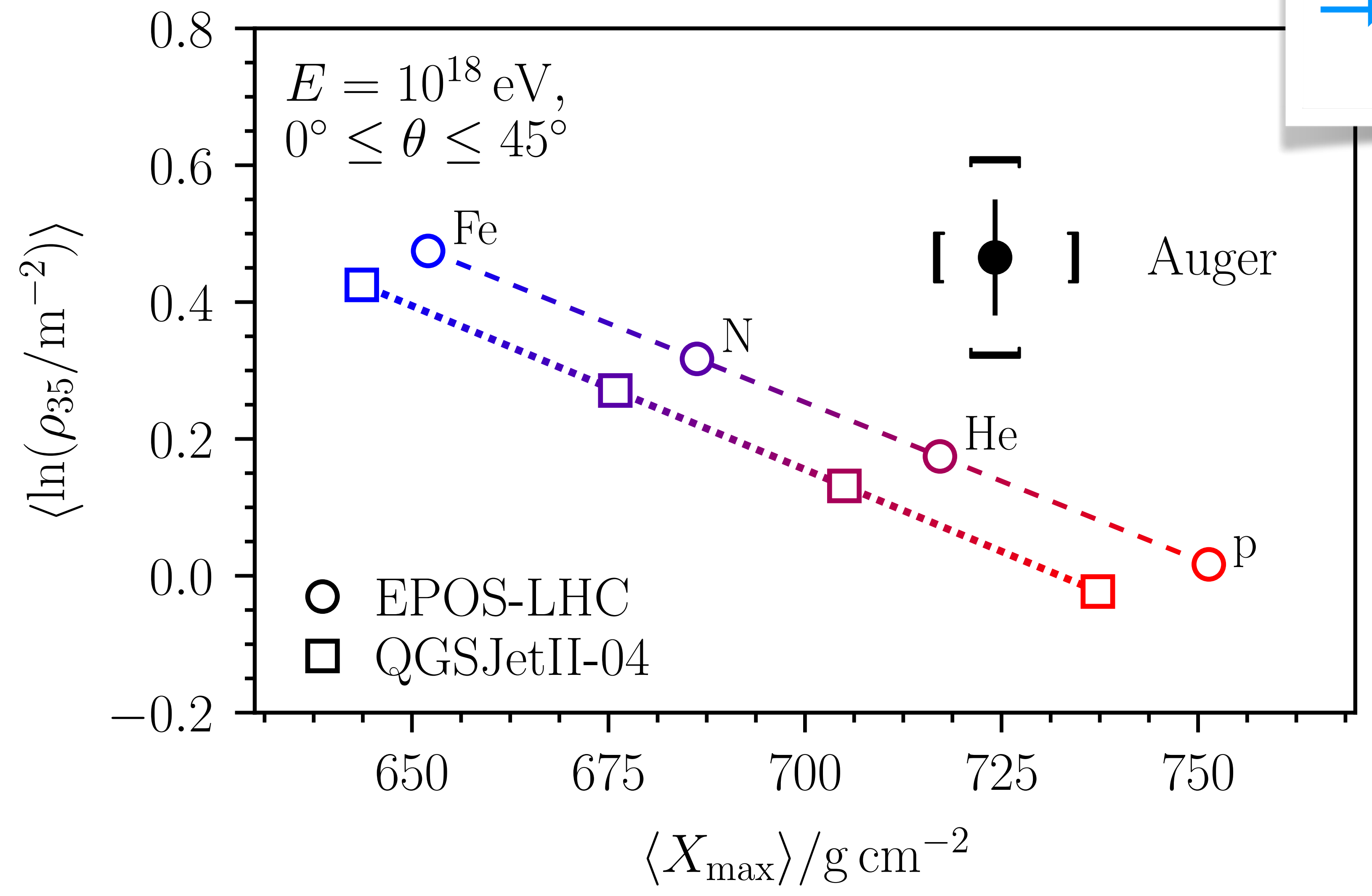


Results from engineering array

$$\rho_{35}(E) = a\left(E/10^{18} eV\right)^{b}$$







Inconsistent results with composition from X_{max}

→ Muon deficit

Fe

$b = 0.91$

$a_{EPOS} = 1.6\ \mathrm{m}^{-2}$

$a_{QGSJetII\text{-}04} = 1.5\ \mathrm{m}^{-2}$

p

$b = 0.92$

$a_{EPOS} = 1.0\ \mathrm{m}^{-2}$

$a_{QGSJETII\text{-}04} = 0.9\ \mathrm{m}^{-2}$

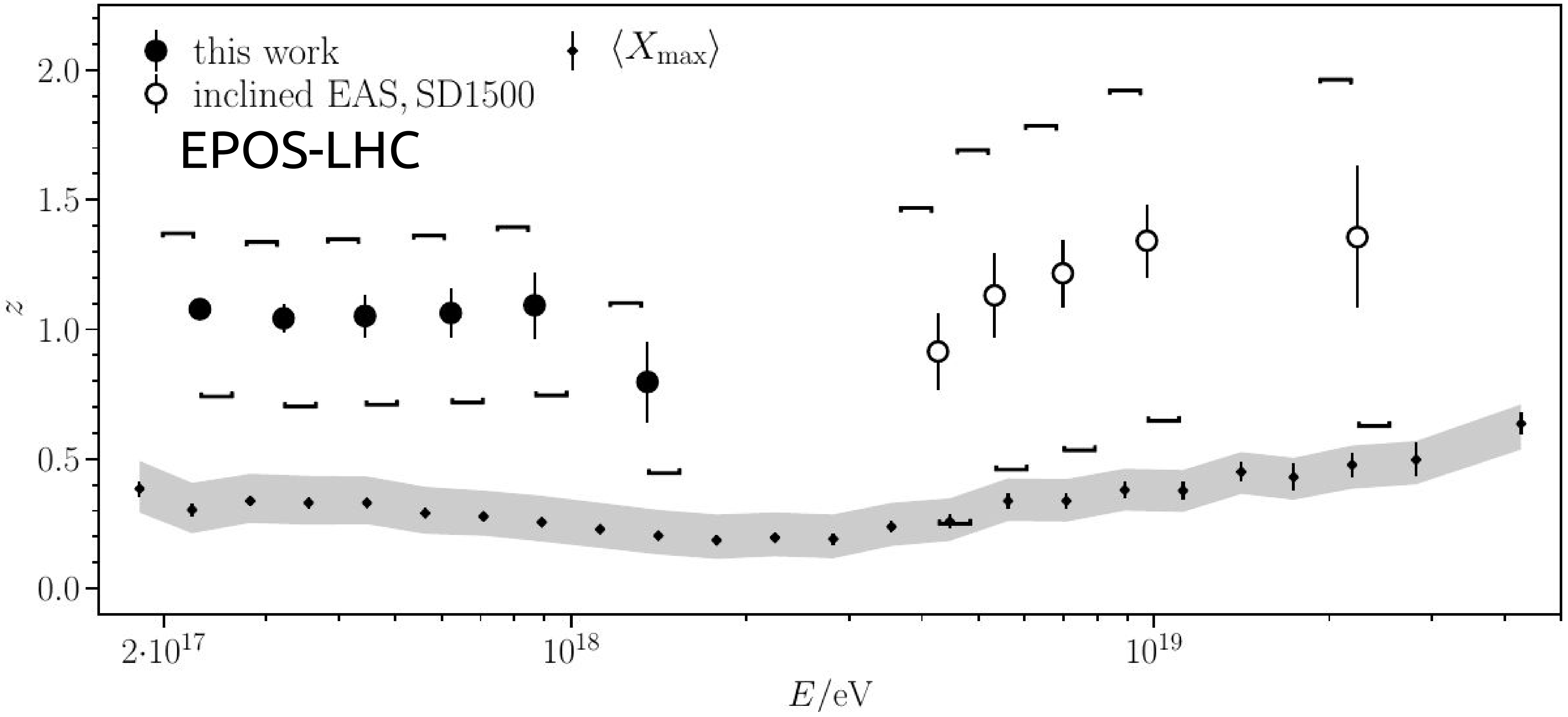
Data

$b = 0.89 \pm 0.04$ (stat) ± 0.04 (sys)

$a = 1.75 \pm 0.05$ (stat) ± 0.05 (sys)

Comparison with other Auger data

$$z = \frac{\langle \ln \rho_{35} \rangle - \langle \ln \rho_{35} \rangle_p}{\langle \ln \rho_{35} \rangle_{Fe} - \langle \ln \rho_{35} \rangle_p}$$

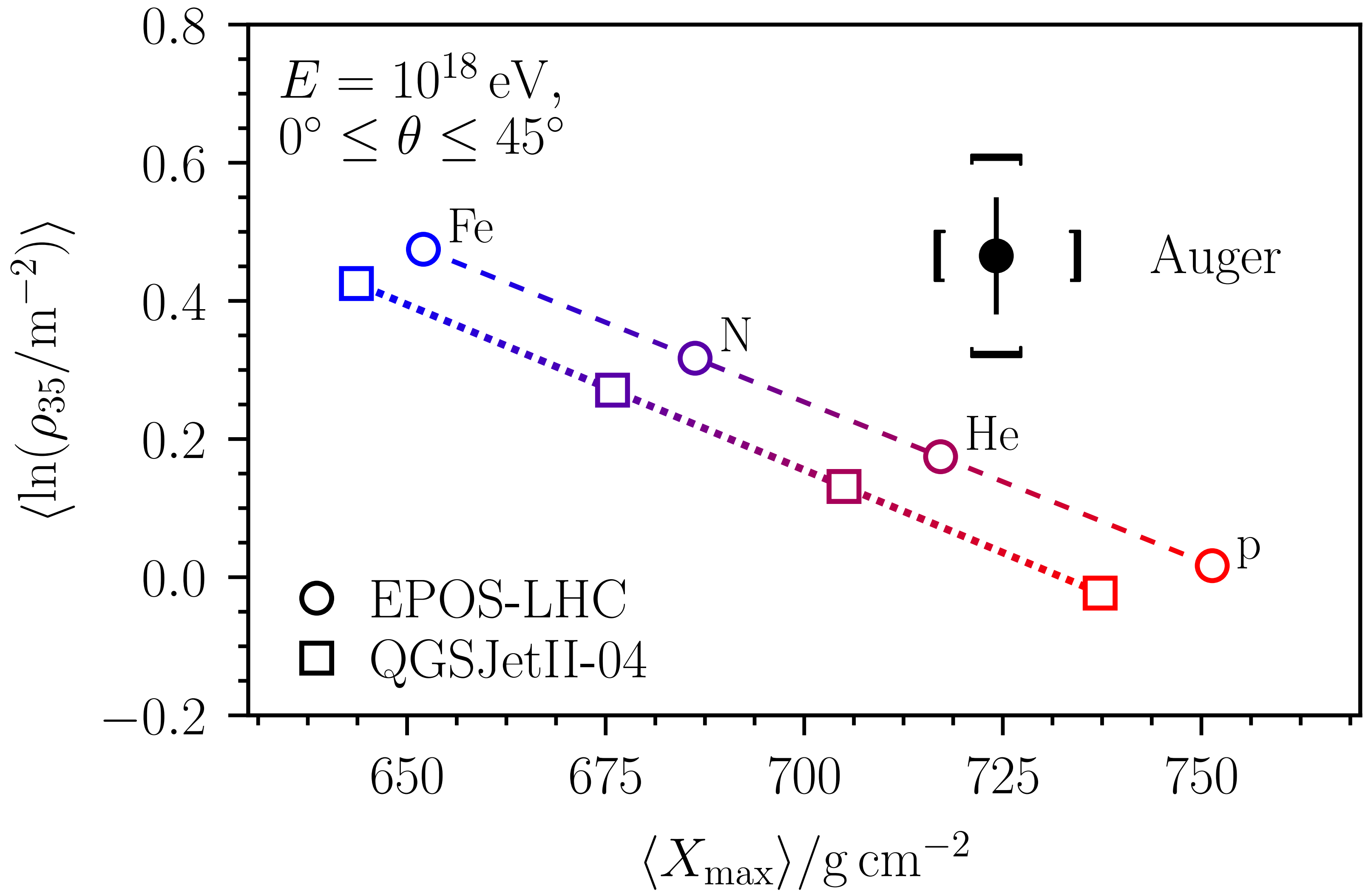


- Comparison muon content and X_{max}
- Muon deficit in lower energies (38% EPOS-LHC, 50% QGSJetII-04)
- Qualitative agreement with evolution from X_{max}?

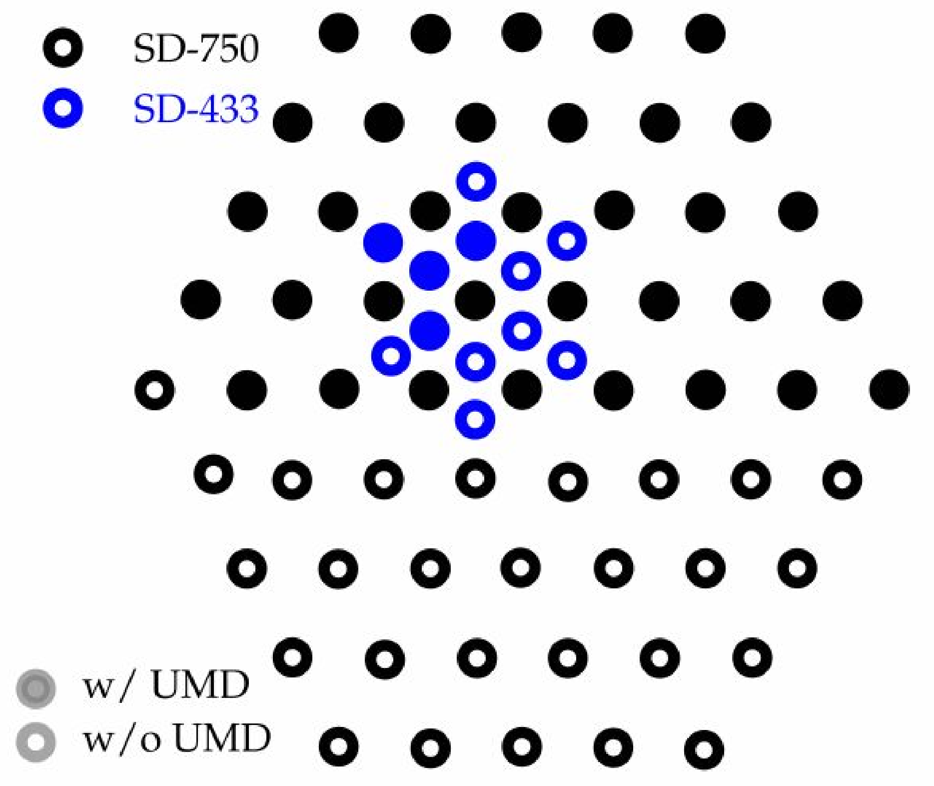
Summary

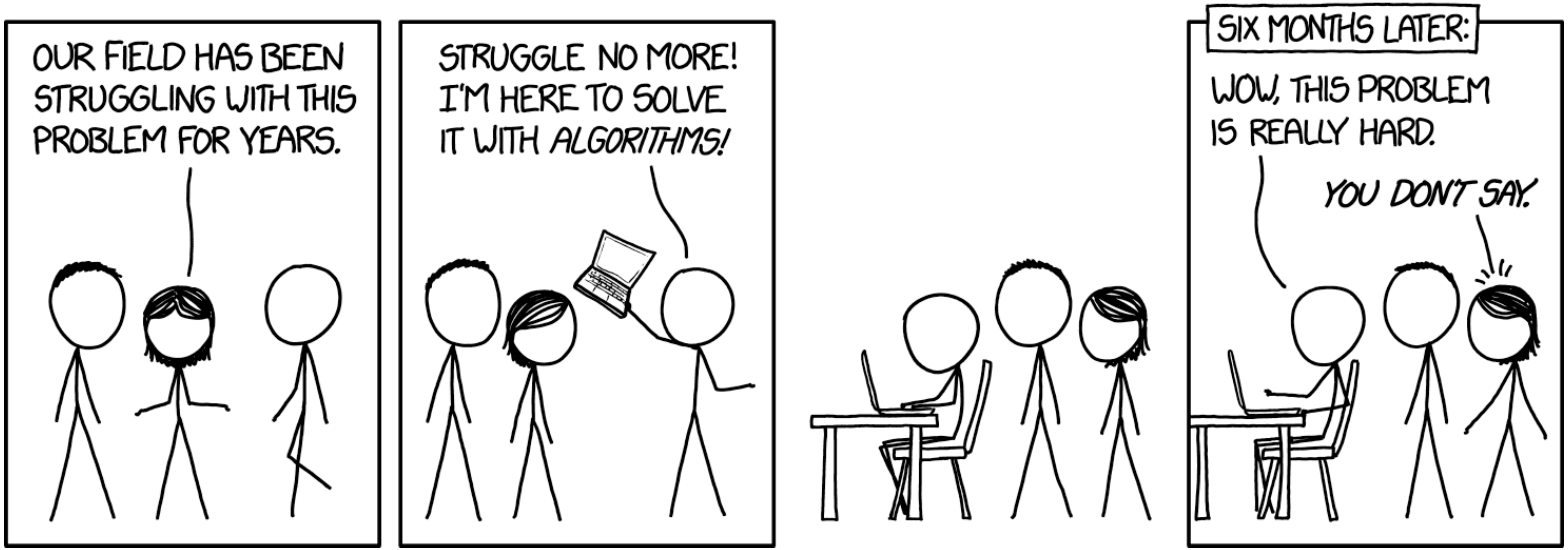
- Underground Muon Detector is expected to be fully deployed by end of 2024
- It will provide a direct measurement of muon component
  - <ρ35>
  - $\sigma_{\rho 35}$
  - Timing

  ➡ Mass composition ↔ Hadronic models



- Cross-calibration of indirect muon estimates of the 1500m array
- Muon deficit wrt
  - QGSJetII-04 (50%) and
  - EPOS-LHC (38%)
- New SiPM results to be expected soon




OUR FIELD HAS BEEN STRUGGLING WITH THIS PROBLEM FOR YEARS.
STRUGGLE NO MORE! I'M HERE TO SOLVE IT WITH ALGORITHMS!
SIX MONTHS LATER:
WOW, THIS PROBLEM IS REALLY HARD.
YOU DON'T SAY.