Subluminal pulses in the Surface-Scintillator detectors of AugerPrime

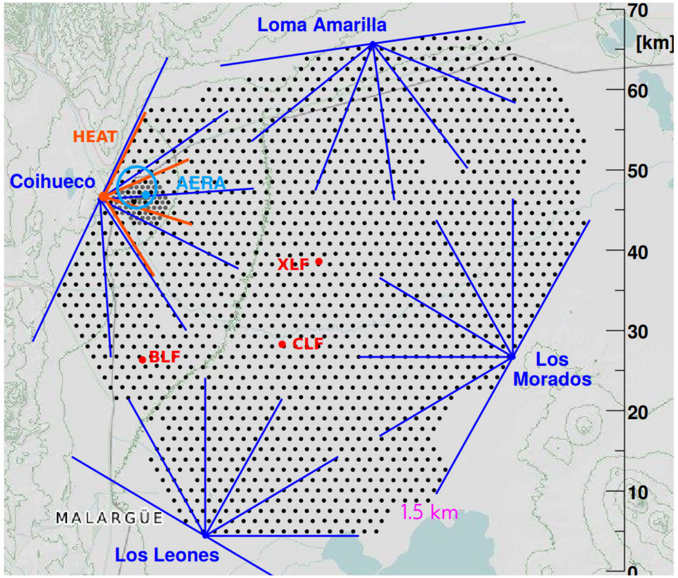
T. Schulz KIT Karlsruhe Institute of Technology, on behalf of the Pierre Auger Collaboration | 21.11.2024

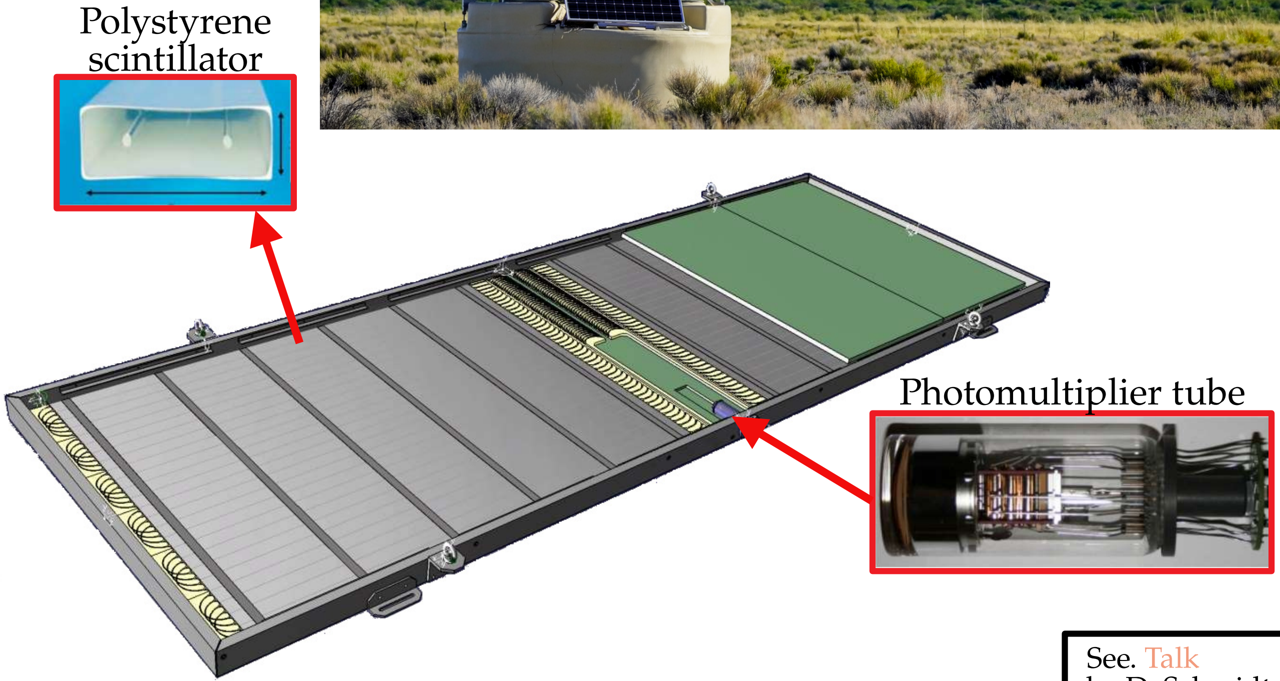
PIERRE AUGER OBSERVATORY

7th International Symposium on Ultra High Energy Cosmic Rays

The Pierre Auger Observatory

- 1660 Water-Cherenkov detectors (WCDs)
- Surface-Scintillator detectors (SSDs) mounted on top
  - SSD active area of 3.84 m^2



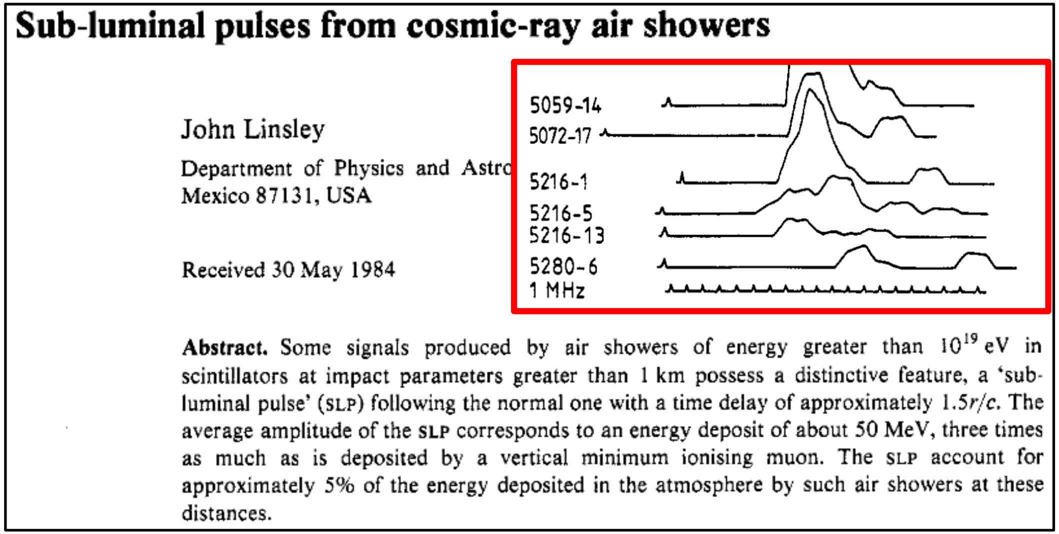


See. Talk by D. Schmidt

Subluminal pulses

- Pulses with **time delays >** r/c defined as subluminal

- **Subluminal pulses** in scintillator measurements of Volcano Ranch experiment suspected to originate from **neutrons**



Sub-luminal pulses from cosmic-ray air showers

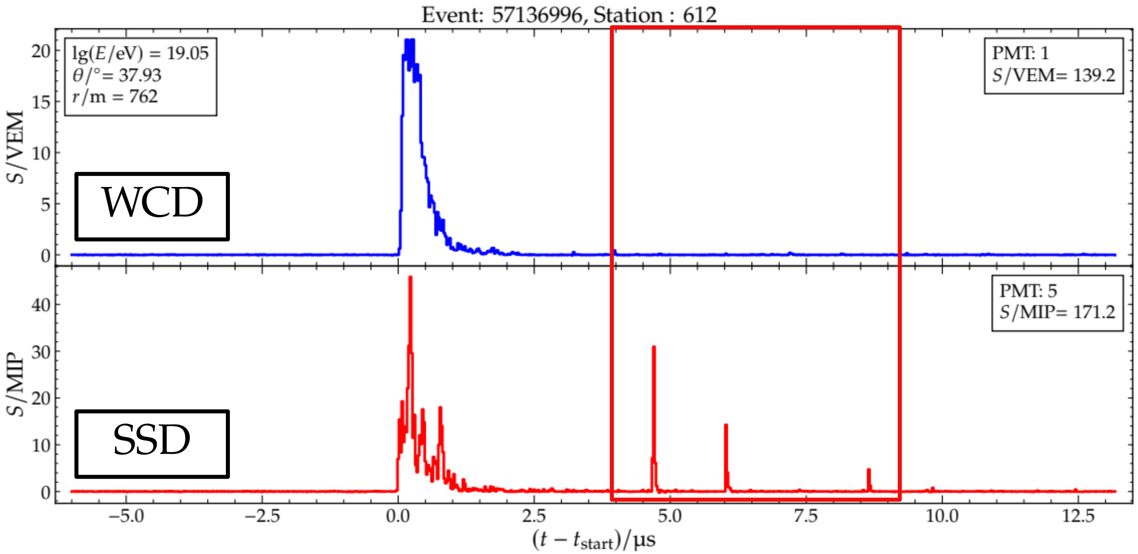
John Linsley

Department of Physics and Astro... Mexico 87131, USA

Received 30 May 1984

5059-14
5072-17
5216-1
5216-5
5216-13
5280-6
1 MHz

Abstract. Some signals produced by air showers of energy greater than 10^{19} eV in scintillators at impact parameters greater than 1 km possess a distinctive feature, a 'sub-luminal pulse' (SLP) following the normal one with a time delay of approximately $1.5r/c$. The average amplitude of the SLP corresponds to an energy deposit of about 50 MeV, three times as much as is deposited by a vertical minimum ionising muon. The SLP account for approximately 5% of the energy deposited in the atmosphere by such air showers at these distances.



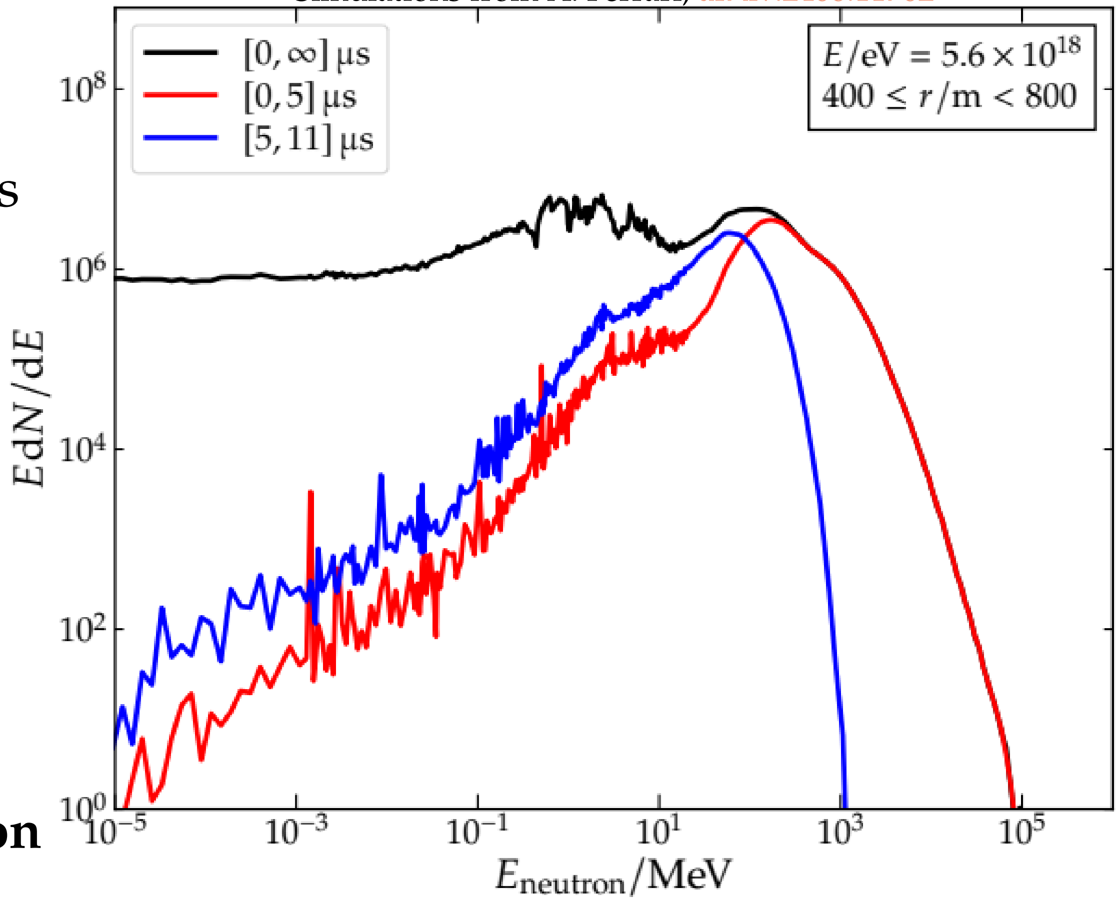
- Delayed pulses seen in SSD measurements of **AugerPrime**, which are not present in the same WCD measurements

→ Are these **"real" particles** or electronic effects?

Neutrons in air showers

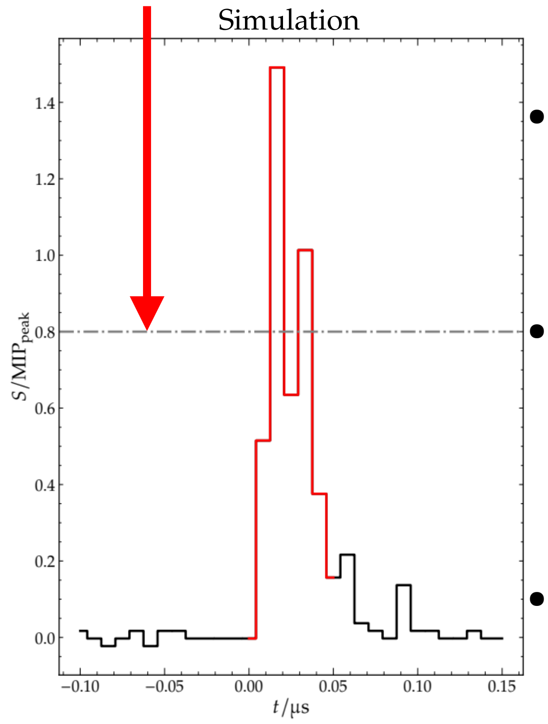
- Span full spectrum due to long lifetime and **no ionization energy loss**
- High energy neutrons created in **same hadronic processes** as pions and kaons
    - Pair-production due to **baryon number conservation**
- **Quasi-elastic peak** from
    - non-elastic neutron-nucleon interactions
    - elastic neutron-nucleon interactions
- Low energy neutrons through **diffusion** in atmosphere

Simulations from A. Ferrari; arXiv:2406.11702

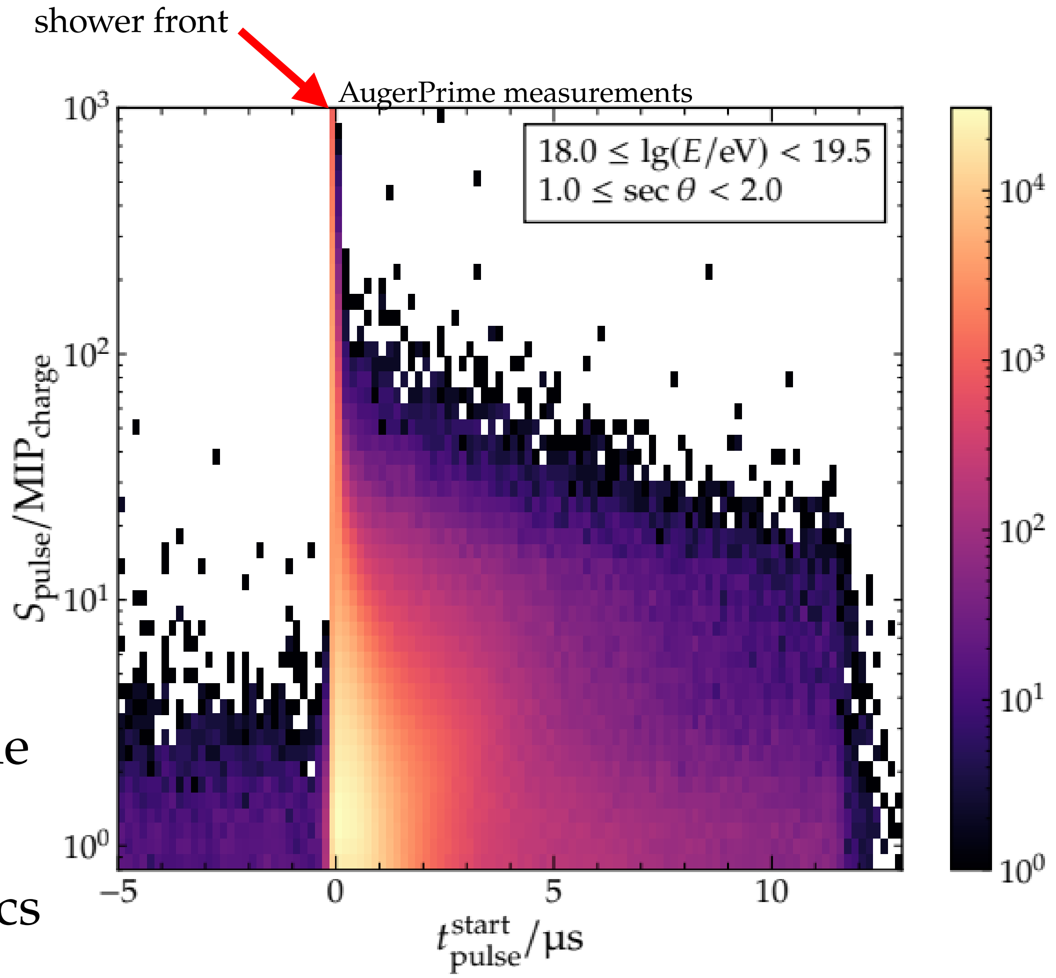


Finding (subluminal) pulses

- **Pulse finding algorithm** to detect all pulses above certain threshold
  - Conservative threshold to avoid impact of **baseline noise / artifacts**



- About **600,000 traces** from 2020-2024
- Pulse shape compatible with **single particle** time structure
- Effects of electronics ruled out in **lab measurements**

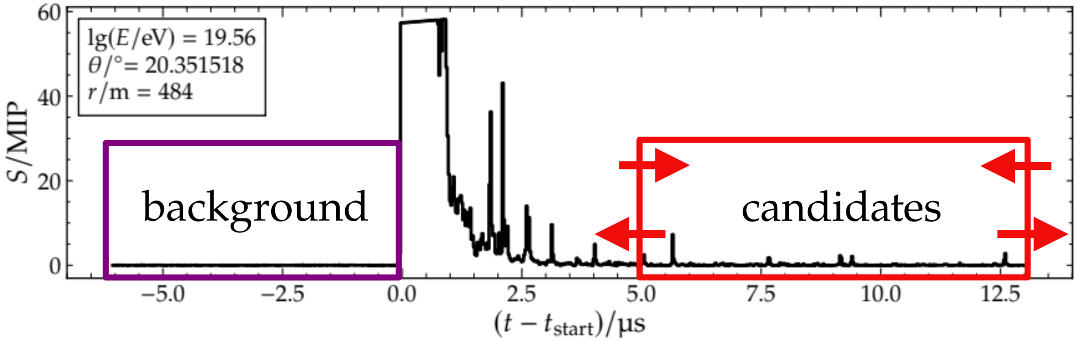


Candidate selection

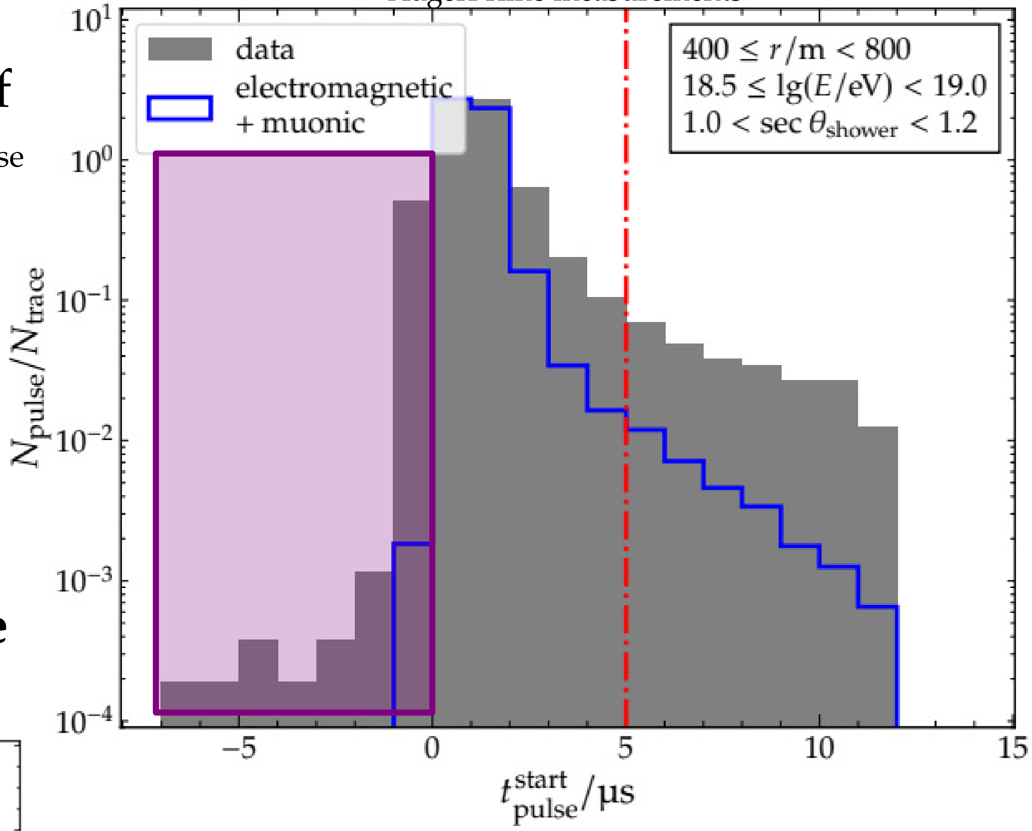
- Background from the EM/µ component of the shower is dependent on E, θ, r and S_{pulse}

- Around **1 – 20%** of pulses from electromagnetic and muonic components (simulations)

- Pulses found **before** shower signal ($t < t_{\mathrm{start}}$), are background, **unrelated to the shower**

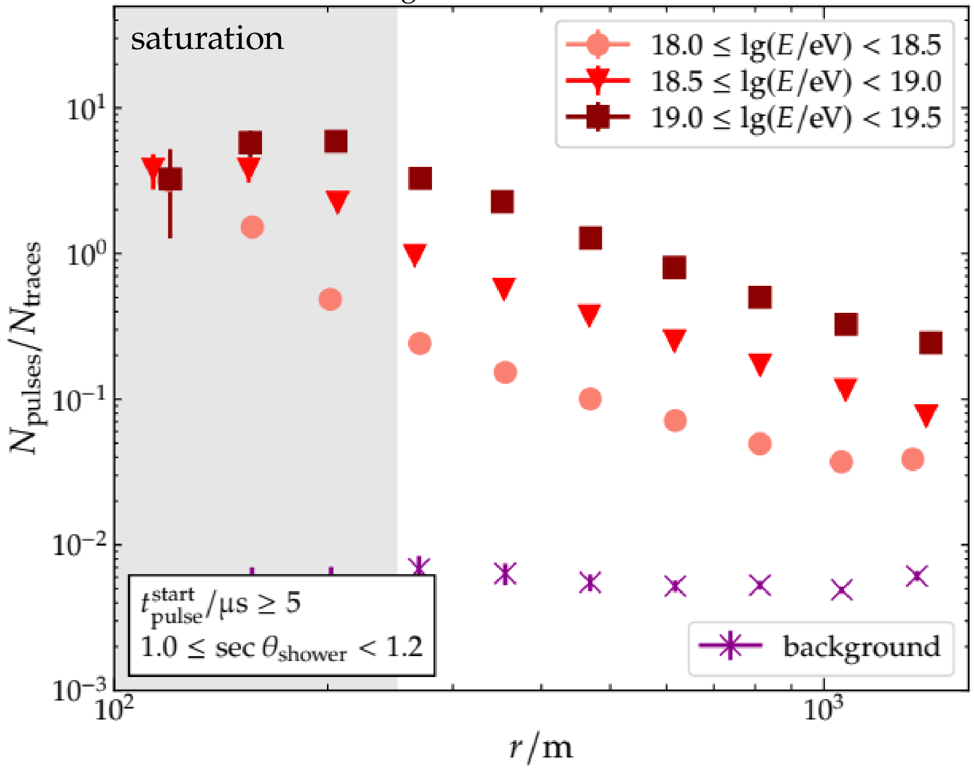


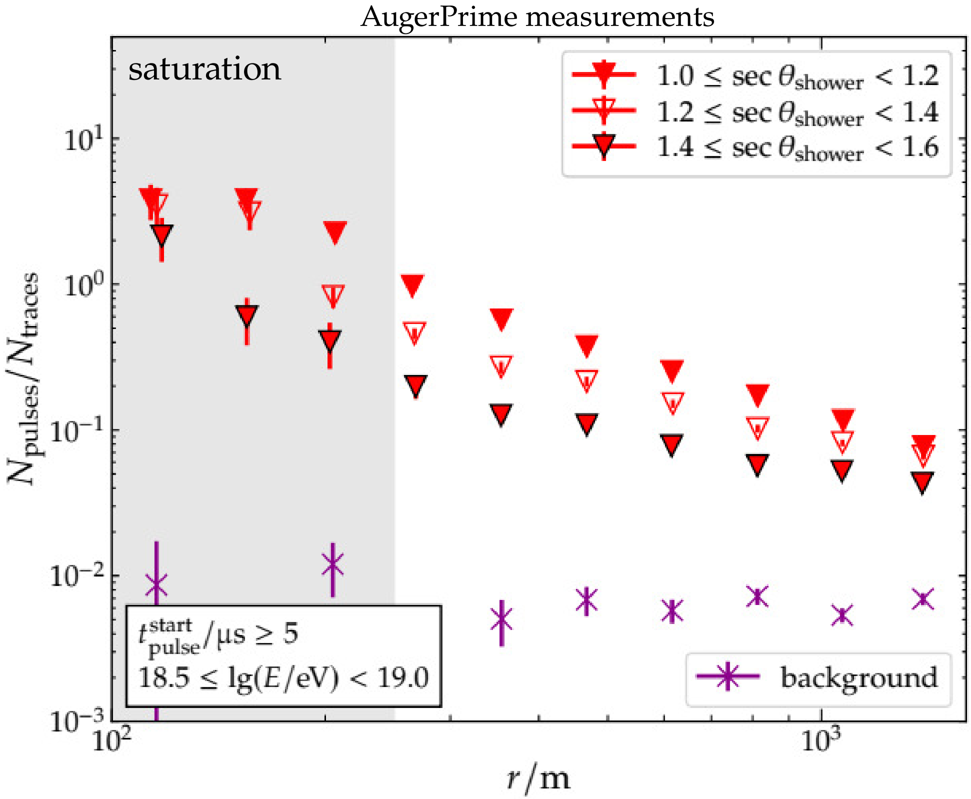
AugerPrime measurements



- Pulses 5 µs **after** the shower signal are considered candidates

Pulse rates I



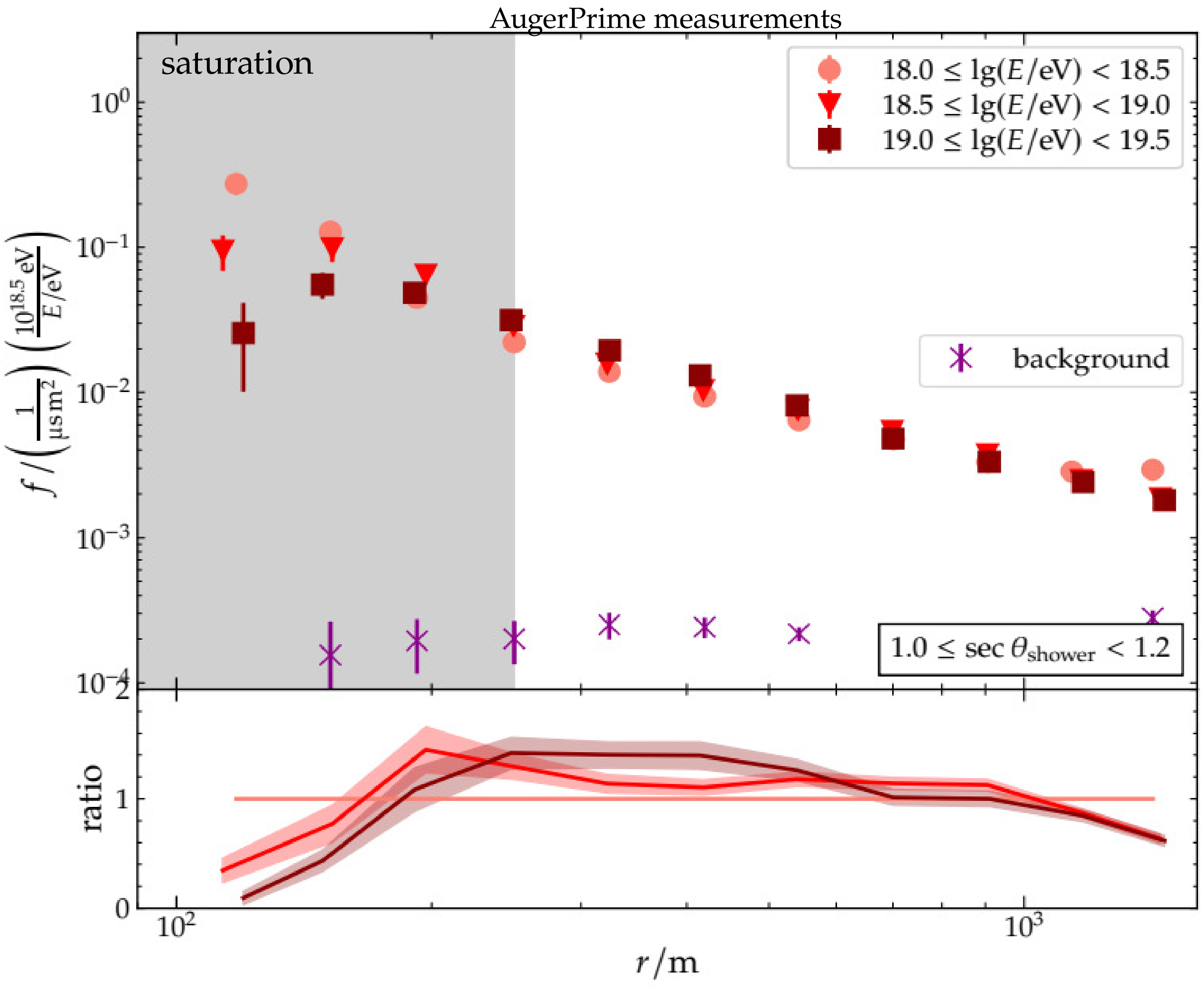


- More than **6 pulses per trace** possible at highest energies
- **Saturation** of baseline limits current analysis
- **Zenith angle and energy** dependence of pulse rate

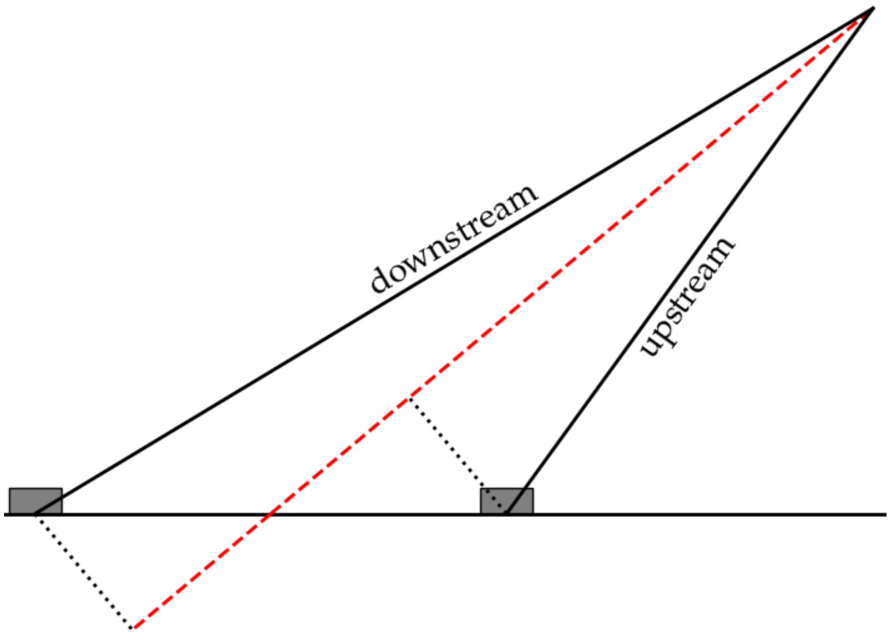
Pulse rates II

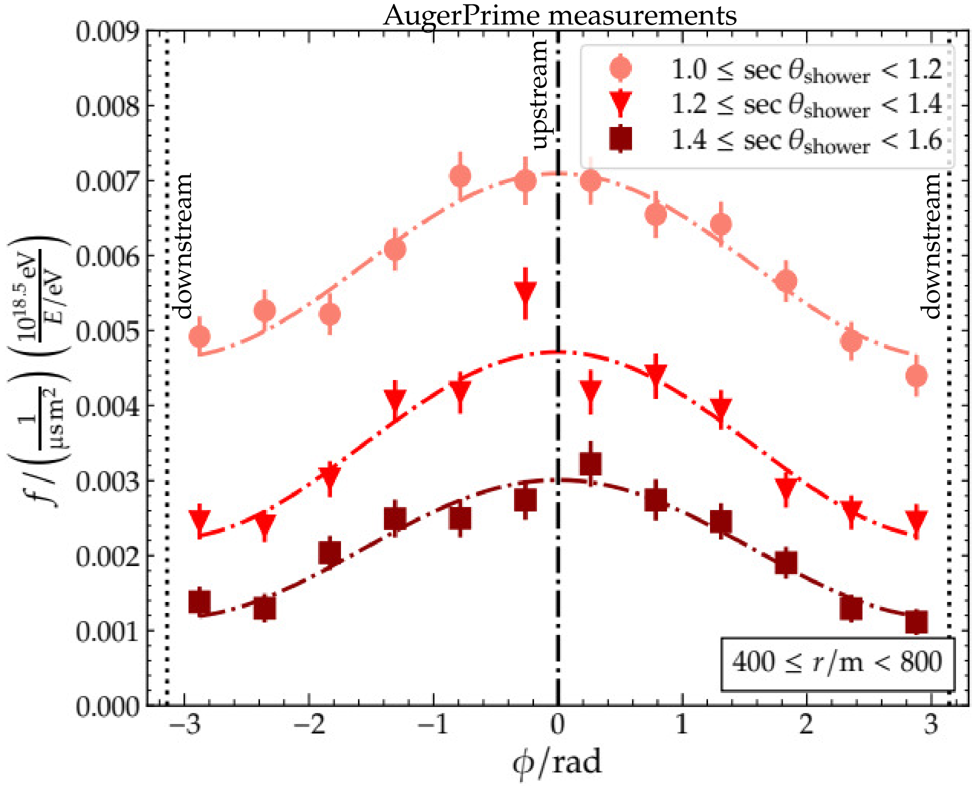
- **Normalization** of pulse rate to
    - detector size
    - observable time window
    - shower energy
- Near **linear scaling** with energy
- Increasing number of neutrons with energy & **reduced attenuation** lead to almost linear energy scaling @ 850 g/cm²

arXiv:2406.11702



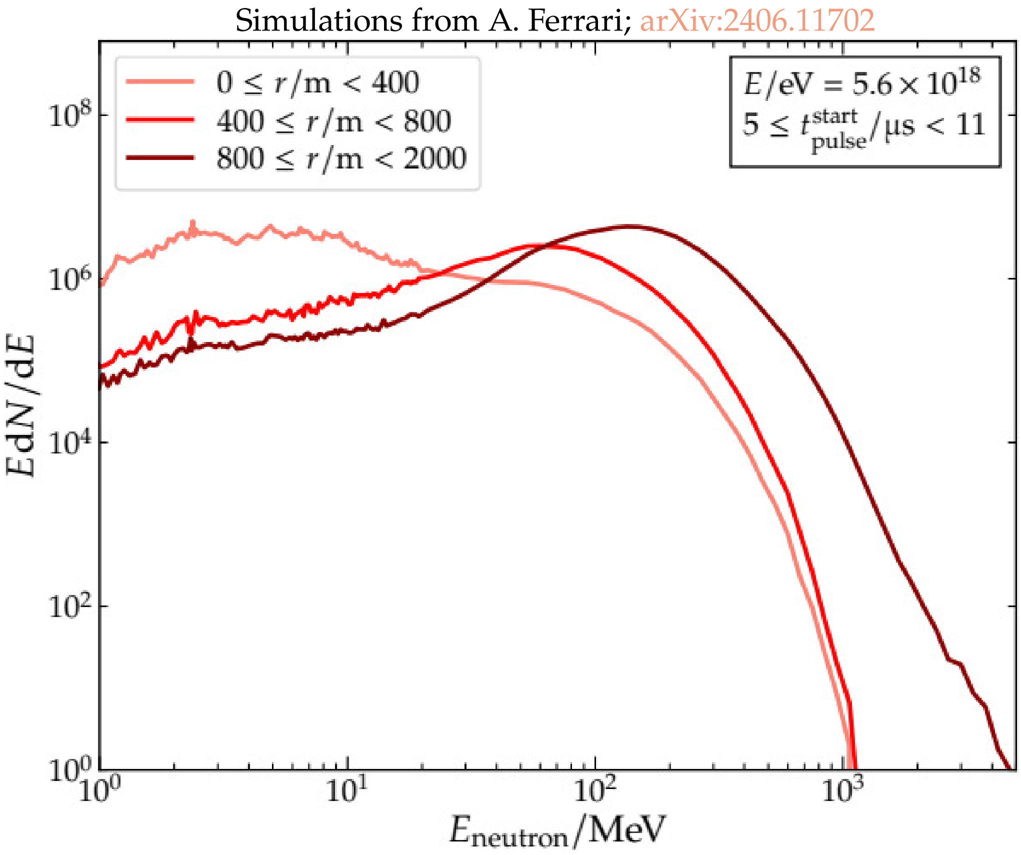
Azimuthal distribution

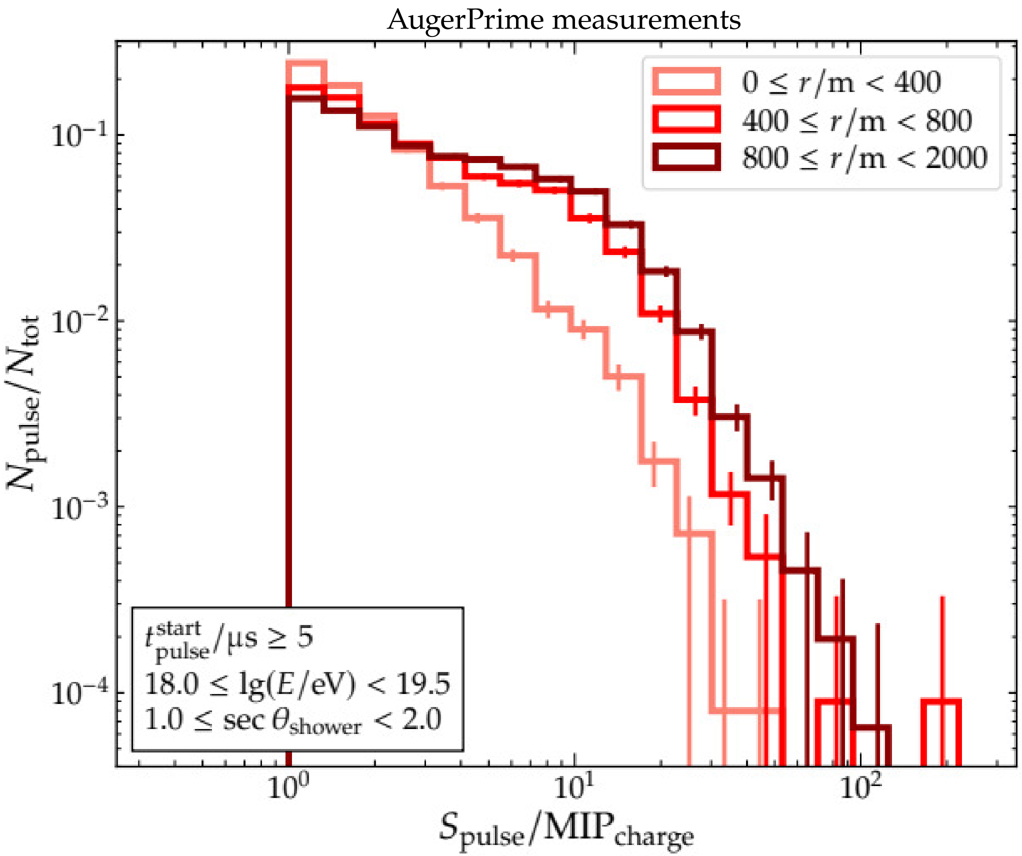




- **Azimuthal asymmetry** expected, depending on shower zenith angle and distance to shower axis
- Relative amplitude of the asymmetry **larger for more inclined showers**

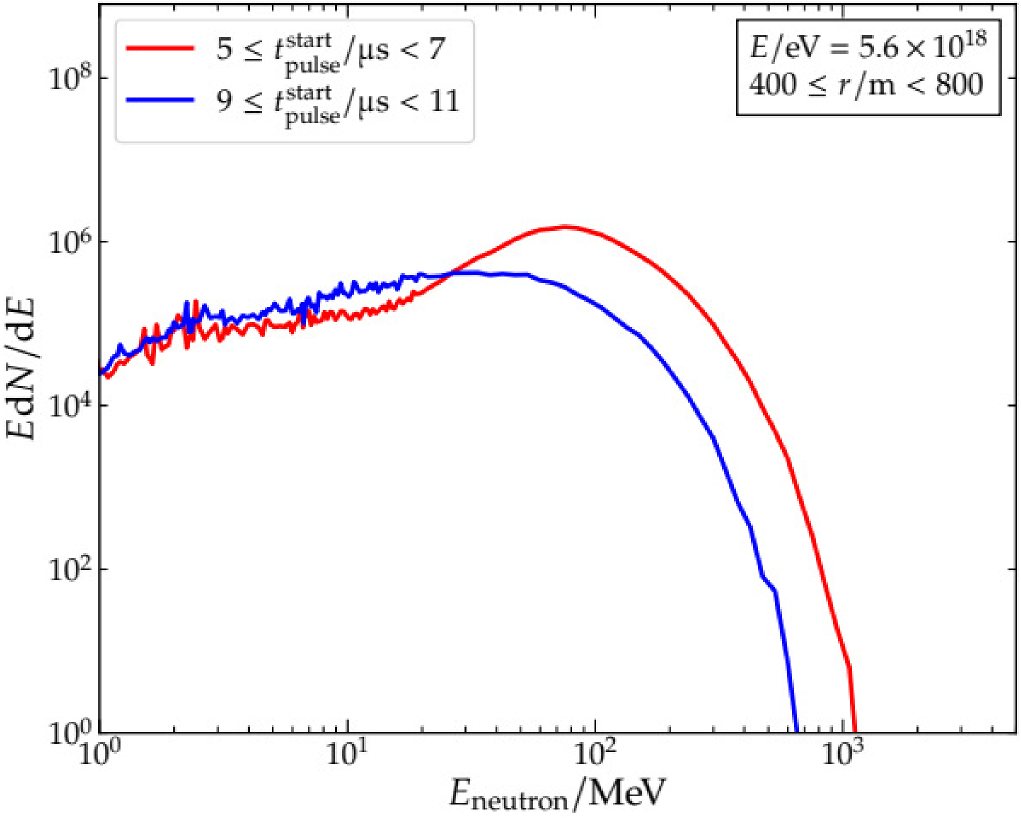
Pulse spectrum I



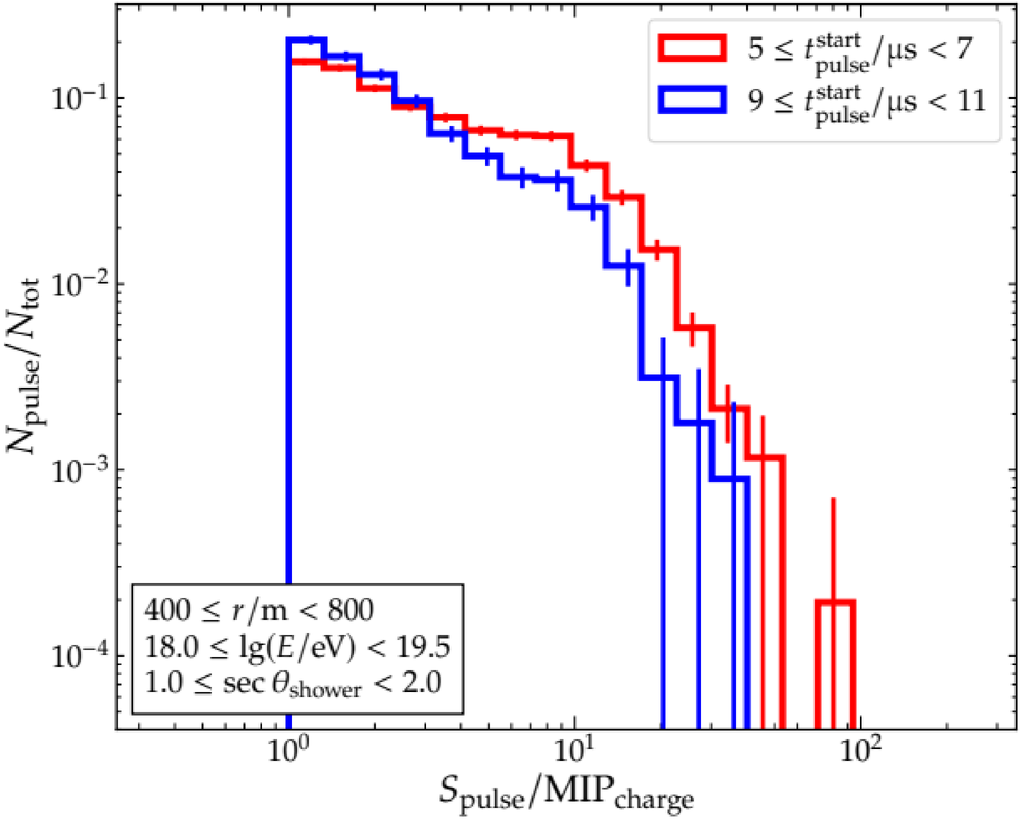


Pulse spectrum II

Simulations from A. Ferrari; arXiv:2406.11702

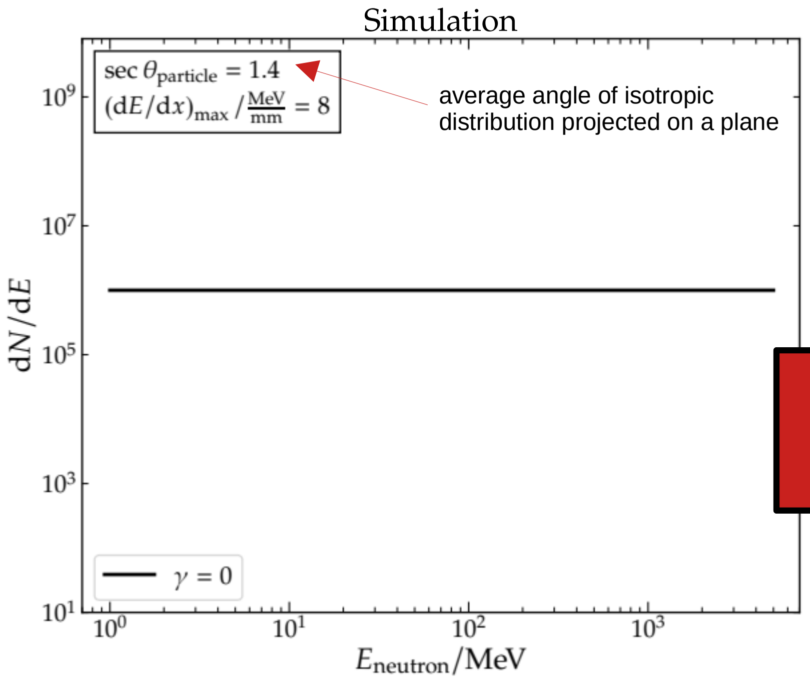


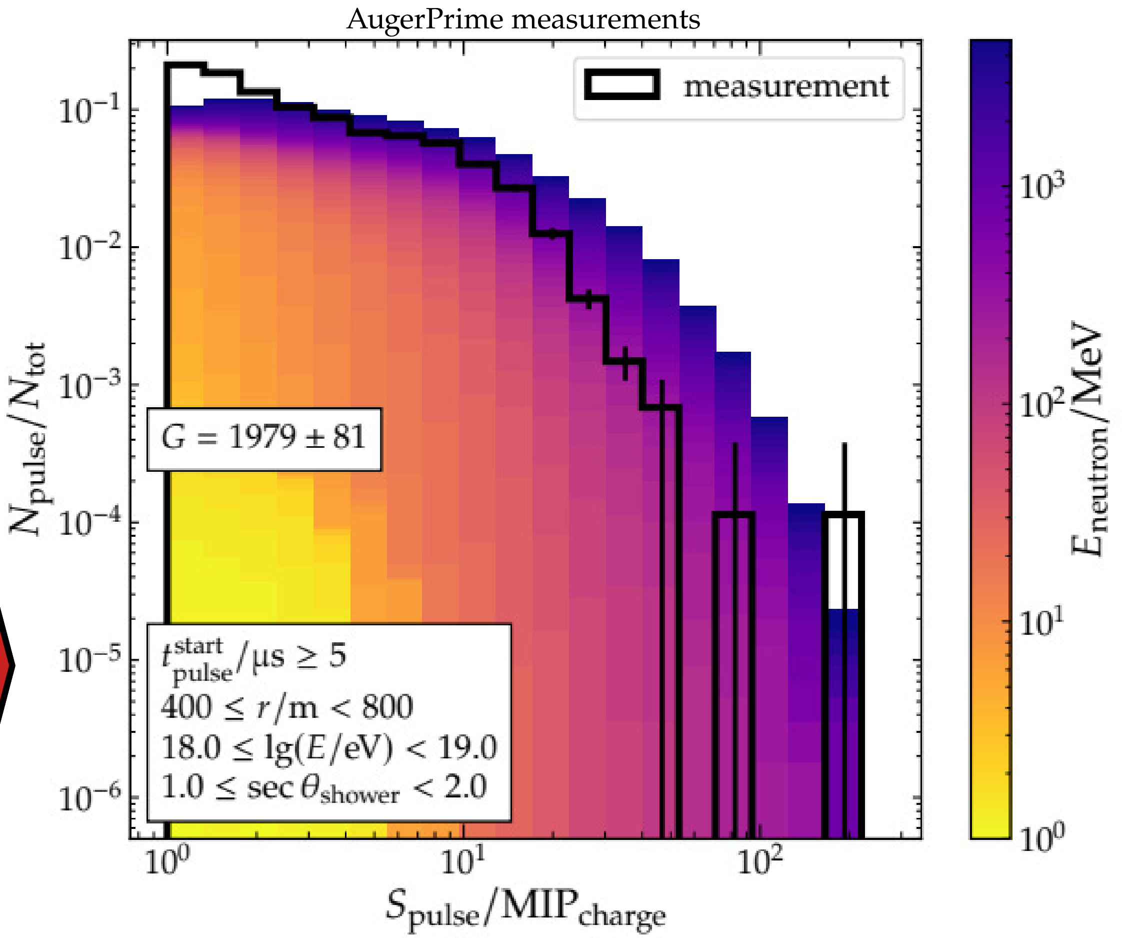
AugerPrime measurements



Forward-folding neutron energy spectrum

- Use several **input spectra** (Power law, Broken Power Law, etc.)
- $G = 2\,\Sigma\, y_i - n_i + n_i \ln(n_i\,/\,y_i)$ **(*G*-Test)**





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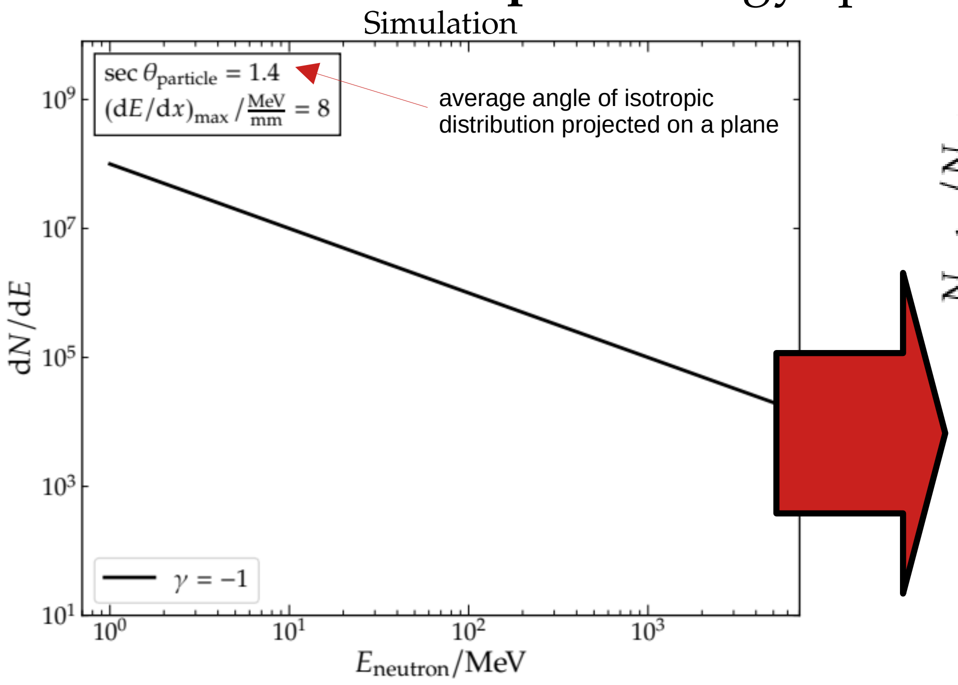
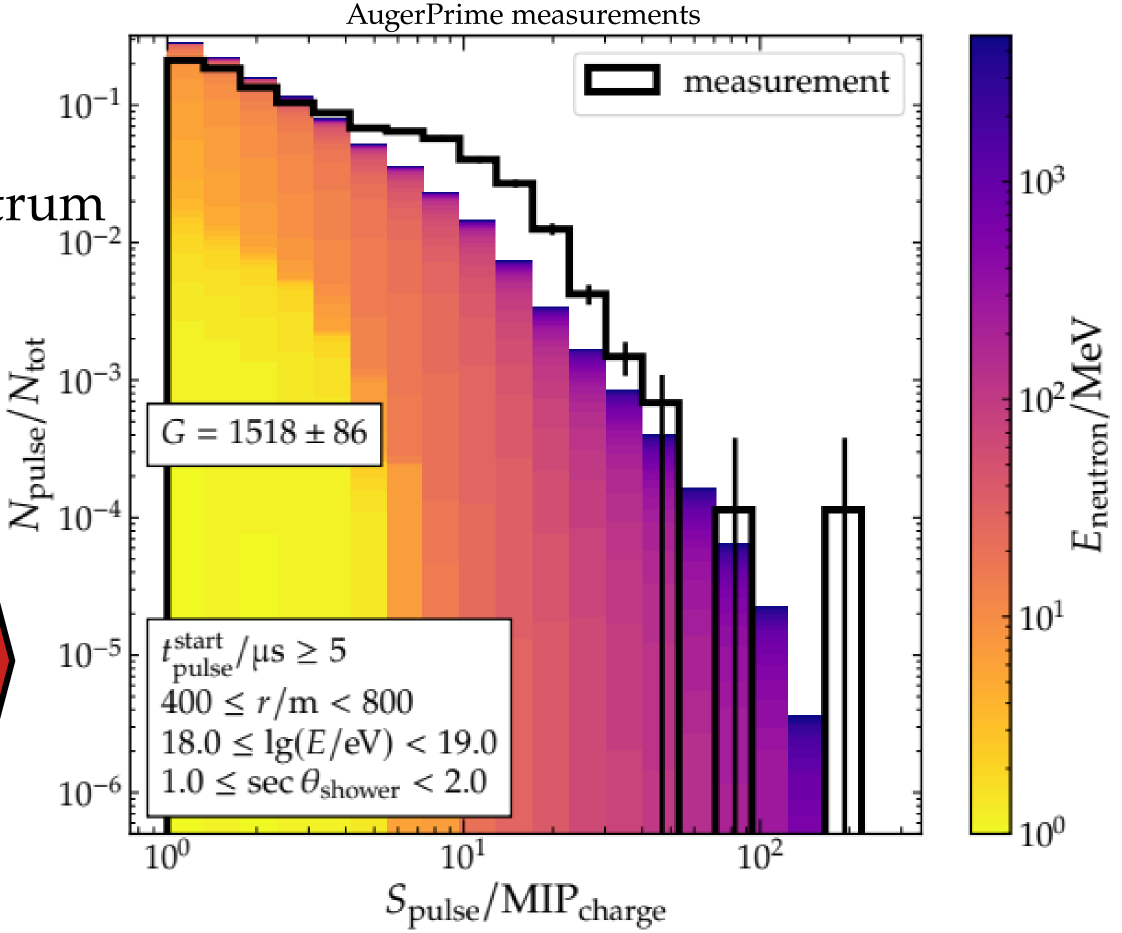
- $G = 2\,\Sigma\, y_i - n_i + n_i \ln(n_i / y_i)$ **(*G*-Test)**
- Sensitive on the **shape** of energy spectrum





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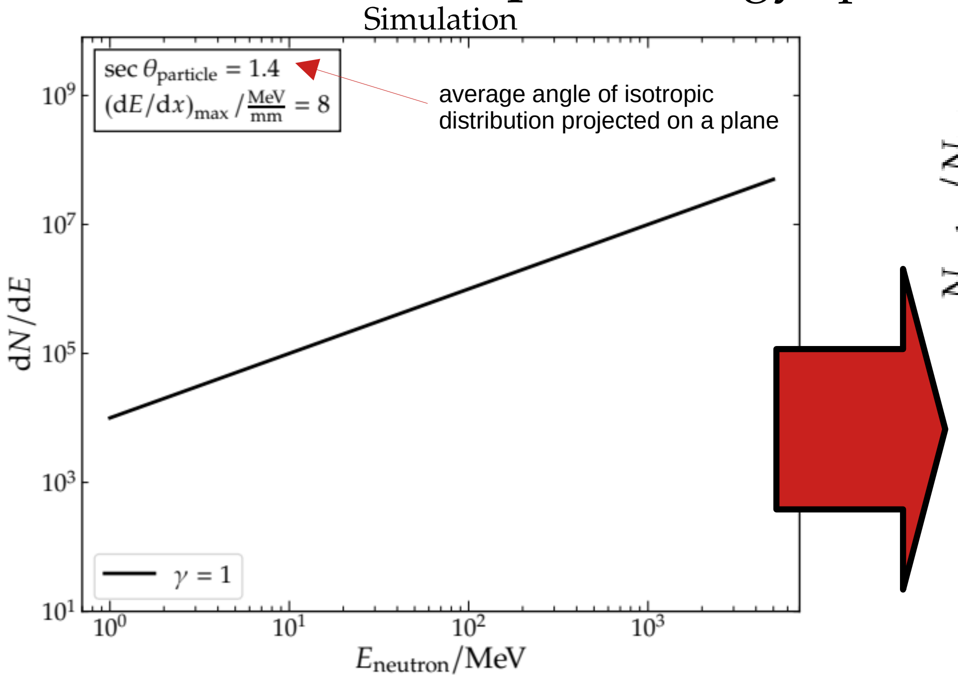

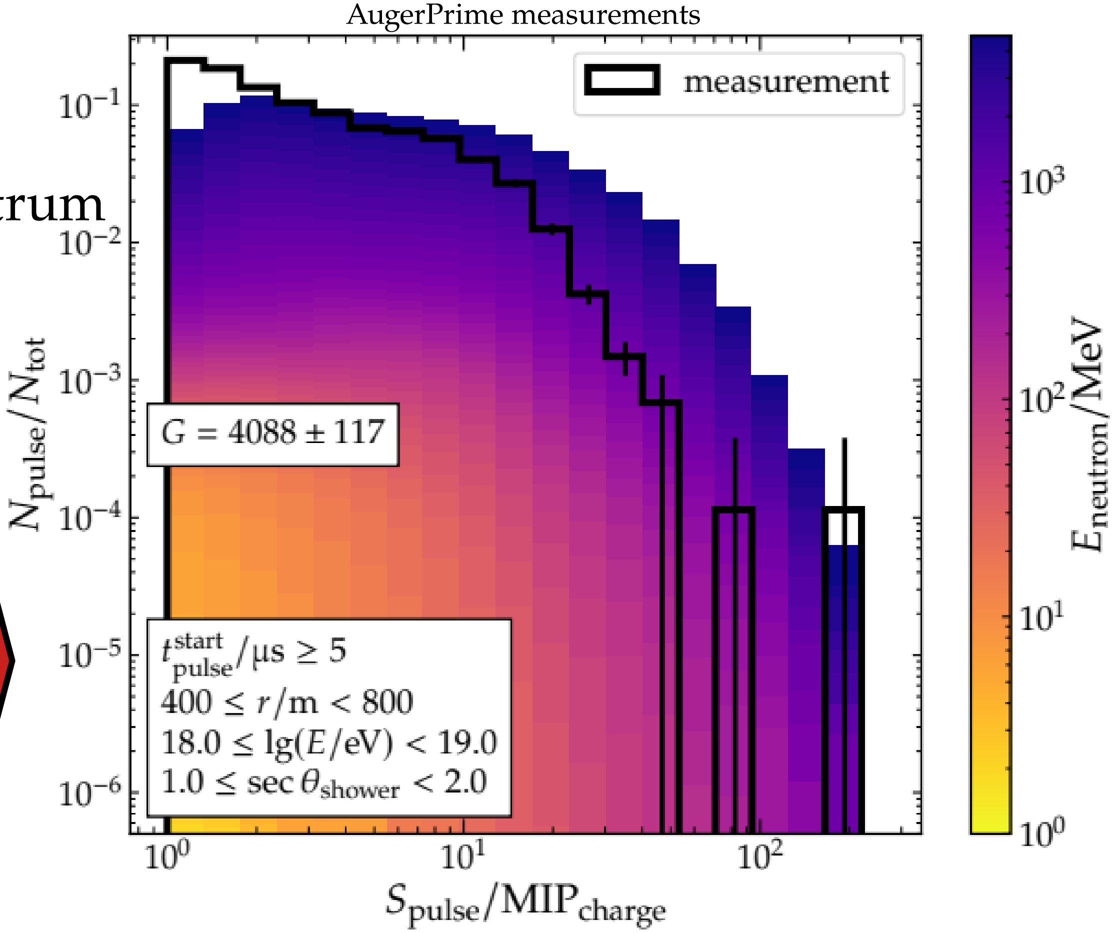

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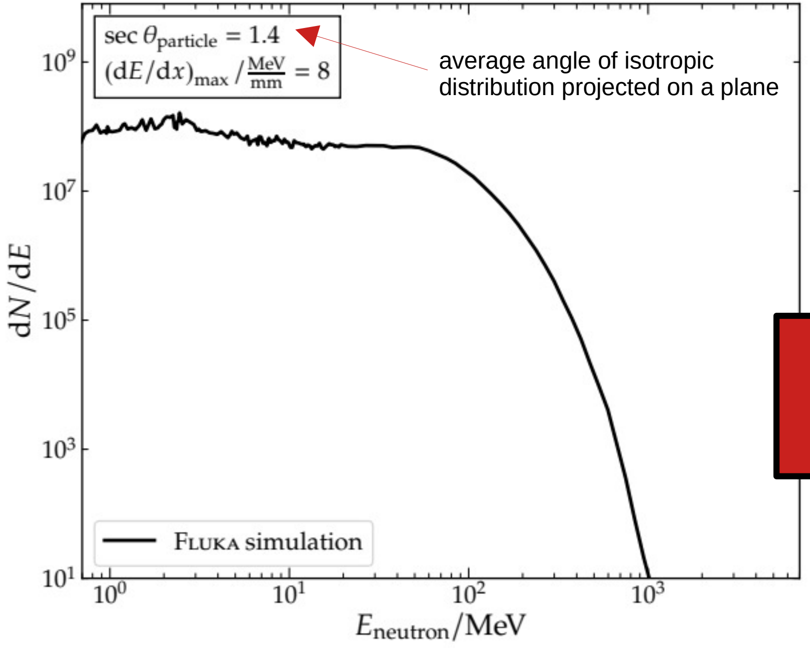
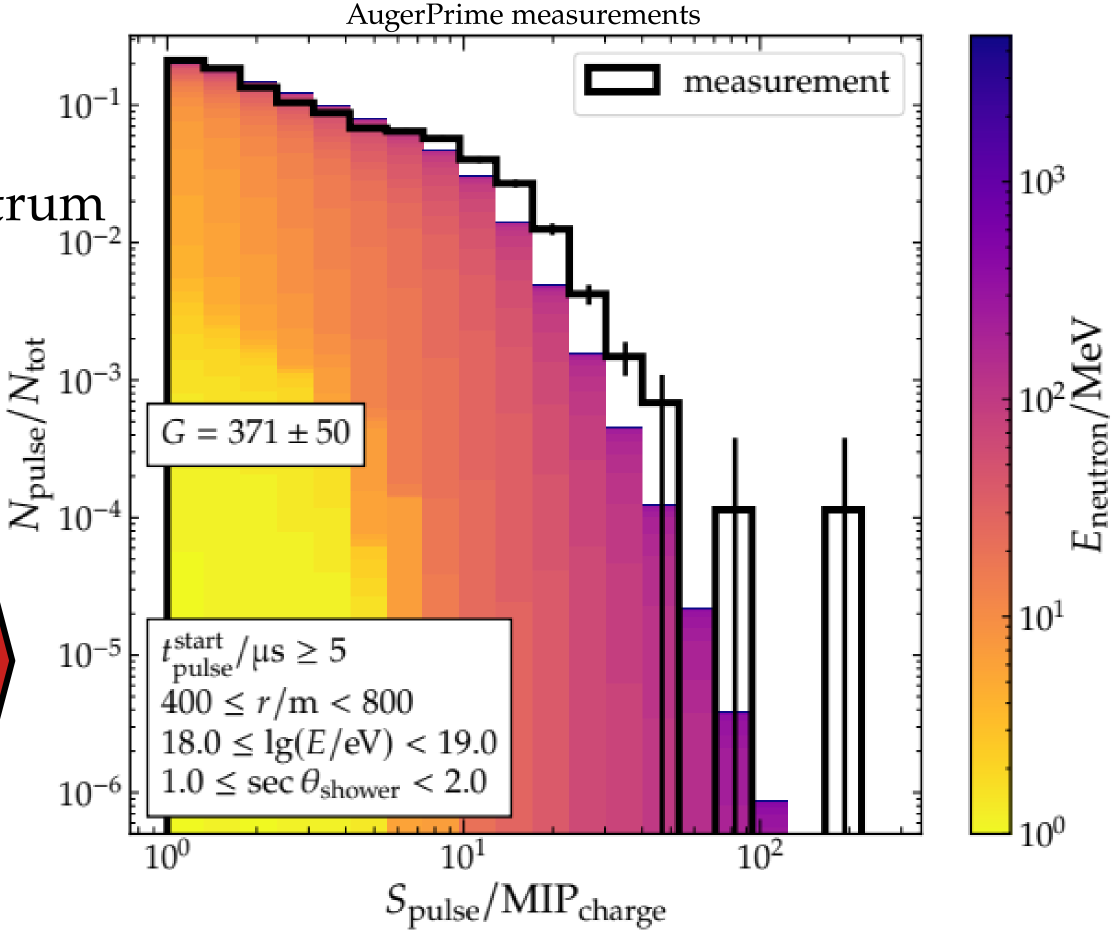
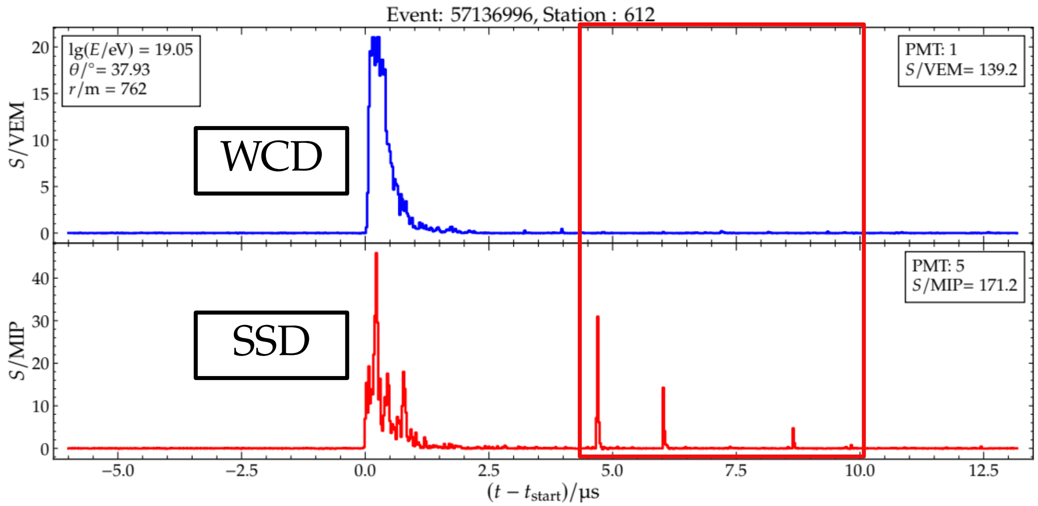
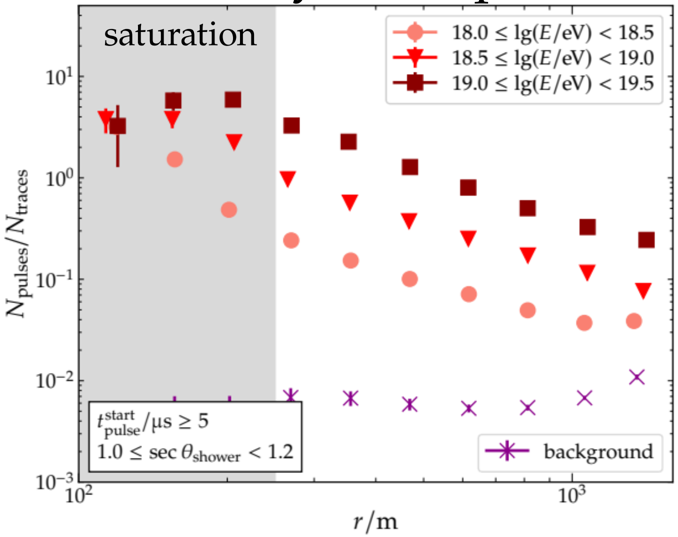


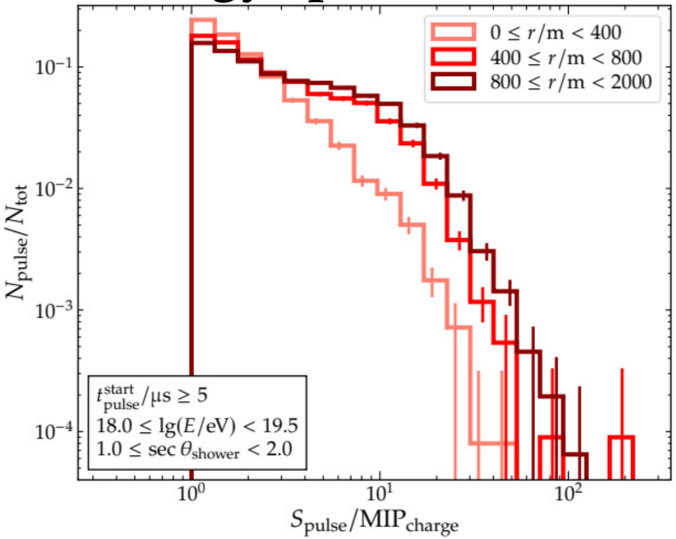


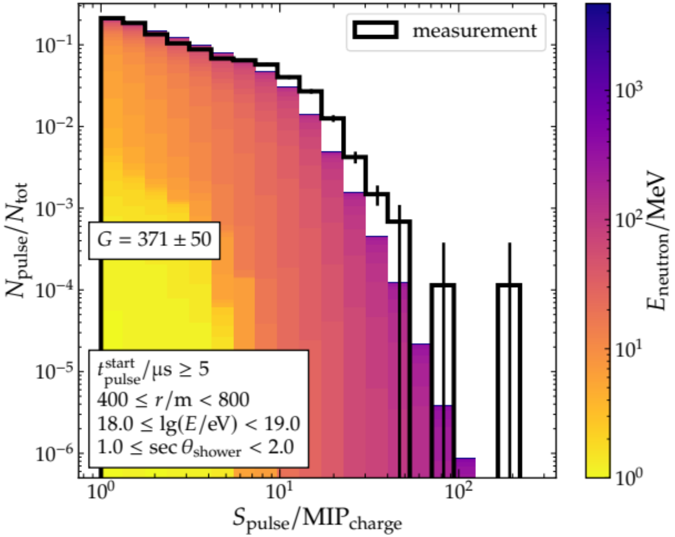
Summary

- **Measurement** of subluminal pulses with the SSDs of AugerPrime
- Observed pulse rate **exceeding** expectations from background
- Pulse spectrum **hardening** with distance
- Sensitivity to shape of **neutron energy spectrum**

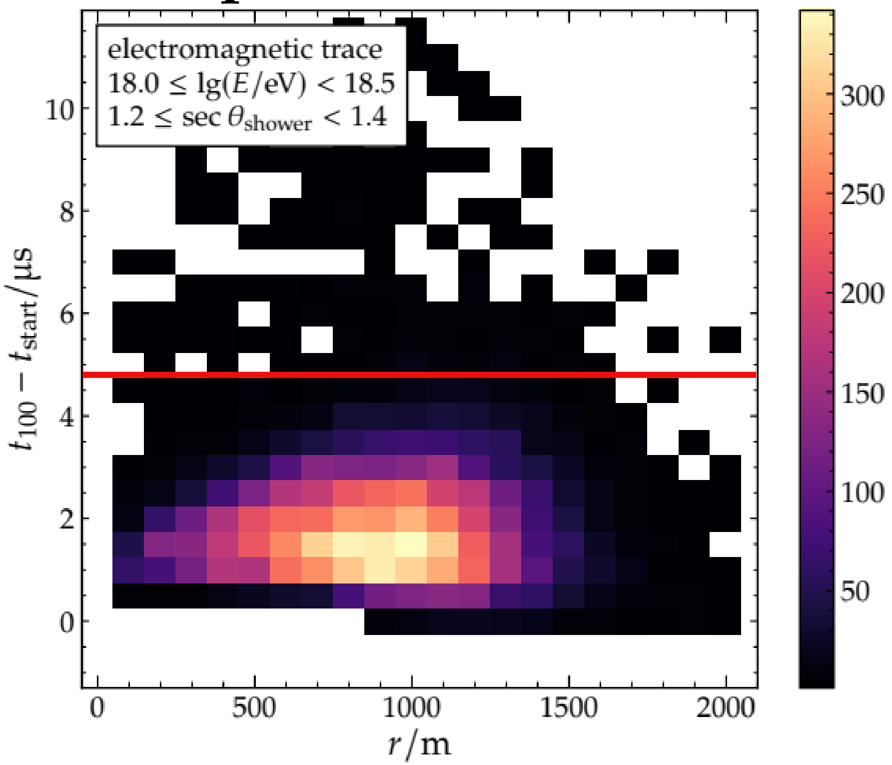


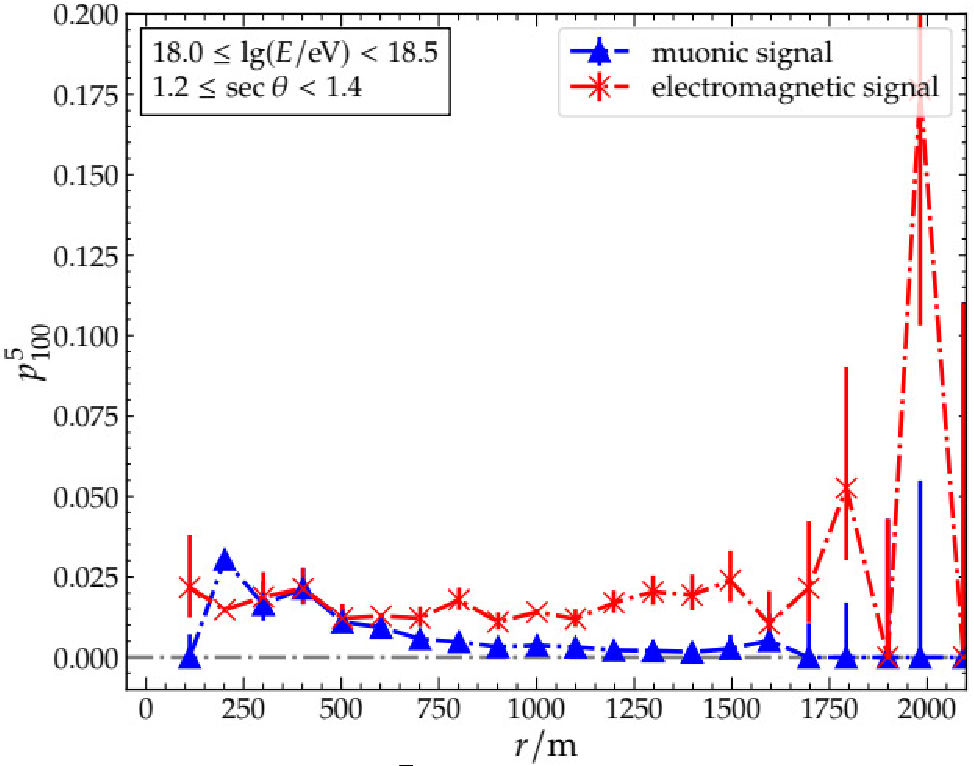






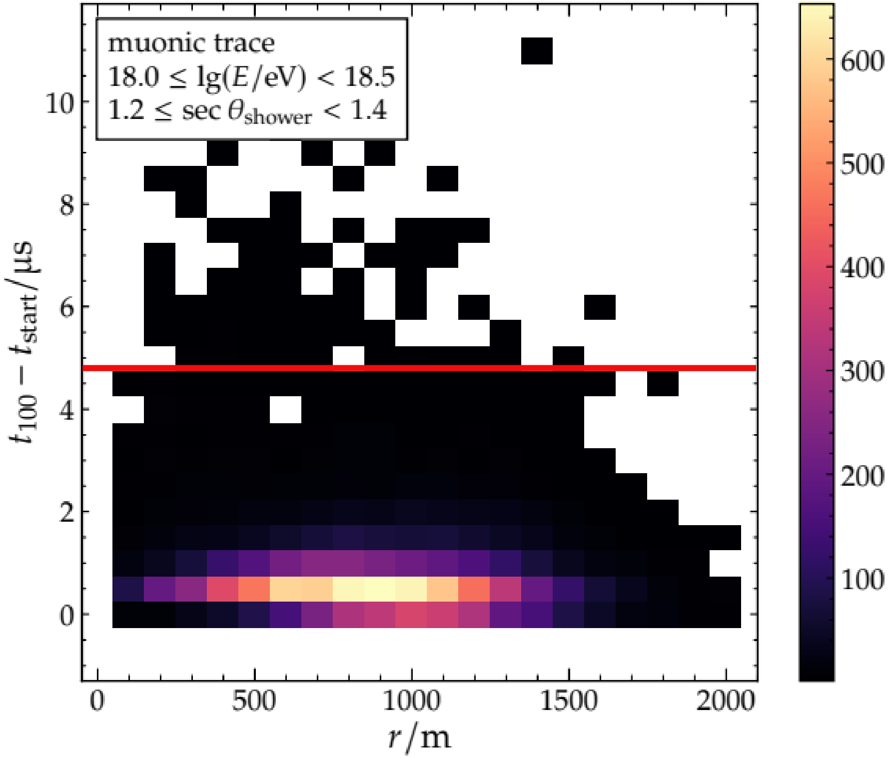
Backup: Time threshold

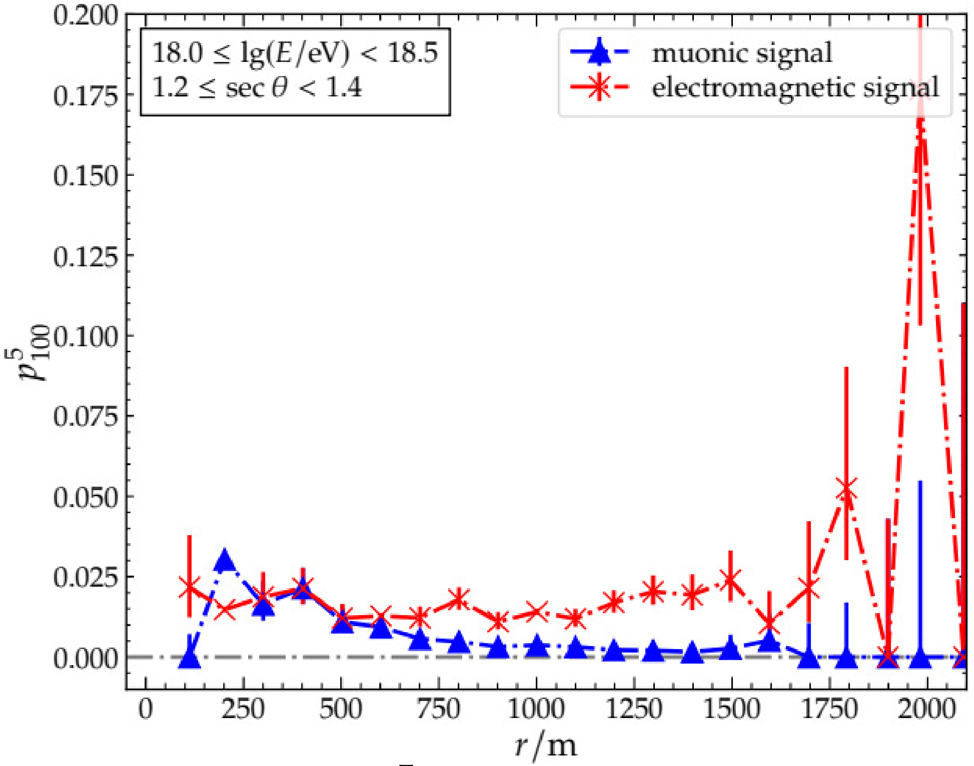




- Time t_{100} when 100% of the signal in a trace is reached in **simulations**
- EM / MU signal of **most showers** contained within 4 – 5 µs
- Probability p_{100}^{5} of how often t_{100} is **larger than 5 µs**
- **Background contribution** which is dependent on E, θ, r, etc.

Backup: Time threshold





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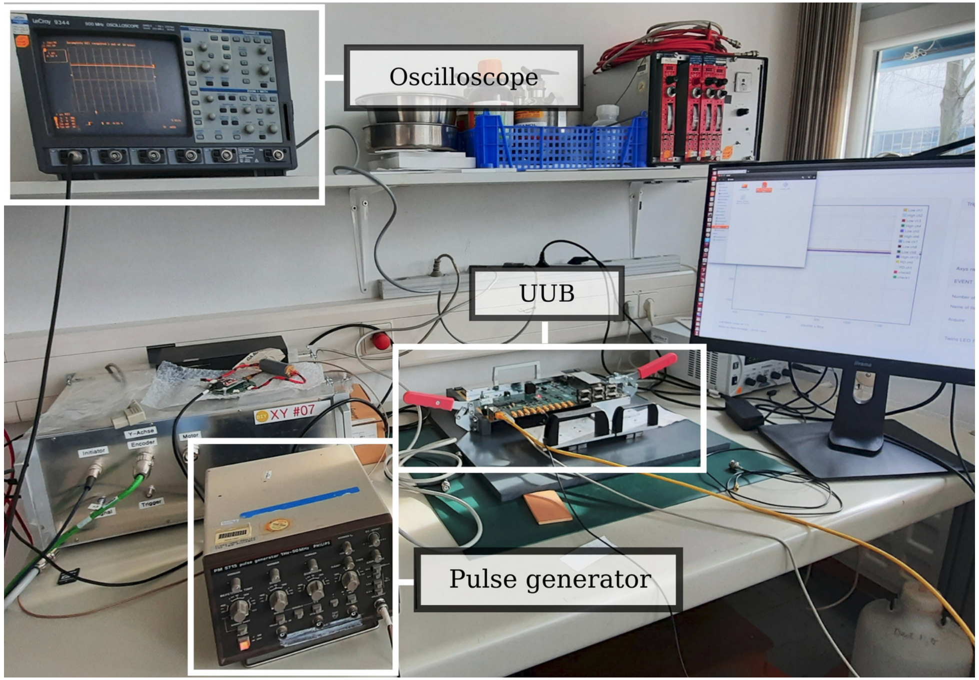
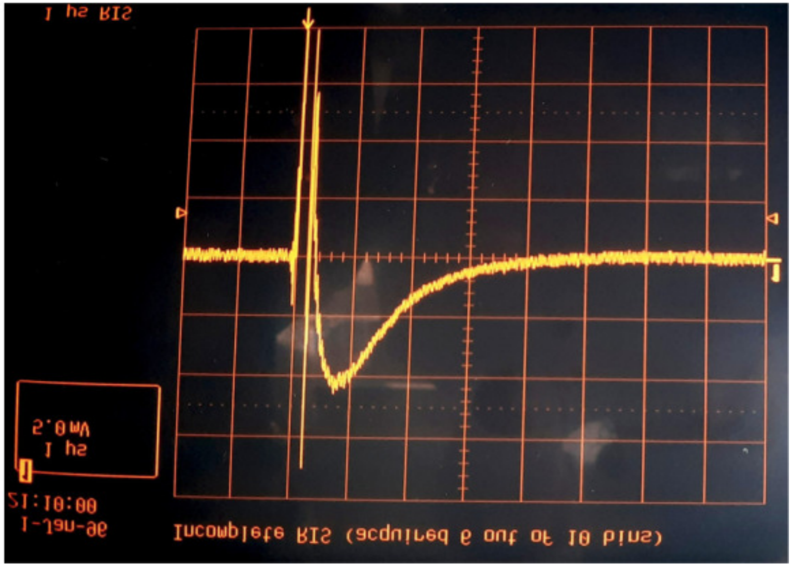
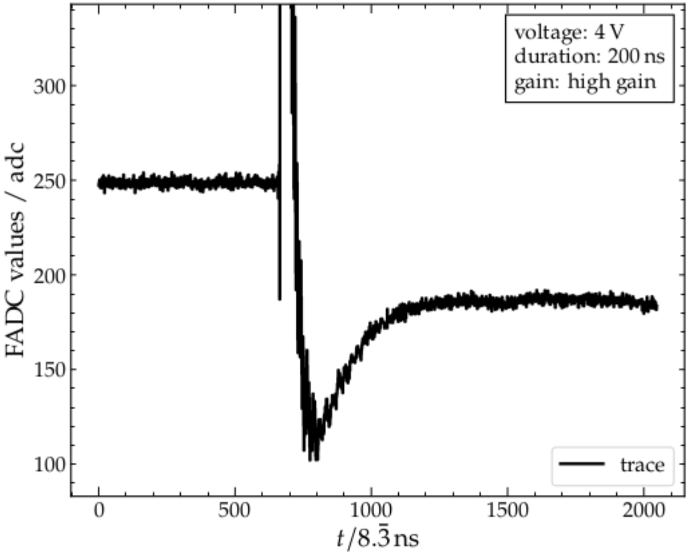
Backup: Electronics Board

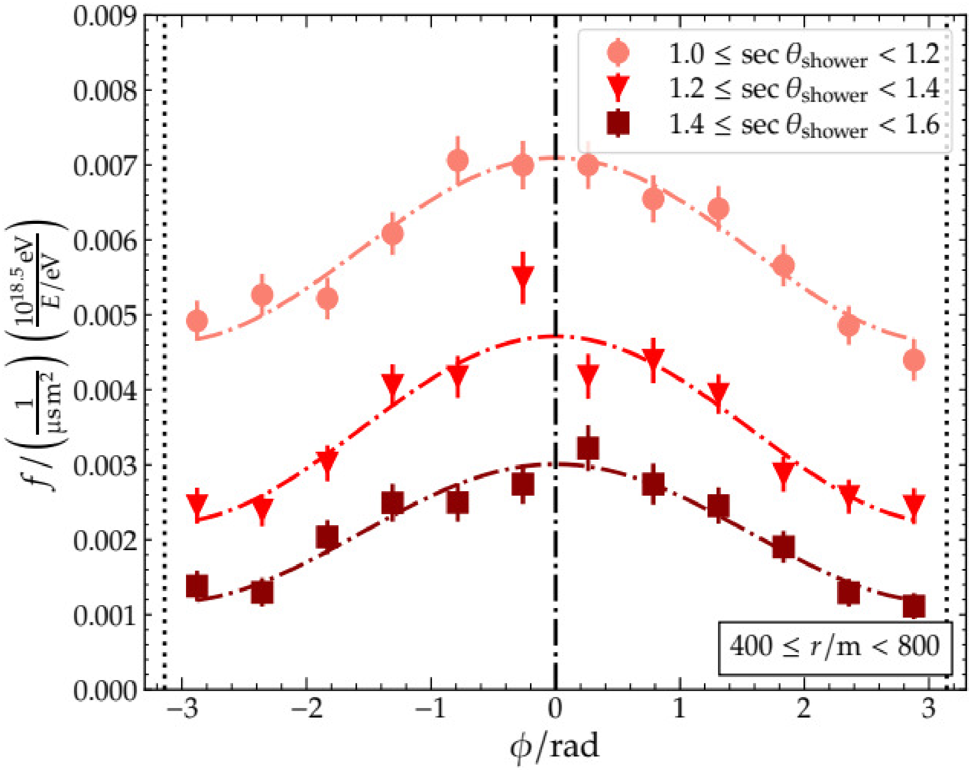


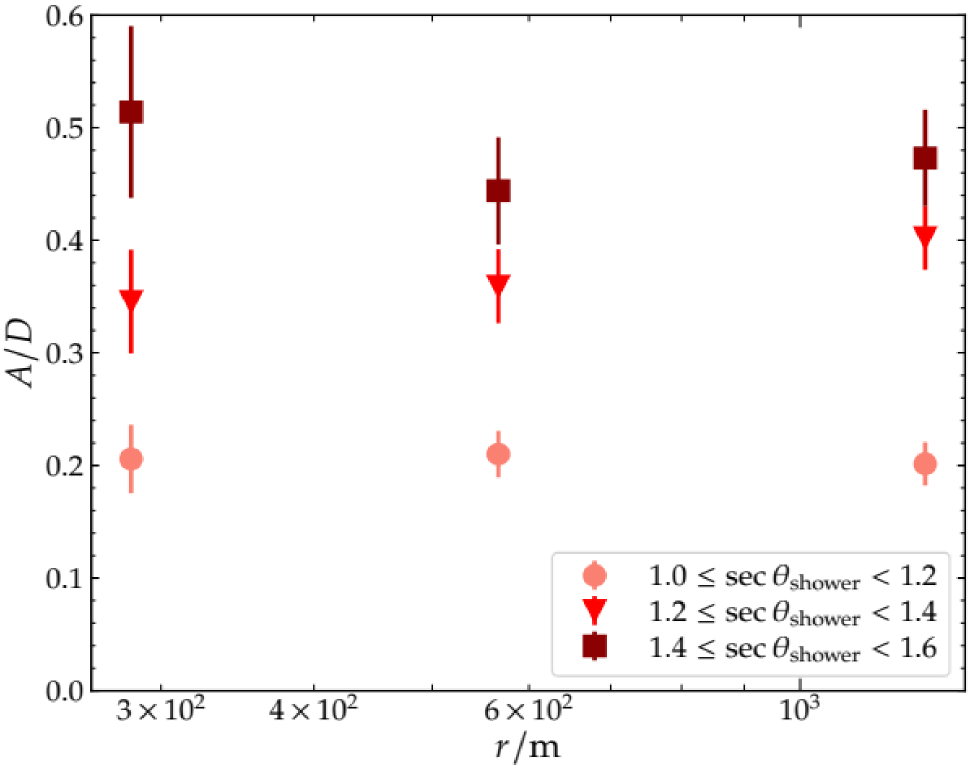




- Undershoot from board visible, however no peak / pulse structures present
- SPE around 0.05 $\mathrm{MIP}_{\mathrm{charge}}$

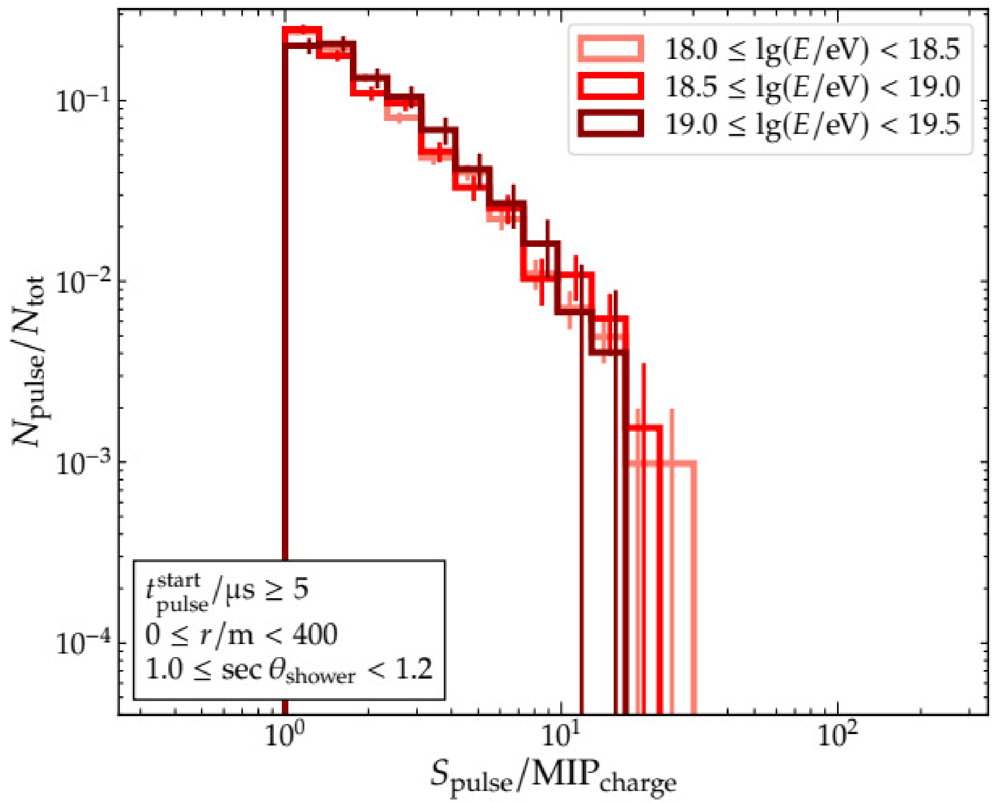
Backup: Azimuthal distribution

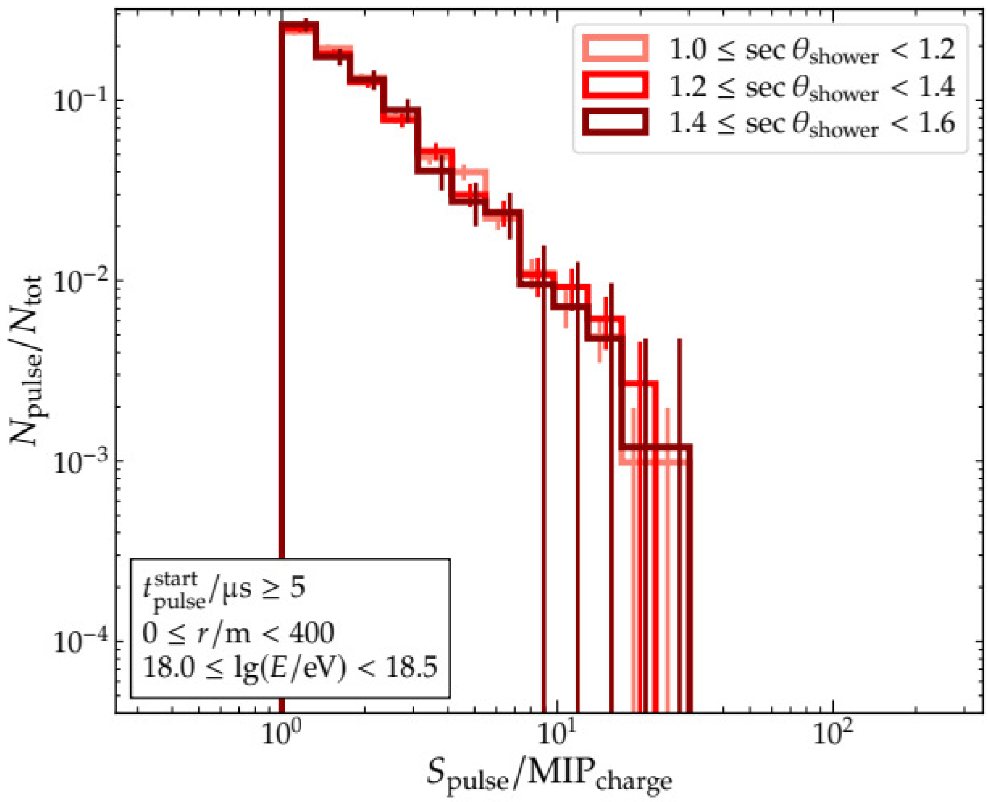




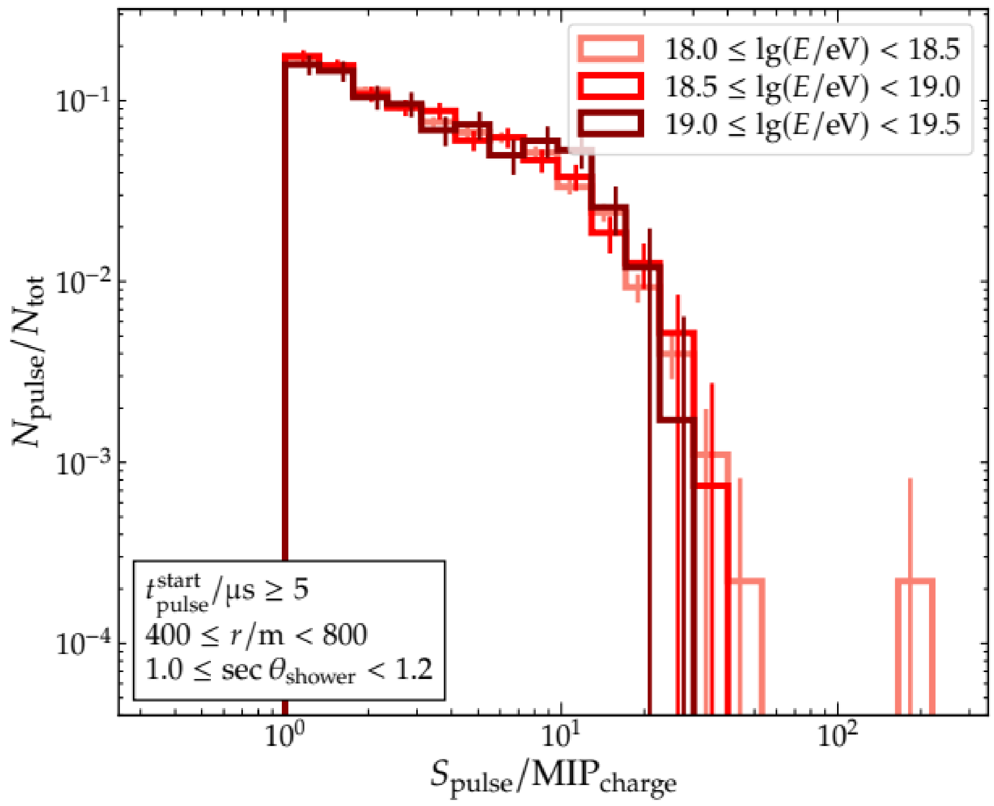
- $f(\Phi) = D + A \cos \Phi$
- Increase of relative amplitude (A/D) with zenith angle as expected

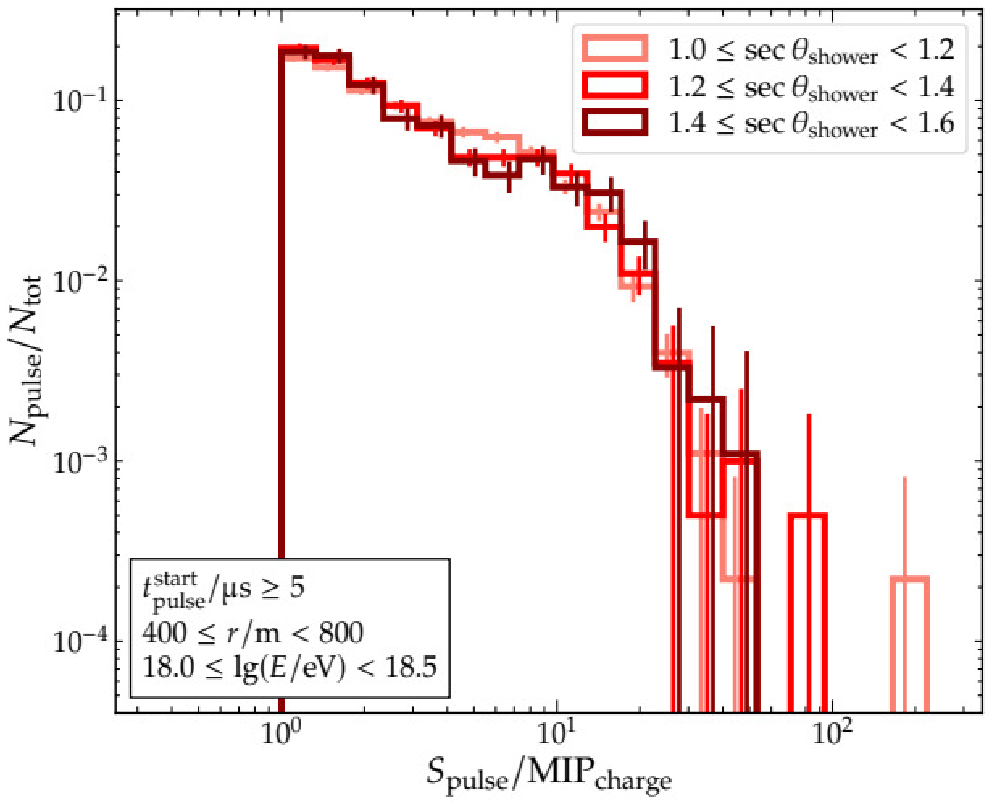
Backup: Pulse spectra I



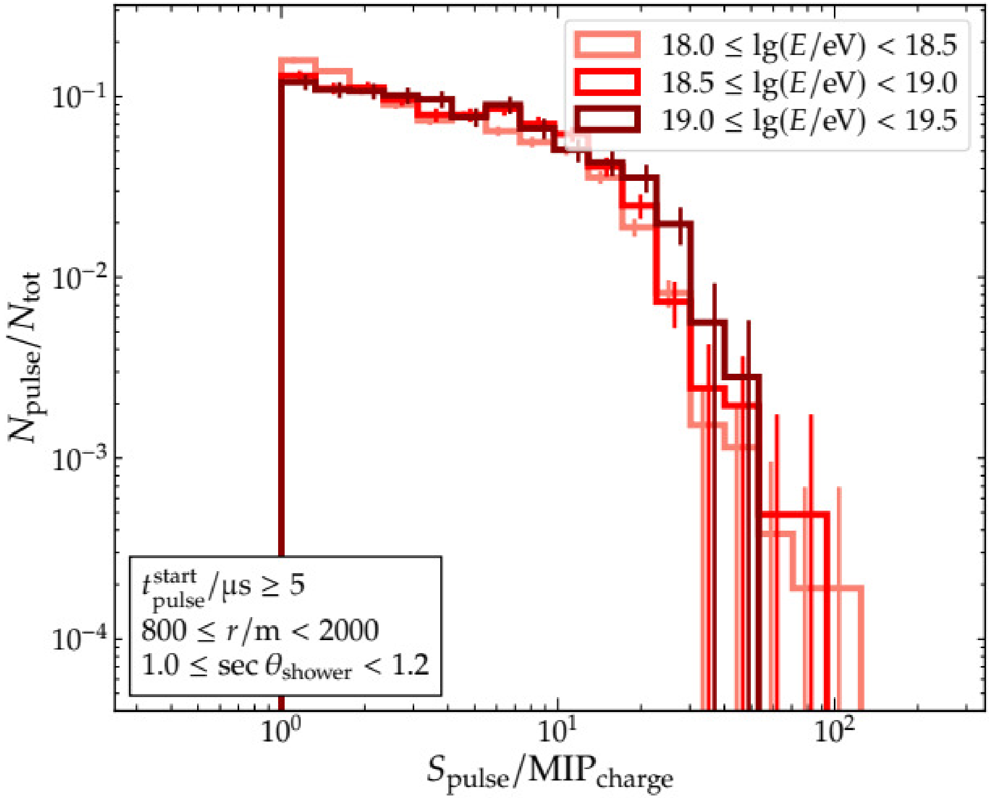


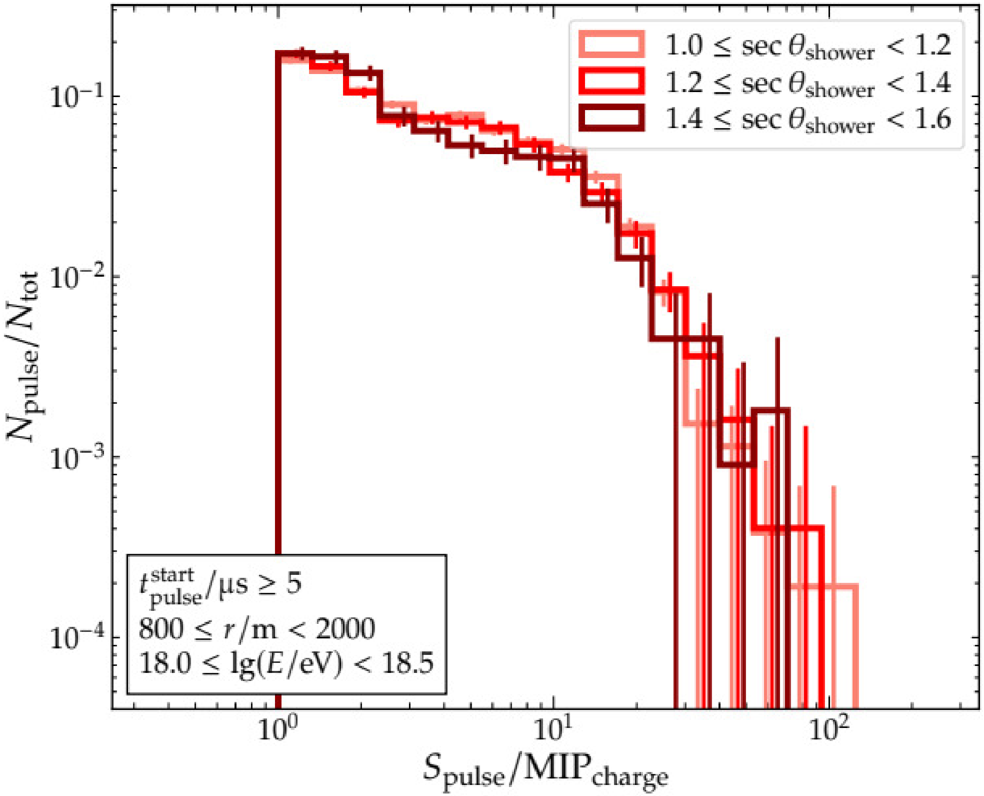
Backup: Pulse spectra II





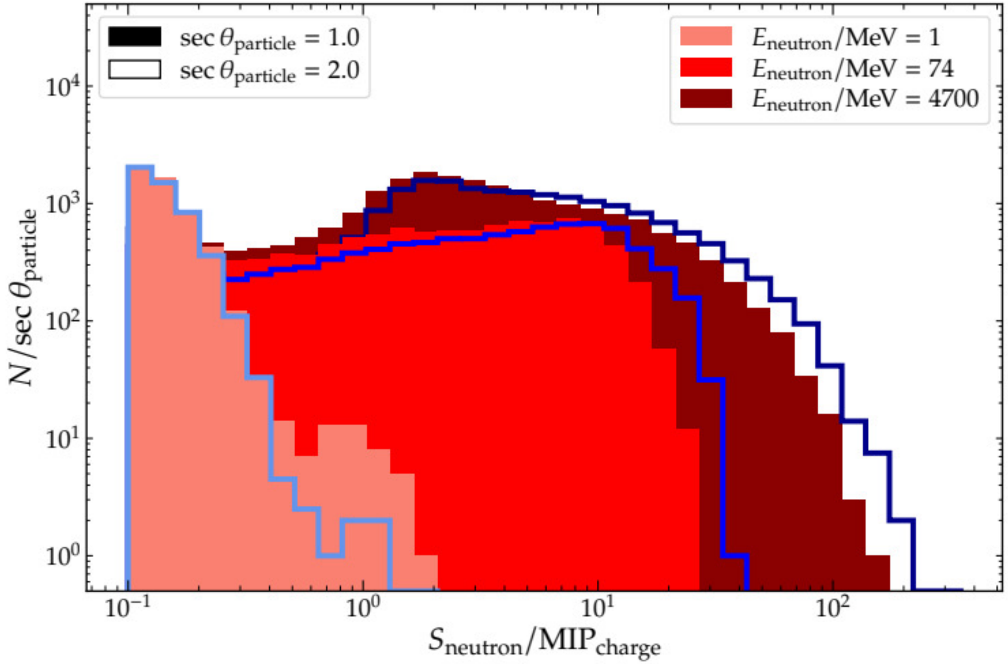
Backup: Pulse spectra III

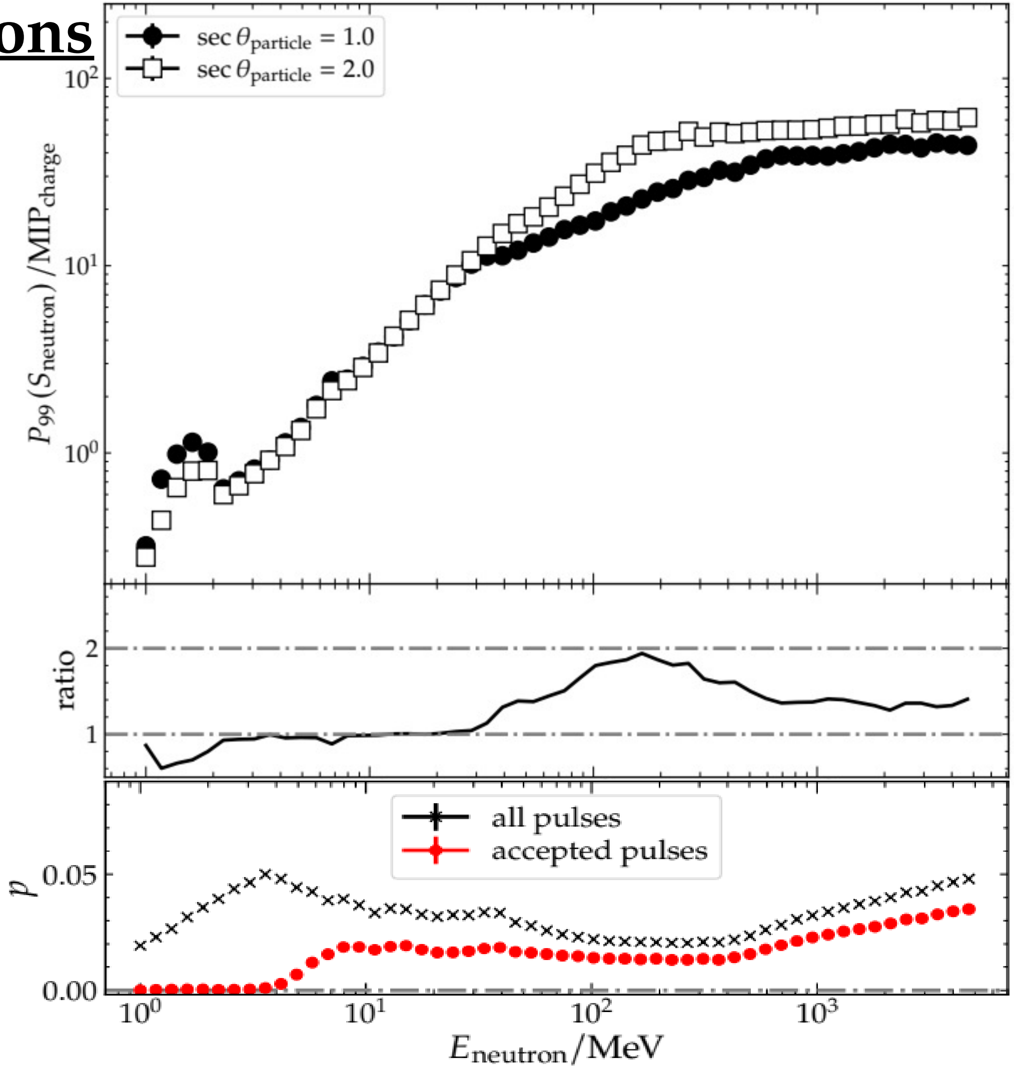




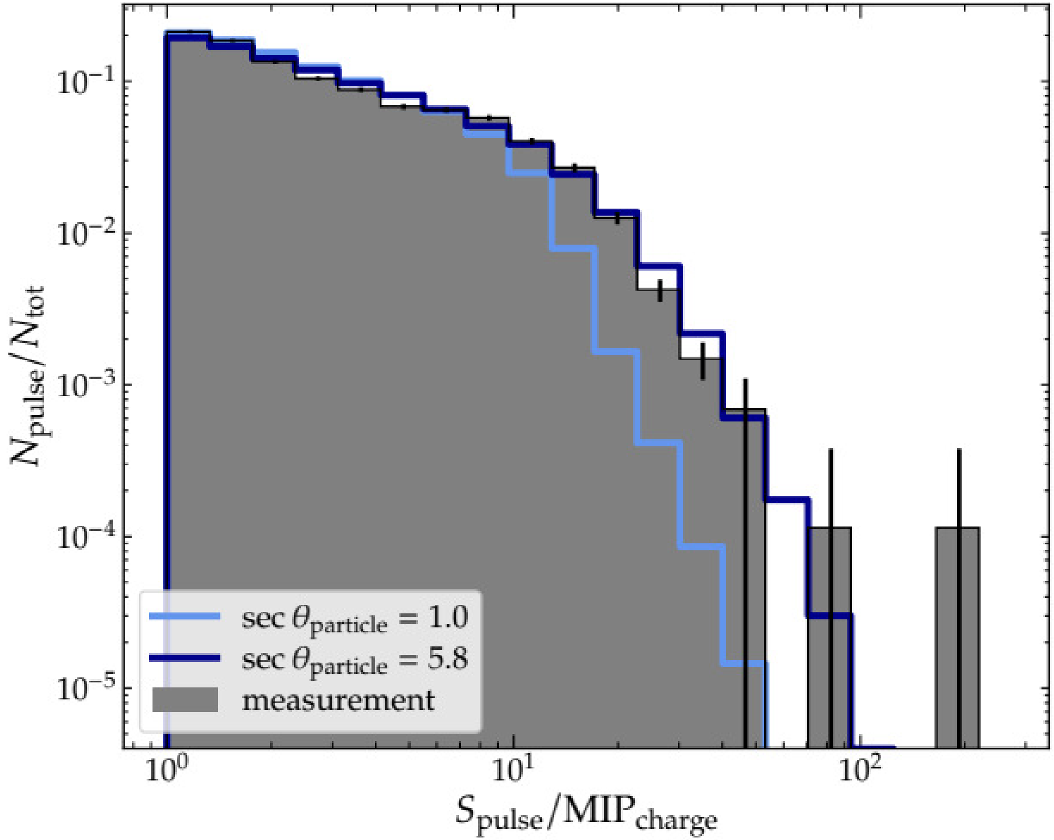
Backup: Detector-response simulations

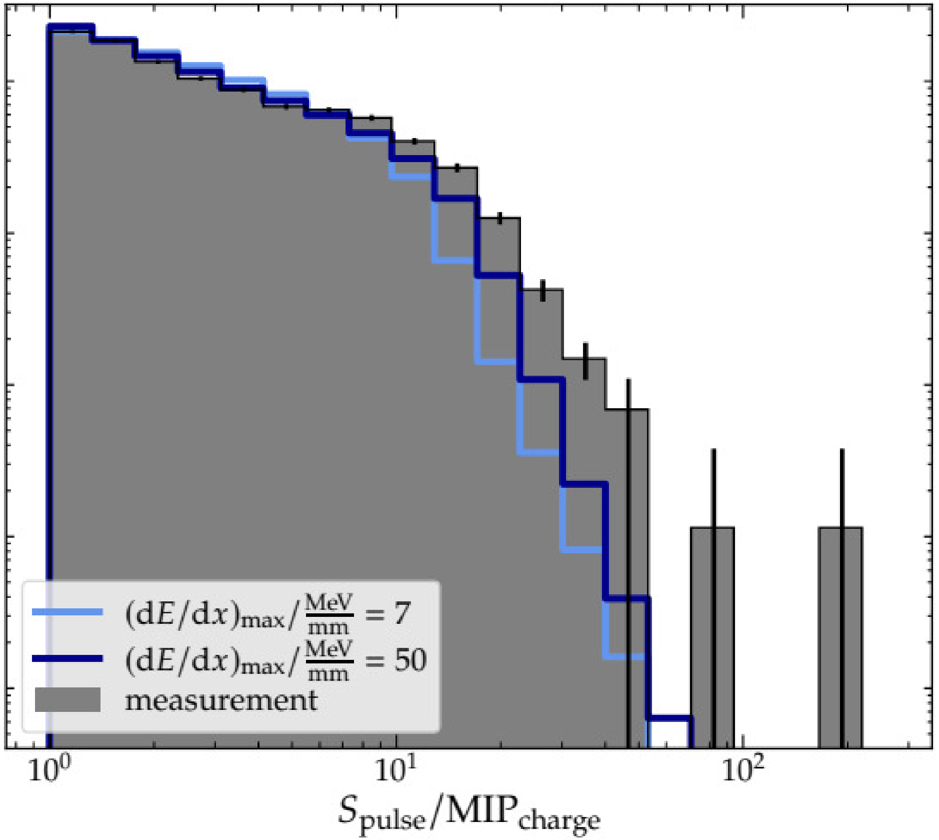
- Dedicated detector response **simulations**
- Neutrons pulses have **broad signal range**
- **Increased detection probability** at large E_{neutron} due to WCD back-scattering





Backup: Impact of angular distribution & quenching





- Strong dependence on zenith angle
- Minor dependence on quenching