Estimating the Depth of Shower Maximum using the Surface Detectors of the Pierre Auger Observatory

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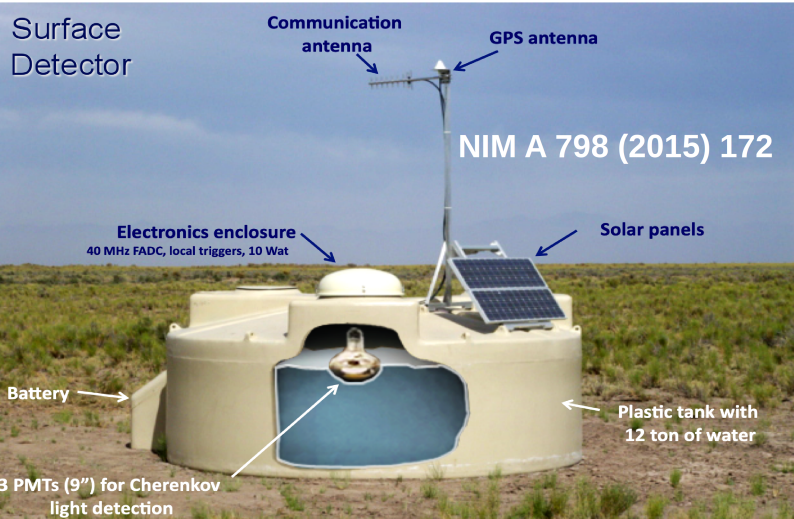**✳ Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina**

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Surface Detectors of Auger Observatory

Surface Detector — Communication antenna, GPS antenna, NIM A 798 (2015) 172, Electronics enclosure (40 MHz FADC, local triggers, 10 Wat), Solar panels, Battery, Plastic tank with 12 ton of water, 3 PMTs (9") for Cherenkov light detection

Data — **E= 17.3 EeV, θ= 32⁰**

633m

1680m
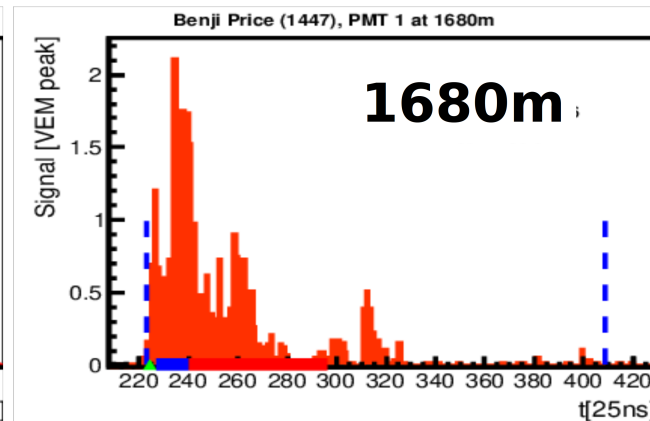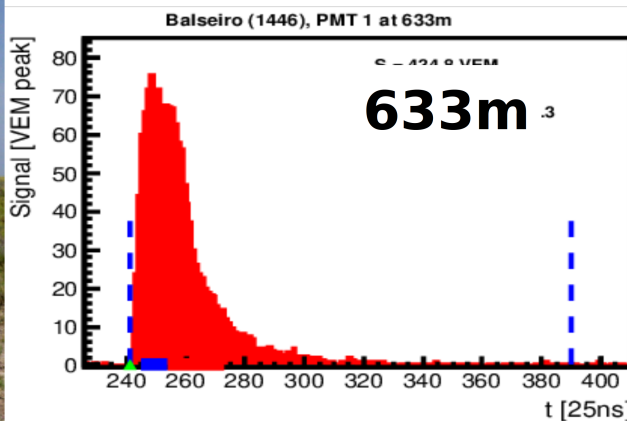
Simulations — **E= 19.4 EeV, θ= 43⁰**

984m

2412m

Water-Cherenkov arrays
- 1500 m spacing; 1600 detectors; (3000 km²)
- 750 m spacing; 60 detectors; (23.5 km²)

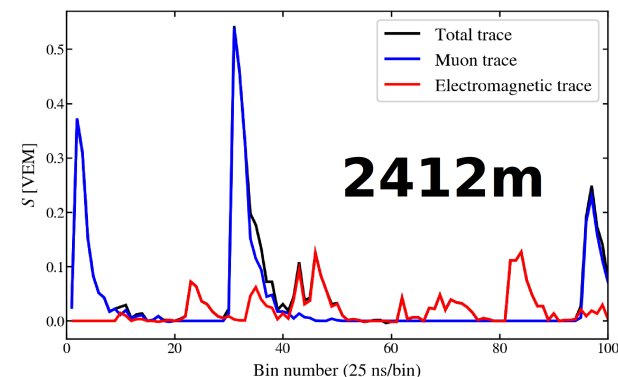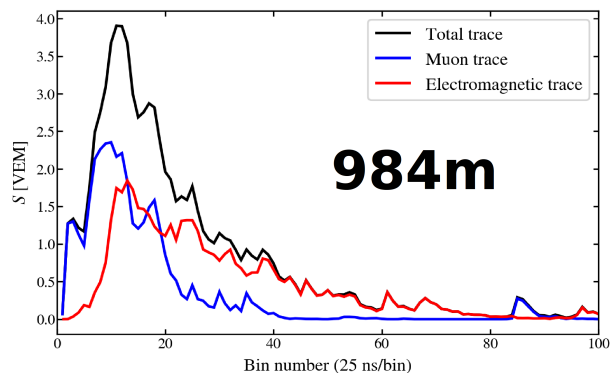**Record a mix of electromagnetic and muonic signals with the muonic signals dominant at large distances**

The Δ-method in a nutshell

- **Measure risetime ($t_{1/2}$) for every water-Cherenkov detector**

- **"Benchmark": Describe risetimes as a function of distance for a narrow energy range**

  - **1500 m array: $19.1 \leq \log_{10}(E/eV) \leq 19.2$**

  - **750 m array: $17.7 \leq \log_{10}(E/eV) \leq 17.8$**

- **Characterize every shower by <u>a single parameter</u>: Δ_s**

- **Golden-hybrid events (<u>data-driven analysis</u>): $X_{max}(FD) = f(\Delta_s)$**

- **Estimate $X_{max}(SD)$**

Risetime definition

50%

10%

$\delta_i = t_{1/2} - t_{1/2}^{bench}$

σ_i

δ_i

Benchmark

Detector Level

$$\Delta_i = \frac{t_{1/2} - t_{1/2}^{bench}}{\sigma_{1/2}}$$

Event Level

$$\Delta_s = \frac{1}{N} \sum \frac{t_{1/2} - t_{1/2}^{bench}}{\sigma_{1/2}}$$
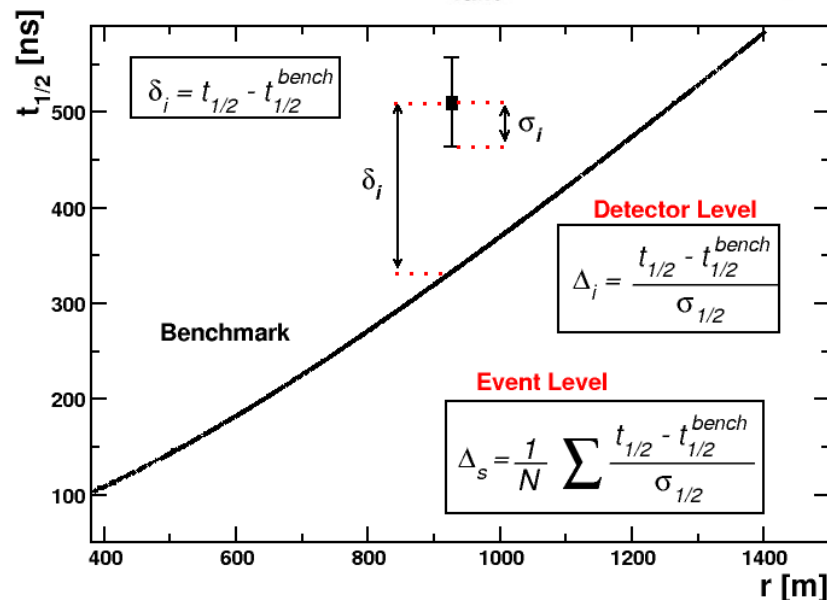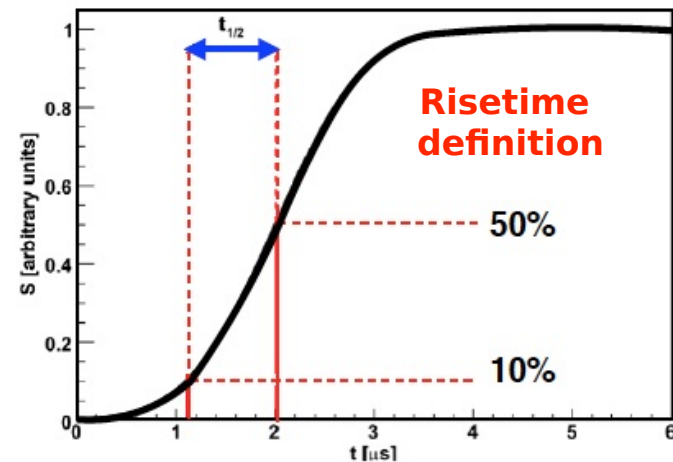
Updated analysis

	Published analysis (Phys.Rev. D96 (2017) no.12, 122003)	New analysis
Data taking period	**January, 1 2004** **Dec, 31 2014**	**January, 1 2004** **August, 31 2018**
Energy range	**0.3-100 EeV**	**3-100 EeV**
Zenith angle range	**< 45 degrees**	**< 60 degrees**
Total number of events (1500m array)	**58,583**	**125,005** **(factor 2.1 bigger)**
Events with E>20 EeV	**1,586**	**3,372** **(factor 2.1 bigger)**
Events with E>70 EeV	**49**	**106** **(factor 2.1 bigger)**

4

Benchmark (1500 m array)

- **Fit FADC traces from low-gain channel (A, B free parameters)**

$$t_{1/2}^{\text{low-gain trace}} = 40\text{ns} + \sqrt{A(\theta)^2 + B(\theta)^2} - A(\theta)$$
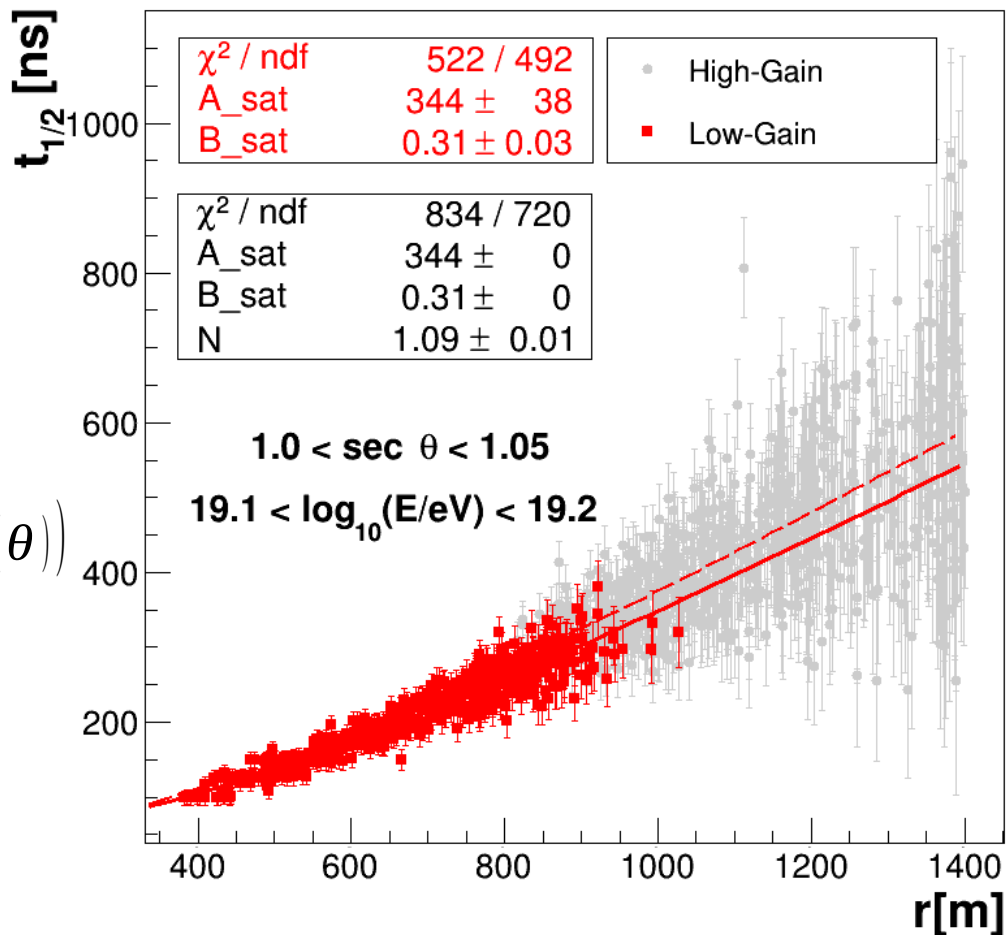
- **Fit FADC traces from high-gain channel (only *N* is a free parameter)**

$$t_{1/2}^{\text{high-gain trace}} = 40\text{ns} + N(\theta) \cdot \left(\sqrt{A(\theta)^2 + B(\theta)^2} - A(\theta)\right)$$
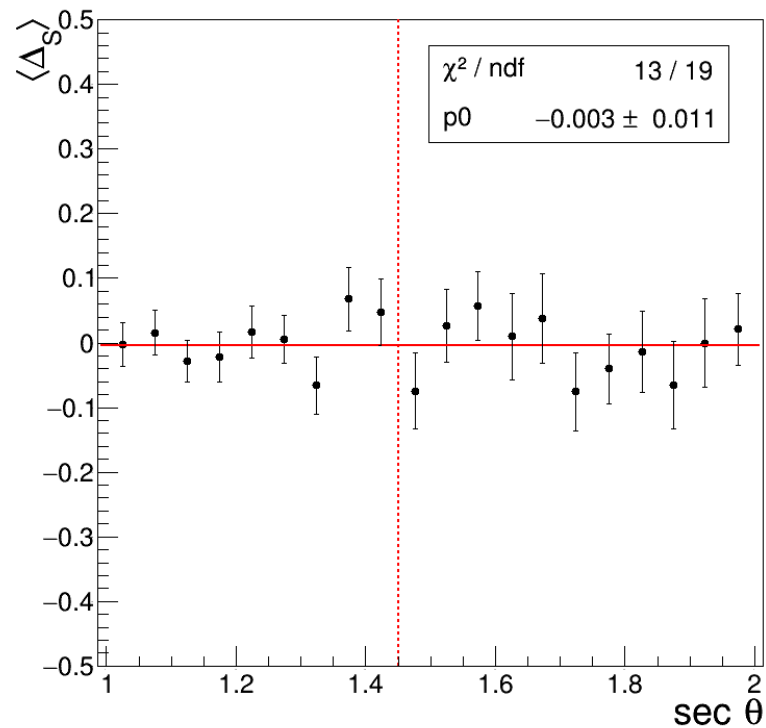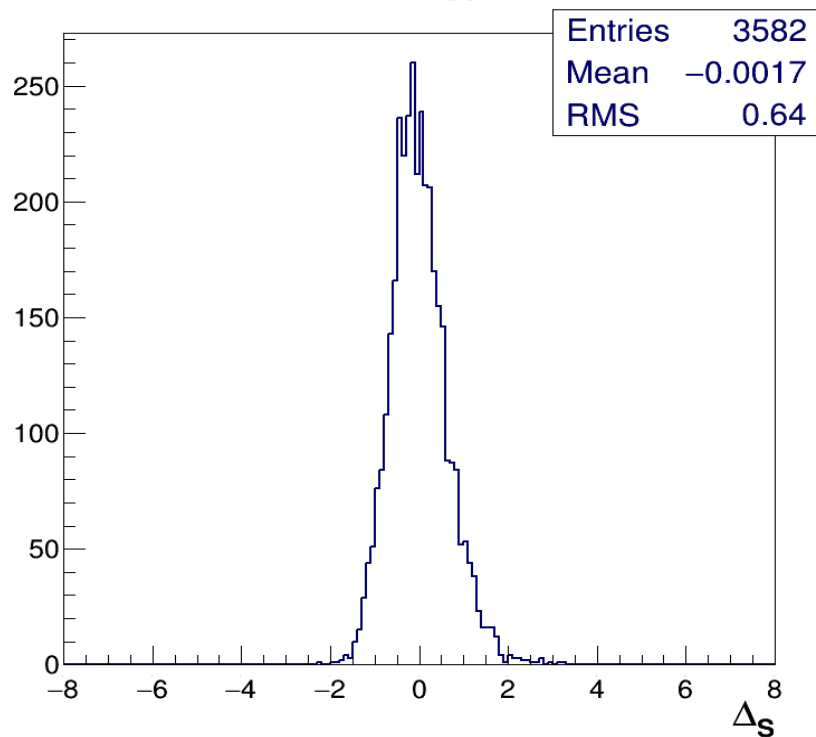
- **Split parameterisations in two angular bins**

| sec θ < 1.45 |

| 1.45 < sec θ < 2.0 |

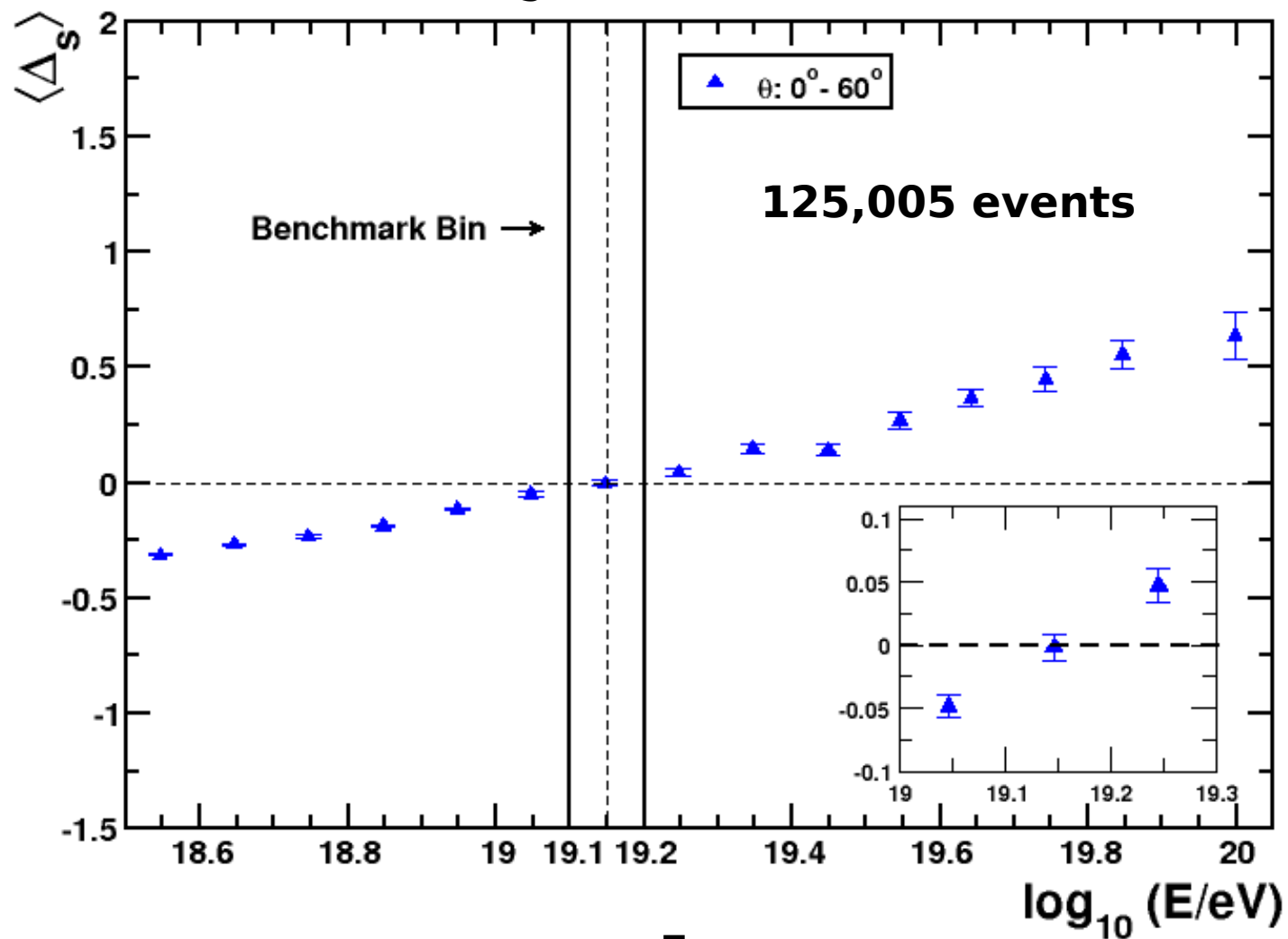| χ^2 / ndf | 522 / 492 |
| A_sat | 344 ± 38 |
| B_sat | 0.31 ± 0.03 |

High-Gain
Low-Gain

χ^2 / ndf	834 / 720
A_sat	344 ± 0
B_sat	0.31 ± 0
N	1.09 ± 0.01

1.0 < sec θ < 1.05

19.1 < $\log_{10}$(E/eV) < 19.2

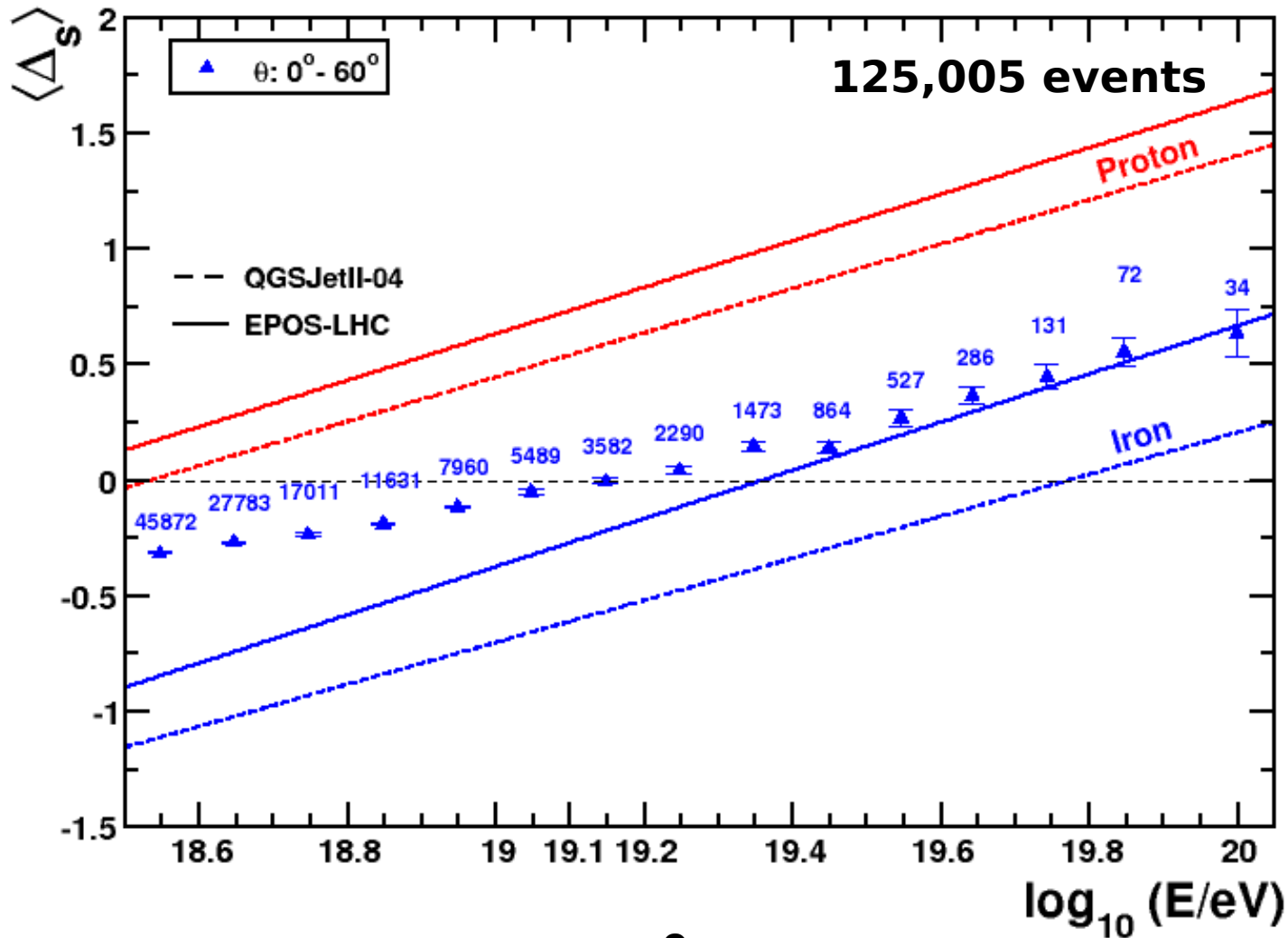# Δ_S at benchmark energy

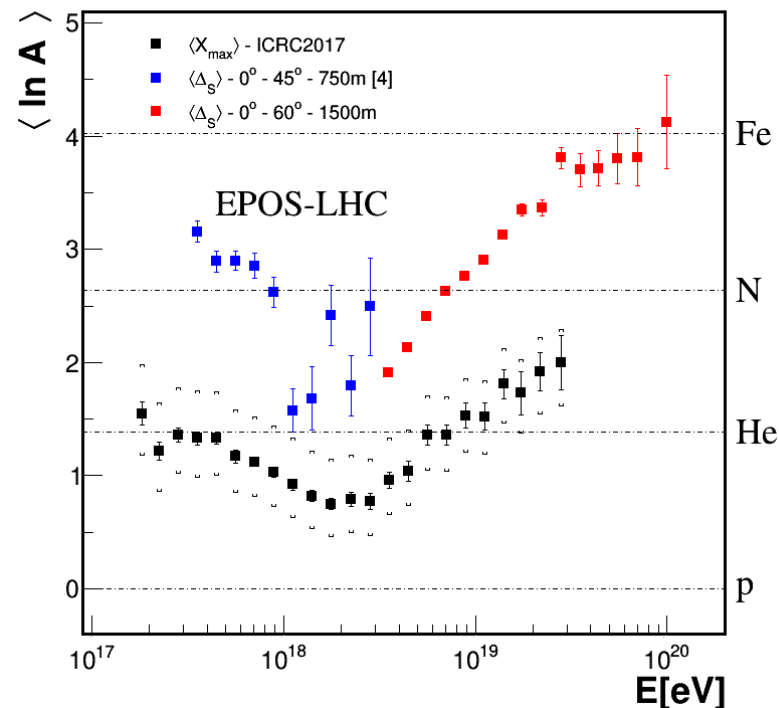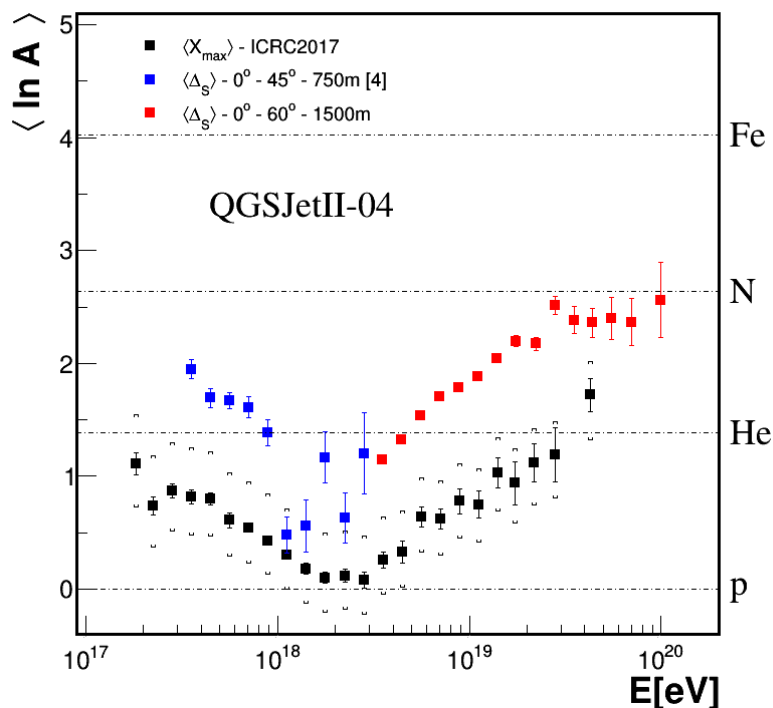**19.1≤ log₁₀ (E/eV)≤19.2   sec θ ≤ 2**

⟨Δ_s⟩ vs Energy

$\langle \Delta_s \rangle$ vs Energy: Comparison with published analysis
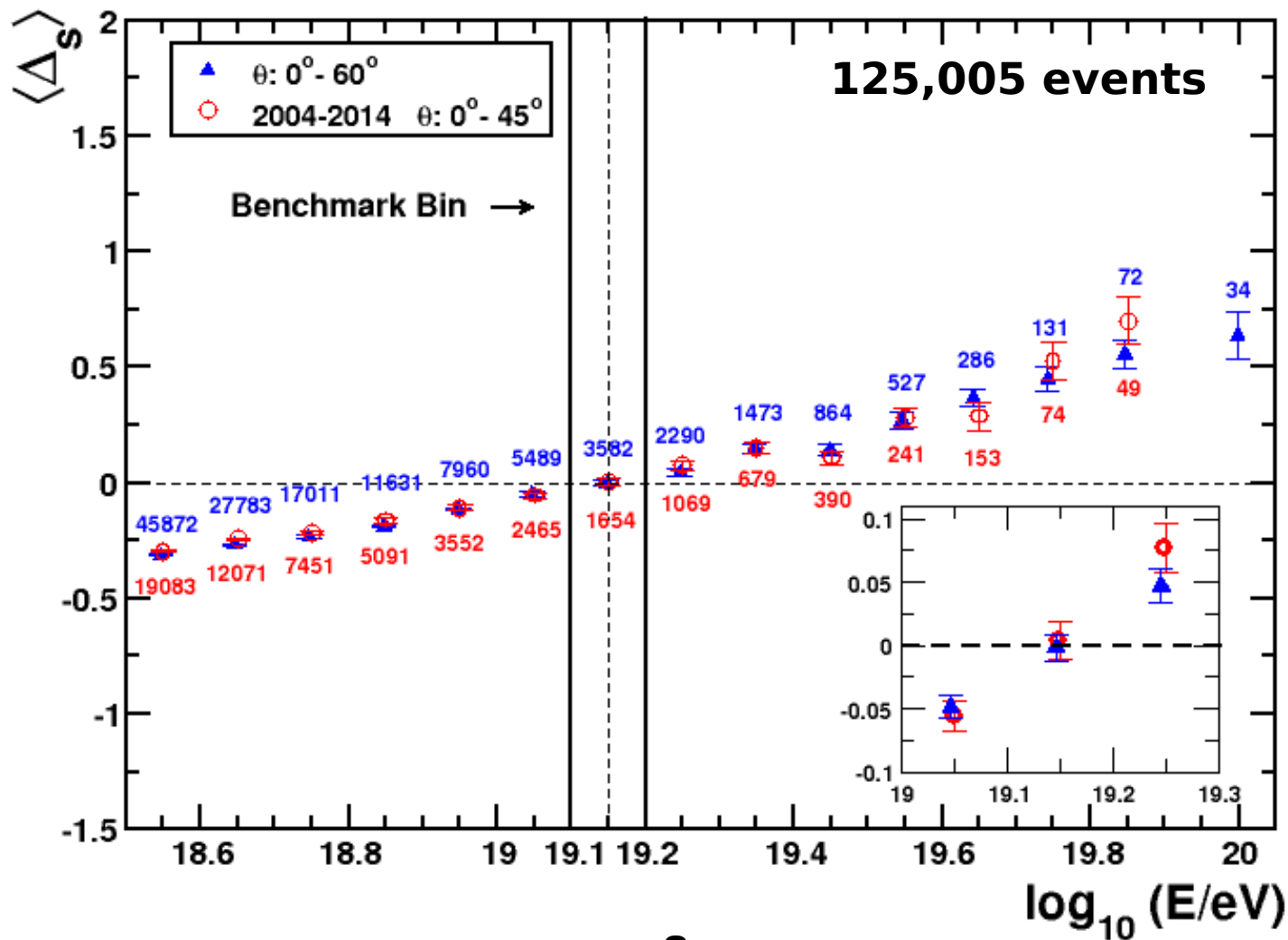
$\langle \Delta_s \rangle$ vs Energy: Comparison with models

# ⟨ln A⟩ from ⟨Δ$_s$⟩ compared to results from fluorescence measurements

Use models to convert measurements to ⟨ln A⟩
- **Simulations do not describe properly the signals recorded by Surface Detectors [Muon Problem adressed in PoS(ICRC2019)214,404,411]**
- **To estimate mass composition, data from Surface Detectors must be calibrated with fluorescence measurements**
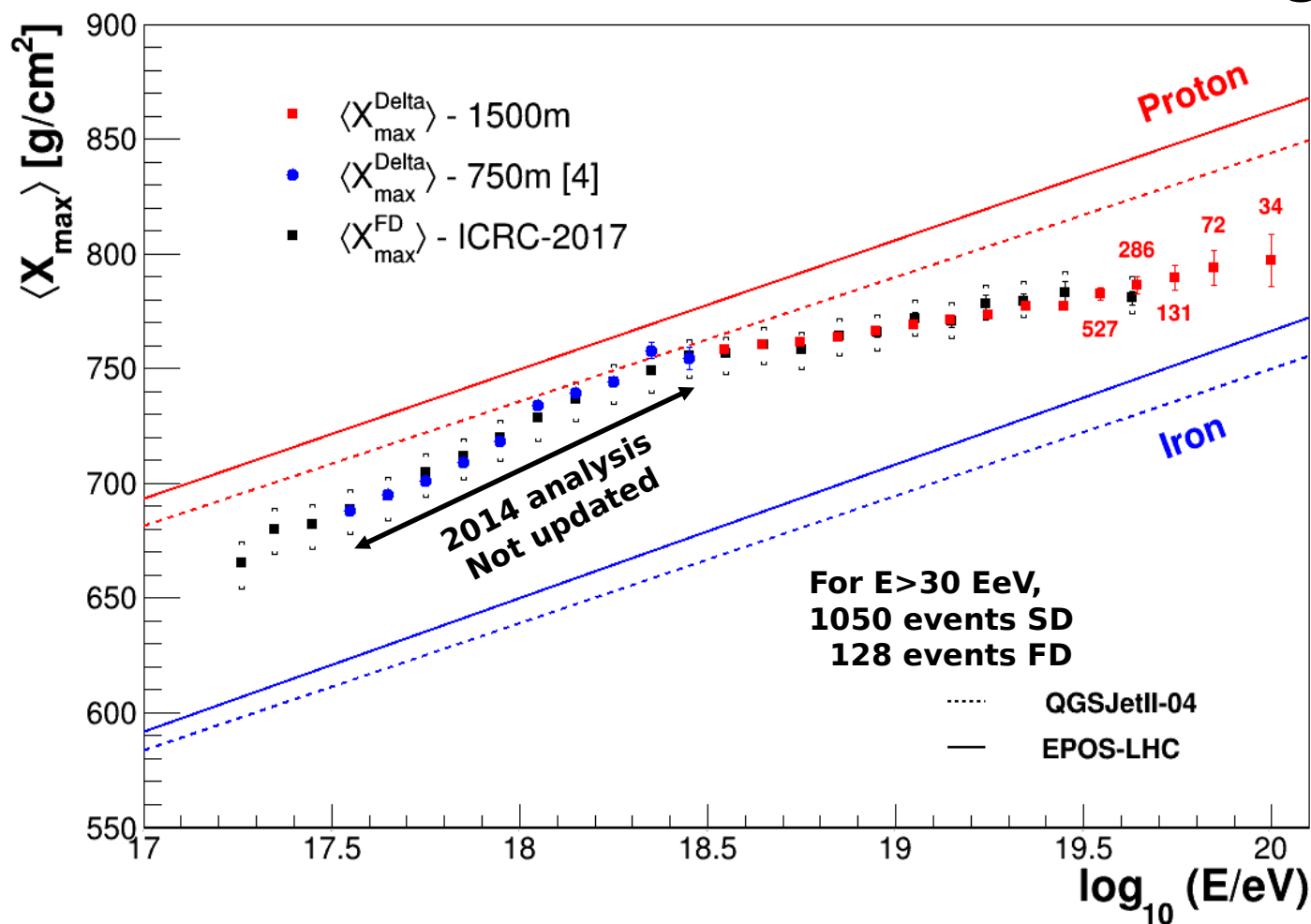
Calibration with X$_{max}$

- **Use golden hybrids (events simultaneously reconstructed by SD and FD)**

- **1500 m array : 2126 events; Correlation factor: 0.48**

$$\langle X_{max} \rangle = (733 \pm 38) + (34 \pm 12) \cdot \langle \Delta_S \rangle + (2 \pm 1) \cdot \log_{10}(E_{SD}/eV)$$

Correlation = 0.48
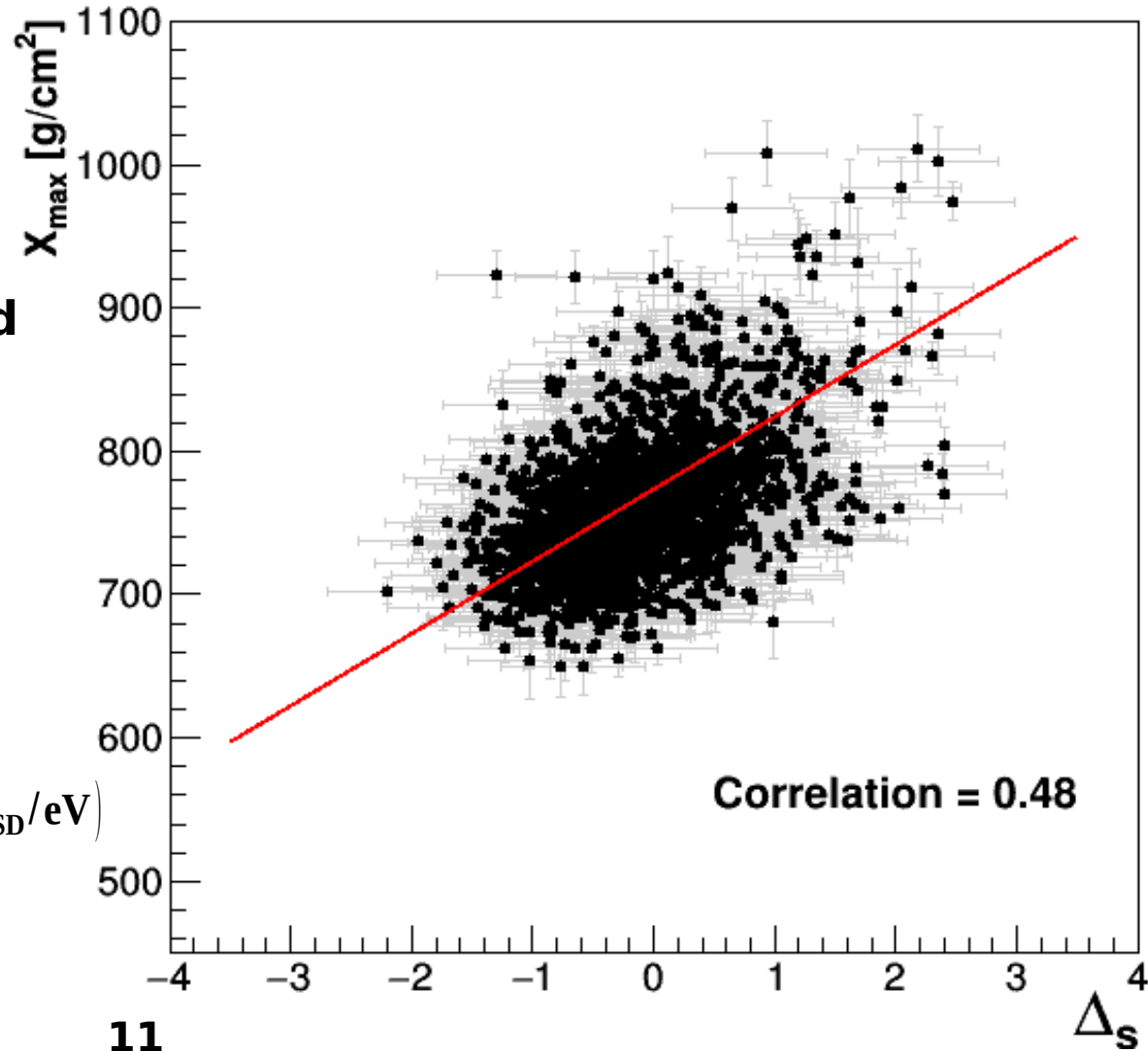
Evolution of $(X_{max})^{SD}$ as a function of energy

Preponderance of intermediate/heavy nuclei as energy increases
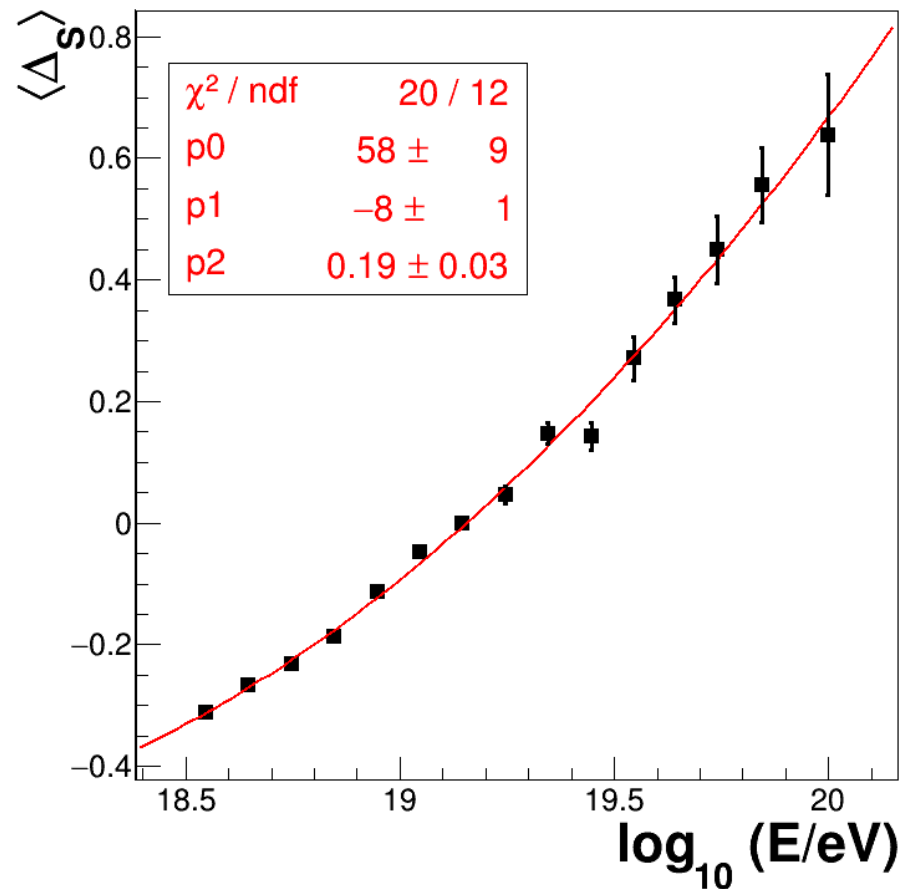
12

Thank you for your attention

Backup
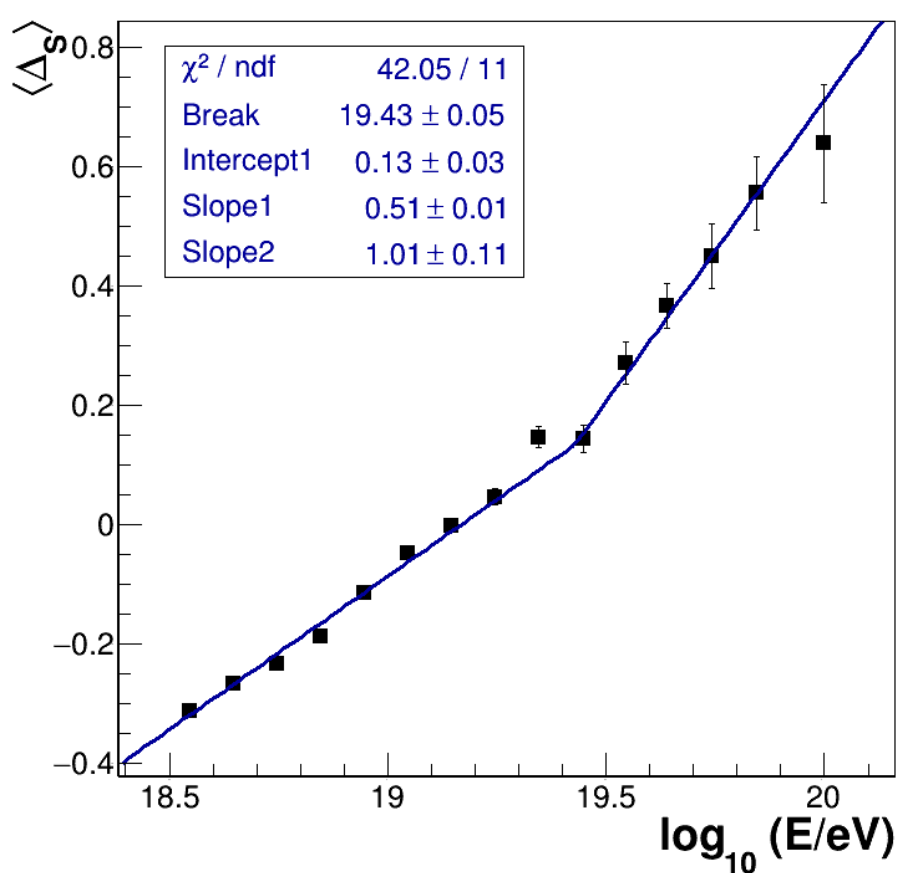

The rate of change of mass composition varies with energy