Study of muons in ultra-high-energy cosmic-ray air showers with the Telescope Array experiment

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INR RAS

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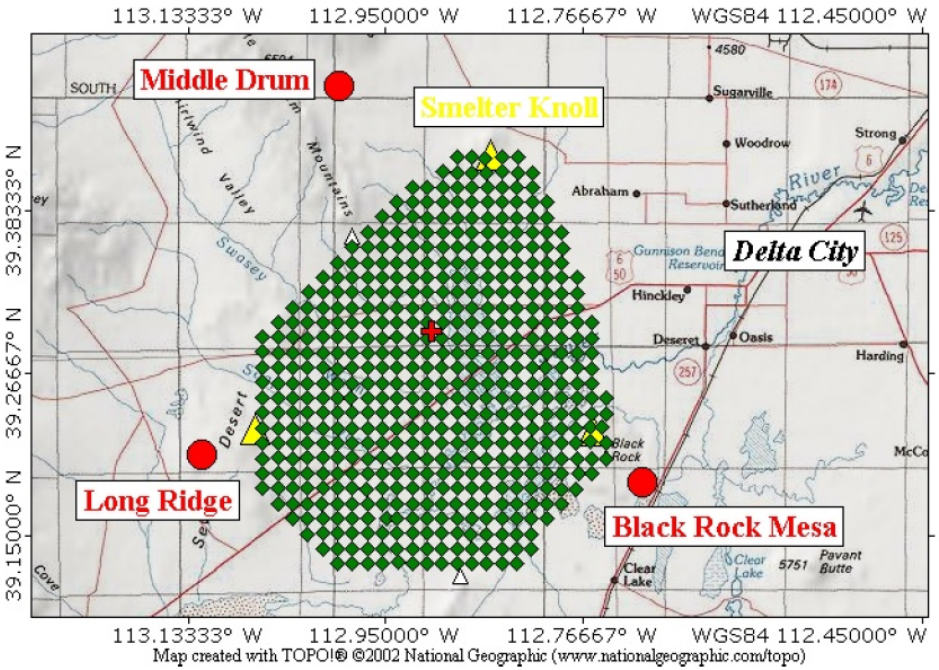
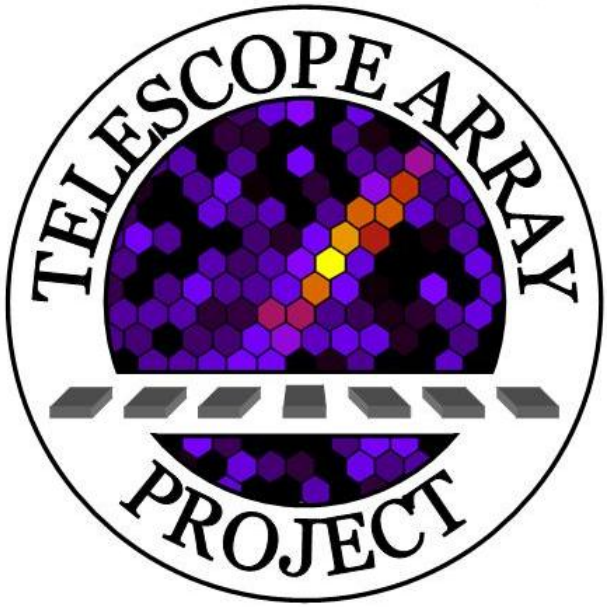
Outline

Telescope Array Observatory

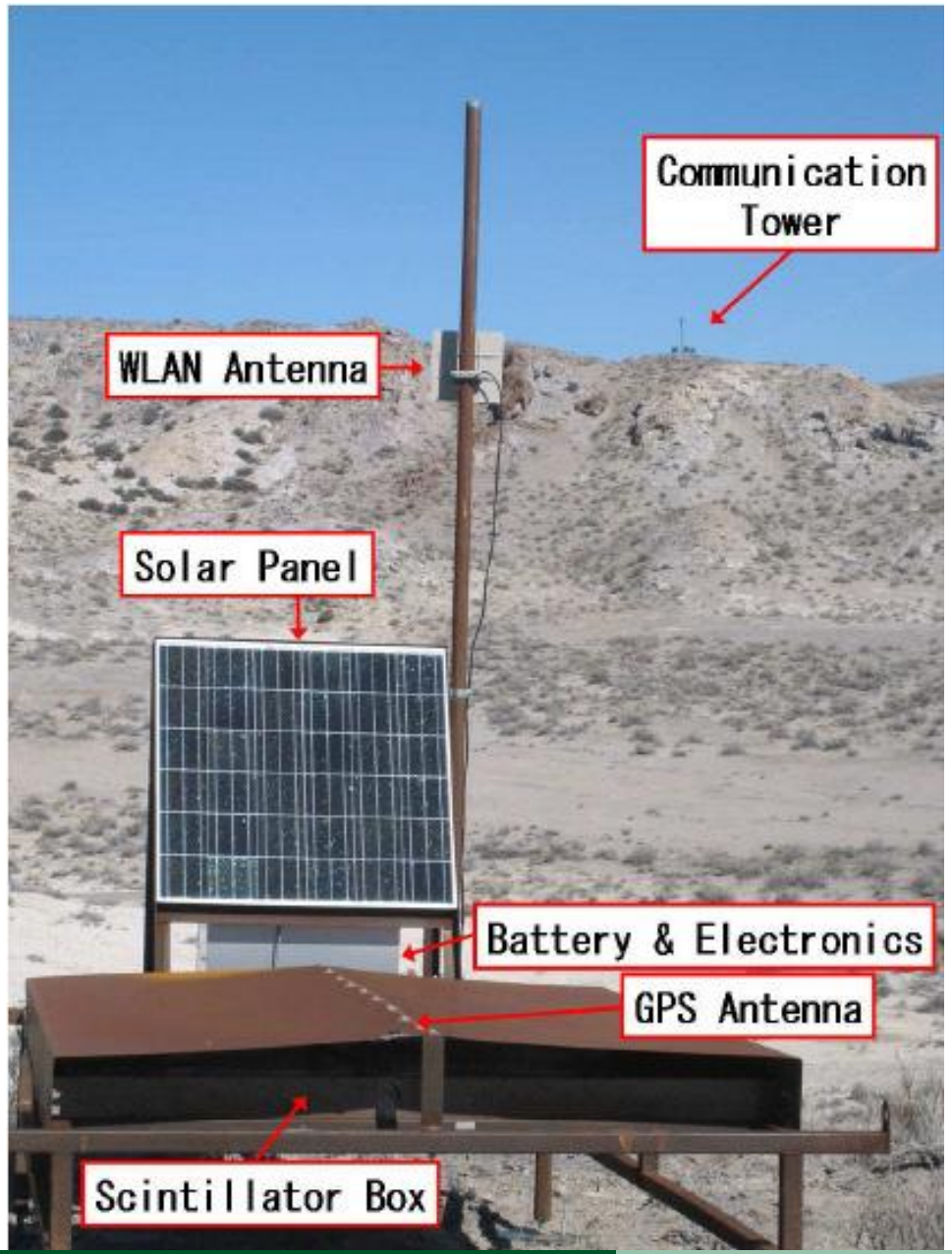


Largest UHECR statistics
in the Northern Hemisphere



- Utah, 2 hrs drive from Salt Lake City
- 507 surface detectors, upgrade to TAx4 a.t.m.
- 3 fluorescence detectors
- 10 years of operation

SD station



- Spacing 1.2 km
- Two layers of plastic scintillator, 1.2 cm thickness
- $S = 3\text{m}^2$
- Data are collected by the WLAN system

Data set

7-year data collected by the TA surface detector:
2008-05-11 — 2015-05-10

Quality cuts:

1. 5 or more triggered counters.
2. Zenith angle $\theta < 45°$.
3. Reconstructed core position of at least 1200 m away from the edge of the array.
4. Timing and lateral distribution fits with $\chi^2_G/d.o.f. < 4$ and $\chi^2_{LDF}/d.o.f. < 4$.
5. Geometry reconstructed with accuracy less than 5°.
6. Fractional uncertainty of the S_{800} less than 25 %.
7. Energies $10^{18.8}$ eV $< E < 10^{19.2}$ eV.

Monte-Carlo sumulations

p and Fe Monte-Carlo sets with QGSJETII-03, QGSJETII-04, EPOS 1.99, SYBILL 2.1

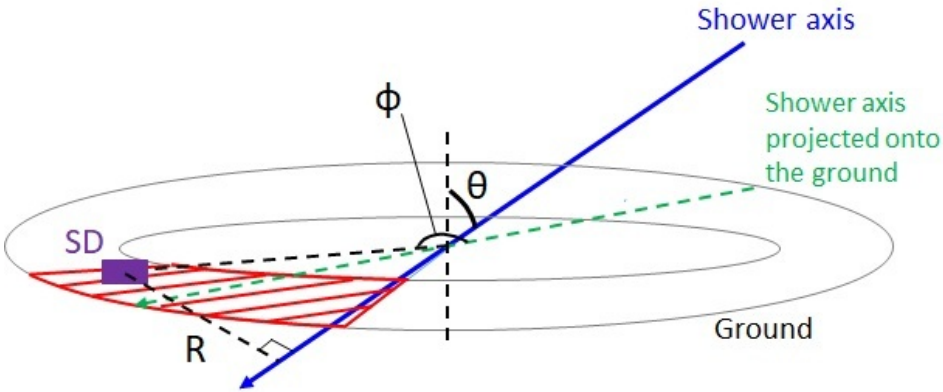
- Low energy hadronic interactions with FLUKA2008.3c.
- Electromagnetic interactions with EGS4.
- "Thinning" and consequent "de-thinning" applied.
- Energy range $10^{16.55}$ eV $< E < 10^{20.55}$ eV.
- Zenith angle randomly distributed in range $0° < \theta < 60°$.
- The azimuth angle and core position are randomly distributed within the SD array.
- The same reconstruction procedure as for experimental data.
- Energy distribution follows the spectrum measured by the HiRes experiment.

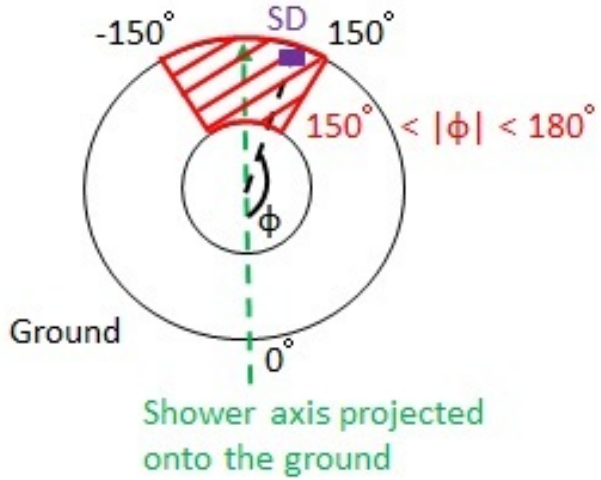
Station selection

Muon purity – the ratio of the energy deposit of air shower muons to that of all particles, which consist of air shower and background components in SD signals.

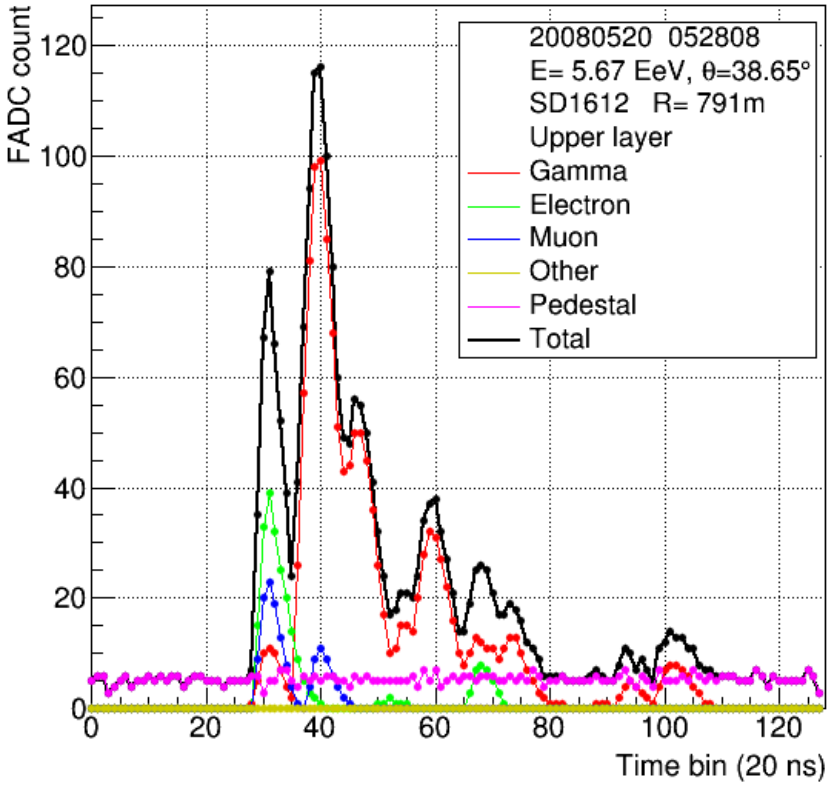
Each station is described with the θ, ϕ and R in the reference system of the event.

With the use of MC (QGSJETII-03 used as a benchmark), one derives criteria for the SD stations with high muon purity.

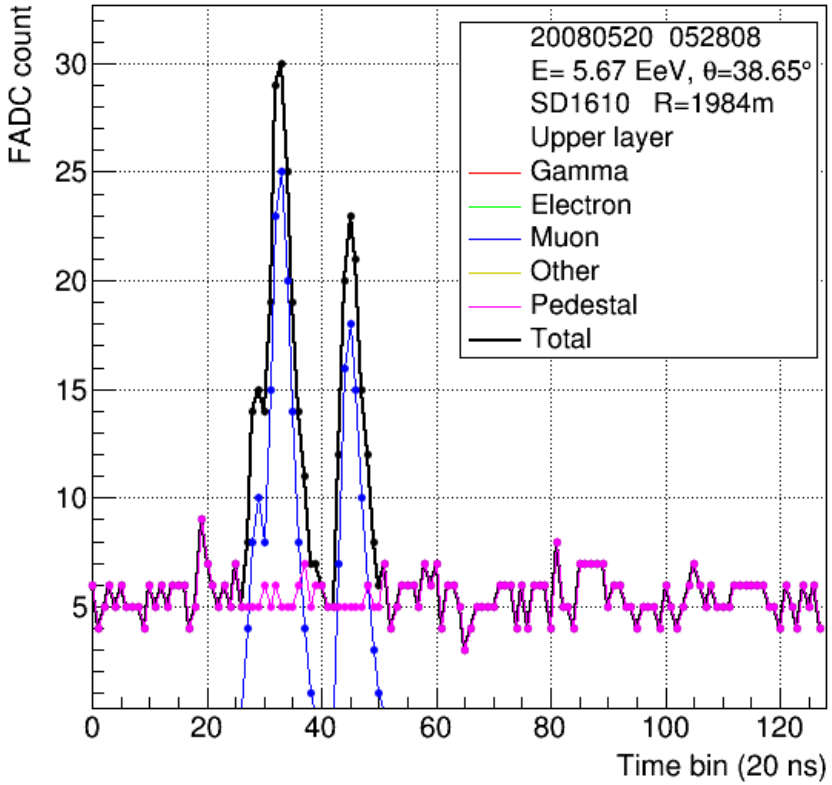




Event waveforms of different particle types in an SD

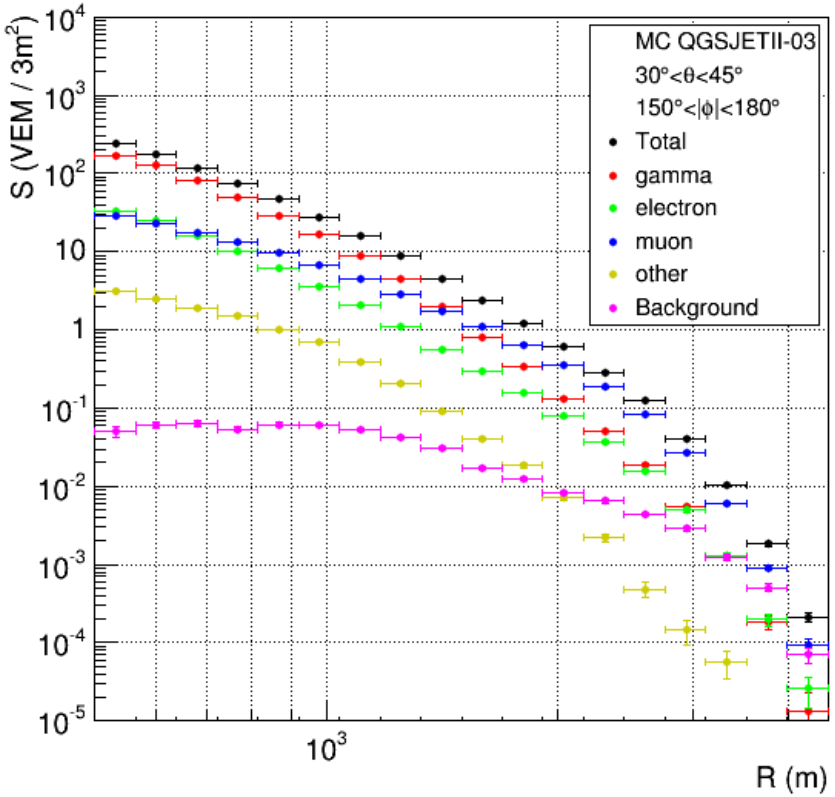


$R = 791$ m.

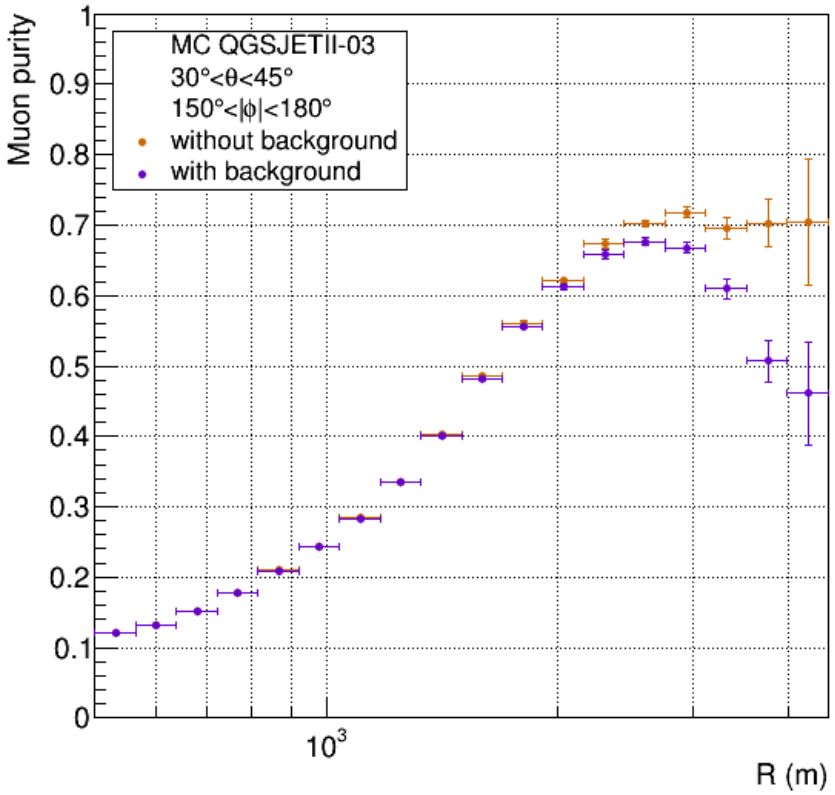


$R = 1984$ m.

High muon purity condition



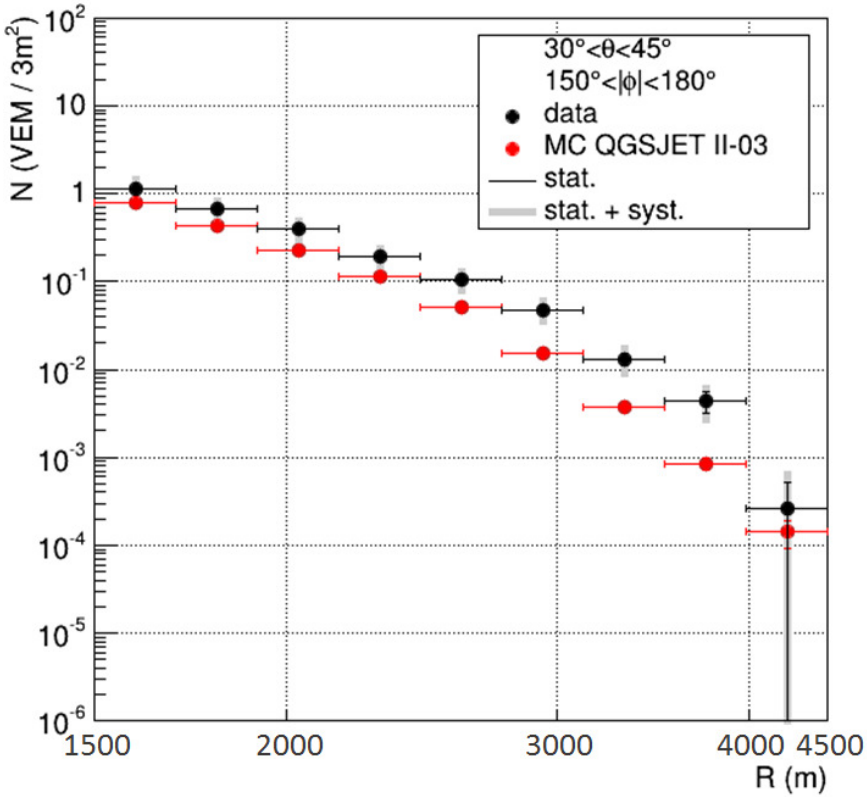
Lateral distributions of the air shower average signal, $30^\circ < \theta < 45^\circ$, $150^\circ < |\phi| < 180^\circ$, 500 m $< R <$ 4500 m.



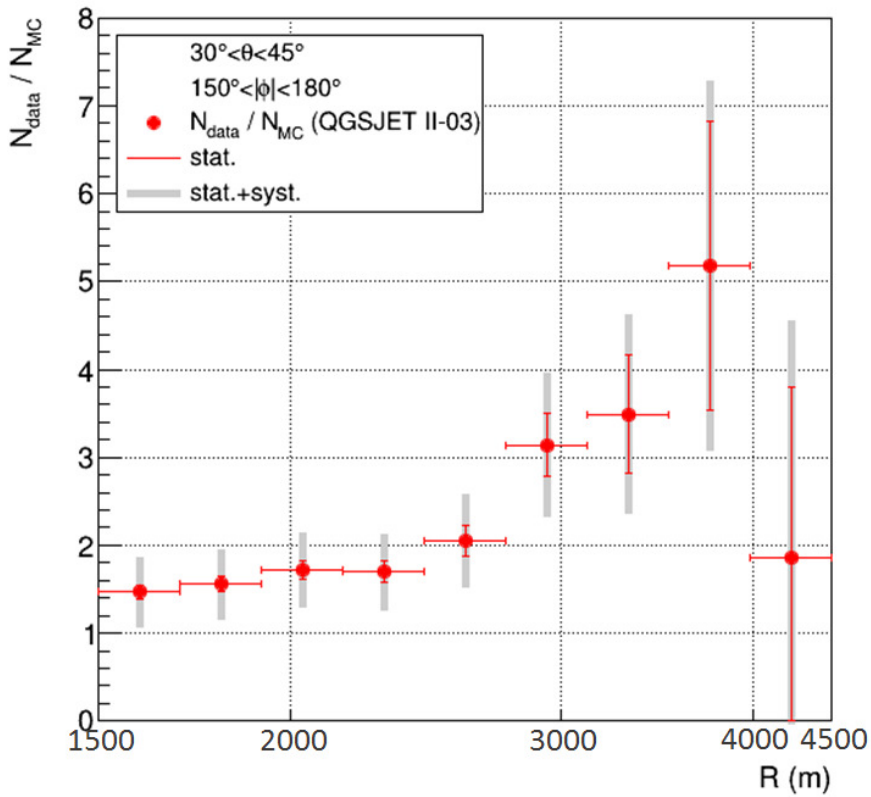
Lateral distribution of the muon purity.

High muon purity condition $(60 - 70\%)$:
$30^\circ < \theta < 45^\circ$, $150^\circ < |\phi| < 180^\circ$, 2000 m $< R <$ 4000 m.

Comparison with QGSJETII-03, proton, 1500 m $< R <$ 4500 m



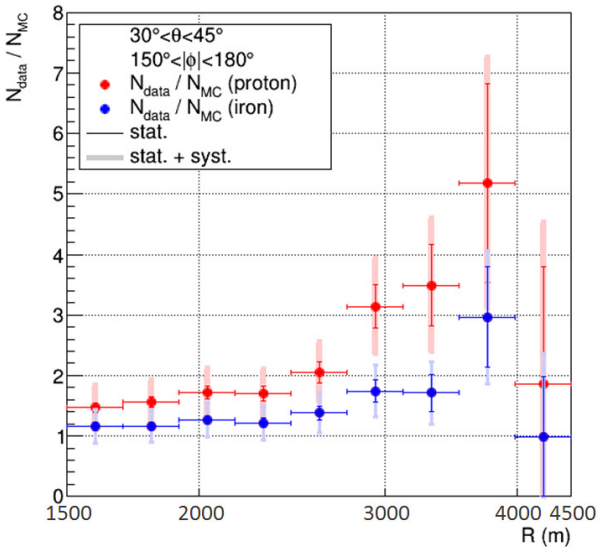
Lateral distributions of the average signal.



The average ratio of the data to the MC.

The average ratios of the data to the MC:
$1.72 \pm 0.10(stat.) \pm 0.37(syst.)$ at 1910 m $< R <$ 2160 m
$3.14 \pm 0.36(stat.) \pm 0.69(syst.)$ at 2760 m $< R <$ 3120 m

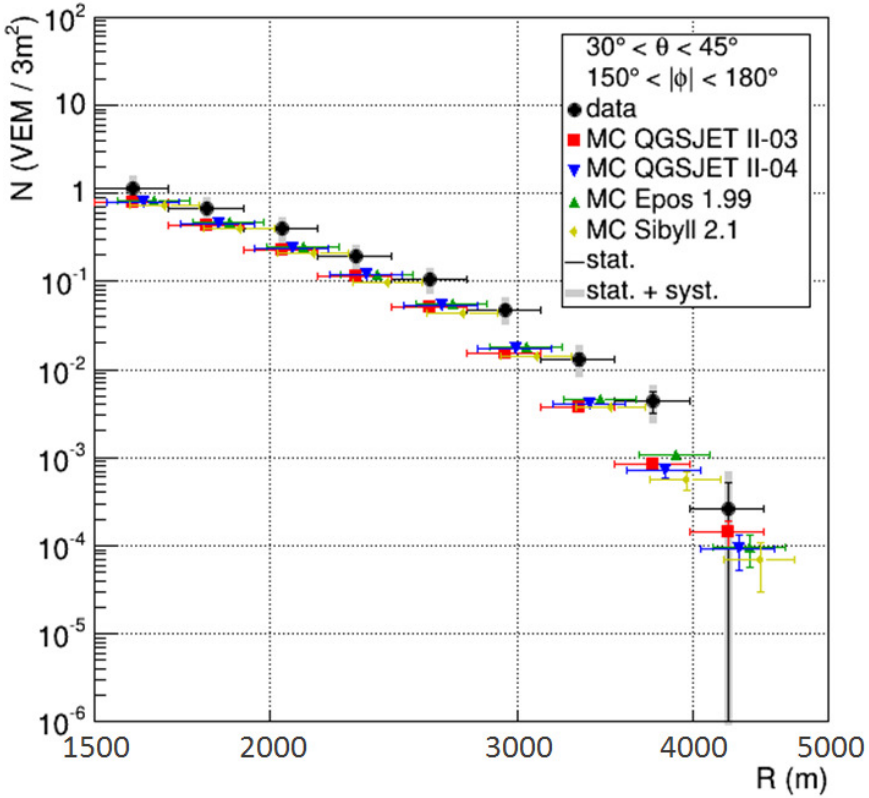
Comparison with QGSJETII-03, proton & iron



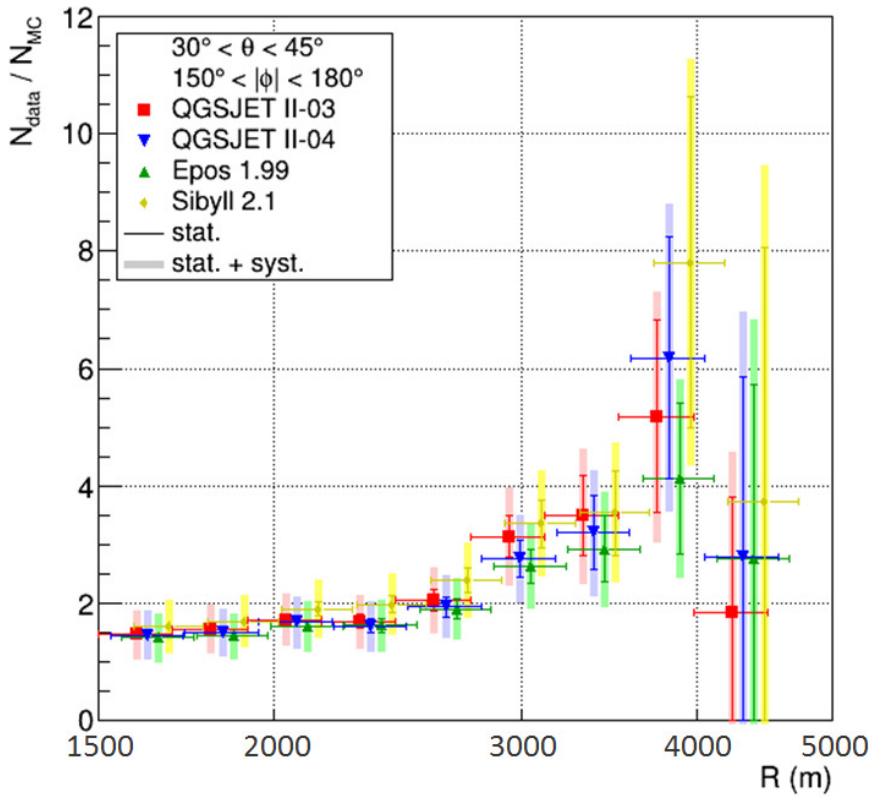
The average ratio of the data to the MC.

R [m]	Ratio $\pm\sigma_{\text{stat.}} \pm \sigma_{\text{syst.}}$	
	Proton	Iron
[1500, 1695]	$1.47^{+0.09}_{-0.08} \pm 0.35$	$1.16^{+0.07}_{-0.06} \pm 0.28$
[1695, 1915]	$1.56^{+0.09}_{-0.08} \pm 0.35$	$1.16 \pm 0.06 \pm 0.26$
[1915, 2160]	$1.72 \pm 0.10 \pm 0.37$	$1.26 \pm 0.07 \pm 0.27$
[2160, 2445]	$1.69 \pm 0.12 \pm 0.37$	$1.22 \pm 0.08 \pm 0.27$
[2445, 2760]	$2.05 \pm 0.18 \pm 0.46$	$1.38 \pm 0.11 \pm 0.31$
[2760, 3120]	$3.14 \pm 0.36 \pm 0.69$	$1.74 \pm 0.19 \pm 0.38$
[3120, 3525]	$3.49 \pm 0.68 \pm 0.86$	$1.71 \pm 0.30 \pm 0.42$
[3525, 4180]	$5.18 \pm 1.64 \pm 1.27$	$2.96 \pm 0.83 \pm 0.72$
[4180, 4500]	$1.85 \pm 1.95 \pm 1.81$	$0.99 \pm 0.99 \pm 0.96$

Comparison with other interaction models



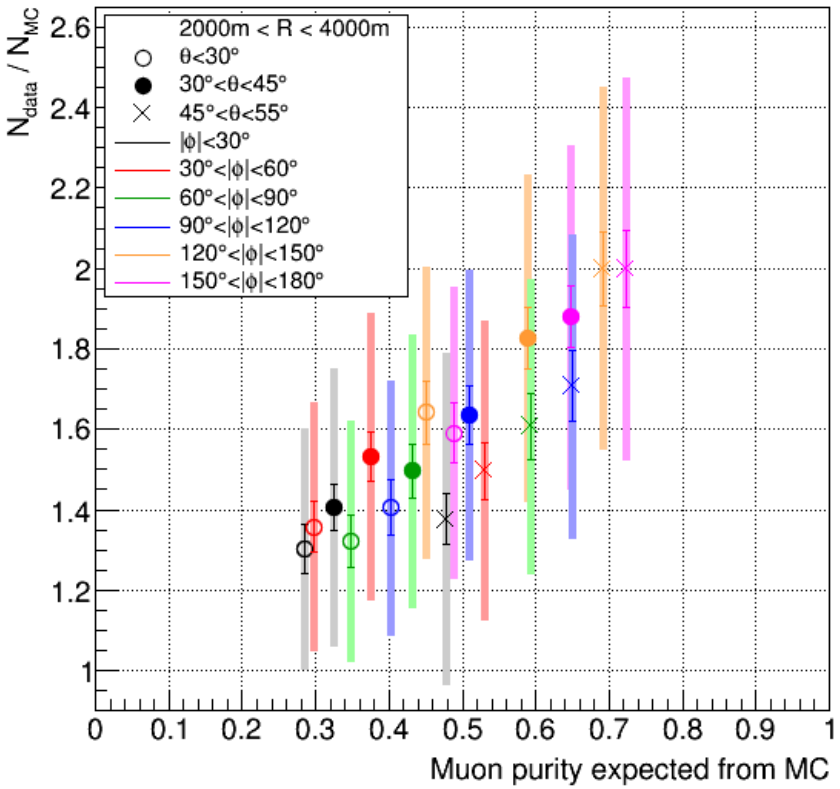
Lateral distributions of the average signal.



The average ratio of the data to the MC.

The average ratios of the data to the MC, QGSJETII-04:
$1.67 \pm 0.10(stat.) \pm 0.36(syst.)$ at 1910 m $< R <$ 2160 m
$2.75 \pm 0.32(stat.) \pm 0.60(syst.)$ at 2760 m $< R <$ 3120 m

Muon purity vs. data/MC ratio



The correlation between the muon purity and the ratio of the signal size of the data to the MC, QGSJET II-03.

65% muon purity:
$\text{data/MC} = 1.88 \pm 0.08(stat.) \pm 0.42(syst.)$

28% muon purity:
$\text{data/MC} = 1.30 \pm 0.06(stat.) \pm 0.29(syst.)$

Conclusions

- A method is established to study muon excess in the air shower data with the TA scintillator SD array.
- It is found that lateral distribution of muons in the data falls slower than that of the MC on a high muon purity condition.
- Muon excess may be a part of the cause of an 27%-energy scale discrepancy between the TA SD and FD measurements.

Backup

Systematic error determination

Source	Systematic error
FD energy determination	$\pm 21\%$
1 MIP calibration	$\pm 1.2\%$
Atmospheric muon cut	$\pm 1\%$
Poisson distribution assumption	$\pm(< 4\%)$
Event reconstruction	$\pm$(4-13%)
SDs not working properly	$\pm(< 1\%)$
Total	$\pm$(22-24%)