Measurement of the muon content in EAS with muon detectors of LHAASO-KM2A

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**speaker*

outline

- motivation
- the average muon content per shower energy
- the fluctuation of muon content of data and mc
- the attenuation length of muon content
- summary

motivation

- Muons are produced through the decay of mesons generated in hadronic collisions during the early stages of an extensive air shower
  - the average number of muons in a shower can be used to validate hadronic interaction models by comparing EAS predictions with experiment data
  - muons can provide important information about hadronic interactions, such as interaction length, production cross-section, and multiplicity, to validate and constrain the predictions of the hadronic interaction model
- Some experiments reported this "muon excess", other measurements, performed under different conditions, show the agreement in the muon number between data and models

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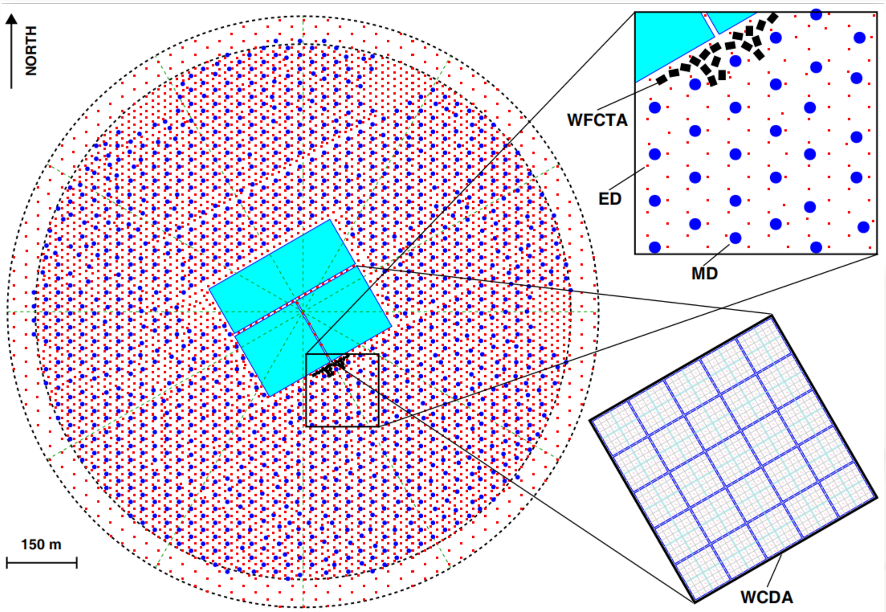
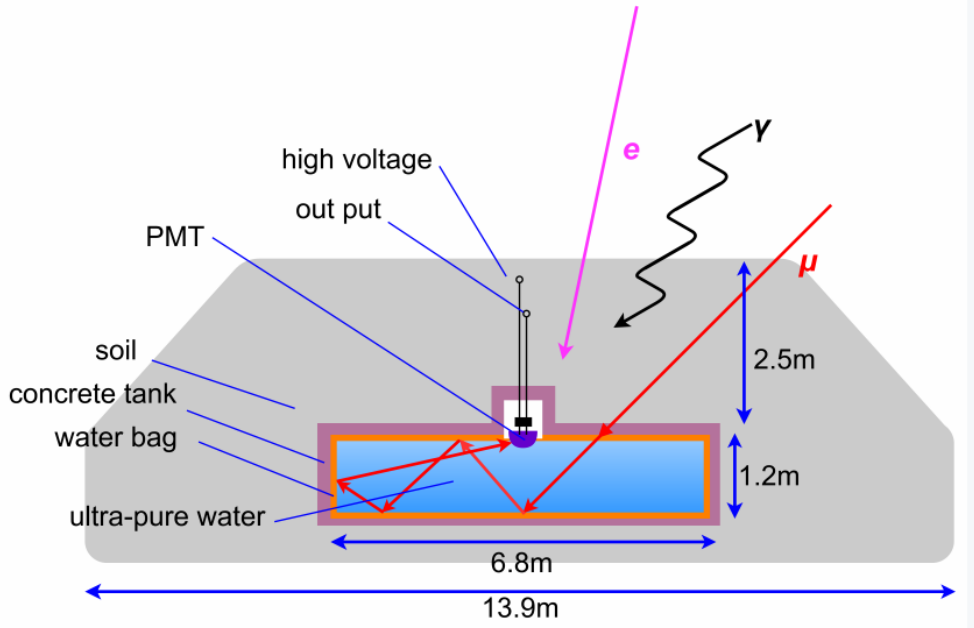
Experiment	altitude, m a.s.l.	X, g/cm^2	E, eV	E_μ, GeV	r/R_0	θ	muon excess (data over MC)
HiRes-MIA [6]	1500	860	$10^{17} - 10^{18}$	$\gtrsim 0.85$	$\gtrsim 10$	N/A	yes
PAO [2,4]	1450	880	$\gtrsim 10^{19}$	$\gtrsim 1$	$\gtrsim 10$	70°	yes
Yakutsk [5]	100	1020	$\gtrsim 10^{19}$	$\gtrsim 1$	$\gtrsim 10$	45°	yes
IceTop [26]	2835	680	$10^{15} - 10^{17}$	$\gtrsim 0.2$	$\gtrsim 3$	13° mean	no
EAS-MSU (this work)	190	990	$10^{17} - 10^{18}$	$\gtrsim 10$	$\lesssim 3$	30°	no

LHAASO and muon detector



Layout of LHAASO



Schematic of the LHAASO muon detector

Large High Altitude Air Shower Observatory, LHAASO

Daocheng, altitude: 4410m ($600 g/cm^2$)

KM2A covers an area of 1.3 km^2

- 1188 muon detectors(MDs) with a spacing of 30 m
- 5216 electronic detectors(EDs) with a spacing of 15m

The sensitive area is 36 m^2

Covered with 2.5 m soil to absorb other charge particles

$E_\mu > 1GeV$

Ultra-pure water: diameter 6.8 m, height 1.2 m

PMT: 8 inches

Resolution 25% at 1 muon; <5% at 10^4 muons

Data and MC sample

- **LHAASO sample**
  - Jan-Dec of 2022
  - Full LHASSO KM2A array
  - Trigger mode: 400ns; 20ED

Time	365 days
Effect time	359.46 days

- **MC sample**
  - Models: EPOS-LHC, QGSJET-II-04
  - Energy: 100TeV-50PeV
  - Components: Proton, He, CNO, MgAlSi, Fe
  - Slope:-2
  - Theta: 0-40°
  - Phi: 0-360°
  - CORSIKA; Geant4

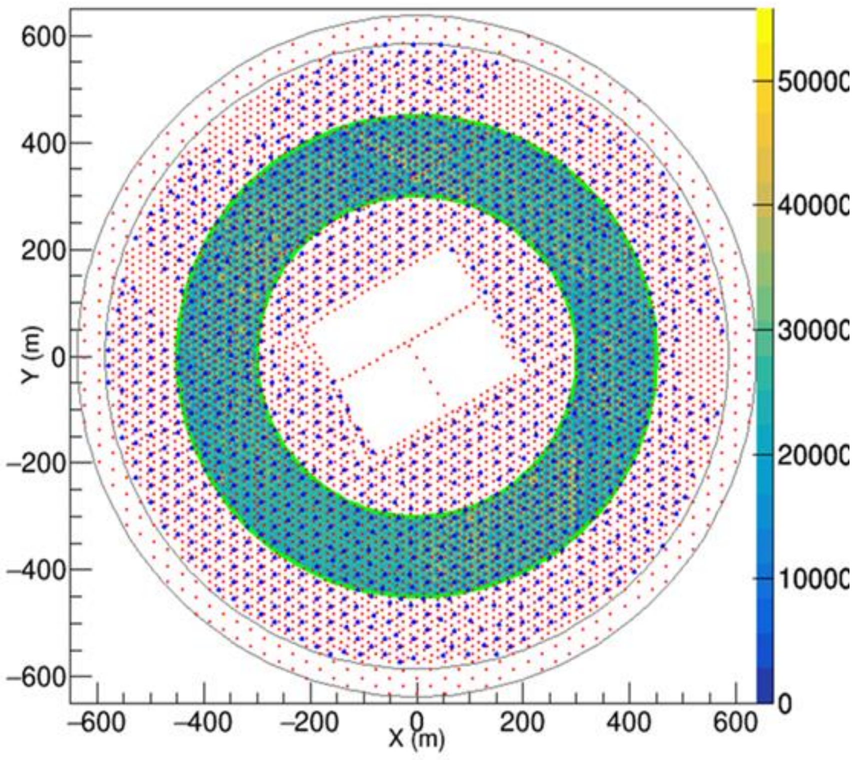
component	100TeV-1PeV	1PeV-10PeV	10PeV-50PeV(QGS)	10PeV - 50PeV(EPOS)
Proton	10^6	10^5	2.5×10^4	5×10^3
He	10^6	10^5	10^4	5×10^3
CNO	10^6	10^5	10^4	5×10^3
MgAlSi	10^6	10^5	10^4	5×10^3
Fe	10^6	10^5	1.5×10^4	5×10^3

Event selection

- **Criteria**
  - Ne>80 (*the number of particles within 40 to 200 meters from the shower axis.*)
  - 300<=R<=450(the distance from shower core to array center)
  - $\theta < 40°$

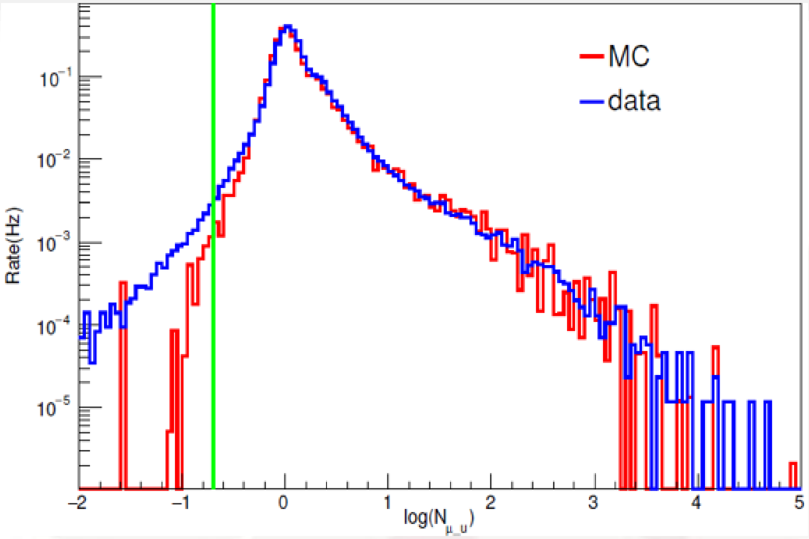
- **Event number**
  - LHAASO: **1.8×10^9**
  - MC: EPOS-LHC: **682 k**

    QGSJET-II-04: **673 k**

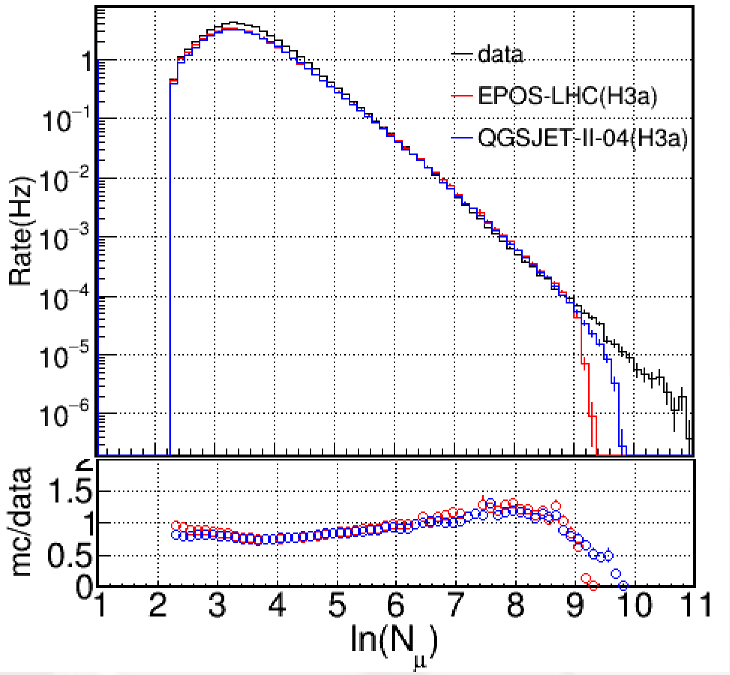


Shower core distribution in LHAASO array

Muon measurement validation



N_{μ_u} of MC and data



Muon number spectrum

N_{μ_u}: muon number measured by one muon detector

N_{μ_u} of MC is consistent with experiment

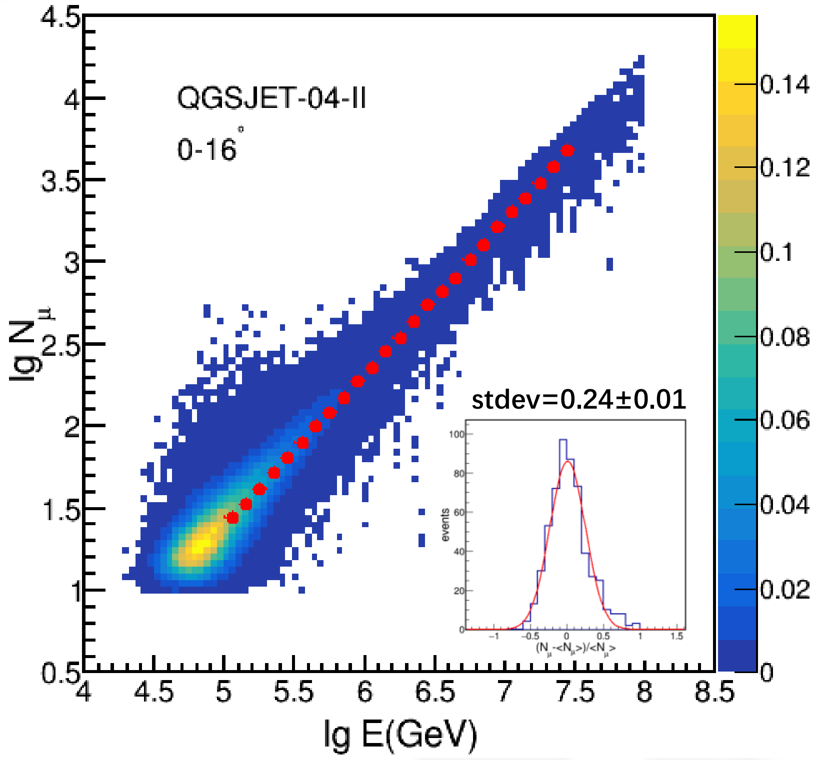
Detectors with a particle number less than 0.2, as indicated by the vertical lines, are excluded from reconstruction in both Monte Carlo (MC) simulations and data

N_{μ}: The muon numbers measured by MD within the range of 40~200 meters from the shower core on the front surface

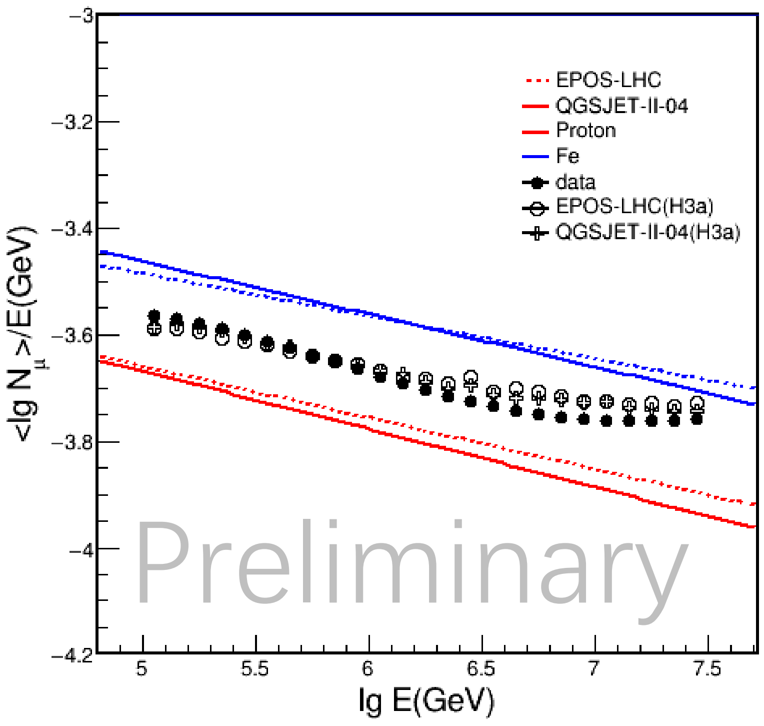
not count the MD closing to the core, reducing the punch through effect

reducing the noise contribution, not counting the MD 200 m far from the core

Average muon number per energy



$< N_\mu >$ *of per energy bin*

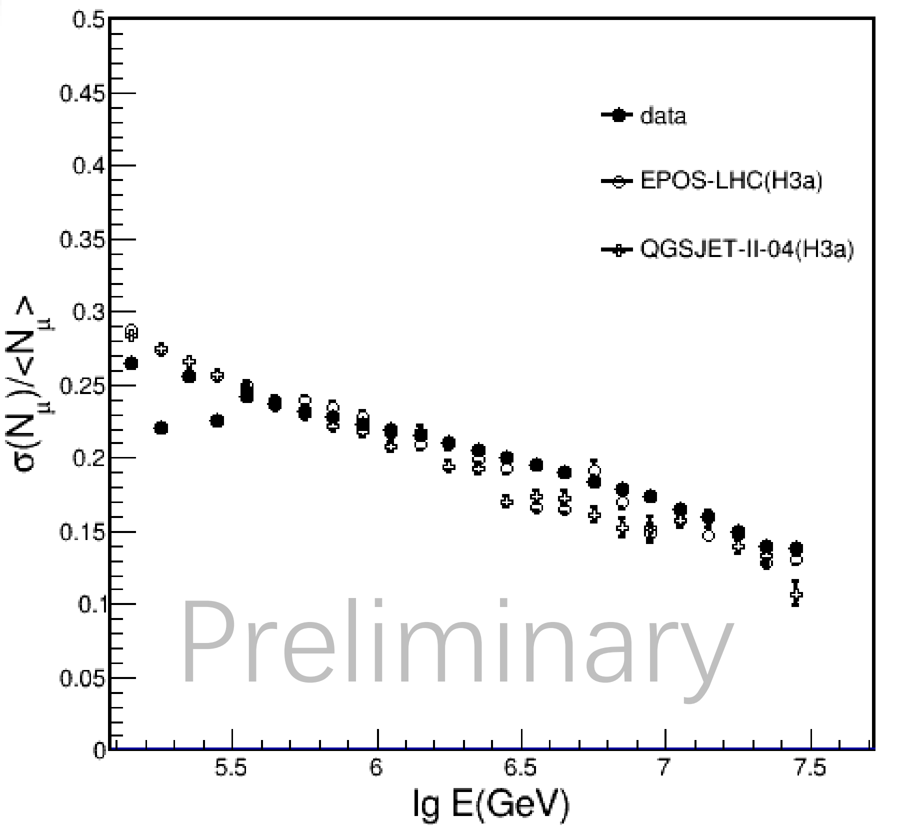


Average muon number of per energy

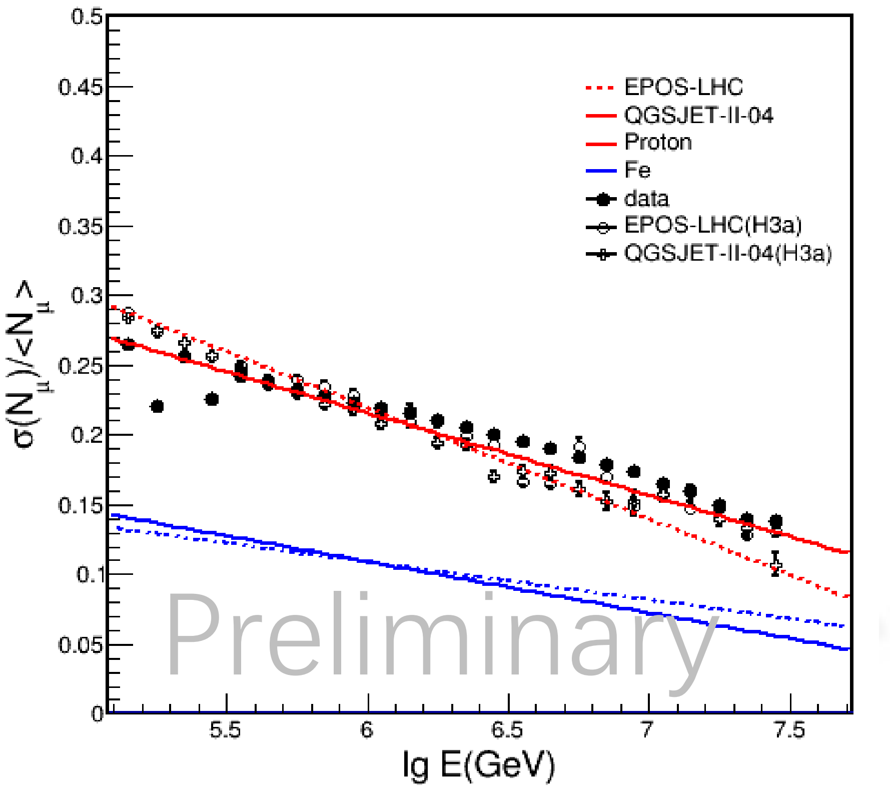
$<N_\mu>$: average muon number

- data is between with pure Proton and pure iron, as the energy increases, $< N_\mu >$ approaches closer to iron
- data looks lighter than Gaisser H3a energy spectrum with the energy above 1PeV
- no muon excess

Relative fluctuation



Relative fluctuation of muon



Relative fluctuation of muon

The relative fluctuation $(N_\mu - < N_\mu >)/ < N_\mu >$

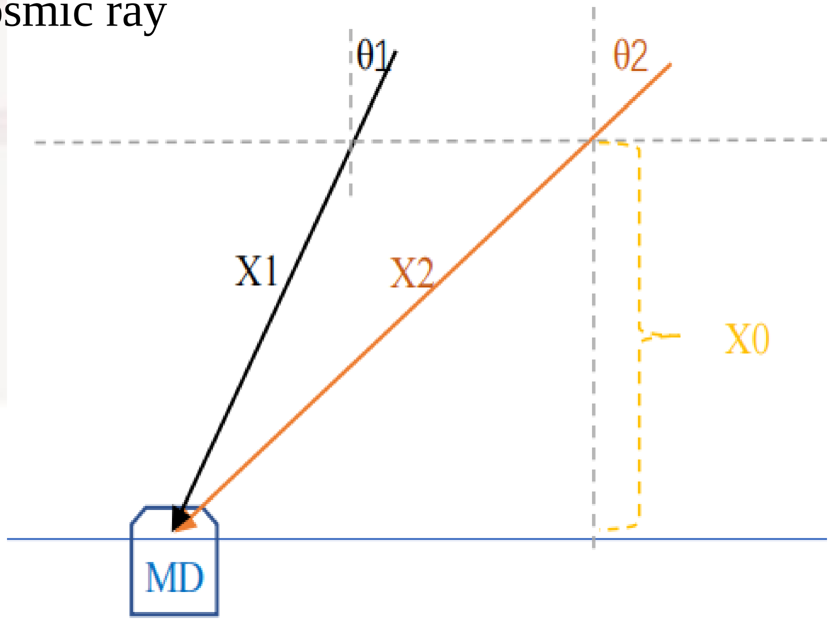
The simulation and experimental results are in good agreement.

The fluctuation of data is larger than iron

Constant Intensity Cut (CIC)

Cosmic ray is isotropic

The same intensity at each direction corresponding to the same energy of cosmic ray



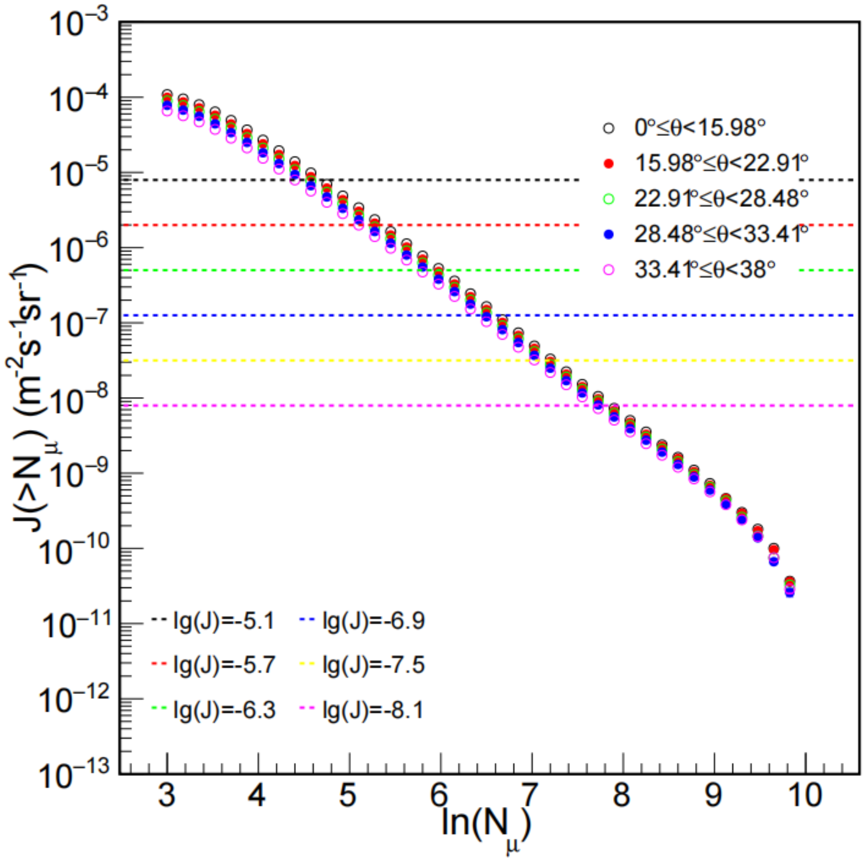
$N_\mu(\theta) = N_\mu^0 e^{-X_0 sec\theta/\Lambda_\mu}$

N_μ^0 is a normalization parameter

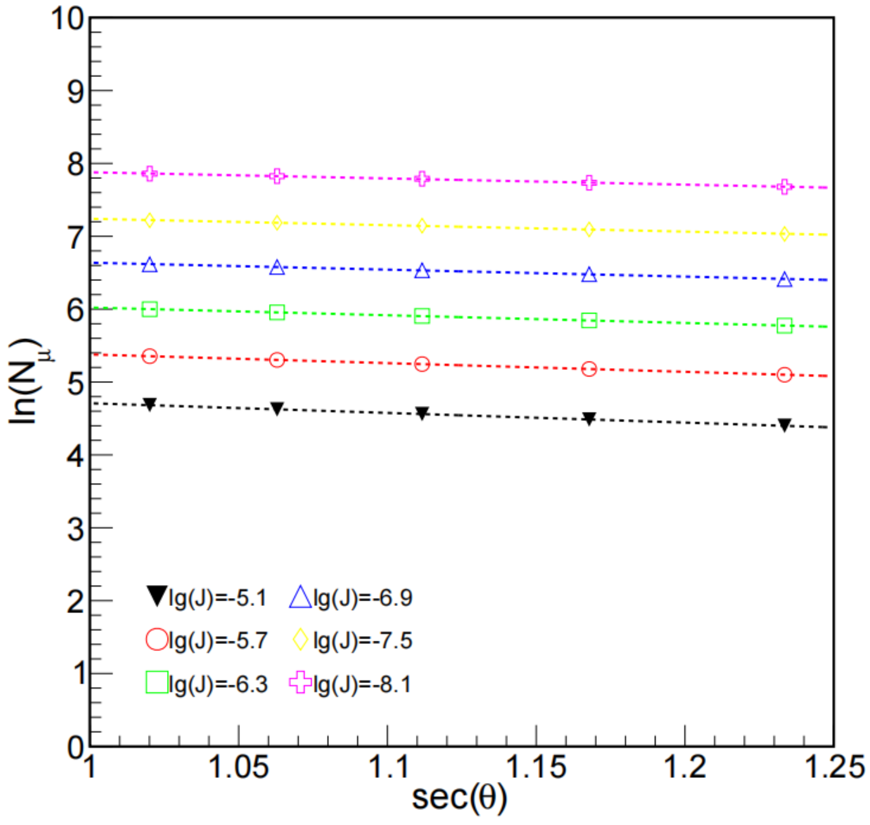
X_0 is the vertical atmospheric depth, 600 g/cm^2 at LHAASO

Λ_μ is the muon number attenuation length

Attenuation curves



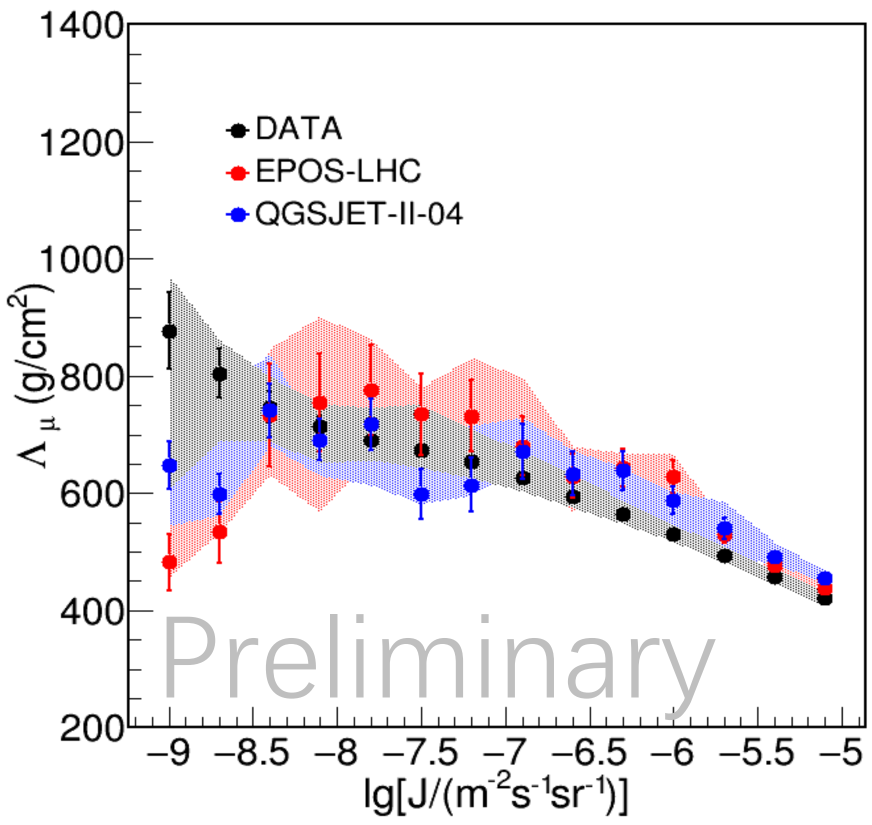
Muon integral intensities



Muon attenuation curves

- 0°-15.98°-22.91°-28.48°-33.41°-38°, $sin^2\Delta\theta = 0.0758$
- *lgJ ∈[-9.0,-5.1]， ΔlgJ=-0.3*

Attenuation length



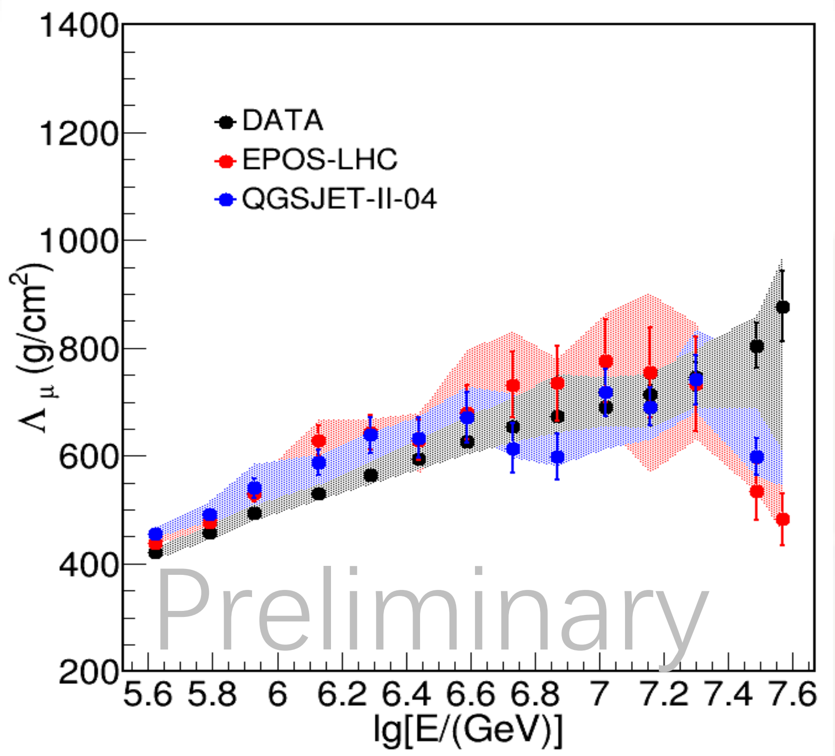
Attenuation length of different flux

- The bars represent the statistical error
- The shaded area represents the systematic error

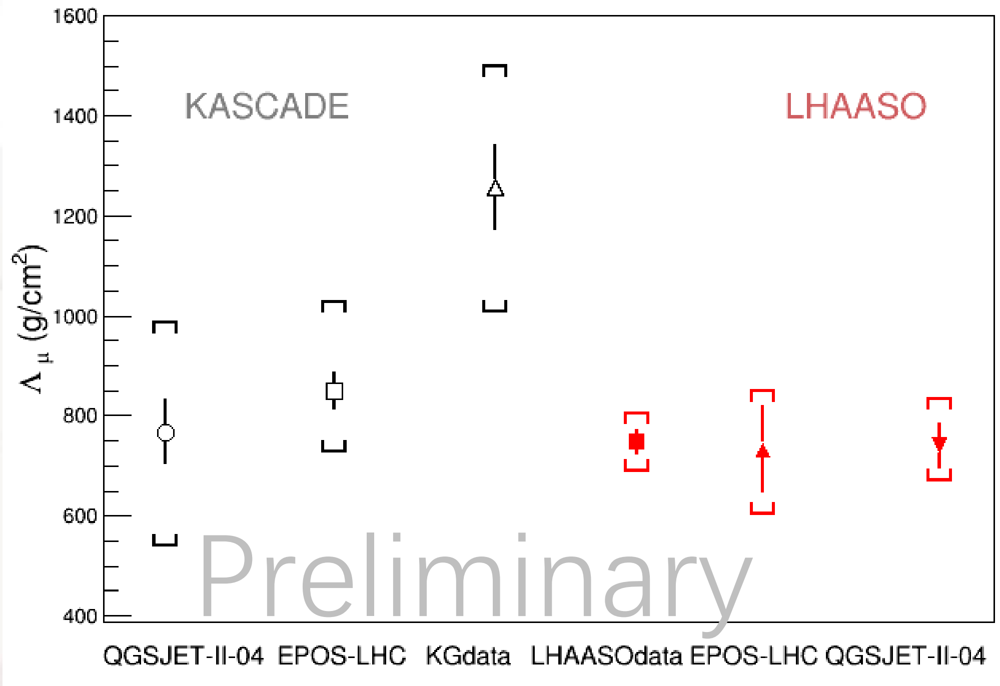
The attenuation length of muon @lgJ=-8.5

Systematics(%) Attenuation length(g/cm^2)		**DATA**	**EPOS-LHC**	**QGSJET-II-04**
$sin^2\Delta\theta$	0.07	3	4	3
	0.08	-0.1	-8	2
Fit four zenith angle bin	first four	-4	10	-6
	last four	-2	-8	11
Core distance	300-375m	6	0.2	2
	375-450m	-4	4	-2
integral bins number	30	0.4	-6	-3
	50	0.2	-5	-2
Atmospheric depth（g/cm^2）	614-657	-4		
	695-759	2		
Total		+7 -7	+11 -13	+11 -7
Baseline（0.075, 0°-38°, 300m-450m, 40, 600-738）		$747 \pm 26^{52}_{52}$	$733 \pm 86^{80}_{95}$	$740 \pm 46^{81}_{51}$

Attenuation length with energy



Attenuation length of different energy



The result of LHAASO and KASCADE(110m a,s,l, $E_\mu > 230 MeV$)(black is the result of KASADE， red is the result of LHAASO)

@lg(E/GeV)=7.31

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- The attenuation length of muon increases with energy
- $\Lambda_\mu = 747 \pm 26^{52}_{52}\ g/cm^2$ for data with lg(E/GeV)=7.31
- The results of LHAASO look match with simulated results of KASCADE.

summary

- No deviation in data measurement
  - After 1 PeV, the data becomes lighter
  - The fluctuations in the data are in agreement with the simulation
  - Presented the attenuation lengths of muon number from 100 TeV to 50 PeV

Thanks for your attention

Back up： systematic error

- Zenith angle bin

① $sin^2\Delta\theta = 0.07$： 0， 15.43°， 21.97°， 27.18°， 31.95°， 36.27°
② $sin^2\Delta\theta = 0.08$： 0， 16.71°， 23.99°， 29.86°， 35.09°， 40°

- Fit four zenith angle bin

① Fit: 0°， 15,98°， 22.91°， 28.48°， 33.41°
② Fit: 15,98°， 22.91°， 28.48°， 33.41°, 38°

- Distance from the shower core to the center of the array

① 300m-375m;
② 375m-450m

- The number of integral bins

① 30
② 50

- Atmospheric depth traversed by muons

① $X_0 * sec\theta = 614g/cm^2 - 657g/cm^2$ (9.97°-25.10°)
② $X_0 * sec\theta = 695g/cm^2 - 759g/cm^2$ (29.33°-38.65°)

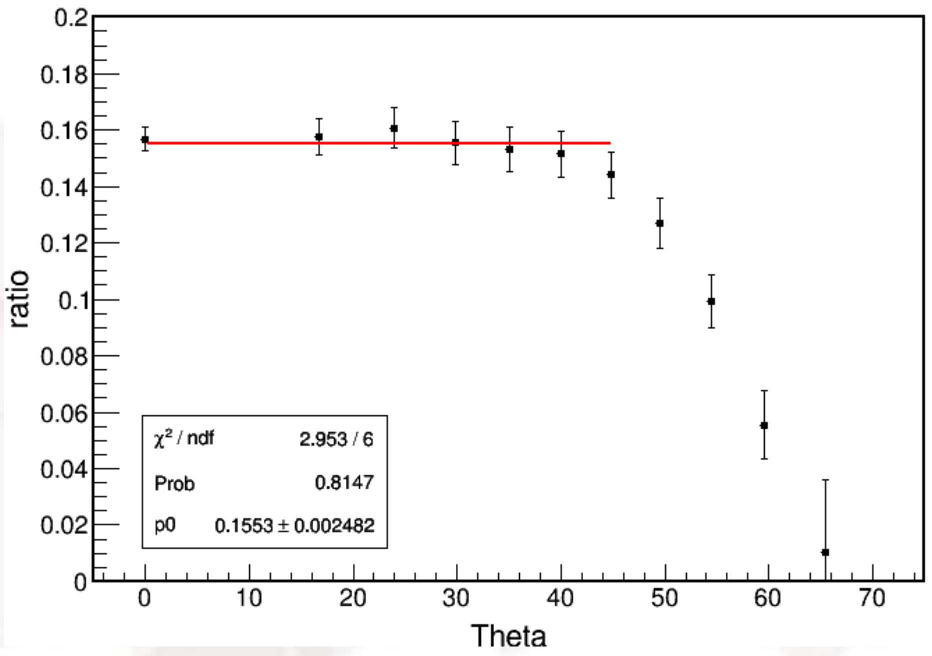
Back up : muon trigger

$$ratio = \frac{NhitM}{VEM}/events$$

NhitM: npe

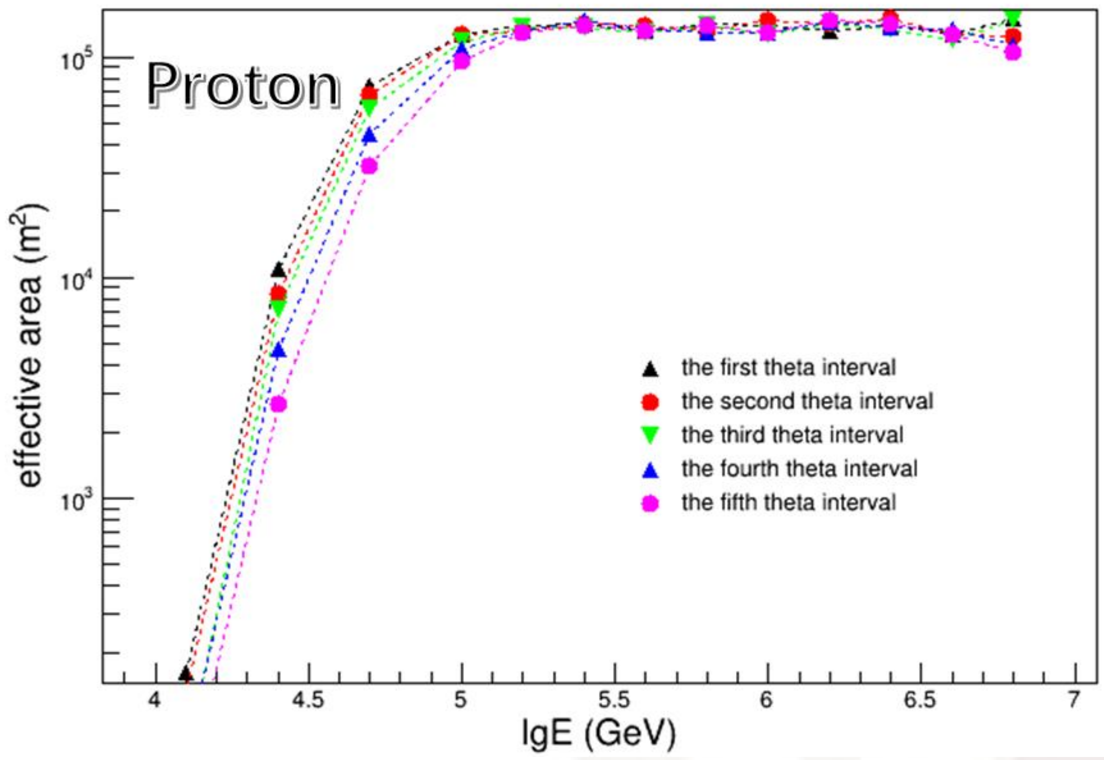
VEM:75

events: plotting points number



Muon trigger of same aperture

Back up : effective area



Effective area

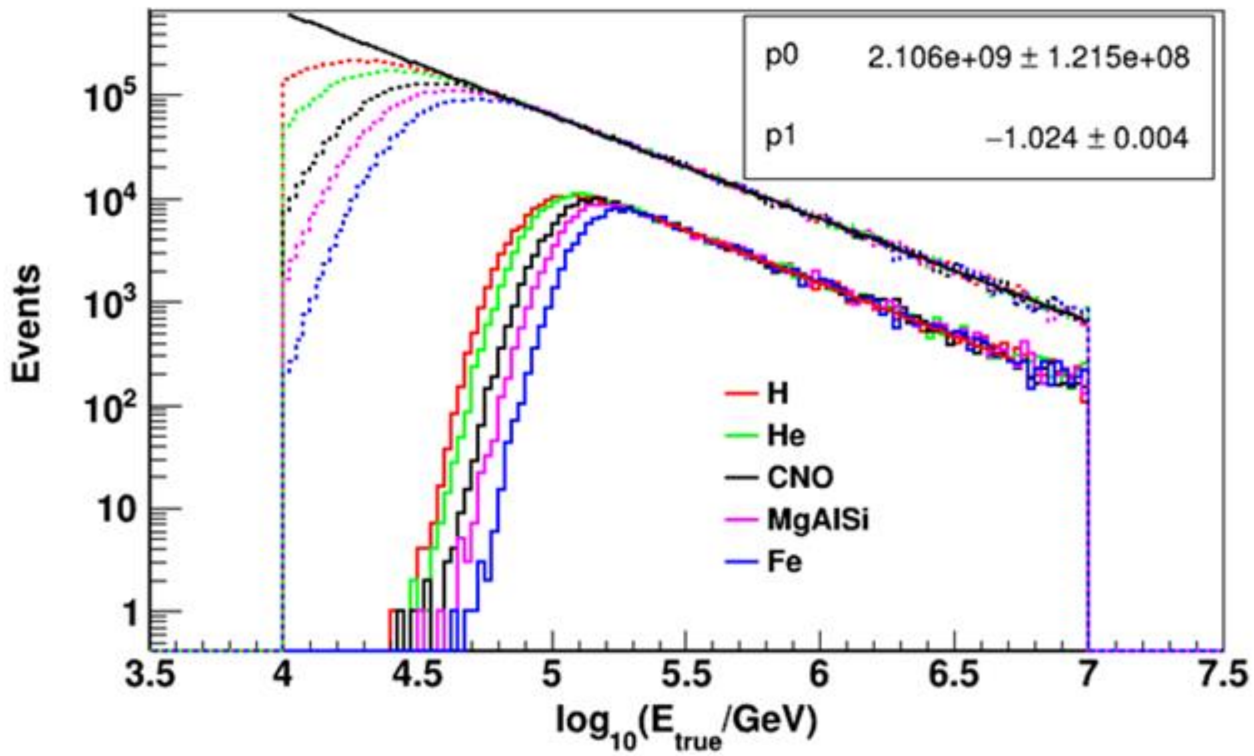
$$\text{effect} = \frac{Ncut}{Ntotal} * S$$

Ncut: The number of events after cut

Ntotal: CORSIKA plotting points number

S: total area

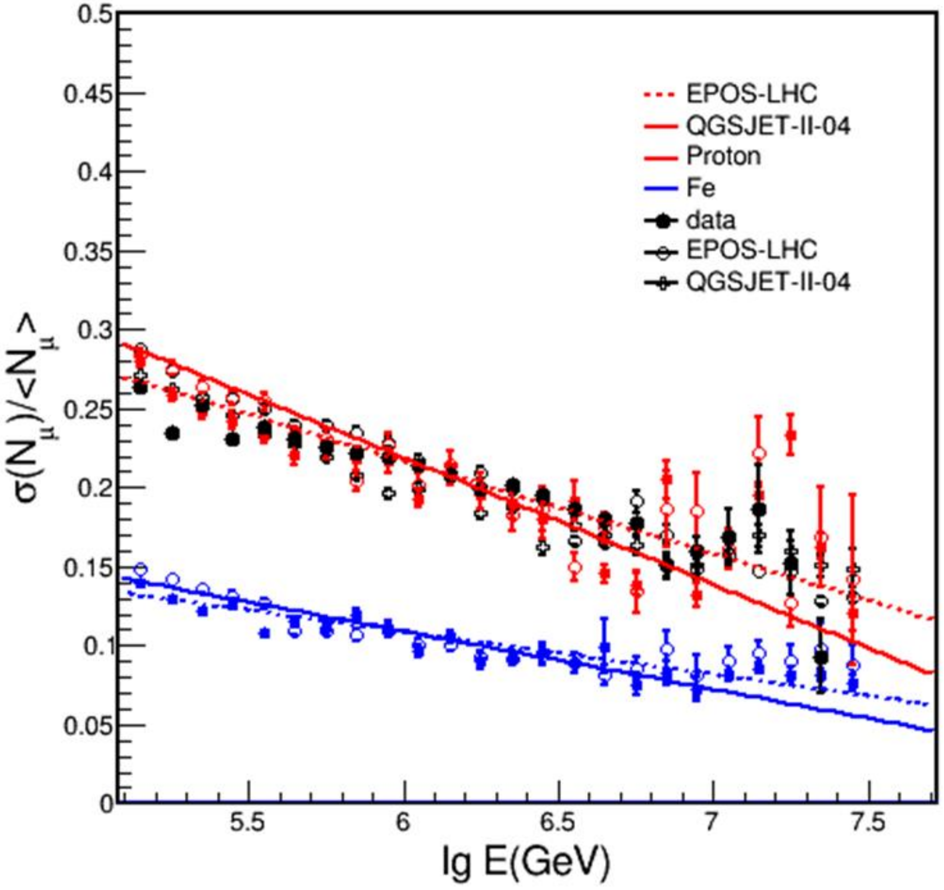
Back up : efficency



efficiency

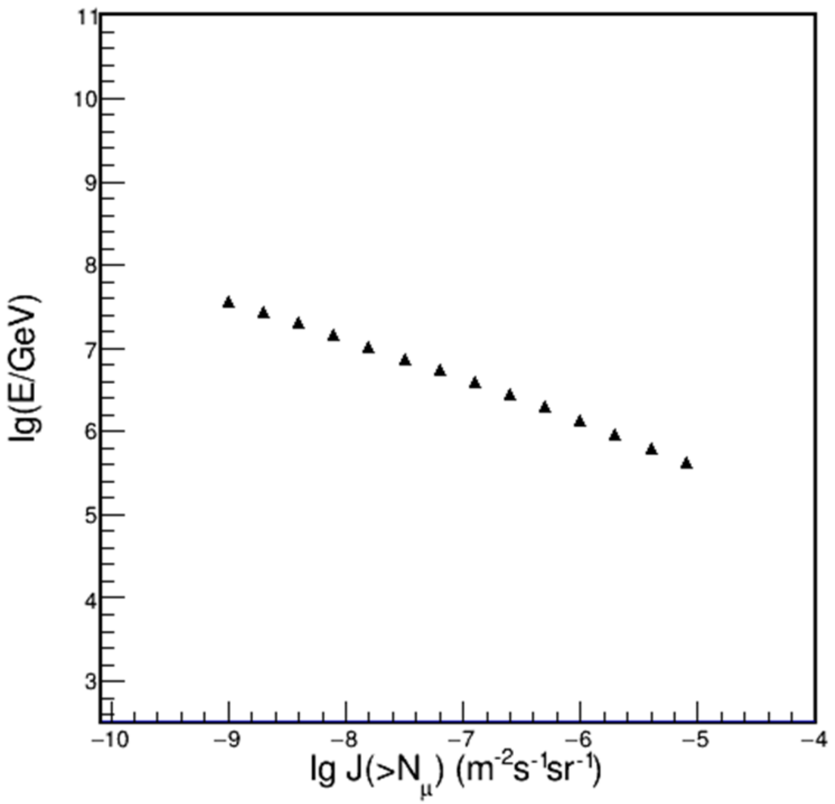
Full efficiency with lgE(GeV)>5.2

Back up : average muon content



average muon content

Back up : energy



Energy vs J

Back up : Pressure correction