Measurement of the attenuation length of muon in the air shower with muon detectors of LHAASO-KM2A

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Outline

- Motivation
- LHAASO and muon detector
- The muon attenuation length
- Conclusions

Motivation

- the muon in extensive air showers (EAS) play an important role for understanding air shower physics.
  - Muon carry information about hadronic interaction of EAS
  - The attenuation of muon affect the evolution of the muon content of EAS
- KASCADE-Grande find the deviation between data and MC.
  - shower energies between 20 PeV-100 PeV
- LHAASO has more than 1100 muon detectors(MD)
  - validate the attenuation length in different energy region

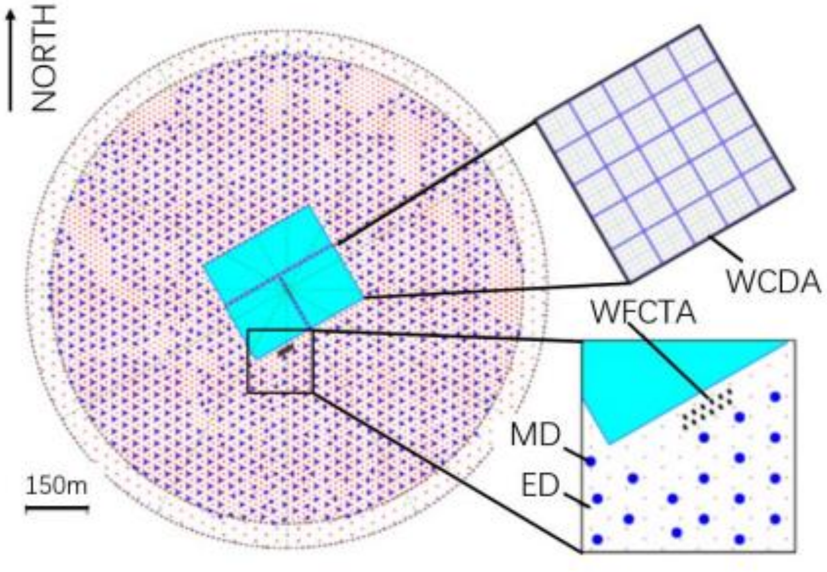
LHAASO and muon detector

Large High Altitude Air Shower Observatory, LHAASO

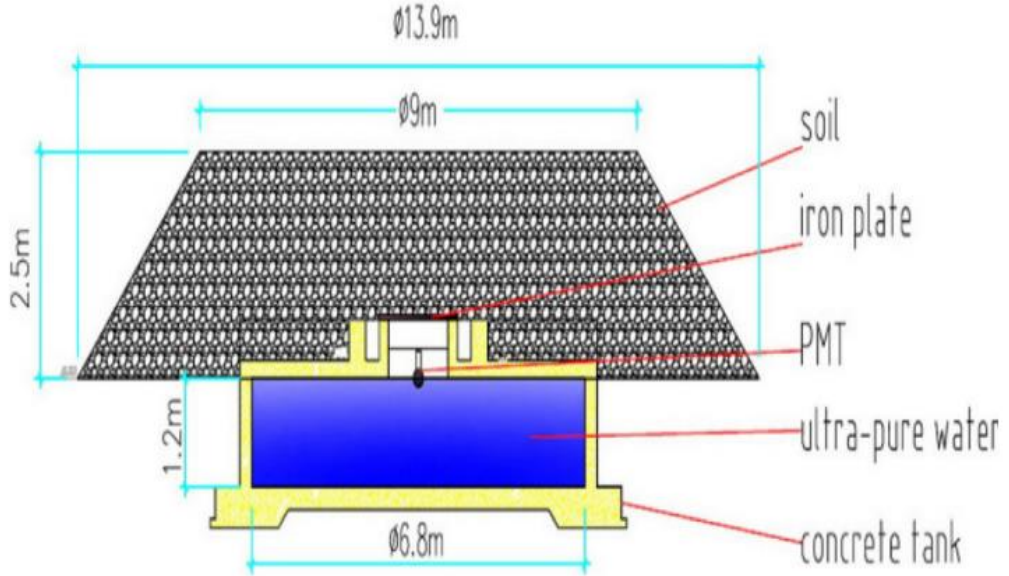
Daocheng SiChuan, altitude: 4410 m ($597 g/cm^2$)

KM2A covers an area of 1.3 km^2

- 1188 MDs with space 30 m
- 5216 electronic detectors (EDs) with space 15m



Layout of LHAASO



schematic of the LHAASO MD

The sensitive area is 36 m^2

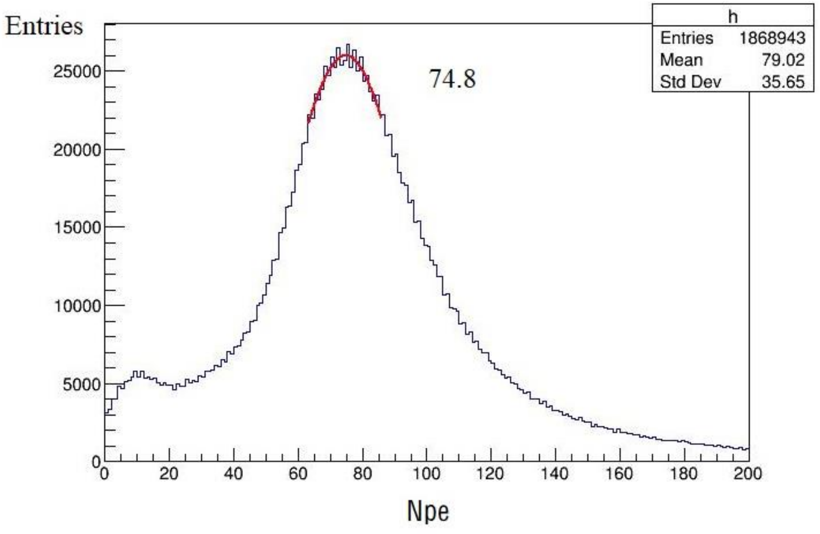
Ultra-pure water: diameter 6.8 m, height 1.2 m

PMT: 8 inches

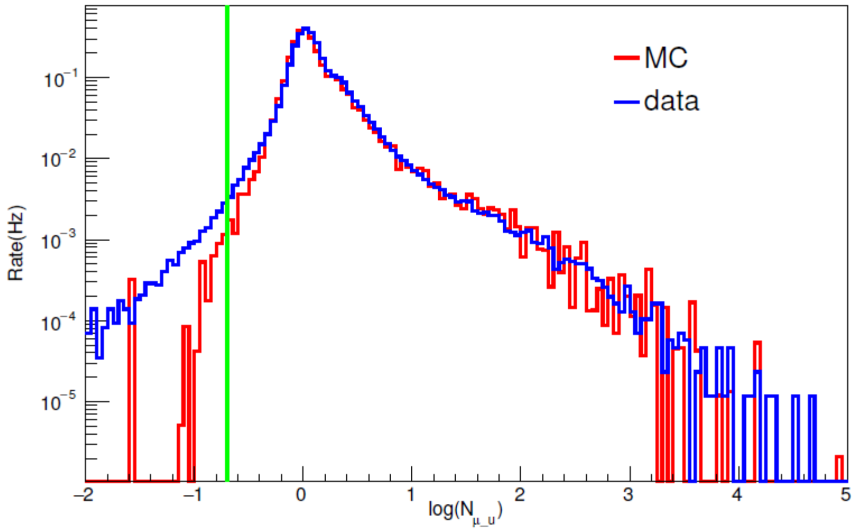
Covered with 2.5 m soil to absorb other charge particles

Cherenkov radiation

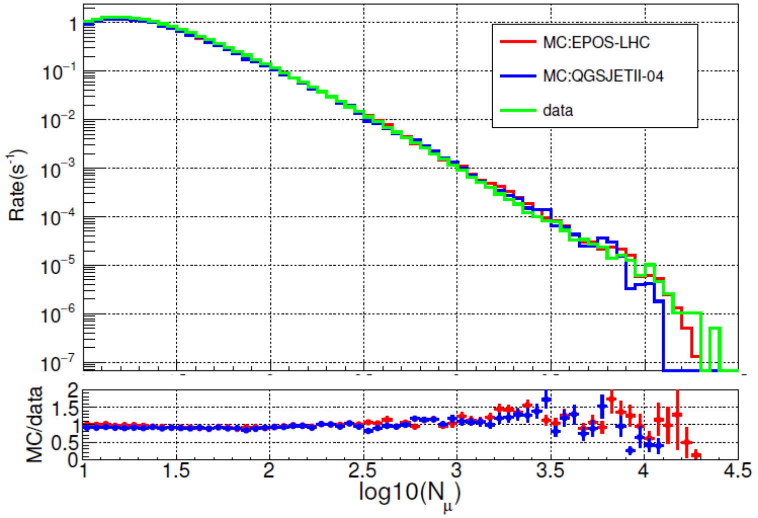
Validation of the muon detector



single muon peak



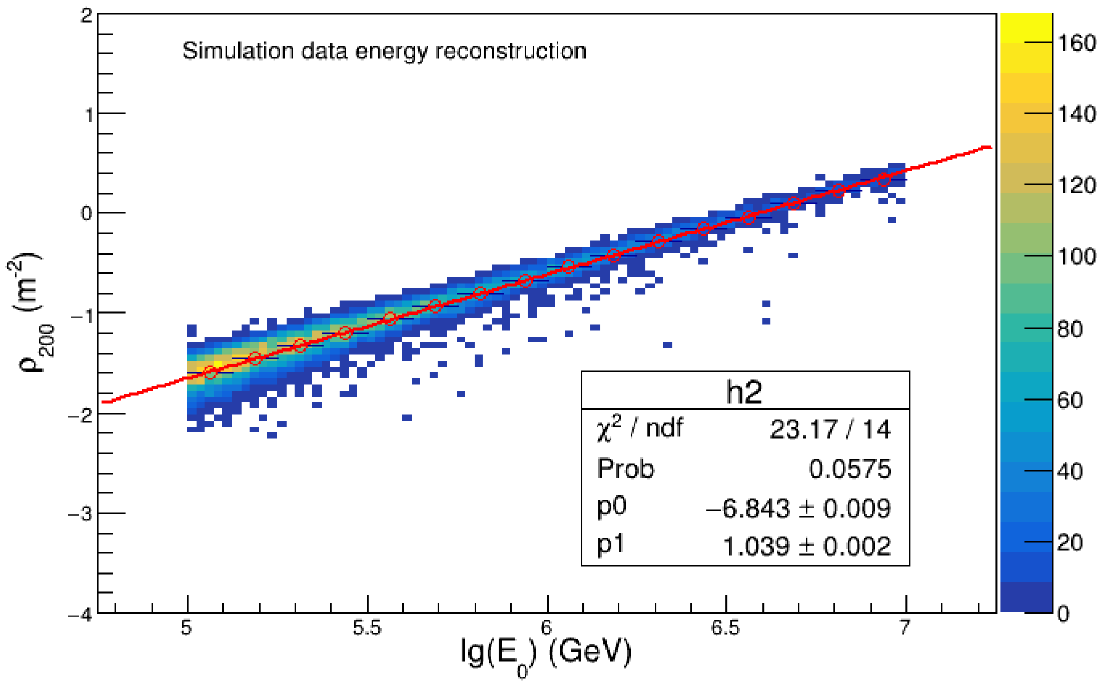
the muon number of unit detector



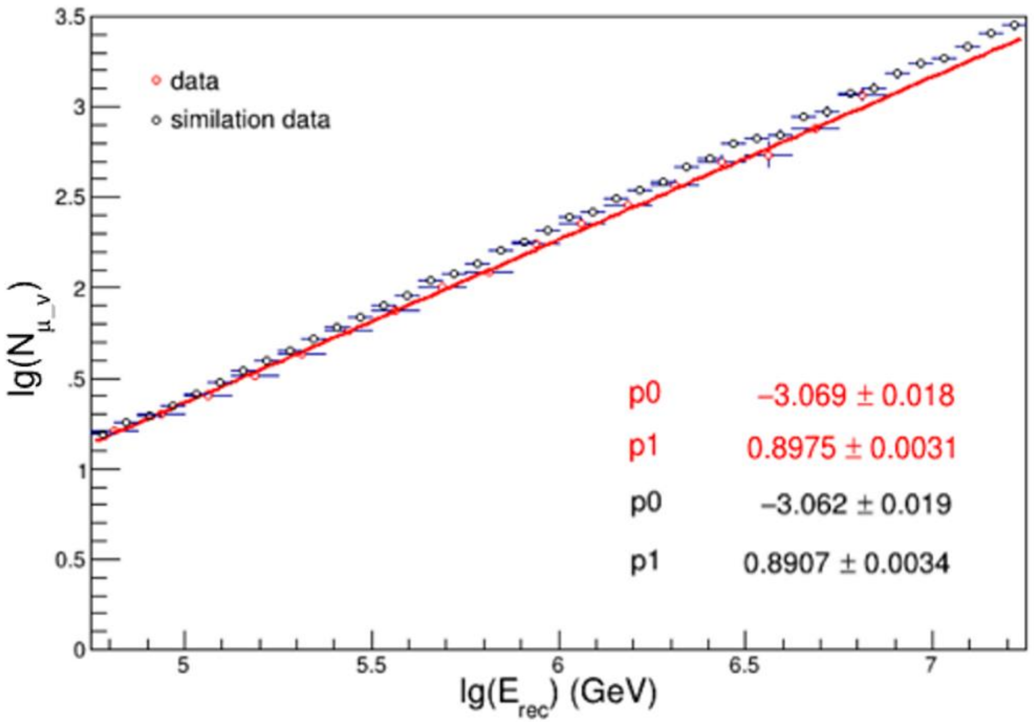
muon spectrum

- The single muon peak is used to calibrate the number of muons of the muon detector
- The muon number of unit detector > 0.2, data and simulation is consistent
- N_μ： the total muon number of all fired muon detector within the ring 40 m-200 m from the core of the shower
  - The muon spectrum is also consistent

$N_{\mu\_v} \sim E_{rec}$



$$lgE_{rec} = (lg\rho_{200} + 6.843)/1.04$$



the relationship between N_{μ_v} and E_{rec}

- the line relation between N_{μ_v} and E_{rec} (reconstruction energy, ρ_{200})
  - N_{μ_v}: the muon number (N_μ) of the near vertical event at the aperture[0,18.5°]
  - data is matched well with simulation
  - $\lg(N_{\mu\_v}) = -3.1 + 0.90 * lg(E_{rec})$ (data), $lg(N_{\mu\_v}) = -3.1 + 0.89 * lg(E_{rec})$ (simulation)

Data and event selection

R_p<=100m, (R_p: distance from shower core to array center)

NpE3>30 (NpE3: number of charge particle of ED within r=40-200 m)

N_μ >10

NtrigE >=30

The same cut conditions were used for data and simulated data to obtain high-quality events

Table： Statics of experimental and simulation data after cut

Model	QGS+Gheisha_ Proton	QGS+Gheisha_ Fe	EPOS+Fluka_ Proton	EPOS+Fluka_ Fe	All components of EPOS+Fluka	data
after cut	42,308	21,206	46,196	23,554	98,055	4.1M

Constant intensity cut

- The intensity of CR is isotropy
  - Under different zenith angles, the same intensity corresponds to same CR primary energy.
- The observed muon number at same flux varies as θ,
  - path increase as θ -> muon decay ->observed muon number decline

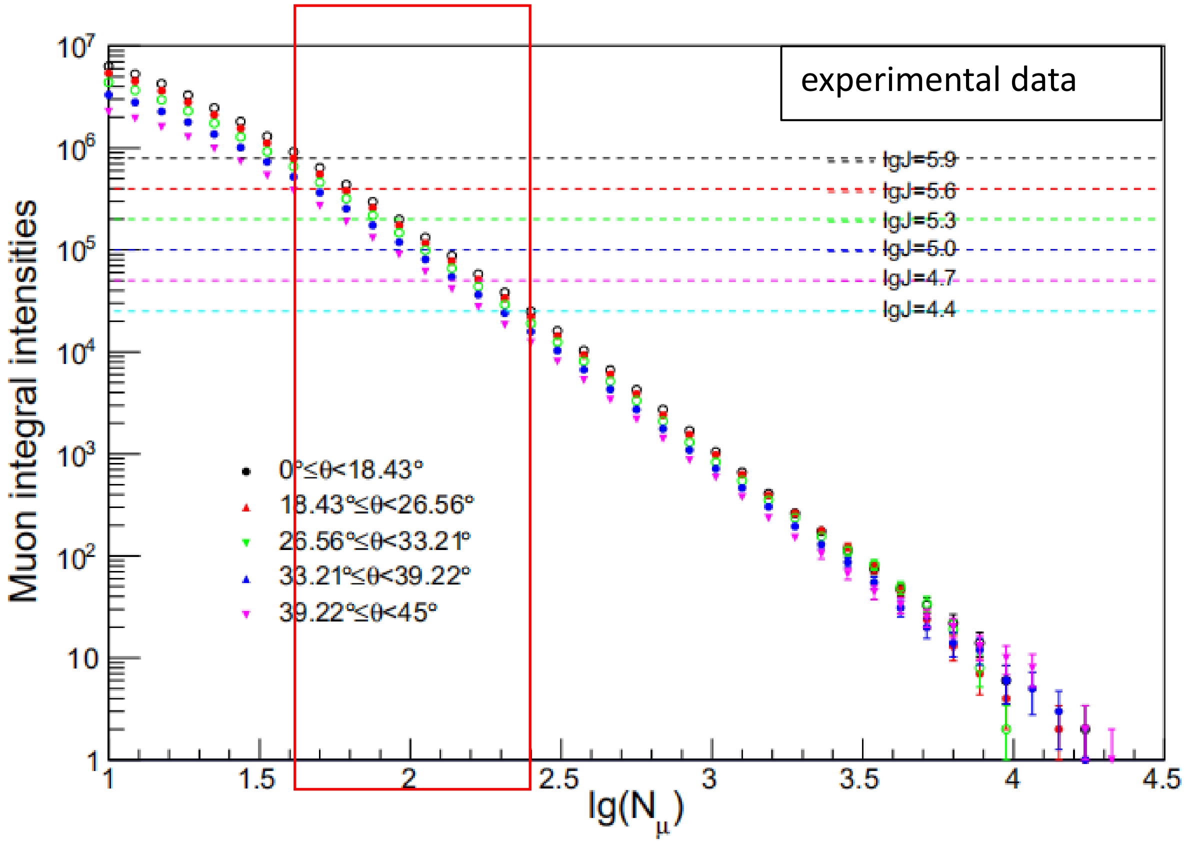
$$N_\mu(\theta) = N_\mu^0 e^{-X_0 sec\theta/\Lambda_\mu}$$

N_μ^0 is a normalization parameter to be determined for each attenuation curve

Λ_μ is the muon attenuation length, as an appropriate physical quantity to study the evolution of the muon content of EAS

X_0 is the average atmospheric depth for vertical shower at the LHAASO attitude for 597 g/cm^2

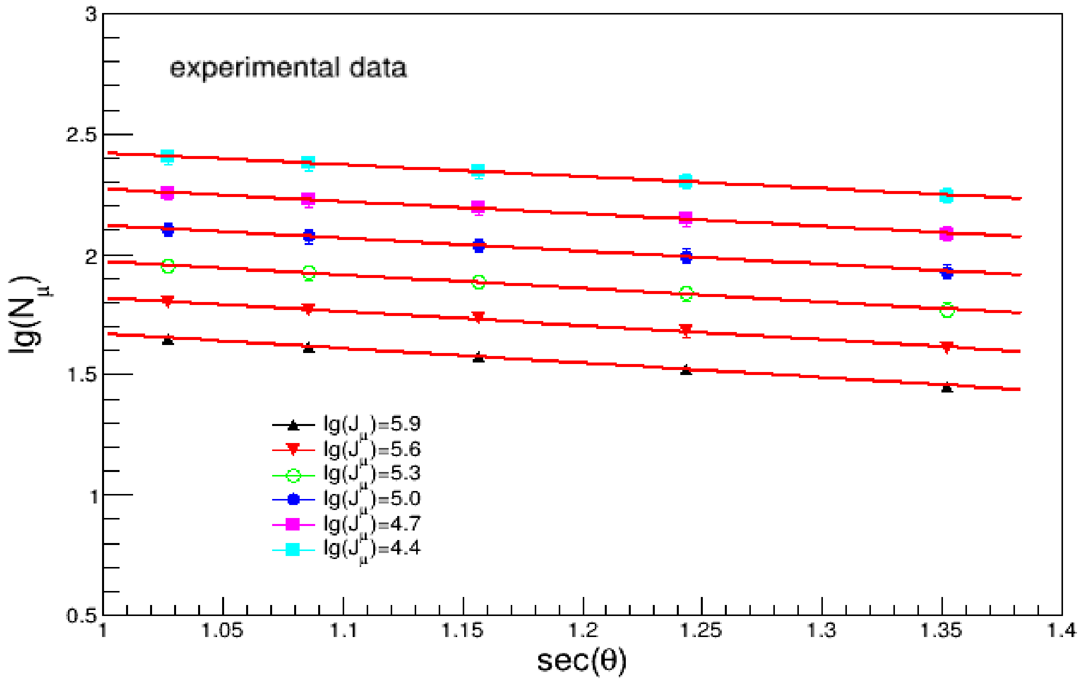
Constant intensity cut



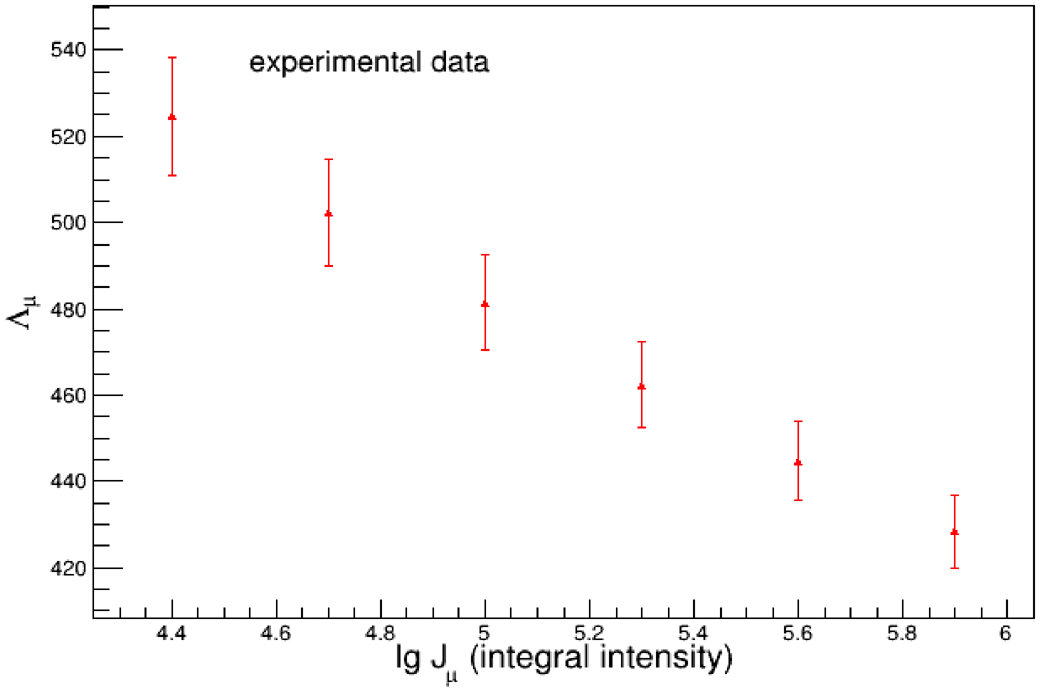
integral muon spectrum

- Five zenith-angle intervals with the same aperture： [0,18.5°], [18.5°, 26.5°], [26.5°, 33.2°], [33.2°, 39.2°], [39.2°, 45°]
- integral muon intensity J(>N_{μ},θ) for each angular bin
- the six intensity cut is performed within $\lg J \approx [4.4, 5.9]$ ΔlgJ=0.3
  - corresponding to N_μ wthinin $\lg(N_\mu) \approx [1.6,2.4]$
  - with full efficiency and maximum statistics

Muon attenuation length of experimental data



muon attenuation curves

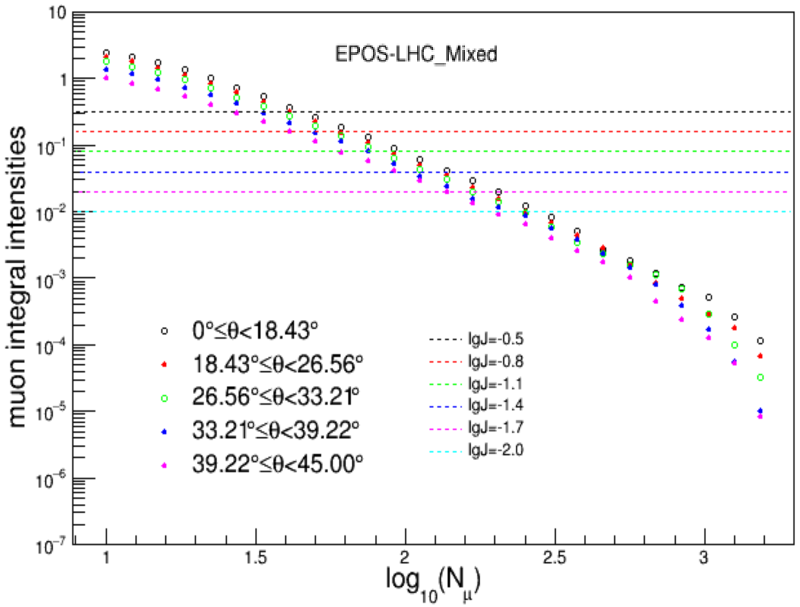


attenuation lengths distribution

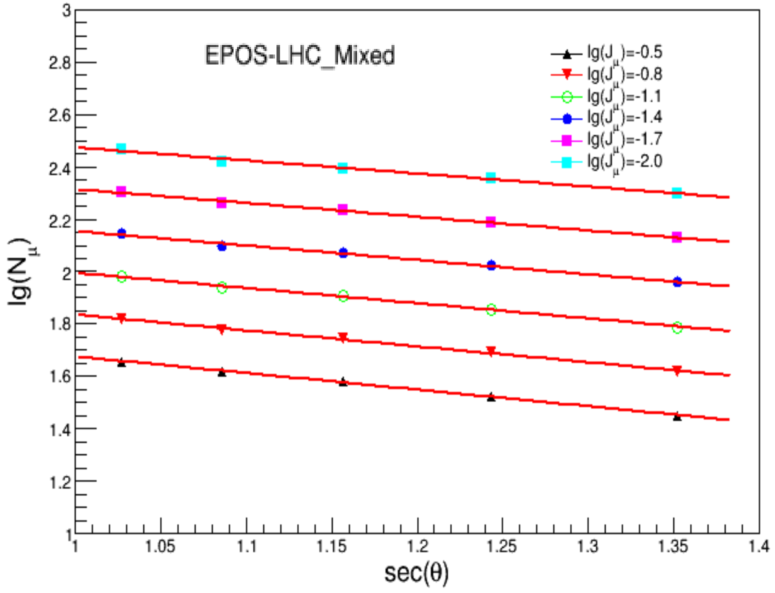
- the points with different colors corresponding to different integral intensity cut
- the slop of curve indicate the attenuation length
- attenuation length by fitting $N_{\mu\_v}(\theta) = N^0_{\mu\_v} e^{-X_0 sec\theta/\Lambda_\mu}$

- point represents the attenuation length, line represents the statistic error
  - the Λ_μ decrease as the J_μ increase
  - the larger J_μ correspond to smaller N_μ (means smaller energy)

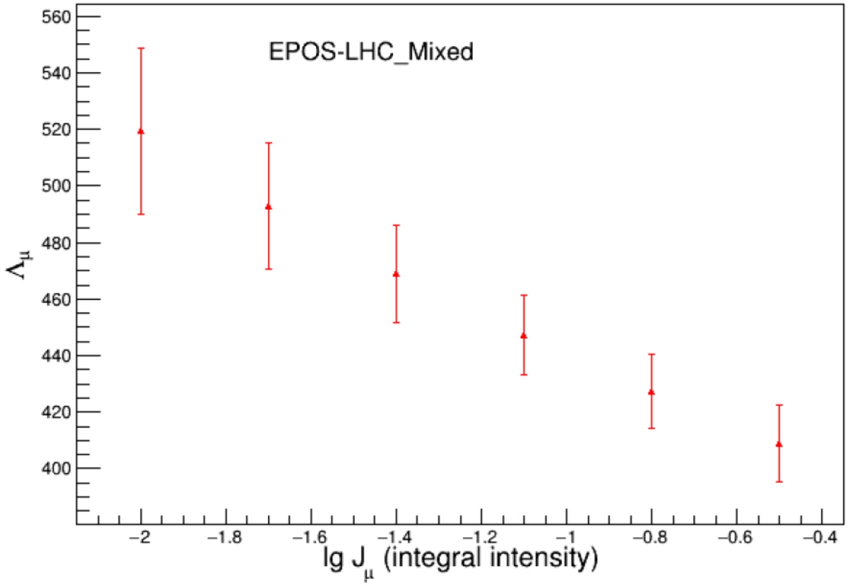
Muon attenuation length of simulation



integral spectrum



muon attenuation curves



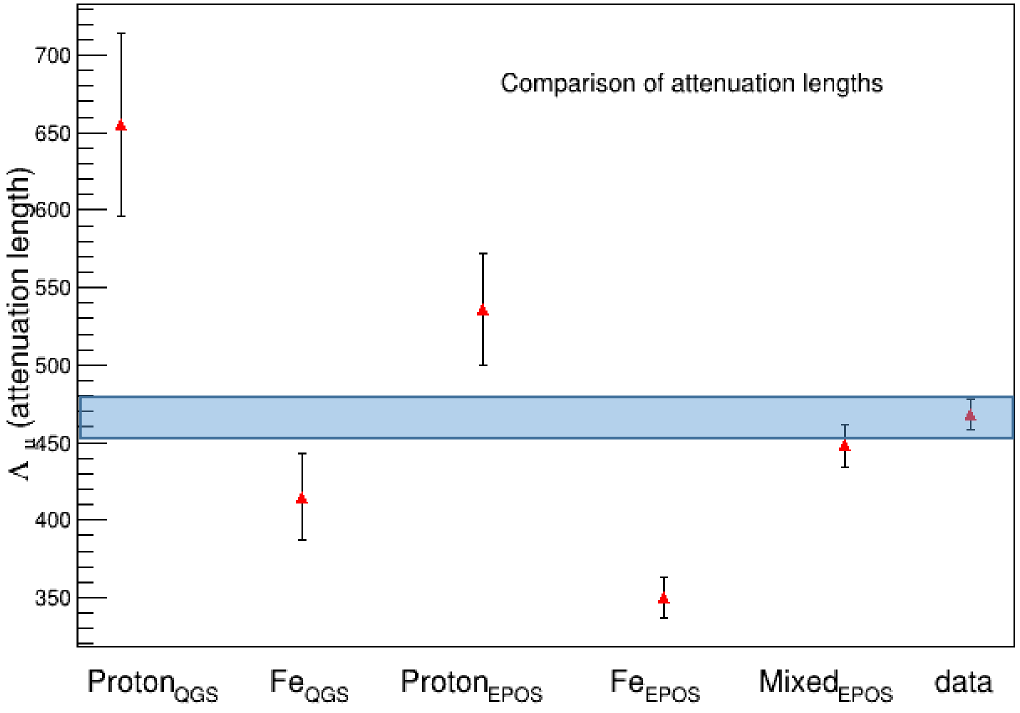
attenuation lengths distribution

- Mixed component following Gaisser CR spectrum
- Five zenith-angle intervals with the same aperture： [0,18.5°], [18.5°,26.5°], [26.5°, 33.2°], [33.2°, 39.2°], [39.2°,45°]
- $\lg(N_\mu) \approx [1.6, 2.4]$ of the same energy with data
- The trend of attenuation with J_μ similar between data and simulation

Check the muon attenuation length at 300TeV

Table: attenuation length of data and simulation

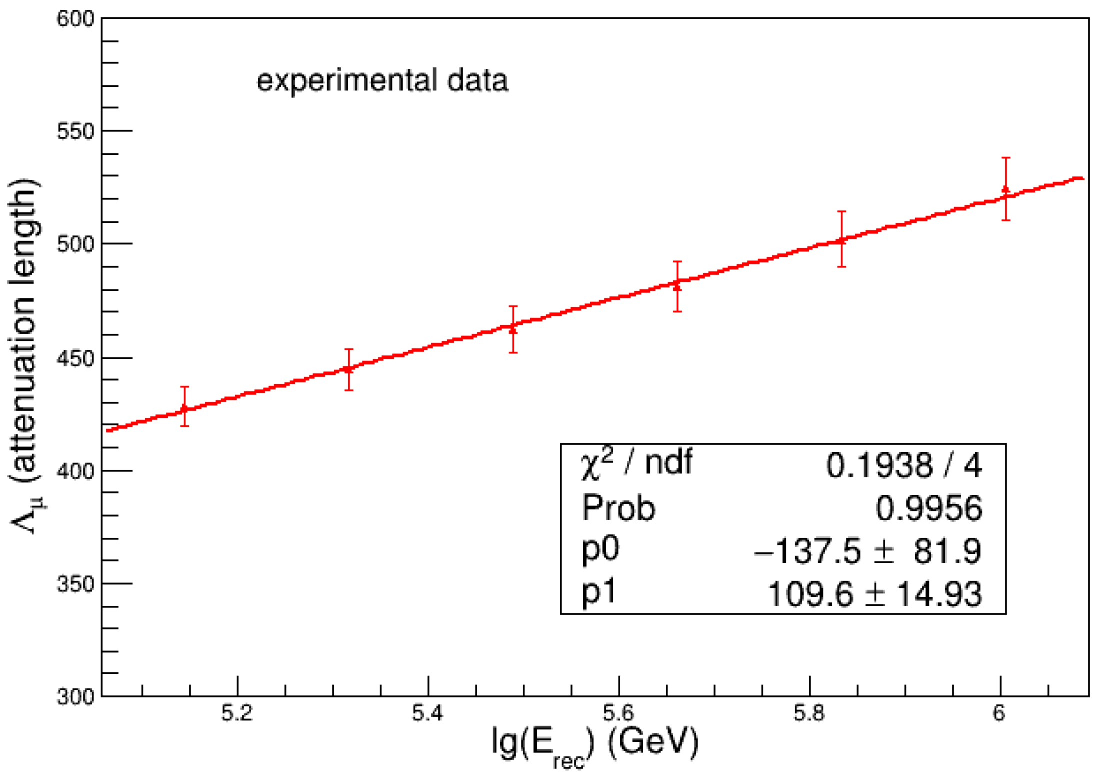
Model	attenuation length (g/cm^2)
QGS+Gheisha_Proton	655 ± 59
QGS+Gheisha_Fe	415 ± 28
EPOS+Fluka_proton	536 ± 36
EPOS+Fluka_Fe	350 ± 13
Mixed	448 ± 14
data	468 ± 10



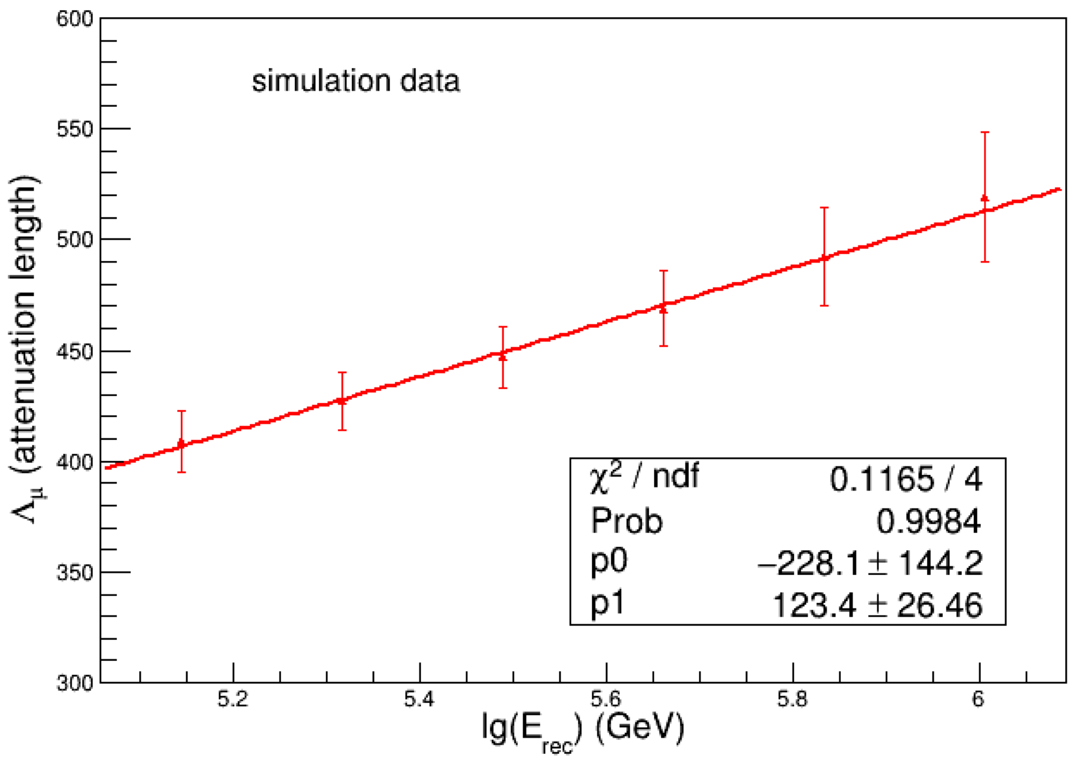
comparison of attenuation lengths

- The same method can be used to obtain the attenuation length of the simulation of other model
- The attenuation length of simulation data mixed components is consistent with the experimental data
- The attenuation length of experiment is located between the proton and iron for both hadronic model

Attenuation length varies with E



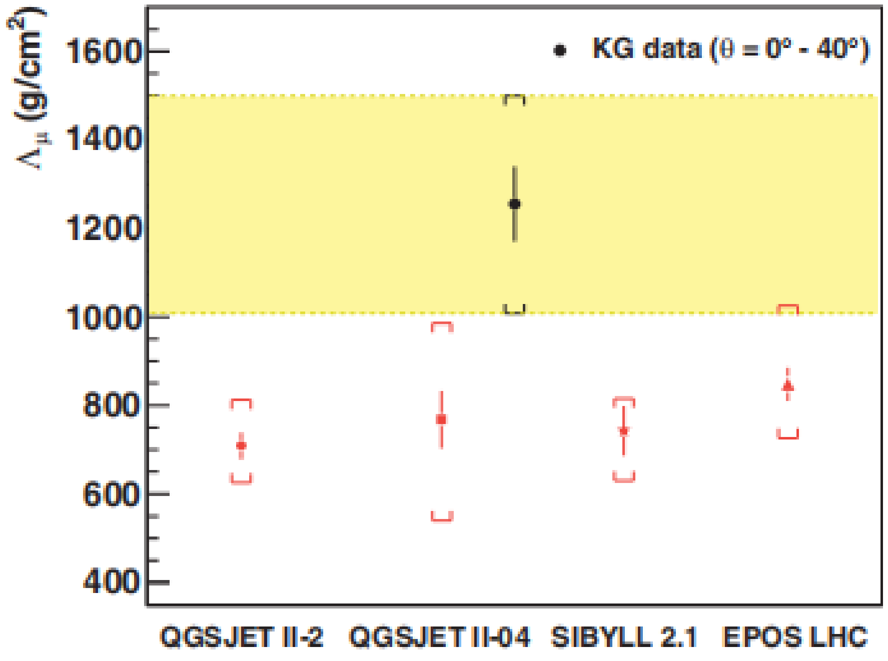
attenuation lengths of experiment



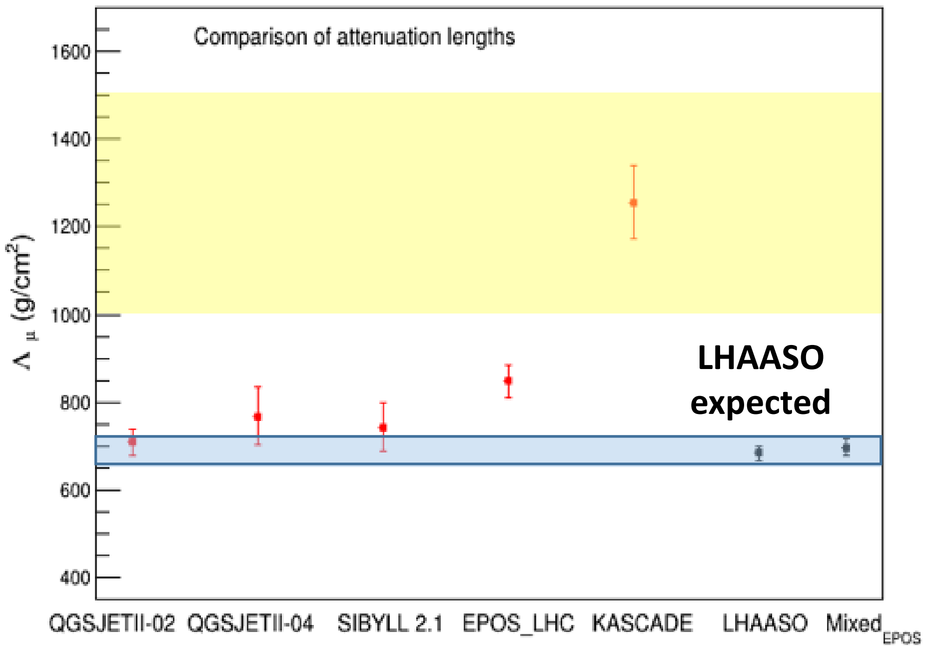
attenuation lengths of simulation

- Attenuation length increase as the reconstruction energy $\Lambda_\mu = -138 + 110 * \lg(E_{rec})$ (data)
- The increase trend of attenuation similar between data and simulation $\Lambda_\mu = -228 + 123 * \lg(E_{rec})$ (simulation)
- Using these formula extend all result to high energy such as KASCADE energy

Comparison of attenuation length



attenuation lengths of KASCADE



attenuation lengths comparison between KASCADE and LHAASO

- KASCADE experimental data shower energies between $10^{16.3}$ and $10^{17}eV$, $\Lambda_\mu = 1256 + 85^{+229}_{-232}\ g/cm^2$
- LHAASO data extended to $10^{16.5}\ eV$
  - expected $\Lambda_\mu = 684 + 10\ \ g/cm^2$ (data), $\Lambda_\mu = 697 + 14\ \ g/cm^2$ (simulation)
- Yellow area is KASCADE data and blue area is expected attenuation length of LHAASO data， the red point is KASCDE result and the black is our result
  - our attenuation length closed to the simulation results of KASCADE, but there is a significant deviation between the experimental results of KASCADE and LHAASO expect

Conclusions

- The attenuation length of the muon of experimental data are measured at diffirent flux cut

  No obvious deviation from MC
- The attenuation length increases as the energy of CRs
- Our expected results are consistent with KASCADE simulation results, but there is a significant deviation from its experimental results

thanks！

appendix:

Generation of simulation data:

Primary particle: Proton, iron, He, CNO, MgAlSi, (Gaisser model γ=-2)

High energy strong interaction model: EPOS-LHC ,QGSJETII-04

Low energy strong interaction model: Fluka, Gheisha

appendix:

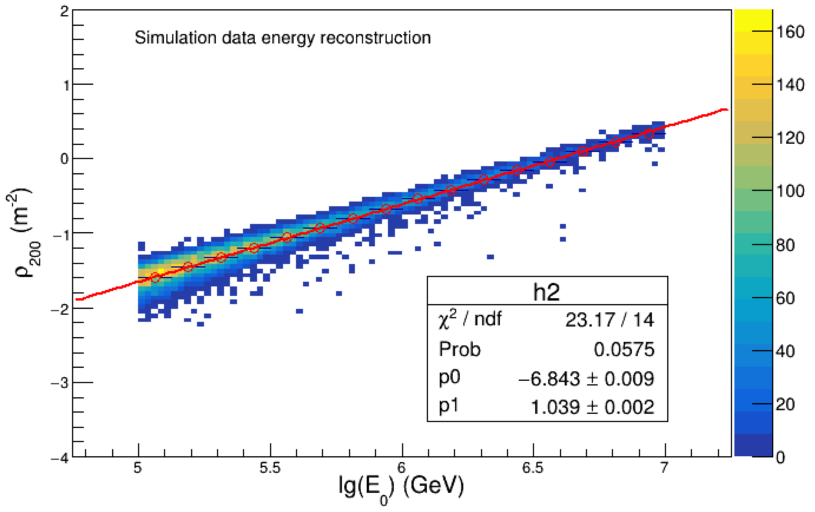
重建精度%	Proton	Fe	He	CNO	MgAlSi
10TeV-100TeV	22.76	6.26	17.27	11.02	10.05
100TeV-1PeV	19.12	7.38	15.37	11.78	9.12
1PeV-10PeV	12.33	8.1	9.71	8.38	9.96

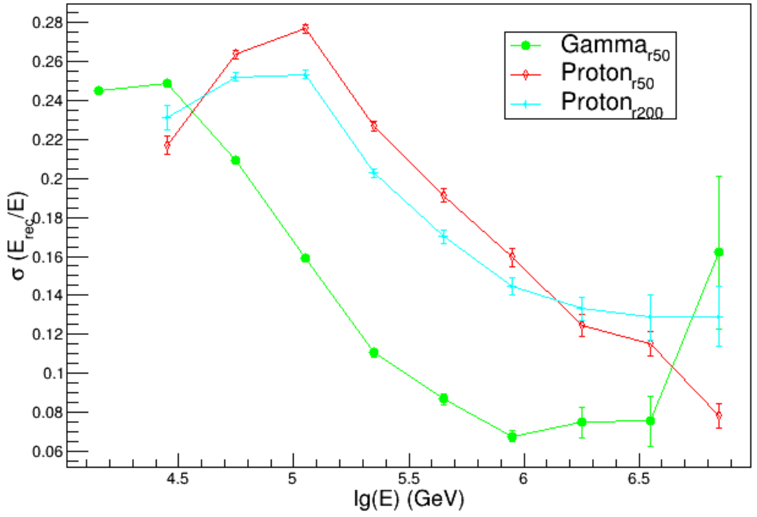
Energy reconstruction

- $lgE = a + blg\rho$
- ρ_{200} : Refers to the number density of detected electromagnetic particles 200 meters away from the shower core
- ρ_{200} Satisfy NKG function， $r_m = 130.0$， $r = 200$。

$$f\left(s,\frac{r}{r_m}\right) = \frac{\Gamma(4.5-s)}{\Gamma(s-0.5)\Gamma(5-2s)}\left(\frac{r}{r_m}\right)^{s-2.5}\left(1+\frac{r}{r_m}\right)^{s-4.5} \qquad \rho_e(r,s,N_e) = \frac{A \cdot N_e}{r_m} f\left(s,\frac{r}{r_m}\right)$$

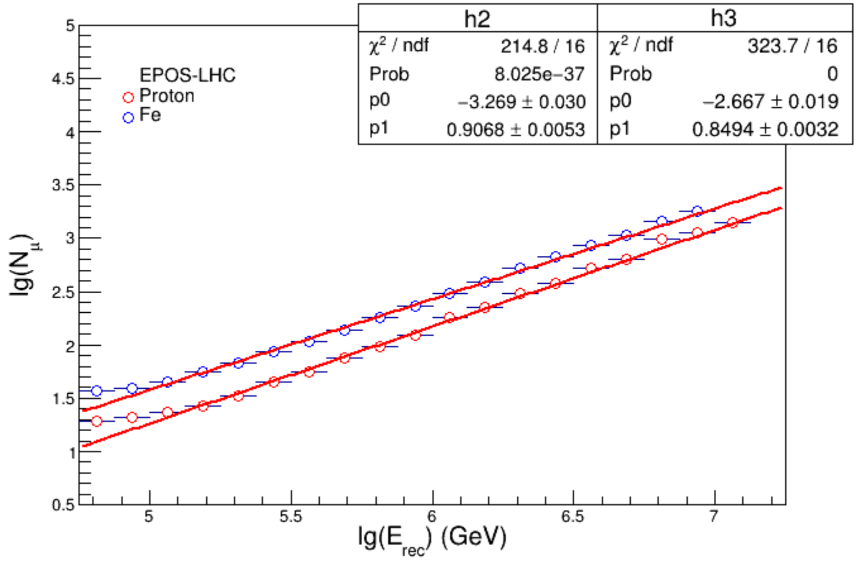
- The relationship coefficient between energy and density is $lgE = (lg\rho + 6.843)/1.04$; the energy reconstruction accuracy can be obtained

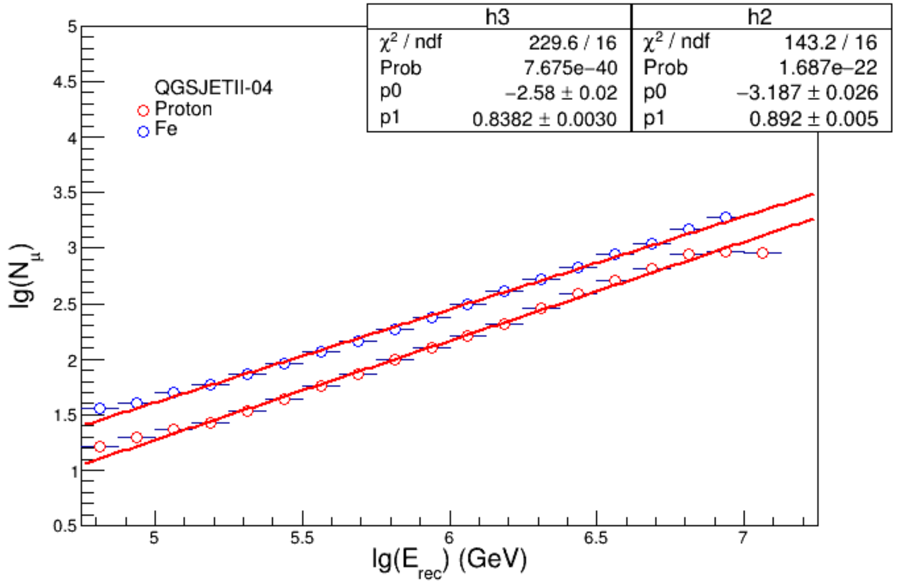




appendix:

Energy reconstruction



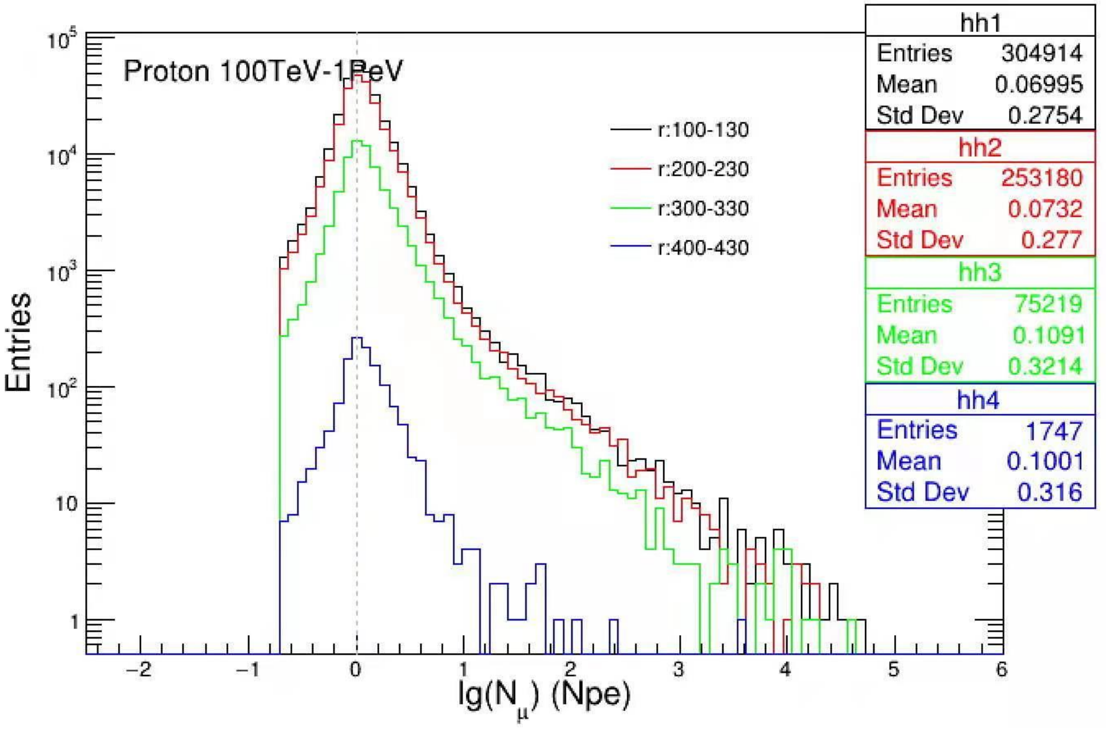


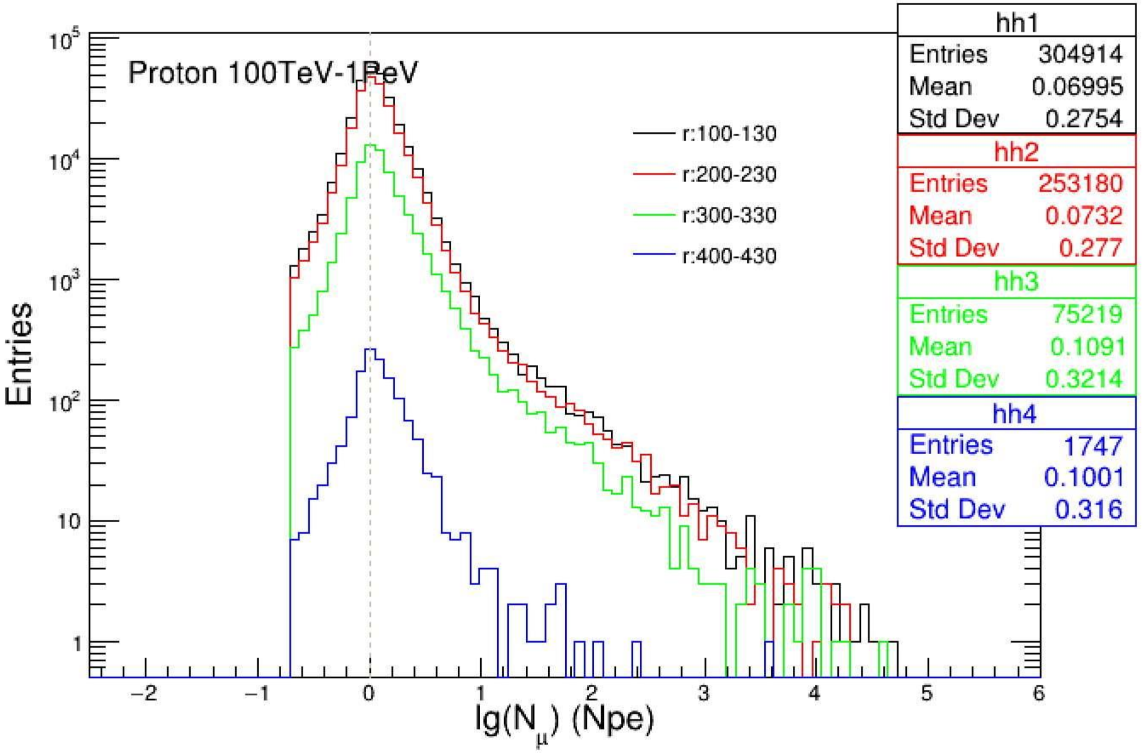
The theta<18° of the relationship between reconstruction energy and Nu

Select the reconstruction energy as $\lg(E_{rec}) = 5.5$

Model $\lg(E_{rec}) = 5.5$	EPOS_LHC		QGSJETII-04	
	Proton	Fe	Proton	Fe
$\lg(N_\mu)$	1.7	2.0	1.7	2
$\lg(J_\mu)$	-1.3	-1.7	3.1	3.1
Λ_μ	536±36	350±13	655±59	415±28

appendix:

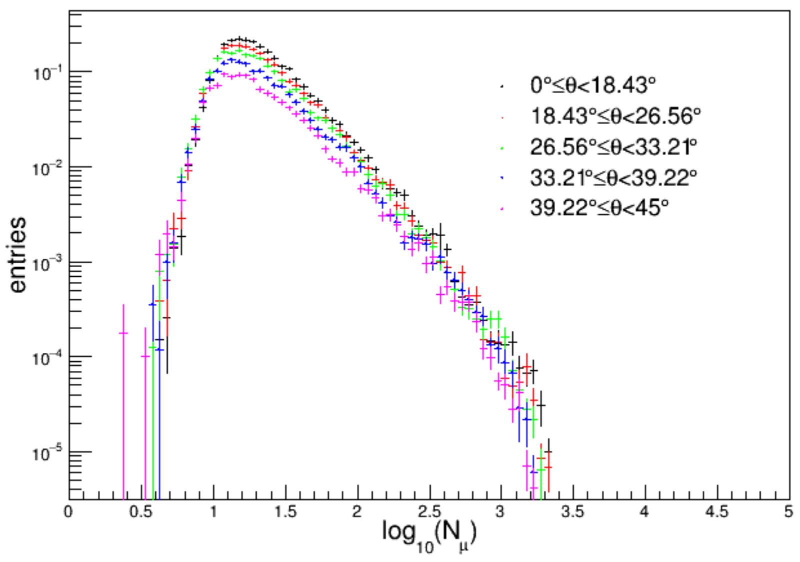




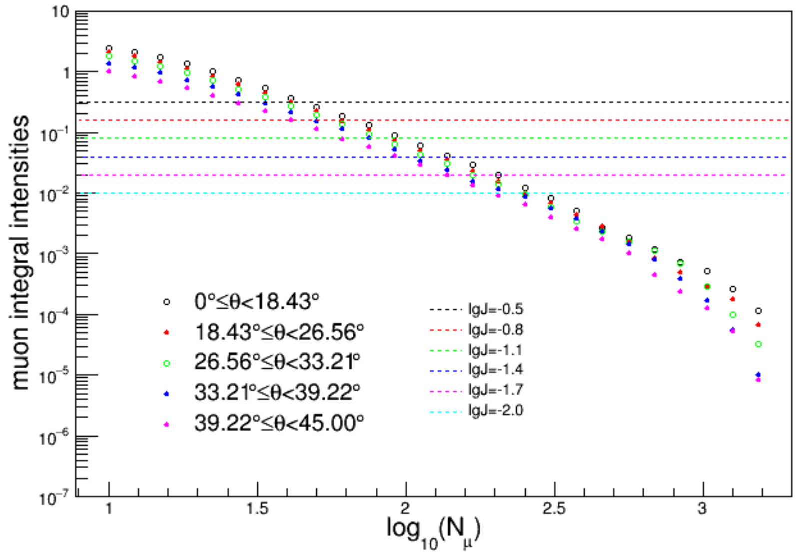
Particle energy:100TeV-10PeV
Primary particle: Proton, Fe
theta: 0-45°

- Different shower cores are selected , the peak values of muon of unit detector are the same
- The detector ring measuring muons has no effect on the measurement of muons

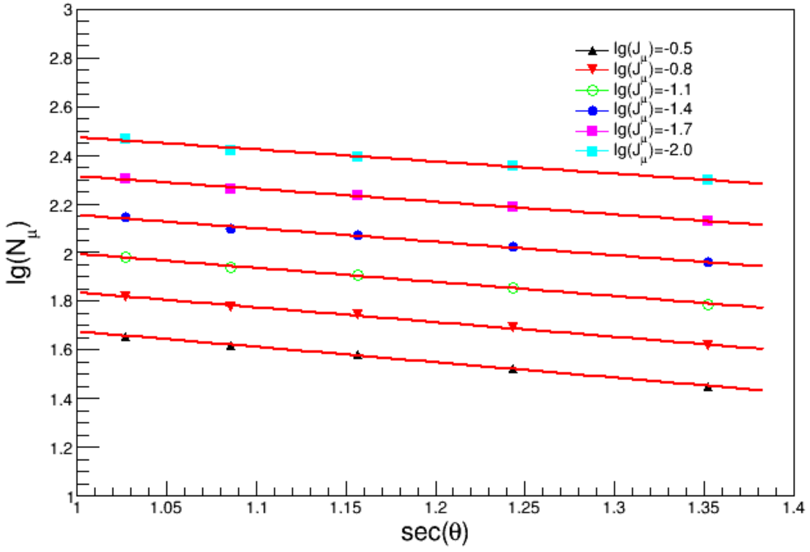
appendix:MC



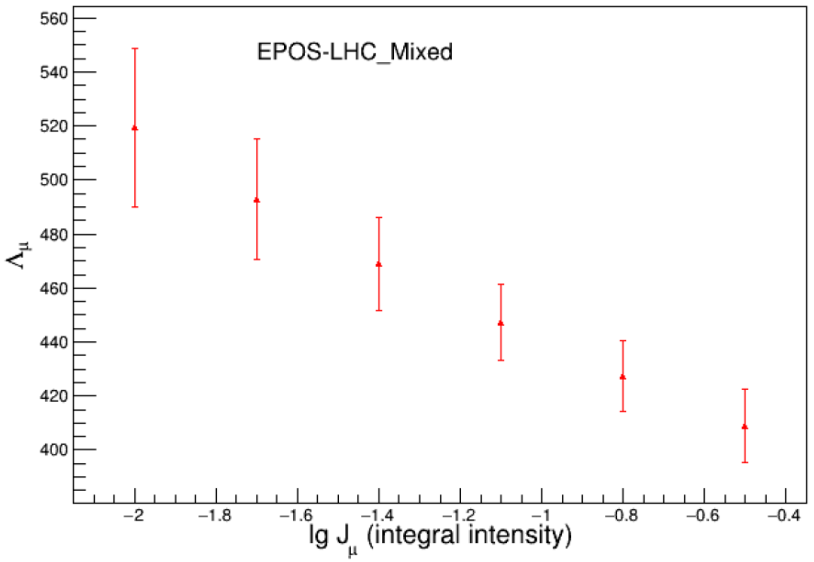
entries
log10(Nμ)
0°≤θ<18.43°
18.43°≤θ<26.56°
26.56°≤θ<33.21°
33.21°≤θ<39.22°
39.22°≤θ<45°



muon integral intensities
log10(Nμ)
0°≤θ<18.43°
18.43°≤θ<26.56°
26.56°≤θ<33.21°
33.21°≤θ<39.22°
39.22°≤θ<45.00°
lgJ=-0.5
lgJ=-0.8
lgJ=-1.1
lgJ=-1.4
lgJ=-1.7
lgJ=-2.0

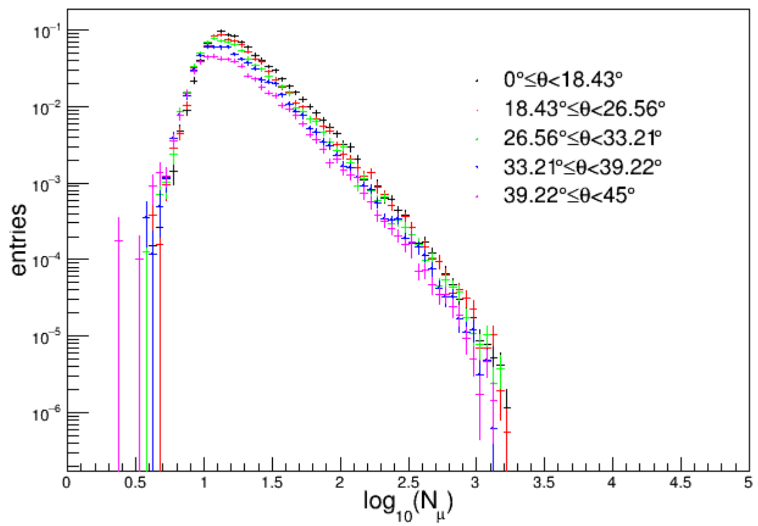


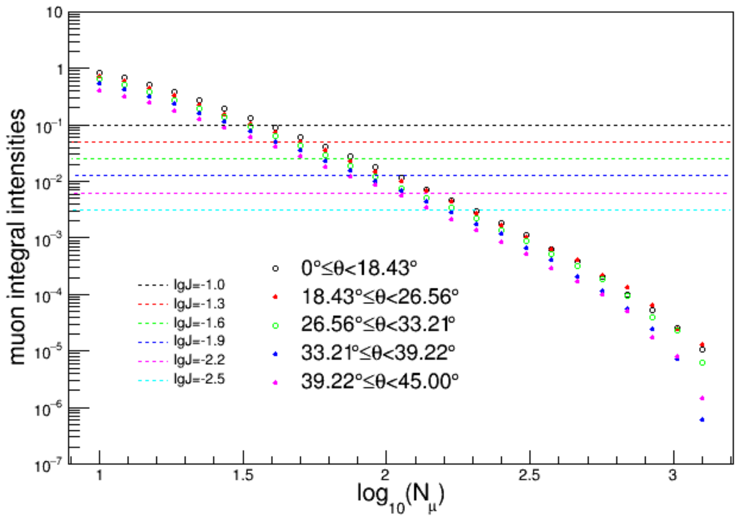
lg(Nμ)
sec(θ)
lg(Jμ)=-0.5
lg(Jμ)=-0.8
lg(Jμ)=-1.1
lg(Jμ)=-1.4
lg(Jμ)=-1.7
lg(Jμ)=-2.0

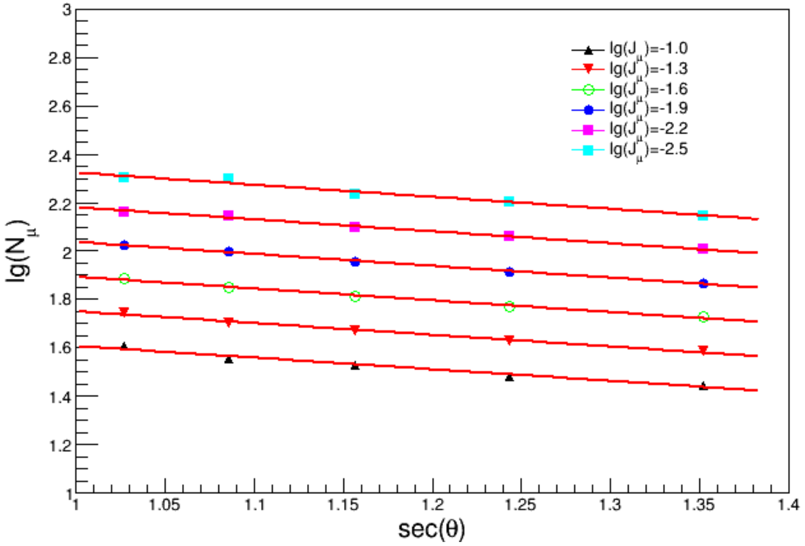


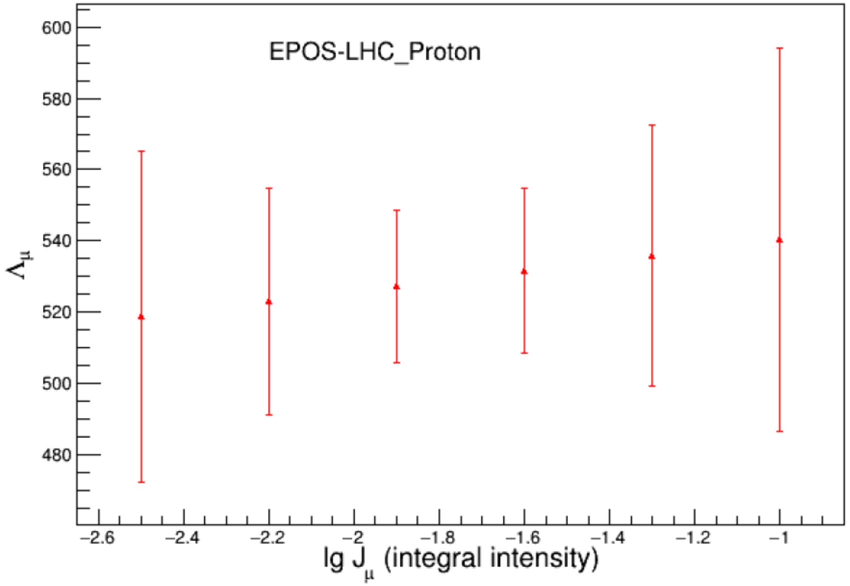
EPOS-LHC_Mixed
Λμ
lg Jμ (integral intensity)

appendix:EPOS_Proton

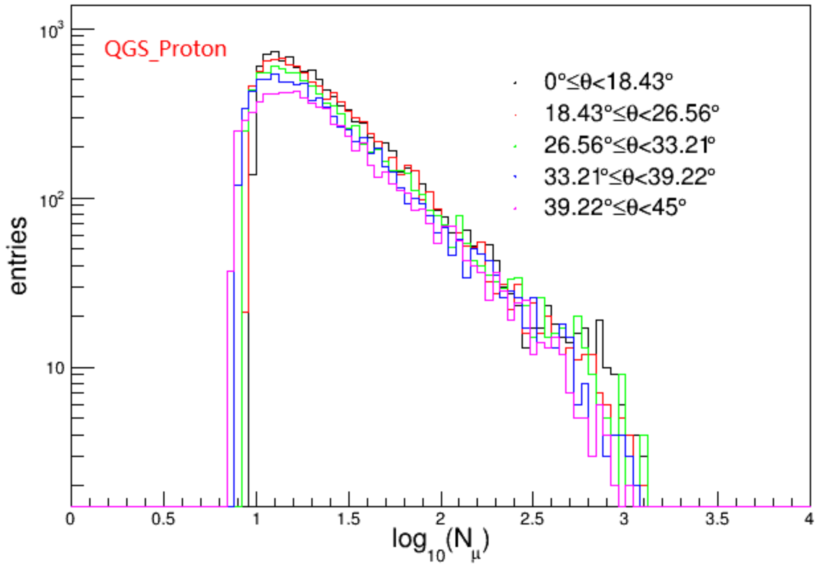


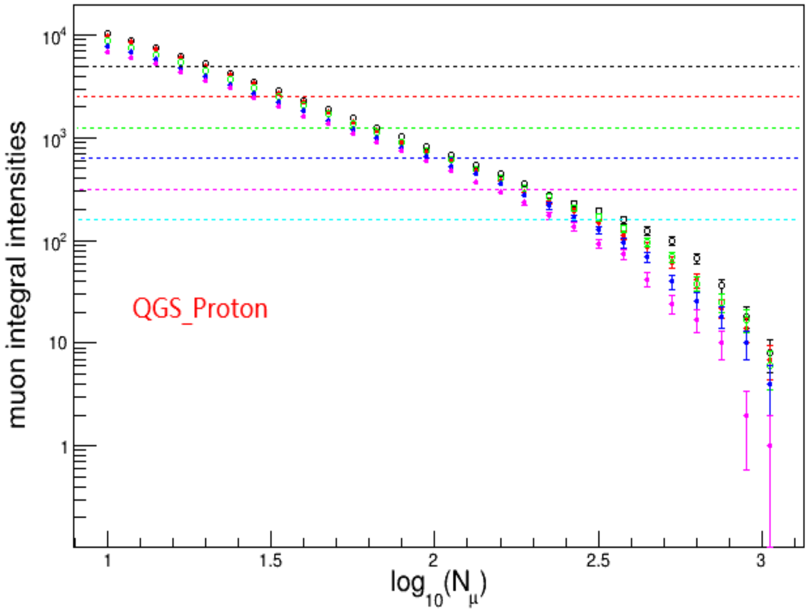


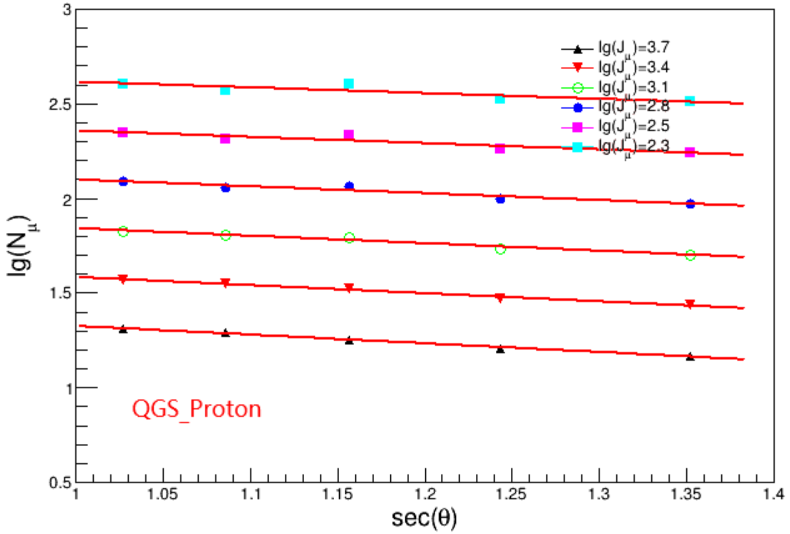


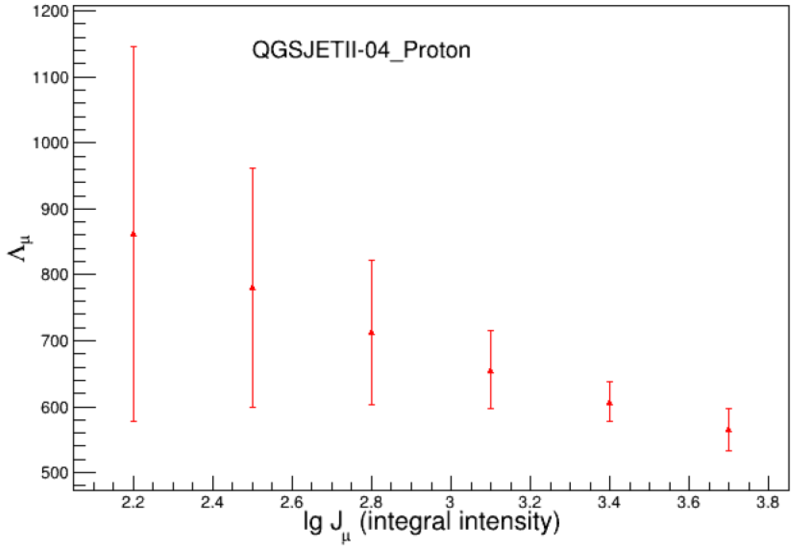


appendix:QGS_Proton









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