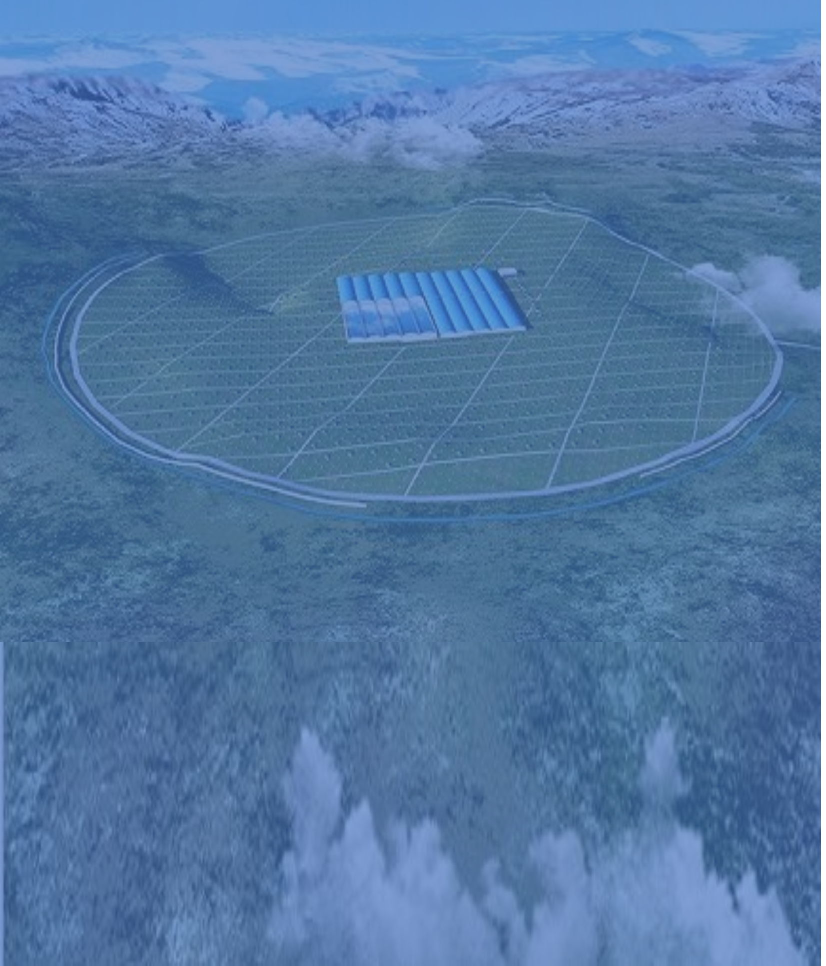
Study of Muon Content Evolution in very High Energy Cosmic Ray Air Showers with LHAASO-KM2A

Xiaoting Feng, Cunfeng Feng , Hengying Zhang, Lingling Ma on behalf of LHAASO collaboration

Xichang 25/08/2025

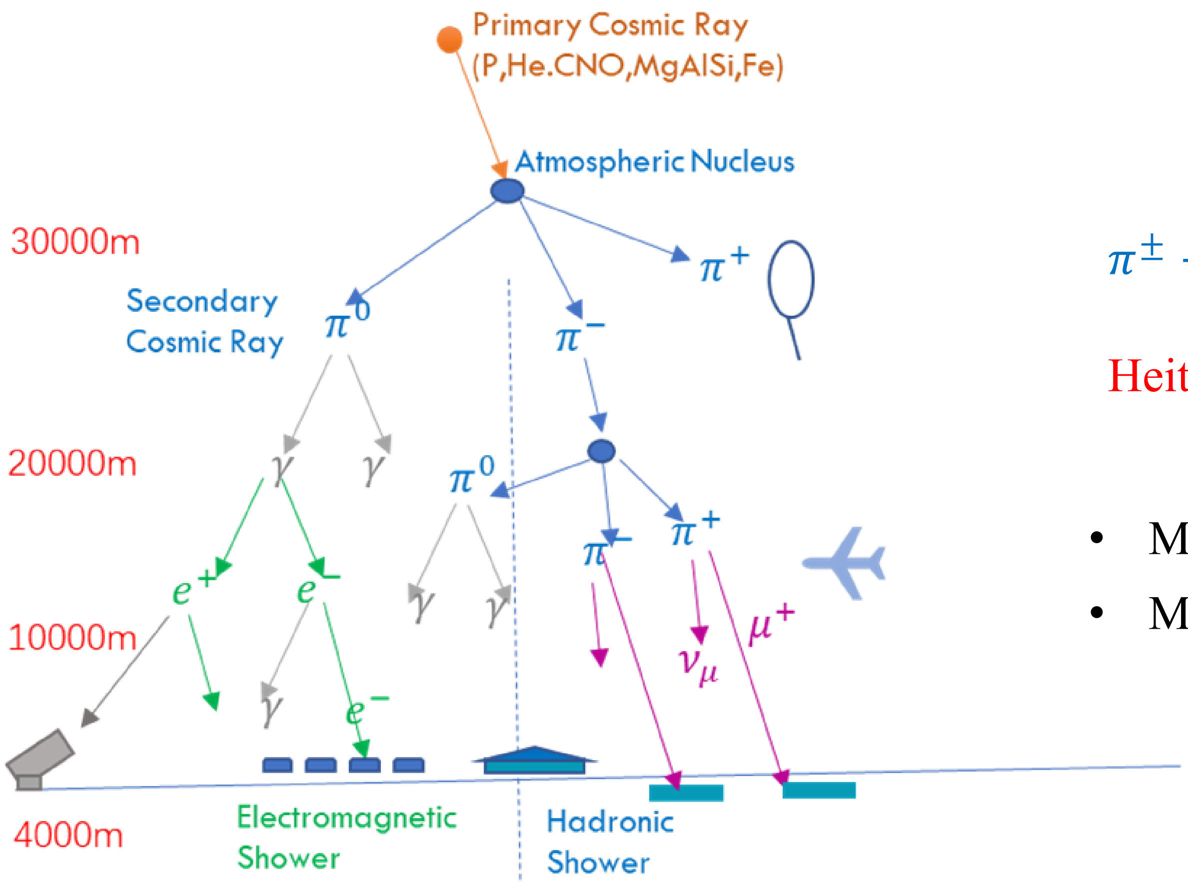
TAUP 2025
19th International Conference on Topic in Astroparticle
And Underground Physics 2025.8.24 - 8.30

Contents



1. Introduction

- CRs composition and EASs



$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$ and $K^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$

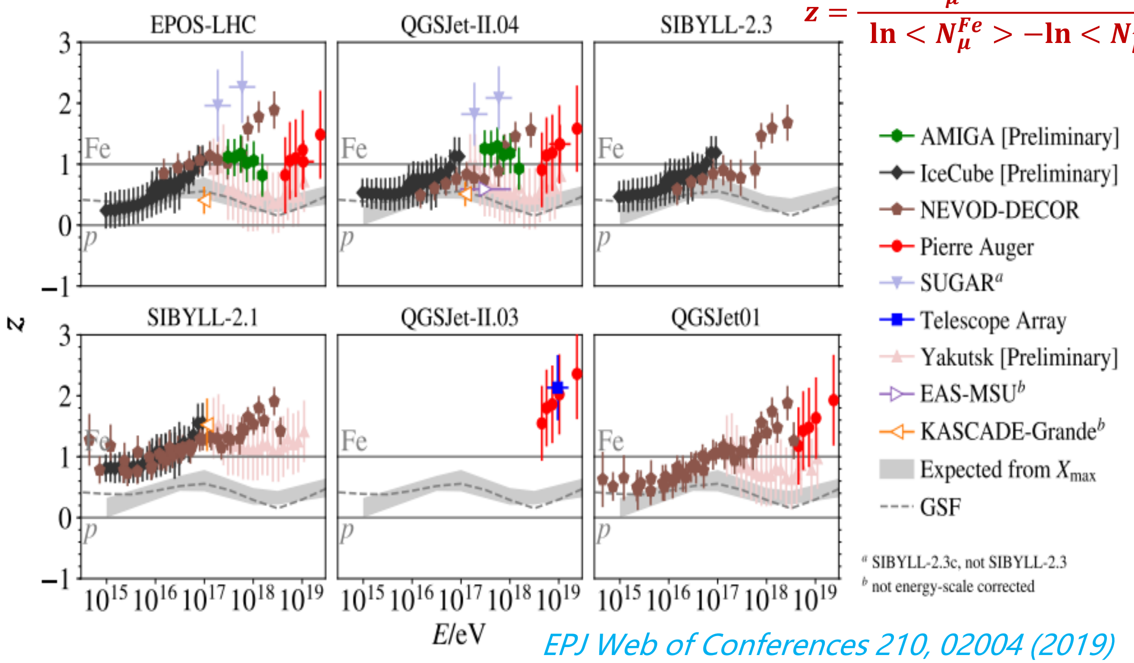
Heitler-Matthews models : $N_{\mu} = A(E/AC)^{\beta}$

- Muons are the main products of hadronic interactions
- Muons are sensitive to the primary particle

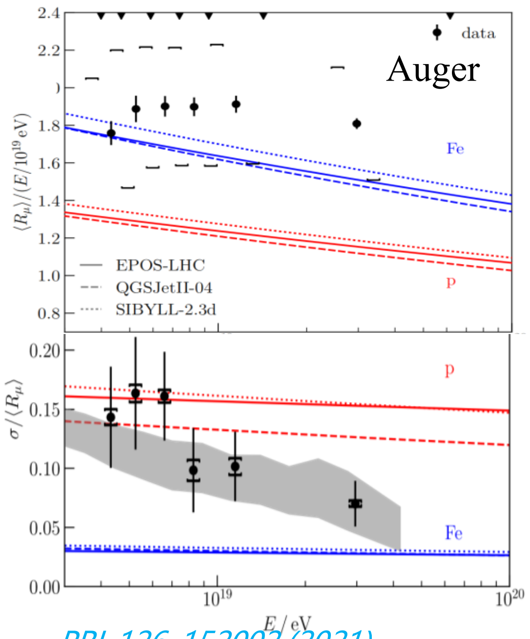
1. Introduction

● Muon puzzle

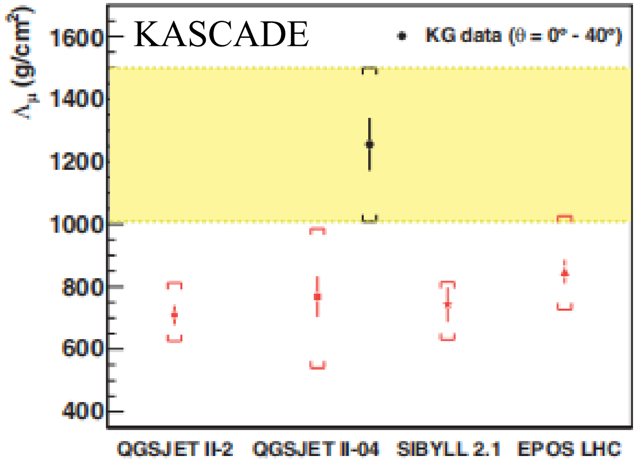
$$z = \frac{\ln < N_\mu^{data} > - \ln < N_\mu^{P} >}{\ln < N_\mu^{Fe} > - \ln < N_\mu^{P} >}$$



EPJ Web of Conferences 210, 02004 (2019)



PRL.126, 152002 (2021)



j.astropartphys.2017.07.001

Muon excess is observed, and becomes more pronounced with increasing energy. Shows strong dependence on the energy scale and hadronic interaction models.

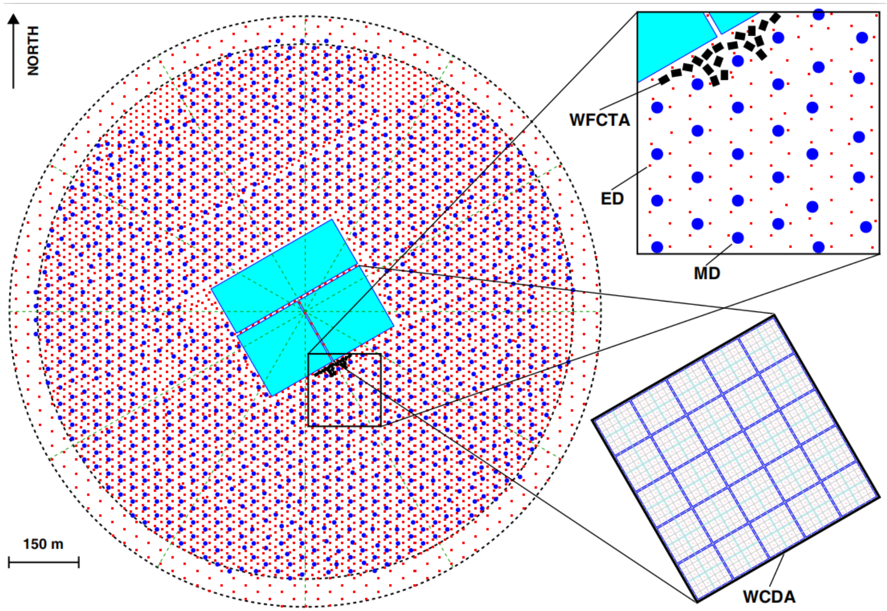
Auger result show **muon fluctuation** are consistent between data and mc.

KASCADE measured a muon content **attenuation length** higher than that predicted by mc.

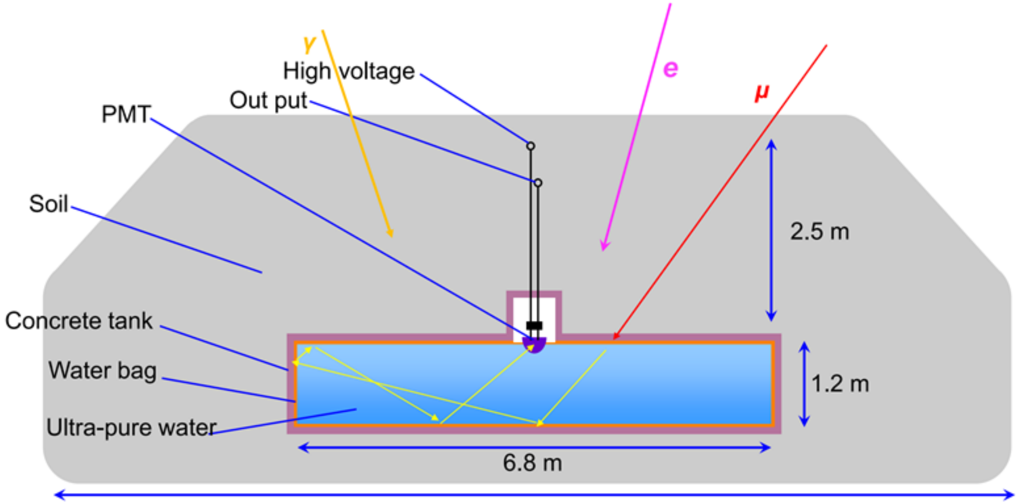
LHAASO

2. Data and MC sample

● LHAASO and muon detector



Layout of LHAASO



Schematic of the LHAASO muon detector

Large High Altitude Air Shower Observatory, LHAASO

Daocheng, altitude: 4410m (600g/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

$E_\mu > 1\text{GeV}$

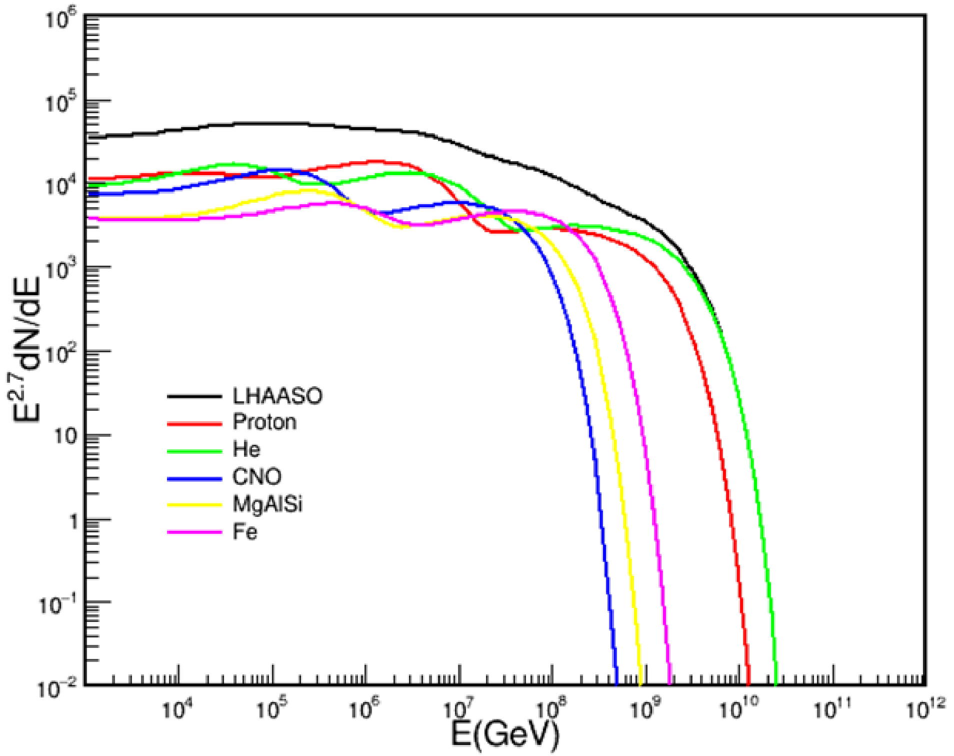
Resolution 25% at 1 muon; <5% at 10^4 muons

2. Data and MC sample

● LHAASO and MC sample

- **LHAASO sample**
  - Aug, 2021- Dec, 2023
  - Full LHASSO KM2A array

- **MC sample**
  - Energy: 10TeV-100PeV
  - Hadronic: EPOS-LHC, QGSJET-II-04, SIBYLL 2.3d
  - Components: Proton, He, CNO, MgAlSi, Fe
  - Spectrum: Gaisser H3a, Horandel, GSF, LHAASO spectrum
  - Slope: -2
  - Theta: 0°-40°
  - Phi: 0°-360°



Five component spectra normalized to the LHAASO

2. Data and MC sample

● Selection criteria and energy reconstruction

- **Criteria**
  - N_e >80 (The sum number of electronic within the distance 40-200m from the shower core)
  - 320<=R<=420 (Distance from the shower core to the array center)
  - $0° < \theta < 40°$

- **Energy reconstruction**

$$E_{rec} = p_0 + p_1 \cdot N_{e\mu}, \quad N_{e\mu} = N_e + 2.8N_\mu$$

$N_{e\mu}$ is independent of composition

10.1103/PhysRevD.106.123028

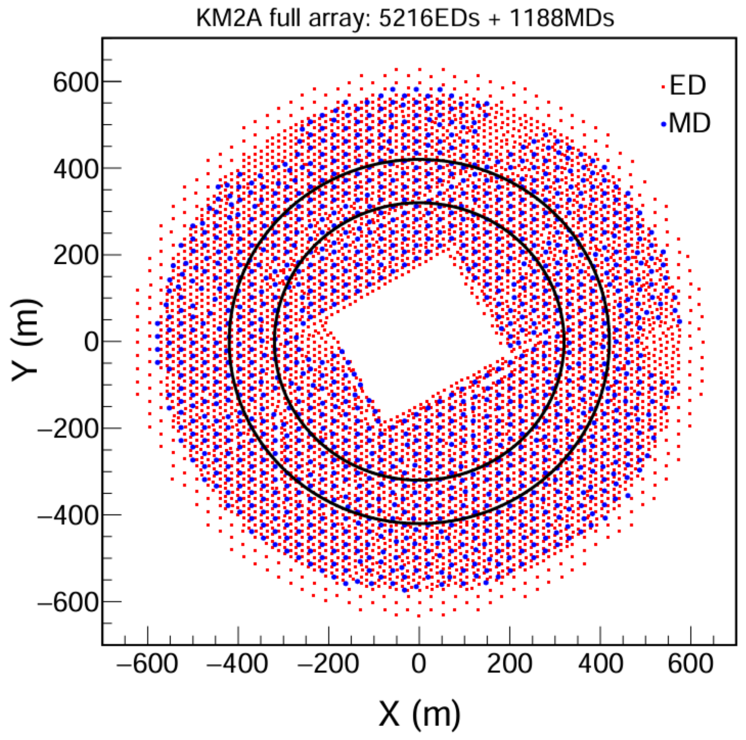
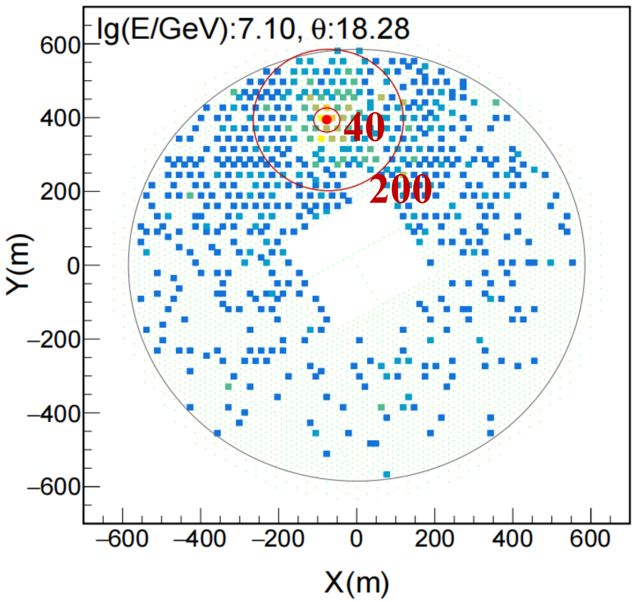
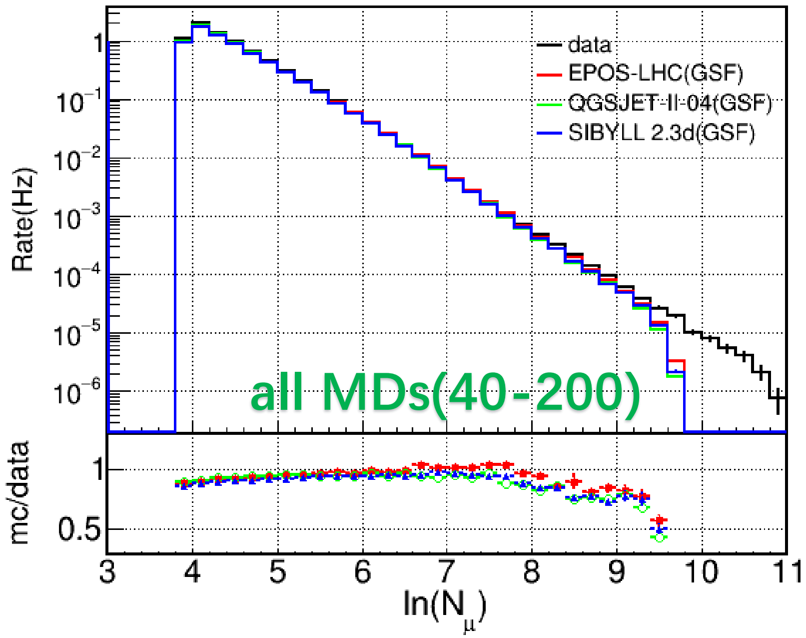


Fig: shower core distribution in LHAASO array

3.1 Muon Content Evolution with composition

- Muon content measurement with LHAASO-KM2A

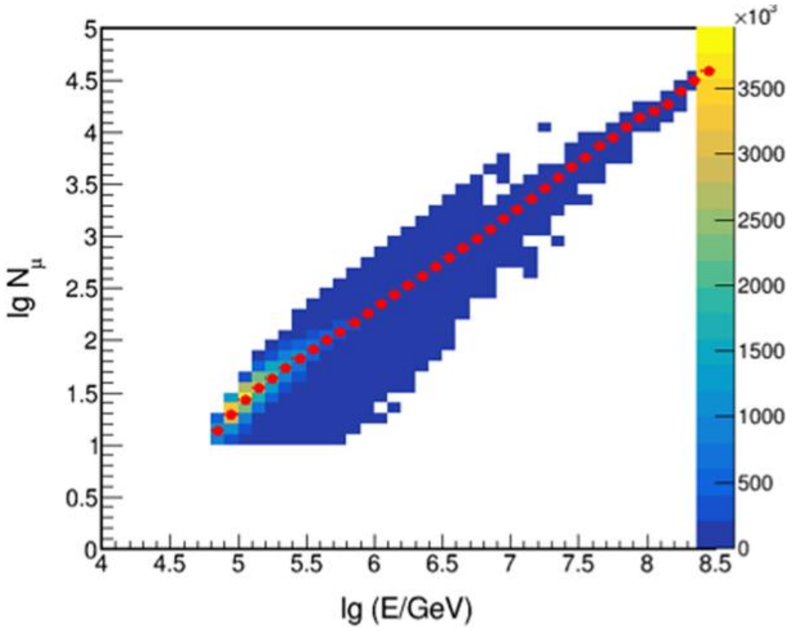


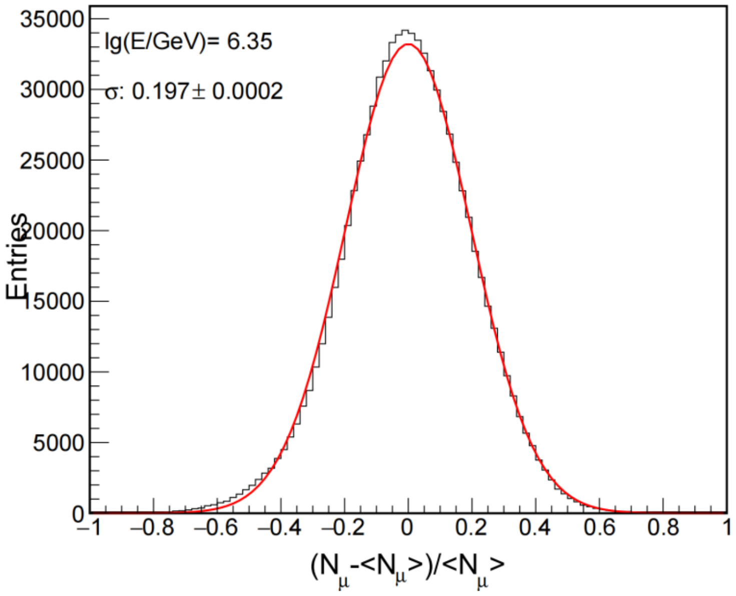


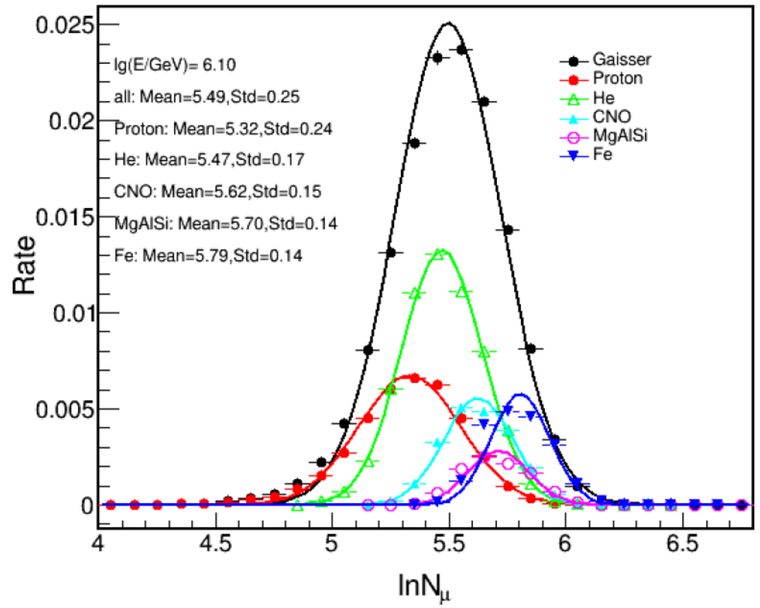
- **N_{μ} (muon content):** the sum number of muon with the distance of 40-200m from the shower core
- Muon content spectrum
  - Expected spectrum (GSF) good agreement with measured spectrum
  - No any spectrum of three hadronic models can recover the deviation for large muon region between the data and MC

3.1 Muon Content Evolution with composition

● Muon content in the air shower





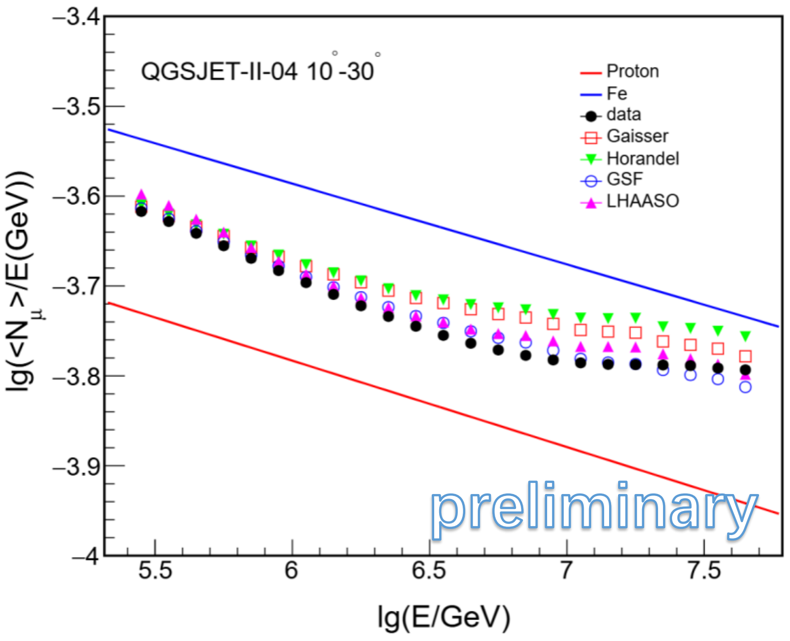


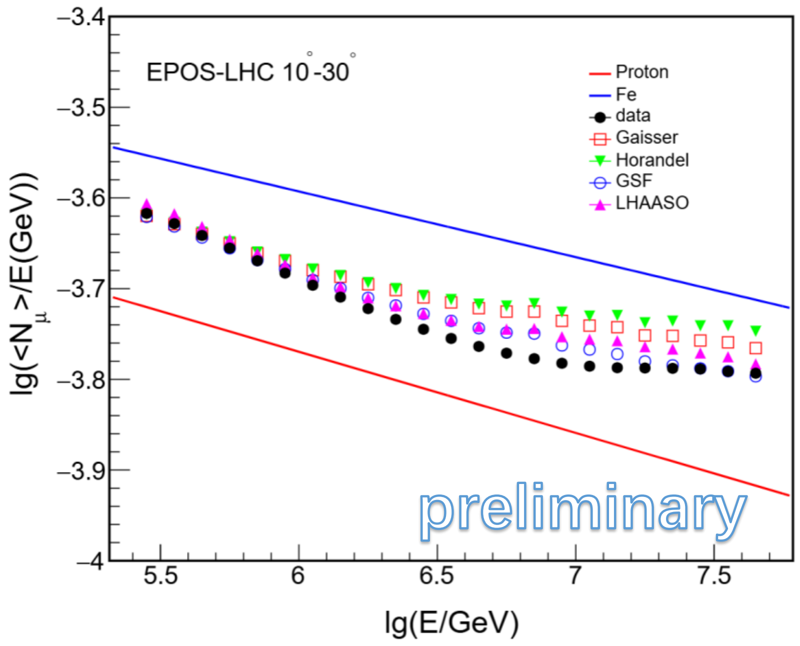
- Muon content increases nearly linearly with energy
- The fluctuation of muon content comes from
  - The intrinsic fluctuation of shower with cosmic ray mass
  - The fluctuation arising from the composition of cosmic ray

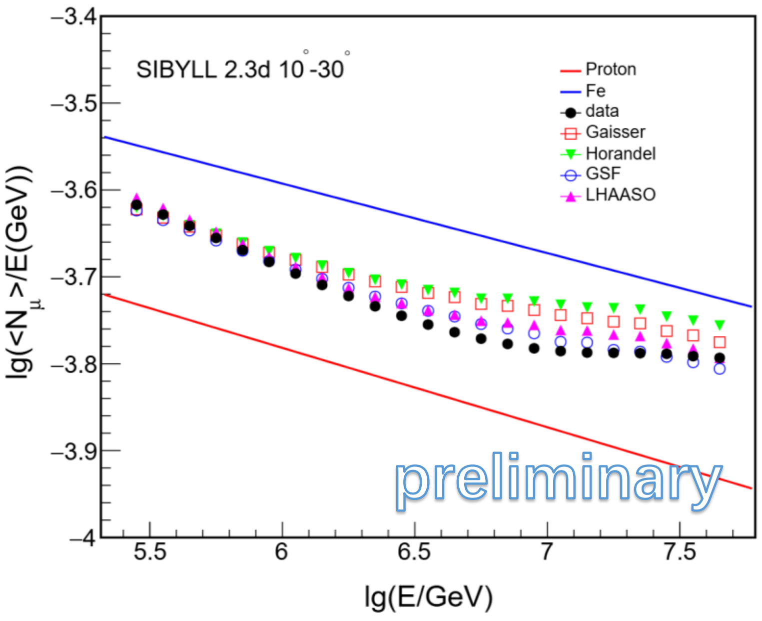
$$\sigma^2(\ln N_\mu) = <\sigma_{sh}^2> + f_b^2 \sigma_{\ln A}^2$$

3.1 Muon Content Evolution with composition

- **Muon content: measured vs expected**



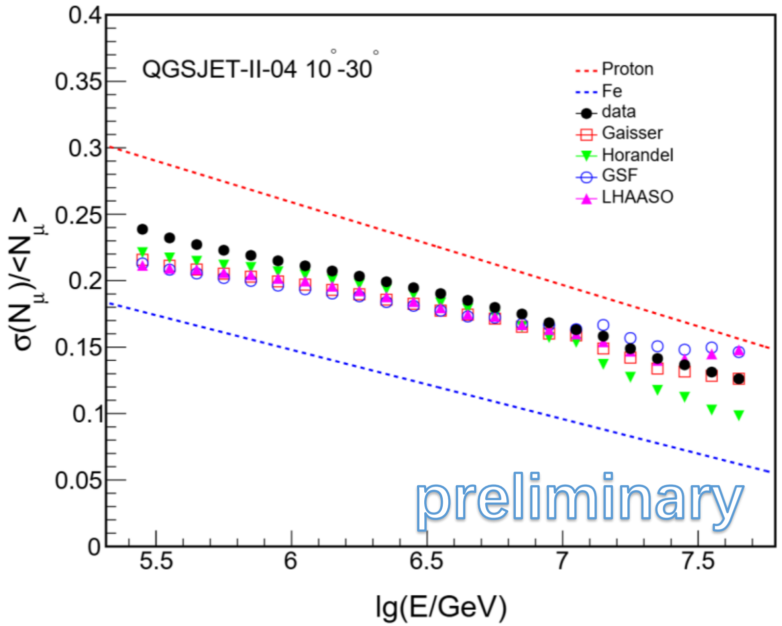


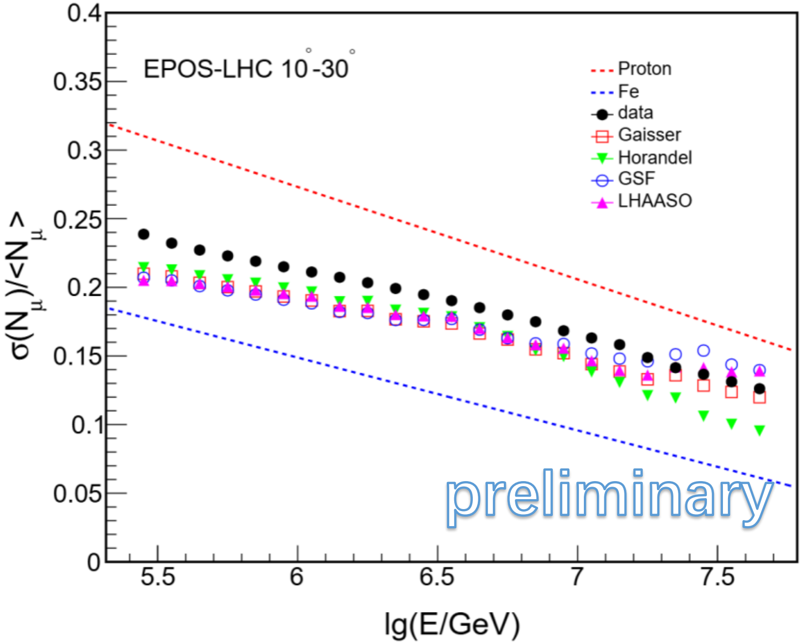


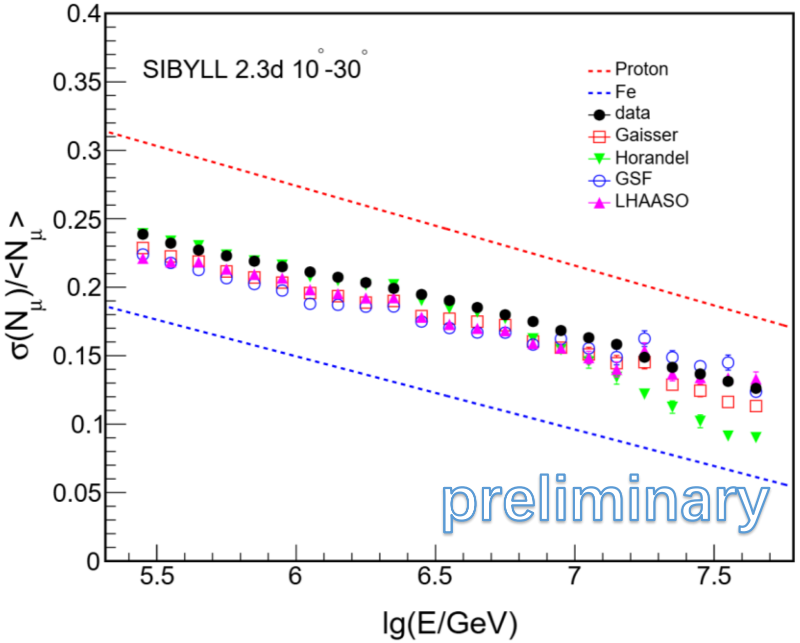
- The average number of muons per energy is sensitive to component
  - Estimate the mean mass
- Muon content of the data
  - Matches all interaction models below PeV
  - The measured muon content less than that predicted by MC in the higher energy region

3.1 Muon Content Evolution with composition

- **The relative fluctuation of muon content**







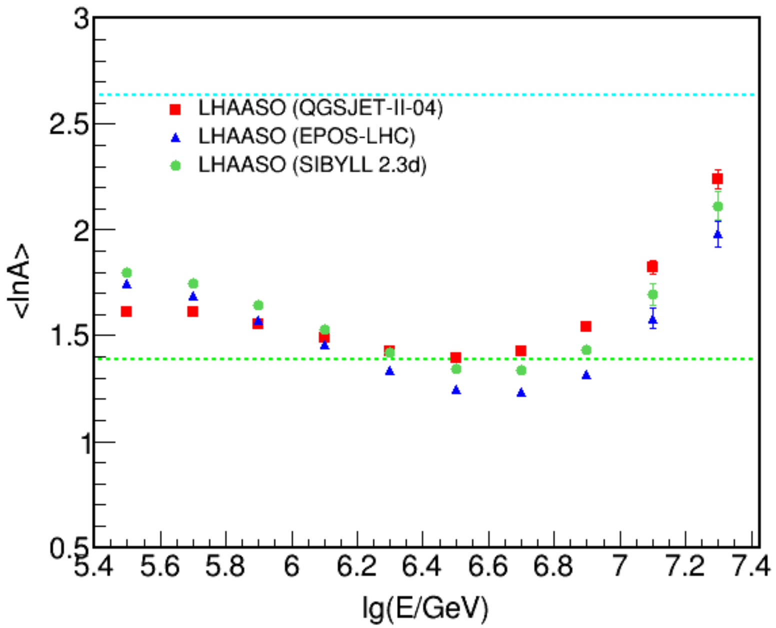
- The fluctuation dependents on the component
  - Estimate the variance of cosmic ray mass
- In the lower energy range, the measured fluctuation of the data is larger than that predicted by MC for QGSJET-II-04 and EPOS-LHC
  - The interaction model underestimate the inherent fluctuation in air shower?

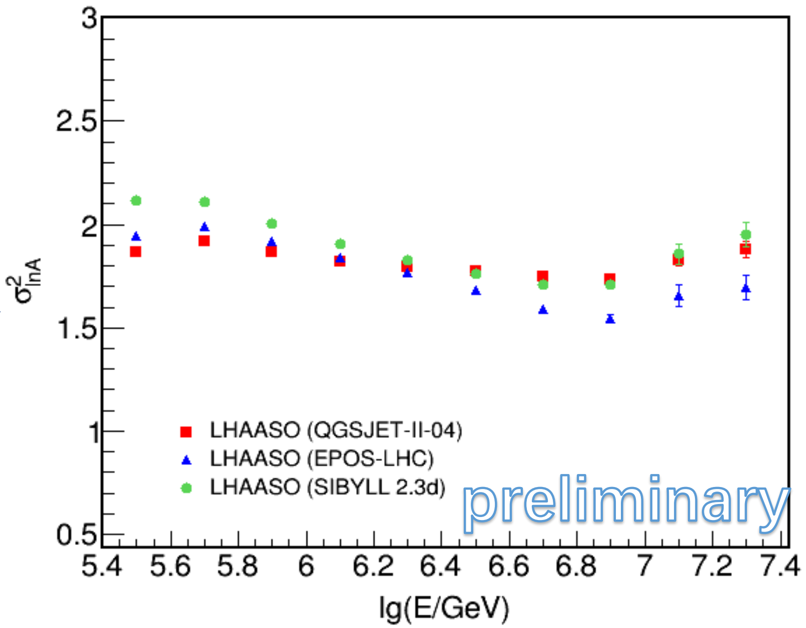
3.1 Muon Content Evolution with composition

● **Measurement of <lnA> and $\sigma^2_{\ln A}$**

$$< \ln A >= \frac{< \ln N_\mu > - f_a}{f_b}$$ *PRL.132, 131002 (2024)*

$$\sigma^2_{\ln A} = \frac{\sigma^2(\ln N_\mu) - \sigma^2_{sh}(< \ln A >)}{x_b \sigma_p^2 + f_b^2}$$ *POS(ICRC2025)251*





- Average log mass and its variance of cosmic ray from three hadronic models show the same variation trend with energy, and above the knee
  - Cosmic ray mass composition become heavier
  - Variance no decrease, which may be related to new population entrance

3.2 Muon Content Evolution with zenith angle

- CIC method

Cosmic ray is isotropic

Same intensity at each direction corresponding to the same energy

Muon content reduced after shower traveling Δx in air

$$N_\mu(E, \Delta x) = N_\mu^0(E) e^{-\Delta x/\Lambda_\mu}$$

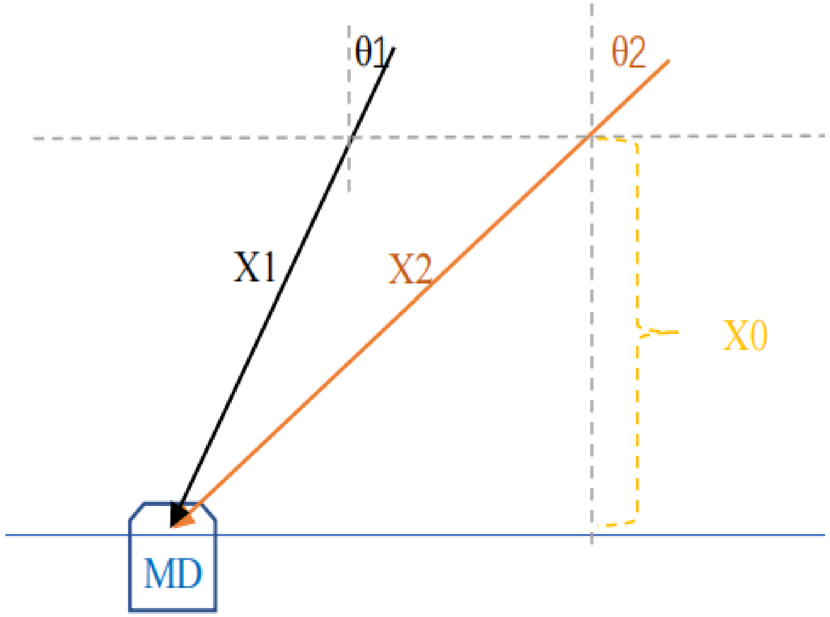
Constant intensity method

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

N_μ^0 is a normalization parameter

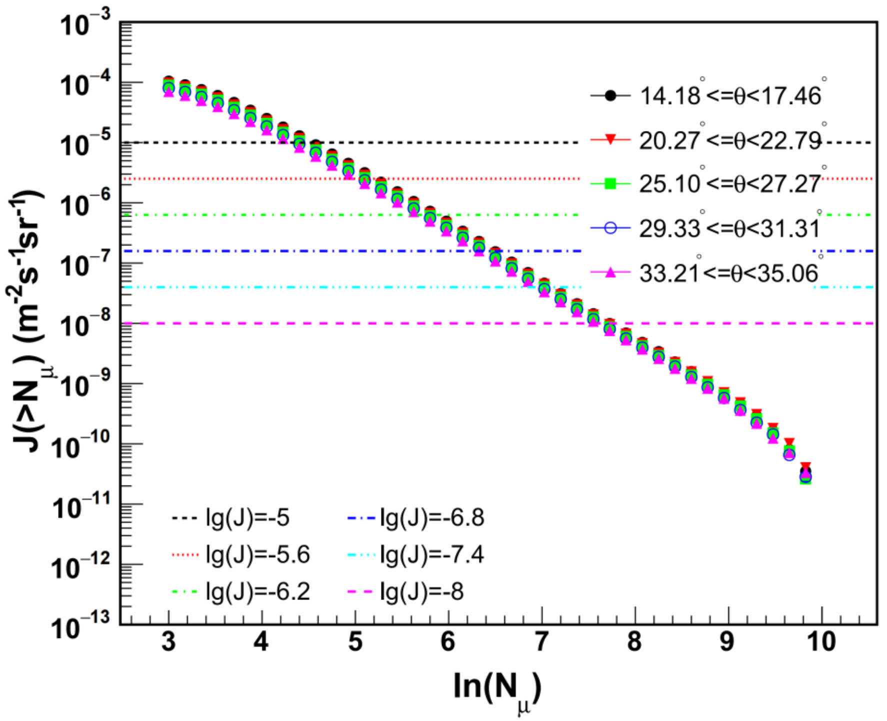
X_0 is the vertical atmospheric depth, 600 g/cm^2 at LHAASO

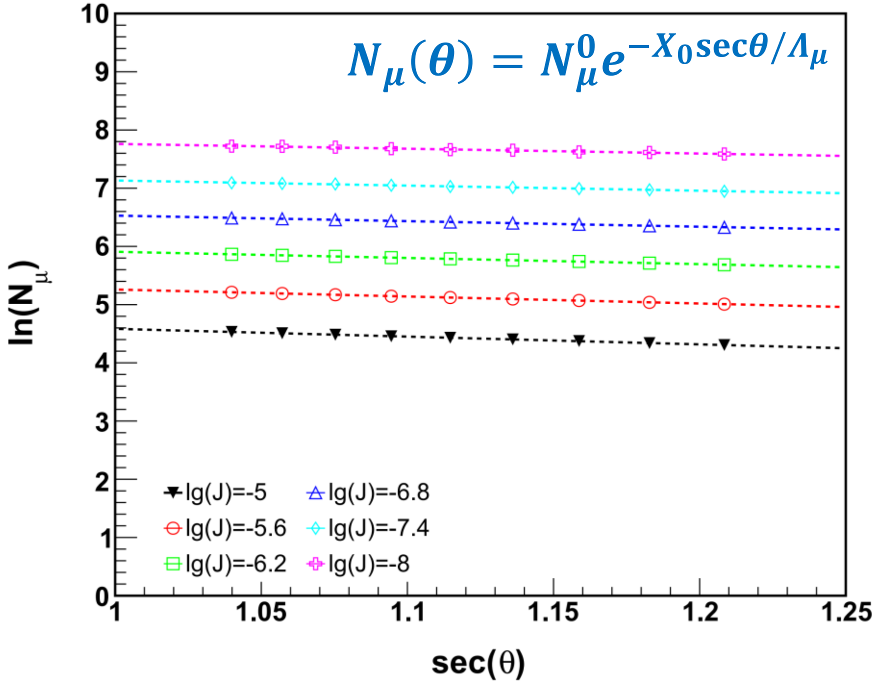
Λ_μ is the attenuation length of muon content



3.2 Muon content Evolution with zenith angle

- The evolution of muon content with zenith angle

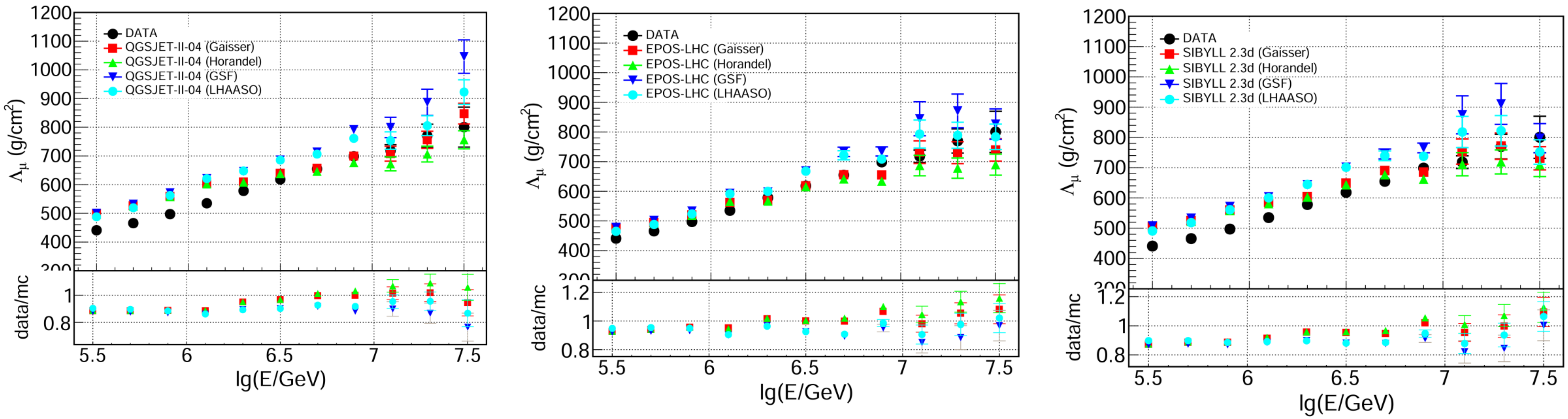




- The integral flux spectrum of muon content is shown for several zenith with equal solid angle ($\sin^2\Delta\theta = 0.03$)
- Muon content decreases as the zenith angle increases for each constant intensity (E)
- The slope corresponds to the attenuation length

3.2 Muon Content Evolution with zenith angle

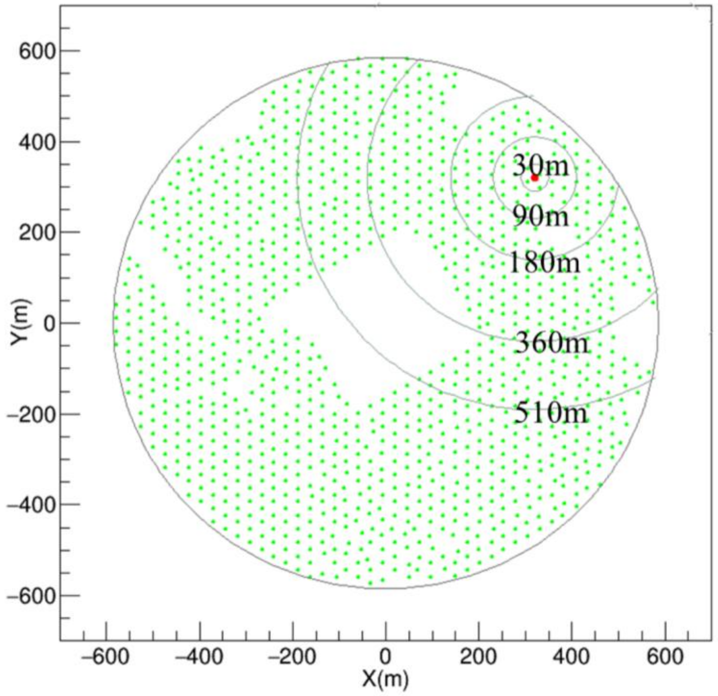
● Comparison of Λ_μ between DATA and MC

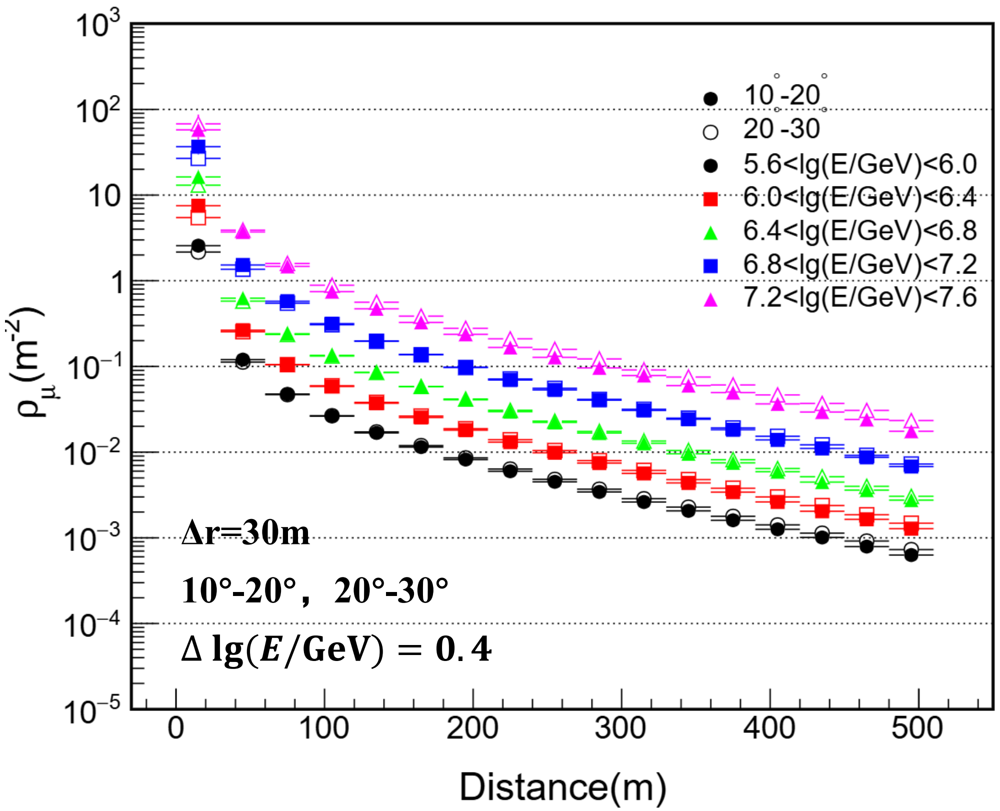


- Λ_μ increases with cosmic ray energy in both MC and DATA
- Λ_μ of the EPOS-LHC model matches well with DATA
- Λ_μ of the DATA is shorter than that of MC of QGSJET and SIBYLL below PeV
- EPOS-LHC model shows a shorter $\Lambda\mu$ than other models below PeV

3.3 Muon Lateral Distribution Evolution

● **Muon lateral distribution**



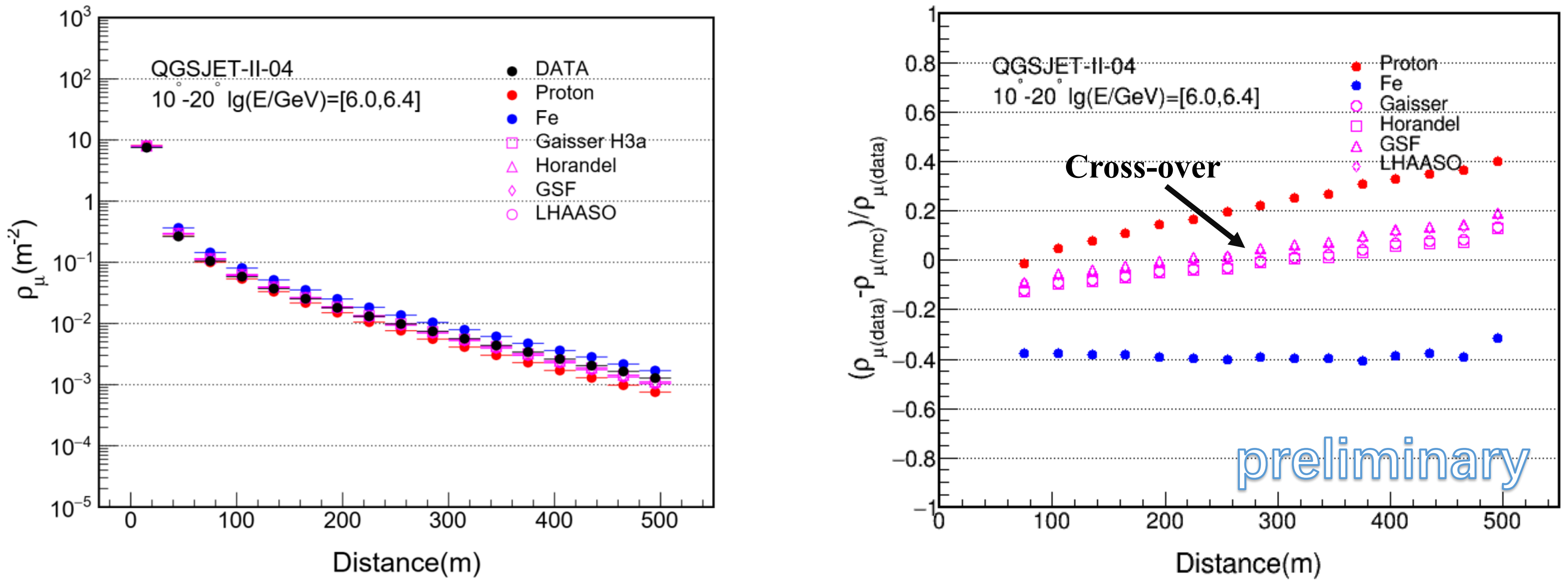


$\rho_\mu(r)$： average muon density at a distance r from the shower core

$$\rho_\mu(r) = C \cdot \frac{1}{r_G^2}\left(\frac{r}{r_G}\right)^{-0.75}\left(1+\frac{r}{r_G}\right)^{-2.5}$$

3.3 Muon Lateral Distance Evolution

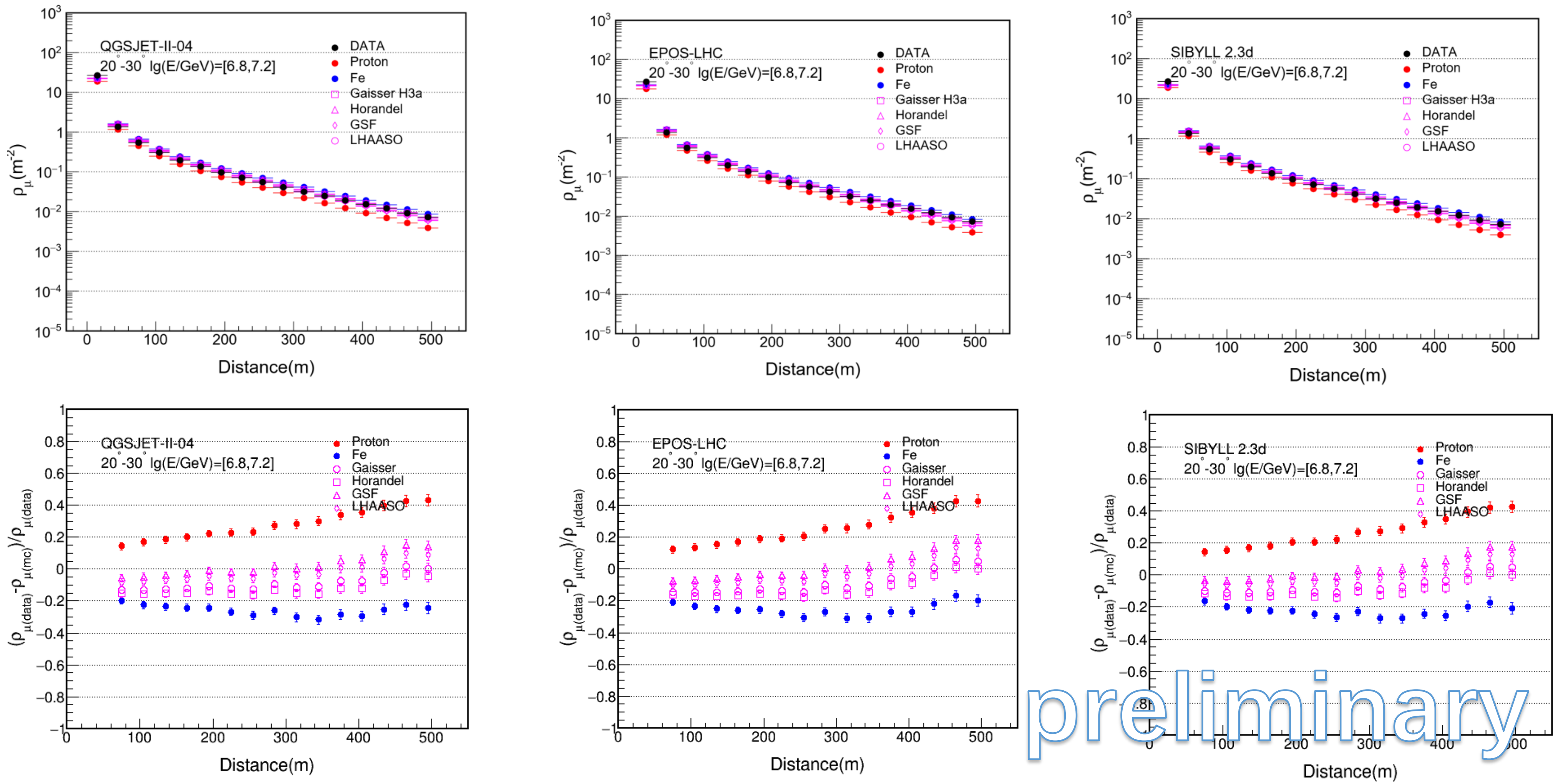
- **Comparison of muon lateral distribution**



- Measured muon density is between the predictions for pure proton and pure iron
  - Muon density of proton decreases rapidly with distance compared to DATA
  - Muon density of iron follows the same trend as the DATA
- Measured muon density is lower than the MC prediction in the core area, but it's higher in the outer regions

3.3 Muon Lateral Distance Evolution

● Muon LDF for different hadronic model



- Behaviors of the three hadronic interaction models are similar

conclusion

- The measured muon content and its fluctuation between proton and iron, no muon excess observed in very high energy region.
- The muon content and its fluctuation is sensitive to cosmic ray composition
  - Mass composition becomes heavier with energy above the knee.
  - Dispersion of mass composition no decrease, new population of cosmic rays enters above the knee.
- The Λ_μ increases with cosmic ray energy both in MC and DATA.
- Compared the muon lateral distribution between DATA and MC
  - Measured muon lateral distribution is between proton and iron
  - MC overestimates muons density near the core and underestimates them far from the core

Thank you!