Studies of Hadronic Interactions Using Cosmic-Ray Air Showers

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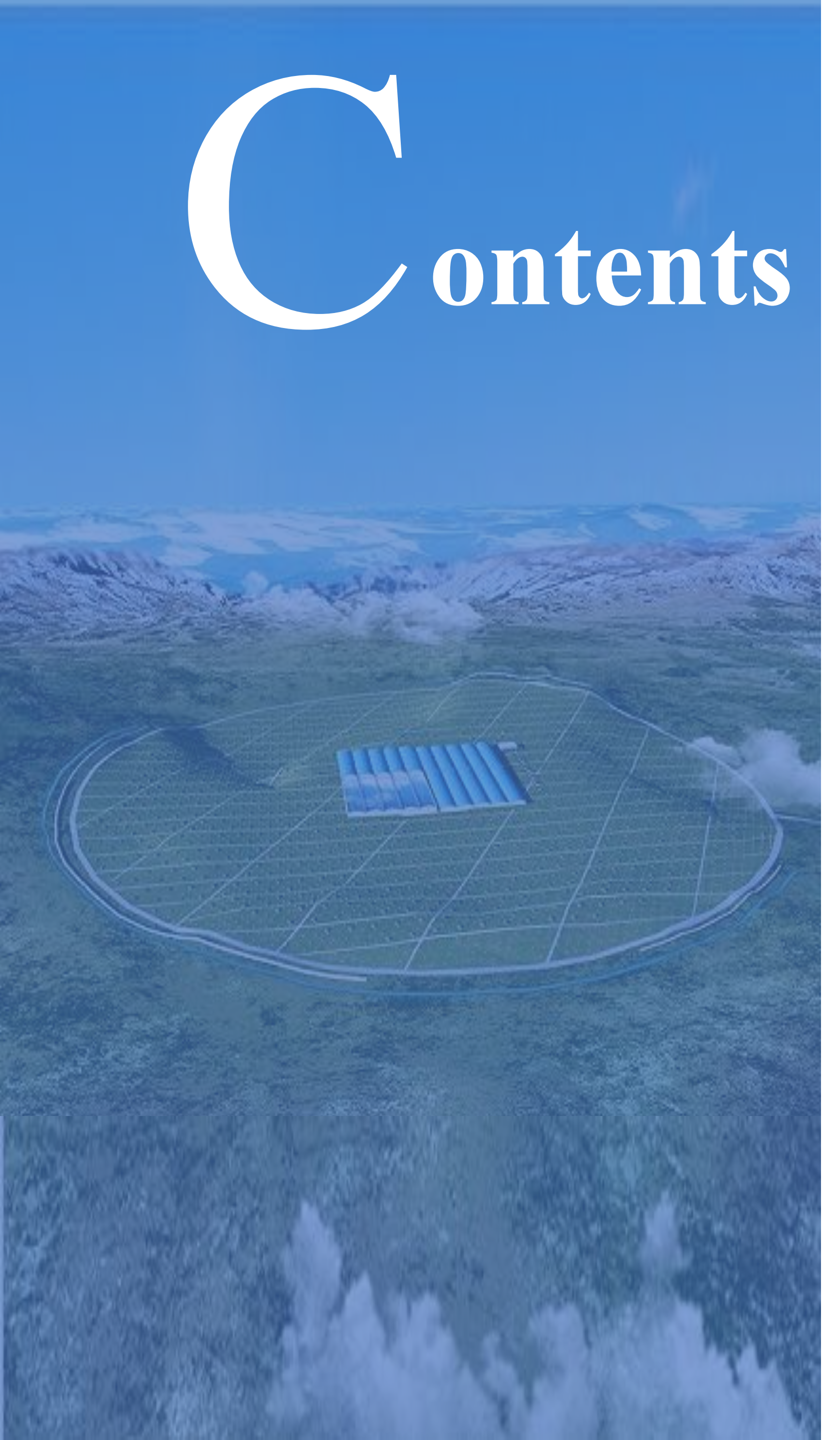

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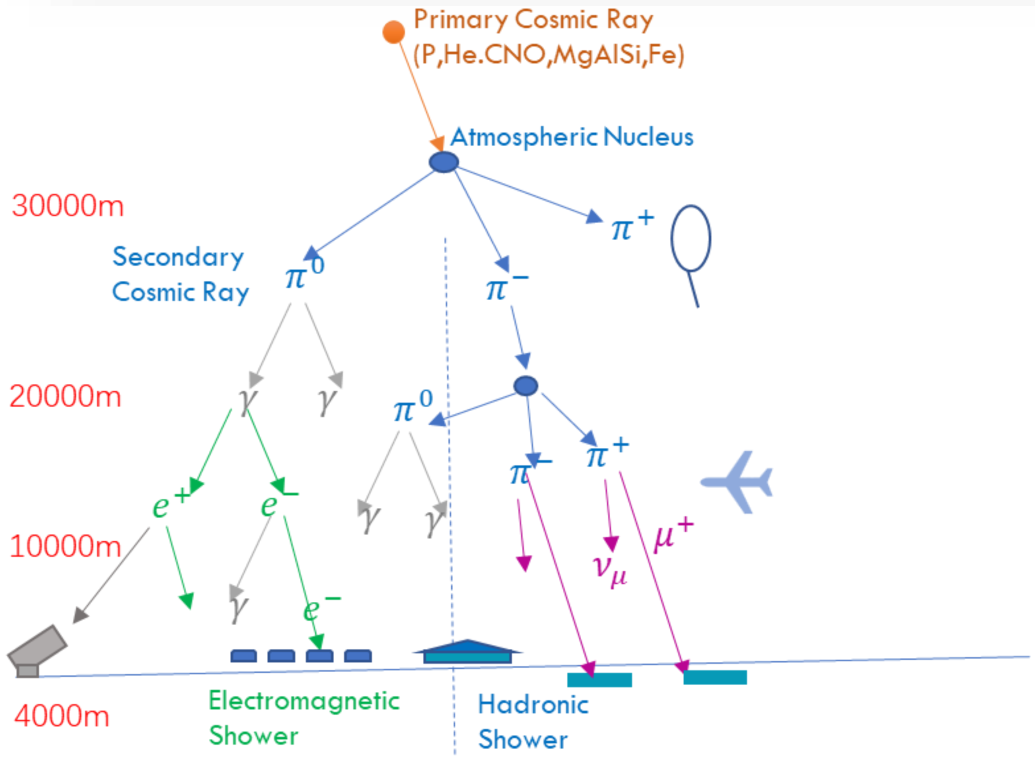
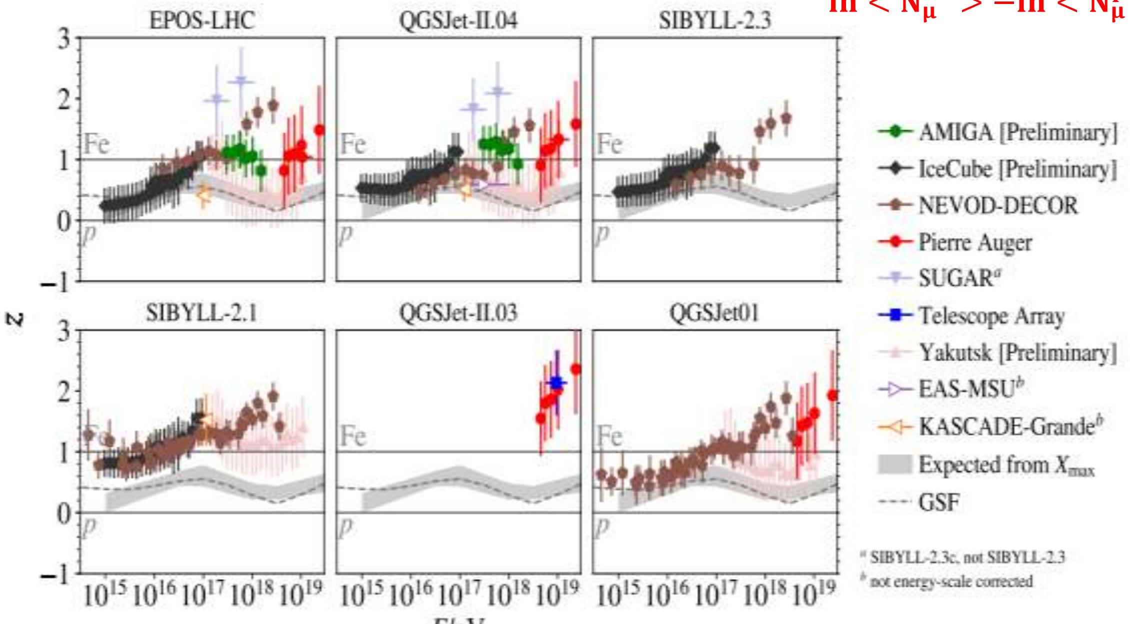
1 Muons in air shower



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



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

- Muons are main products of hadronic interactions

- **Muon excess** is observed, shows strong dependence on hadronic interaction models.

Muons can serve as an effective probe for studying the hadronic interaction models and composition of cosmic rays

1 Air shower simulation and hadronic interaction models

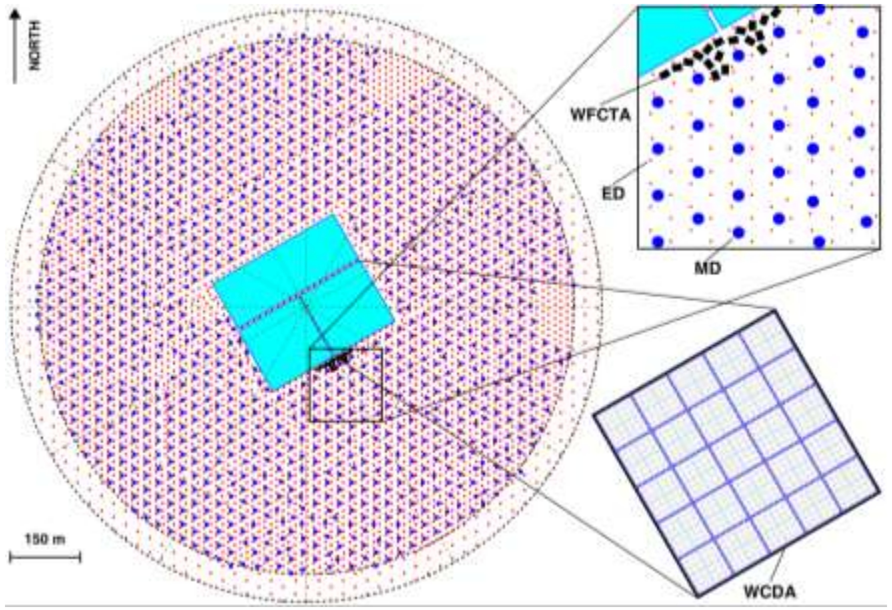
- **CORSIKA**
  - Energy: 10TeV-100PeV
  - Components: Proton, He, CNO, MgAlSi, Fe
  - Interaction models:
    - **EPOS-LHC**: parton ladder, core-corona, collective hadronization
    - **QGSJET-II-04**: Reggeon/Pomeron field theory, diffraction, screening
    - **SIBYLL 2.3d**: soft process + minijet, leading-particle production

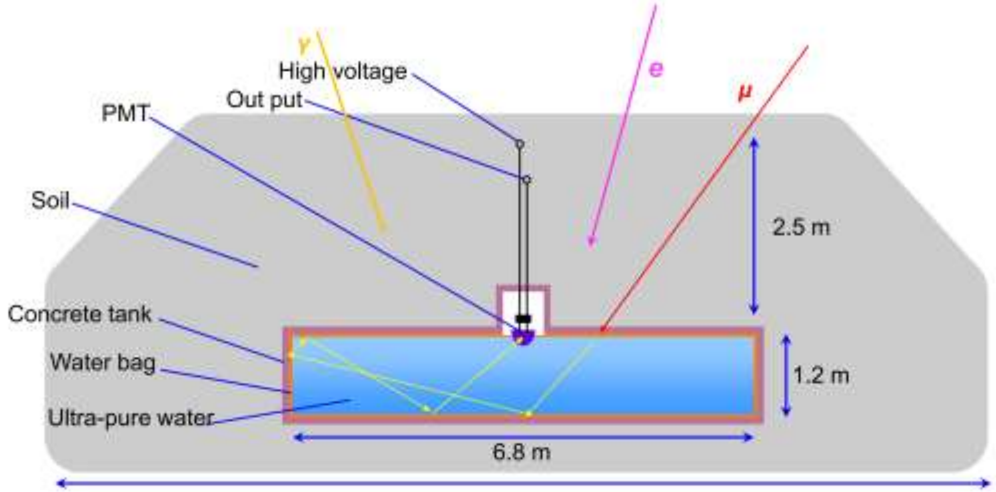
    with **FLUKA** as low energy model(<80GeV)

Muon-sensitive physics:

π/K production · baryon production · forward energy flow · diffraction

1 LHAASO and MDs





- 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

- Effective area per detector unit: **36 m^2**; sampling ratio >**4%**
- Soil overburden: filters out electrons and photons (**E_μ>1 GeV**)

1 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**

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

  - $\mathbf{N_{e\mu}}$ is independent of composition
  - **$\mathbf{N_\mu}$: The sum number of muons within the distance 40-200m from the shower core**

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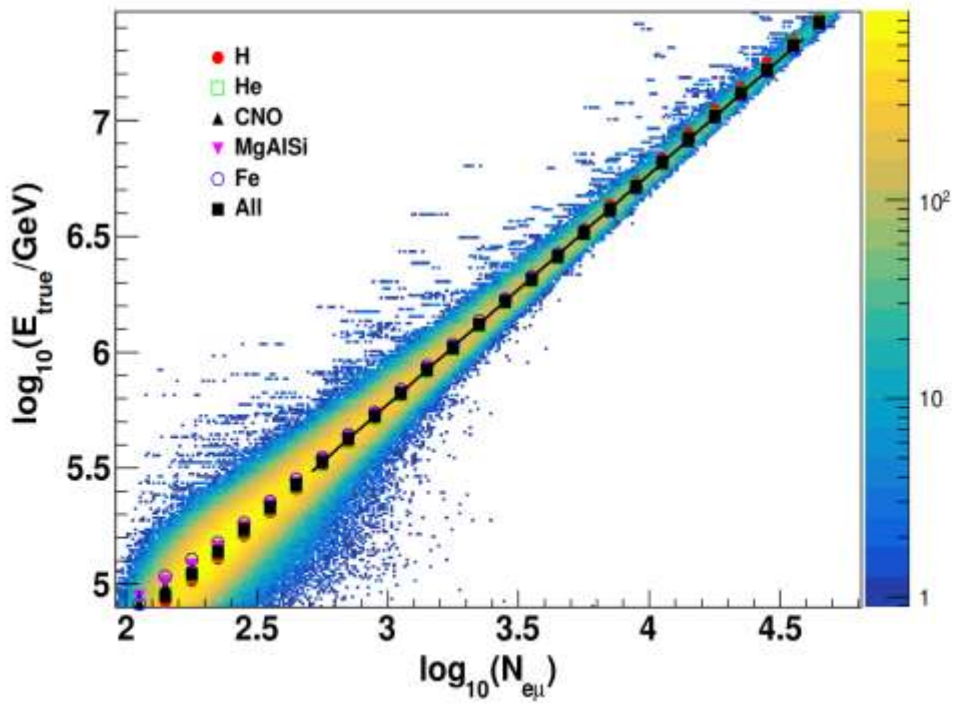
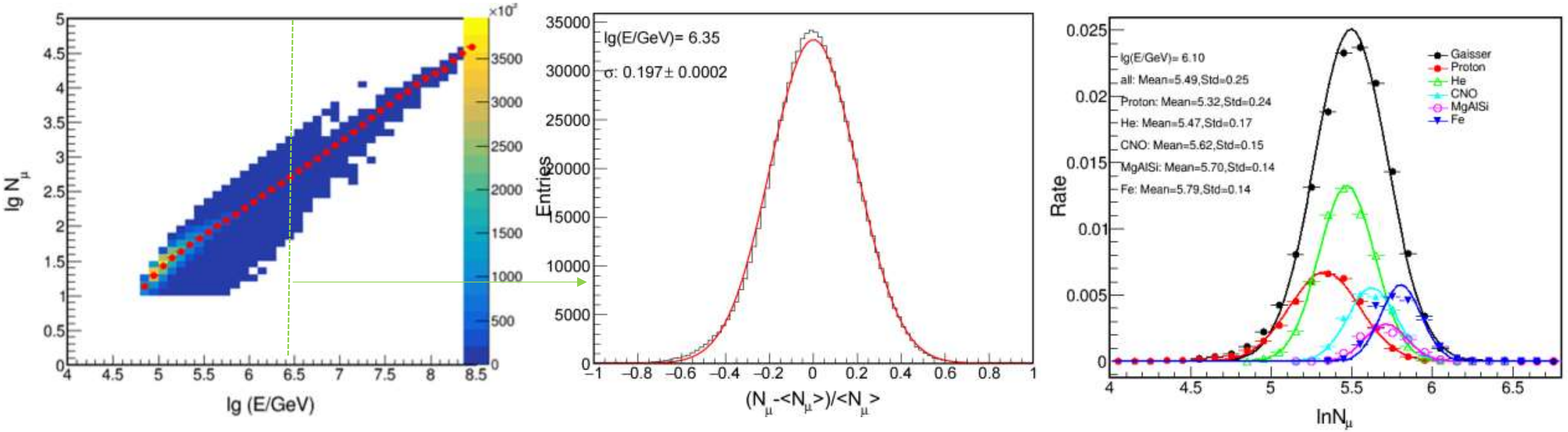


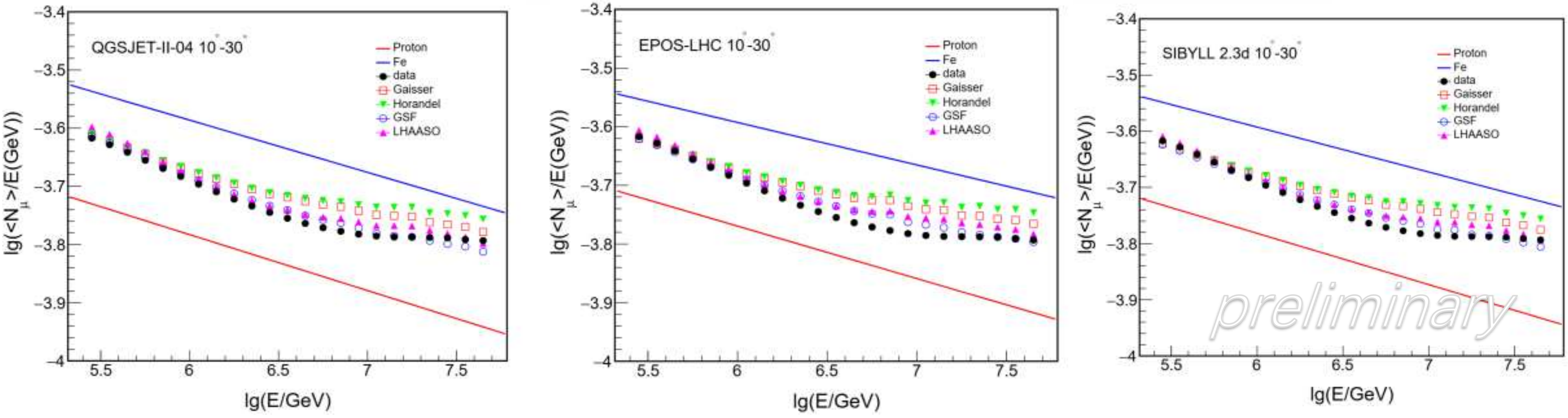
Relationship between $\mathbf{N_{e\mu}}$ and the true energy

2 Muon content in the air shower



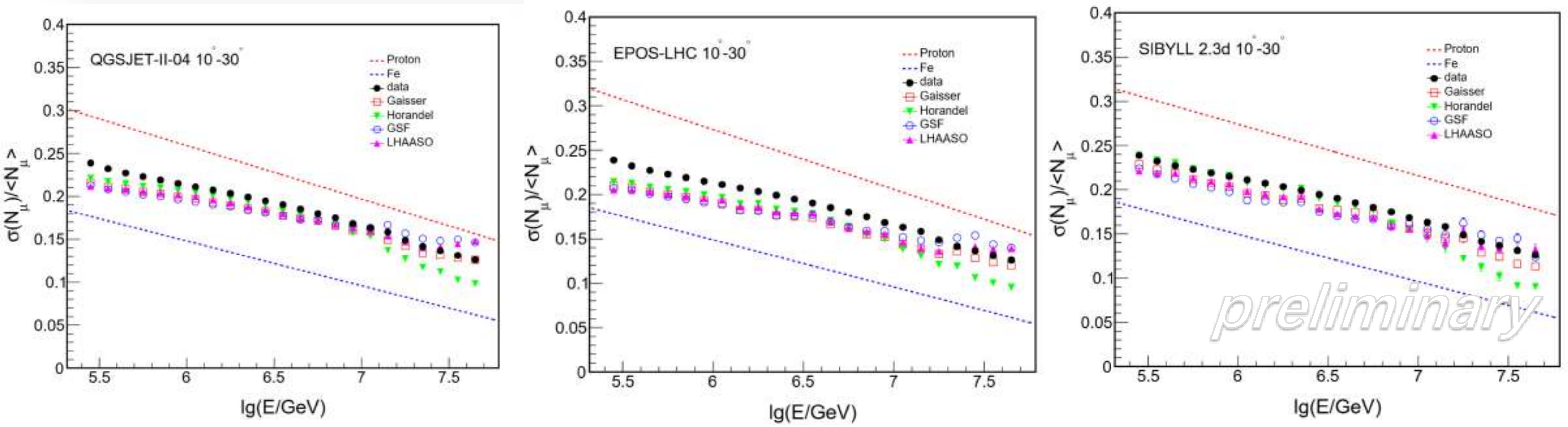
- Muon content increases nearly linearly with energy.
- Muon content fluctuation for the shower.
- The **fluctuation of muon content** comes from
  - The **intrinsic fluctuation** of shower with mass A.
  - The **mixture of cosmic ray mass** (components).

Muon content: measured vs expected



- The average number of muons at fixed energy is **sensitive to mass composition**.
- No significant muon excess is observed.

2 The relative fluctuation of muon content



- The relative fluctuation of muon content is **sensitive to mass composition**.
- For different hadronic interaction models, the predicted fluctuation is generally **lower than the data**.

  - Do the interaction models underestimate the intrinsic shower fluctuations?

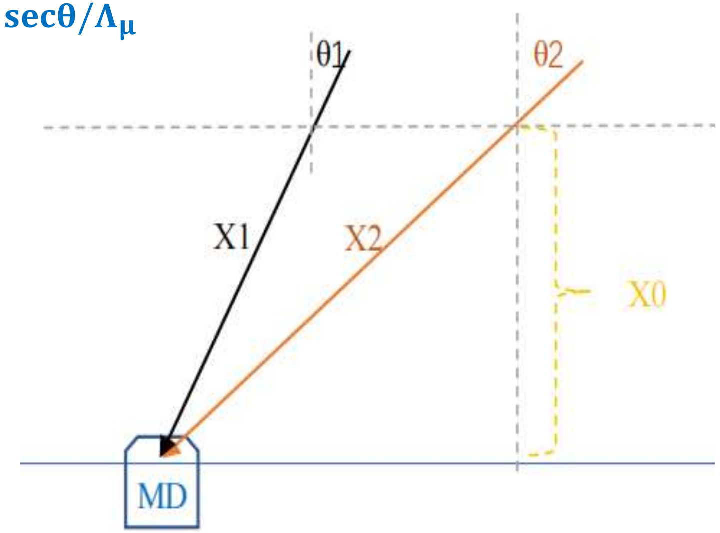
Attenuation length measurement with CIC

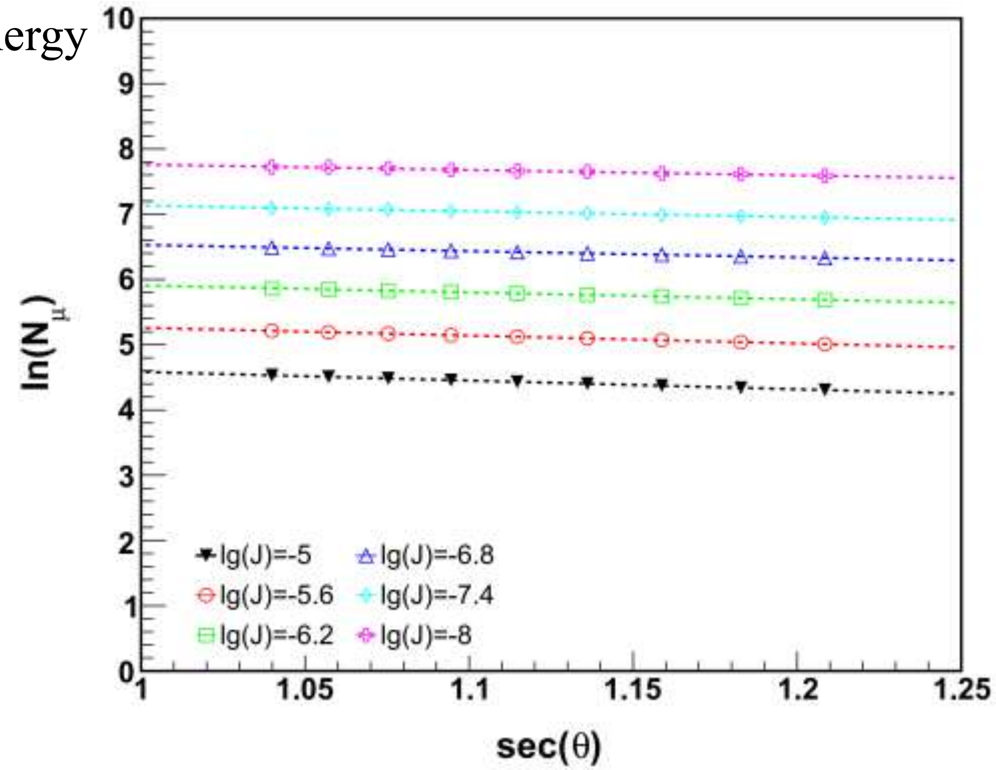
Cosmic ray is isotropic

Same intensity at each direction corresponding to the same energy

Muon content reduced after shower traveling Δx in air

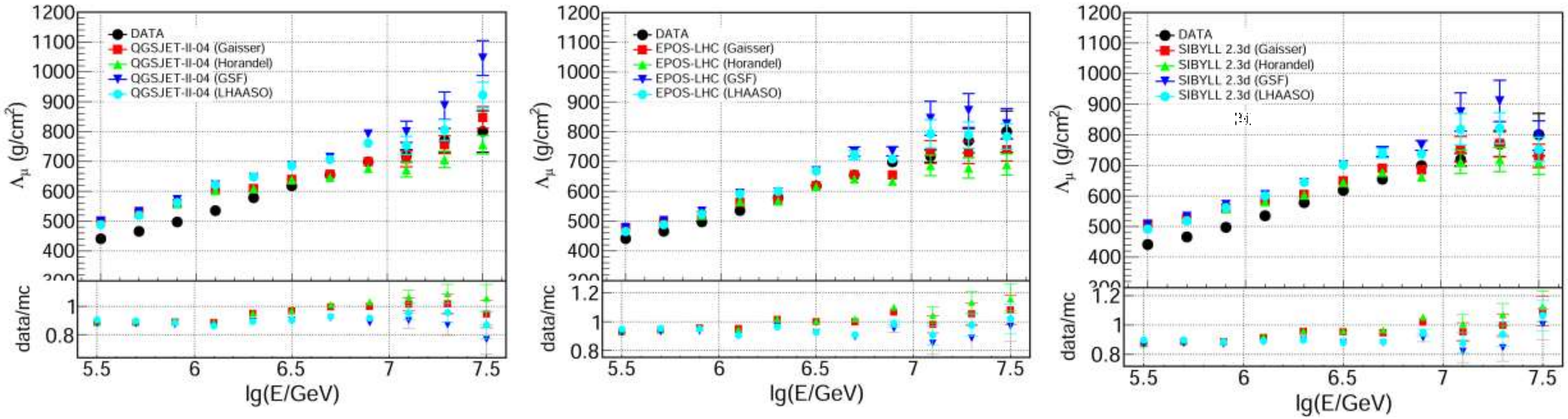
$$N_\mu(\theta) = N_\mu^0 e^{-X_0 \sec\theta / \Lambda_\mu}$$





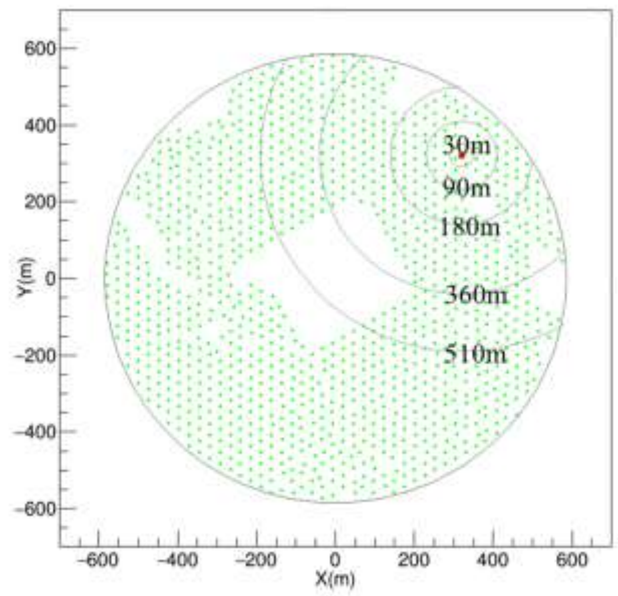
- The integral flux spectrum of muon content is shown for several zenith with equal solid angle **($\sin^2\Delta\theta = 0.03$).**
- Muon content decreases as the zenith angle increases for each constant intensity (E).
- The **slope** corresponds to the **attenuation length.**

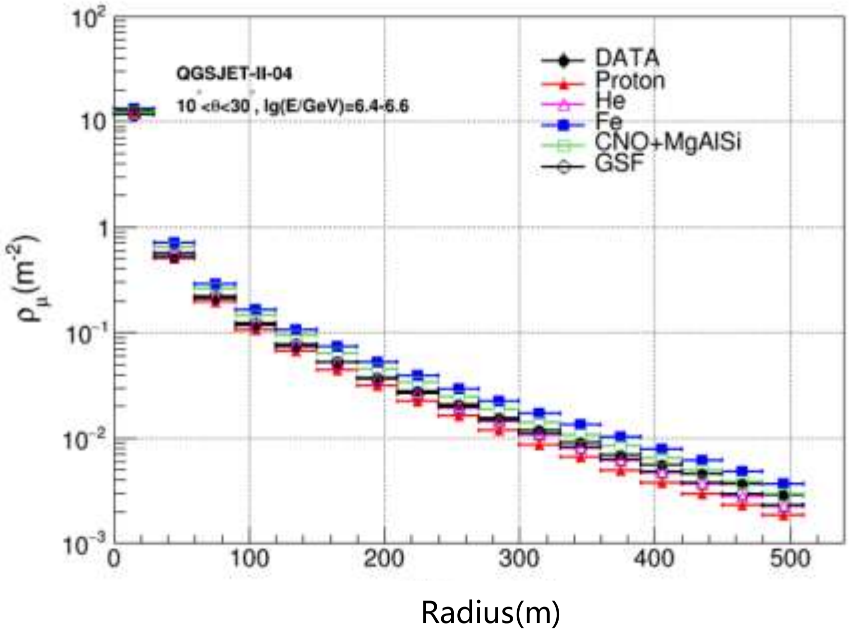
3 Comparison of MC and DATA results

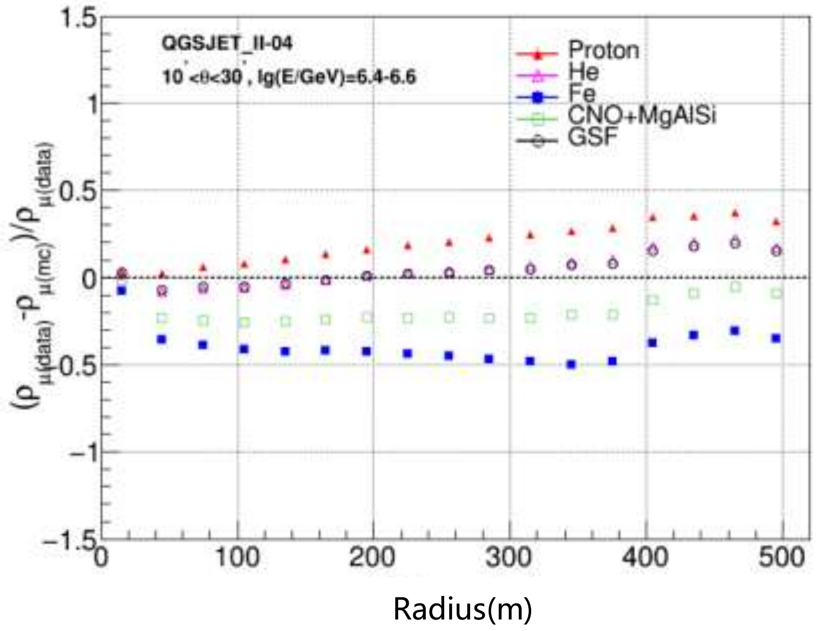


- The Λ_μ **increases** with cosmic ray energy in both **MC and DATA**
- The Λ_μ of the **EPOS-LHC** model **matches well** with DATA
- The Λ_μ of the DATA is shorter than that of MC of **QGSJET and SIBYLL** below PeV
  - MC underestimates the muon attenuation rate?
  - Or overestimates the proportion of high-energy muons?

4 Muon lateral distribution







Δr=30m

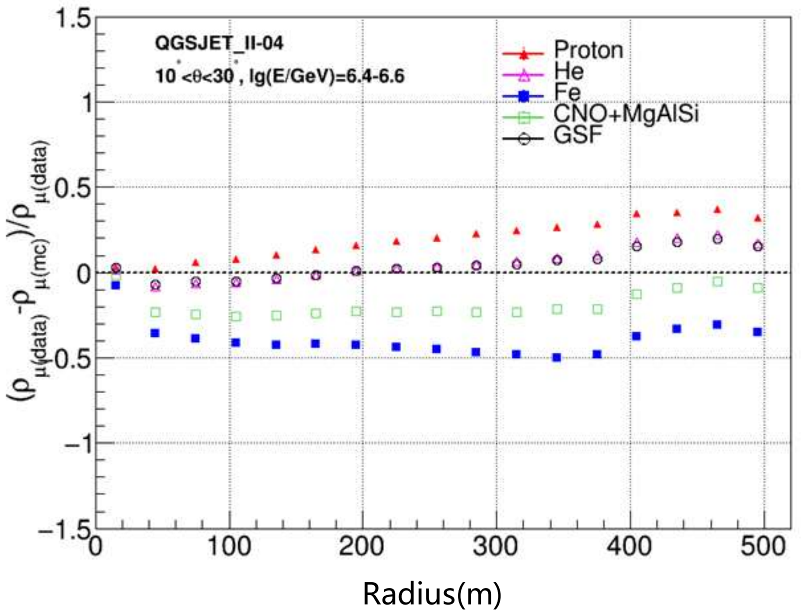
10°-30°

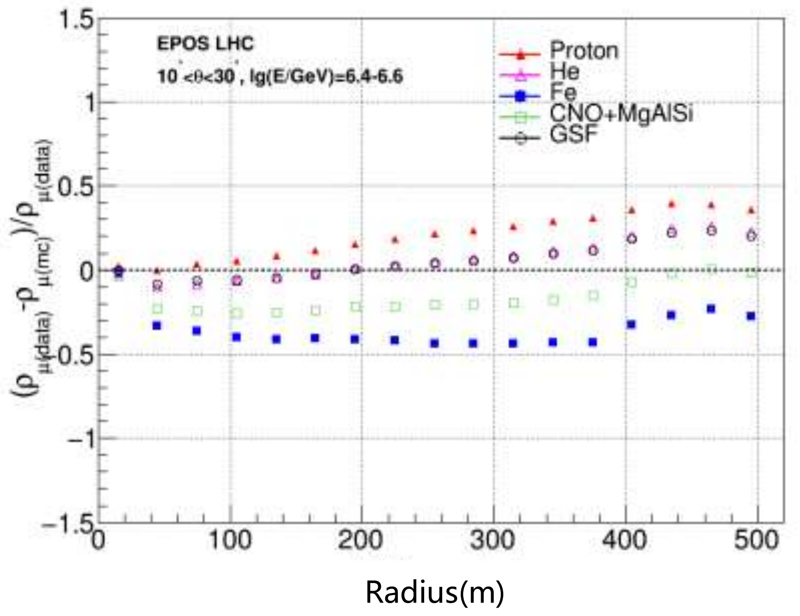
$\lg(E/GeV) = 6.4 - 6.6$

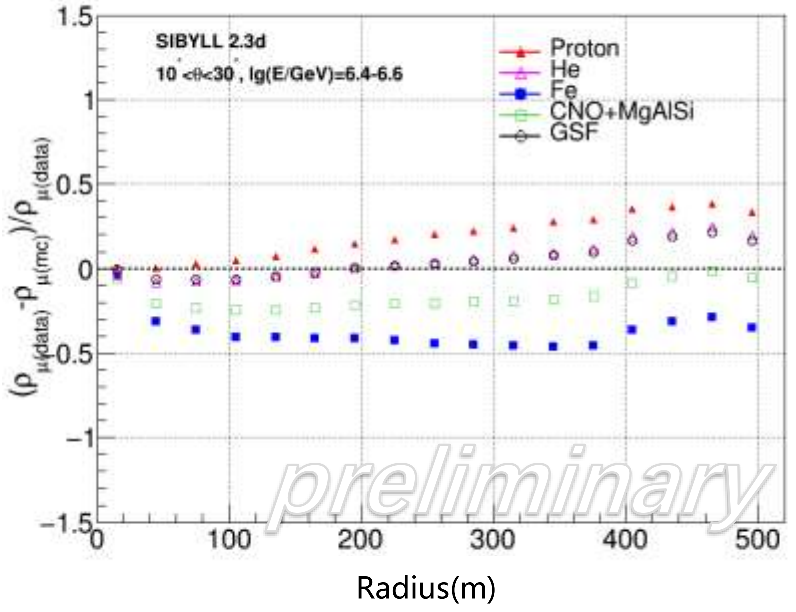
$\rho_\mu(r)$: muon density at a distance r from the shower core

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

4 Muon lateral distribution for hadronic model

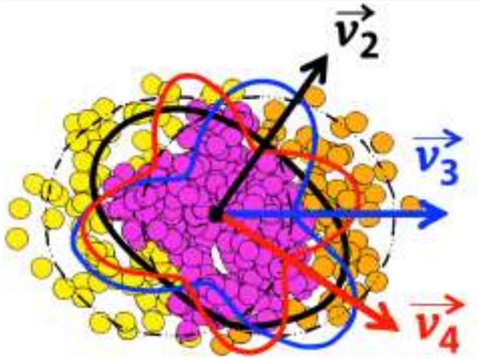






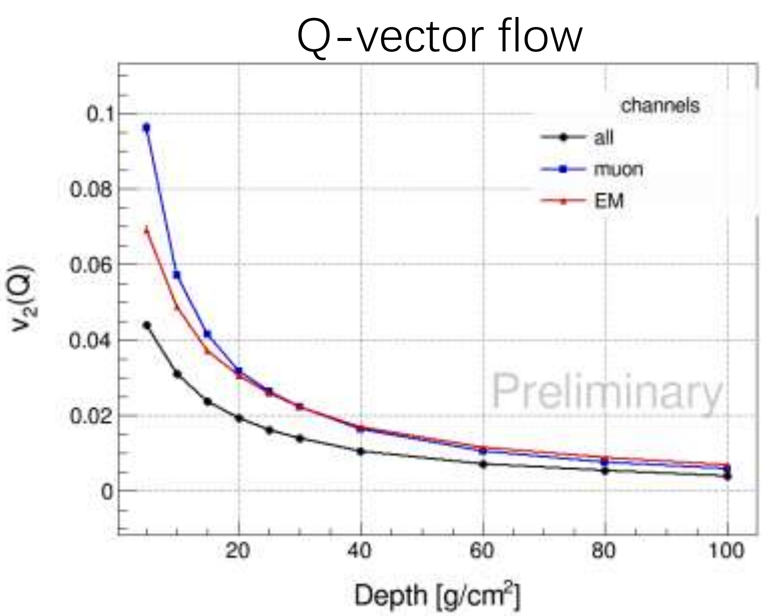
- The behaviors of the **three hadronic interaction** models are **similar.**

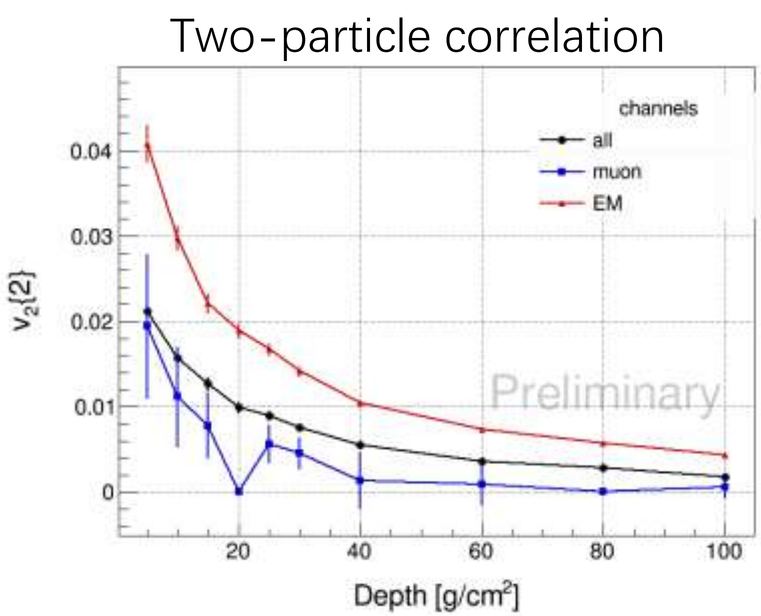
5 Collective flow in cosmic ray air shower

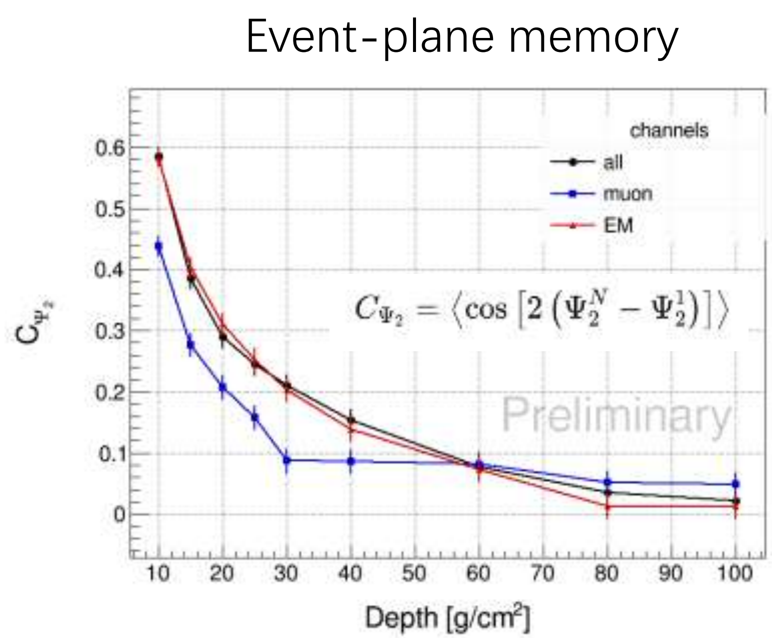


$$dN/d\phi \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_\mathbf{r})$$

v_2 is correlated to QGP formation







Collective-flow-like correlation is gradually washed out

Summary

- The measured **muon content and its fluctuation** within proton and iron, **no muon excess** observed in very high energy region.
- The **muon content and its fluctuation** is **sensitive to cosmic ray composition**
- The $\mathbf{\Lambda_{\mu}}$ of the DATA **is shorter** than that of MC of QGSJET and SIBYLL below PeV
- 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.
- **Flow-like correlations** are progressively washed out as the air shower develops.

Thanks for your attention!