Study of Cosmic-Ray Extensive Air Showers

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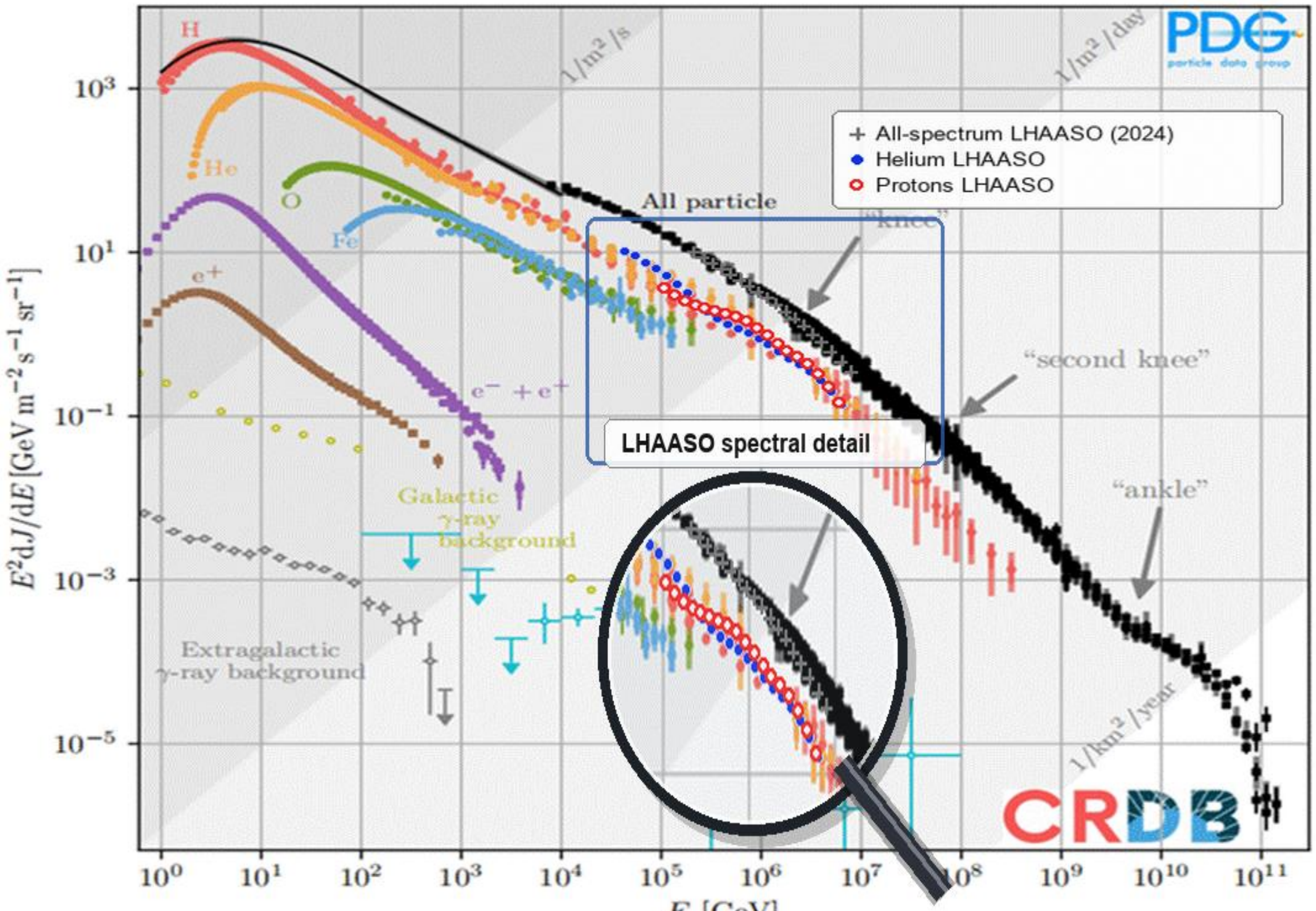
LHAASO天体辐射与宇宙线成分谱观测研究及新技术研究

Content

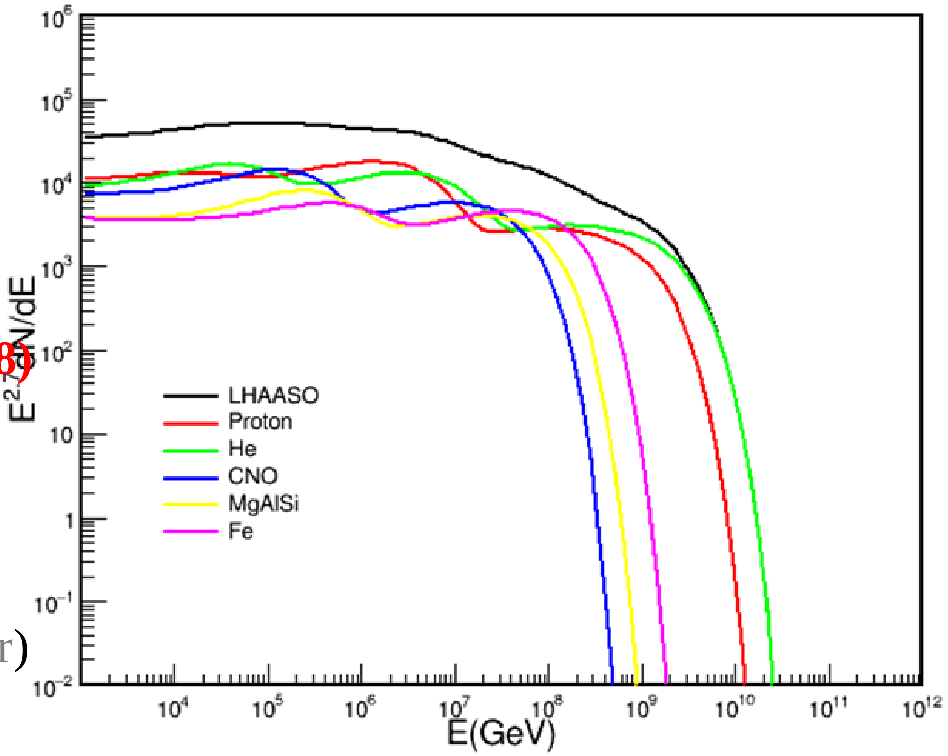
Cosmic-Ray spectra



- LHAASO has achieved high-precision measurements of the **all-particle**, **proton**, and **helium** cosmic-ray spectra.
- Uncertainties in **hadronic interaction models** are becoming a major systematic.

Data sample and Selection criteria

- **MC sample**
  - Energy: 10TeV-100PeV
  - Components: Proton, He, CNO, MgAlSi, Fe
  - Hadronic interaction models:
    - EPOS-LHC, QGSJET-II-04, SIBYLL 2.3d (corsika-7.7)
    - **EPOS-LHCR, QGSJET-III-01, SIBYLL 2.3e (corsika-7.8)**
  - Spectrum: Uni, Gaisser H3a, GSF, Bixj spectrum
- **Criteria**
  - N_e >80 (40-200m)
  - 320<=R<=420 (Distance from the shower core to the array center)
  - $0° < \theta < 40°$



- **Muon content N_μ:** the number of muons recorded by MDs within **40-200 m** from the shower core
  - Reduce the punch-through effect; Reduce the fluctuation

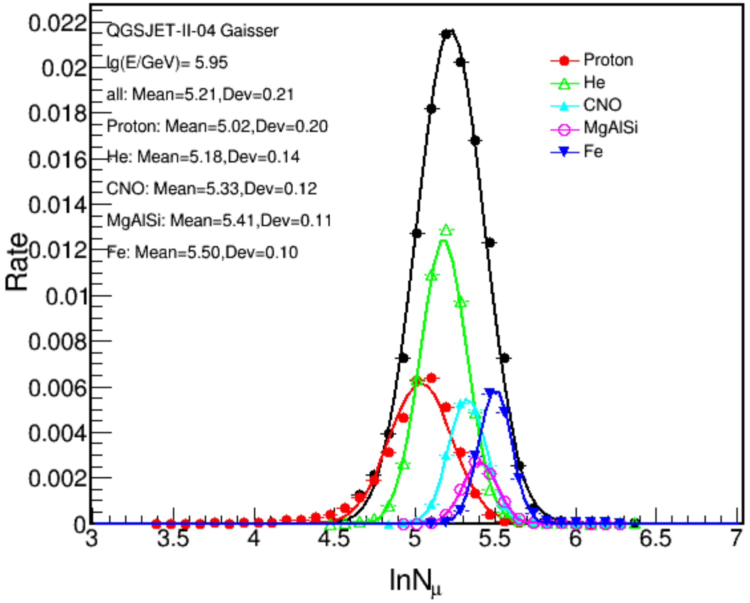
Parameterization method

- The number of muons depend on the energy E and mass A of the cosmic ray: $N_\mu = A(E/AC)^\beta$
- For a fixed energy, taking the logarithm of N_μ and A:

$$\mathbf{<\ln N_\mu> = f_a + f_b} * <\ln A> \quad \Rightarrow \quad <\mathbf{\ln A}> = \frac{<\ln N_\mu> - \mathbf{f_a}}{\mathrm{f_b}}$$

- There are two independent sources of muon fluctuations: the intrinsic shower-to-shower fluctuations and the lnA dispersion arising from the mass distribution

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



- The average variance of muon content weighted according to the lnA

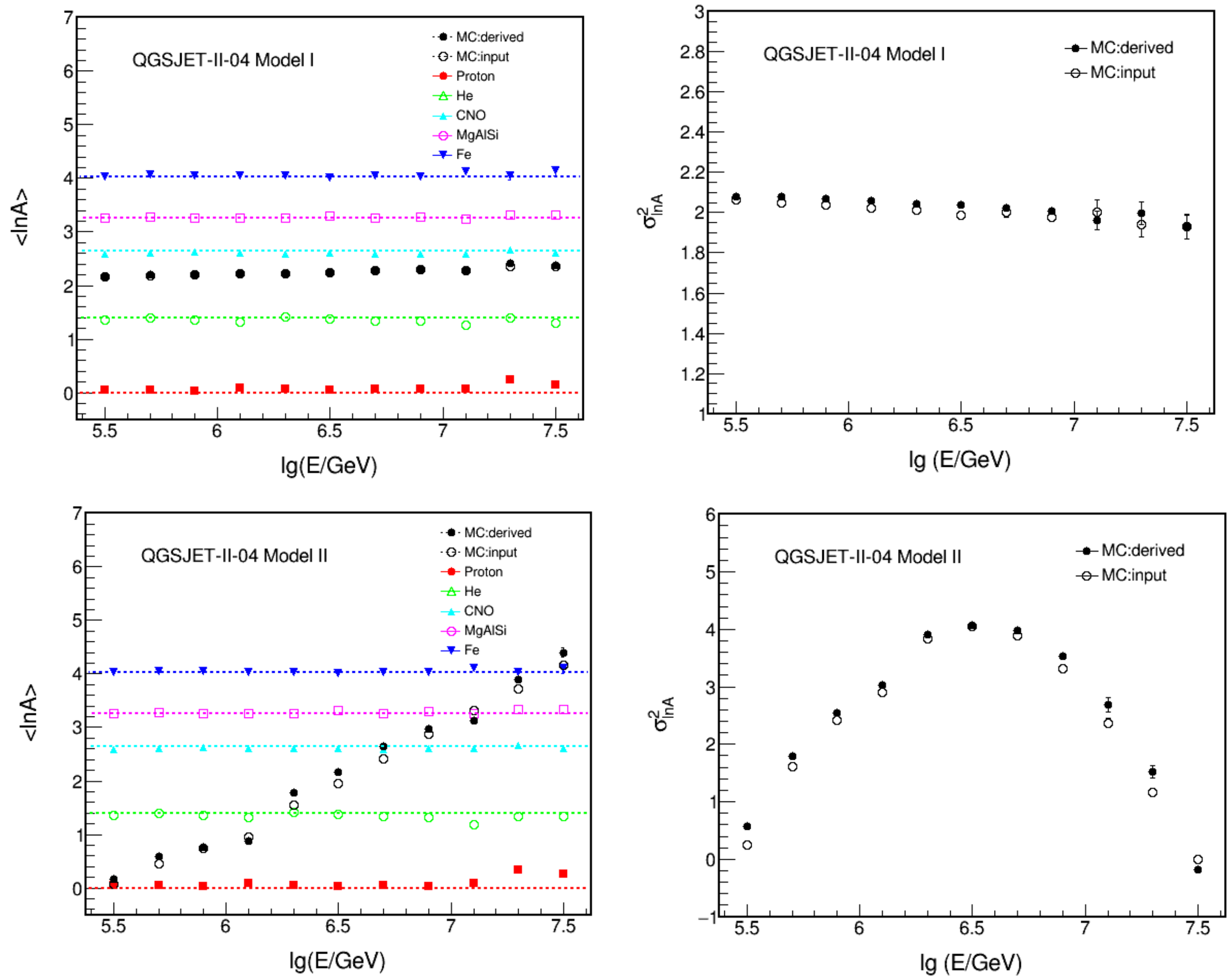
$$<\sigma_{sh}^2> = \sigma_p^2[1 + \mathbf{a} <\ln A> + \mathbf{b} <(\ln A)^2>]$$

- The variance of the lnA : $\boldsymbol{\sigma_{\ln A}^2} = \frac{\sigma^2(\ln N_\mu) - \sigma_{sh}^2(<\ln A>)}{b\sigma_p^2 + f_b^2}$

Method Validation of MC

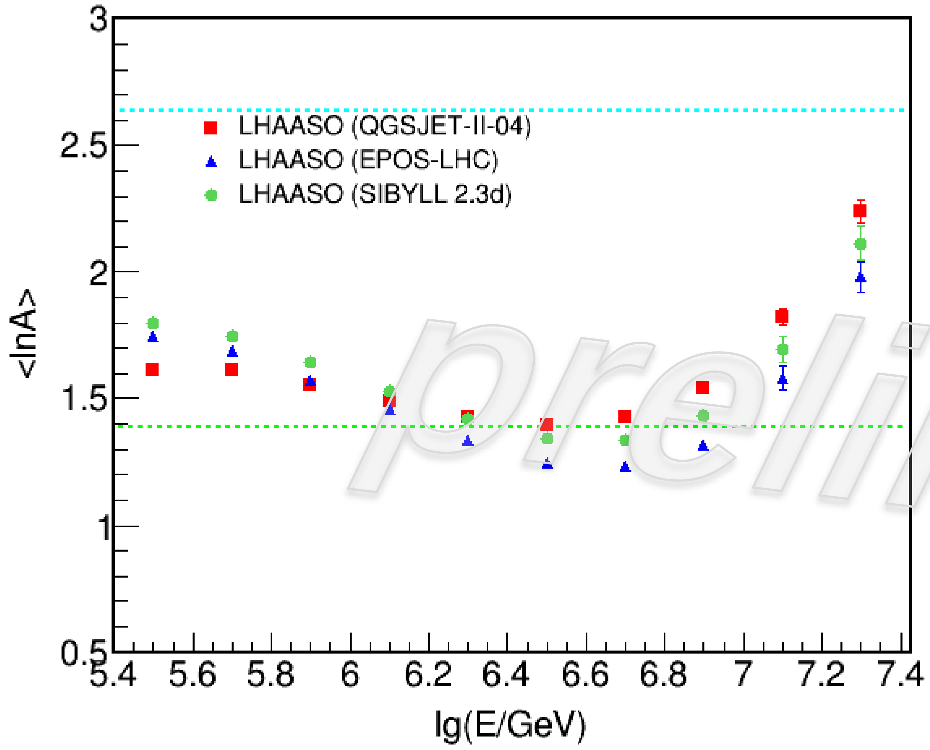
Model I

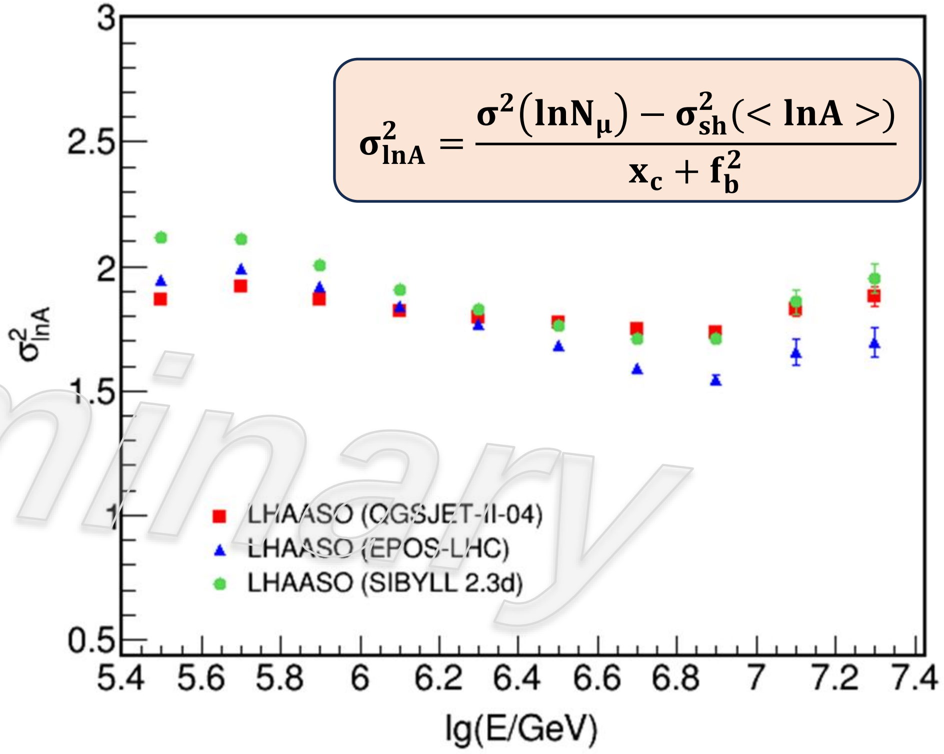
Model II



The mass and variance derived from the parameterization method closely match the original values

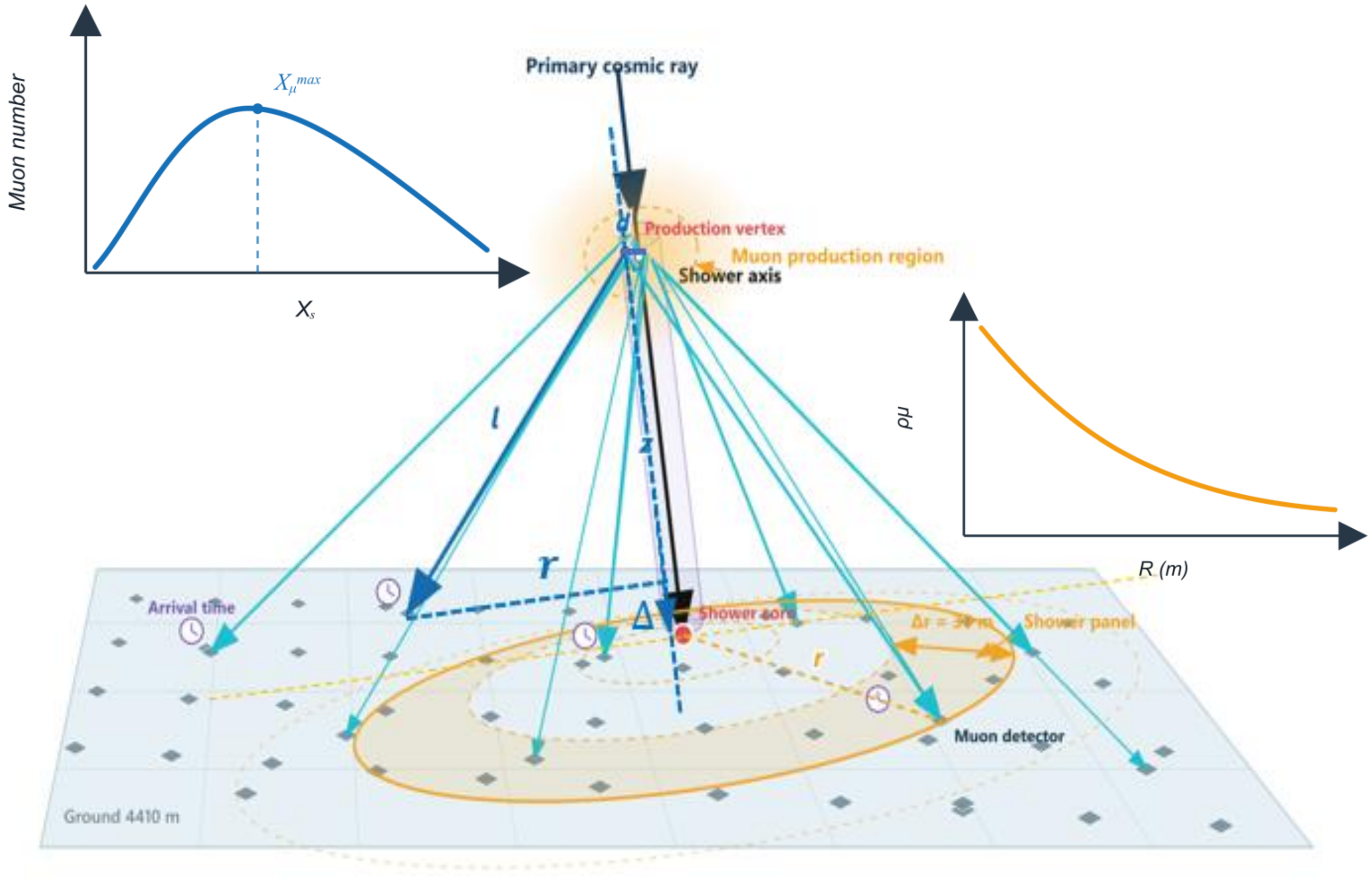
Measurement of $\sigma^2_{\ln A}$ of cosmic-ray





- 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 longer decrease**, which may be related to new population entrance

Muon lateral density and production depth



- Muon lateral distribution:

$$\rho_\mu(r) = \frac{N_\mu(i)}{36 \cdot M(i)}$$

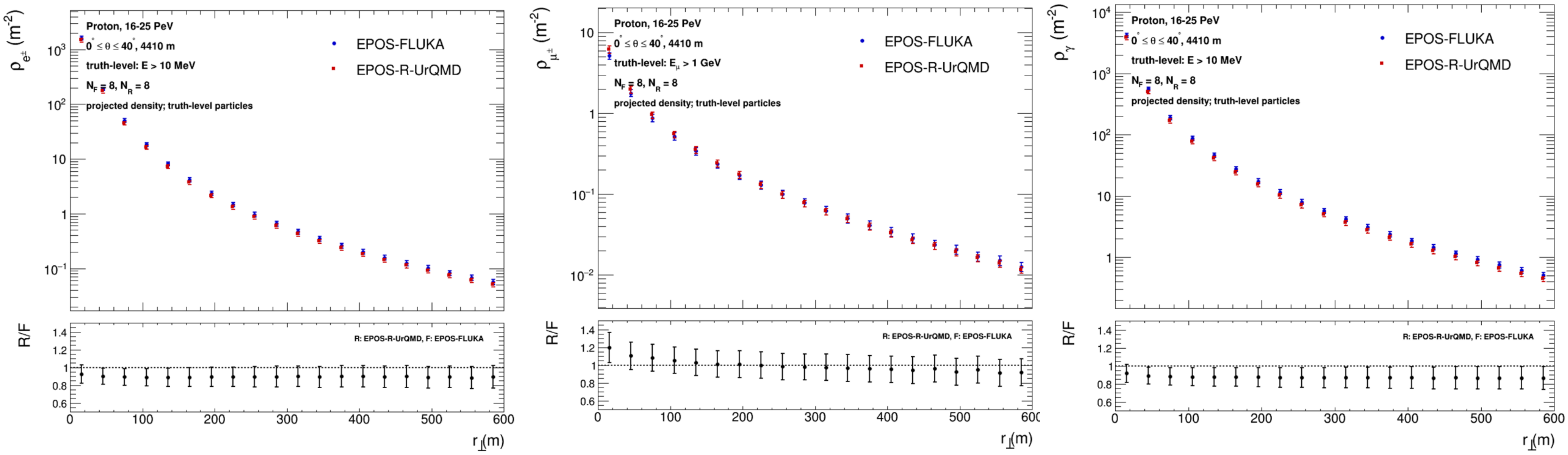
$$\rho_\mu(r, N) = N \frac{1}{r_g^2} \left(\frac{r}{r_g}\right)^\alpha \left(1 + \frac{r}{r_g}\right)^\beta$$

- Muon production depth:

$$\mathrm{z} = \frac{1}{2}\left(\frac{(\mathbf{r}-\mathbf{d})^2}{\mathbf{ct_g}} - \mathrm{ct_g}\right) + \Delta * \frac{\mathrm{r}-\mathrm{d}}{\mathrm{r}}$$

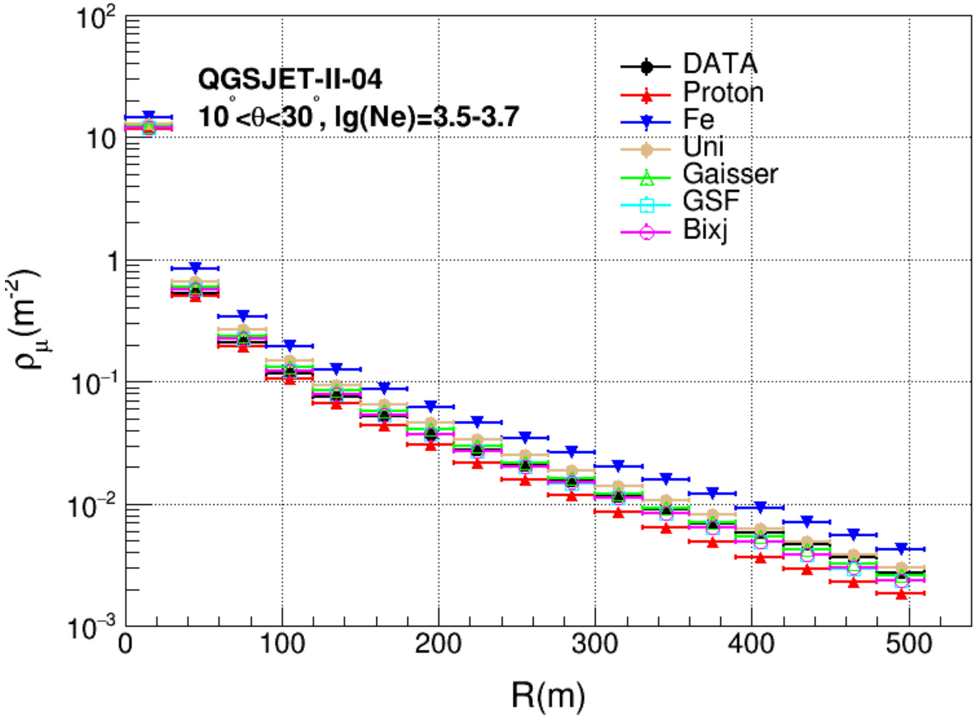
$$\mathrm{ct_g} = \mathrm{l} - \left(\mathrm{z} - \Delta \cdot \frac{\mathrm{r}-\mathrm{d}}{\mathrm{r}}\right) \propto \mathrm{t_{tot}}$$

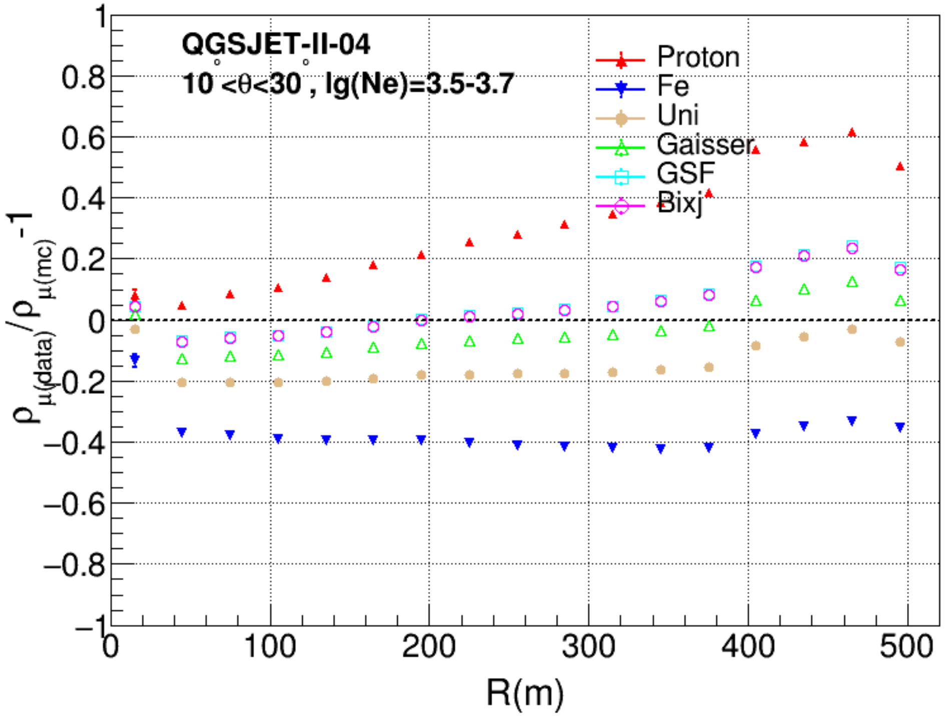
Lateral density comparison : EPOS-LHC vs. EPOS-LHCR



- At 4410 m, LHC and LHC-R predict different lateral distributions of secondary particles.
- EPOS-LHC-R predicts slightly fewer e and γ than EPOS-LHC.

Muon lateral distribution

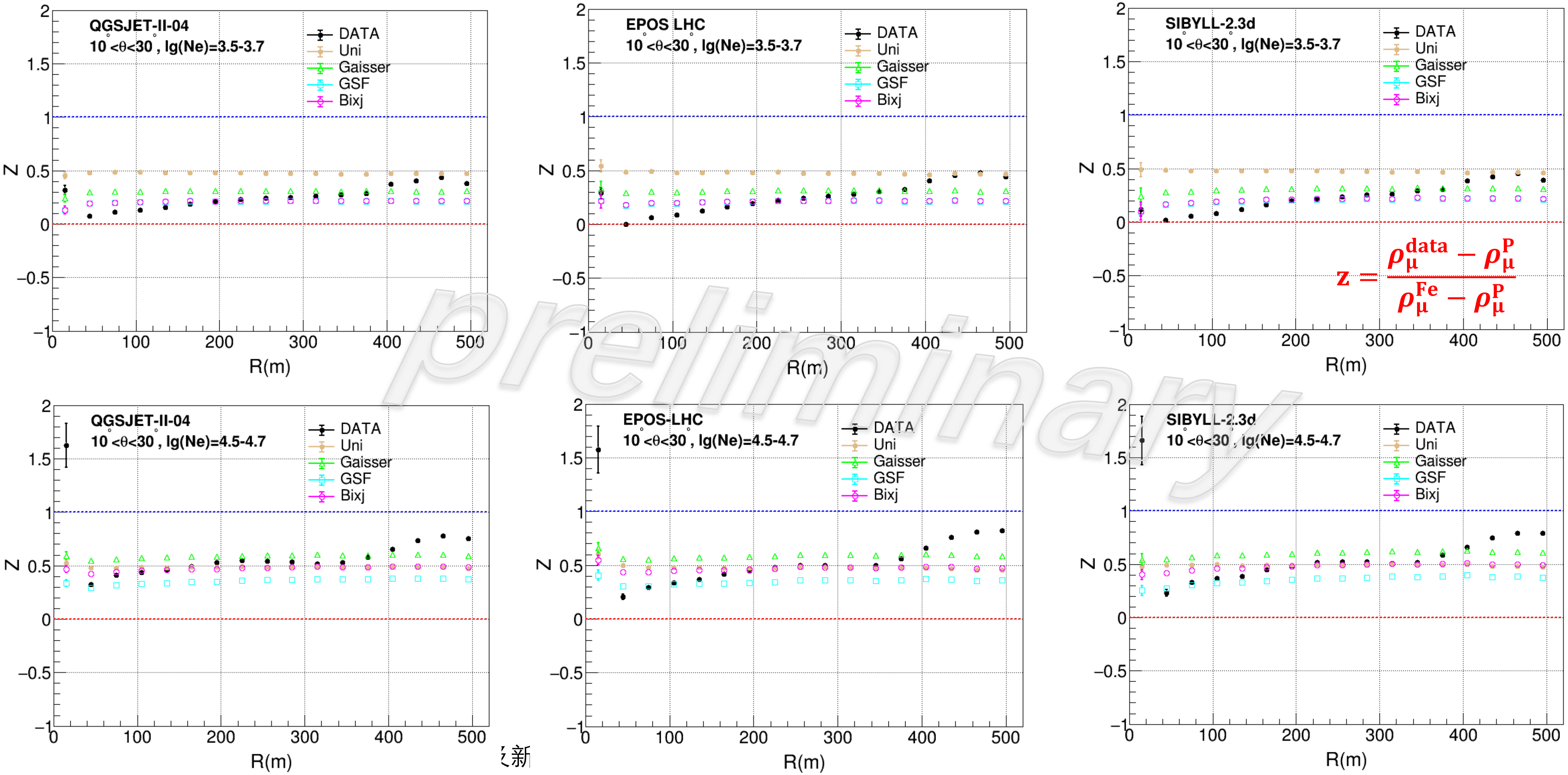




- The measured muon density is **between** the predictions for **pure proton and pure iron**
  - The muon density of **proton** **decreases rapidly** with distance compared to DATA
  - The muon density of **iron** follows the **same trend** as the DATA
- The measured muon density is lower than the MC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

04/3D Observation of EASs

Muon lateral density ratio



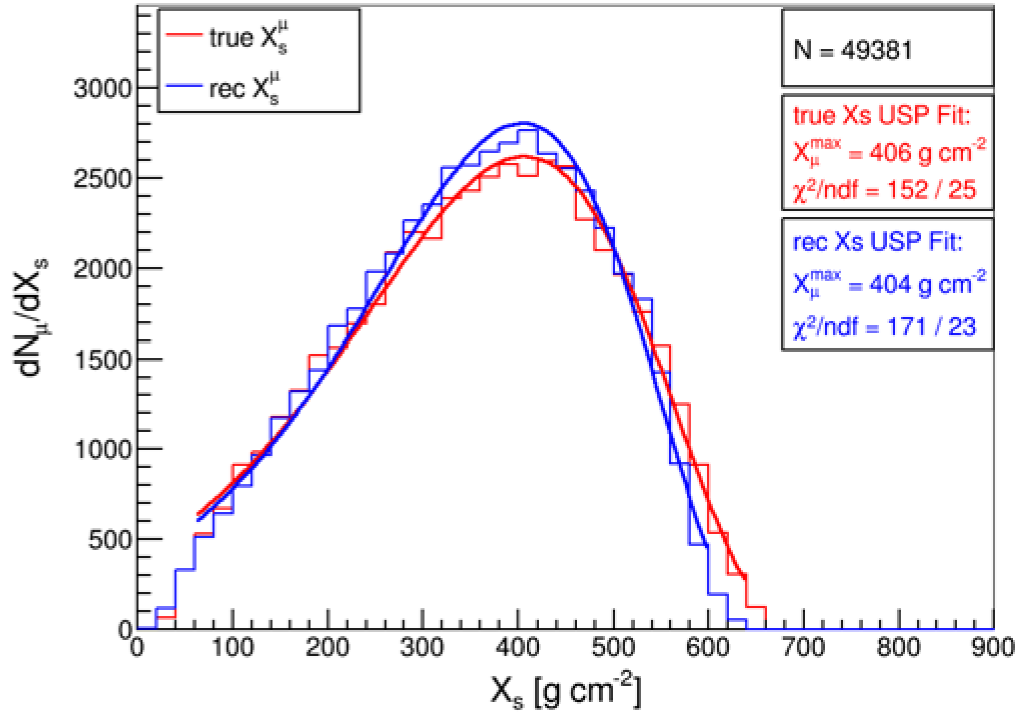
$$z = \frac{\rho_\mu^{data} - \rho_\mu^{P}}{\rho_\mu^{Fe} - \rho_\mu^{P}}$$

Measurement of the X^{μ}_{max} of muons

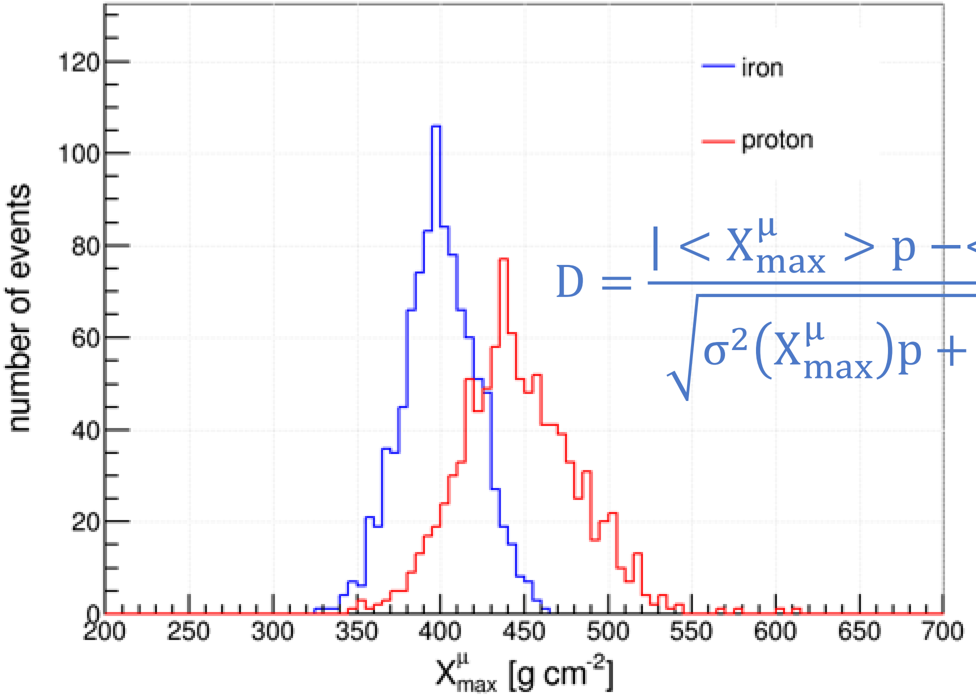
USP function:

$$\frac{dN}{dX} = \left(1 + \frac{R}{L}(X - X^{\mu}_{max})\right)^{R^{-2}} \exp\left(-\left(\frac{X - X^{\mu}_{max}}{LR}\right)\right)$$

X^{μ}_{max}: Maximum depth of muon production;



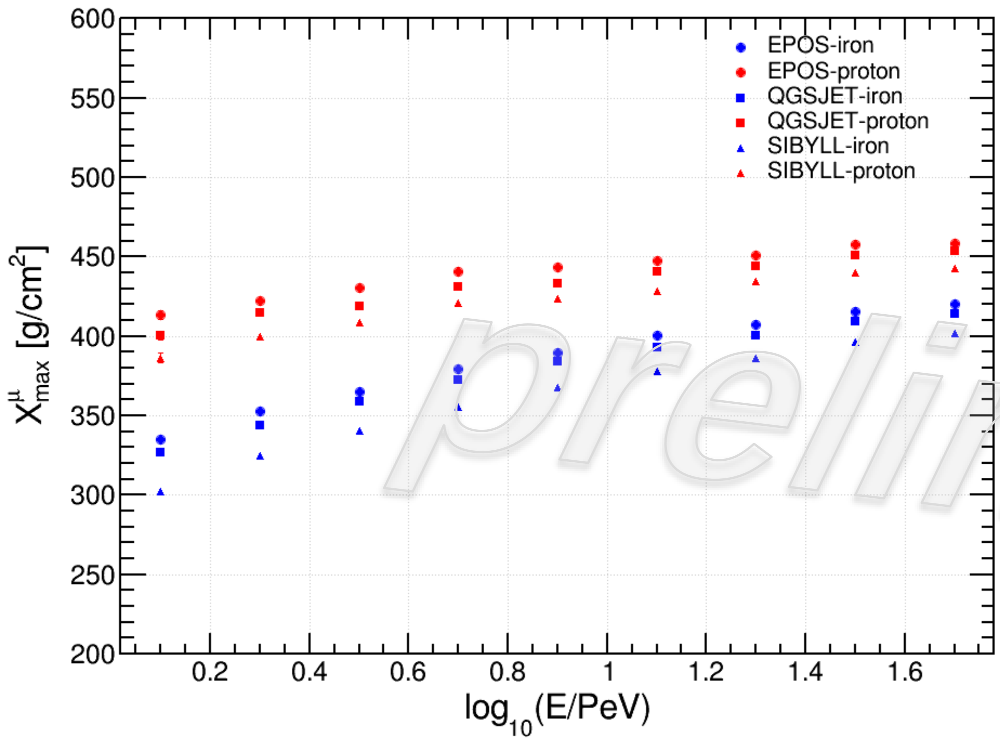
Muon Production Depth distribution @ one event

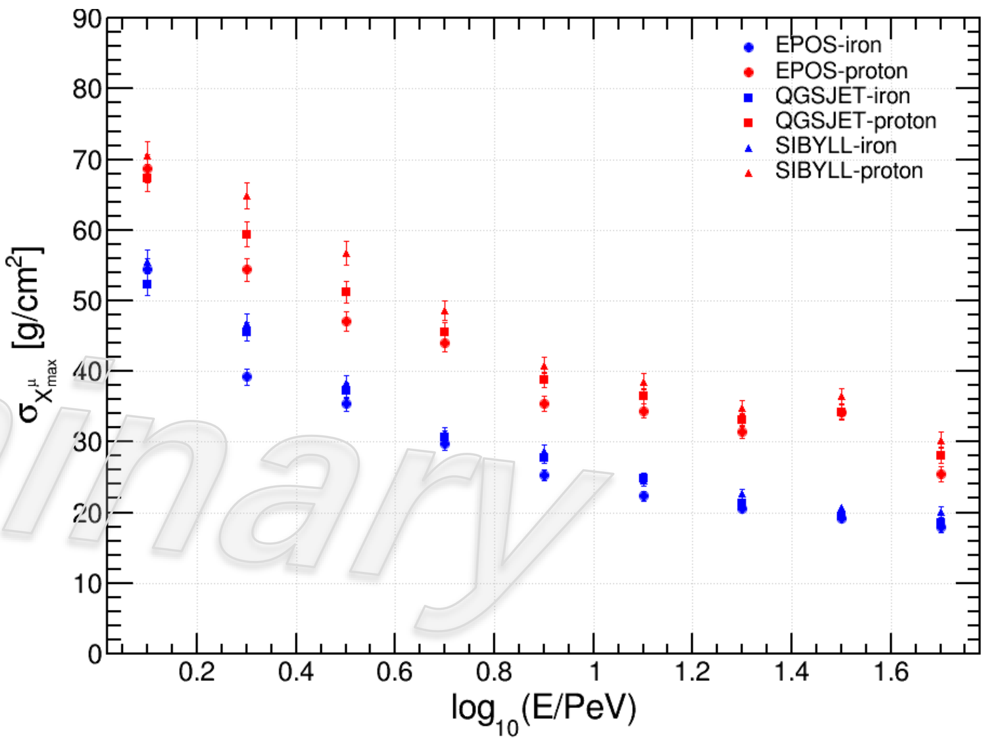


$$D = \frac{|<X^{\mu}_{max}>p - <X^{\mu}_{max}>Fe|}{\sqrt{\sigma^2(X^{\mu}_{max})p + \sigma^2(X^{\mu}_{max})Fe}}$$

X^{μ}_{max} distribution of Proton and Fe @10PeV

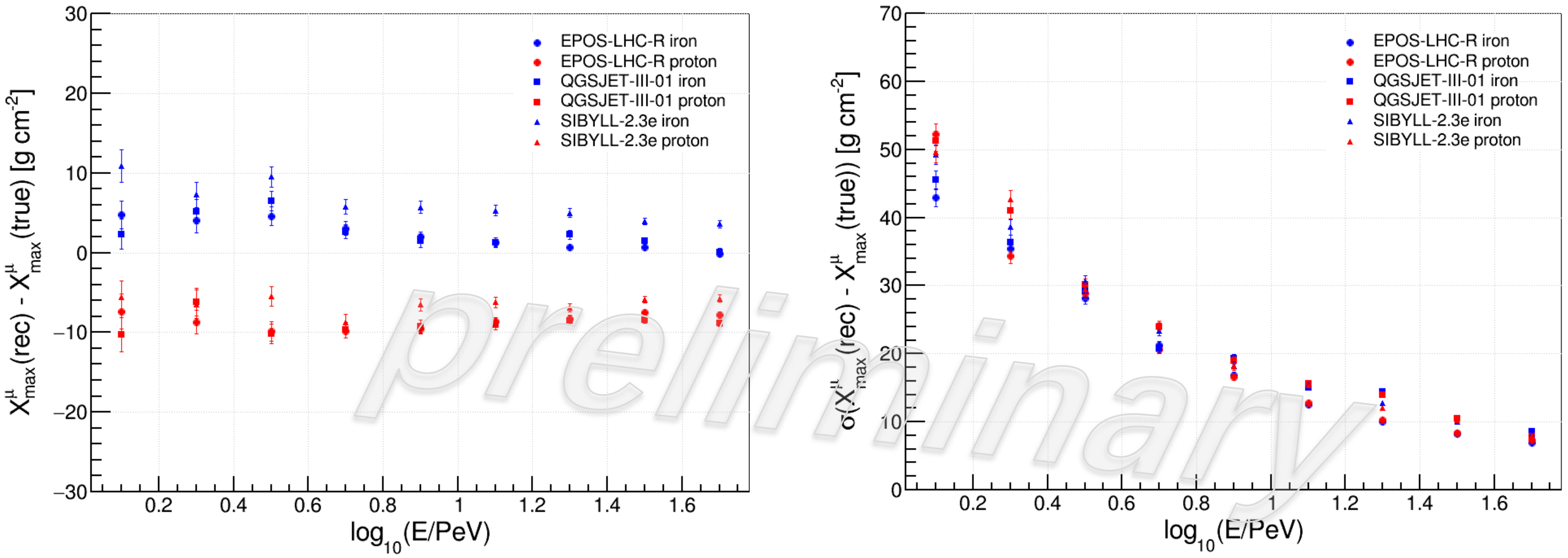
Features of the X^{μ}_{max}





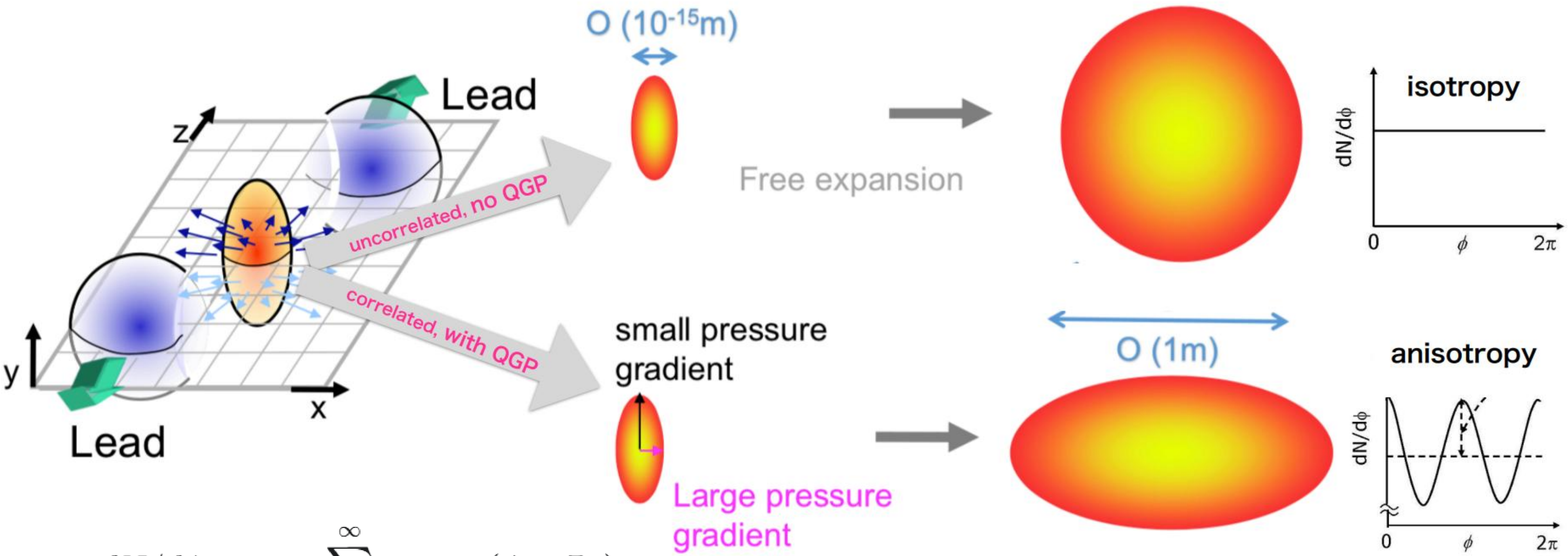
- Average **X^{μ}_{max} (< X^{μ}_{max} >)** **increases with energy**, while its **uncertainty ($\sigma(X^{\mu}_{max})$)** **decreases**, showing similar trends for proton and iron primaries.
- Both < X^{μ}_{max} > and $\sigma(X^{\mu}_{max})$ are **composition-sensitive**.
- < X^{μ}_{max} > is sensitive **to hadronic interaction models**, whereas $\sigma(X^{\mu}_{max})$ is relatively insensitive.

Reconstruction performance of X^{μ}_{max}



- For both Proton and Fe, the bias **remains within ±10 g/cm²** above 1 PeV, and decreases with energy.
- The resolution is **better than 50 g/cm²** above 1 PeV, and also decrease with energy.

Collective flow: signal of QGP



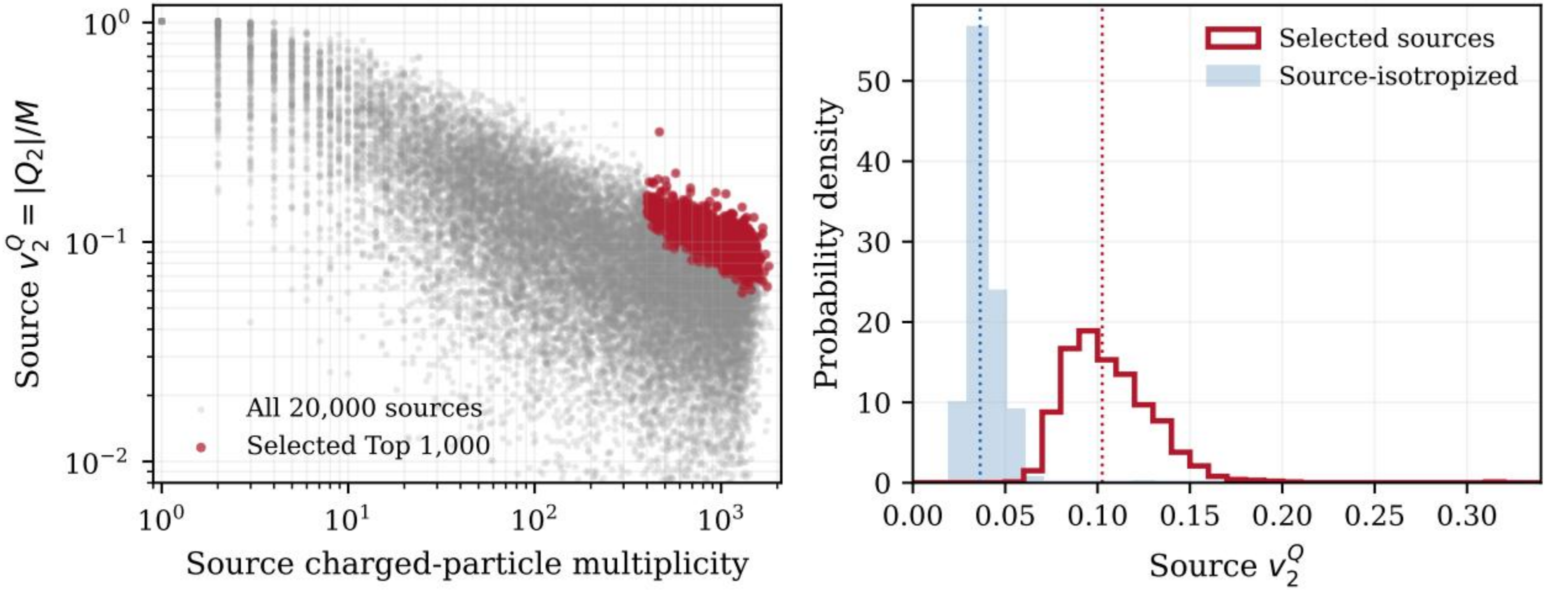
$$dN/d\phi \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_r)$$

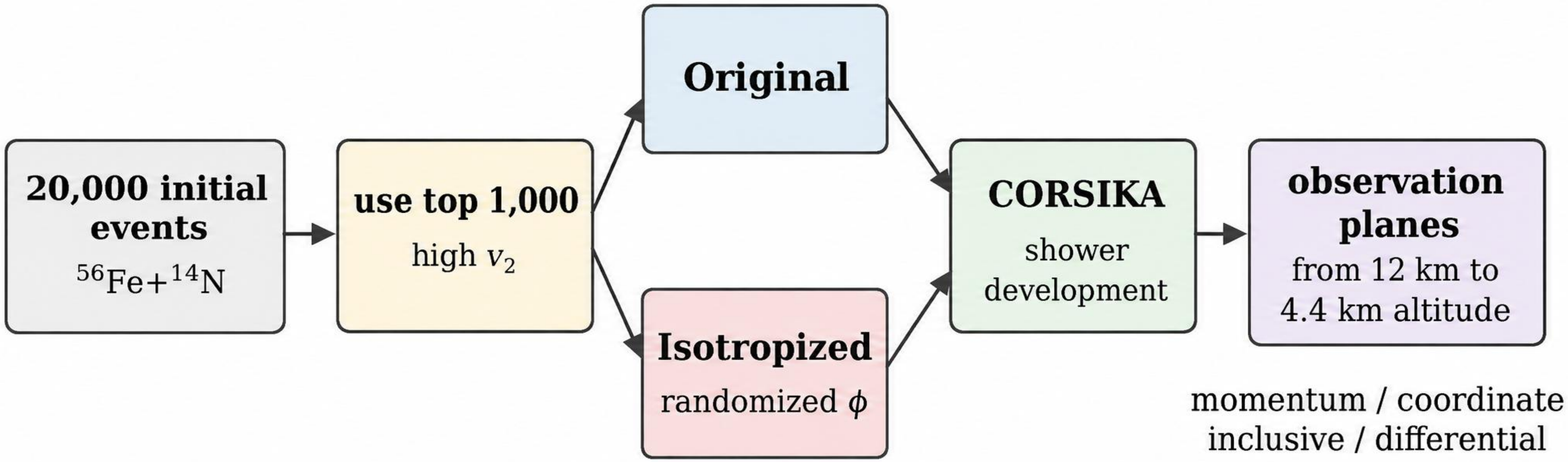
v_2 characterizes elliptic flow

If there is v_2, can the signal survive the shower development?

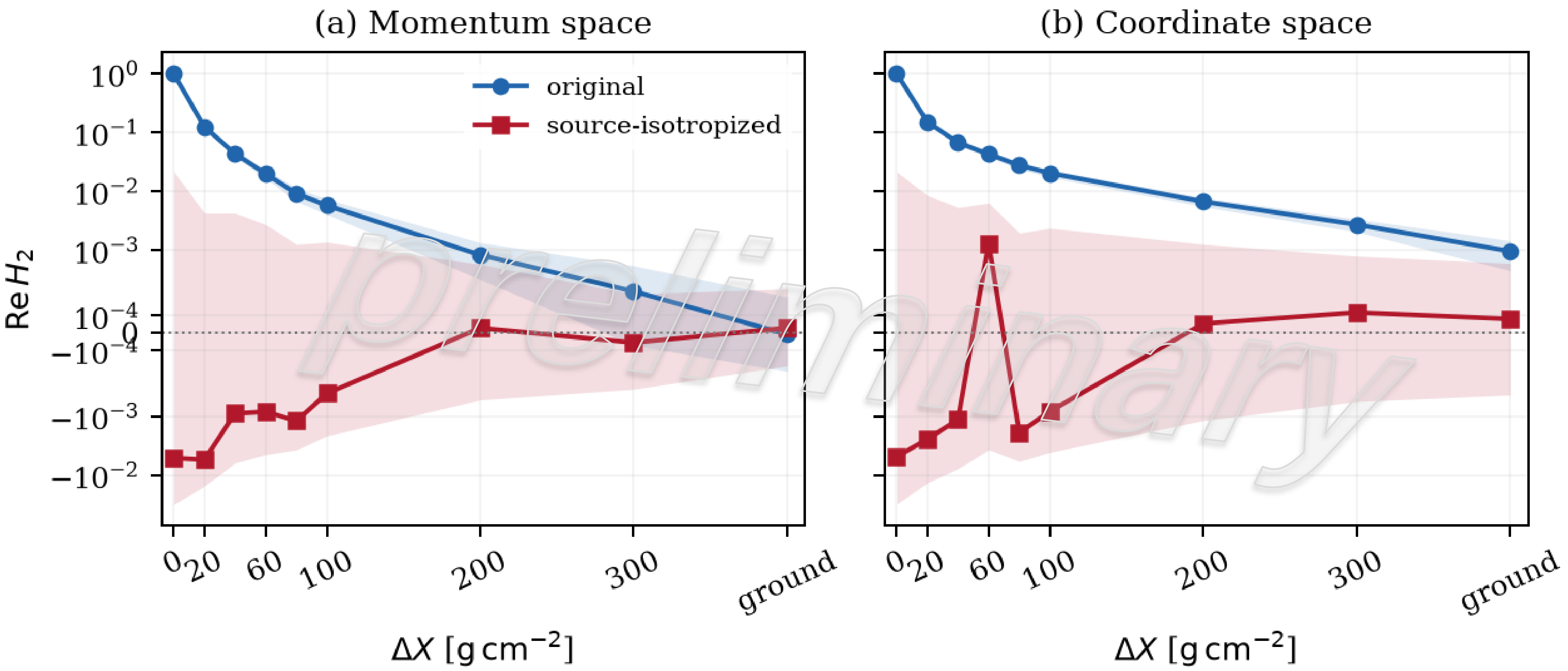
Simulation Setup

- Primary: Fe (hit N)
- Energy: 26PeV ($\sqrt{s_{NN}}$ =1TeV)
- Zenith: 0°
- First interaction: 12 km
- Model: EPOS-LHCR, UrQMD
- Geomagnetic field: **off**





$\mathrm{Re}H_2$ vs. atmospheric depth



- **Rapid attenuation:** >80% lost within the first 20 g/cm^2.
- **Momentum space:** indistinguishable from baseline by ~300 g/cm^2.
- **Coordinate space:** longer retention, but only ~10^{-3} remains at ground.

Summary

- 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.
- 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
- Using LHAASO-KM2A simulated data, the **muon production maximum** depth of air showers can be reconstructed based on **geometrical relations**, with high accuracy.
- The **v2 signal** persists to larger atmospheric depths in coordinate space, but decreases to the 10^{-3} level at ground level.