Cosmic Ray Energy Spectrum, Composition and Hadronic Interaction Model Tests in the Knee Region

Lingling Ma for LHAASO Collaboration

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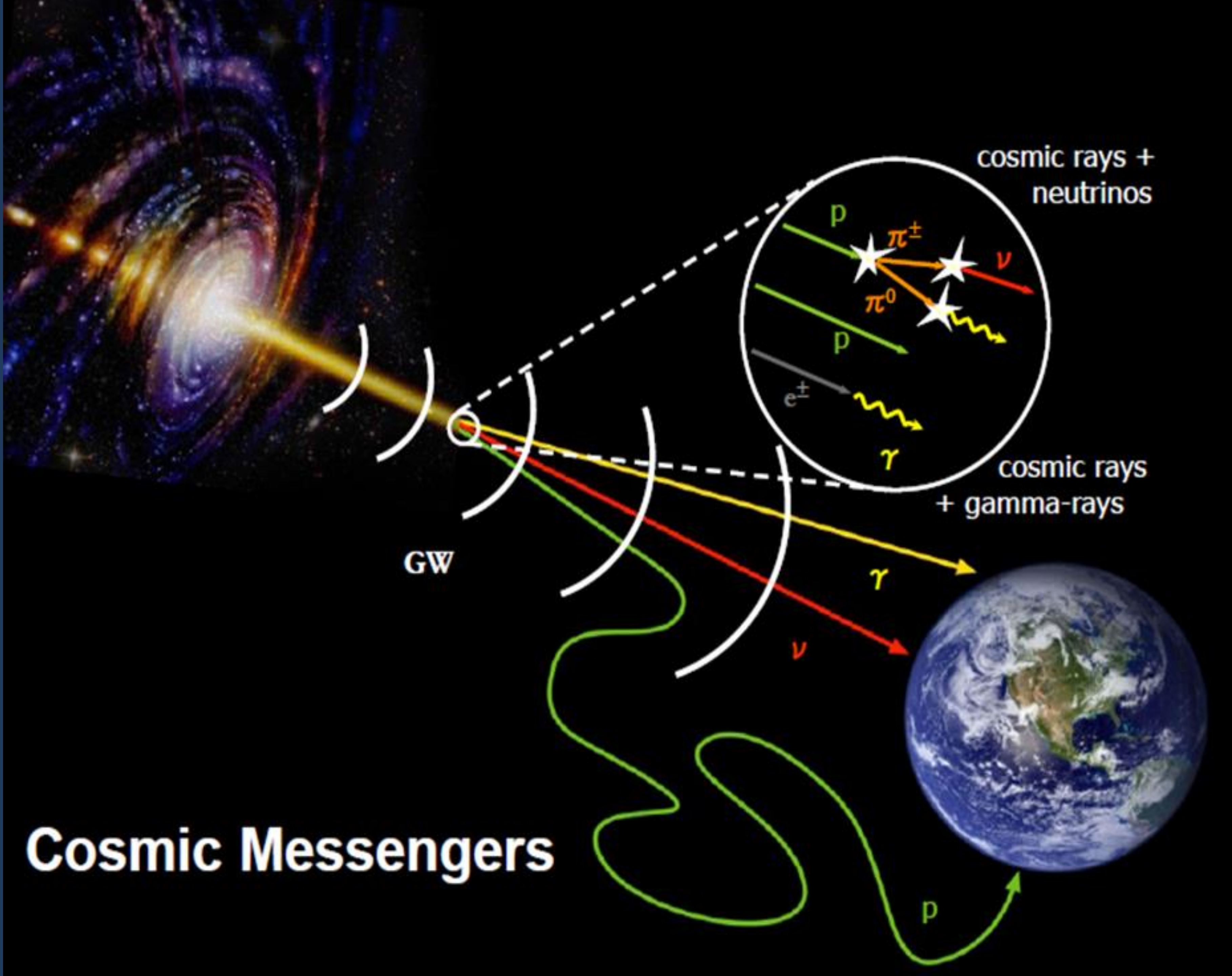
Outline

- Status and challenges in the measurements of energy spectrum and compositions
- The most precise measurements of all-particle energy spectrum, <lnA> and σ(lnA) from 0.3PeV to 30PeV by LHAASO
- Hadronic interaction model test by LHAASO

It is hard to trace cosmic rays back by their arriving directions



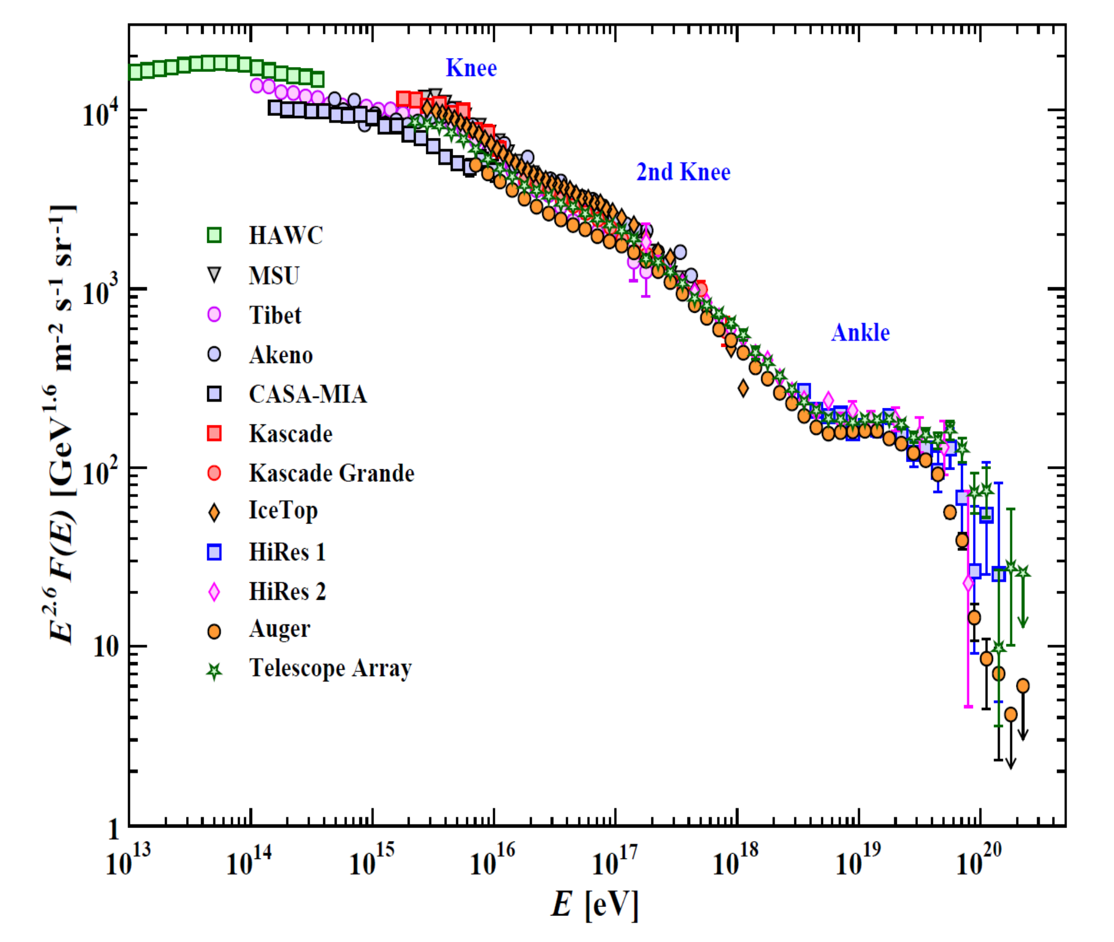
Knee: a 65 years old puzzle

- The most striking features in the energy spectrum, whose origin remains enigmatic.
  - Index: -2.7->-3.1
  - Position: around 4PeV

- A key to the origin, acceleration and propagation
  - Acceleration upper limits of Galactic cosmic ray sources

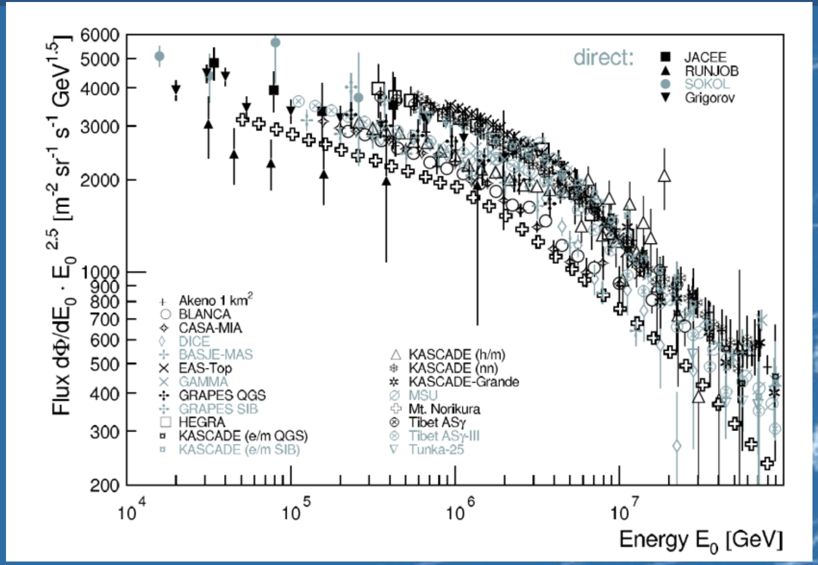
    Z dependent Ec = ZEp
  - New physics：

    A dependent Ec = AEp

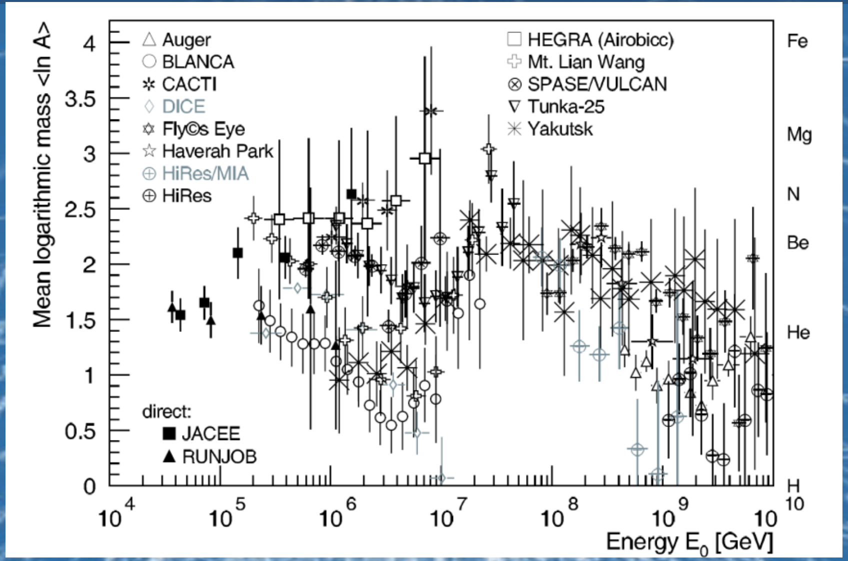


The measurements of the **all-particle energy spectrum and composition(<lnA>),** the single component energy spectrum are crucial to unveil the nature of the knee

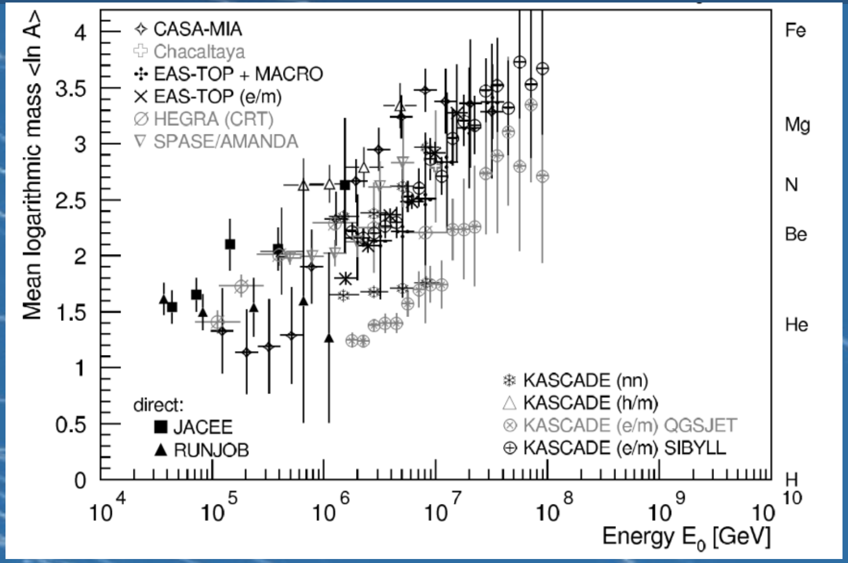
Mess measurements of energy spectrum and compositions



all-particle energy spectrum



<lnA> from Xmax



<lnA> from secondary particles

Indirect measurements → Energy and composition information is lost →

- ✓ Big fluctuations
- ✓ Reconstruction of energy and composition are dependent on each other
- ✓ Hadronic model is uncertain
- ✓ The energy scale is uncertain

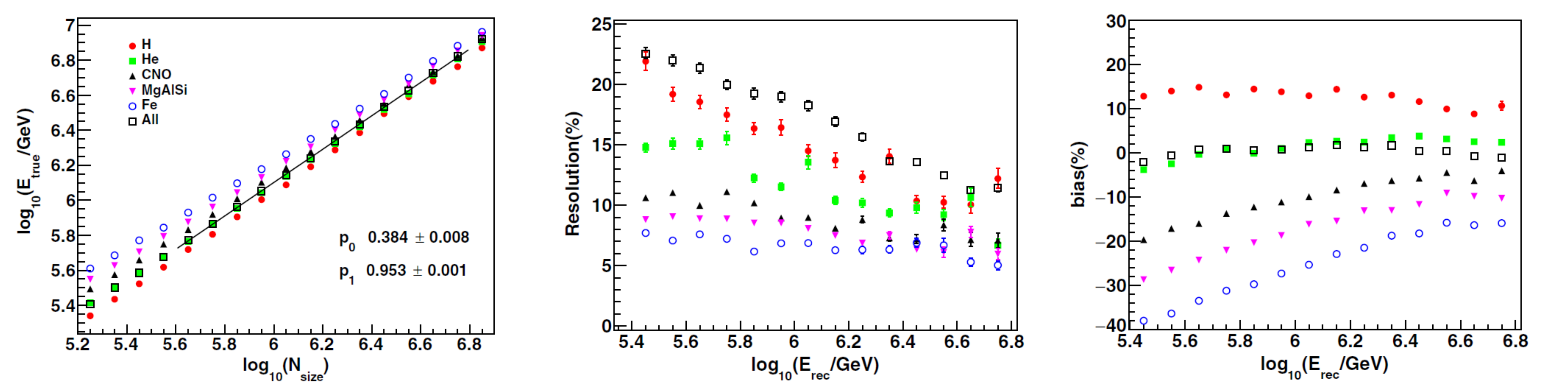
Challenges in the measurements of all-particle energy spectrum and <lnA>

➢ All-particle energy spectrum

- The traditional energy estimator (shower size or density) not only is a function of energy, but also is a function of mass.

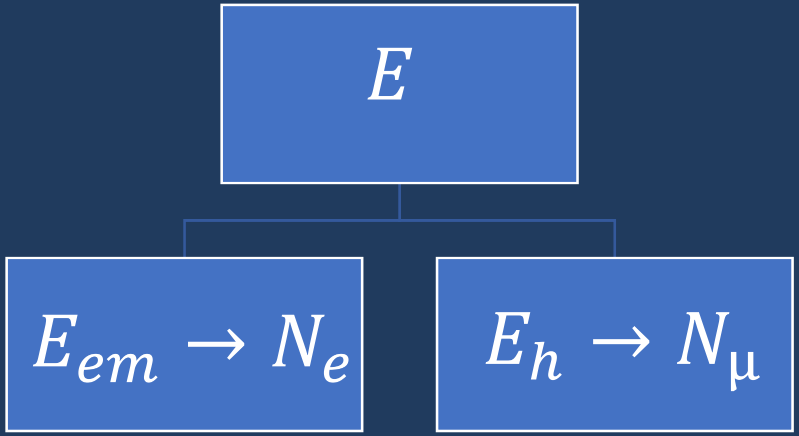
➢ Mean logarithmic mass <lnA>

- Dependent on the energy and hadronic models



(a) E_{true} vs. N_{size}

Calorimetric energy estimator based one the Heitler-Matthews model



$$E_\circ = \xi_c^e N_{max} + \xi_c^\pi N_\mu$$

$$E_0 \approx 0.85\ \text{GeV}(N_e + 25 N_\mu)$$

PRD 106, 123028 (202

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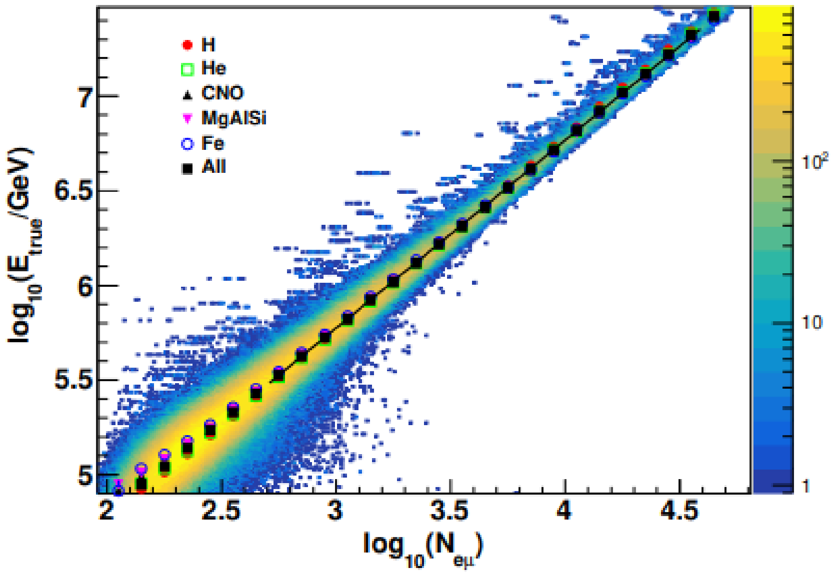
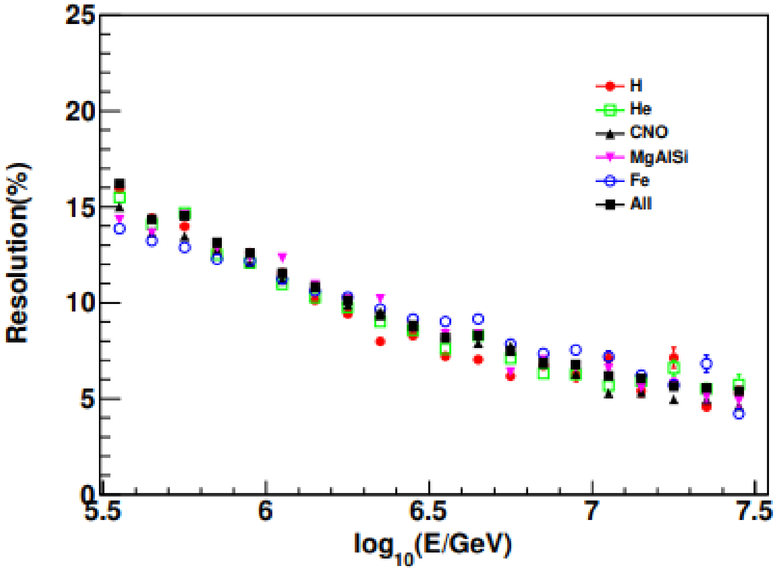
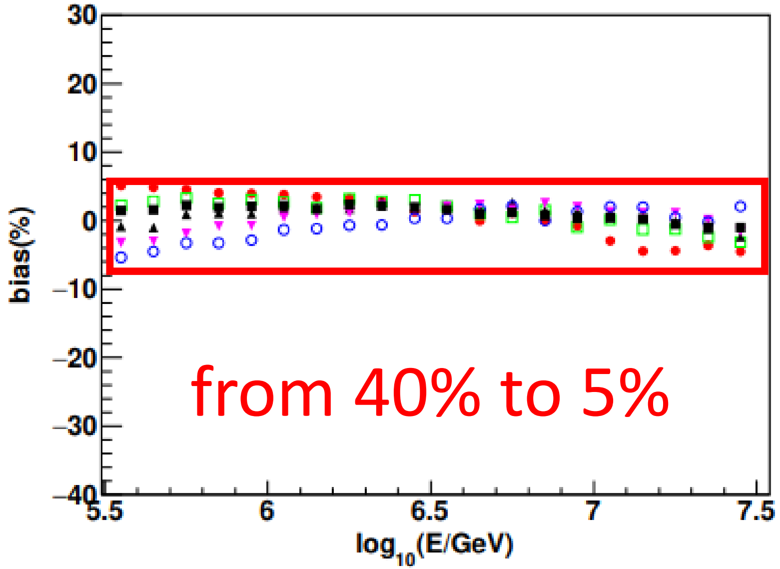
Only works at the shower maximum

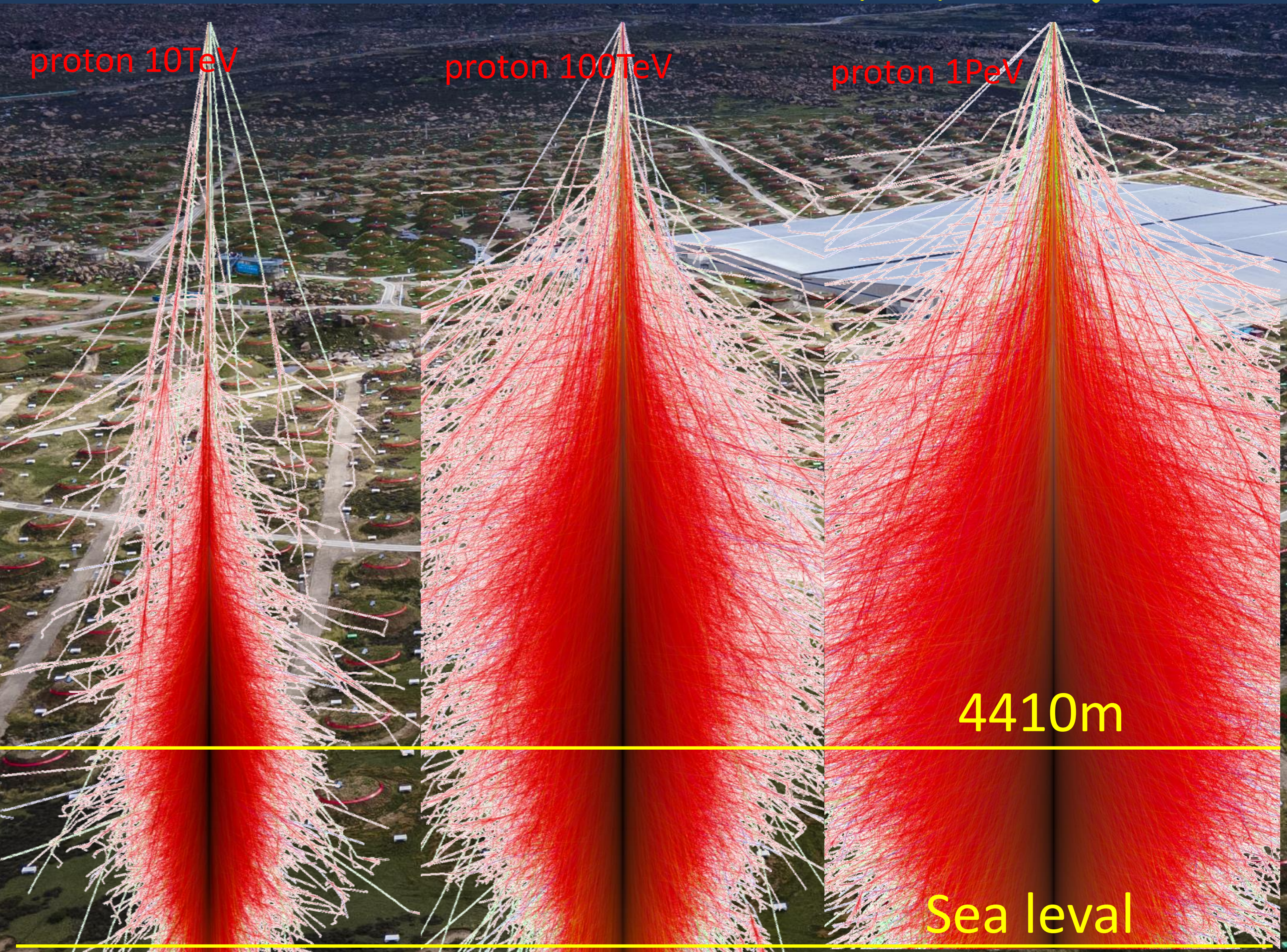


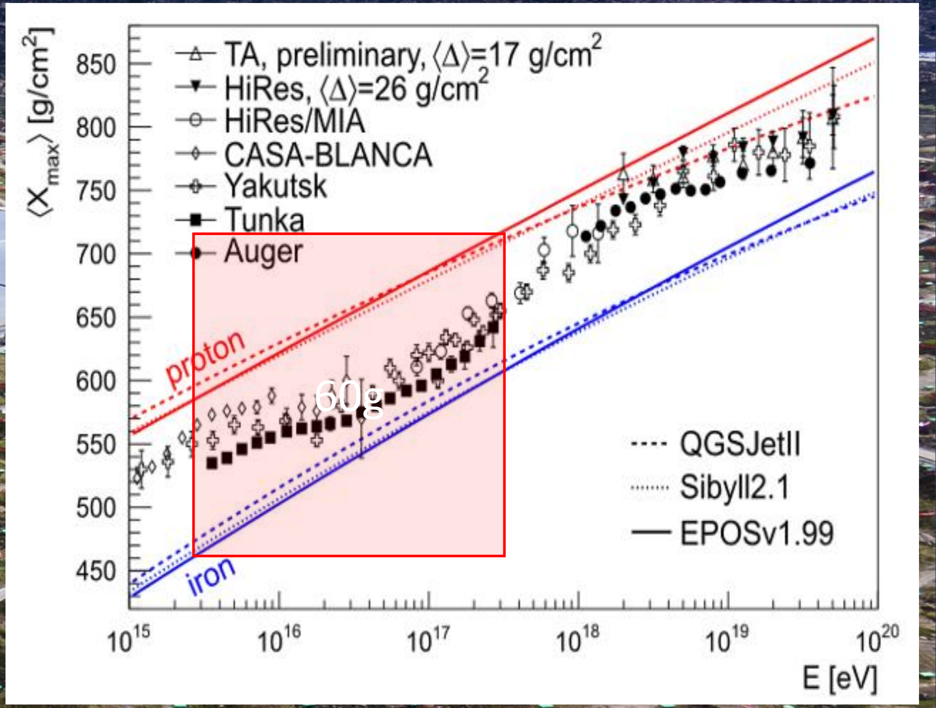




The most precise measurements of all-particle energy spectrum and <lnA> from 0.3PeV to 30PeV by LHAASO

Large High Altitude Air Shower Observatory@4410 a.s.l.
LHAASO 高海拔宇宙线观测站

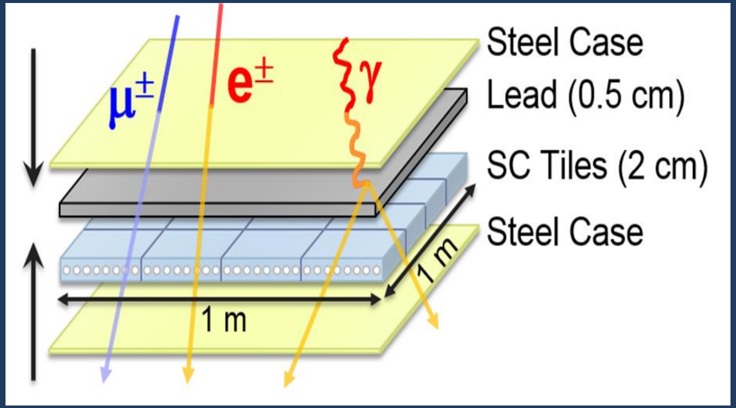




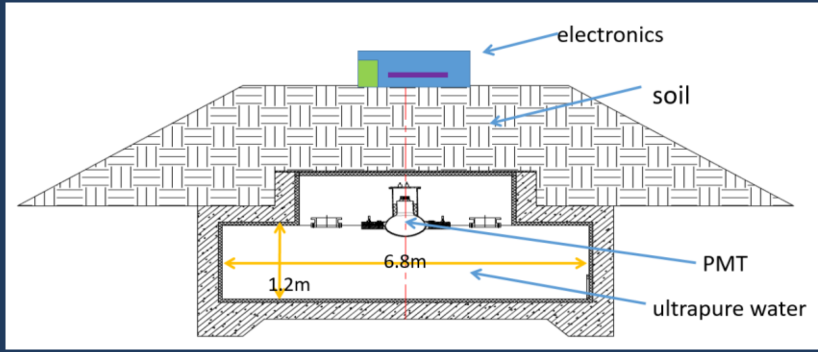
Vertical Air depth of LHAASO site: 600g/cm2

The best altitude for cosmic rays around the knee region

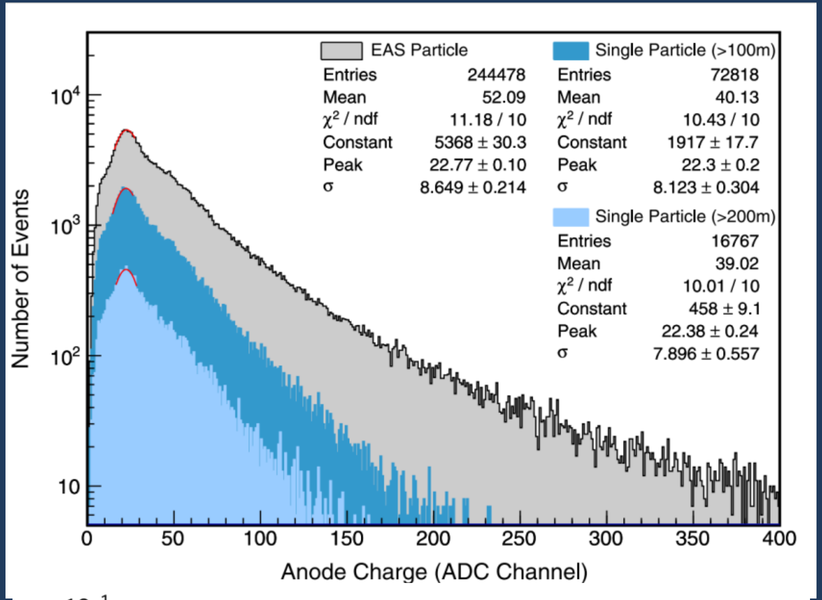
Precise measurements of N_e and N_μ

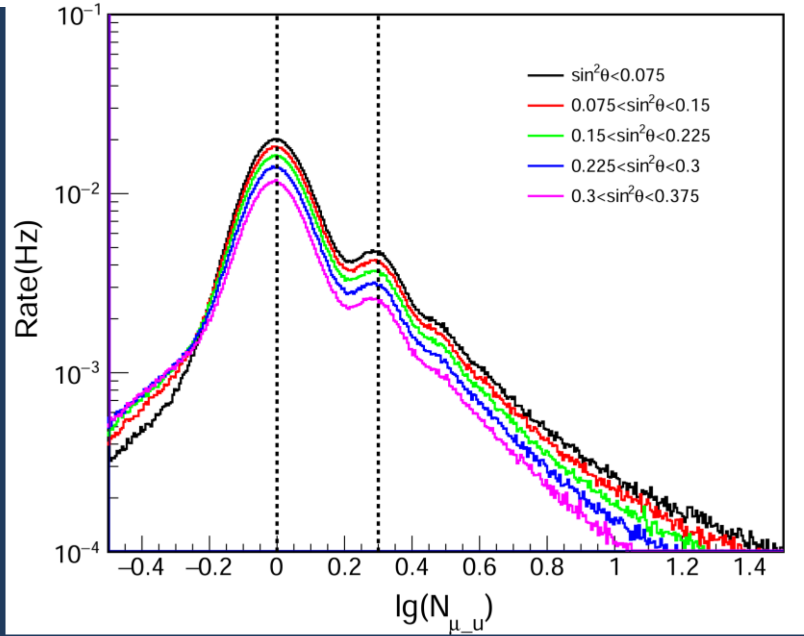


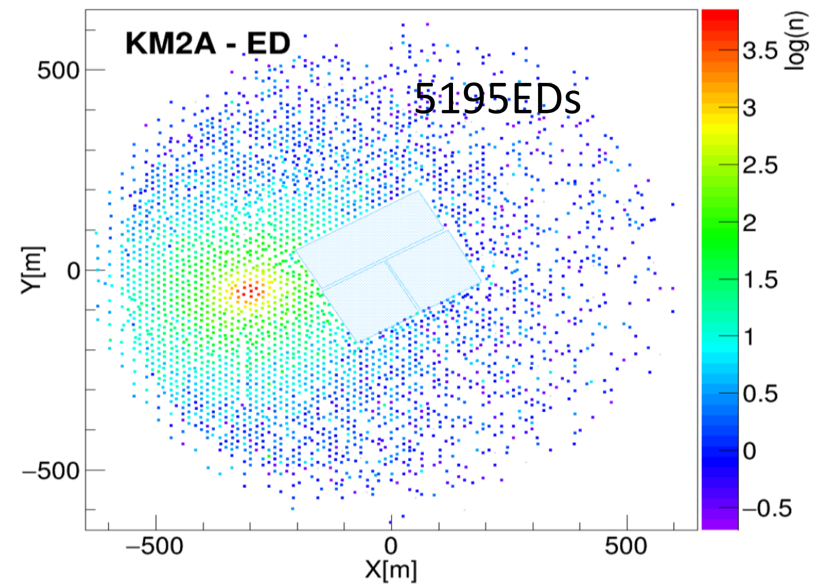
Area: 1m^2
Spacing: 15m

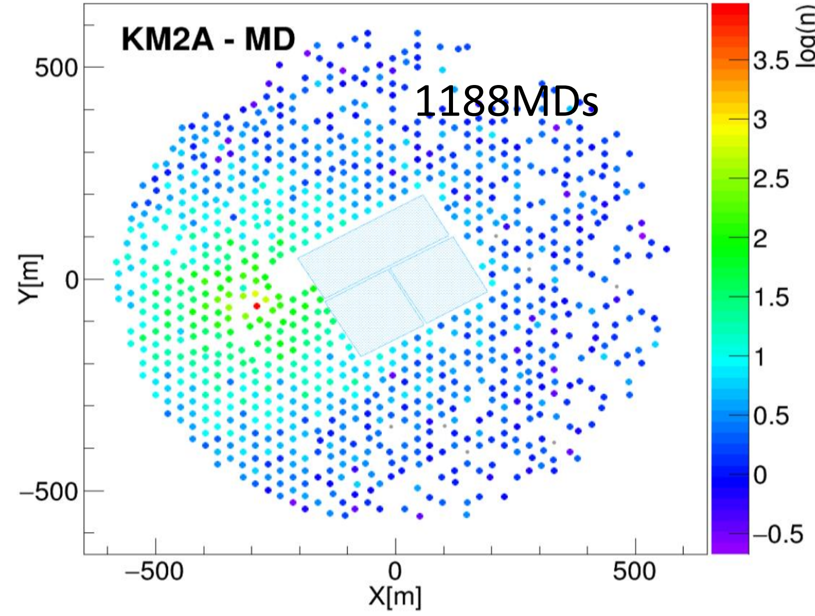


Area: 36m^2
Spacing: 30m



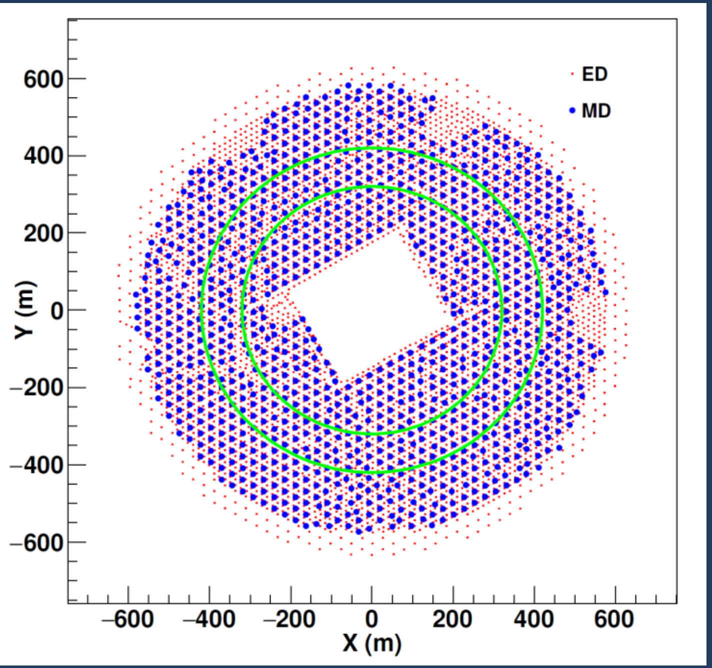


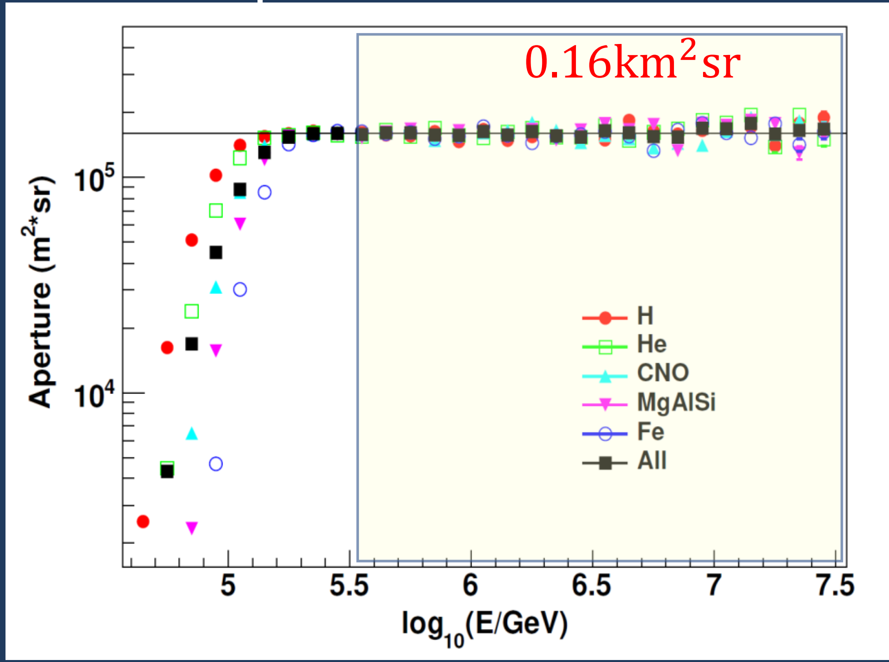




Data selection criteria

- **Zenith angle:** $10° < \theta < 30°$
  - slant air depth: $610 g/cm^2 < X < 692 g/cm^2$
  - Near the Xmax of the cosmic rays around the knee
- **Core position:** $320m < r < 420m$
  - Keep the observation of showers completely





Full efficiency is achieved above 300TeV

Geometric aperture:

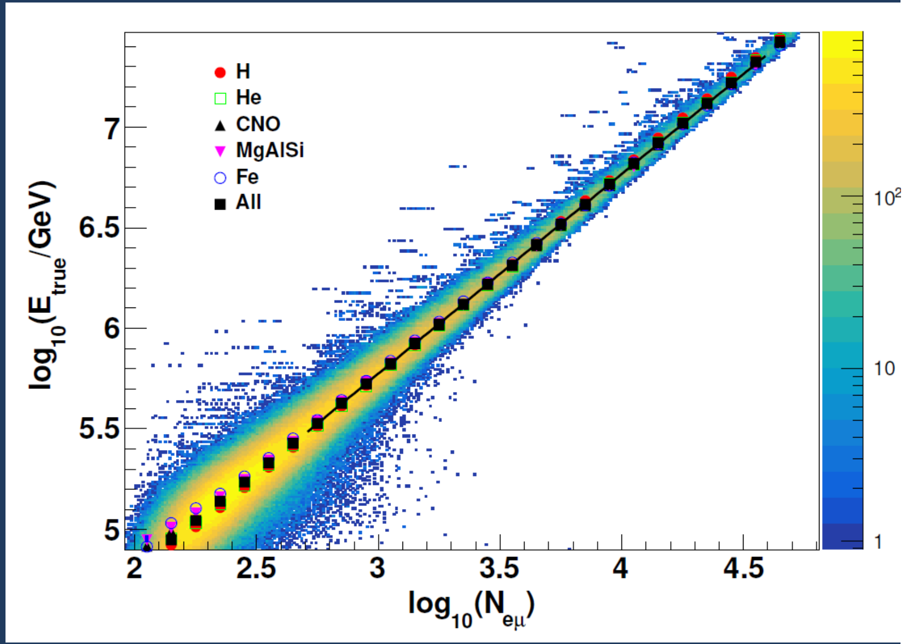
$$\pi\left(R_1^2 - R_2^2\right) \int_{10°}^{30°} \sin\theta \cos\theta d\theta \int_0^{2\pi} d\varphi = 0.16\mathrm{km}^2\mathrm{sr}$$

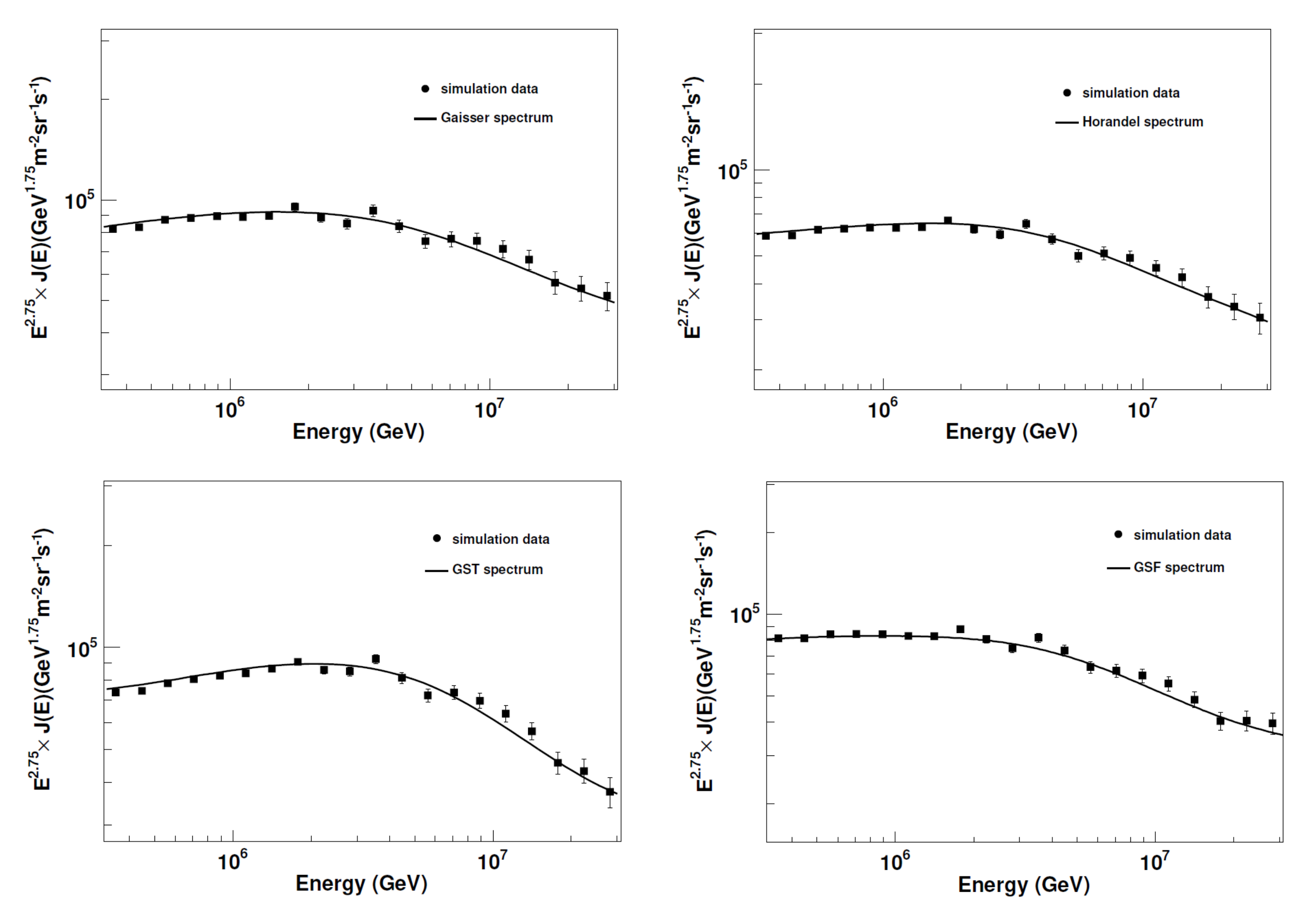
Energy reconstruction

$$E_0 \approx 0.85\ \mathrm{GeV}\boxed{(N_e + 25N_\mu)}$$

Coverage of detectors

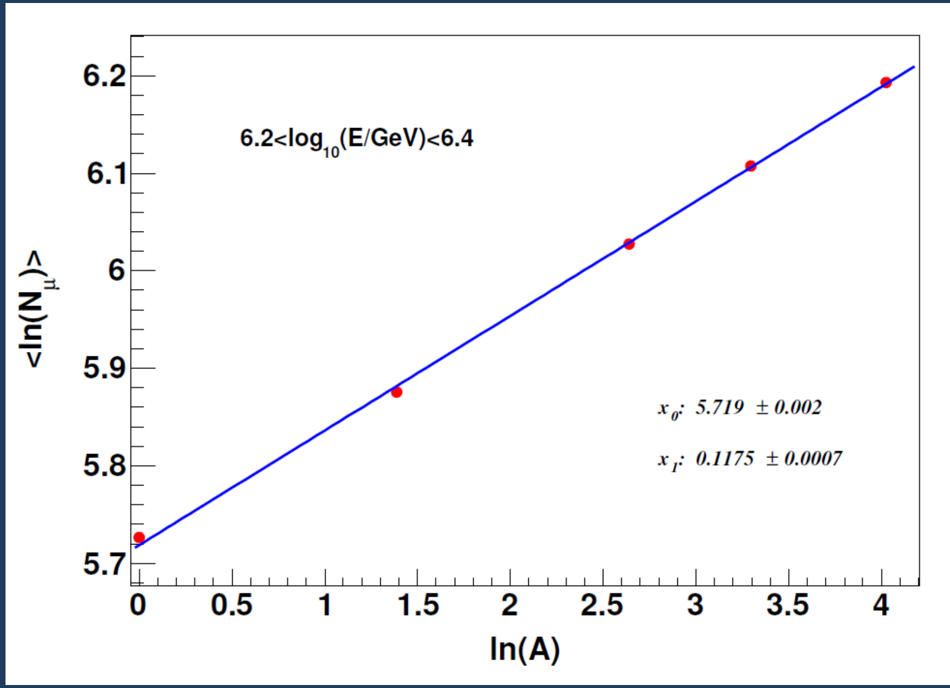
$$\boldsymbol{N_{e\mu} = N_e + 2.8N_\mu}$$

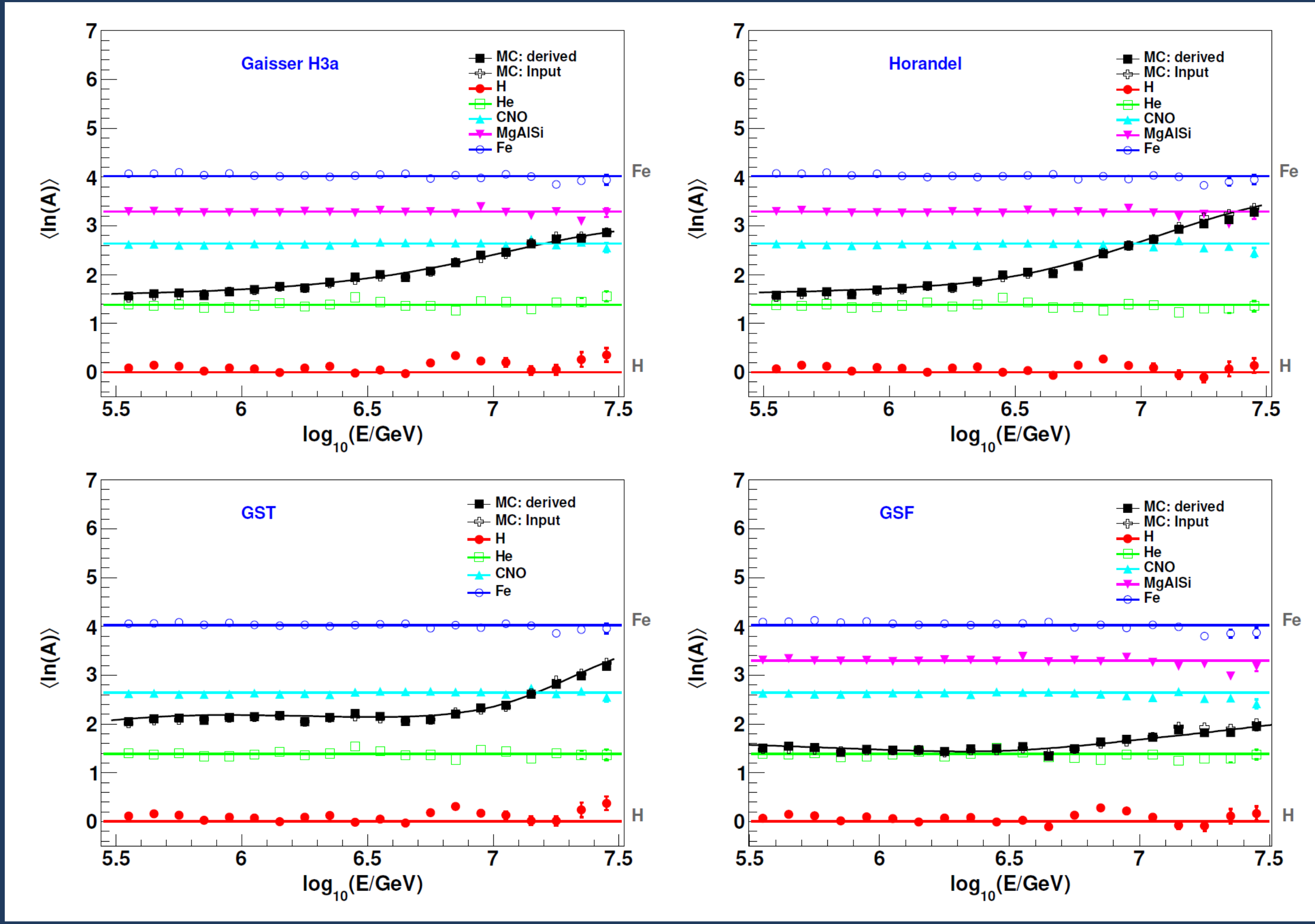




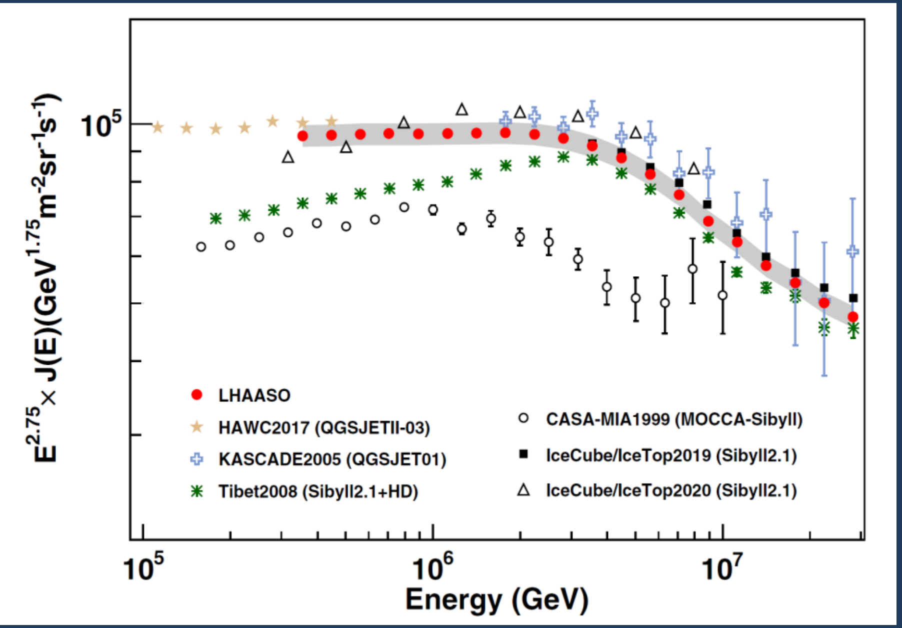
<lnA> reconstruction

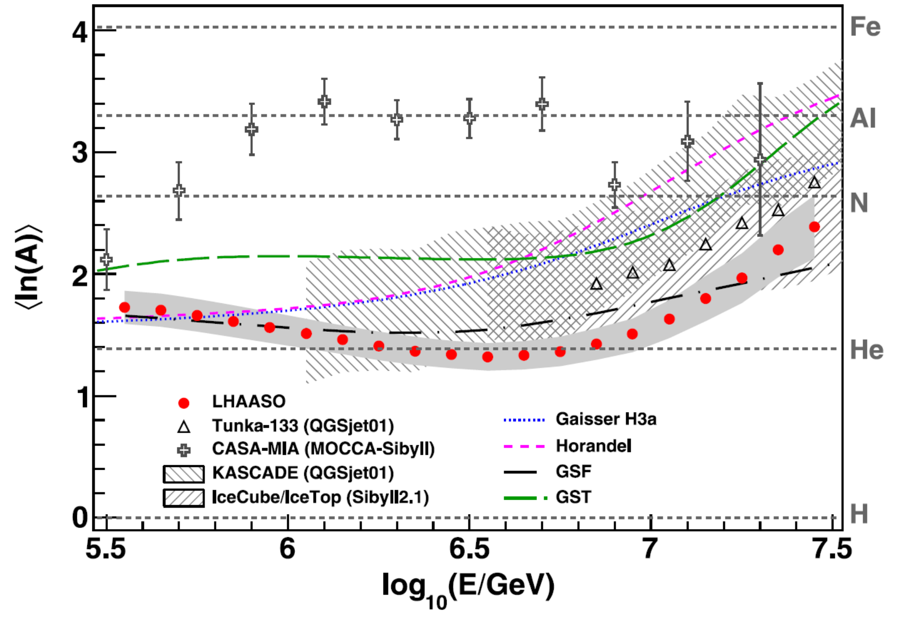
$$\ln N_\mu = x_0 + x_1 \ln A$$





The most precise measurements of all-particle energy spectrum and <lnA> from 0.3PeV to 30PeV





	Flux	<lnA>
Air pressure	$\pm 3\%$	$\pm 4\%$
Composition models	$\pm 1.5\%$	$\pm 3\%$
Interaction models	$\pm 2.5\%$	$\pm 6\%$

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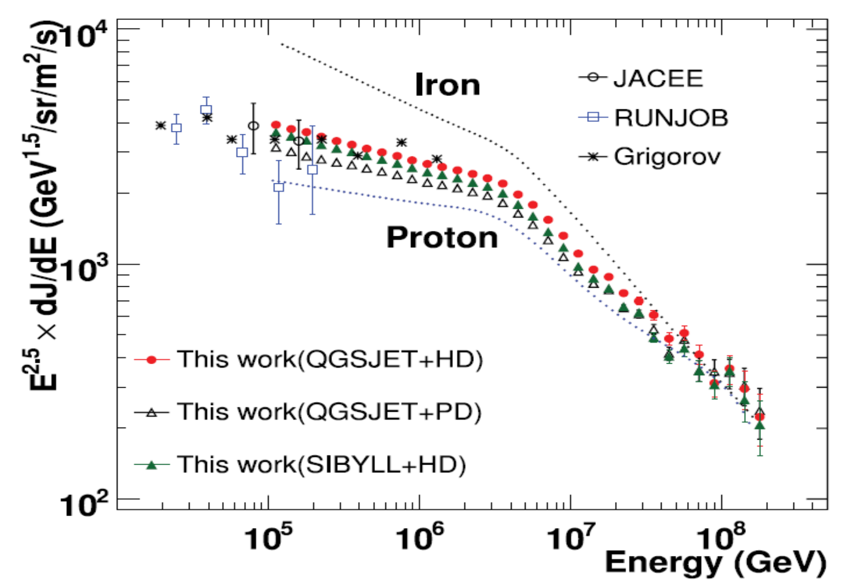
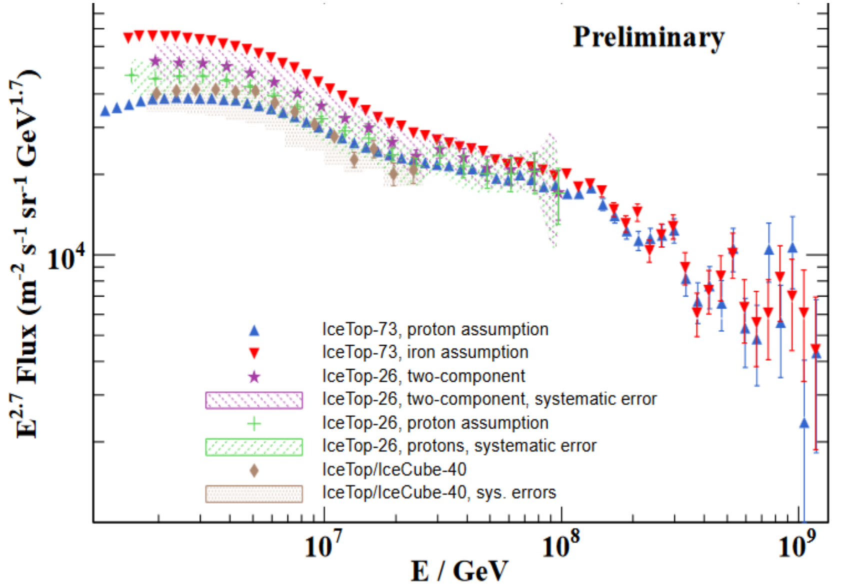
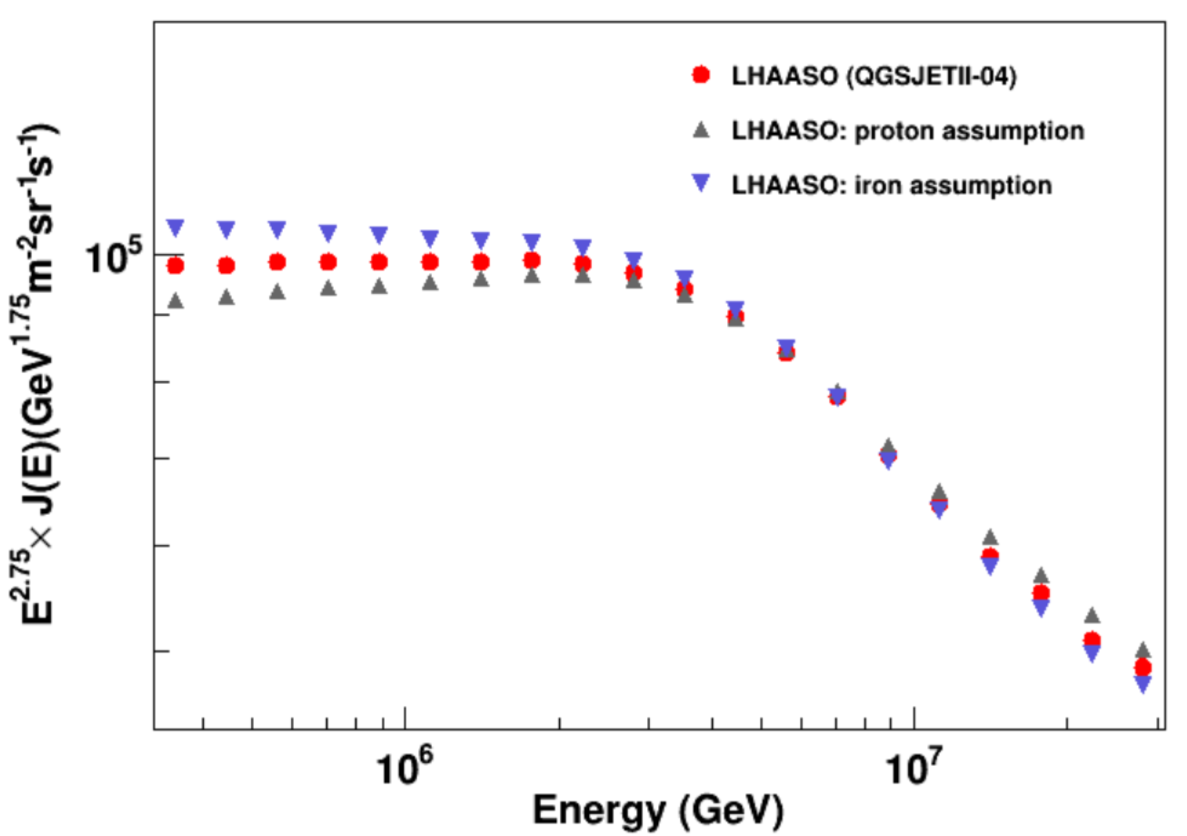
By C.F. Feng, H.H. He and H.Y.Zhang

Advantages of calorimetric energy measurement





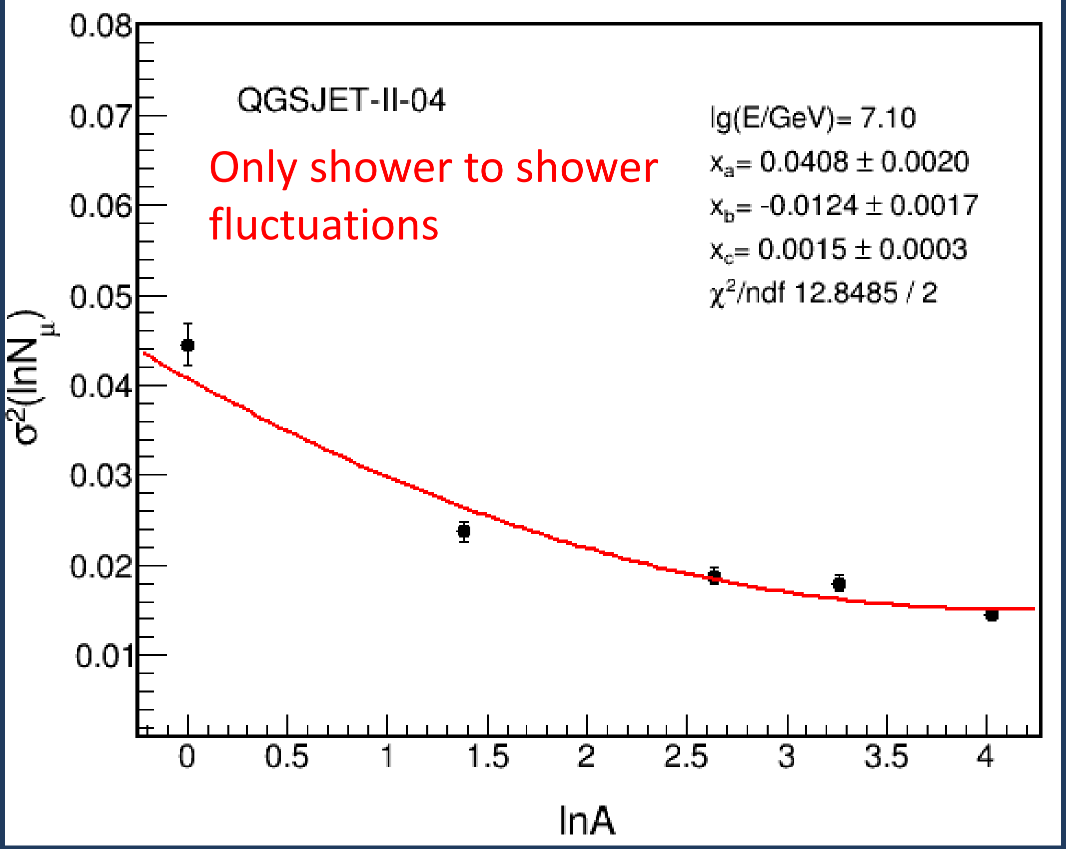


The maximum uncertainty caused by two extreme composition models (pure proton and pure iron) is reduced from 300% to 12%

Variance of the logarithmic mass of cosmic rays

variance of the logarithmic mass of cosmic rays σ^2_{lnA}

- Together with the all-particle energy spectrum and $\langle \ln A \rangle$, σ^2_{lnA} will give more information about the composition distributions and will further constrain the composition models.
  - Example: for Pure proton or pure iron σ^2_{lnA}=0
- The same data selection criteria are used as measurements of the all particle spectrum and <lnA>

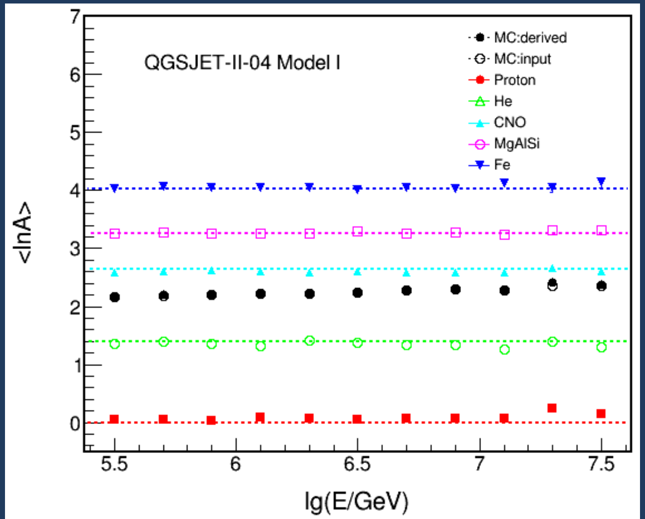


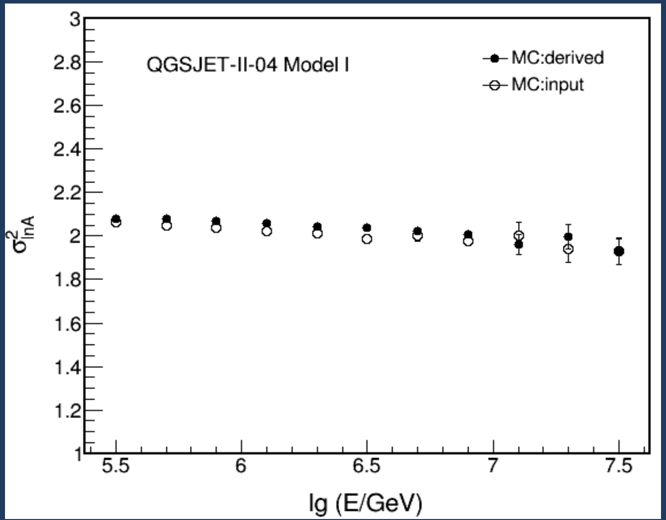
$$< lnN_\mu > = f_a + f_b * lnA$$

$$\sigma^2(lnN_\mu) =< \sigma^2_{sh} > + f_b^2 \sigma^2_{lnA}$$

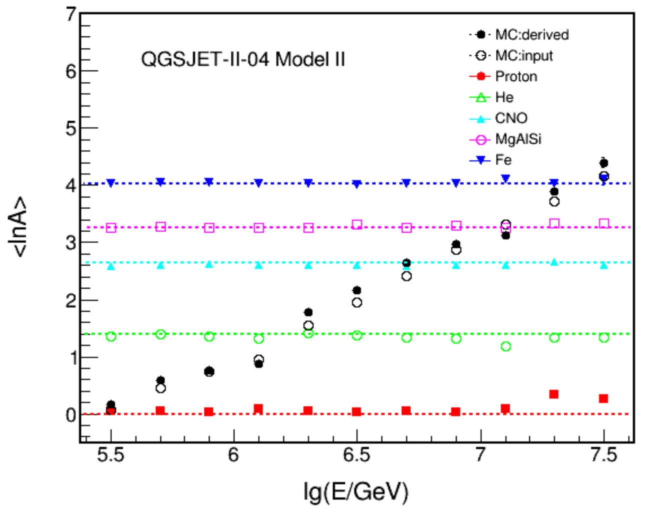
$$< \sigma^2_{sh} > = \sigma^2_p [1 + a < lnA > + b < (lnA)^2 >]$$

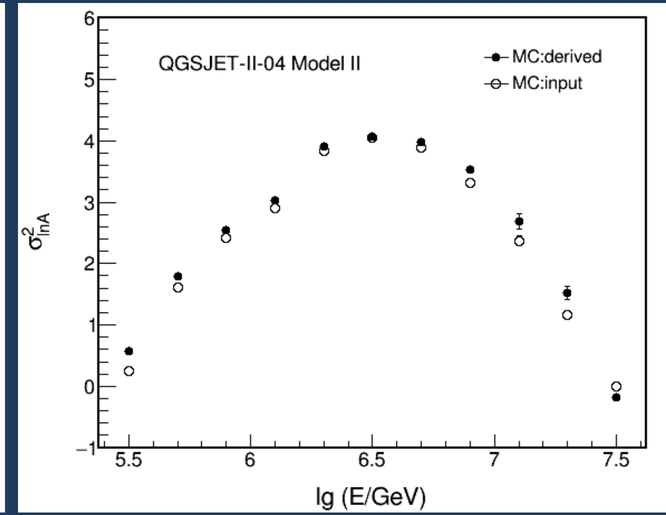
Method validation by MC data



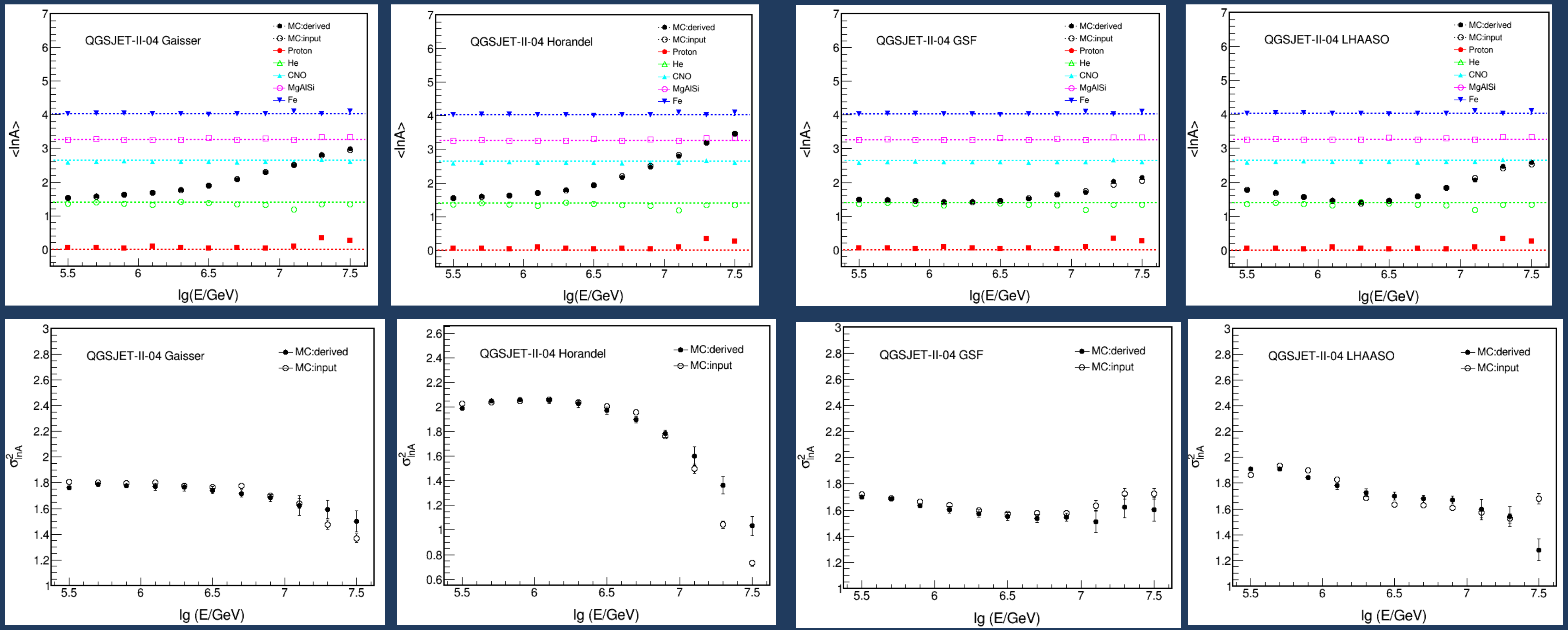


- Two extreme models
  - Uniform model
  - Linear model





Validation test by MC data

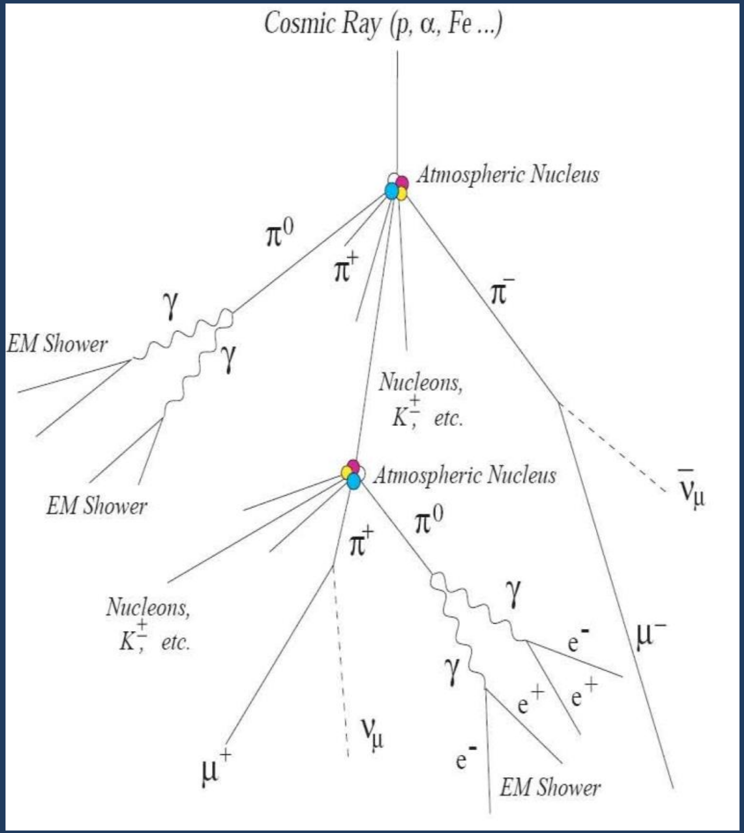


Summary and outlook

- With the hybrid observation of ED and MD in LHAASO the most precise measurements of the all-particle energy spectrum and <lnA> has been achieved.
- The measurement of $\boldsymbol{\sigma^2_{lnA}}$ is in the study.
- The measurements of these three variables will soon be increased to 300 PeV, which will cover the second knee region.
- Together with these three measurements, more accurate composition model can be established.
- The nature of the knee can be unveiled in the near future

Hadronic interaction test by LHAASO

The development of cosmic ray air shower is driven by the hadronic interaction



- Cross section
  - P-air, pi-air
- Elasticity / Inelasticity
- π^0 production
  - In the first interaction
- Multiplicity

They are not well measured in the collider experiments, the explorations have some uncertainties.

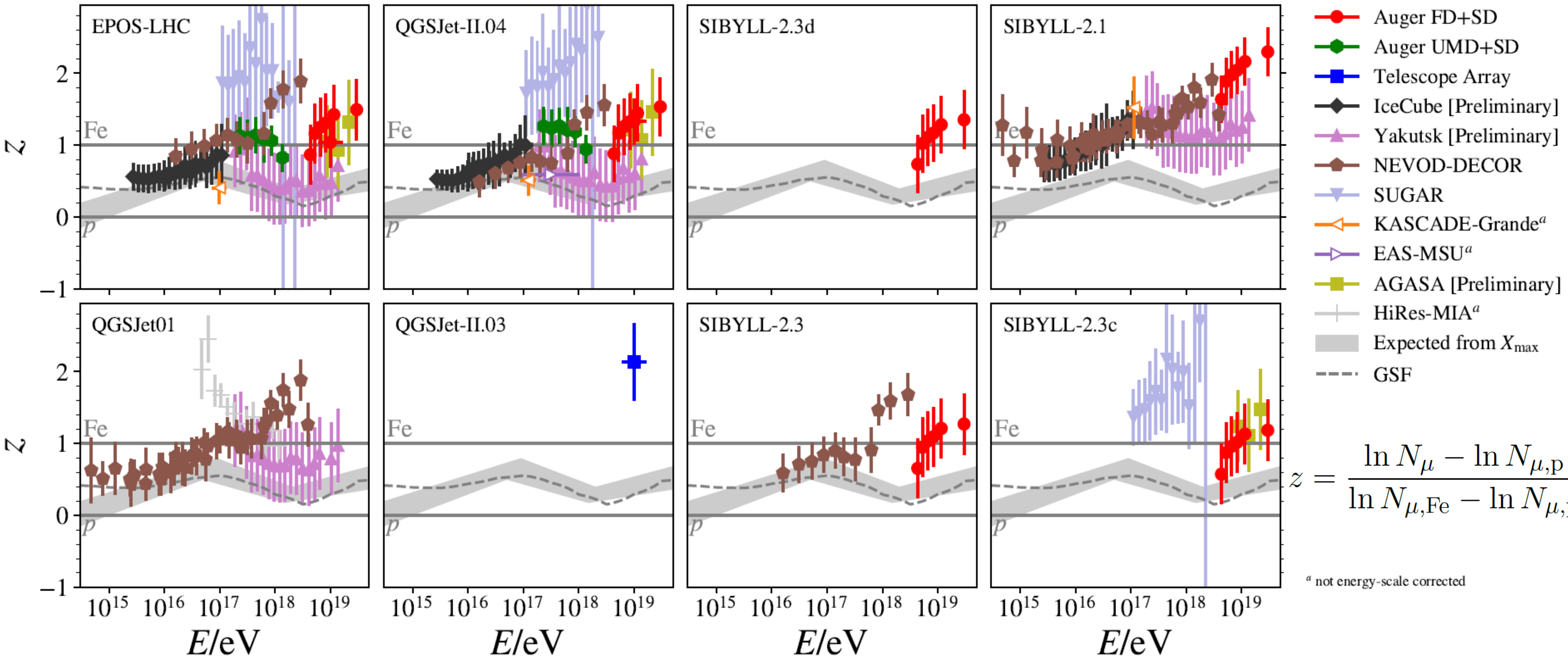
EPOS, QGSJET, SIBYLL

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

μ: a tracer of hadronic interaction

More than 20 years puzzle （muon excess）

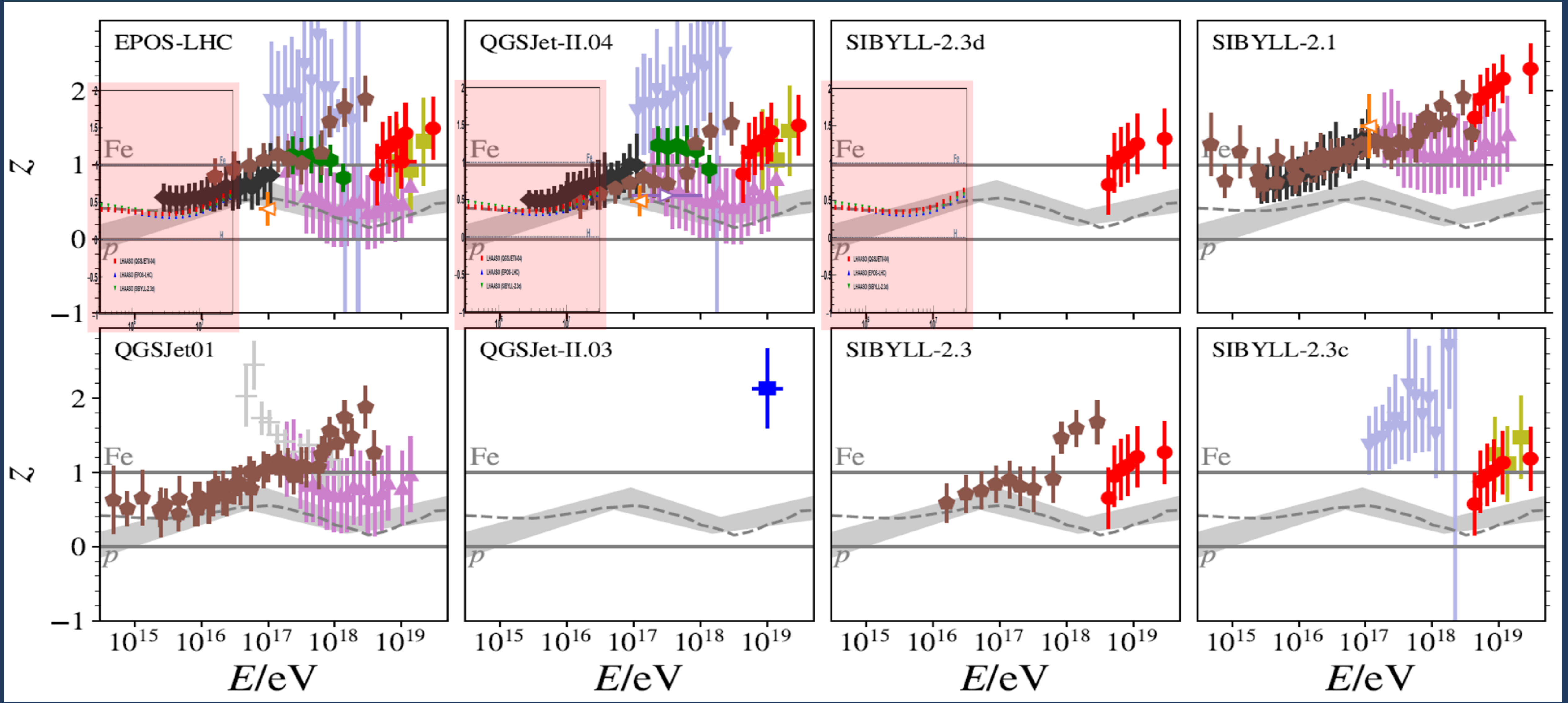


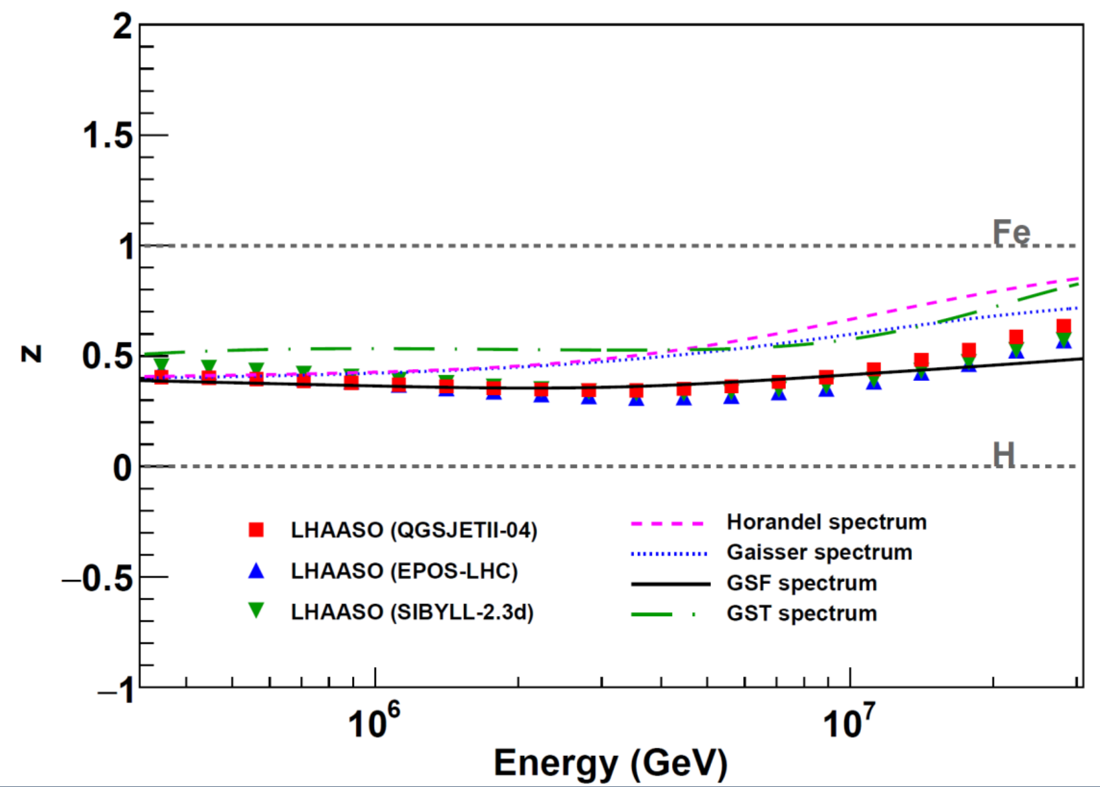
$$z = \frac{\ln N_\mu - \ln N_{\mu,\mathrm{p}}}{\ln N_{\mu,\mathrm{Fe}} - \ln N_{\mu,\mathrm{p}}}$$

[a] not energy-scale corrected

<lnA> measured by LHAASO is scaled to the z value

no significant excess is observed





Because the compositions of cosmic rays are not known clearly, the inconsistency between the measurement and the expectations may be caused by the uncertainty of the composition models, the hadronic models can not be tested clearly by the z value

Select pure proton samples to test the hadronic models

Avoid the uncertainty of the composition models of cosmic rays

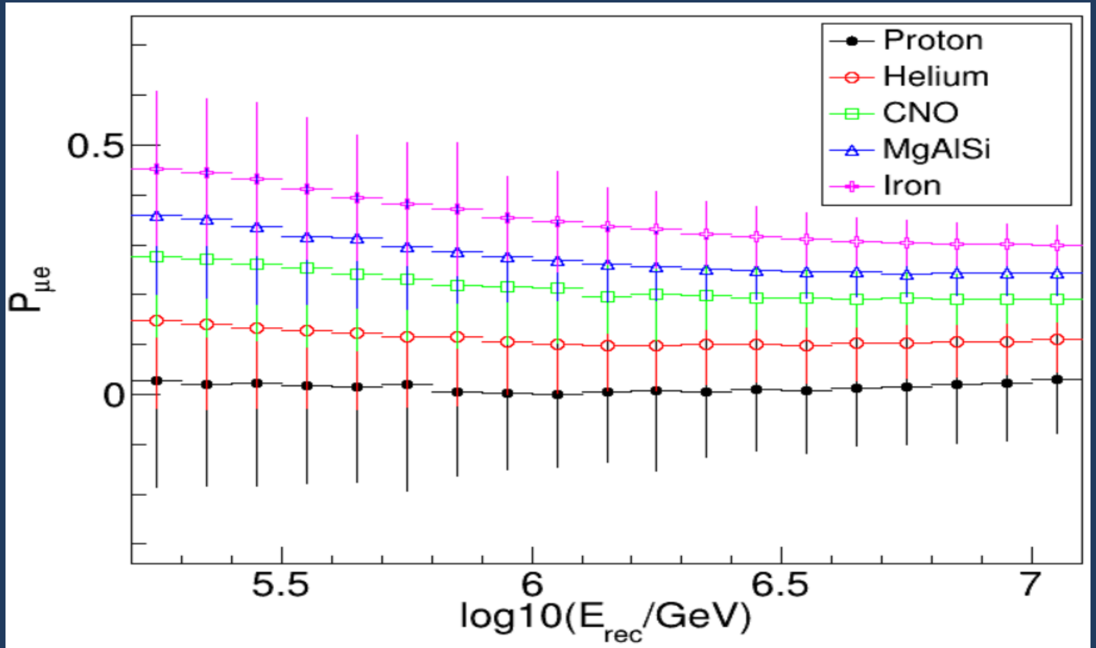
$$N_\mu \propto A^{1-\beta}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^{\beta}$$

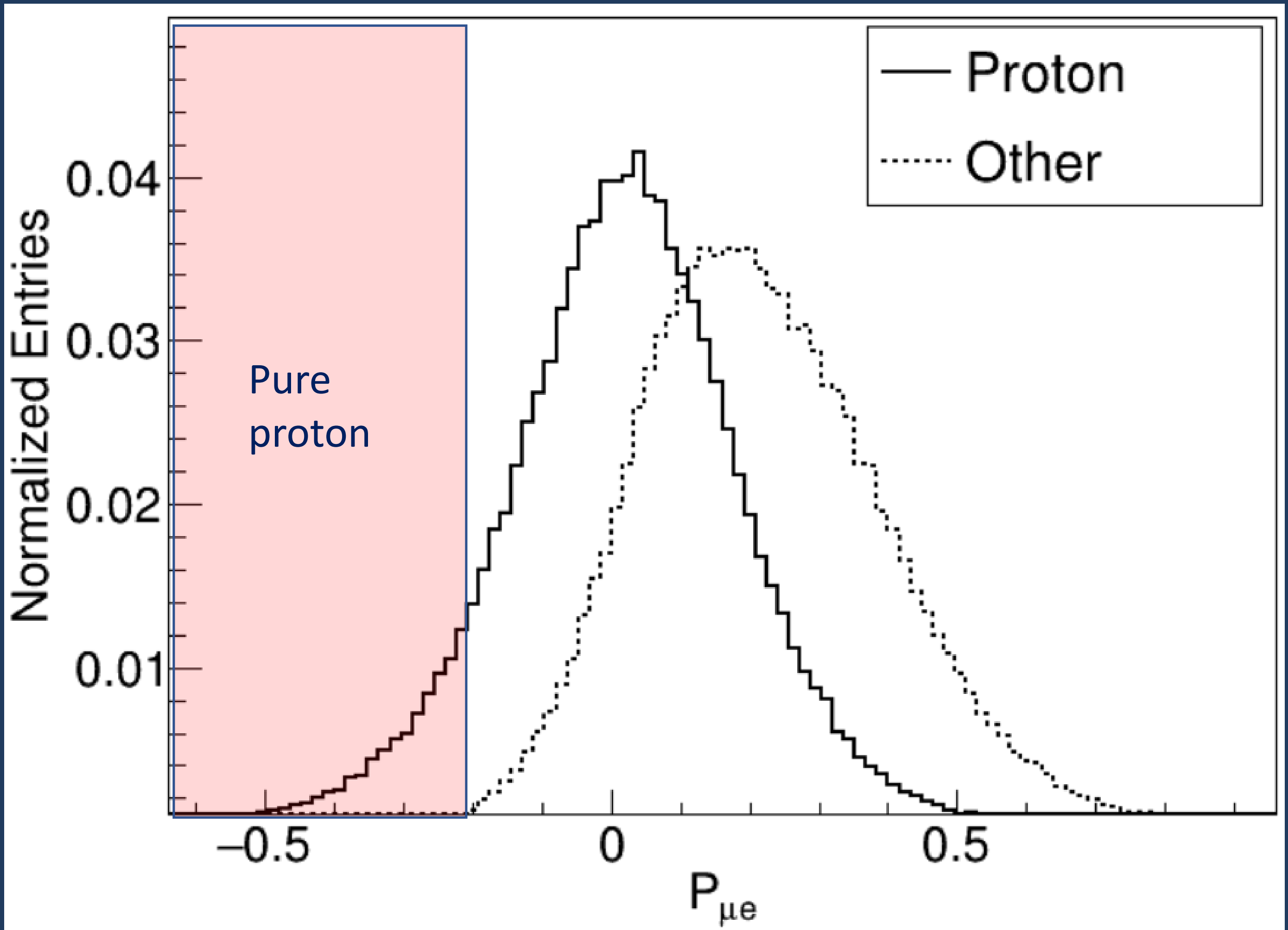
$$N_e \propto A^{1-\alpha}\left(\frac{E_0}{1\ \mathrm{PeV}}\right)^{\alpha}$$

$$P_{\mu e} = \log_{10}\frac{N_\mu}{N_e^{0.82}}$$

N_μ : 40~200 m

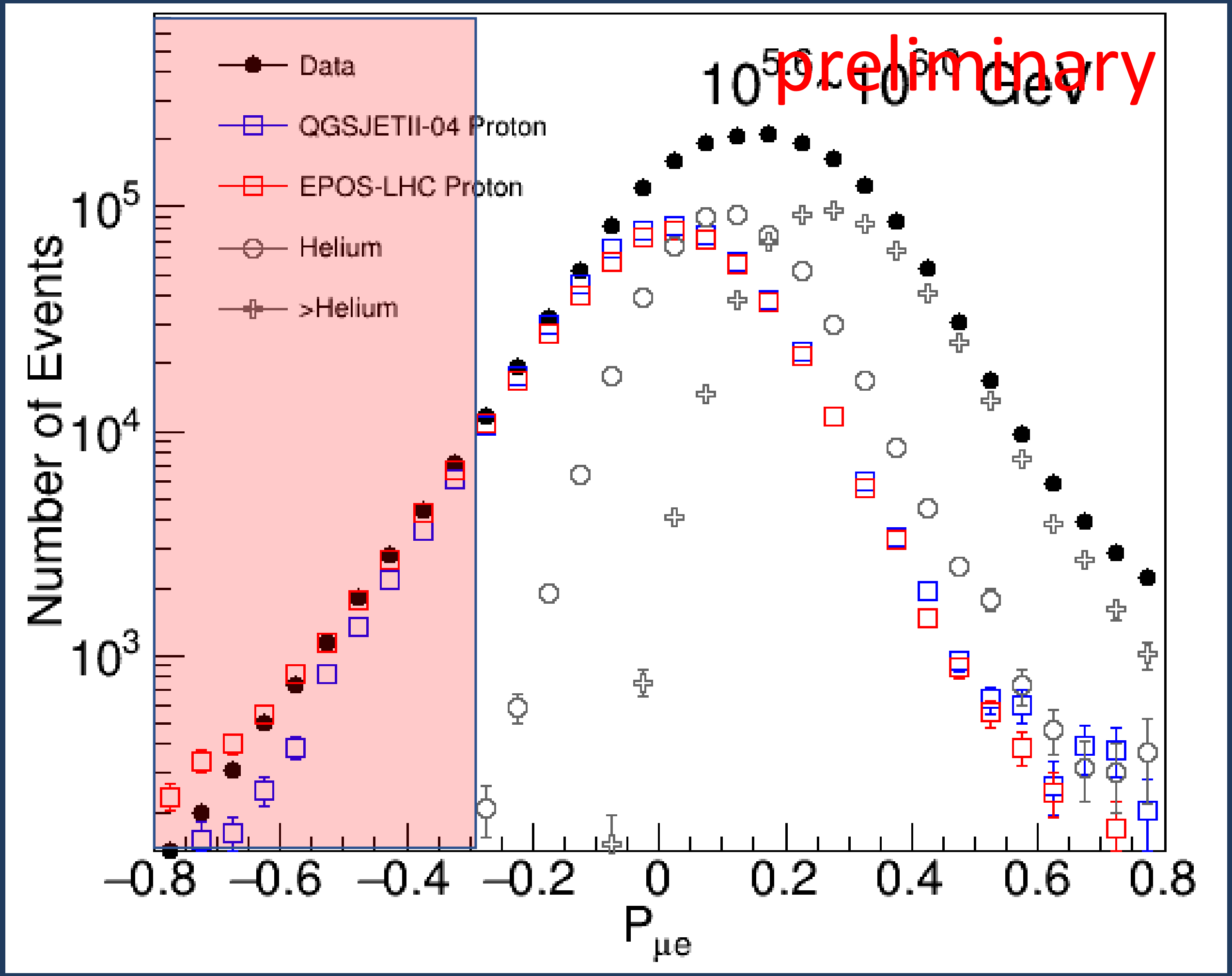
N_e : 40~200 m





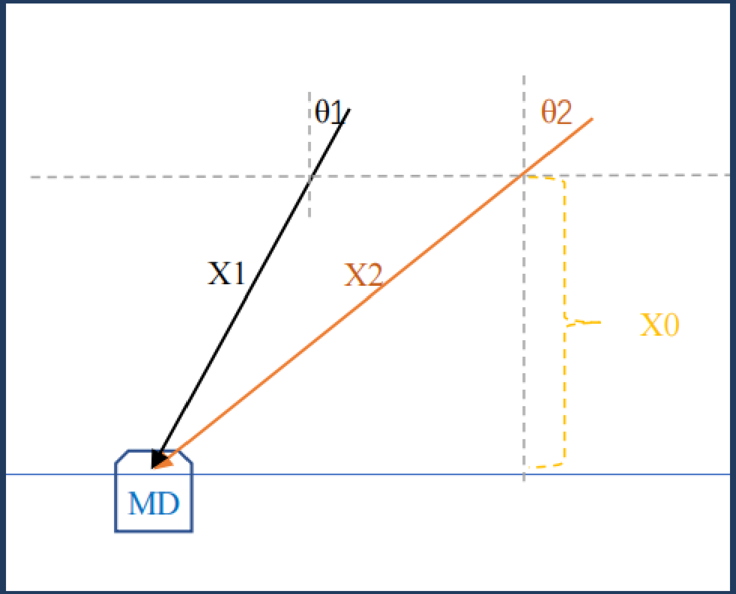
$$\frac{\left|p_{\mu e}^{p} - p_{\mu e}^{Fe}\right|}{\sqrt{RMS_p^2 + RMS_{Fe}^2}} \approx 2.4$$

The expectations by EPOS-LHC are more consistent with the data



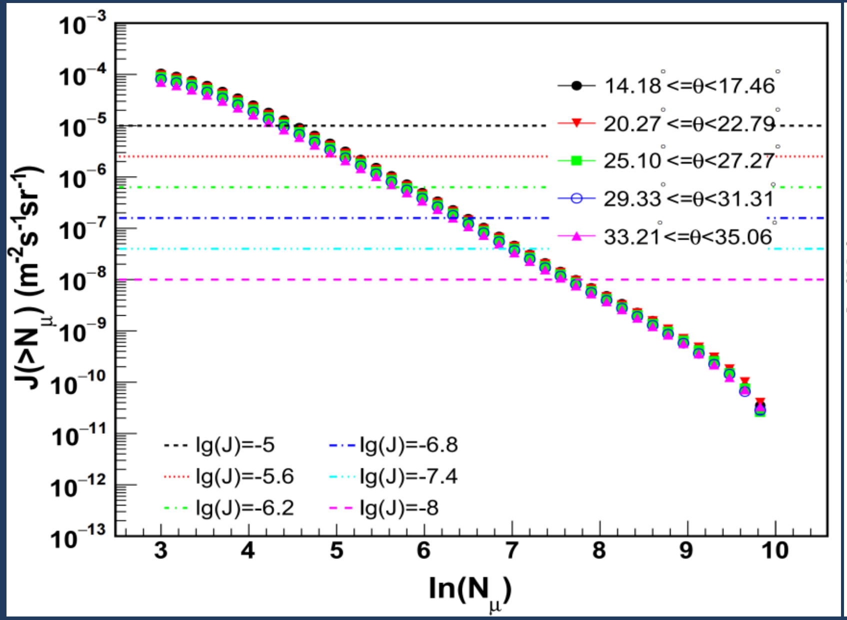
Carried out by: Z.Y. You , L.P. Wang
L.L. Ma , S.S. Zhang

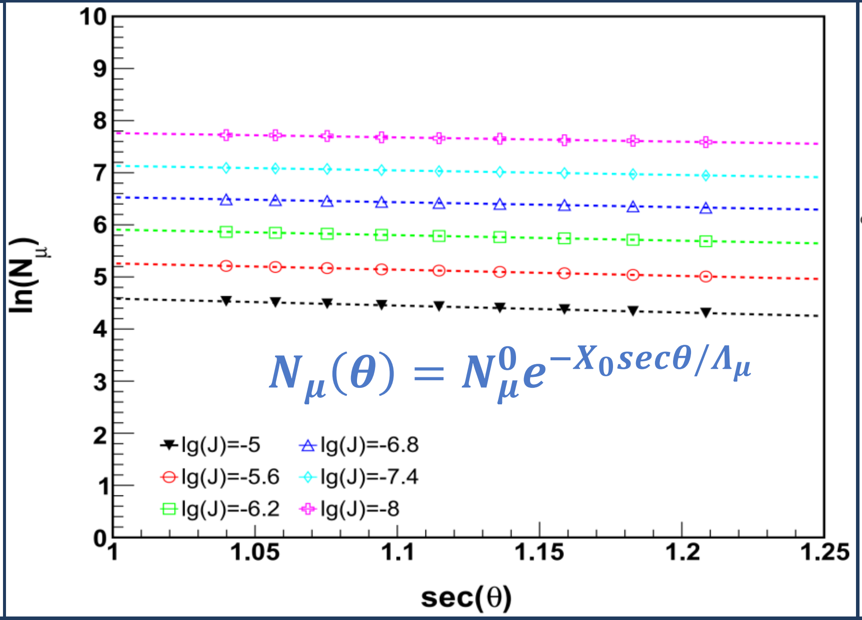
Attenuation length of muon content

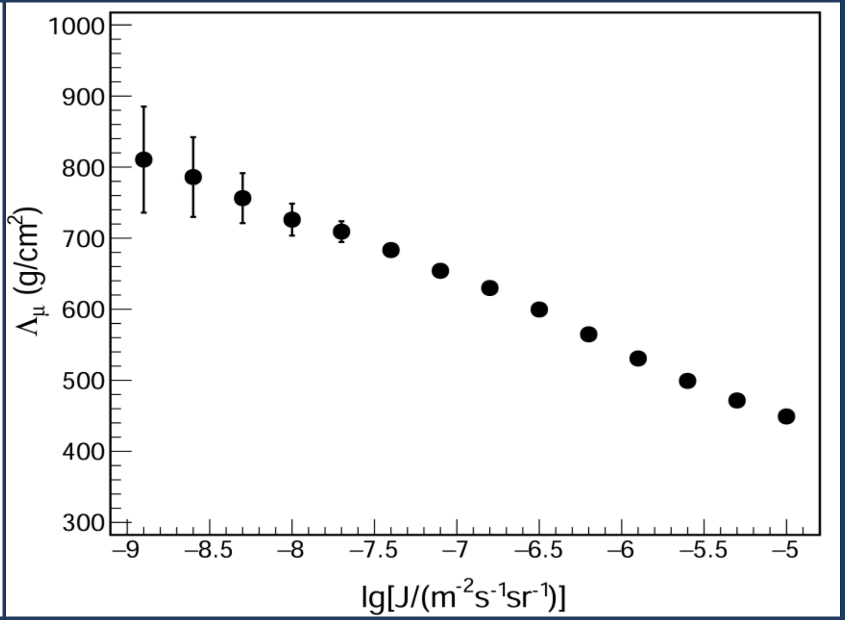


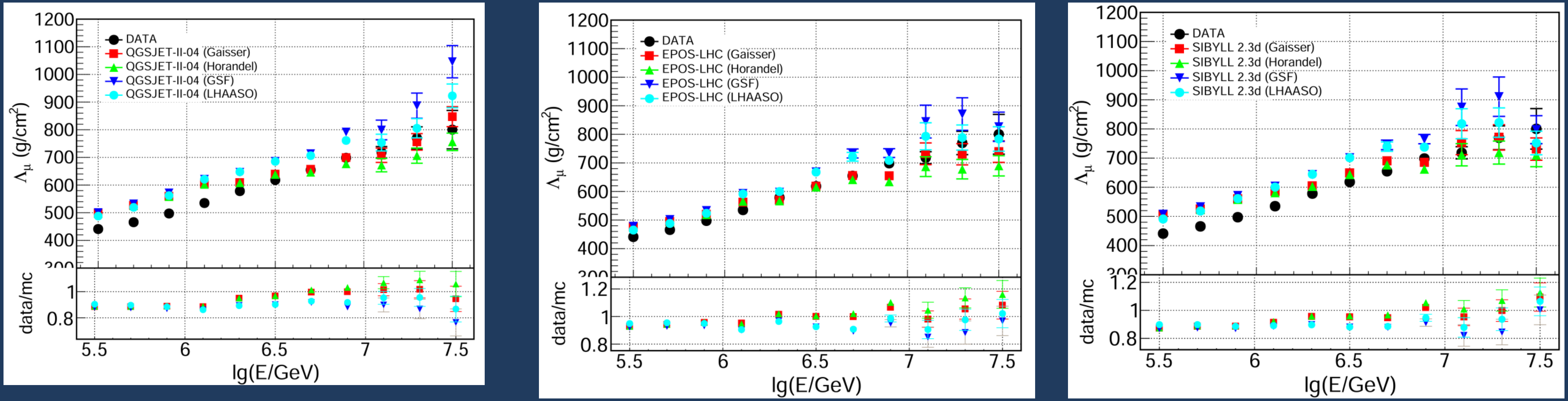
Larger zenith angles result in greater attenuation due to more air mass passed by the muons.

Constant Intensity Cut method (CIC) is used for events with different zenith angle ranges









The Λ_μ for both expectations and measurements increases with energy
The expectations by EPOS-LHC are more consistent with the data

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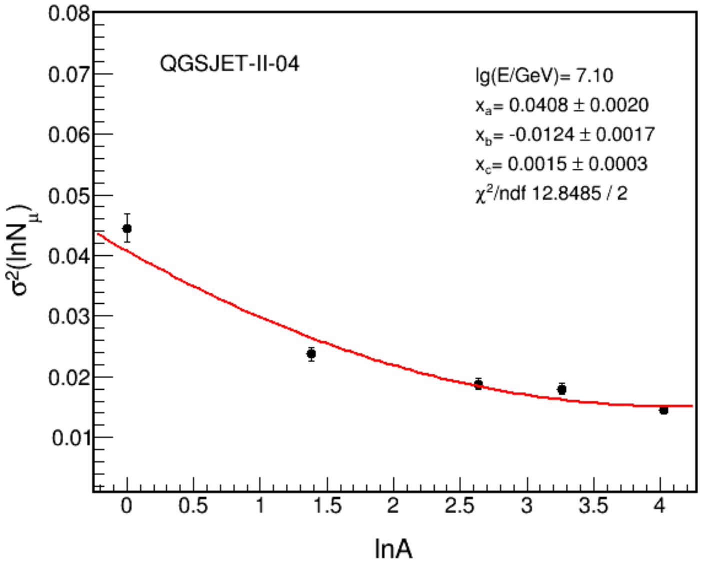
By X.T.Feng, F.C.Feng ,H.Y.Zhang L.L.Ma

Summary and outlook

- No significant muon excess was observed from 0.3PeV to 30PeV
- The expectations by EPOS-LHC are more consistent with the data
- The lateral distributions can also be used to test the hadronic models
- The first interaction cross section, the fluctuations of the energy remained in the hadronic part will be studied by the distributions of Xmax and lnNu

Thank you for your attention

Parameter Measurement : x_a, x_b, x_c



- The parameters x_a, x_b, x_c depending on the hadronic interaction properties and on the mass distribution of nuclei

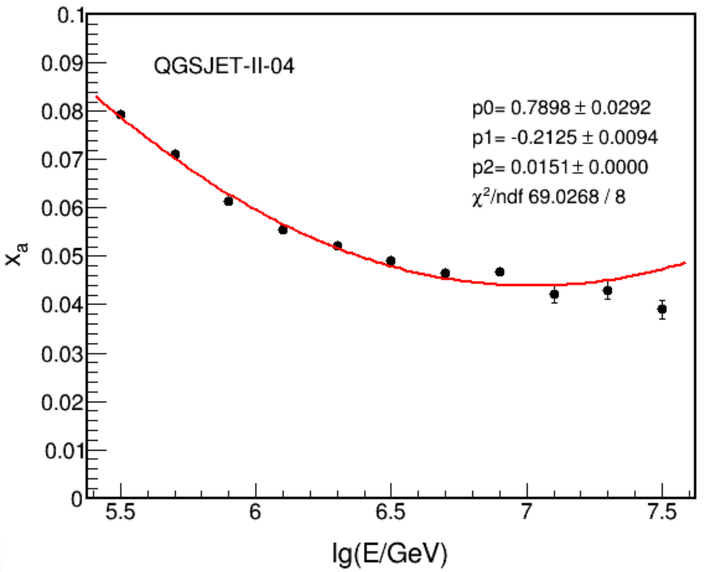
$$\sigma_{sh}^2(lnA) = x_a + x_b(lnA) + x_c * (lnA)^2$$

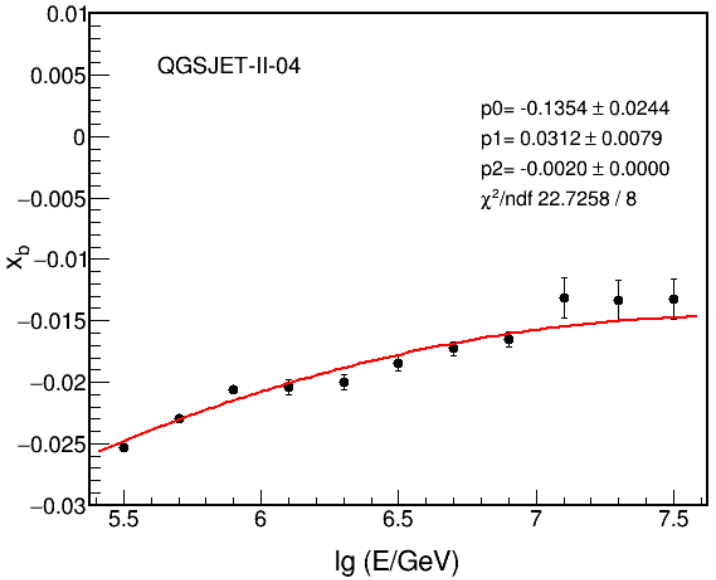
- x_a is the variance of muon content of proton showers

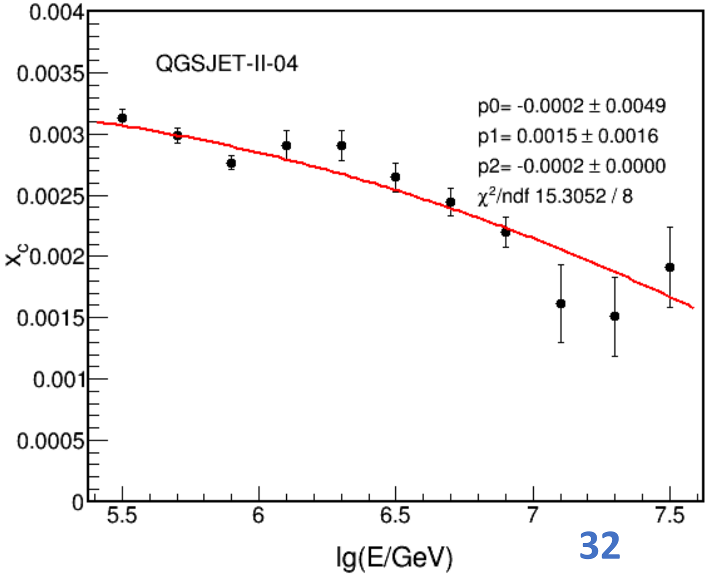
$$x_a = 0.7898 - 0.2125 \cdot \lg(E/GeV) + 0.0151 \cdot [\lg(E/GeV)]^2$$

$$x_b = -0.1354 + 0.0312 \cdot \lg(E/GeV) - 0.0020 \cdot [\lg(E/GeV)]^2$$

$$x_c = -0.0002 + 0.0015 \cdot \lg(E/GeV) - 0.0002 \cdot [\lg(E/GeV)]^2$$



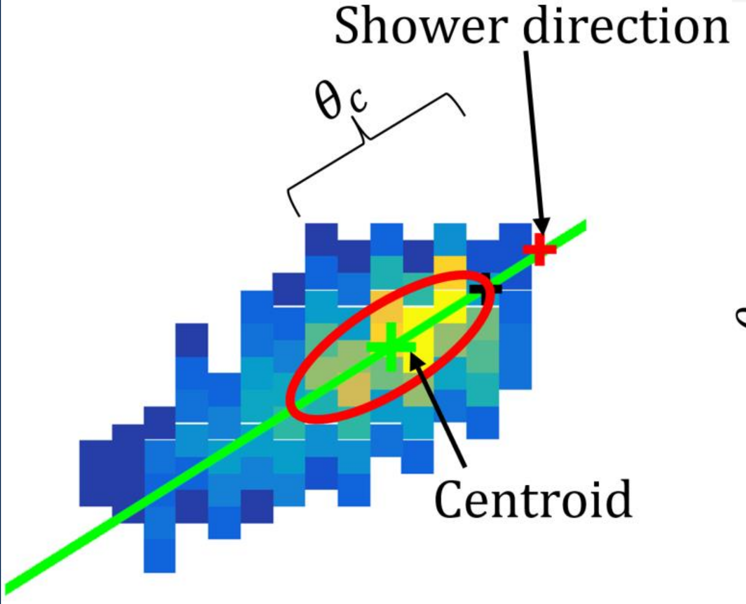


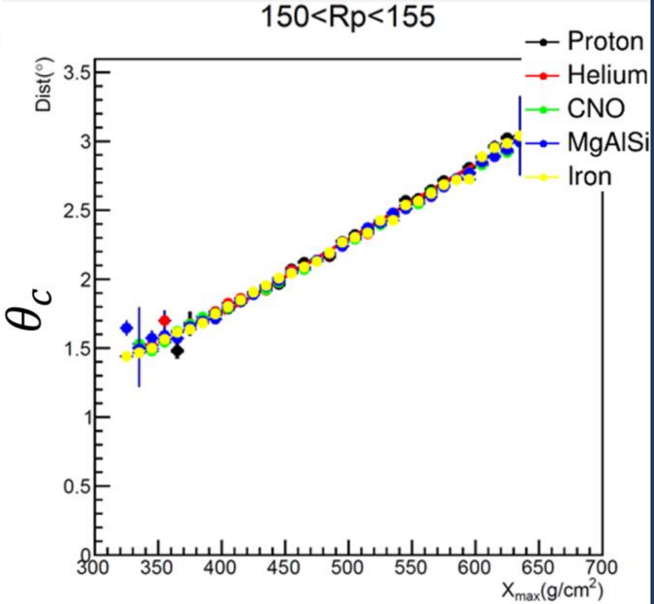


高海拔宇宙线观测站 LHAASO Large High Altitude Air Shower Observatory

X_{max} in EAS

$$P_{\theta c} = \frac{\theta_c^{250} - \langle\theta_c^{250}\rangle}{\langle\theta_c^{250}\rangle|_{PeV}}$$





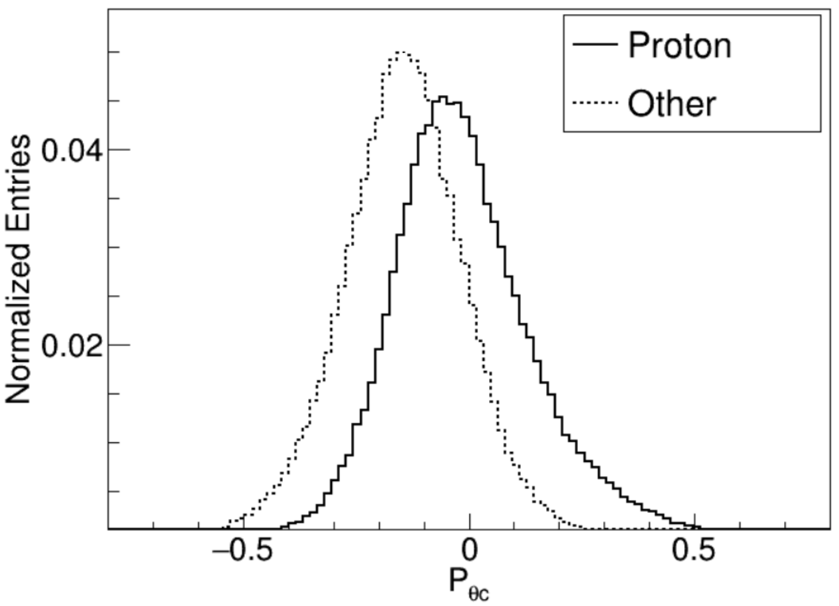
- Remove geometric dependence:

$$\theta_c^{250} = \frac{\theta_c}{\cos(\theta)} + 0.011 \times \left(R_p - 250\right)$$

- Remove energy dependence:

$$\langle\theta_c^{250}\rangle = p_0 + p_1 \cdot \log_{10} E + p_2 \cdot \log_{10}^2 E$$

- $\langle\theta_c^{250}\rangle|_{PeV}$: The average value of θ_c for proton events near R_p at 250 m and 1 PeV

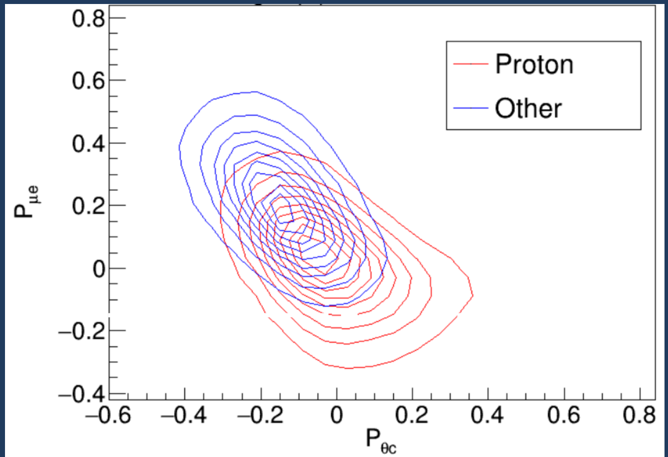


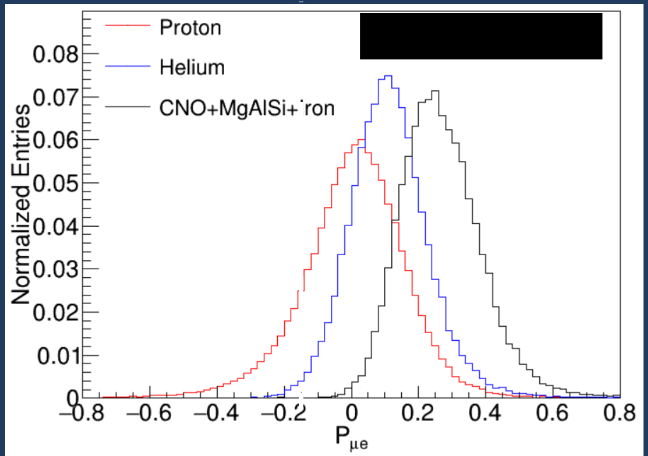
Test of $P_{\theta c}$

For selected events

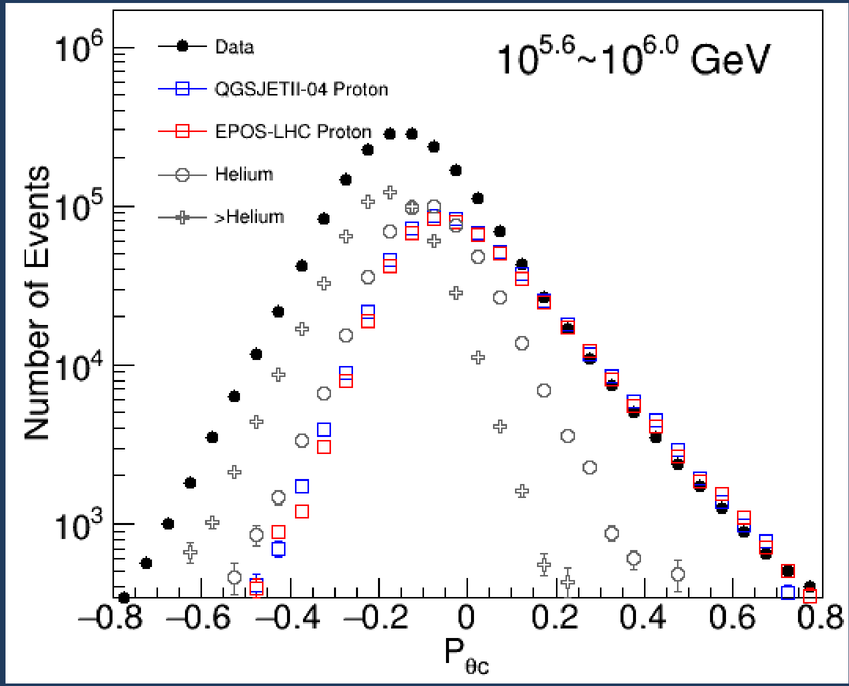
By selecting events using $P_{\mu e}$, proton events with purity of 95% can be obtained.

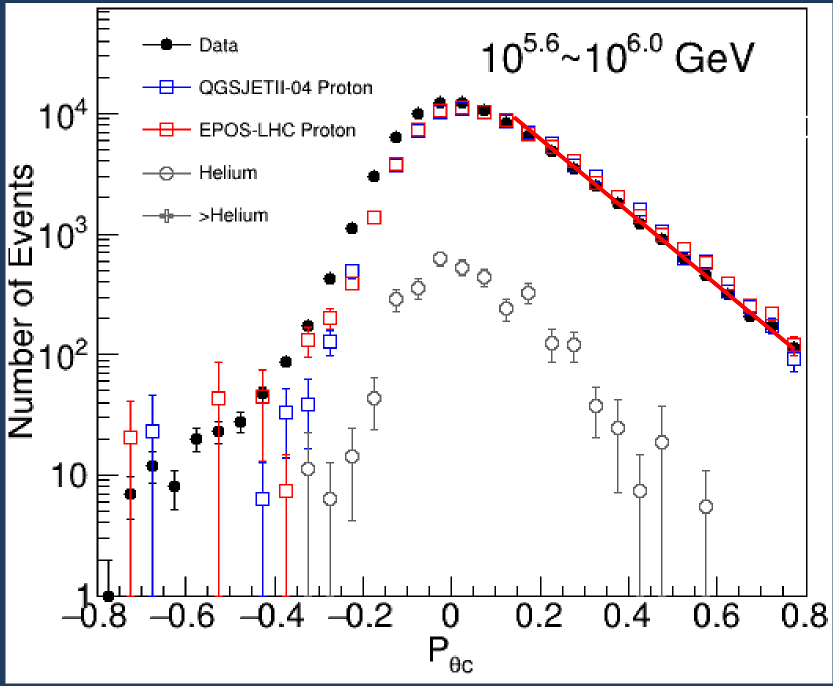
First interaction depth in the air for proton events

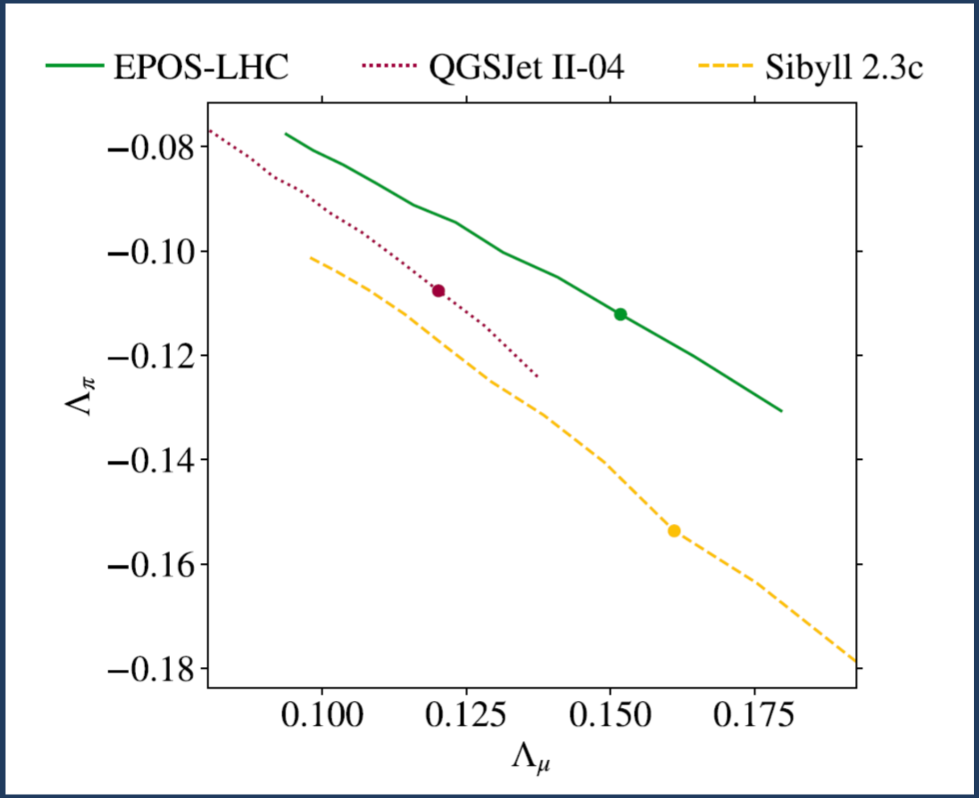


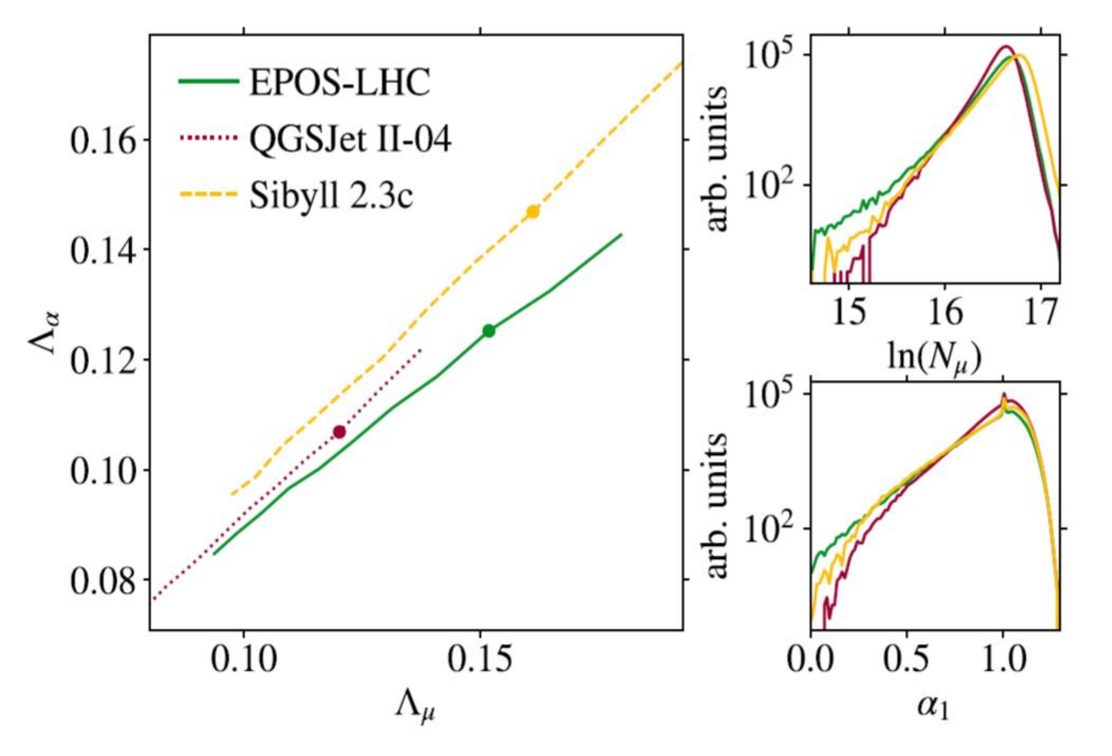


Before select









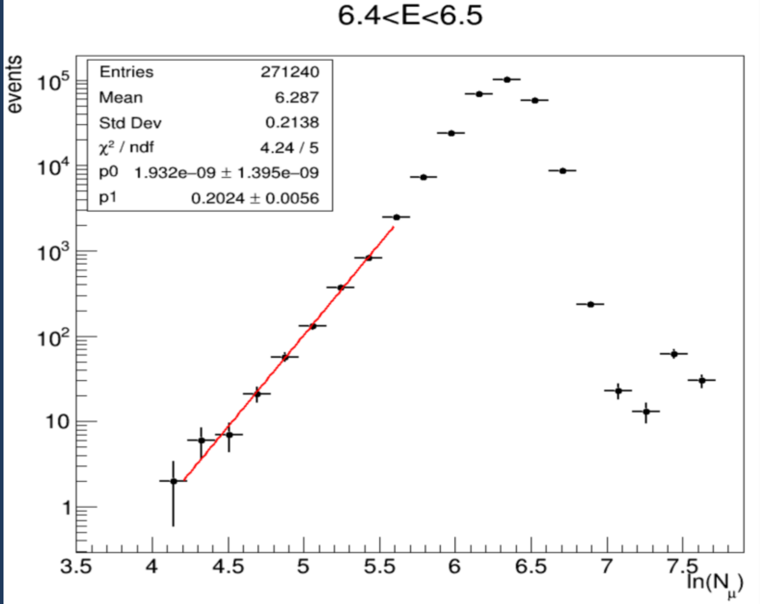
- ✓ Λ_μ is closely related to the high-energy tail of the energy spectrum of neutral pions (π^0) produced in ultra-high-energy proton-air interactions. **By measuring Λ_μ, the high-energy spectrum of π^0 can be indirectly constrained.**
- ✓ Λ_μ is directly related to parameters in hadronic interaction models (such as the α_1 distribution). **By measuring Λ_μ, hadronic interaction models (e.g., EPOS-LHC, QGSJET-II.04, and SIBYLL 2.3c) can be tested and refined**.

Event selection: 320<R<420

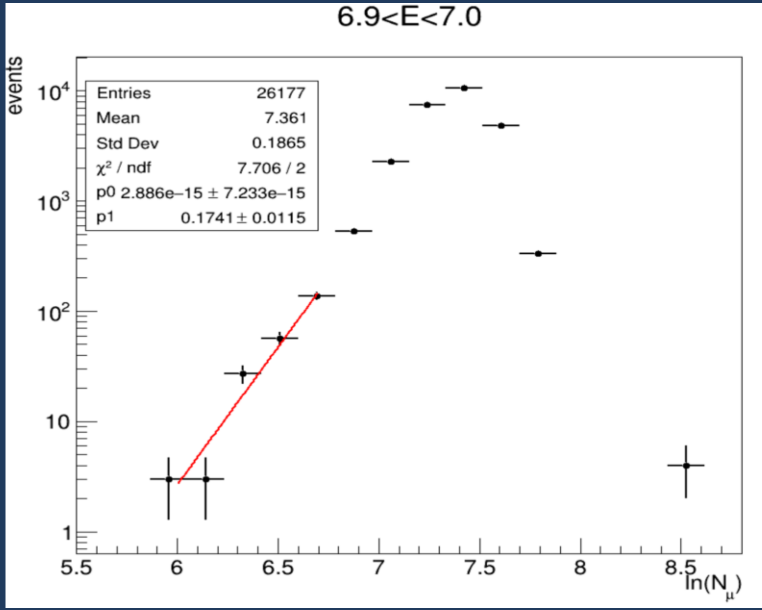
threshold:300TeV

$10° < \theta < 30°$

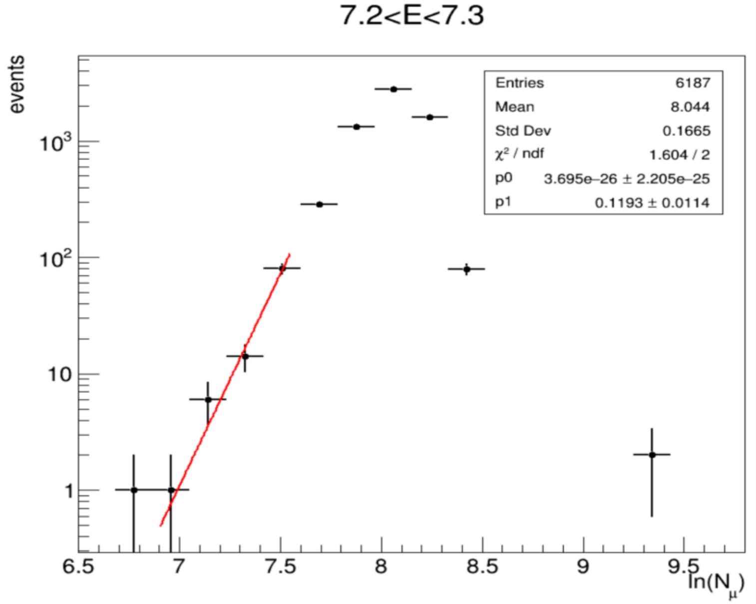
Fit function: $Ce^{\frac{x}{\Lambda_\mu}}$



Fit scale:4.2-5.6



Fit scale:6.0-6.7



Fit scale:6.9-7.55

For LHAASO:

- The largest effective-area muon detector array: $4.27 \times 10^4 m^2$
- High-accuracy muon detection: 1% resolution of muon