中国科学院高能物理研究所

2023弥散伽马射线与宇宙线研讨会

The preliminary measurements of all-particle energy spectrum and mean logarithmic mass of cosmic rays from 0.3 to 30 PeV with LHAASO-KM2A

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LHAASO

高海拔宇宙线观测站

Outline

- Motivation
- Event selection and efficiency
- Energy reconstruction
- All-particle energy spectrum
- Mean logarithmic mass <lnA>
- Summary

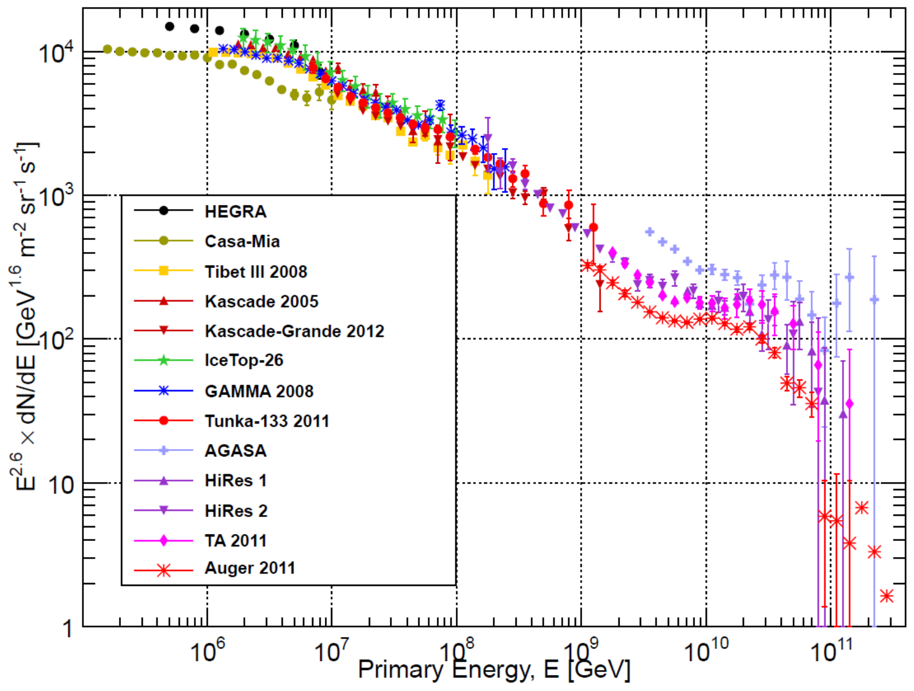
Motivation

◆ The all-particle energy spectrum exhibits two interesting structures from 10^{14} to 10^{18} eV, the "knee" and the "second knee". An explanation of these features is thought to be an important step in understanding the origin of the high-energy particles.

◆ A finite energy attained during the acceleration process
leakage of particles from the Galaxy

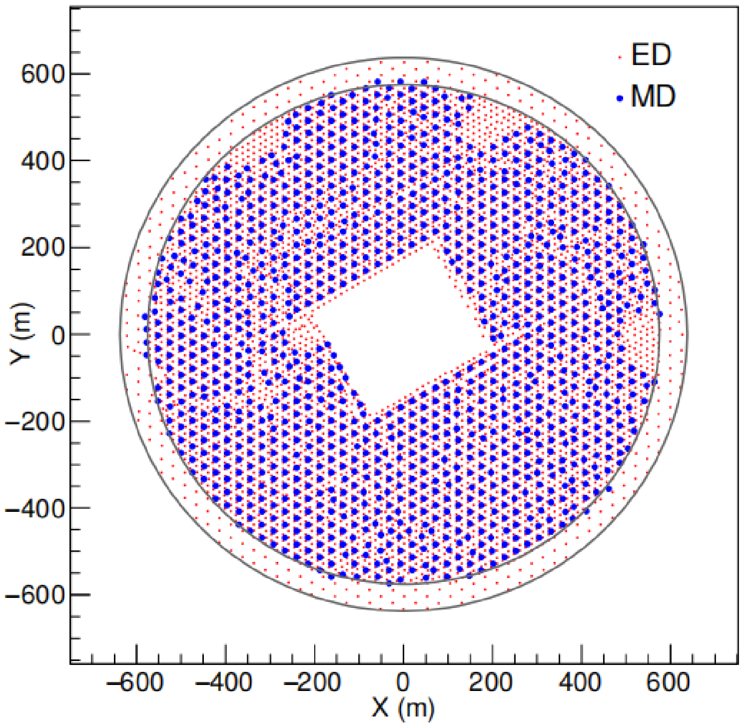
◆ The entanglement of primary energy, cosmic-ray components and hadronic interaction models

◆ The problem of composition dependence on energy reconstruction must be solved to measure cosmic ray energy spectra accurately.



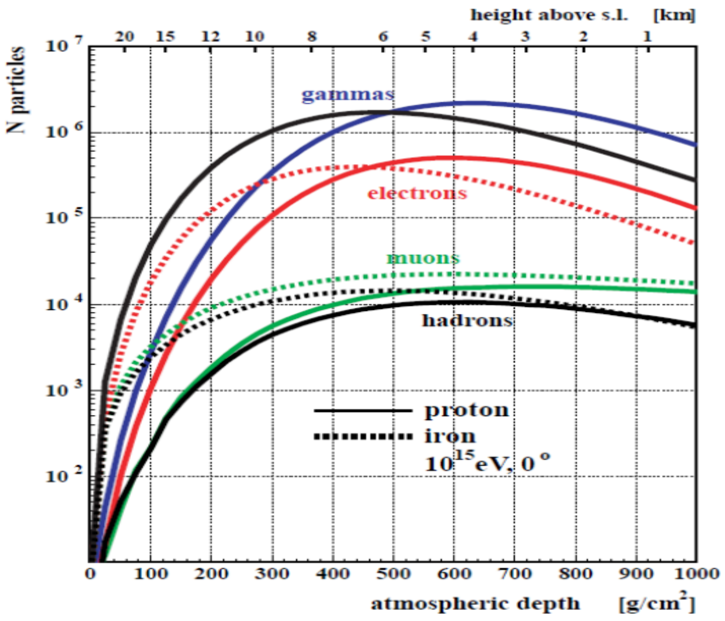
T. K. Gaisser et al. arXiv:1303.3565v1

Why can we do it?



The layout of the KM2A full array. The red and blue dots indicate the EDs and MDs in operation, respectively.

1. the air shower maximum depth of cosmic rays in the knee region;
2. 5,216 electromagnetic particle detectors and 1,188 muon detectors;



Andreas Haungs. Journal of Physics G: Nuclear and Particle Physics, 29(5):809–820, apr 2003.

The KM2A detector can measure the electromagnetic particles and muon content of an air shower simultaneously with high precision for energy in the knee region, in which the number of secondary particles reach approximately maximum resulting in least fluctuations.

KM2A full array simulation data

QGSJETII-04_fluka and EPOS-LHC_fluka

Proton He CNO MgAlSi Fe,

Theta: 0-40°

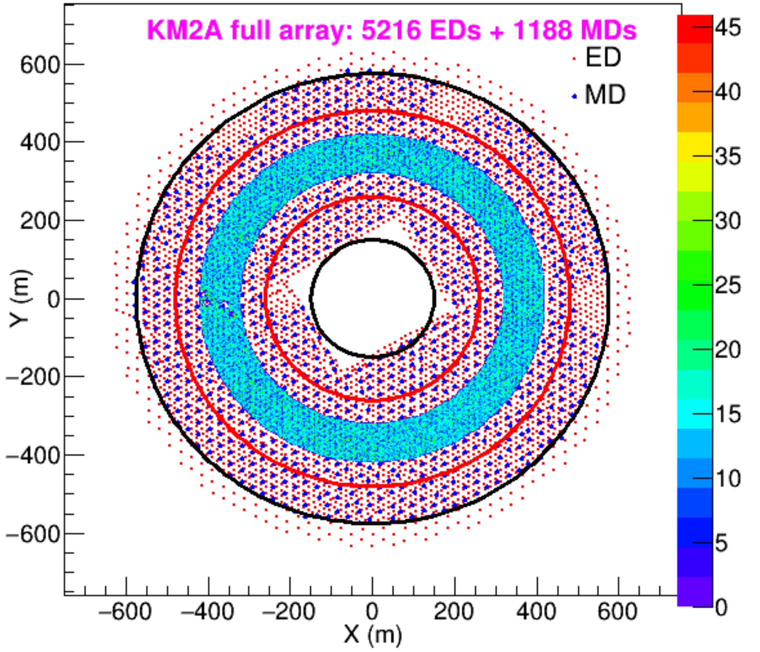
Slope: -2

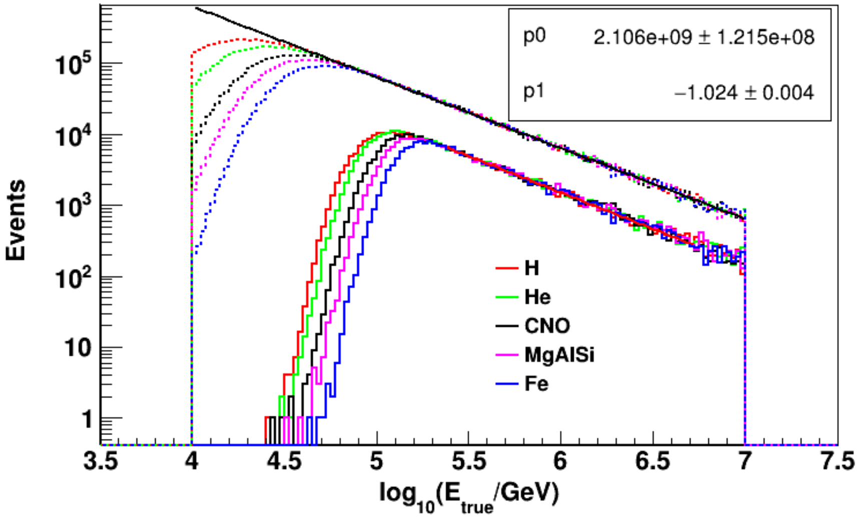
Radius：260-480m

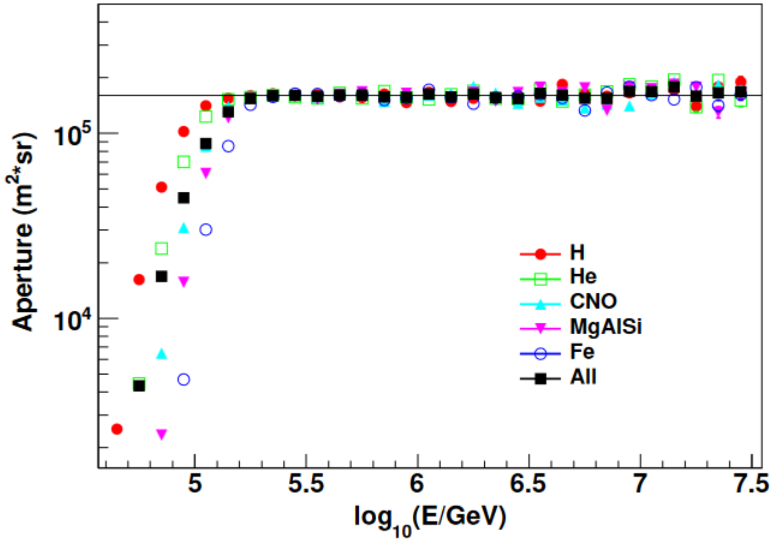
Event cut:

1) 10° <theta<30°
2) CoreR>320 && CoreR<420
3) Ne >80 (40-200m)

core position of reconstruction data



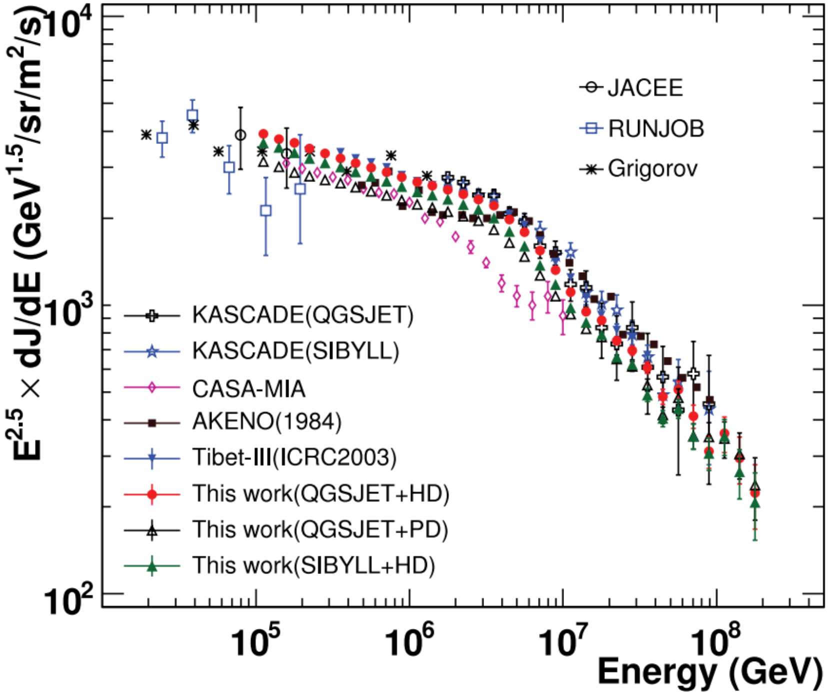




geometric aperture: 320-420m,10°-30°→

$$\pi(R_1^2 - R_2^2)\ \int_{10^\circ}^{30^\circ} \sin\theta \cos\theta\, d\theta \int_{0^\circ}^{360^\circ} d\varphi = 0.16\ (\mathrm{km^2 sr})$$

How to reconstruct cosmic rays energy?



Tibet ASγ Collaboration, The Astrophysical Journal 678, 1165 (2008)

1. Tibet ASγ : $\boldsymbol{N_{size}}$

   20% in chemical composition models between HD and PD

   10% in interaction models between QGSJET01c and SIBYLL2.1

2. KASCADE: the number of electrons $\mathbf{lg}\boldsymbol{N_e}$ and muons $\mathbf{lg}\boldsymbol{N_\mu^{tr}}$

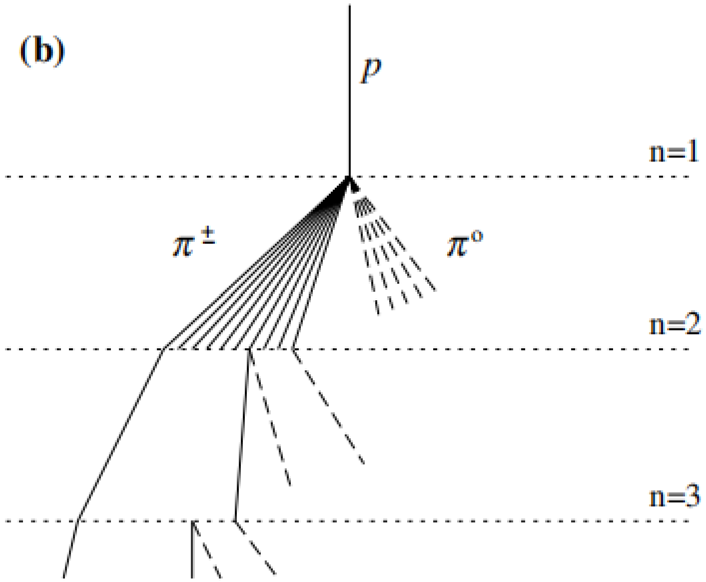
   Muon Tracking Detector: $5.4 \times 2.4 \times 44\ m^3$ tunnel

3. CASA-MIA : 870 g/cm^2 , a combination parameter of muons number and electromagnetic particles number ,

   $\boldsymbol{E_0}$=0.8GeV($\boldsymbol{N_e}$+25$\boldsymbol{N_\mu}$)

◆ **Cosmic-ray components and hadronic interaction models**

Principle of Energy Reconstruction



The total energy of the primary particle is divided into two channels, hadronic and electromagnetic.

N_{ch} charged pions and $\frac{1}{2}N_{ch}$neutral pions

$E_{em} = \xi_c^e N_{max}$

critical energy ξ_c^e=85 MeV

electrons $N_e = N_{max}/g$ and g=10

$N_\pi = (N_{ch})^n$

$E_\pi = \frac{E_h}{(N_{ch})^n}$

critical energy $\xi_c^\pi = 20\text{GeV}$

muon $N_\pi = N_\mu$

Conservation of energy implies that the primary energy is split into electromagnetic and hadronic parts $E_0 = E_{em} + E_h$

$$E_0 = \xi_c^e N_{max} + \xi_c^\pi N_\mu$$

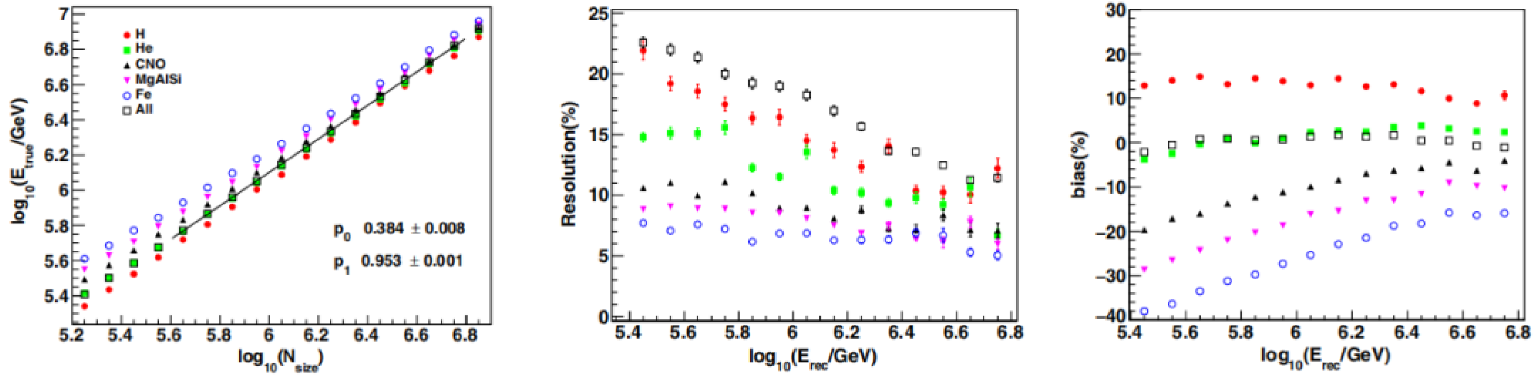
$$= \quad g\xi_c^e \left(N_e + \frac{\xi_c^\pi}{g\xi_c^e} N_\mu\right)$$

$$\boldsymbol{E_0 \approx 0.85GeV\left(N_e + 25N_\mu\right)}$$

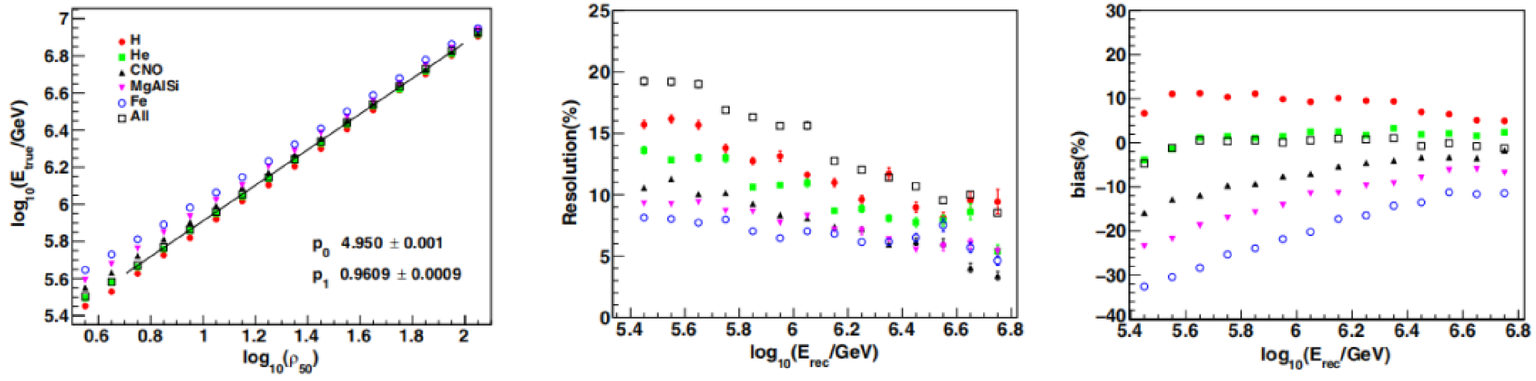
The energy assignment is unaffected by A because the expression intrinsically accounts for all of the primary energy being distributed into a hadronic channel (seen as muons) and into electromagnetic showers. J. Matthews Astroparticle Physics 22 (2005) 387–397

Energy reconstruction depends on cosmic ray components

LHAASO-KM2A can measure the total number of electromagnetic particles N_{size} and ρ_{50} by fitting the modified NKG function.



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



(b) E_{true} vs. ρ_{50}

Energy reconstruction independent on primary cosmic ray components

As Heitler's EM model and Matthews' hadronic showers model introduced that the primary energy is finally divided between pions and electromagnetic particles in subshowers.

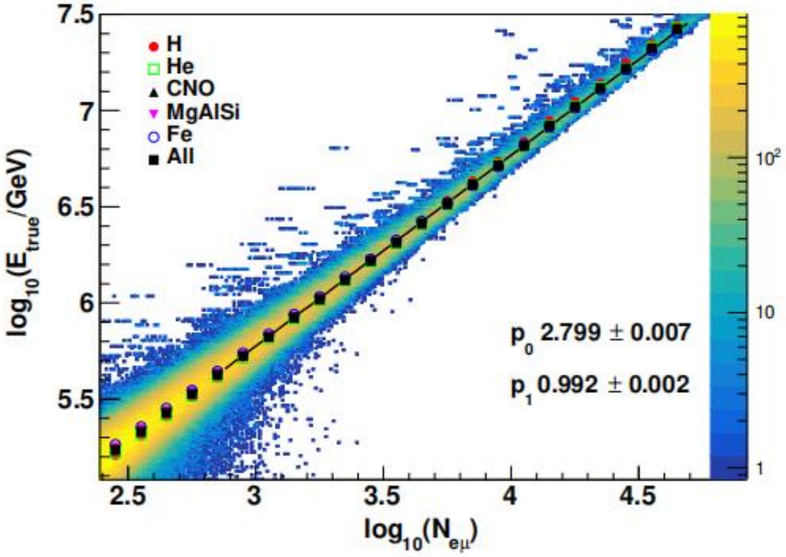
$$E_0 = E_e + E_h \qquad E = 0.85GeV(N_e + 25 * N_\mu)$$

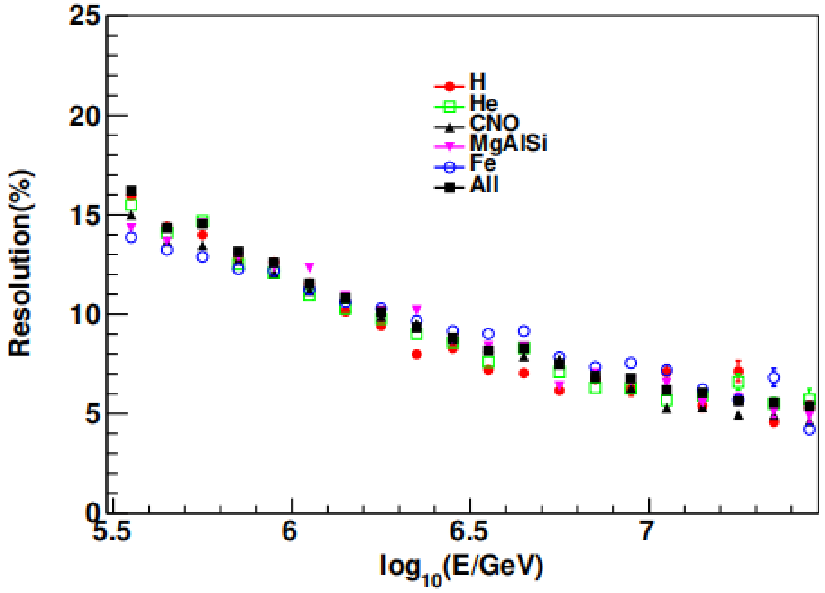
J. Matthews Astroparticle Physics 22 (2005) 387–397

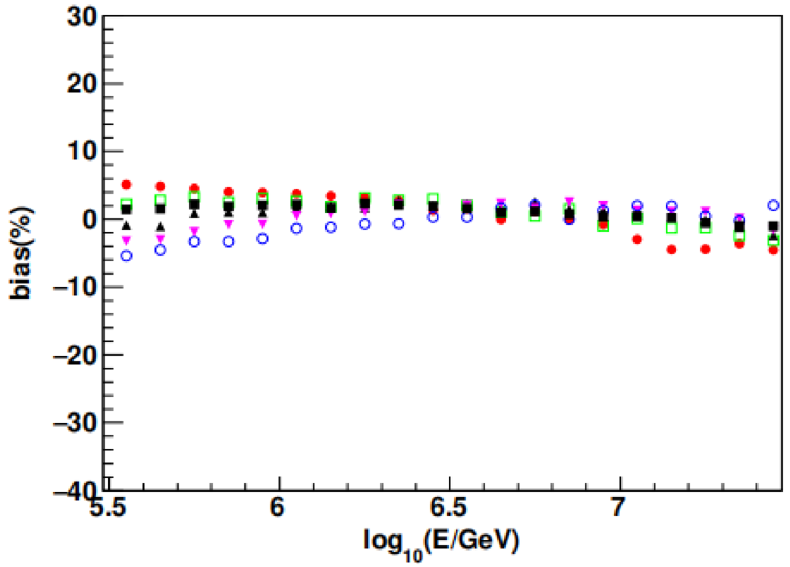
one combined variable to reconstruct the cosmic ray energy weakly dependent on the components

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

H.Y. Zhang, H.H. He and C.F. Feng PRD 106, 123028 (2022)



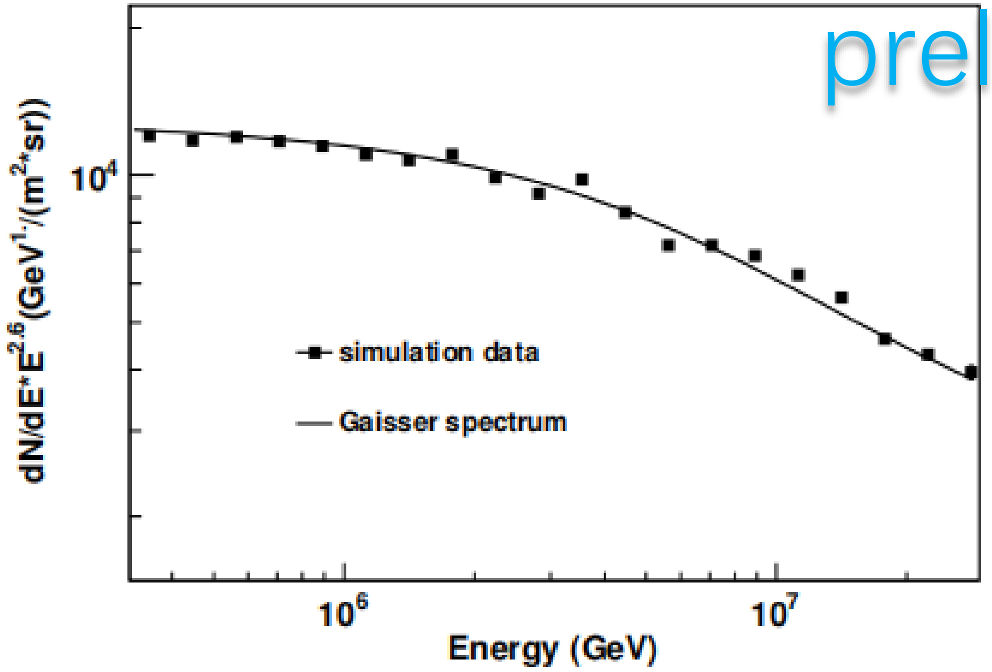


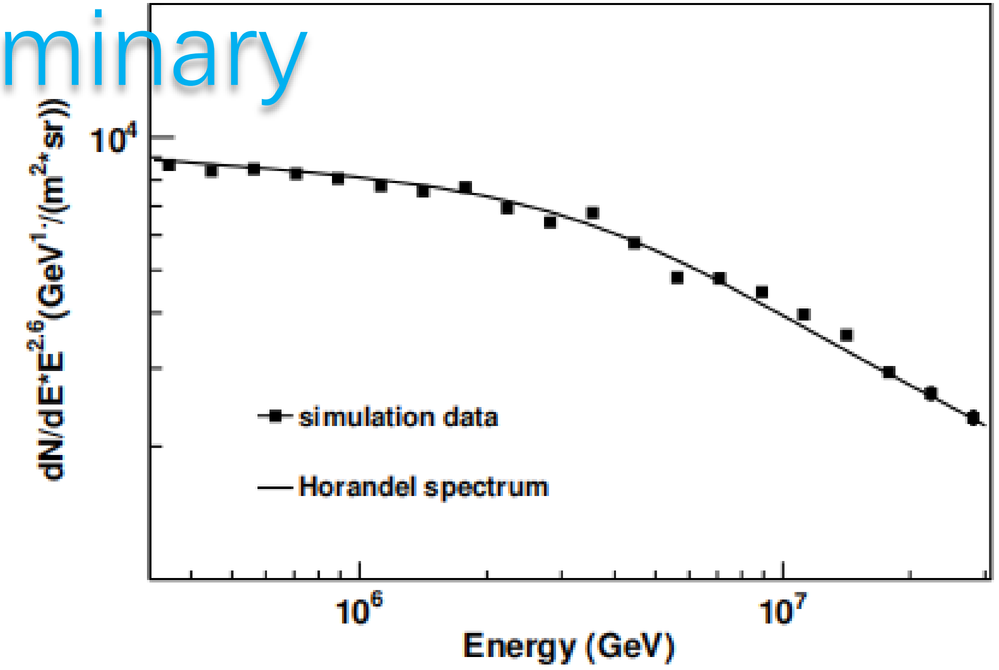


Energy resolution 12%@1PeV
Bias less than 5%

Check all-particle energy spectrum measurement method

$$flux = \frac{\Delta N}{\Delta E * aperture * T}$$

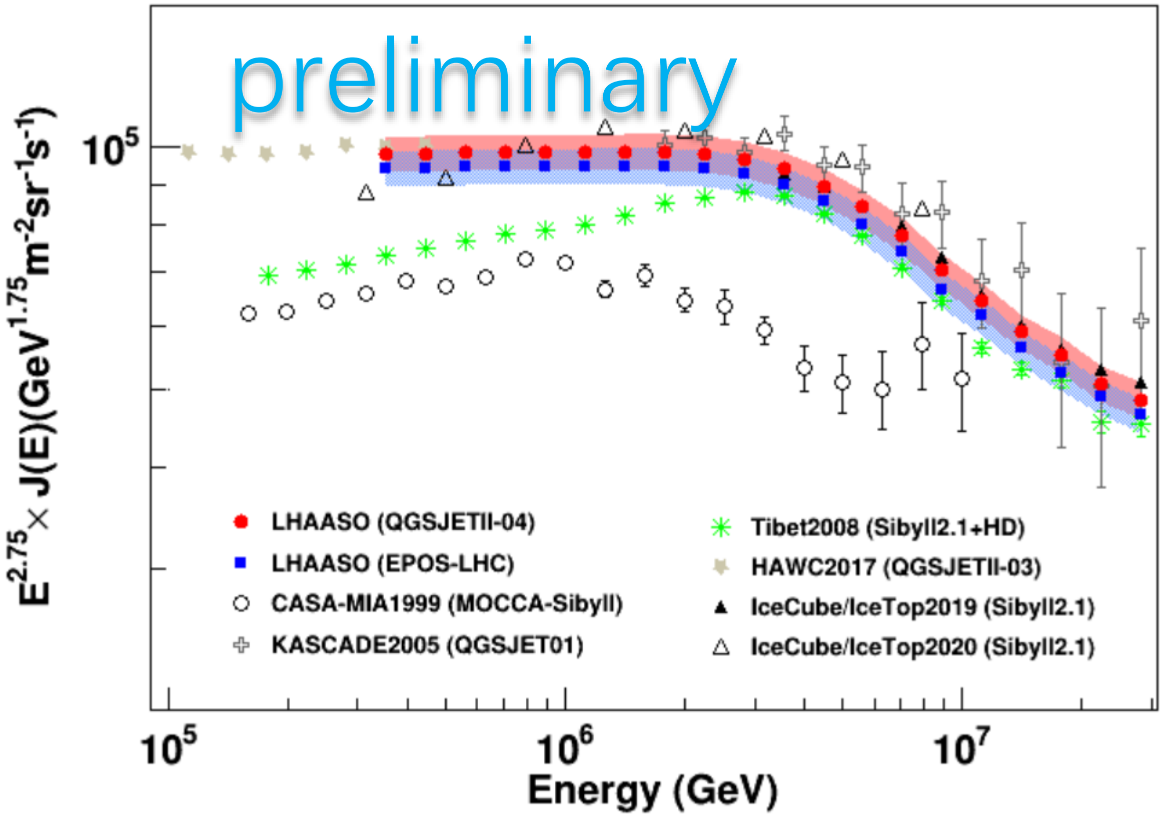




Line： primary spectrum : Gaisser model and Horandel model

Point: Results of measuring the all-particle energy spectrum based on simulation data

All-particle energy spectrum of cosmic ray



$$J(E) = \Phi_0 \cdot (E)^{\gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^s\right)^{(\gamma_2-\gamma_1)/s}$$

T. Antoni et al., Astropart. Phys. 24, 1 (2005).

$$flux = \frac{\Delta N}{\Delta E * aperture * T}$$

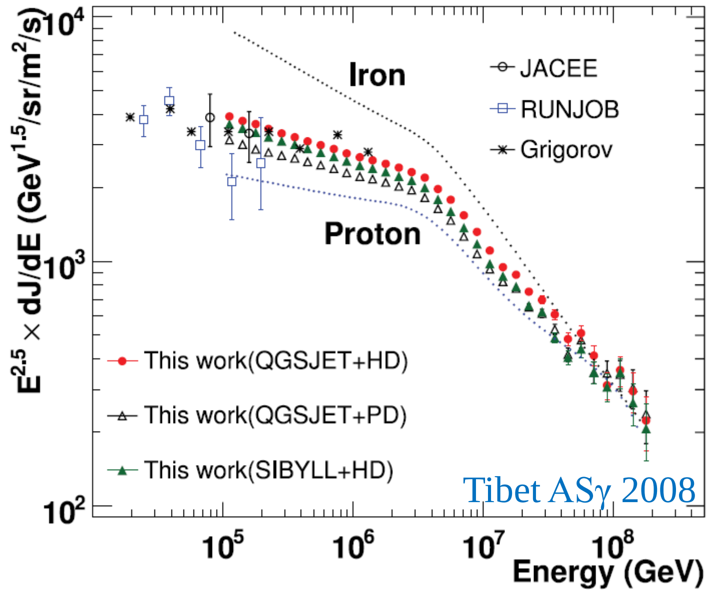
$$\text{stat. err} = \frac{\sqrt{\Delta N}}{\Delta E * aperture * T}$$

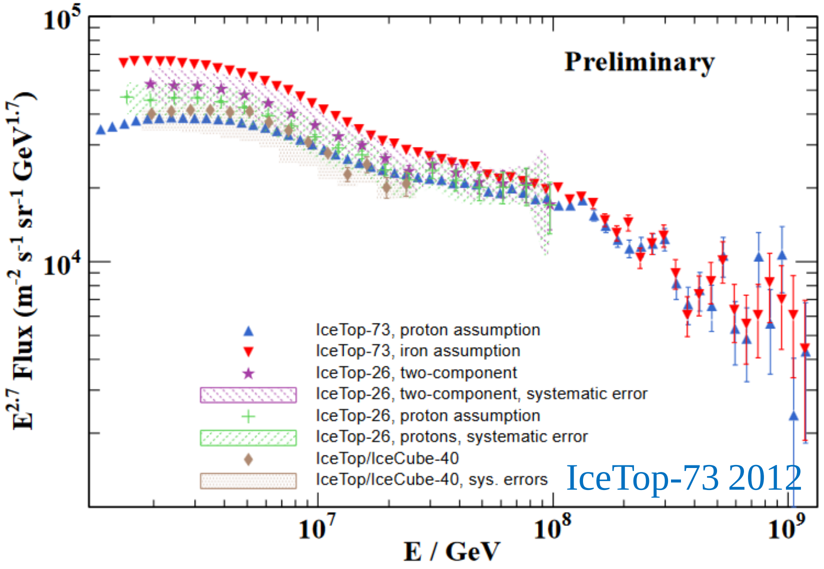
Red dot: 2021.09-2022.12 data measured all-particle energy spectrum of cosmic ray

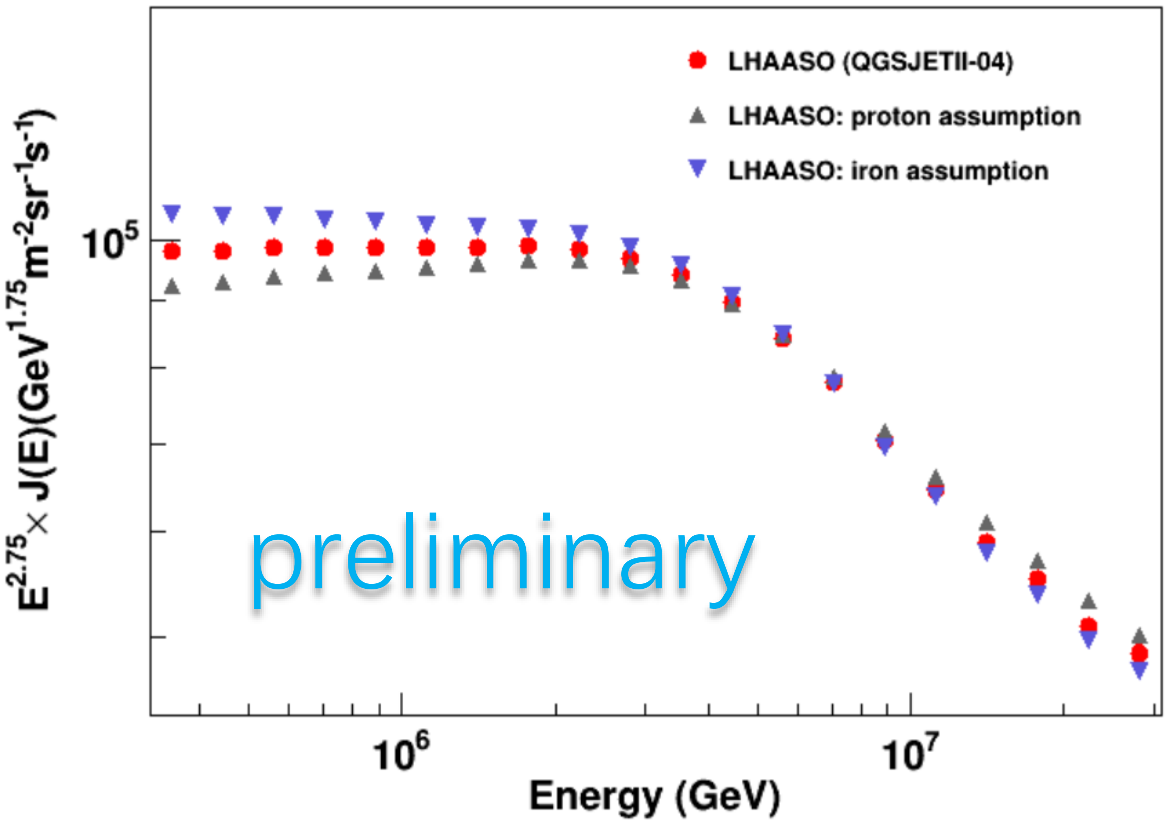
QGSJETII-04	EPOS-LHC
Knee: 3.72±0.05 PeV	Knee: 3.62±0.05 PeV
$\gamma_1 = -2.743 \pm 0.0004$	$\gamma_1 = -2.743 \pm 0.0004$
$\gamma_2 = -3.131 \pm 0.005$	$\gamma_2 = -3.130 \pm 0.005$
Sharpness=4.1 ± 0.1	Sharpness=4.2 ± 0.1

Shadow band: systematic uncertainty 5%

All-particle energy spectrum of cosmic ray



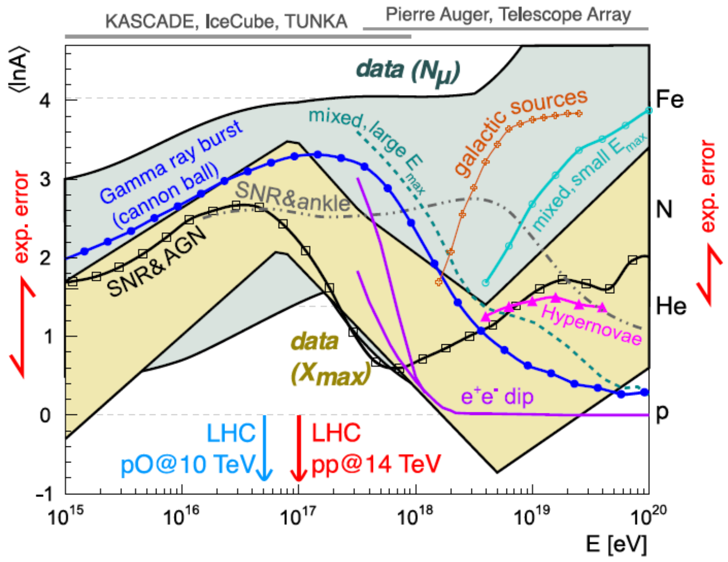




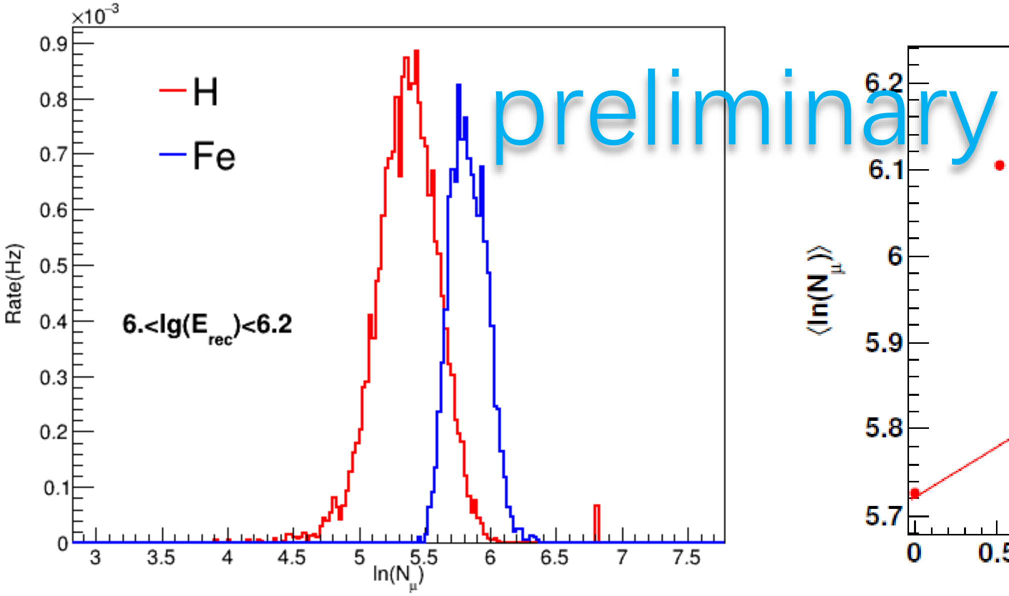
The difference between the pure proton and pure iron models is approximately 12%. The impact of composition uncertainties on the energy reconstruction is significantly reduced.

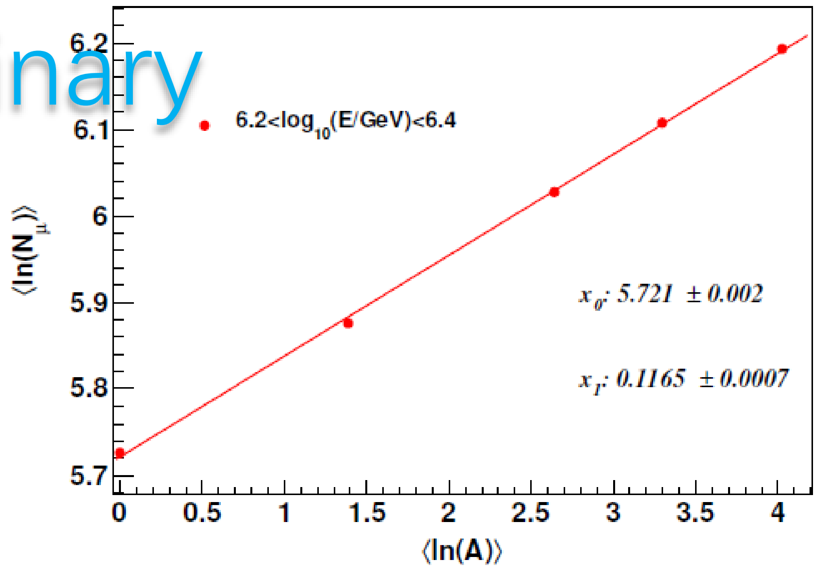
Measurement of muon content

Muons are the direct messengers of the hadronic processes occurring in the shower. The number of muon is a sensitive parameter to study the composition of cosmic rays and test hadronic interaction model.



EPJ Web Conf. 210 (2019) 02004





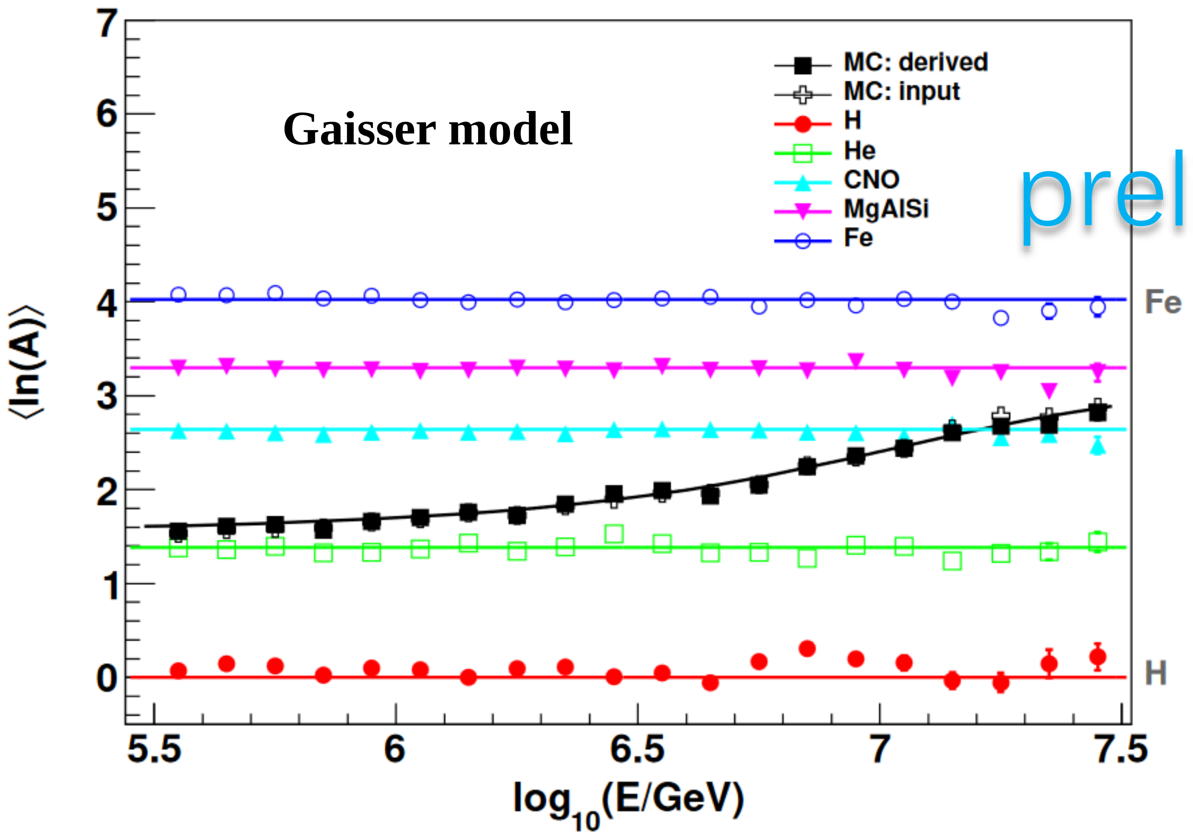
$$N_\mu = A\left(\frac{E/A}{\varepsilon_c}\right)^\beta$$

muon number depends on cosmic ray energy and mass A

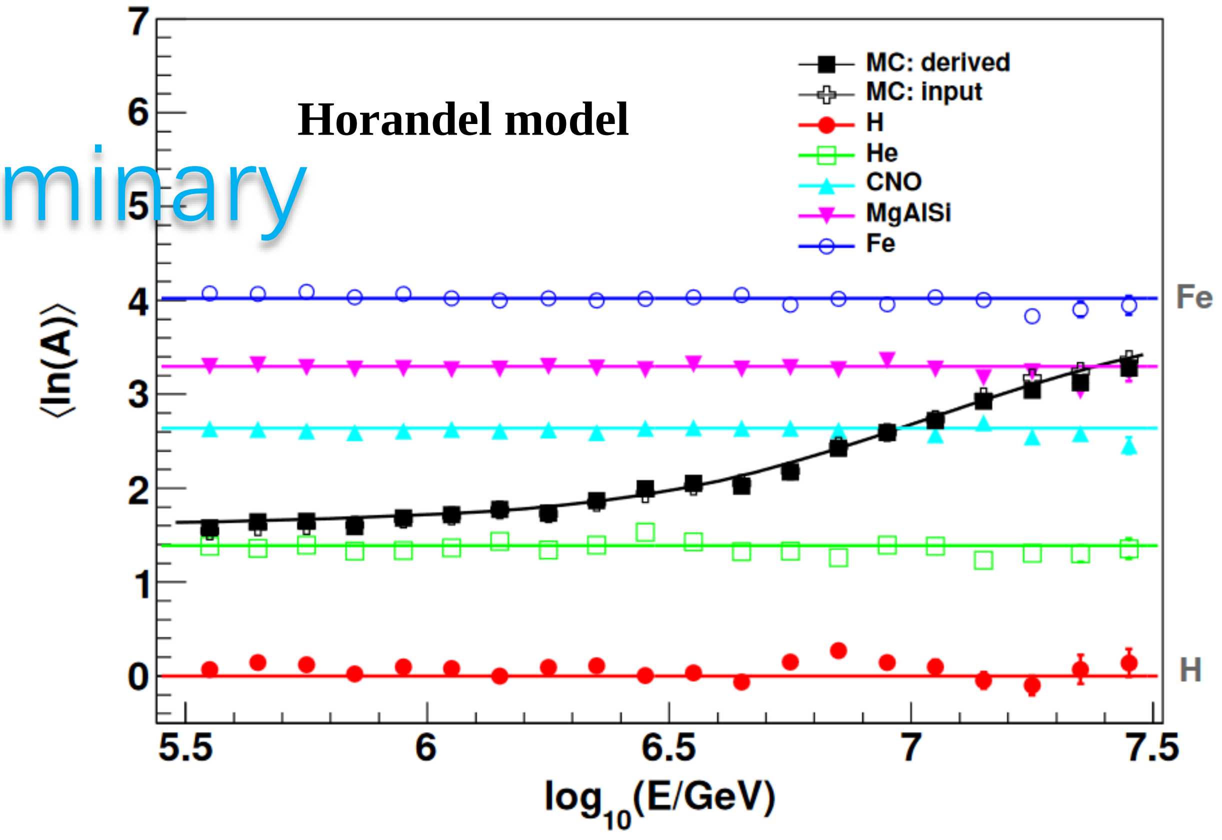
$\langle \ln N_\mu \rangle \rightarrow \langle \ln A \rangle$

Check the derived mean mass method with assumption model

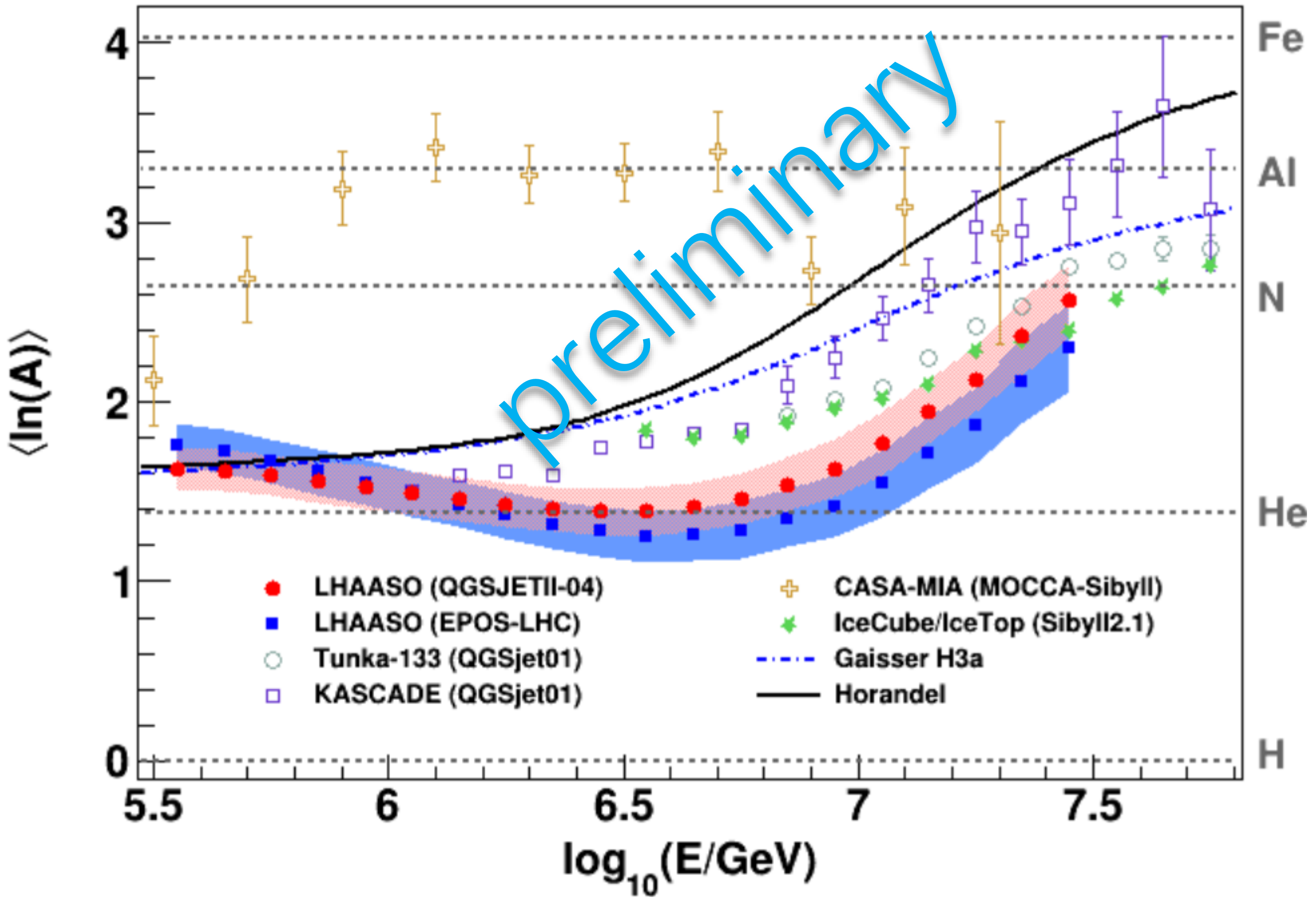
$\langle \ln N_{\mu} \rangle \rightarrow \langle \ln A \rangle$ Check method



preliminary



Mean logarithmic mass $\langle \ln A \rangle$ of cosmic rays

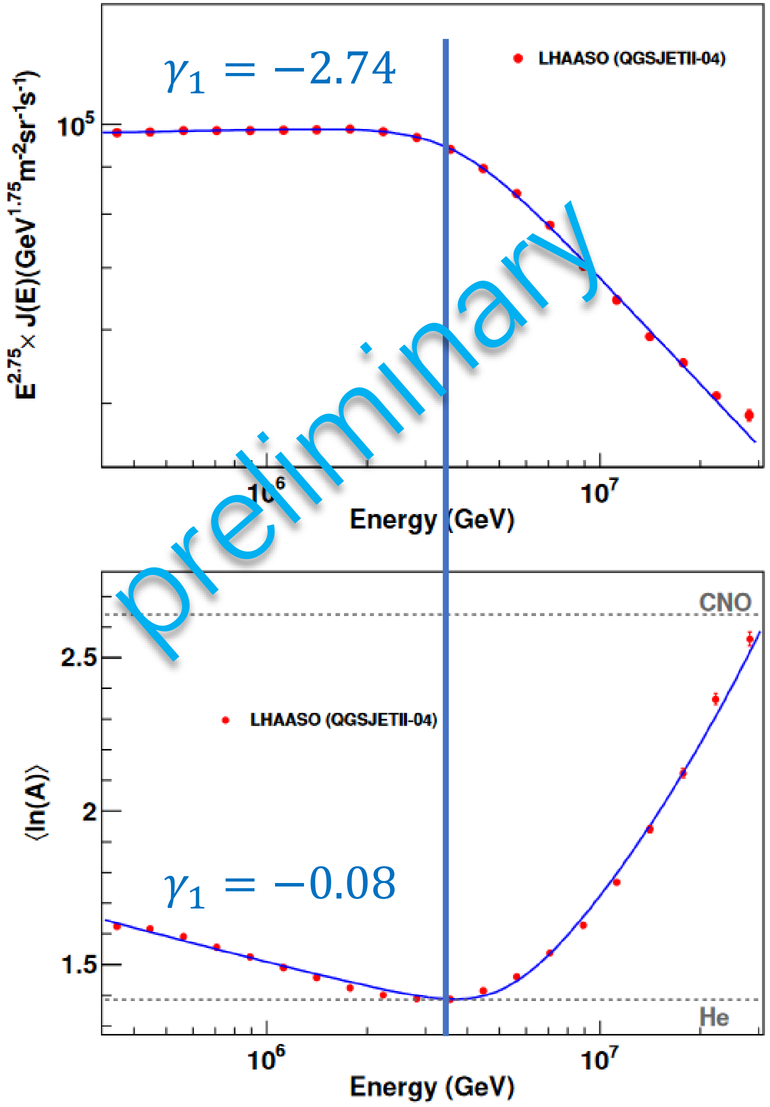


Using $N_{e\mu}$ reconstruction energy

It decreases by 14% between 0.3 PeV and 3 PeV and becomes heavier after the knee.

Shadow band: systematic uncertainty 10%

All-particle energy spectrum and mean logarithmic mass $\langle \ln A \rangle$ of cosmic rays



$$J(E) = \Phi_0 \cdot (E)^{\gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^s\right)^{(\gamma_2 - \gamma_1)/s}$$

T. Antoni et al., Astropart. Phys. 24, 1 (2005).

1. It decreases by 14% between 0.3 PeV and 3 PeV and becomes heavier after the knee.
2. The ⟨ln(A)⟩ of the knee is heavier than He (ln(A) = 1.39) and lighter than CNO (ln(A) = 2.64), suggesting that the first cut-off of the all-particle energy spectrum is due to light components, instead of the medium-heavy components.

Summary

- A new variable $\boldsymbol{N_{e\mu}}$, combining the number of electromagnetic particles and muons, that shows very weak dependency on primary compositions;
- All-particle energy spectrum of cosmic ray: γ_1=-2.743±0.0004， γ_2 =-3.131±0.005，knee：3.72±0.05 PeV, first time measured sharpness parameter 4.1±0.1
- The mean logarithmic mass in the energy range 0.3 -30 PeV is measured. Around "knee" region, the cosmic ray component becomes heavier.
- The knee of all-particle energy spectrum is the knee of light components, instead of the medium-heavy components.

Thanks for your attention!