第十四届全国粒子物理学术会议（2024）山东·青岛

LHAASO-KM2A精确测量宇宙线能谱和平均对数质量

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On behalf of the LHAASO collaboration

2024.08.14

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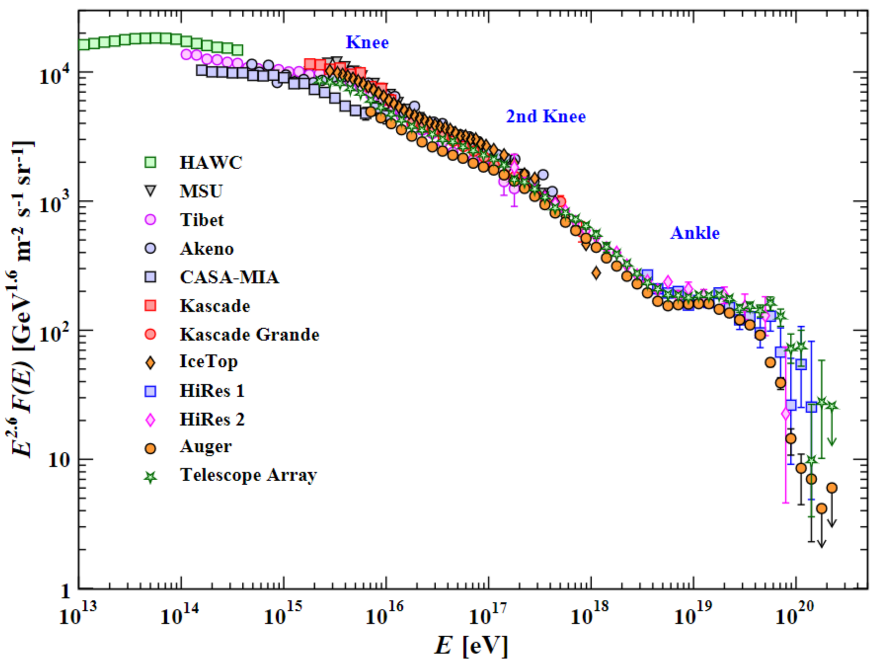
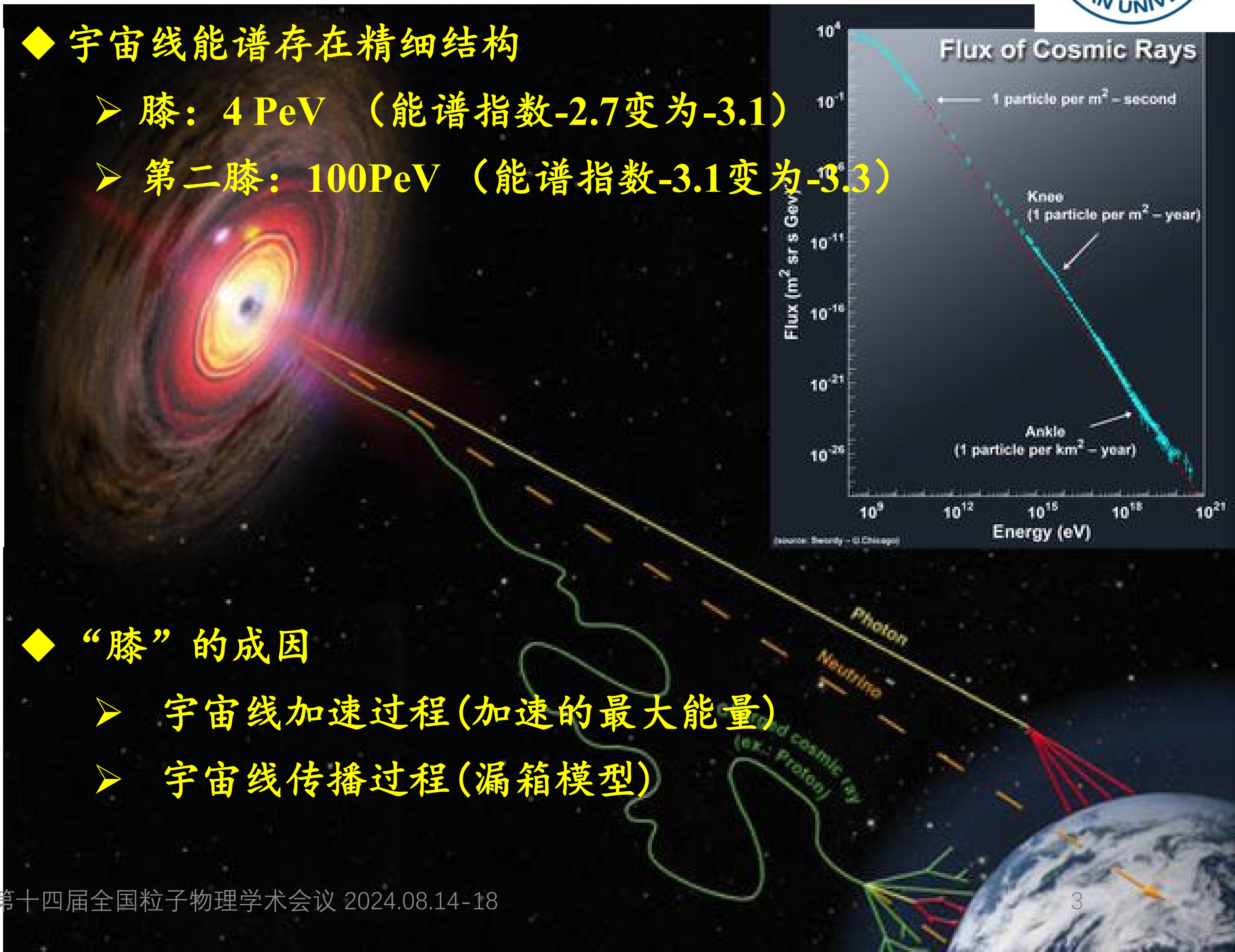


地面探测器间接测量宇宙线

- 原初宇宙线能量、宇宙线成分和强相互作用模型相互纠缠



- 宇宙线能谱存在精细结构
  - 膝：4 PeV （能谱指数-2.7变为-3.1）
  - 第二膝：100PeV （能谱指数-3.1变为-3.3）

- “膝”的成因
  - 宇宙线加速过程(加速的最大能量)
  - 宇宙线传播过程(漏箱模型)

LHAASO-KM2A实验全粒子能谱和平均对数质量的结果

PHYSICAL REVIEW LETTERS **132,** 131002 (2024)

Editors' Suggestion | Featured in Physics

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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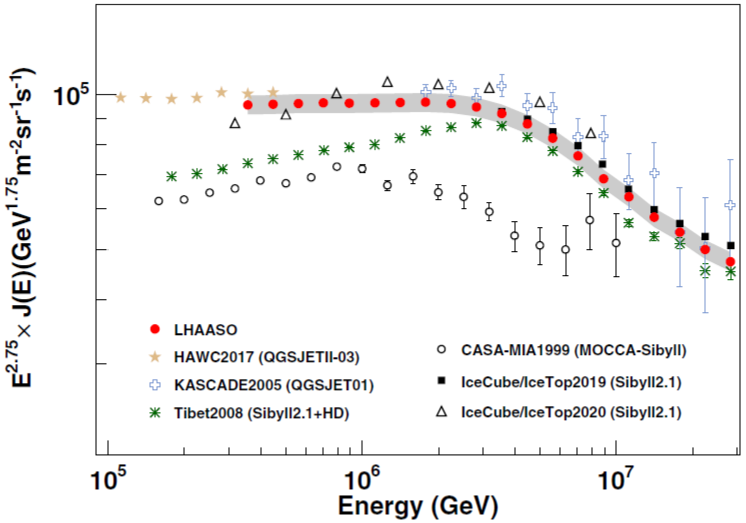
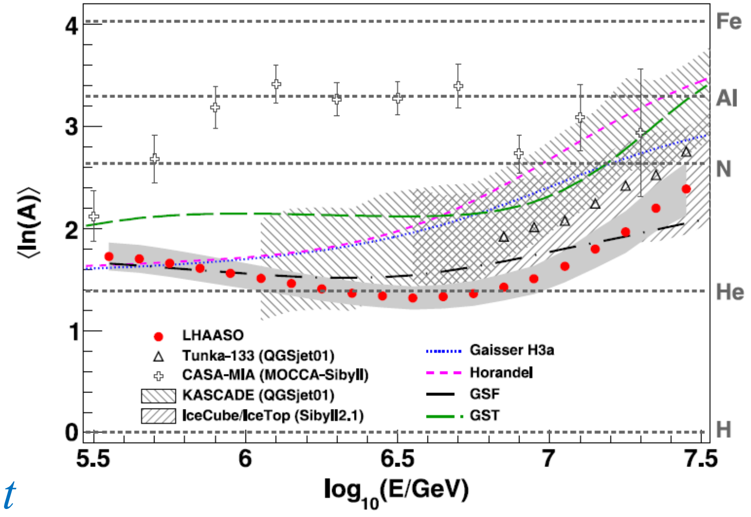
(LHAASO Collaboration)

The high precision achieved in this measurement and the robustness of the measurement with respect to unknowns (details of the cosmic ray mass composition, hadronic physics in the air shower development)make this paper an important milestone for the field and justify publication in the letter format.

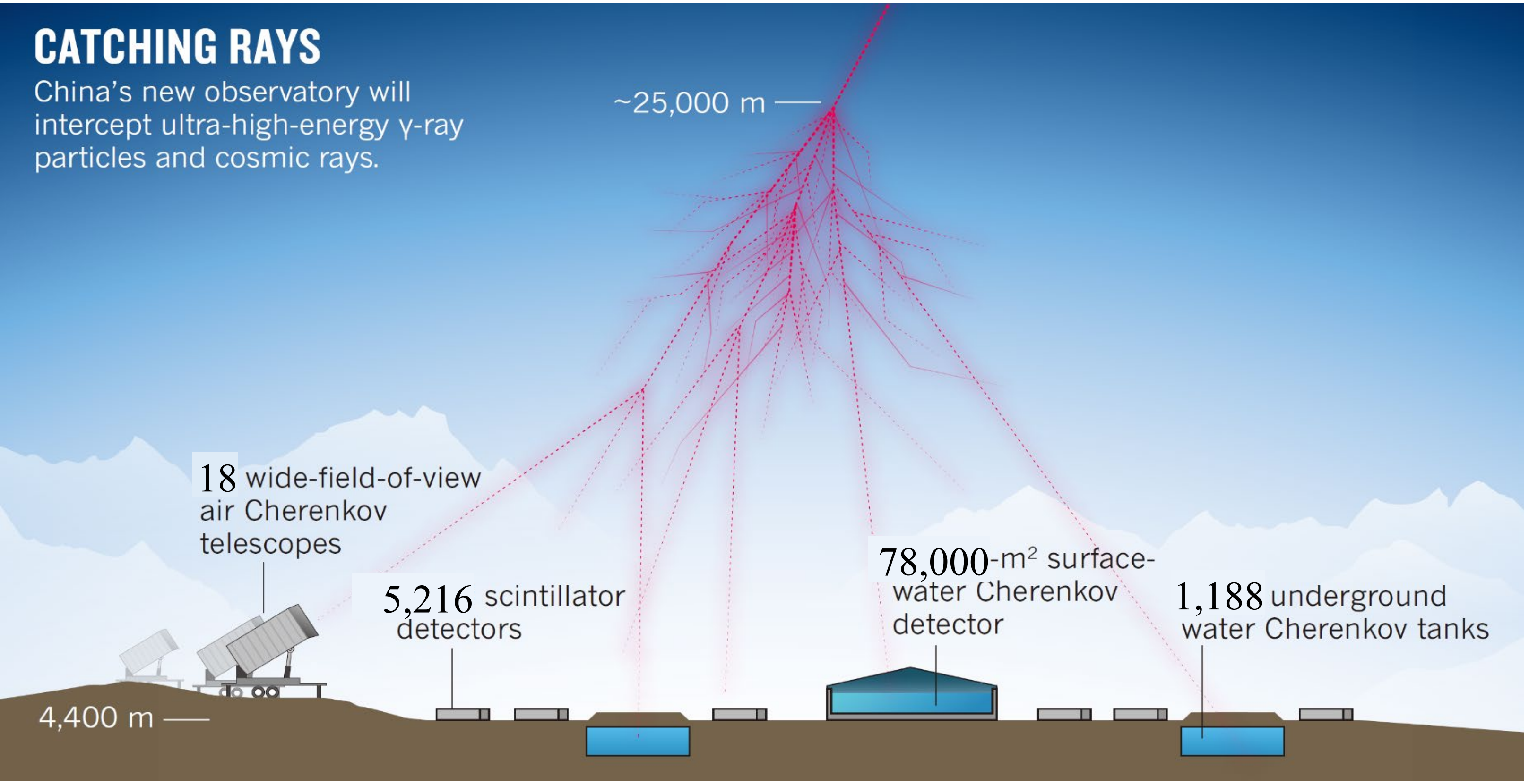


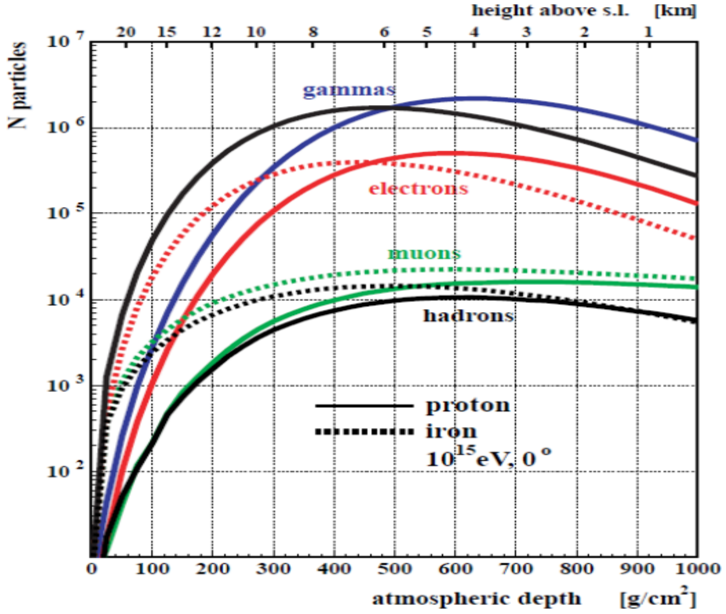


PRL 132,131002 (2024)

- 宇宙线平均对数质量随能量变化，与全粒子能谱的行为相反；
- 宇宙线平均对数质量在0.3 PeV和3 PeV之间下降了24%，在“膝”之后变重；
- ⟨ln(A)⟩最接近于氦（ln(A)=1.39），比 CNO（ln(A)=2.64）轻，这表明全粒子能谱的“膝”是由轻成分引起的，而不是中重成分。

LHAASO实验的优势





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

- ✓ 5,216个电磁粒子探测器和1,188个缪子探测器，可以同时测量次级电磁粒子和缪子信息；
- ✓ “膝”区宇宙线大气簇射发展最大处，统计涨落最小；

KM2A数据事例筛选和效率

QGSJETII-04_fluka, EPOS-LHC_fluka, SIBYLL-2.3d_fluka

Proton He CNO MgAlSi Fe,

Theta: 0-40°

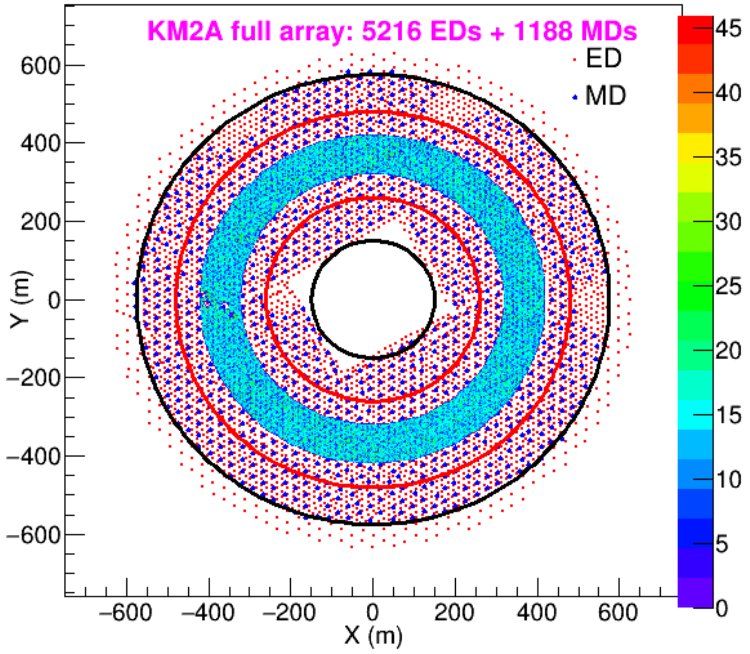
Slope: -2

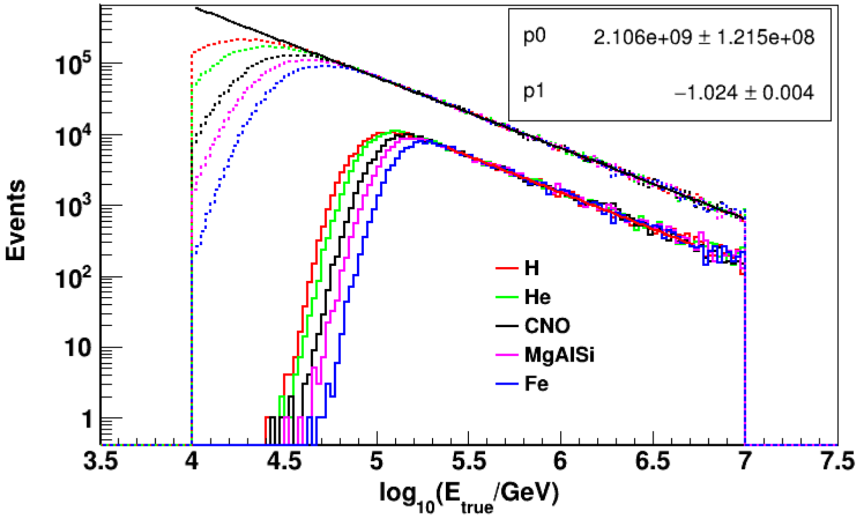
Radius : 260-480m

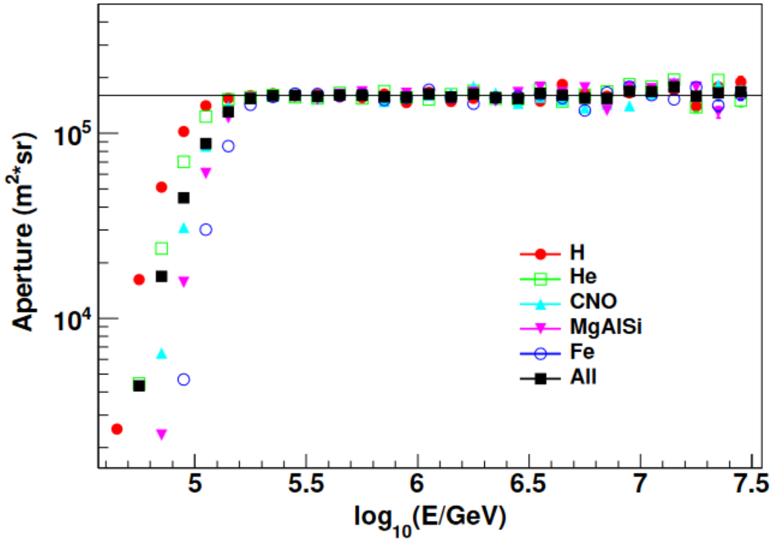
事例筛选条件:

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

core position of reconstruction data



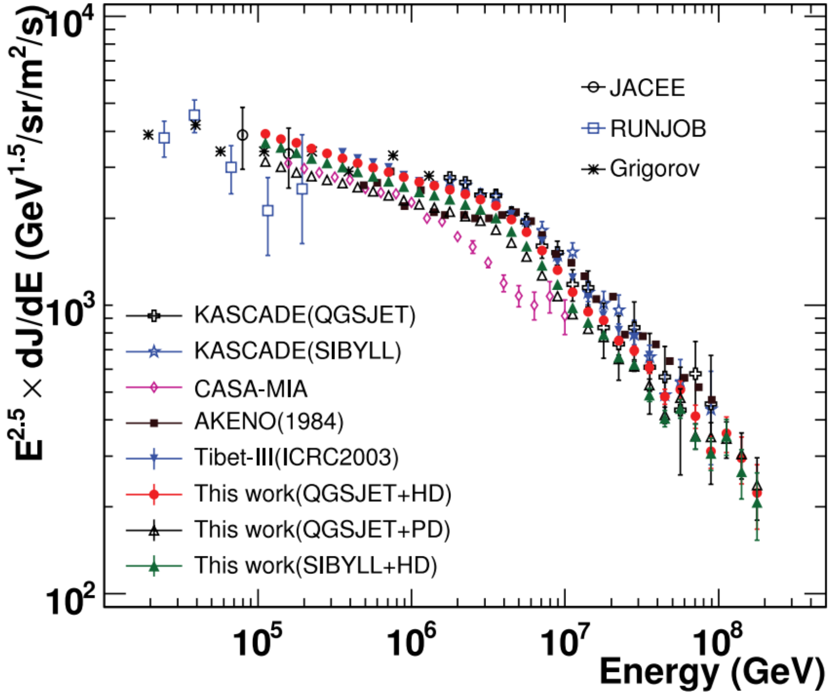




geometric aperture: 320-420m,10°-30°→

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

如何重建宇宙线能量？



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 × 2.4 × 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**

全粒子能谱测量的关键问题:
能量重建中成分依赖 & 模型依赖

传统能量重建方法的成分依赖性：

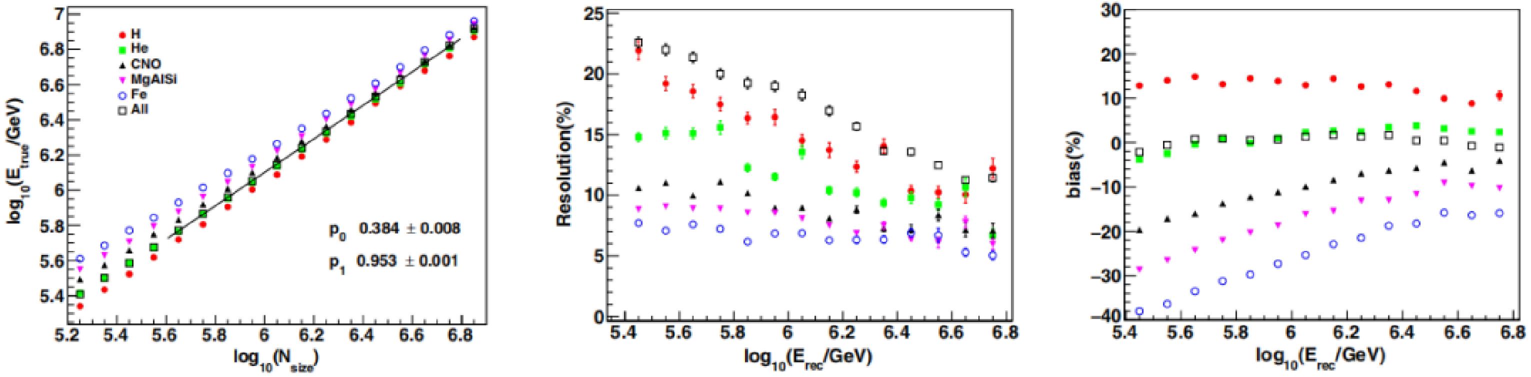
$$N_e \propto A\left(\frac{E_0}{A}\right)^{\alpha} = A^{1-\alpha}E_0^{\alpha} \qquad N_\mu \propto A\left(\frac{E_0}{A}\right)^{\beta} = A^{1-\beta}E_0^{\beta}$$

$$lnE_0 = \frac{1}{\alpha}lnN_e + \left(1-\frac{1}{\alpha}\right)\ln A + \mathrm{const}$$

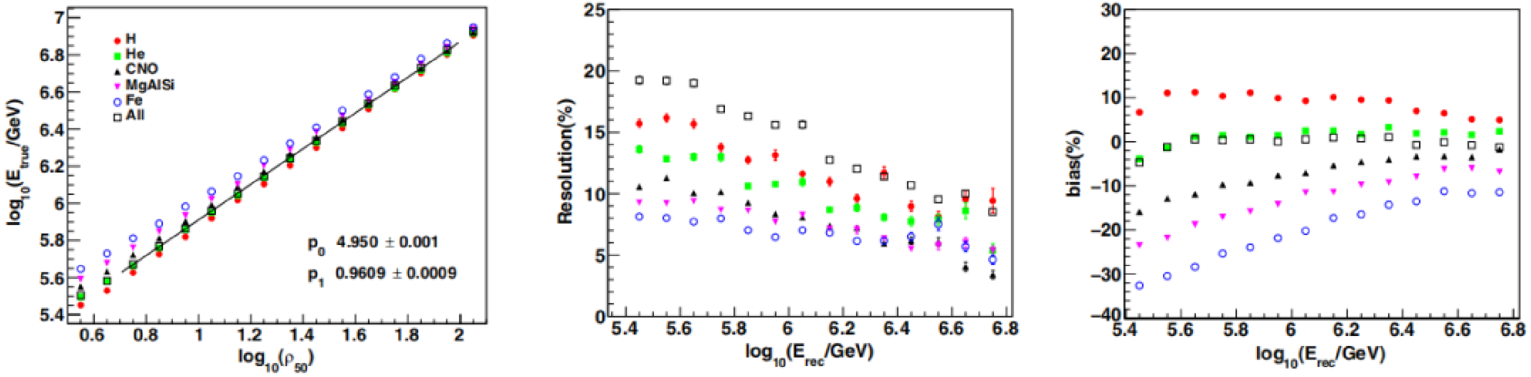
At knees where ln*A* changes abruptly, larger systematic error in energy estimation

成分依赖的能量重建方法

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

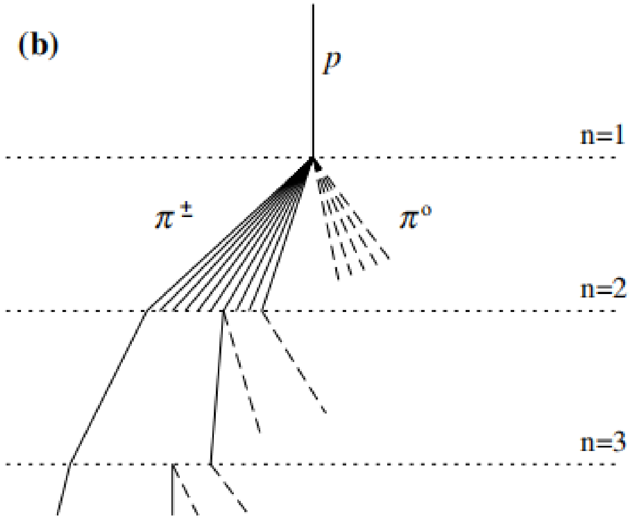


(a) E_{true} vs. N_{size}



(b) E_{true} vs. ρ_{50}

能量重建方法



原初宇宙线总能量分为两部分，即强子部分和电磁部分

N_{ch} 带电$\pi^\pm$和 $\frac{1}{2}N_{ch}$ 中性π^0

$E_{\mathrm{em}} = \xi_c^e N_{max}$
临界能量 ξ_c^e=85 MeV
electrons $N_e = N_{max}/g$ and g=10

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

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

临界能量 $\xi_c^\pi = 20\mathrm{GeV}$
muon $N_\pi = N_\mu$

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

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

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

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

能量分配不受A的影响，本质上考虑了所有原初粒子能量被分配到强子通道（看作缪子）和电磁簇射中。

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

成分弱依赖的能量重建方法

根据Heitler的电磁模型和Matthews的强子簇射模型，原初能量最终在簇射发展中被分配给π介子和电磁粒子

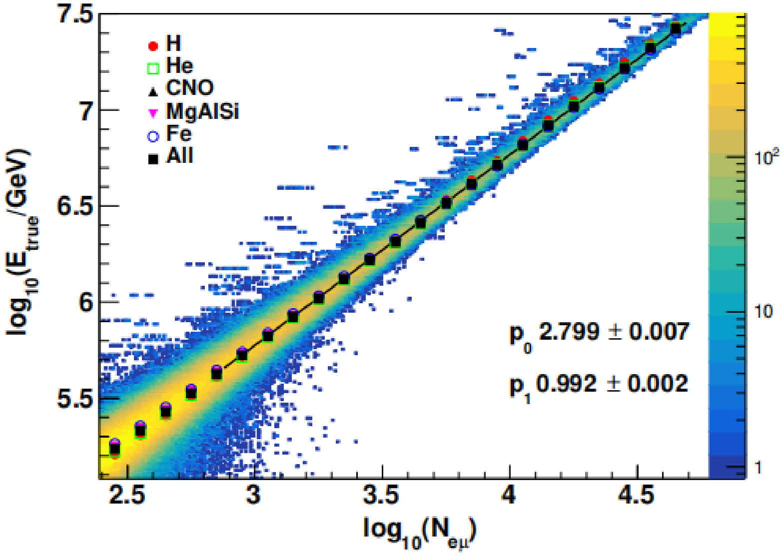
$$E_0 = E_e + E_h \qquad E = 0.85GeV(N_e + 25 * N_\mu)$$

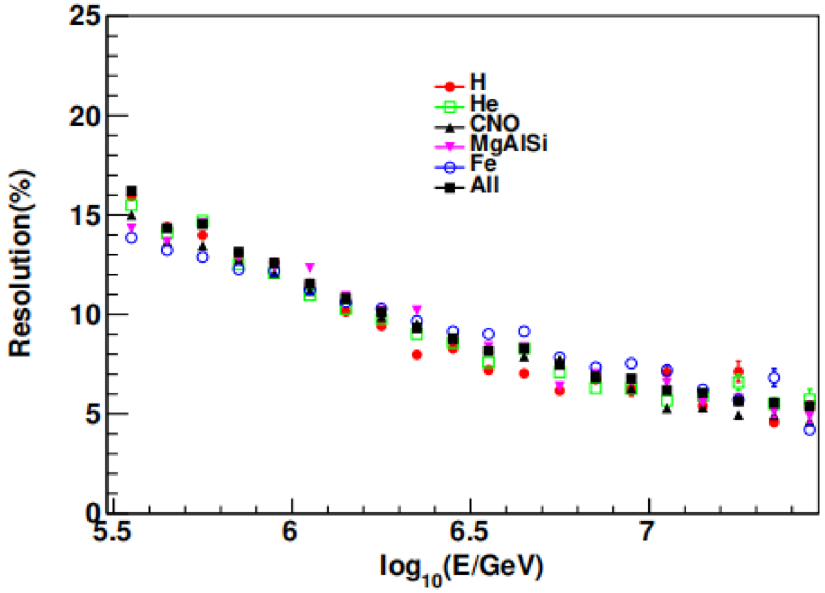
J. Matthews Astroparticle Physics 22 (2005) 387–397

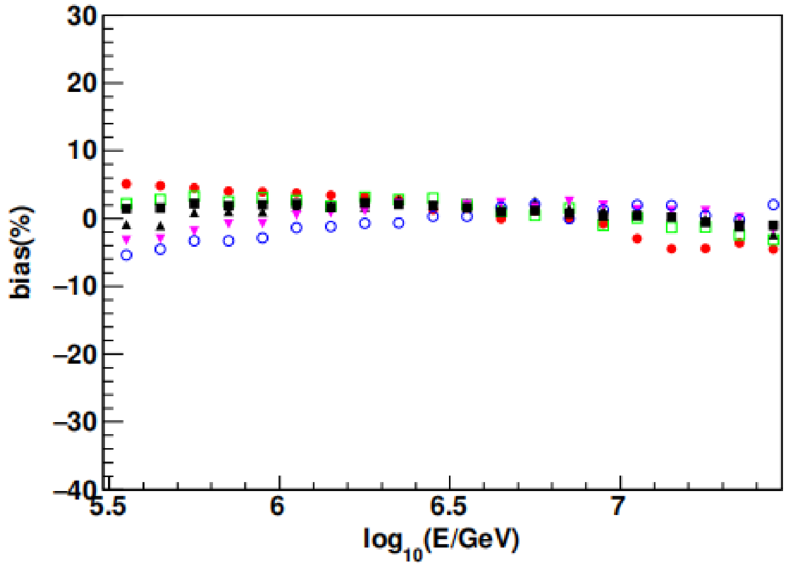
组合变量用于重建宇宙射线能量，对宇宙线成分的依赖性较弱

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

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



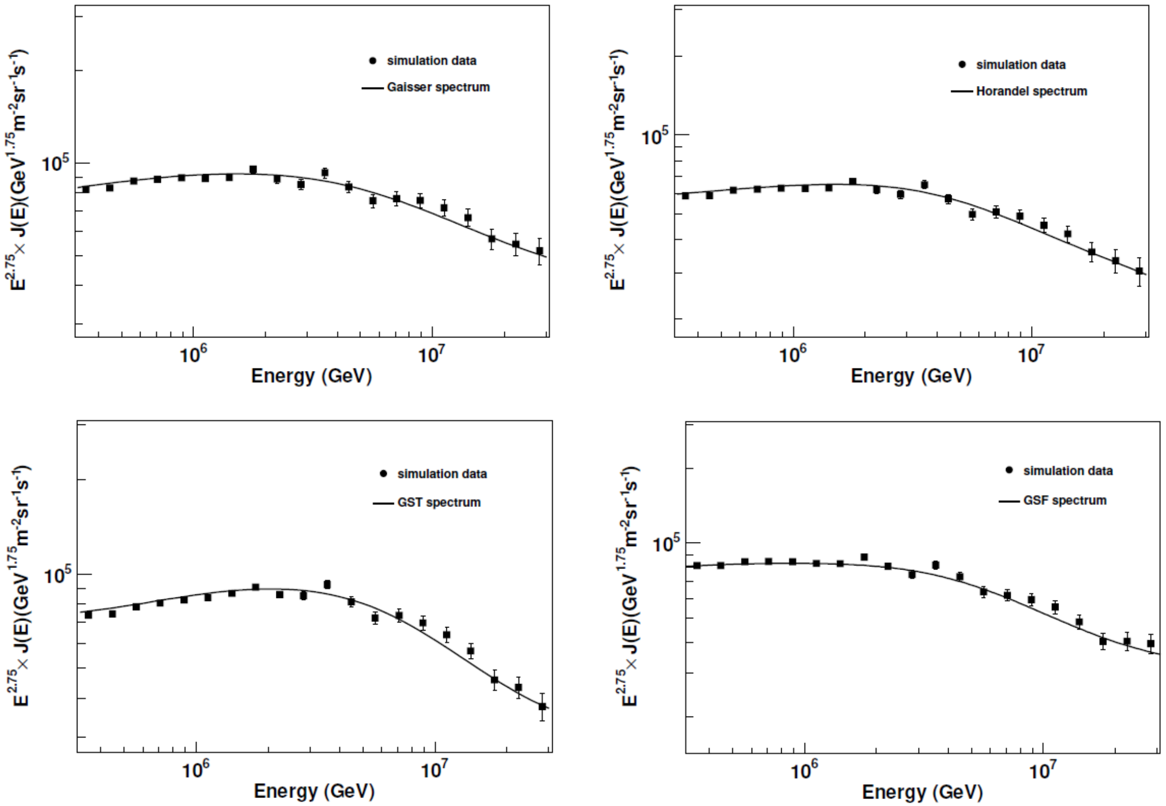




能量分辨率12%@1PeV
能量重建偏差好于 6%

全粒子能谱测量方法的验证

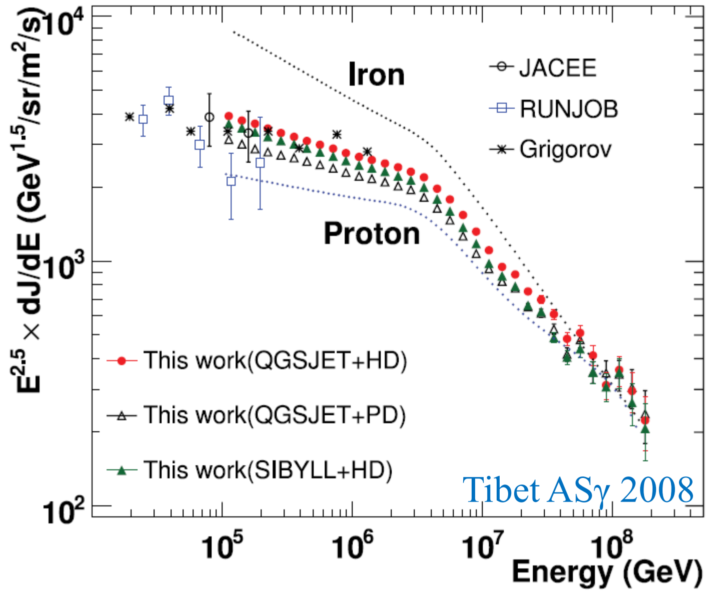
$$flux = \frac{\Delta N}{\Delta E * aperture * T}$$

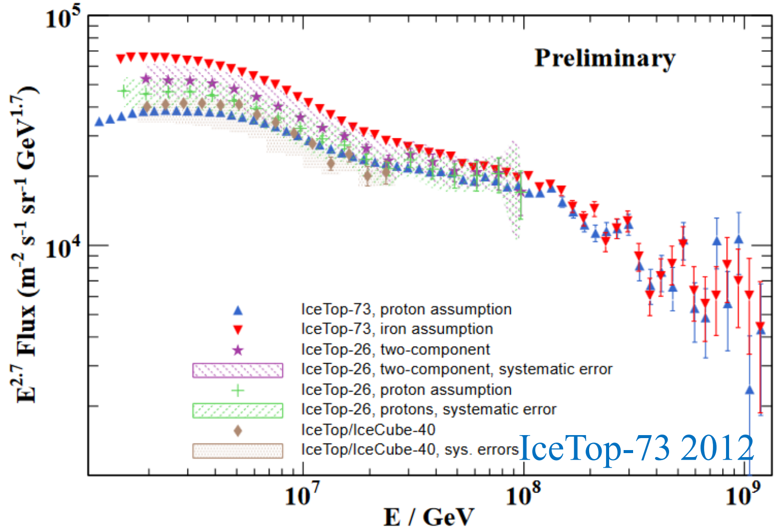


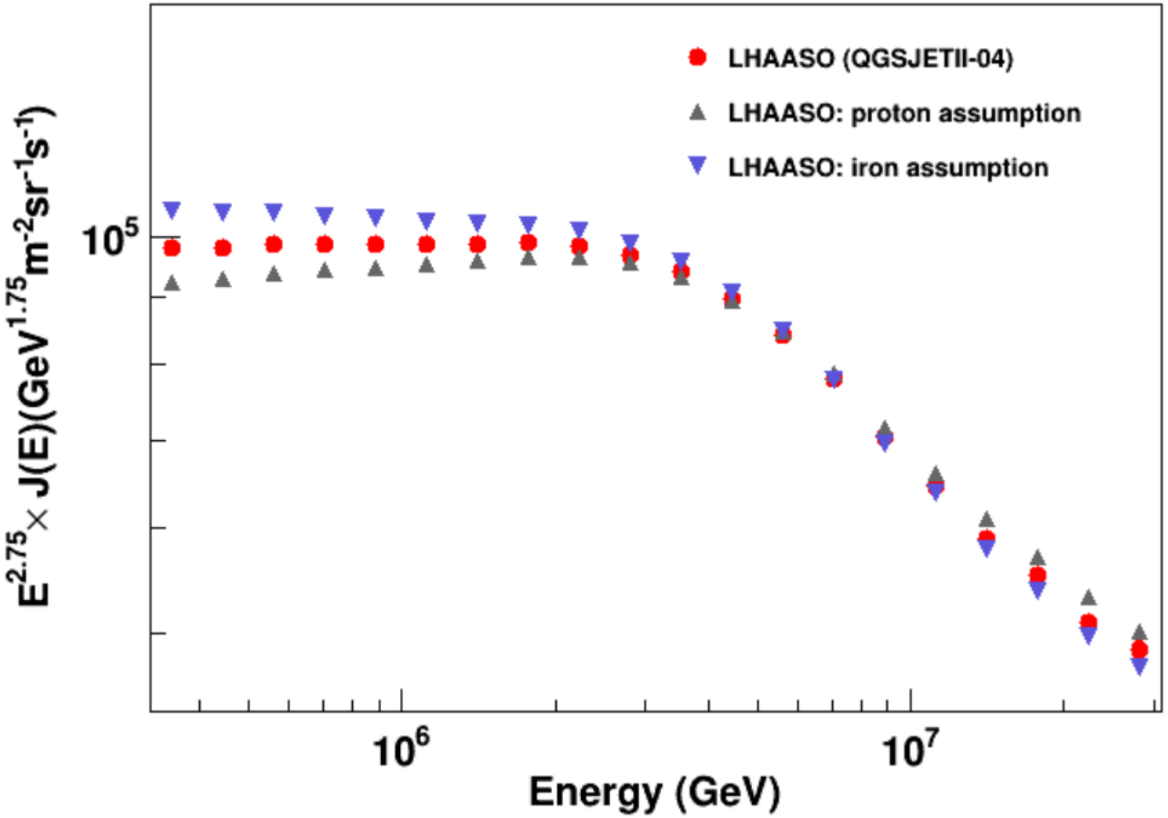
Line： primary spectrum : Gaisser H3a, Horandel, GST, GSF model

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

成分弱依赖的能量重建方法的优势

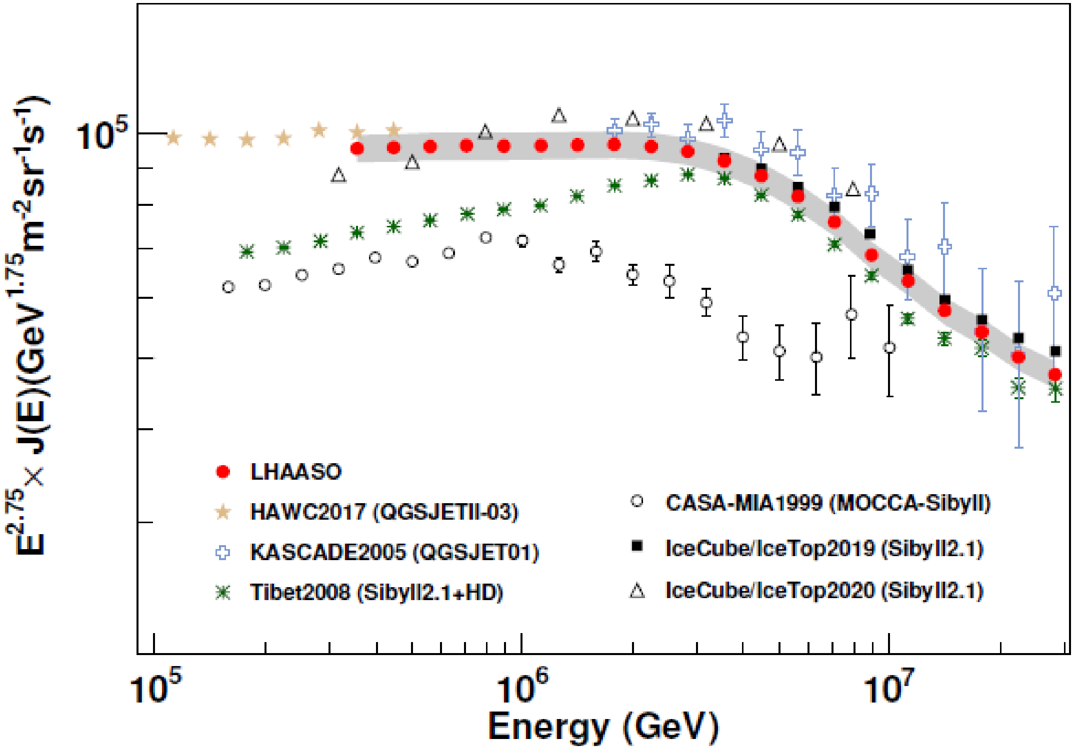






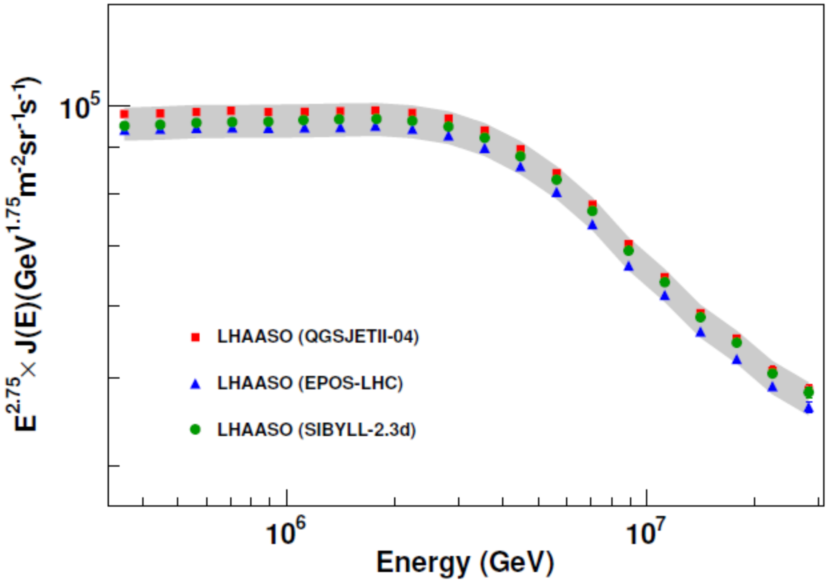
- 纯质子和纯铁模型之间的差异约为12%，成分不确定性对全粒子能谱流强的影响显著降低

宇宙线全粒子能谱



实验数据：2021.09-2022.12

$$J(E) = \frac{\Delta N(E)}{\Delta E * A_{eff} * T} \qquad \mathrm{stat.\,err} = \frac{\sqrt{\Delta N}}{\Delta E * A_{eff} * T}$$



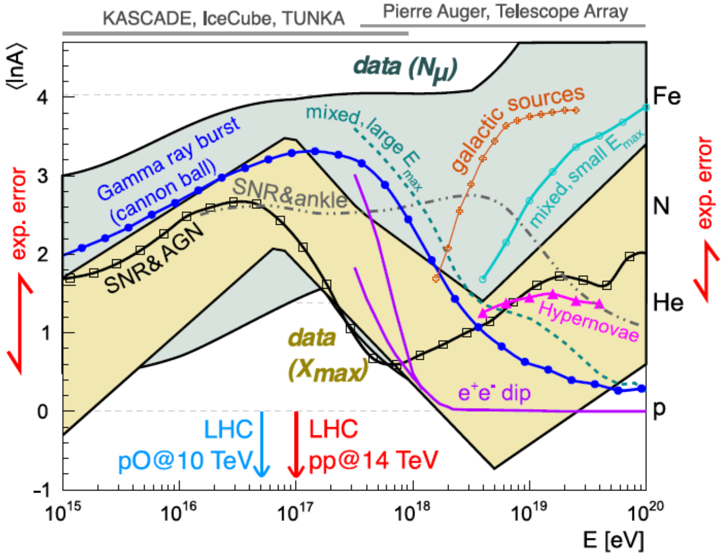
$$J(E) = \Phi_0 \cdot (E)^{\gamma_1}\left(1 + \left(\frac{E}{E_b}\right)^s\right)^{(\gamma_2-\gamma_1)/s}$$

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

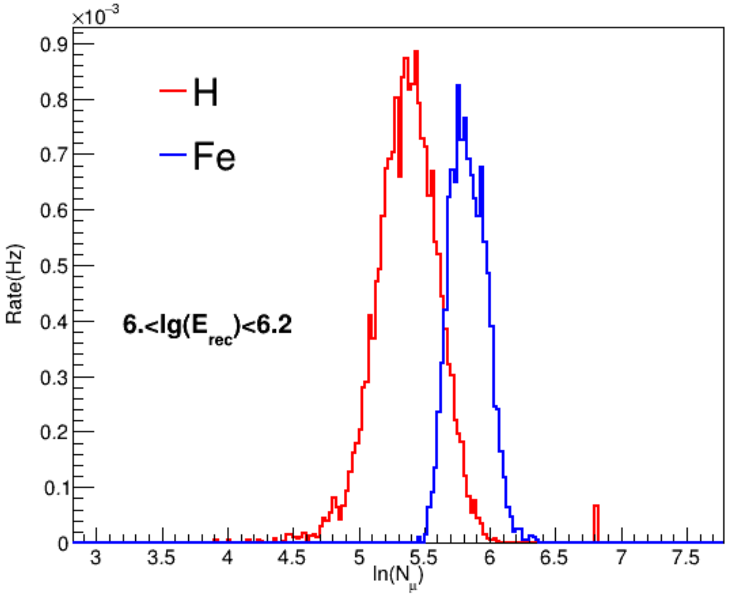
$$E_b = 3.67 \pm 0.05 \pm 0.15\ \text{PeV}$$
$$\gamma_1 = -2.7413 \pm 0.0004 \pm 0.0050$$
$$\gamma_2 = -3.128 \pm 0.005 \pm 0.027$$
$$\mathrm{s} = 4.2 \pm 0.1 \pm 0.5$$

缪子含量测量

缪子是宇宙线大气簇射发展中强子簇射的直接信使。缪子含量是研究宇宙线成分和检验强相互作用模型的敏感参数。



EPJ Web Conf. 210 (2019) 02004



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

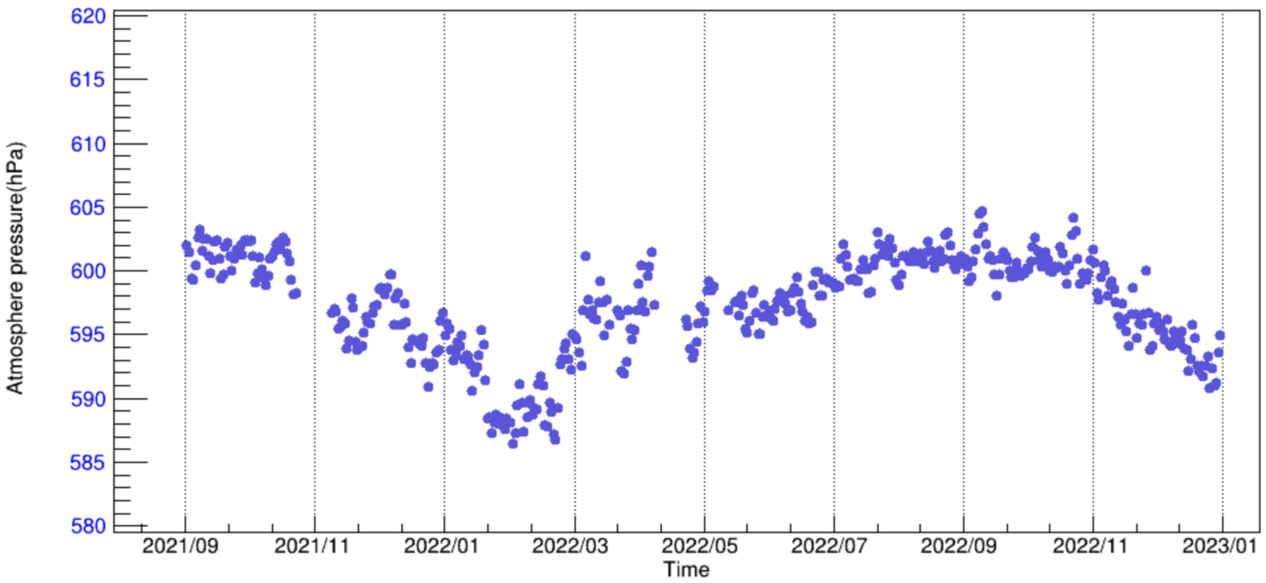
muon number depends on cosmic ray energy and mass A

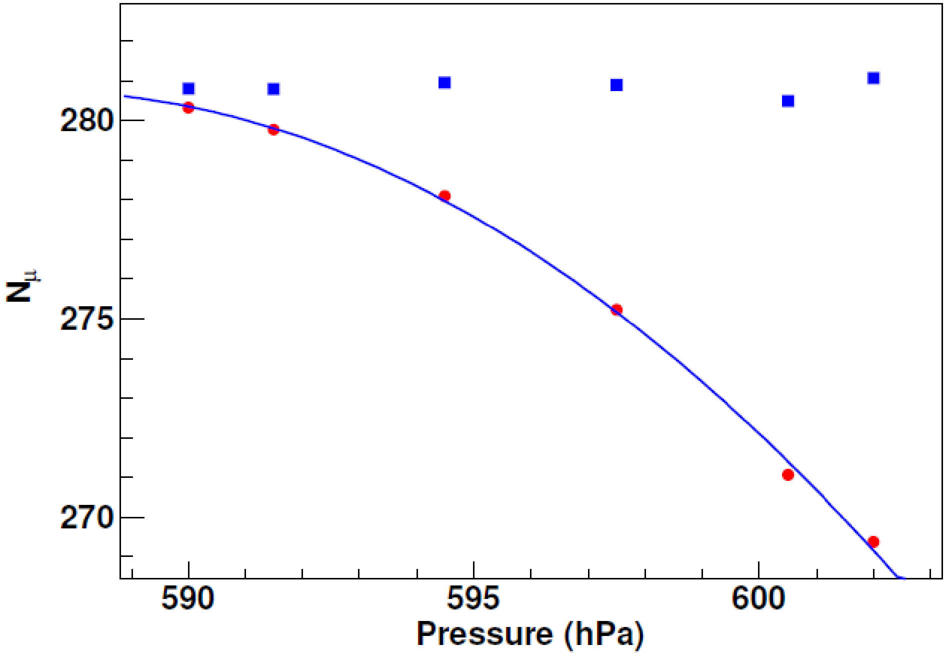
$$\langle \ln N_\mu \rangle \rightarrow \langle \ln A \rangle$$

$$\langle \ln(N_\mu) \rangle = x_0 + x_1 \cdot \langle \ln(A) \rangle.$$

大气压强修正

年变化的大气压强为12 hPa





The aim of the Constant Intensity Cut (CIC)* method is to provide a way to relate data from different atmospheric pressure at roughly the same primary energies, without any reference to MC simulations.

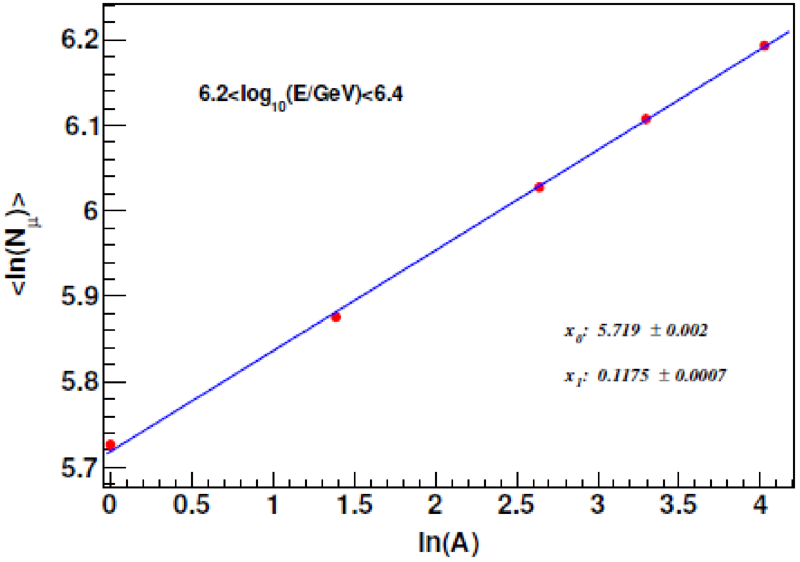
大气压强对缪子含量测量的影响为4.4%，大气压强修正后降至0.6%。

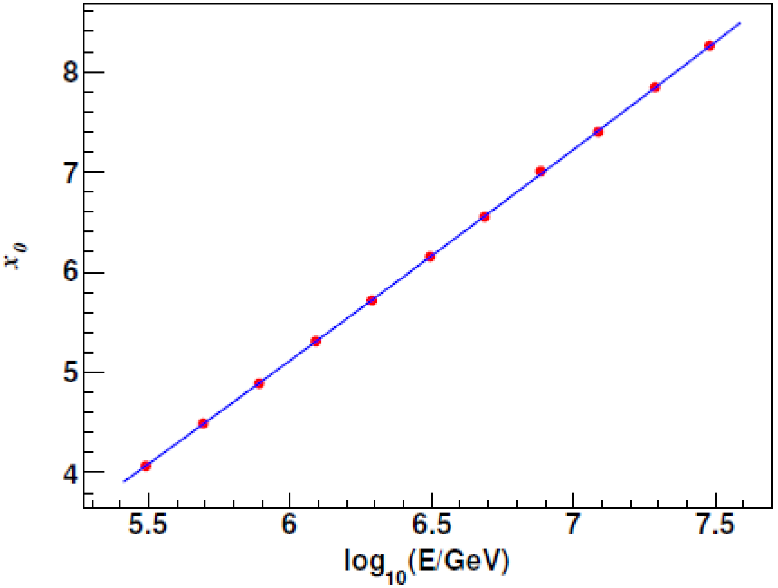
the ground pressure at an altitude of 4,397 m is 586.6 hPa (CORSIKA atmosphere 1)

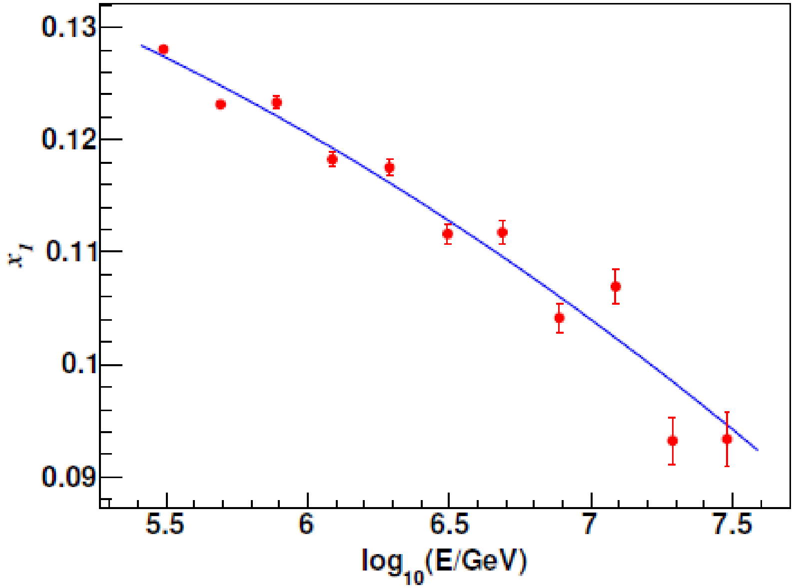
*Phys. Rev. Lett. 6, 22 (1961)

缪子含量推导宇宙线平均对数质量

$$\langle \ln(N_\mu) \rangle = x_0 + x_1 \cdot \langle \ln(A) \rangle .$$



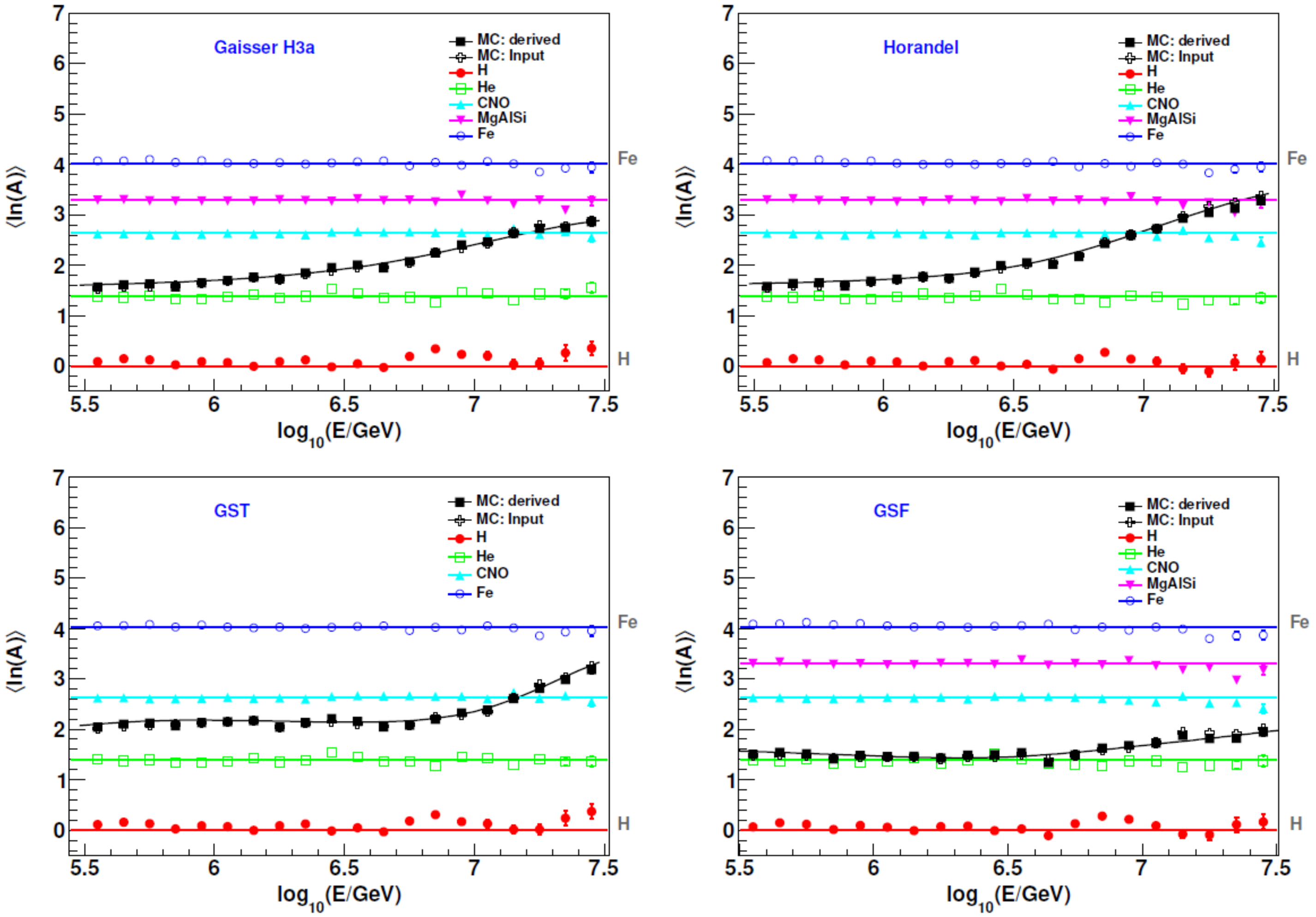


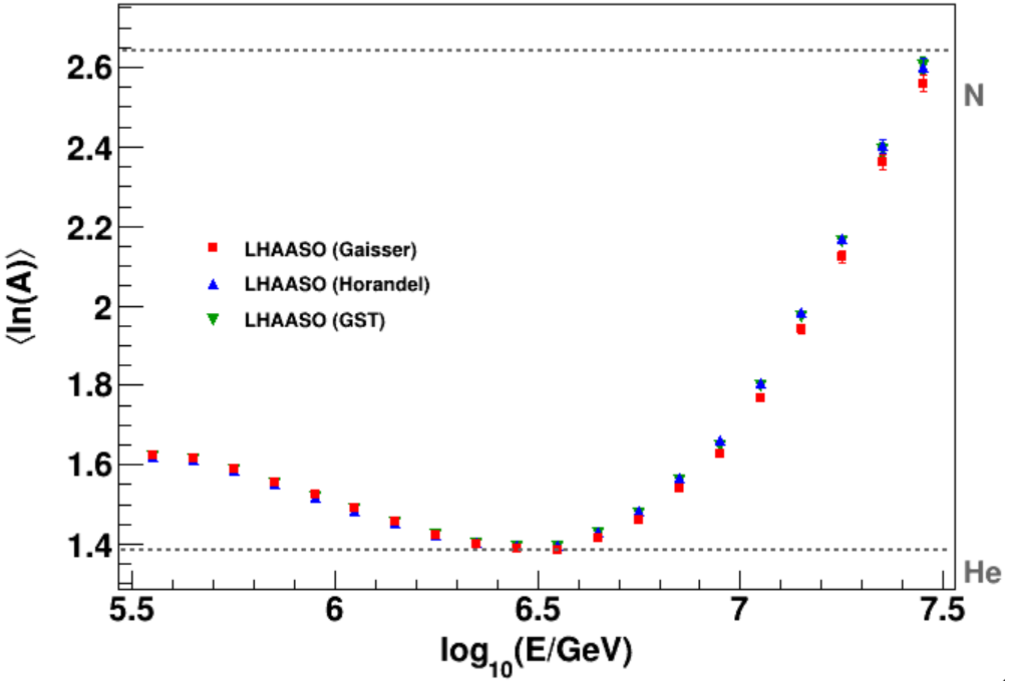


通过拟合函数插值得到0.1能量bin内的x0,x1

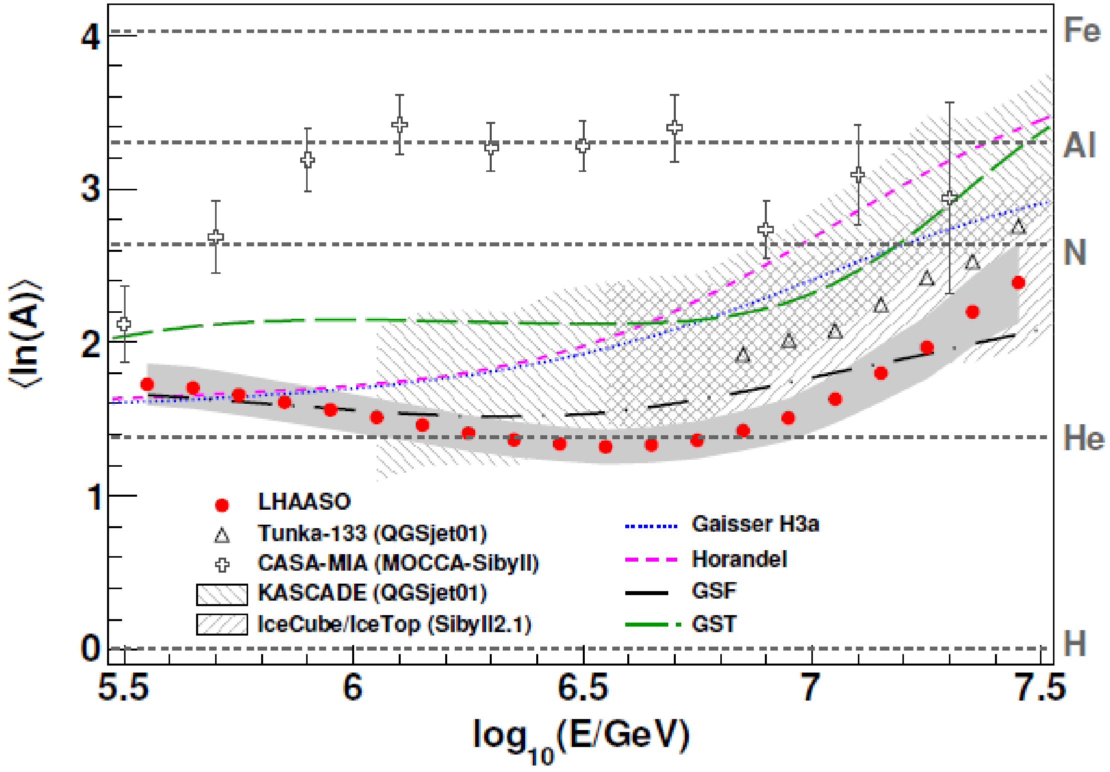
宇宙线平均对数质量推导方法的验证

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

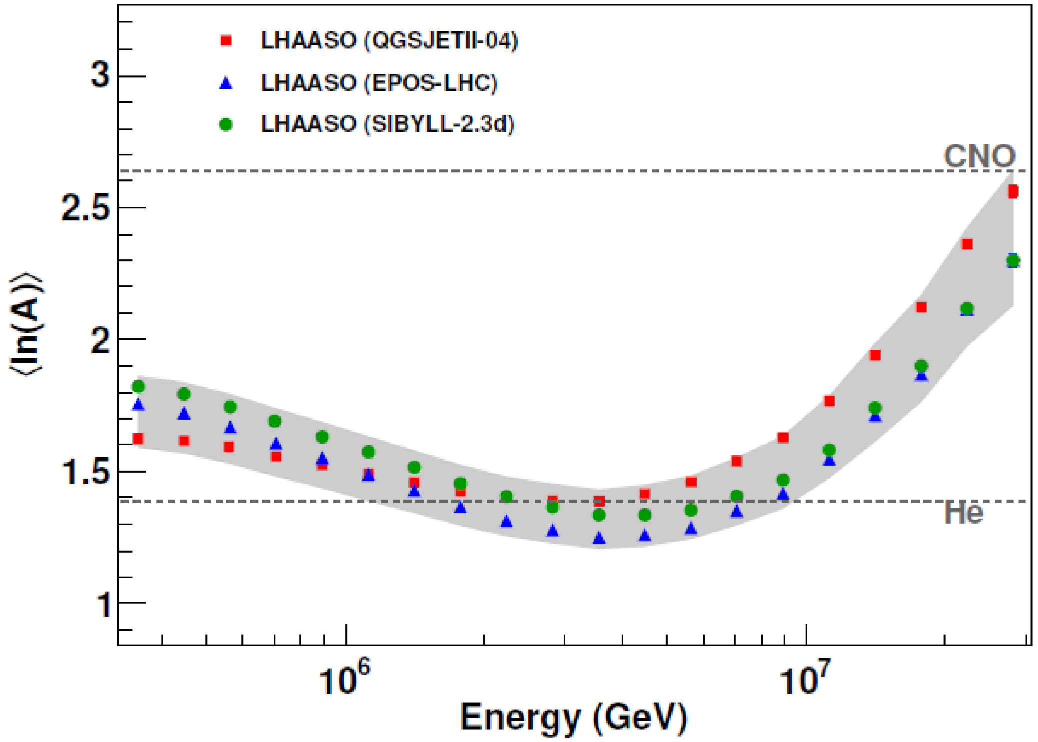




宇宙线平均对数质量

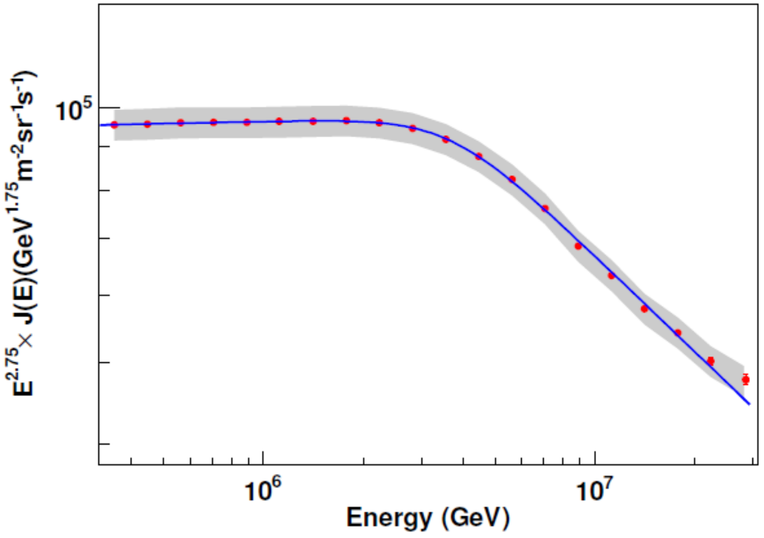


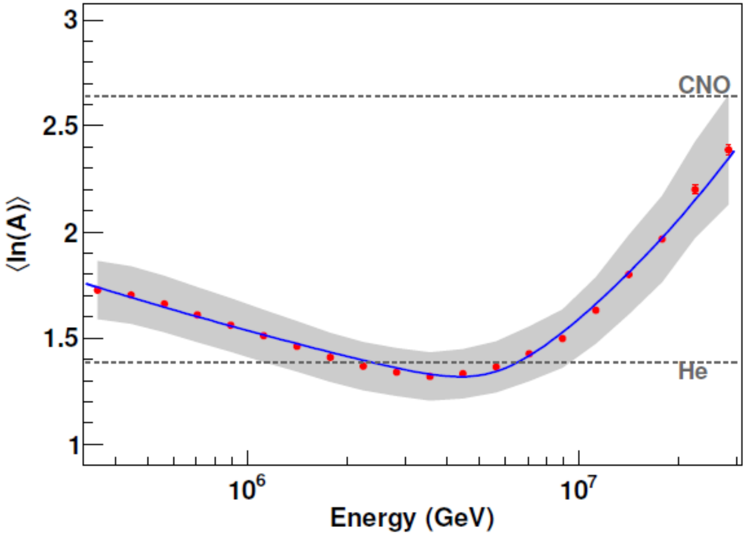
At 300 TeV, our measurements are consistent with the predictions of the Horandel or Gaisser models.



Shadow band:
air pressure, composition model, energy uncertainty, and the parameters x_0 and x_1 obtained by fitting the simulation data
systematic uncertainty ±9%

宇宙线全粒子能谱和平均对数质量





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

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

1. 宇宙线平均对数质量随能量变化，与全粒子能谱的行为相反；
2. 宇宙线平均对数质量在0.3 PeV和3 PeV之间下降了24%，在“膝”之后变重；
3. ⟨ln(A)⟩最接近于氦（ln(A)=1.39），比 CNO（ln(A)=2.64）轻，这表明全粒子能谱的“膝”是由轻成分引起的，而不是中重成分。

总结

- 新的组合变量$N_{e\mu}$，结合了电磁粒子和缪子信息，此能量重建方法对原初宇宙线成分的依赖性非常弱；
- 在0.3-30 PeV能量范围内测量了宇宙线平均对数质量，在“膝”区之后宇宙线成分变重；
- 全粒子能谱的“膝”是轻成分的“膝”，而不是中重成分的“膝”。
- 宇宙线平均对数质量的结果，首次发现了一个类似“肘”的结构特征，与全粒子能谱的行为相反。

谢谢