The preliminary result of mean logarithmic mass of cosmic rays in the knee region with LHAASO-KM2A

Cunfeng Feng[1*], Hengying Zhang[2], Huihai He[2] **for the LHAASO collaboration**

1, Shandong University (* speaker, fengcf@sdu.edu.cn)

2, Institute of High Energy Physics, Chinese Academy of Sciences

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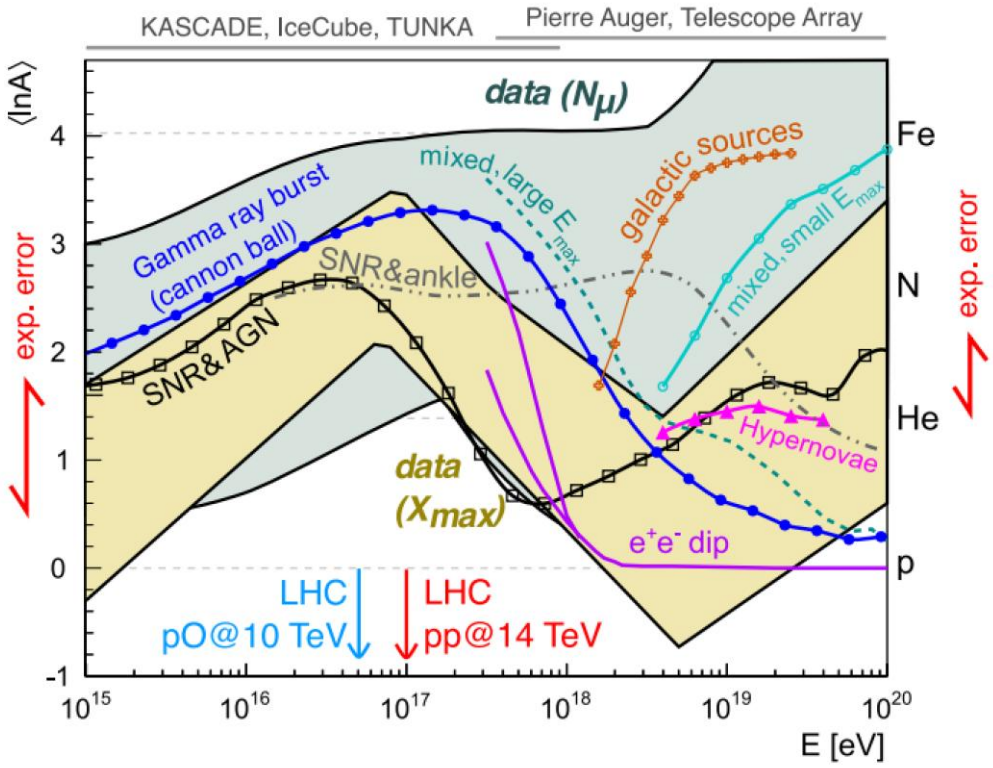
Outline

- Introduction
- LHAASO-KM2A and muon measurement
- Energy reconstruction independent on composition
- Mean logarithmic mass <lnA>
- Summary

Introduction

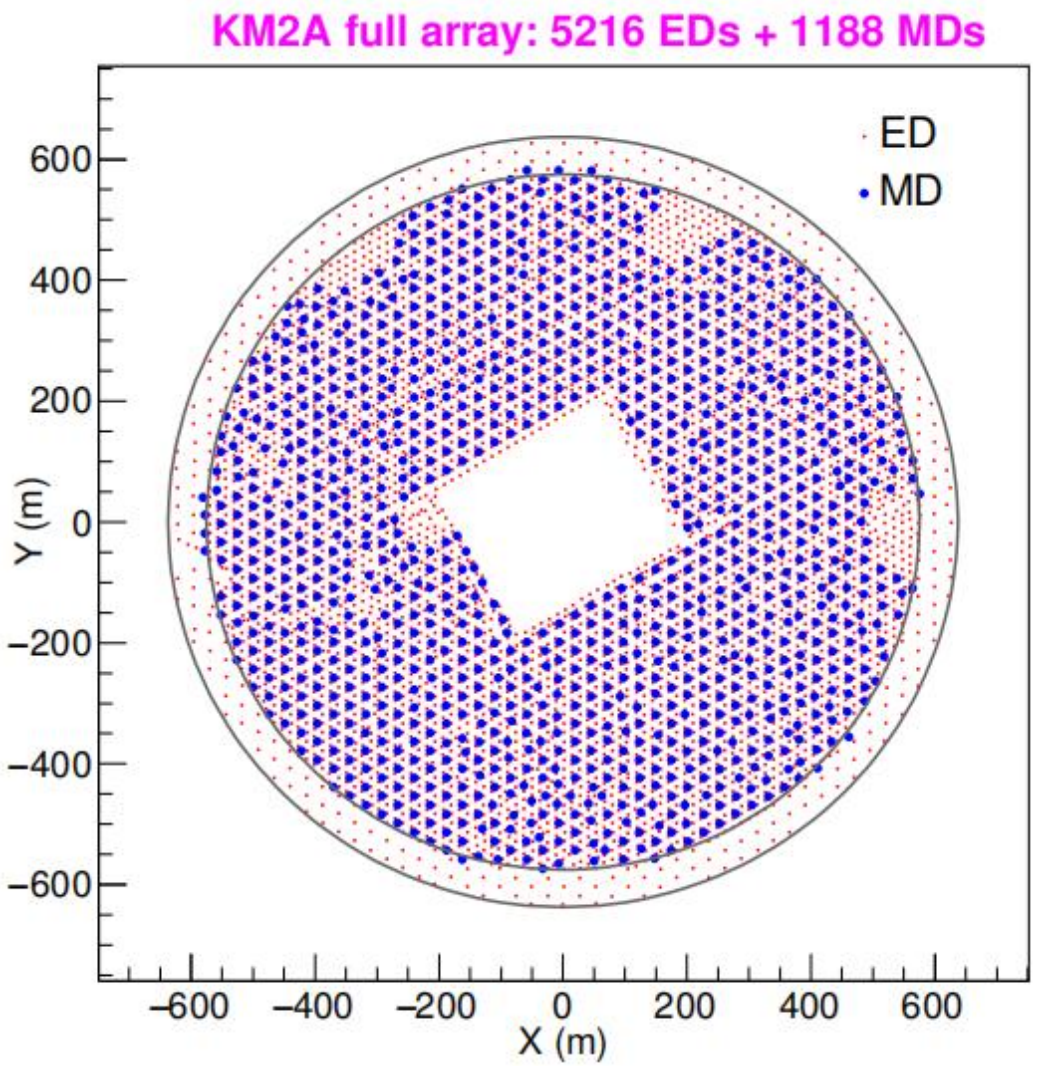
The energy-dependent mass composition of cosmic rays carries a unique imprint from the origin and propagation of cosmic rays.

- It's a challenge to infer accurately the CR mass in knee region via EAS experiment.
- Two leading observables to infer <lnA>:
  - X_{max}: the atmospheric depth where air shower reach maximum
  - N_{μ}: the number of muons produced in the shower
  - Uncertainties main contribution:
    - Experiment
    - Simulation with hadronic interaction models



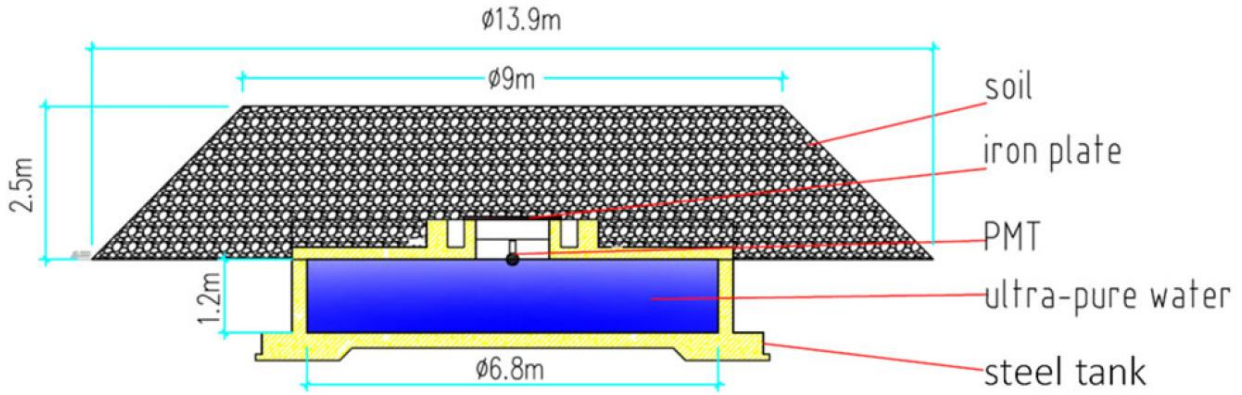
Mass composition of cosmic rays quantized by $\langle \ln A \rangle$ as a function of cosmic-ray energy
H.P. Dembinski et al. EPJ Web Conf., 210:02004, 2019
The curves represent predictions by models about the origin of cosmic rays

LHAASO-KM2A



The layout of the KM2A full array.

- Atmosphere depth X_0 = 600 g/cm^2
  - the air shower maximum depth of cosmic rays in the knee
- 5,216 ED (electromagnetic particle detectors) with **15 m spacing**
  - scintillator detector, area 1 m^2
  - sampling ratio: 0.44%
- 1,188 MD (muon detectors) with **30 m spacing**
  - buried water Cherenkov detector, threshold: 1 GeV
  - sensitive area 36 m^2, sampling ratio: **4%**



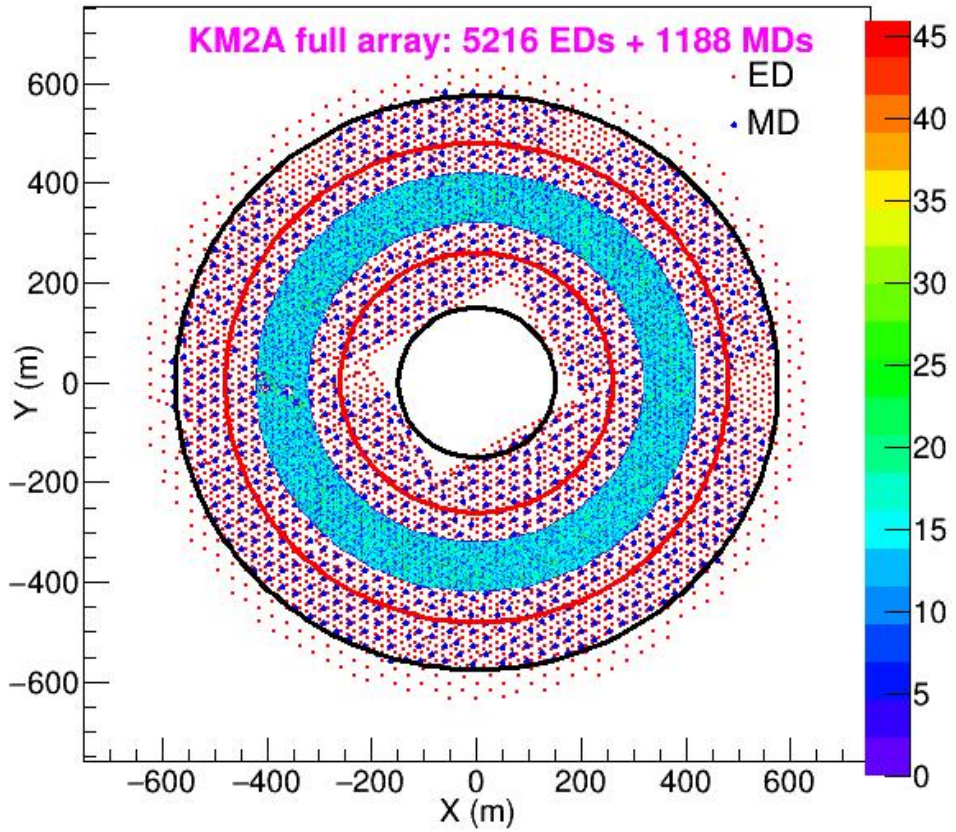
MD layout

Simulation and data

QGSJETII-04_fluka / EPOS-LHC_fluka
Proton He CNO MgAlSi Fe,
Theta:0-40°
Slope: -2
Radius : 260-480m

	10TeV – 100TeV	100TeV – 1PeV	1PeV-10PeV	10PeV-50PeV
Proton	1×10^7	1×10^6	1×10^5	1×10^4
He	1×10^7	1×10^6	1×10^5	1×10^4
CNO	1×10^7	1×10^6	1×10^5	1×10^4
MgAlSi	1×10^7	1×10^6	1×10^5	1×10^4
Fe	1×10^7	1×10^6	1×10^5	1×10^4

core position of reconstruction data

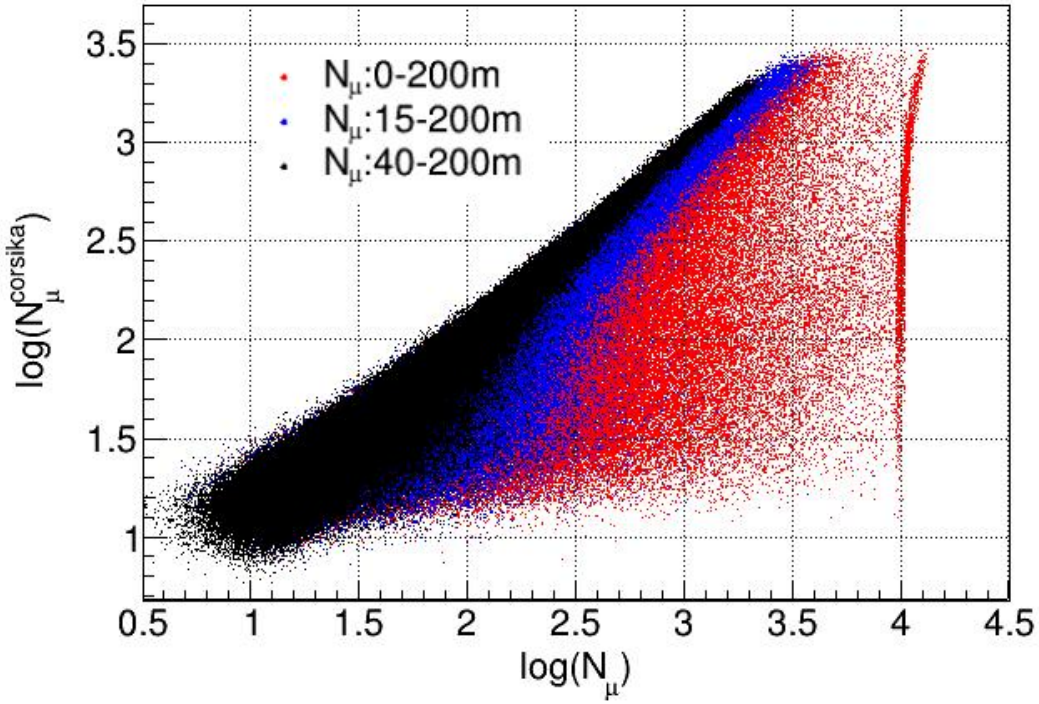


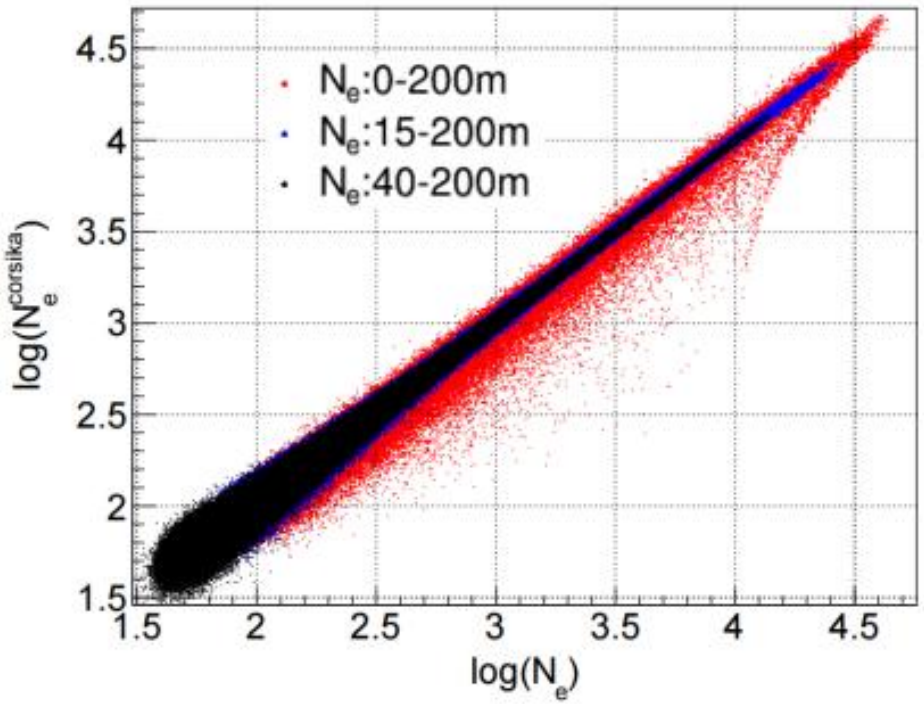
Event cut:

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

Experimental data: 2021.09-2022.12

Muons and electromagnetic particles measurement（ N_e and N_μ ）





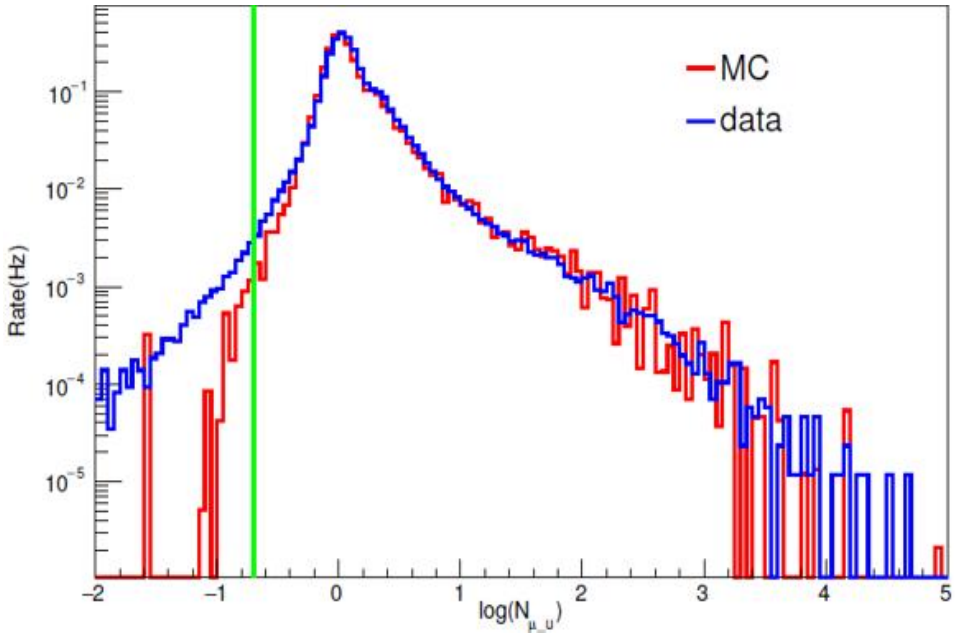
The muons number within 40-200 m can represent the truth muons number within wide energy range.

N_μ: sum the number of muons within radius 40-200 m from shower axis.

The number of electromagnetic particle within the ring 40-200 m is proportional to the truth

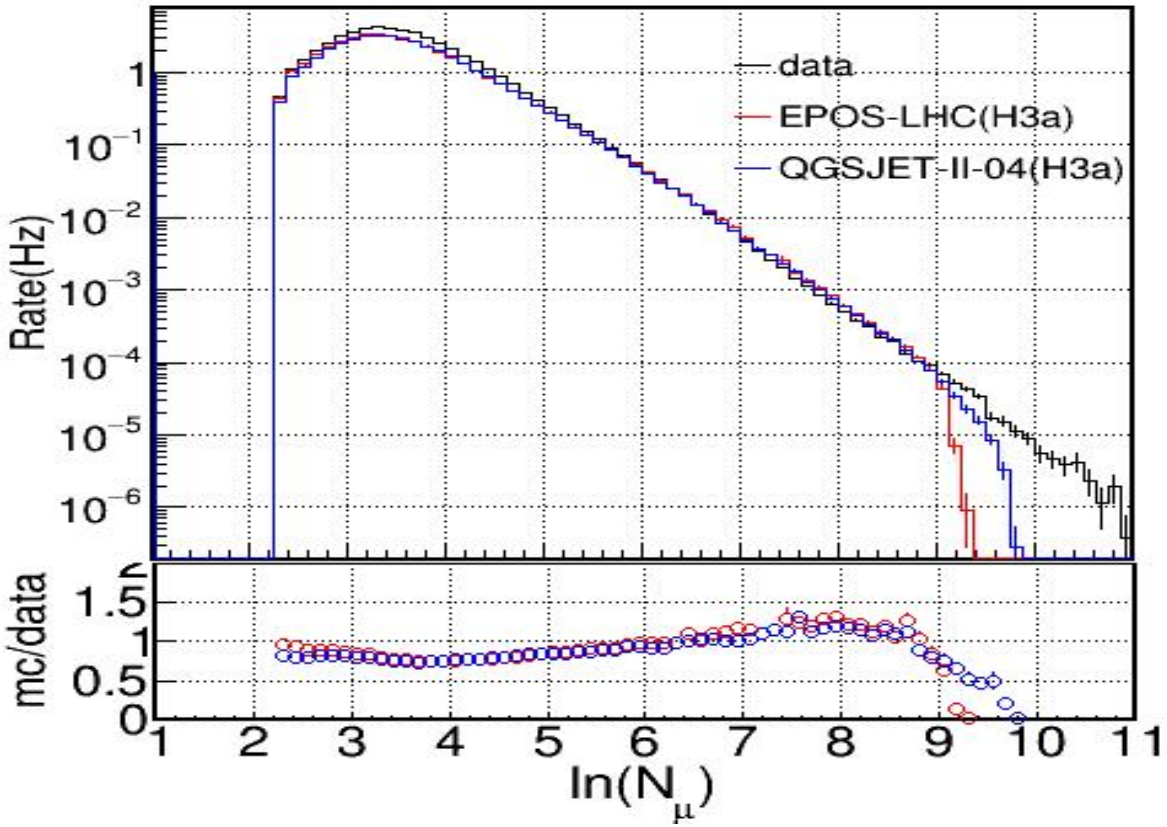
N_e ： sum the electromagnetic particle within radius 40-200 m from the shower axis.

Muon measurement validation



The muon number distribution in one MD together with the simulation results.

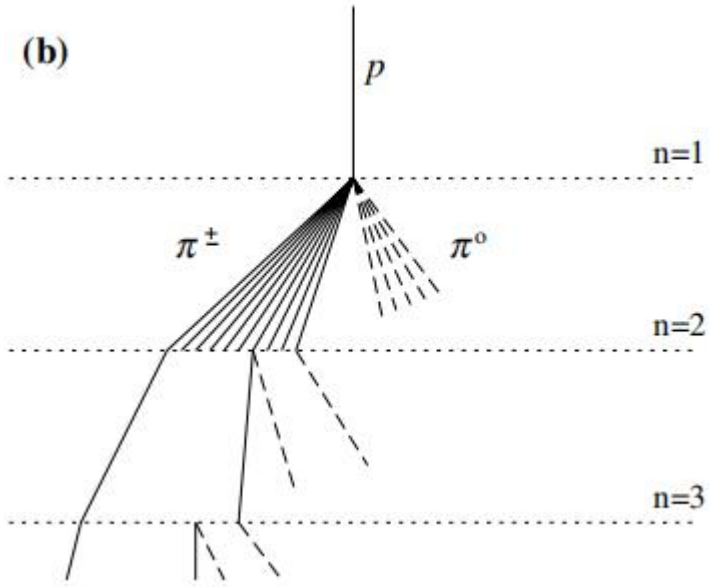
The MC results agree well with measurement above 0.2 muon.
LHAASO exclude the MD less than 0.2 muon in reconstruction.



N_μ spectrum of the air shower. Data compare with simulation of EPOS-LHC and QGSJET-II-04.

The H3a spectrum of Gaisser is used for the simulation.

Principle of Energy Reconstruction



LHAASO-KM2A: measure the N_e and N_μ of the shower simultaneously.

N_e and N_μ different from Mattews model defination. sampling ratio for ED 0.5% and MD 4.5%

We propose one new complex variable:

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

J. Matthews extend Heitler EM splitting model to hadronic interaction.

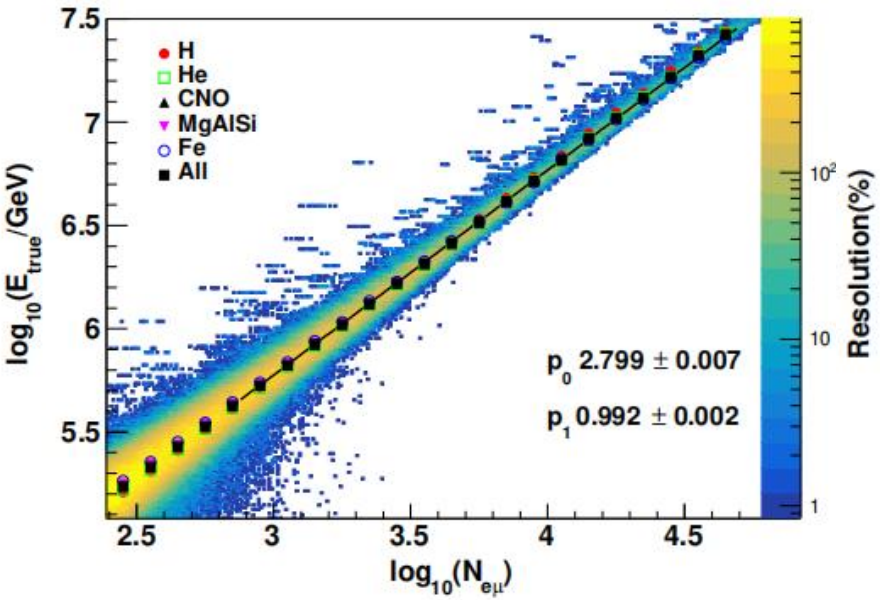
$$E_0 = E_{em} + E_h$$

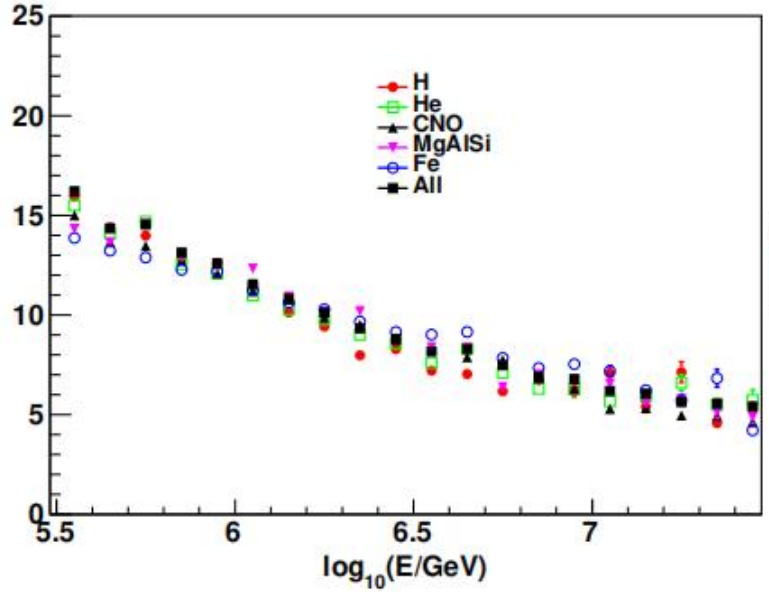
$$\boldsymbol{E_0 \approx 0.85GeV\left(N_e + 25N_\mu\right)}$$

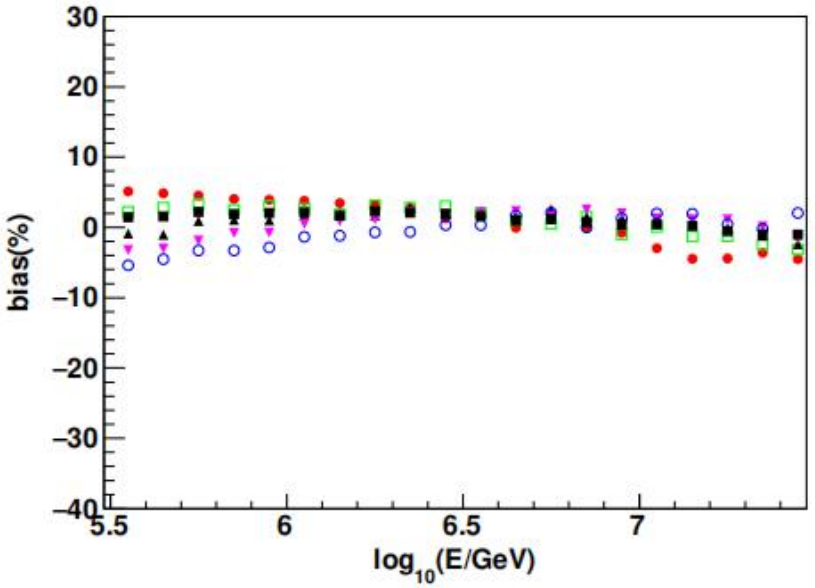
J. Matthews Astroparticle Physics 22 (2005) 387–397

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

Energy reconstruction independent on primary cosmic ray components







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

The relation between the energy and the complex variable $N_{e\mu}$.

The relation for all components is same

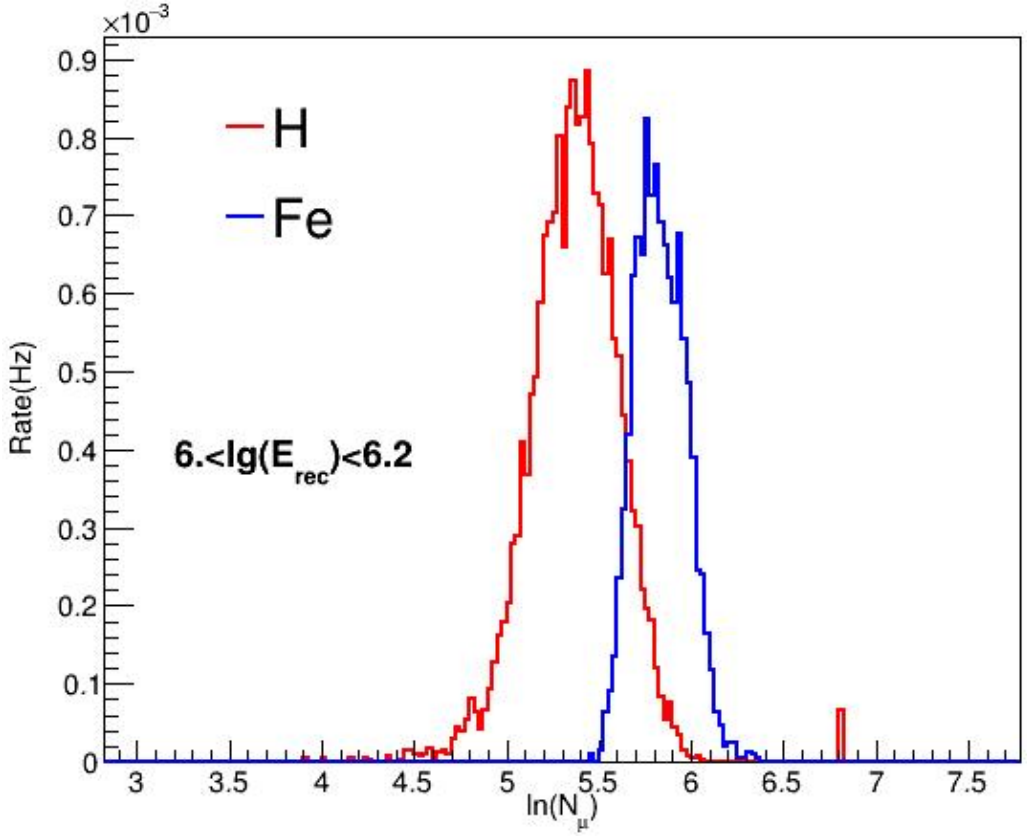
Energy reconstruct with $N_{e\mu}$ is indenpadent on components.

For eaxmple, @ 1 PeV
Energy resolution < 12%
The maxium bias for different composents < 5%

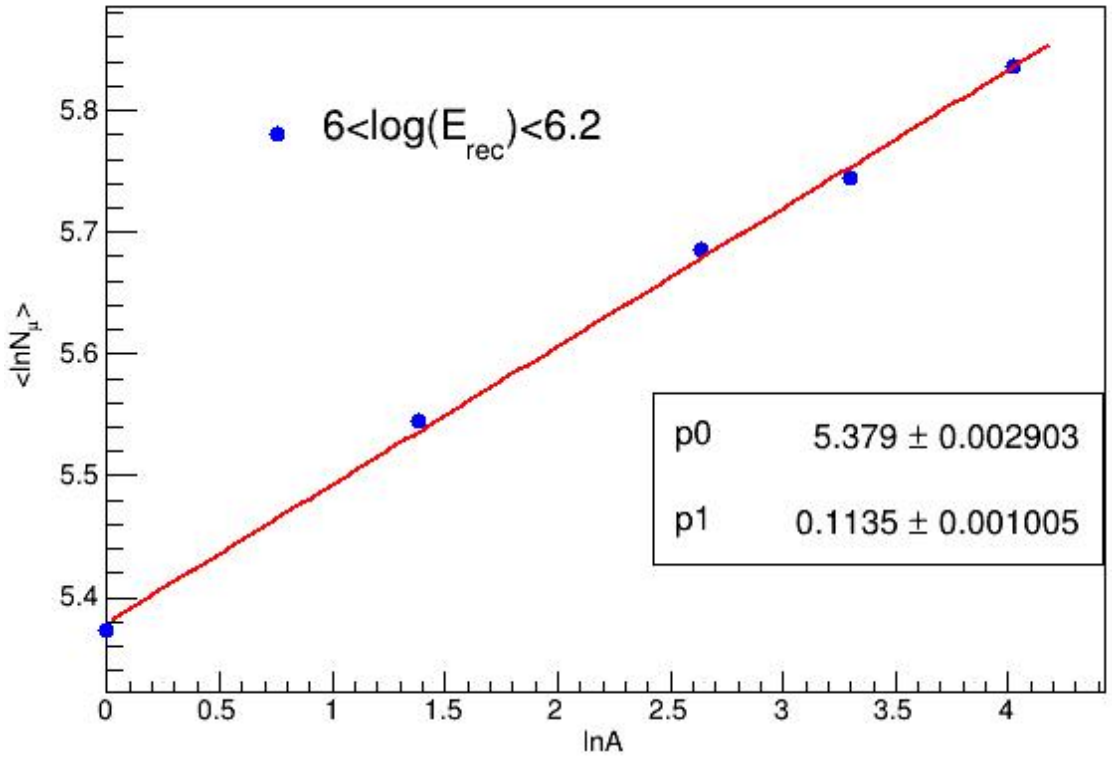
Energy reconstruction with $N_{e\mu}$
better resolution, less bias between components

Mean mass estimation

muon number depends on cosmic ray energy and mass A: $N_\mu = A\left(\frac{E/A}{\varepsilon_c}\right)^\beta$



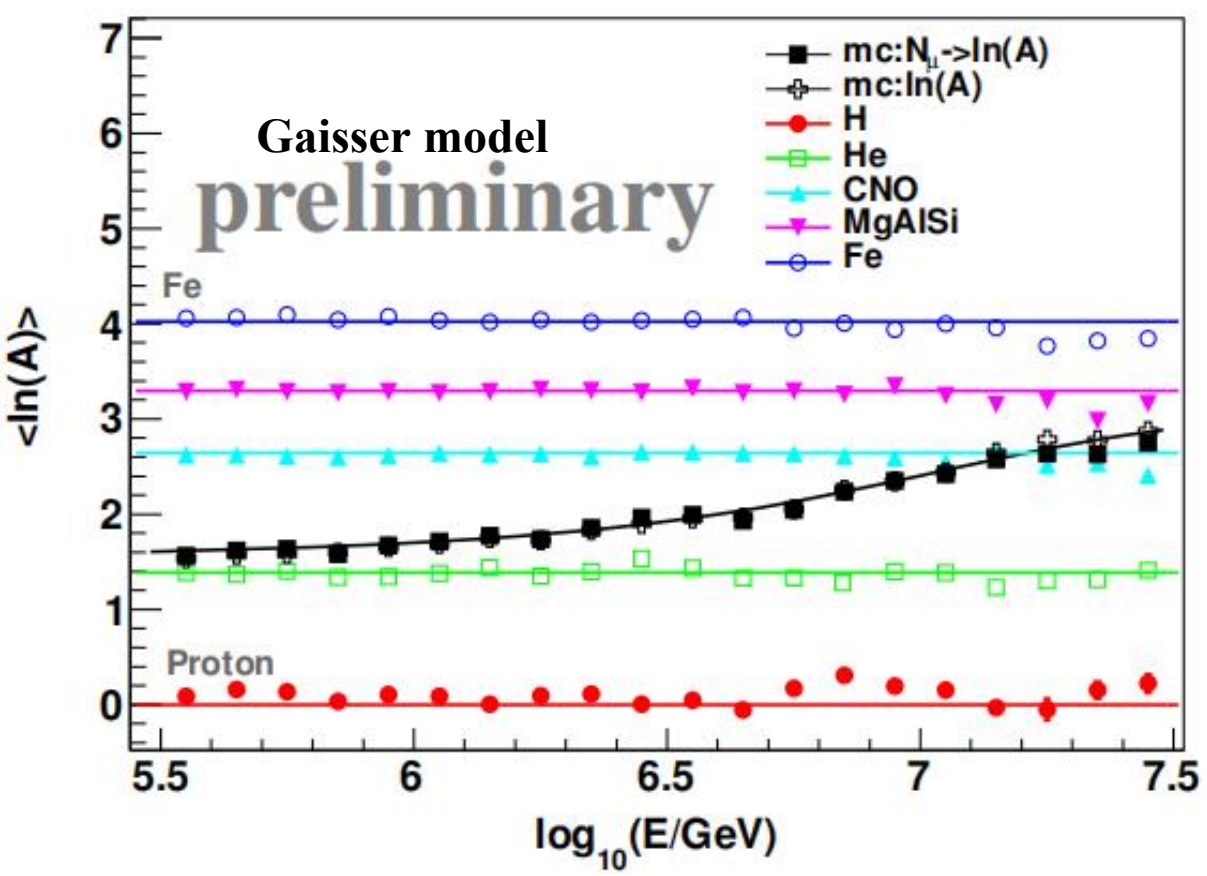
Number of muons distribution for proton (red) and iron (blue) within one energy slot.

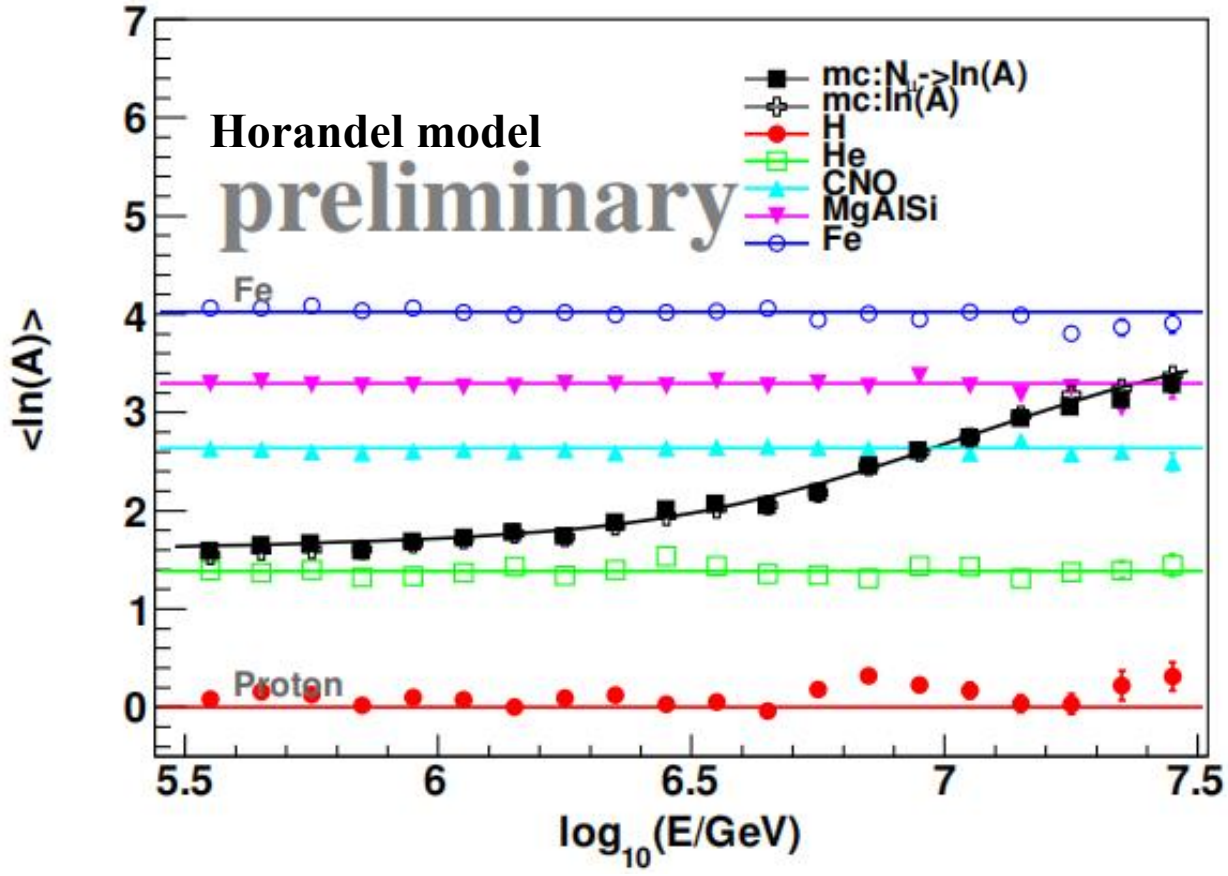


$\langle \ln N_\mu \rangle \rightarrow \langle \ln A \rangle$

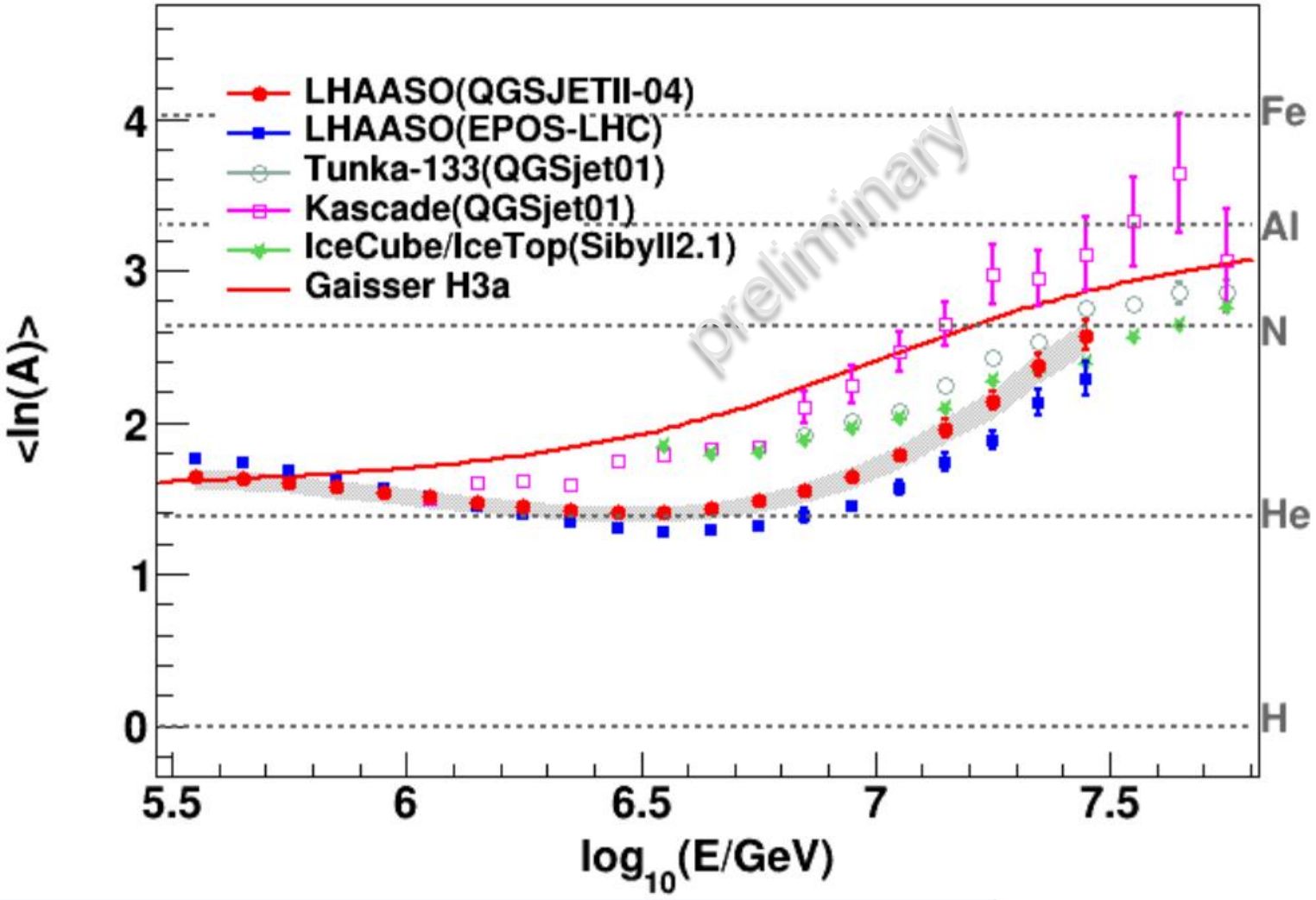
Check the derived mean mass method with assumption energy spectrum model

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





Mean logarithmic mass ⟨ln A⟩ of cosmic rays



The mean logarithmic mass distribution as the cosmic ray energy.

- ✓ Energy reconstruction with $N_{e\mu}$.
- ✓ **cosmic ray component becomes heavier above the knee.**

The all-particle energy spectrum knee is the knee of light components, instead of the medium-heavy components.

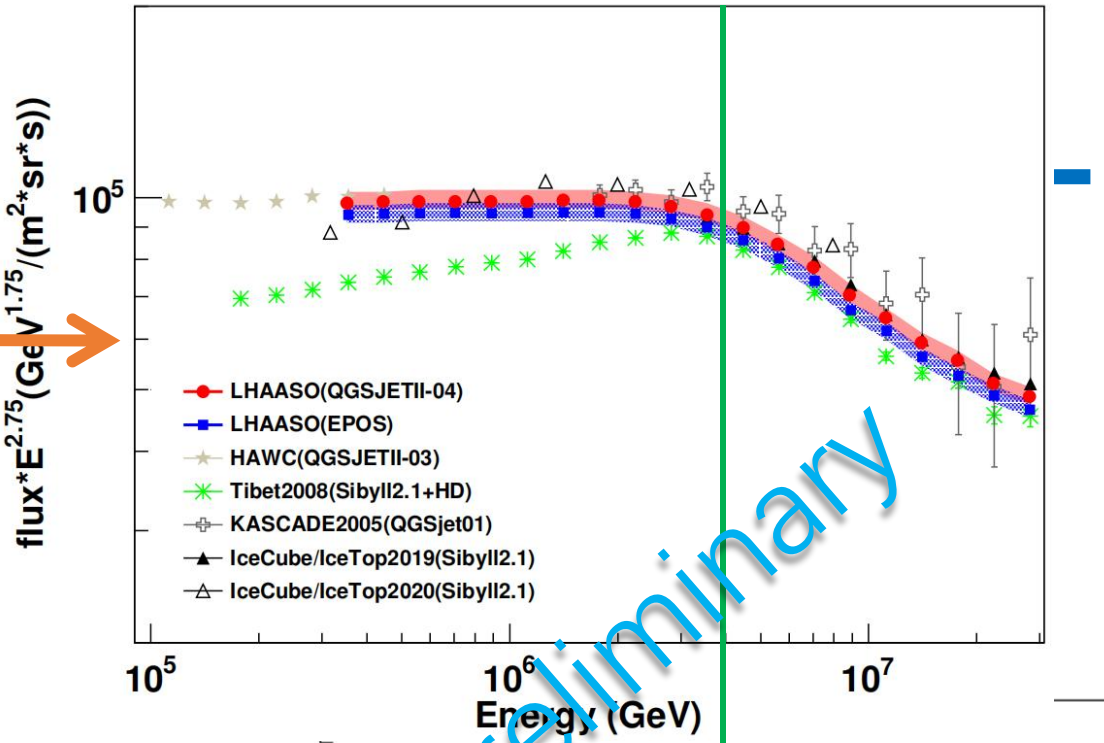
Correlation with the all particle spectrum

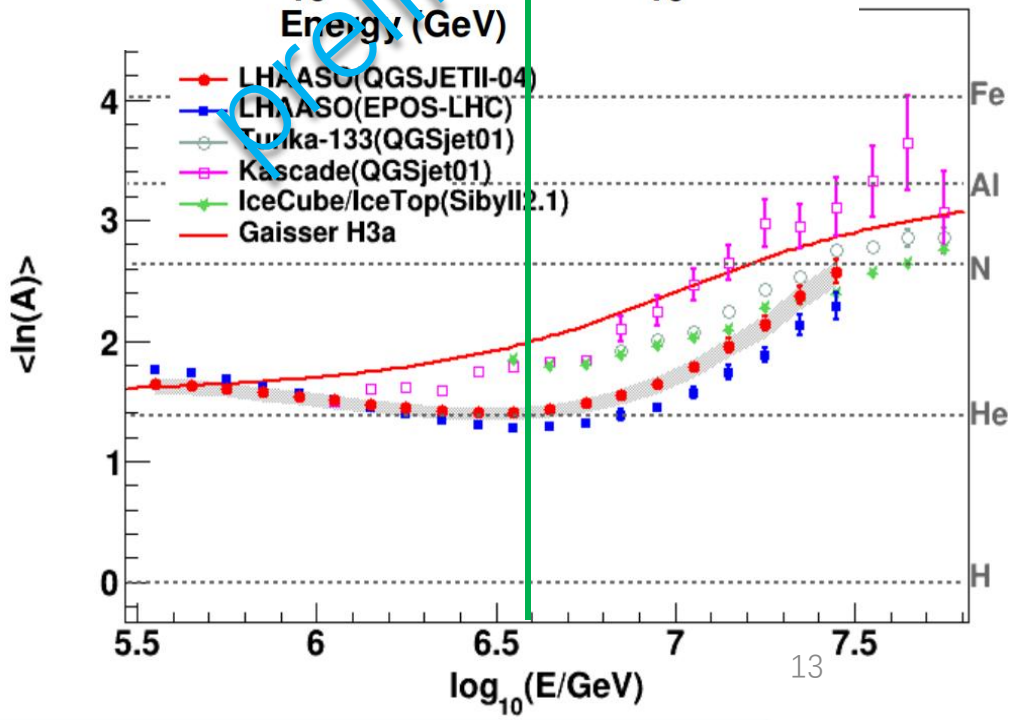
Preliminary all particle spectrum of LHAASO reported in ICRC 2023.

The energy spectrum turned above 3 PeV was found

The mean logirithematic mass also start to heavier above 3 PeV.

The energy spectrum almost flat before 3 PeV, but mean mass is decreasing, probable the spectrm of light component still harder.





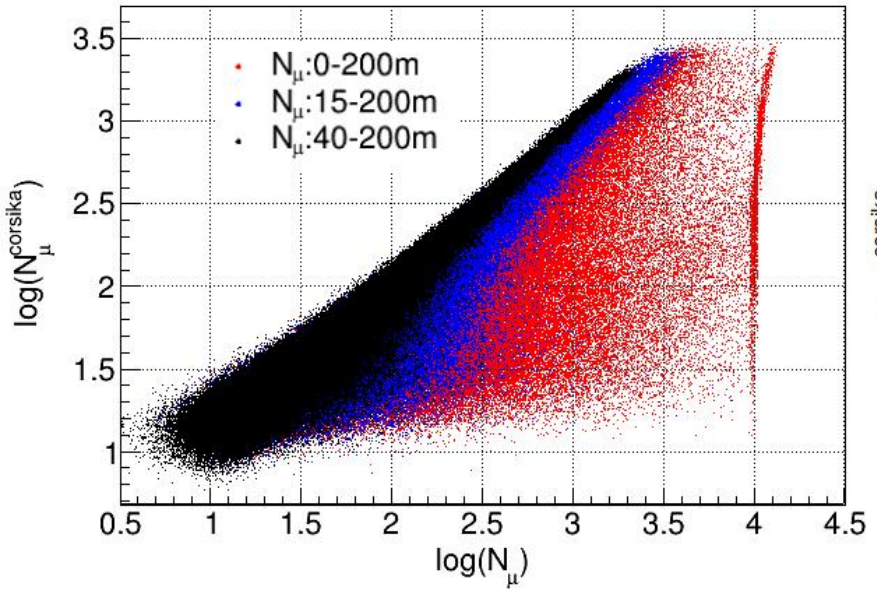
Summary

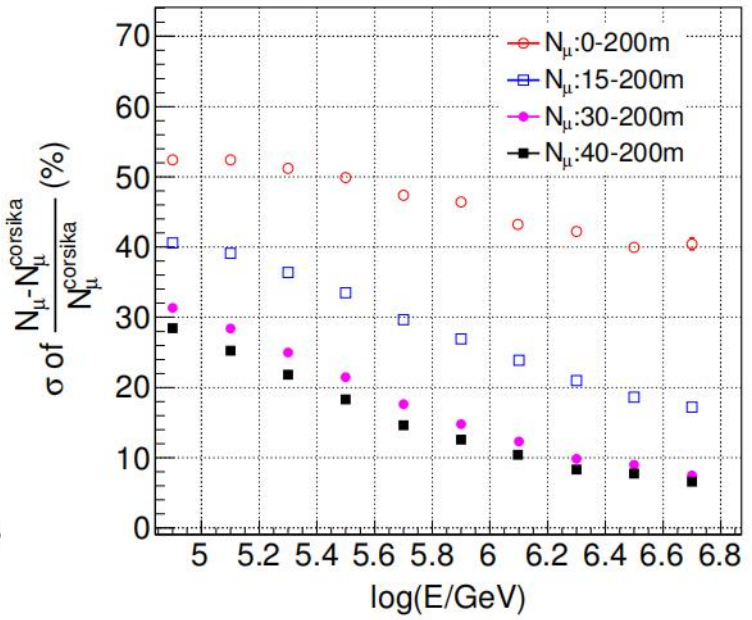
- With the composite variable $\boldsymbol{N_{e\mu}}$, energy reconstruction is independent on the composition of cosmic ray;
- The mean logarithmic mass in the energy range 0.3 -30 PeV is measured for the first time. Around “knee” region, the cosmic ray component becomes heavier.
- The all-particle energy spectrum knee is the knee of light components, instead of the medium-heavy components.

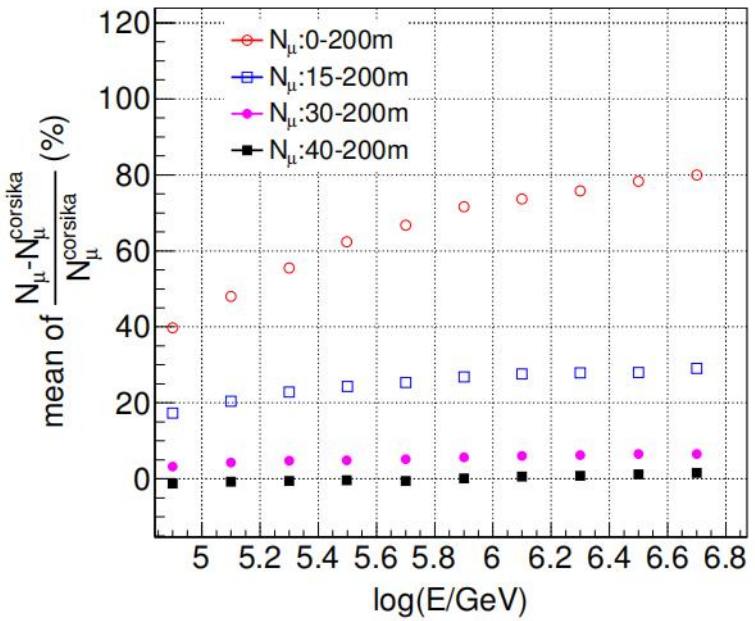
Thanks for your attention!

BACKUP

Muons and electromagnetic particles measurement（ N_e and N_μ ）







Simulation

$N_\mu^{corsika}$: the total muons number in CORSIKA within 200 m radius, scaled with the MD sampling

N_μ : measured muons number, the total mouns number by counting over all the MDs within 200 m radius

Without counting the MDs in radius 40 m from the shower axis, the resolution is the best and the bias is almost zero.