Very-High Energy Cosmic Ray All-particle Spectrum and Air Shower Studies with LHAASO

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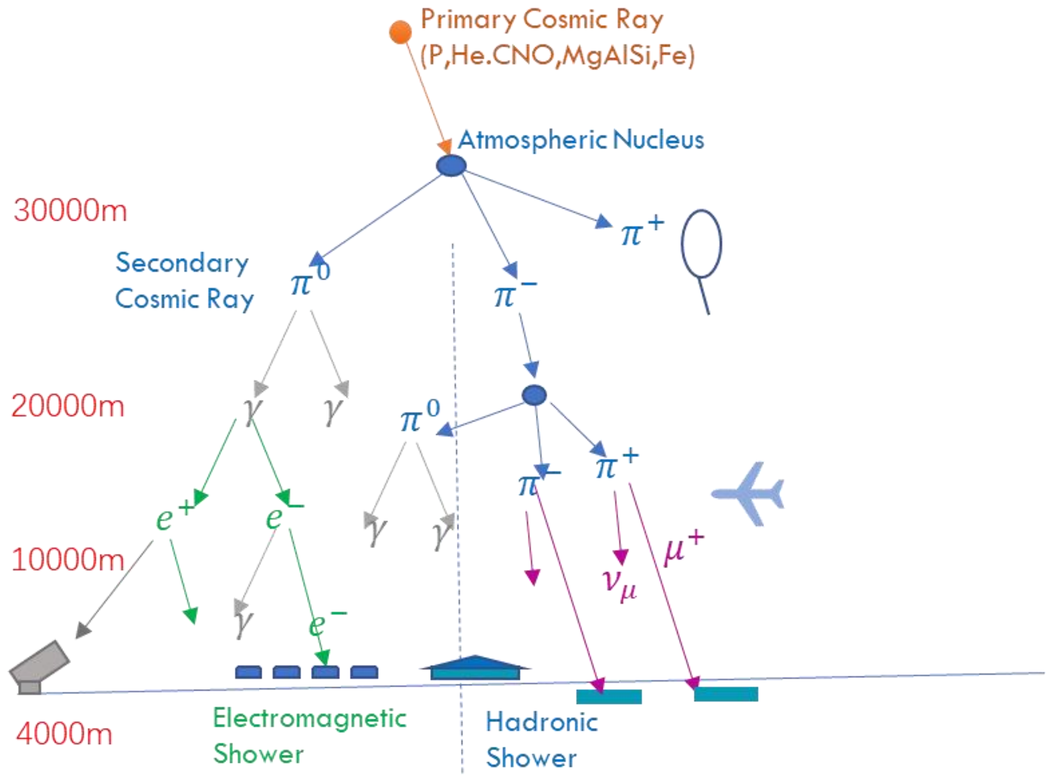
Outline

- Introduction of air shower and LHAASO
- Composite energy estimators independent of CR composition
- All-particle energy spectrum
- Muon content of the air shower and mean logarithmic mass
- Fluctuation of the muon content and variance of the mass
- Attenuation length of the muon content
- Summary

Introduction

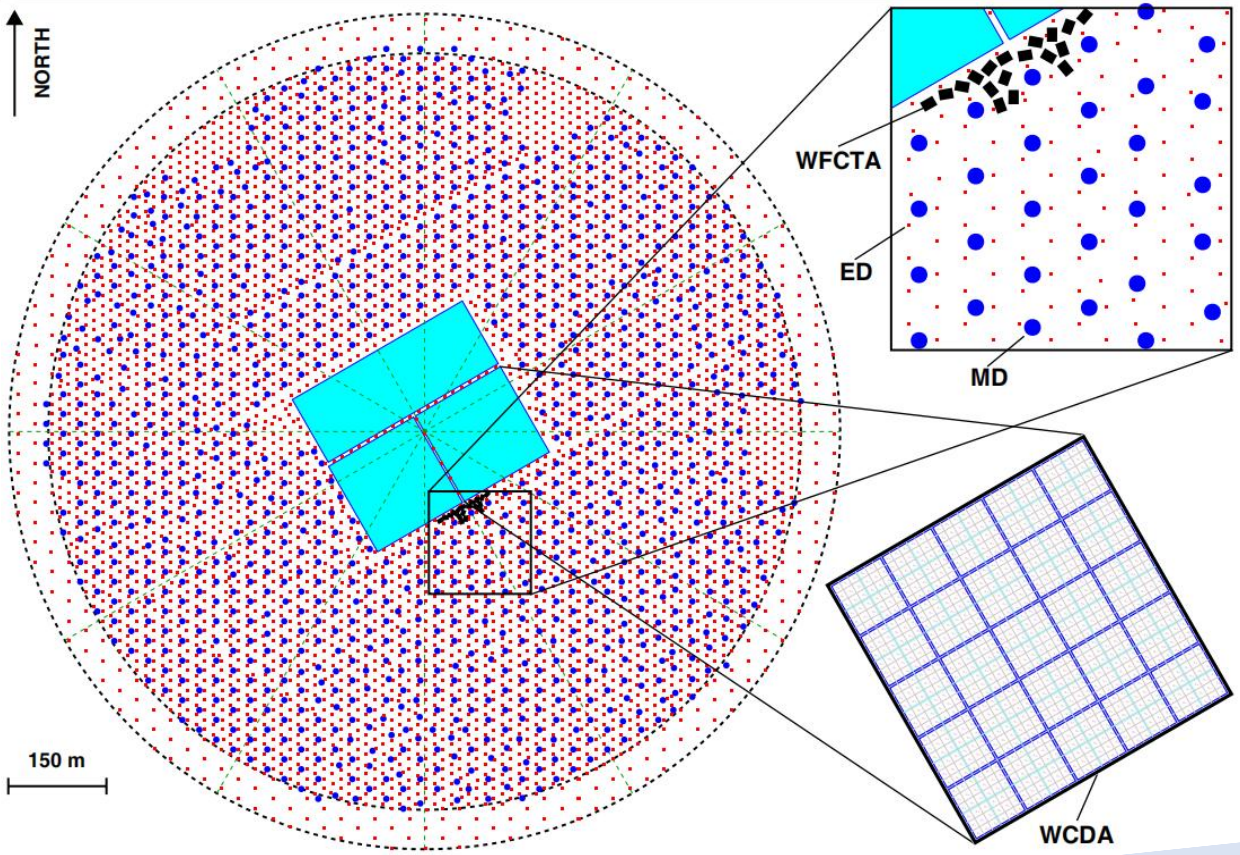
- **Air shower important for very-high energy CR**
  - test the hadronic interaction
  - identify the CR component
  - estimate the CR primary energy

- **LHAASO: ideal experiment for very-high energy air shower study**



LHAASO experiment

- Altitude: 4410 m a.s.l.
  - depth: 600g/cm^2
  - shower maximum for VHE CR
- KM2A:
  - cover 1 km^2 with 1188 MD and 5216 ED.
  - ED: 1 m^2, sampling ratio: 0.4%
  - MD: 36 m^2, sampling ratio:4%
- WFCTA
  - Air Cherenkov light
- WCDA: water Cherenkov detector array
  - full cover, unit size: 5m*5m

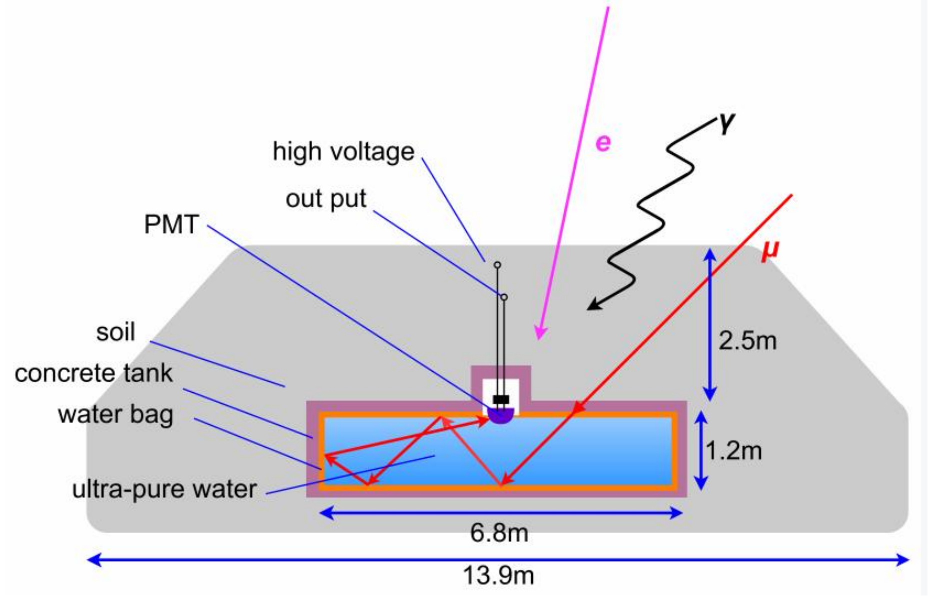


Layout of LHAASO

Has been full operational since August 2021 !

Air Shower reconstruction

- Muon content N_{μ}:
  - counting muon within 40-200 m from the air shower axis
    - Reduce the punch-through effect
    - Reduce the fluctuation
- Number of electromagnetic particles N_e:
  - Counting particles of the fired EDs within 40-200 m from the shower axis



Schematic of the LHAASO muon detector

Composite shower energy estimator

--independent of CR mass

combine **muon content and electromagnetic particles** of the shower

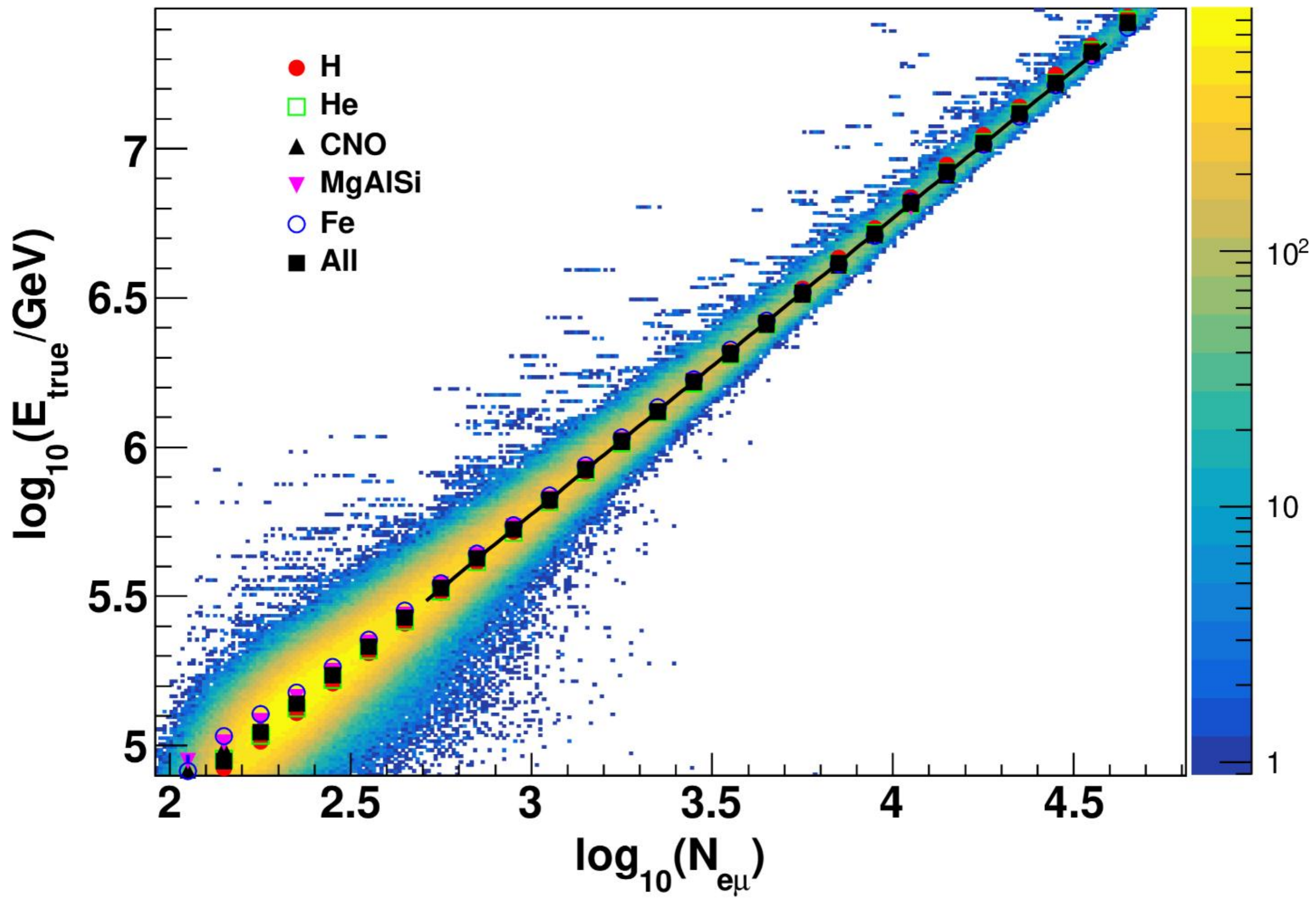
$$N_{e\mu} = N_e + 2.8N_\mu$$

Keep similar relation with shower energy for various CR component.

Independent of CR composition

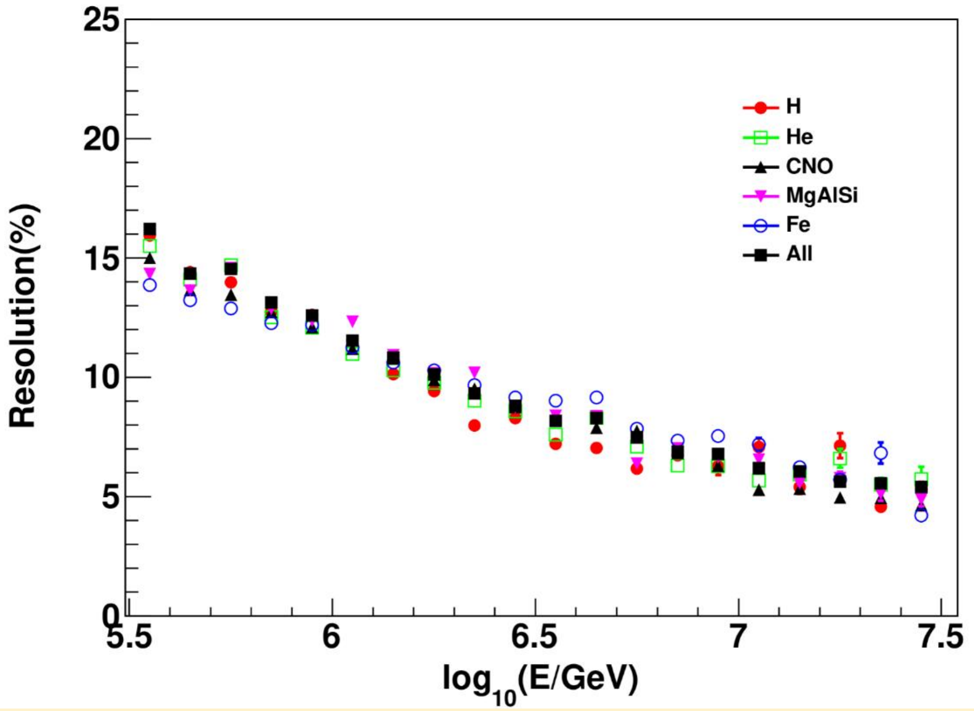
Shower energy reconstruct

$$E_{rec} = p_0 + p_1 \cdot N_{e\mu}$$



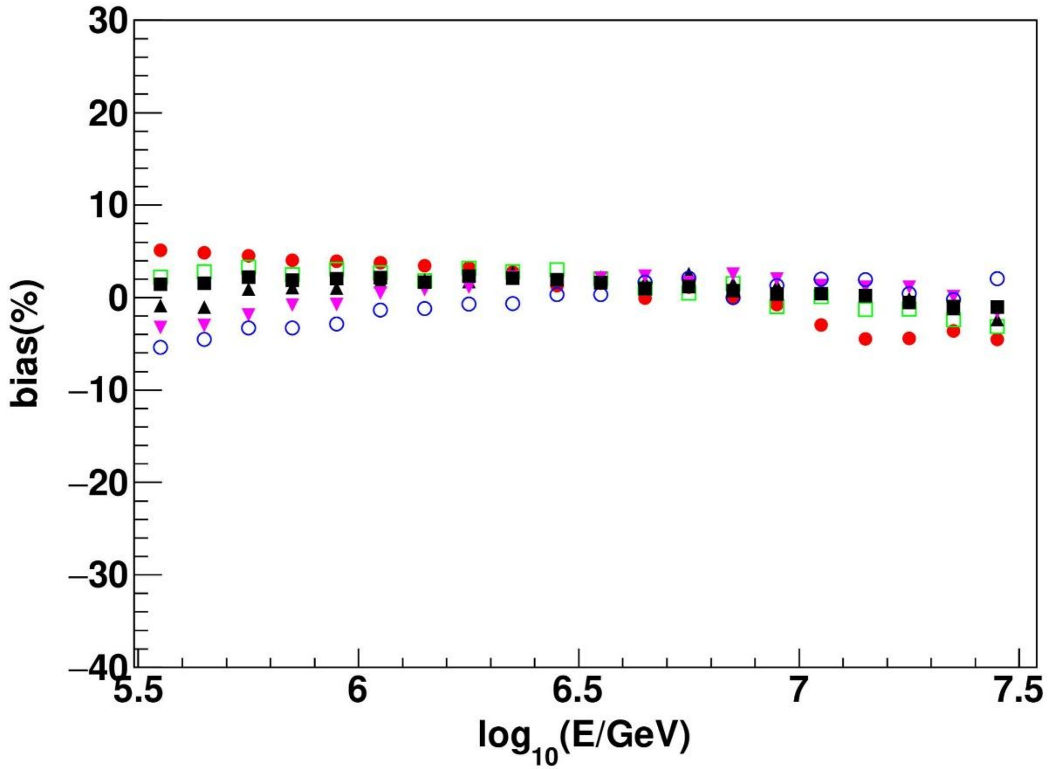
Composite shower energy estimator

--independent of CR mass



The energy resolution is better than 15% above 300 TeV, better than 10% above 1 PeV.

"All": composite CR according the Gaisser H3a



The bias is less than 6% for various component

Applied in LHAASO all-particles spectrum.

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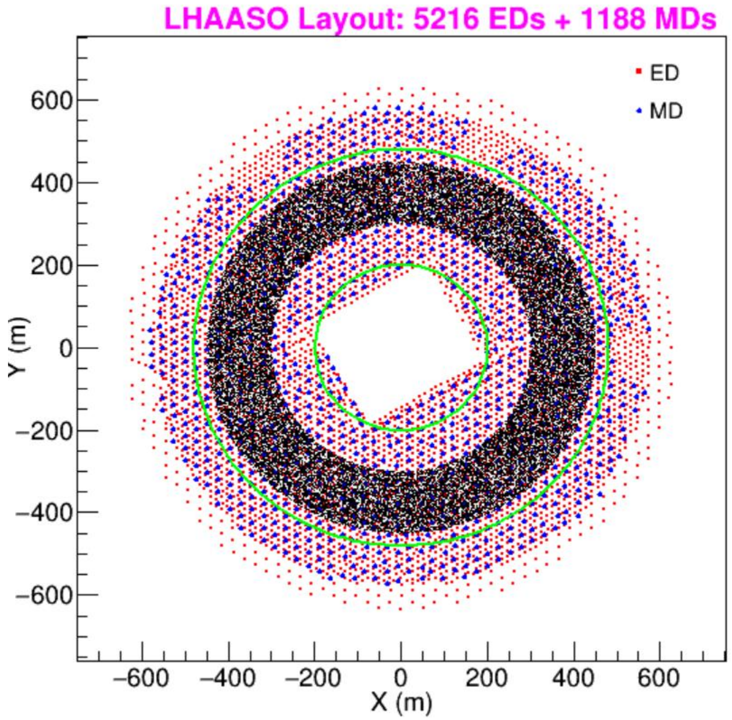
All-particle energy spectrum measurement

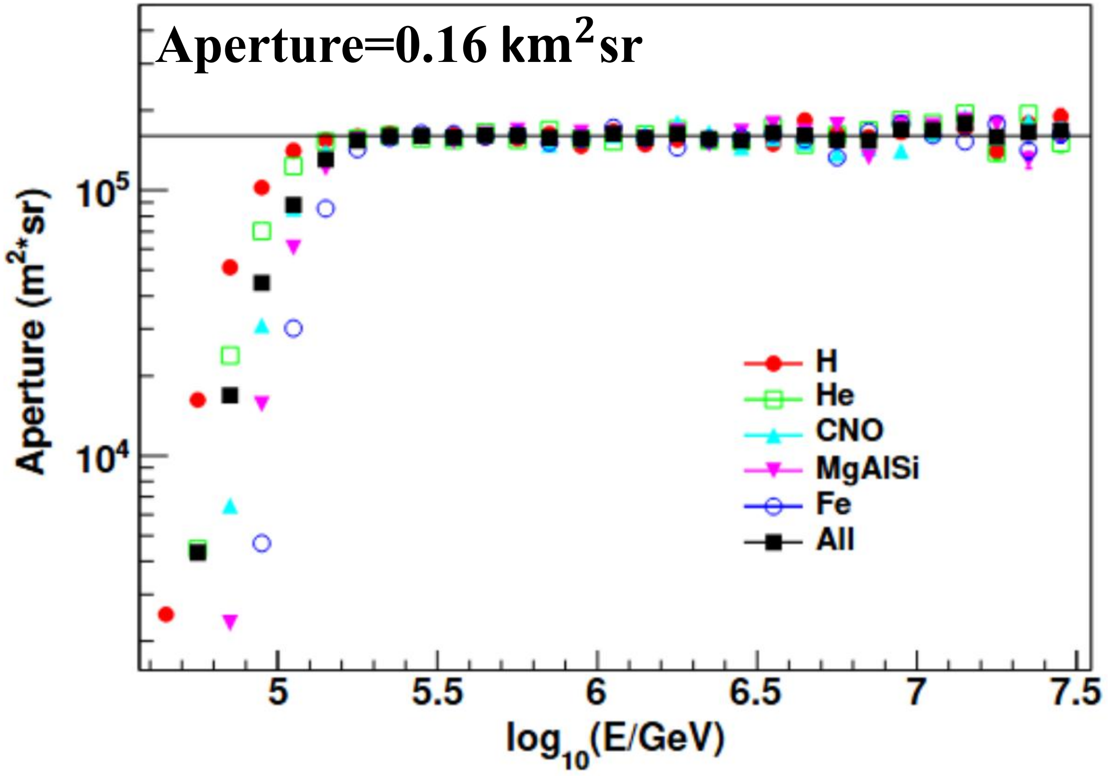
Event Selection:

θ: 10-30° (X_{max}: 610-690 g/cm^2)

R: 320-420m

Ne: >100





The effective aperture is estimated with the MC data.

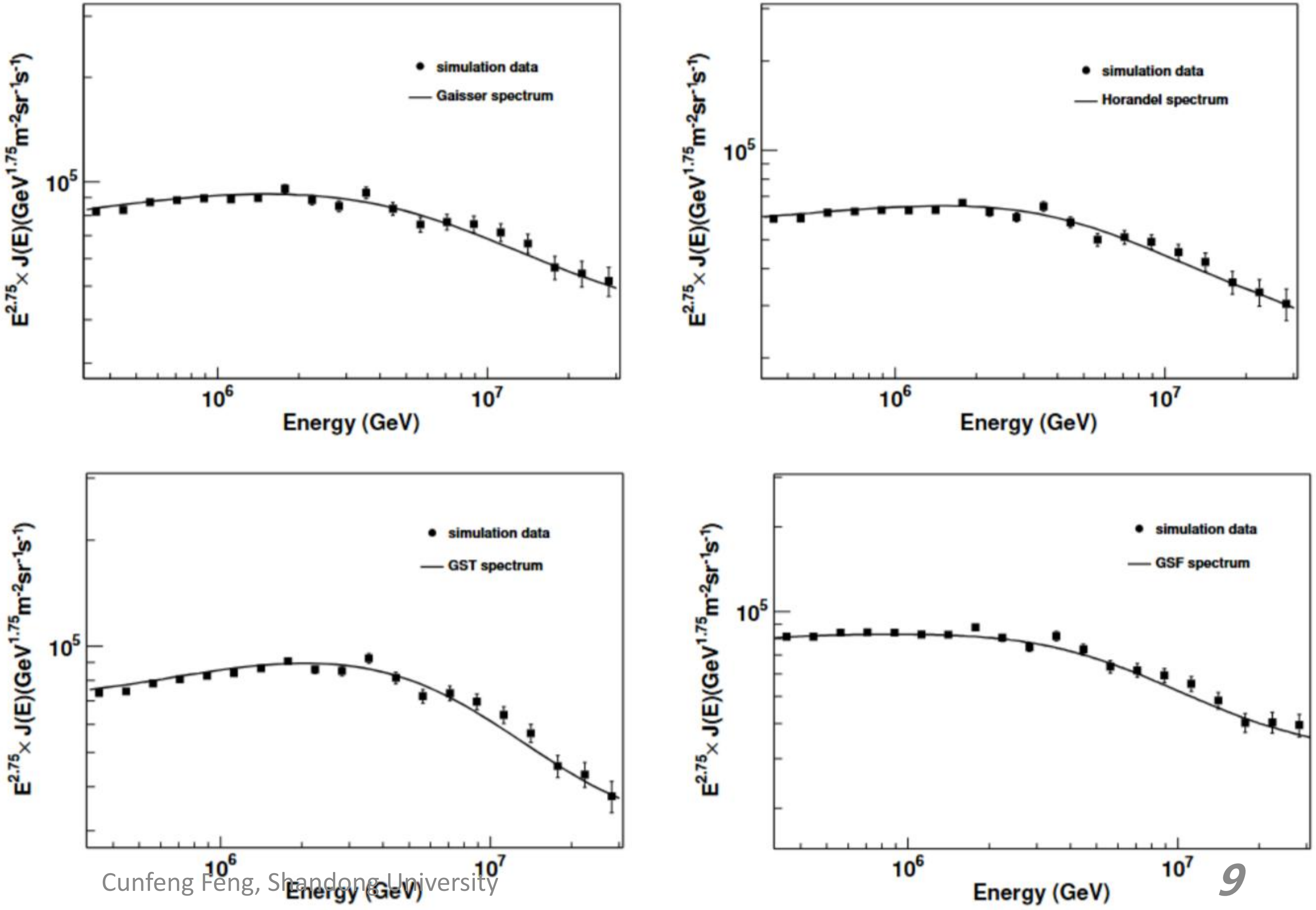
The effective aperture is constant above 0.3 PeV.

Energy spectrum reconstruction closure test

Four composition models used
- Gaisser model
- Horandel model
- GST model
- GSF model

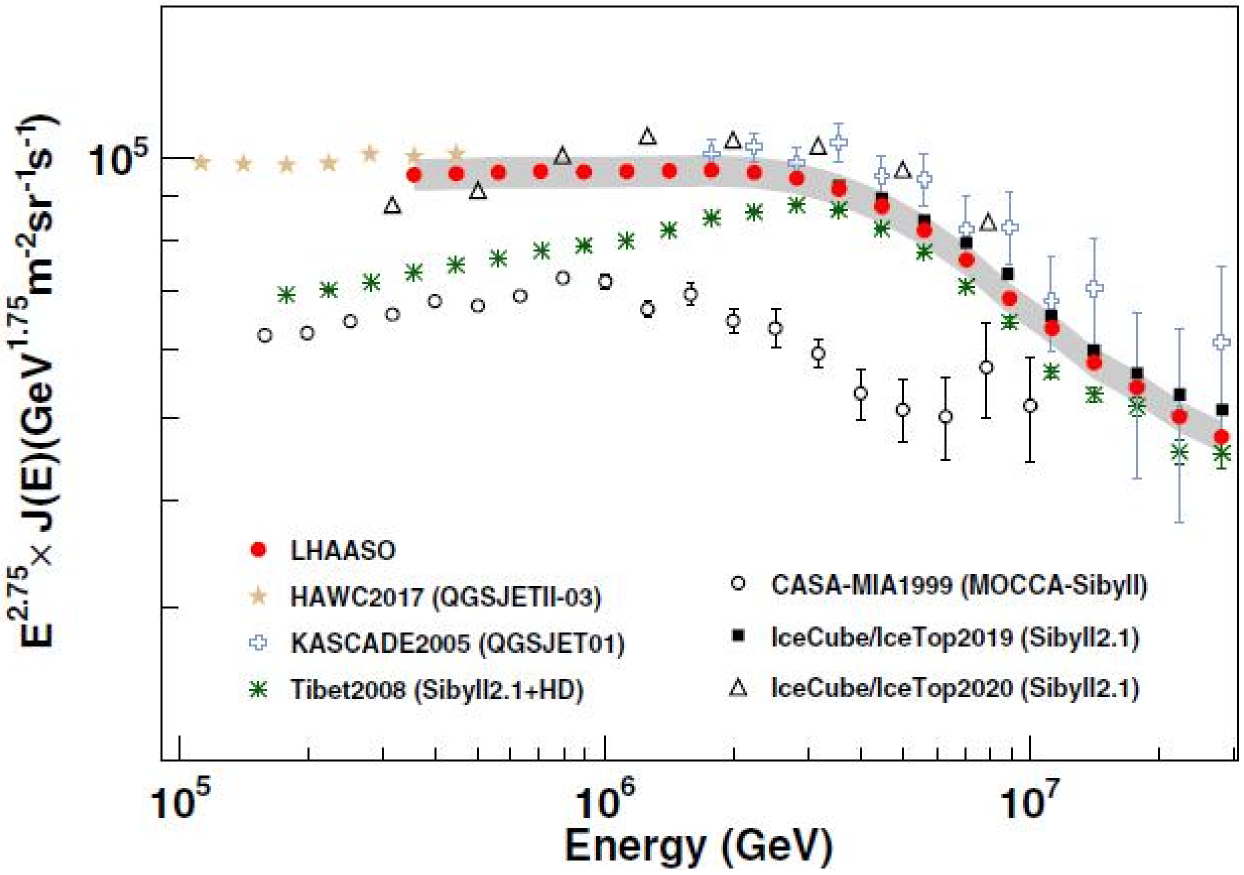
Closure test:
- ➢ Curves: truth of the models
- ➢ Marks: reconstructed with above energy estimator

Reconstructed match well with truth



All-particle energy spectrum of LHAASO

$$J(E) = \frac{\Delta N(E)}{\Delta E \cdot A_{\text{eff}} \cdot T}$$



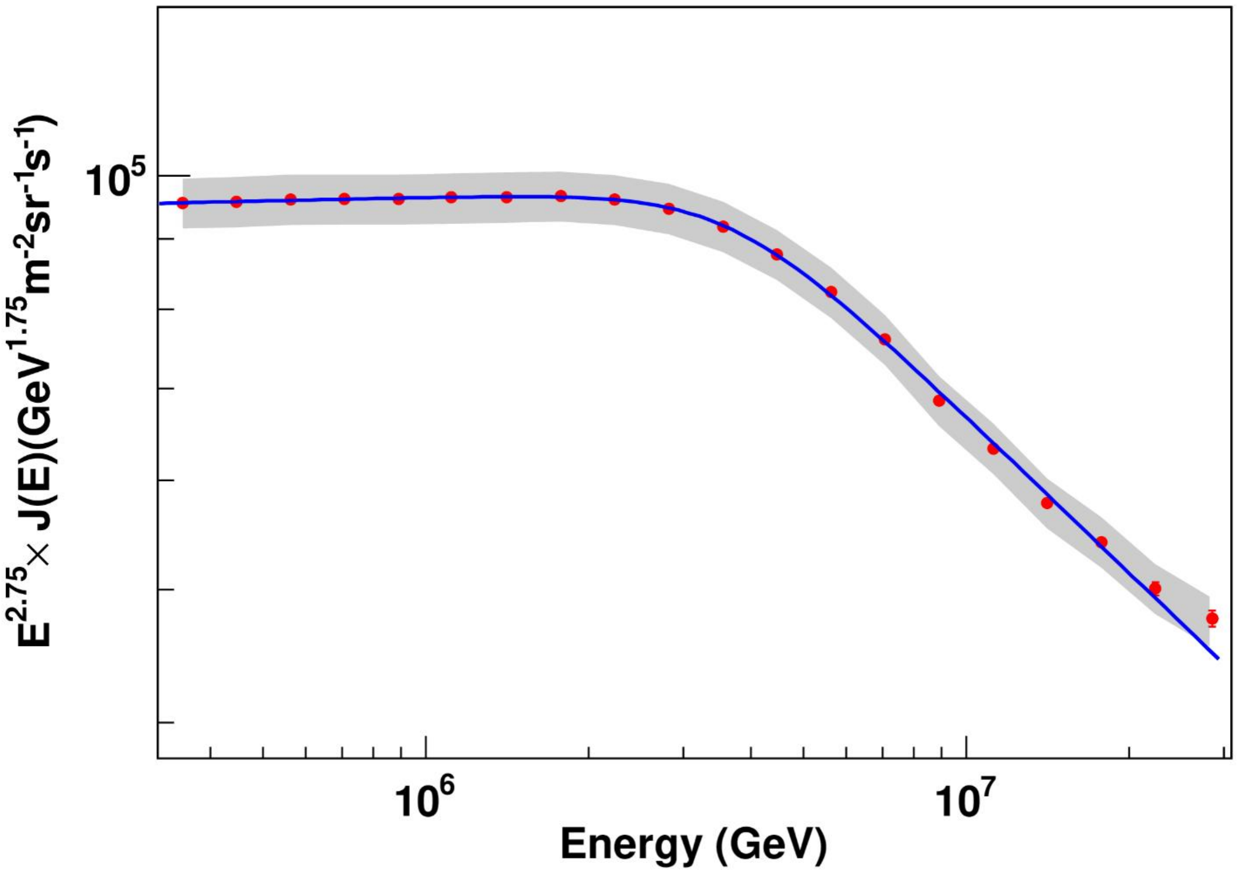
shadow indicating the systematic, including:
detection precision、air pressure、composition models、hadronic interaction model

All-particle energy spectrum of LHAASO

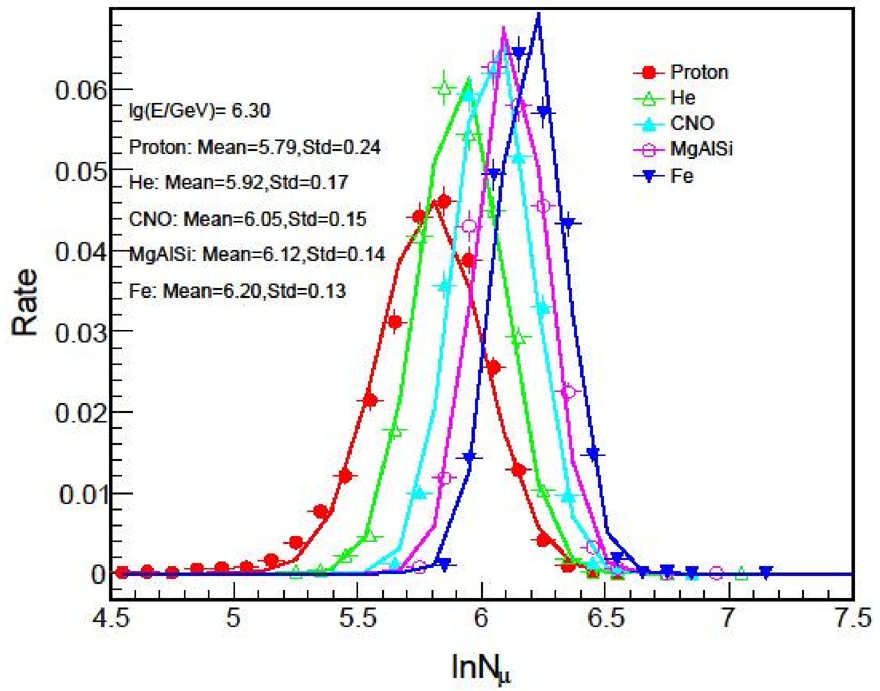
$$J(E) = \Phi_0 \cdot (E)^{\gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^s\right)^{(\gamma_2-\gamma_1)/s}$$

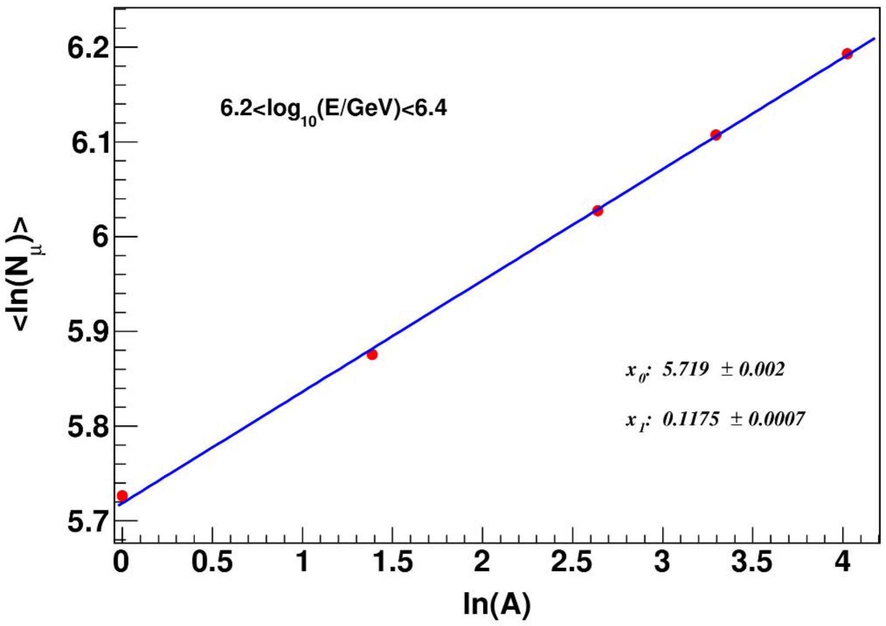
The energy of the Knee: 3.67+-0.05+-0.15 PeV
The difference of index: 0.387+-0.005+-0.027

The precision is one order better than previous results in this energy region.



Moun content of the air shower



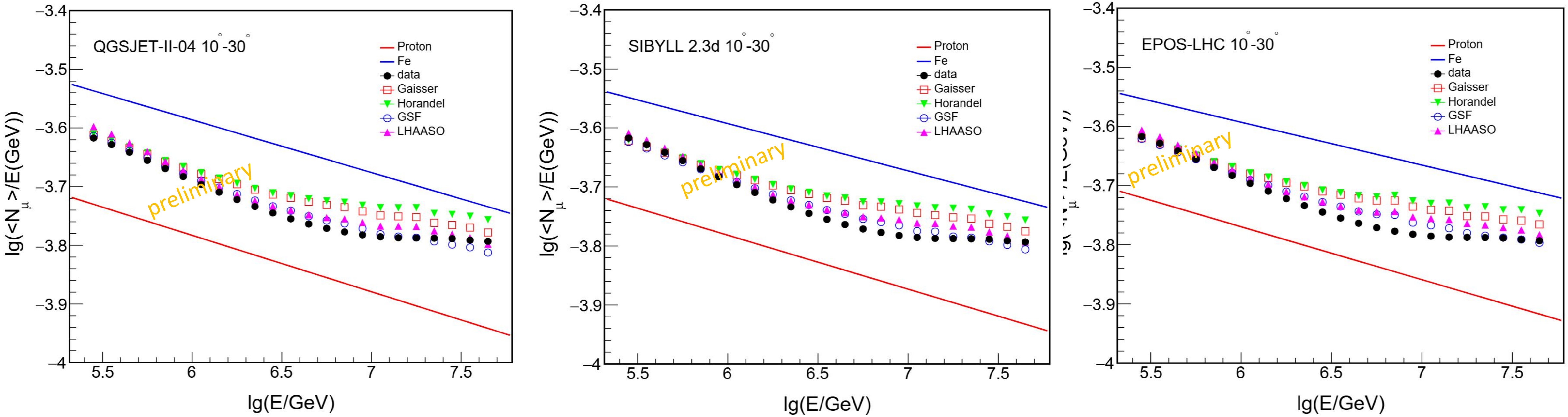


Muon content distribution for component mass A at a given energy bin:

- Muon content distribute with one width
- $< ln(N_\mu) >$ increase linearly with ln(A)

$$< ln(N_\mu) >= \alpha + \beta < ln(A) >$$

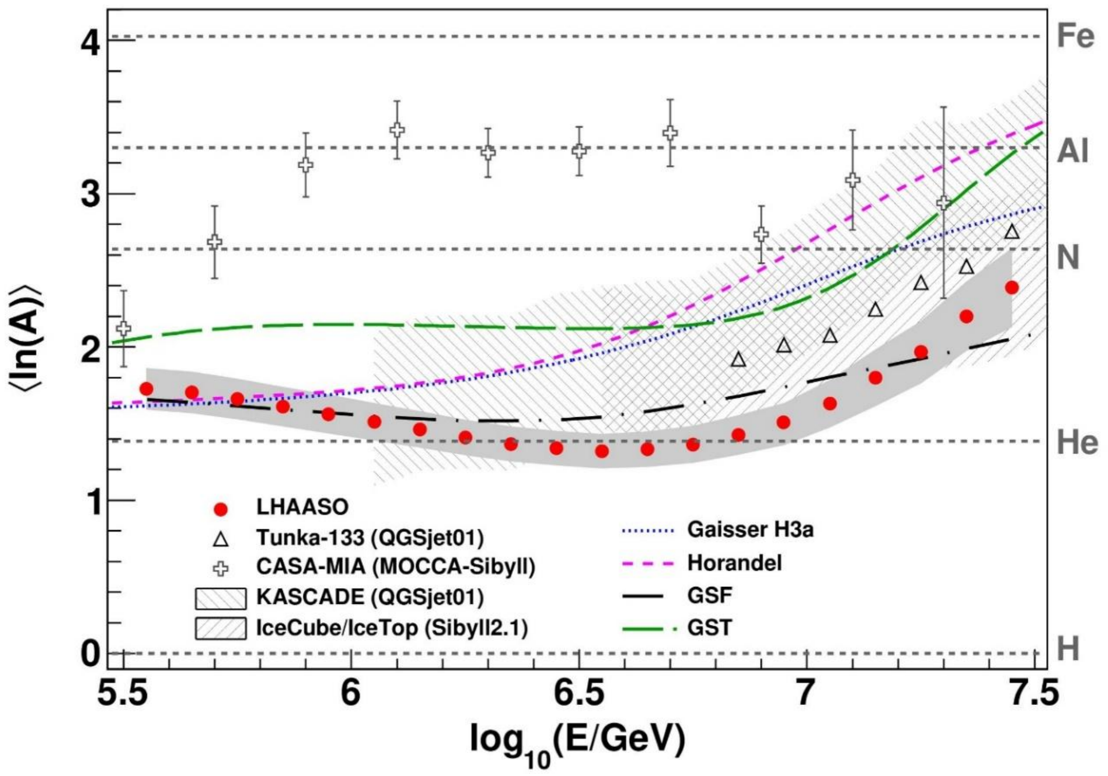
Muon content measurement

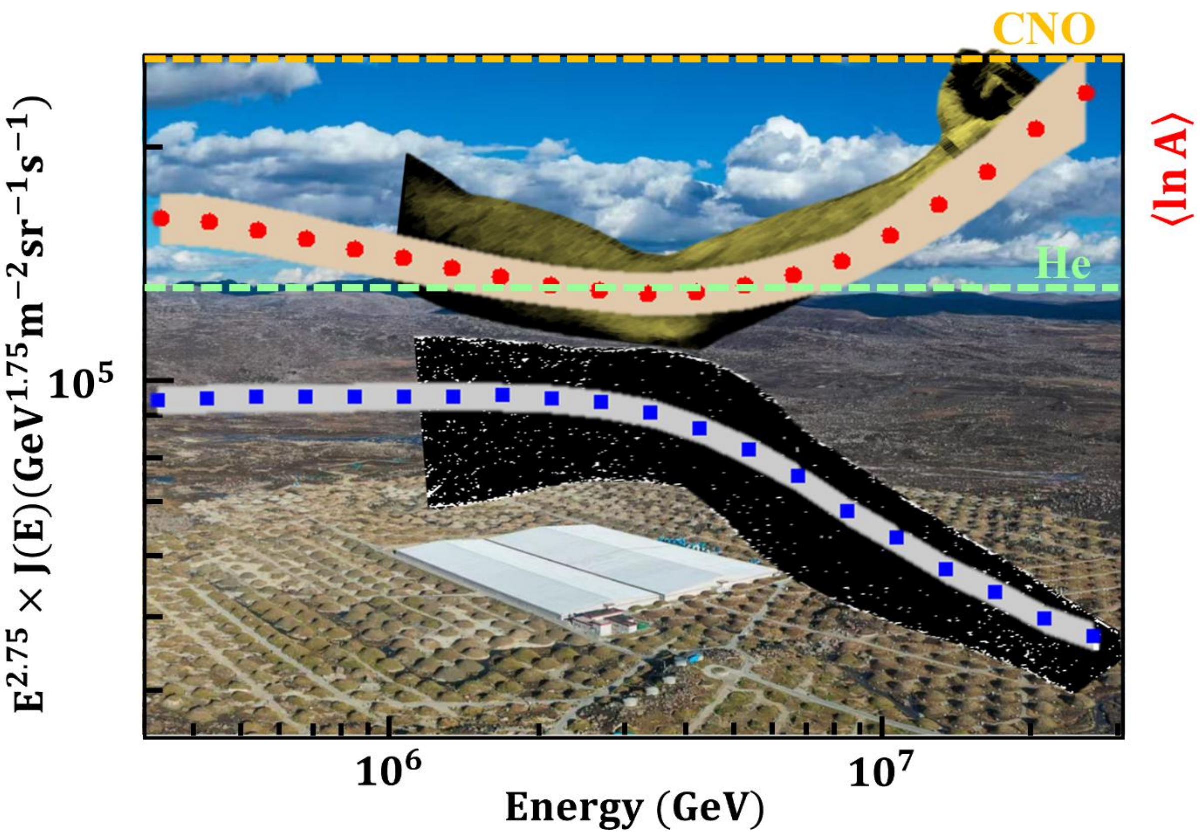


Logarithmic muon content per energy distribution of LHAASO

- Muon content sensitive to composition
- Observed is less than the expected above PeV for all hadronic models.
- No muon deficit observed within this energy region

Mean logarithmic mass of CR measured with muon content





Mean logarithmic mass of CR measured by LHAASO

- The knee is dominated by light component.
- Lighter than a few composition models

The knee is induced by the light CR component.

- ✓ The light component is the first cut-off in all-particle spectrum.

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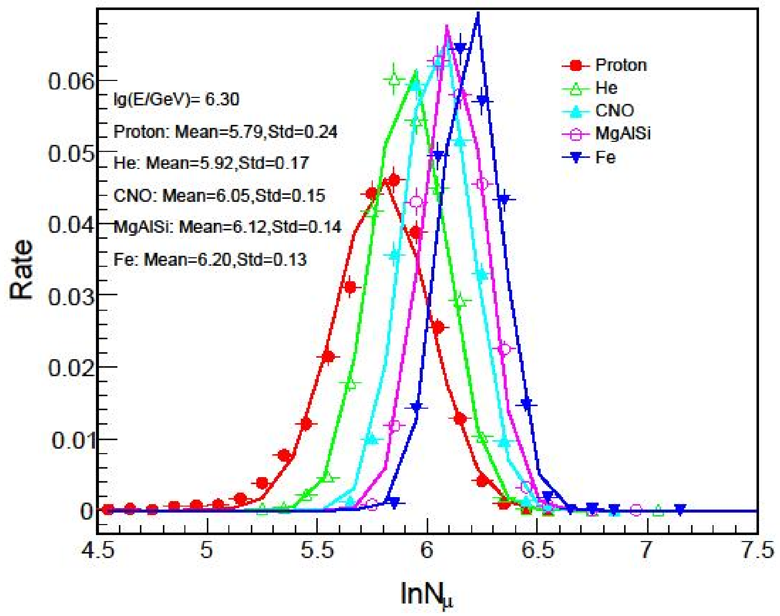
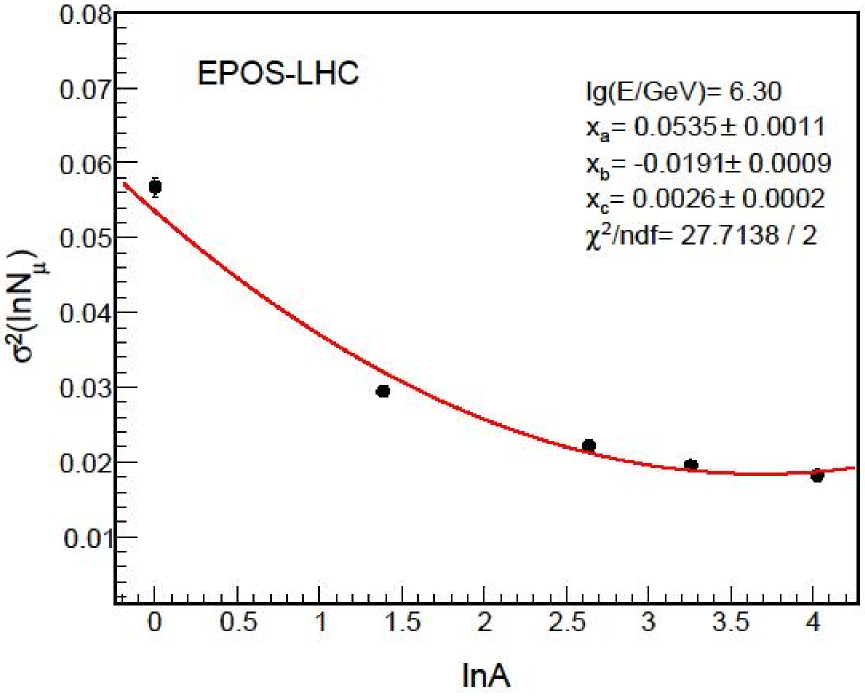
The fluctuation of muon content





The width of fluctuation of the muon content $\sigma^2(\ln N_\mu)$ varies as the mass of component.

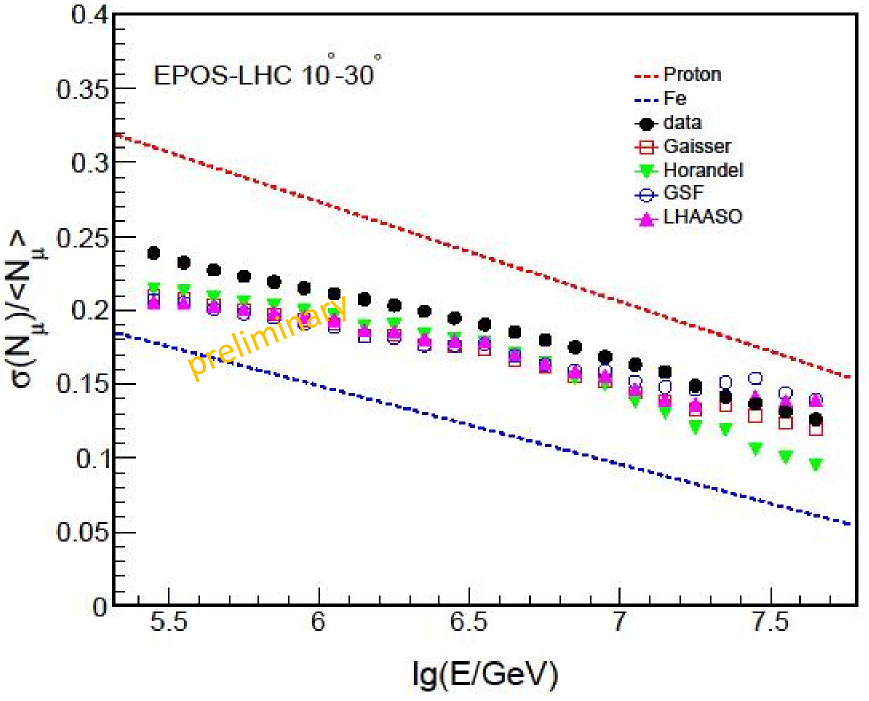
A quadratic function fit the intrinsic $\sigma^2(\ln N_\mu)$ and lnA according the simulation results.

The CR composition will impact $\sigma^2(\ln N_\mu)$.

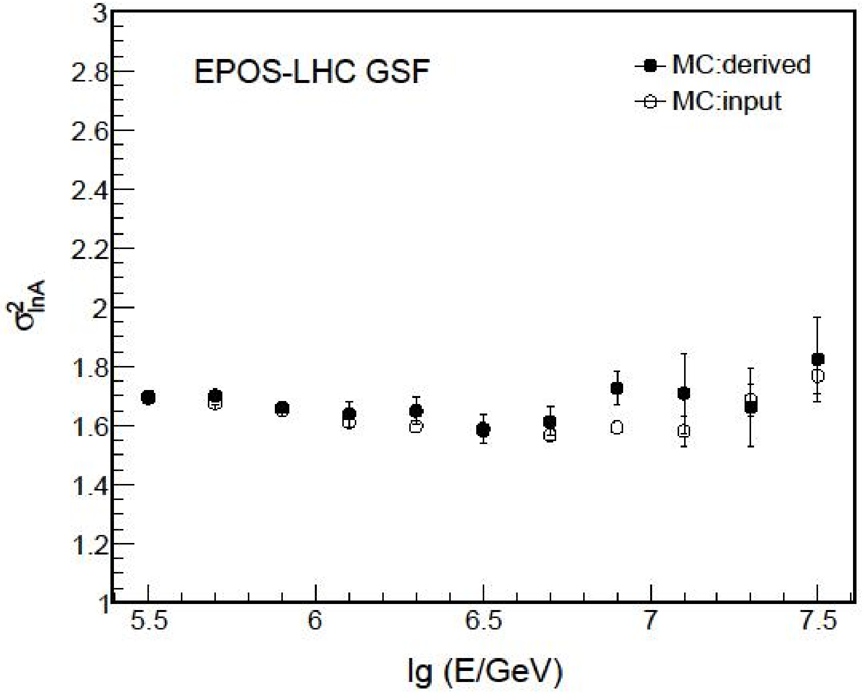
$$\sigma^2(\ln N_\mu) = \sigma^2(\ln N_\mu)_{\_intrinsic} + \beta^2\sigma^2{}_{lnA}$$

$$\sigma^2(\ln N_\mu) \rightarrow \sigma^2{}_{lnA}$$

The fluctuation of muon content and variance of CR mass



$\sigma(\ln N_\mu) \rightarrow \sigma^2{}_{lnA}$



The relative fluctuation of muon content $\sigma(N_\mu)/< N_\mu >$ measured by LHAASO

- ➢ Larger than expected values of the composition models
- ➢ Between pure Fe and proton.

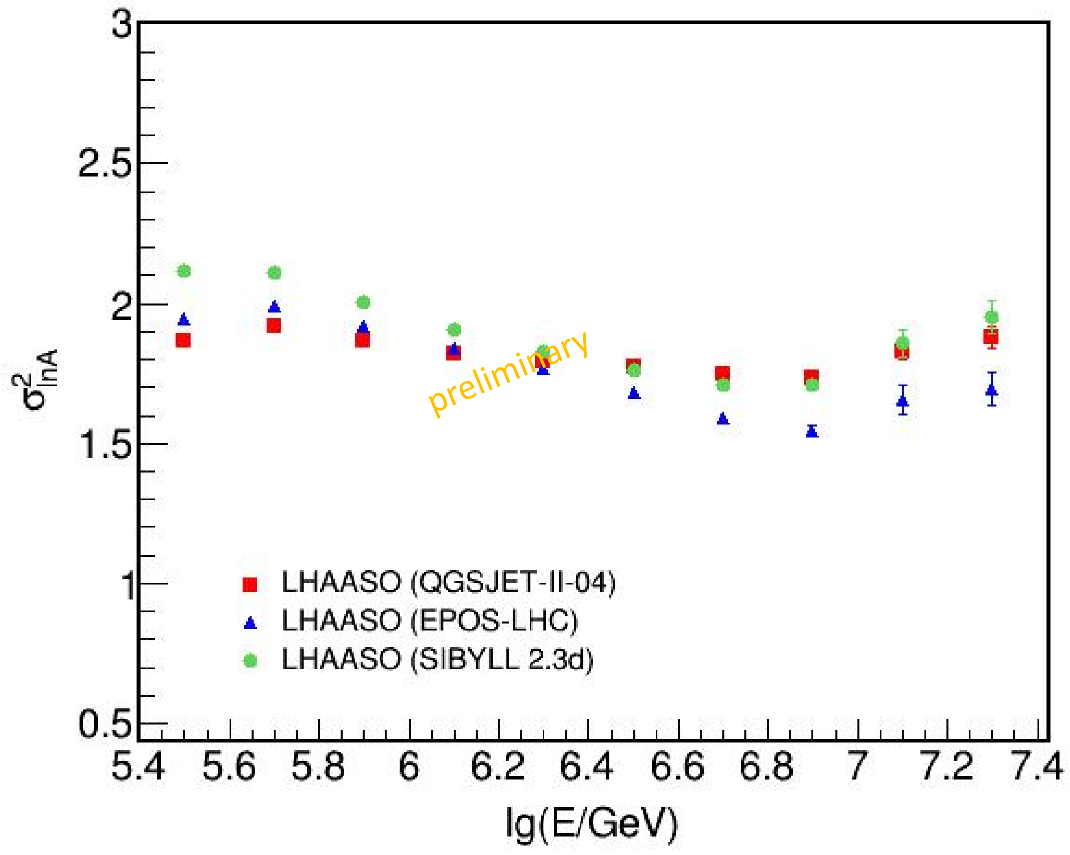
Closure test with the GSF composition model.

- ✓ The derived results match well with the truth inputs

Preliminary result of CR mass variance

- The hadronic interaction models influence the results.

- But similar evolutionary trends for 3 models
  - The variance decrease before 10 PeV.
  - The variance increase above 10 PeV.
    - New population (extragalactic?) join?



The variance of CR mass measured by LHAASO.

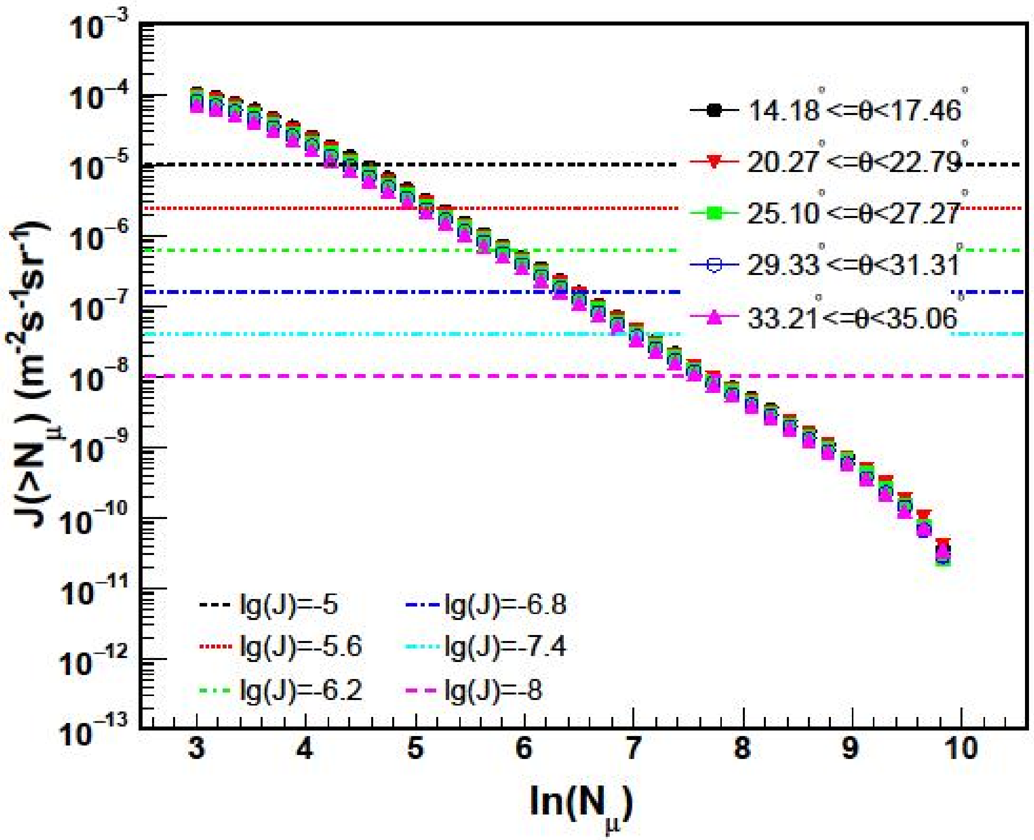
Attenuation length of muon content

Constant intensity cut method

The muon content attenuates as the zenith angle for same energy air shower.

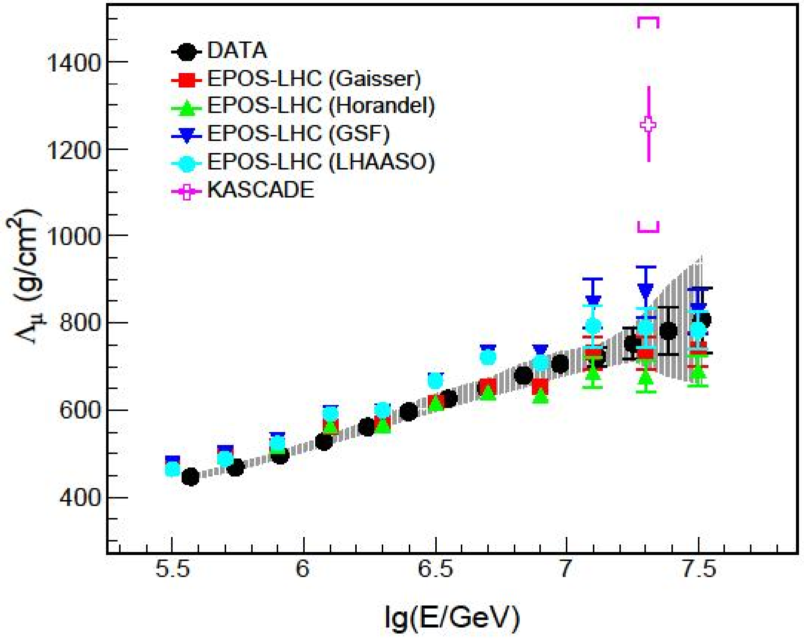
$$N_\mu(\theta) = N_\mu^0 e^{-X_0 sec\theta/\Lambda_\mu}$$

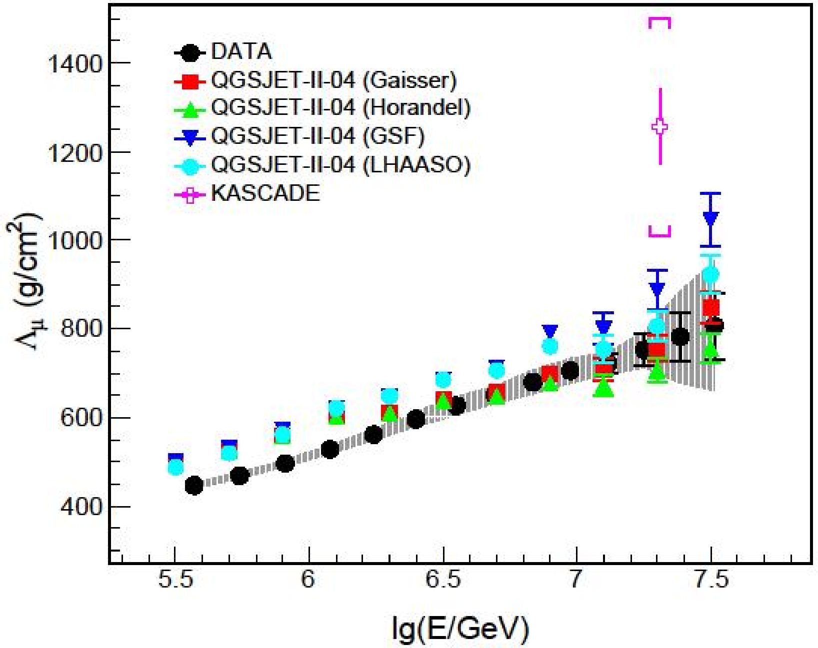
Attenuation length: Λ_μ



LHAASO integral flux spectrum of muon content at several equal solid angles.

Attenuation length of muon content





- The Λ_μ increases as the cosmic ray energy.
- The Λ_μ of the EPOS model match well with LHAASO.
- The Λ_μ is shorter than QGSJET and SIBYLL below PeVs.

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Summary

- The knee of all-particle energy spectrum at 3.67 PeV.
- The light components dominate the knee.
- The variance of CR mass increase above 10 PeV.
- The muon content less than expected, no muon deficit observed.
- The fluctuation of the muon content measured.
- The attenuation length of muon content measured, the result prefers the EPOS-LHC model.

Thanks for your attention!