Measurement of cosmic ray mean mass around the knee region by muon content in air shower with LHAASO-KM2A

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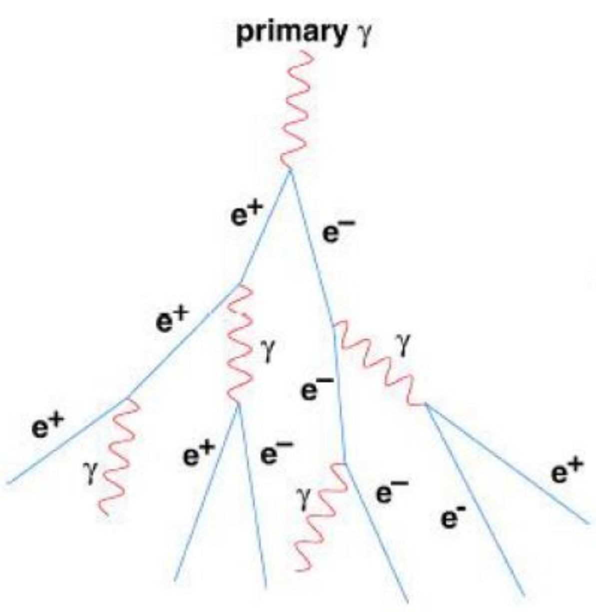
Outline

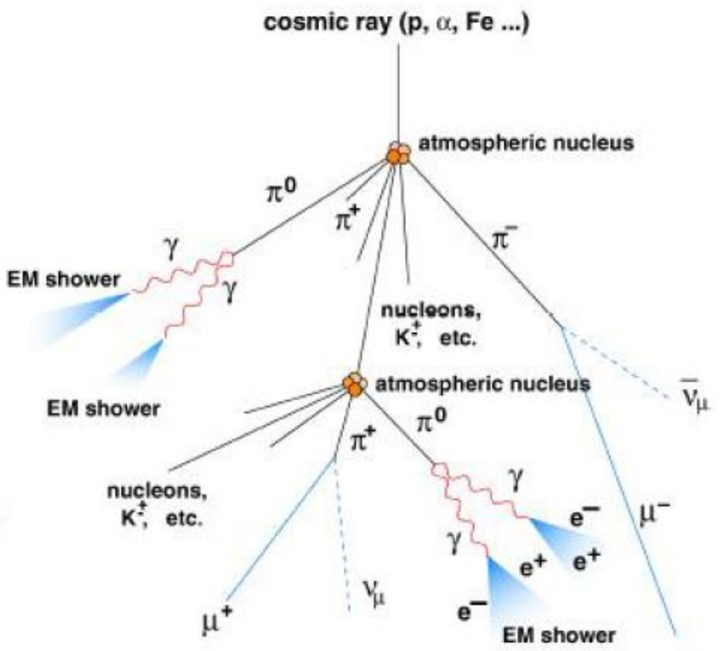
- Motivation
- Experimental set-up and MC simulation
- Analysis results
- Preliminary Summary

Motivation

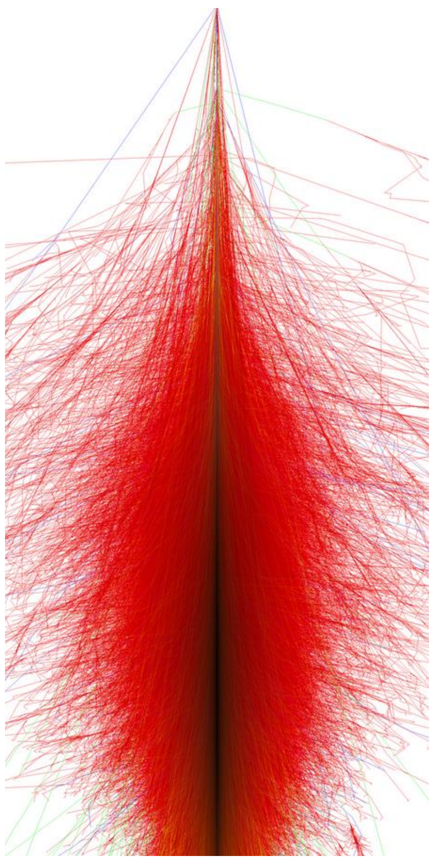
electromagnetic cascade



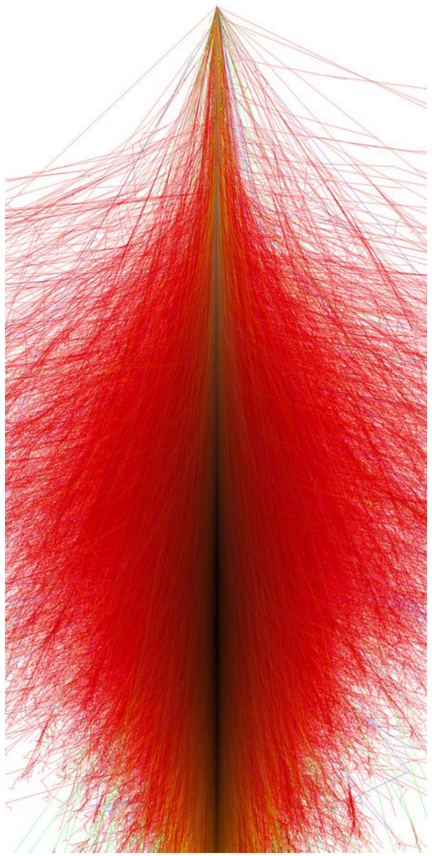
hadronic cascade



$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$ and $K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$



100TeV Proton

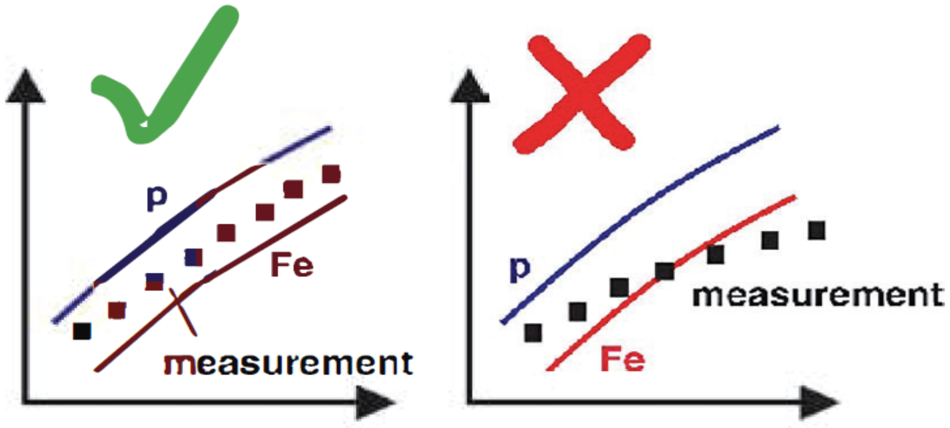


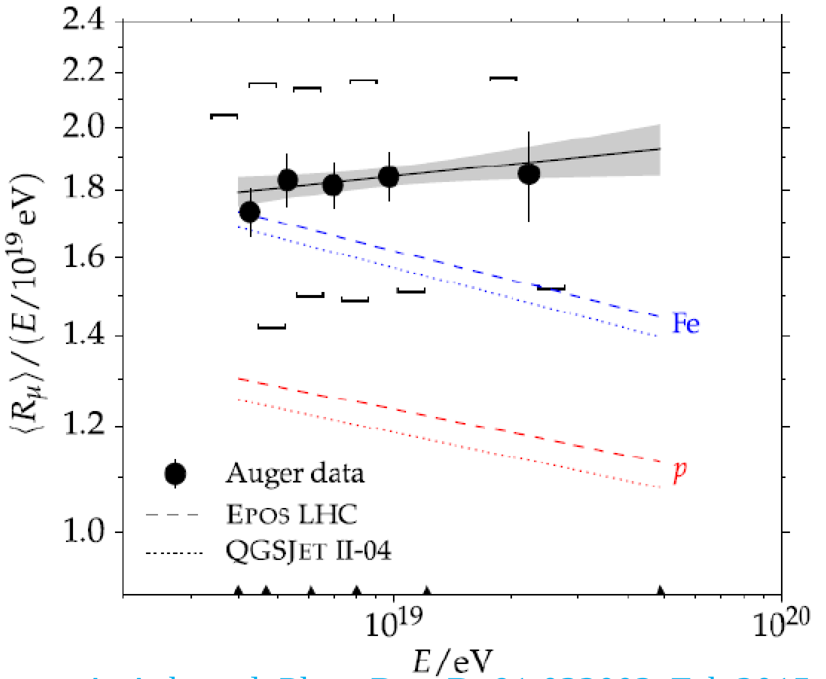
100TeV Fe

Muon carry information about their parent particle, pions and kaons, production in hadronic interaction. Studying muons becomes therefore a sensitive and direct way to probe the hadronic physics and to identify possible deficiencies of hadronic interaction models.

Muon content

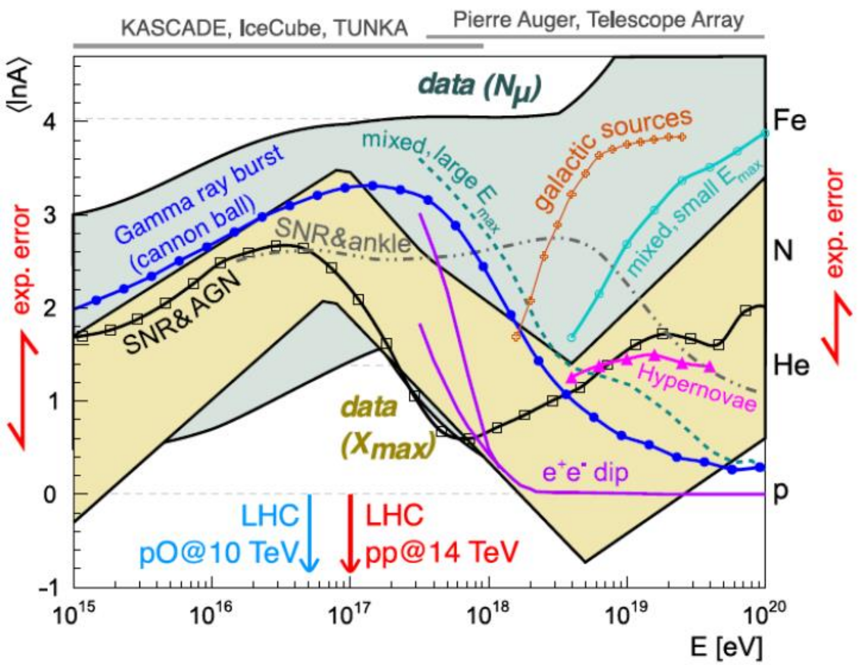
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$





A. Aab et al. Phys. Rev. D, 91:032003, Feb 2015.

1) hadronic interaction mode
2) cosmic ray mass composition



H.P. Dembinski et al. EPJ Web Conf., 210:02004, 2019.

LHAASO

40000 m^2

1188 muon detectors

Experimental set-up

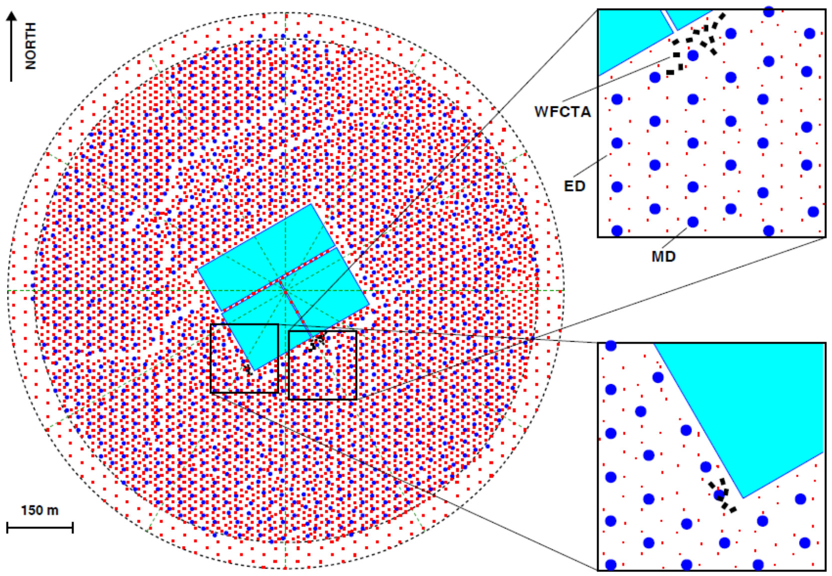
Large High Altitude Air Shower Observatory, LHAASO at 4410 m a.s.l. ($600 g/cm^2$) in Daocheng, China

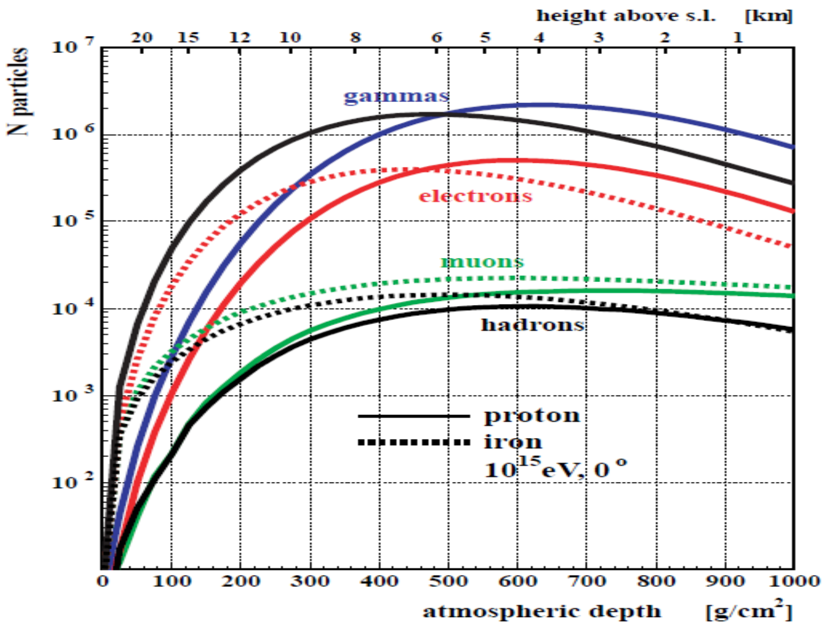
- 1 km^2 array (KM2A)

  electromagnetic particle detectors (5195 EDs)

  muon detector (1188 MDs)

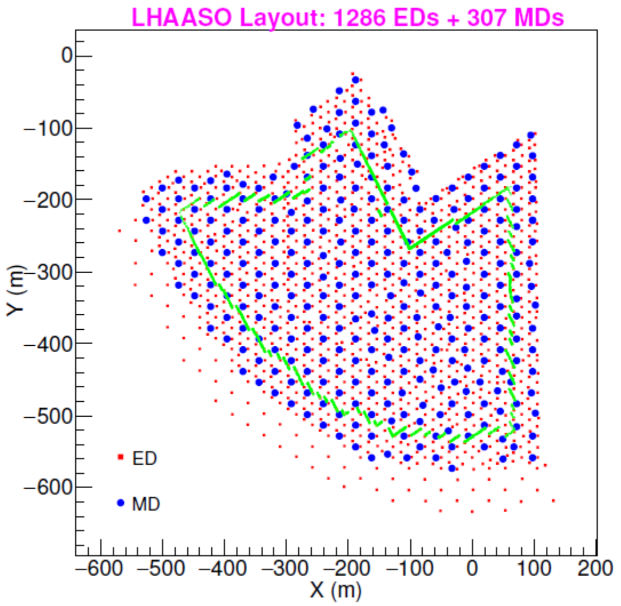
- water Cherenkov detector array(WCDA)
- wide-field-of-view Cherenkov/fluorescence telescope array (WFCTA)

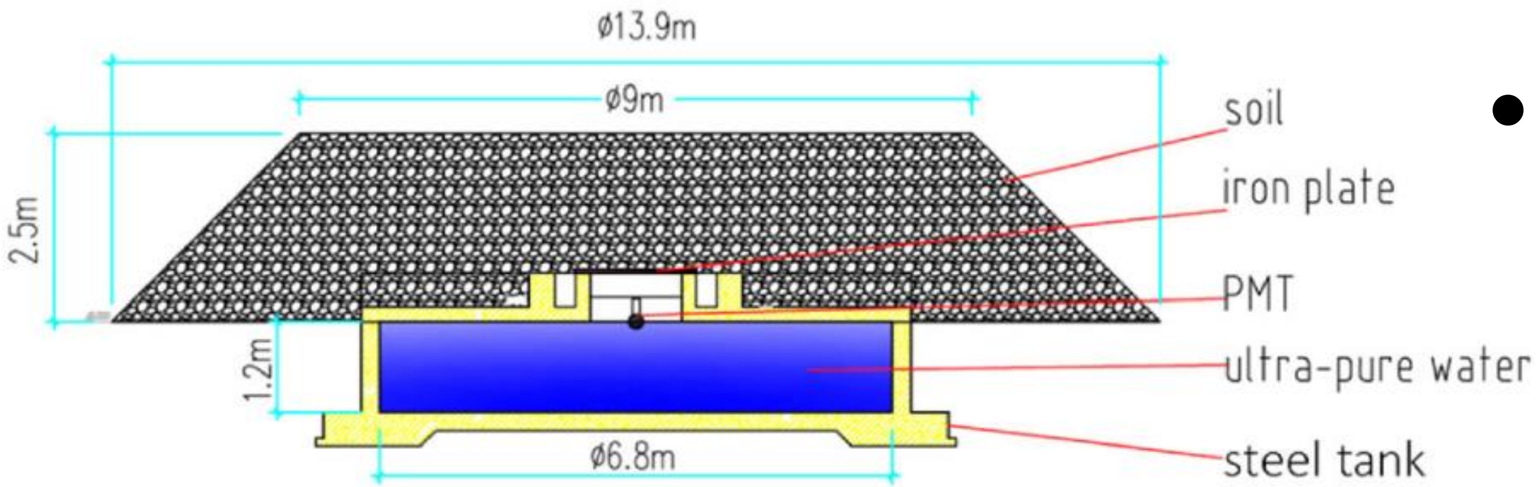




Andreas Haungs. Journal of Physics G: Nuclear and Particle Physics, 29(5):809–820, apr 2003.

KM2A quarter-array





Schematic diagram of muon detector

- A layer of 2.5 m thick soil is overburdened on the MD tank to absorb the secondary electrons/positrons and gamma-rays in air showers.

Monte Carlo Simulation and experimental data

- CORSIKA (Cosmic Ray Simulations for KAscade)

  primary cosmic ray： Proton, He, N, Al, Fe

  high energy hadronic interaction model: EPOS-LHC， QGSJETII-04

  low energy hadronic interaction model: FLUKA,Gheisha

Table 1: Corsika simulation: EPOS-Fluka.

Component	A	Energy range(eV)	γ	θ(deg)	φ (deg)
Proton	1	$10^{13} \sim 10^{17}$	-2	0-70	0-360
He	4	$10^{13} \sim 10^{17}$	-2	0-70	0-360
CNO	14	$10^{13} \sim 10^{17}$	-2	0-70	0-360
MgAlSi	27	$10^{13} \sim 10^{17}$	-2	0-70	0-360
Fe	56	$10^{13} \sim 10^{17}$	-2	0-70	0-360

- G4KM2A(detector response)

  array： ED and MD

  simple radius： 1000m

Table 2: G4KM2A simulation: the number of cosmic ray shower.

Component	$10^{13} \sim 10^{14}$ eV	$10^{14} \sim 10^{15}$ eV	$10^{15} \sim 10^{16}$ eV	$10^{16} \sim 10^{17}$ eV
Proton	4×10^7	4×10^6	6×10^5	10^5
He	10^7	10^6	10^5	2.5×10^4
CNO	10^7	10^6	10^5	2.5×10^4
MgAlSi	10^7	10^6	10^5	2.5×10^4
Fe	4×10^7	4×10^6	6×10^5	10^5

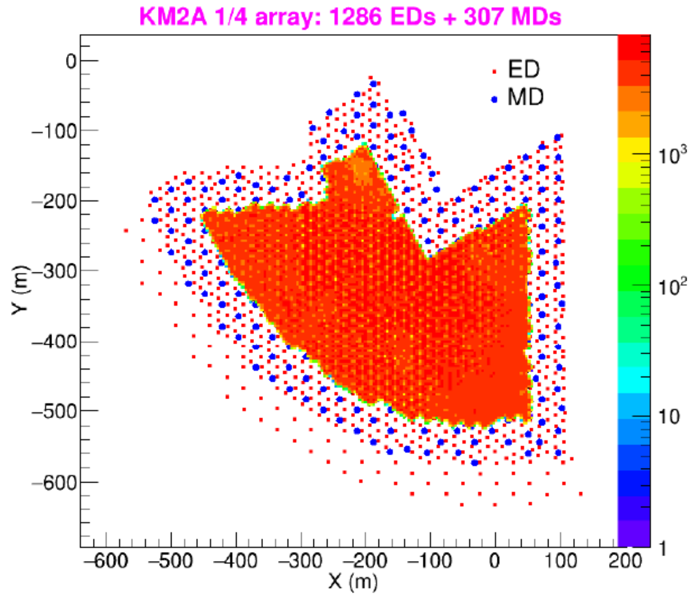
Normalizing to Gaisser H3a model energy spectrum or horandel energy spectrum

- Experimental data

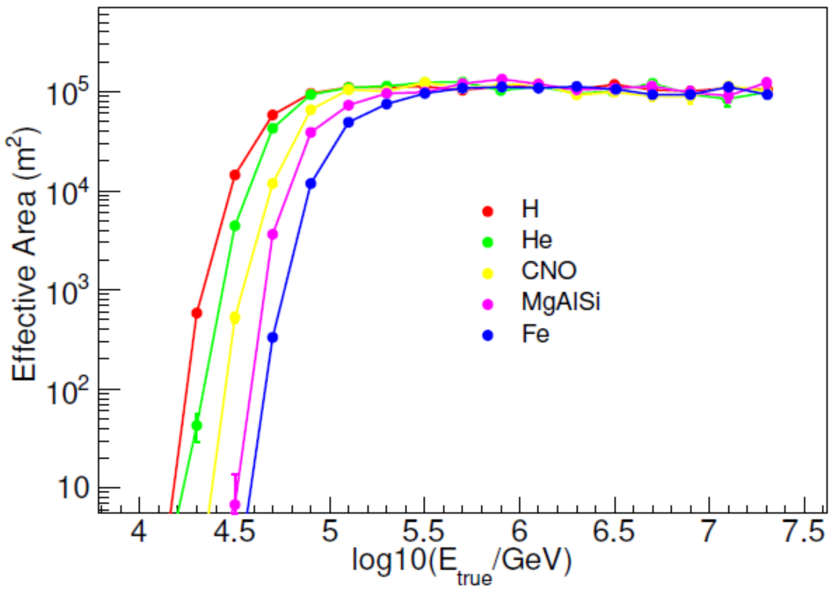
2020.07.19—2020.07.25，

2020.08.01—2020.08.15

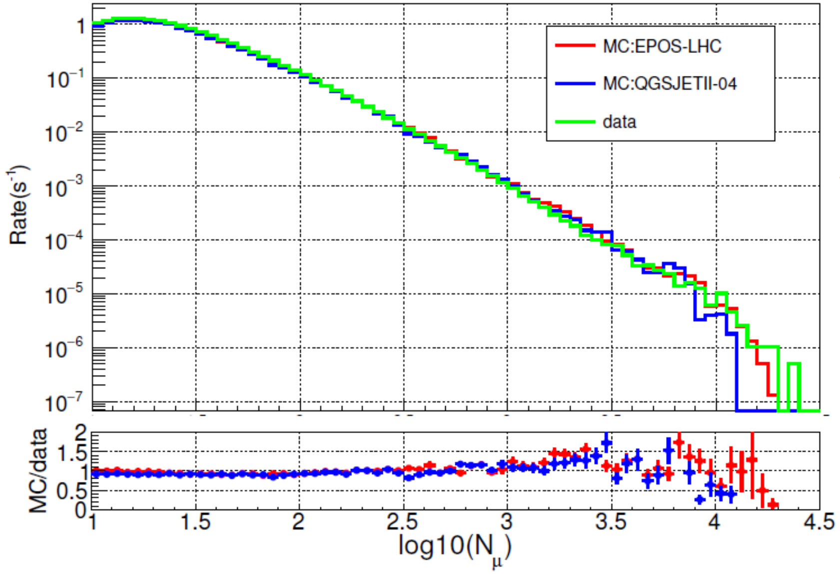
Event selection

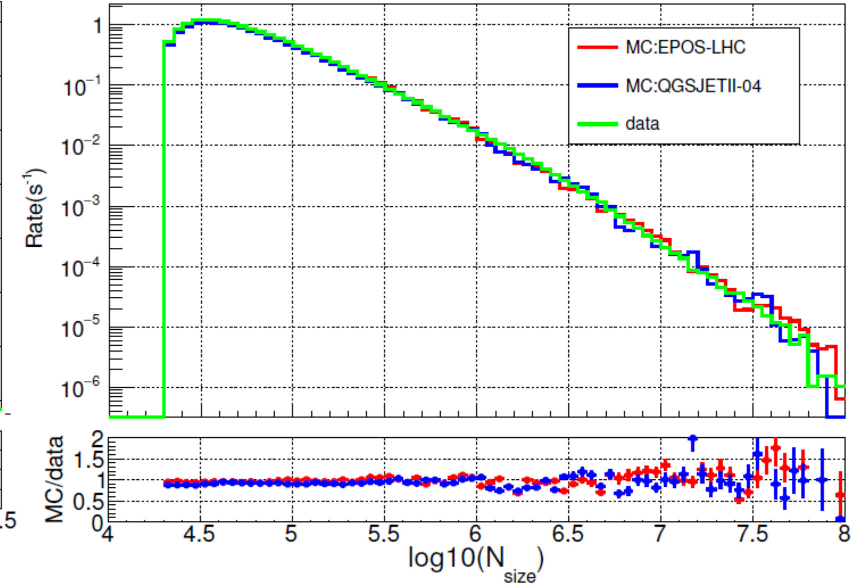


$$S_{eff} = \frac{N_{cut}}{N_{sample}} \cdot S_{sample} \cdot \cos\theta$$



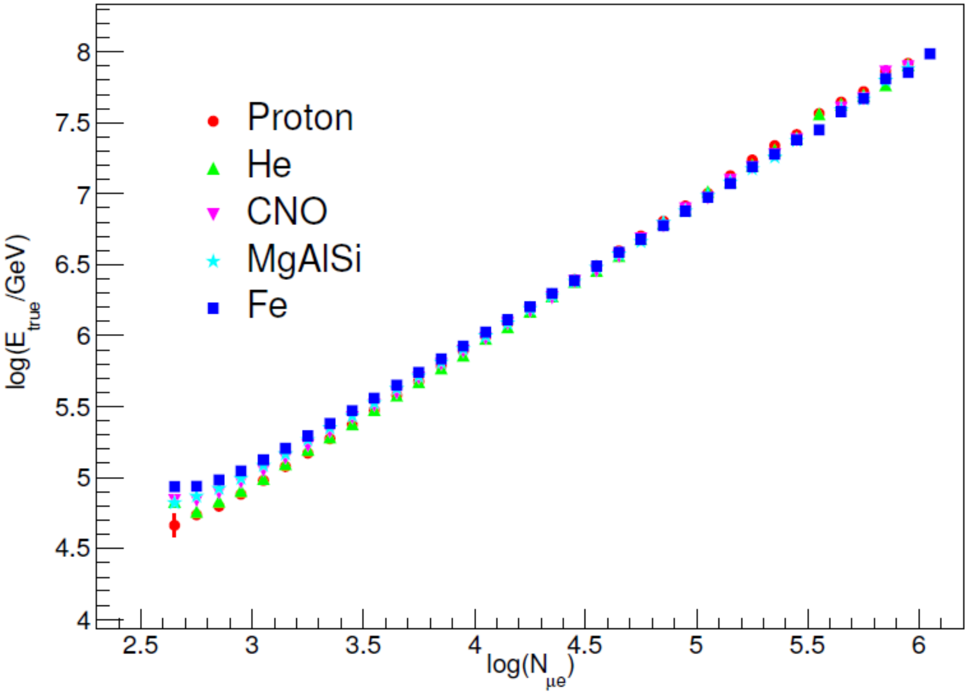
- N_μ : the sum of muons from the selected MDs with a distance of 40m to 200m from the shower core.
- N_{size}: reconstructed by fitting the charged particle lateral distribution measured using a modified Nishimura-Kamata-Greisen (NKG) function.





Energy reconstruction

$$N_{\mu e} = \sqrt{N_{size} * N_{\mu}}$$

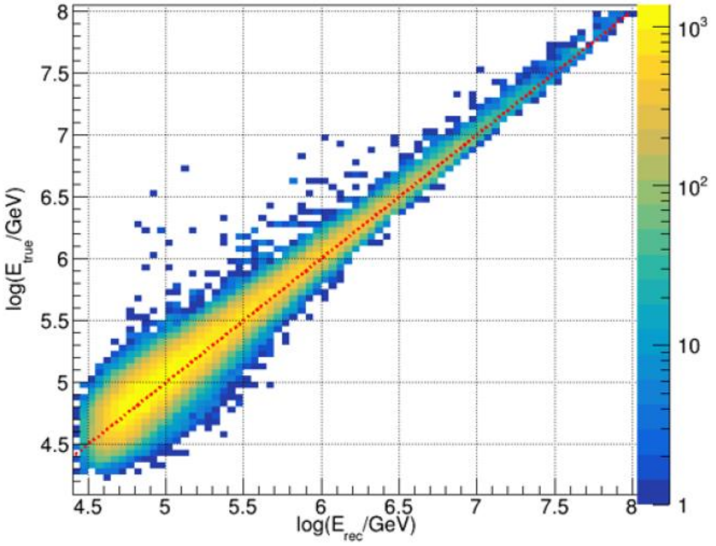


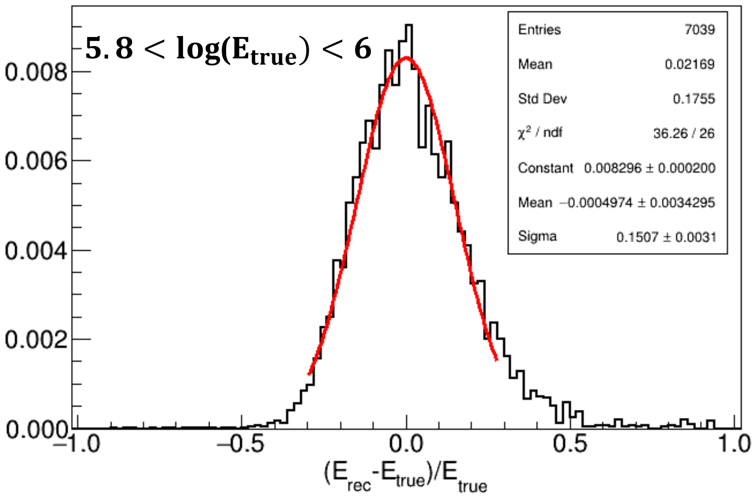
$N_{\mu e}$ weakly depend on cosmic ray mass composition

- N_{μ} : the sum of muons from the selected MDs with a distance of 40m to 200m from the shower core.
- N_{size}: reconstructed by fitting the charged particle lateral distribution measured using a modified Nishimura-Kamata-Greisen (NKG) function.

$$\rho(r) = \frac{N_{size}}{2\pi r_m^2} \frac{\Gamma(4.5 - s)}{\Gamma(s - 0.5)\Gamma(5 - 2s)} \left(\frac{r}{r_m}\right)^{s-2.5} \left(1 + \frac{r}{r_m}\right)^{s-4.5}$$

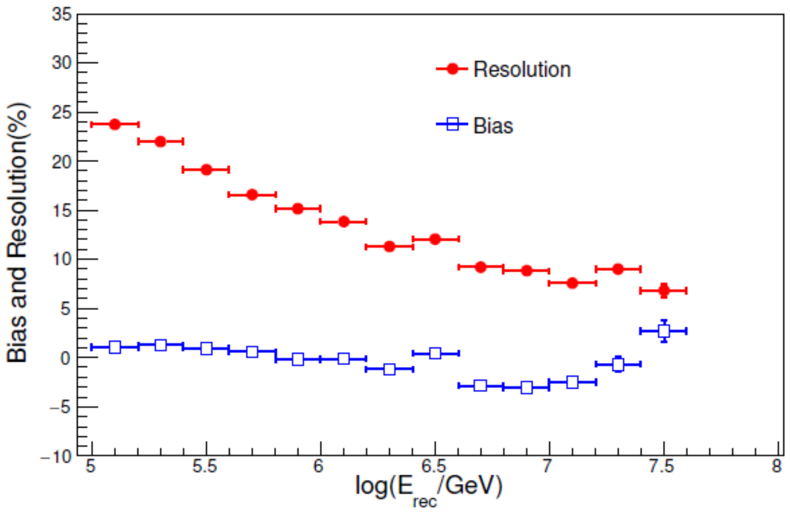
Energy reconstruction

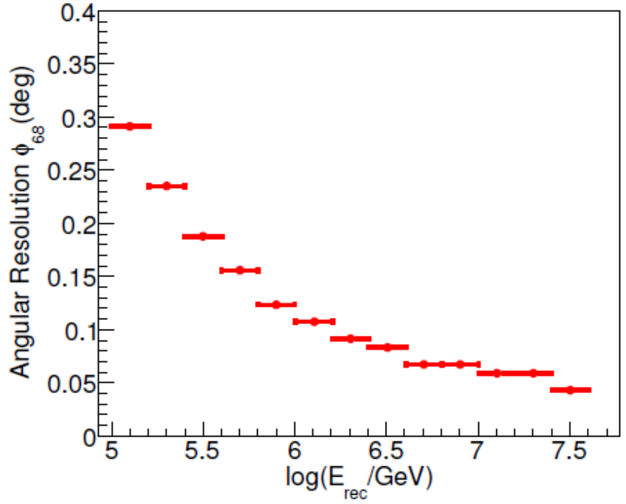


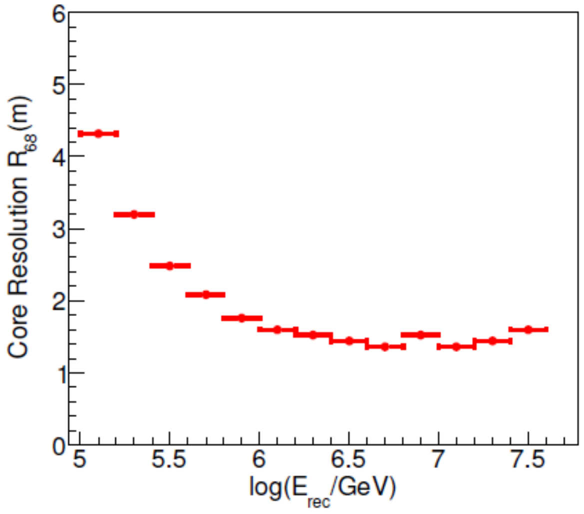


$$N_{\mu e} = \sqrt{N_{size} * N_{\mu}}$$

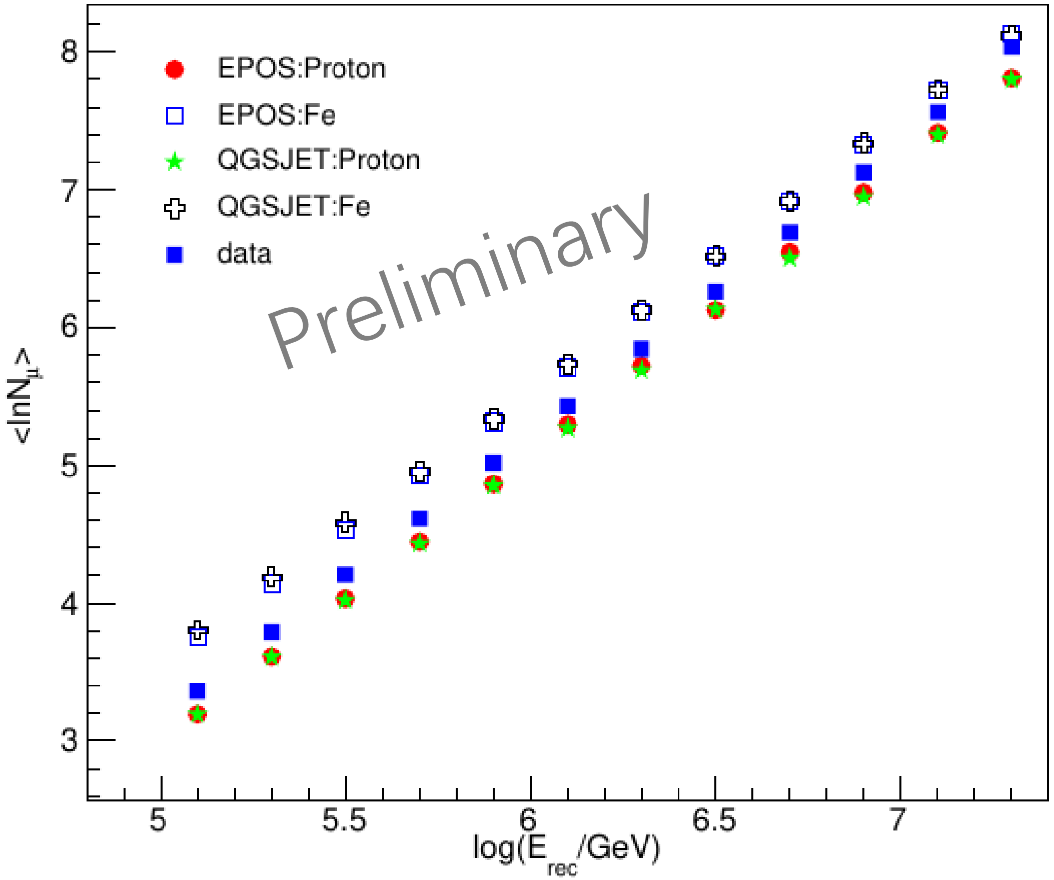
$$\log(E_{rec}/GeV) = a + b \cdot \log(N_{\mu e}) + c \cdot \log^2(N_{\mu e})$$



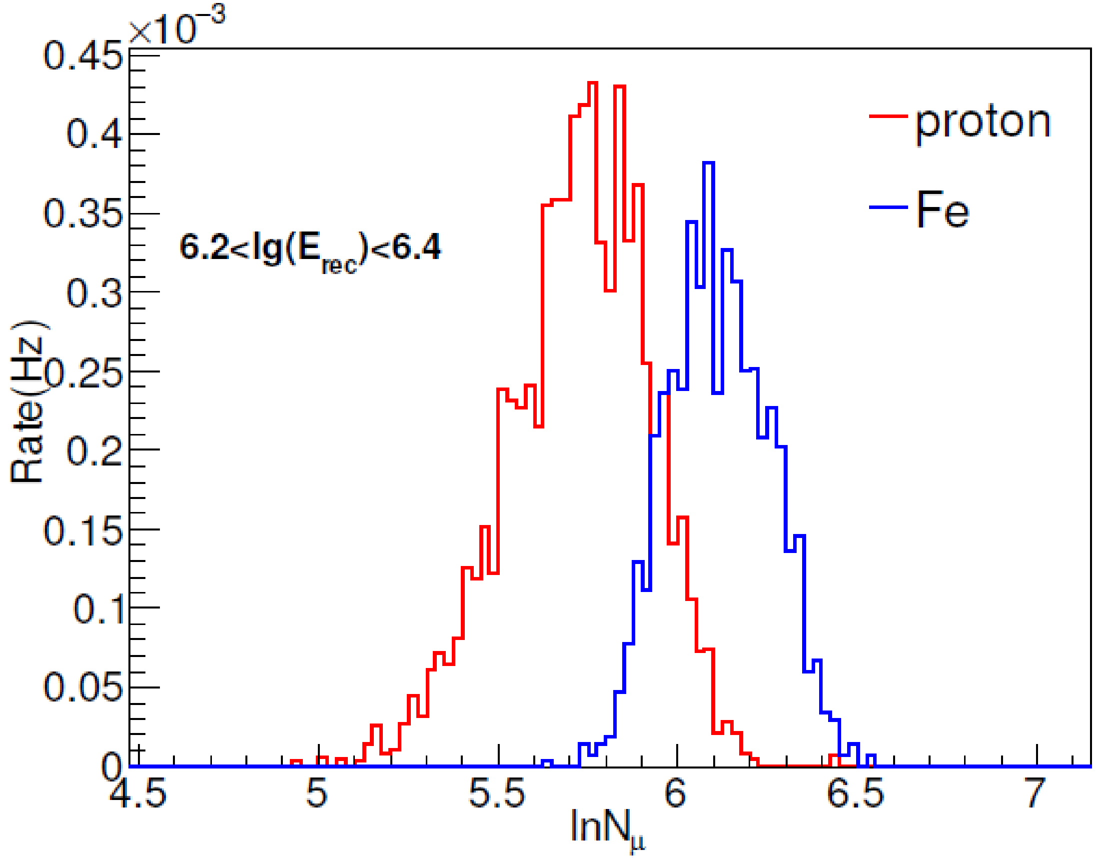




Muon content measurement



$\ln(N_\mu)$ as a function of $\log(E_{\mathrm{rec}})$.

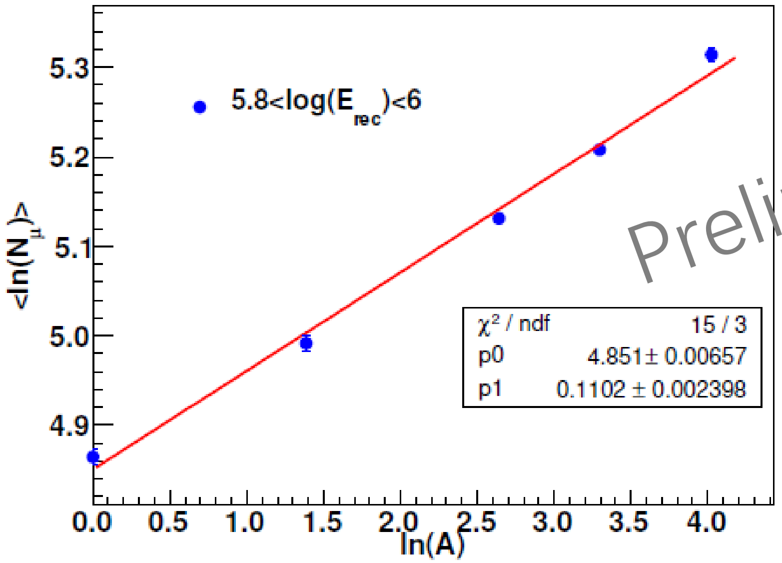


Mean mass measurement

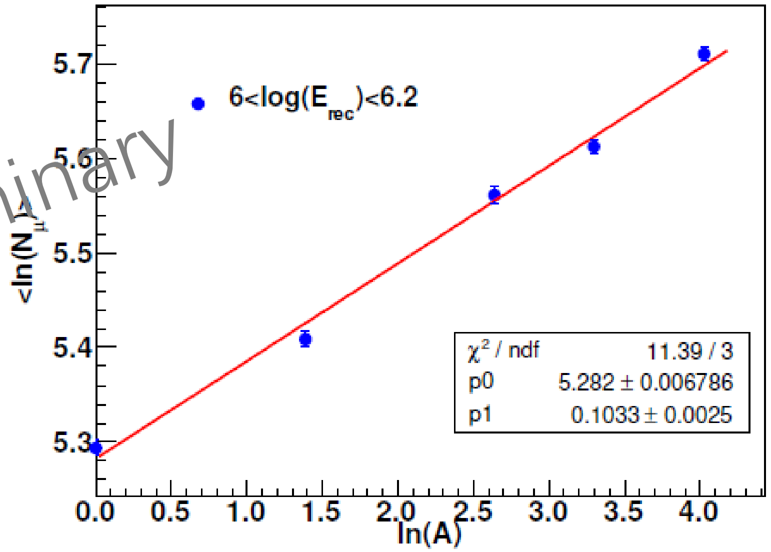
Matthews-Heitler model

$$N_\mu = A\left(\frac{E}{A\,\varepsilon_c}\right)^{\beta} \quad \Rightarrow \quad \ln N_\mu = p0 + p1 * \ln A$$

Nμ ∝ A for the same energy interval, the mean number of muons in air shower for each energy interval is measured by analyzing the signal of muon detectors, so the mean logarithmic mass of the cosmic ray derived from the mean number of muons.

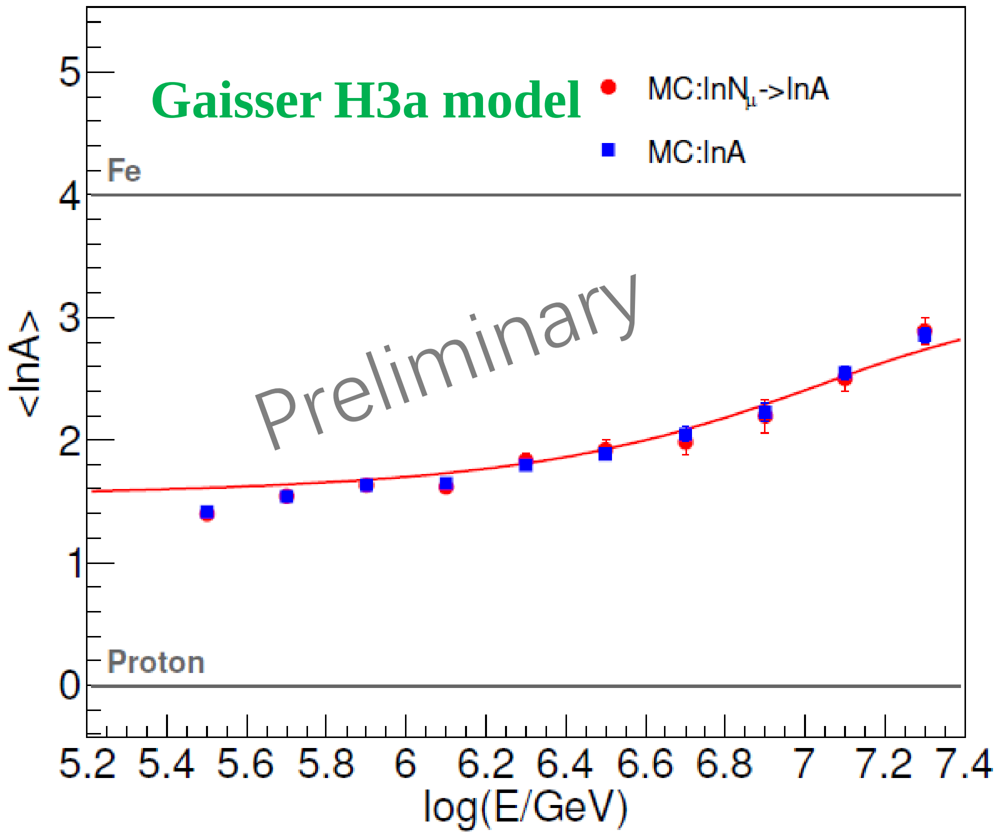


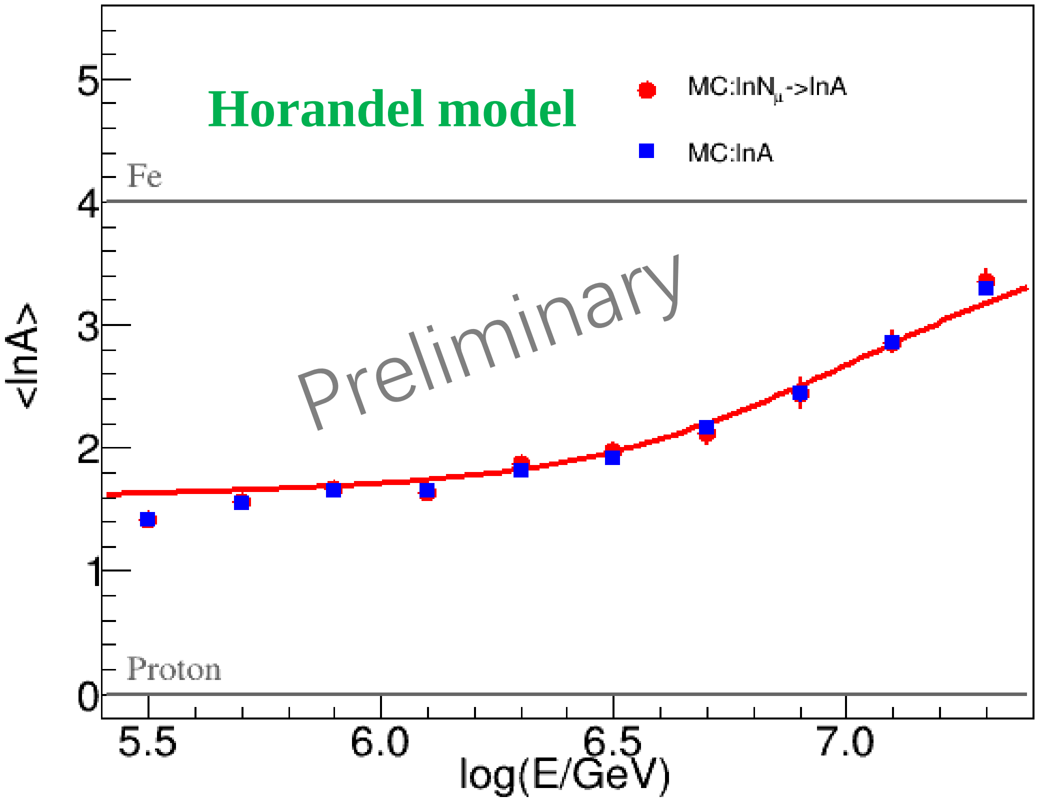
Preliminary



Methods validation

$$\ln N_\mu = p0 + p1 * \ln A \;\rightarrow\; \langle \ln A \rangle = \left(\langle \ln N_\mu \rangle - p_0\right)/p_1$$



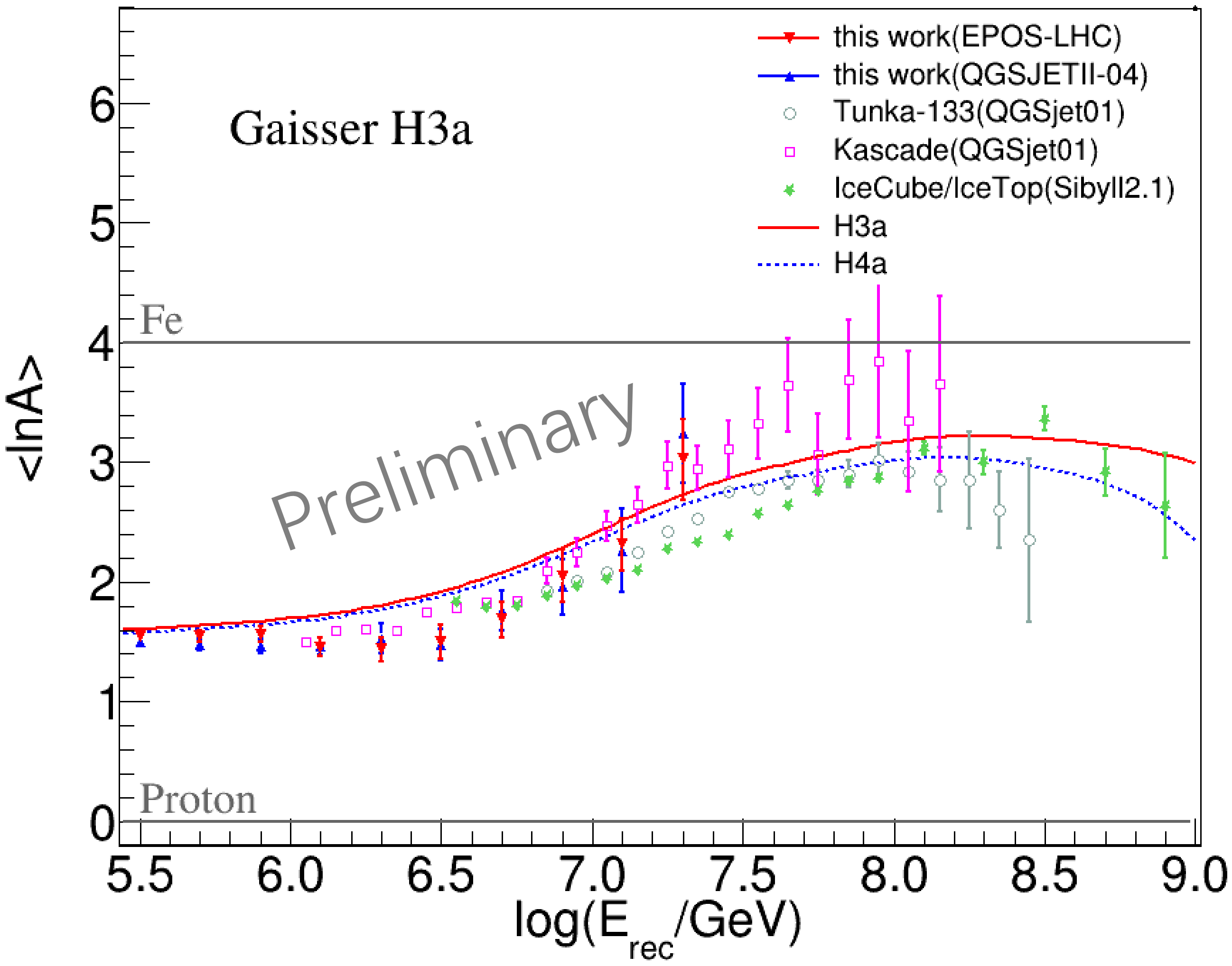


The red point(mc:lnNμ->lnA) the lnA derived from the above function for five mass groups;

The bule square (mc:lnA) is the triggered mass of shower after event selection;

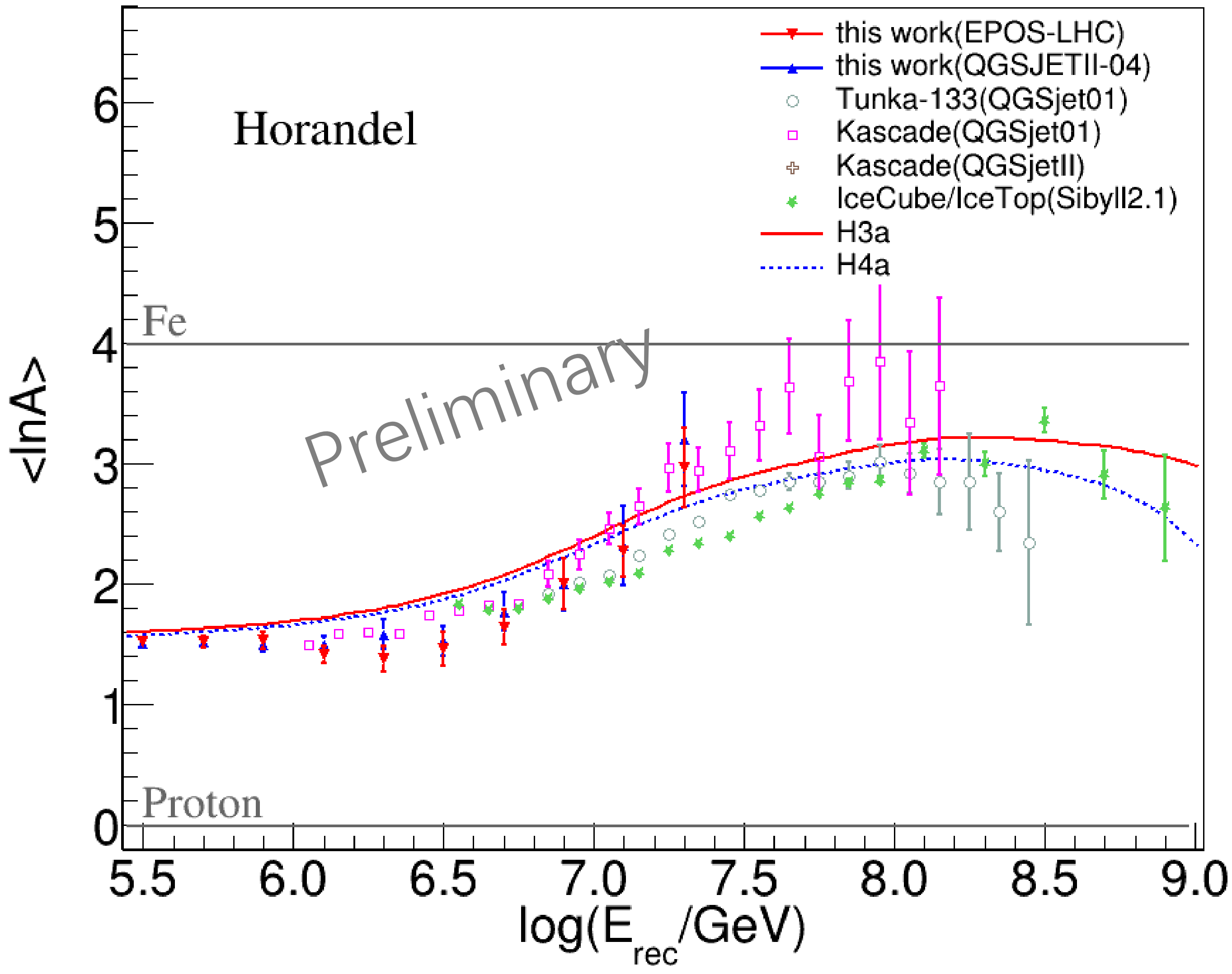
Mean mass measurement – using Gaisser H3a energy spectrum model

$$\langle \ln A\rangle = \left(\langle \ln N_\mu\rangle - p_0\right)/p_1$$



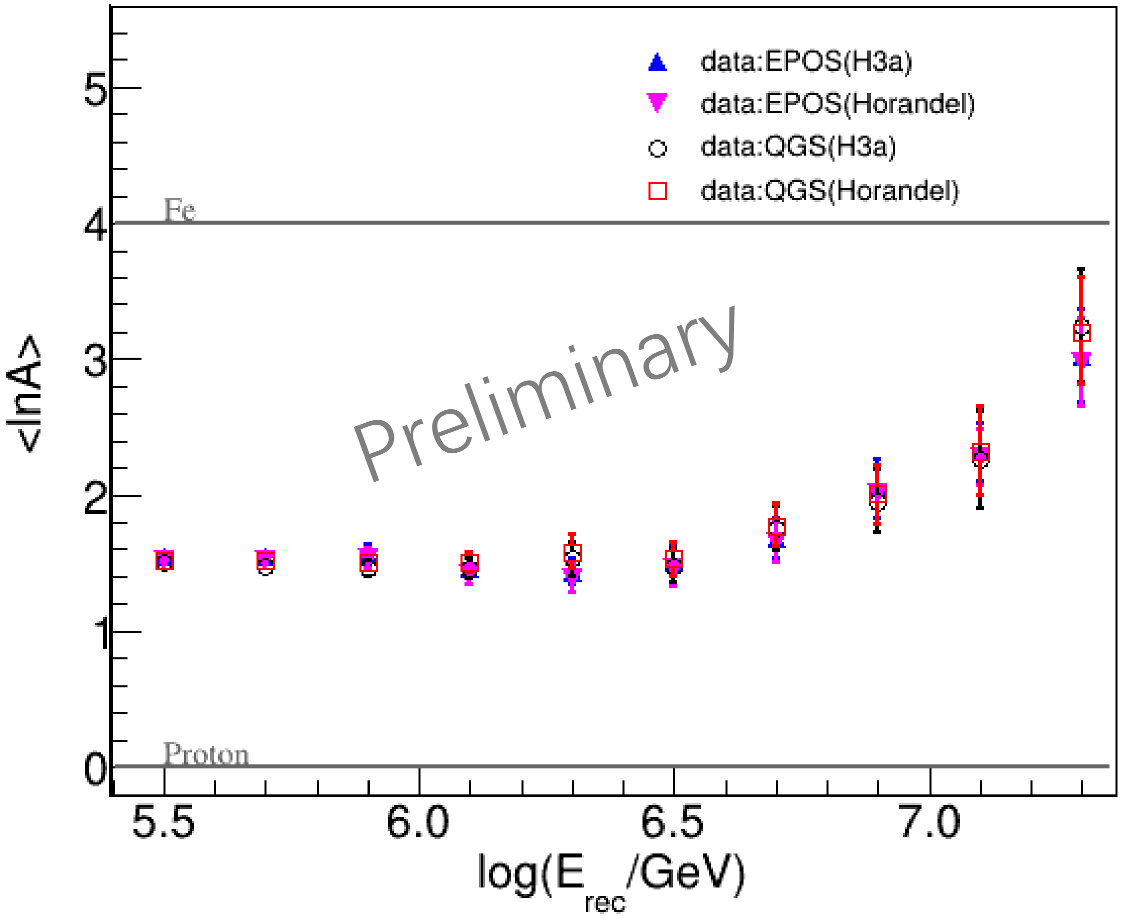
- The derived mean mass become heavier after several PeV.
- Different hardornic interaction model systematic error： ~8%
- IceCube/IceTop (H,He,O,Fe)
- Tunka-133 Xmax
- Kascade(QGSjet01) (H,He,C,Si,Fe)
- H3a –Gaisser H3a model
- H4a –Giasser H4a model

Mean mass measurement – using Horandel energy spectrum model



- Different energy spectrum model systematic error： ~4%

Mean mass measurement



能量	EPOS	⟨ln A⟩			QGS	⟨ln A⟩		
log(E/GeV)	H3a	σ	Horandel	σ	H3a	σ	Horandel	σ
5.5	1.543	0.044	1.518	0.044	1.502	0.041	1.511	0.041
5.7	1.546	0.051	1.523	0.051	1.480	0.048	1.519	0.047
5.9	1.563	0.069	1.533	0.069	1.462	0.061	1.503	0.059
6.1	1.457	0.074	1.416	0.075	1.461	0.072	1.503	0.071
6.3	1.435	0.103	1.380	0.103	1.525	0.126	1.583	0.124
6.5	1.497	0.139	1.461	0.140	1.480	0.131	1.531	0.126
6.7	1.684	0.148	1.646	0.148	1.762	0.164	1.776	0.159
6.9	2.050	0.217	2.007	0.214	1.956	0.230	2.004	0.216
7.1	2.314	0.217	2.275	0.214	2.263	0.351	2.321	0.330
7.3	3.023	0.338	2.970	0.328	3.237	0.417	3.205	0.390

Preliminary Summary

- The experimental data agree with the simulation.
- A composite variable $N_{\mu e}$, combining the shower size and the muon number, is almost weakly dependent on the cosmic ray mass and used to reconstruct the shower energy.
- The mean number of muon is measured by using KM2A muon detectors around the knee region, no obvious excess is found in muon abundance at least up to 30 PeV comparing with the simulation results of iron and proton.
- The derived mean mass become heavier after several PeV.
- Hadronic interaction model: 8%
- Different energy spectra model: 4%

Thanks