Unveiling the Nature of the Cosmic Ray Knee by LHAASO

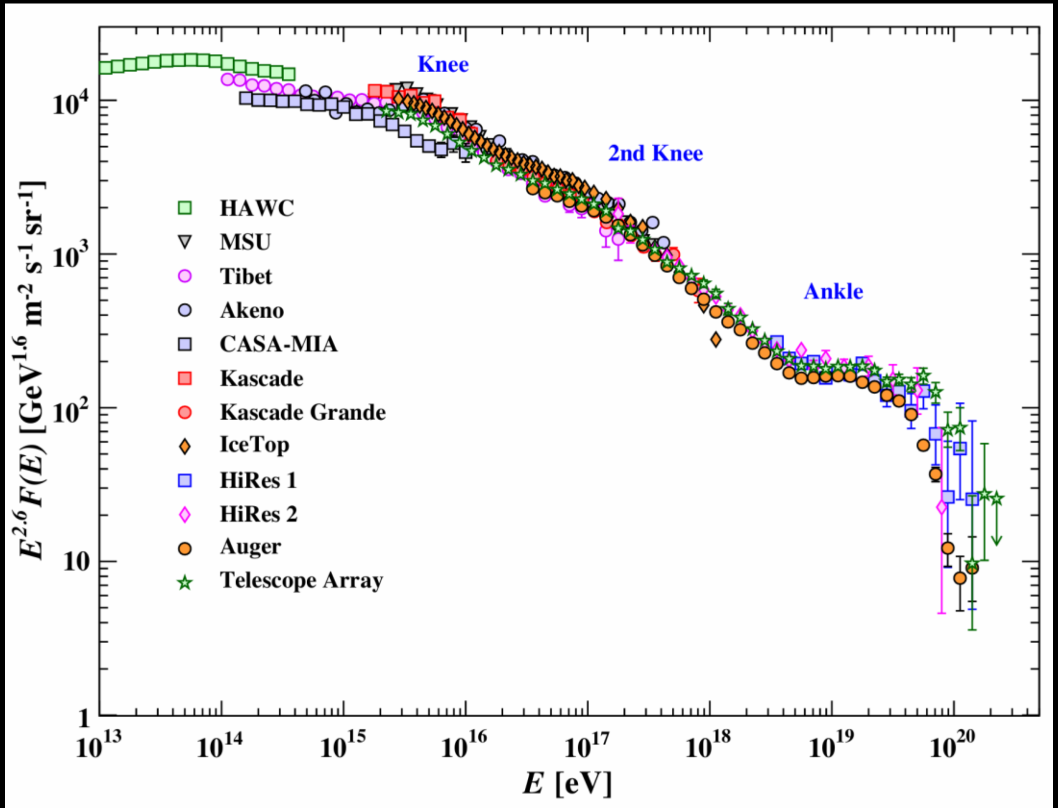
Huihai He
Institute of High Energy Physics, CAS
2024-12-10

Outline

- Introduction
- A calorimetric energy estimator PRD 106, 123028(2022)
- The all particle energy spectrum and <lnA> in 0.3-30 PeV PRL 132, 131002 (2024)
- The total logarithmic mass
- The nature of the cosmic ray spectrum knee arXiv:2411.13793
- Discovery of an ankle-like structure
- Summary

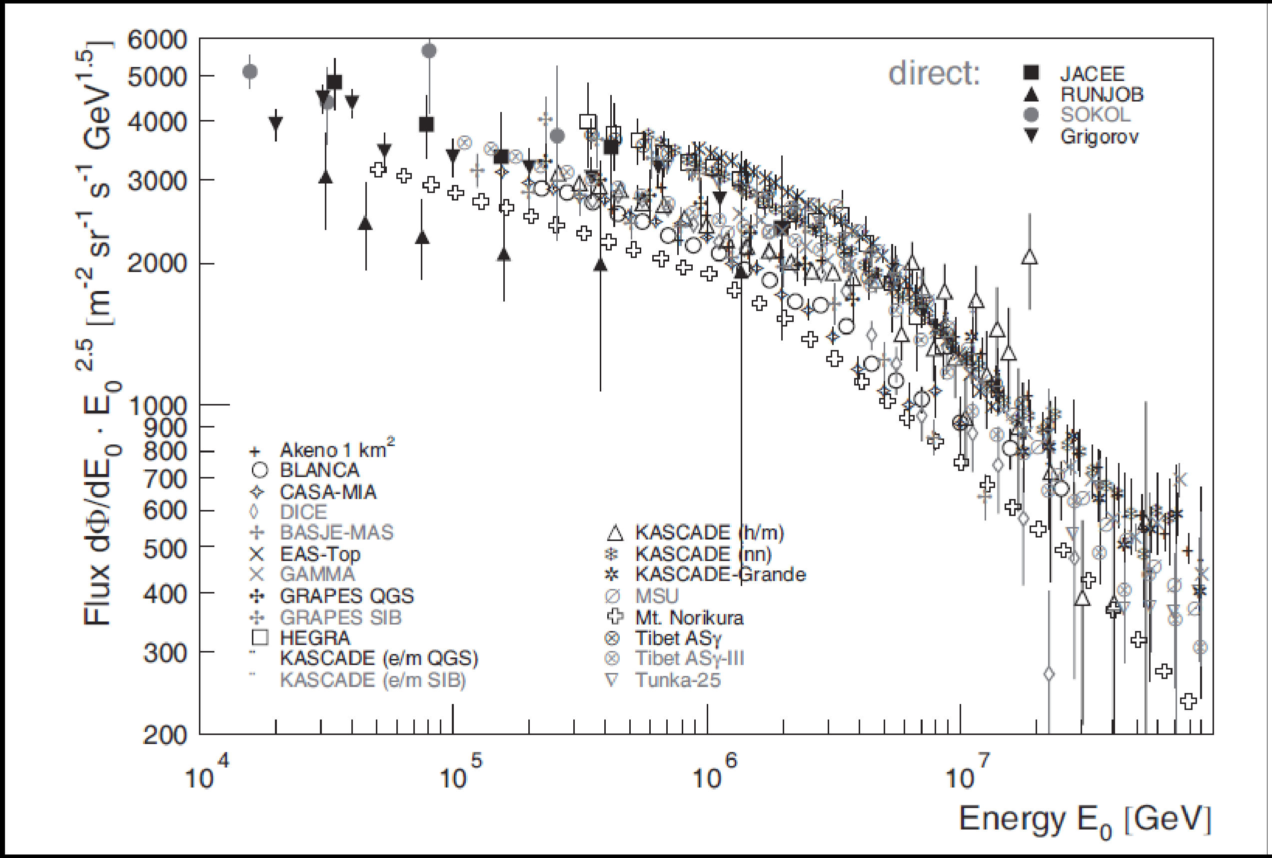
The knee: a 65-year-old puzzle

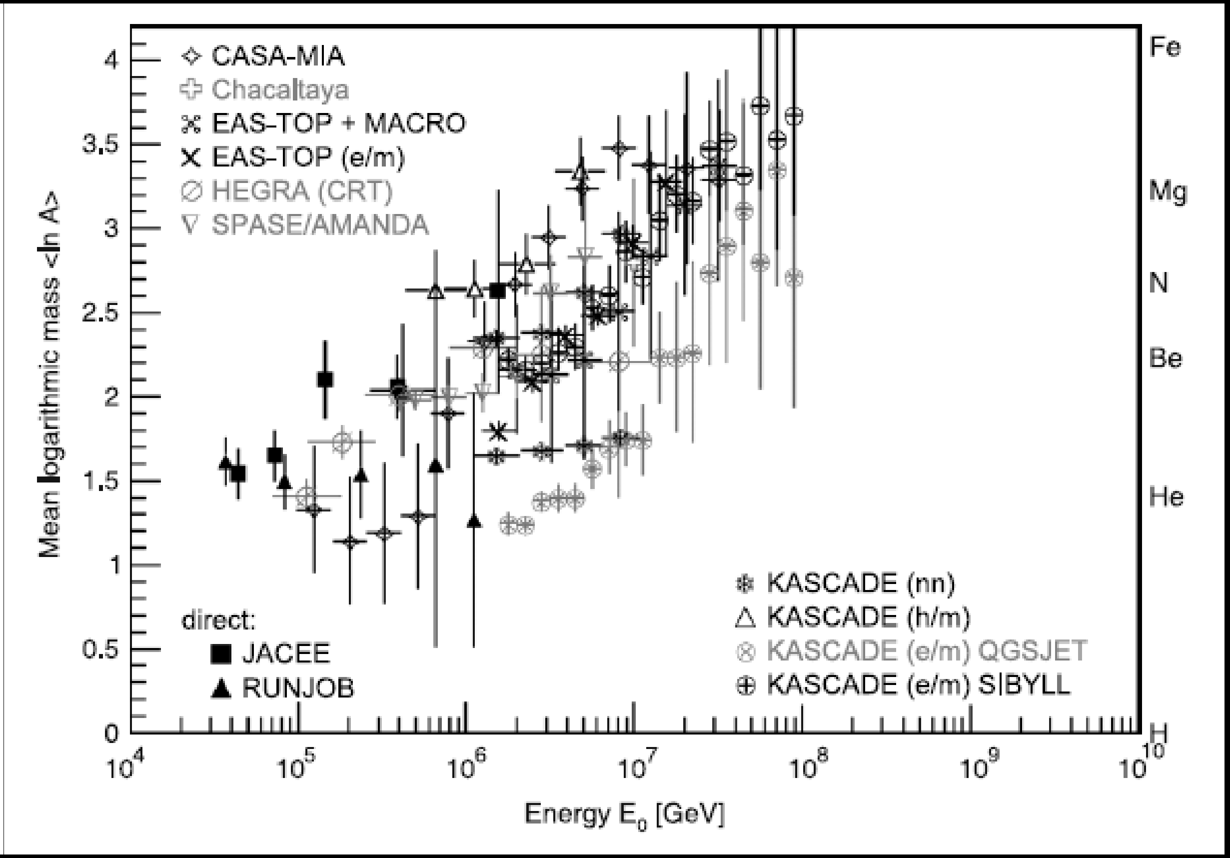
- The most striking feature in the cosmic ray energy spectrum, whose origin remains enigmatic
- A key to the origin, acceleration and propagation of GCRs
- A result of subsequent cutoffs for individual elements, starting with the proton component
  - Z-dependent: $E_c = ZE_p$, associated with acceleration or propagation processes
  - A-dependent: $E_c = AE_p$, associated with new physics
  - Constant: $E_c = E_p$



Credit: Beringer et al.

A mess in current measurements





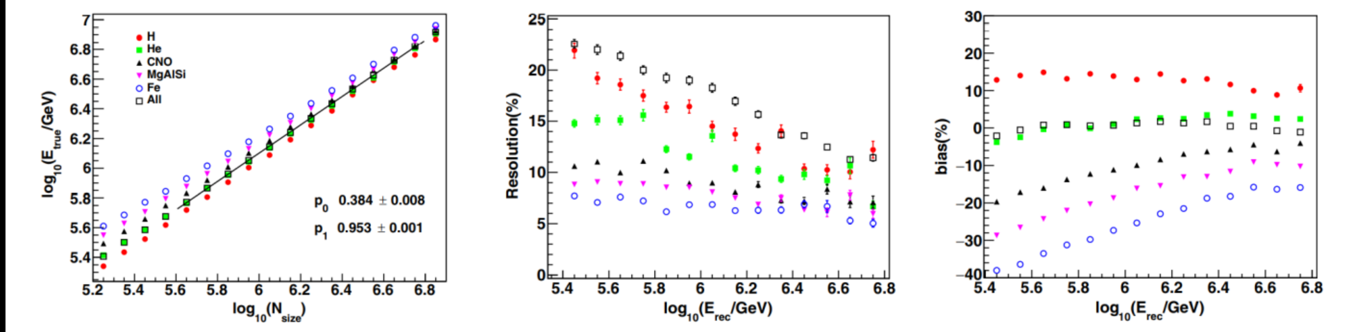
Precision measurements of the spectrum and mass are mandatory

Challenges in indirect measurement

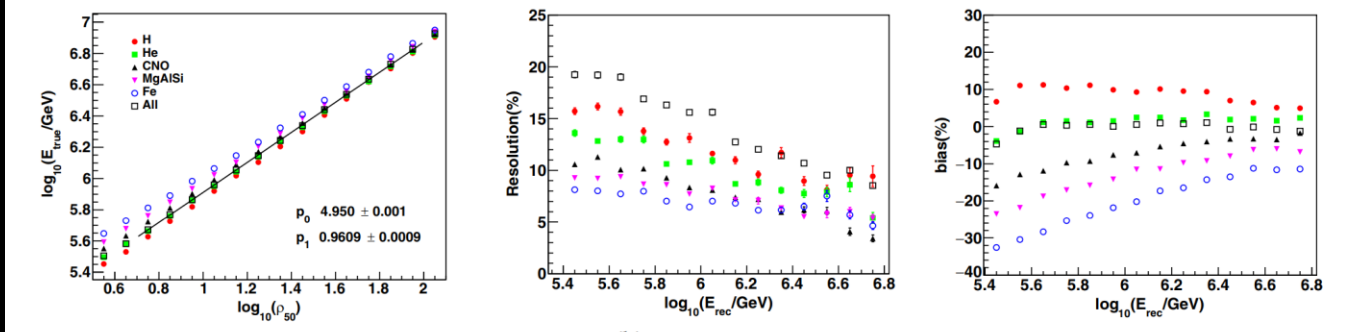
- Spectra of single species: seriously dependent on MC
  - Interaction models
  - Composition models
  - Consistency between MC and data
- All particle spectrum
  - Composition-dependency in primary energy reconstruction
  - Model-dependency in both composition discrimination and energy reconstruction
  - Measurement of shower front, and far from shower maximum
- <lnA>: energy-dependent, interaction model dependent

Problems of traditional energy estimators

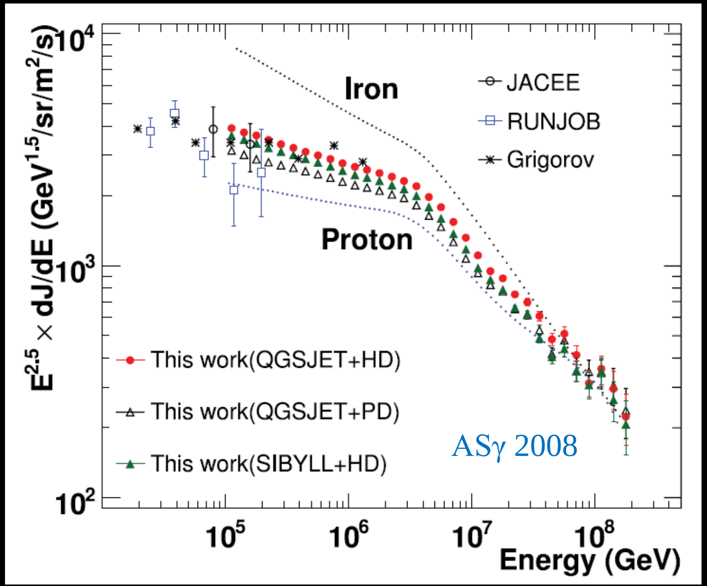
- Shower size (or density) is a function of primary energy and mass

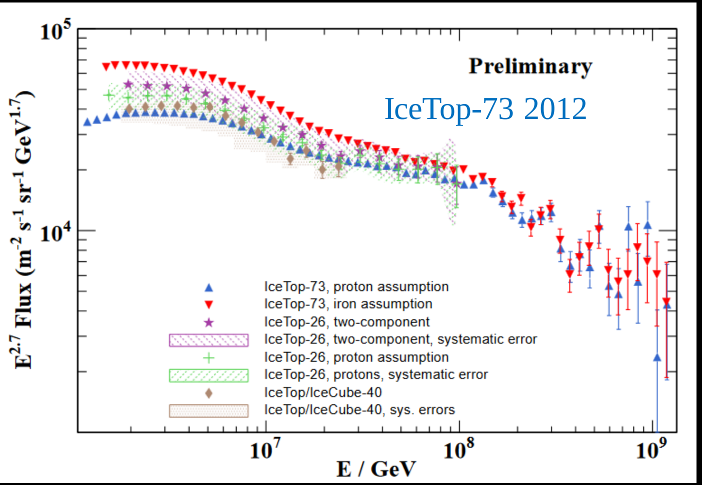


(a) E_{true} vs. N_{size}



(b) E_{true} vs. ρ_{50}





A composition-independent energy estimator

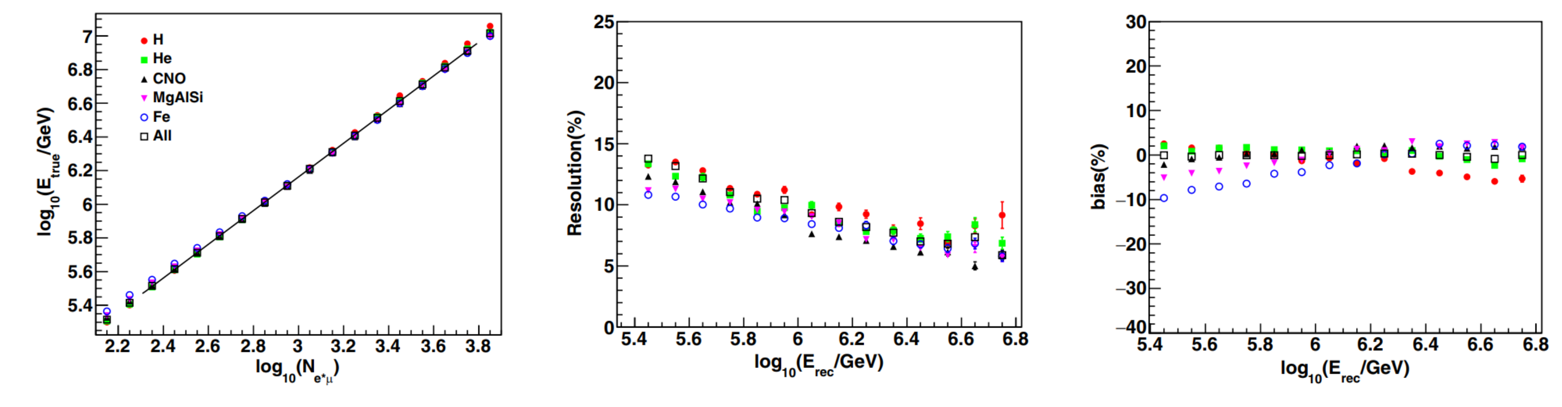
necessary and sufficient condition: α =1

- Superposition principle

$$N_e \propto E^{\alpha} A^{1-\alpha}$$

$$N_\mu \propto E^{\beta} A^{1-\beta} \qquad (\alpha = 1.046, \beta = 0.9)$$

$$N_{e*\mu} \equiv N_e^{\frac{1-\beta}{\alpha-\beta}} N_\mu^{\frac{\alpha-1}{\alpha-\beta}} = N_e^{0.68} N_\mu^{0.32} \propto E$$

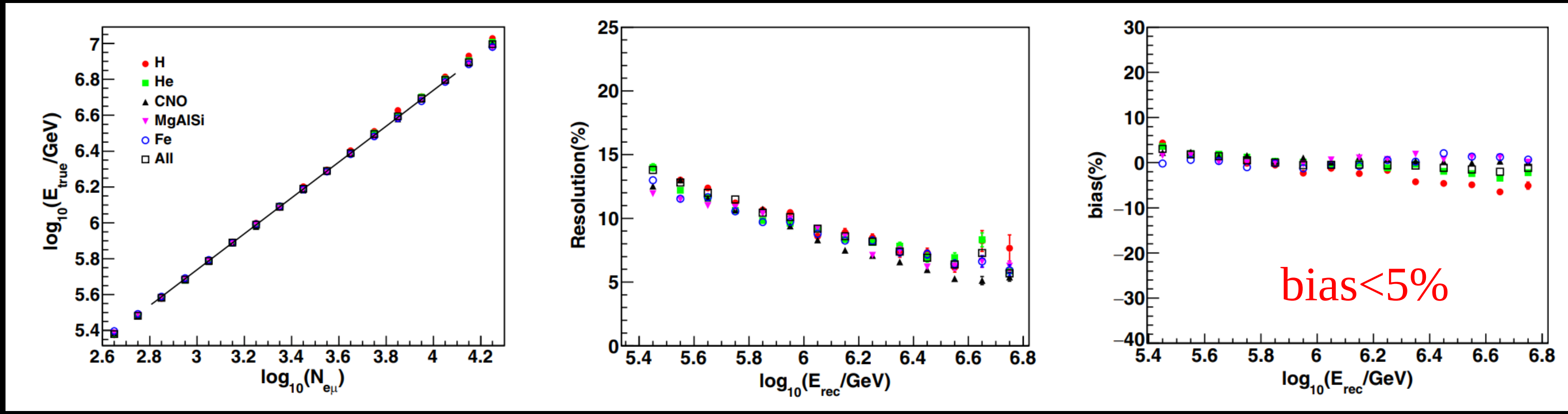


- Heitler-Matthews model
  - calorimetric

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

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

$$N_{e\mu} \equiv N_e + \frac{\xi_c^\pi}{g\xi_c^e} N_\mu = N_e + 25 N_\mu \propto E$$

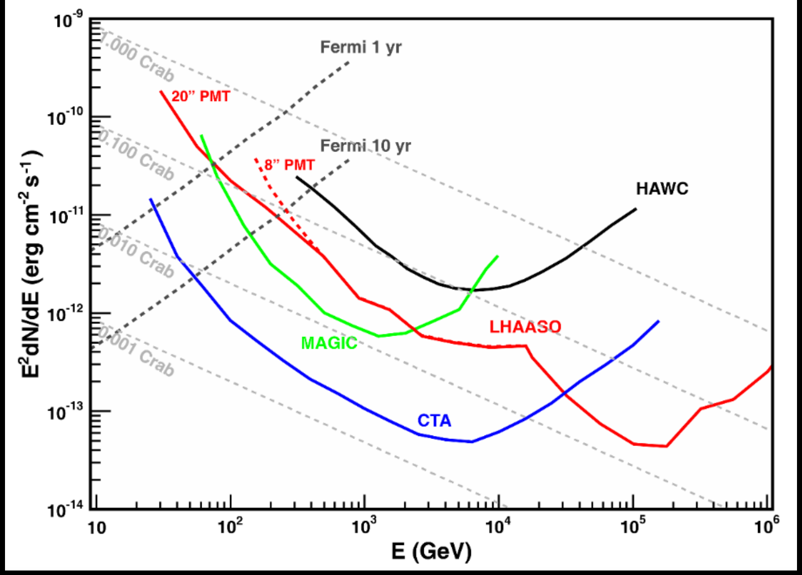


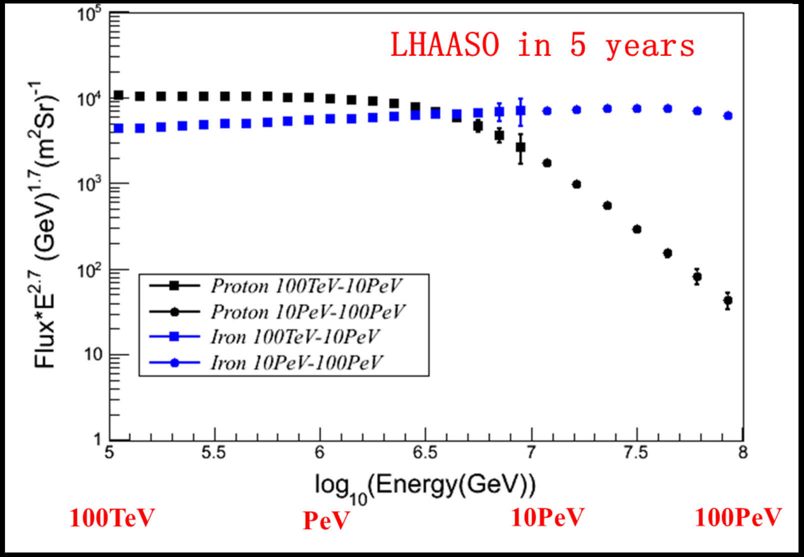
Works only at shower maximum!

Weaker dependence on interaction models

Major scientific goals

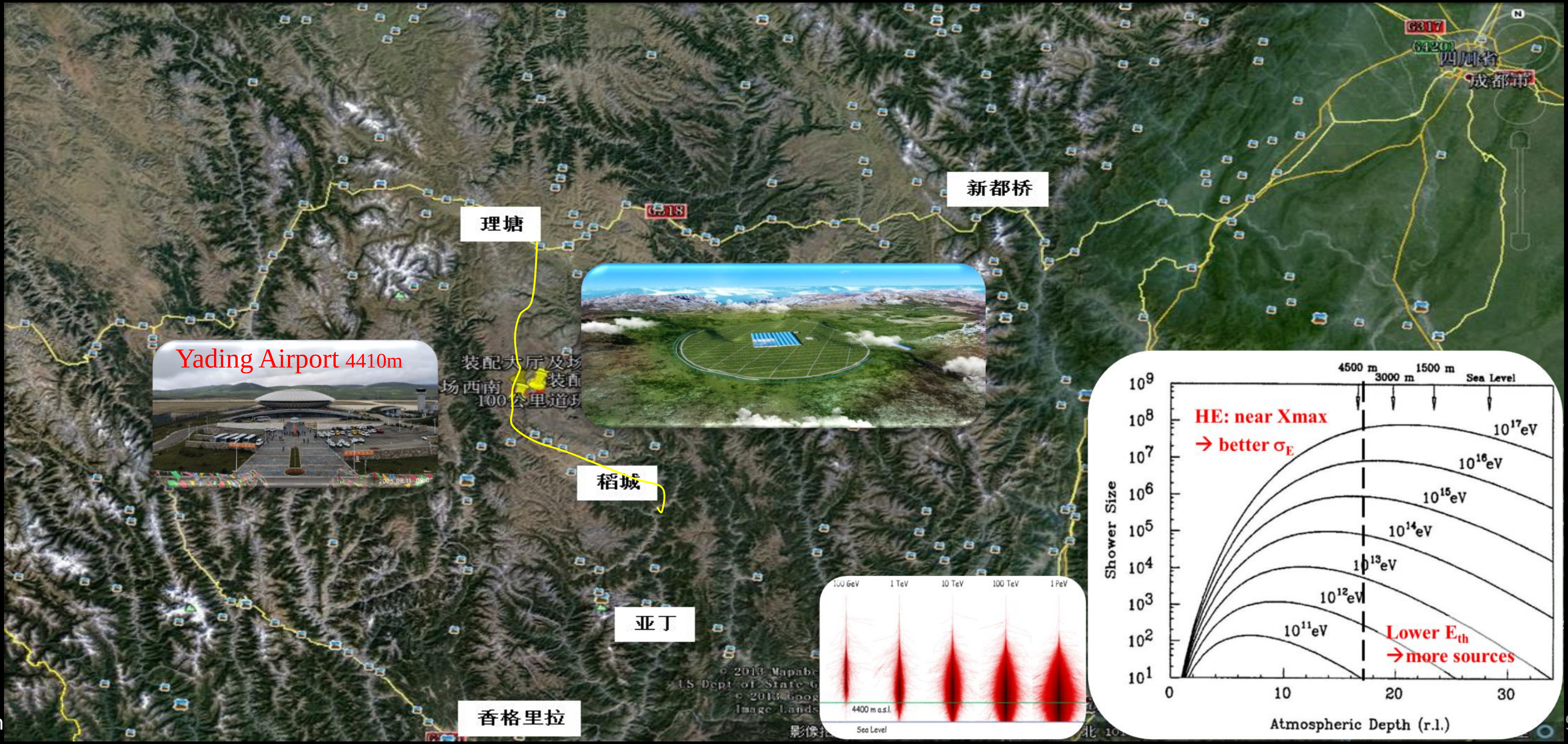
- Origin of GCRs
  - Searching for GCR sources by measuring SED with an unprecedented sensitivity of 1% I_{Crab} at 50 TeV
  - Energy spectra for individual compositions with energy from 10 TeV to 1 EeV, where the spectrum knees are located
- Gamma ray astronomy
  - Searching for TeV γ sources, especially extended and transient ones, with an unprecedented survey sensitivity of 1% I_{Crab} at 3TeV.
- New physics frontier
  - dark matter, Lorentz invariance, new physics beyond LHC energy, etc





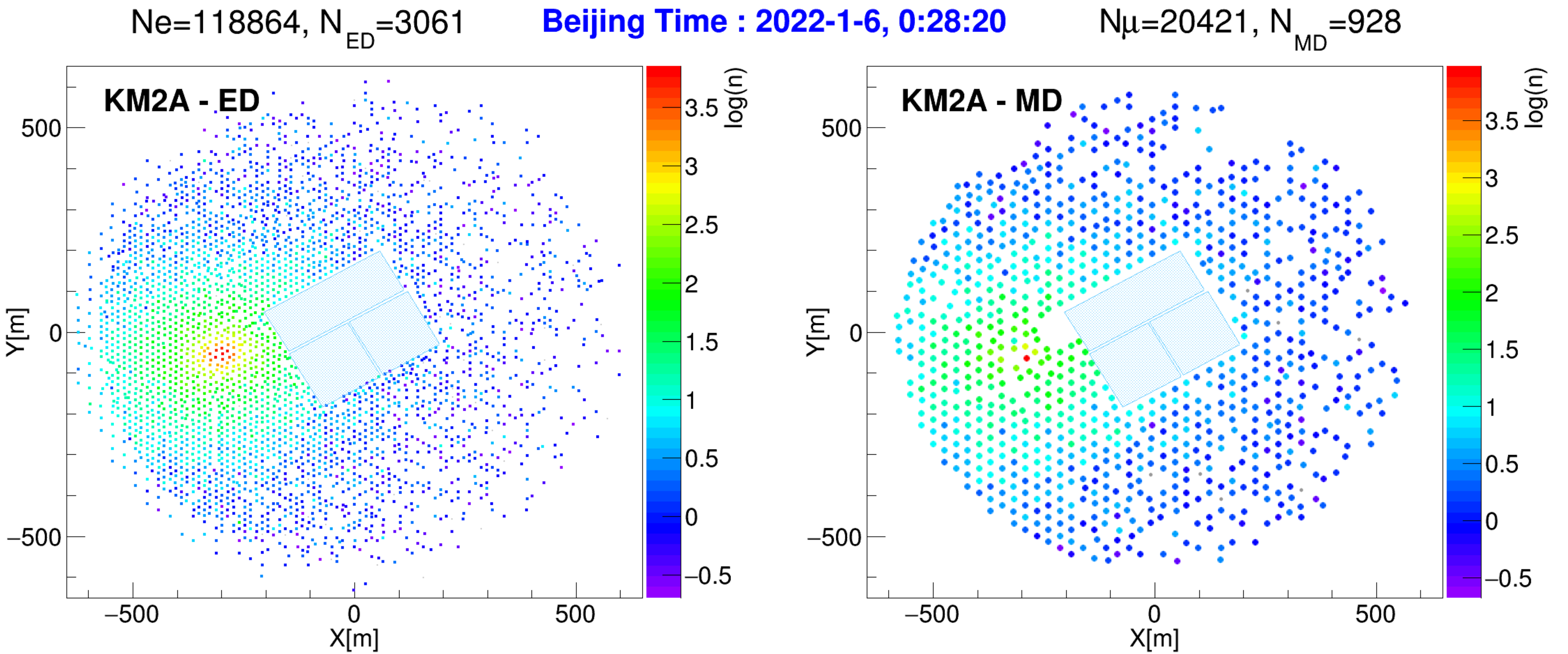
Large High Altitude Air Shower Observatory

Mt. Haizi (4410 m a.s.l., 29°21’ 27.6” N, 100°08’19.6” E), Sichuan, China

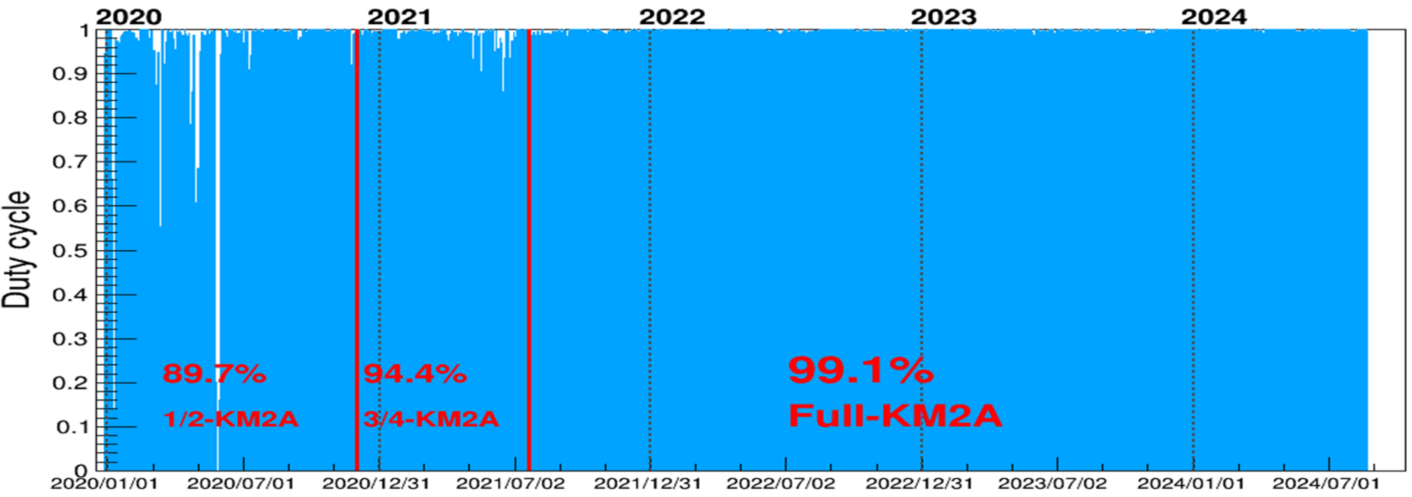


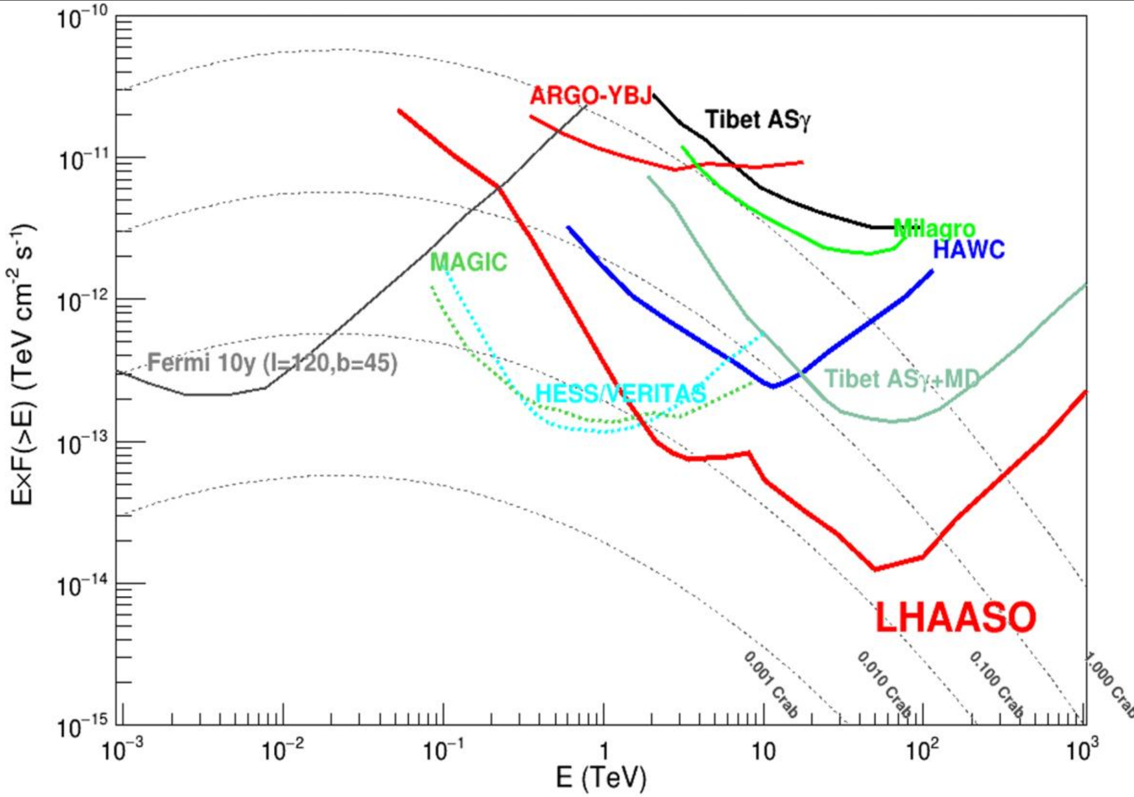
KM2A: Kilometer-square Array

- **Area: 1.3 km^2**
- **Energy Range: 0.01-10 PeV (γ), 10^{14}-10^{18} eV (h)**

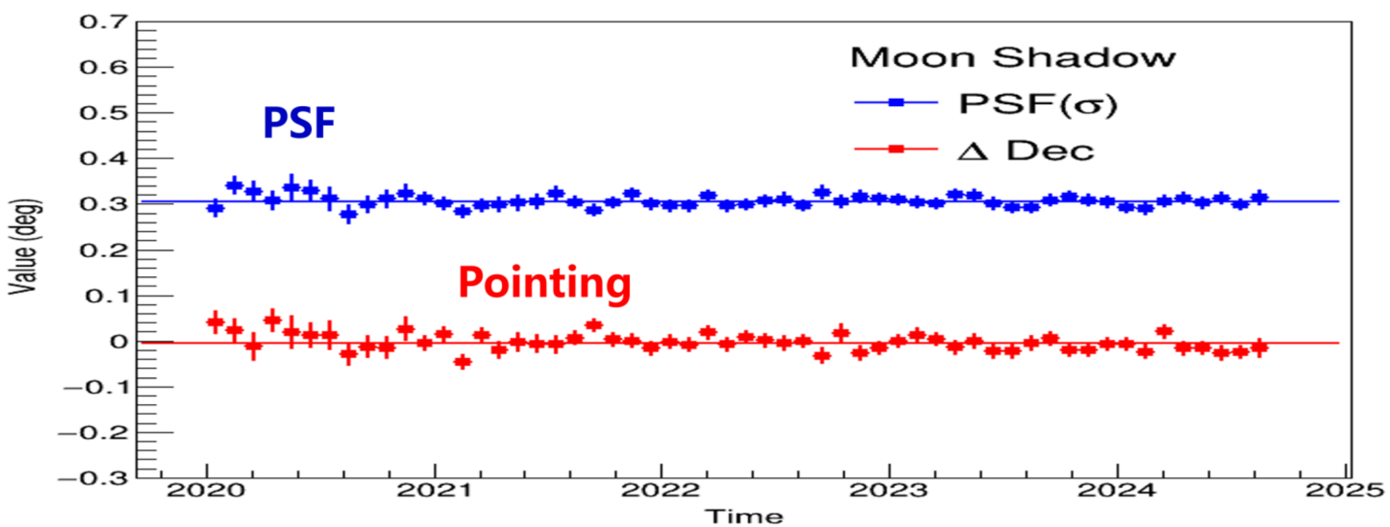


Duty cycle >99%, 4.5 years data

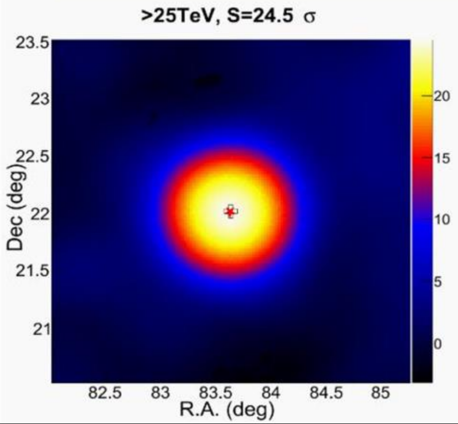




Stable pointing and angular resolution

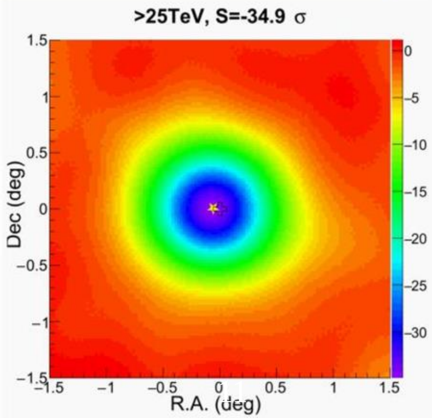


Crab Nebula



per Month

Moon shadow

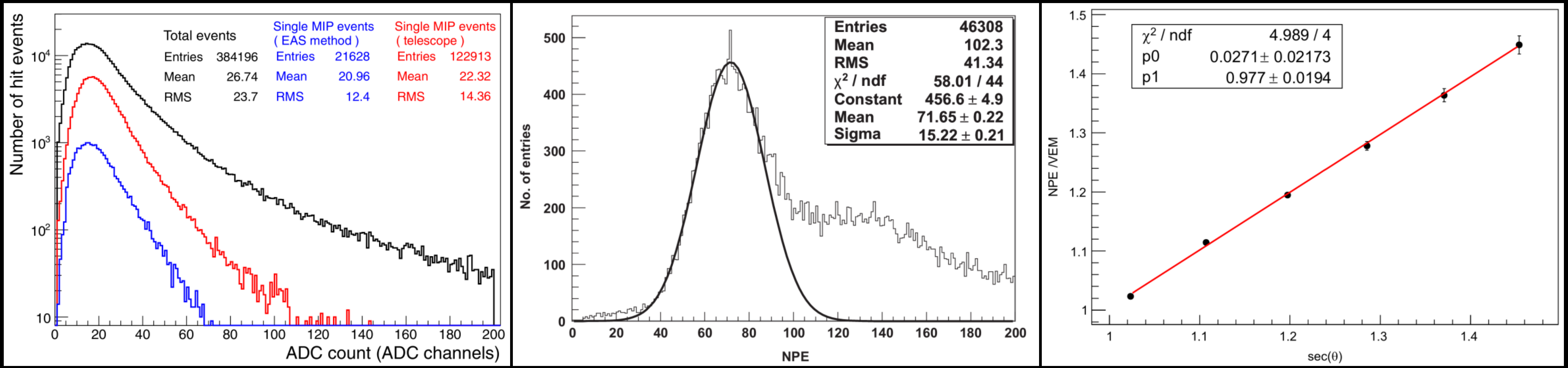


KM2A detector calibration for data and MC

- For data, as counters, detector charges
  - of EDs are calibrated by using single particles in EAS
  - of MDs are calibrated by using VEMs

APP 100 (2018) 22–28

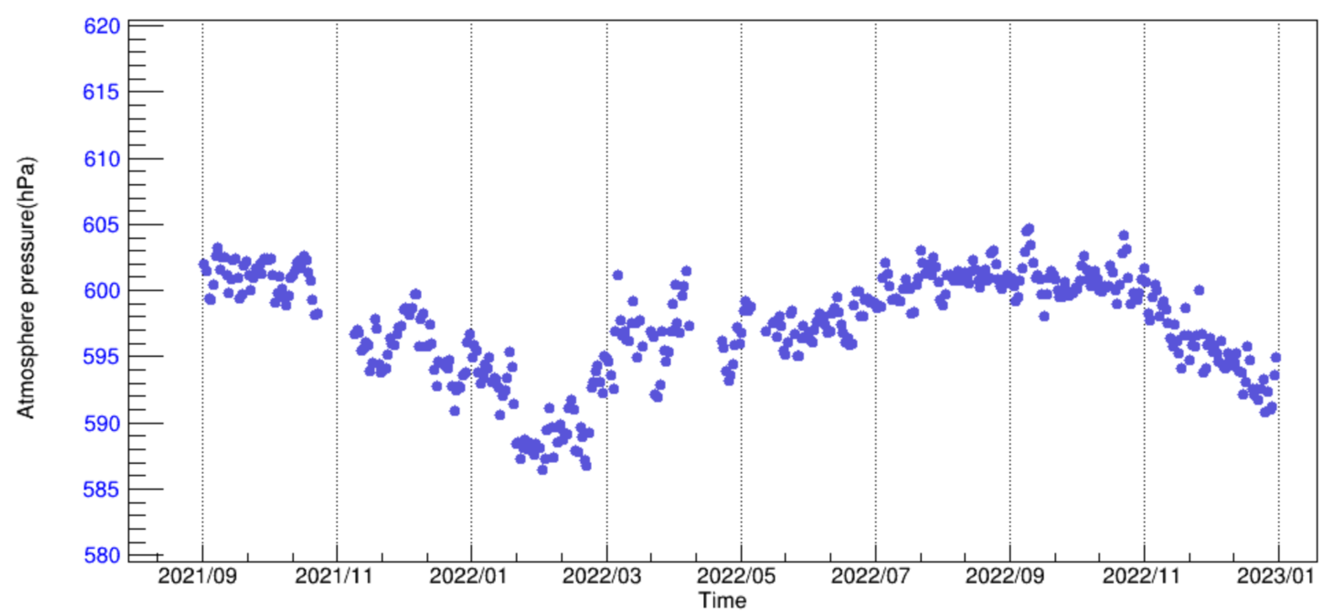
NIMA 789 (2015) 143–149

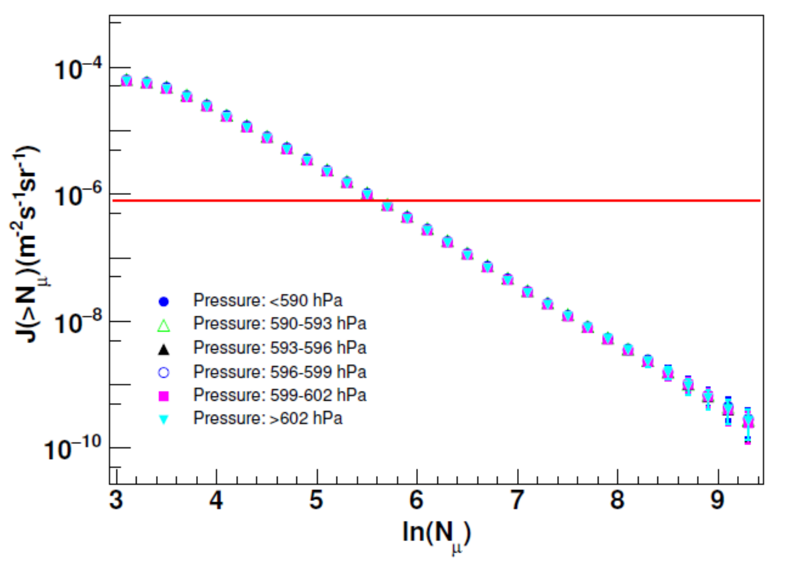


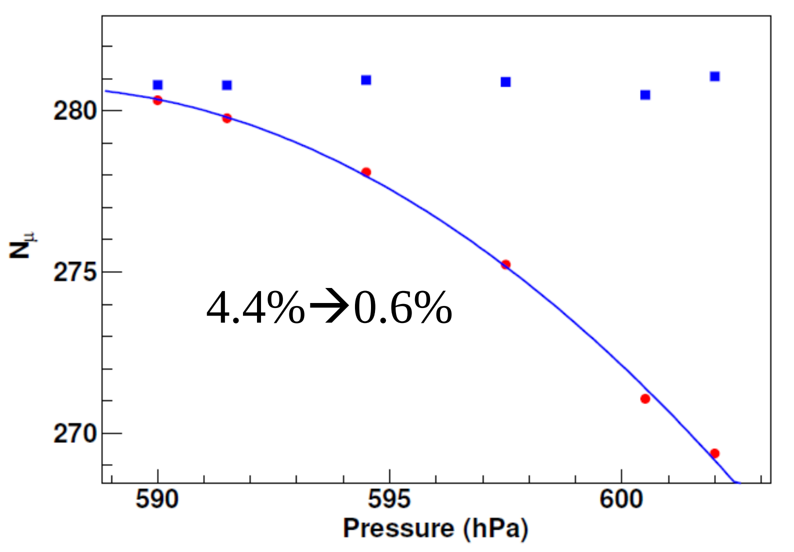
- For MC, charges of EDs and MDs are calibrated as for data

Air pressure correction

- CIC (constant intensity cut) is used to calibrate the air pressure effect
- Both N_e and N_μ of data are corrected to the air pressure in MC



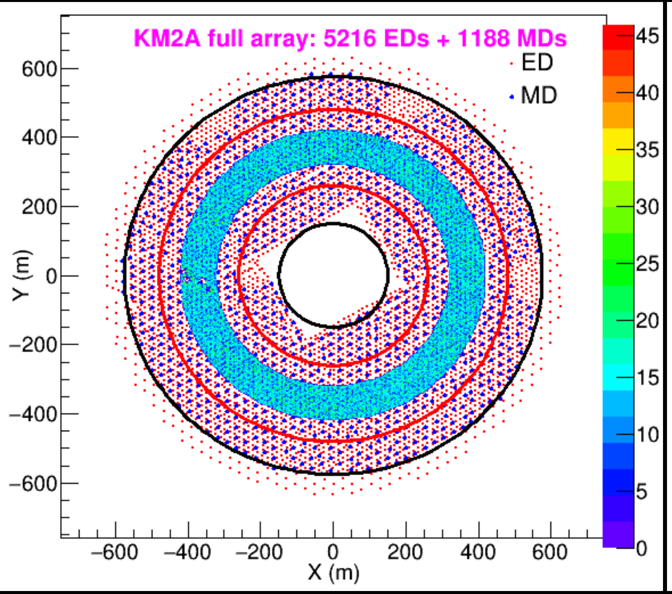


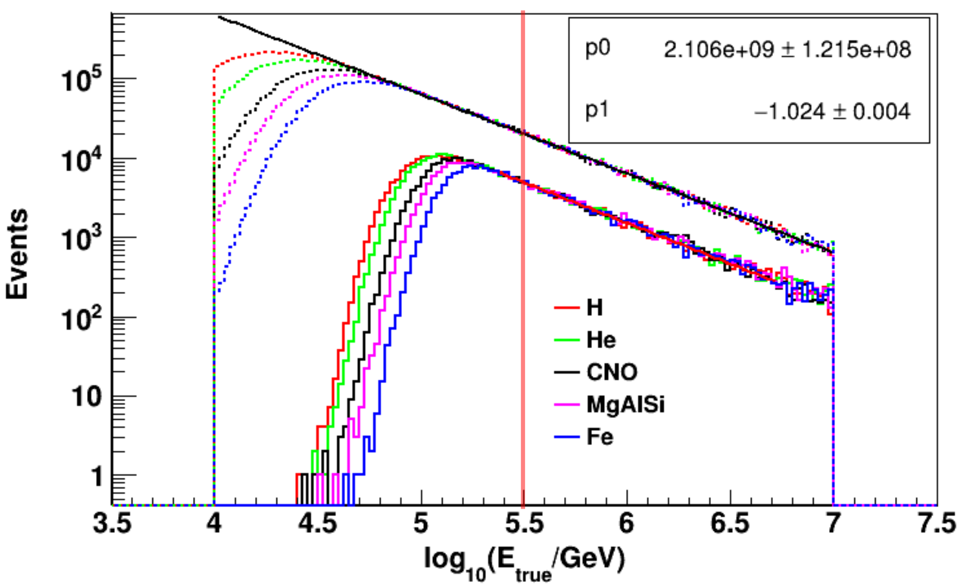


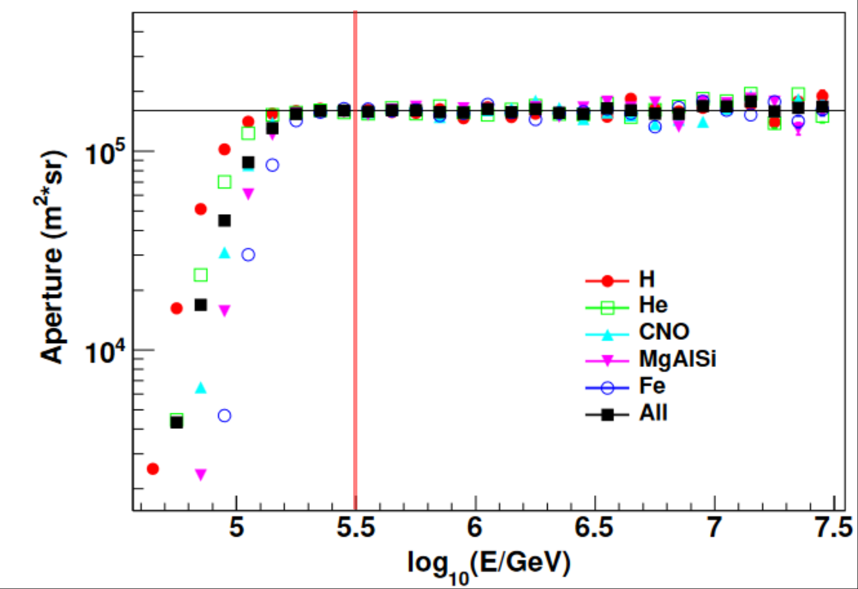
Event selection

- Event selection criteria:
  - θ: 10° - 30° → (610-690 g/cm^2) ~ Xmax (0.3-30 PeV)
  - R_{core}: 320 - 420 m → shower well contained, full efficiency @>0.3PeV GF is MC-independent
- Ne & Nμ in (40-200m) to avoid punch-through

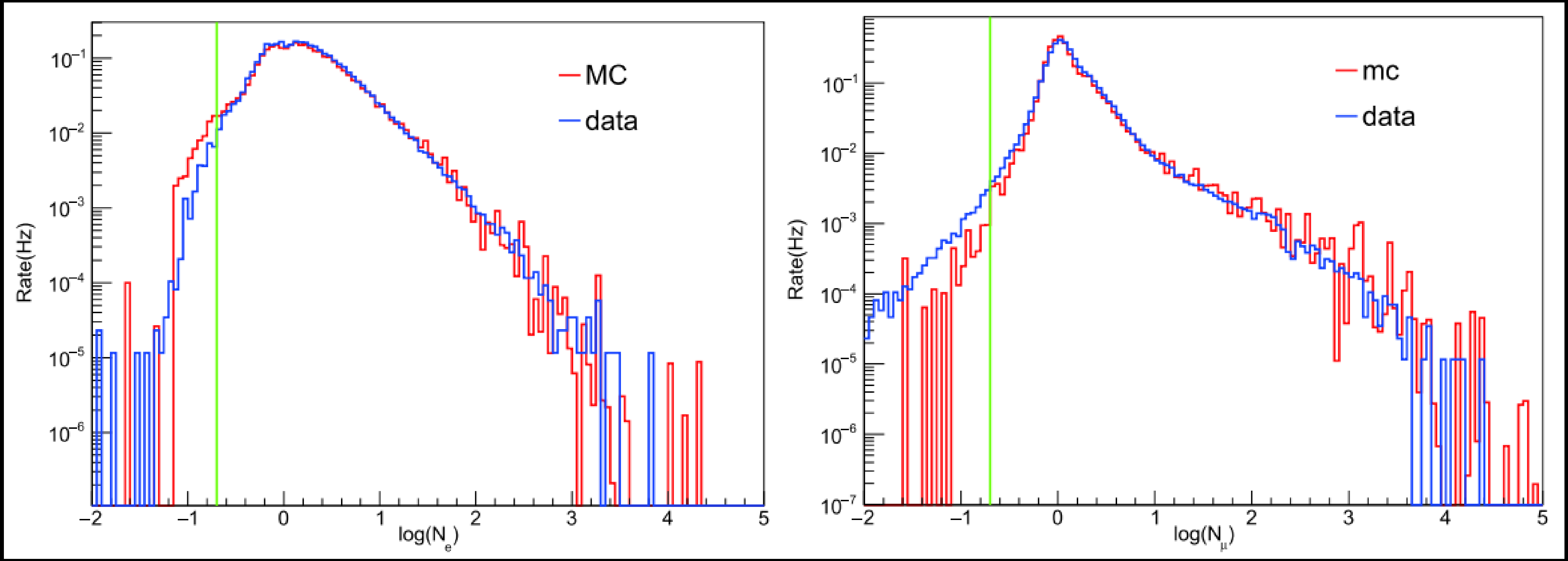
$$GF = \pi(R_1^2 - R_2^2)\int_{10^\circ}^{30^\circ} \sin\theta\cos\theta\, d\theta \int_{0^\circ}^{360^\circ} d\varphi = 0.16(km^2 sr)$$





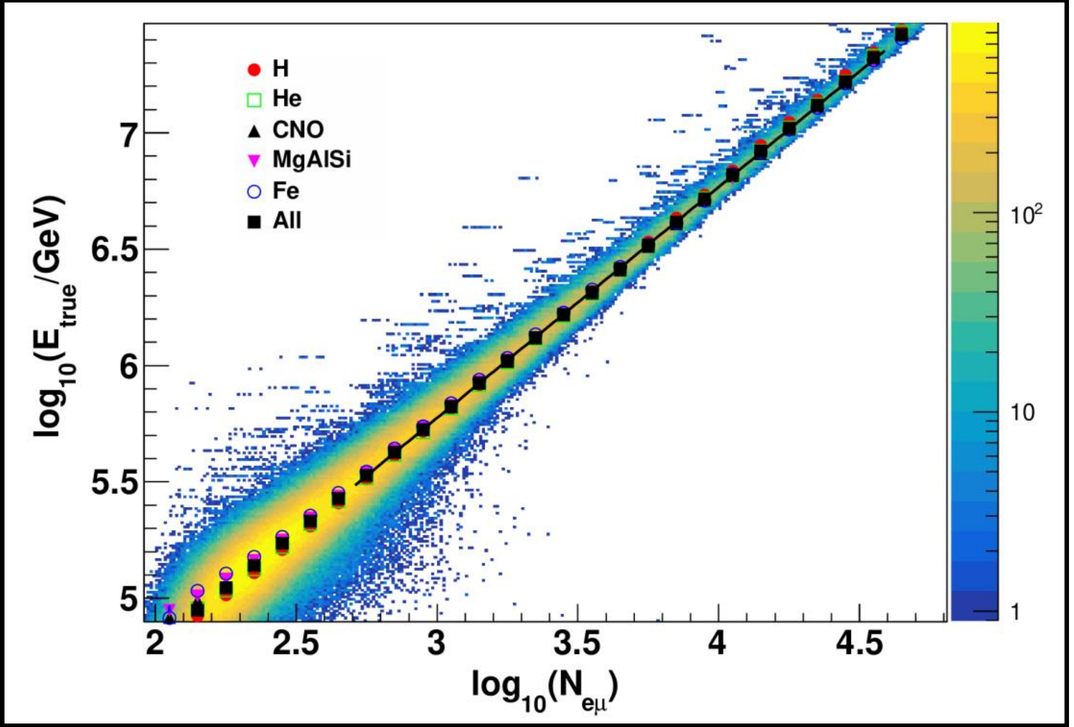


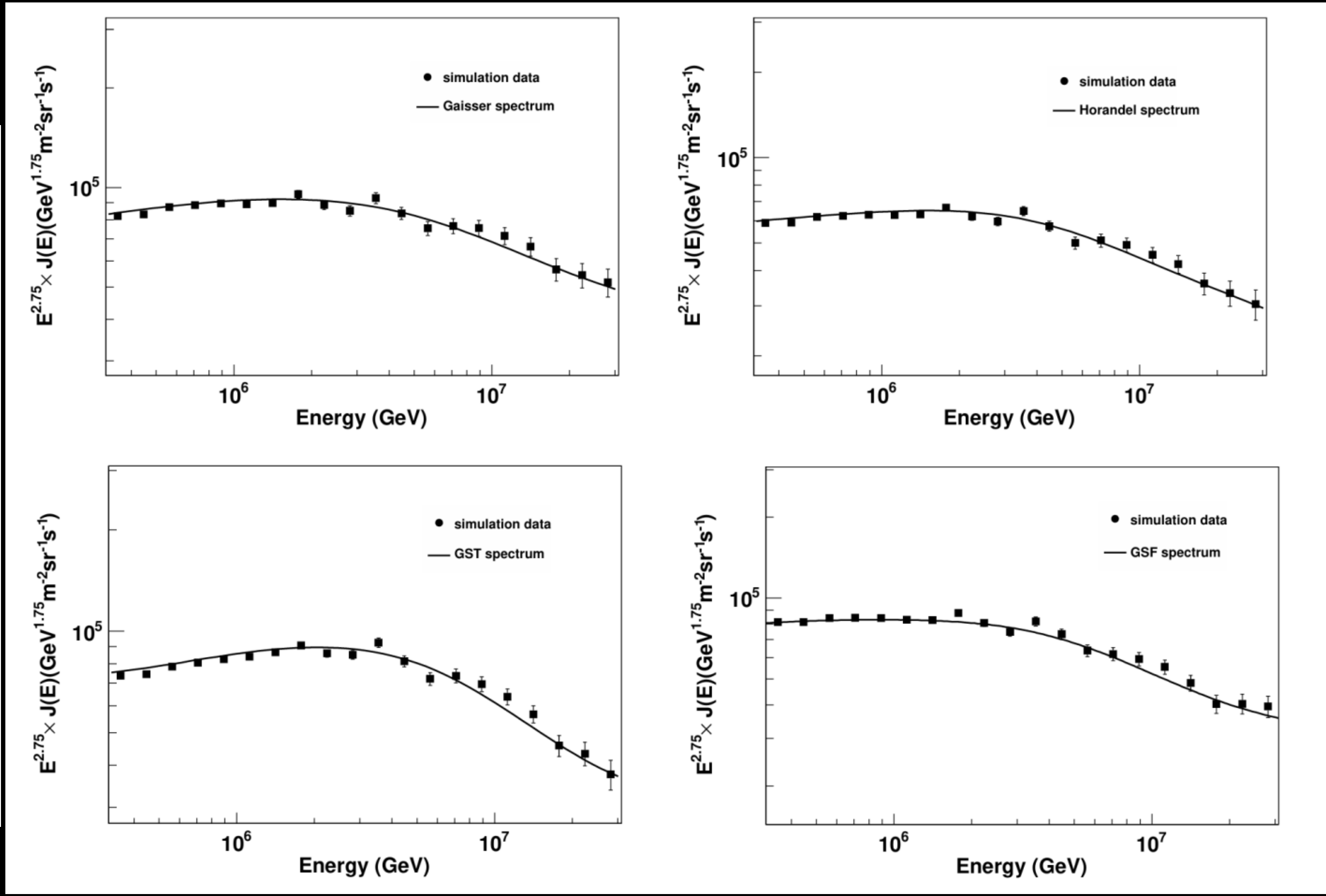
Comparison between MC and data



Energy reconstruction

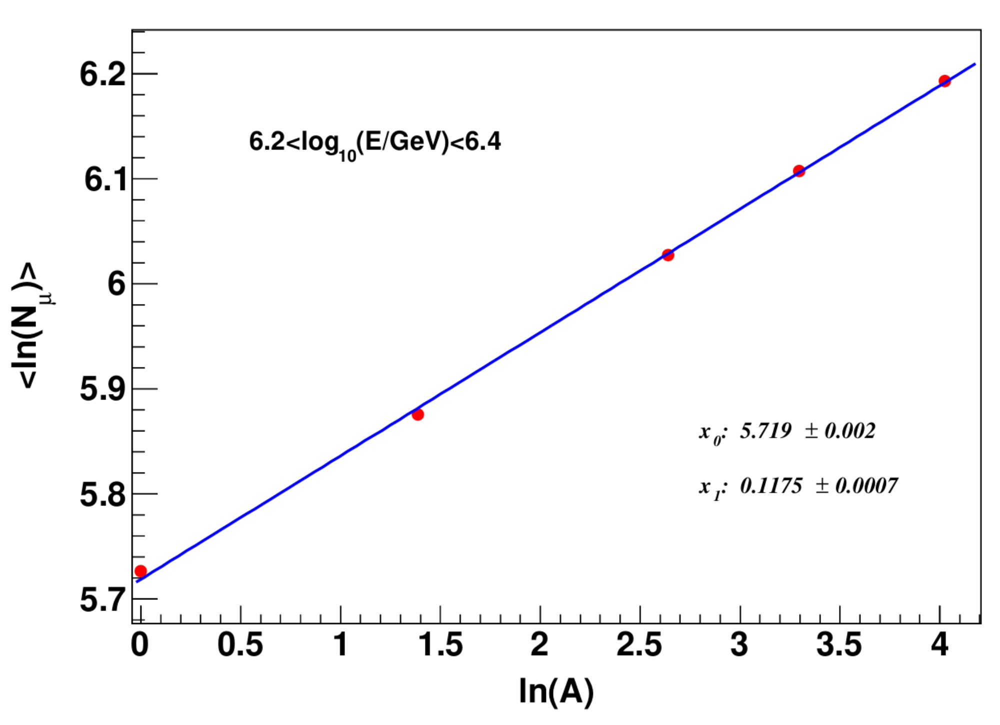
$$N_{e\mu} = N_e + 2.8N_\mu$$

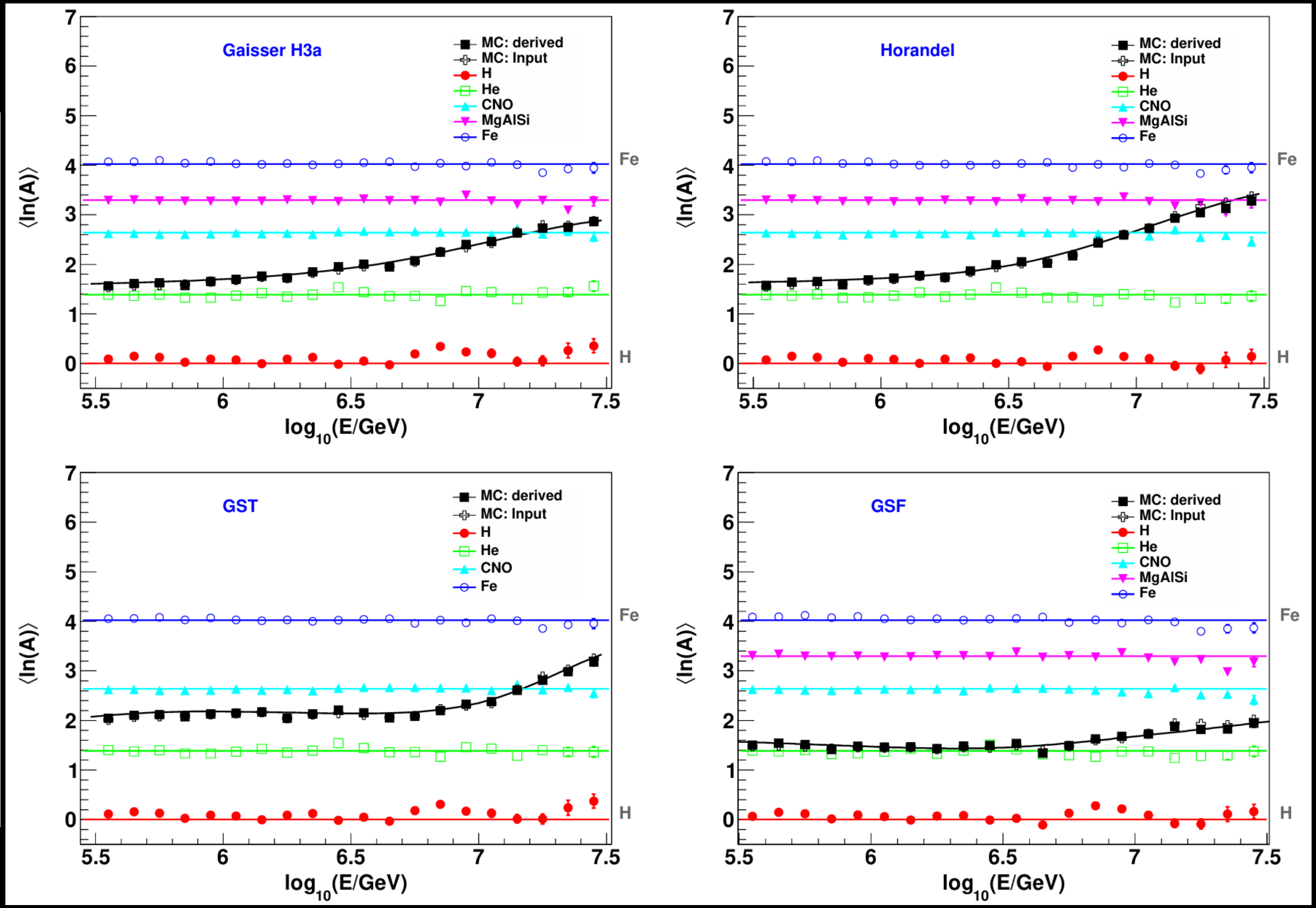




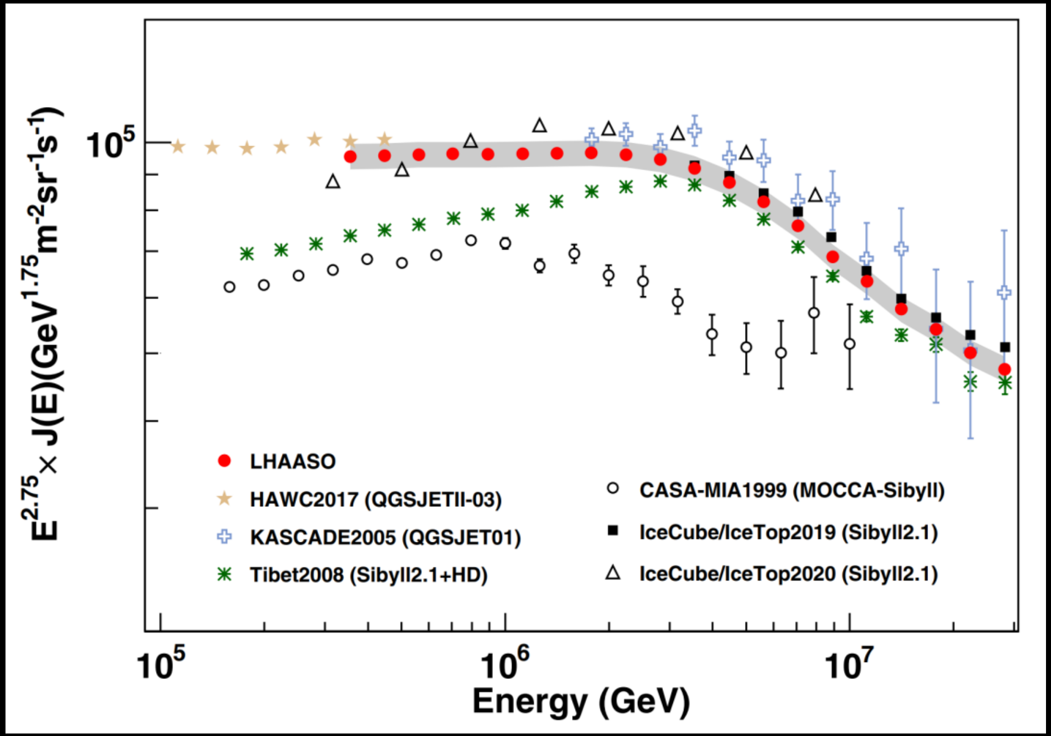
<lnA> reconstruction

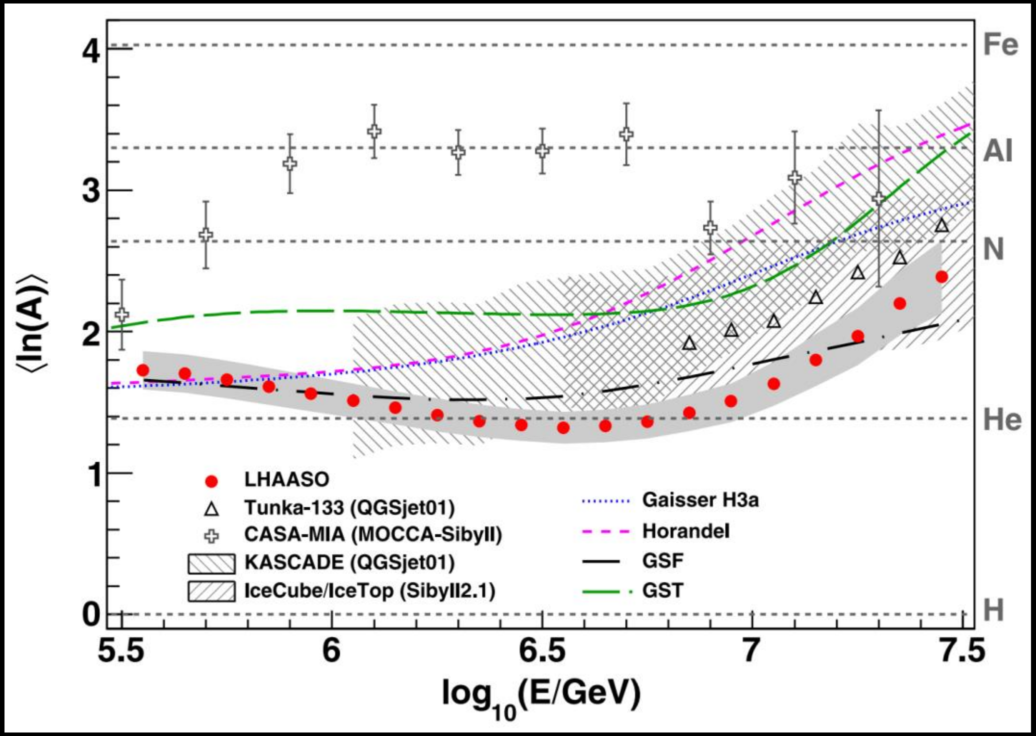
$$\ln N_\mu = x_0 + x_1 \cdot \ln A$$





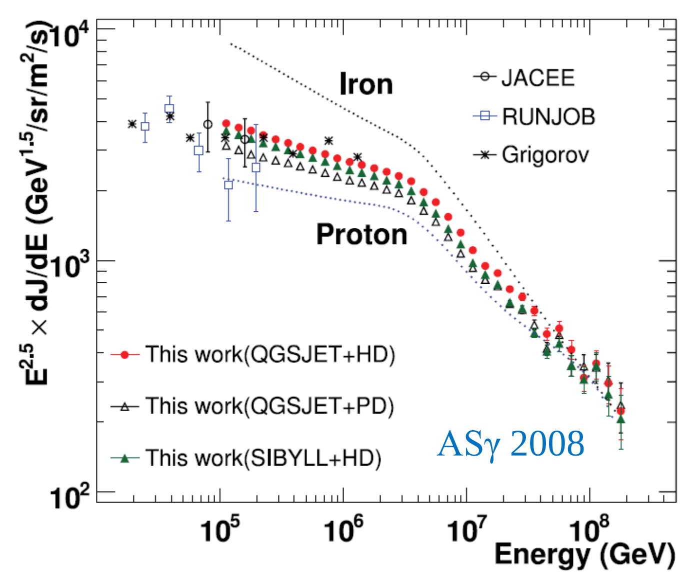
All-particle energy spectrum & <lnA>

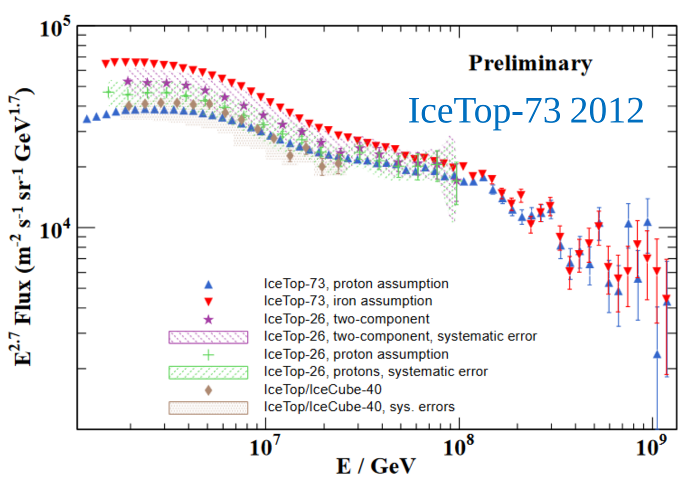


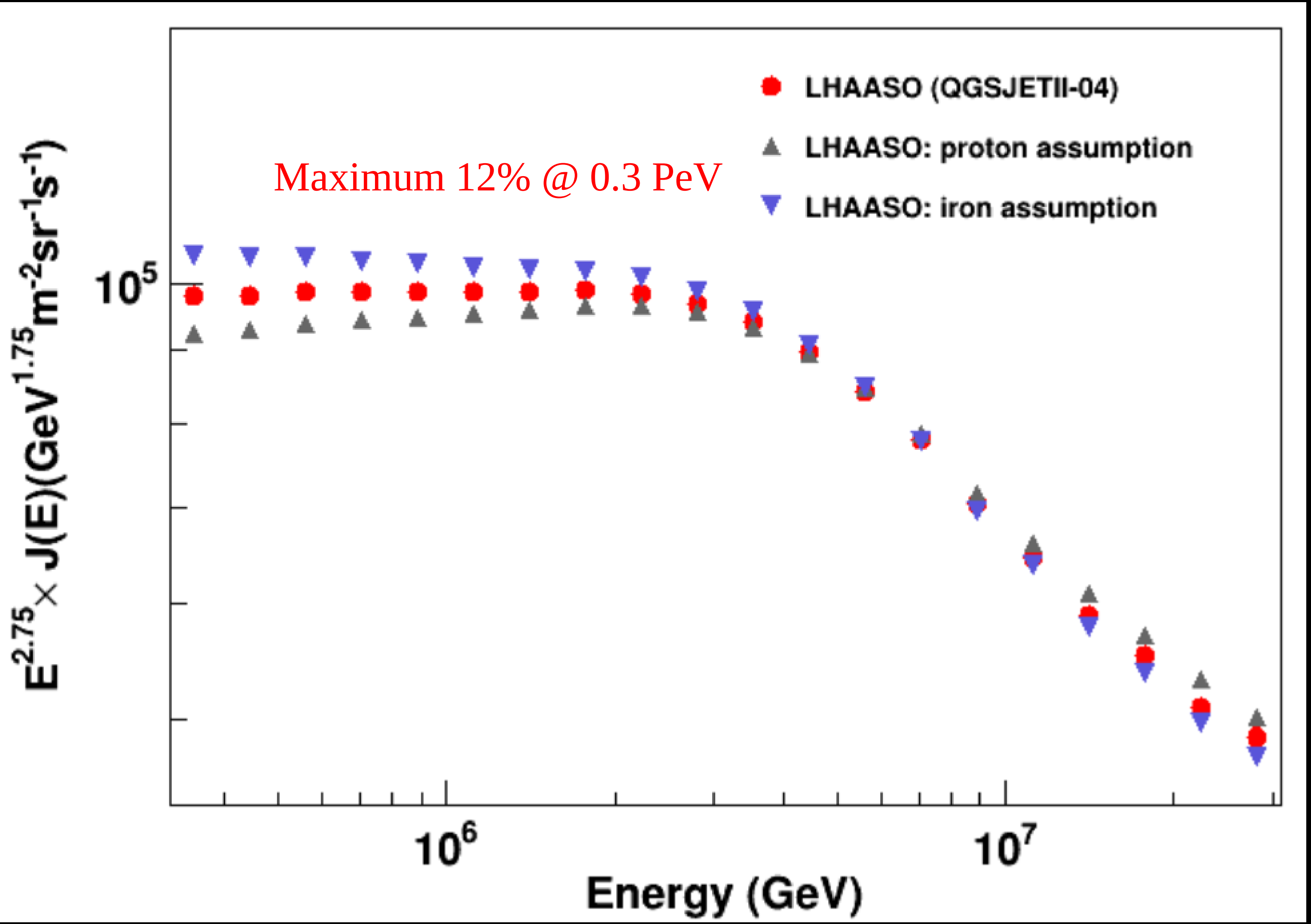


	Flux $J(E)$	$\langle \ln(A) \rangle$
Air preesure	$\pm 3\%$	$\pm 4\%$
Composition models	$\pm 1.5\%$	$\pm 3\%$
Interaction models	$\pm 2.5\%$	$\pm 6\%$

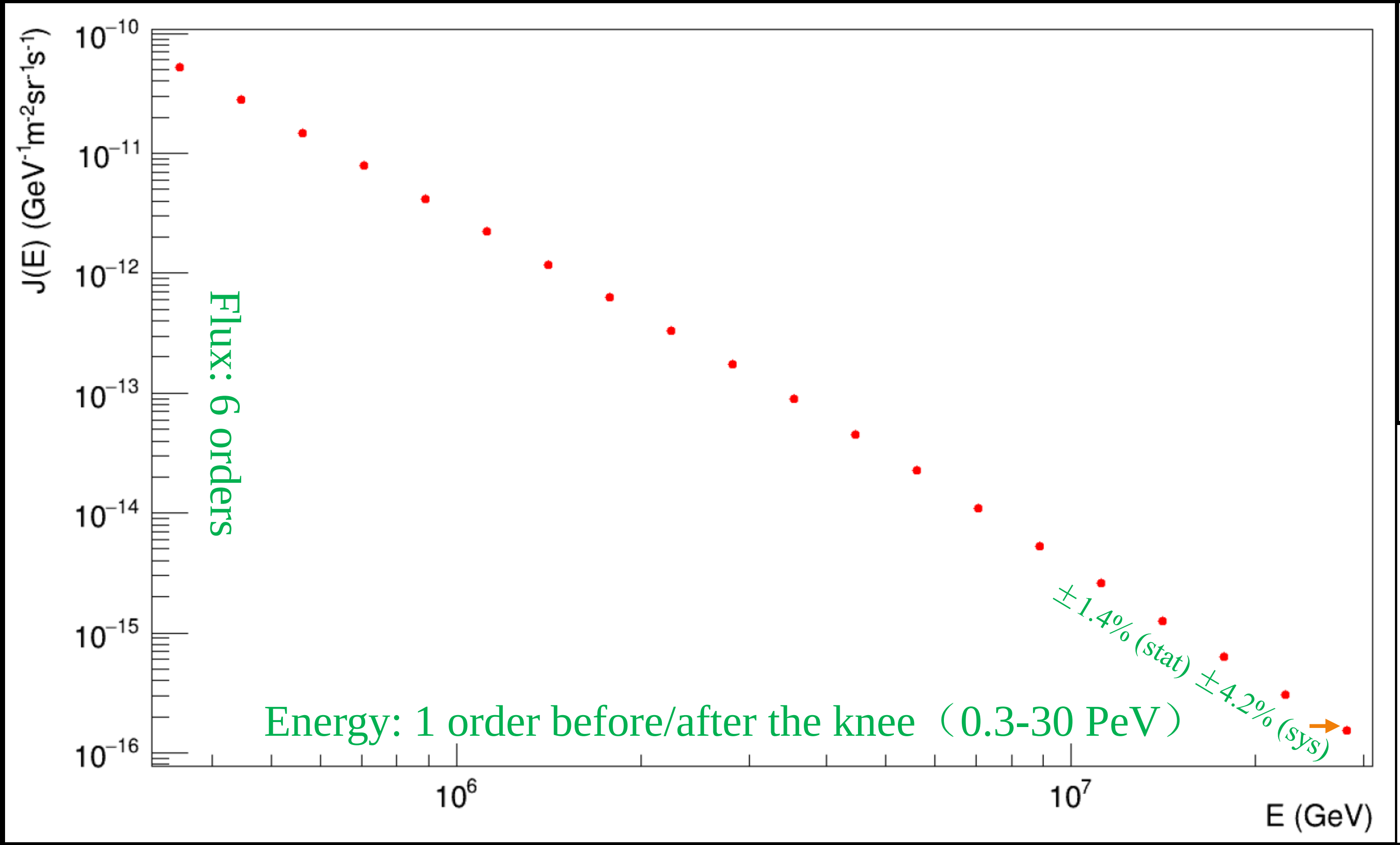
From 350%(150%) to 12%

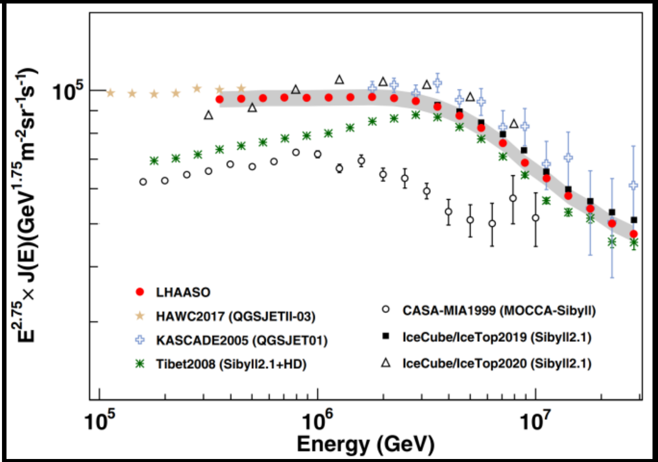


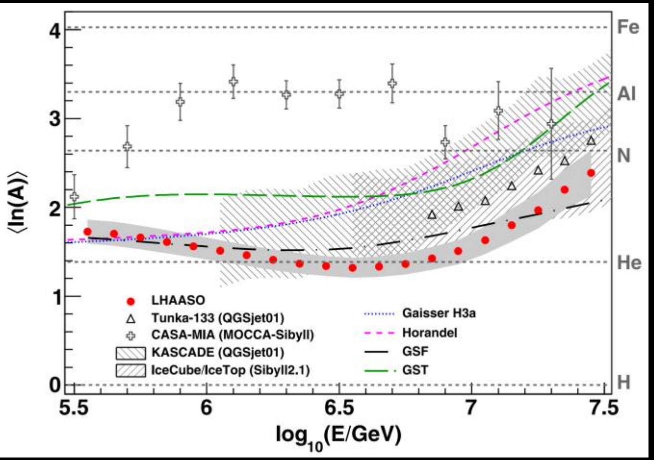




Precision measurement of the knee by KM2A







TLM: the touchstone for testing if proton spectrum breaks @ knee

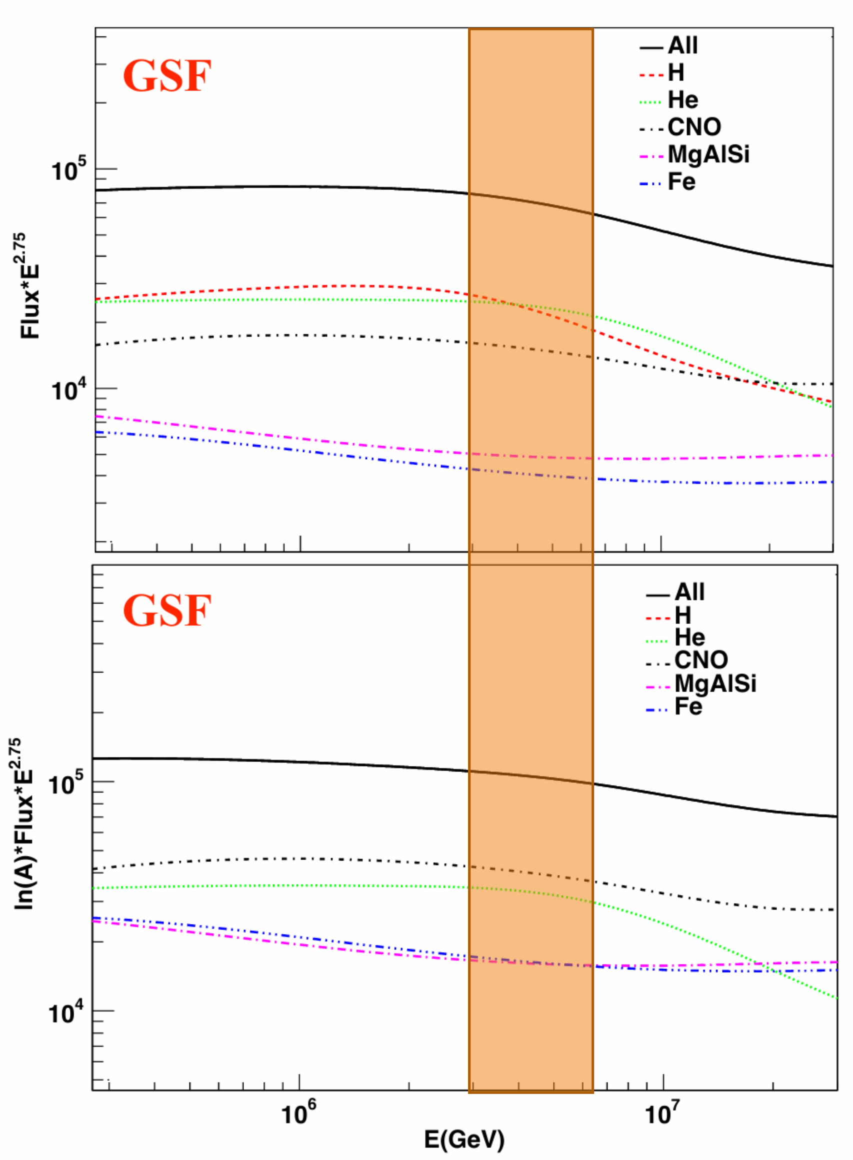
$$F \equiv \sum_i f_i \quad m \equiv \langle \ln A \rangle \equiv \frac{\sum_i f_i \ln A_i}{\sum_i f_i}$$

- Total logarithmic mass

$$M \equiv \sum_i f_i \ln A_i = F \times m$$

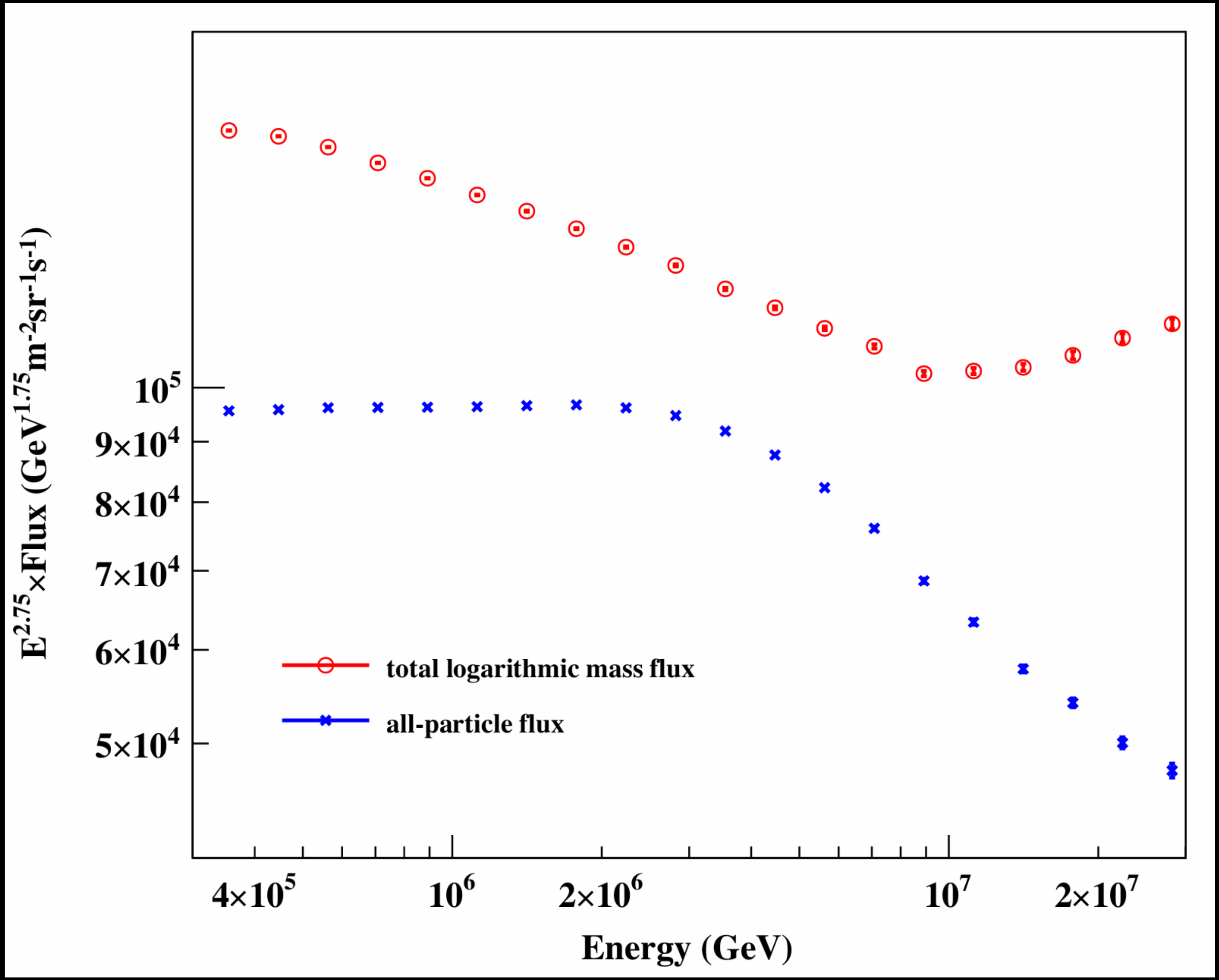
	P	He	CNO	MgAlSi	Fe
lnA	0	1.39	2.64	3.30	4.03

- More sensitive to structures of heavy nuclei (especially Fe)
- P (lnA=0) doesn't contribute to TLM, thus TLM servs as a touchstone for testing if proton spectrum breaks at the knee
  - No → a similar structure in TLM as in the all-particle energy spectrum
  - Yes → how much does proton contribute to the knee?



hhh@ihep.ac.cn

The all-particle and TLM spectra by KM2A



hhh@ihep.ac.cn

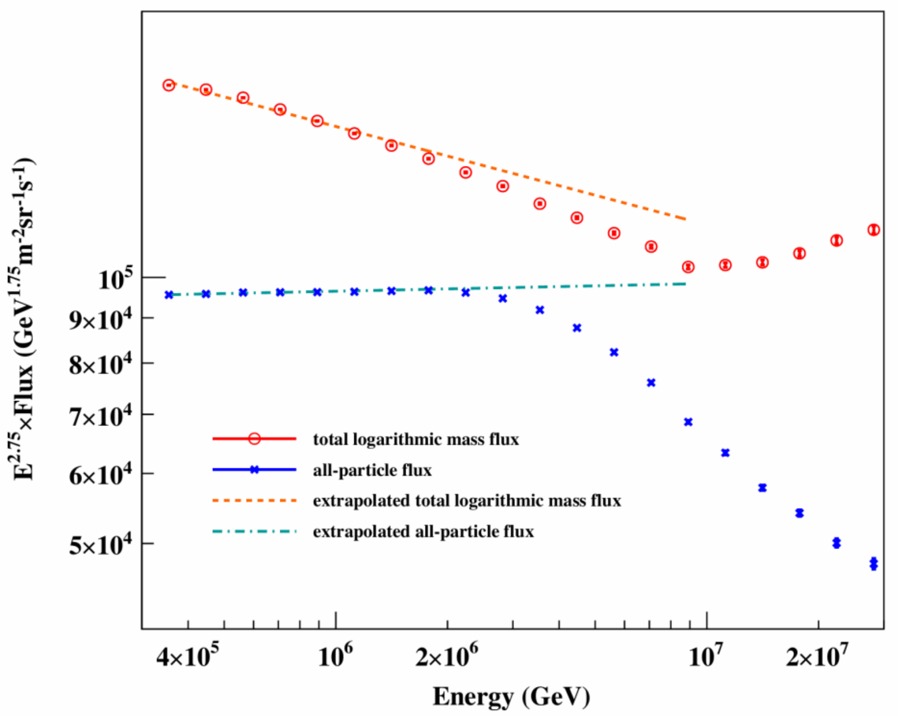
Does proton spectrum break at the knee?

- Parameters from LHAASO paper
  - All-particle flux $F' = F_0 \left(\frac{E}{1\ PeV}\right)^{\gamma_F}$
  - <lnA> $m' = m_0 \left(\frac{E}{1\ PeV}\right)^{\gamma_m}$
  - ➢TLM $M' = F' \times m' = F_0 \times M_0 \left(\frac{E}{1\ PeV}\right)^{\gamma_F+\gamma_m}$
- Loss
  - All-particle flux $\Delta F = F' - F$
  - TLM $\Delta M = M' - M$
  - <lnA> of ΔF

$$m_{\Delta F} = \frac{\Delta M}{\Delta F} = q_p \times m_p + (1 - q_p) \times m_{\geq He} = (1 - q_p) \times m_{\geq He}$$

- TLM anticipation

$$M'' = M' - \Delta F \times m_{\Delta F}$$

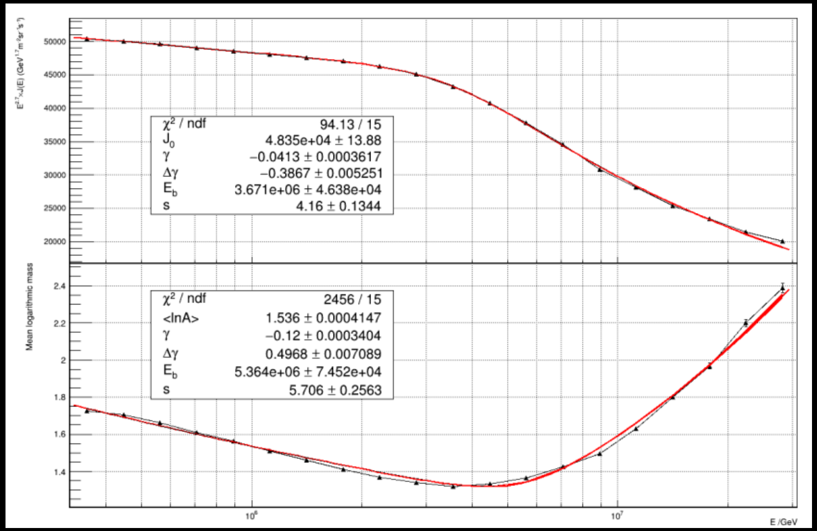


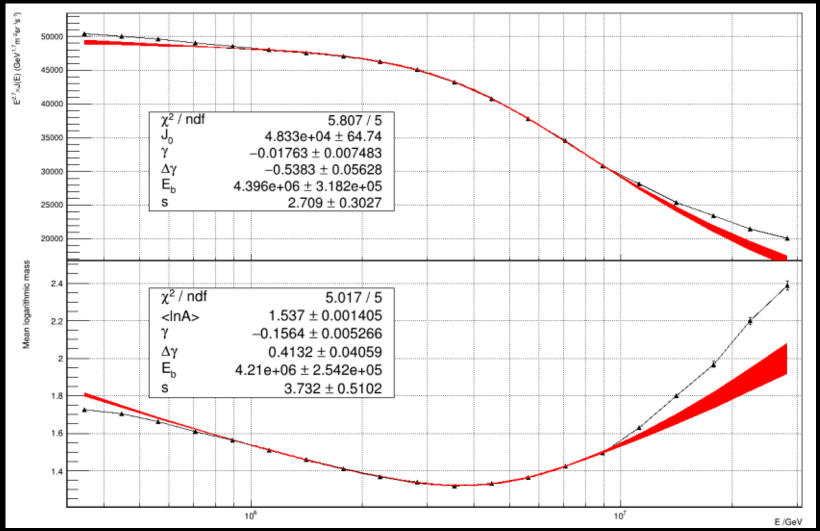
- H_0: no, q_p=0 → best-fit $m_{\Delta F} = \ln 4$
- H_1: yes, q_p>0 → best-fit $m_{\Delta F} = 0.66 \pm 0.02$
- Significance of rejecting H_0: 36.8σ

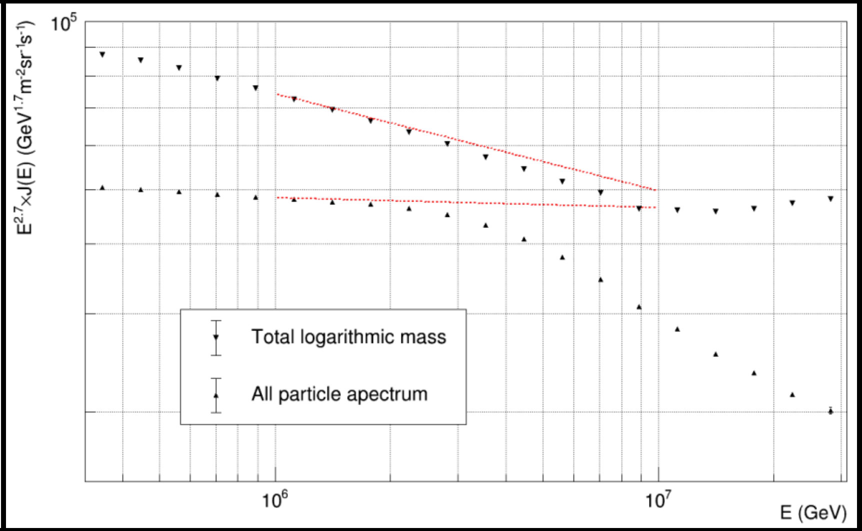
→Proton spectrum breaks at the knee!

Does proton spectrum break at the knee?

- Parameters fitted around the knee (1-10 PeV)







- Significance of rejecting H_0: 12.0σ

→Proton spectrum breaks at the knee!

hhh@ihep.ac.cn

Only proton spectrum breaks at the knee?

- H_0: yes, q_p=1
- H_1: no, q_p<1
- Significance of rejecting H_0
  - Paper: 41.8σ
  - 1-10 PeV: 6.3σ

$$m_{\Delta F} = \frac{\Delta M}{\Delta F} = \left(1 - q_p\right) \times m_{\geq He}$$

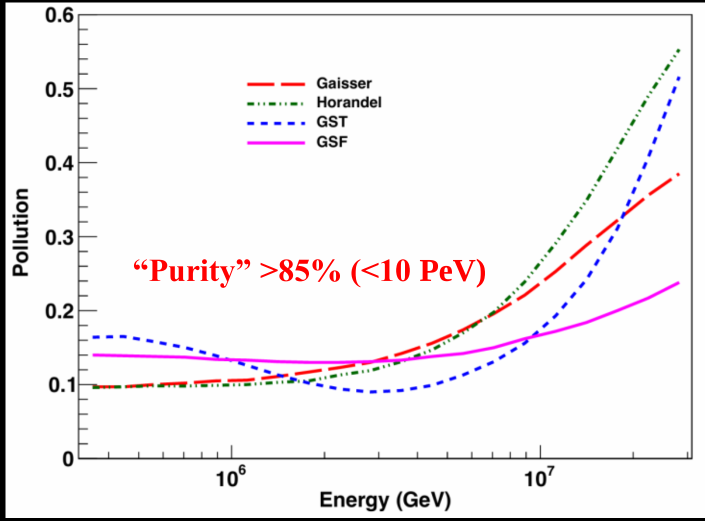
- proton proportion
  - Paper: 52.7%±1.2%≤q_p≤83.7%±0.04%
  - 1-10 PeV: 72.6%±4.5%≤q_p≤90.6%±1.5%

→Proton dominates the knee but it's not the only one whose spectrum breaks!

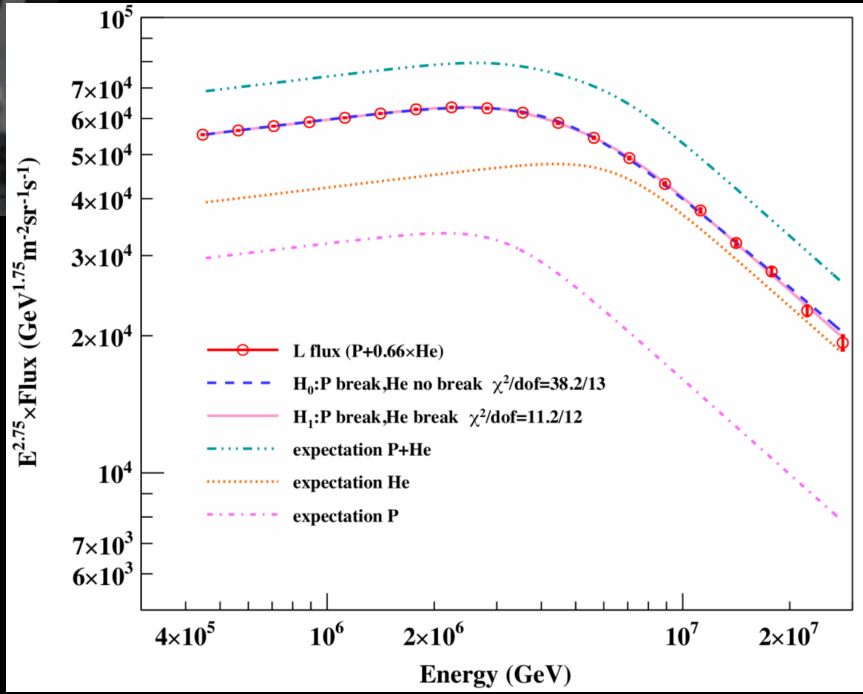
Z/A dependent?

- A light cocktail

$$L = F - \frac{M}{\ln 56} \approx F_P + 0.655 F_{He}$$



	all	TLM	Light
P	1	0	1
He	1	1.39	0.655
CNO	1	2.64	0.345
MgAlSi	1	3.30	0.181
Fe	1	4.03	0



- Hypothesis test: 5.2 σ

$$H_0\colon J(E) = J_0\left(\frac{E}{1\ PeV}\right)^{\gamma}\left\{f_P\left[1+\left(\frac{E}{E_P}\right)^{s}\right]^{\Delta\gamma/s} + (1-f_P)\left(1-\frac{\ln 4}{\ln 56}\right)\right\}$$

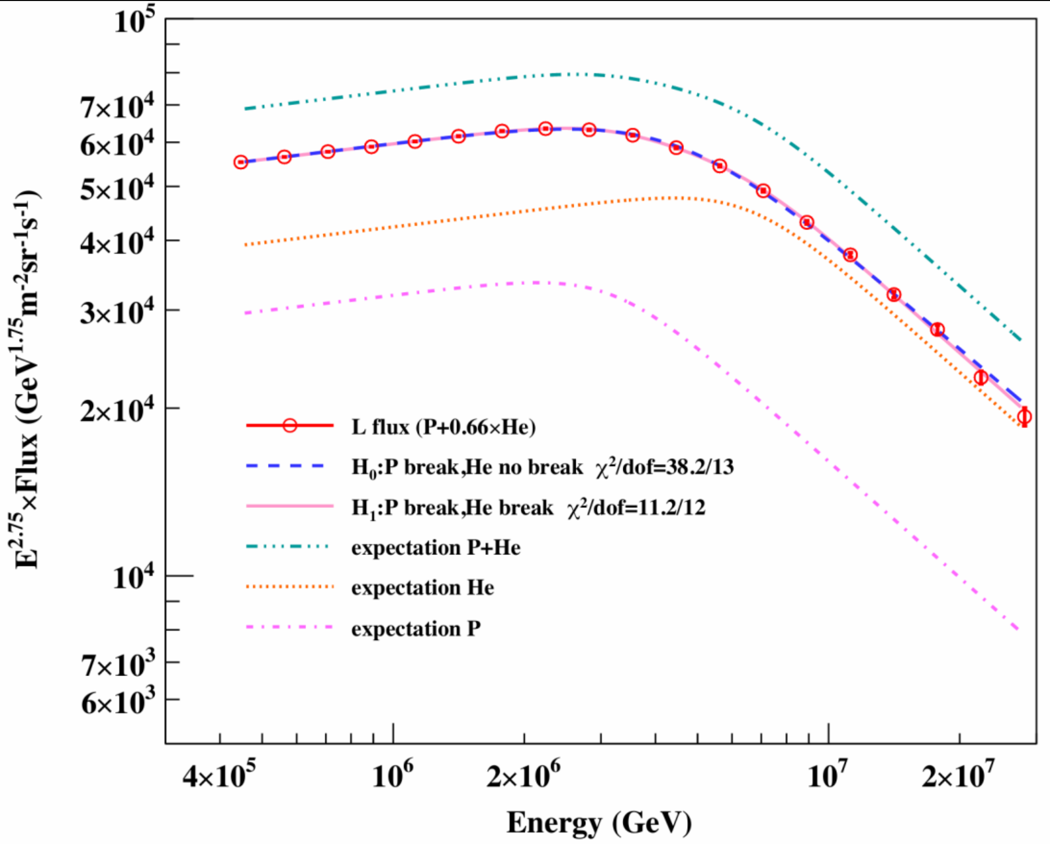
$$H_1\colon J(E) = J_0\left(\frac{E}{1\ PeV}\right)^{\gamma}\left\{f_P\left[1+\left(\frac{E}{E_P}\right)^{s}\right]^{\Delta\gamma/s} + (1-f_P)\left(1-\frac{\ln 4}{\ln 56}\right)\left[1+\left(\frac{E}{nE_P}\right)^{s}\right]^{\Delta\gamma/s}\right\}$$

➢n=2.06±0.09, rule out A-dep with 22 σ, agree with Z-dep

Features of the proton knee

- E_p = 3.2±0.2 PeV
- Spectral index before the cutoff: -2.6559±0.0009
- Change of spectral index: -0.79±0.03
- Sharpness： 5.1±0.5
- f_p=0.43±0.06

- Light: 2.35±0.06×10^{-12} /GeV/m^2/sr/s
- (all: 3×10^{-12} /GeV/m^2/sr/s)

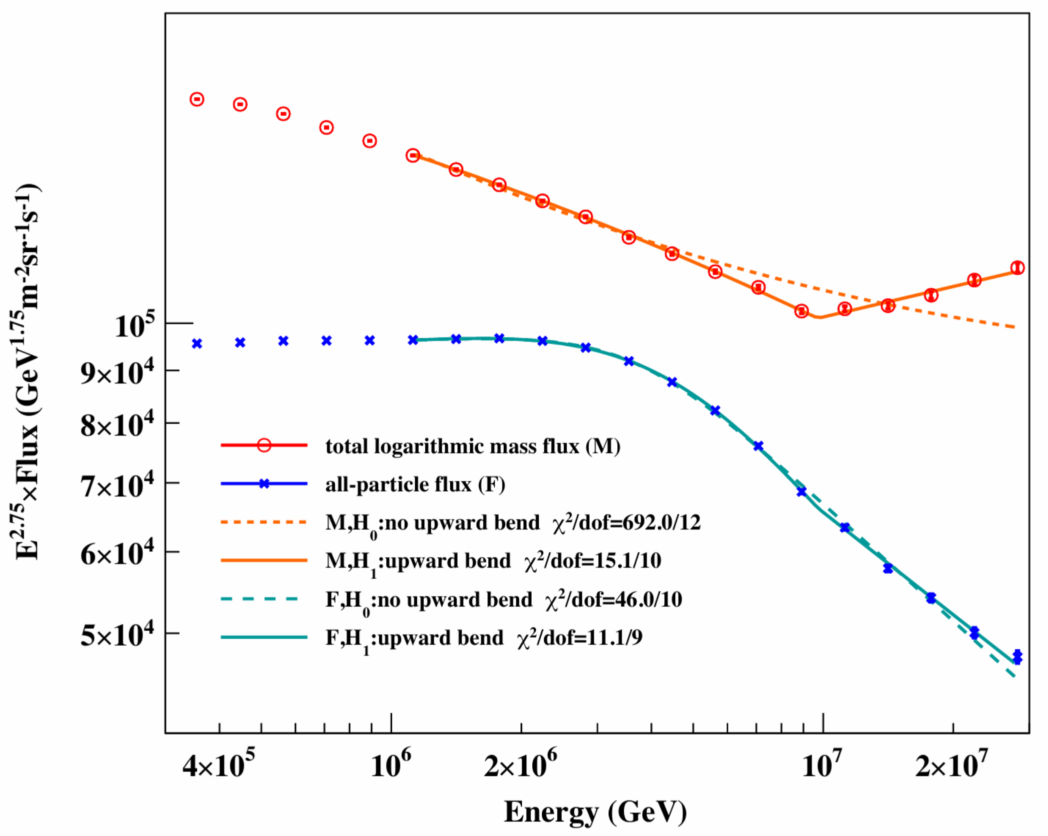


hhh@ihep.ac.cn

Discovery of an ankle-like structure due to Fe

- Break energy: 9.7±0.2 PeV

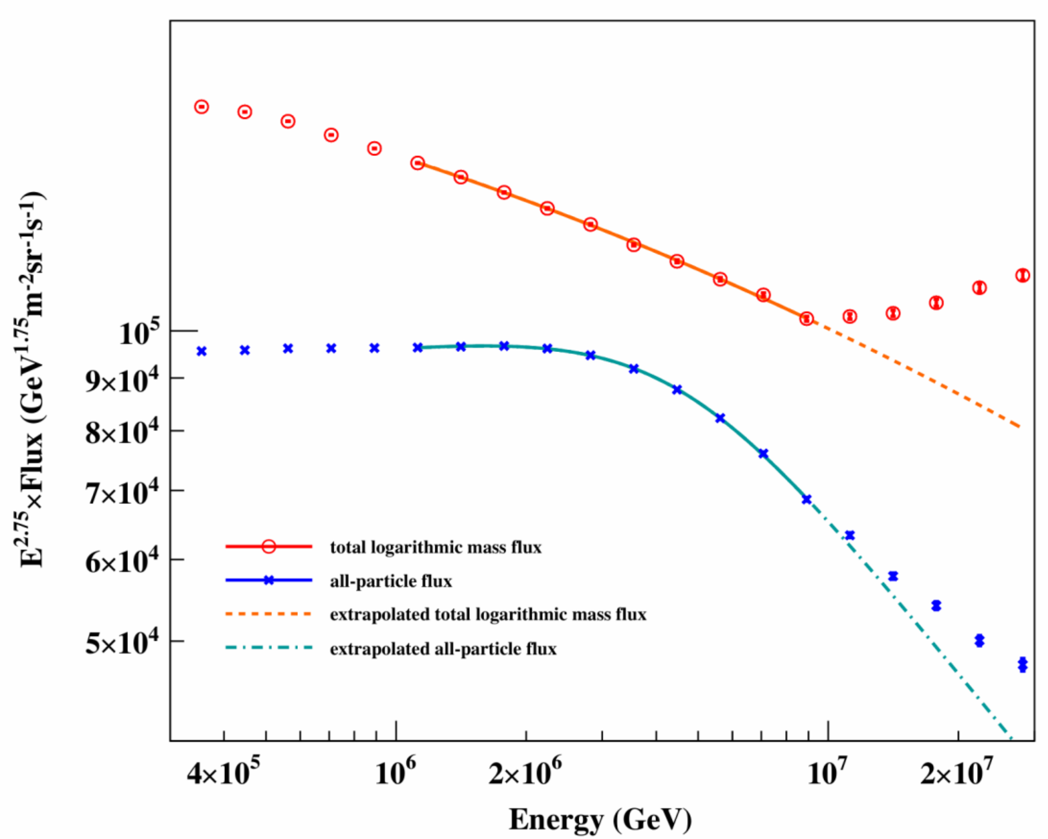
	significance	index before break	index after break
TLM	25.9σ	2.950±0.005	2.65±0.01
All-particle	5.9σ	3.25±0.05	3.08±0.01

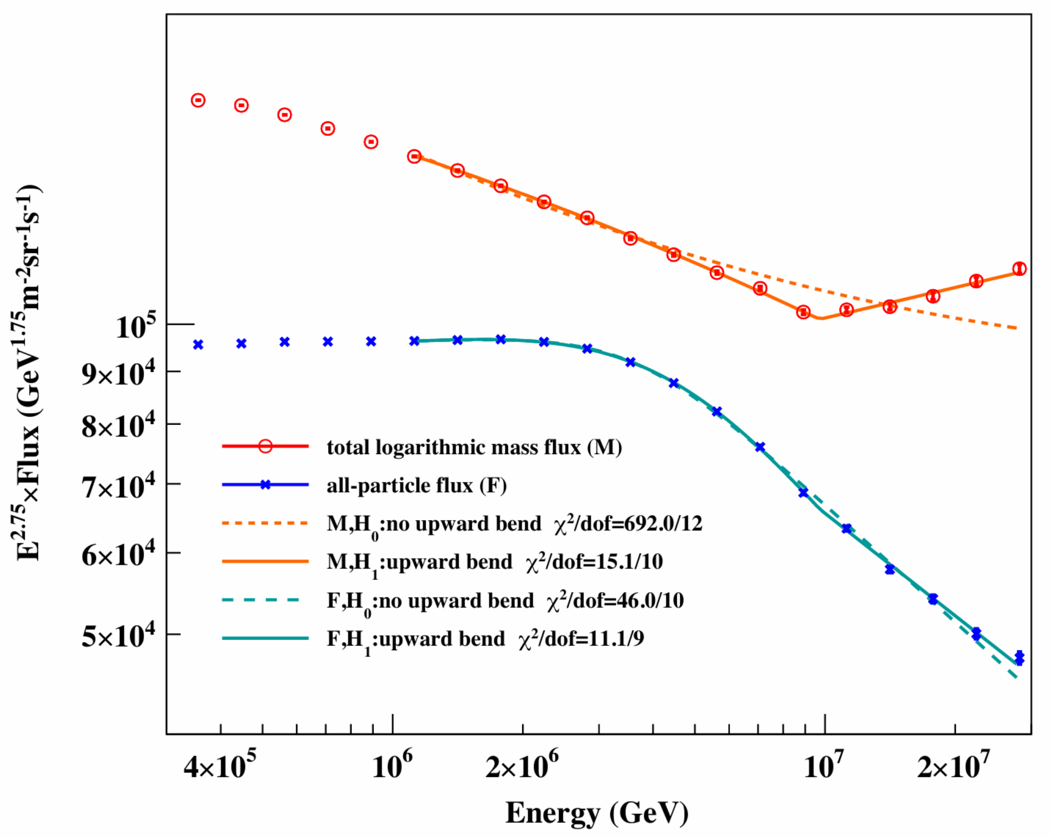


Discovery of an ankle-like structure due to Fe

- Break energy: 9.7±0.2 PeV

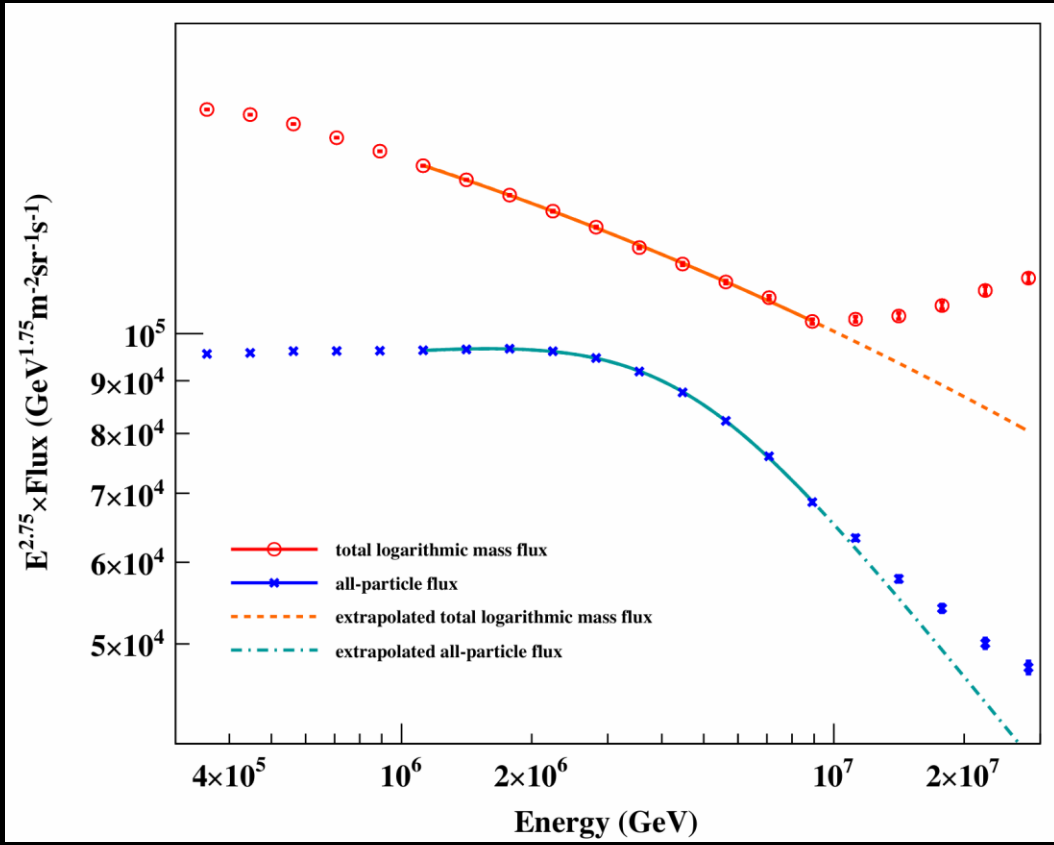
	significance	index before break	index after break
TLM	25.9σ	2.950±0.005	2.65±0.01
All-particle	5.9σ	3.25±0.05	3.08±0.01

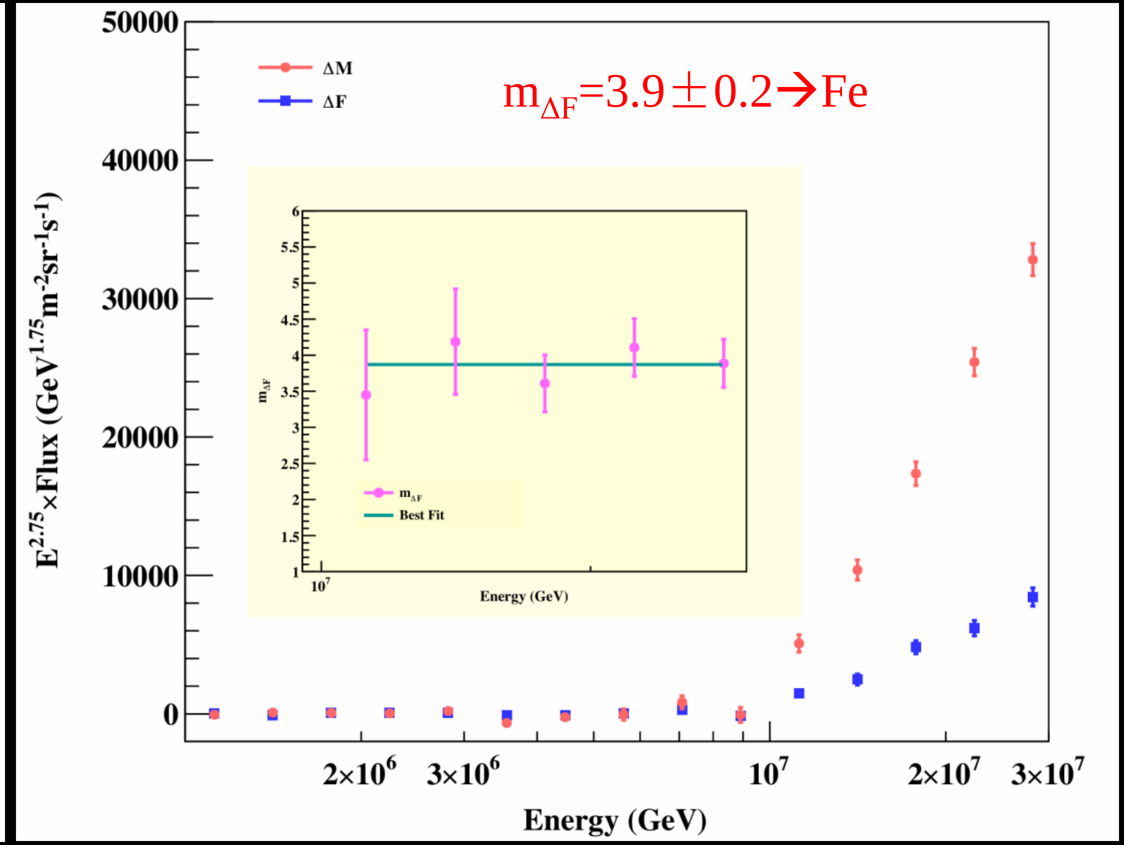




Discovery of an ankle-like structure due to Fe

- Break energy: 9.7±0.2 PeV

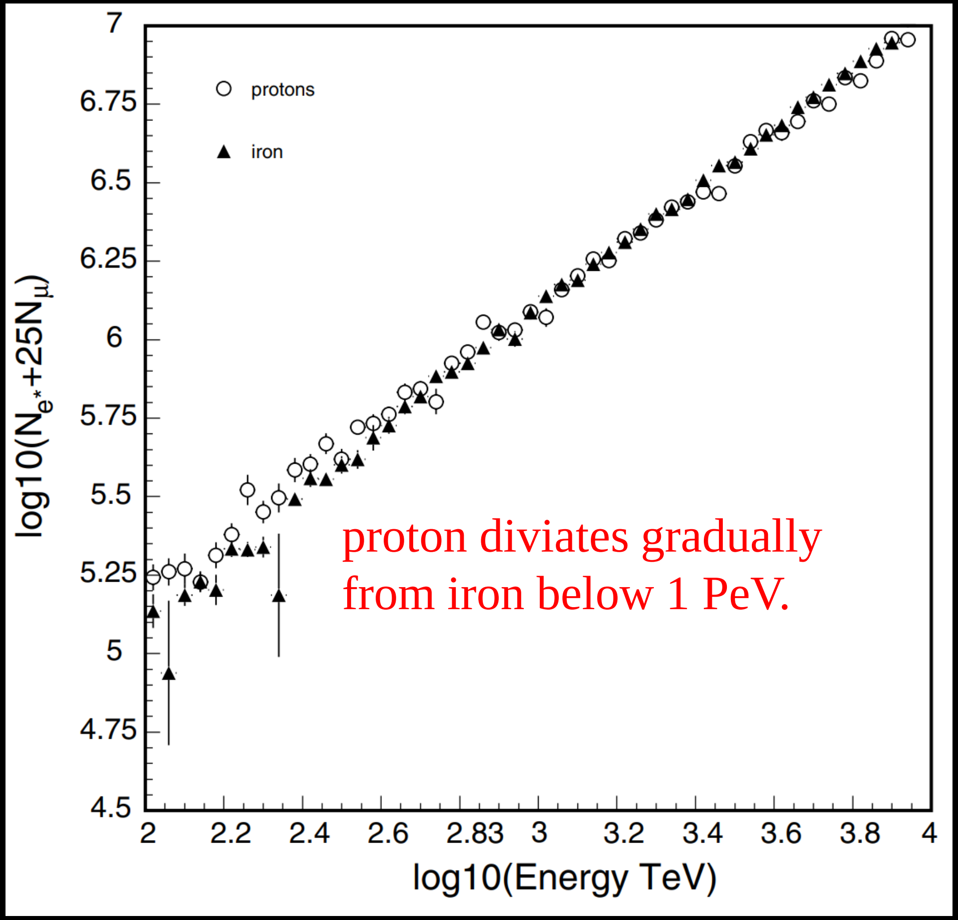


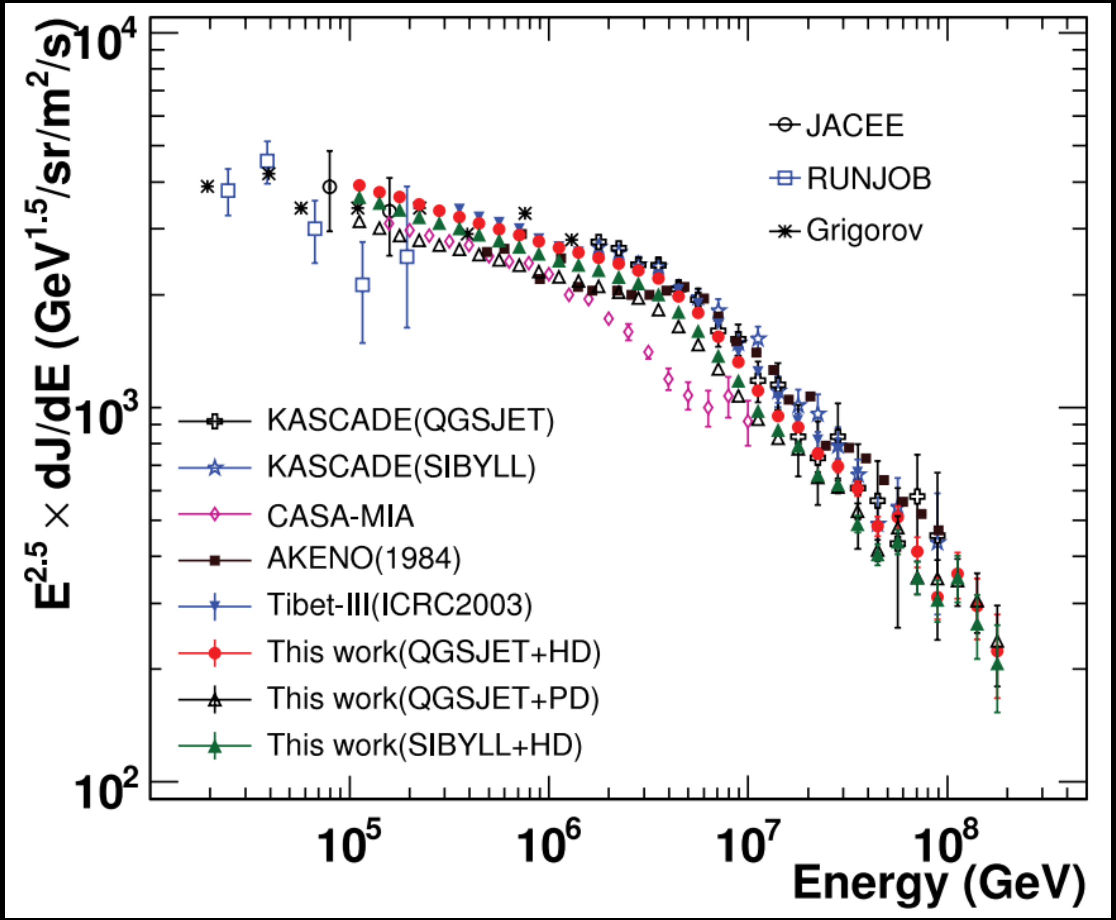


Summary

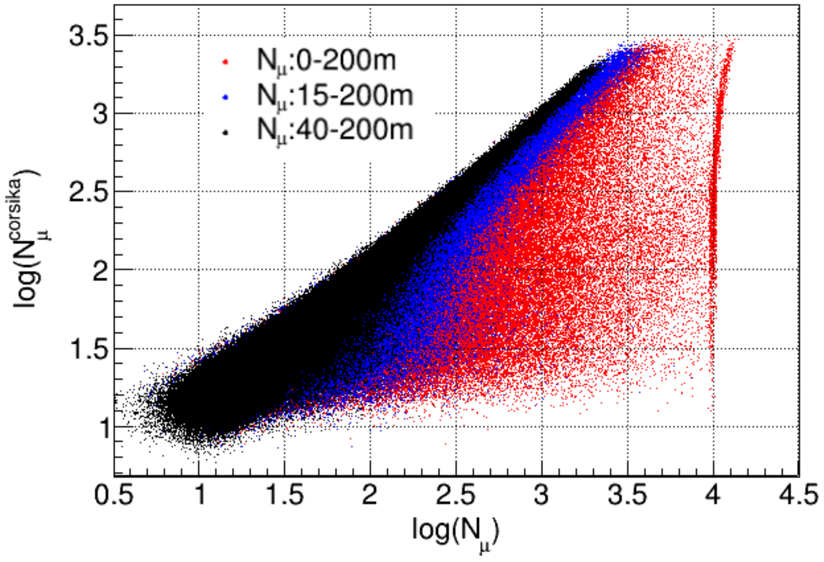
- A calorimetric energy estimator is developed for the LHAASO-KM2A experiment
- The all-particle energy spectrum and <lnA> is measured with unprecedent precision
- The total logarithmic mass is introduced and a cocktail method is developed
- The CR knee is attributed to P and He with rigidity-dependent cutoff energy
- An ankle-like structure due to Fe at 9.2 PeV is discovered

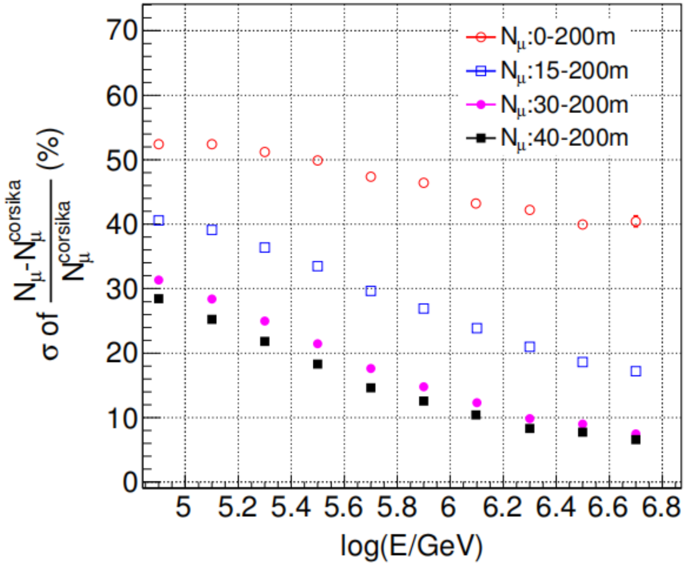
CASA-MIA: 860 g/cm^2

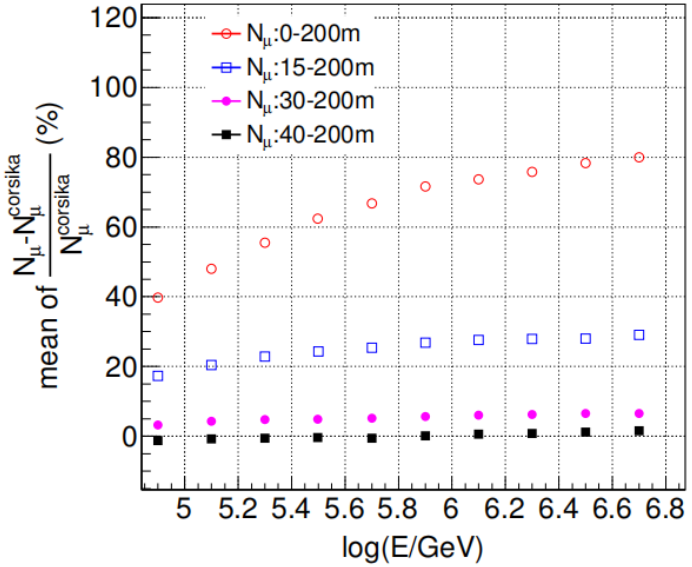




Muons and electromagnetic particles measurement（N_e and N_μ）







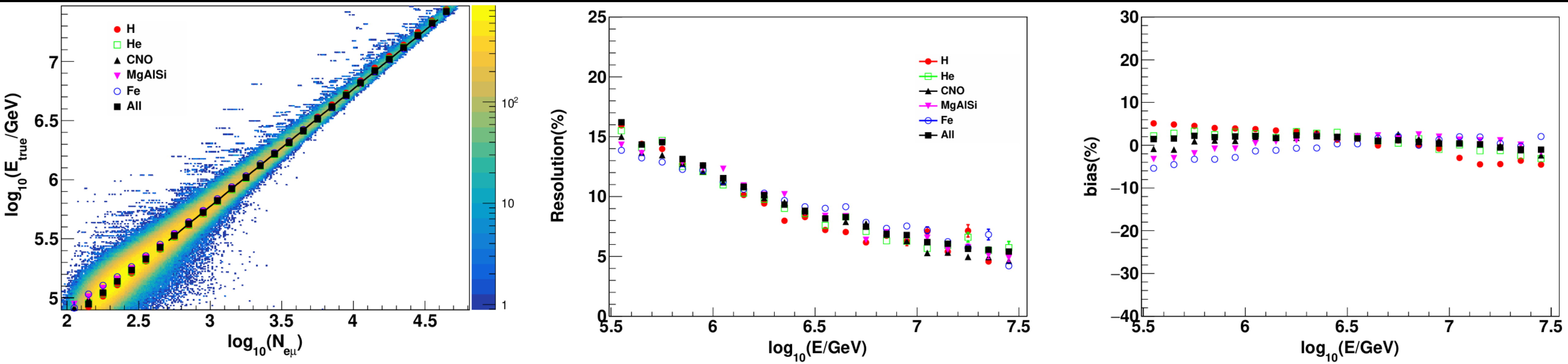
Simulation

$N_\mu^{corsika}$: 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 of the shower axis, the resolution is the best and the bias is almost zero.

Reconstruction of event energy and mass



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

Energy reconstruction: model-dependence

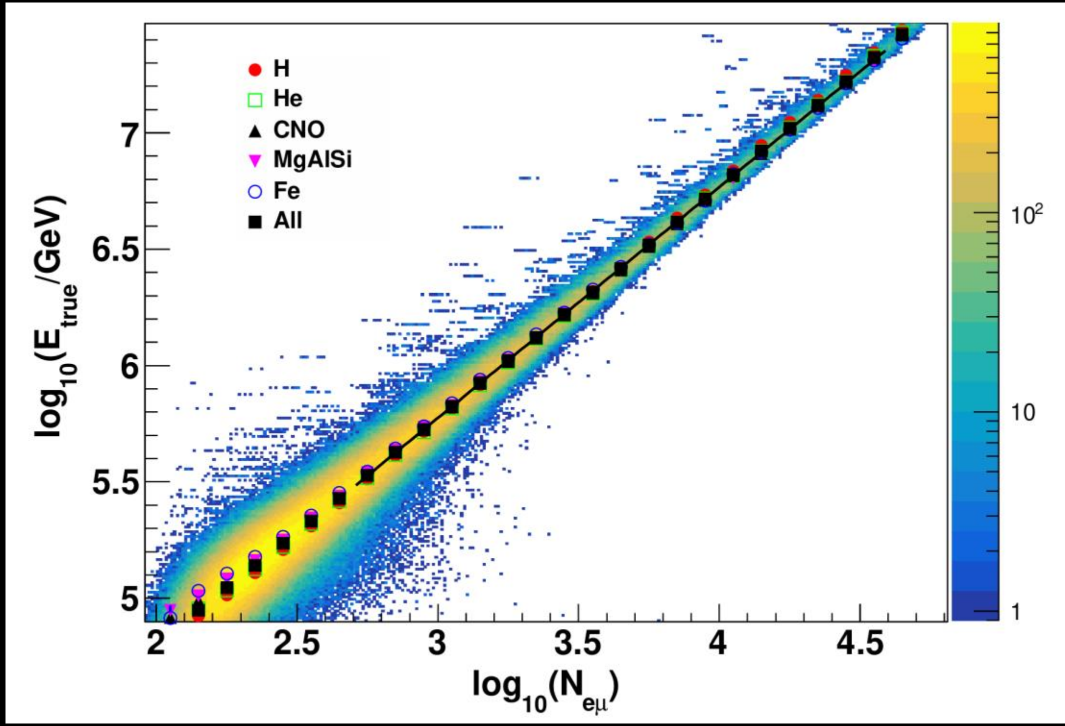


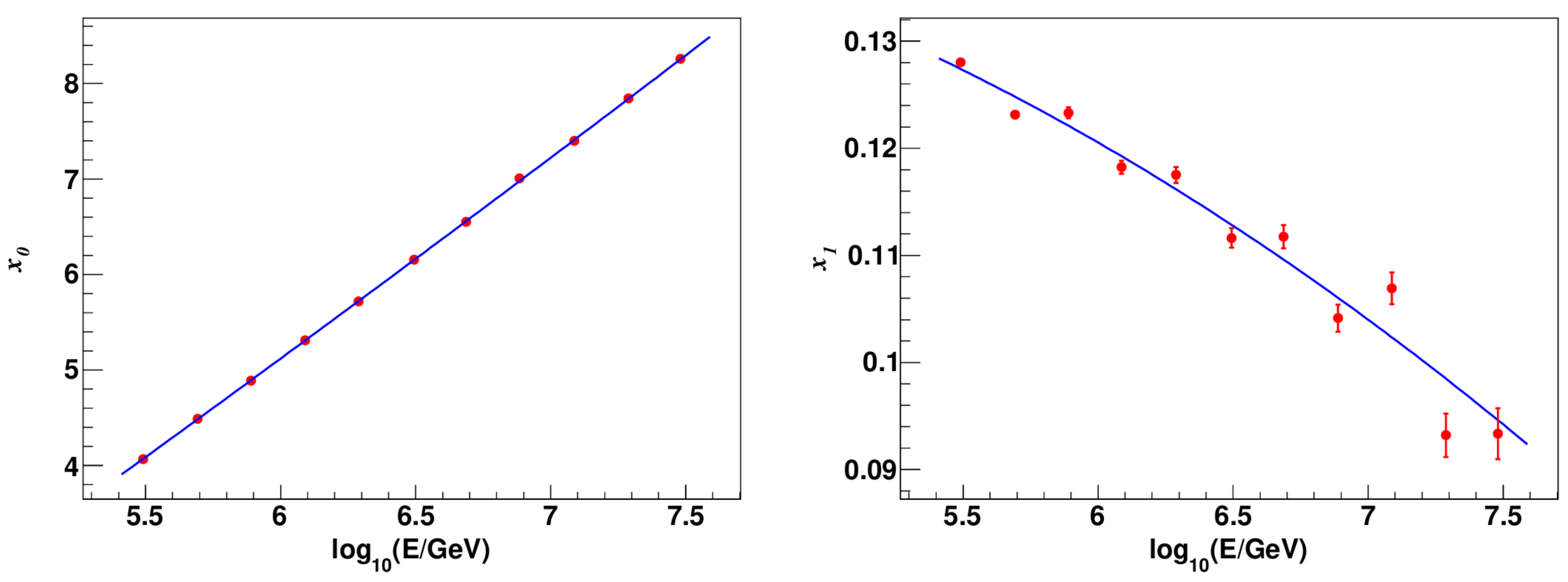
TABLE S1. The fit parameters p_0 and p_1 for different composition models.

Model	p_0	p_1
Gaisser	2.799	0.992
Horandel	2.798	0.992
GST	2.802	0.992
GSF	2.797	0.992

TABLE S2. The fit parameters p_0 and p_1 for different high-energy hadronic interaction models.

Model	p_0	p_1
QGSJETII-04	2.799	0.992
EPOS-LHC	2.789	0.992
SIBYLL-2.3d	2.784	0.995

Reconstruction of <lnA>



	P	He	CNO	MgAlSi	Fe
All	1	1	1	1	1
TLM/log(56)	0	0.345	0.655	0.819	1
P+0.655He	1	0.655	0.345	0.181	0
All-(P+He)			0.569	0.773	1