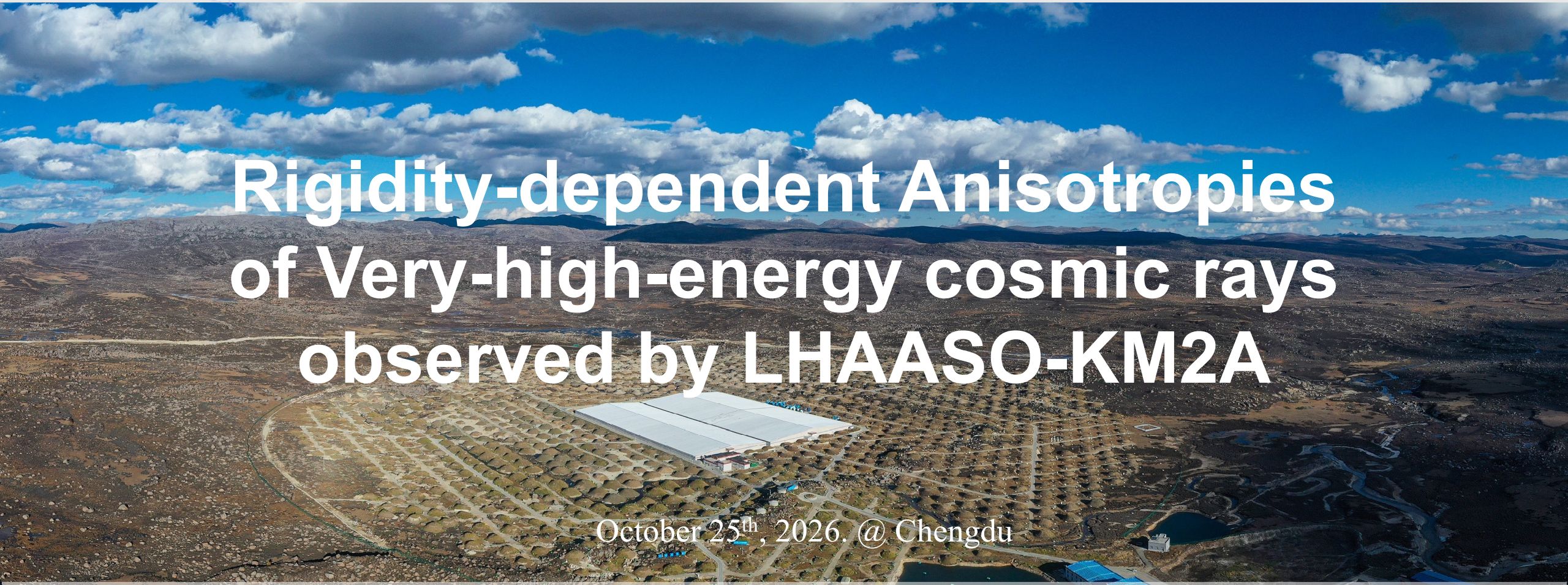
高海拔宇宙线观测站
Large High Altitude Air Shower Observatory



Rigidity-dependent Anisotropies of Very-high-energy cosmic rays observed by LHAASO-KM2A

October 25th, 2026. @ Chengdu

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Outline

- Introduction
- Data analysis
- Results
- Summary

Introduction

Ground-based experiments

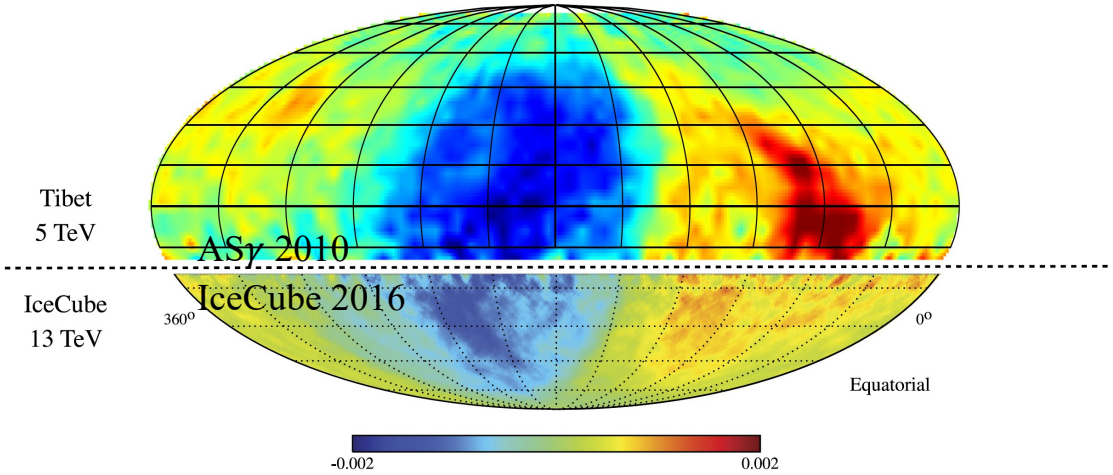
- All particle
- 1TeV ~ 10 PeV (Galactic cosmic rays)

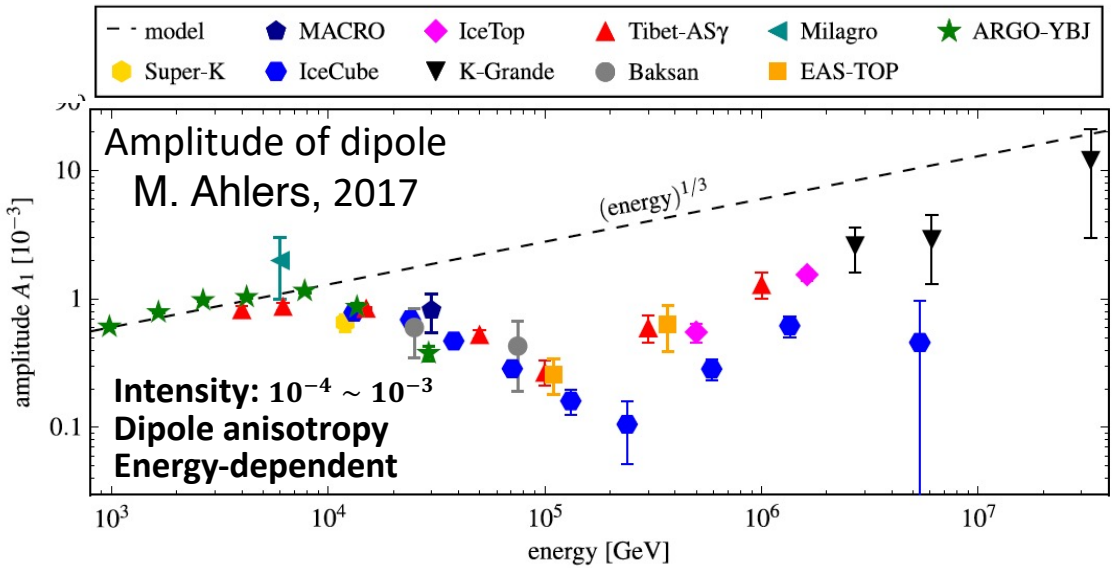
Dipole predicted by theory

- Dipole: $\delta^* = 3K \cdot \nabla \ln n^*$
- CR sources' distribution and the CRs' propagation

Probe CRs source and propagation mechanism

- CR background, local source
- Spatial-dependent diffusion, local magnetic field, …





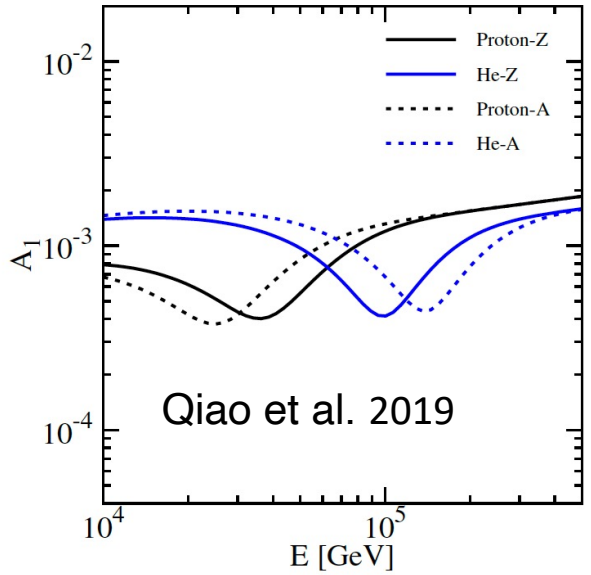
Introduction

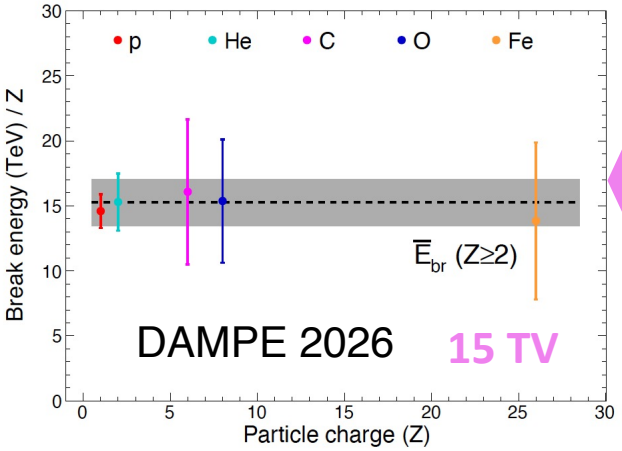
For the local source model, the structure of 1-100 TeV is the result of competition with background CRs.

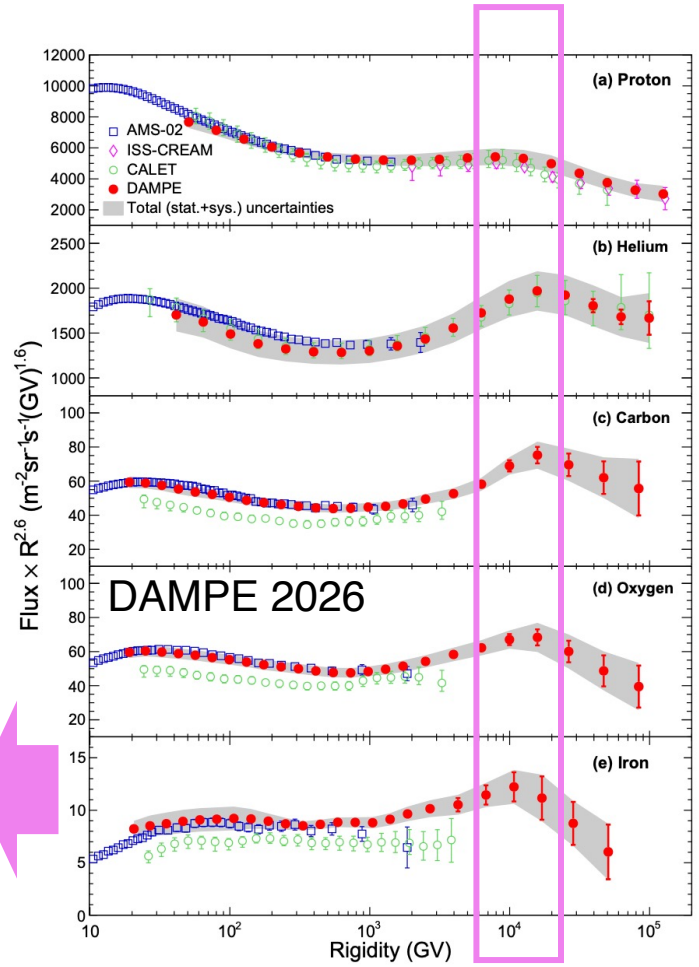
Cut-off energy of a local source:
Z-dependent **and** A-dependent.

Charge-dependent spectral softening (P, He, C, O, Iron)

What about anisotropies: charge-dependent transition?







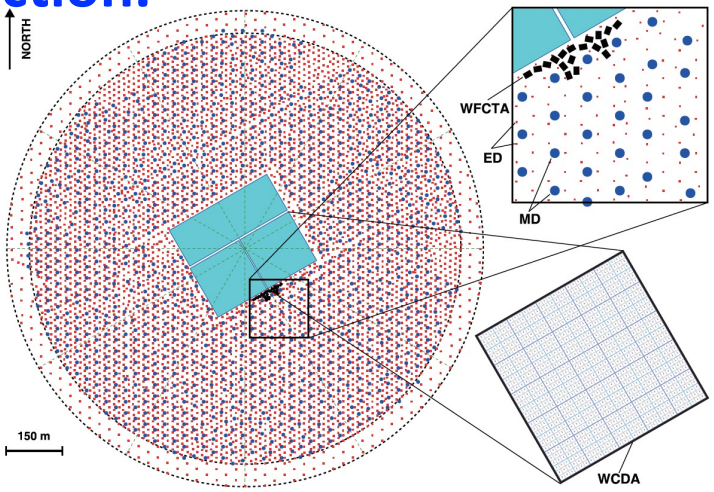
Introduction

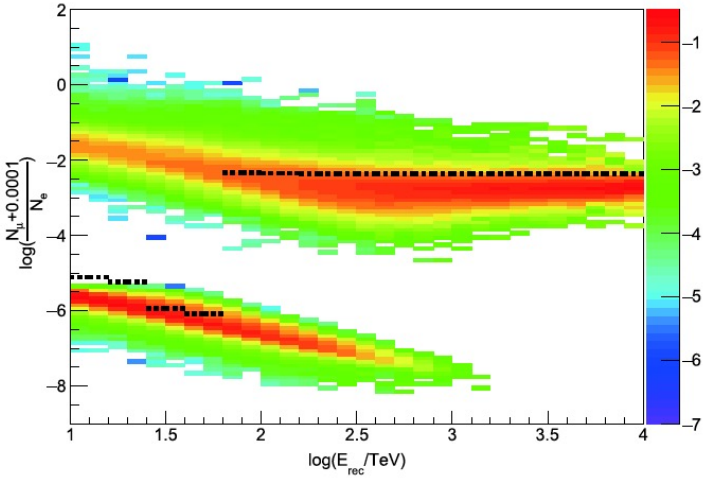
LHAASO

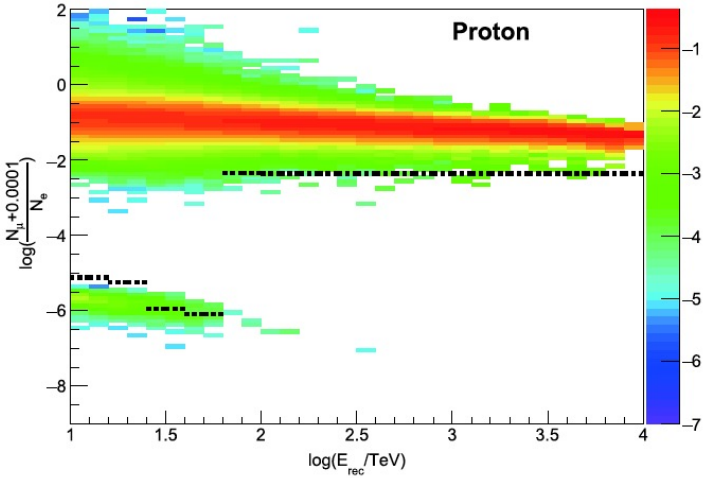
- KM2A: 5195 EDs + 1188 MDs

KM2A equipped with the biggest muon detector array in the world:

- MDs help in the separation of γ and CRs
- Muons also help us select the specific cosmic rays and rigidity reconstruction.

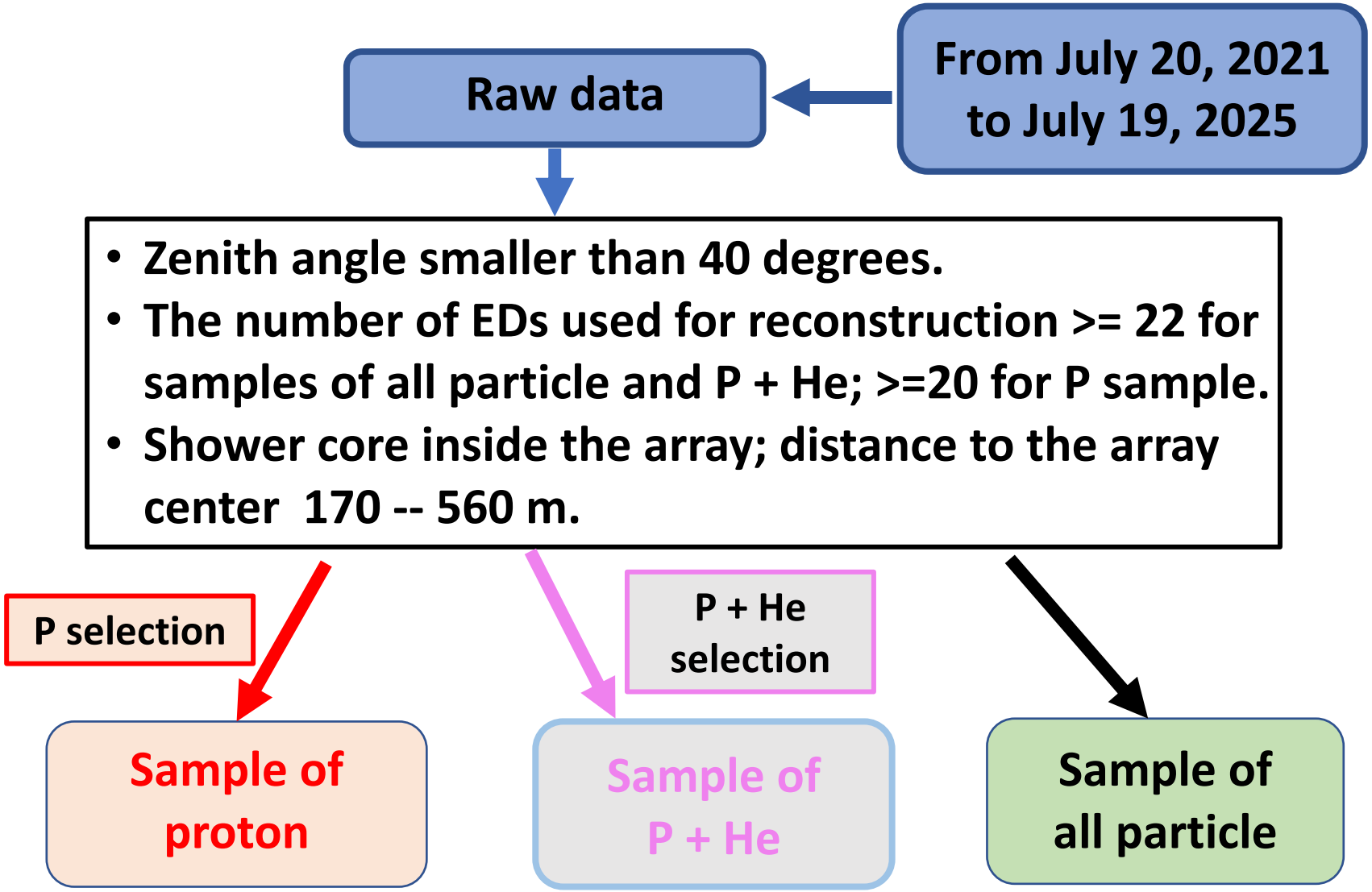




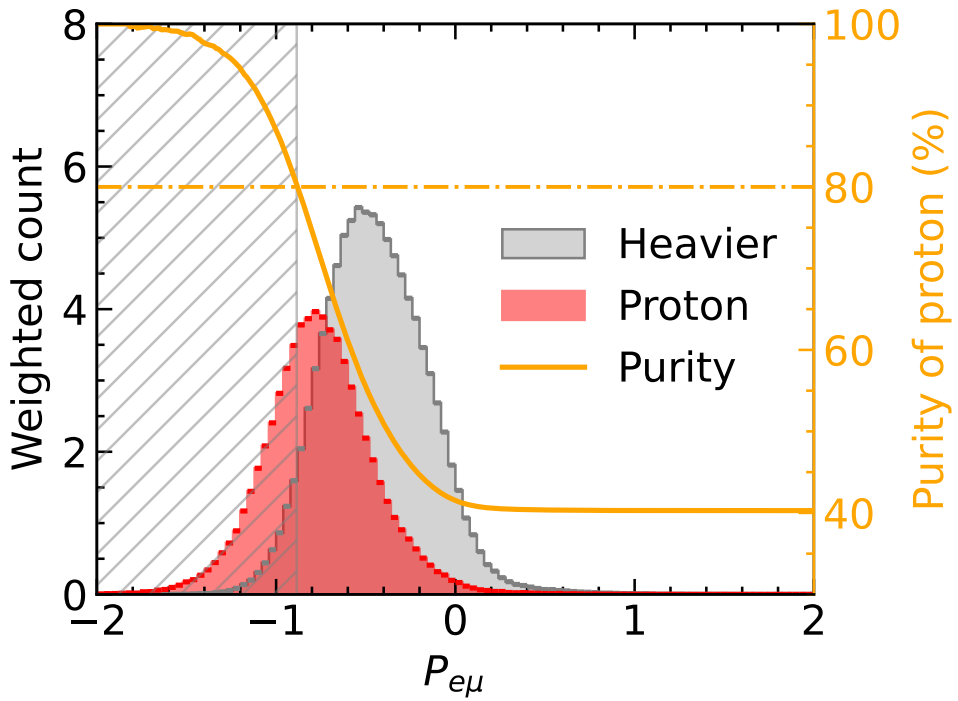


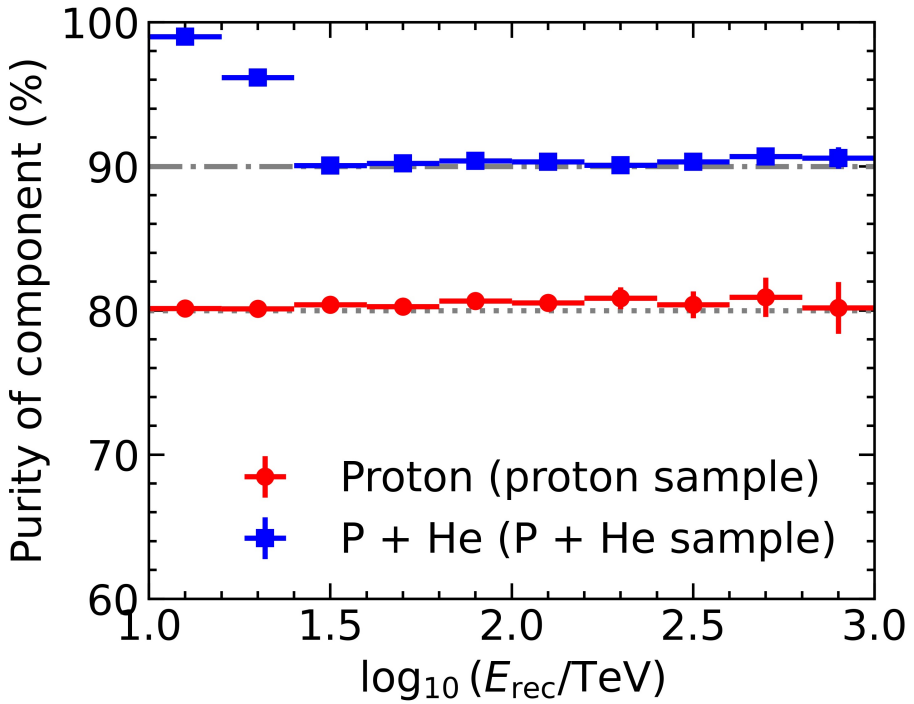
LHAASO, CPC (2021)

Data analysis -- selection criteria



Data analysis -- selection of target particles



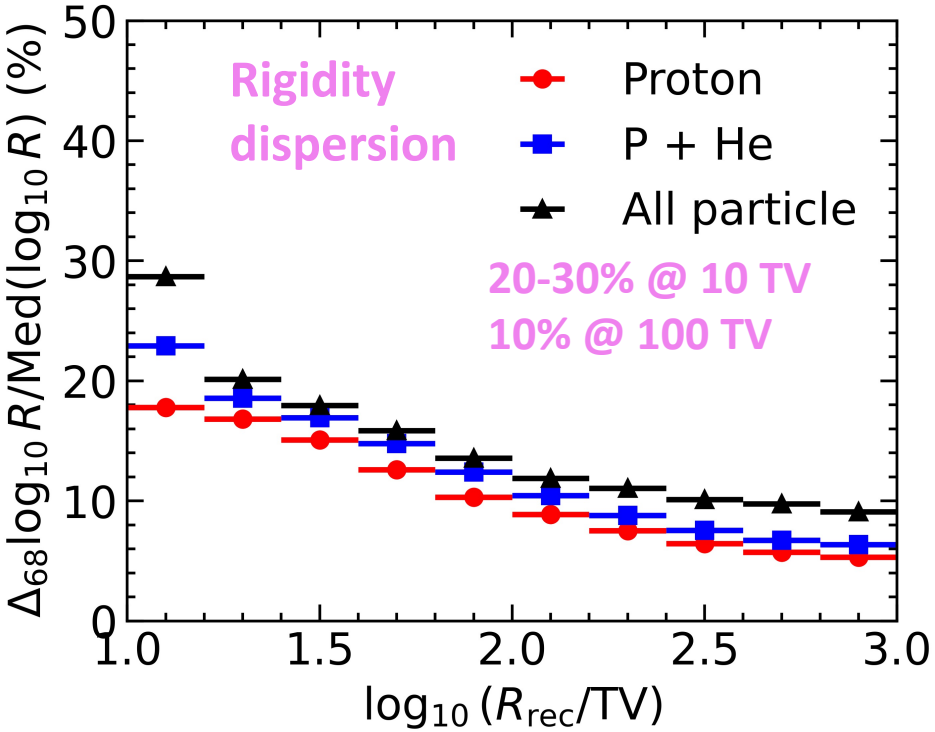


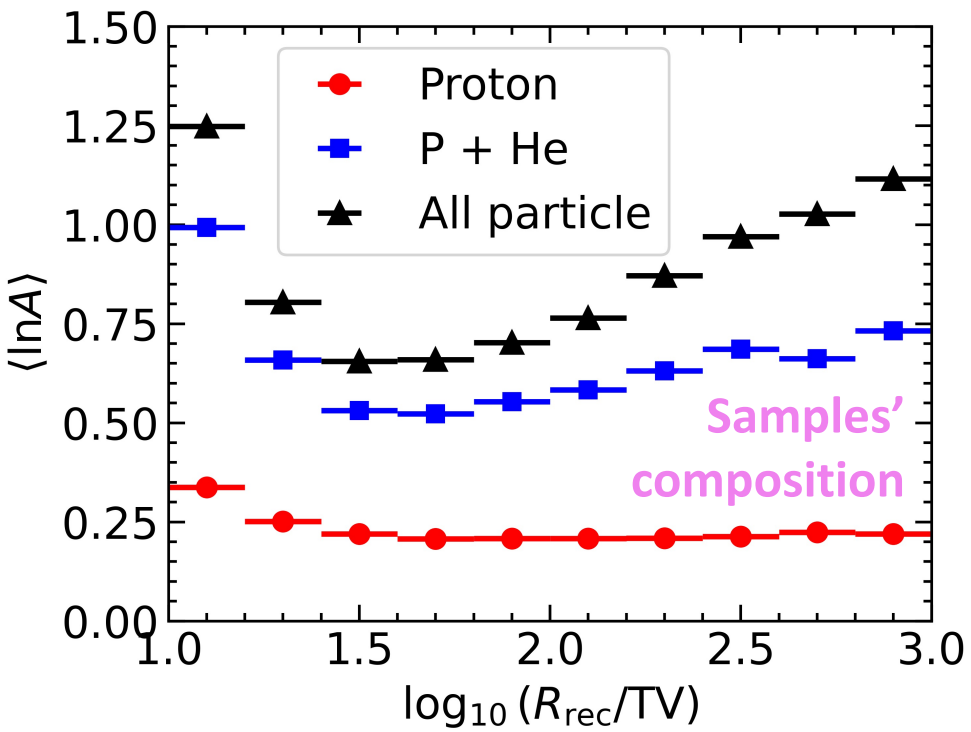
Particle identity parameter:

$$P_{e\mu} = \log_{10} \frac{N_\mu + 10^{-4}}{N_e}$$

- **P + He samples with a purity cut of 90%.**
- **Proton samples with a purity cut of 80%.**

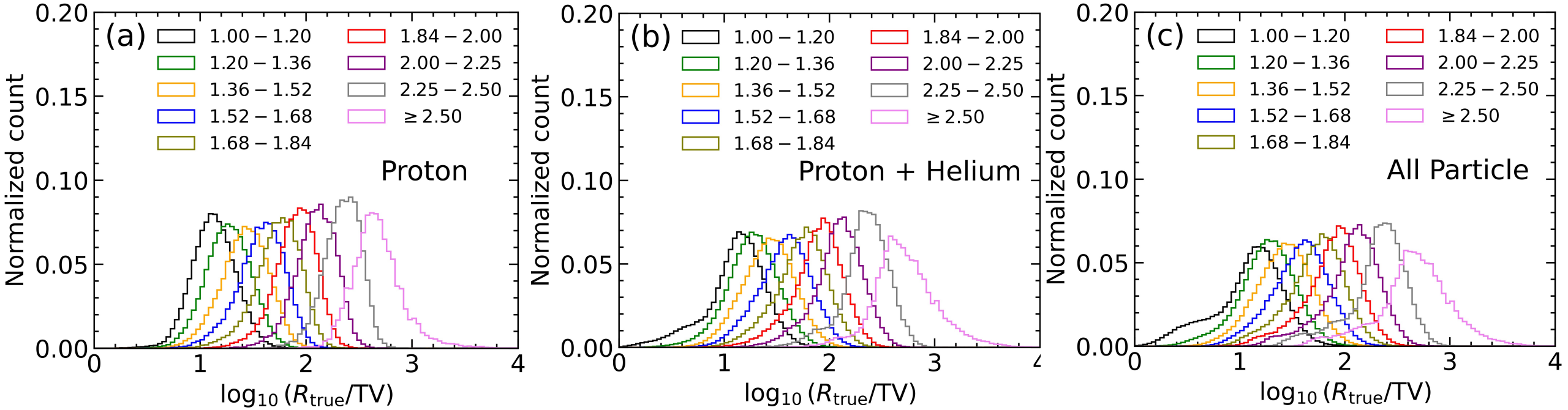
Data analysis -- rigidity reconstruction





- **Rigidity proxy:** $R_{\mathrm{prox}} = 0.9\times\log_{10}(S_{50}) - 0.5\times(\log_{10} N_{\mu} - \log_{10} N_e^{0.8})$
- **The reconstructed rigidity:** $\log_{10} R_{\mathrm{rec}} = f(R_{\mathrm{prox}}, \theta_{rec})$

Data analysis -- rigidity distributions



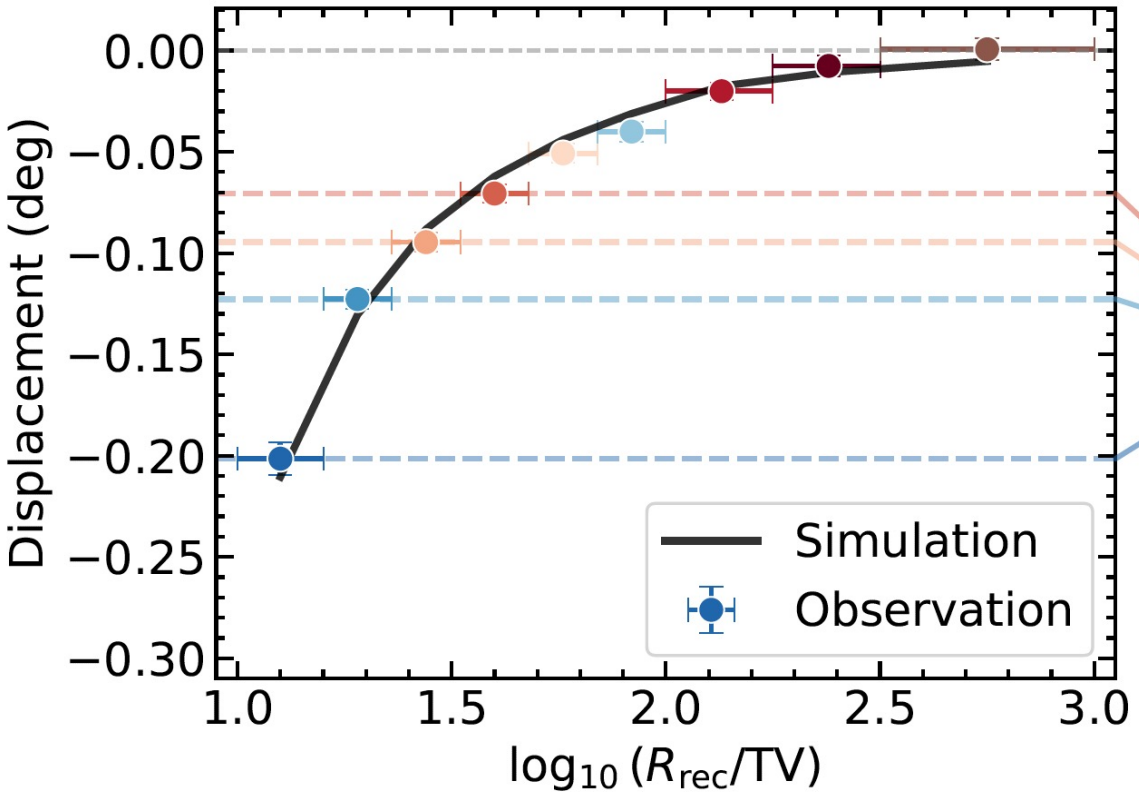
Data are binned into 9 bins according to reconstructed rigidity.

log10(Rrec/TV)	1.00-1.20	1.20-1.36	1.36-1.52	1.52-1.68	1.68-1.84	1.84-2.00	2.00-2.25	2.25-2.50	>=2.50
Proton (TV)	13.4	18.5	27.0	39.2	56.4	82.3	127.2	225.9	451.2
P + He (TV)	13.9	18.8	26.8	38.8	56.2	81.3	126.8	229.4	495.1
All particle (TV)	13.6	18.8	26.8	38.8	56.2	81.5	125.6	223.5	472.4

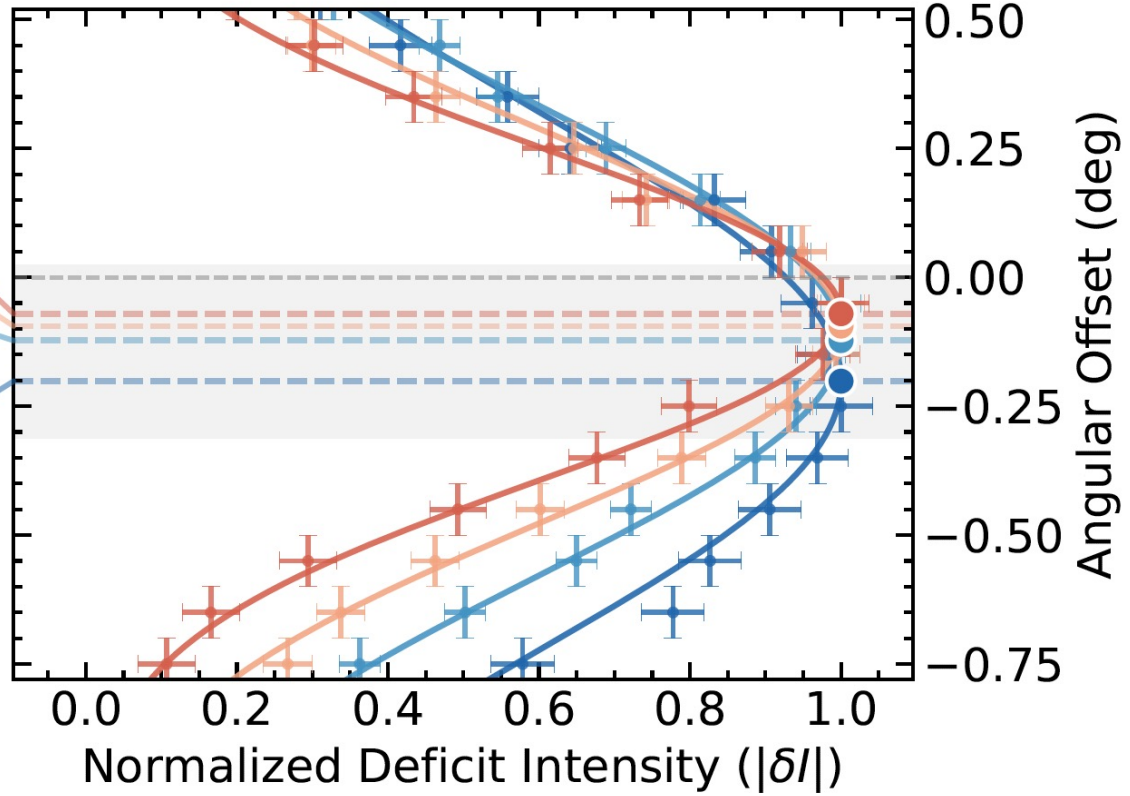
Data analysis – moon shadow analysis

All particle

Observation VS. Simulation



Observation



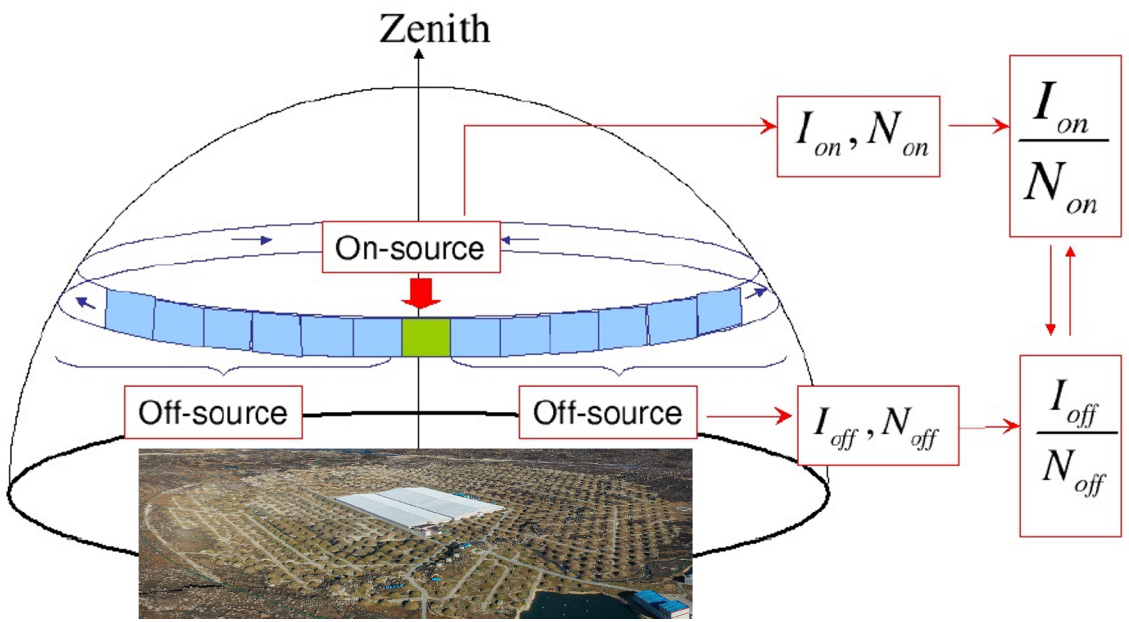
The median rigidities are corrected using the moon shadows.

Data analysis -- estimation of relative intensity

Iterative method

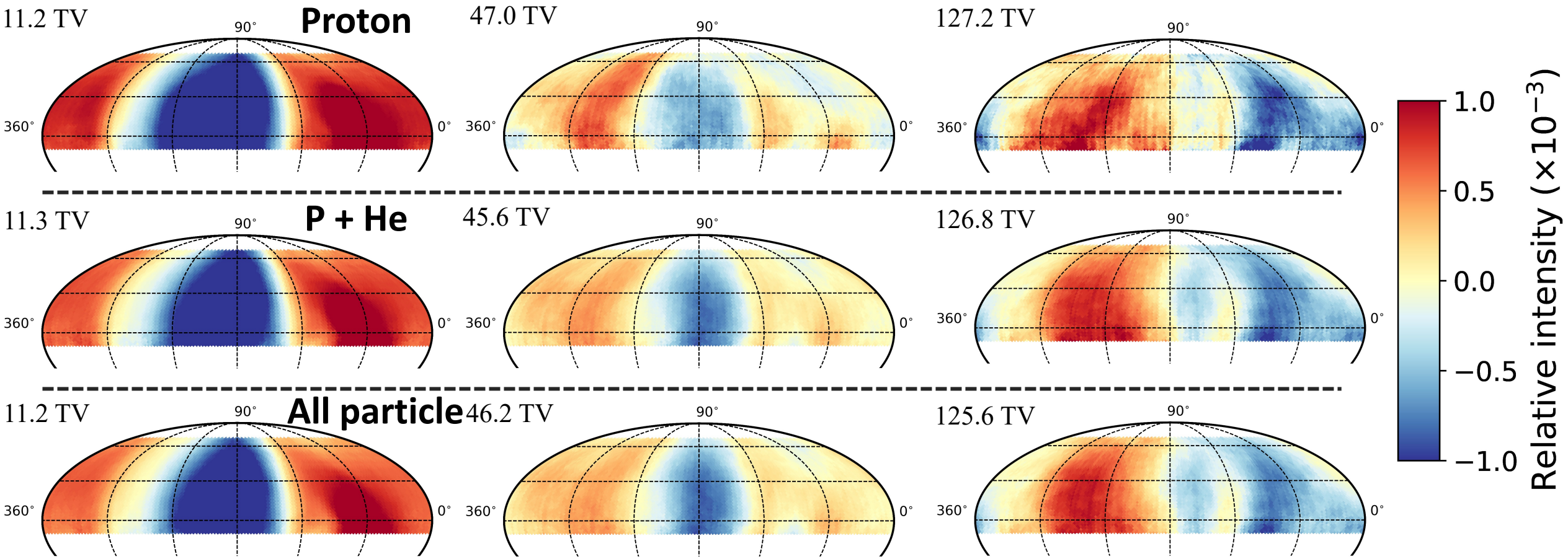
- All-distance equi-zenith angle method;
- 180 time bins, 40 zenith rings;
- 2 deg * 2 deg in the equatorial coordinate system.

$$\chi^2 = \sum_{t,\theta,\phi} \frac{\left(\frac{N_{t,\theta,\phi}}{I_{i,j}} - \frac{1}{n_\theta - 1}\sum_{\phi' \neq \phi}^{n_\theta} \frac{N_{t,\theta,\phi}}{I_{i',j'}}\right)^2}{\sigma^2_{t,\theta,\phi}}$$



Results -- sky maps

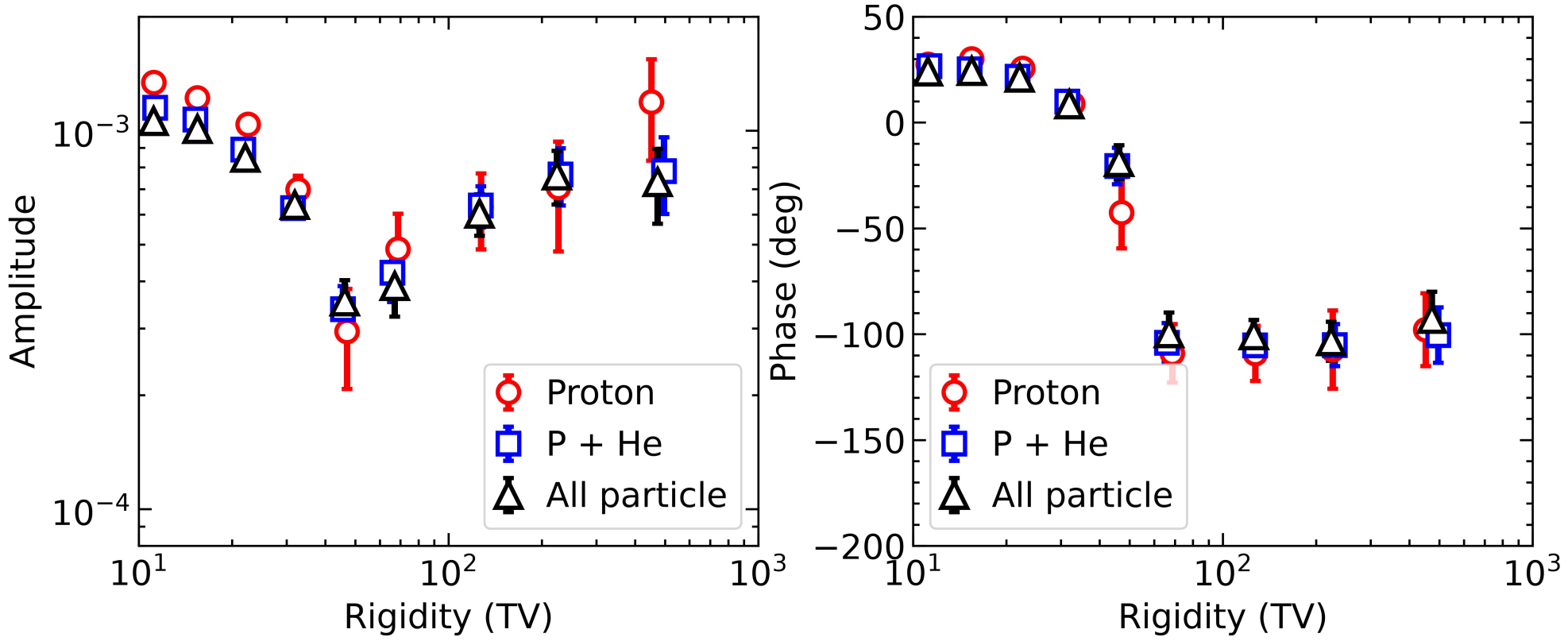
Top-hat smooth with a 20-degree radius.



A transition occurs around 50 TV.

The patterns of the different samples are similar.

Results -- sidereal time anisotropies



The relative intensity is projected along right ascension, and the harmonic decouple is used: $I(\alpha) = 1 + \sum_{k=1}^{2} A_k \cos(k(\alpha - \phi_k))$

Different samples share a similar rigidity-dependent evolution!

Results -- Z-dependent or A-dependent?

The chi-square comparison

- **A two-Gaussian function for the amplitude**

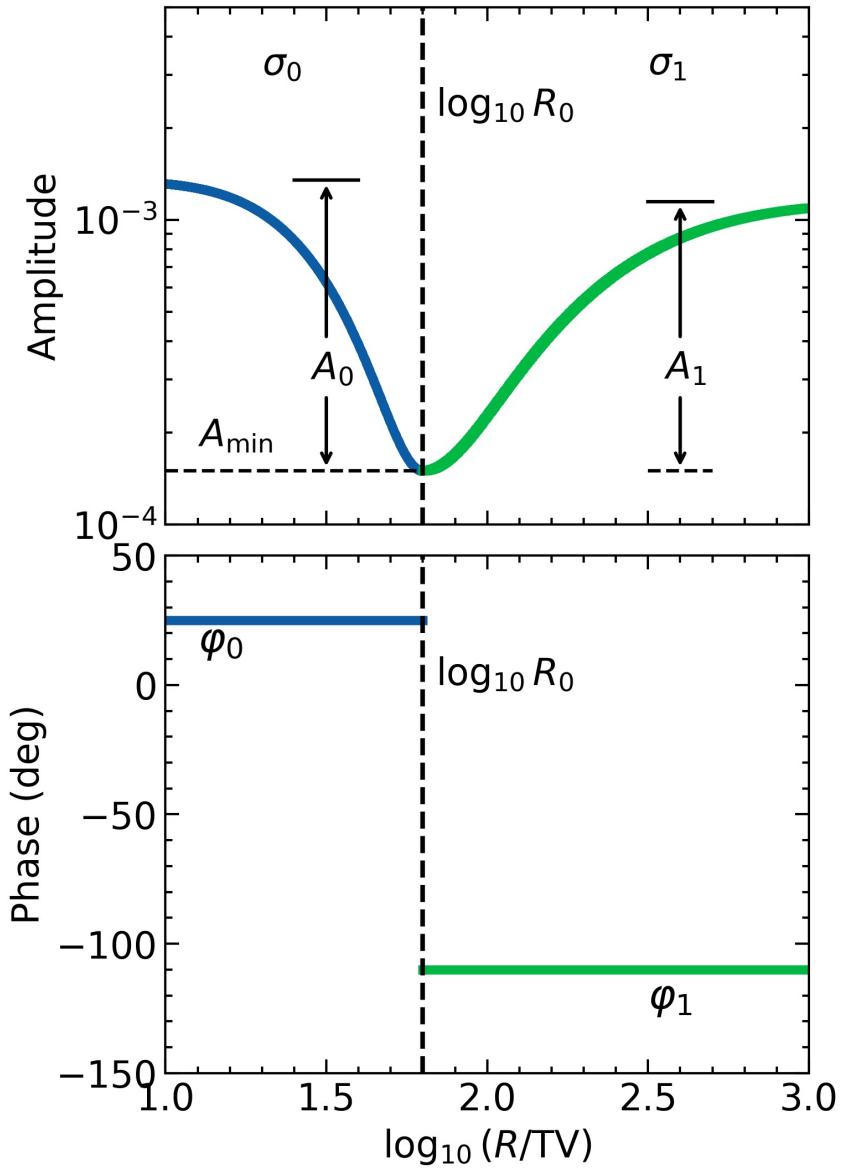
$$A(\log_{10} R) = \begin{cases} (A_{min}+A_0) + A_0 \exp\left(-\dfrac{(\log_{10} R - \log_{10} R_0)^2}{2\sigma_0^2}\right), & \text{if } R < R_0 \\ (A_{min}+A_1) + A_1 \exp\left(-\dfrac{(\log_{10} R - \log_{10} R_0)^2}{2\sigma_1^2}\right), & \text{if } R \geq R_0 \end{cases}$$

For nuclei heavier than protons:

$$A_0 \rightarrow A_0 f_h, \qquad A_1 \rightarrow A_1 f_h$$

- **A step function for the phase**

$$\varphi(\log_{10} R) = \begin{cases} \varphi_0, & \text{if } R < R_0 \\ \varphi_1, & \text{if } R \geq R_0 \end{cases}$$



Results -- Z-dependent or A-dependent?

- **Take into account the rigidity dispersion, for the i-th bin of measurements**

$$\tilde{A}_i = \sum_j \omega_j \int A(\log_{10} R) f_{i,j}(\log_{10} R) d\log_{10} R\,,$$

$$\tilde{\varphi}_i = \sum_j \omega_j \int \varphi(\log_{10} R) f_{i,j}(\log_{10} R) d\log_{10} R$$

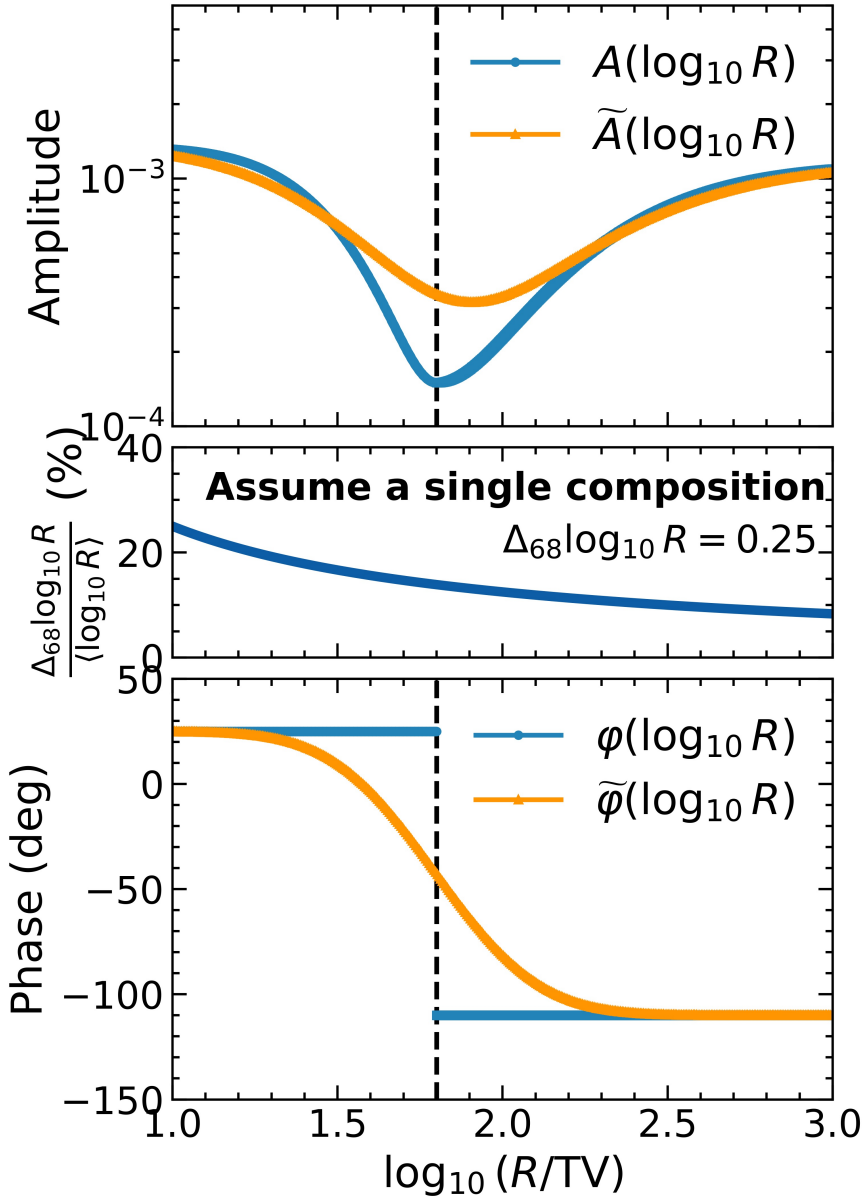
For the j-th nucleus's rigidity distribution in the i-th bin

$$\int f_{i,j}(\log_{10} R) d\log_{10} R = 1$$

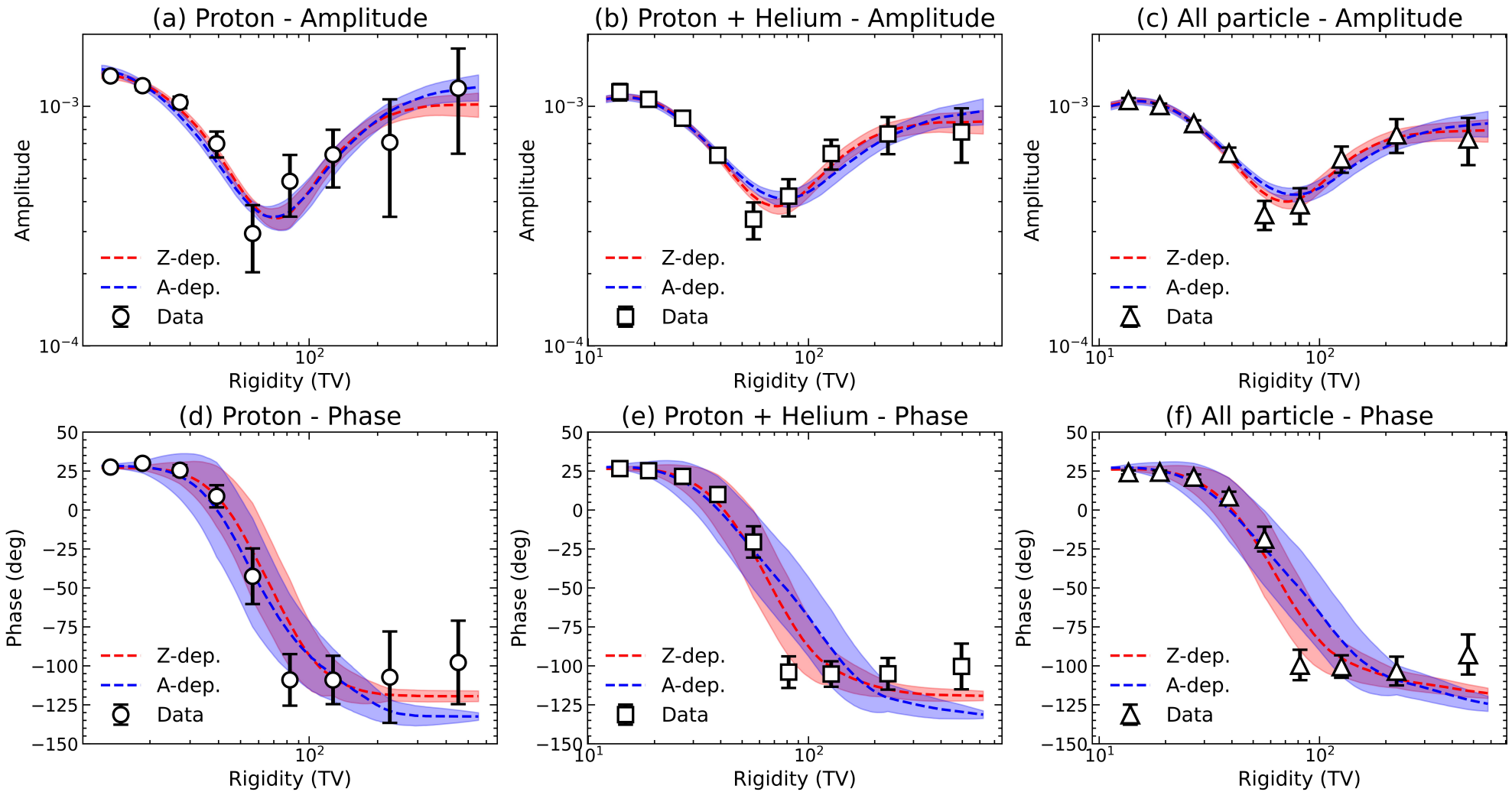
Normalized nuclei fraction $\sum_j \omega_j = 1$.

$$\chi^2 = \sum_i \left(\frac{\left(\tilde{A}_i - A_{i,obs}\right)^2}{\sigma_{A,i}^2} + \frac{\left(\tilde{\varphi}_i - \varphi_{i,obs}\right)^2}{\sigma_{\varphi,i}^2} \right)$$

For the A-dependent test, $R \to E/n$.



Results -- Z-dependent or A-dependent?



Hypothesis	χ^2/ndf	P-value
Z-dep.	63.94/45	0.036
A-dep.	135.12/45	2.2e-10

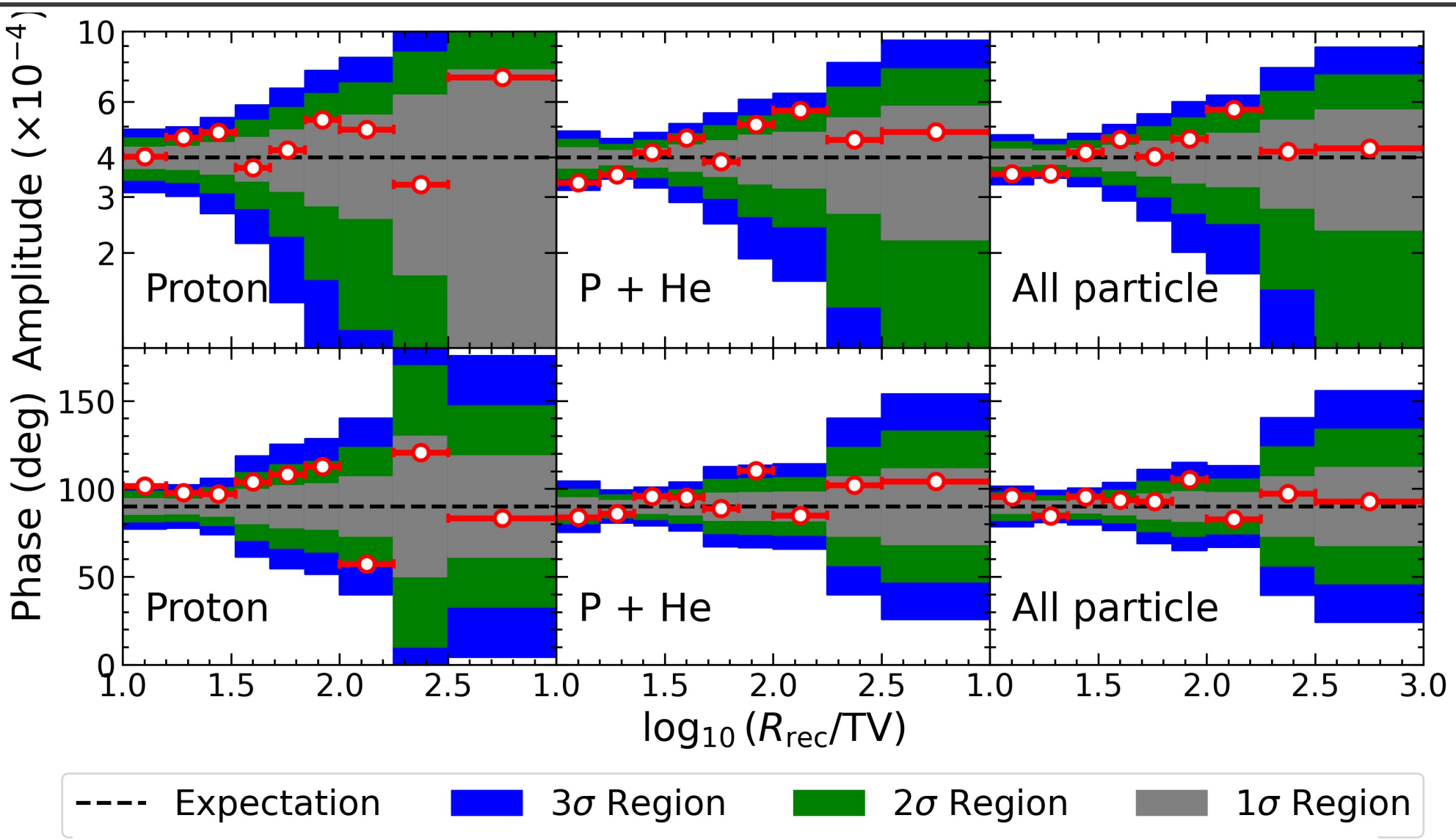
Data favors the Z-dependent assumption.

Summary

- **The rigidity is reconstructed using the electromagnetic and muon secondaries with KM2A data.**
- **The anisotropies of all particles, P + He, and proton samples are measured.**
  - **--Rigidities are corrected with the cosmic-ray moon shadows.**
  - **-- Different samples share a similar rigidity-dependent evolution behavior.**
  - **-- A transition occurs at about 50 TV.**
- **The Z-dependent hypothesis is preferred by the measurements.**

Backup

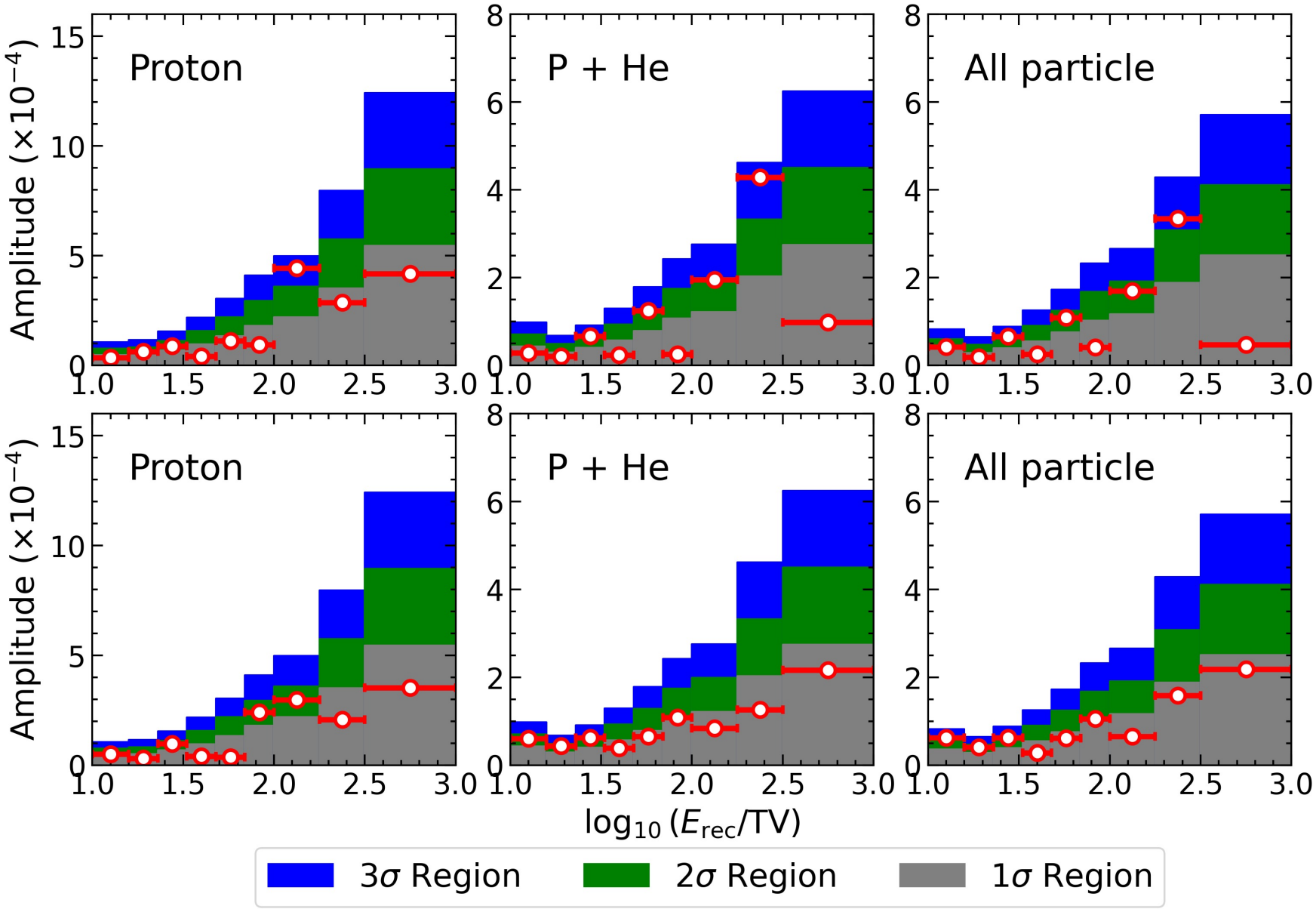
Solar time anisotropies



Consistent with Compton-Getting expectation!

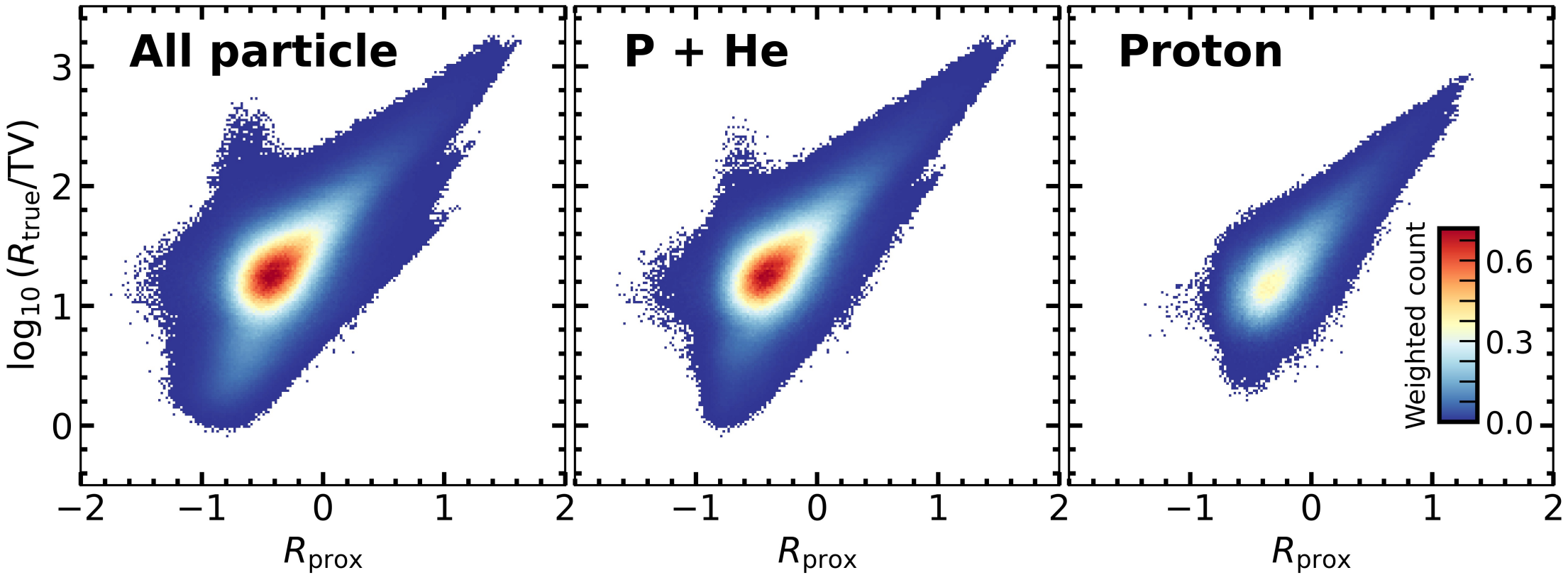
Anti- and ext-sidereal time anisotropies

Consistent with the expectation of background fluctuation!

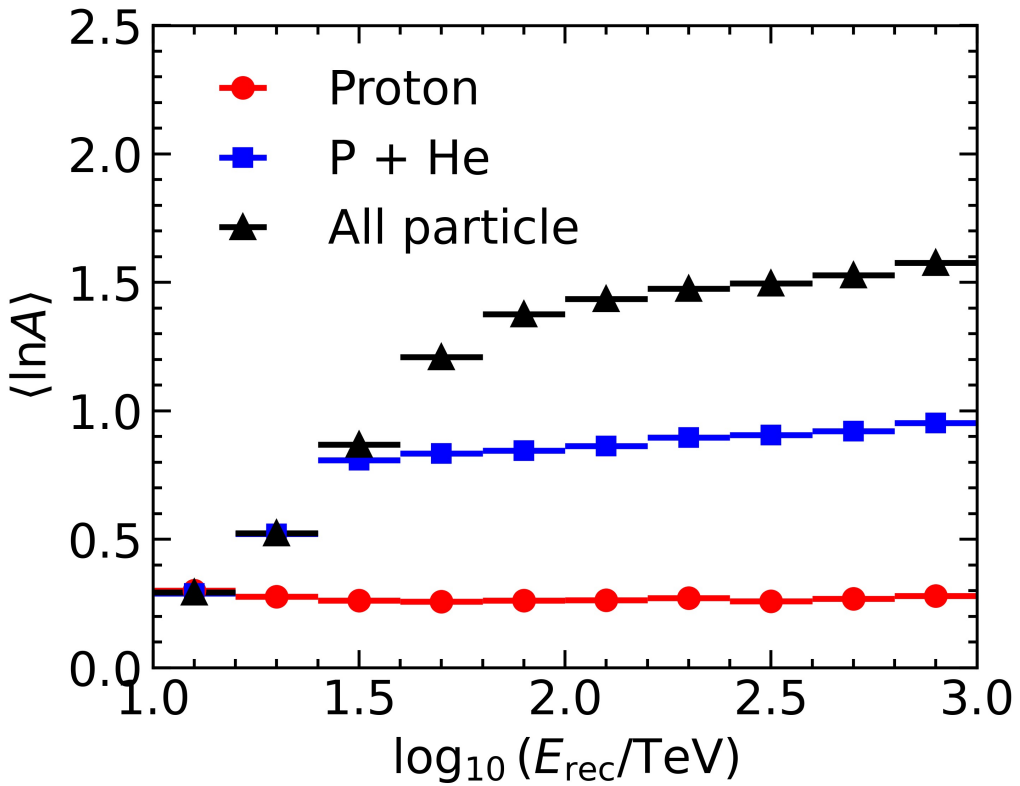


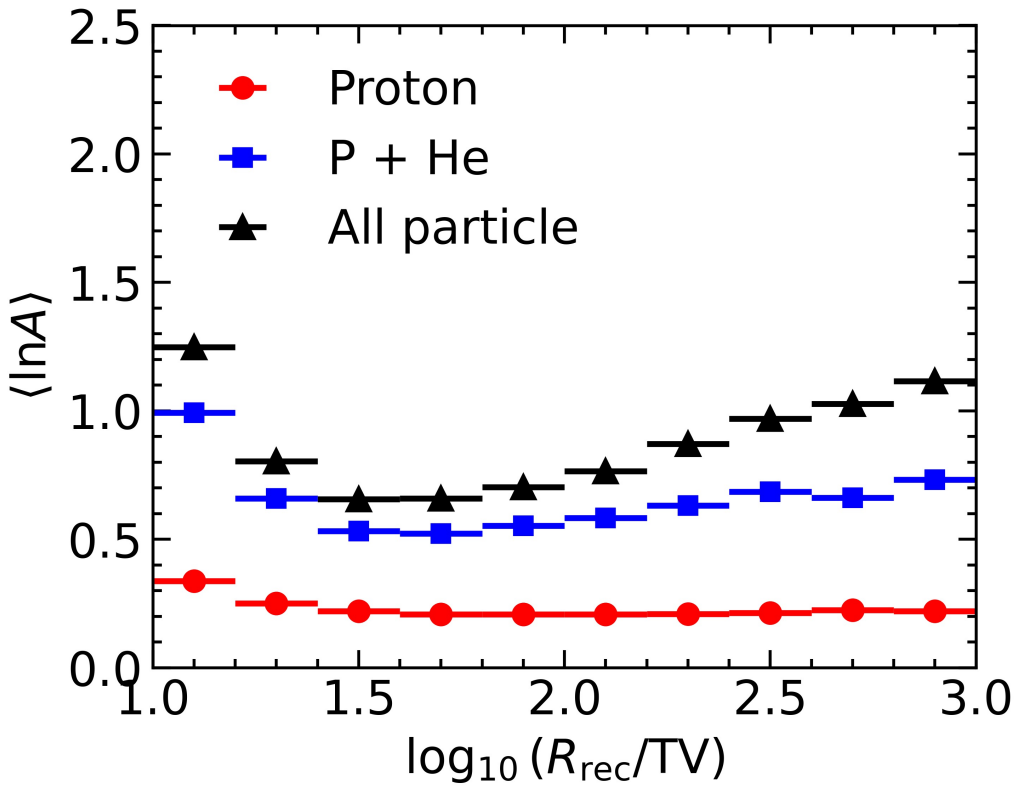
hejy@pmo.ac.cn

Rprox VS log10Rtrue



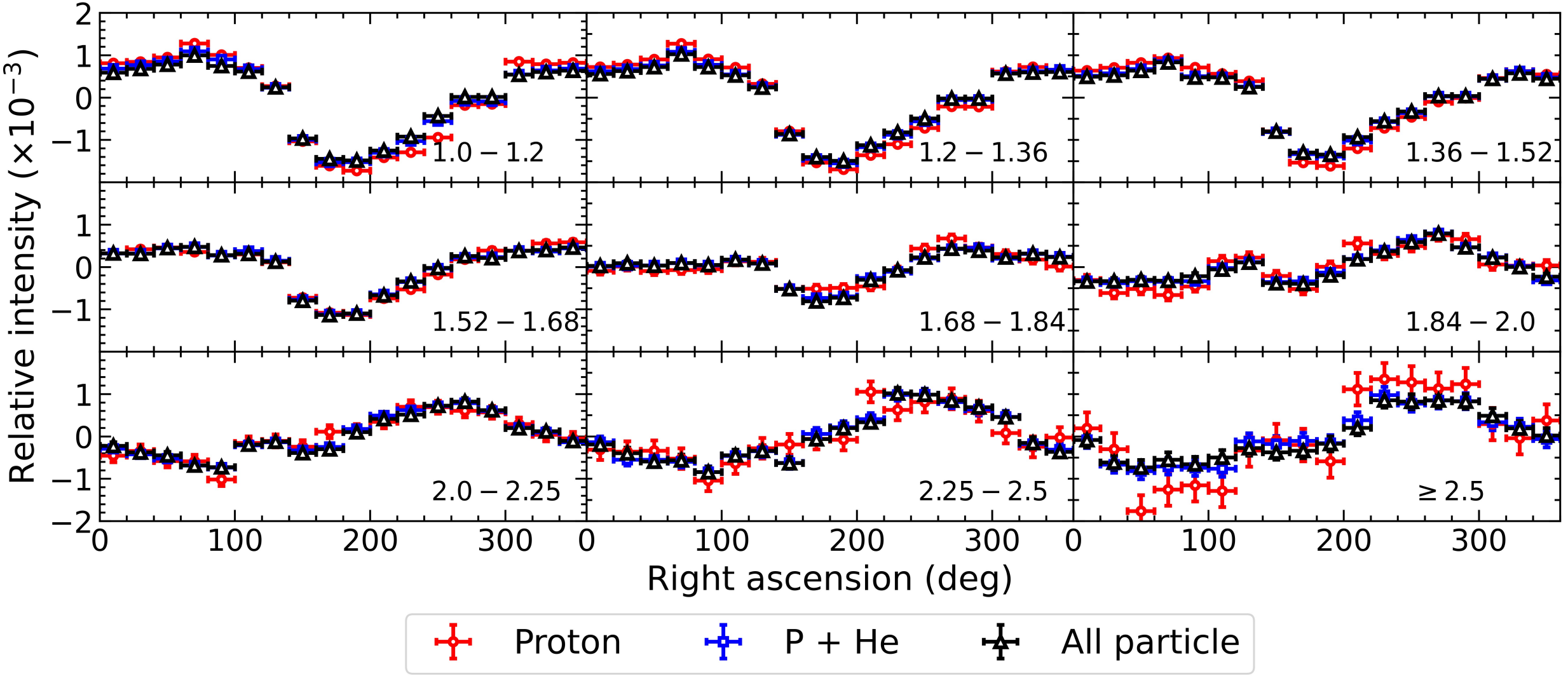
<lnA> in rigidity- and energy-binned samples



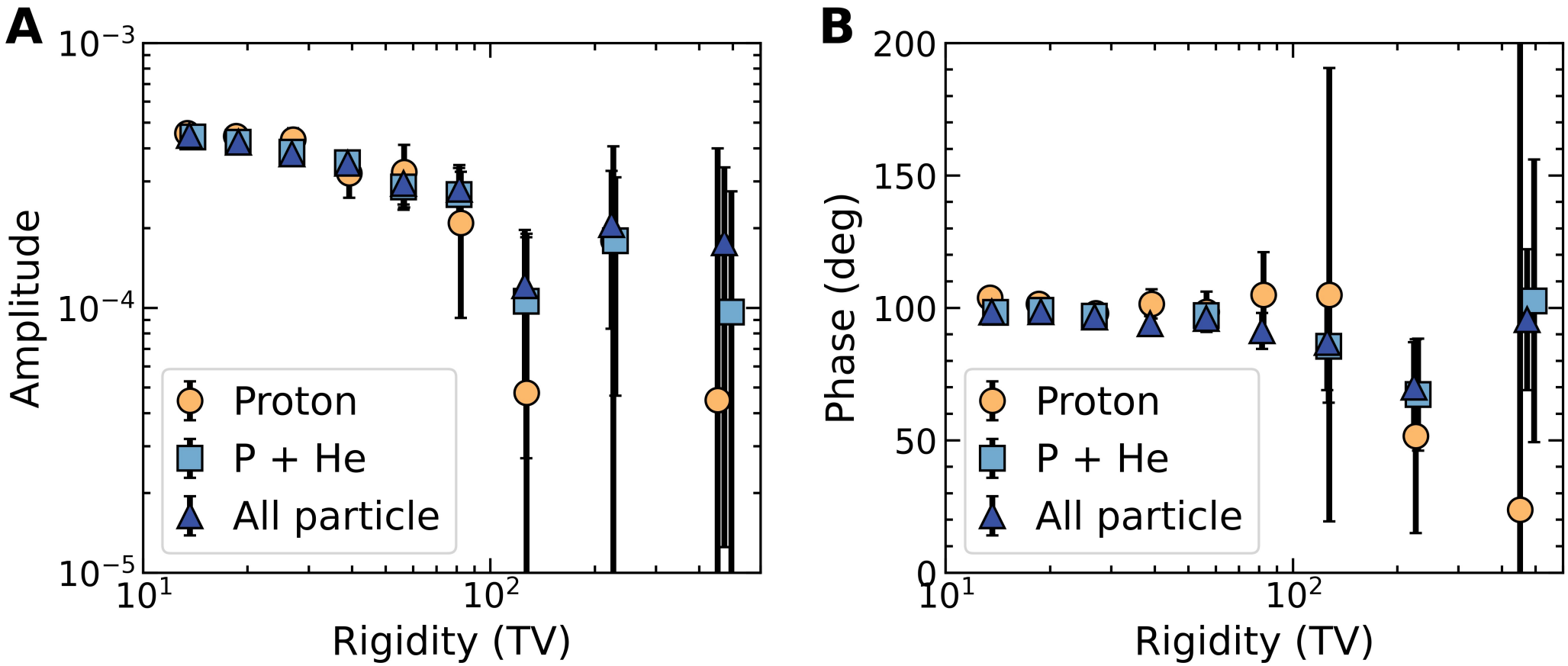


The compositions of rigidity-binned all particle samples are comparable to energy-binned P + He samples.

Relative intensity along the right ascension

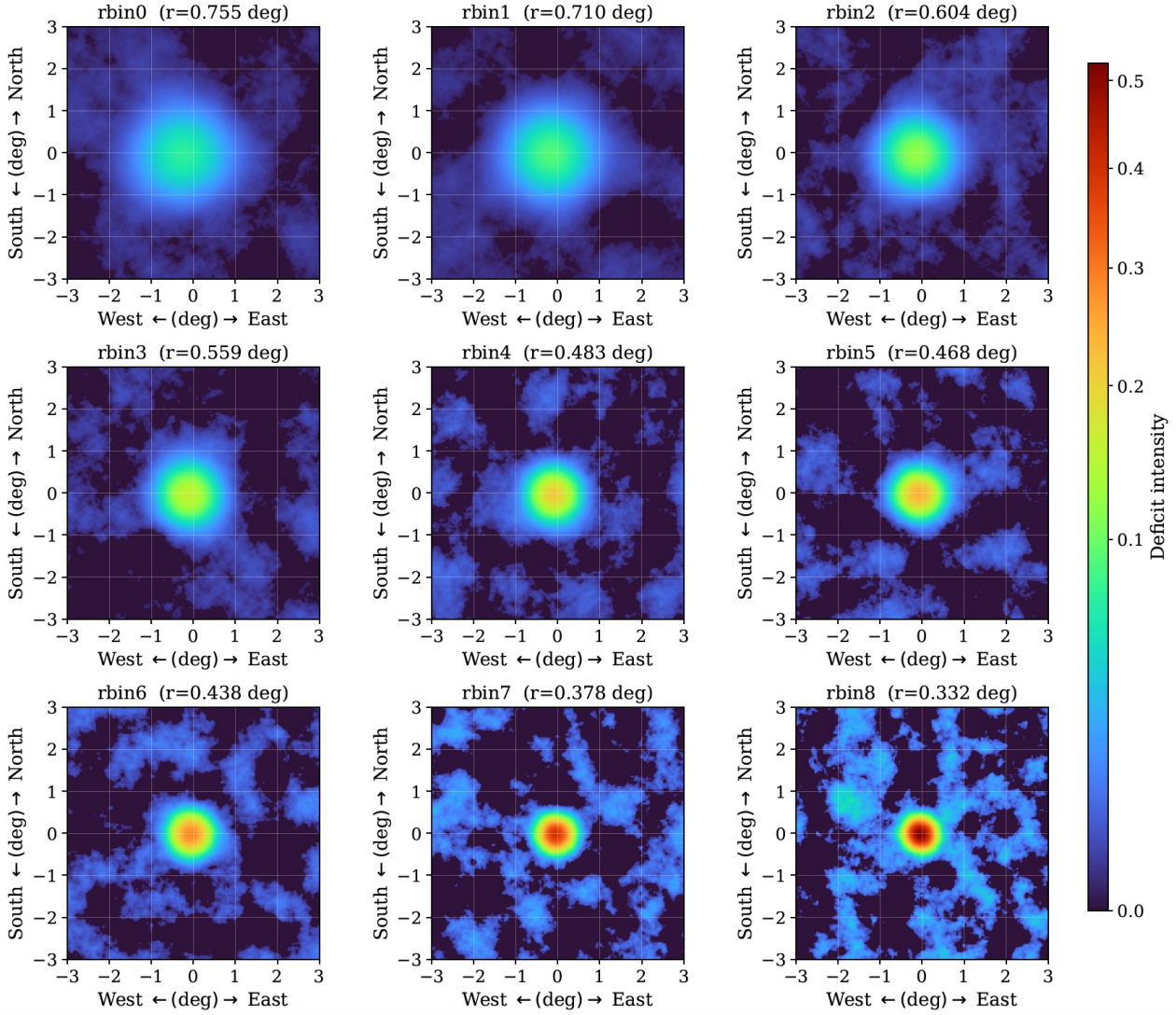


Higher-order anisotropies – Octuple VS. Rigidity

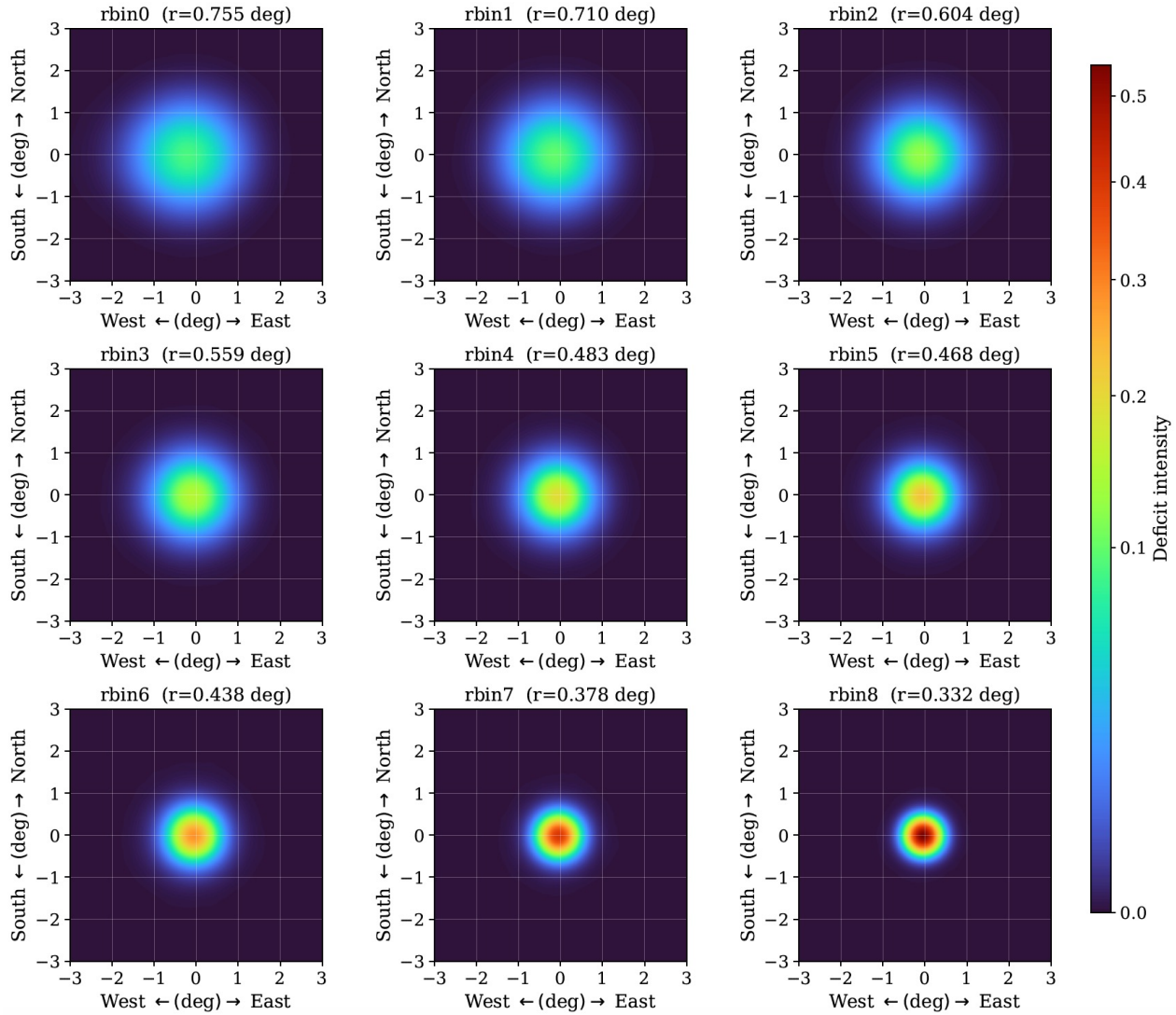


Sky maps of MC – all particle as an example

Observation

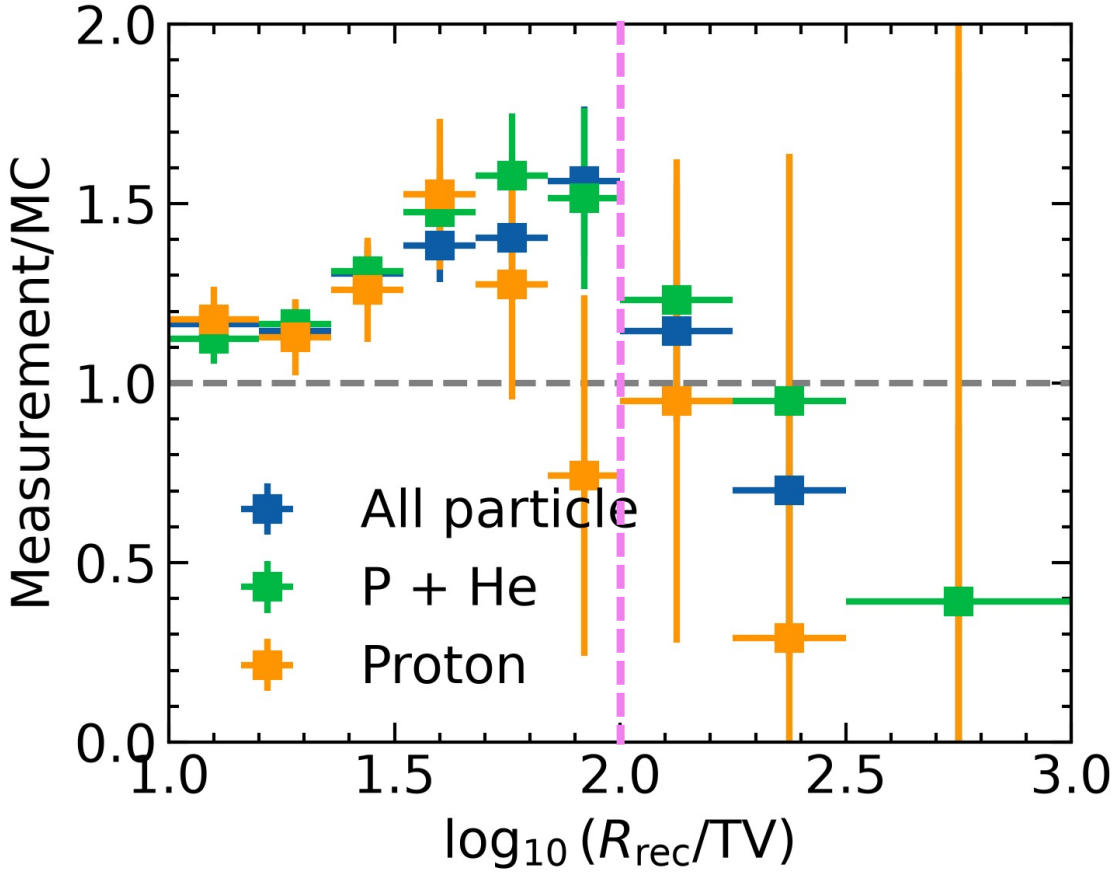


Simulation



Rigidities correction

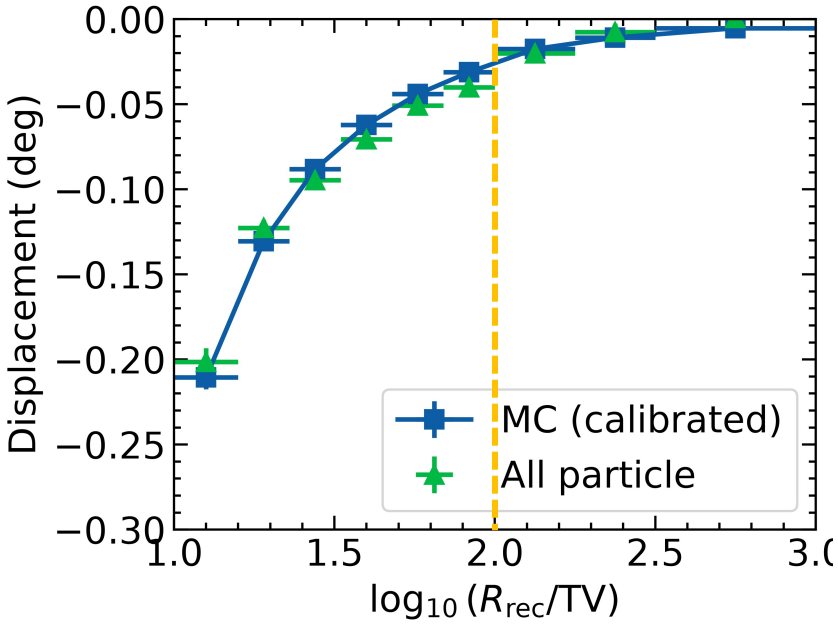
Rigidity samples

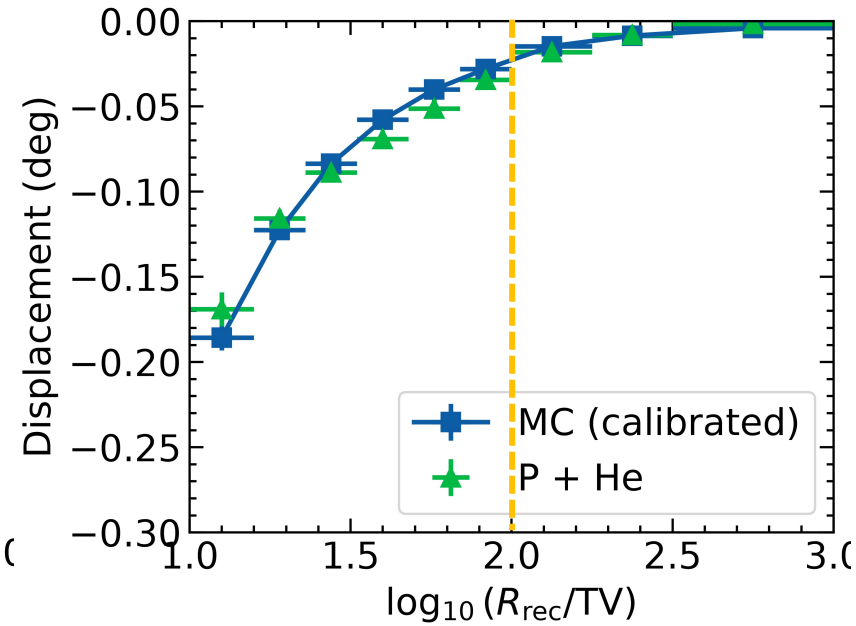


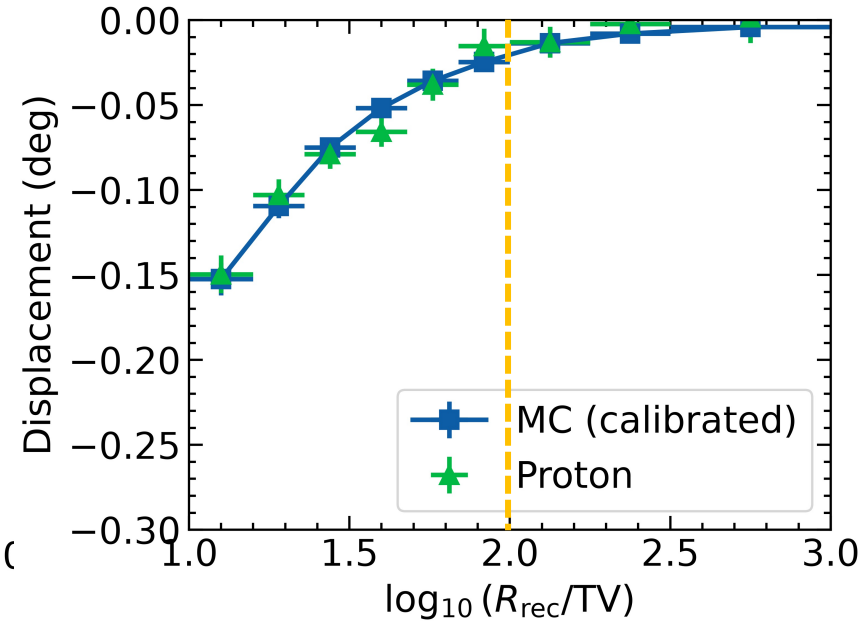
Sample	Mean	Error
All particle	1.217	0.030
P + He	1.234	0.036
Proton	1.200	0.058

Sample	Mean	Error
All particle	0.821	0.020
P + He	0.810	0.024
Proton	0.833	0.040

Rigidity correction

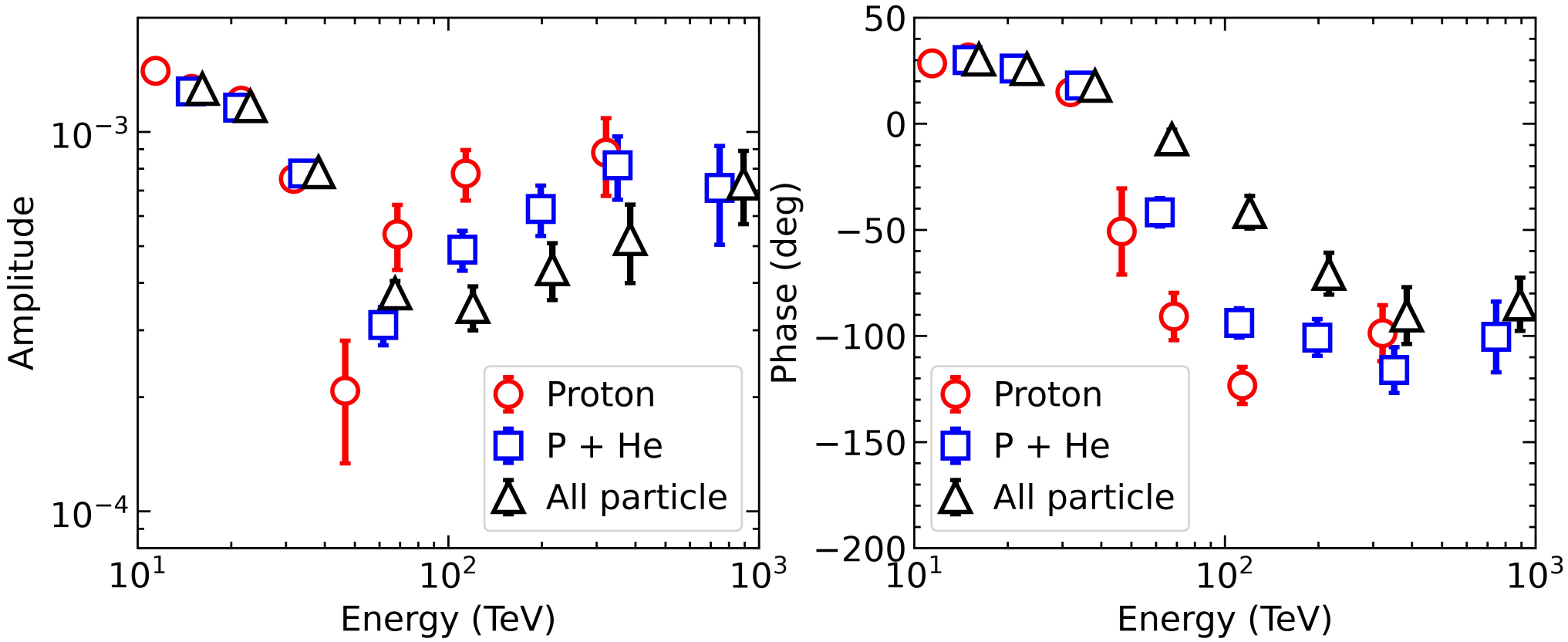




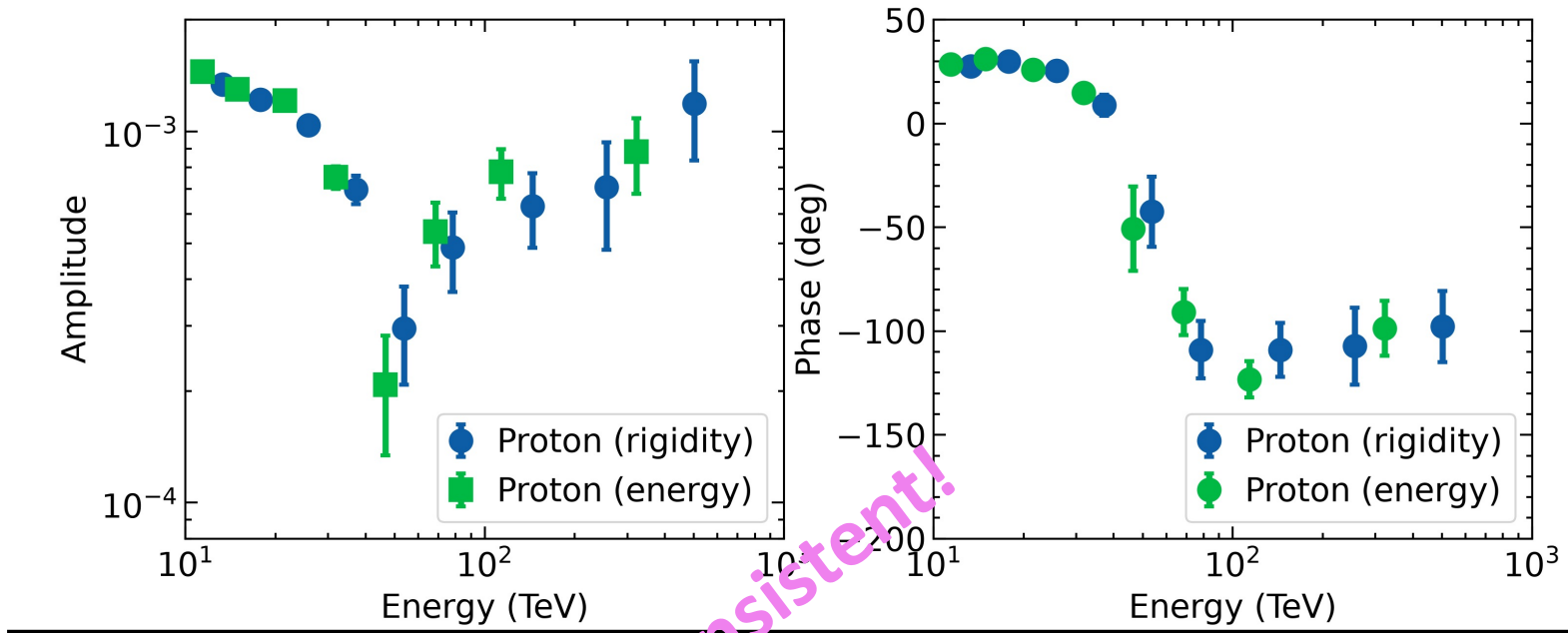


Rigidity Correction for < 100 TV

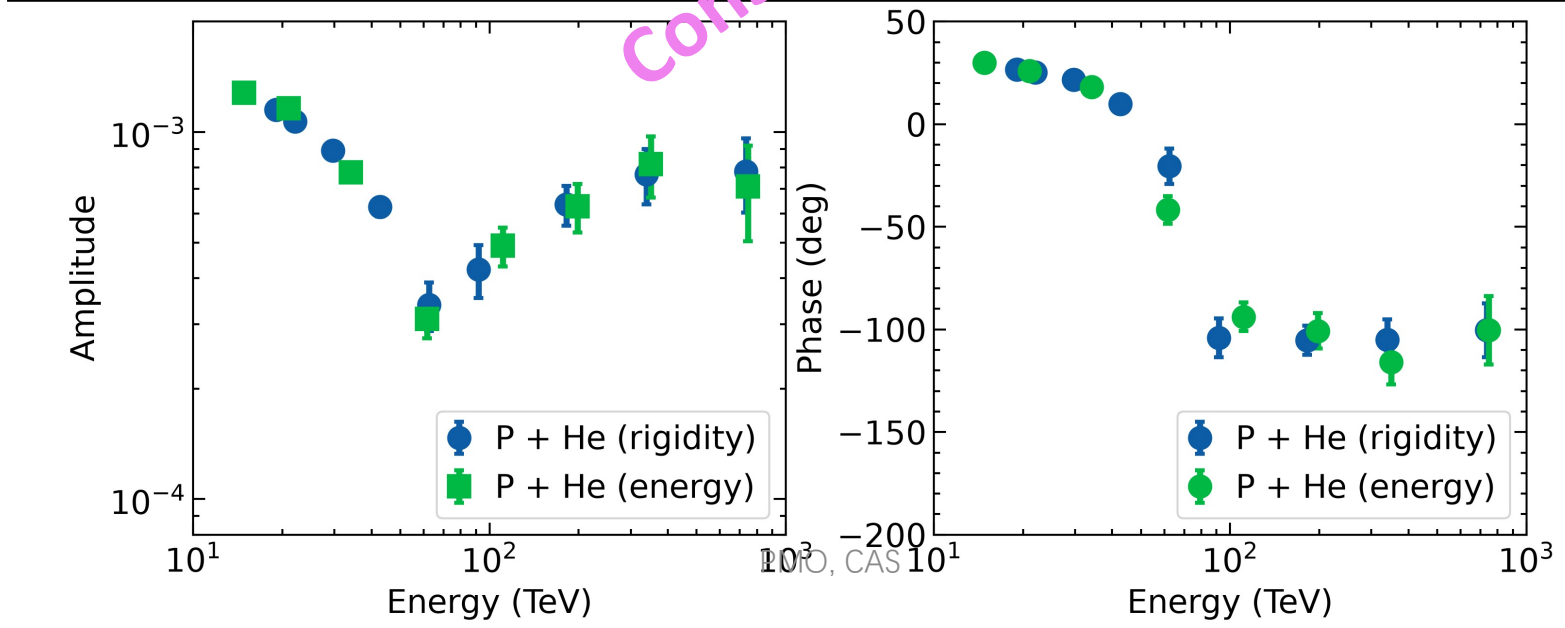
Results of energy-binned samples



Anisotropies – Rigidity- VS Energy-binned samples



Consistent!



Anisotropies – Rigidity- VS Energy-binned samples

