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

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Outline

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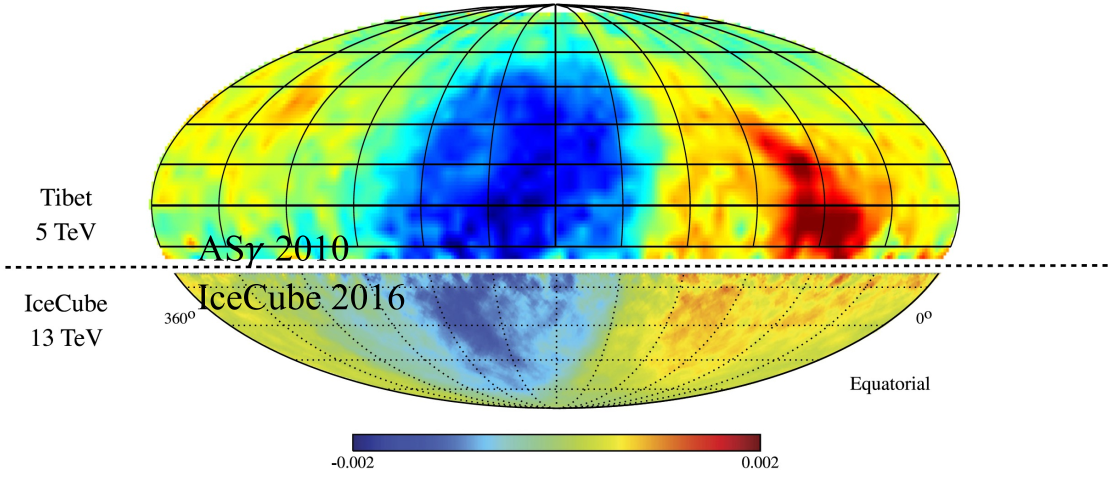
- Data analysis
- Results
- Summary

Introduction

LHAASO



Ground-based experiments

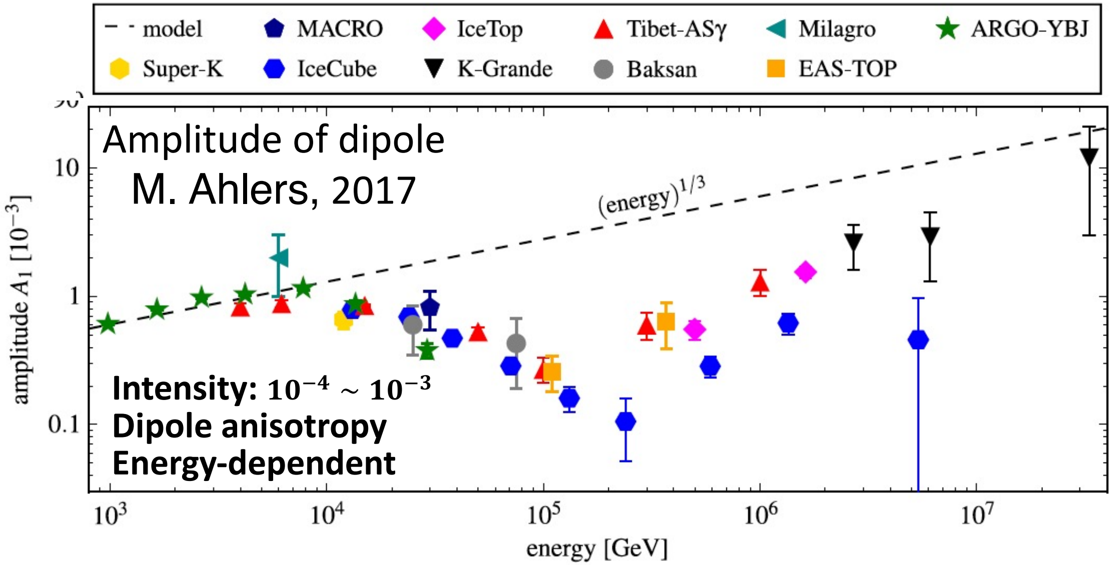
- All particle
- 1TeV ~ 10 PeV (Galactic cosmic rays)

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, …



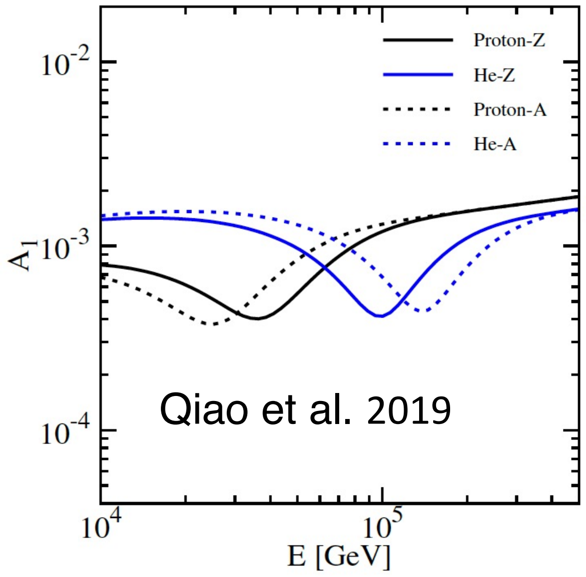
Introduction

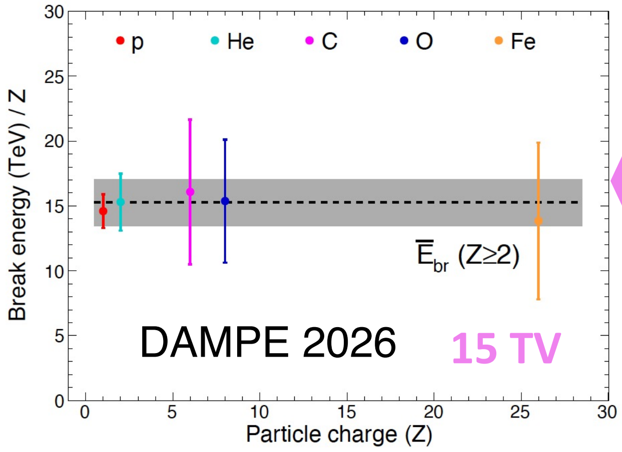
For the local source model, the structure of 1-100 TeV is the result of competition with background CRs.

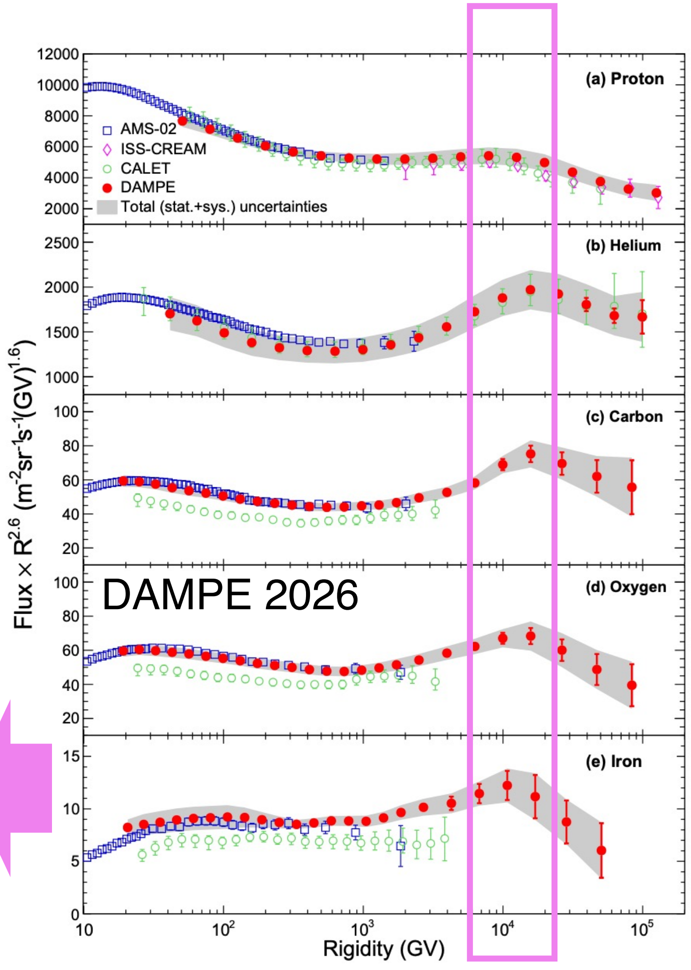
Cut-off energy of a local source: Z-dependent and A-dependent.

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

What about anisotropies: charge-dependent transition?







Introduction

LHAASO

- KM2A: 5195 EDs + 1188 MDs
- WCDA: 3120 WCDs
- WFCTA: 18 WFCTs

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.

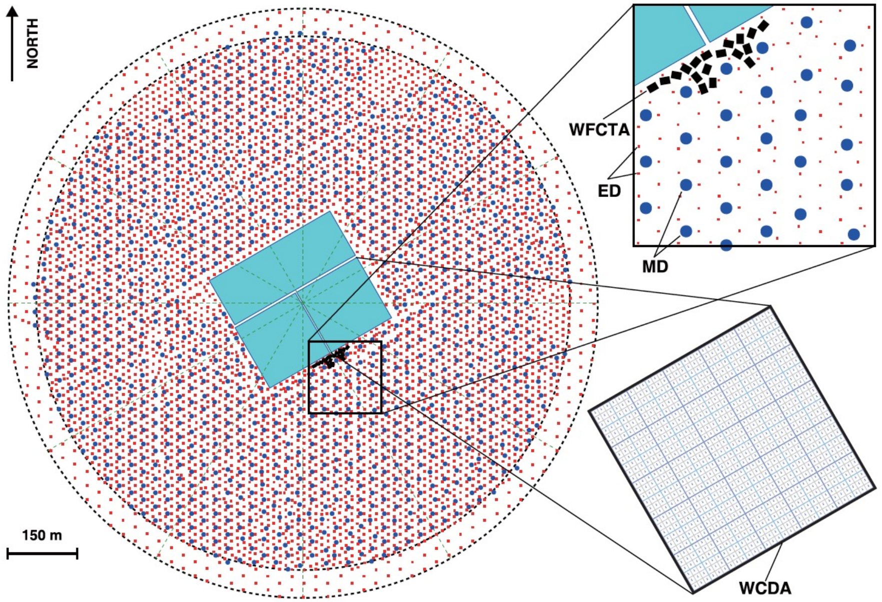


Fig. 1. (color online) Layout of LHAASO.

LHAASO Science Book (2021)

Data analysis -- selection criteria

Raw data

- Zenith angle smaller than 40 degrees.
- The number of EDs used for reconstruction >= 22 for samples of all particle and P + He; >=20 for P sample.
- Shower core inside the array; distance to the array center 170 -- 560 m.

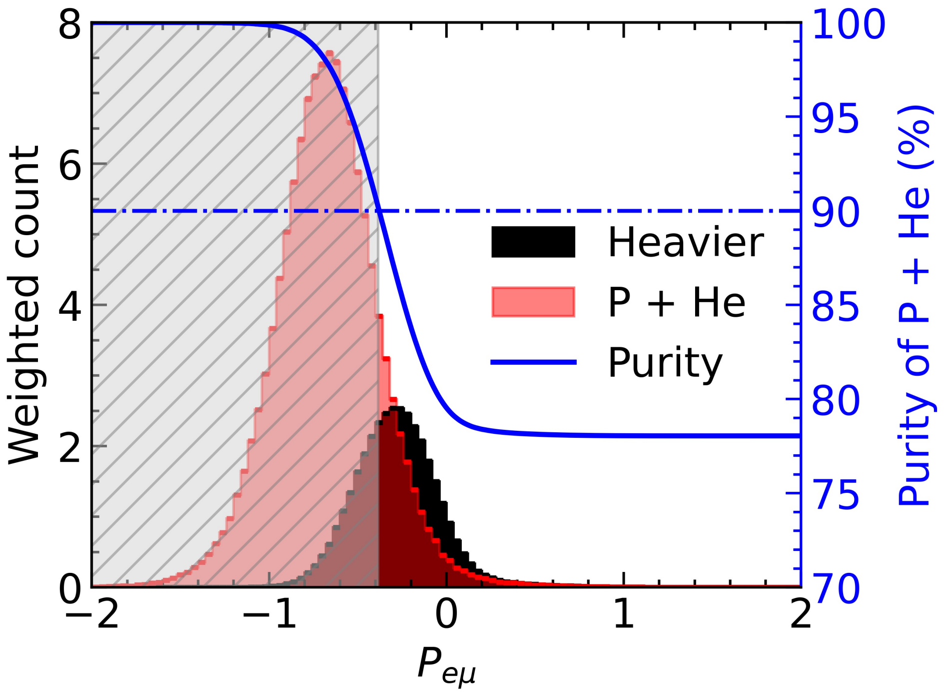
From July 20, 2021 to July 19, 2025

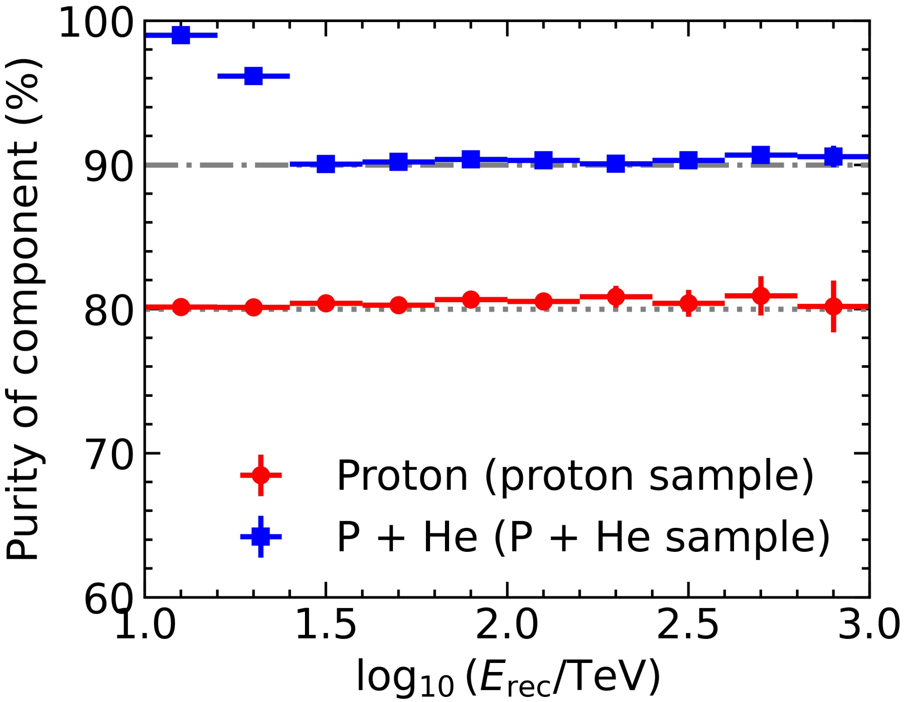
P selection → **Sample of proton**

P + He selection → **Sample of P + He**

Sample of all particle

Data analysis -- selection of target particles



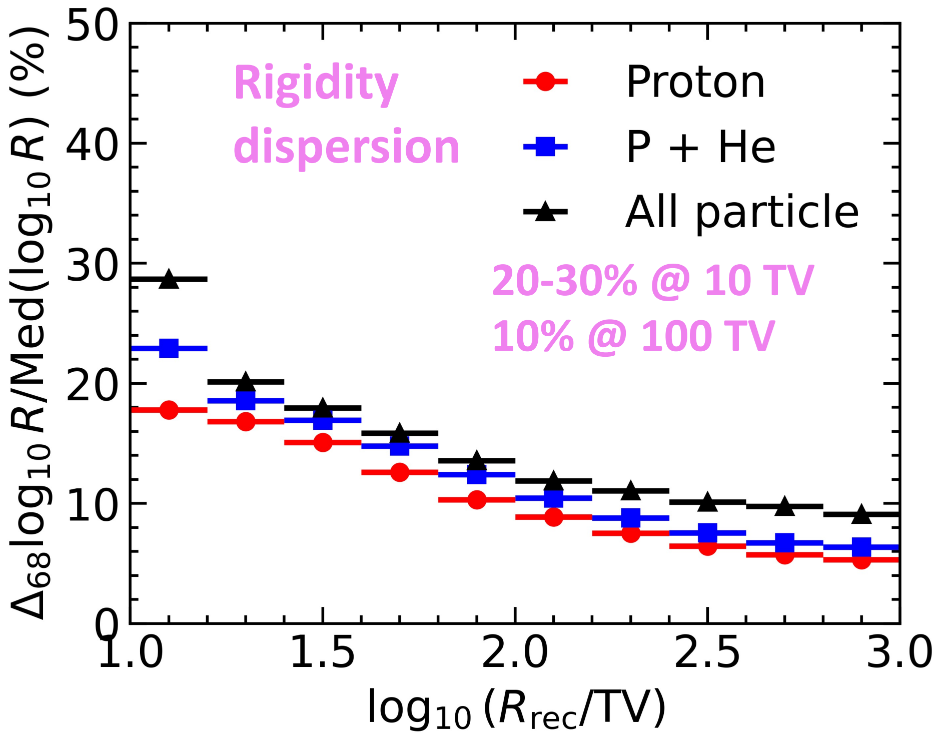


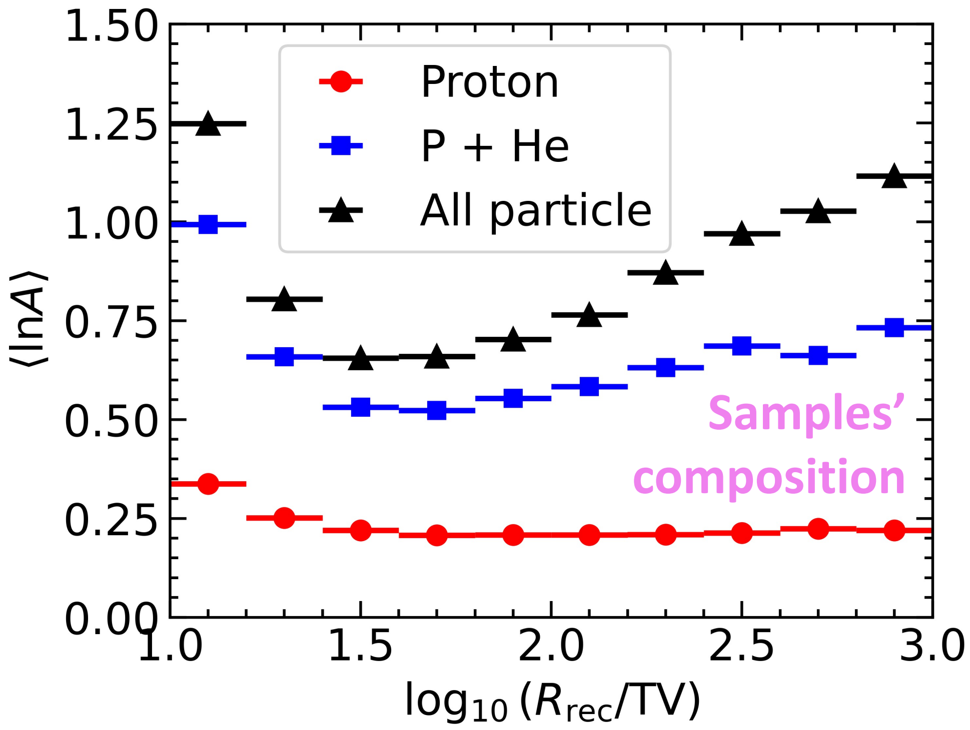
Particle identity parameter:

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

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

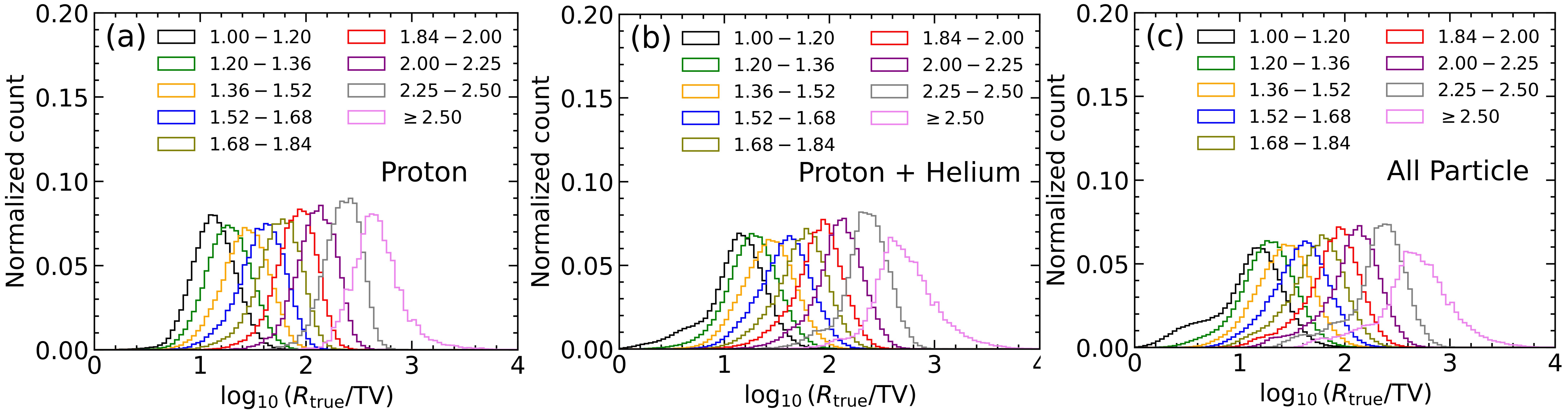
Data analysis -- rigidity reconstruction





- **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



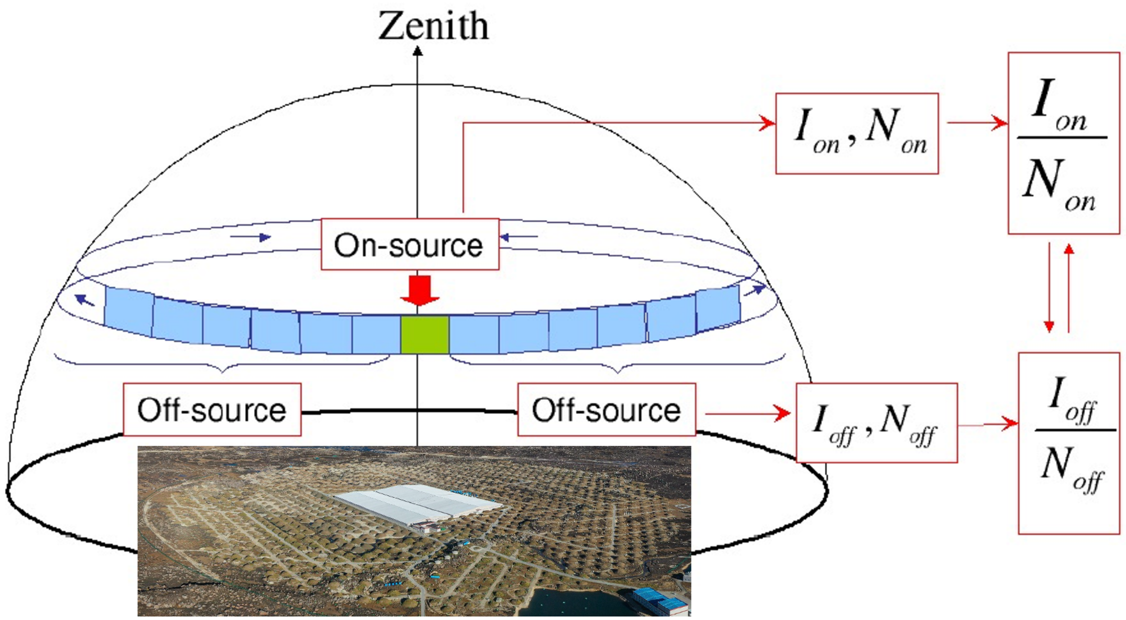
Data are binned into 9 bins according to reconstructed rigidity.

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 -- estimation of relative intensity

Iterative method

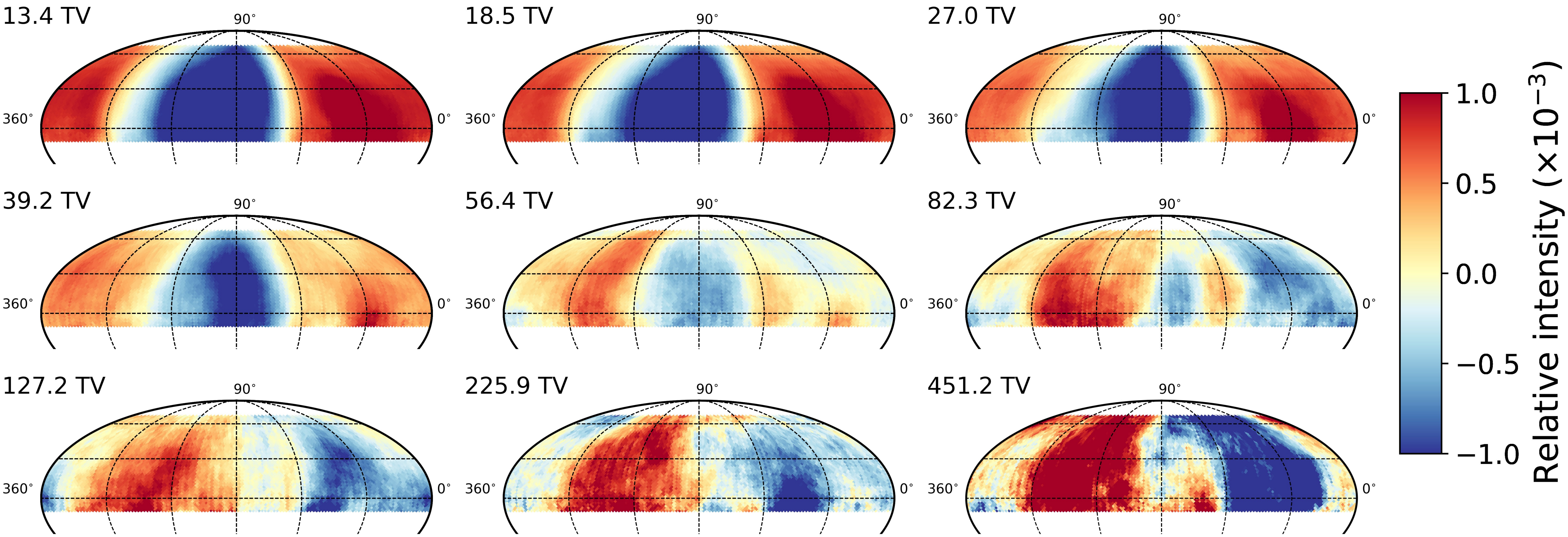
- **All-distance equi-zenith angle method;**
- **180 time bins, 40 zenith rings;**
- **2 deg * 2 deg in the equatorial coordinate system.**



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

Results -- sky maps (Proton)

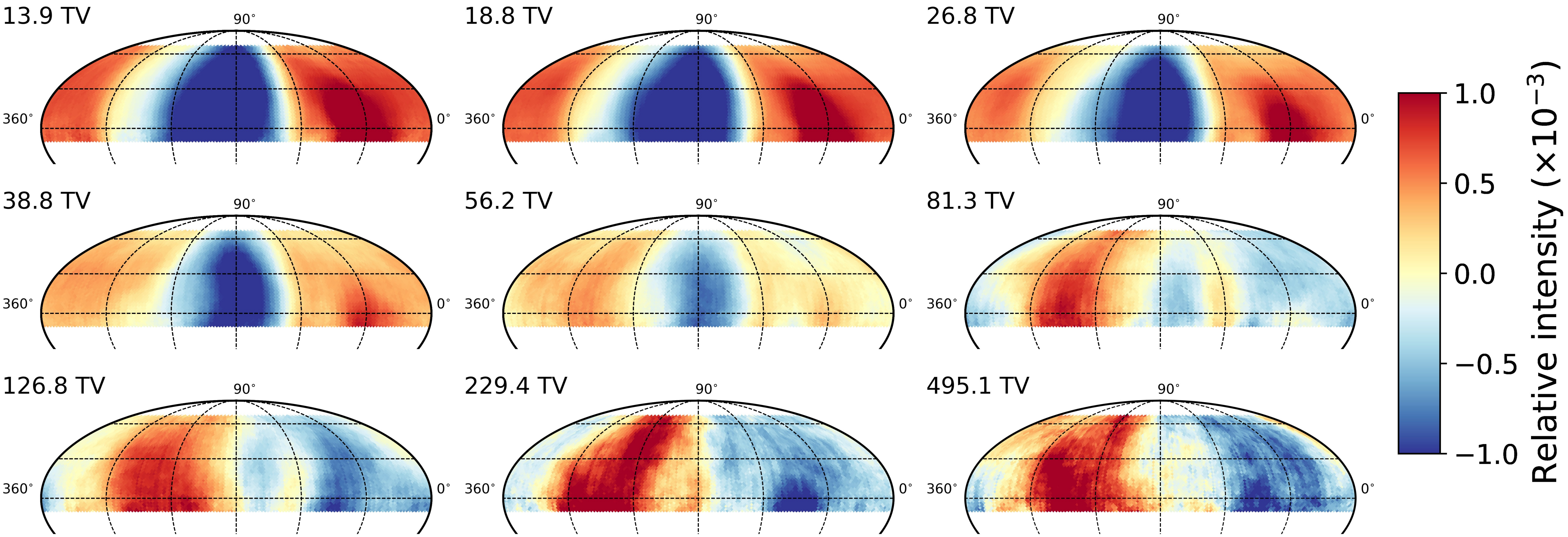
Top-hat smooth with a 20-degree radius.



A transition occurs at about 60 TV.

Results -- sky maps (P + He)

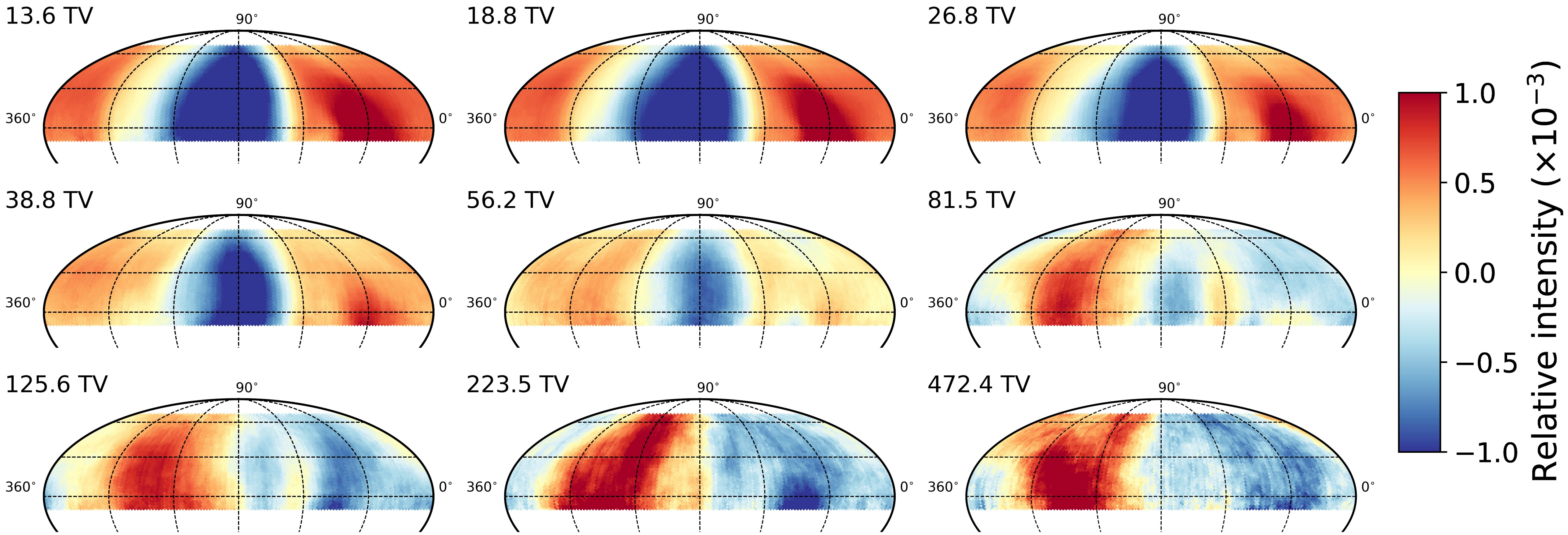
Top-hat smooth with a 20-degree radius.



- **A transition occurs at about 60 TV.**
- **Patterns are similar to those of proton samples.**

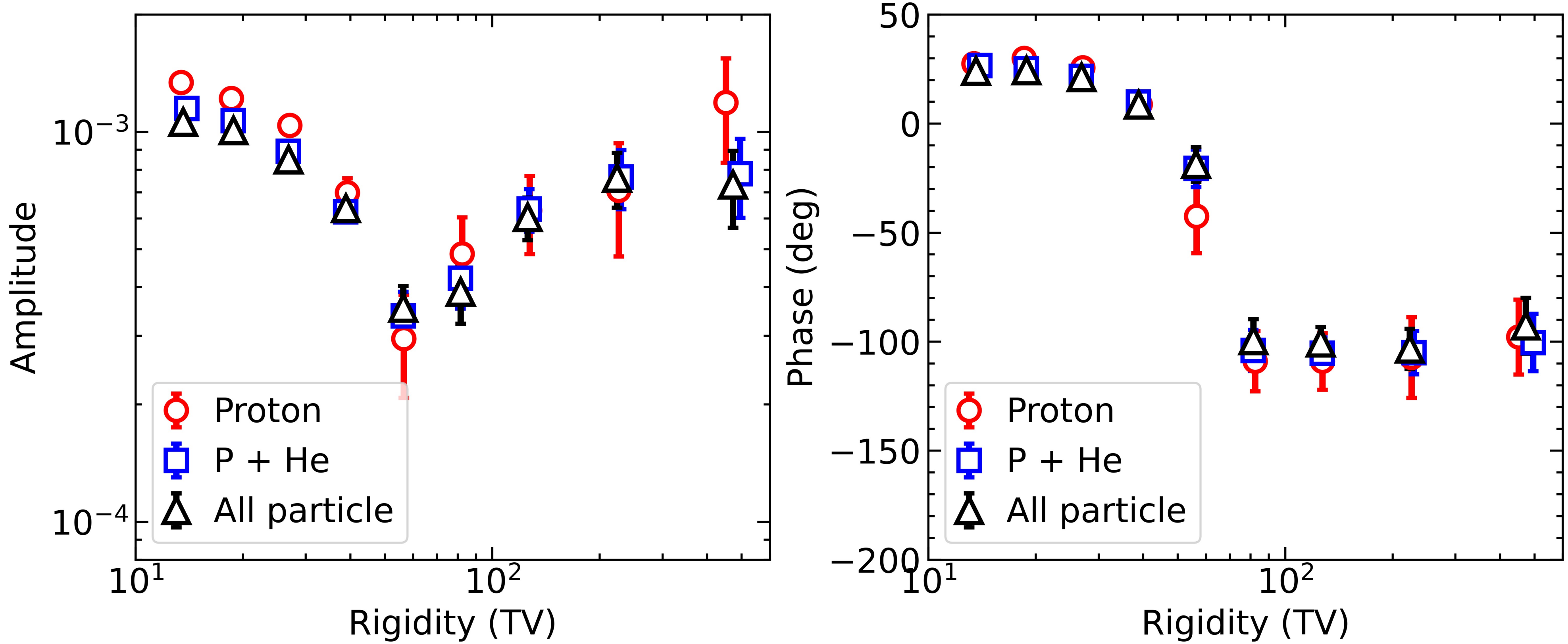
Results -- sky maps (All particle)

Top-hat smooth with a 20-degree radius.



- **A transition occurs at about 60 TV.**
- **Patterns are similar to those of proton samples and P + He samples.**

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**

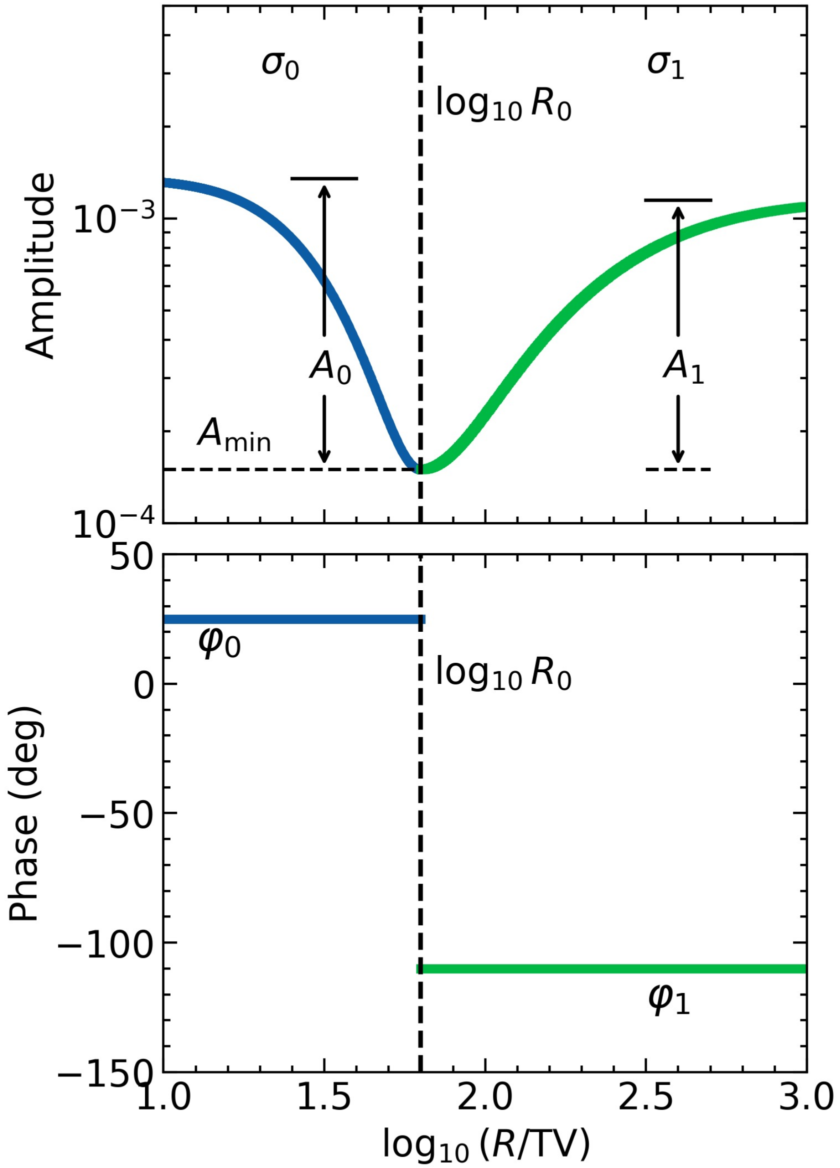
$$A(\log_{10} R) = \begin{cases} (A_{min}+A_0) + A_0 \exp\left(-\frac{(\log_{10} R - \log_{10} R_0)^2}{2\sigma_0^2}\right), & \text{if } R < R_0 \\ (A_{min}+A_1) + A_1 \exp\left(-\frac{(\log_{10} R - \log_{10} R_0)^2}{2\sigma_1^2}\right), & \text{if } R \geq R_0 \end{cases}$$

For nuclei heavier than protons:

$$A_0 \to A_0 f_h, \qquad A_1 \to A_1 f_h$$

- **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**

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

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

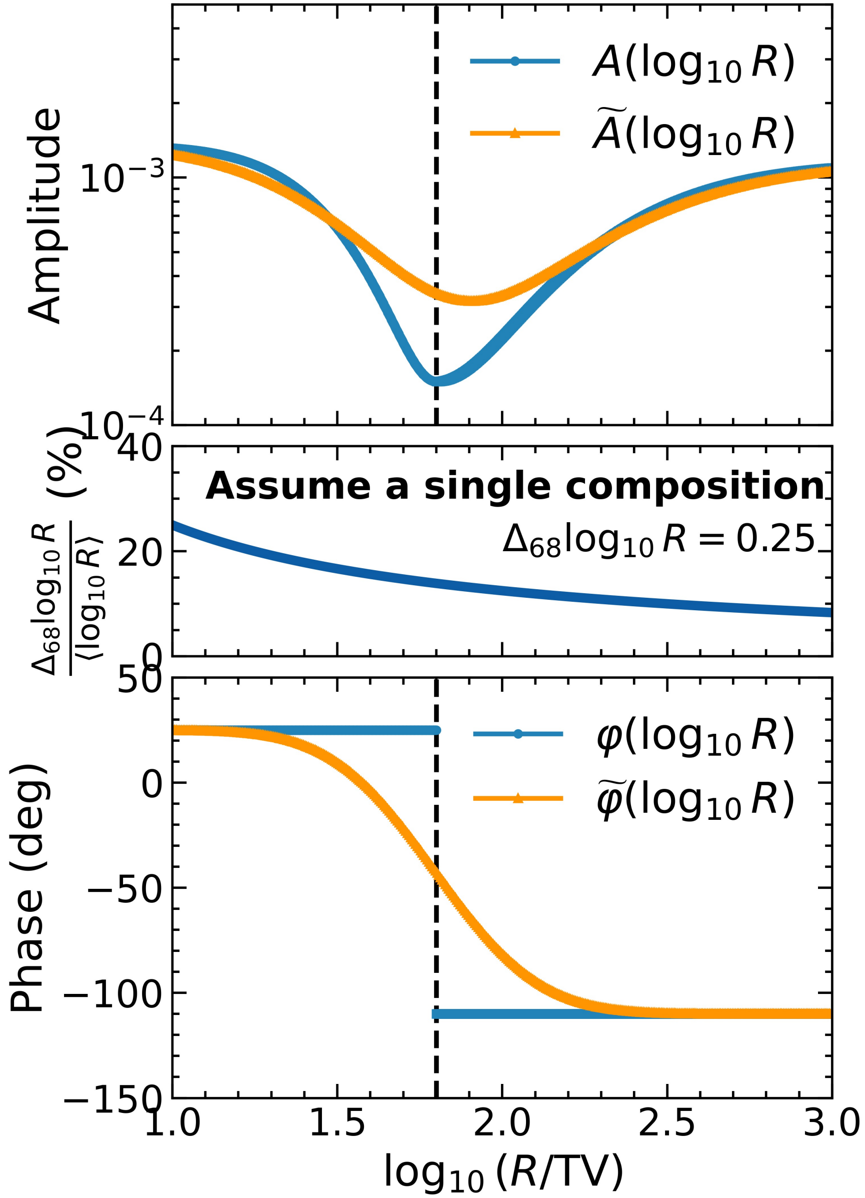
For the j-th nucleus's rigidity distribution in the i-th bin

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

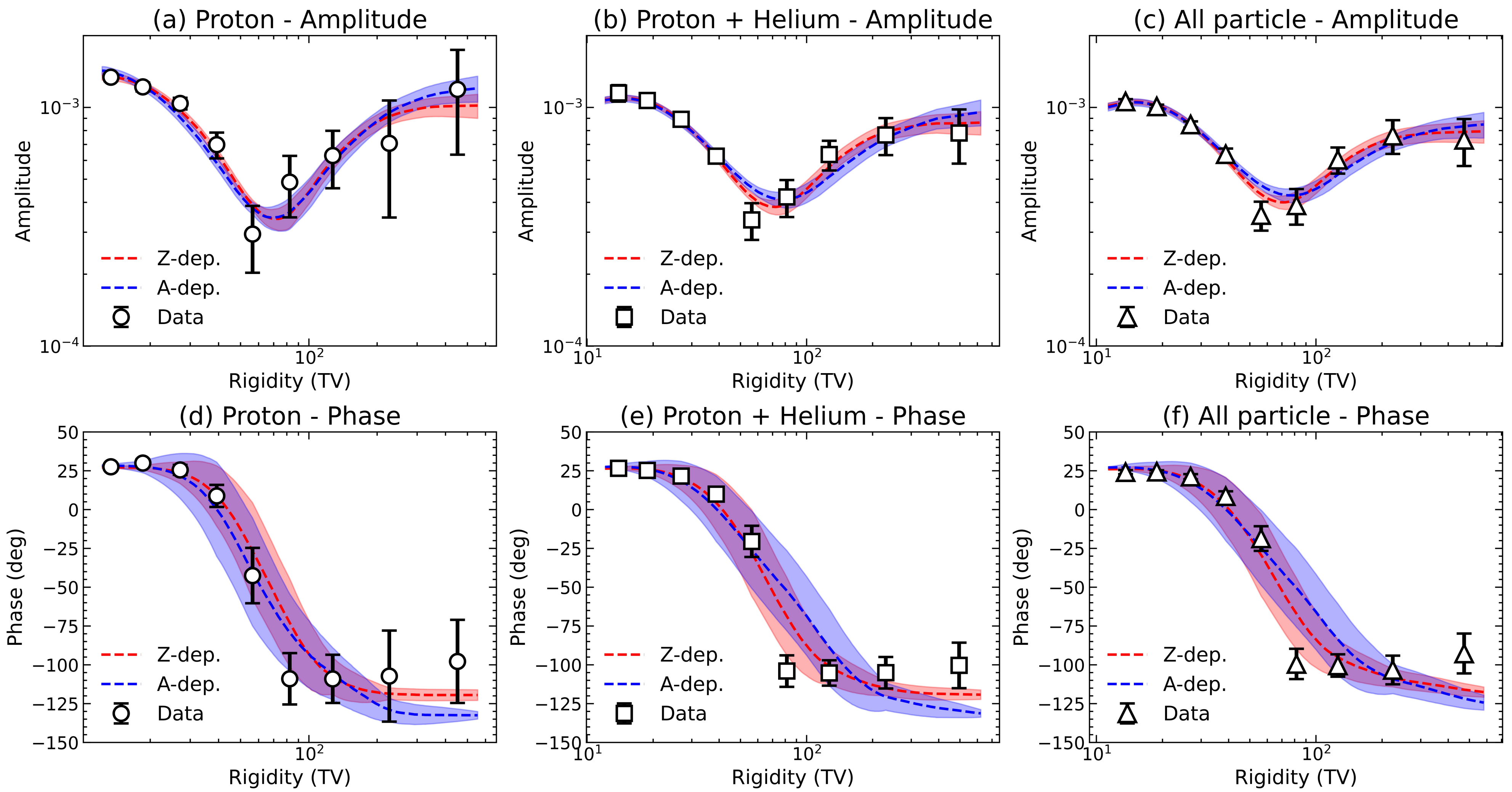
Normalized nuclei fraction $\sum_j \omega_j = 1.$

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

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

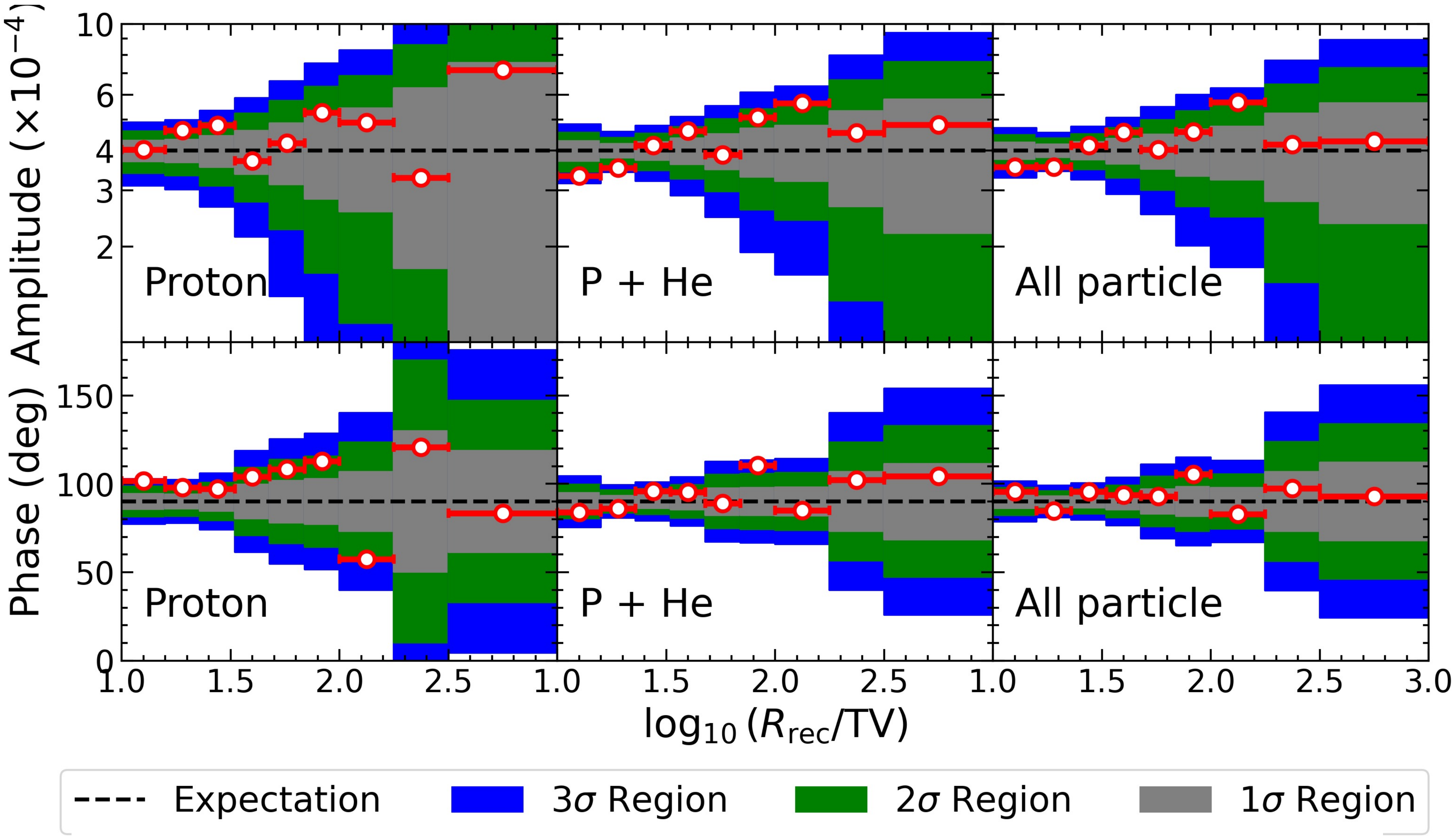
Data favors the Z-dependent assumption.

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.
  - Different samples share a similar rigidity-dependent evolution behavior.
  - A transition occurs at about 60 TV.
- The Z-dependent hypothesis is preferred by measurements.

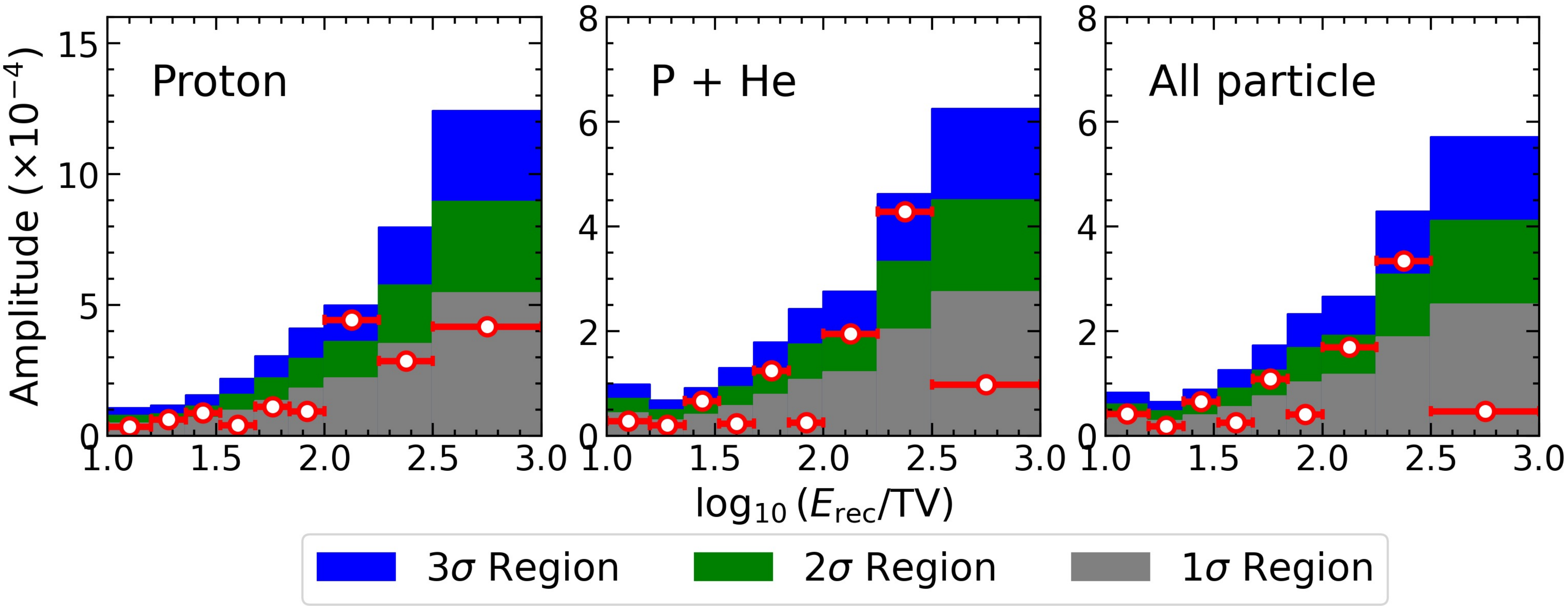
Backup

Solar time anisotropies



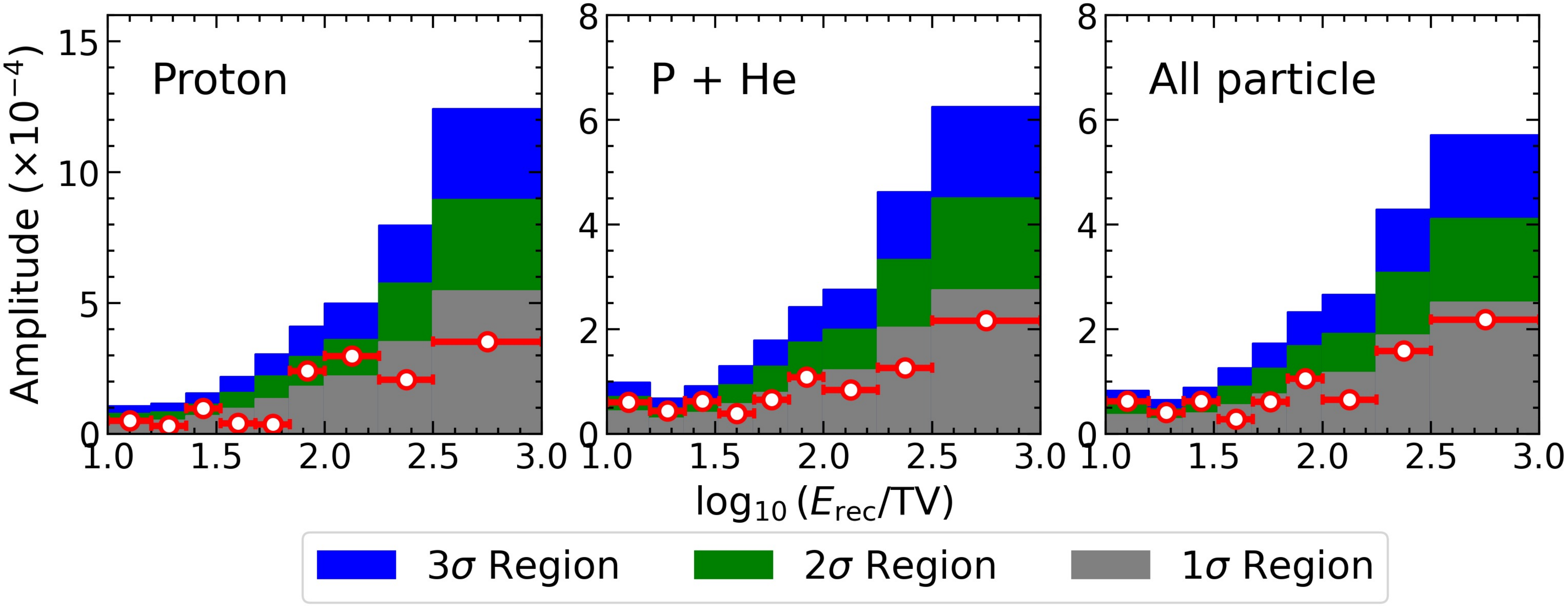
Consistent with Compton-Getting expectation!

Anti-sidereal time anisotropies



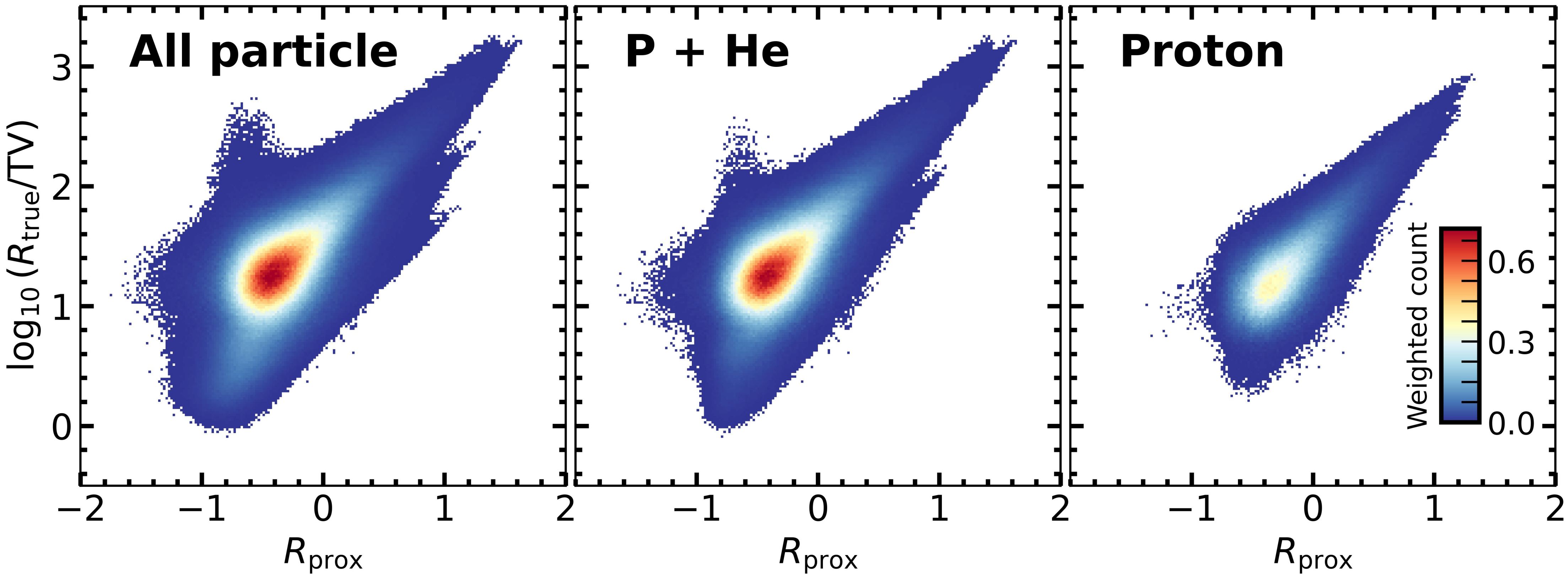
Consistent with the expectation of background fluctuation!

Ext-sidereal time anisotropies

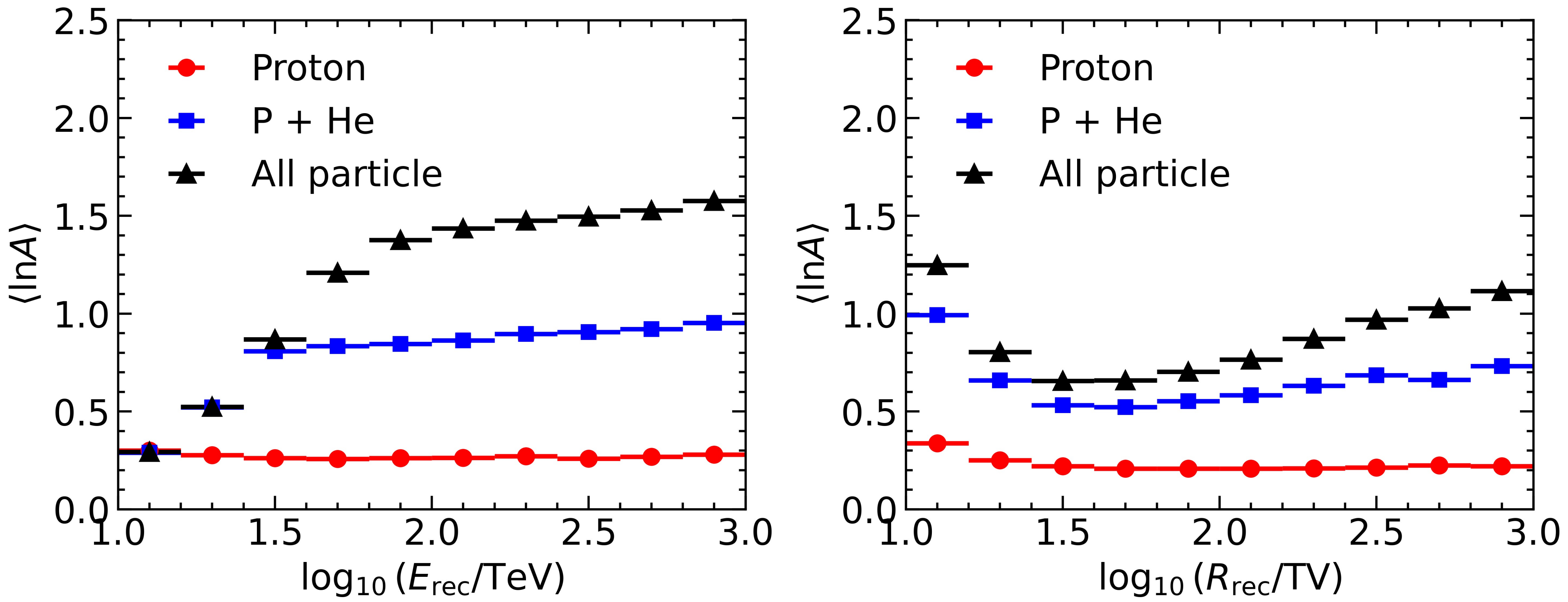


Consistent with the expectation of background fluctuation!

Rprox VS log10Rtrue

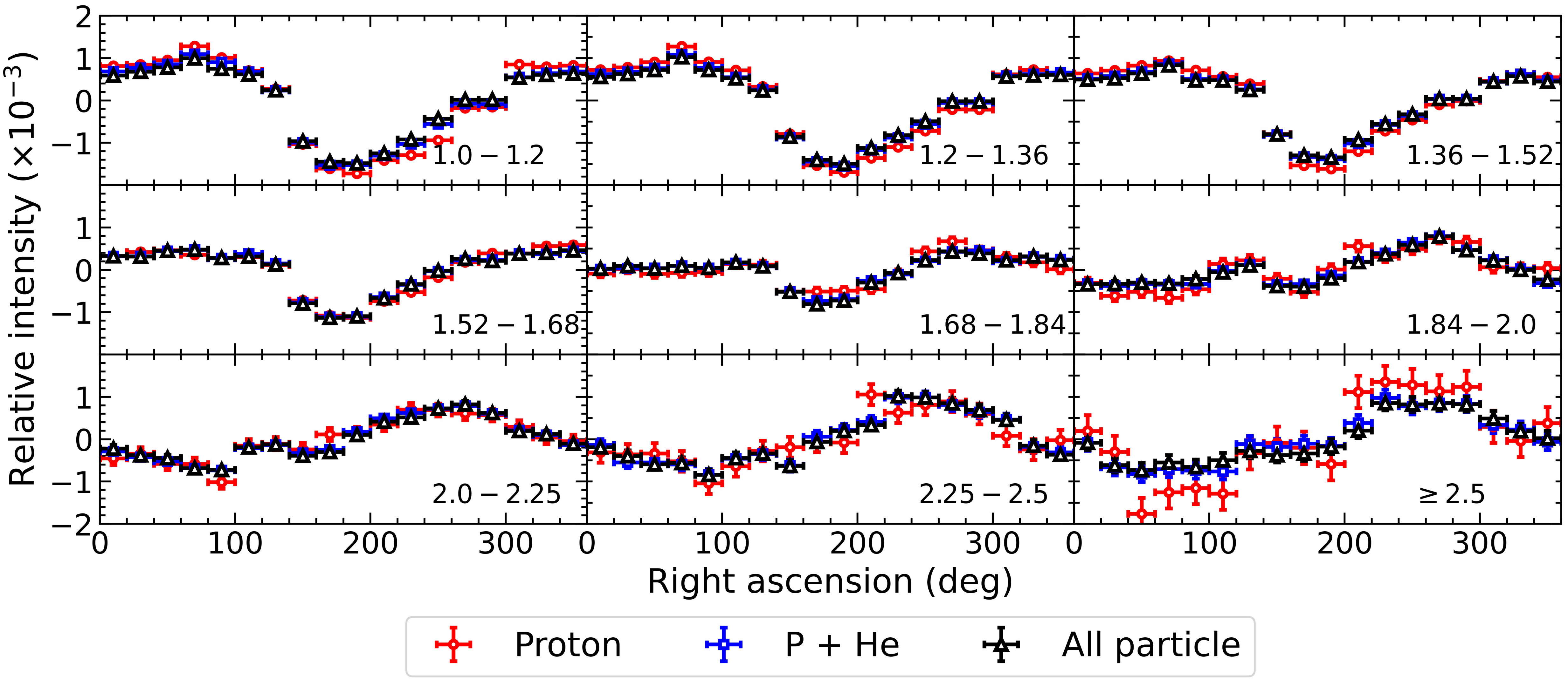


<lnA> in rigidity- and energy-binned samples

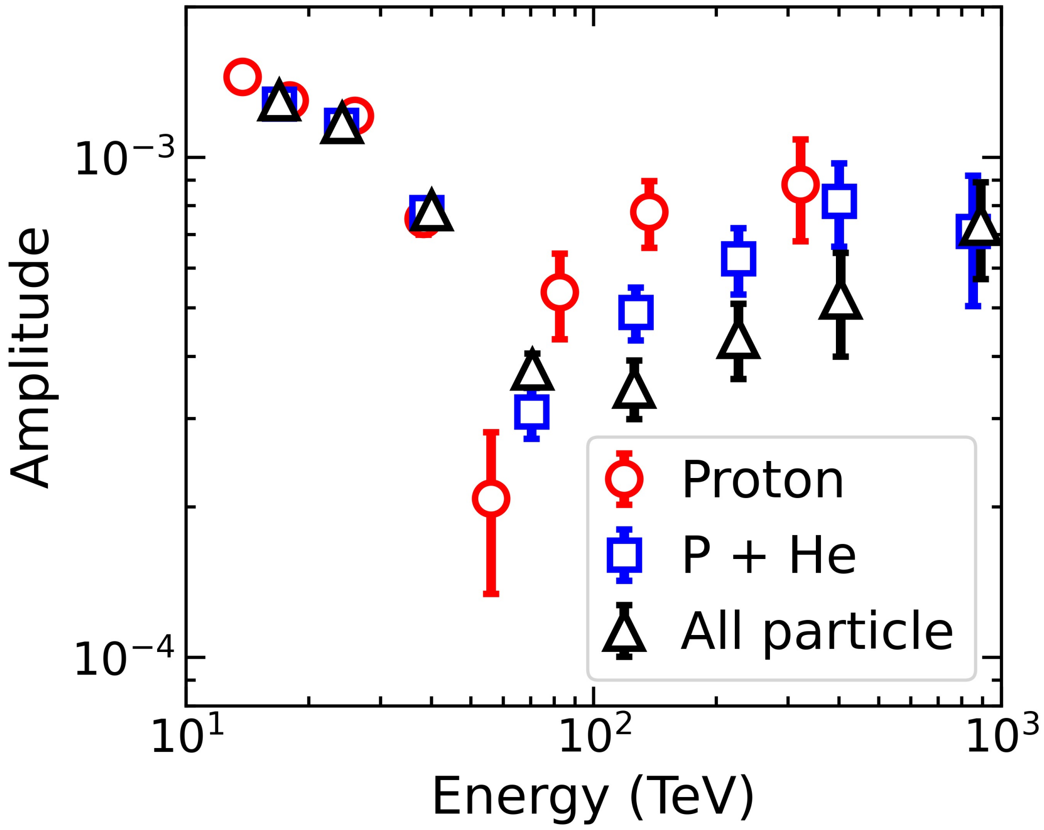


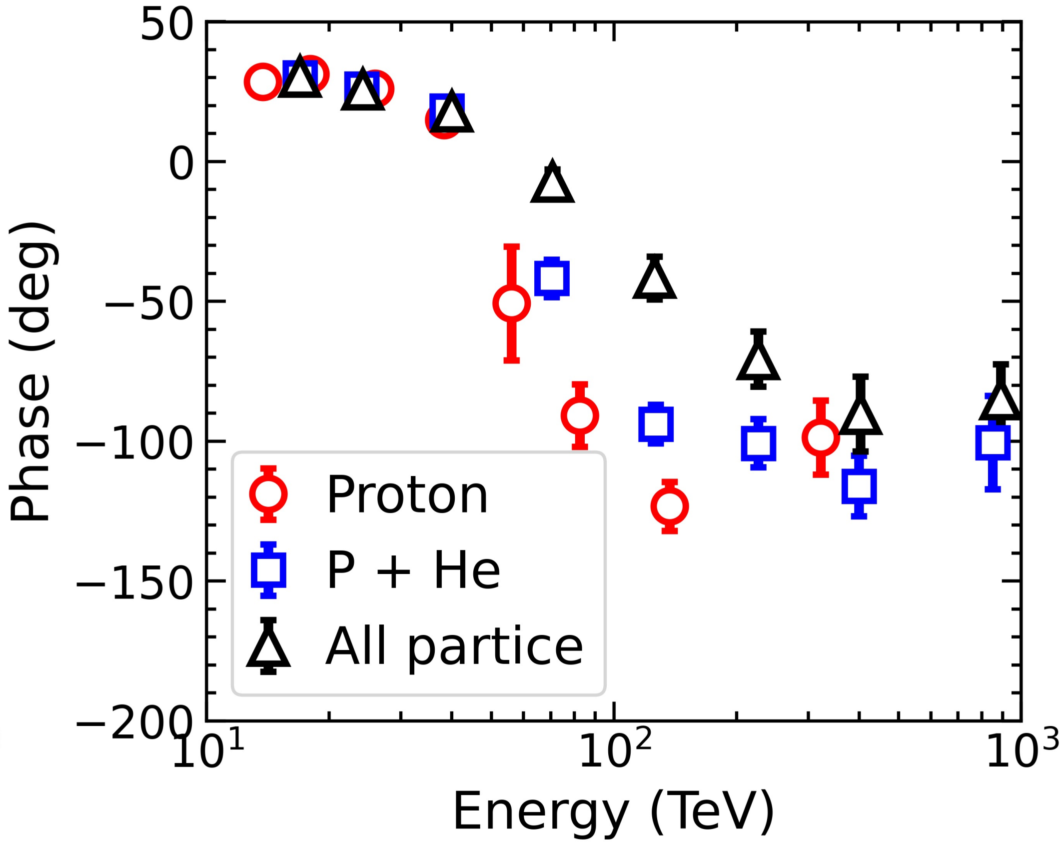
The compositions of rigidity-binned all particle samples are comparable to energy-binned P + He samples.

Relative intensity along the right ascension

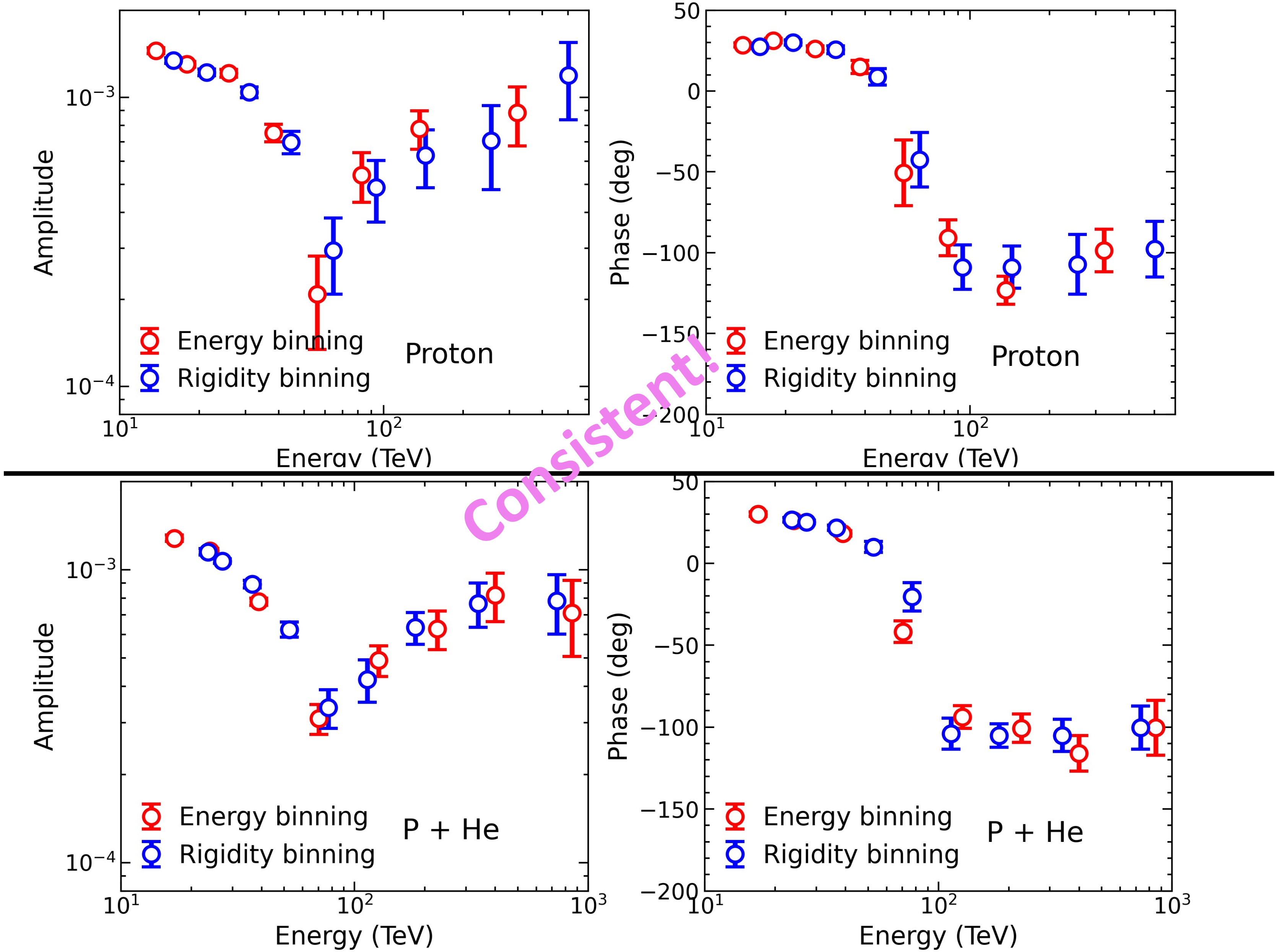


Results of energy-binned samples





Anisotropies – Rigidity- VS Energy-binned samples



Anisotropies – Rigidity- VS Energy-binned samples