



Searching for Large-scale and Medium-scale Anisotropy of Ultra-high Energy Cosmic Ray with LHAASO-KM2A

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On behalf of the LHAASO Collaboration

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Content

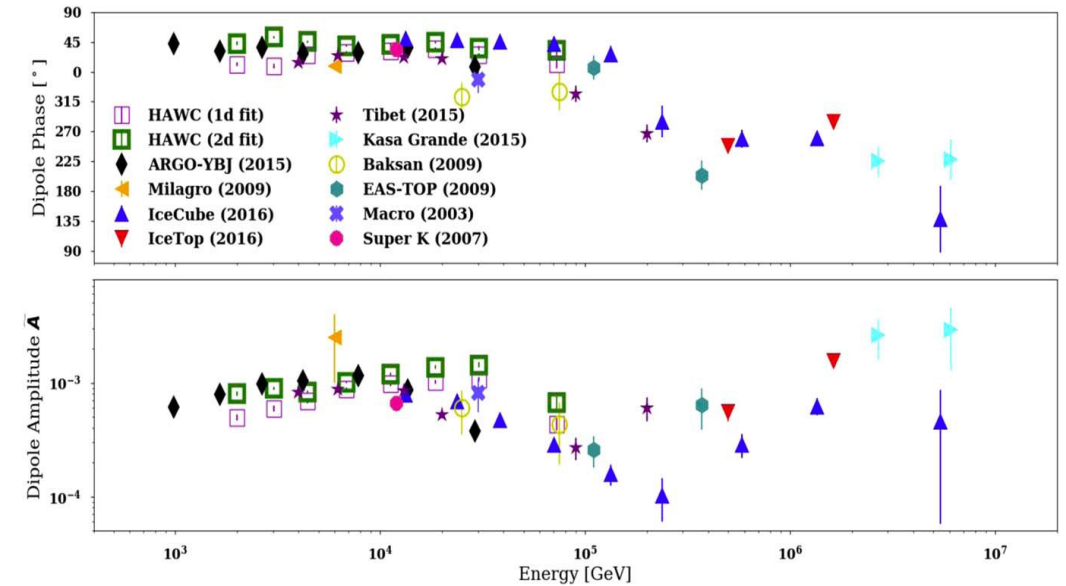
- ◆ **Introduction**
- ◆ **Data Analysis**
- ◆ **Results**
- ◆ **Summary**

◆ Introduction

◆ Many experiments have observed energy-dependent cosmic-ray anisotropies, $10^{-4} \sim 10^{-3}$, 500 GeV~32EeV.

◆ Complementary to spectrum and chemical components study, a source and magnetic field probe.

LHAASO-KM2A measures anisotropy on a range of 10TeV~10 PeV



Abeysekara et al. 2018

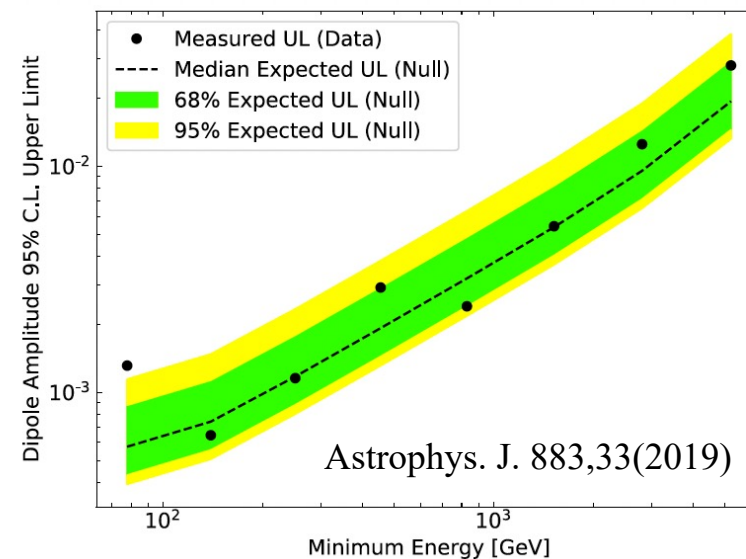
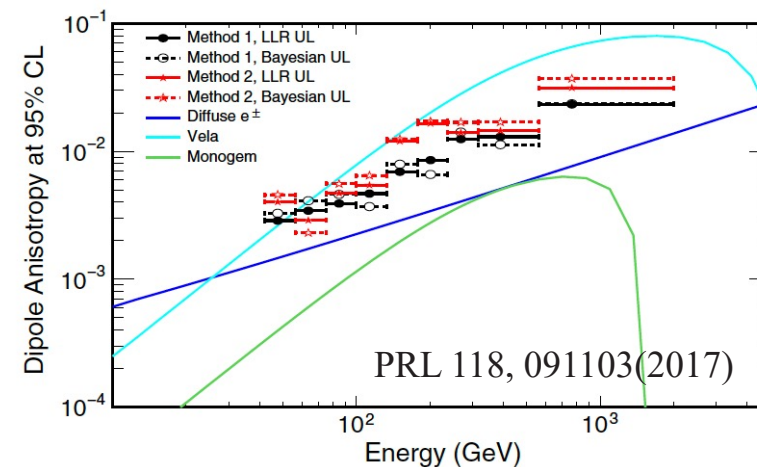
◆ Introduction

◆ Cosmic-Ray electron and positron anisotropies, above 60GeV, upper limit, Fermi-LAT 2010; above 42GeV , upper limit, Fermi-LAT 2017

◆ Cosmic-Ray Proton Anisotropy, above 78 GeV, upper limit, Fermi-LAT 2019

◆ High energy cosmic-ray proton anisotropies have not been measured.

LHAASO-KM2A, wide field of view, large effective detection area, big statistical sample for >10 TeV cosmic-ray proton.



◆ Introduction

◆ Tibet AS γ 2007, “skewed” structures after subtracting best fit

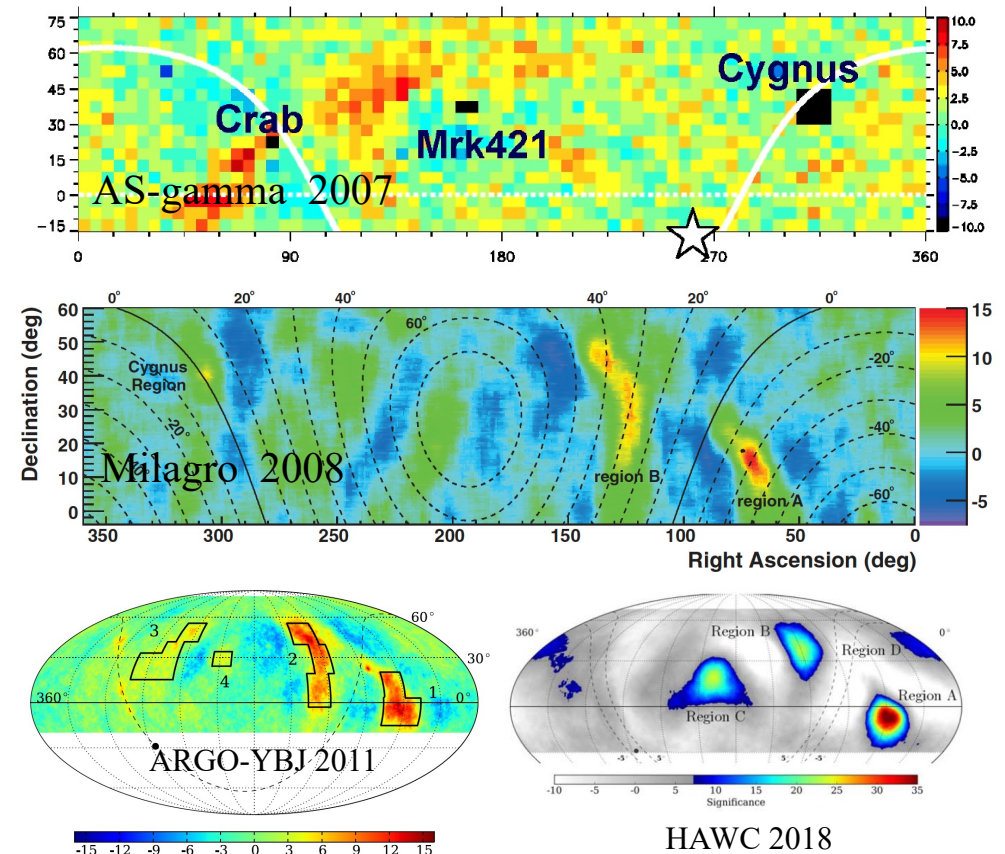
◆ Milagro 2008, medium scale structures,

$$dN \sim E^\gamma e^{-E/E_c}, E_c \sim 10 \text{ TeV}$$

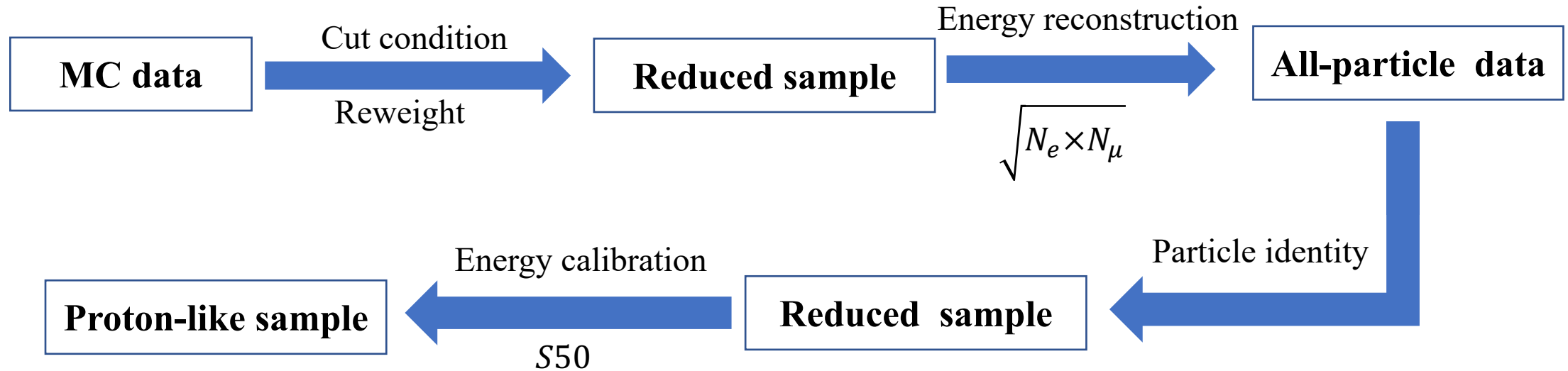
◆ Medium scale (< 60 deg) anisotropy, IceCube,

ARGO-YBJ, HAWC, ~ 70 TeV.

Measurements at higher energy with LHAASO-KM2A



◆ Data analysis



◆ Experimental data

KM2A Full array 1-year data, 2021.07.20—2022.07.19

◆ Data analysis

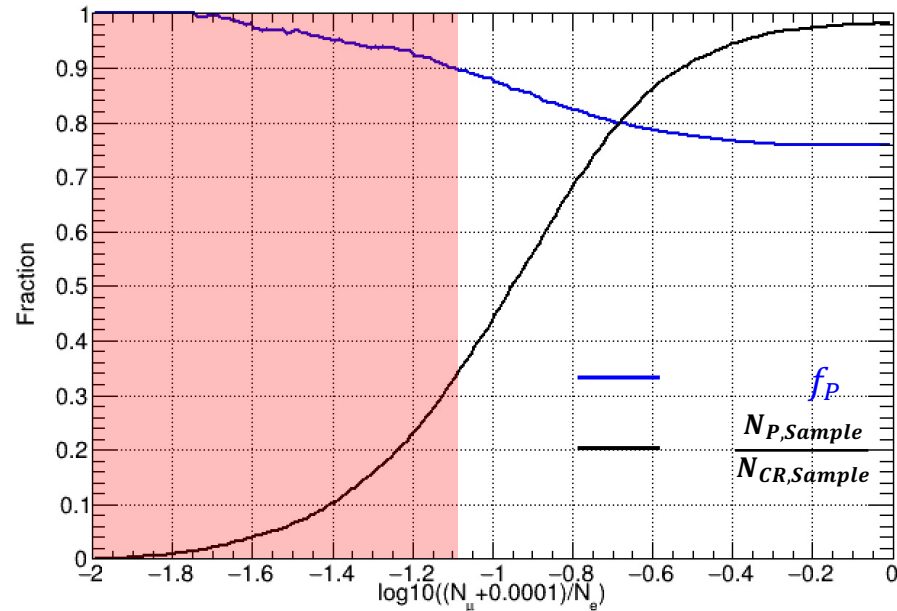
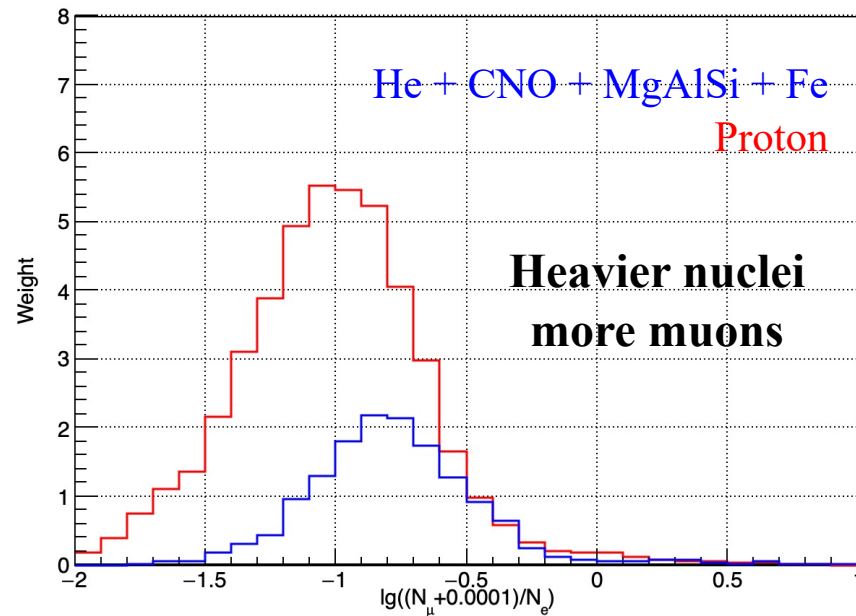
● Sample of Proton

◆ Cut conditions + $R = \log_{10} \left(\frac{N_{\mu} + 0.0001}{N_e} \right)$ cut

◆ $R > -2$ for sample of proton

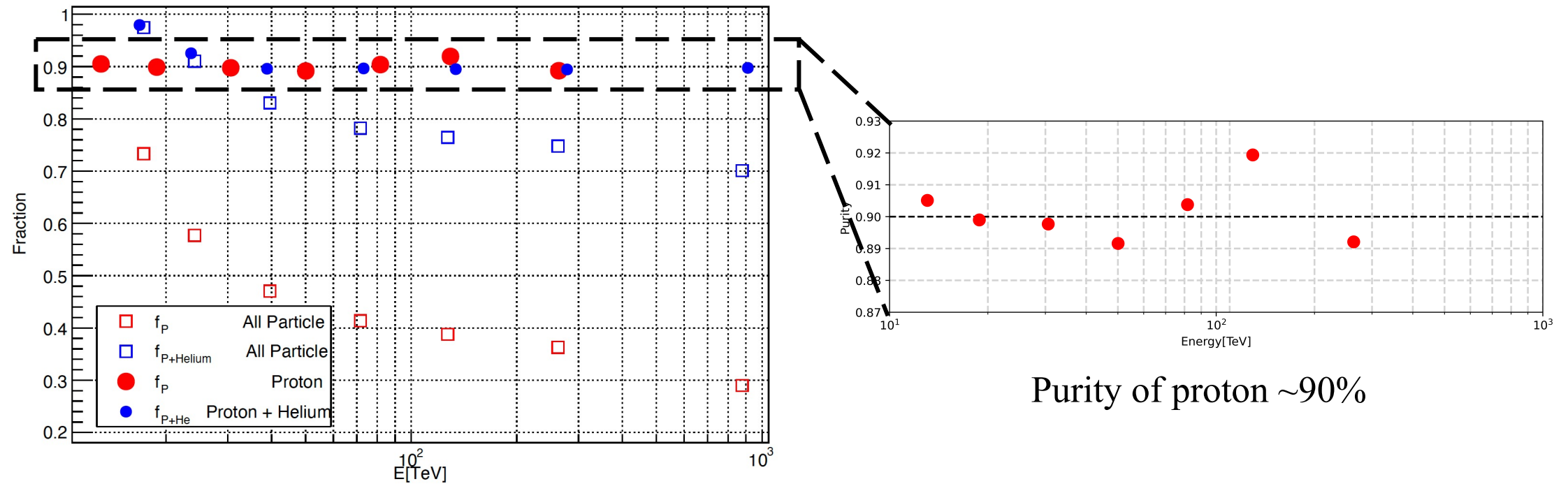
◆ $R^*(E_{rec,CR}); \sim 90\%$ purity

$$1.0 \leq \lg(E_{rec,CR}) < 1.2$$



◆ Data analysis

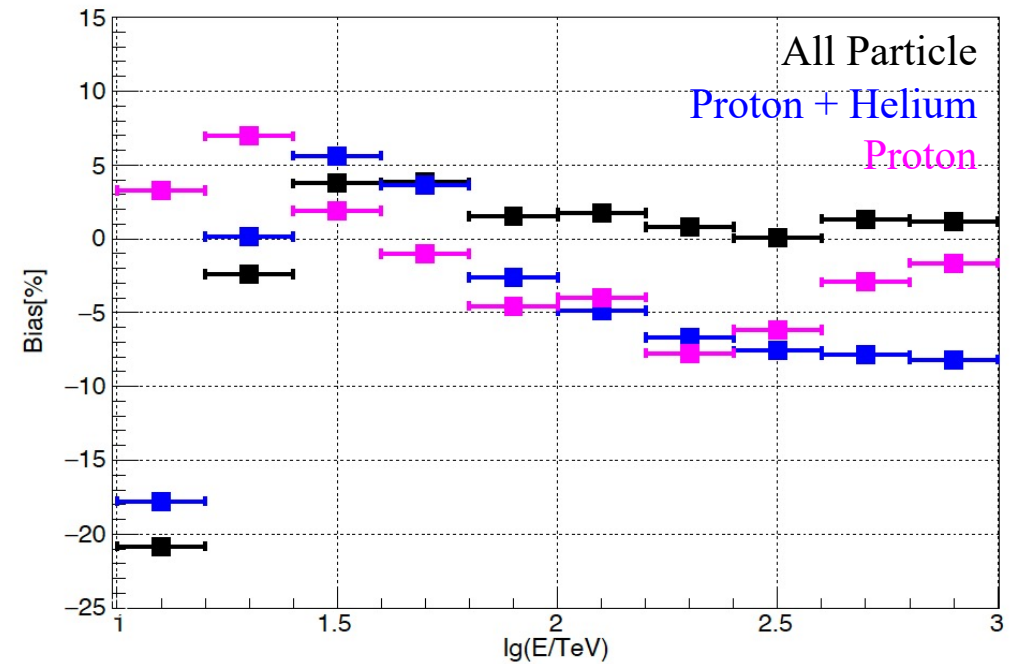
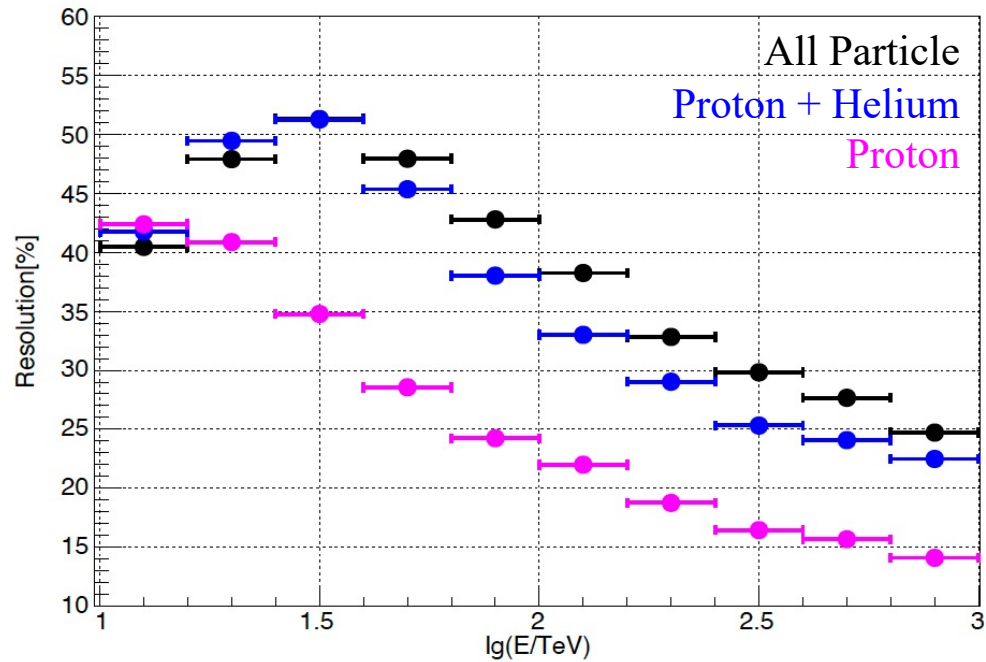
● Purity of samples



Purity of proton ~90%

◆ Data analysis

● Energy resolution and bias



◆ Data analysis

● Background Estimation

- ◆ All-distance equi-zenith method

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

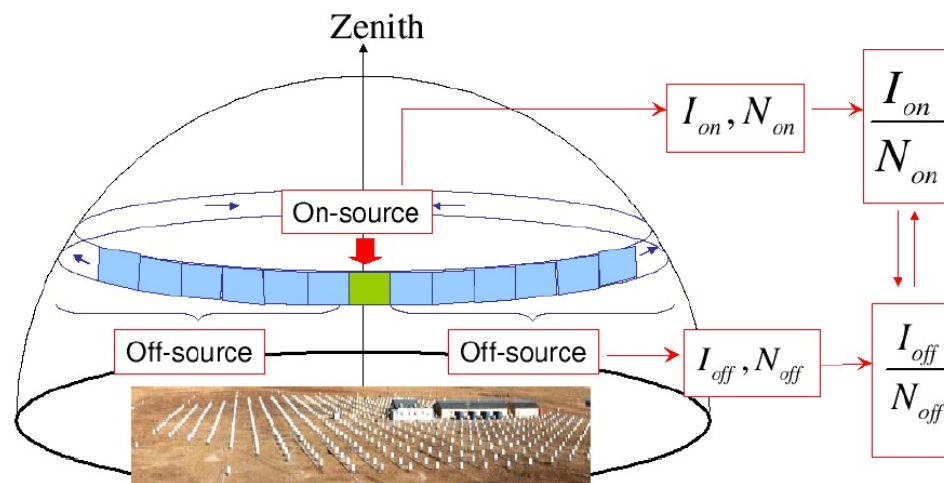
● Medium Scale Structure

- ◆ The spherical harmonics function expansion:

$$\delta I(\alpha, \delta) = \frac{N_{on} - N_{off}}{N_{off}}$$

$$\delta I(\alpha, \delta) = \sum_{l=0}^3 \sum_{m=-l}^l a_{lm} Y_{lm}\left(\frac{\pi}{2} - \delta, \alpha\right)$$

Subtract $l \leq 3$



◆ Results -- large scale structure

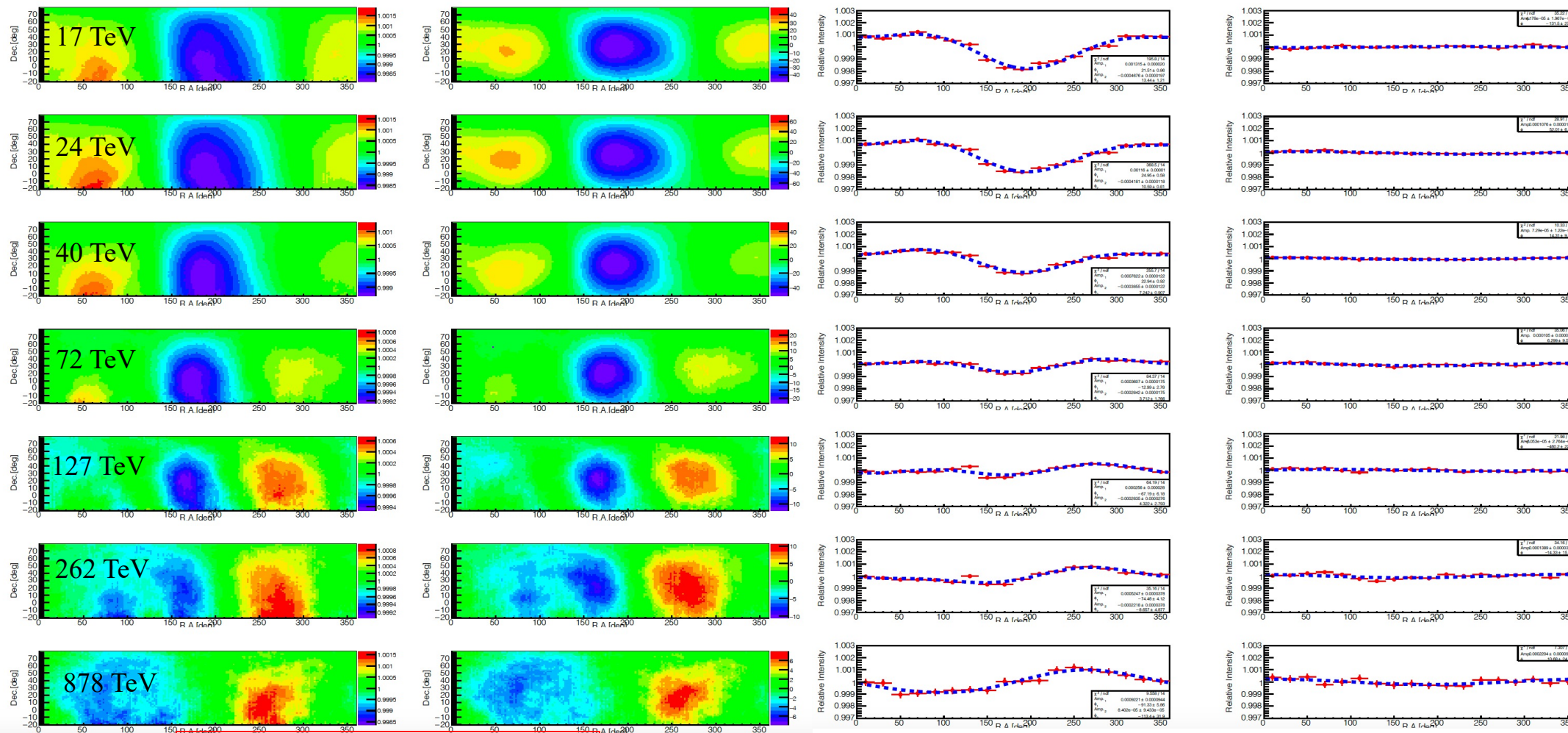
All particle @ $R_{smooth} = 30^\circ$

Relative intensity

Significance

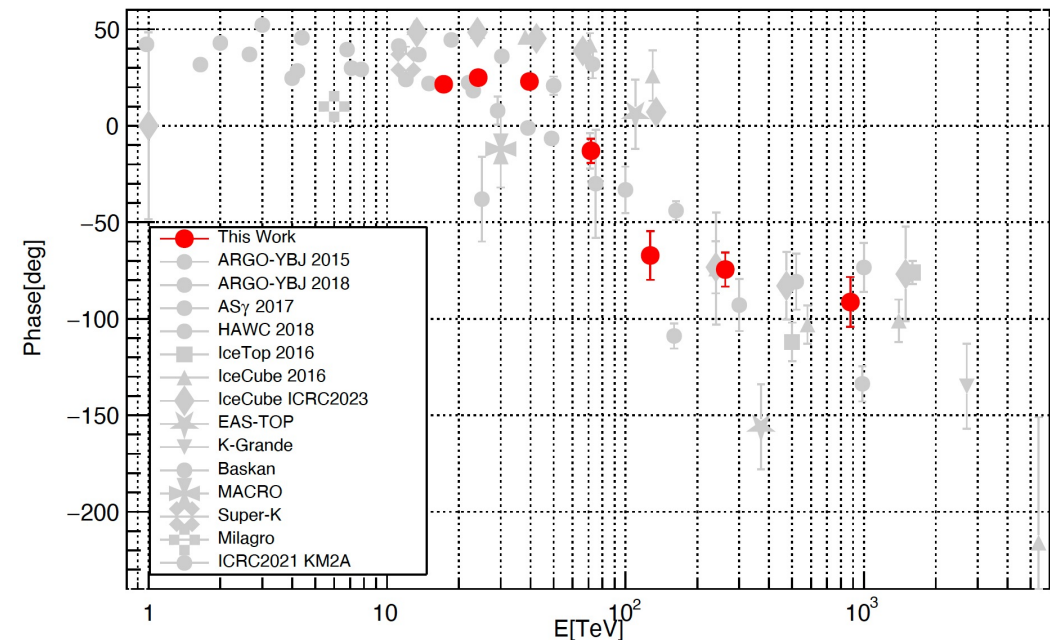
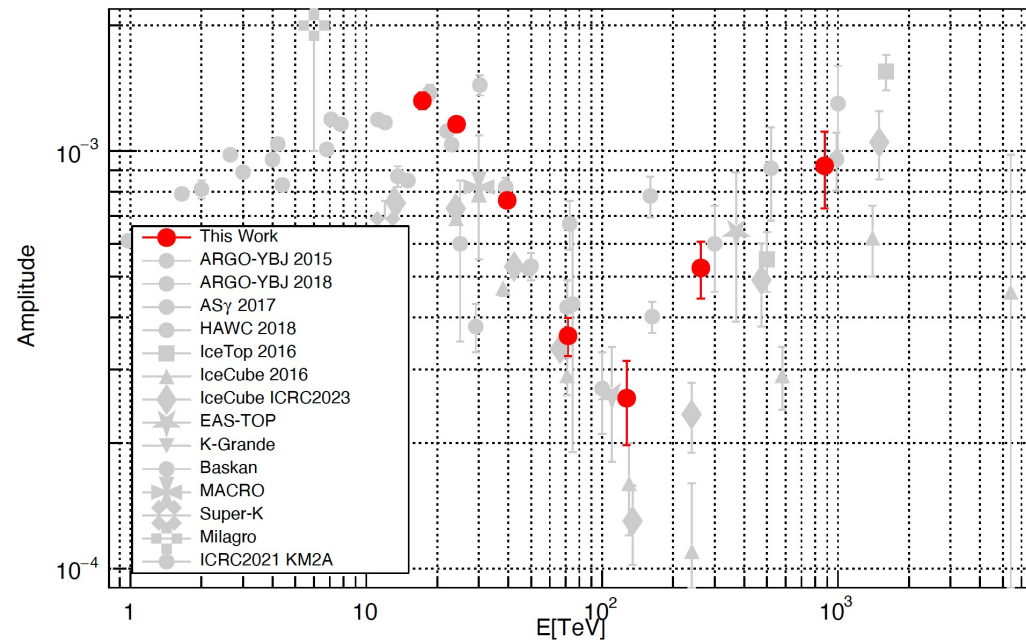
Sideral Time

Anti-Sideral Time



◆ Results

Anisotropy of all particles compared with other experiments



Results are consistent with other experiments.

◆ Results

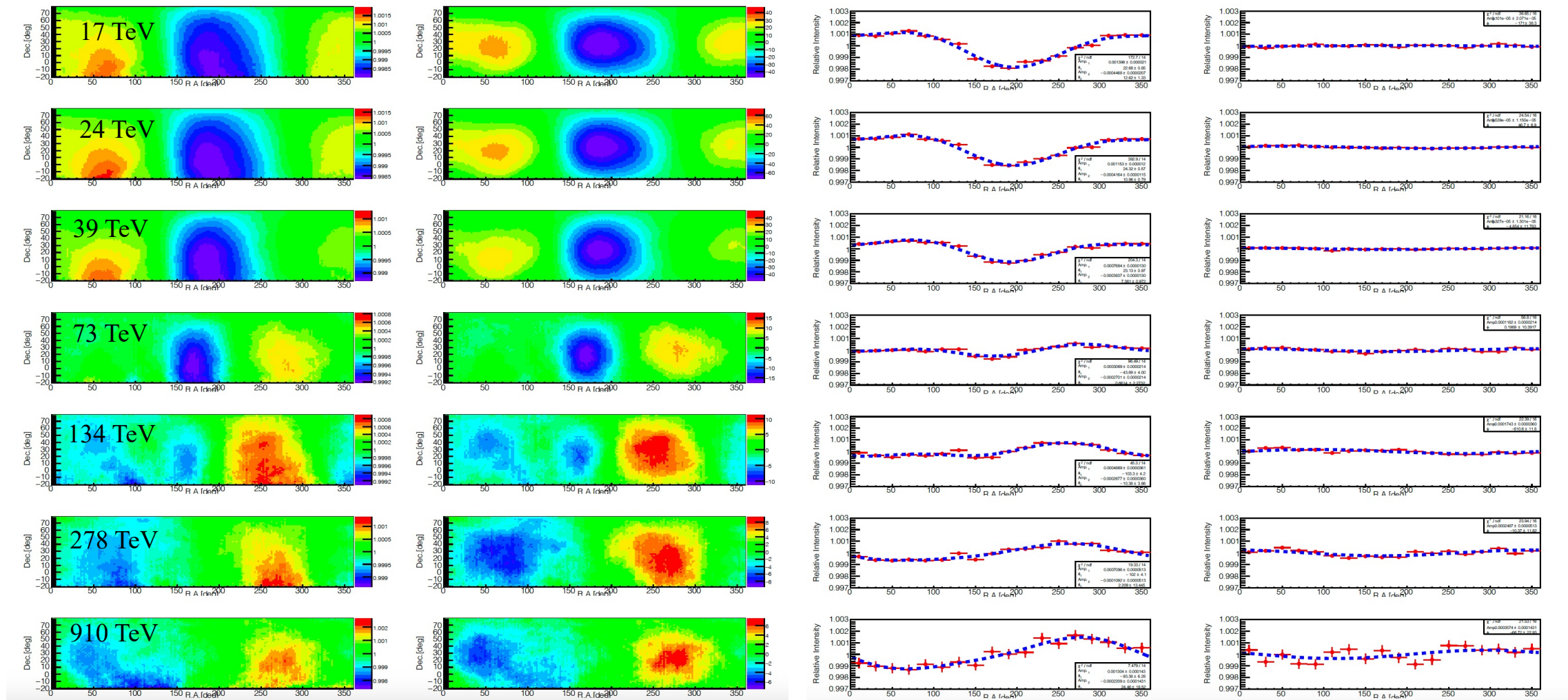
P + He @ $R_{smooth} = 30^\circ$

Relative Intensity

Significance

Sideral Time

Anti-Sideral Time



◆ Results

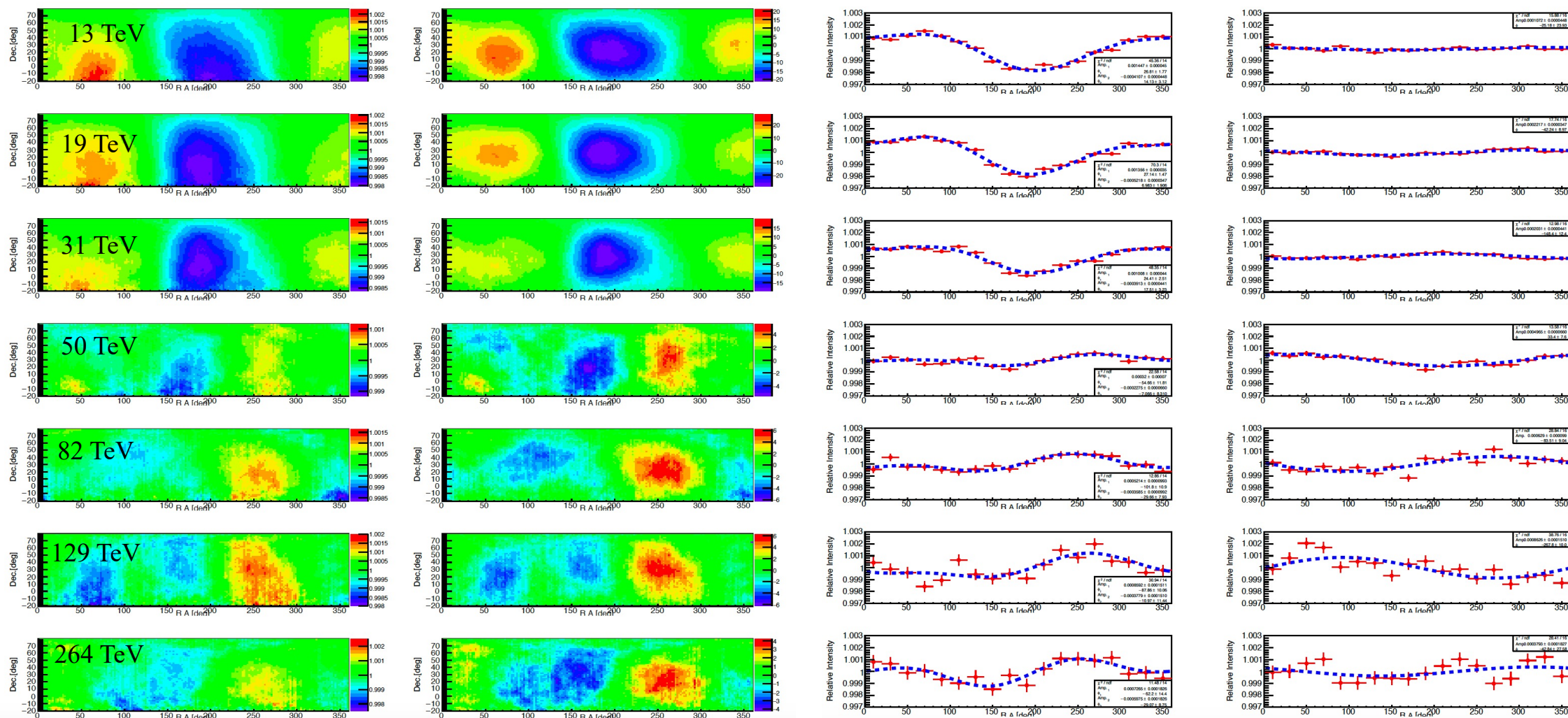
Proton@ $R_{smooth} = 30^\circ$

Relative Intensity

Significance

Sideral Time

Anti-Sideral Time



2023/10/23

Patten changes at ~50TeV

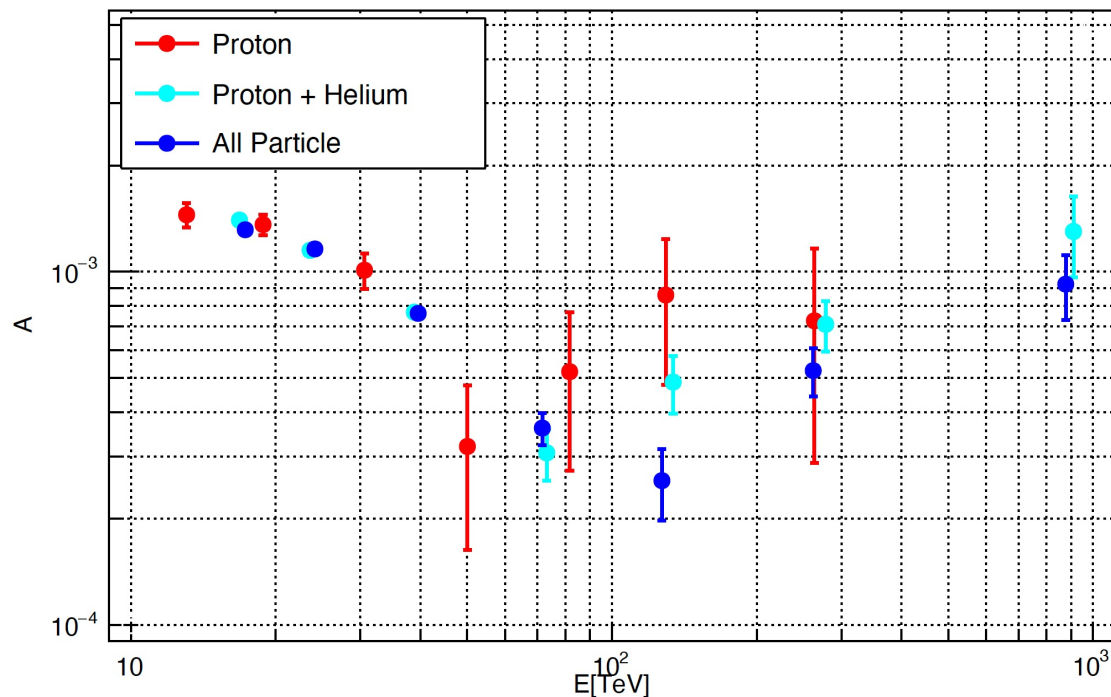
hejy@pmo.ac.cn

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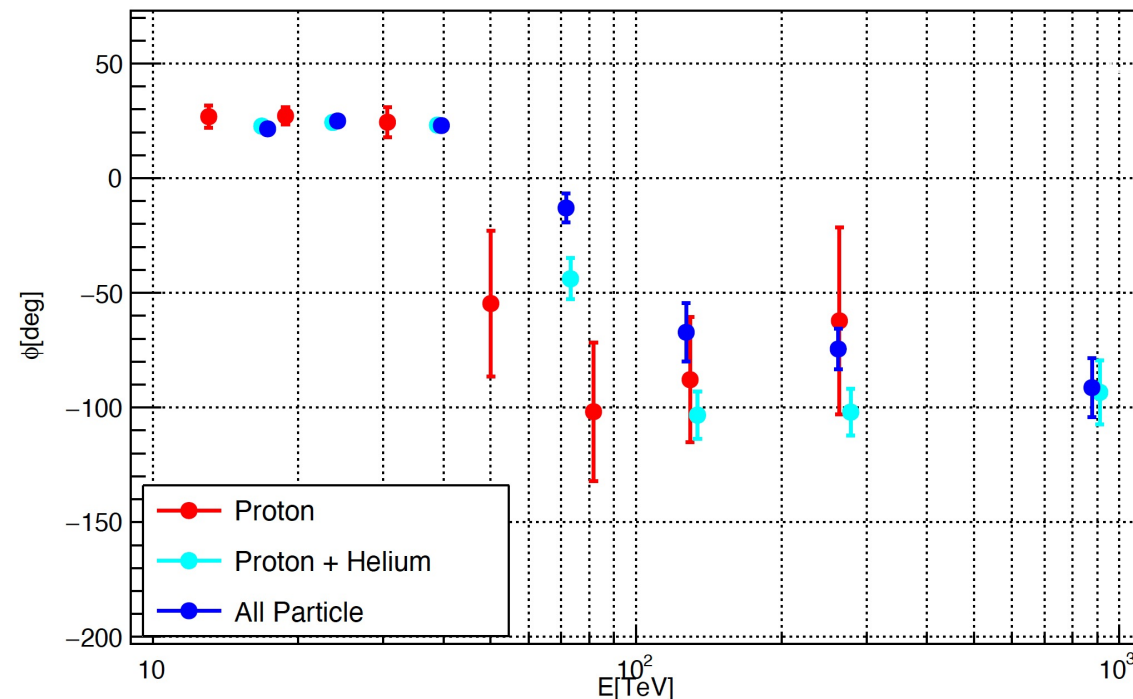
◆ Results

The anisotropies of different samples are compared.

Amplitude



Phase



Dip point energy: Proton~50TeV

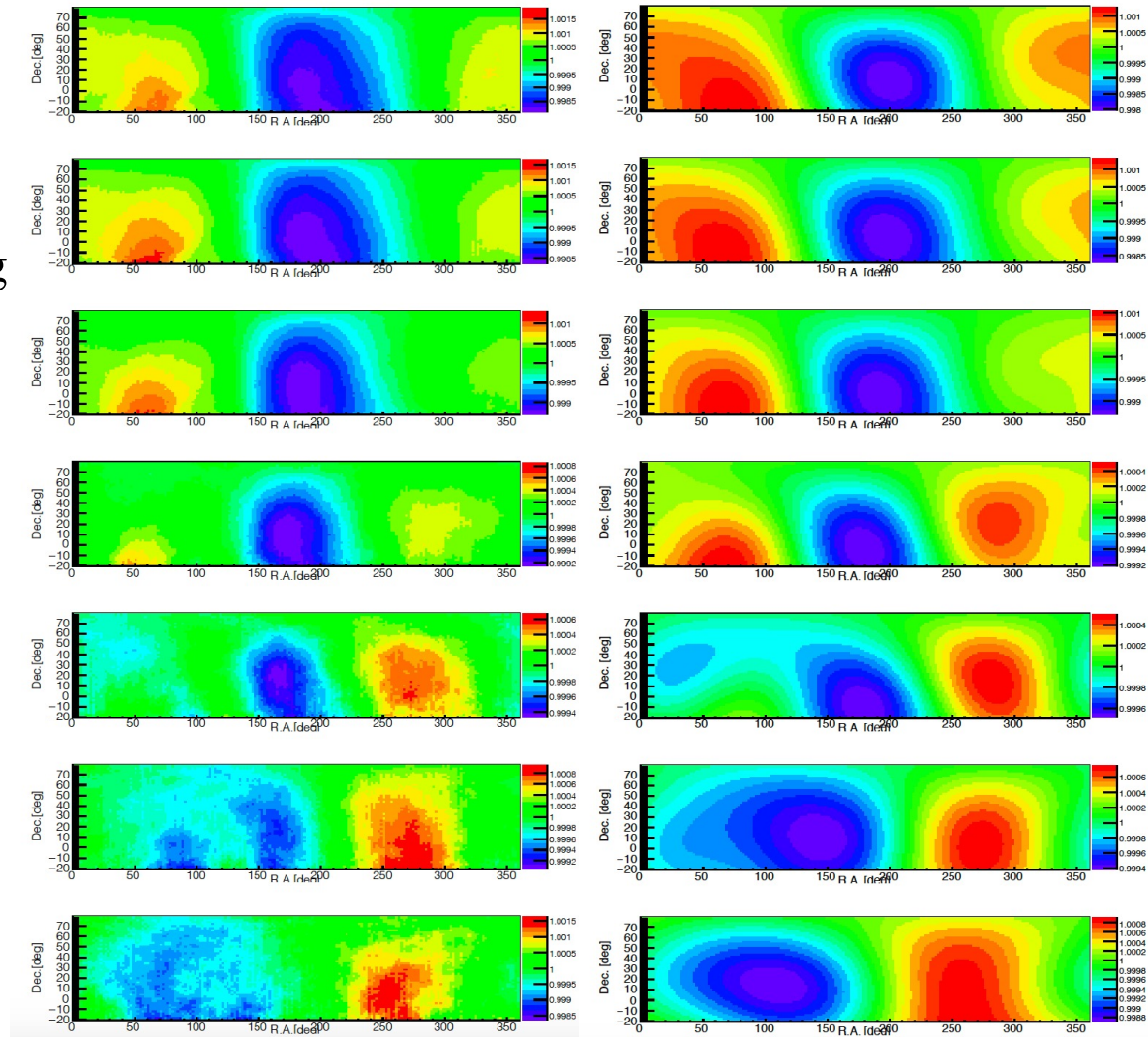
Proton + Helium ~ 70 TeV

Similar trends as a model predicted

B.Q. Qiao, et al. JCAP12(2019)007
Proton-Z ~35TeV
P + He ~65 TeV

◆ Results -- medium scale structure

Observed maps
Smooth with 30 deg



Best fit with spherical
harmonics function

The model can not
reproduce all structures



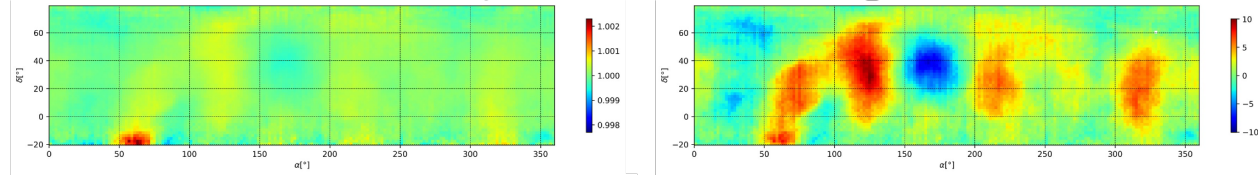
Residual structures

◆ Results

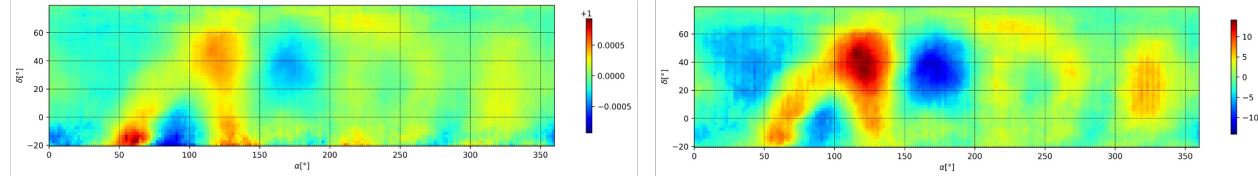
Residual maps @ $R_{smooth} = 18^\circ$

Relative Intensity Significance

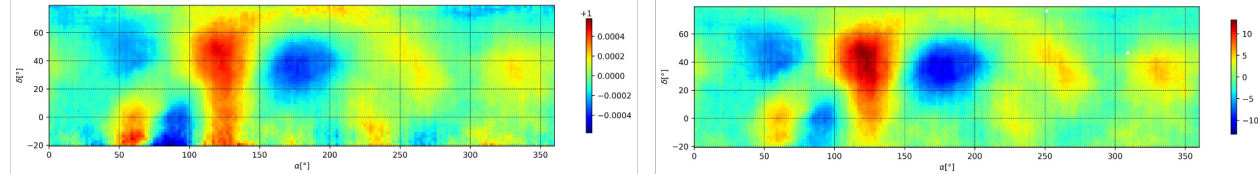
17.29 TeV



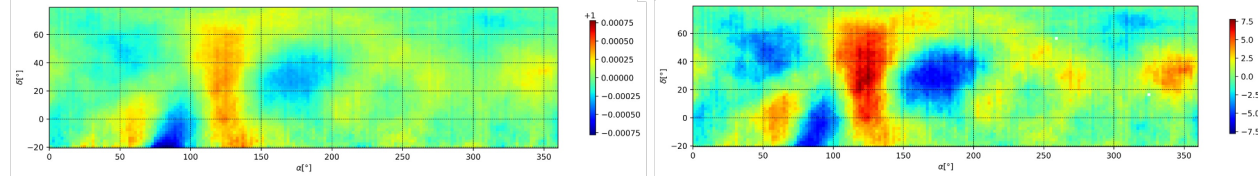
24.13 TeV



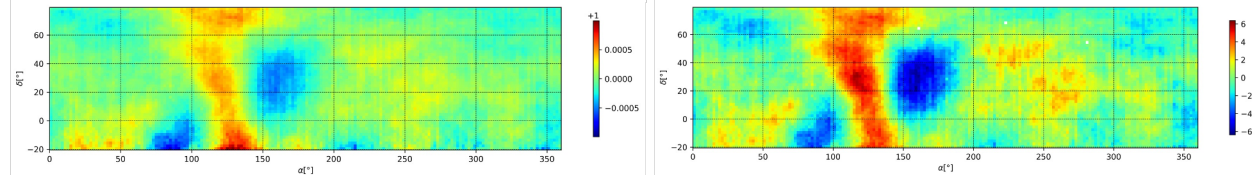
39.56 TeV



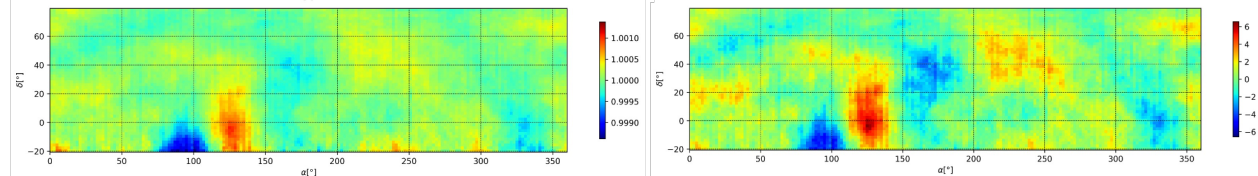
71.66 TeV



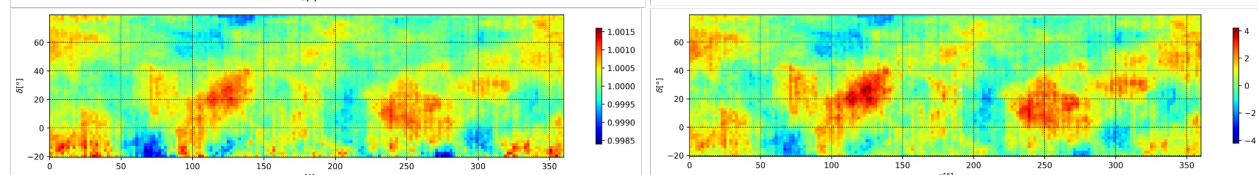
127.03 TeV



262.07 TeV



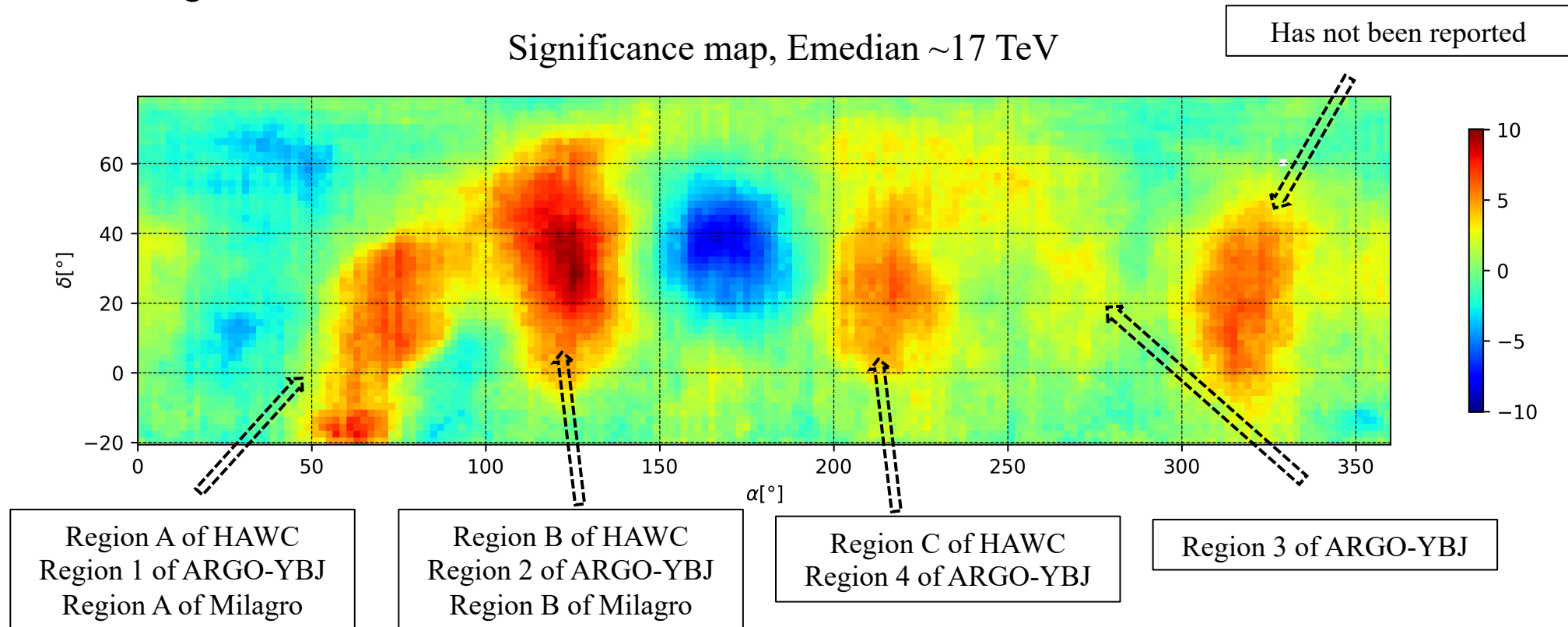
877.77 TeV



Hot spots with
big significance
on residual maps.

◆ Results

Subtract $l \leq 3$
Smooth with 18 deg



KM2A has observed the midscale regions reported by other experiments.

◆ Results

WCDA

N_{hit}	$E_{\text{med}}/\text{TeV}$	number of CRs
60-100	1.1	1.11025e+11
100-200	1.9	7.27811e+10
200-300	3.2	2.14185e+10
300-500	5.1	1.53454e+10
500-800	9.5	7.11632e+09
800-1100	18.4	2.44981e+09
1100-2000	37.6	1.78765e+09
2000-3120	136.0	2.89945e+08

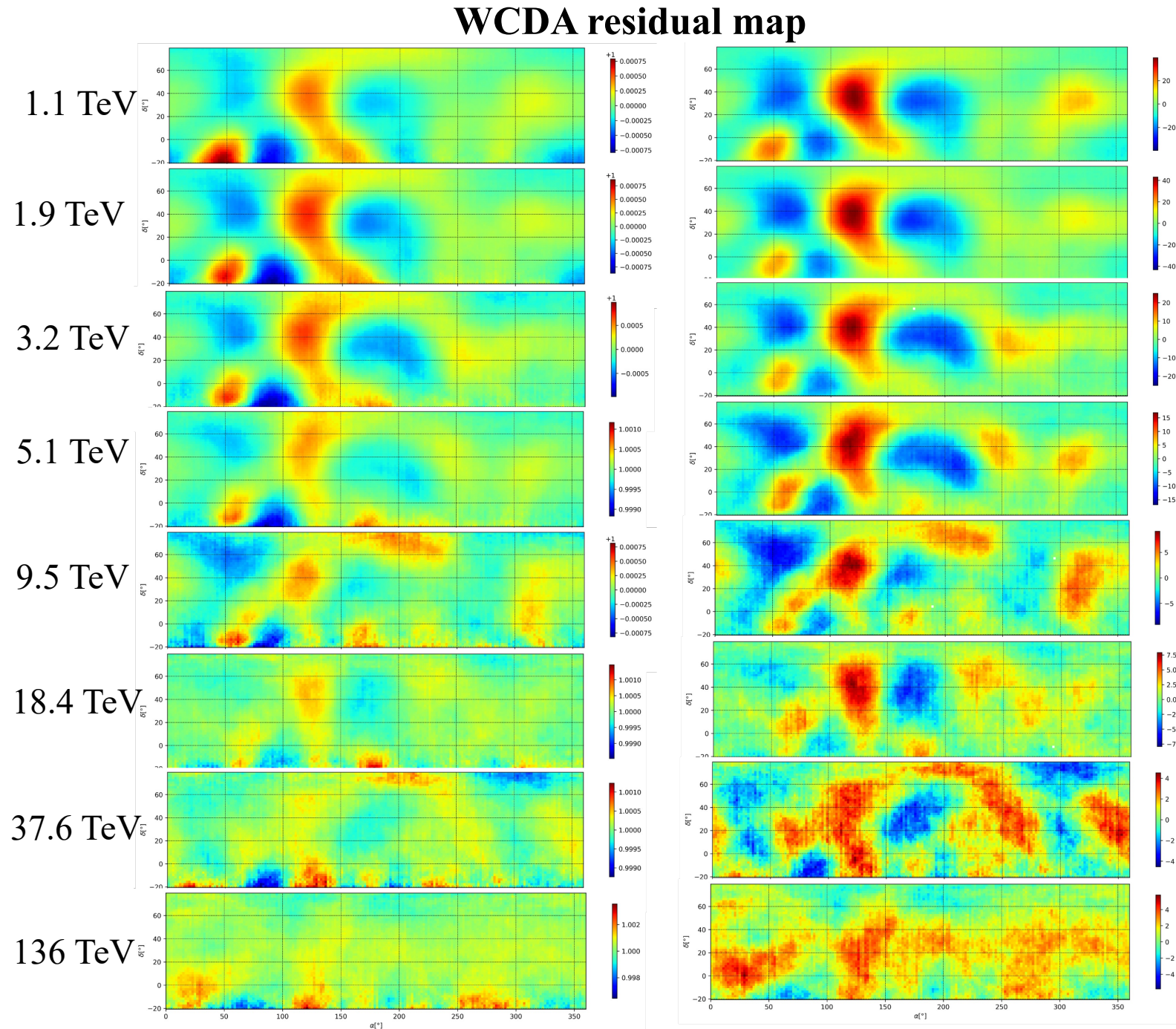
KM2A

$E_{\text{median}}/\text{TeV}$	# of events
17.29	5.16e09
24.13	1.45e10
39.56	1.34e10
71.66	6.52e09
127.03	2.62e09
262.07	1.40e09
877.77	2.25e08

+ Non and Nbkg maps
Provided by Wei Liu et al.

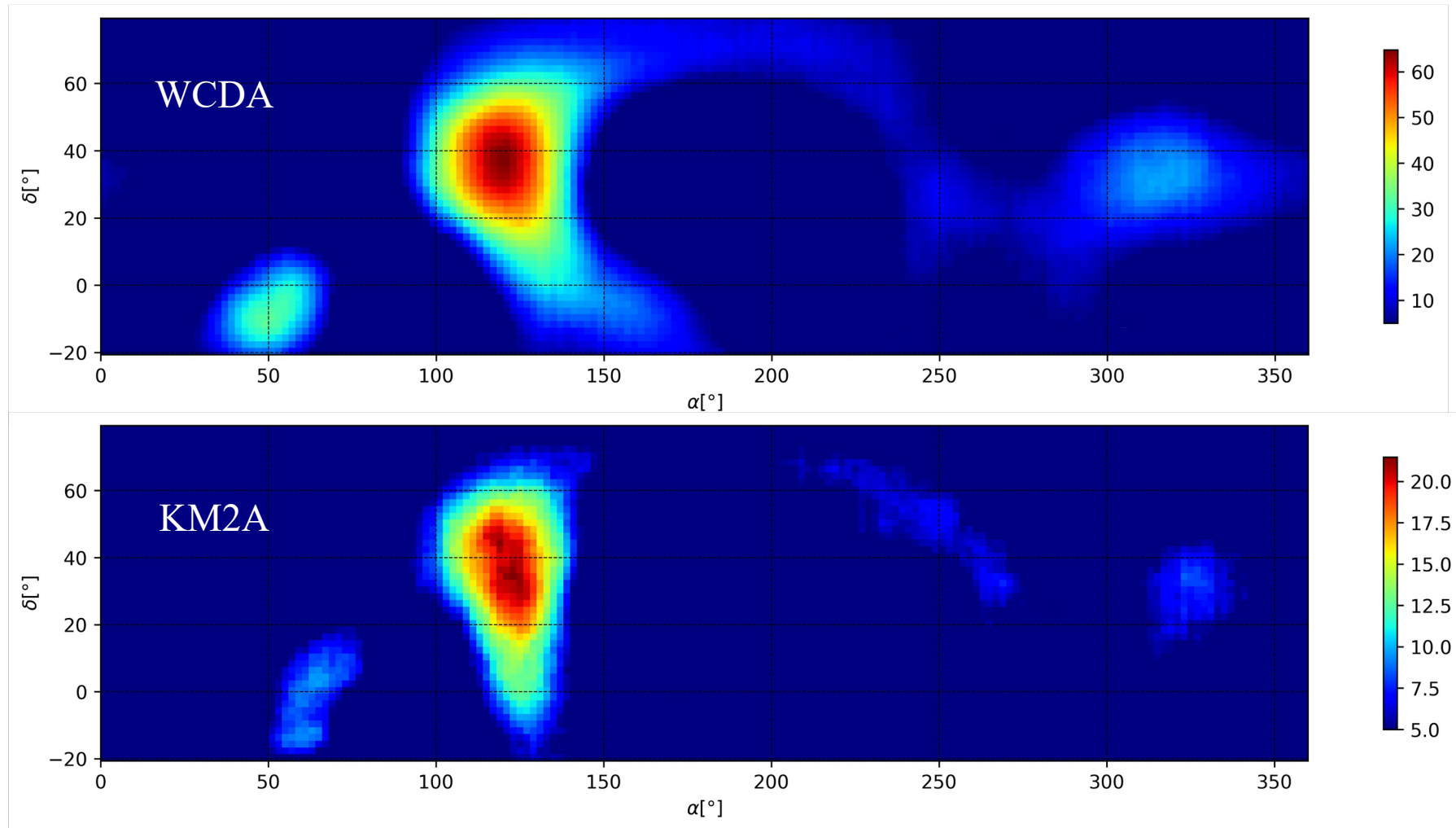
◆ Results

The medium-scale regions on KM2A maps are also seen on WCDA maps.



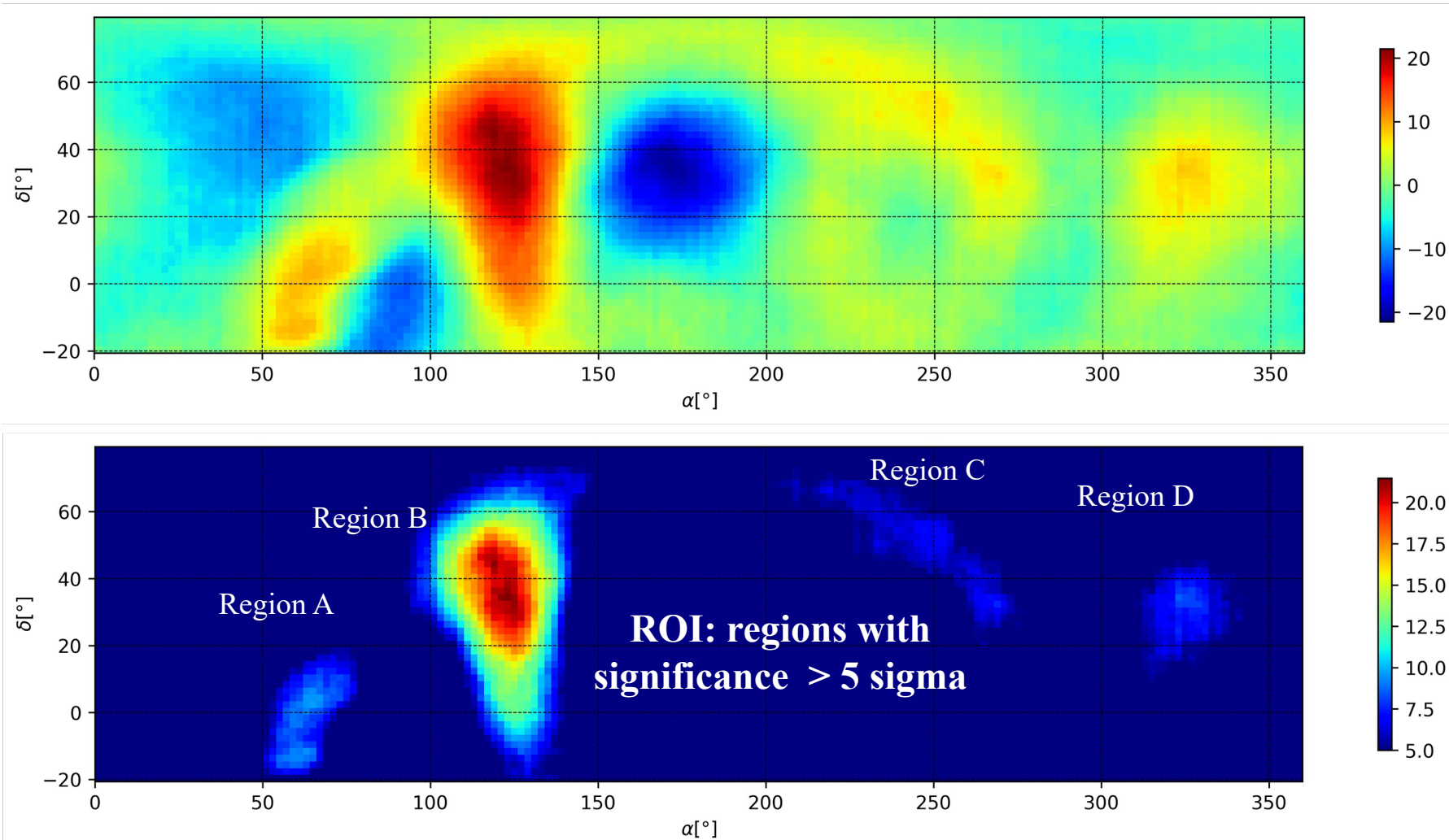
◆ Results

Regions with >5 sigma significance @combined map



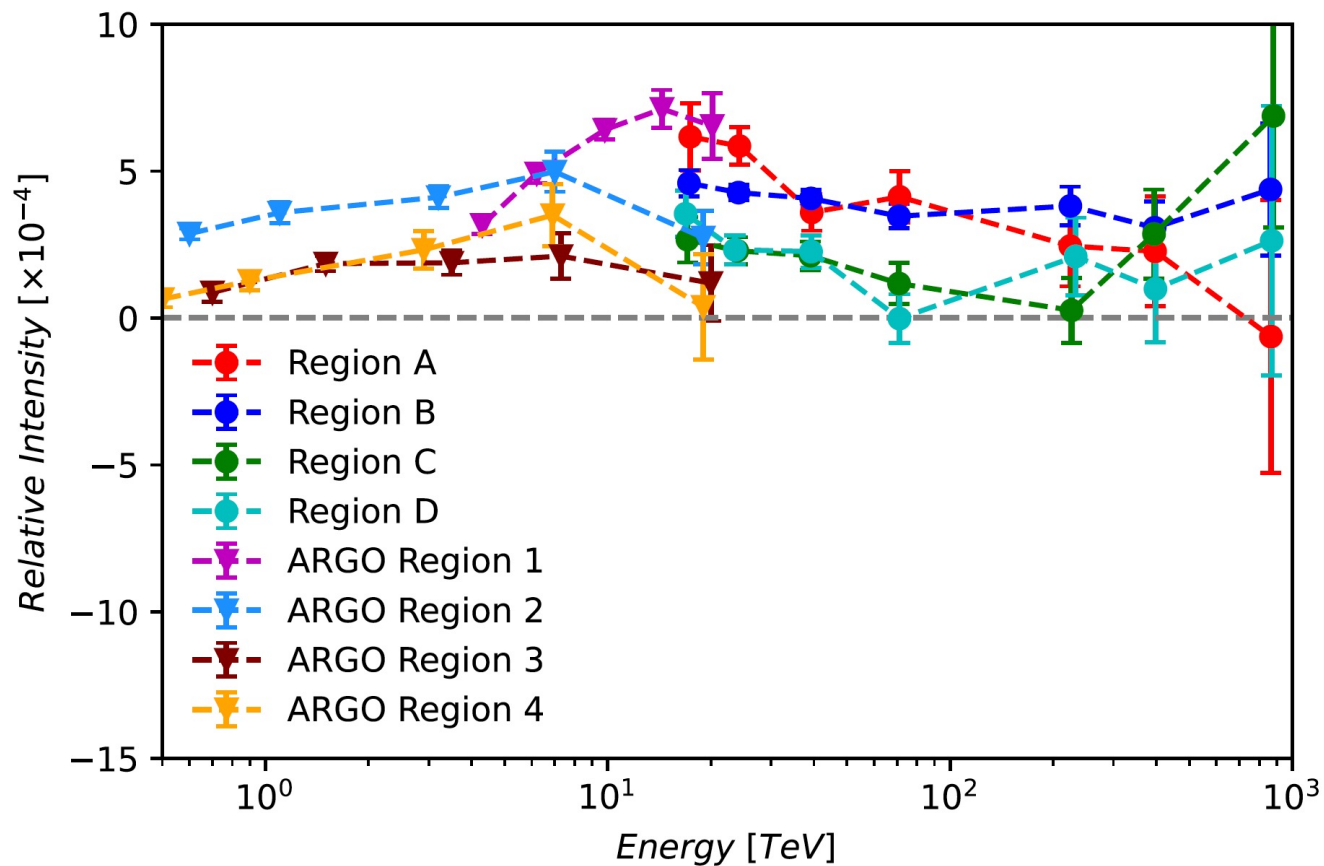
◆ Results

Significance map, $\log_{10}(E/\text{TeV}) > 1.0$, $E_{\text{median}} \sim 35 \text{ TeV}$



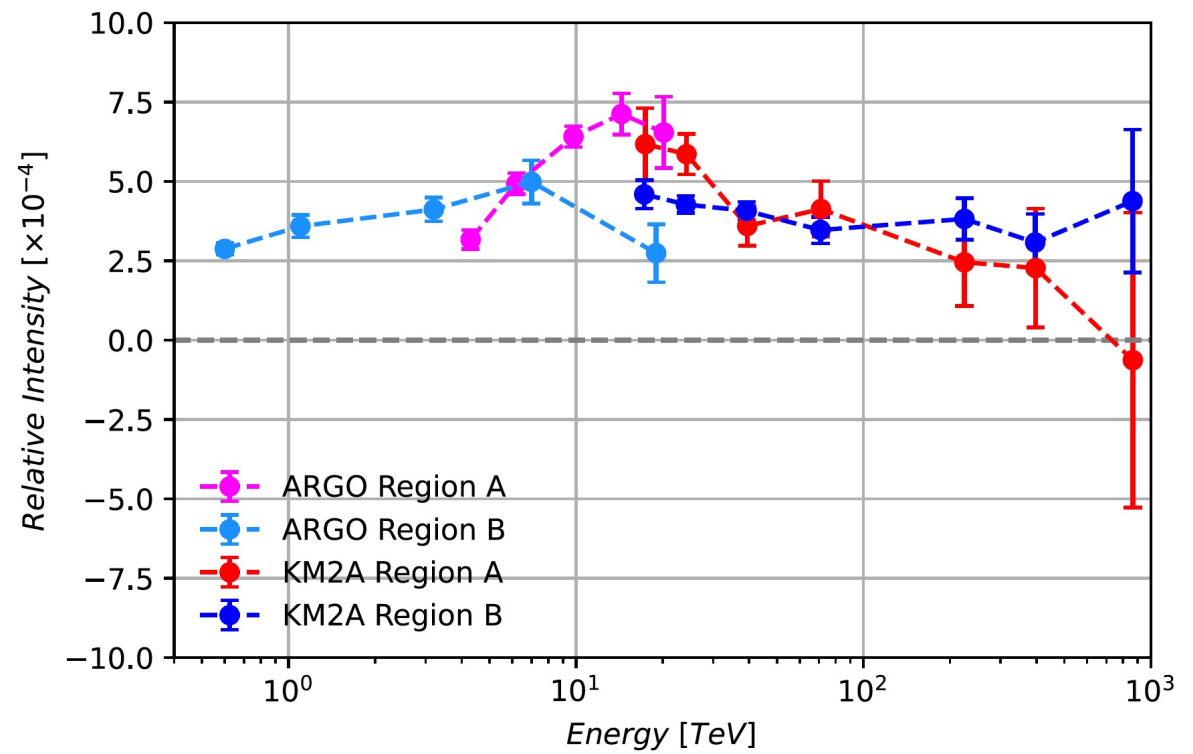
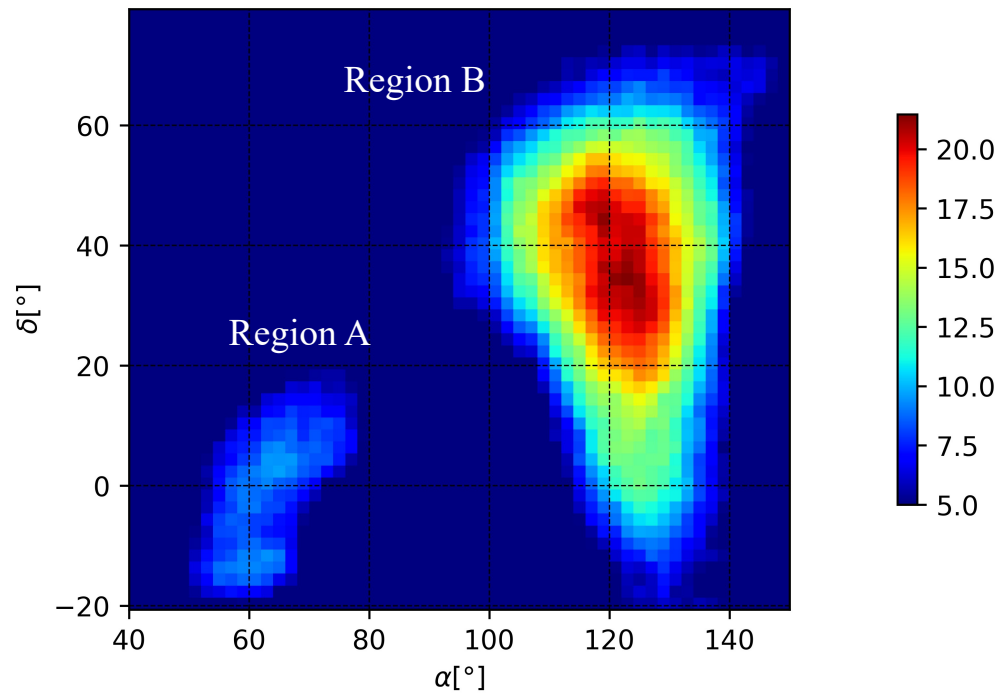
◆ Results

Spectra of relative intensity compared with ARGO-YBJ



Results of region A and region B are consistent with ARGO-YBJ at the same energy.

◆ Results



Region A: decrease

Region B: flat up to hundreds of TeV

◆ Summary

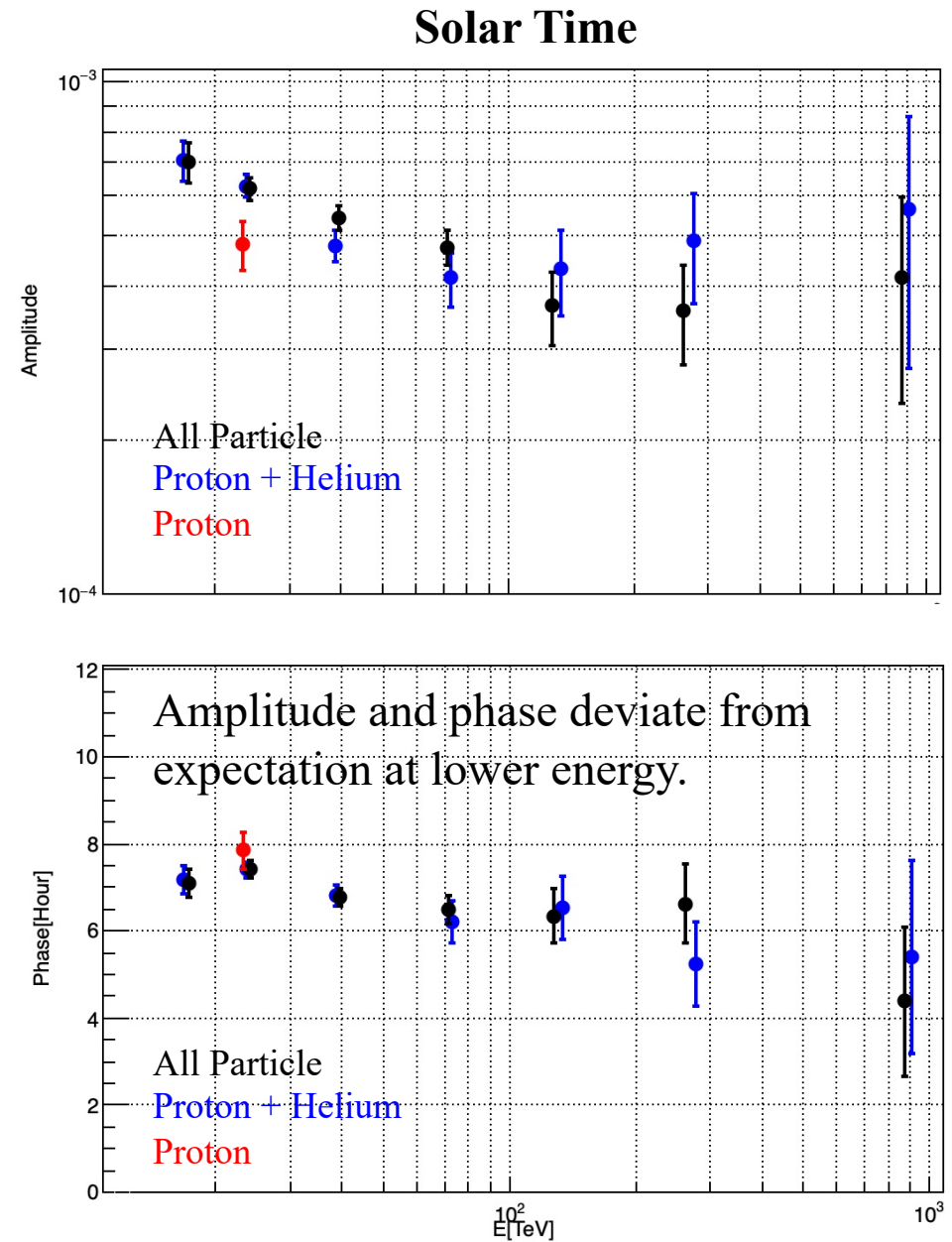
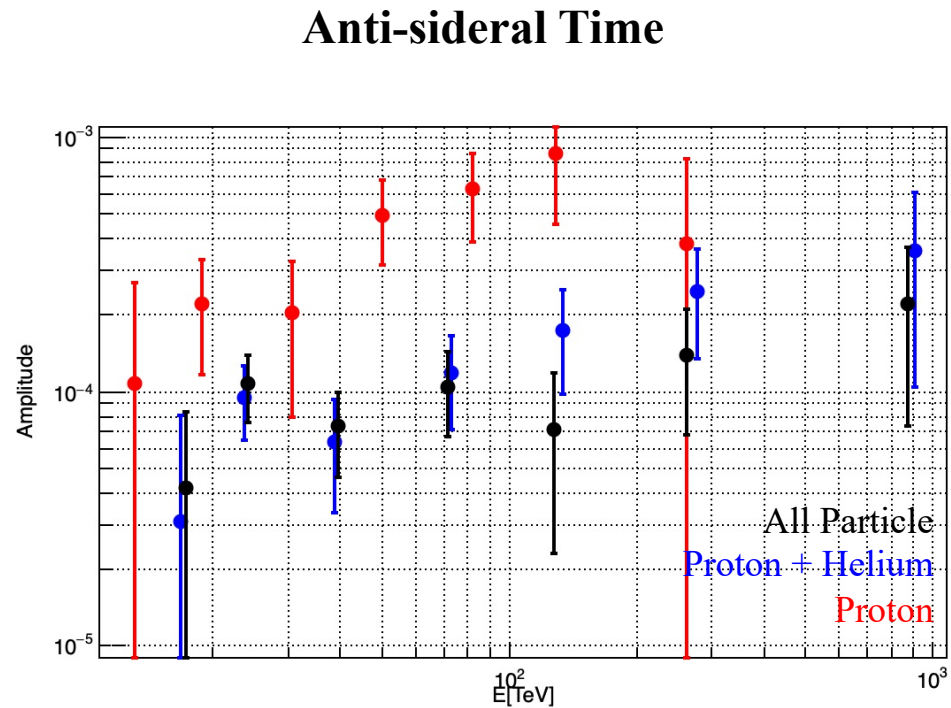
- ◆ Anisotropies of three samples (all particle, P + He, proton) are compared, the amplitude and phase of the three samples are different with the evolution of energy dependence.
- ◆ Regions reported by previous experiments (HAWC, ARGO-YBJ, Milagro) are seen by LHAASO-KM2A.

The region ($\alpha \sim 320^\circ$, $\delta \sim 30^\circ$), a new medium-scale structure?

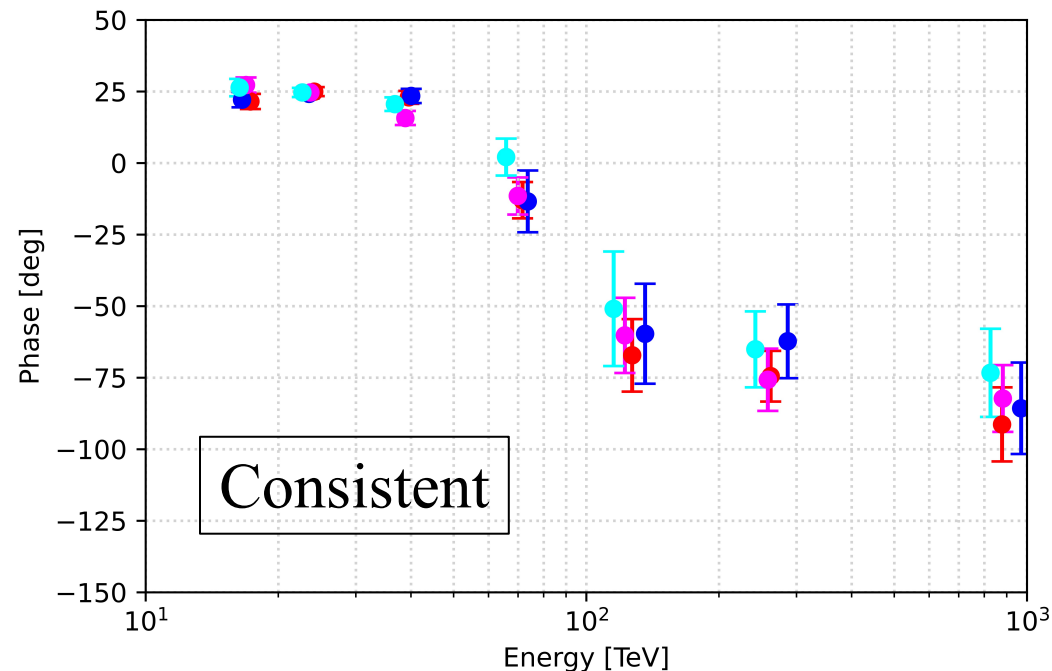
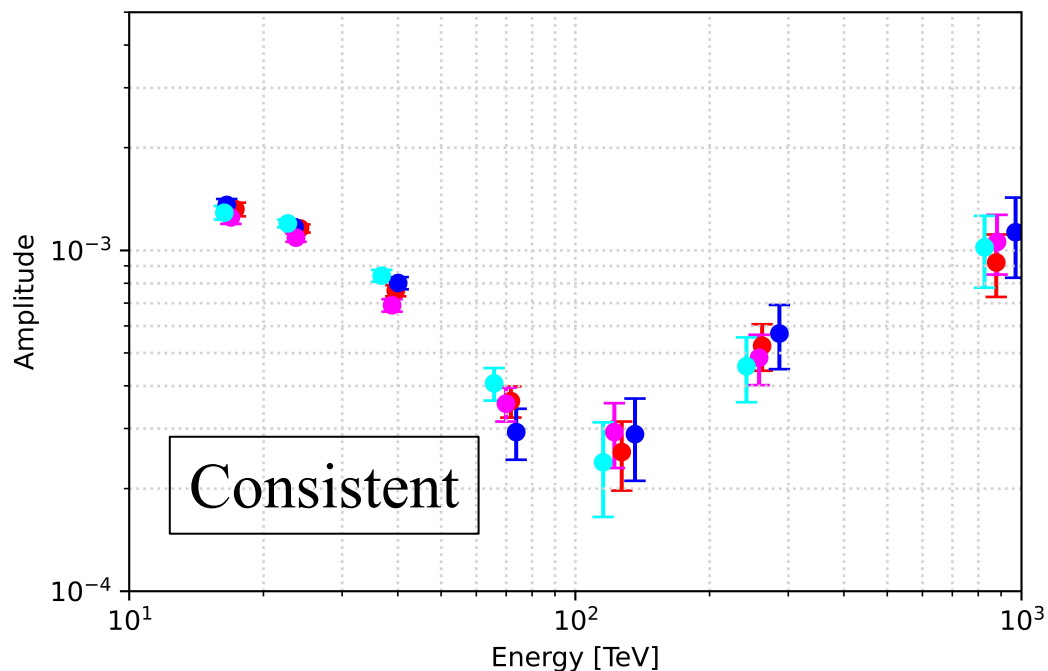
- ◆ Region A and Region B are so bright up to hundreds of TeV, and the relative intensity spectrum of Region B is very flat.

Backup

Anisotropies on anti-sidereal time and solar time



Test different methods of energy reconstruction (all particle)



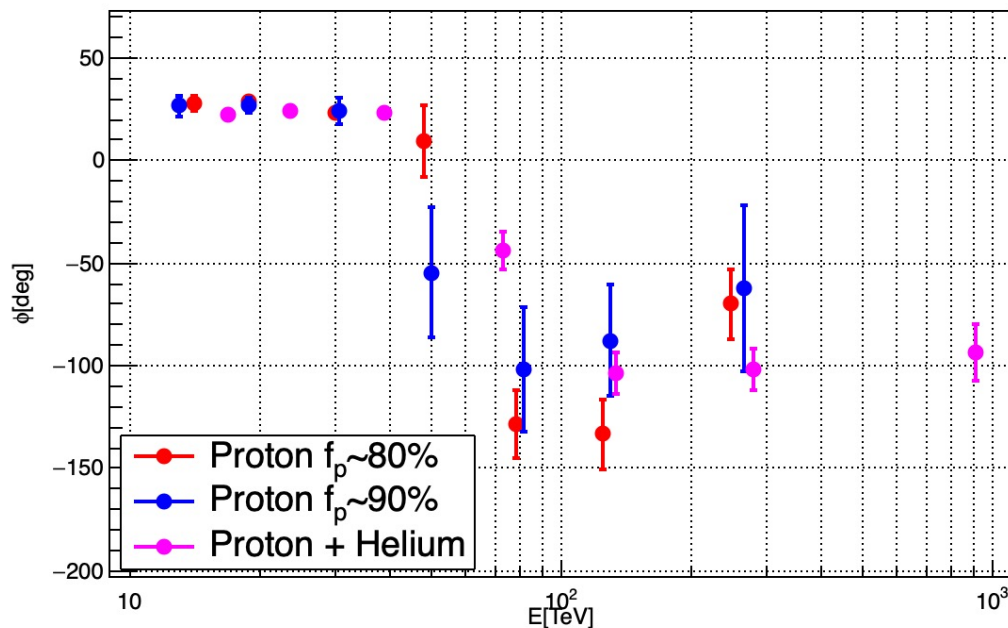
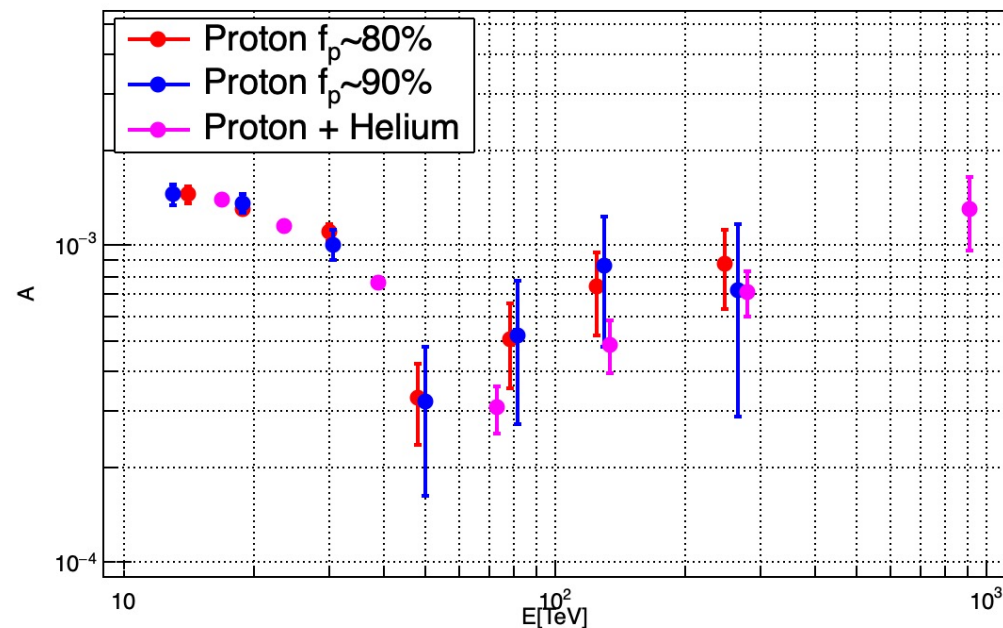
Red: $E_{rec}(\sqrt{N_e N_\mu}), \theta_{rec} < 50^\circ$

Blue: $E_{rec}(\sqrt{N_e N_\mu}), \theta_{rec} < 40^\circ$

Magenta: $E_{rec}(N_e \cos(\theta_{rec}) + 2.7 * \cos(\theta_{rec})), \theta_{rec} < 50^\circ$

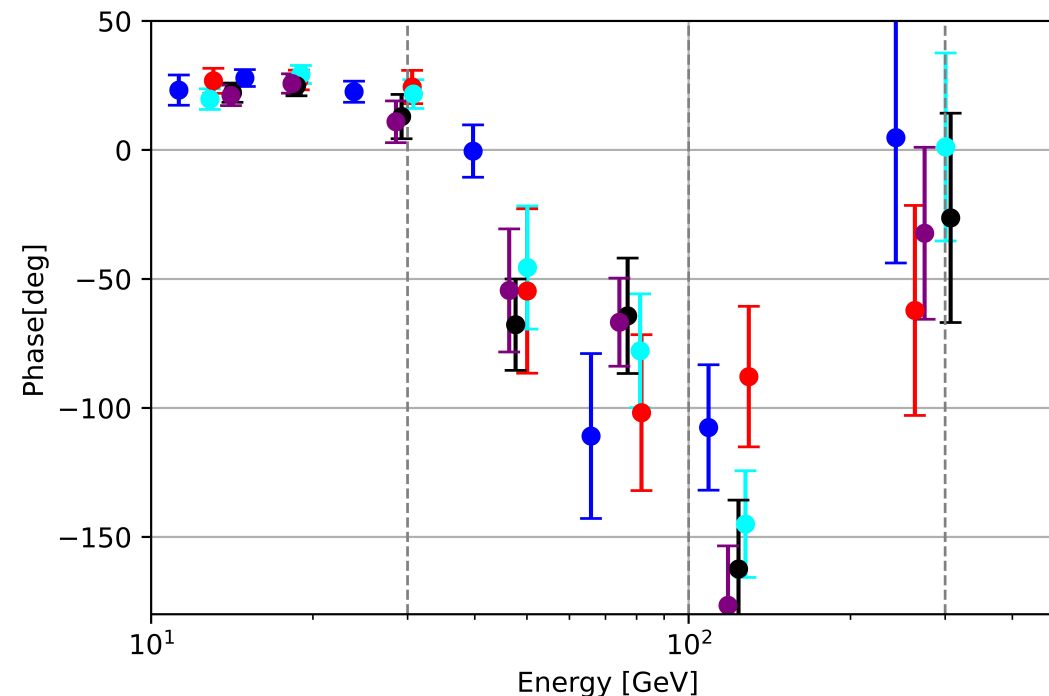
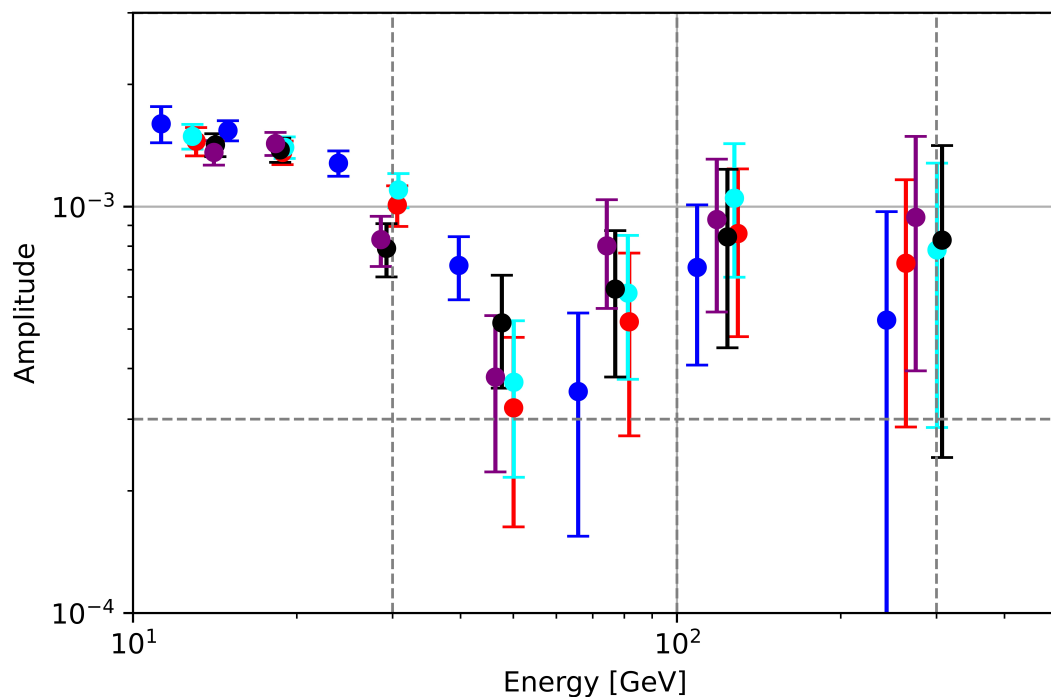
Cyan: $E_{rec}(N_e \cos(\theta_{rec}) + 2.7 * \cos(\theta_{rec})), \theta_{rec} < 40^\circ$

Test different proton sample's purity



Amplitude is stable, and phase drops at high energy.

Test different methods of energy reconstruction (proton)



Reconstruct energy $E_{Plike}(S50)$ after selecting samples $E_{CR}(N_e N_\mu)$

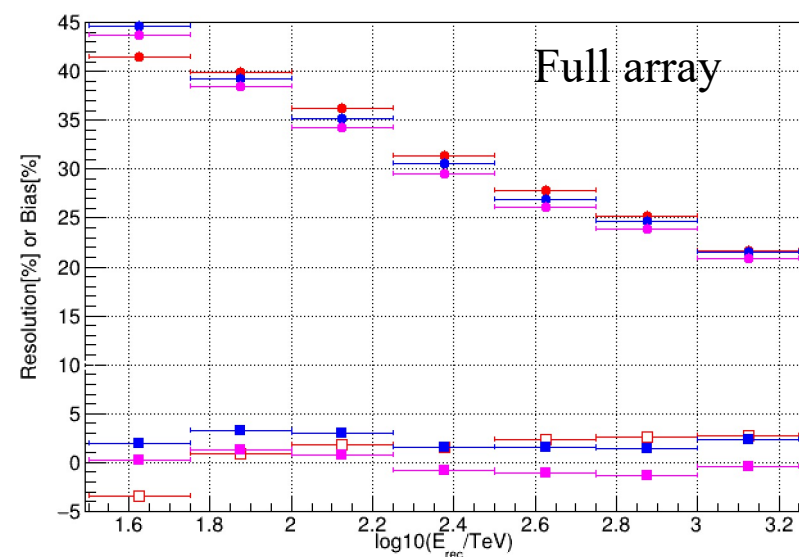
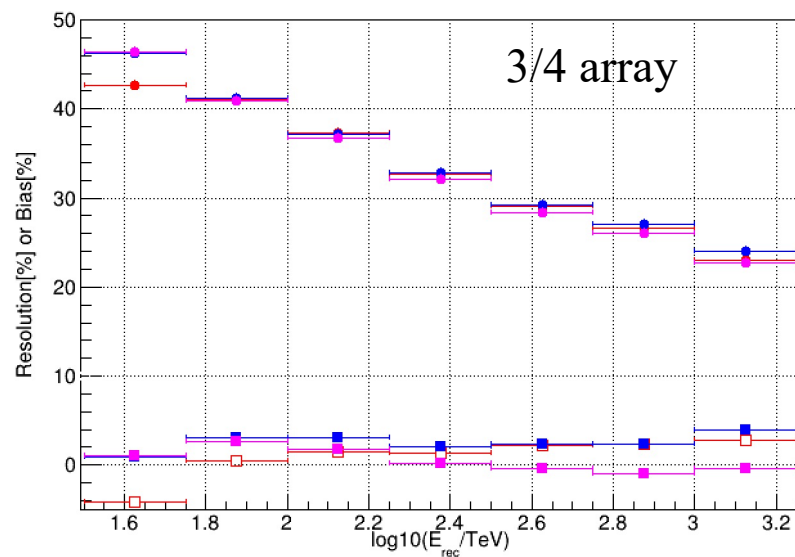
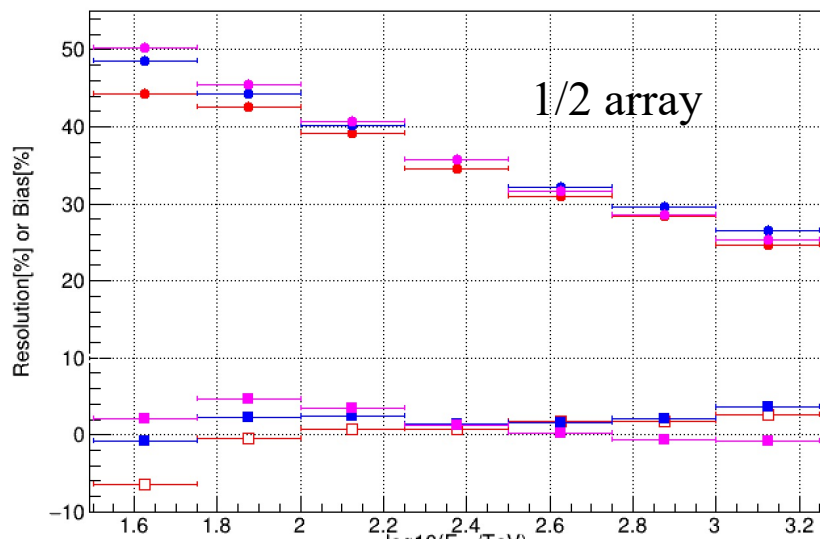
Selecting samples $E_p(S50)$

Reconstruct energy $E_{Plike}(S50)$ after selecting samples $E_p(S50)$

Selecting samples $E_{CR}(N_e \cos(\theta) + 2.7N_\mu \cos(\theta))$

Reconstruct energy $E_{Plike}(N_e \cos(\theta) + 2.7N_\mu \cos(\theta))$ after selecting samples $E_{CR}(N_e \cos(\theta) + 2.7N_\mu \cos(\theta))$

Resolution and Bias



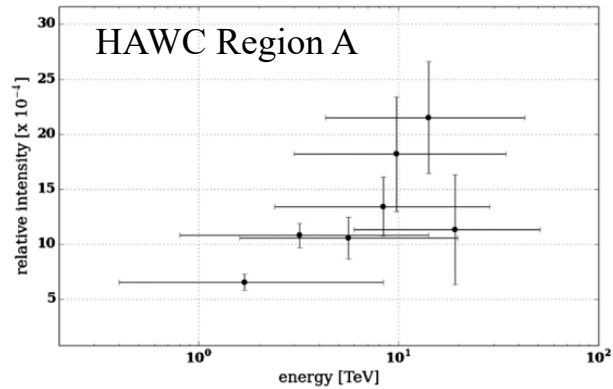
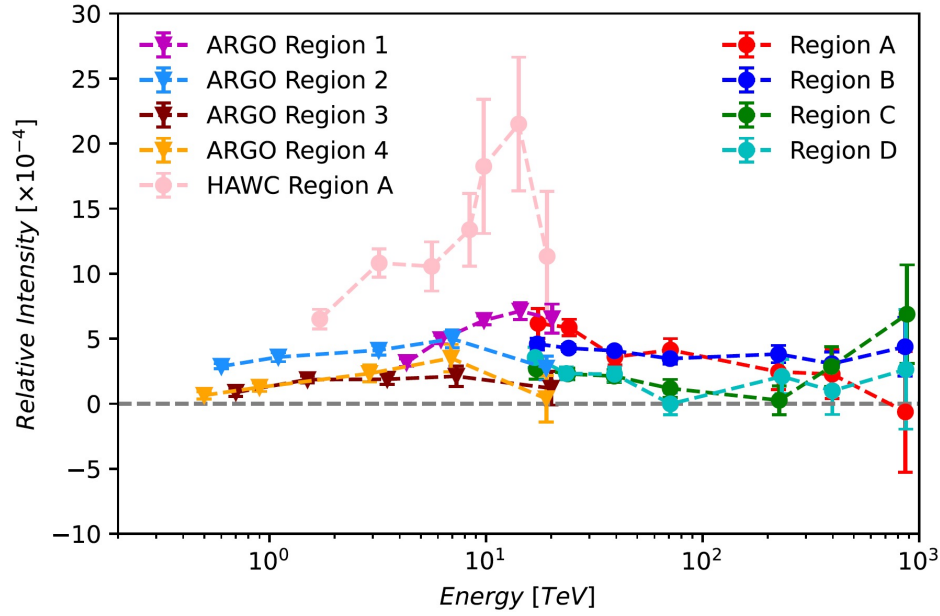


Figure 10. Spectrum of Region A in relative intensity in different energy proxy bins. The energies of the data were determined from Figure 9. The error bars on the median energy values correspond to a 68% containing interval.

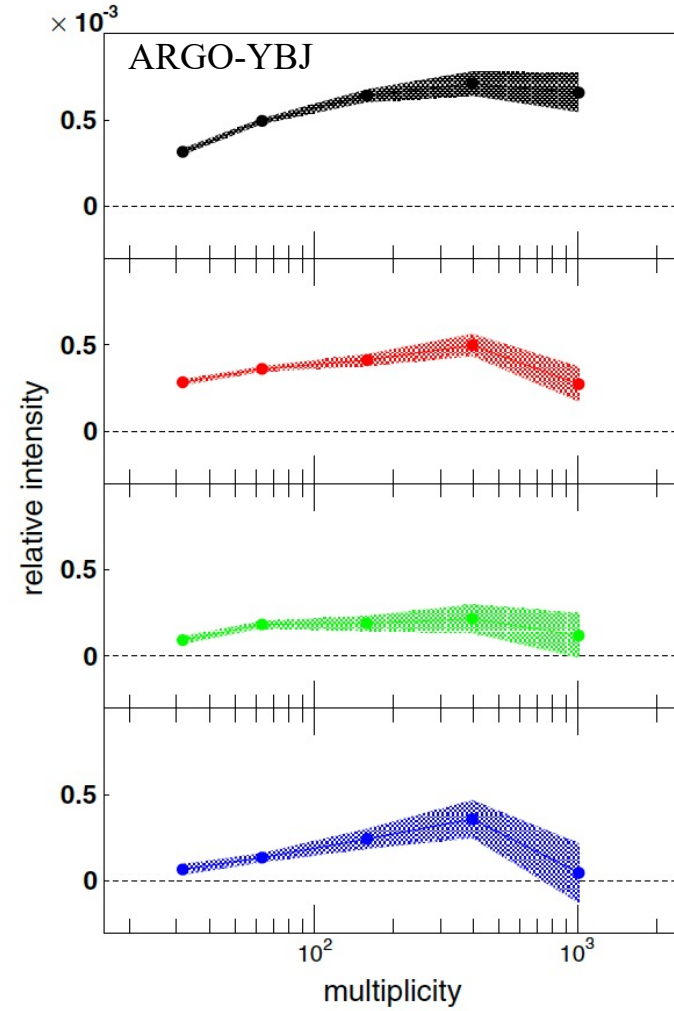


FIG. 6 (color online). Size spectrum of the four MSA regions observed by ARGO-YBJ (regions 1 to 4 starting from the top). The vertical axis represents the relative excess $(e - b)/b$. The statistical errors are represented as colored bands around the experimental points.

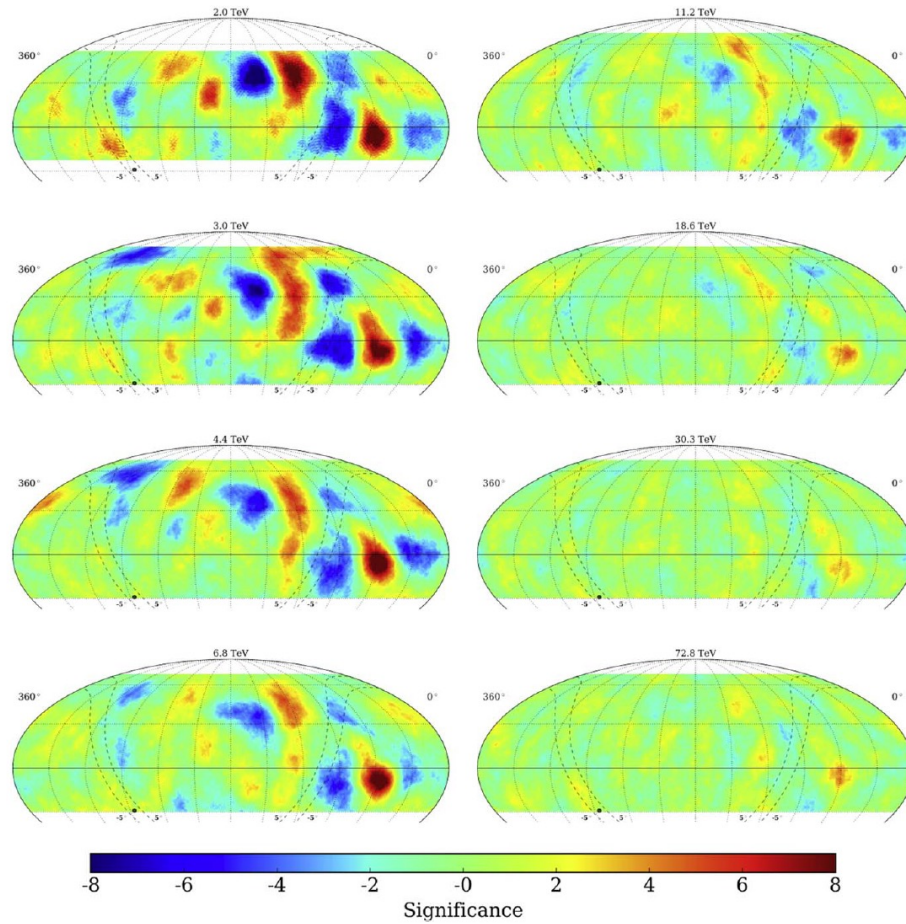
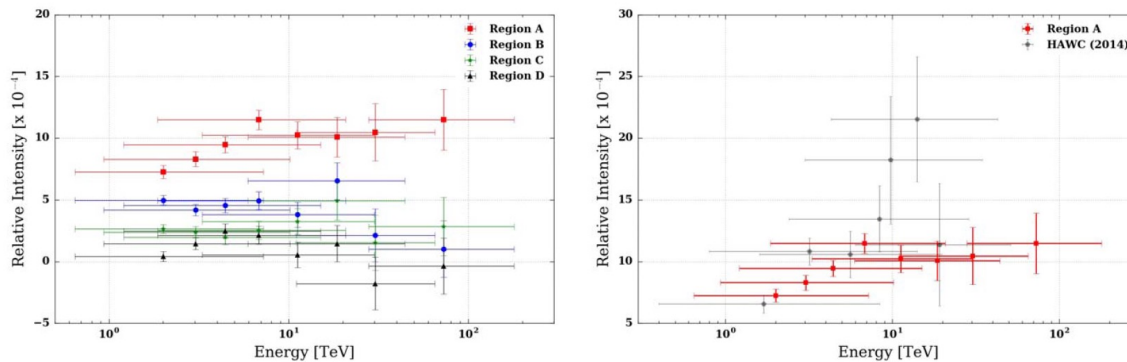


Figure 10. Small-scale anisotropy maps in statistical significance (smoothed 10°) for eight energy bins separated by a likelihood-based reconstructed energy variable. A multipole fit to the moments with $\ell \leq 3$ has been removed.



HAWC + IceCube (2019)

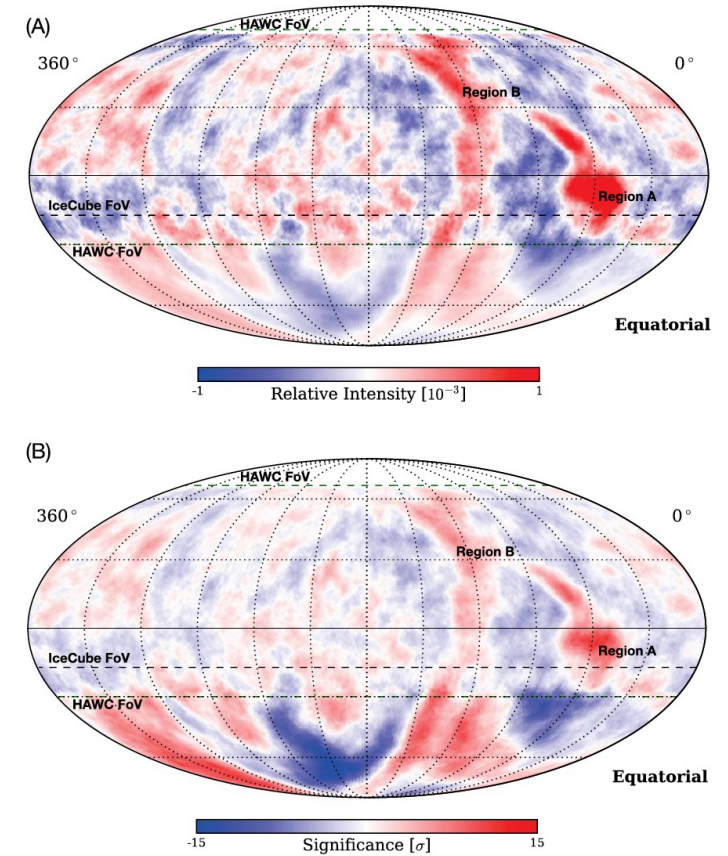


Figure 5. (A) Relative intensity δI_a (Equation (2)) after subtracting the multipole fit from the large-scale map and (B) corresponding signed statistical significance S_i (Equation (3)) of the deviation from the average intensity in J2000 equatorial coordinates.