Anisotropy of mass components of high-energy cosmic rays in the KASCADE experiment data

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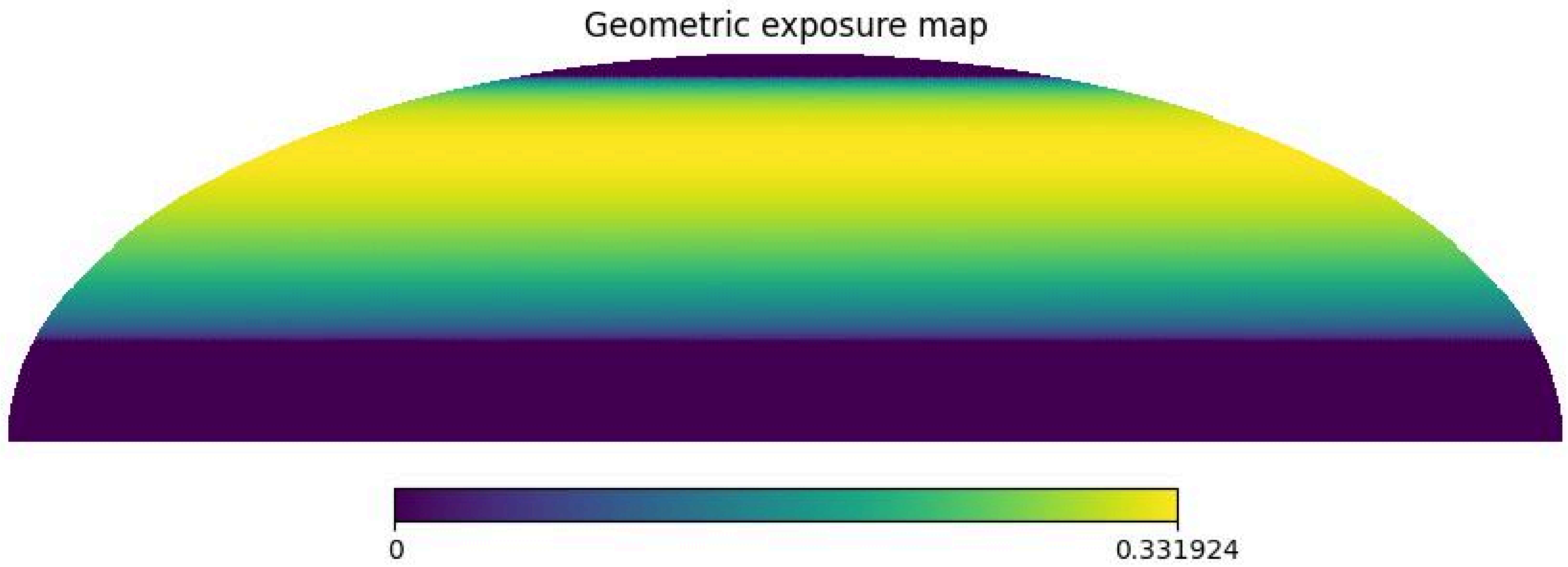
01

Methods for Anisotropy Analysis

Exposure and Monte Carlo

1.1

For the anisotropy analysis in this work, isotropic Monte Carlo datasets are required for medium- and small-scale anisotropy studies. These datasets are generated using the relative exposure map, i.e., a function corresponding to the detector sensitivity for a given arrival direction.



Exposure map used for the KASCADE detector latitude and a maximum zenith angle <30°

$$\frac{dN}{d\cos\theta} \propto \cos\theta, \quad \phi \sim \mathcal{U}(0, 2\pi)$$

In this part of the work, the geometric exposure is used, which corresponds to this distribution.

Large-Scale Anisotropy (1.2)

The East-West method is invariant with respect to various diurnal effects.

The dipole in sidereal time corresponds to a physical result, while the dipoles in solar and antisidereal time serve as criteria for the reliability of the result.

$$a = \frac{2}{N}\sum_{i=1}^{N}\cos(t_i + \zeta_i)$$

$$b = \frac{2}{N}\sum_{i=1}^{N}\sin(t_i + \zeta_i)$$

First harmonic expansion.
ζ_i takes the values 0 and π in the local eastern and western hemispheres, respectively

$$\hat{D}_\perp = \frac{\pi}{2\langle\sin\theta\rangle}\sqrt{a^2 + b^2}$$

$$\hat{\alpha}_d = \frac{\pi}{2} + \arctan\left(\frac{b}{a}\right)$$

From this coefficients the amplitude of dipole and its phase

$$\sigma = \frac{\pi}{2\langle\sin\theta\rangle}\sqrt{\frac{2}{N}}$$

$$p(D_\perp > \hat{D}_\perp) = \exp\left(-\frac{\hat{D}_\perp^2}{2\sigma^2}\right)$$

Significance can be calculated analytically

Small-Scale and Medium-Scale Anisotropy 1.3

Landy-Szalay estimator for cumulative autocorrelation

$$w(\psi) = \frac{DD(\psi) - 2DR(\psi) + RR(\psi)}{RR(\psi)}$$

where DD(ψ) is the number of event pairs in the analyzed dataset, RR(ψ) is the number of event pairs in the Monte-Carlo sample corresponding to an isotropic distribution, and DR(ψ) is the number of cross-pairs

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Pseudo-power spectrum

$$\delta I(\vec{n}) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\vec{n}) \quad \Big| \quad C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Pseudo-correlation function

$$\tilde{\xi}(\psi) = \frac{1}{4\pi} \sum_{l=0}^{\infty} (2l+1) \tilde{C}_l P_l(\cos\psi)$$

Corrected

Power spectrum

$$\bar{C}_l = 2\pi \int_{-1}^{1} \bar{\xi}(\psi) P_l(\cos\psi) d(\cos\psi)$$

Pre-trial and post-trial p-value

A **pre-trial p-value** is the fraction of isotropic MC sets that show a stronger signal than our real data.

A global significance, or **post-trial p-value**, is the fraction of MC sets where the minimum pre-trial p-value is less than or equal to the real data's pre-trial p-value.

Due to the limited angular scale of about 60 degrees, we analyze **angles less then 60 degrees** and **multipoles l greater than 3.**

For real data, different energy bins and particle types are considered independent.

Comparison of the Sensitivity of the Autocorrelation Function and the Power Spectrum

1.4

Let us try to introduce a certain analogue of the cumulative power spectrum:

$$C_i^{sum} = \sum_{j=i}^{N_{bin}} C_j^{bin}$$

Anisotropy is modeled using a certain function $f(\vec{n})$,where the parameter ϵ determines the level of anisotropy in the map.

$$I(\vec{n}) = 1 + \epsilon \frac{f(\vec{n})}{\max(f(\vec{n}))}$$

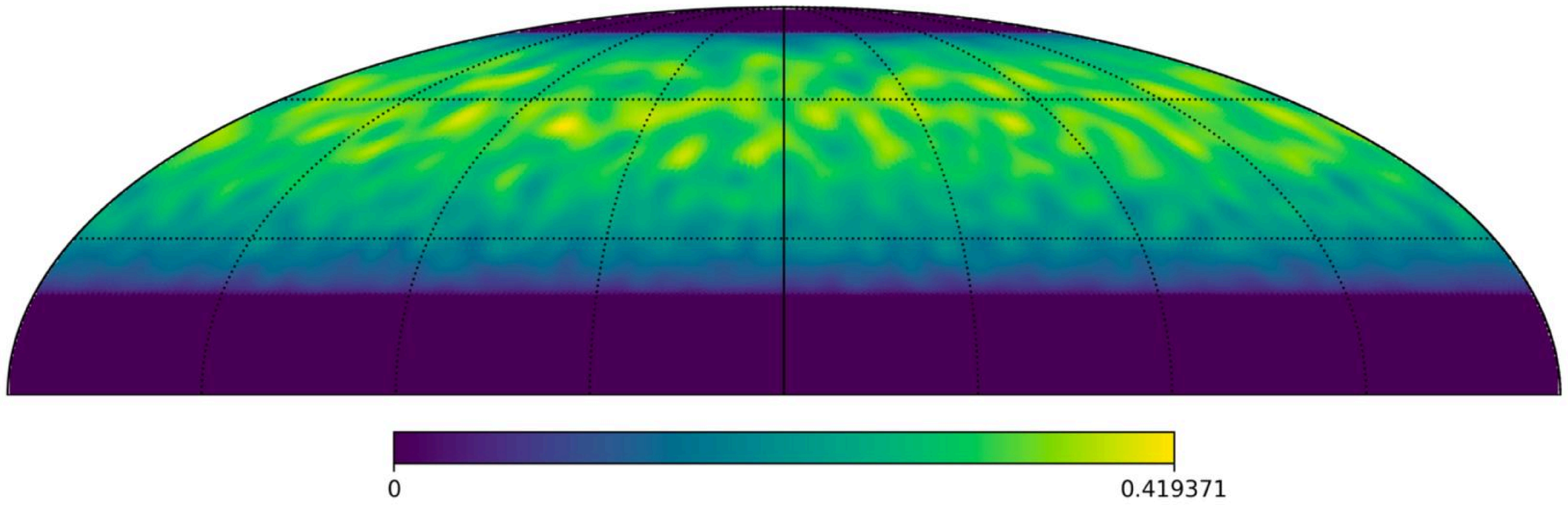
The comparison is performed at the level of the median post-trial p-value over 10,000 datasets, taking cosmic variance into account for the power spectrum models.

Gaussian power spectrum model

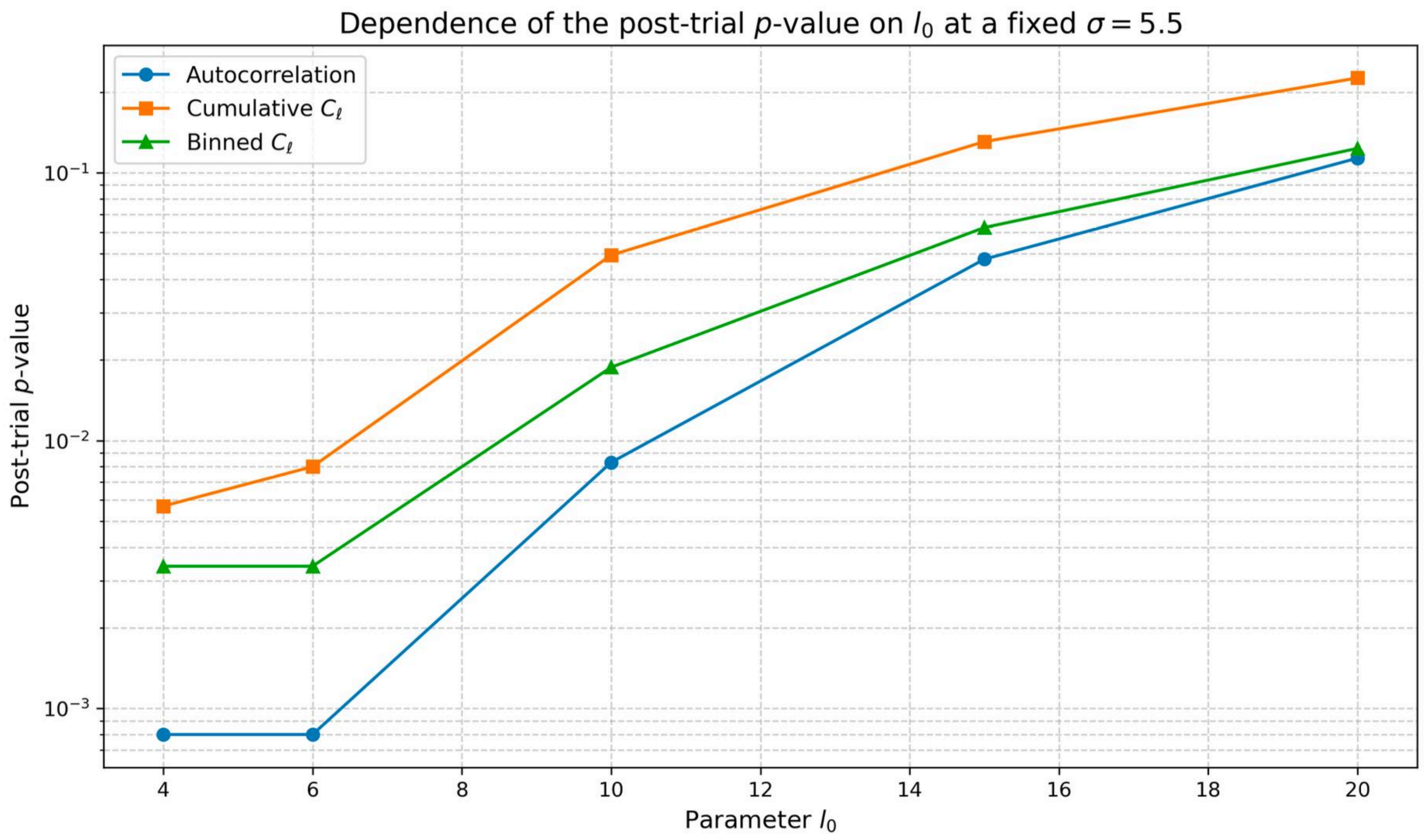
This model is defined by the power spectrum:

$$C_l = \exp\left(-\frac{(l - l_0)^2}{2\sigma^2}\right)$$

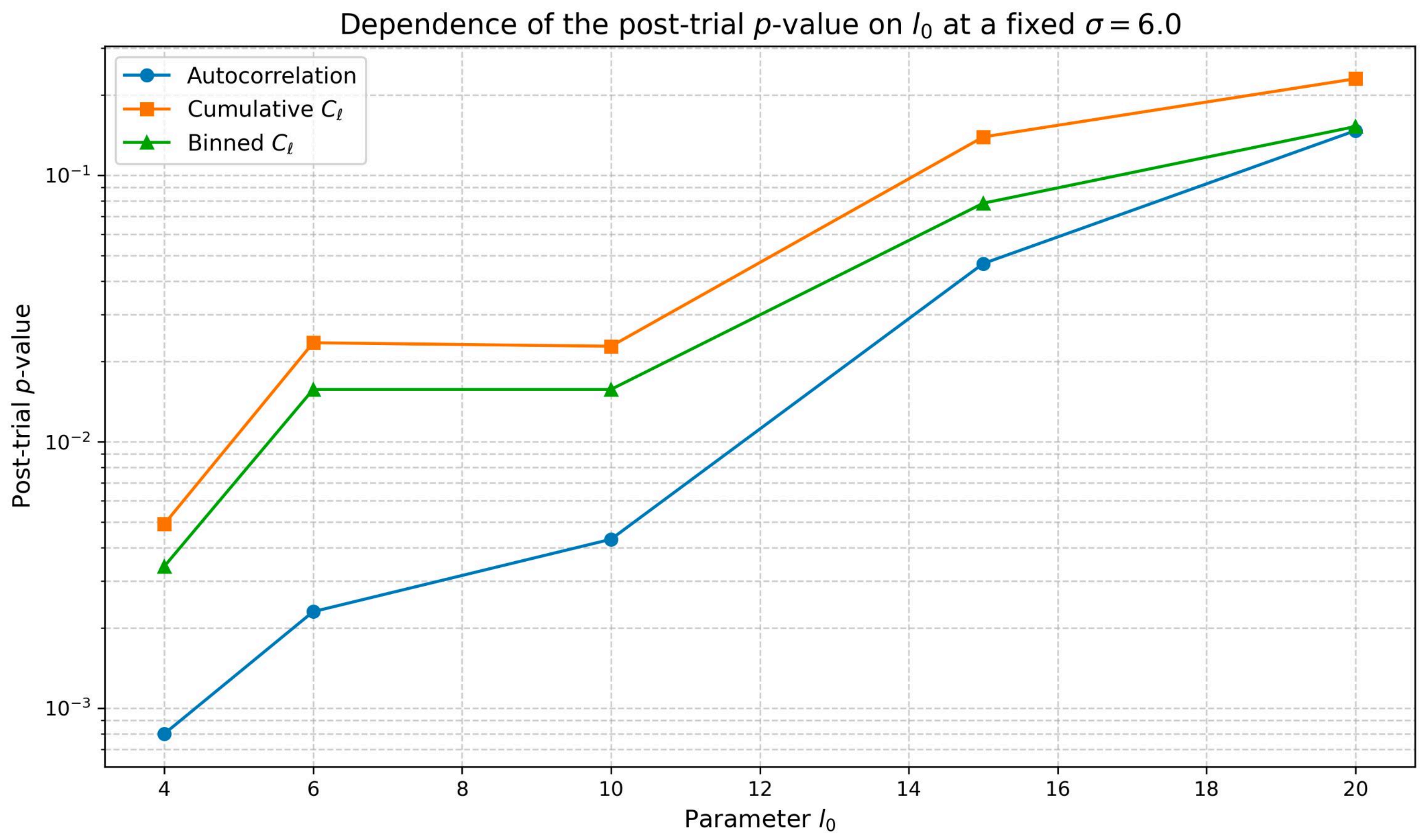
Anisotropic map for this model with (σ = 10) and (l_0 = 30), taking into account the detector exposure.



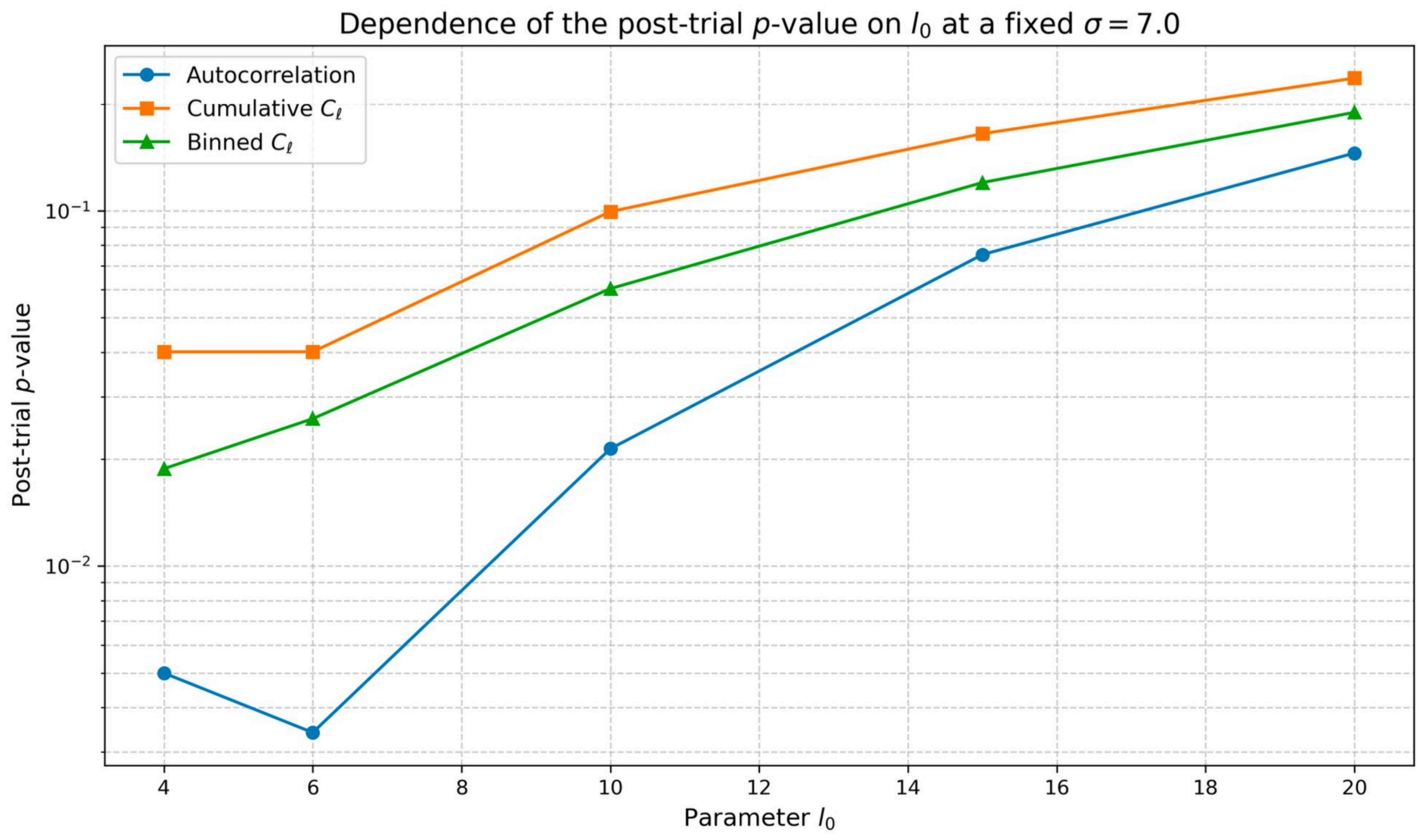
Gaussian power spectrum model



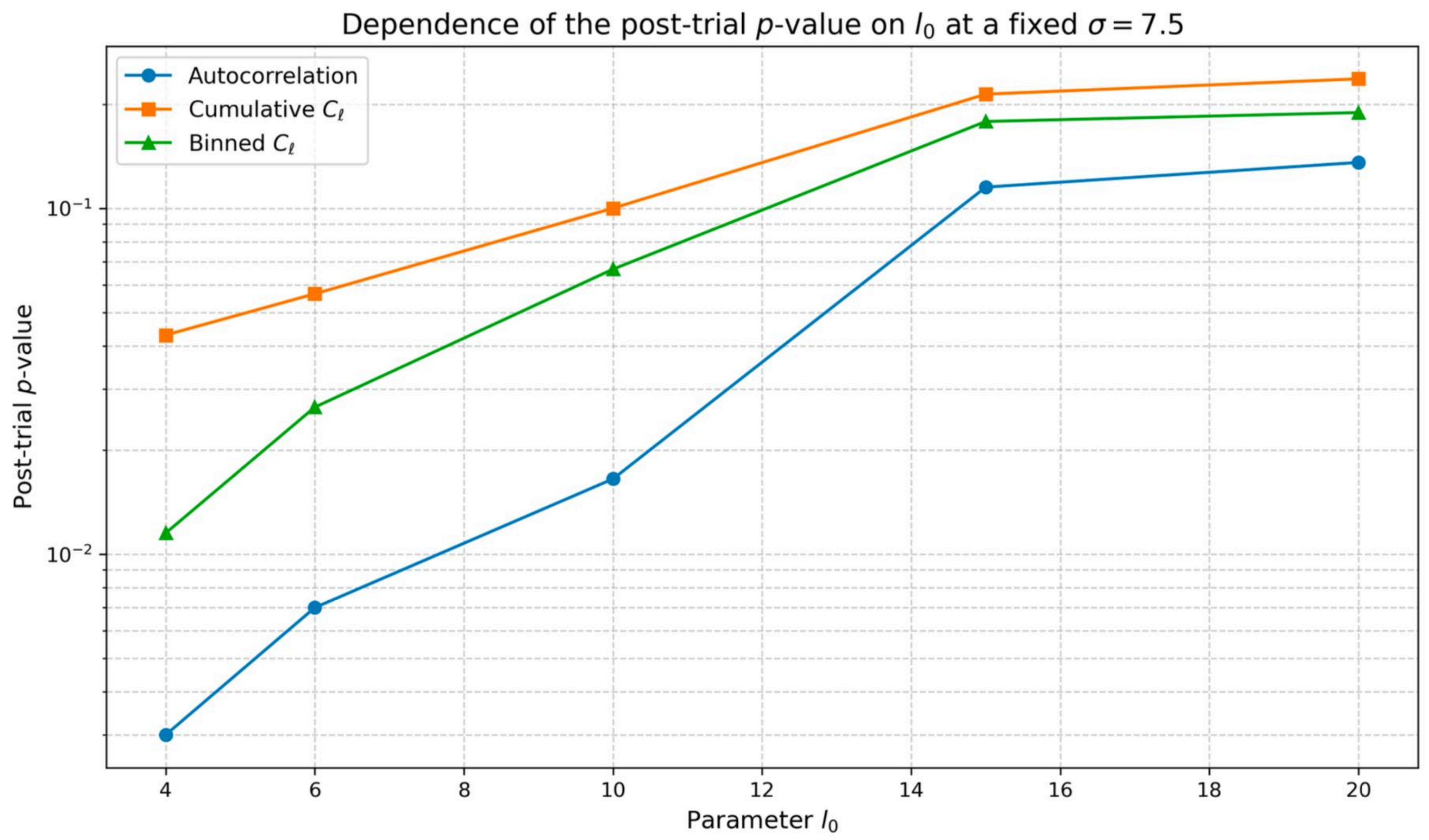
(a) $\sigma = 5.5$



(b) $\sigma = 6$



(c) $\sigma = 7$

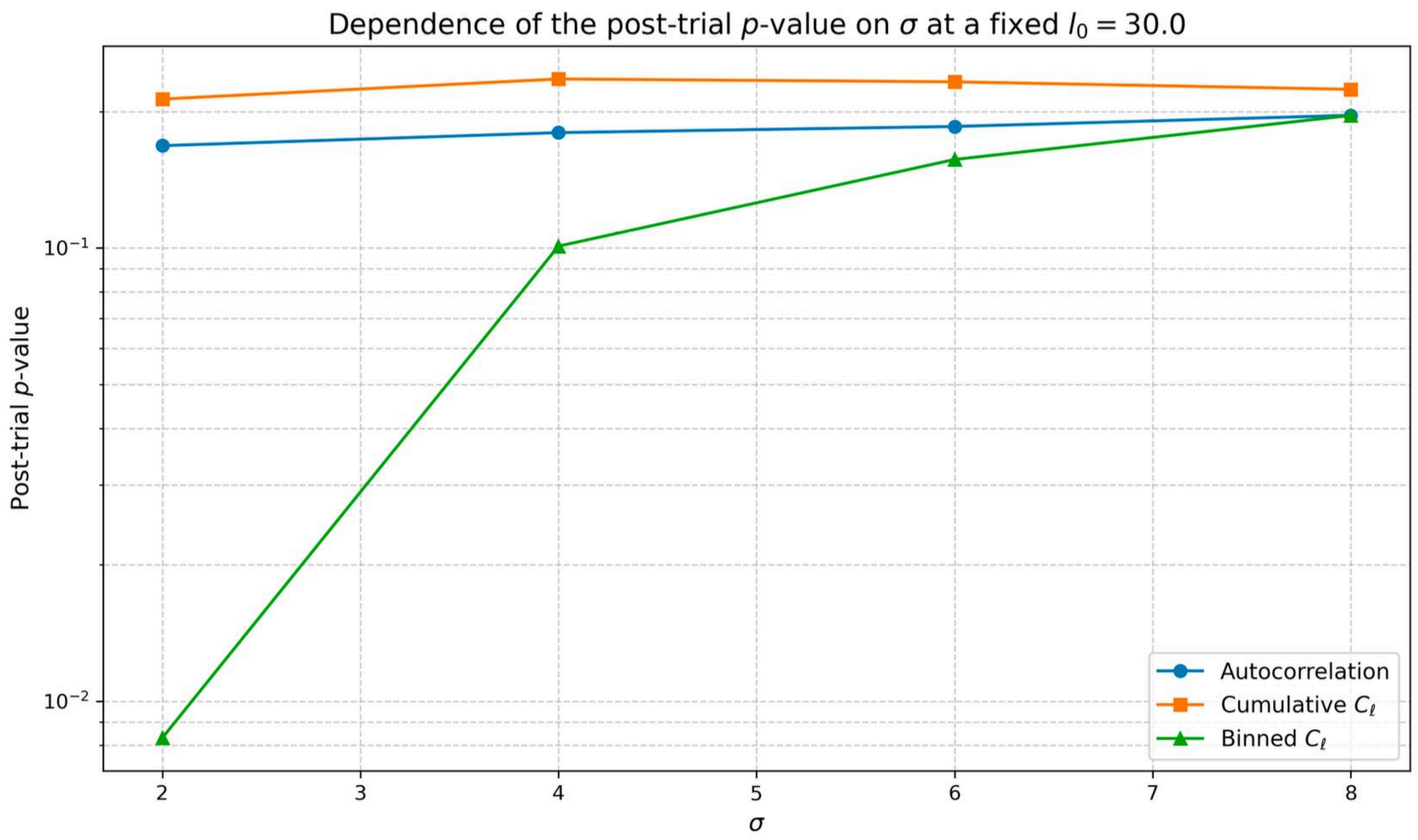


(d) $\sigma = 7.5$

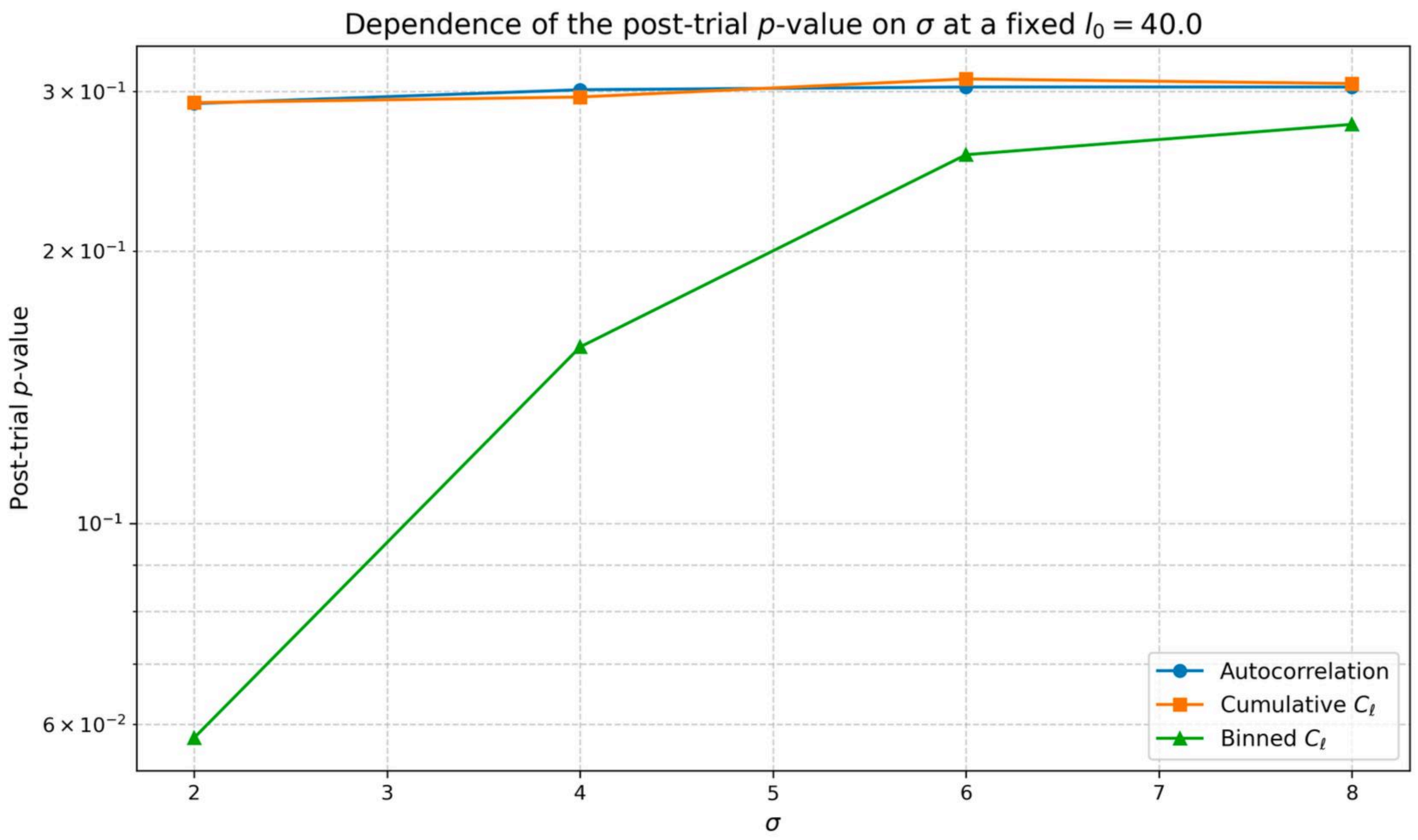
Comparison of the autocorrelation function and the power spectrum for this model at different values of (l_0) and fixed (σ).

$\epsilon = 0.3$

Gaussian power spectrum model



(a) $l_0 = 30$



(b) $l_0 = 50$

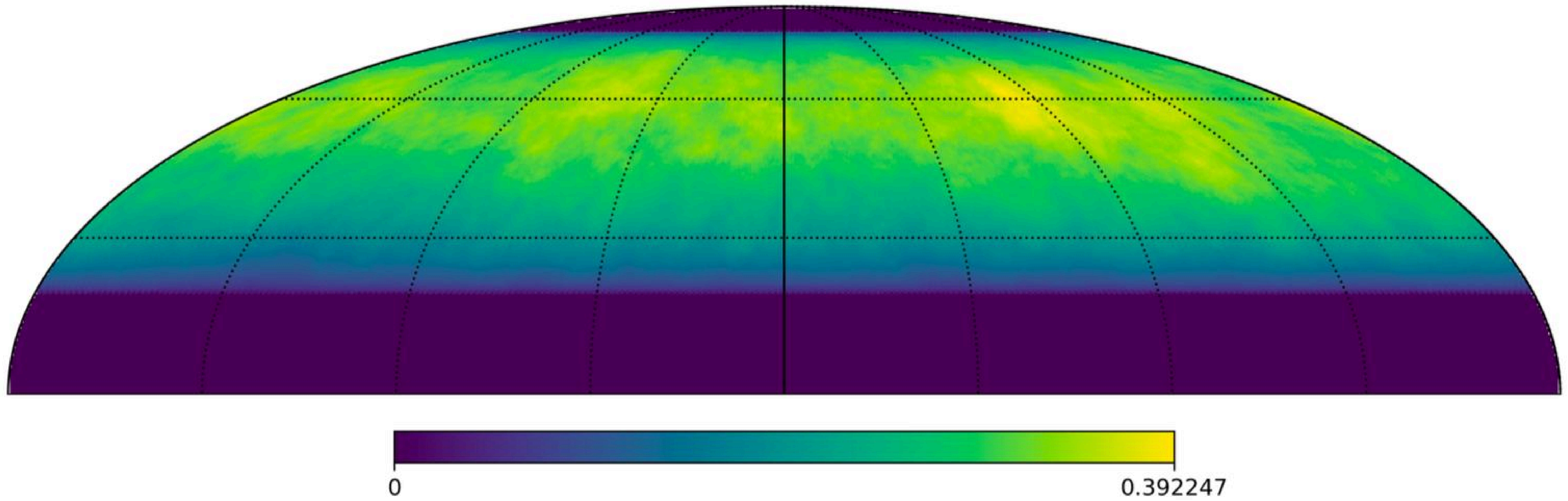
Comparison of the autocorrelation function and the power spectrum for this model at different values of (σ) and fixed (l_0). $\epsilon = 0.35$

Turbulent diffusion model

This model is defined by the power spectrum:

$$C_l = \frac{1}{(2l+1)(l+1)(l+2)}$$

Anisotropic map for this model, taking into account the detector exposure.



Comparison of the median post-trial p-value values for this model. $\epsilon = 0.3$

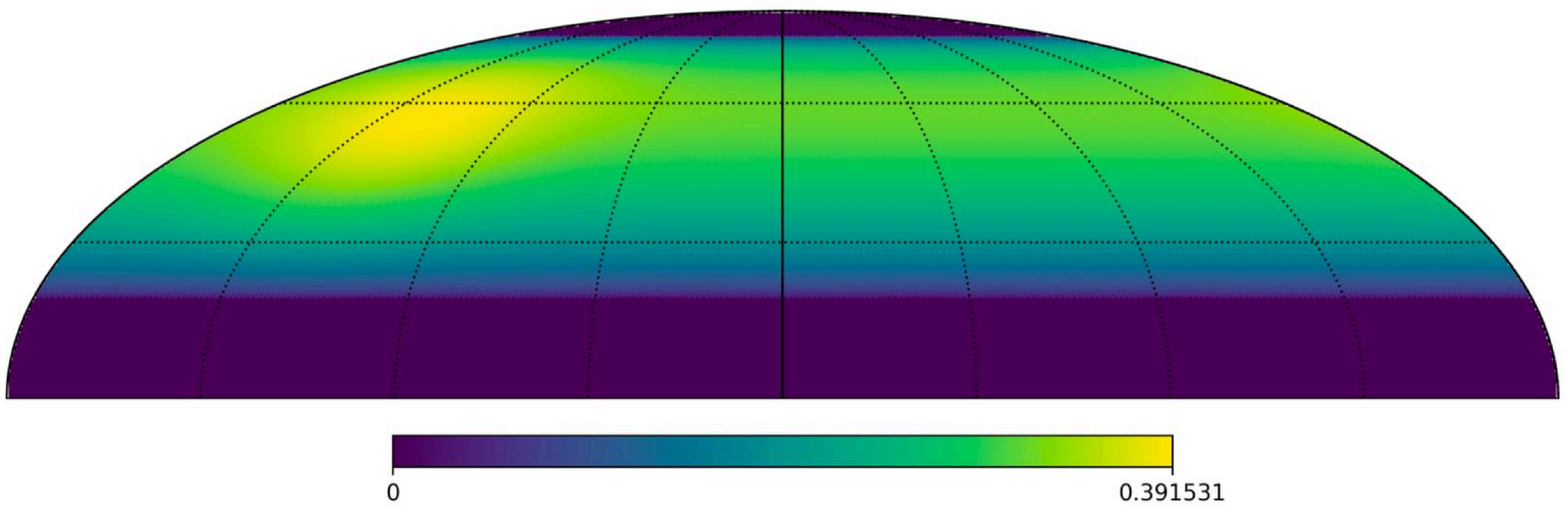
Method	Median post-trial p-value
Autocorrelation	0.0011
Binned power spectrum	0.0061
Cumulative power spectrum	0.1162

Gaussian source model

This model is defined as follows:

$$f(\vec{n}) = \exp\left(-\frac{\psi^2(\vec{n}, \vec{n}_0)}{2\sigma^2}\right)$$

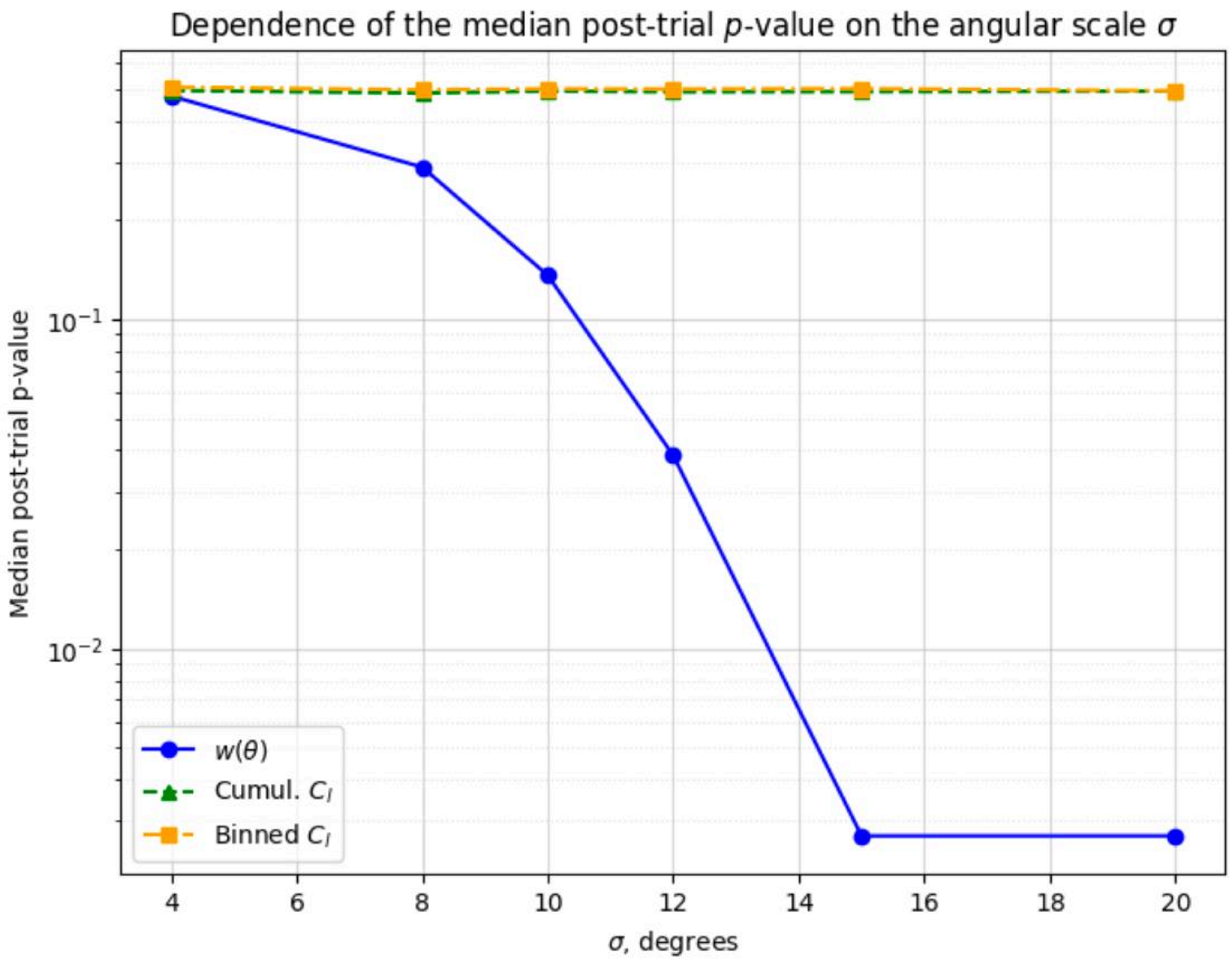
Anisotropic map for this model, taking into account the detector exposure.



Gaussian source model

Comparison of the autocorrelation function and the power spectrum for this model at different values of angular scales (σ).

$$\epsilon = 0.25$$



02

Analysis of KASCADE Experiment data

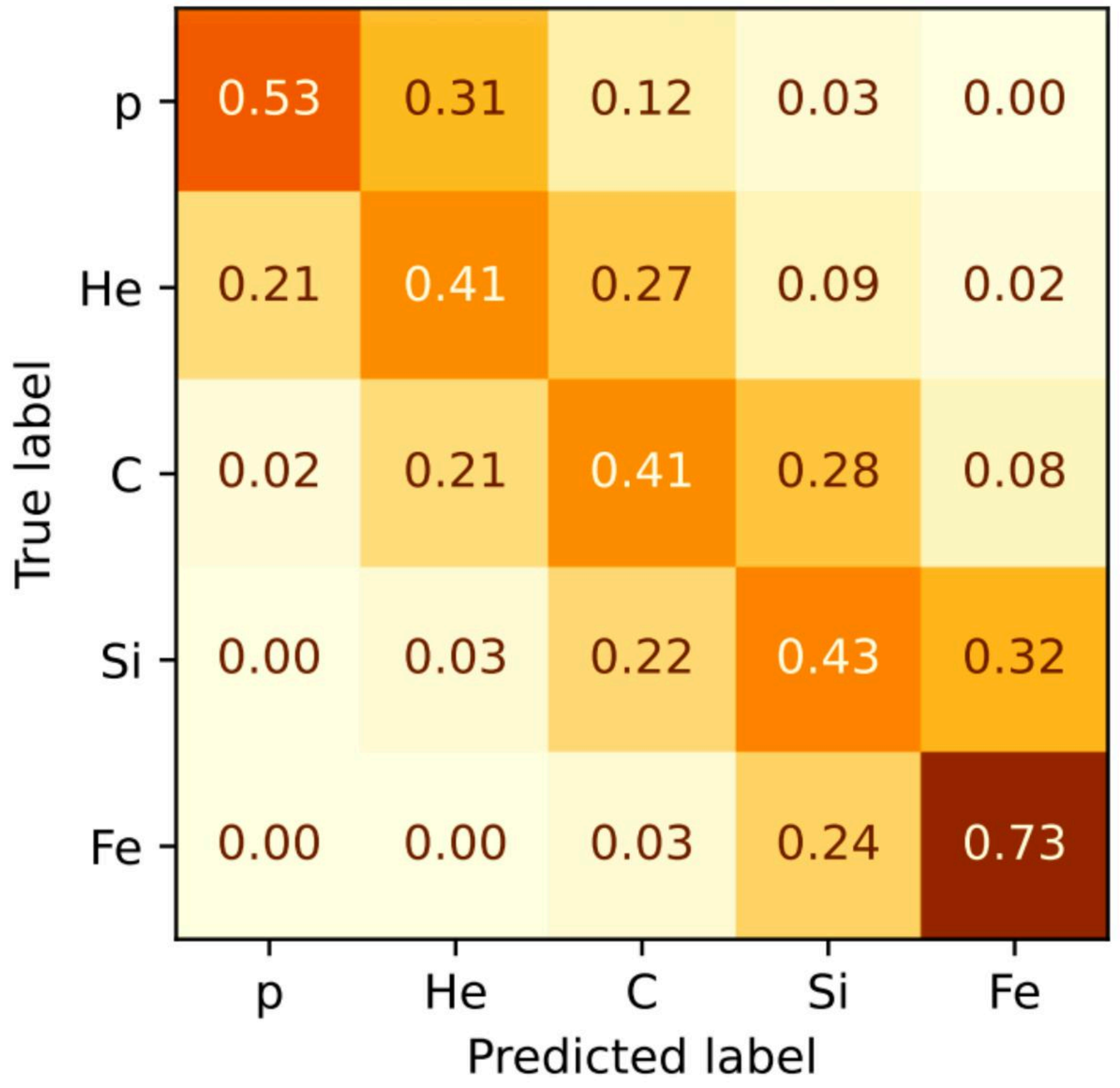
Experiment data, and Monte Carlo

2.1

The approaches discussed above were applied to the archival data from the KASCADE experiment. The KASCADE air-shower array operated from 1996 to 2013 at the KIT Campus in Karlsruhe, Germany (49° N, 8.4° E, 110 m a.s.l.).
The experiment measured extensive air showers in the primary energy range from approximately 500 TeV to 100 PeV. Although KASCADE collected data in several configurations, in this work we focus exclusively on the main KASCADE array.

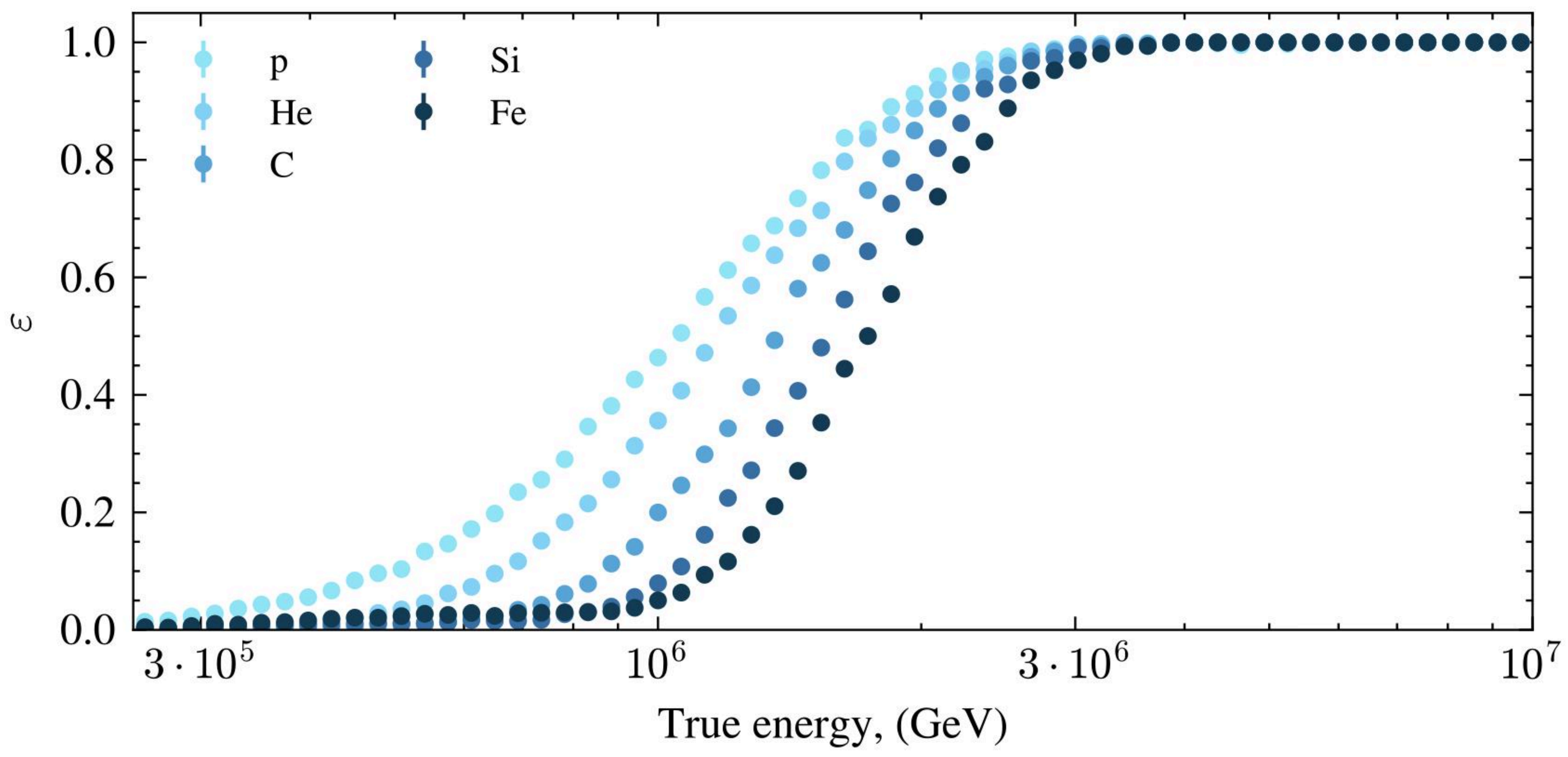
In this work, a particle-type-classified unblinded dataset corresponding to 10% of the full dataset is analyzed.

Confusion matrix of the convolutional neural network:



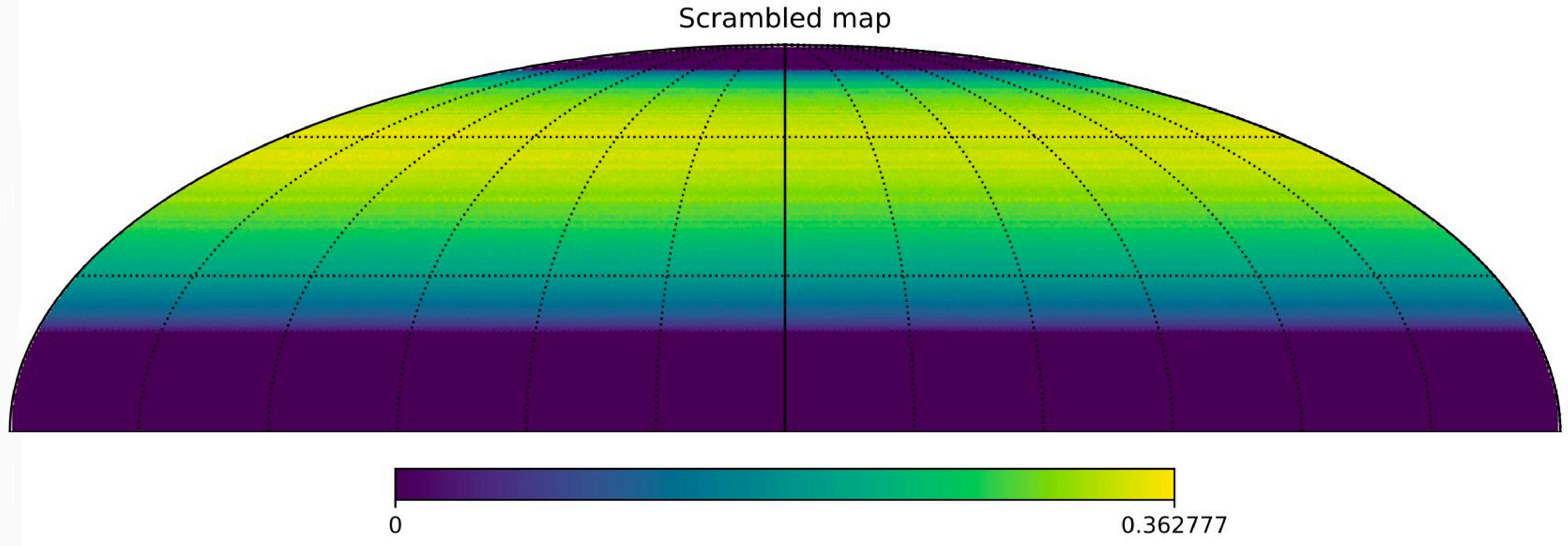
M. Yu. Kuznetsov, N. A. Petrov, I. A. Plokhikh, and V. V. Sotnikov. Methods of machine learning for the analysis of cosmic rays mass composition with the KASCADE experiment data. JINST, 19(01):P01025, 2024.

As mentioned earlier, the exposure of the KASCADE detector does not correspond to the geometric exposure, which follows, for example, from the analysis of the detector efficiency depending on the type and energy of the primary particle.

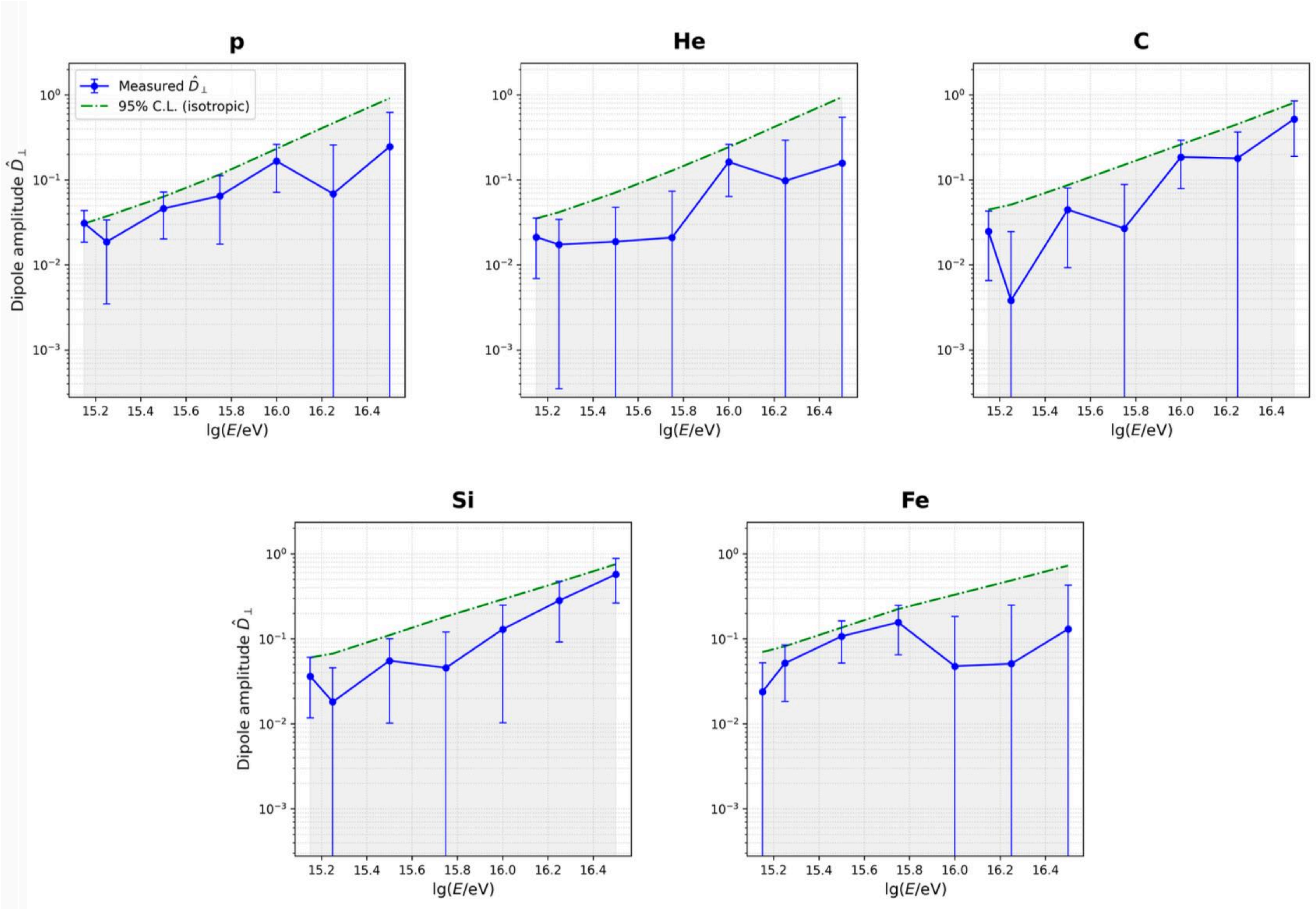


Dependence of the detector efficiency on energy for different particle types.

In this case, it is necessary to use exposure reconstruction methods. In this work, **the time-scrambling** method is used. An example of a map for protons at $lg(E/\mathrm{eV}) > 15.15$:

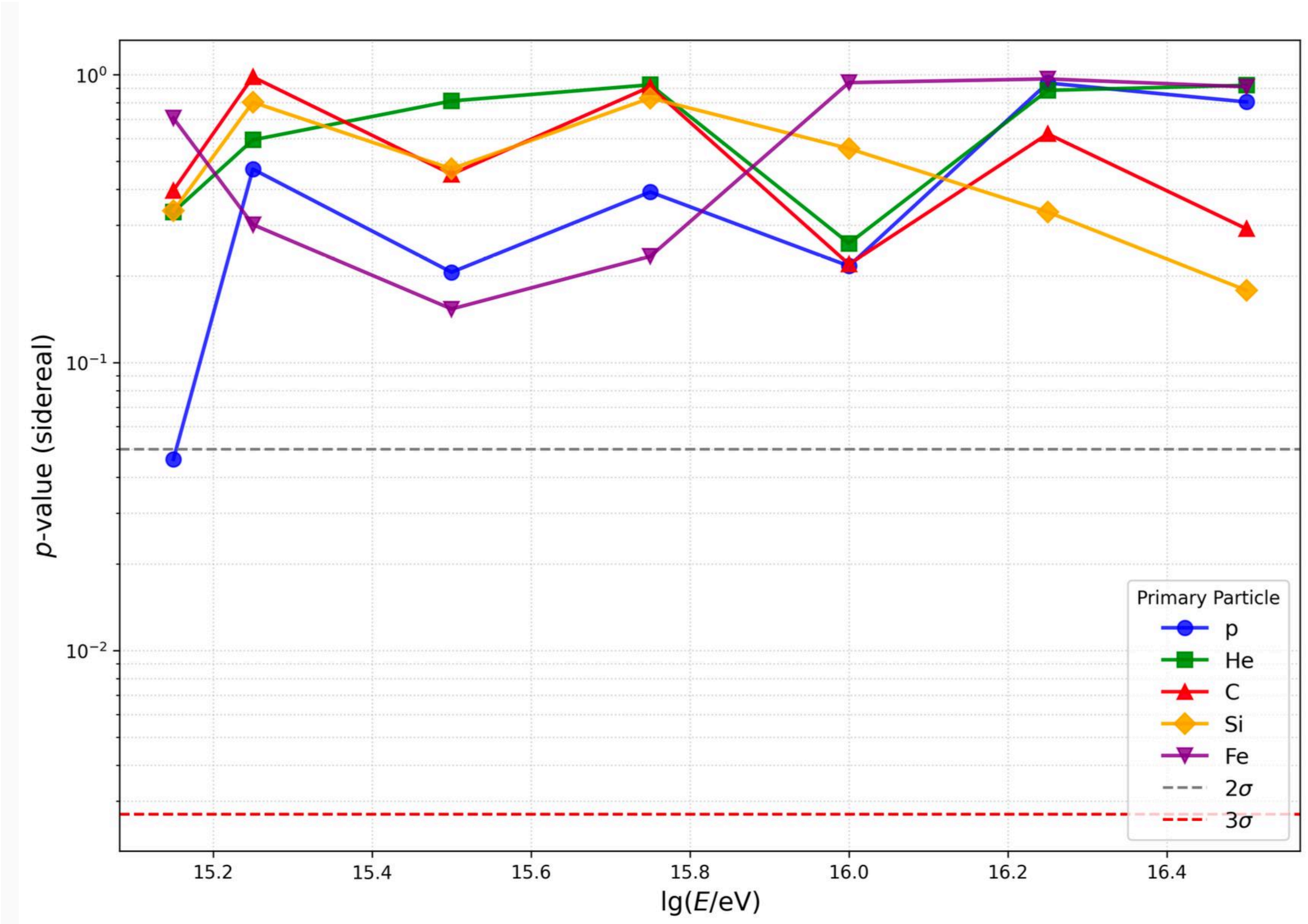


Large-Scale Anisotropy Analysis (2.2)



Values of the transverse dipole component for different particle types and energy intervals.

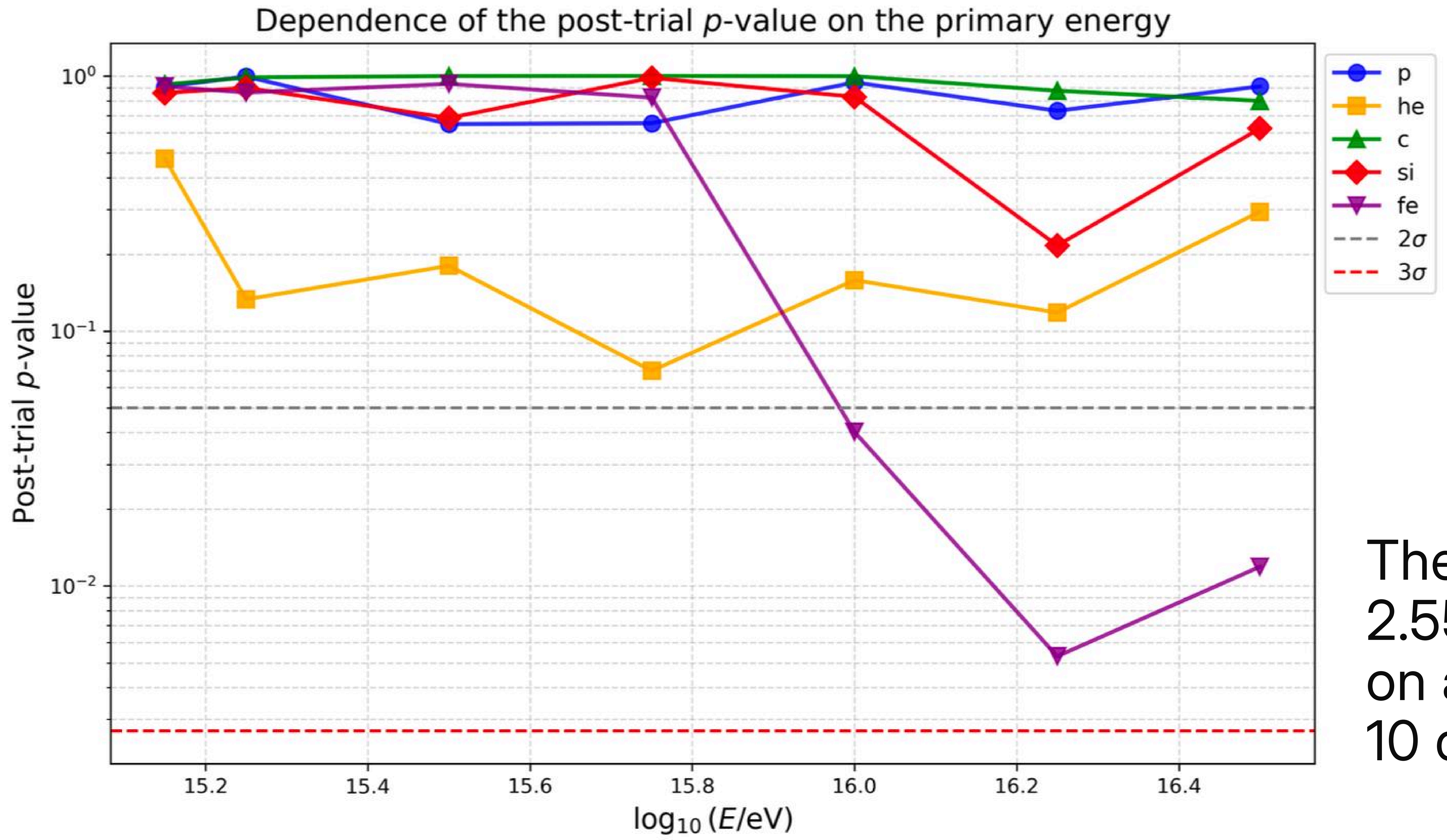
The lowest p-value is $p_{sid} = 0.046$ for protons at $lg(E/\mathrm{eV}) > 15.15$



p-value values obtained using the East-West method for different particle types and energy intervals.

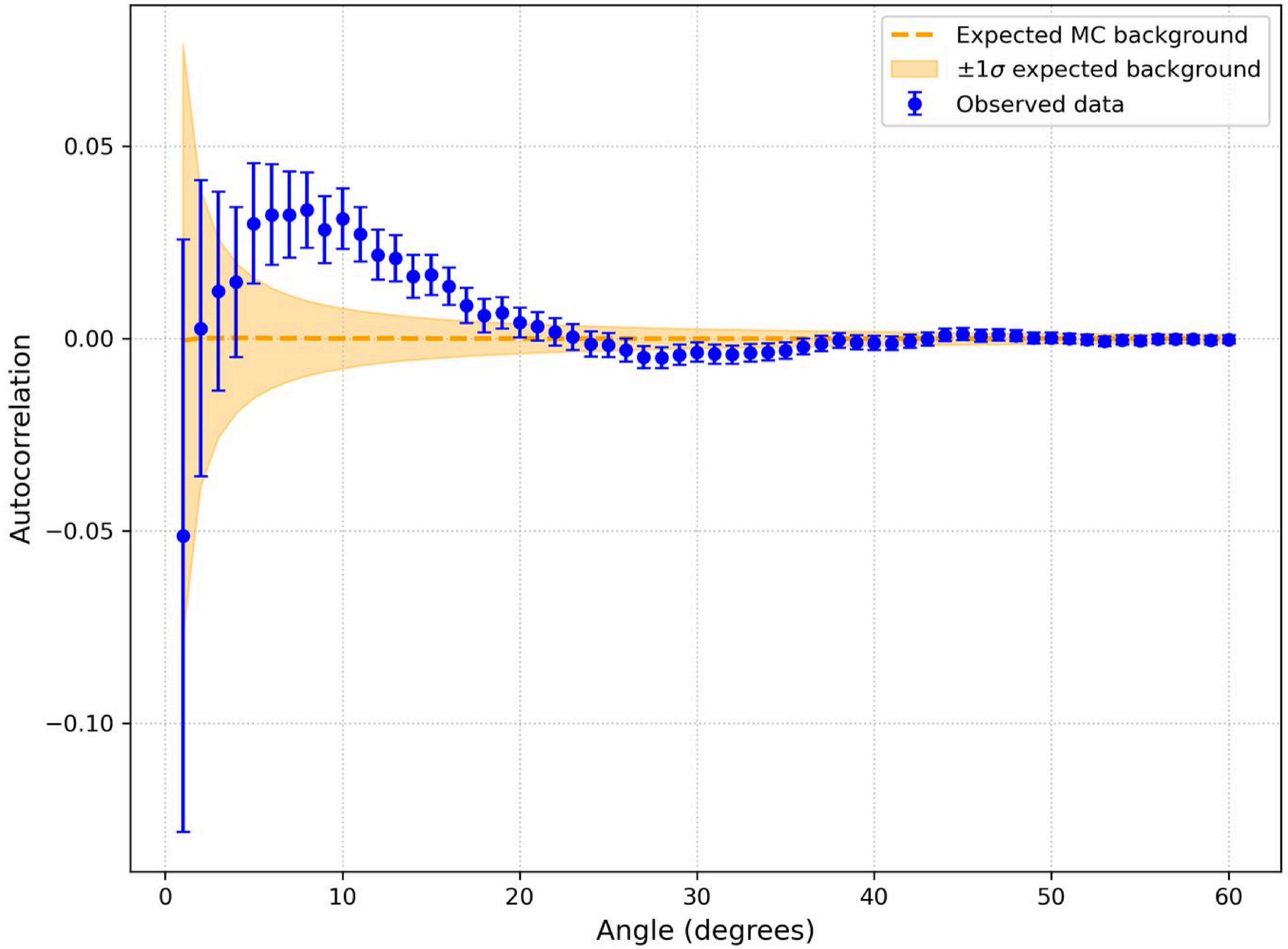
Autocorrelation Analysis

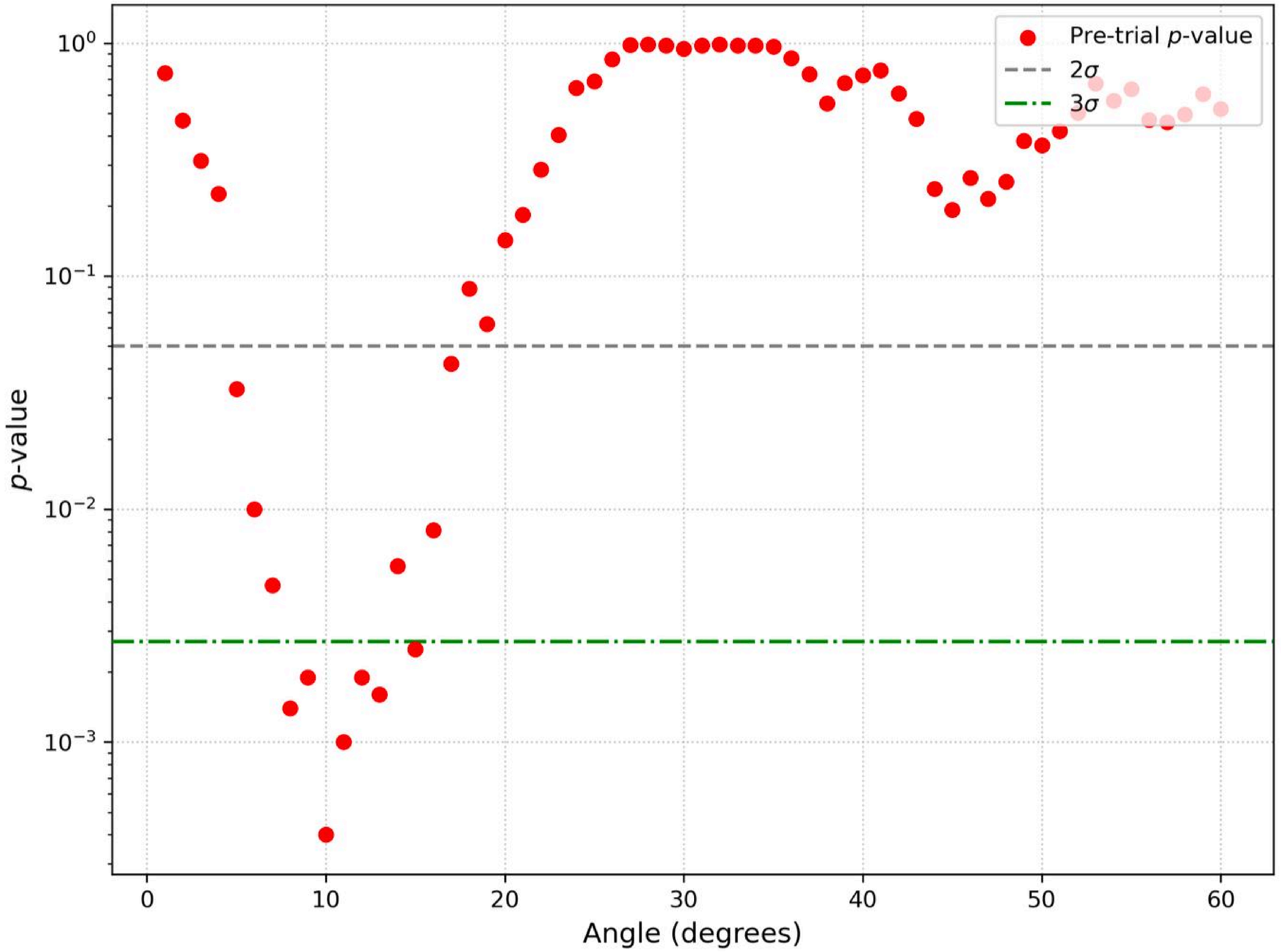
2.3



p-value values obtained using the autocorrelation method for different particle types and energy intervals.

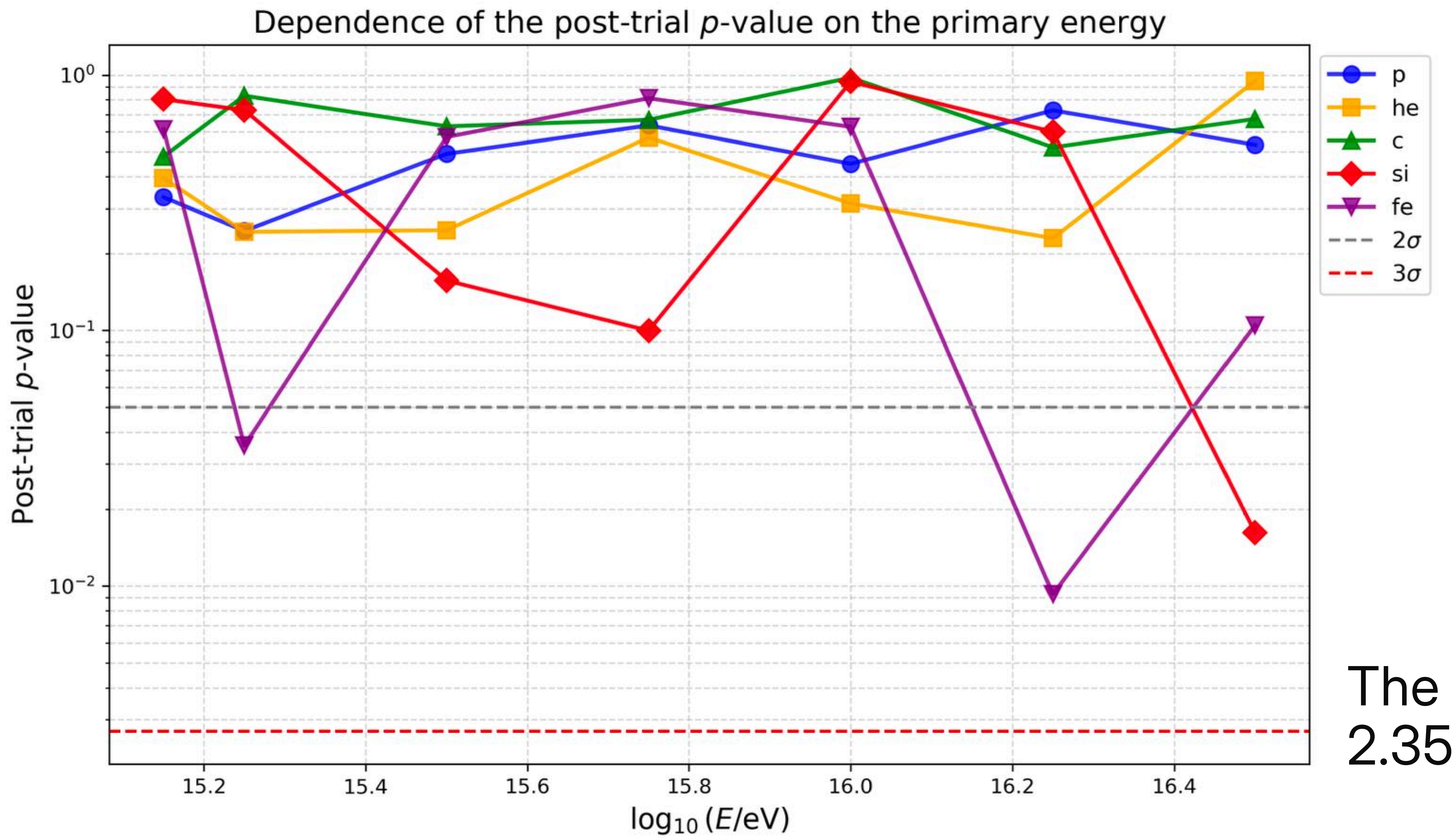
The lowest p-value corresponds to 2.55σ for iron (Fe) at $\lg(E/\mathrm{eV}) > 16.25$ on an angular scale of about 10 degrees.





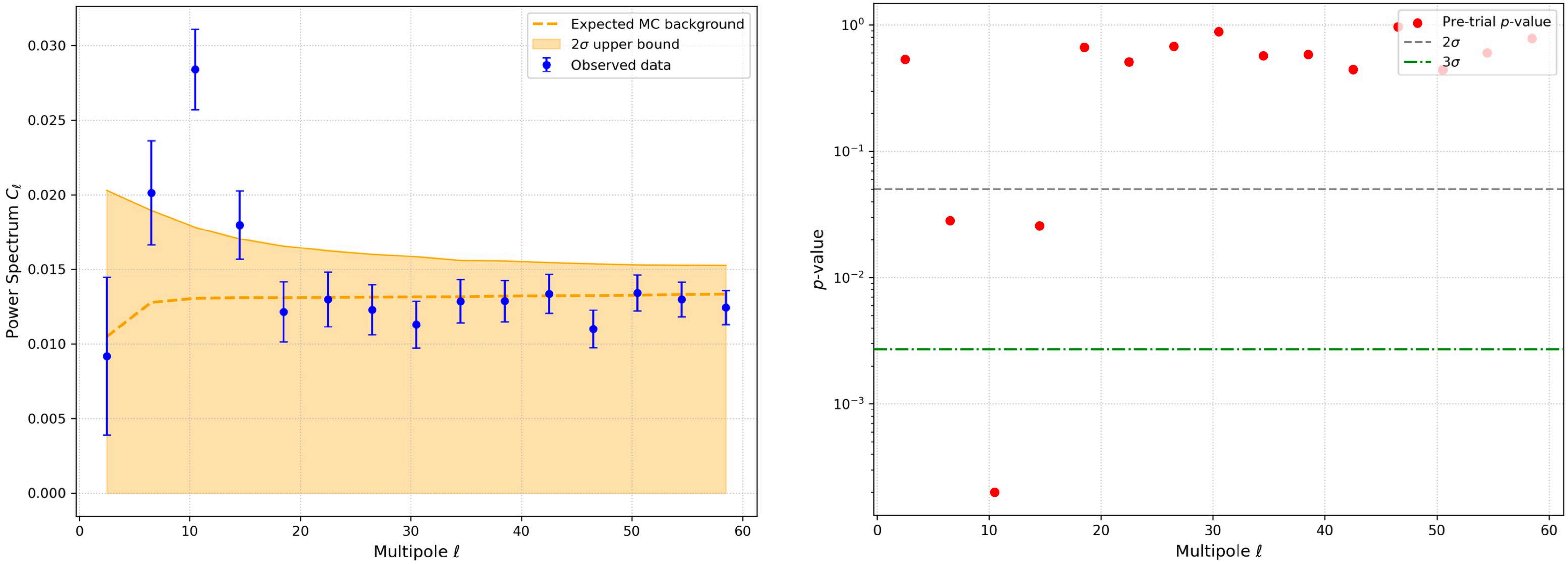
Autocorrelation and corresponding pre-trial p-value for iron (Fe) at $\lg(E/\mathrm{eV}) > 16.25$

Multipole Analysis (2.4)



p-value values obtained using the power spectrum method for different particle types and energy intervals.

The lowest p-value corresponds to 2.35σ for iron (Fe) at multipole l = 12.



Power spectrum and corresponding pre-trial p-value for iron (Fe) at $\lg(E/\mathrm{eV}) > 16.25$

Conclusions

Methods

1. **Effectiveness of the Autocorrelation Method**

   The analysis demonstrated that the autocorrelation function method is more effective compared to the angular power spectrum. In realistic scenarios of diffuse anisotropy, it exhibits higher statistical sensitivity and successfully responds even to isolated multipoles at intermediate angular scales.

2. **Shortcomings of the Cumulative Metric**

   At the same time, the attempt to enhance the sensitivity of the power spectrum by using a cumulative metric did not yield the expected results: this approach proved ineffective due to the significant accumulation of statistical noise.

Data analysis

The analysis of 10% of the KASCADE experimental data confirmed isotropy for most particle types on all angular scales.
The only exception is iron (Fe) where anisotropy on angular scales of about (10°) was observed. This points to a possible regular structure (consistent with the Gaussian power spectrum model) and disfavors scenarios of turbulent diffusion or a single Gaussian source.

It is important to note that the result appears to be independent of magnetic rigidity. For iron (Fe) at $\lg(E/\mathrm{eV}) > 16.25$ it is $R \approx 0.68\ \mathbf{PeV}$
The absence of signals at equivalent magnetic rigidity thresholds for other particles is explained by the following:

- For protons and helium, anisotropy at these scales was not analyzed due to a lack of data.
- For carbon and silicon, the signals might have been suppressed due to classification uncertainties (the particle mixing effect).

For a definitive and reliable interpretation, an analysis of the full KASCADE experiment dataset is required.

Thank you for your attention

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