
Martin Urban, Martin Erdmann, Gero Müller

III Physics Institute A – RWTH Aachen University
Recent galactic magnetic field parameterizations predict deflection

- Direction and magnitude
- Here Janson and Farrar model: JF12

Protons
20-200 EeV
Galactic Coordinates
Expected Arrival Direction

- Only calculated for protons
- Implemented as magnetic field lens
  - Rigidity dependent transformation matrix
- Compare correlation analyses without and with GMF correction
Astrophysical Simulation

- Propagate $10^7$ high energetic nuclei from sources to edge of Galaxy (CRPropa 3)
- Send cosmic rays to Earth using lensing technique with JF12 regular field lens

Isotropy using geometric exposure of Pierre Auger experiment

- 10% signal + 90% isotropy
- 231 events with $E \geq 52$ EeV
  - Like published dataset by Auger collaboration
- 22 sources
Angular distance

- Angular distances between cosmic ray and closest
  - Source (uncorrected)
  - Energy dependent expected arrival direction (corrected)

- Protons at small angles
- Preselection:
  - e.g. $\alpha, \alpha_{\text{GMF}} < \alpha_{\text{max}} = 5^\circ$
Magnetic Field Observable: Angular Asymmetry

- Change in angular distance: \[ A \equiv 2 \frac{N(\alpha > \alpha_{\text{GMF}}) - N(\alpha < \alpha_{\text{GMF}})}{N_{\text{tot}}} \]
  \[ = 0.96 \]
Magnetic Field Observable: Clustering

- Number of correlating events
  - per source
  - Expected arrival direction

- Cluster distribution probability
  - \( P = \text{multinomial distribution} \)

- Observable: \( \Delta \log_{10} P = \log_{10}(P_{\text{GMF}}) - \log_{10}(P) = -3.8 \)
Combine observables

- Astrophysical simulations
  - 231 cosmic rays
  - JF12 regular field

+ Expected arrival directions:
  - AGN sources
  - JF12 regular field

Investigate different hypotheses
Random Sources

- Astrophysical simulations
  - 231 cosmic rays
  - JF12 regular field

+ Expected arrival directions:
  - AGN sources
  - JF12 regular field

Random source directions
- 10000 variations
- 0.47 % show improvement in both observables

Source directions important
Uncertainty in Source Direction

- Astrophysical simulations
  - 231 cosmic rays
  - JF12 regular field

+ Expected arrival directions:
  - AGN sources
  - JF12 regular field

☐ AGN with 15° directional uncertainty
  - 10000 variations

Large uncertainties reduce sensitivity
Directional characteristics of galactic magnetic field

- Astrophysical simulations
  - 231 cosmic rays
  - JF12 regular field
- Expected arrival directions:
  - AGN sources
  - Inverted JF12 full

- Isotropic cosmic ray arrival directions
  - 10000 variations

Correct characteristics of magnetic field is essential to detect signal

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Sensitivity to detect signal in isotropic background

- Scan of signal fraction
- 100 different signal realizations for each signal fraction $f_{\text{signal}}$
  - Detection efficiency $\varepsilon_{\text{det}}$: Number of simulations with $\geq 3$ (5) $\sigma$ difference from isotropy
Summary

- Enhanced correlation method: expected arrival directions
  - Include deflections in magnetic field

- Observables for magnetic field investigations
  - Angular asymmetry
  - Clustering

- Analysis method
  - is sensitive to galactic magnetic field structure
  - is sensitive to selected source positions
  - is sensitive to few percent signal fractions
BACKUP
Are the correlated cosmic rays unique?

- Astrophysical simulations
  - 231 cosmic rays
  - JF12 regular field

+ Expected arrival directions:
  - AGN sources
  - JF12 regular field

☐ Isotropic cosmic ray arrival directions
  - 10000 variations
  - 0.29 % show improvement in both variables

Correlated cosmic rays can be found by the method
Random Component of Galactic Magnetic Field

- Astrophysical simulations
  - 231 cosmic rays
  - JF12 regular field

+ Expected arrival directions:
  - AGN sources
  - JF12 regular + striated + random

- Isotropic cosmic ray arrival directions
  - 10000 variations
  - 0.10 % show improvement in both variables

Random component has no effect on analysis
Correlations of cosmic rays with expected arrival direction within 5°
Motivation for 5 ° cut

- Mean deflection for $E > 55$ EeV
- 10 Mpc distance
- Protons

Galactic Magnetic Lenses

Probability of a particle entering galaxy in pixel $n$ is observed in direction $m$

Simulated probability distribution of extragalactic arrival

Probability distribution projected onto the Earth

Lenses suited for sources at Mpc distance from the observer

H-P Bretz, M.E., P. Schiffer, D., T. Winchen, AP 54C (2014) 110

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Multinomial Probability

- Probability of cluster configuration

\[ P(n_1, \ldots, n_{22}, N - N_{\text{hit}}) = \frac{N!}{n_1! \cdots n_{22}!(N - N_{\text{hit}})!} p_1^{n_1} \cdots p_{22}^{n_{22}} (1 - p_{\text{iso}})^{N - N_{\text{hit}}} \]

→ \( N \): Total number of cosmic rays
→ \( N_{\text{hit}} \): Number of cosmic rays correlation with neutrinos \( N_{\text{hit}} = \sum_i n_i \)
→ \( p_{\text{iso}} \): summed average source hit probability
→ \( i \): source identifier
→ \( p_i \): source average hit probability
→ \( n_i \): number of cosmic rays associated with source \( i \)
Sensitivity with Two-Point-Autocorrelation

- No signal visible in two-point-autocorrelation

![Graph showing sensitivity with two-point-autocorrelation](image_url)