
Martin Erdmann, Gero Müller, Martin Urban
23-July-2015
Magnetic fields: key to cosmic ray origin

Extragalactic fields (nG, 10 Mpc)

Galactic field (μG, 10 kpc)

Large scale simulation (Dolag et al)

Simulated effect on cosmic rays (Farrar et al)

Parameterizations from 40,000 Faraday rotation & synchrotron radiation measurements

Thrust observable transferred to sky


Principal axes, thrust major & minor

\[
T_k = \max_{n_k} \left( \frac{\sum_i |\omega_i^{-1} p_i \cdot n_k|}{\sum_i |\omega_i^{-1} p_i|} \right)
\]

\(\omega = \) acceptance factor

Thrust major directions at highest energy cosmic rays

Seed E>60EeV
thrust calculation E>5EeV within 0.25 rad

Results of thrust analysis are being compared with galactic field parameterizations

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Cosmic ray propagation

CRPropa 3.0


Modern programming design suited for high statistics simulations

Propagation of nuclei from sources to observer including the relevant interactions & magnetic field deflections

Interactive for you
https://vispa.physik.rwth-aachen.de/

most valuable tool for comparisons with data
Galactic magnetic lenses

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

Simulated probability distribution of extragalactic arrival

E=10 EeV protons

Probability distribution projected onto the Earth

Lenses suited for sources at Mpc distance from the observer

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New Analysis Concept

Source hypothesis: AGN (Active Galactic Nuclei)

Simulate expected proton arrival direction

Magnetic field effect

test validity of source candidates & field parameterization without imposing possibly unphysical conditions on measured data
Simulated cosmic rays

22 sources: **AGN**
(near IceCube published Neutrinos)

231 **cosmic rays**, energy $E>52$ EeV
(observatory exposure: Pierre Auger)
7% proton signal
93% background (e.g. heavy nuclei)
Expected Arrival Directions

for sufficiently strong galactic field: proton identification to some extent
Gradient Observables

1) Change in angular distances $\alpha - \alpha_{GMF}$

![Diagram showing change in angular distances]

2) Change in clustering strength (singlets, doublets, ...)

- Count cosmic rays clustering at AGN
- Count cosmic rays clustering at expected arrival direction
1) Angular asymmetry

Angular Difference $\alpha - \alpha_{\text{GMF}}$

$\alpha_{\text{GMF}}$

No: distance smaller without correction

Yes: smaller distance with field corrections

Positive asymmetry:

$$A = \frac{N(\alpha > \alpha_{\text{GMF}}) - N(\alpha < \alpha_{\text{GMF}})}{N(\alpha > \alpha_{\text{GMF}}) + N(\alpha < \alpha_{\text{GMF}})} = 1.3$$

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2) Clustering strength

**Cluster size**

- AGN
- expected arrival direction

**Multinomial probability**

= probability of cluster configuration

\[
P(n_1, \ldots, n_{22}; N - N_{\text{hit}}) = \frac{N!}{n_1! \ldots n_{22}! (N - N_{\text{hit}})!} \cdot \frac{1}{22} \prod_{i=1}^{22} p_i^{n_i} \prod_{i=23}^{N} (1 - p_{\text{iso}})^{N - N_{\text{hit}}}
\]

- \(N\) : total number of cosmic rays
- \(N_{\text{hit}}\) : number of cosmic rays correlating with neutrinos \(N_{\text{hit}} = \sum n_i\)
- \(p_{\text{iso}}\) : summed average neutrino hit probability \(p_{\text{iso}} = \sum p_i\)
- \(i\) : neutrino identifier
- \(p_i\) : neutrino \(i\) average hit probability
- \(n_i\) : number of cosmic rays associated with neutrino \(i\)

Simulated data multinomial probability w/o field: \(\lg P = -9.5\), with field: \(\lg P = -18.2\)

**Clustering improvement by magnetic field corrections**: \(\Delta \lg P = -8.7\)
Comparison with chance effects

- **AGN** nominal directions
- Typical field strength of galactic magnetic field
- Arbitrary **field directions**
- Isotropic **cosmic rays** (observatory)

**Observables away from chance distributions**

![Graph showing improvement in clustering with data points compared to simulation.](image)
Test of sources

Are AGN directions important, magnetic field could move cosmic rays towards them anyway?

- Nominal cosmic ray arrival directions
- Nominal galactic magnetic field
- Isotropic AGN directions

Directional correlations of sources and cosmic rays can be distinguished
Galactic field direction

**nominal field**

**reverse field (antiprotons)**

Directional characteristics of galactic magnetic field: expect striking effect
Conclusions

- Development of new methods & observables for understanding magnetic field effects on cosmic rays
- New analysis procedure for galactic magnetic field corrections

 ESA/Hubble

 Cosmic Ray Observatories

 Pierre Auger Observatory

 with magnetic field corrections

 investigations of cosmic particle origin and acceleration enter new phase

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Test of sources

Does magnetic field move arbitrary cosmic rays towards AGN directions?

- Nominal AGN directions
- Nominal galactic magnetic field
- Isotropic cosmic ray arrival directions

Directional correlations of sources and cosmic rays can be distinguished