PROBING GALACTIC AND INTERGALACTIC MAGNETIC FIELDS USING ULTRA HIGH ENERGY COSMIC RAYS

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- Introduction to Ultra-High Energy Cosmic Ray (UHECR) astronomy.

- Motivation for analysing UHECR data and application to magnetic fields.

- Description of method used to analyse data.

- Performance of method when applied to Monte Carlo Data sets.

- Improvements to be made to the analysis, as well as areas still needing investigation.

Cosmic rays (CRs), being charged particles, experience the Lorentz force as they move through cosmic magnetic fields:

$$\vec{F} = q\vec{v} \times \vec{B}$$

Their gyroradius is given by:

$$r_g = \frac{E}{cq\left|\vec{B}_\perp\right|}$$

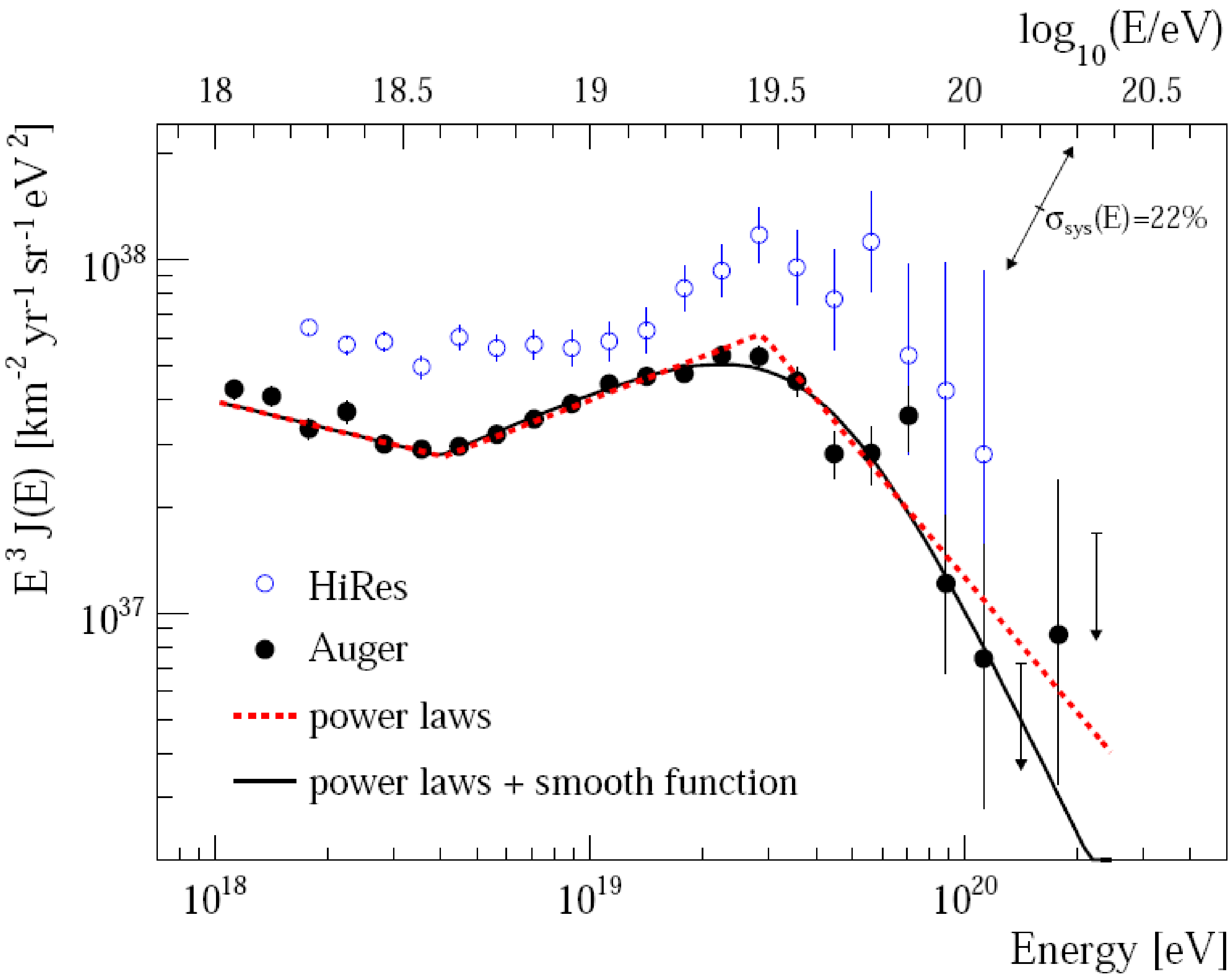
(For a 1 EeV proton in 1 μG field, $r_g \approx$ 1 kpc

Consequently, we expect particles of higher energy – for a given charge – to undergo smaller deflections, and perhaps even contain information about their point of origin. This is termed 'directionality'.

If it is possible to gain information about UHECR source positions from analysing CR data sets, it may provide knowledge about the intervening magnetic fields.

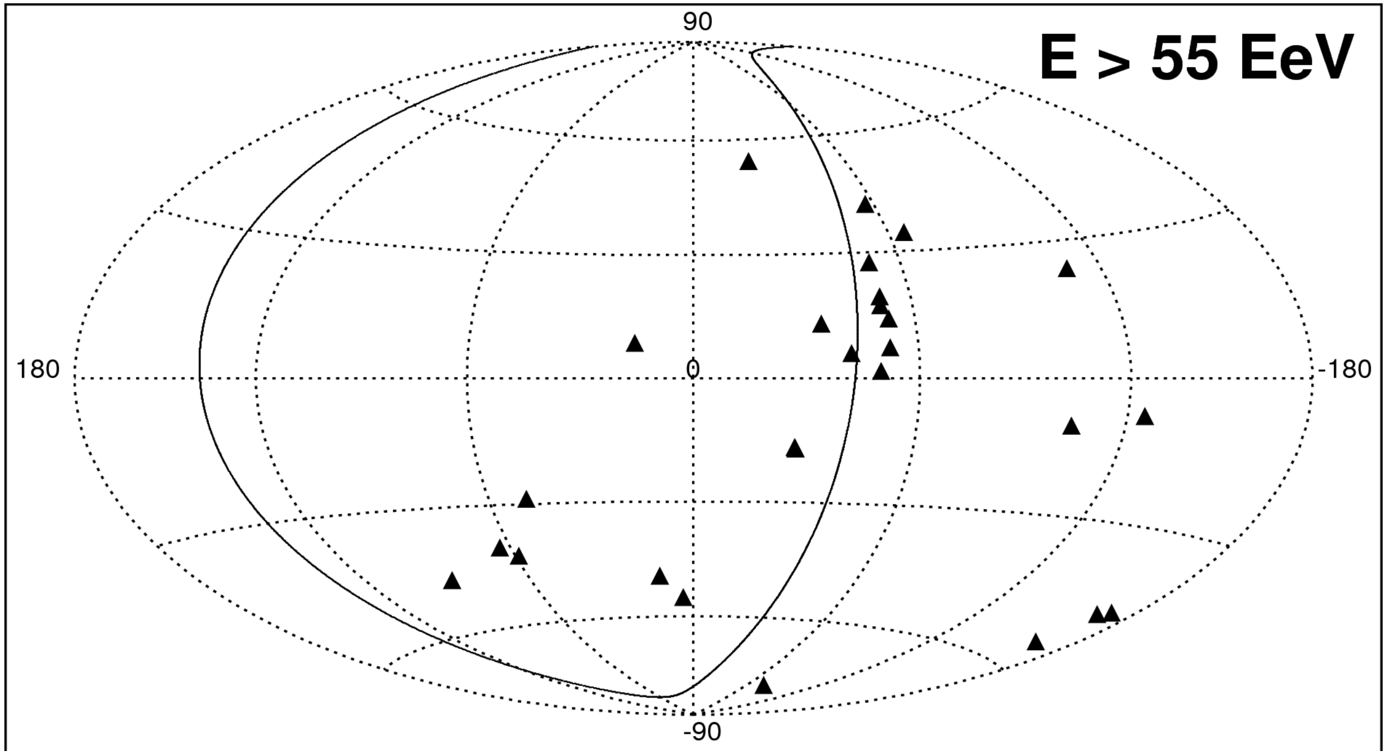
At energies above about 6×10^{19} eV, we are helped by the fact that the source horizon is expected to be of the order of 100 Mpc.

This is due to interactions with the CMB which reduce the CR energy significantly. This is termed the Greisen-Zatsepin-Kuz'min (GZK) effect, and the most recent measurements of the UHECR spectrum are consistent with it. [Pierre Auger Collab., Phys. Letters B **685** (2010) 239]



log10(E/eV)
18
18.5
19
19.5
20
20.5
E³ J(E) [km⁻² yr⁻¹ sr⁻¹ eV²]
10^38
10^37
σsys(E)=22%
HiRes
Auger
power laws
power laws + smooth function
10^18
10^19
10^20
Energy [eV]

The Pierre Auger Observatory in Argentina has been taking data since 2004; it is designed to detect CRs of the highest energies, and so its data sets are ideal for charged particle astronomy. [Pierre Auger Collab., Nucl. Instr. and Meth. A **523** (2004) 50]

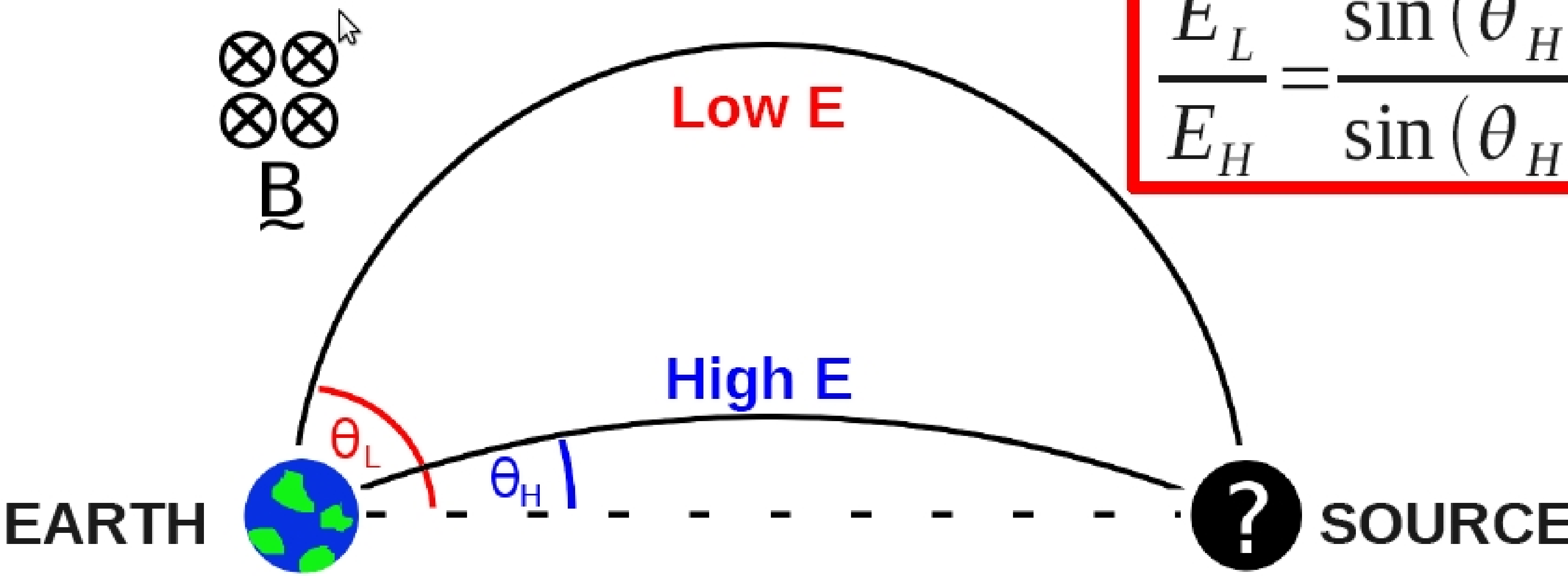


The method used to analyse the data is designed to look for evidence of a “magnetic spectrometer” effect.

This means that it aims to find energy-dependent deflections of cosmic rays from some (unknown) source direction.

Several assumptions are made:

- We detect multiple CRs from at least one source.
- The particles are of a uniform composition, or at least the majority.
- The particle trajectories are not vastly different.
- The deflections due to the turbulent magnetic field are less than or comparable to those due to the regular field.



Eq. 1

$$\frac{E_L}{E_H} = \frac{\sin(\theta_H)}{\sin(\theta_H)}$$

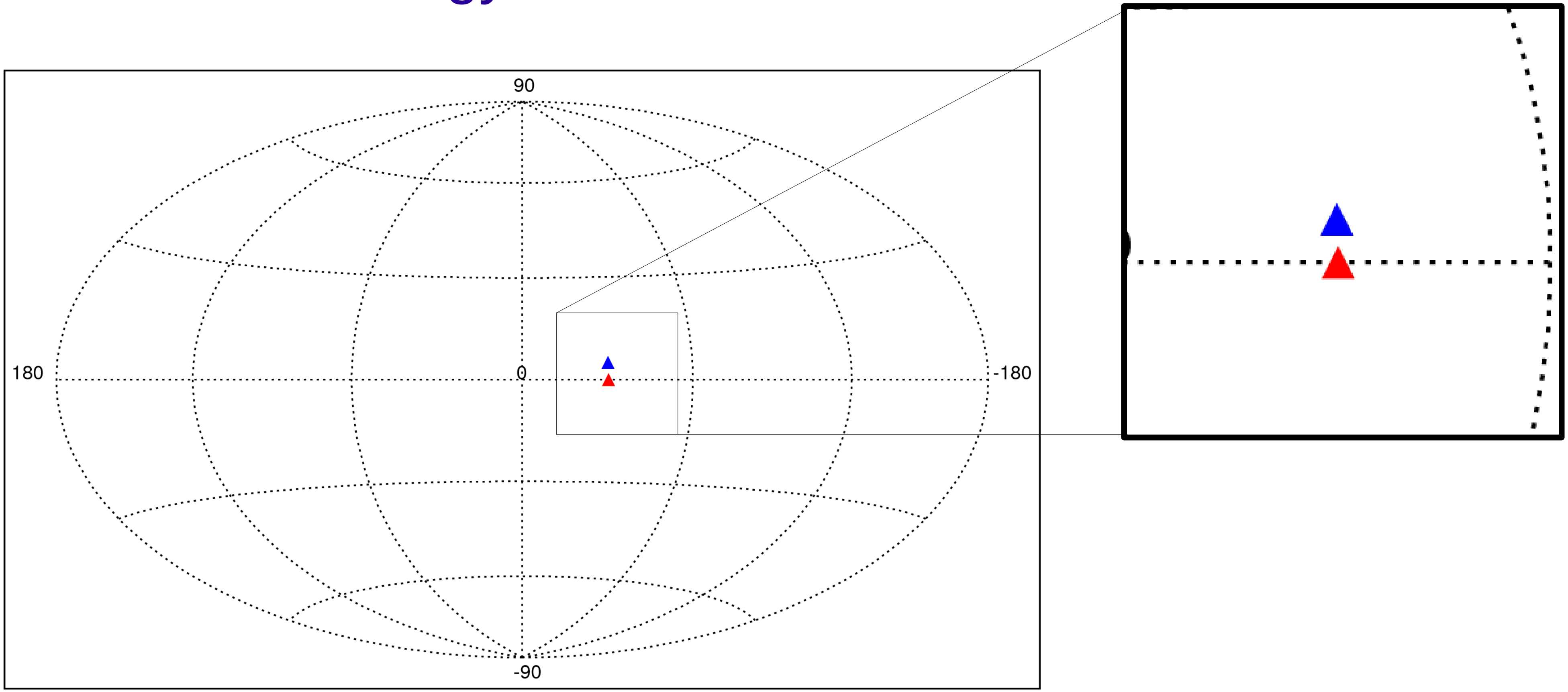
This is a highly simplified case, but it illustrates the main points.

Using these basic principles, we can attempt to associate cosmic ray events with source directions in the sky.

This can be achieved with essentially no magnetic field parameters needing to be input.

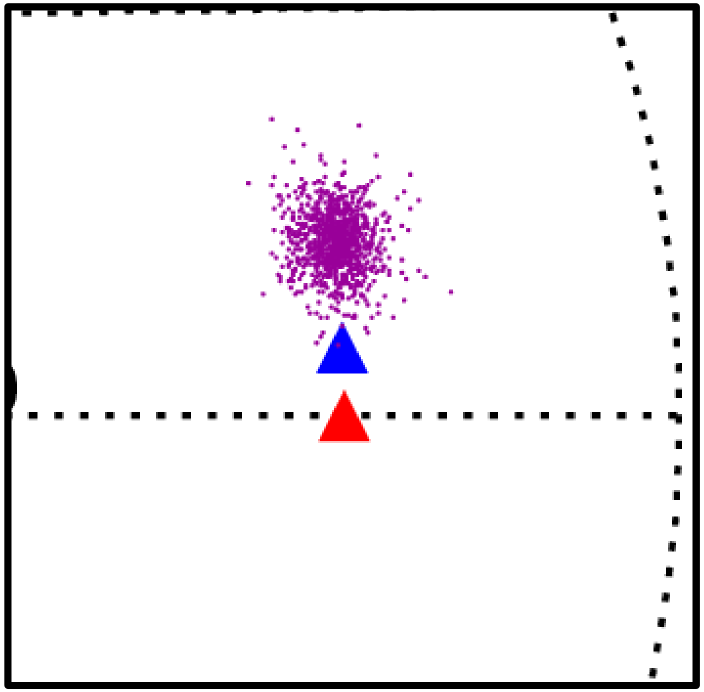
Consequently, if we succeed in associating cosmic rays with source directions, information about the intervening magnetic fields can be derived.

From the data set, pairs of events are taken, and each pair is considered individually. The information used is the arrival direction and energy of each event.

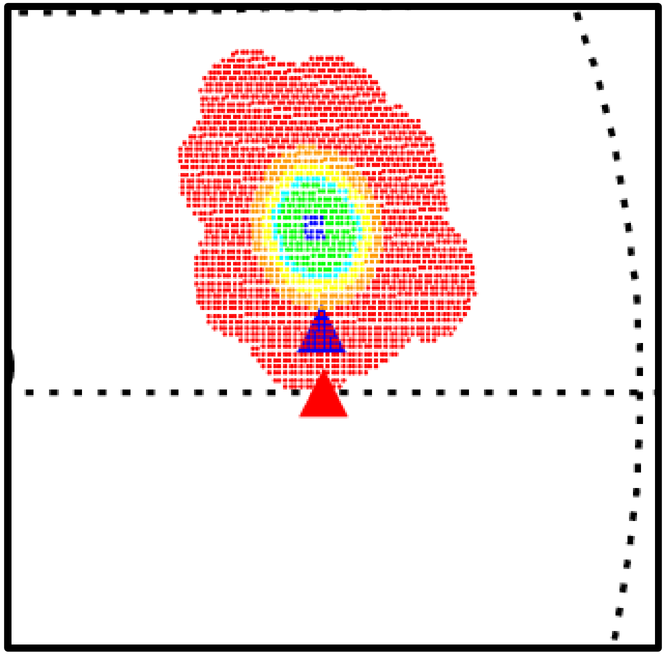


A 'source' position is calculated for this pair by assuming a magnetic spectrometer effect and solving Equation 1.

This is done many times for each pair, with arrival directions and energies resampled within errors. This gives an error distribution on the sky for the source position.

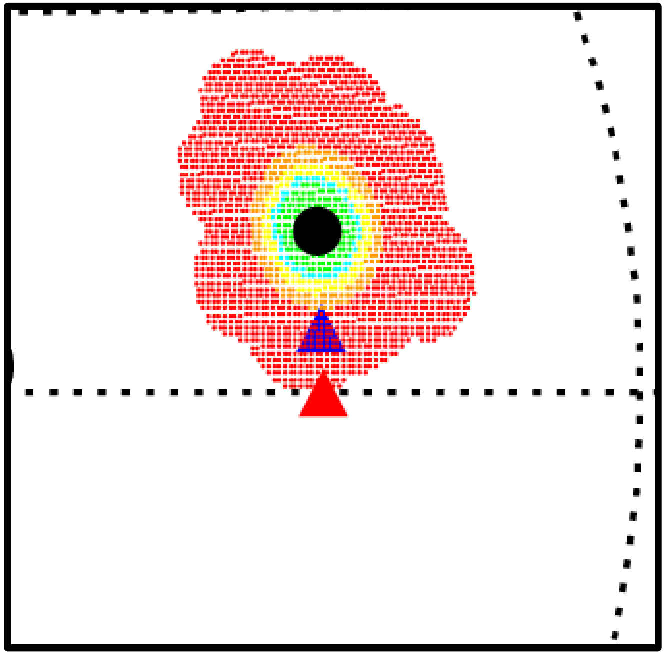


A top hat is next used to smooth the overall distribution. This produces a map showing the relative density of reconstructed sources around the sky.

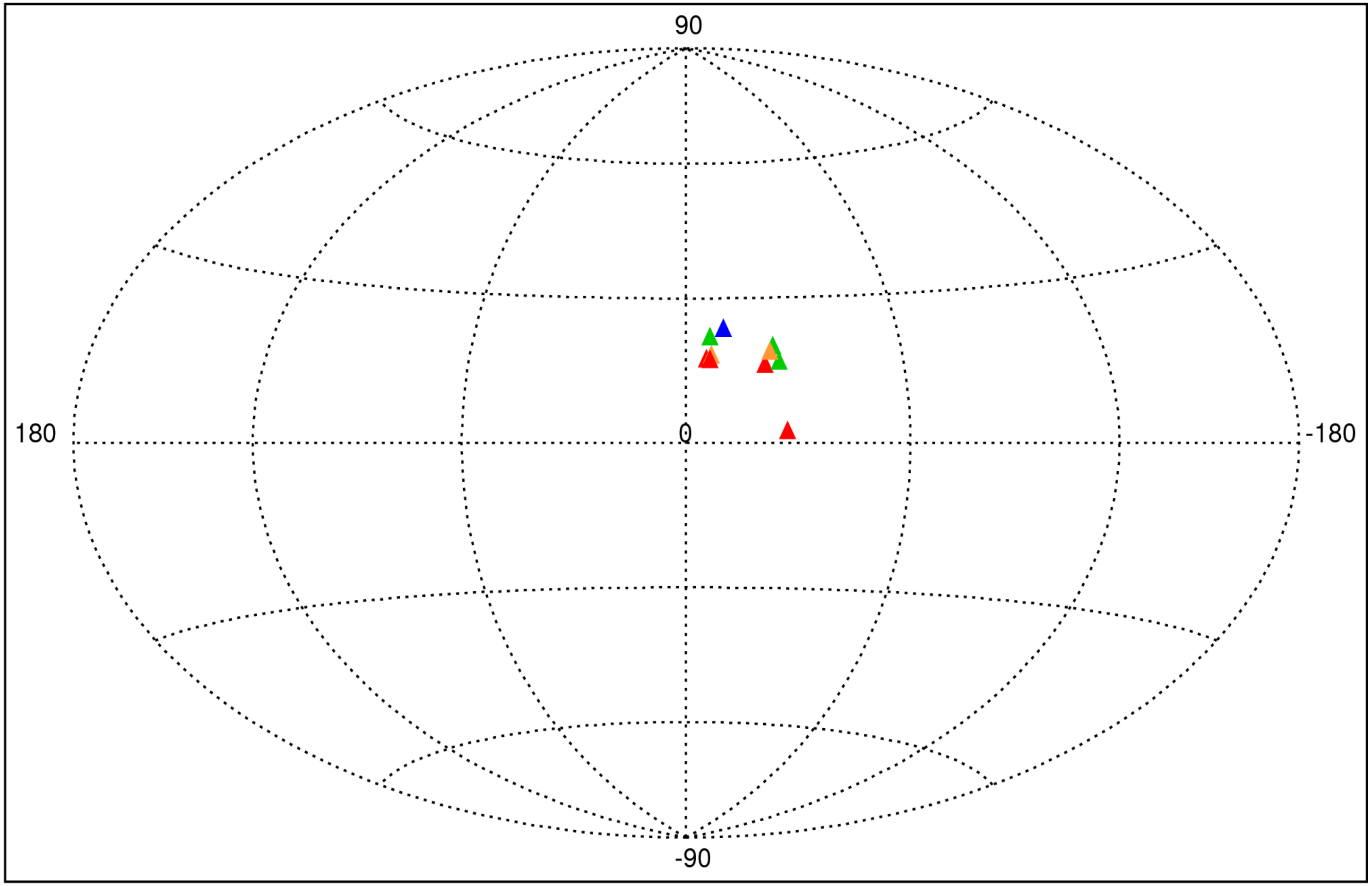


High values of this distribution mean many error distributions, from independent pairs, are located close to each other. This may indicate a possible source position.

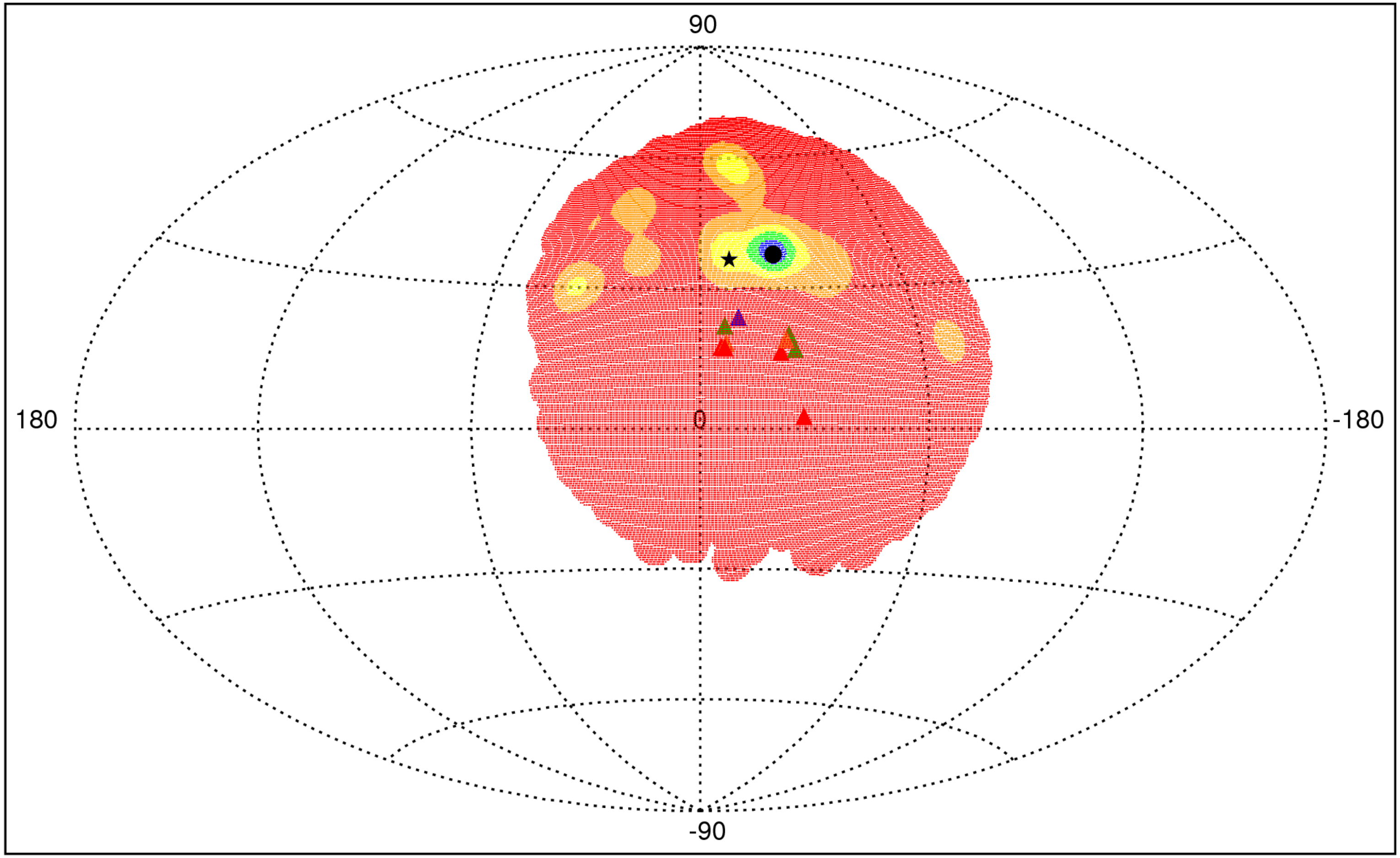
We select the maxima of this distribution and call these our 'sources'.



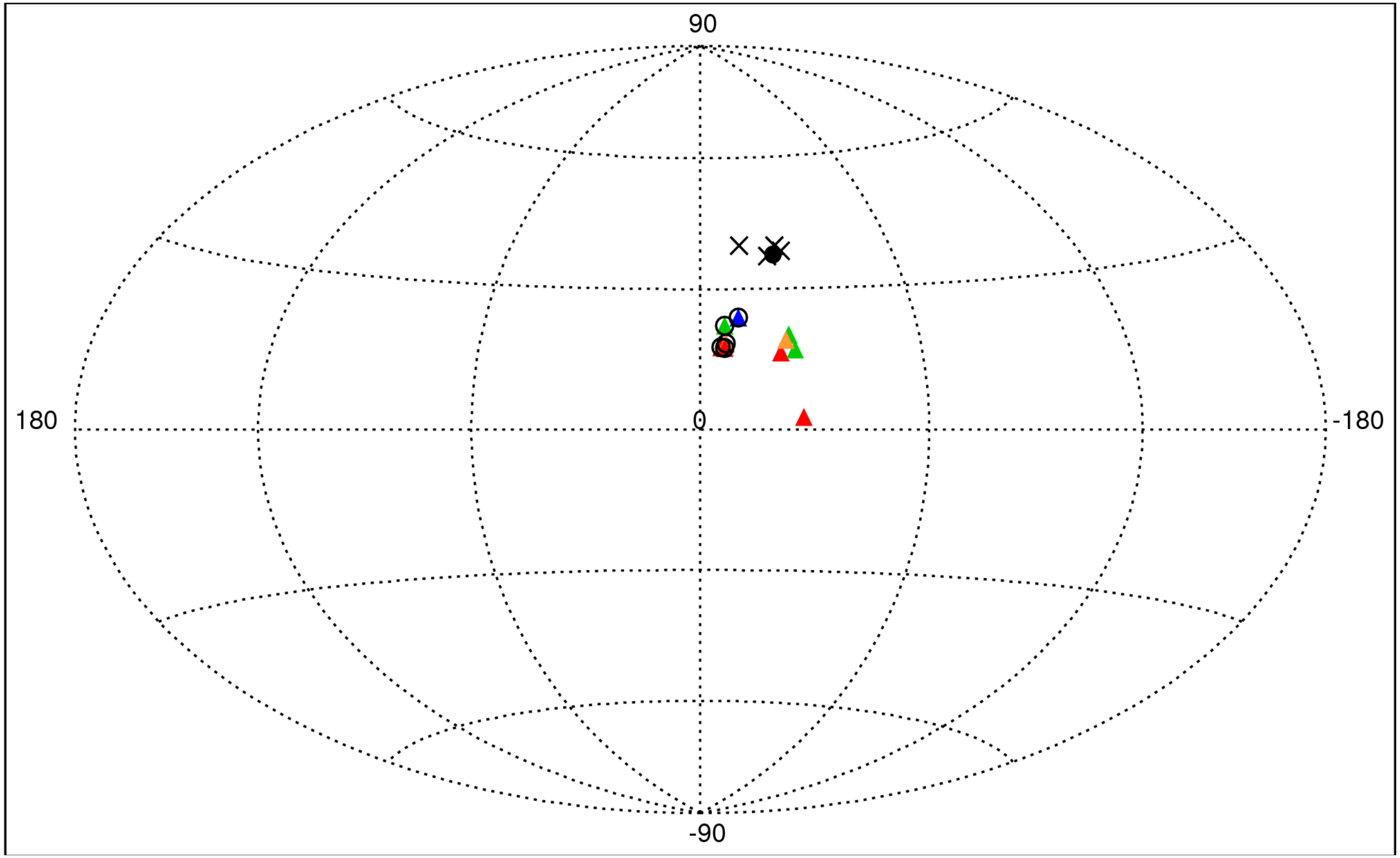
Take a 10 event MC set:



We apply the analysis and find the 'source':



Once this source is located, we consider pairs whose individual error distributions lie close to the source to be associated with that source:

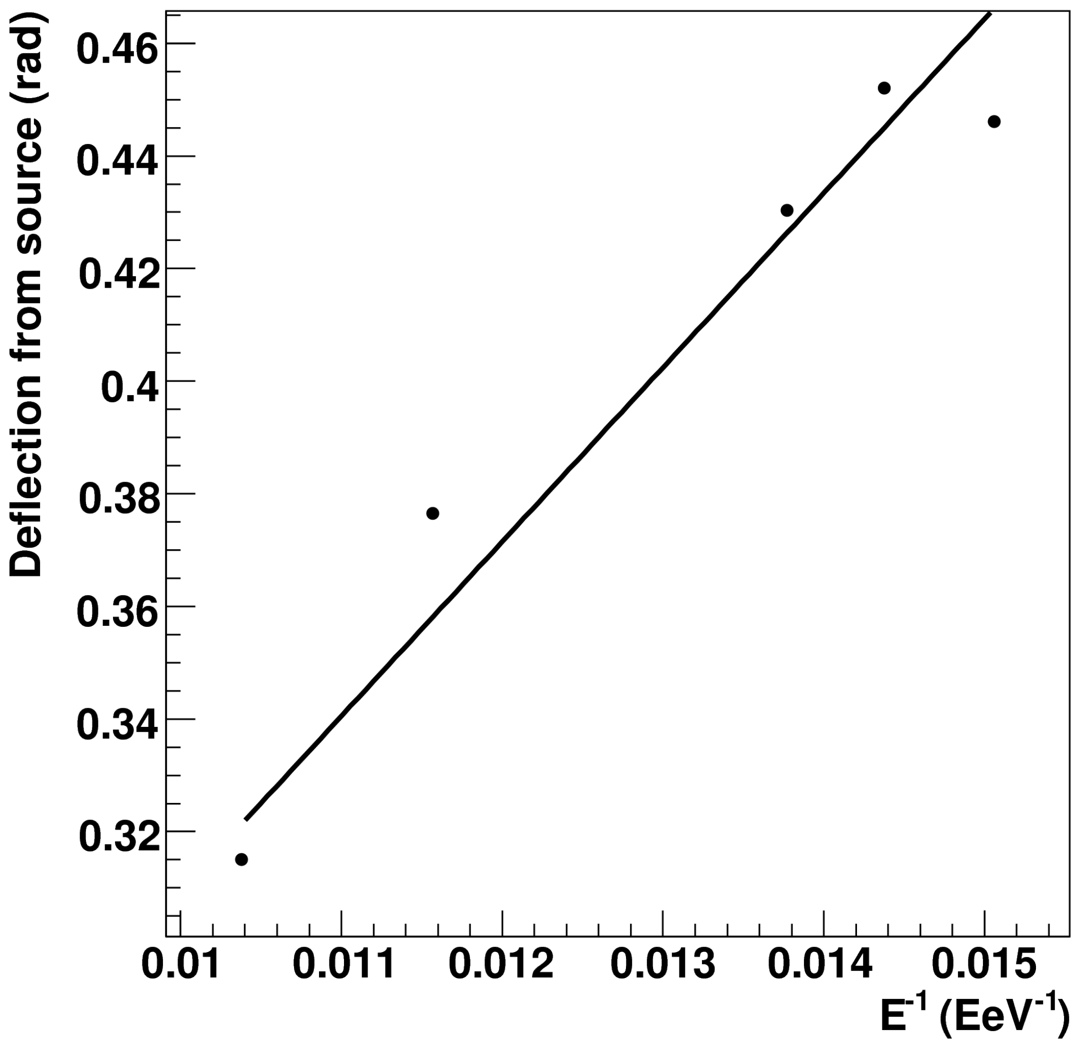


Once we have associated these events with a source, plotting the angular deviation from the source vs. E^{-1} and fitting a straight line can give a measure of the 'deflection power', D, which is defined through:

$$\Delta\theta \approx \frac{cq\left|\int \vec{B}\times d\vec{l}\right|}{E} \equiv \frac{D}{E}$$

This gives an estimate of the magnetic field component perpendicular to the line of sight between Earth and the source.

An example plot is shown here:

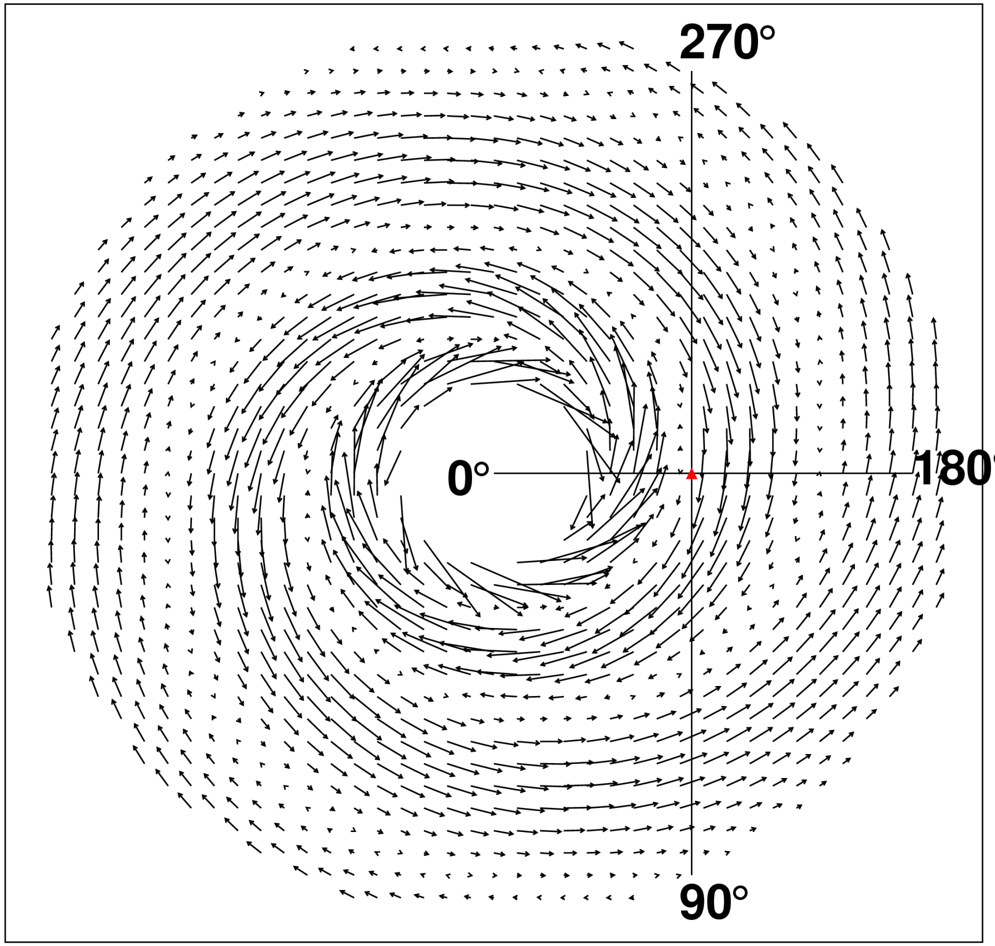


Monte Carlo data sets are being used to investigate accuracy and sensitivity of analysis under a range of different parameters.

Early results from varying the Galactic magnetic field normalisation are shown here.

The field used is a logarithmic spiral field as described by Stanev [T. Stanev, ApJ **479** (1997), 290].

$$B(r,\theta,z) = N\frac{3R_{SUN}}{r}\cos\left(\theta - \beta\ln\left(\frac{r}{r_0}\right)\right)\exp\left(-\frac{|z|}{z_0}\right)$$



$$R_{SUN} = 8.5\,\text{kpc}$$
$$\beta = -5.67$$
$$r_0 = 10.55\,\text{kpc}$$
$$z_0 = \begin{cases} 1\,\text{kpc} & |z| < 0.5\,\text{kpc} \\ 4\,\text{kpc} & |z| > 0.5\,\text{kpc} \end{cases}$$

Three values of N are used (0.5,2 and 5) which give field strengths at the Solar System of ≈ 0.74 μG, 3.0 μG and 7.4 μG, respectively.

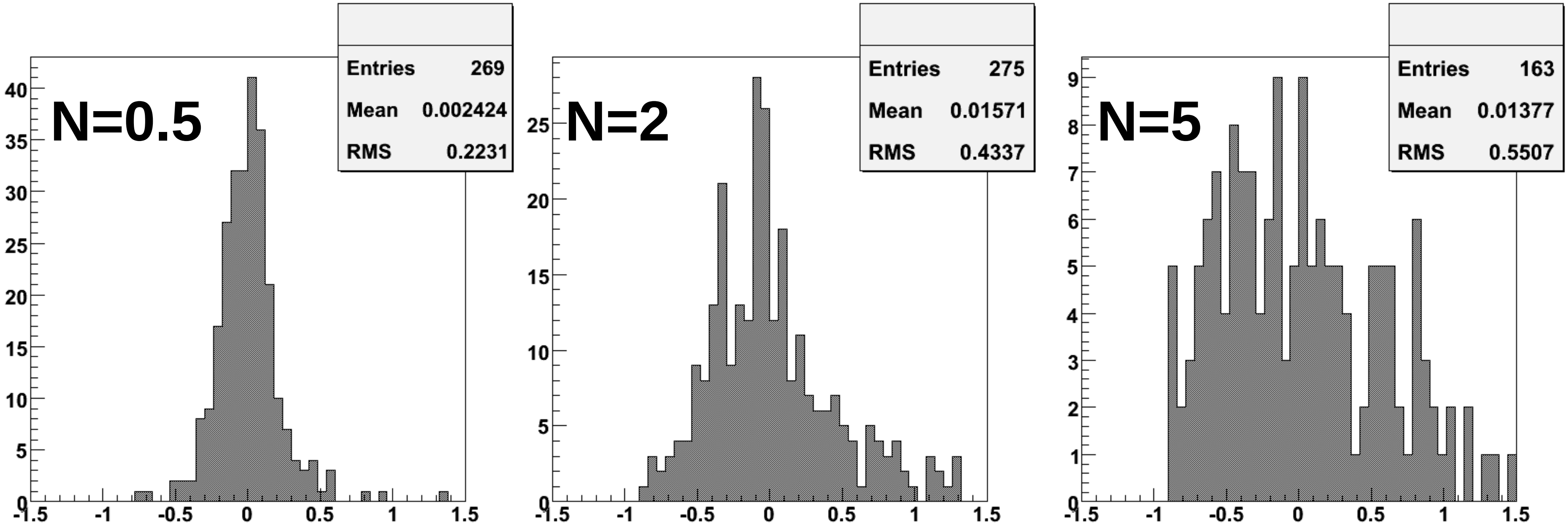
No turbulent component is currently included, but at the energies of interest, it is not expected to have a great effect.

No intergalactic magnetic field is included either, but it will be in the future.

The analysis is applied just as it would be for a real data set. At its conclusion, the deflection power is calculated for the events, and from this the value of $\left| \int \vec{B} \times \vec{dl} \right|$ calculated.

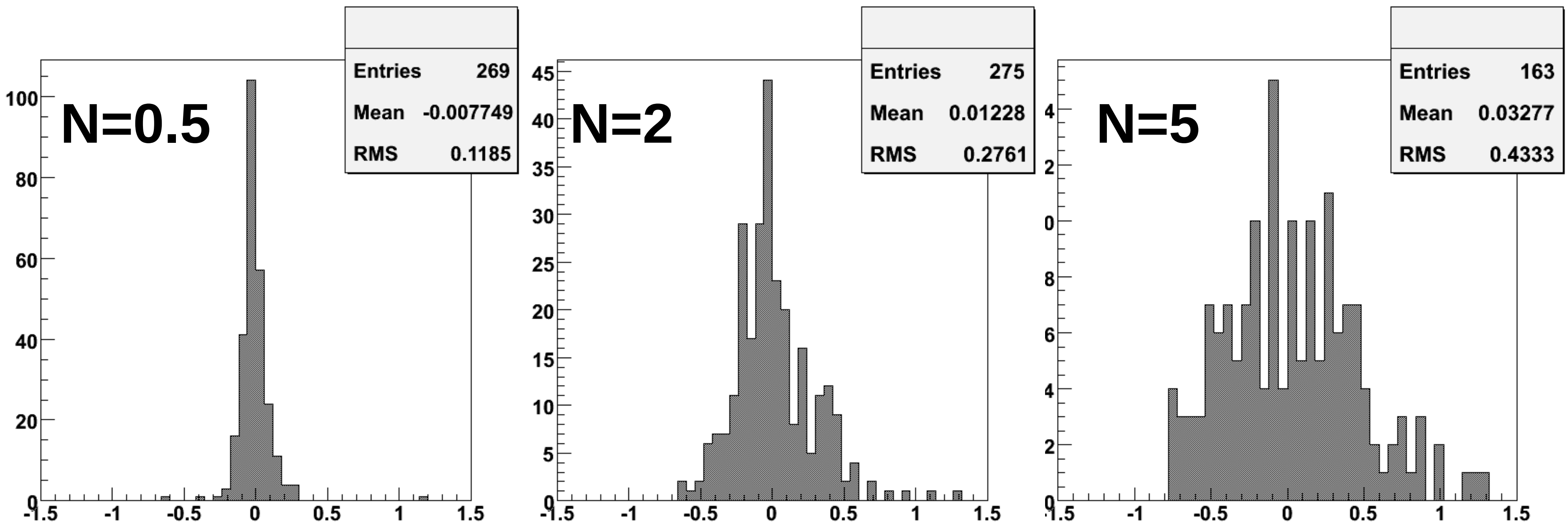
This can be compared with the 'true' value, calculated by performing the integration explicitly through the magnetic field model used to generate the data sets.

Here we compare the values of $\left| \int \vec{B} \times \vec{dl} \right|$ derived from the current analysis with the values calculated from the model.



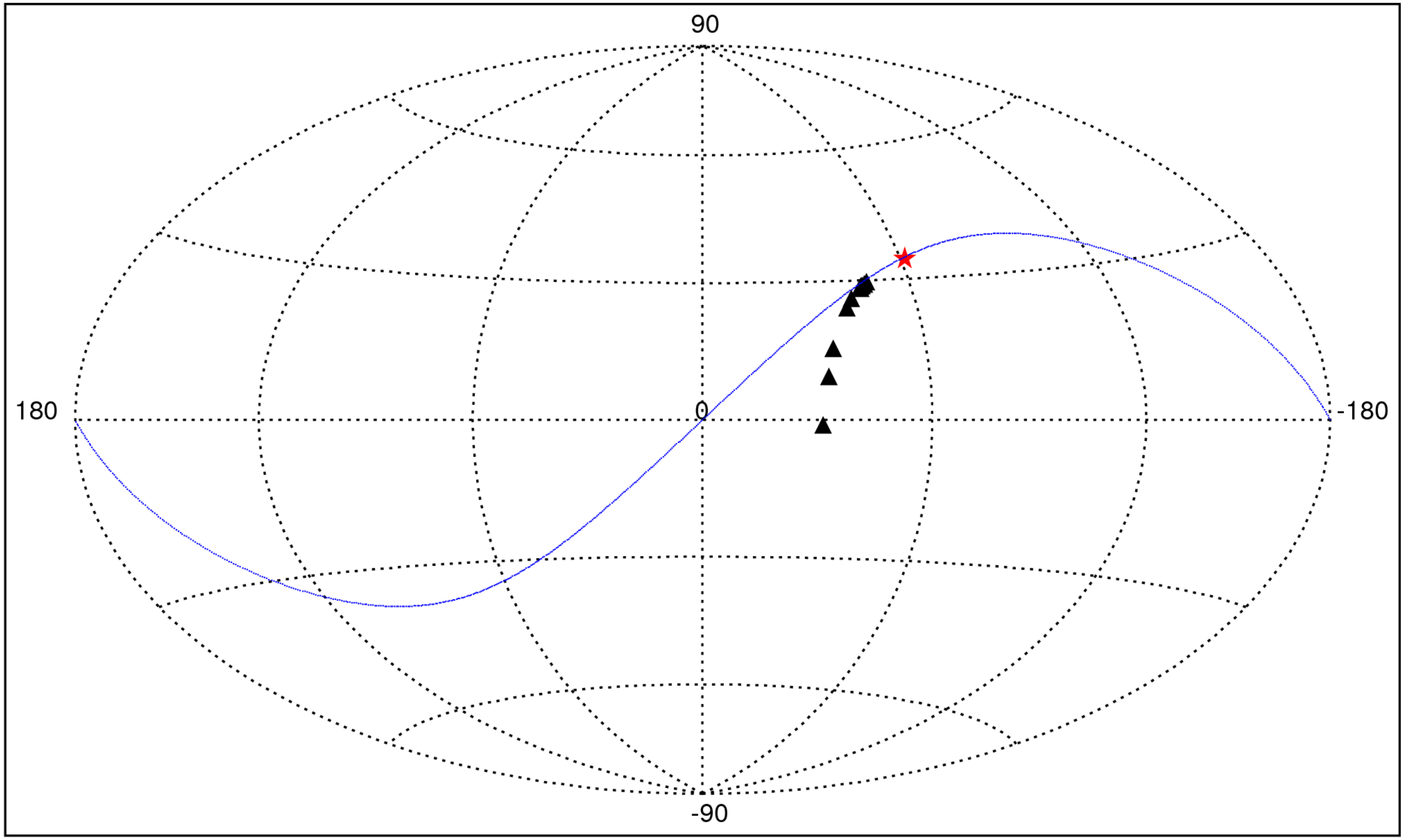
$$\frac{\left(\int \vec{B} \times \vec{dl}\right)_D - \left(\int \vec{B} \times \vec{dl}\right)_{MODEL}}{\left(\int \vec{B} \times \vec{dl}\right)_{MODEL}}$$

We note that even for low magnetic field strengths, the distribution is quite wide. This is in part due to the errors in determining the source location.

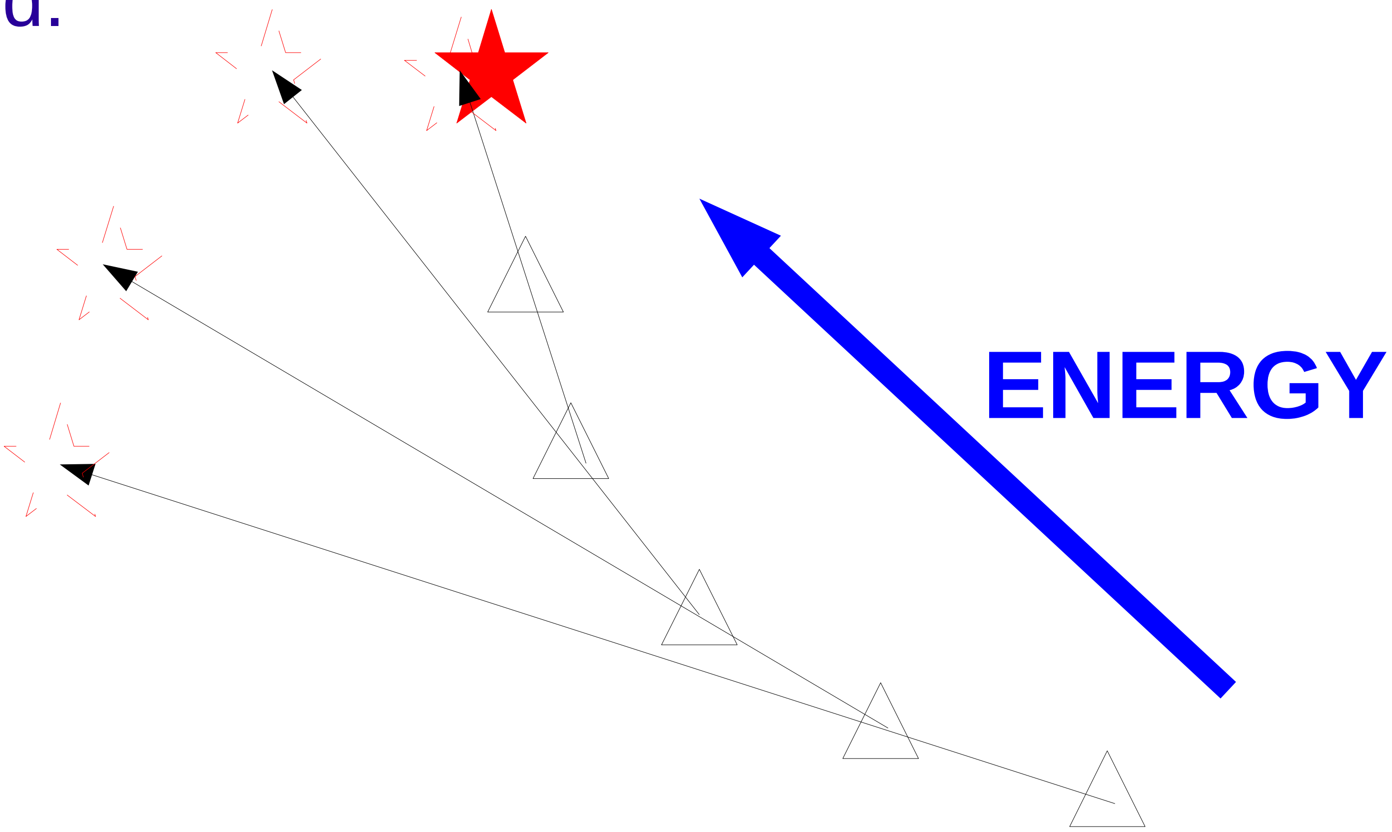


$$\frac{\left(\int \vec{B}\times d\vec{l}\right)_D - \left(\int \vec{B}\times d\vec{l}\right)_{MODEL}}{\left(\int \vec{B}\times d\vec{l}\right)_{MODEL}}$$

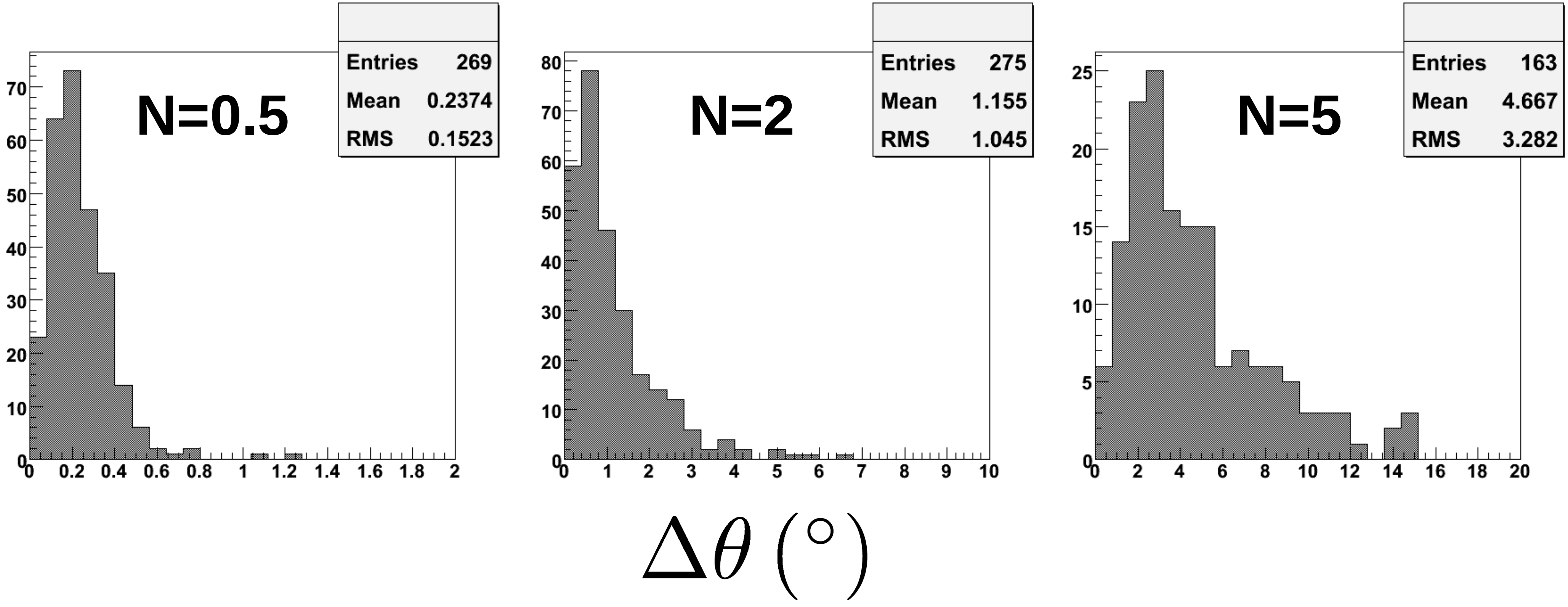
Currently, the source-finding process is simple and may not be optimal for realistic Galactic Magnetic Field models.



We find that 'non-linear' structure may introduce errors in the reconstructed source location. Using MC data sets, the process through which source locations are found is being improved.



For each normalisation, we calculate the distribution of angles between the reconstructed and true source.



Work is still needed to improve and understand the analysis. Planned work in the future includes:

- Improving the source direction reconstruction.

- Investigating the sensitivity and accuracy of the analysis under a greater range of parameters, including CR composition, number of sources etc.

- Including turbulent and intergalactic magnetic fields in the Monte Carlo simulations.

In conclusion, we see that by taking only the arrival direction and energy data from an ultra high energy cosmic ray data set, it may be possible to reconstruct the position of the source from which the CRs have originated.

Using the deflections of the CRs from these sources, we can estimate the integrated magnetic field – perpendicular to our line of sight – through which the CRs have travelled.

The statistical error associated with this is currently quite large, but it may be reduced by improving our estimate of the source positions.

Monte Carlo data are currently being used to investigate the sensitivity of the analysis under a variety of different situations.