Observation of an anomaly in the arrival direction of event pairs

C. Timmermans, S. J. de Jong
Nikhef/Radboud University

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Abstract

We have created pairs of events. The events in a pair are recorded in a short period of time and arrive from approximately the same direction. This analysis shows that when further selecting these event-pairs based upon global criteria, an anomaly appears for event-pairs within about 10 degrees of (-45,17) in Galactic coordinates. The probability that the distribution of time differences between events in these pairs is in agreement with a background only hypothesis is only $2.6 \cdot 10^{-6}$. When taking the look-elsewhere effect into account, this probability increases to $7.4 \pm 0.8\,\%$.

Introduction

For this analysis the herald archive, reconstruction version v5r2, was taken on 13/6/2014. The bad periods between 1/1/2004 and 31/1/2013 have been excluded from the data set. We first ensured that the events are in time order, and afterwards made the following standard selection:

- Cut 22 > 0 (compatiblility reconstruction and estimate)
- Cut 23 > 1 (T5 cut)
- Cut 44 > 0 (event core in the array)

Next, event-pairs are defined using the following criteria:

- The time difference has to be less than 60 seconds
  - **Signal region** for time differences below 20 seconds
  - **Background data** for time differences between 20 and 60 seconds
- the opening angle between the events, as measured at Earth, has to be less than 40 degrees.
- The distance on ground between the event cores is more than 10 kilometers.
- At least one event has to have an energy of at least 1 EeV

The first two criteria define events arriving from approximately the same direction in a short period of time. Both criteria are very loose in order not loose too many "real" event pairs. Furthermore, the random coincidences that enter our selection at larger time differences are used to perform background estimates. The last two criteria ensure that at least one event has an accurate direction reconstruction, and that the two different events in a pair are not in fact two fragments of the same event.

Event pairs

For all event pairs, we store the following information:

- The time difference between the events
- The time of the first event
- The energies of both events of the pair
- the distance on ground between the shower cores
- The angular distance between the events at Earth
- (θ, ϕ) and (L, B) of the highest energy event

It can be expected that the set of event-pairs is dominated by random coincidences, especially at large time and angular differences between the events in a pair. This is confirmed by the uniformity of the distribution of the time differences between the events of a single pair (Figure 1-left). This plot does not show an exponential behaviour as the search for an event pair always continues for 60 seconds, also after finding a match. The drawback of this method is that also in the final selection one runs the risk of having one event being part of several pairs.

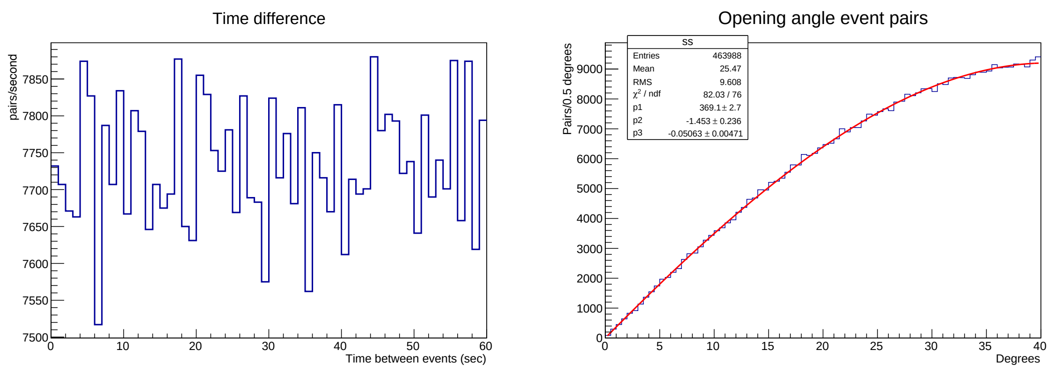

Figure 1: Left: Time difference between events in a pair. Right: Angular distance between events in a pair

The distribution of the angular distance between events in a pair shows no strange features and has a fit probability of 30%, as can be observed in the right part of Figure 1. This smooth structure reflects the available phase-space and is fitted using a third degree polynomial leaving the constant term fixed at 0. The other fit parameters are given in the plot.

Searching for a global excess in the expected number of event pairs

In this section we count all event pairs with an opening angle between events of at most a variable maximum, and a time difference between the events in a pair up to a variable maximum. We compare this number to an expectation value that is determined from the background sample.

The expectation value

Figure 1 shows that the time difference between event pairs follows a flat distribution. The region of interest is time difference below 20 s. Time differences between 20 s and 60 s are used to estimate the expected random background. The expectation value for the number of pairs with a maximal opening angle ϕ and maximal time difference between events Δ $E(\phi, \Delta)$ is determined by rescaling the background event pairs with the same maximal opening angle or

$$E_1(\phi, \Delta) = \frac{B(\phi) \times \Delta}{40}$$

where $B(\phi)$ is the number of background event pairs with a maximal opening angle of ϕ and a minimal time difference between the events in a pair of 20 seconds, and a maximal time difference of 60 seconds.

Alternatively, to limit the statistical bin-to-bin fluctuations in the angular distribution, the expectation value can be obtained using all the background events, and use the fit shown in the right part of Figure 1 to correct for the maximal opening angle, or:

$$E_2(\phi, \Delta) = \frac{B(40^\circ) \times \Delta \times A(\phi)}{40 \times A(40^\circ)}$$

where $A(\phi) = 369.1\phi - 1.453\phi^2 - 0.05063\phi^3$. Both expectation values are used, and they lead to similar results.

Deviations from the expectation value of the number of event pairs in the signal region

The Poisson probability for detecting at least the recorded number of event pairs in the signal region is determined from the expectation value(s). Figure 2 shows the Poisson probability that, given the expectation value, the number of recorded event pairs with a maximal opening angle (horizontal axis) and maximal time difference (vertical axis), equals or exceeds the measured value. In this representation the bins are highly correlated, and the event content moves from zero (low-left corner) to maximal (upper-right corner).

The figure shows a global consistency with the background estimate to a very large extent. Excluding the smallest time differences, which concern only very few event pairs, the main excess is at a maximal opening angle of 4.5 degrees, and a maximal time difference of 5.4 seconds. This excess is only very small, 689 measured pairs with an expectation of 659.07 (664.58), leading to a Poisson probability of 11.8 (16.7) %. Even though this excess is not significant, these parameters will be used as a starting point for the next studies.

Expectation value in Galactic coordinates

Before investigating the excess in Galactic coordinates, we show the expectation value for the events under study using an unbiased sample of event pairs. This unbiased sample consists of 285640 event pairs that is the complete background data set with a time difference between events in the pair of between 20 seconds and 60 seconds and an angular distance of between 10 degrees and 40 degrees. In order to further avoid possible hotspots, the date of these event pairs is randomised to be within a month of the

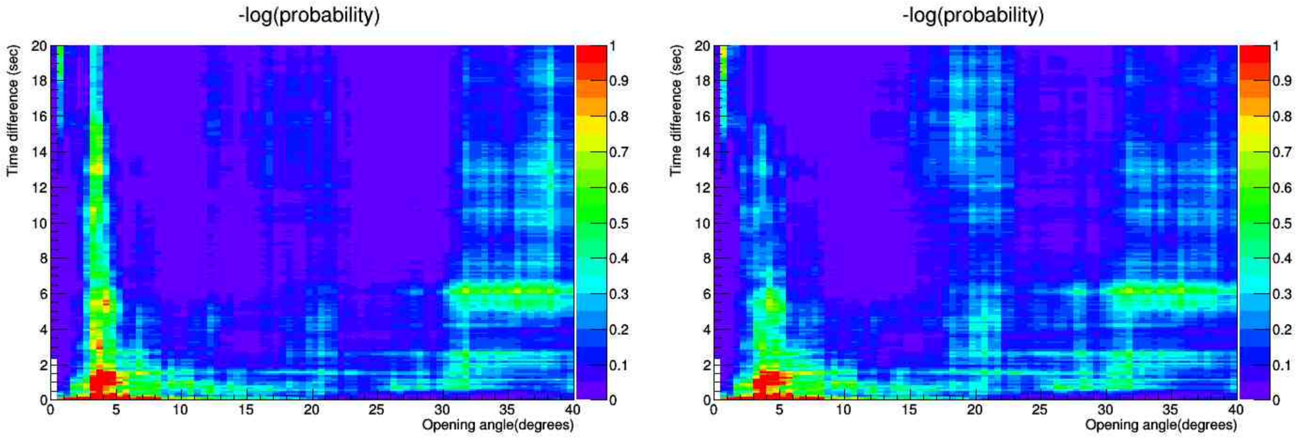

Figure 2: Probability for the measured number of event-pairs to be consistent with the expected value. Left: expectation estimate E_1. Right: expectation estimate E_2.

recorded time, after which the galactic coordinates are re-calculated. This date-randomising is performed ten times for each event pair. Given a total expected number of event pairs of 659, Figure 3 shows the expected number of recorded event pairs within an opening angle of less than 10 degrees to each direction in galactic coordinates.

Event pairs in Galactic coordinates

For all locations in Galactic coordinates we count the number of selected event pairs that have an arrival direction differing at most 10 degrees from the examined location. The resulting plot using the 689 selected event pairs with a maximal angular distance between events of 4.5 degrees, and a maximal time difference between events of 5.4 seconds is given in Figure 4. A hotspot of 26 event pairs is observed for pairs originating from within 10° of $(-45°, 17°)$.

In order to estimate the chance probability of such an occurrence, pseudo data sets are created by randomly selecting 689 event pairs out of the unbiased sample described before. In exactly the same way as for the signal pairs we count the number of pairs within 10 degrees of each point in galactic coordinates. In 41 out of 1000 datasets the maximum number of pairs within 10 degrees of any point is 26 or more. This is interpreted as the probability that random data creates a hotspot of at least 26 pairs anywhere in galactic coordinates is $4.1 \pm 0.7\,\%$.

Sanity Check

Figure 2 shows a small excess in the measured number of pairs for which the opening angle between events is between 30 and 40 degrees, and for which the time difference between events is below 6.2 seconds. As the angular difference is large, the possibility of a physical relation between the events in these pairs is

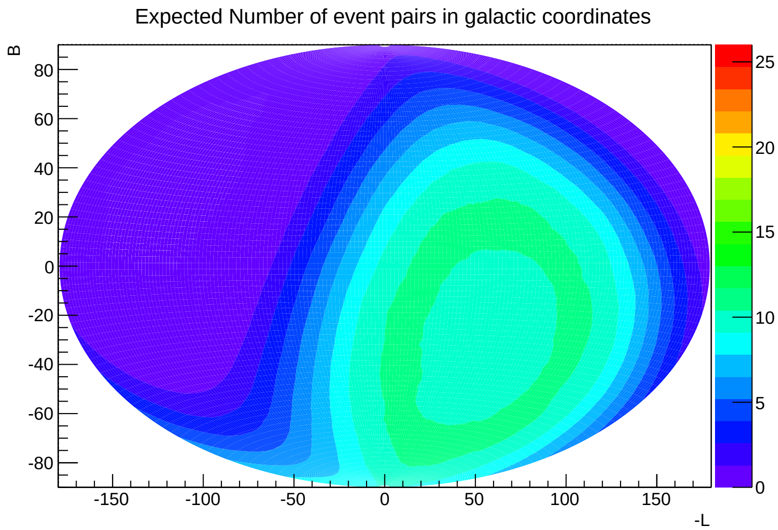

Figure 3: Expectation value for the number of event pairs within 10 degrees of each point in Galactic coordinates. The expected total number of event pairs is 659.

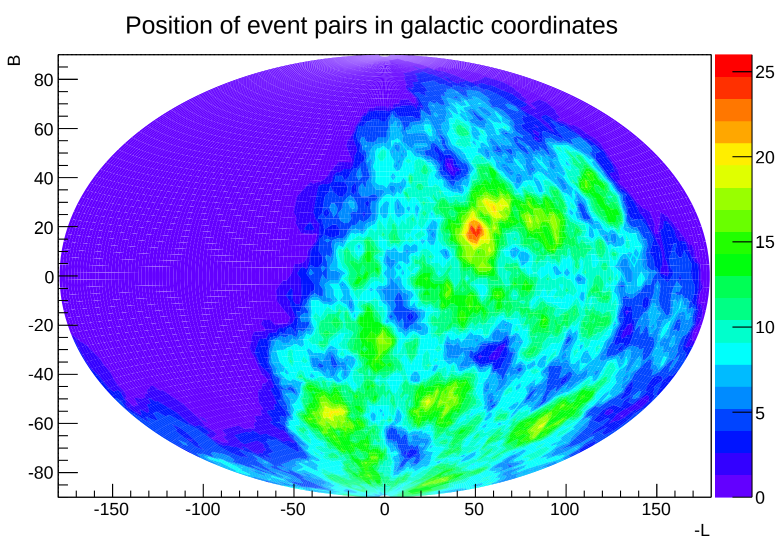

Figure 4: Distribution of event pairs within 10° from each point in Galactic coordinates

highly unlikely. The selected 18474 event pairs are again used to count the number of pairs that differ maximally 10 degrees from any position in galactic coordinates as shown in the left part of Figure 5. In

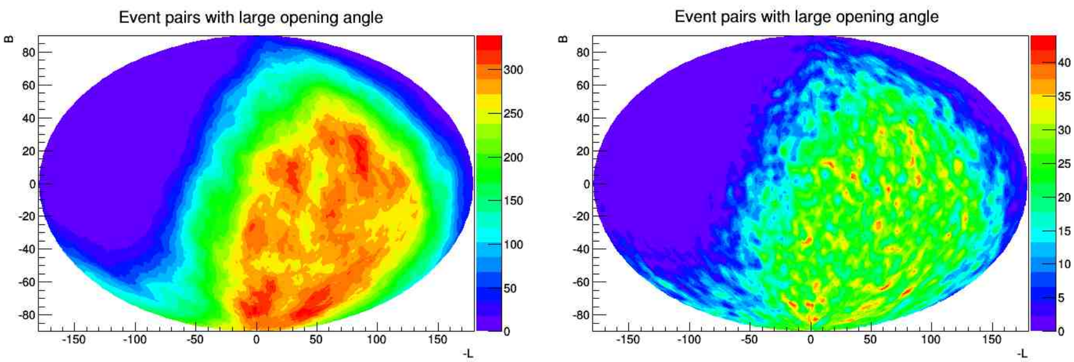

Figure 5: Distribution of event pairs in Galactic coordinates

this case, the maximal hotspot contains 339 events. In background sets this occurs in 36 out of 40 (or 90 %) data sets. Therefore, there is no anomaly observed in this part of the data set. The right plot of Figure 5 shows the number of event pairs within 3 degrees of a given point in galactic coordinates. Again, no anomaly is observed in this part of the data set.

Time difference distribution of event pairs close to $(-45°, 17°)$

The results above lead to the question: "Do event pairs that seem to originate from within 10 degrees of $(-45°, 17°)$ show a special signature in time difference between events?"
The distribution of time difference between events in pairs for which the angular difference between events is less than 4.5 degrees, and originate within 10 degrees of $(-45°, 17°)$ is given in Figure 6, both in bins of 5.4 (left), and 1 second (right). This figure shows a clear enhancement at small time differences. When estimating the background from all but the first bin of the left part of Figure 6, one obtains an average background value of 9.5 ± 1.0 events. The Poisson probability of obtaining at least 26 pairs when expecting 9.5 pairs is $2.6 \cdot 10^{-6}$. The 26 event pairs for which the time between events is less than 5.4 seconds are listed in Table 1. The year in which the event pairs are recorded is given in Figure 7, showing that most of the event pairs were recorded in 2008 and 2009, whereas for all event pairs the rate is more or less constant since 2008. There is no clear signature in either the hour of day or month of the year in which these event pairs are recorded, as shown in Figure 8.

Given that the expectation value of the number of event pairs is not uniform due to the acceptance of the detector, a better background estimate can be obtained by asking what is the probability that, given a total number of event pairs of 689, and an expected number of pairs of 659, an excess with a probability of less than $2.6 \cdot 10^{-6}$ is obtained anywhere in the field of view of our detector. The data presented in Figure 3 is used, together with a simulation approach as before. In 74 out of 1000 simulated data sets at least one point the random probability of obtaining the realised number of event pairs is less than

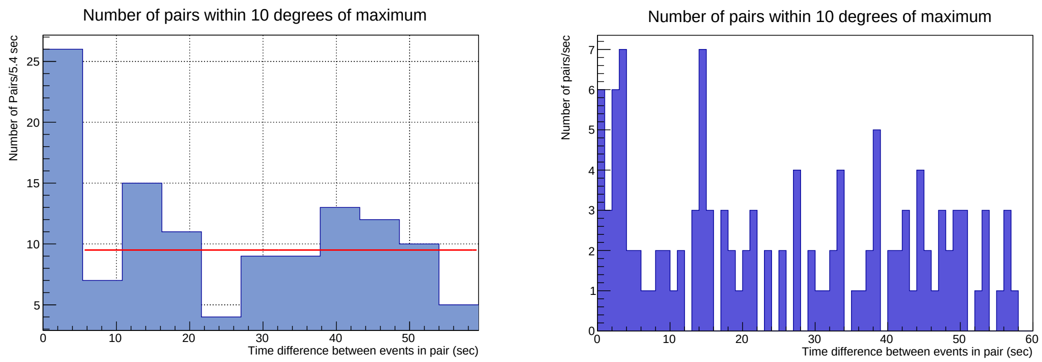

Figure 6: Time difference between events in a pair vs number of pairs within 10° of $(-45^\circ, 17^\circ)$

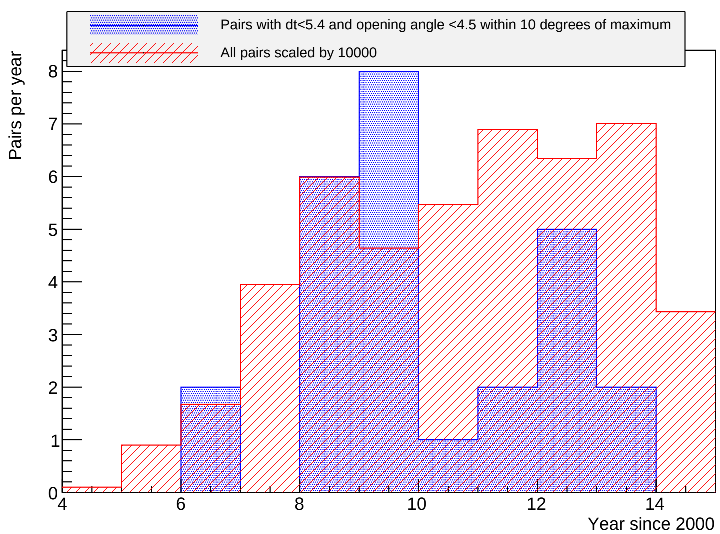

Figure 7: Year event-pairs are recorded. Note that the distribution for all pairs (red) is scaled down by a factor of 10000.

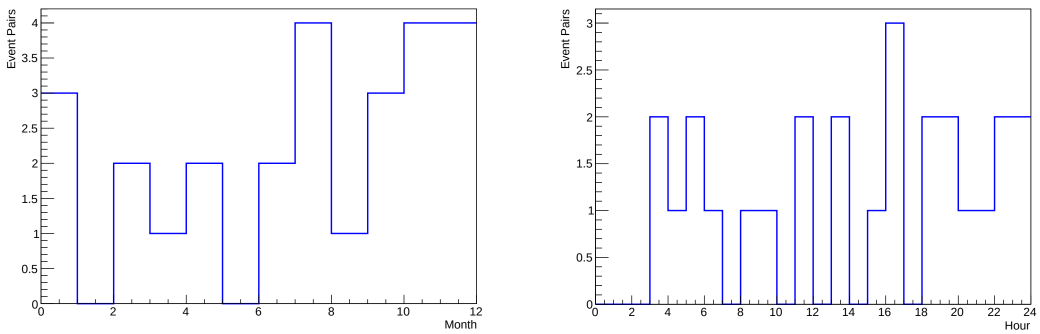

Figure 8: Month (left) and hour of day (left) of the 26 event pairs close to $(-45°, 17°)$

$2.6 \cdot 10^{-6}$. Therefore, the random expectation that an excess with a probability of at most $2.6 \cdot 10^{-6}$ is observed anywhere in the galactic plane is estimated to be $7.4 \pm 0.9\,\%$.

Optimisation

The peculiar structure of the time difference between events in a pair, shown in Figure 6 is a motivation to perform an optimisation. For this optimisation, the expectation value of the number of event pairs that seem to originate close to $(-45°, 17°)$ is estimated from the background data. In the three dimensional space of:

- the maximal time difference between events in a pair ranging between 0.01 and 20 seconds in bins of 0.01 sec.
- maximal angular difference between events in a pair ranging between 3 and 6 degrees in bins of 0.1 degrees.
- opening angle of the arrival direction to $(-45°, 17°)$ between 6 and 16 degrees in bins of 0.1 degrees

a minimal probability of an agreement to the expectation value has been searched. The left part of Figure 9 shows the minimal probability of agreement with expectation after scanning in time difference for each of the angular bins. The final optimisation results in a maximal time difference of 4.16 seconds, at an opening angle between event pairs of 4.4 degrees, and an angular distance to $(-45°, 17°)$ of at most 9.9 degrees. The probability that the background of 6.45 event pairs fluctuates up to 23 in the first 4.16 seconds is $9.14 \cdot 10^{-8}$. However, as this parameter is minimised, its value must be used with caution and cannot be interpreted as a true probability. Finally, there are 496 event pairs with an opening angle of at most 4.4 degrees and a time difference between events below 4.16 seconds. Creating a plot in galactic coordinates of the number of event pairs within 9.9 degrees of each position provides the right of Figure 9. The probability of obtaining 23 events within 9.9 degrees of any point has been determined by creating 10000 random data sets, similar as before. In only 50 of those datasets, the maximum number of events close to any point in the galaxy was 23 or more. This is interpreted as a random probability of obtaining a hot spot of at least 23 pairs of $0.50 \pm 0.07\,\%$. Similar, the chance of obtaining a probability of $9.14 \cdot 10^{-8}$

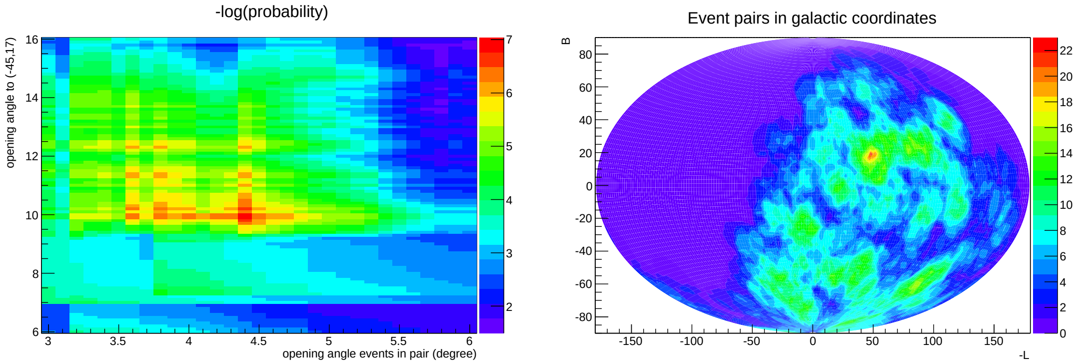

Figure 9: Time difference between events in a pair vs number of pairs within 10° of $(-45°, 17°)$

anywhere is $1.07 \pm 0.10\,\%$. It should be noted that this decreased probability is not a logical outcome of the optimisation procedure, unless the assumption is made that the distribution of the difference between event times of pairs arriving from a direction close to $(-45°, 17°)$ is more peaked towards zero than the average time difference of events in a pair originating from any other direction.

The Angular Resolution of the SD

The angular accuracy of the SD, defined as the angular distance to the true direction in which 68 % of the events are expected, is 2° for low energy events registered in 3 tanks, as given in [1]. When taking a point spread function as $P(\theta) = \theta/\sigma^2 \exp(-\theta^2/2\sigma^2)$, this accuracy corresponds to $\sigma = 2/1.51 = 1.3°$ (ref. [2]). This point spread function is used to generate 30 event pairs with an angular difference below 4.5°, similar to what we found in data. This signal is generated on top of a background simulation, for which events are generated according to the distribution shown in Figure 1. Each background distribution consists of 659 events at an opening angle of 4.5°. For 1000 simulated datasets, the probability for the average number of recorded events to be in agreement with a background only hypothesis is shown in each angular bin in Figure 10. In this figure, different values for the angular resolution are taken. The observed excess is in agreement with the angular resolution of the detector. However, when adding a deflection due to Galactic magnetic fields of order $10° Z(40EeV/E)$, as described in [3], the simulation no longer describes the data.

Discussion

The assumption that the excess of the 26 (or 23) event pairs has a physical origin leads to some constraints. The energies of the events in the pairs are low, ranging from 0.2 to 3.9 EeV (assuming hadronic primaries). If one assumes that the time differences between events in a pair is not random, it follows that these time differences originate either from differences in propagation time from the common origin to Earth, or are due to properties of the source itself.

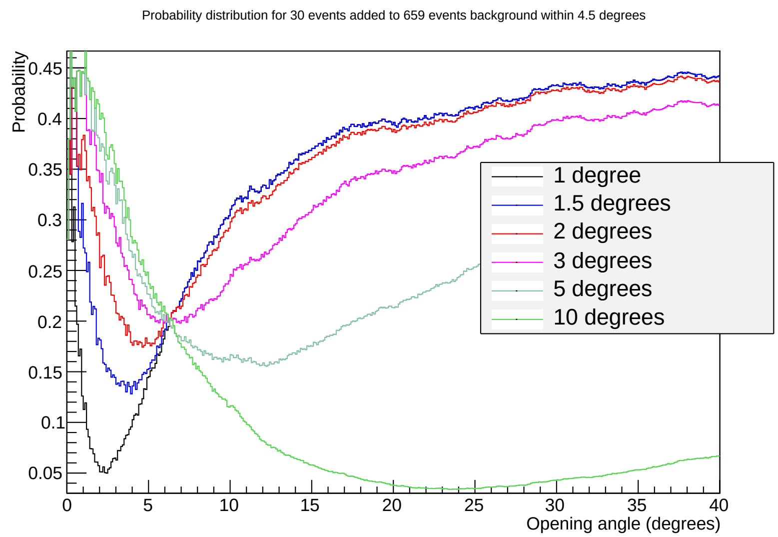

Figure 10: Probability that simulated data with signal added agrees with background. σ values of 1, 1.5, 2, 3, 5, and 10 degrees are used in the single event point spread function.

Differences in propagation time can arise due to different velocities (or γ), or different path lengths. The path lengths may differ due to different rigidities. Taking both effects into account one gets:

$$t_2 - t_1 = \frac{\Delta}{\beta_2} + \frac{L}{2}\left(\frac{1}{\gamma_2^2} - \frac{1}{\gamma_1^2}\right) \tag{1}$$

In this equation Δ is the path length difference, and L the path length. Both expressed in light seconds. Furthermore, γ_2 is the gamma-factor of the slowest particle, traveling the longest path, and $\beta_2 \cdot c$ is its velocity. Unless one assumes an extremely lucky scenario where the Earth happens to be located in a position where initially diverging paths are almost crossing, one is left with the option that the paths are almost parallel, ending up at a distance of only about 10 km at Earth. The only way such a path length difference can lead to a significant time difference is when the second particle is extremely slow. β_2 would have to be of order 10^{-5} or less. Ignoring this option, only the second term of equation 1 is of interest. For an iron-like nucleus of 1 EeV, the Lorentz factor is about $\gamma = 10^7$. Therefore one gets:

$$t_2 - t_1 = \frac{L \cdot 10^{-14}}{2}\left[\left(\frac{10^7}{\gamma_2}\right)^2 - \left(\frac{10^7}{\gamma_1}\right)^2\right] \tag{2}$$

Differences in velocities may end up in second-like time differences for distances of about 10^{14} light seconds, or 10^7 light years, assuming that one of the nuclei is iron like, and the other much lighter. However, for charged particles this constraint in path-length differences can only be achieved if the rigidities of the particles are the same to a very large extend. Even though this rough distance estimate is very similar to the distance of a near source candidate like Centaurus-A, it is very difficult to see how the rigidities of the emitted particles could be this similar Therefore, the natural option is that the emitted particles are electrically neutral (neutron, photon, or neutrino).

The likeliness of the 52 events in the 26 pairs to a photon expectation has been analysed by L. Lu using the rise time of these events. The rise time of the examined events does not show a photon like signature for any of them.

Following the neutron paper [2], we use a top hat of $1.59\sigma = 2°$ around each of the events. We then compare the events near $(-45°, 17°)$ with the 2MRS catalog. We show the data for the optimised criteria of 4.16 sec maximal time difference between events in a pair, and a maximal opening angle of 4.4°. Figure 11 shows the location of these event pairs and 2MRS objects.

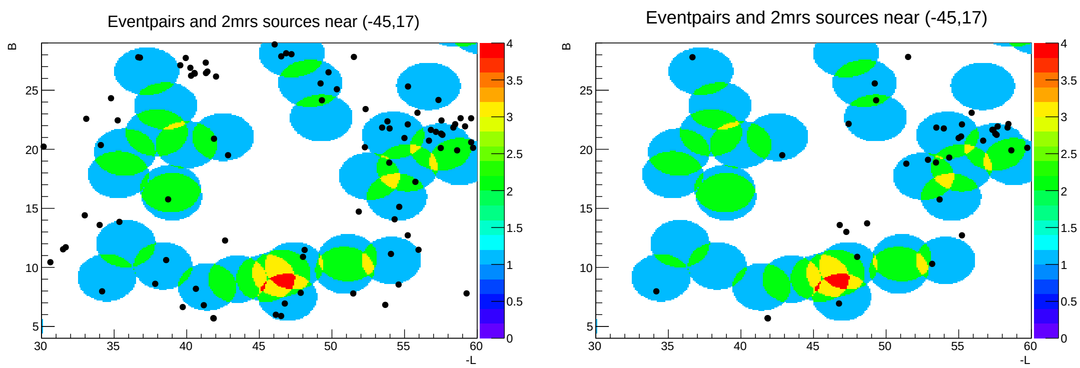

Figure 11: Distribution of event pairs in Galactic coordinates near $(-45°, 17°)$ at an angle of less than 2.0 degrees, compared to the location of 2MRS objects. In the left plot redshifts are below 0.018 and luminosities above 11. In the right plot distances are below 0.01 and luminosities are above 10.5.

A possible candidate particle would be the neutron. However, at 1 EeV its mean decay length is about $900 \times \gamma/3 \cdot 10^7 \simeq 30$ kLy. This means that the most distant source would be somewhere near the halo of our galaxy. The time difference between a neutron and a photon from a source at such a distance is given by $\Delta_T = L/(2C\gamma^2)$, or in the order of $1\,\mu$s. Therefore, the time difference observed (order seconds) would reflect the time difference at the source.

When assuming that sources are at larger distances, of order 10 MLy, the only neutral particles in the standard model capable of travelling from that source to Earth are photons and neutrino's. One should note that for 1 EeV photons this distance exceeds the (50 %) cosmic horizon caused by reactions from high energy photons with the CMB (and IR backgrounds). This horizon is expanding as the energy increases.

Conclusion

A small global excess in the number of event pairs recorded with an opening angle of maximally 4.5 degrees, and a time difference of at most 5.4 seconds has been explored further. The location of the 689 event pairs in galactic coordinates show a hotspot of 26 events within 10 degrees of $(-45°, 17°)$. The random probability of creating such a hotspot at any location has been determined to be $4.5 \pm 0.7\,\%$. The time structure of all pairs within 10 degrees of $(-45°, 17°)$ shows an excess in the first several seconds.

This is not necessarily expected from the previous selection, unless the assumption is made that a single hotspot is the cause of the observed global enhancement. Using the same binning as before, the probability of obtaining 26 event pairs in the first time bin is $2.6 \cdot 10^{-6}$. When taking the look-elsewhere effect into account, this probability becomes $7.4 \pm 0.9\,\%$. Further optimisation of cuts in order to minimise the random probability that the expectation value of the number of event pairs leads to the recorded number of event pairs in the first time bin, reduces the probability of observing the number of pairs in the first bin of 4.16 seconds to $9.14 \cdot 10^{-8}$. A side-effect of this optimisation is a decrease of the probability that the observed galactic distribution appeared by chance from a pure random distribution to $1.07 \pm 0.10\,\%$. The data is consistent with an interpretation of neutral particles, most likely photons or neutrino's, originating from several sources within ten degrees of $(-45°, 17°)$, even though the rise-time of the analysed events does not point to a photon-like behaviour. The 2MRS catalog of possible source objects is not inconsistent with a neutral cosmic ray interpretation. However, how events from these sources could lead to the observed time differences in the event pairs has not been discussed.

Acknowledgements

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References

[1] Bonifazi, C. (for the Pierre Auger Collaboration) 2009, in Proc. 31st ICRC, arXiv:0901.3138

[2] The Pierre Auger Collaboration, ApJ, 789 (2014) L34

[3] K. Kotera and A. V. Olinto, Ann. Rev. Astron. Astrophys. **49** (2011) 119

Table 1: Event pair list

ΔT (s)	UTC	E_1	E_2	Dist.(km)	Ω	θ	ϕ	L	B	Date
0.62348	1154299547	0.84	1.06	18.17	3.71	5.35	-168.84	-38.54	23.68	Sun Jul 30 16:45:47 2006
3.55773	1166458856	2.11	0.24	29.89	4.35	40.81	-139.07	-46.52	9.52	Mon Dec 18 09:20:56 2006
5.12989	1201151834	2.96	0.92	17.74	3.94	54.85	-36.48	-47.01	15.05	Wed Jan 23 22:17:14 2008
5.07941	1201181768	1.51	0.70	14.72	2.84	43.67	-151.88	-50.09	19.35	Thu Jan 24 06:36:08 2008
3.74245	1212032370	1.03	0.40	15.80	3.24	24.32	-123.19	-46.96	7.48	Wed May 28 21:39:30 2008
2.76064	1219086274	1.13	0.61	28.49	3.50	28.88	-21.06	-35.29	17.86	Mon Aug 18 13:04:34 2008
4.85471	1224780662	1.48	0.45	47.70	2.82	12.93	-101.50	-43.76	12.98	Thu Oct 23 10:51:02 2008
3.47156	1226766549	0.35	2.18	30.09	1.62	27.50	-133.43	-51.10	10.81	Sat Nov 15 09:29:09 2008
4.15366	1232175068	0.46	1.94	33.00	2.50	36.05	-33.19	-54.48	15.96	Fri Jan 16 23:51:08 2009
3.23394	1237094344	2.55	0.38	18.08	3.33	29.78	-43.84	-41.42	8.34	Sat Mar 14 23:19:04 2009
2.86451	1237191343	1.02	1.10	21.09	1.67	11.90	-136.67	-38.89	16.66	Mon Mar 16 02:15:43 2009
1.21150	1239010928	0.90	1.93	46.13	4.19	43.03	-139.60	-43.48	9.01	Mon Apr 6 03:42:08 2009
1.32540	1254947258	0.51	1.91	40.56	1.50	41.53	-162.17	-48.51	25.59	Wed Oct 7 14:27:38 2009
2.46182	1258110625	1.06	1.02	30.39	2.70	43.38	-40.24	-47.40	10.15	Fri Nov 13 04:10:25 2009
1.42878	1259415873	0.49	1.06	35.29	3.58	8.96	-130.71	-54.23	21.19	Sat Nov 28 06:44:33 2009
0.93596	1259606569	0.99	1.51	50.75	3.14	49.22	-149.99	-38.99	16.00	Mon Nov 30 11:42:49 2009
2.71398	1291201747	0.70	1.00	15.16	0.83	29.99	-46.38	-50.87	9.78	Wed Dec 1 04:09:07 2010
3.99255	1306729506	1.09	0.66	23.60	2.08	38.07	-150.62	-55.20	18.44	Sun May 29 22:25:06 2011
2.28668	1317592477	3.87	1.66	16.36	3.14	38.14	-144.30	-38.36	10.13	Sun Oct 2 15:54:37 2011
0.27179	1344972507	0.28	1.43	23.37	3.13	19.49	-20.61	-42.50	21.03	Tue Aug 14 13:28:27 2012
3.20051	1346455806	1.85	0.57	33.35	4.34	40.16	-138.39	-45.43	9.10	Fri Aug 31 17:30:06 2012
0.03395	1346539427	3.61	1.36	25.47	1.97	40.00	-157.85	-49.28	22.66	Sat Sep 1 16:43:47 2012
3.54849	1355162957	1.30	1.51	43.27	4.21	50.06	-155.88	-35.73	19.76	Mon Dec 10 11:09:17 2012
2.03036	1355671396	0.35	1.57	50.69	1.38	25.48	-163.81	-37.94	21.42	Sun Dec 16 08:23:16 2012
0.62277	1373774320	1.61	2.19	46.71	1.97	53.33	-153.07	-39.99	20.38	Sat Jul 13 21:58:40 2013
0.10542	1376435499	0.52	3.11	16.83	3.73	33.37	-149.89	-52.57	17.71	Tue Aug 13 17:11:39 2013