Shifts of Signal including deflections by Earth's Magnetic Field and systematic pointing shifts

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1 Introduction

Our data shows systematic shifts in ax and ay (see Stefan's memo) apparently introduced by some problem with angle reconstruction (called mispointing here). We also know that charged particles are deflected by earth's geomagnetic field (and also the heliospheric magnetic field). This memo is a study of how these effects may affect source searches and detection of the shadow of the moon in cosmic rays.

This study shows:(1) that mispointing causes a shift in the apparent position of a source. The magnitude of the shift is to move the apparent position of a source going overhead by about -0.3 degrees in declination and (2) that shadow of the moon is shifted both in declination and right ascencion. Selecting events with zenith angles less than about 30° minimizes the shifts due to mispointing.

Two effects which must be considered are: (1) first is the deflection expected due to singly charged particles traversing the earth's magnetic field. In addition effects of the heliospheric magnetic fields should effect our results but these are not considered in this work. (2)The second is the shift in RA and DEC which should arise because of the shifts in ax and ay that are seen in the data. The latter will shift the apparent position of each event in the celestial sphere.

Deflection due to earth's magnetic field is approximated to be 1.7° per TeV in the plane containing the local zenith and east direction. This was estimated by calculating deflection due to $\int Bdl$ along the particle trajectory assuming a diploar magnetic field of the earth. Specifically in this plane the angle made with respect to the local vertical is shifted by $\frac{1.7^\circ}{E(TeV)}$.

The effect of reconstruction not pointing in the true direction is estimated by the curves obtained by Stefan for ax and ay as a function of the zenith angle from examination of data. Specifically, these combined shifts for magnetic deflection and mispointing are

$$ax_1 = -5.9 \times 10^{-7}\theta^2 + cos(thx \pm \frac{1.7^\circ}{E}) \tag{1}$$

$$ay_1 = ay_0 - 1.22 \times 10^{-5}\theta^2 - 0.002 \tag{2}$$

where

$$thx = cos^{-1}(sin\theta cos\phi) \tag{3}$$

$$ay_0 = sin\theta sin\phi \tag{4}$$

2 Simulation procedure

I have studied the effects described above by a systematic simulation procedure whose elements are briefly described below:

1. Source transit: For a given source position in ra and dec its transit accross the sky is generated in local coordinates.
2. Moon position: Actual moon transit accross the sky is taken into account. For each Julian day and second , RAmoon and DECmoon are first calculated. For this celestialposition, local coordinates θ and ϕ are calculated.
3. Throws based on Experimental distributions.

   Based on the actual experiment event rate and observed zenith angle distribution events are generated within $\pm$ 15° of the moon. For each generated event from their RA and DEC, local coordinates are calculated. A total event rate of 300 Hz and a $\cos^4\theta$ angular distribution has been assumed.
4. Pick an energy based on MC distributions: Eenergy for each event is picked from an energy distribution for triggers as calculated using simulations for Milagrito triggers(a la Stefan).
5. Introducing magnetic field deflection and observed ax and ay shfit:

   From the local coordiantes of each event, the direction cosines, ax, ay and az are calculated. Then for cosmic rays these are shifted to account for magnetic field and reconstruction mispointing using equations 1 and 2 given above. New values of ax and ay, ax1 and ay1, are then used to calculate a new z direction cosine: az1 = $\sqrt(1. - ax_1^2 - ay_1^2)$. From

ax_1,ay_1 and az_1, new values of local angles are then calculated. For photons magnetic field deflections are not included.

6. Including the spreading due to assumed angular resolution:

   Finally the local angles are wiggled in theta and phi with appropriate gaussian distributions. If σ is the angular resolution then theta has gaussian with width σ and phi has a gaussian with a width of $\sigma/\sin\theta$. In some of the plots, an angular resolution of 0.2° is used in order to highlight the offest and smearing of offsets and/or magnetic field deflections.

7. Calculating the final RA and DEC for the event:

   Now the celestial coordinates for this event are recalculated obtaining the final value of RA and DEC, let us call these ra1 and dec1.

To visulaize how the shadow is shifted, events with original values of RA and DEC such that the angular distance of the event with respect to the true moon position is less than the radius of the moon, 0.25° are examined for three cases (so moon is converted into a source !):

1. With no magnetic field deflection or reconstruction systematics,
2. With magnetic field deflection only,
3. With magnetic field and reconstruction systematics

For cases (2) and (3) there are two plots for each, one for all events and the other for events with energy greater than 6 TeV. The latter was chosen to correspond to a nhit cut of 150 tubes, i.e. an event sample approximately 20 percent of the full sample.

3 Results:

3.1 Shift of a gamma ray source:

To begin with I calculate the effect of ax, ay shifts on a gamma ray source traversal. I consider a source located at ra=305 and dec=45 degrees. Source emits photons which are not influenced by the magnetic field. For each instant in source traversal, local coordinates are calculated, axay shifts are introduced according to equations 1 and 2, (without the magnetic deflection terms)new local coordinates are calculated and then new celestial coordinates are calculated. Deviations from source position of these new celestial coordinates are calculated and they are called dra and ddec, units are degrees. A single source transit (this source goes almost overhead) is considered. I show the relations between(1) local coordinates, zenith and azimuth,(2) zenith and azimuth as a function of time during the traversal and (3) the correlation between deviations from source position in ra and dec (dra and ddec) with zenith and azimuth. In these plots, magnetic field deflections are only applied to cosmic ray background events not to the source photons.

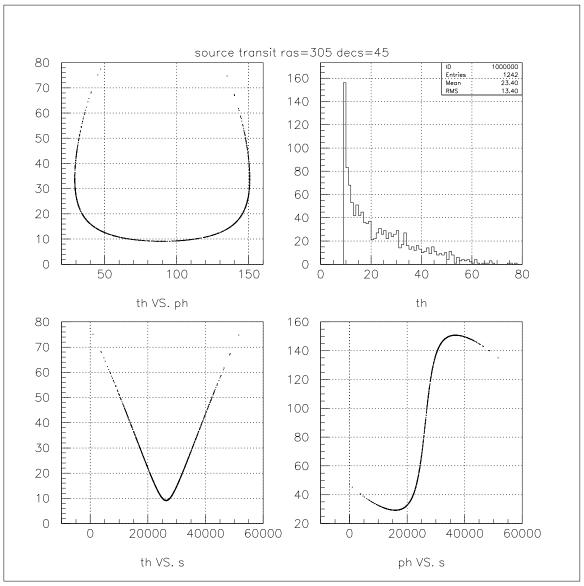

Figure 1: Correlations of theta and phi. Theta distribution
Theta and phi as a funtion of time in seconds

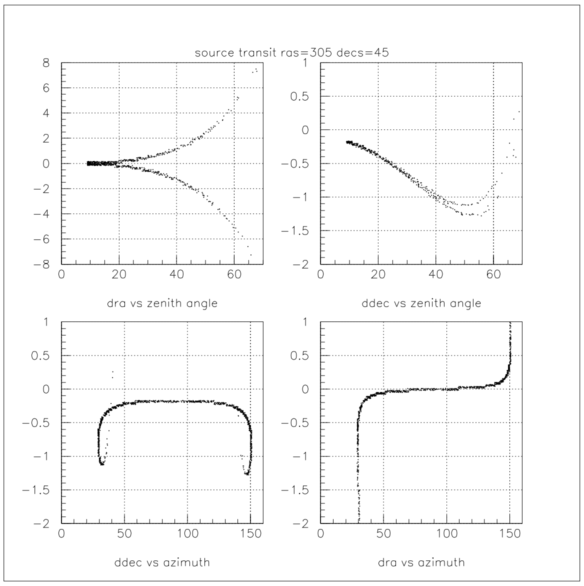

Figure 2: Correlations of deviation from source position

in ra and dec as a function of theta and phi

Figure 2 shows the increase of dra and ddec as a function of theta and phi. This figure shows that these shifts can be minimized by making a cut on zenith angle of less than 30 degrees.

Now we examine effects on source signal due to these shifts. A generous source strength, about equal to the background level, is used. Using the procedure outlined in the previous section with an angular resolution of 0.2° a simulation was done to generate plots of Figures 3 and 4.

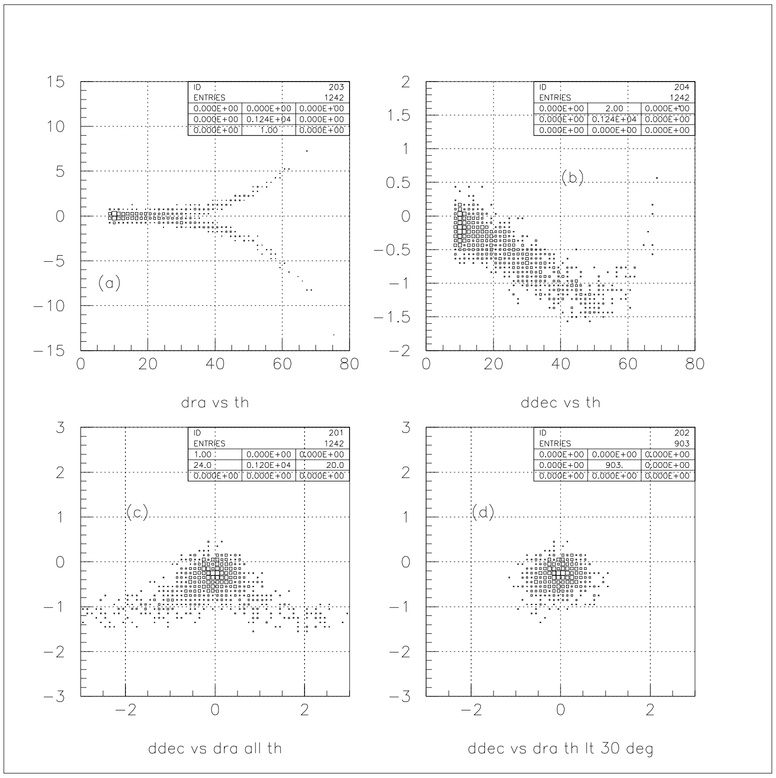

Figure 3: Shifts in RA and DEC with respect to source position of source gamma rays as function of zenith angle and the effect of making a zenith angle cut on ddec vs dra distributions

Figure 3(a) shows the distribution of deviation of RA, dra, from true source position as a function of zenith angle. This is for source events It is seen that the magnitude of the deviation increases with zenith angle as shown in Figure 1 but here the spread due to angular resolution is included. The two branches correspond to rising and setting branches of source transit.

Figure 3(b) shows the deviation of DEC, ddec, from true source position. Again the deviation becomes more negative with zenith angle until very large zenith angles are reached where the θ^2 terms start to dominate in equations 1 and 2.

Figure 3(c) shows a diplot of ddec versus dra for all events. The large dra tails are due to increase in shift at large zenith angles.

Finally, Figure 3(d) shows the improvement of source definition when a zenith angle cut of $\theta < 30°$ is made.

Figure 4 shows similar plots for two source transits added together without any theta cuts. The first diplot shows the source when no shifts have been included and background of cosmic rays is added in.

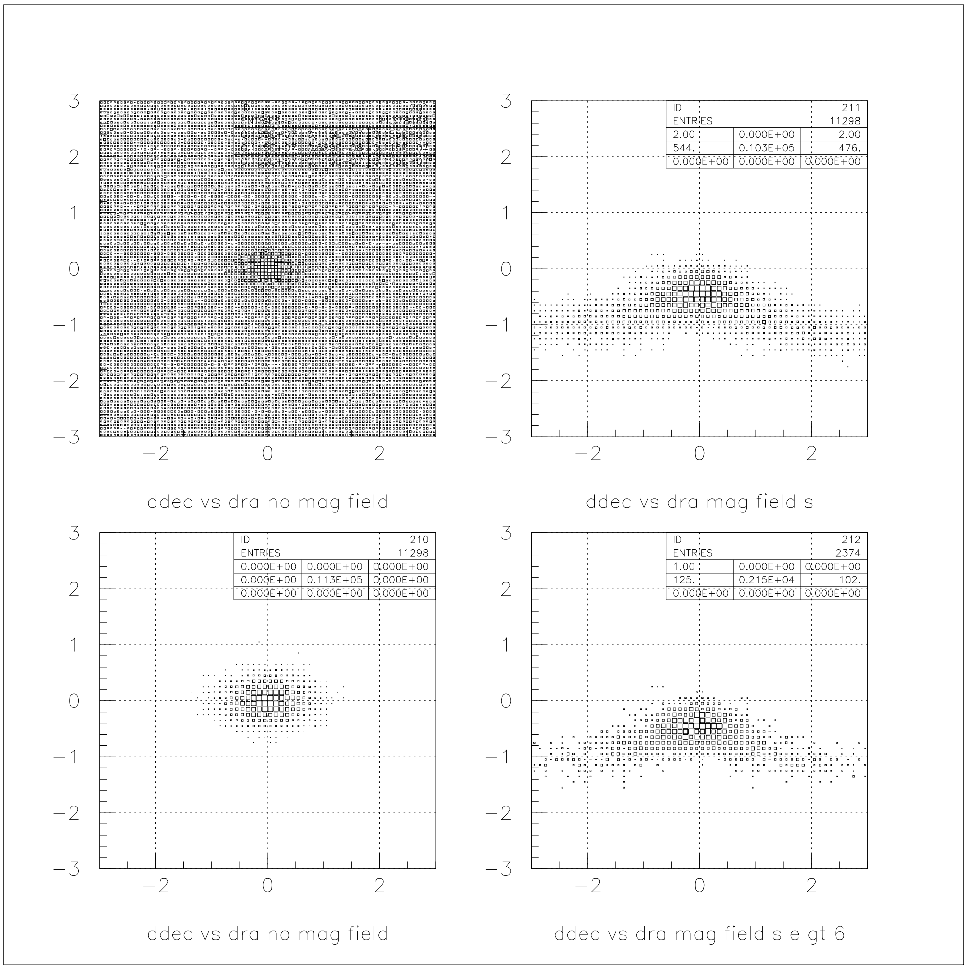

Figure 4: Source signal and effects of ax ay shifts
wiggled with angular resolution of 0.2 deg
for all energies and energy > 6 TeV

From a study of these figures, it is seen that effect of ax, ay shifts is to shift the position of the source towards smaller declination from the true source position. This effect is dramatically shown in Figure 5 where full distributions including background are shown for event density plots (events per square degree) as a function of angular distance from (1) the true source position and (2) a source position shifted by -0.3 degrees in declination. A marked improvement is seen in determination of source signal as indicated by the fits to a gaussian plus a flat background.The fitted sigma approaches true sigma when fit is made around the shifted position.The average shift in RA is relatively small.

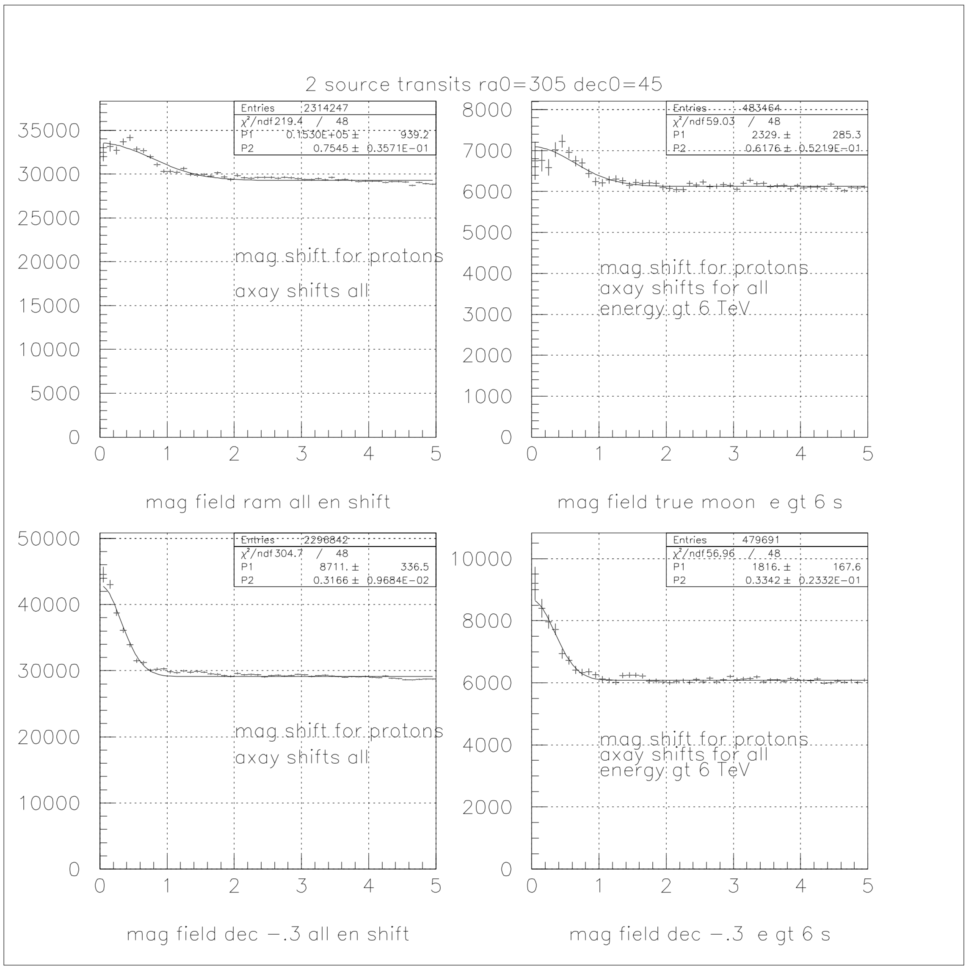

Figure 5: Source signal at true position and at shifted positions wiggled with angular resolution of 0.2 deg for all energies and energy > 6 TeV

The constant P1 is source signal and P2 is the fitted value of angular resolution with total number of events fixed. The discussion in this section shows that the best source signal is obtained not at the true source position but one where source location is shifted in dec by -0.3°

3.2 Moon Shadow:

3.2.1 Perfect Angular Resolution:

A MC sample consisting of 90 moon transit was generated. The sample contains about 1.3 million events within 5 degrees of the moon. This corresponds to about 5000 events hitting the moon. Next five figures show the distribution of these events with respect to the true moon position under variety of conditions. All of the figures do not have any angle wiggling for angular resolution. These plots show the moon as if it were a source.

Figure 6 shows the distribution of deviation from the true position of the moon for events which hit the moon, where local angles have been wiggled but no magnetic deflection or ax ay shifts included. This indicates the best moon shadow that can be obtained with this MC data.

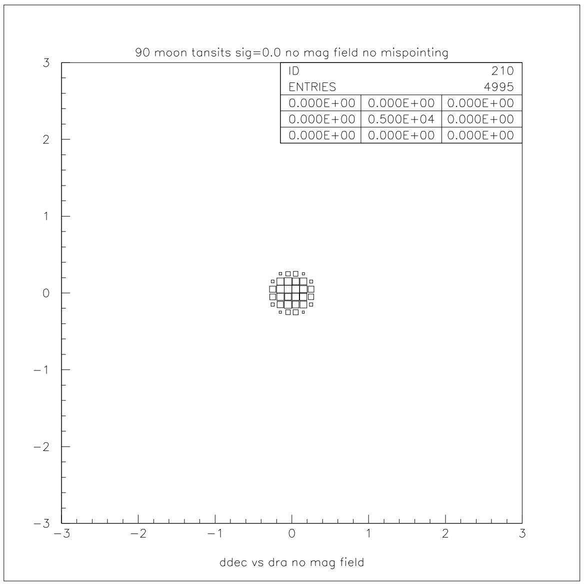

Figure 6: DEC-DECmoon vs RA-RAmoon, No magnetic field
no mispointing,

Figure 7 shows the distribution of deviation from the true position of the moon for events which hit the moon with deflection due to the earth's magnetic field included. Observe that the moon is elongated towards smaller RA and the ' shadow ' center is shifted by about -0.5°.

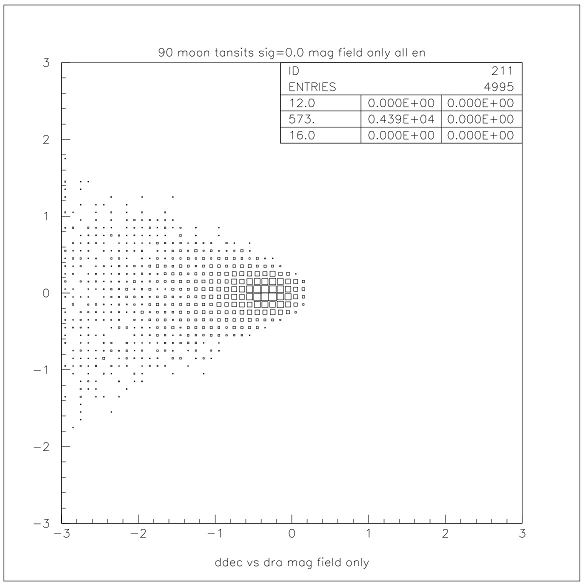

Figure 7: DEC-DECmoon vs RA-RAmoon, magnetic field, no mispointing all energies

Figure 8 shows the distribution of deviation from the true position of the moon for events which hit the moon including magnetic deflection and mispointing in reconstruction as given by equations 1 and 2. Now the ' shadow ' center is shifted both in RA and DEC by about -0.5°.

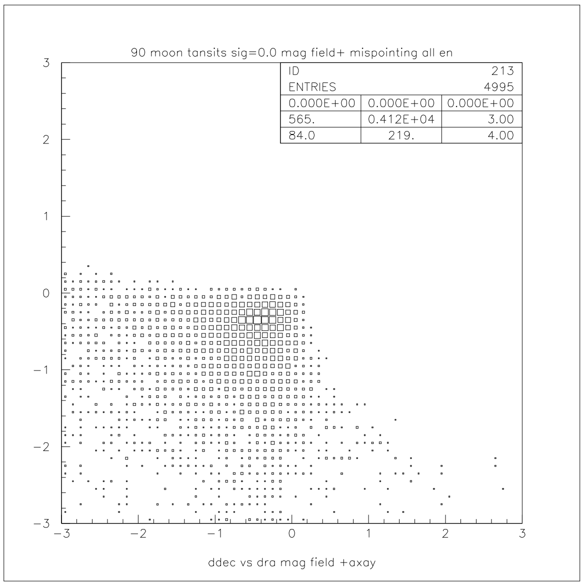

Figure 8: DEC-DECmoon vs RA-RAmoon, magnetic field and mispointing included,

Figure 9 shows the distribution of deviation from the true position of the moon for events which hit the moon for events with energy greater than 6 TeV. This energy was chosen to match the reduction of events when a nhit cut of 150 was made on the data. In this figure magnetic deflection is included but mispointing is not. The shift in RA is only about -0.2°.

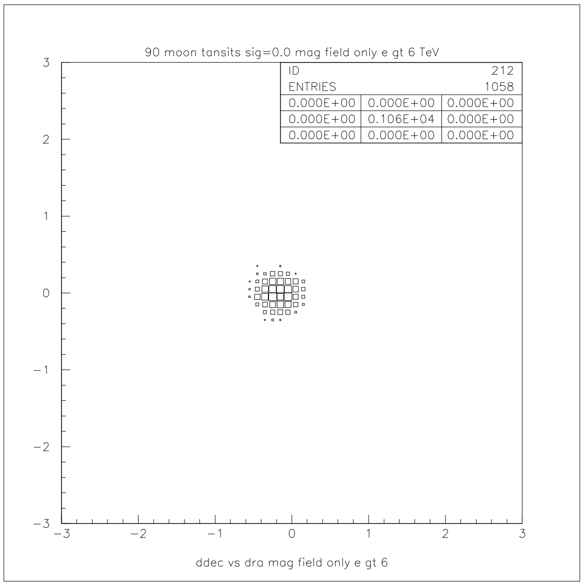

Figure 9: DEC-DECmoon vs RA-RAmoon, magnetic field, no mispointing, energy > 6 TeV

Figure 10 shows the distribution of deviation from the true position of the moon for events which hit the moon for events with energy greater than 6 TeV, now including magnetic deflection and mispointing due to reconstruction. In this case, an additional shift in dec of about -0.4° is introduced over the shift in Figure 9.

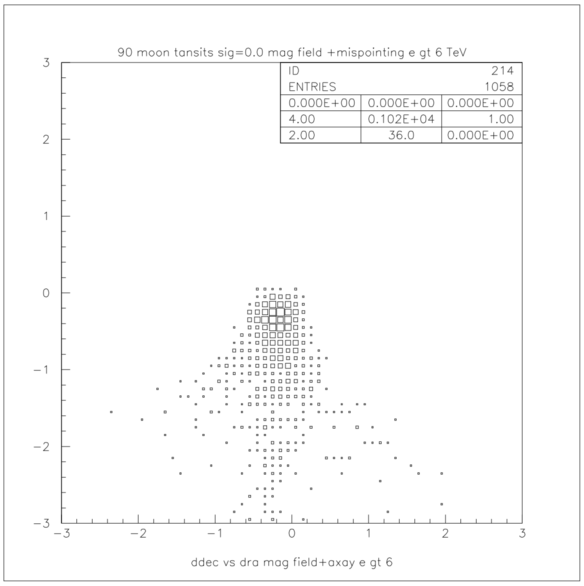

Figure 10: DEC-DECmoon vs RA-RAmoon, magnetic field,mispointing, energy > 6 TeV

It is clear from these plots that the best moon shadow will not be obtained at true moon position. To illustrate this I show a set of fits to the moon shadow for a simulation set corresponding to 90 moon transits in which the apparent position of the moon has been shifted. The first set of fits are for all events and the apparent position of the moon has been shifted in steps of -0.2 in both RA and DEC, Figure 11. The second set are for events with energy > 6 TeV and the apparent position of the moon has been shifted in steps of -0.2 only DEC, Figure 12

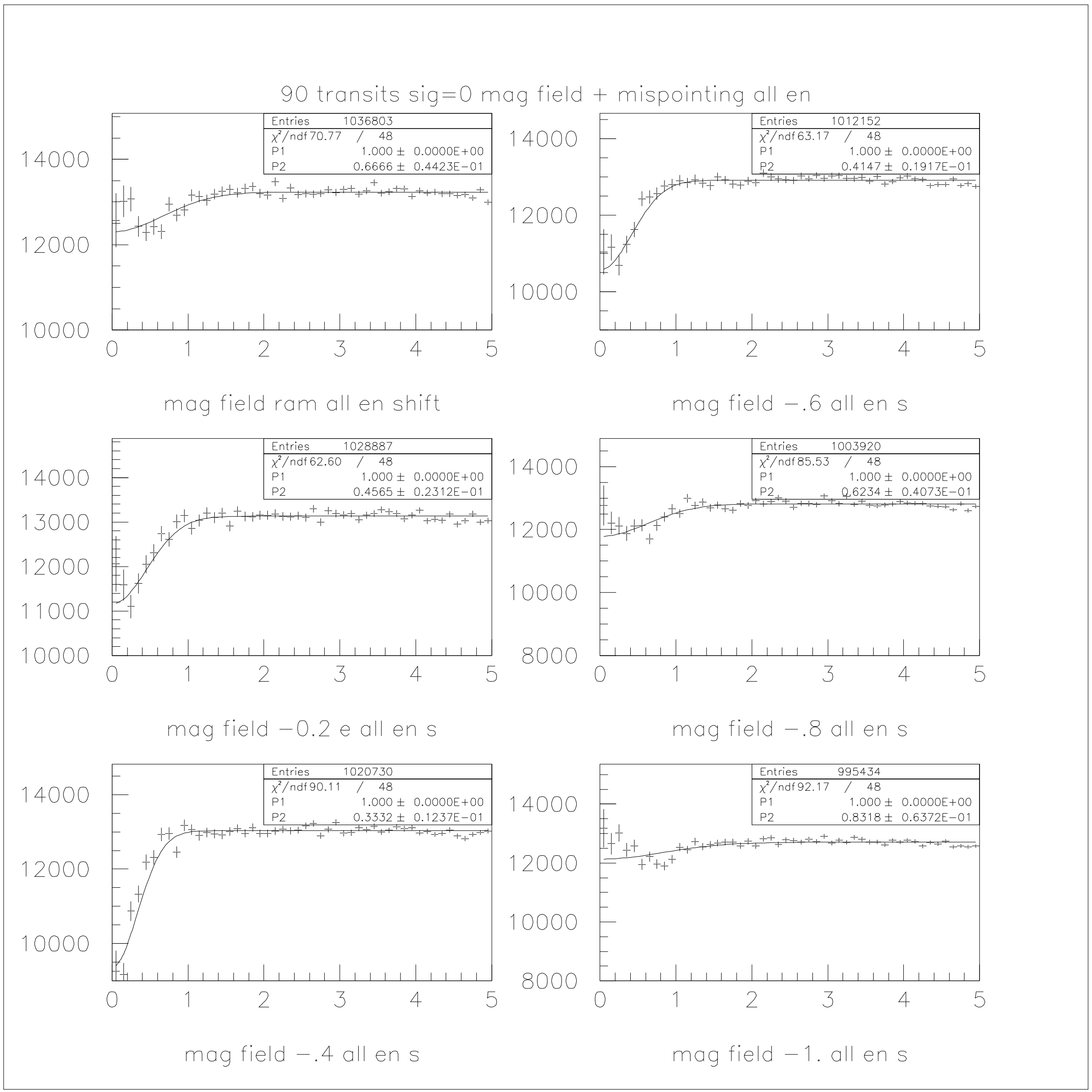

Figure 11: Fits to event density vs space angle from different apparent moon positions shifted in dec by steps of -0.2 degrees inclusing field and mispointing, all energies

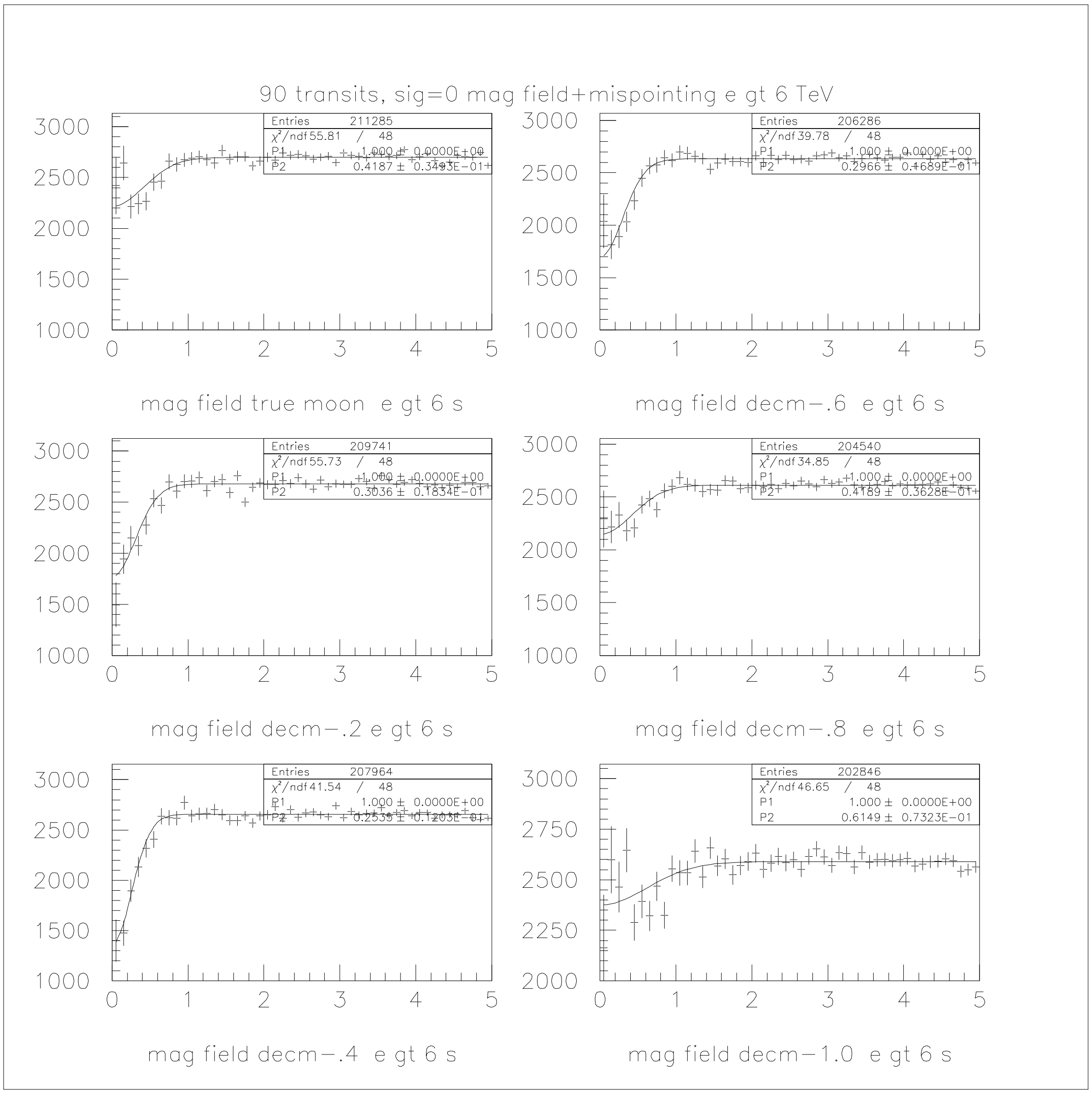

Figure 12: Fits to event density vs space angle from different apparent moon positions shifted in dec by steps of -0.2 degrees inclusing field and mispointing, energy > 6 TeV

These results show that to find the shadow of the moon we have to allow the apparent position of the moon to vary by amounts and directions which depend on the energy of the event or equivalently on Nhit cuts on the data.

3.2.2 Angular Resolution of 0.4°:

Gus's study has shown that angular resolution, as estimated from study of deleo improves with Nfit or Nhit and becomes better than 0.5° for Nfit > 40, I study what may happen to the shadow of the moon if an angular resolutio of 0.4° is assumed.

The following results are for a 30 day moon transit.

Ideally, if we had no magnetic field deflections and if we were not mispointing the result that would be obtained for the angular resolution from fitting the moon shadow is shown in Figure 13

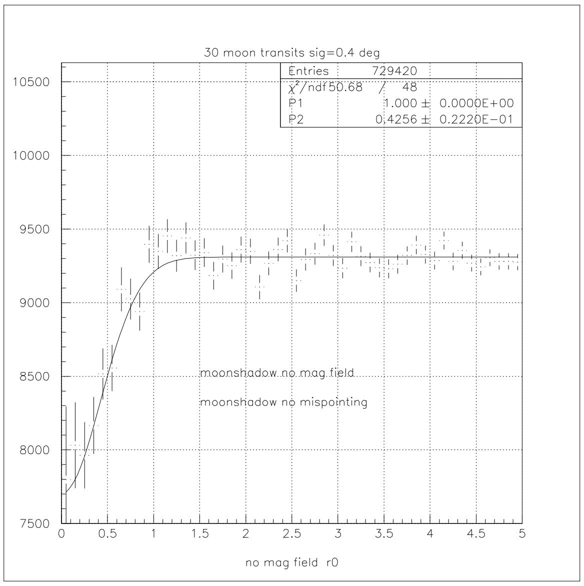

Figure 13: Event density per square degree vs angular distance from the moon. No magnetic field and no mispointing. All energies Fit to constant plus a gaussian as in Fig 5

In these fits total number of events is fixed and P1 equal to 1 means full moon shadow. P2 is the fitted angular resolution.

What happens to the moonshadow if only earth's magnetic field deflections are included is shown in Figure 14

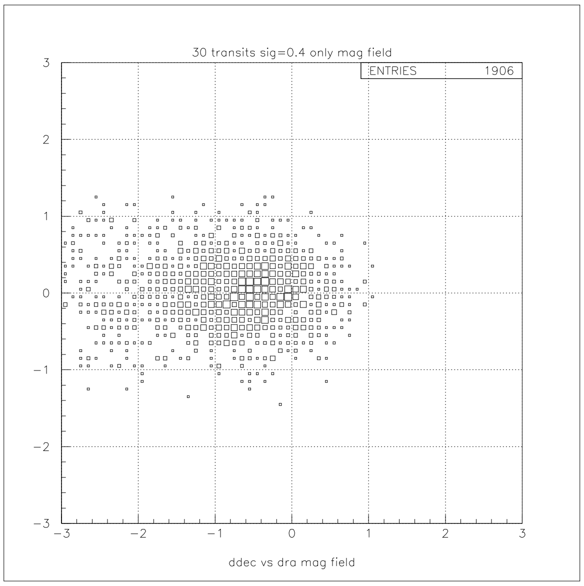

Figure 14: Diplot of deviations from true moon position in DEC versus RA including magnetic field

Shadow of the moon shifts towards smaller values of RA.

Next mispointing is added together. Now the shadow also shifts to smaller values of DEC. The center of shadow is somewhere around (-0.4,-0.4) in RA and DEC

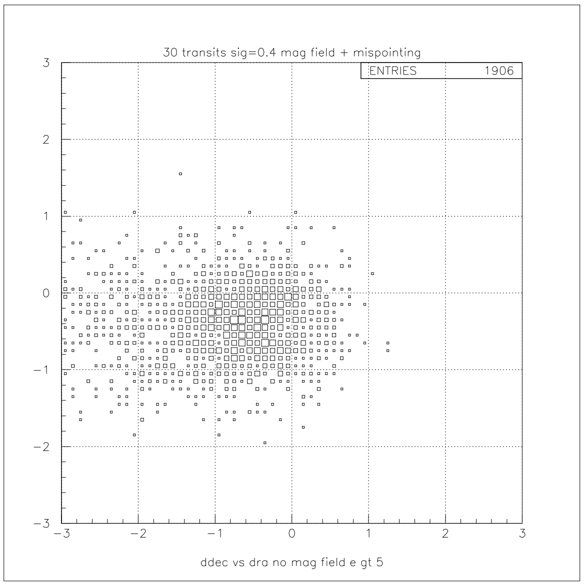

Figure 15: Diplot of deviations from true moon position in DEC versus RA including magnetic field and mispointing

In figure 15, the event density distributions vs angular distance for events of all energies and with magnetic field and mispointing are fitted with respect to apparent moon positions shifted diagonally in the ' south-east ' direction by steps of -0.2 degrees in RA and DEC of true moon position. Again the total number of events are kept constant and fit is to a flat distribution plus a gaussian for moon shadow.

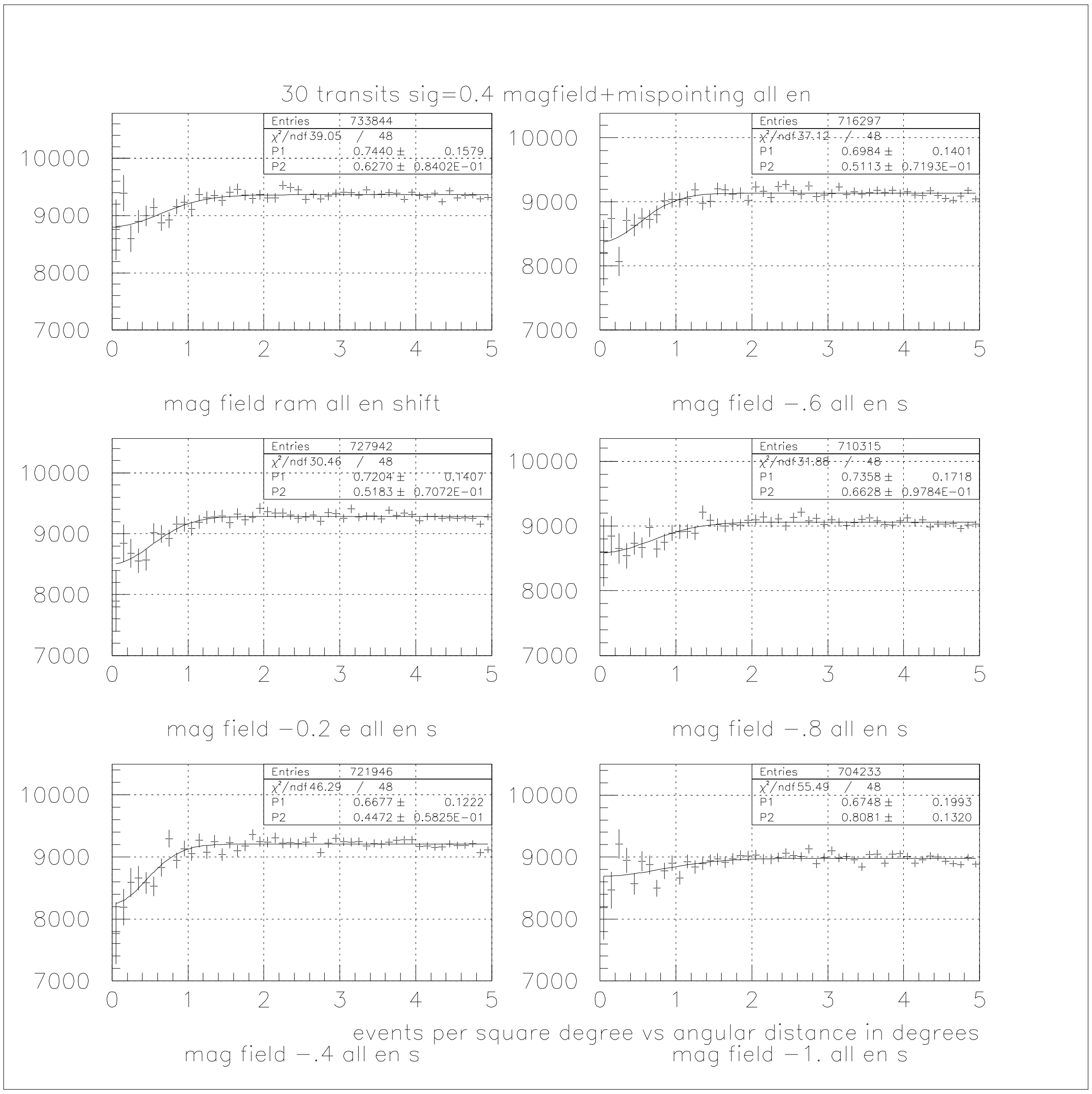

Figure 16: Fits to event distributions for all energies

The best shadow distribution for all events, Figure 16, is seen for a shift of -0.4 degrees and the fitted value of angular resolution is 0.44 ± 0.07 degrees and the shadow magnitude is about 77 % of the ideal shadow.

Next we do the same for high energy events, events with energy greater than 6 TeV. Figure 17 shows the deviations from true moon position of events where magnetic field shifts and mispointing are included The moon shadow is seen to shift about -0.4 degrees in DEC and only about -0.2 degrees in RA.

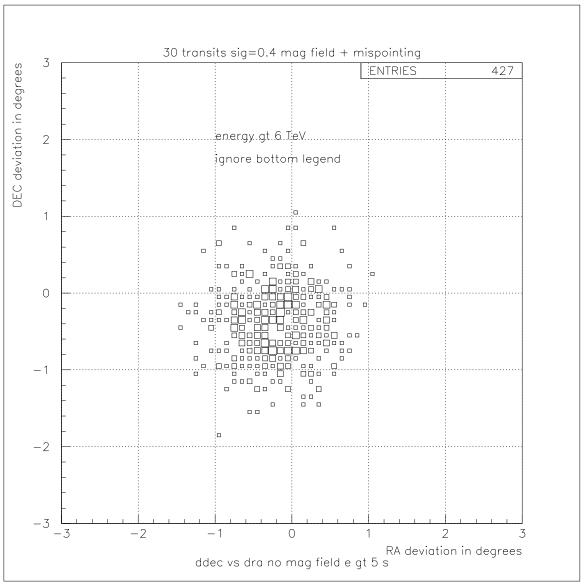

Figure 17: Diplot of deviations from true moon position in DEC versus RA including magnetic field and mispointing

Figure 18 displays fits to the event density distributions for events with energy greater than 6 TeV with the apparent position of the moon shifted by steps of -0.2 in DEC. The best fit to a moonshadow is obtained by a shift of -0.4 degree in DEC, Figure 18.

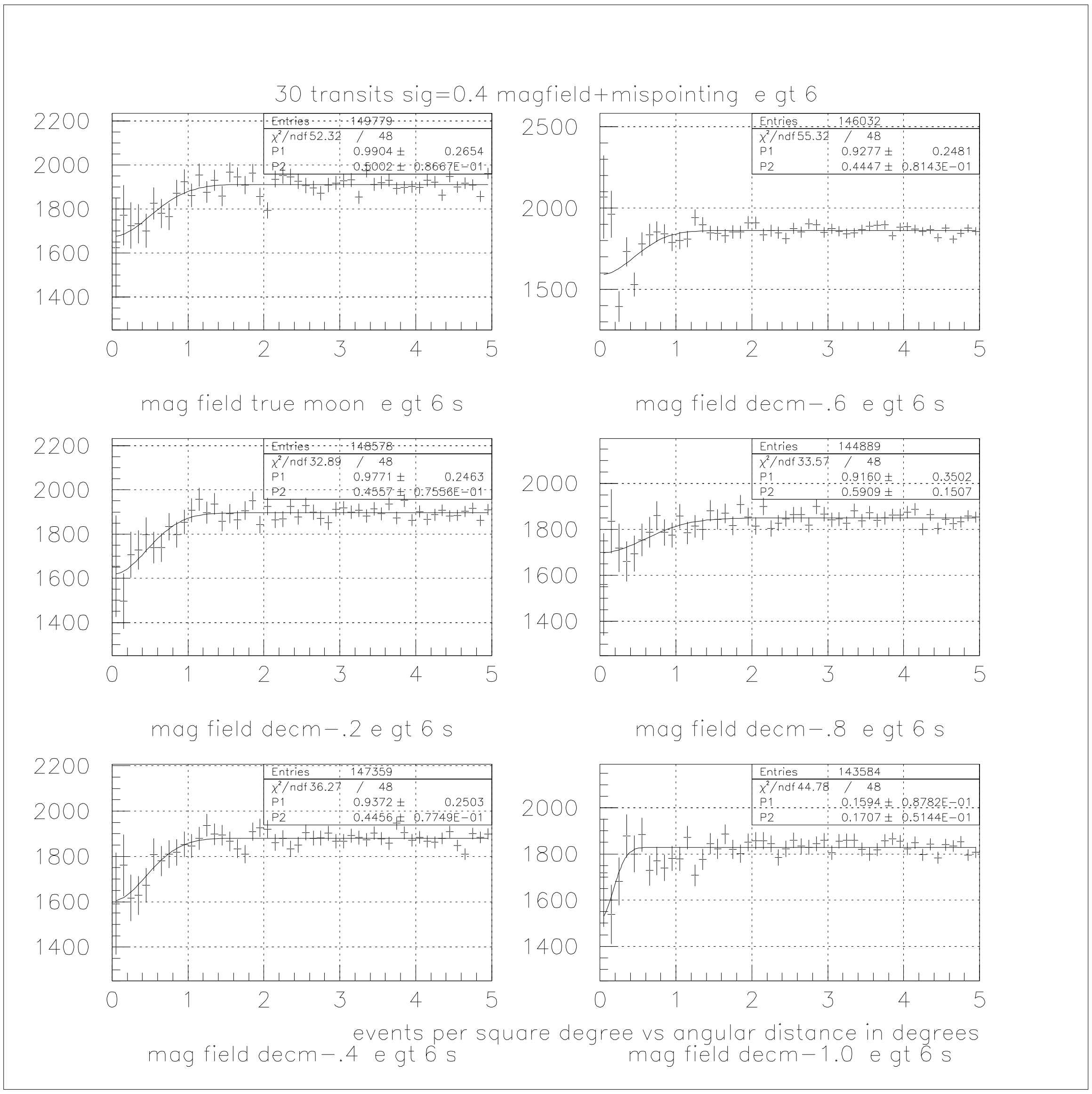

Figure 18: Fits to event distributions for energies > 6 TeV for apparent moon position shifted in steps of -0.2 degrees in declination.