Anisotropy Studies

With the Pierre Auger Surface Array Data

Antoine Letessier-Selvon - for the Pierre Auger collaboration
University Pierre & Marie Curie (upmc-Paris)/in2p3-cnrs

PLAN

- Determination of Arrival Directions

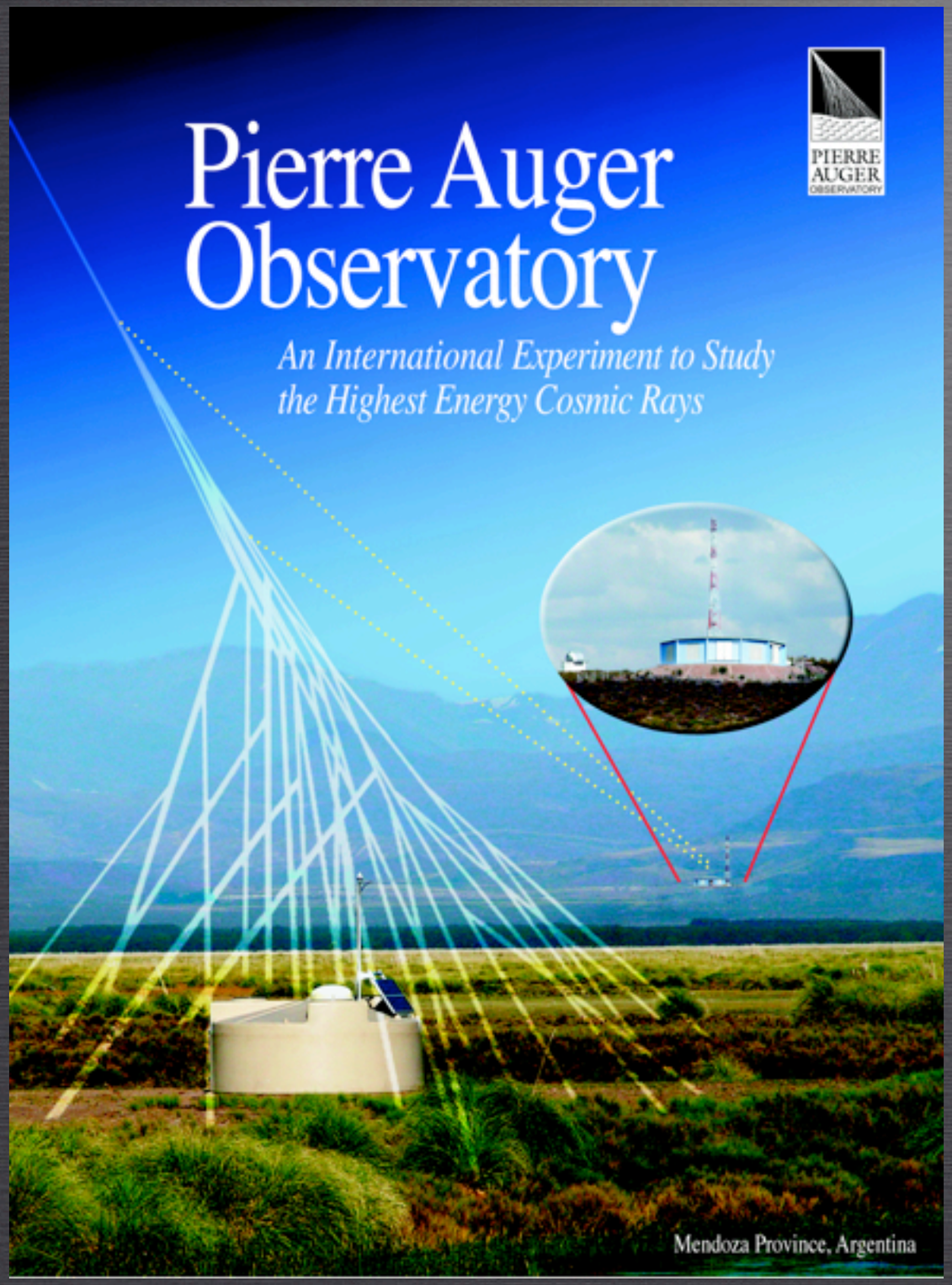
- Search for Modulations in Right Ascension

-Search for point sources :

. VCV AGN updates

. Search with other Catalogs

THE PIERRE AUGER OBSERVATORY



A hybrid detector:

Surface Detector Array of 1600 water tanks sampling the lateral profile of the Extensive Air Showers

Air Fluorescence Detector of 4 Telescopes sampling the longitudinal profile of the EAS

-

This allows cross-calibration to be performed on set of showers detected at the same time by both detectors

Determination of Arrival directions

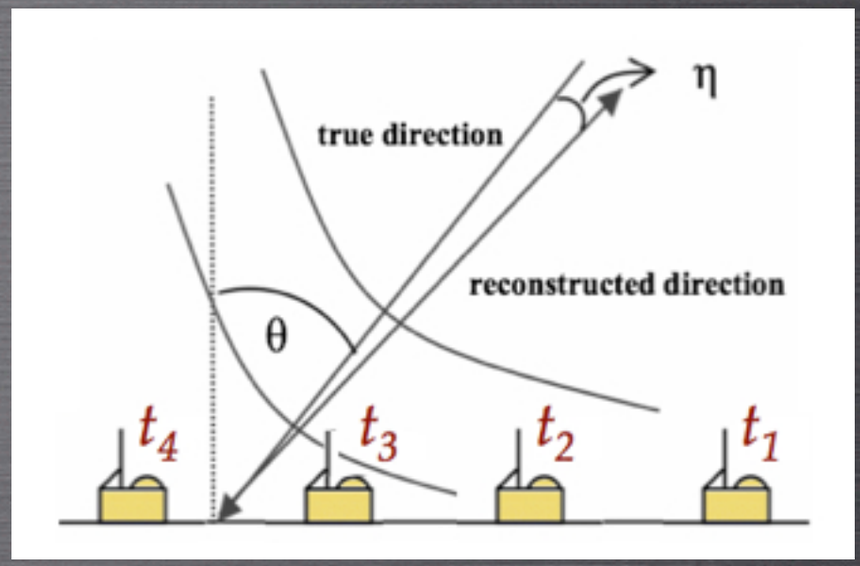
The variance of T_s in the SD stations is given by the sum of the detector clock precision (b^2) and of the variance of T_1. It then becomes:

$$V[T_s] = a^2 \left(\frac{2\ T_{50}}{n}\right)^2 \frac{n-1}{n+1} + b^2,$$

where T_{50} is the time interval that contains the first 50% of the total signal as measured by the photomultiplier FADC (flash analog-to-digital converters) traces. The parameter a is a scale factor, containing all the assumptions considered in the model and the treatment done to the FADC traces. The parameter b should be given by the GPS clock accuracy (about 10 ns) and the FADC trace resolution ($25/\sqrt{12}$ ns), that is $b \simeq 12$ ns. Both a and b are determined from the data.

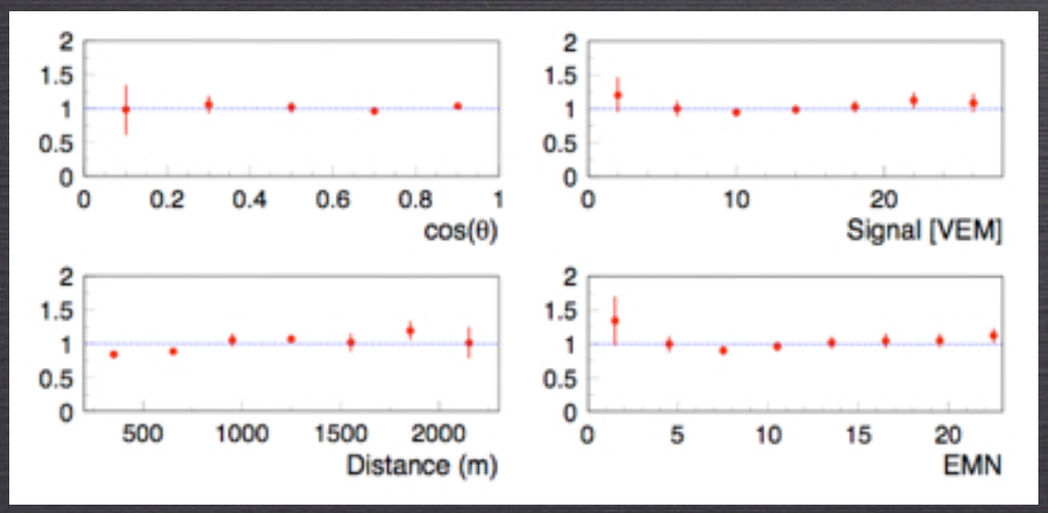
A special sub-array of pairs of water Cherenkov detectors has been deployed as a part of the surface array. These are adjacent detectors located ~11 m apart,

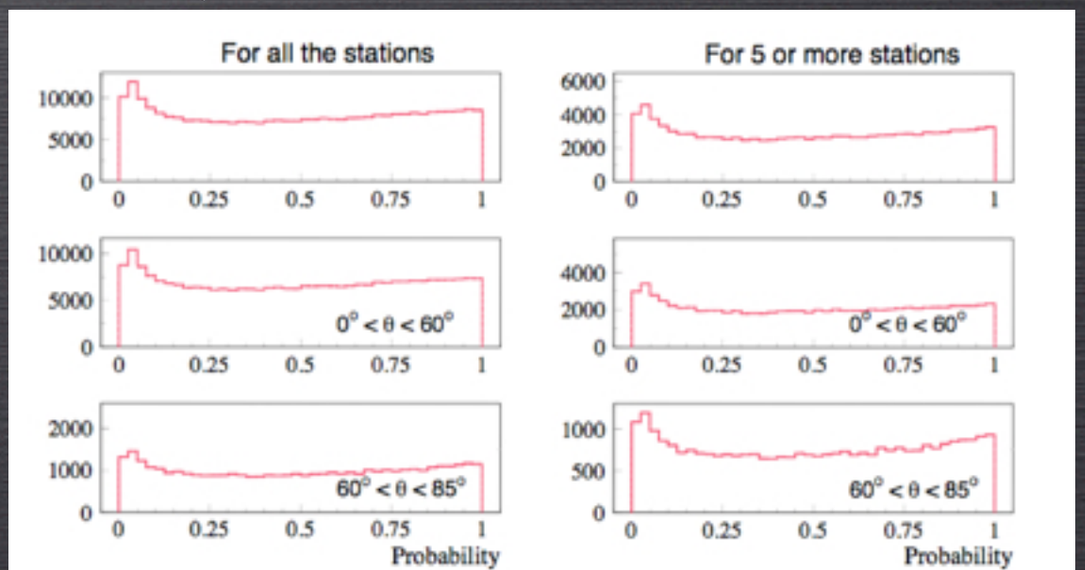
Adjust shower front model to start of ADC trace in SD tanks



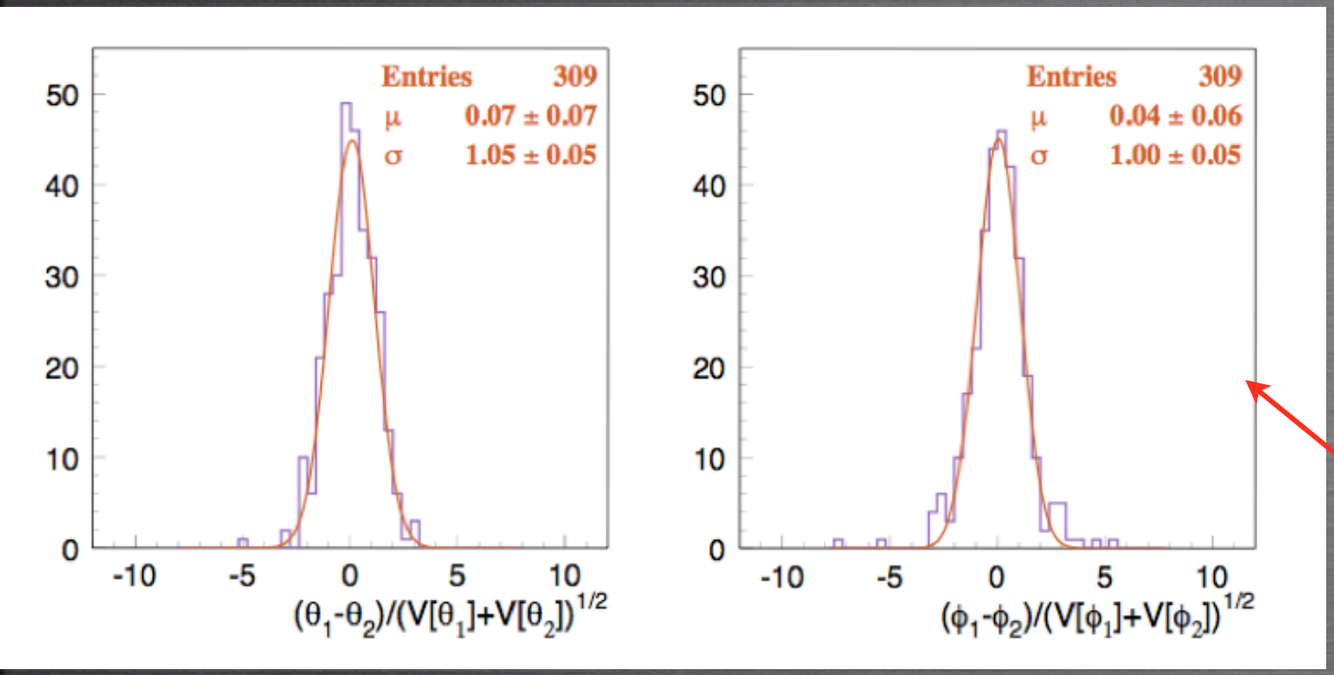
Use a model adjusted to data for the measurement uncertainty

Correct model produces flat χ^2 distribution and Normalized pulls



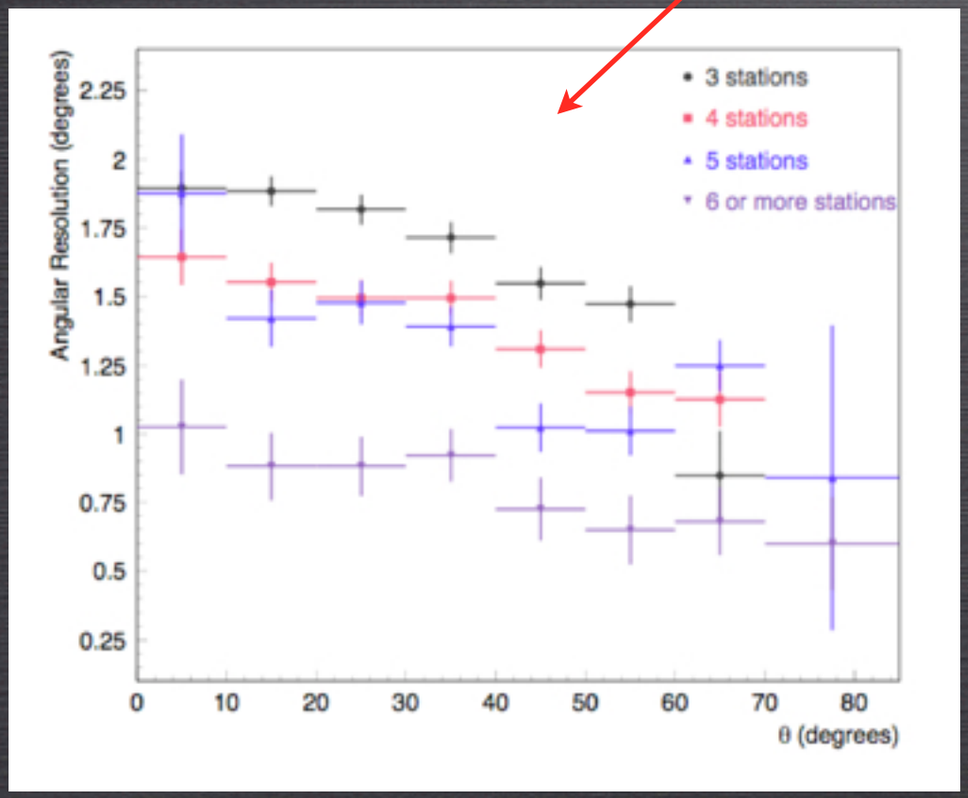


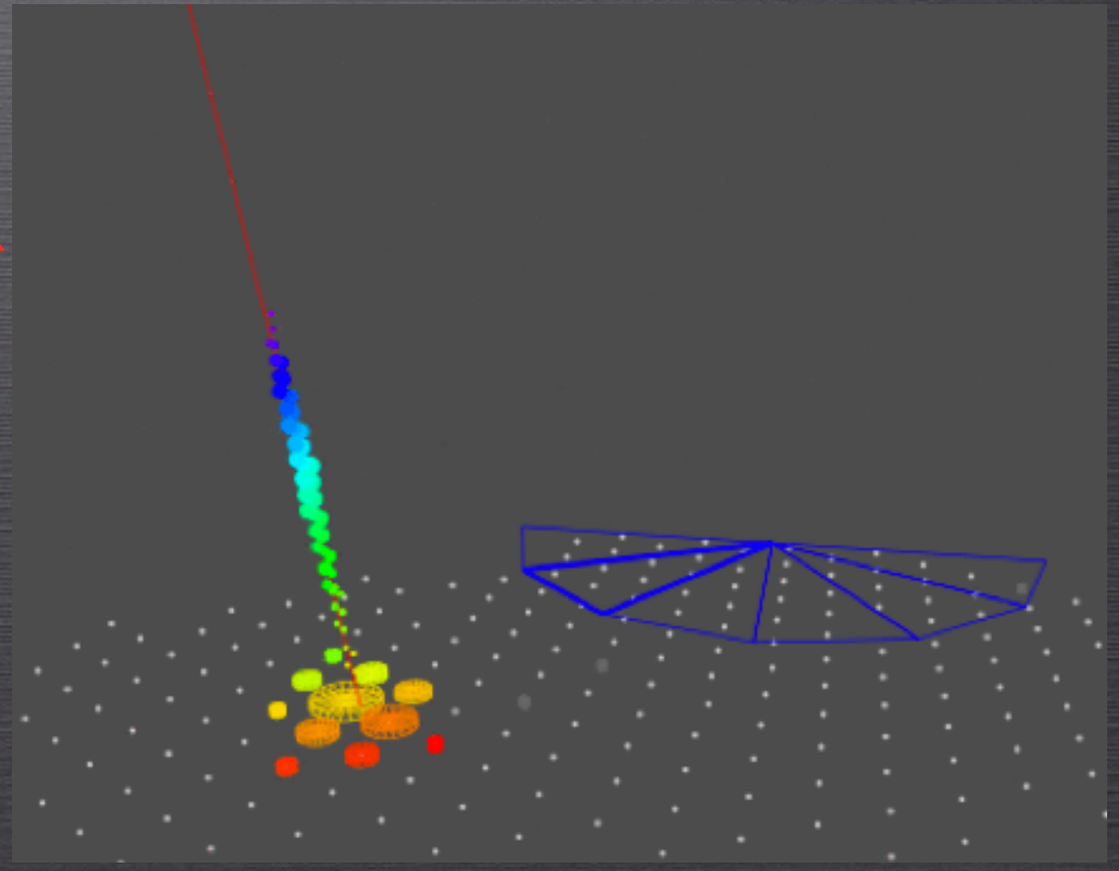
Checks with 2 independent reconstructions



-Twin Tanks and Super hexagon

Hybrids

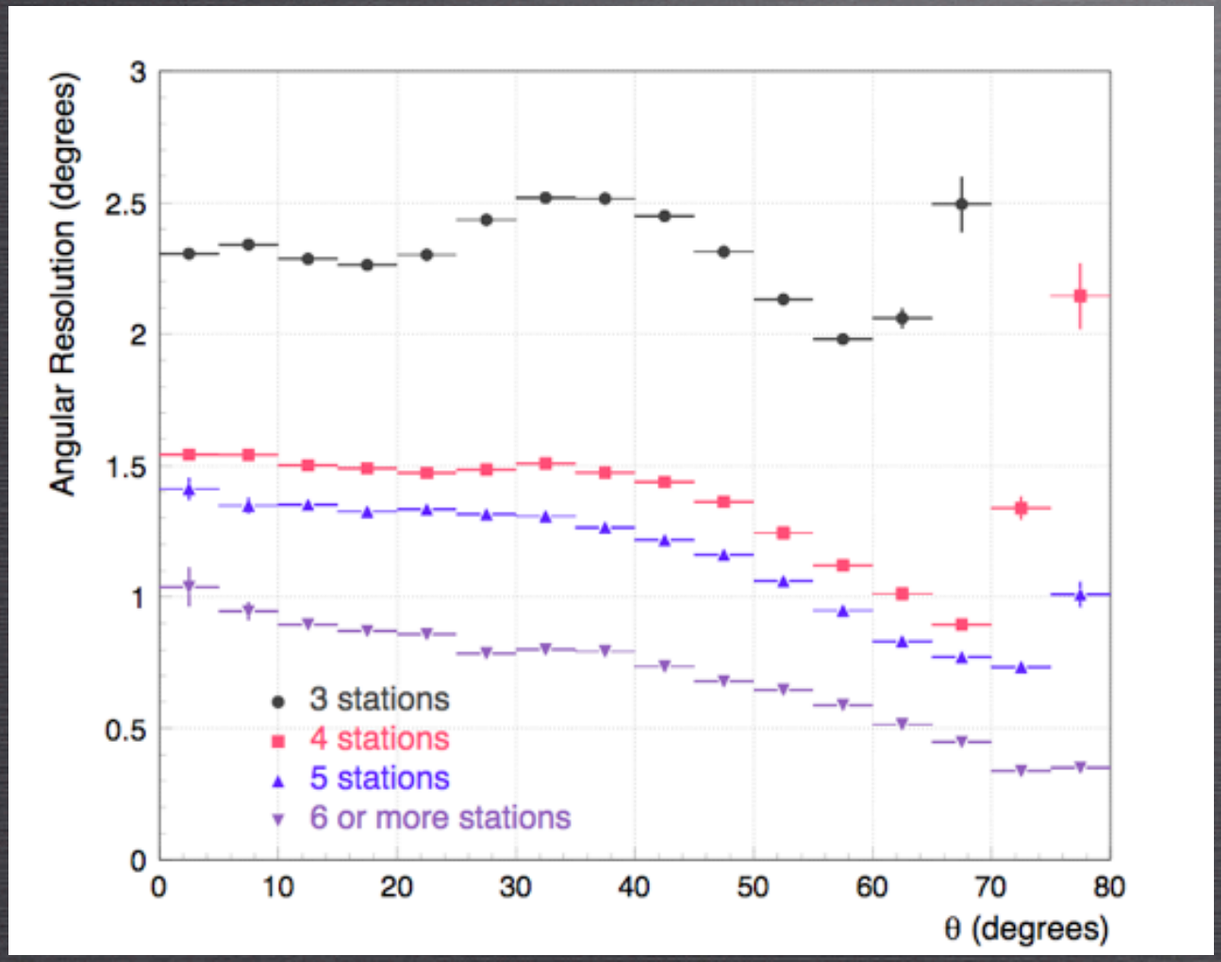




Resolution determined on an event by event basis

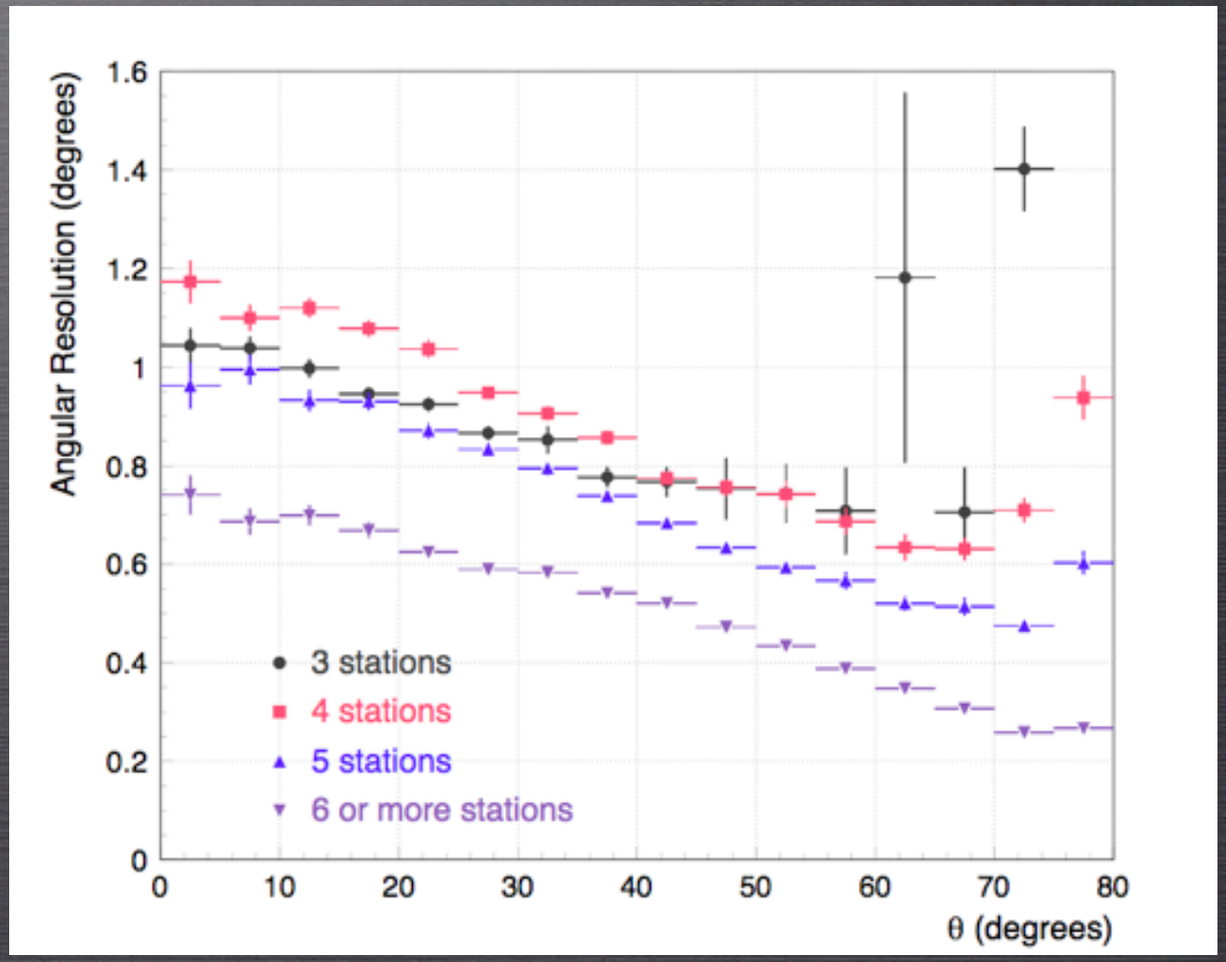
Resolution defined as :
Angular distance containing 68% of a neutral point source

All Events



Resolution is always better than 2.5°

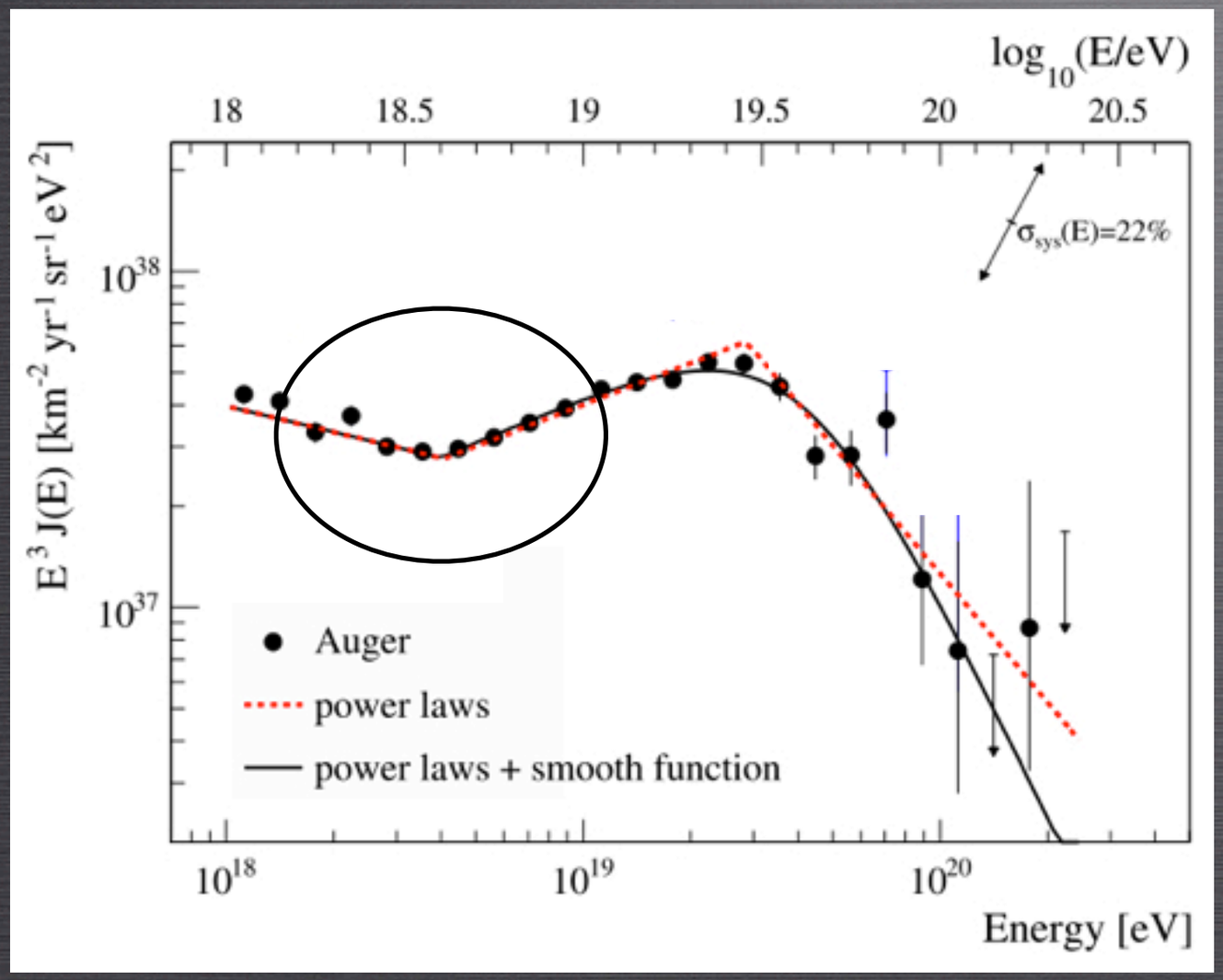
E > 3 EeV



Above 10 EeV resolution is always better than 0.8°

SEARCH FOR
RIGHT ASCENSION MODULATIONS
AT
EEV ENERGIES

GALACTIC OR EXTRA-GALACTIC ORIGIN OF EEV COSMIC RAYS ?



2 possible scenarios

1/ Galactic to extra-galactic transition occurring at the ankle :
amplitude of dipolar pattern steadily increasing with energy up to the ankle (however very model dependent on sources distribution and galactic magnetic field)

2/ transition at lower energy : relative motion of the observer with respect to the sources "rest frame" influences the large scale distribution of CRs

Measuring the large scale anisotropy pattern as a function of energy is one of the main observable for discerning between the 2 scenario

First harmonic analysis

Auger Collaboration, submitted to Astro. Part. Phys.

Searching for large scale patterns at the %-level is challenging :
it requires that the sky exposure be controlled within the
corresponding accuracy

Combination of diurnal and yearly modulations may
generate spurious variation at the sidereal frequency

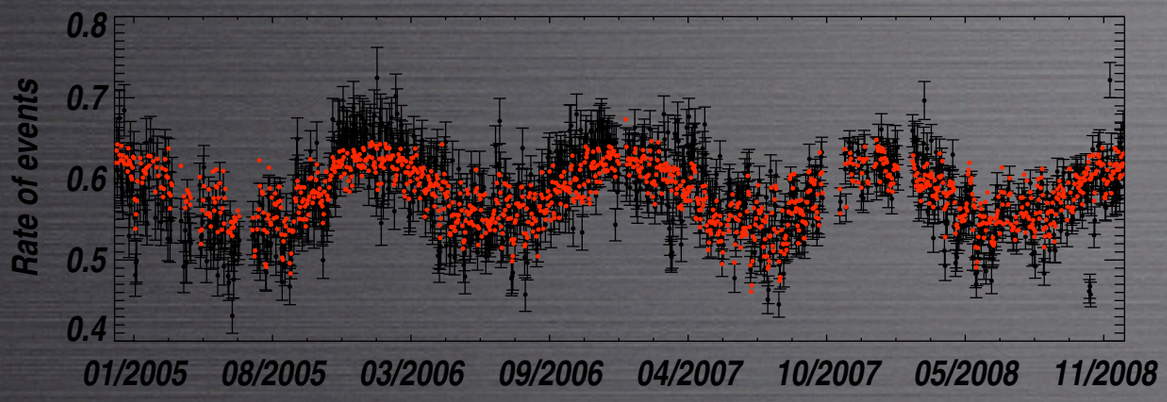
We need to take into account the
detector growth and instabilities
as well as the «weather effects».
-

Control Systematics using several techniques :
- standard Rayleigh analysis,
- East-West differential method,
- Fourier transform in modified time
-
Cross-check all results varying corrections
and data selection

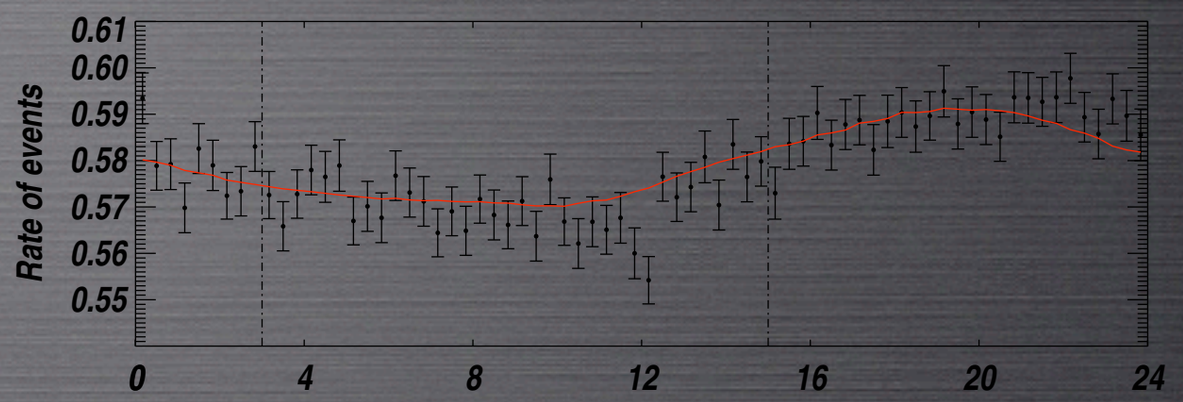
Atmospheric (weather) effects

Auger Collaboration, Astropart. Phys., 32 (2009)89

Influence of atmospheric conditions on shower size at ground produces a rate modulation above a fixed threshold :



Annual modulation



Dayly modulation

$$\frac{1}{R}\frac{dR(>S_{th})}{d\xi} \simeq (\gamma_S - 1)\,\alpha_\xi$$

α is the coefficient of relative variation of the rate corresponding to the atmospheric parameter ξ

γ_s is the spectrum index

For ξ = pressure and density measure from data the corresponding α

Correct the measured shower to a reference temperature, density and pressure (Taken as the annual mean values of those quantities at the Auger site)

$$\tilde{S}(1000) = \left[1 - \alpha_P(\theta)(P - P_0) - \alpha_\rho(\theta)(\rho_d - \rho_0) - \beta_\rho(\theta)(\rho - \rho_d)\right] S(1000)$$

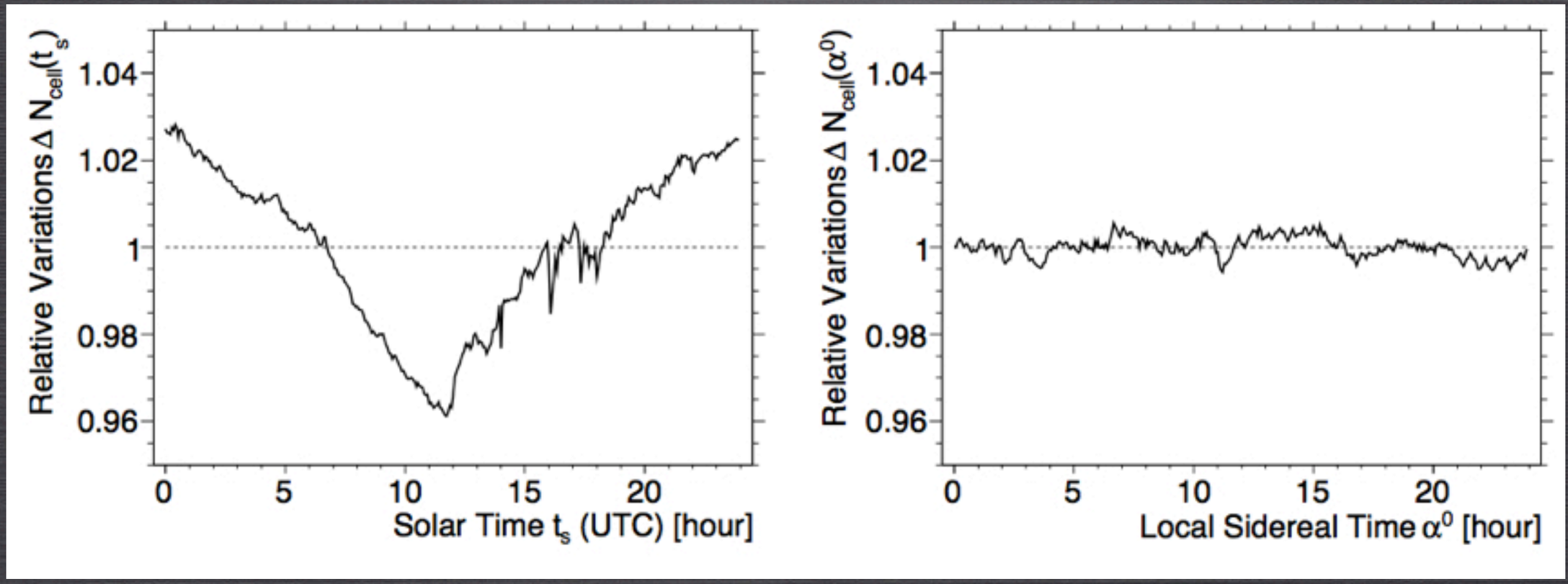
Detector growth and coverage calculation

We record each second the id of every active detector in the field, we deduce the number of active hexagon (and its relative variation) as a function of time :

$$N_{\text{cell}}(t) = \sum_j n_{\text{cell}}(t + jT), \qquad \Delta N_{\text{cell}}(t) = \frac{N_{\text{cell}}(t)}{\langle N_{\text{cell}}(t) \rangle}$$

$$\langle N_{\text{cell}}(t) \rangle = 1/T \int_0^T dt\, N_{\text{cell}}(t)$$

relative coverage as a function of Solar (UTC) and local Sidereal time :
(6 years data set from 01/01/2004 until 31/12/2009)



$$w_i \equiv [\Delta N_{\text{cell}}(\alpha_i^0)]^{-1}$$

will be used to weight the events recored at time α_i^0

Rayleigh analysis weighted by exposure

$$a = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i, \qquad b = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

$$w_i \equiv [\Delta N_{\mathrm{cell}}(\alpha_i^0)]^{-1}$$

$$\mathcal{N} = \sum_{i=1}^{N} w_i$$

$$r = \sqrt{a^2 + b^2}, \qquad \varphi = \arctan \frac{b}{a}.$$

East-West method

$$I_E(\alpha^0) - I_W(\alpha^0) = -\frac{N}{2\pi} \frac{2\langle \sin\theta \rangle}{\pi \langle \cos\delta \rangle} r \sin(\alpha^0 - \varphi)$$

$$a_{EW} = \frac{2}{N} \sum_{i=1}^{N} \cos(\alpha_i^0 + \zeta_i), \qquad b_{EW} = \frac{2}{N} \sum_{i=1}^{N} \sin(\alpha_i^0 + \zeta_i)$$

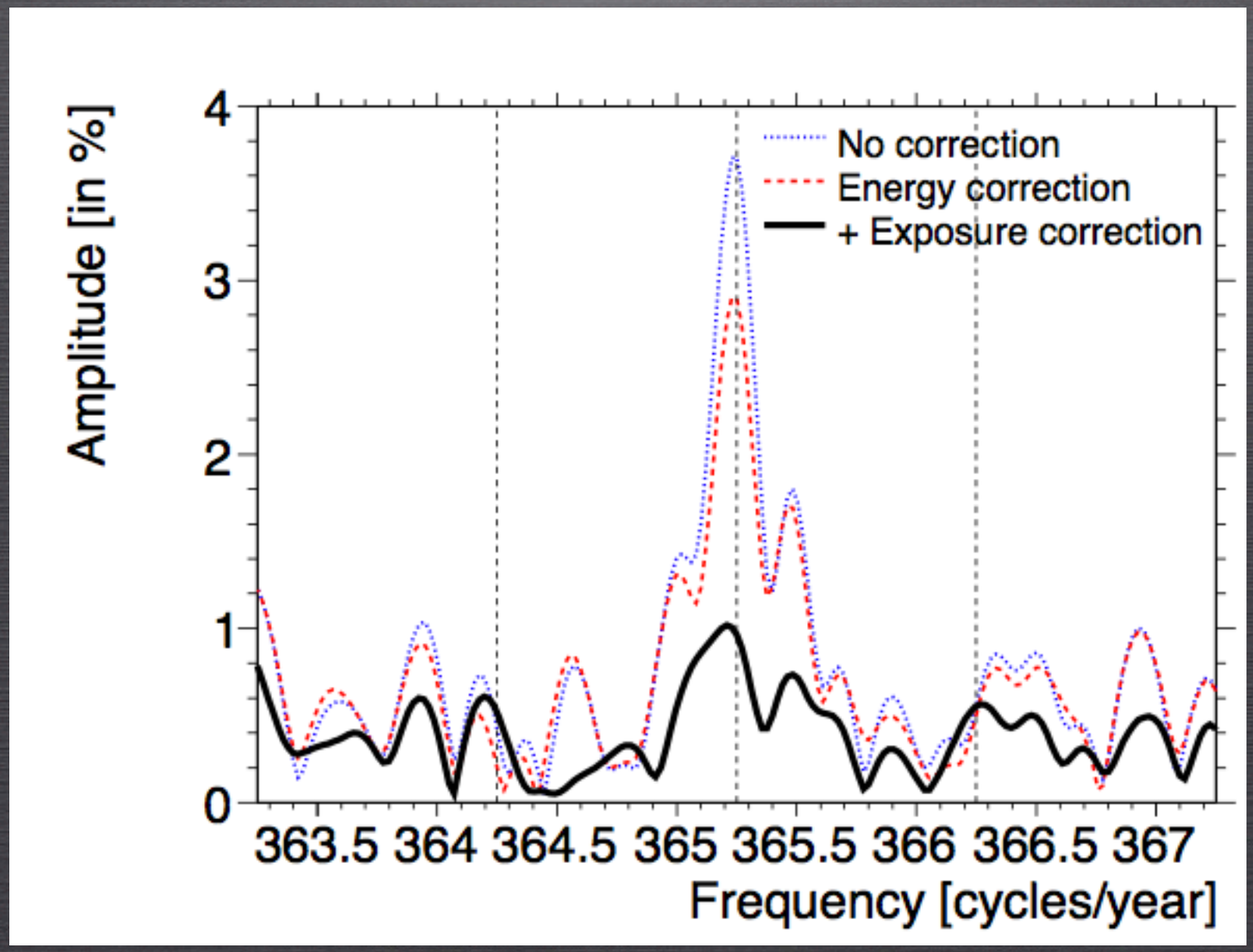
ζ_i equals 0 if the event is coming from the East or π if coming from the West

$$r = \sqrt{a_{EW}^2 + b_{EW}^2}, \qquad \varphi_{EW} = \arctan\left(\frac{b_{EW}}{a_{EW}}\right)$$

Fourier transform in modified time :

$$\tilde{\alpha}_i^0 = \frac{2\pi}{T_{sid}} t_i + \alpha_i - \alpha_i^0$$

Allow analysis of solar, anti-sidereal, and random frequencies :

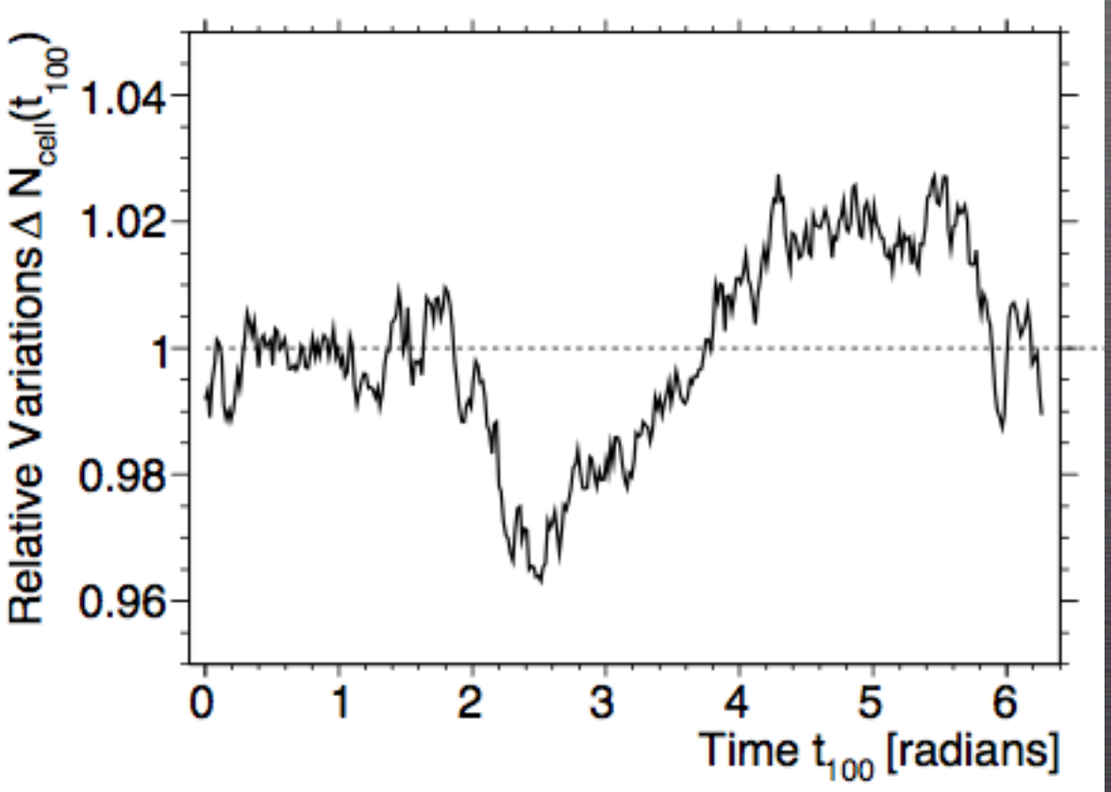


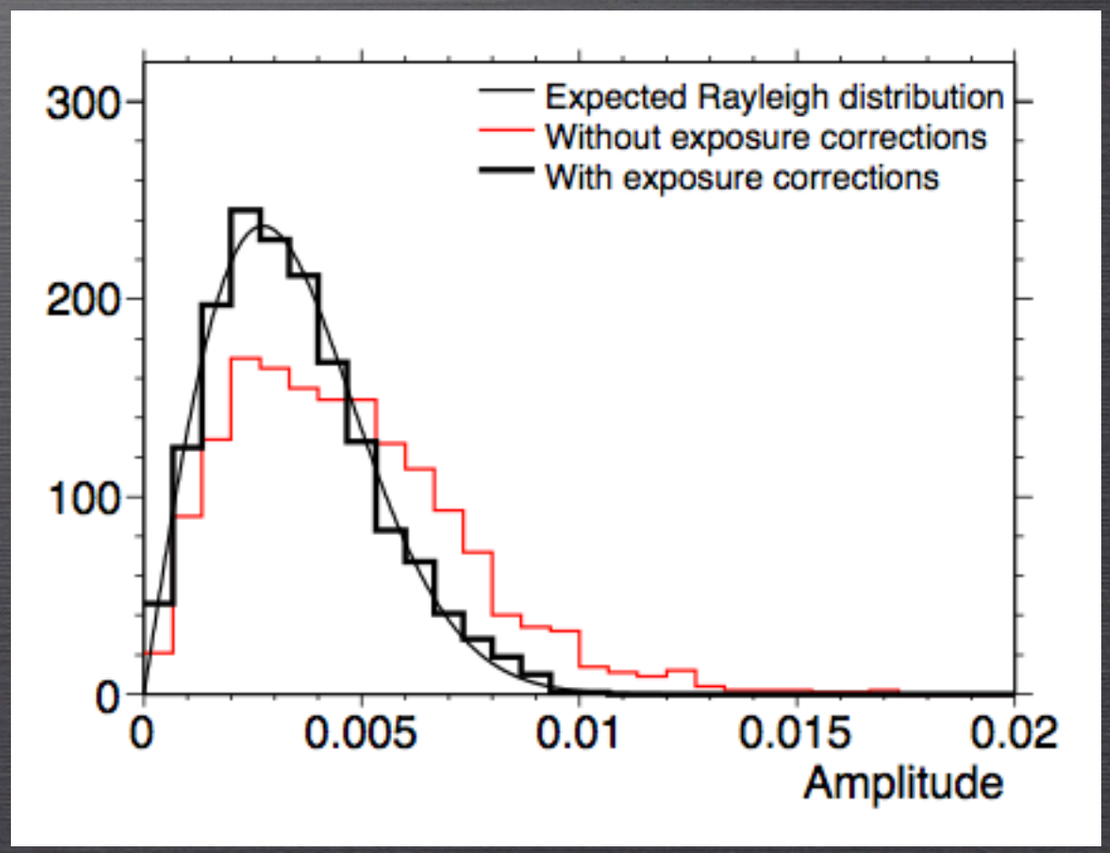
Consistency checks - I

a) Effect of exposure and energy correction at solar and anti-sidereal frequencies

	$r_{solar}[\%]$	$P(> r_{solar})[\%]$	$r_{anti-sid}[\%]$	$P(> r_{anti-sid})[\%]$
no correction	3.7	$\simeq 2\,10^{-37}$	0.36	43
energy corrections	2.9	$\simeq 4\,10^{-23}$	0.15	85
+exposure correction	0.96	0.2	0.49	19

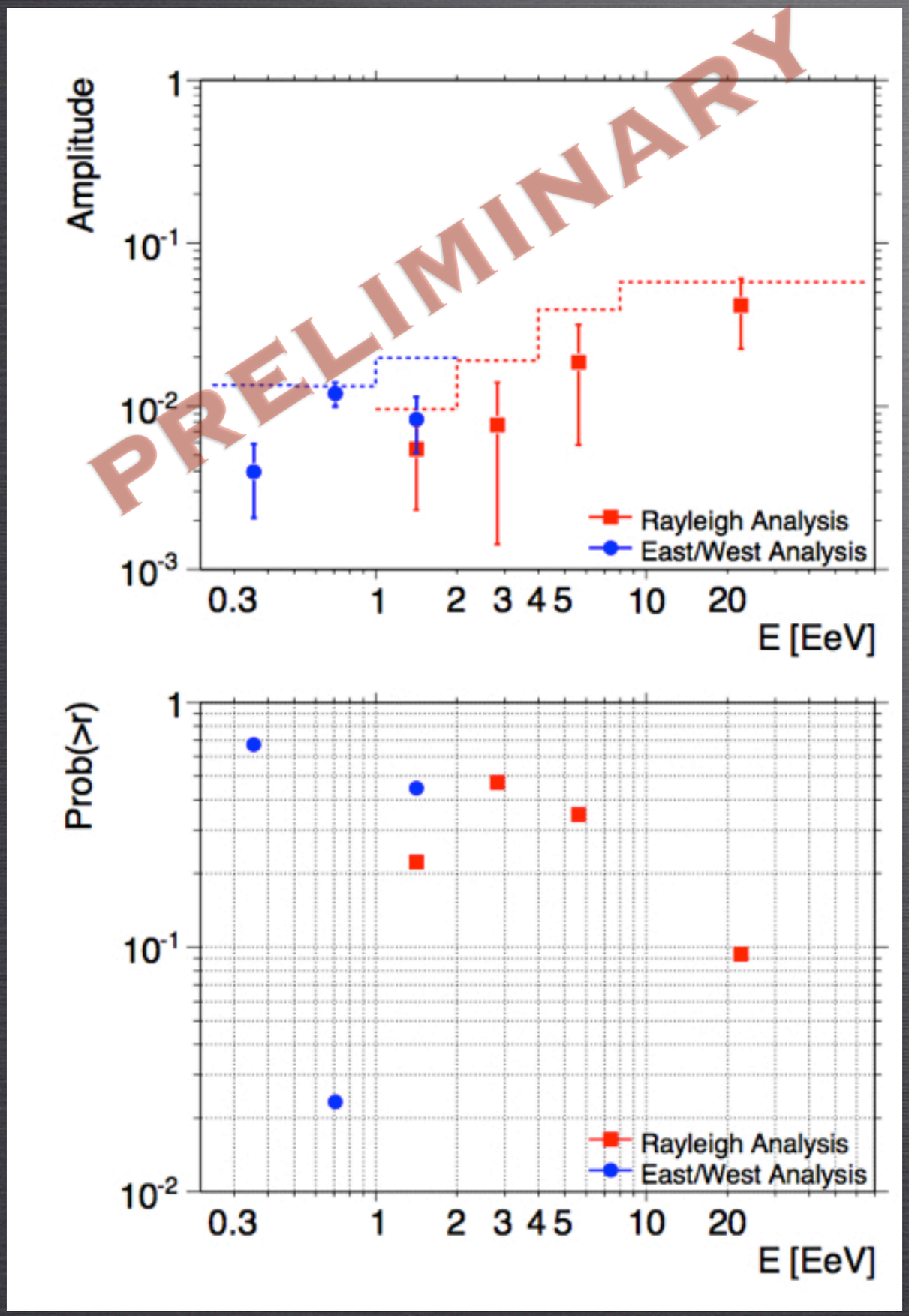
b) Effect of exposure correction at random frequencies between 100 and 500 cycle/year





Left : Relative variation of the integrated number of unitary cells as a function of t100, corresponding to 100 cycles/year. Right : Rayleigh analysis above 1 EeV for 1600 random frequencies ranging from 100 to 500 cycles/year.

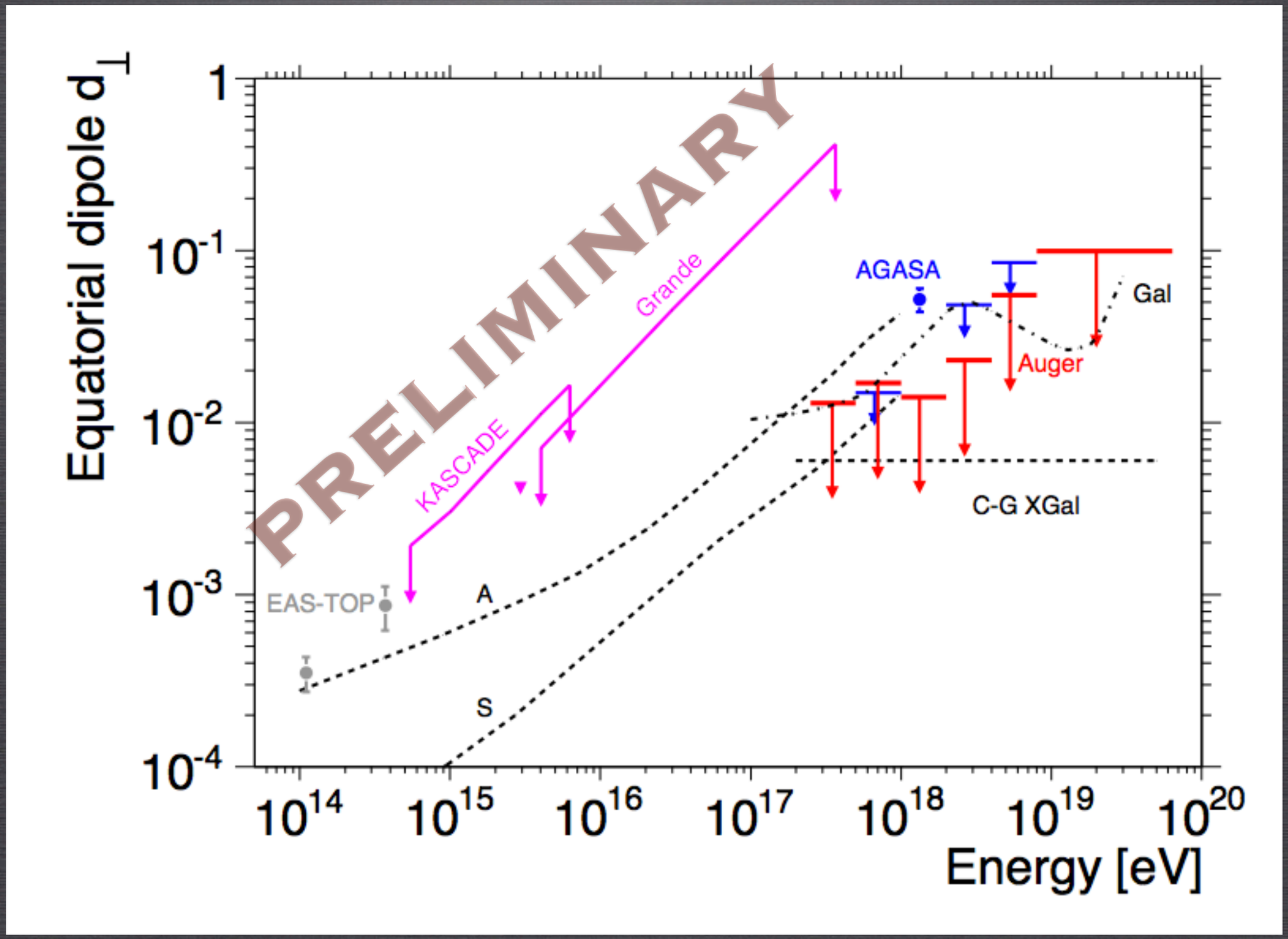
Results on modulation amplitudes



Amplitude of the first harmonic as a function of energy. The dashed line indicates the 99% C.L. upper bound on the amplitudes that could result from fluctuations of an isotropic distribution.

Corresponding probabilities to get at least the same amplitude from an underlying isotropic distribution.

Corresponding upper limits



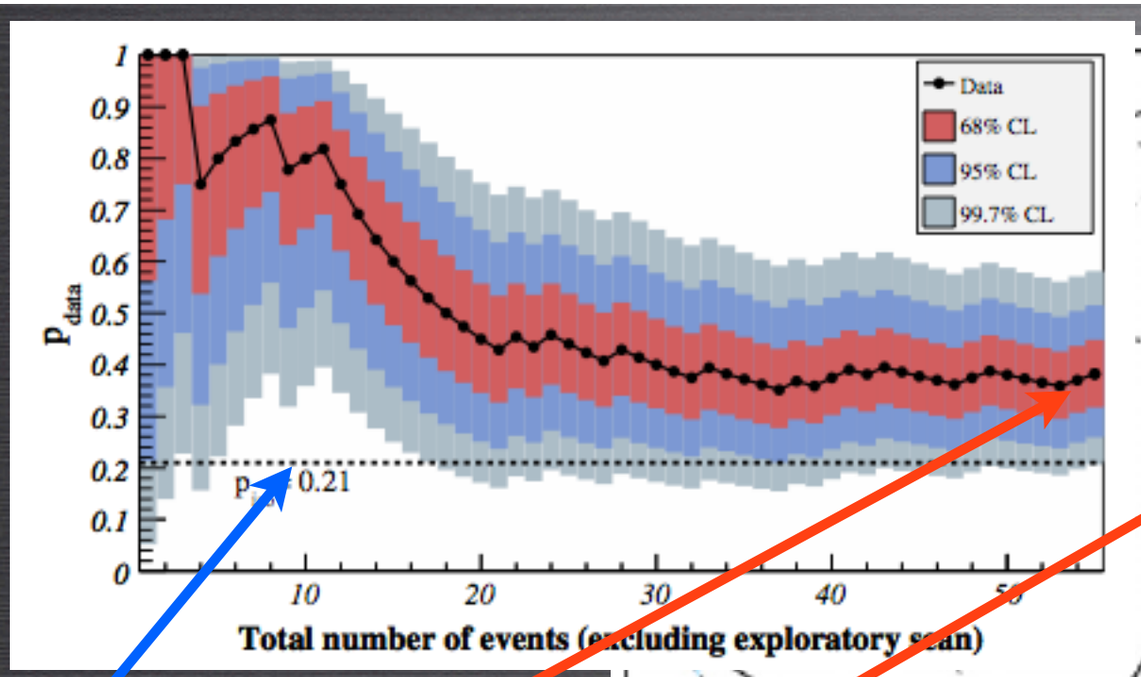
J. Linsley "if the number of events available in an experiment is such that the RMS value of r is equal to the true amplitude, then in a sequence of experiments r will be significant (say P(> r) < 1%) in one experiment out of ten whereas the phase will be within 50° of the true phase in two experiments out of three."

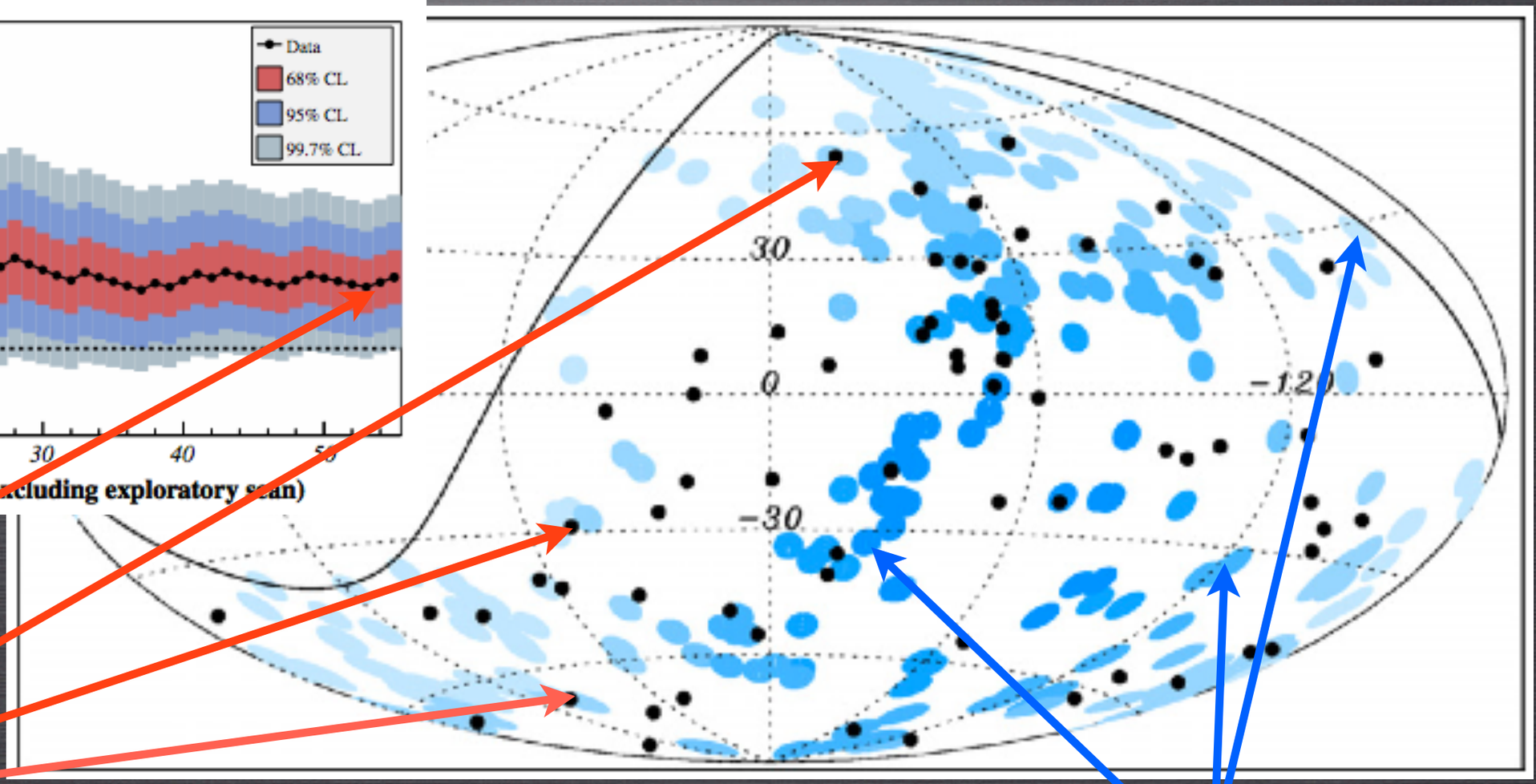
ANISOTROPIES AT ULTRA-HIGH ENERGIES

Update of the VCV correlation

Auger Collaboration Astroparticle Physics 34 (2010) 314

Period	Dates	Exposure (km^2 sr y)	N	k	k_{iso}	P
I	1 January 2004–26 May 2006	4390	14	8	2.9	–
II	27 May 2006–31 August 2007	4500	13	9	2.7	2×10^{-4}
III	1 September 2007–31 December 2009	11,480	42	12	8.8	0.15
Total	1 January 2004–31 December 2009	20,370	69	29	14.5	–
II + III	27 May 2006–31 December 2009	15,980	55	21	11.6	$\mathbf{3 \times 10^{-3}}$





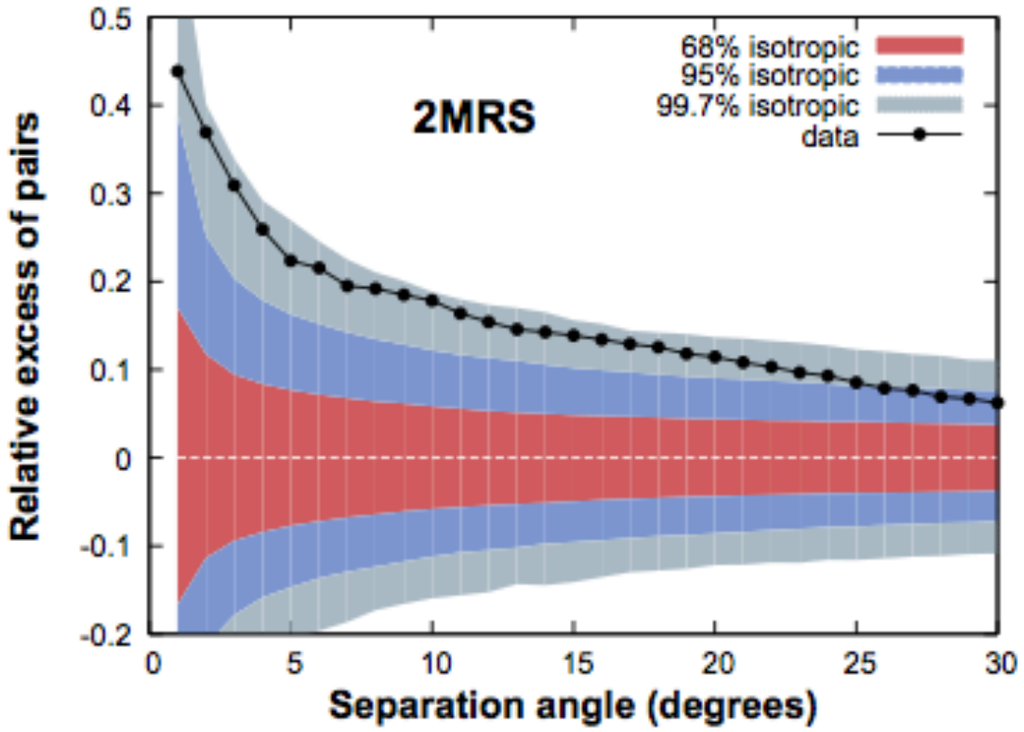
P_{ISO} = 0.21

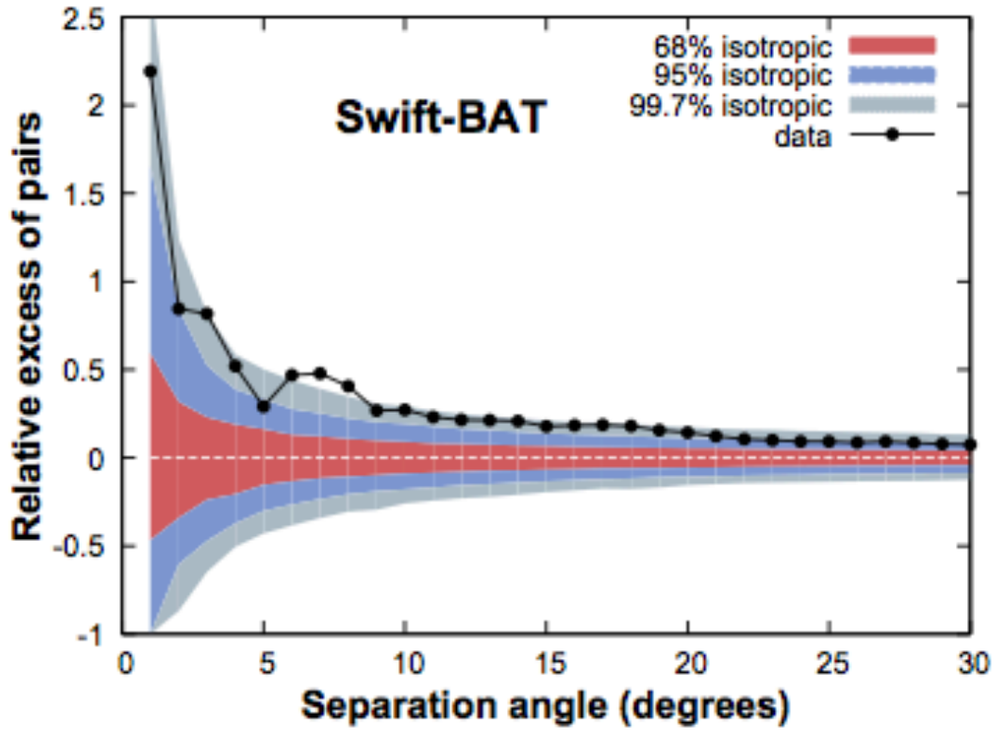
P_{DATA} = 0.38 $^{+0.07}_{-0.06}$

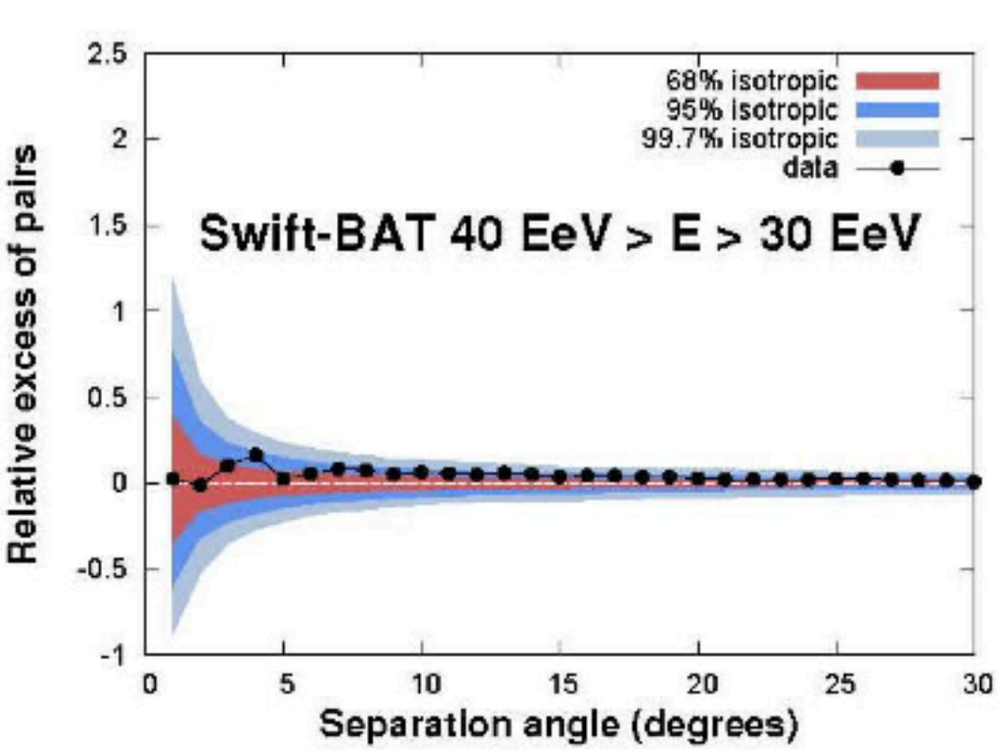
The 69 arrival directions of CRs with energy E > 55 EeV
Blue circles of radius 3.1° are centred at the positions of the 318 AGNs in the VCV catalog that lie within 75 Mpc and that are within the field of view of the Observatory.

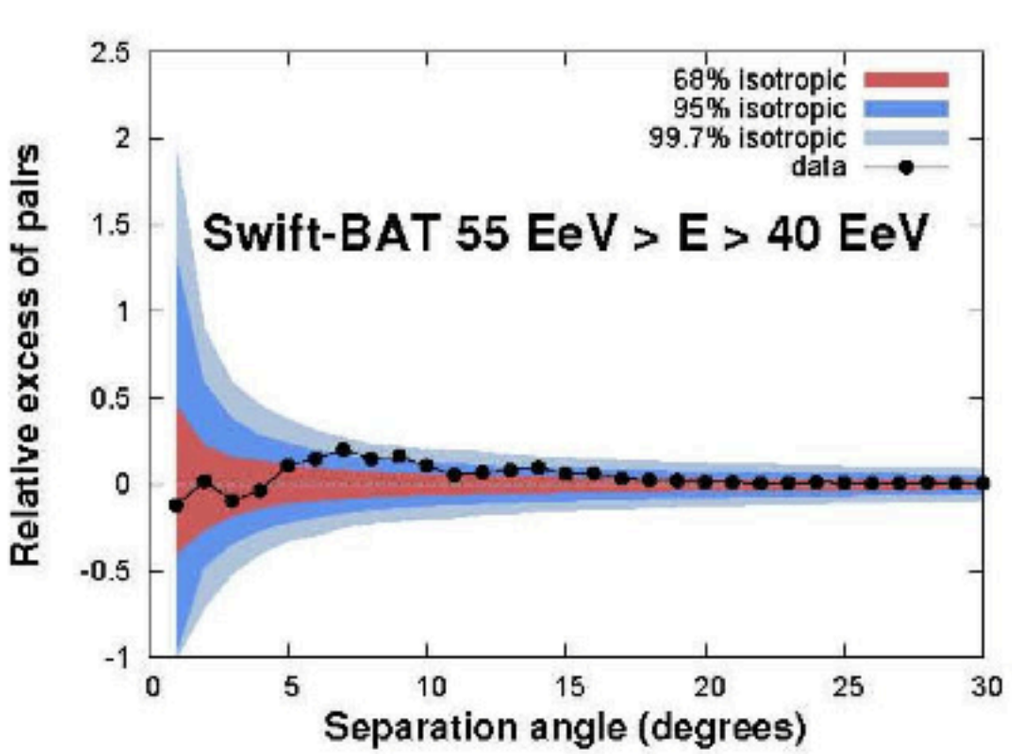
NOTE THAT : 0.38*15 ~ 6

Cross-correlation analyses with 2MASS and swift-BAT



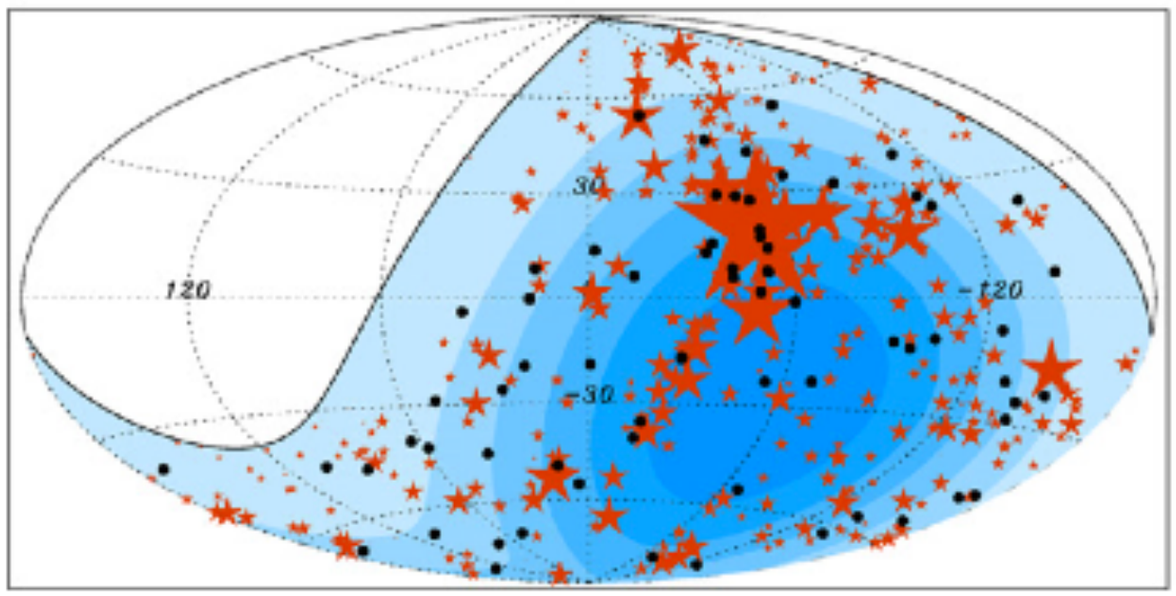




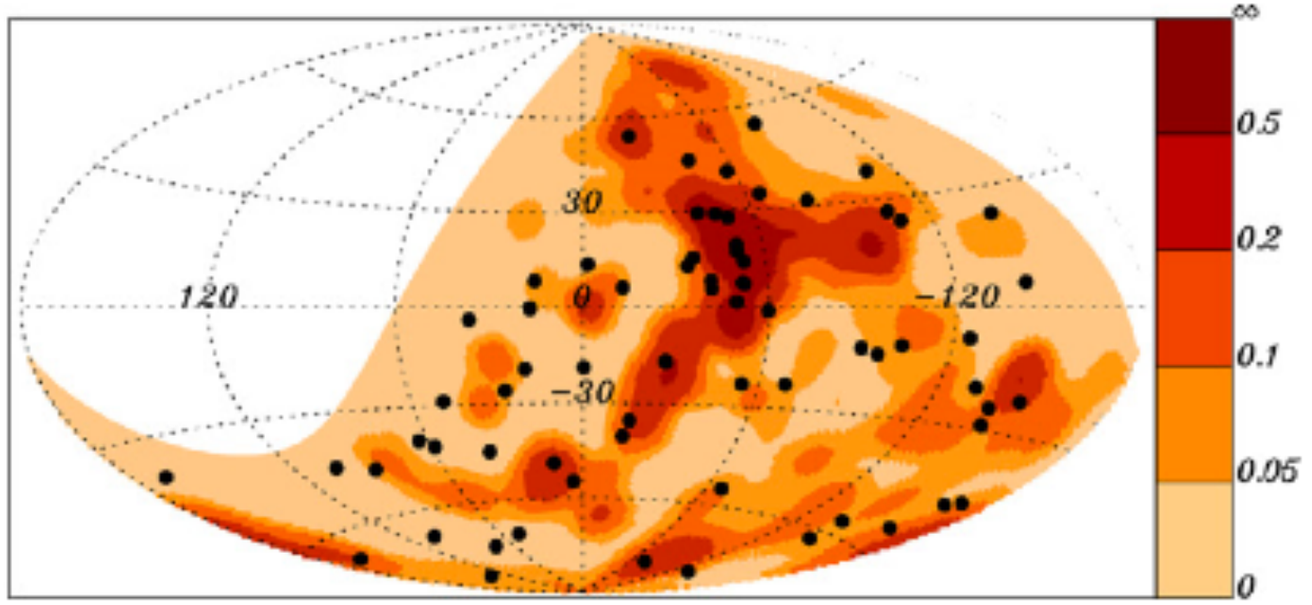


Top : events with E > 55 EeV and positions of 2MRS galaxies (left) and Swift-BAT AGN (right) that lie within 200 Mpc.
Bottom : Cross correlation with swift-bat at lower energy thresholds.

Likelihood on density maps



AGNs of the 58-month Swift-BAT red stars proportional to the assigned weight.

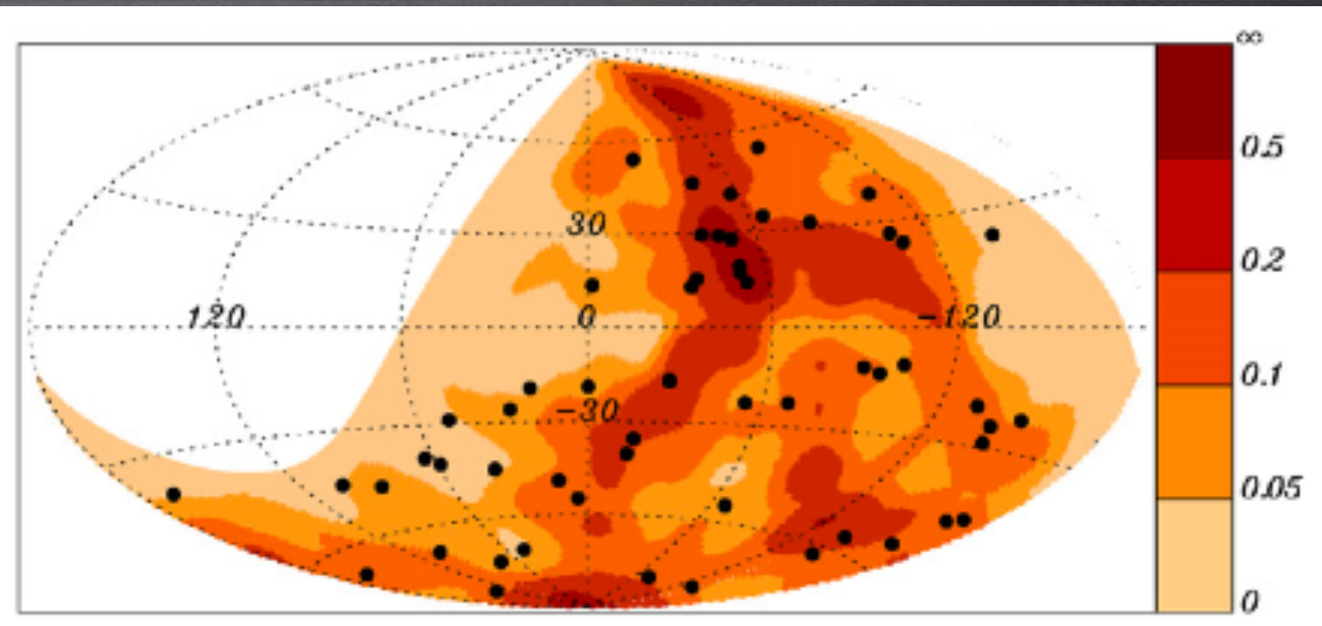


Corresponding density map smoothed at 5° together with 69 CRs with energy E > 55 EeV.

$$\phi(\hat{\mathbf{n}}) = \sum_{i=1}^{N_{\rm cat}} w(z_i)\, e^{-\frac{d(\hat{\mathbf{n}}_i,\hat{\mathbf{n}})^2}{2\sigma^2}}$$

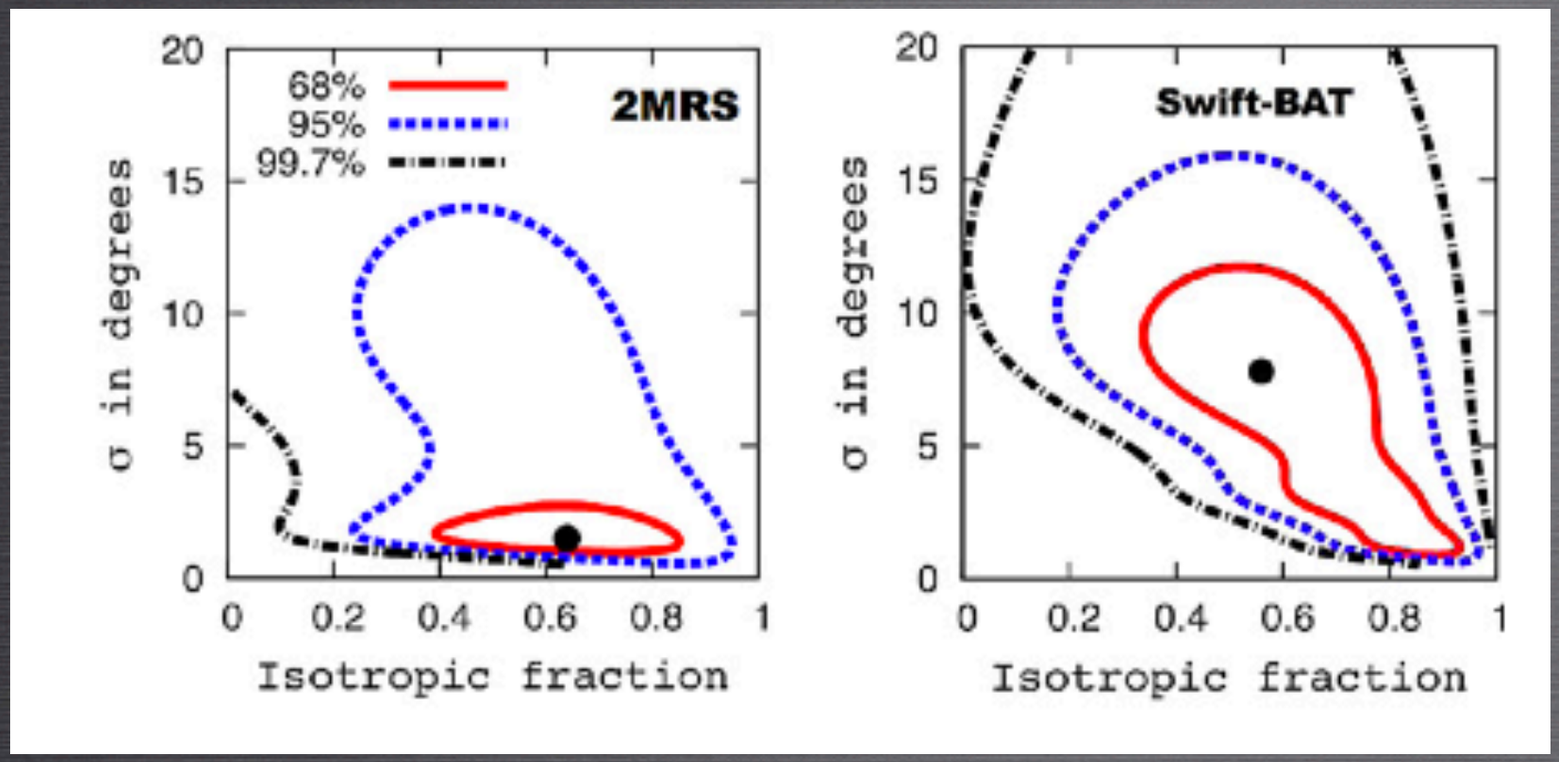
2 parameters adjusted on data

$$F(\hat{\mathbf{n}}) = \frac{\varepsilon(\hat{\mathbf{n}})\mu(\hat{\mathbf{n}})}{I}\left[\frac{f_{\rm iso}}{\Omega} + (1-f_{\rm iso})\frac{\phi(\hat{\mathbf{n}})}{\langle\phi\rangle}\right]$$

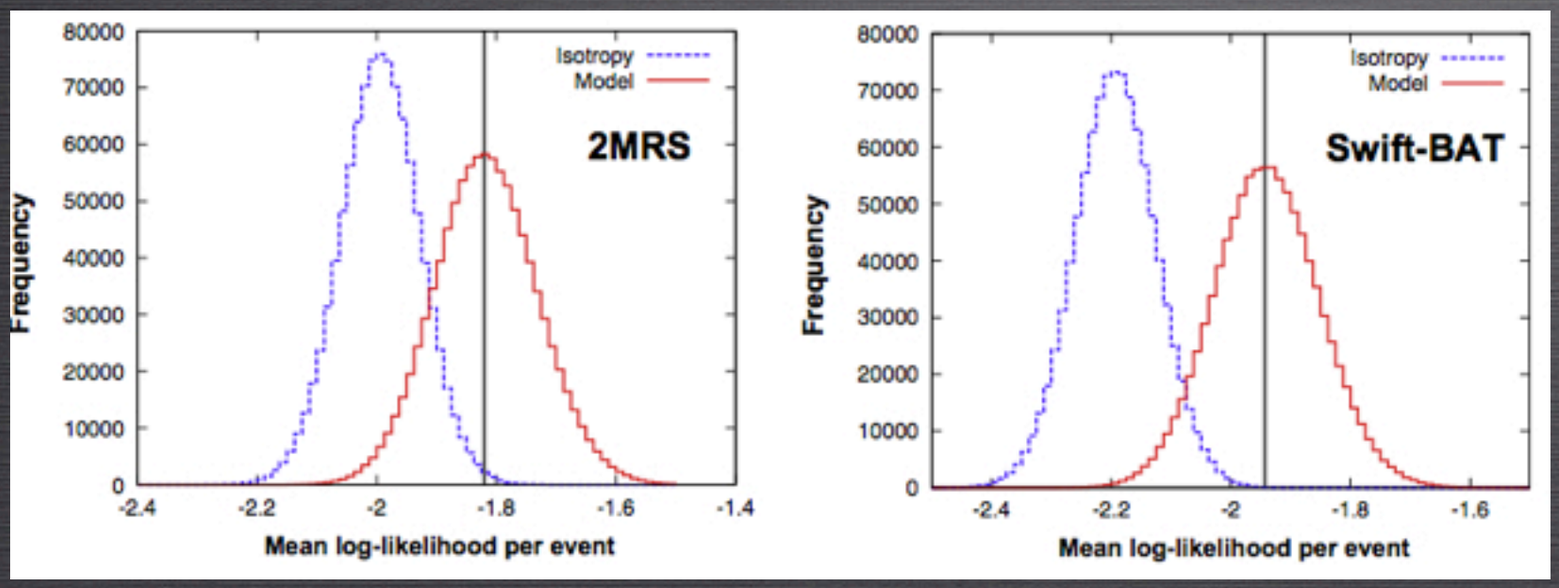


Same with 2MASS catalog and galactic latitudes > 10 .

Confidence intervals for the parameters

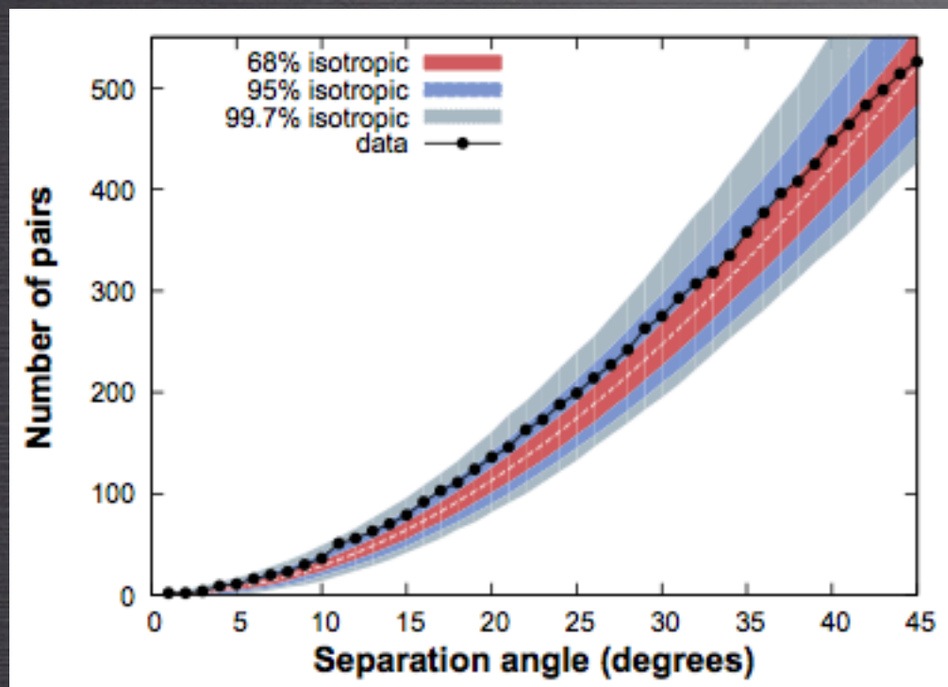


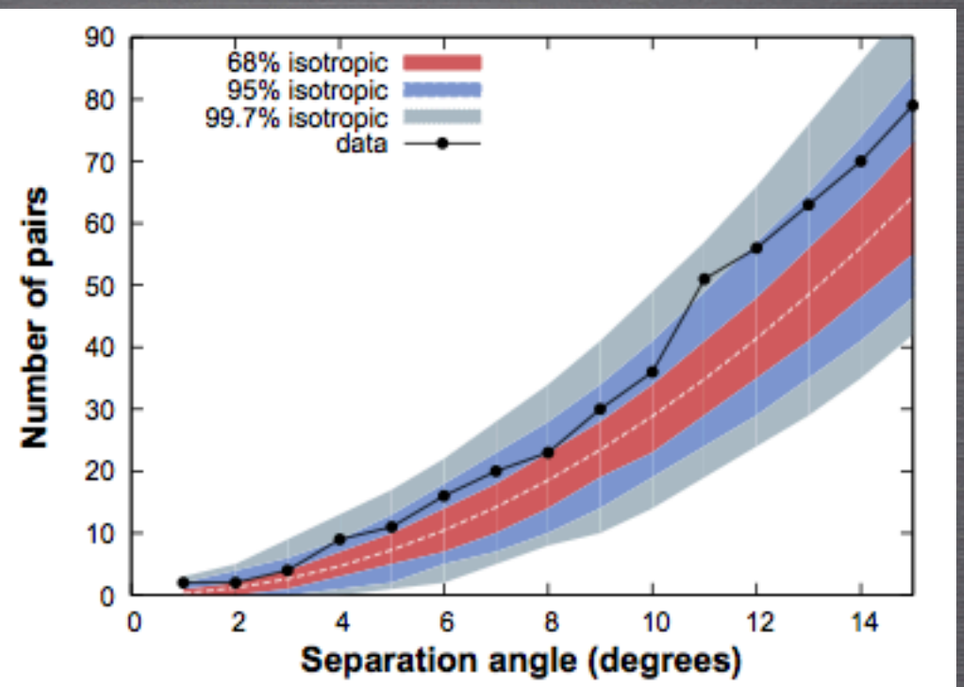
$$\mathcal{LL} = \sum_{k=1}^{N_{\text{data}}} \ln F(\hat{\mathbf{n}}_{\mathbf{k}})$$



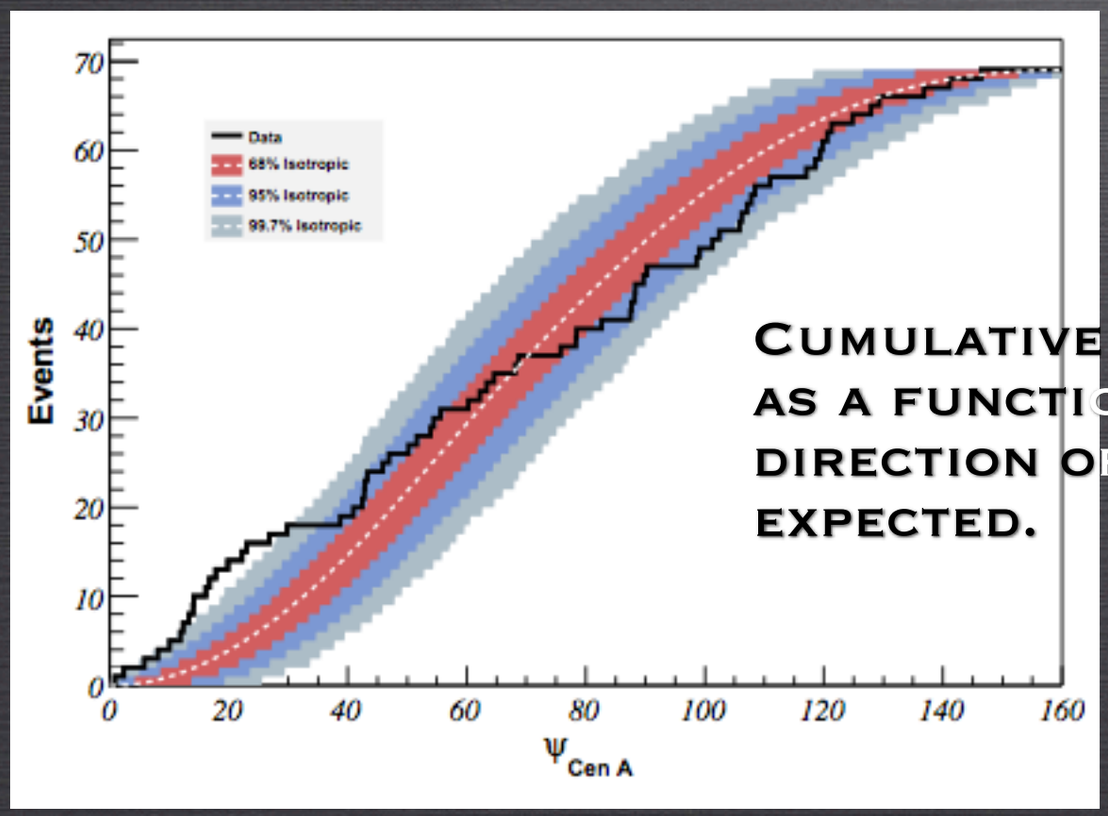
Contours for all data. Parameters are only weakly constrained.
likelihood distribution : f ~ 2 10^{-4} (2mass) 4 10^{-3} (S-B),
goes to ~ 2 10^{-2} with period I excluded

Autocorrelation and Cen A excess



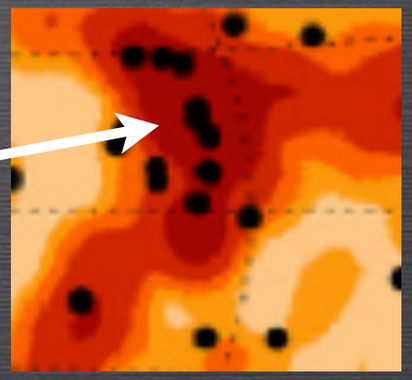


Cumulative autocorrelation function - all data above 55 EeV.
Largest excess @ 11° (51 pairs, 34.8 expected). Chance prob ~10% for similar excess at any angle.



Cumulative number of events with E > 55 EeV as a function of angular distance from the direction of Cen A. 13 events within 18°, 3.2 expected.

CenA



CenA contributions :
- 6 pairs < 4°, 28 pairs < 11°
- 18,8% of flux
  expectations are
  4.7 ISO, 13.3% 2MASS, 28,8 % S-B)

CONCLUSIONS

1] Right ascension modulations :

- No significant amplitude measured

- Stringent limits (1-3%) set between 0.3 and 3 EeV

- Interesting evolution of the phase as a function of energy

2] LSS correlation

- Update of VCV correlation P_data ~ 38% (ISO = 21%) - correlation is still there but not as strong as expected from the earlier report

- Excess of events in the 18° CenA region (13 observed 3.2 expected)

- Data above 55 EeV seems also to traces LSS as represented by 2MASS or swift-bat catalogs

In addition to larger statistics, substantial progress in our understanding of CR nature and origin at and above the ankle region will only come form the combination of composition and anisotropy measurements