

THE PIERRE AUGER OBSERVATORY: ON THE ARRIVAL DIRECTIONS OF THE MOST ENERGETIC COSMIC RAYS



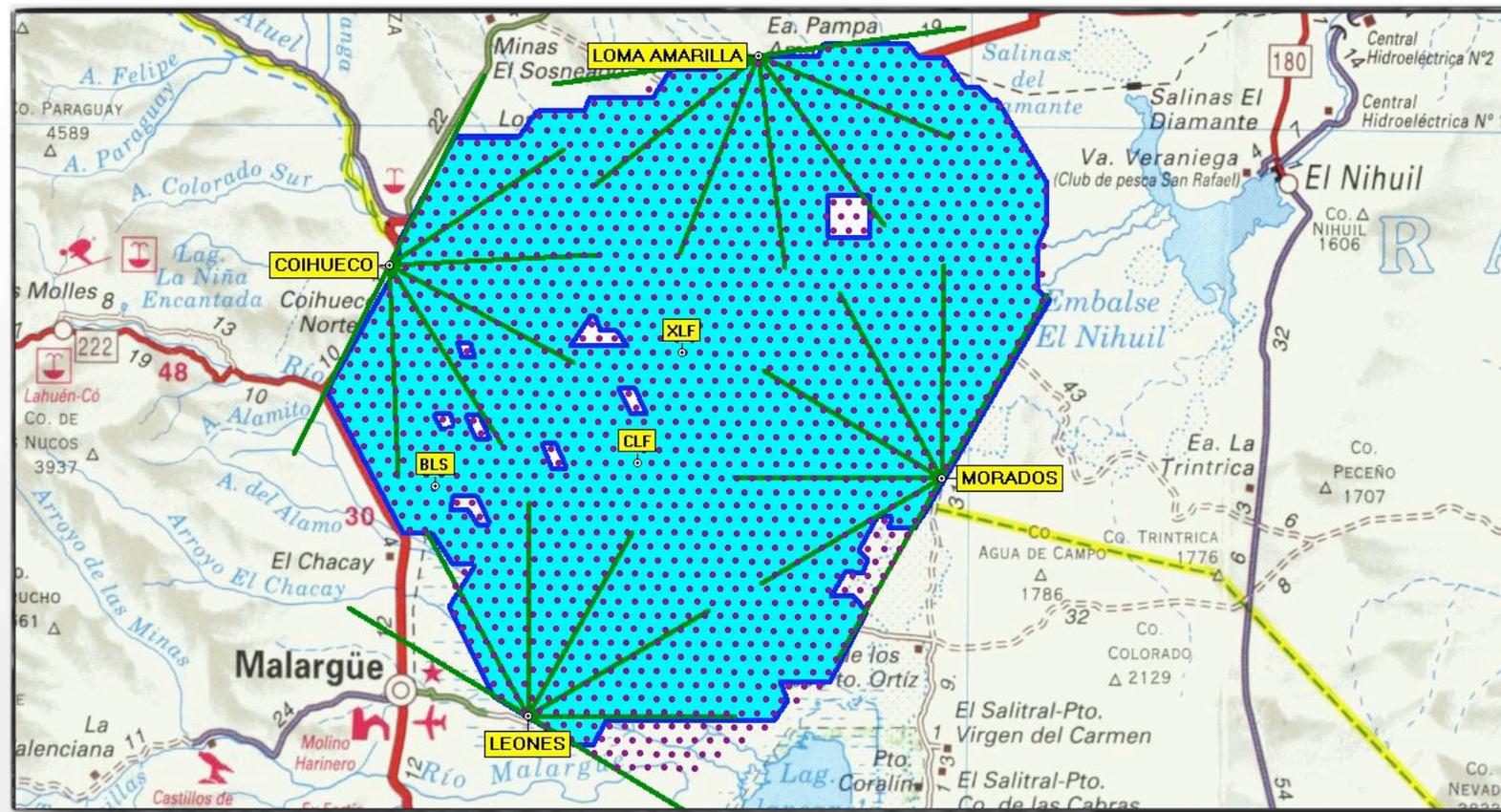
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OUTLINE

- ▶ PROLOGUE
- ▶ DATA-SET: STATISTICS AND RESOLUTIONS
- ▶ ARRIVAL DIRECTION ANALYSIS:
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 - ▶ A-PRIORI: UPDATE OF THE CORRELATION WITH VCV CATALOGUE
 - ▶ A-POSTERIORI: CEN-A REGION
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- ▶ CONCLUSIONS



PROLOGUE



PROLOGUE

- *The Pierre Auger Southern Observatory is taking data since 2004 in Argentina. It is completed since June 2008*
- *With data from 1/1/2004 to 31/8/2007 (8890 km² sr y), it reported evidence of anisotropy in the arrival directions of 27 CRs above ≈ 60 EeV*
- *Arrival directions were correlated with positions of nearby ($z < 0.018$) objects from Veron-Cetty & Veron 12th catalogue of quasars and active nuclei*
- *The observed correlation identified neither the CR sources nor a specific class: it established anisotropy at 99% c.l., and provided clue to the extragalactic origin of UHECRs*

THE UPDATED DATA-SET



- ❑ *Data between 1/1/2004 and 31/3/2009:*
- ❑ *Zenithal angle < 60 deg*
- ❑ *Fiducial cut: ≥ 5 active stations around the EAS core -> $17040 \text{ km}^2 \text{ sr y}$*
- ❑ *New event reconstruction: arrival directions differ by < 0.1° , E by < 5%*
- ❑ *58 events with $E > 55 \text{ EeV}$ (56 EeV in old rec)*

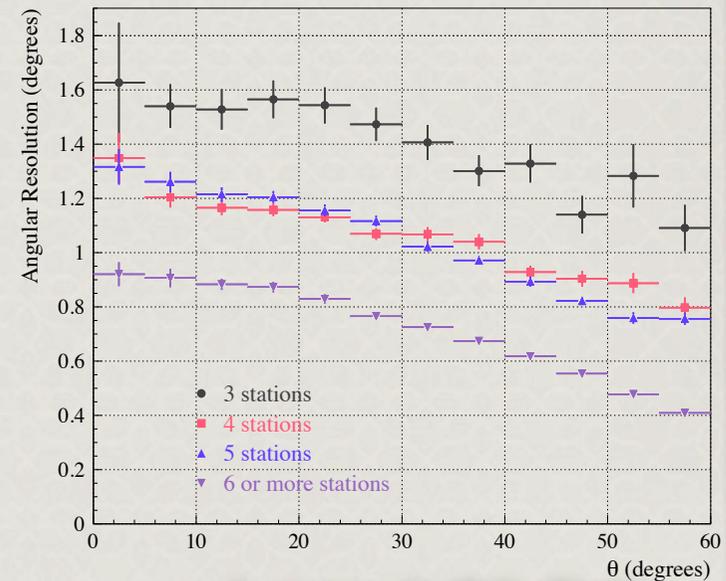
ENERGY RESOLUTION

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

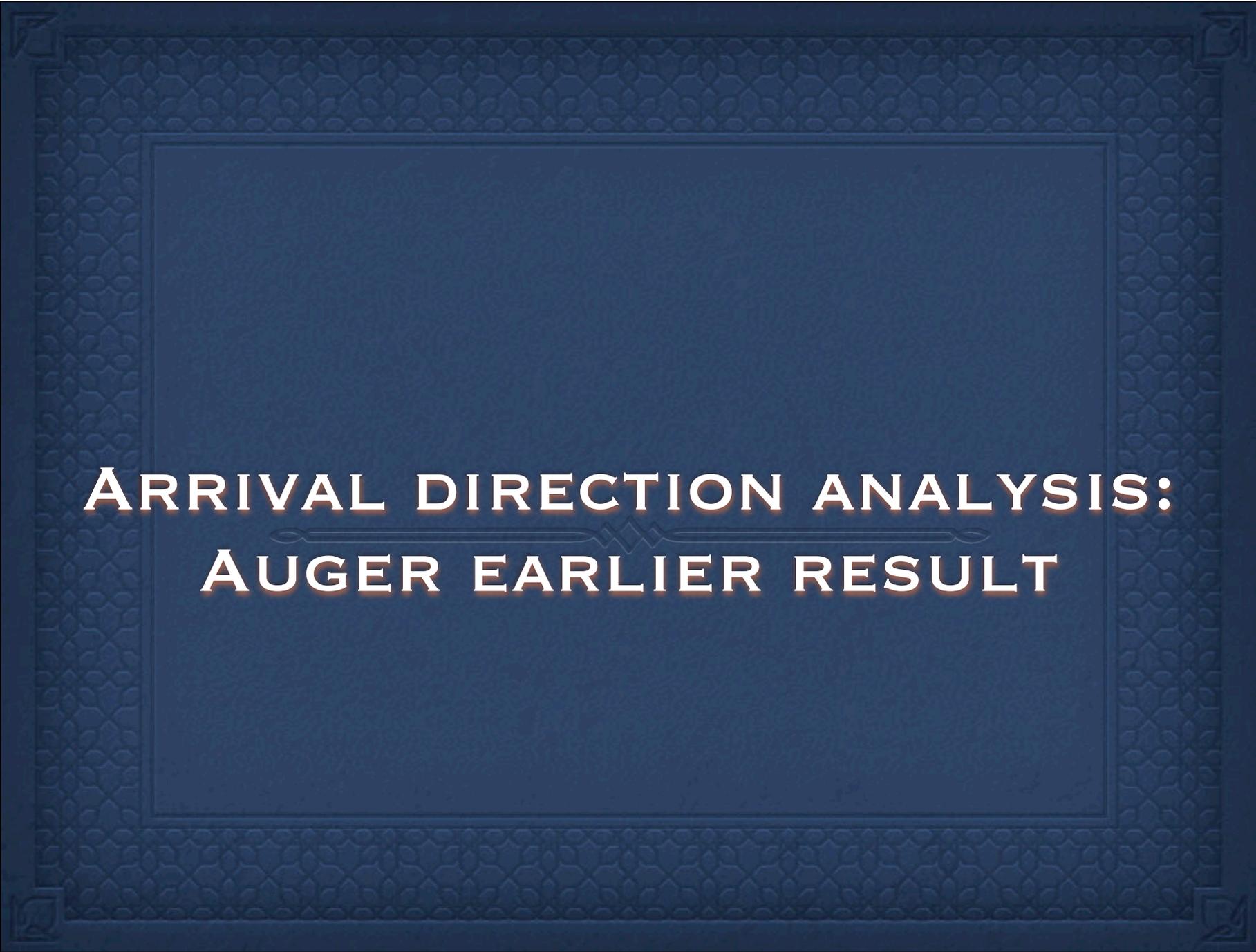
STATISTICAL $\approx 14\%$ (@ 50 EeV)

SYSTEMATICAL $\approx 22\%$

ANGULAR RESOLUTION

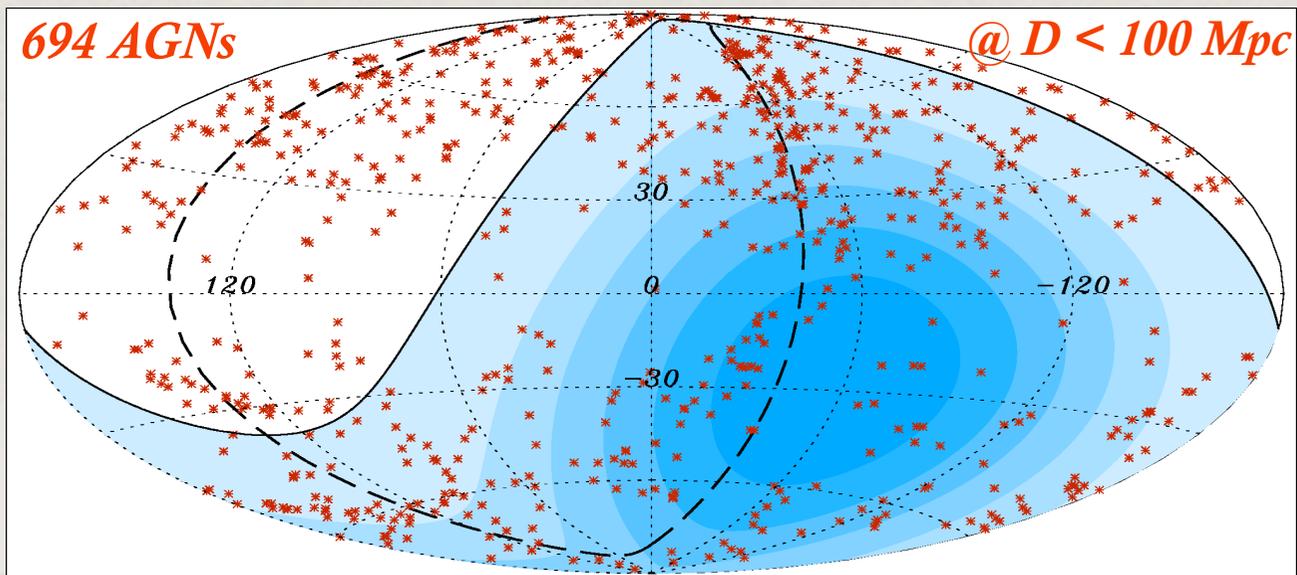


< 1 DEG @ 50 EeV



**ARRIVAL DIRECTION ANALYSIS:
AUGER EARLIER RESULT**

- *To demonstrate anisotropy: search for correlation with AGNs in the Veron-Cetty & Veron catalogue (quasars and active nuclei)*
- *VCV is not homogenous and it is incomplete*
- *VCV tracer of nearby matter*
- *Helpful tool to demonstrate anisotropy with small statistics*
- *But it may affect our ability to identify sources unambiguously*



EXPLORATORY SCAN: 1 JAN 2004-27 MAY 2006

- *Integrated exposure: 4390 km² sr y*
- *Scan in ψ (angular distance between CR and AGN), E_{th} (CR energy), z_{max} (AGN distance)*
- *Scan implemented to find the minimum of the binomial probability P that $\geq k$ out of N evs correlate by chance*

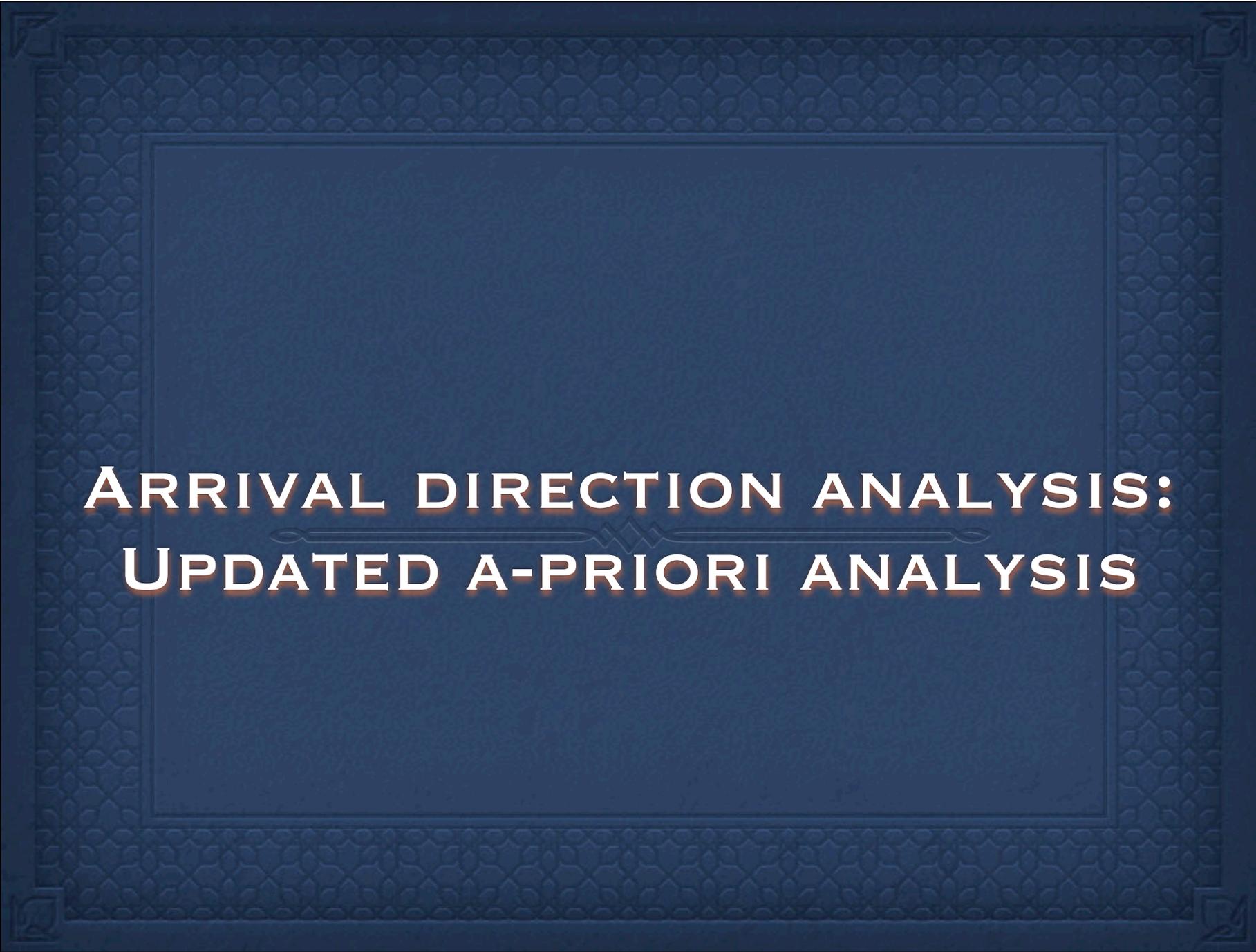
$$P(E, z, \psi) = \sum_{j=k}^{N(E)} \binom{N(E)}{j} p(z, \psi)^j (1 - p(z, \psi))^{N(E)-j}$$

$p(z, \psi)$ = exposure-weighted chance probability for a CR to fall within ψ of the sources

- *Minimum value of P found for $E_{th} = 56 \text{ EeV}$ $\psi = 3.1^\circ$ $z_{max} = 0.018$*
- *12/15 events correlate (3.2 expected by chance, $p(z, \psi) = 0.21$)*
- *Scan -> proper penalization difficult to calculate -> Prescription adopted*

INDEPENDENT DATA: 27/5/2006-31/8/2008

- *Integrated exposure: 4500 km² sr y*
- *A-priori fixed parameters: $E_{th} = 56 \text{ EeV}$ $\psi = 3.1^\circ$ $z_{max} = 0.018$*
- *8/13 events correlate (2.7 expected by chance)*
- *Probability to happen by chance from an isotropic flux: $P \approx 1.7 \cdot 10^{-3}$*
- *Test built to have 1% probability to incorrectly reject isotropy.*
- *Test passed: 99% c.l. anisotropy*



**ARRIVAL DIRECTION ANALYSIS:
UPDATED A-PRIORI ANALYSIS**

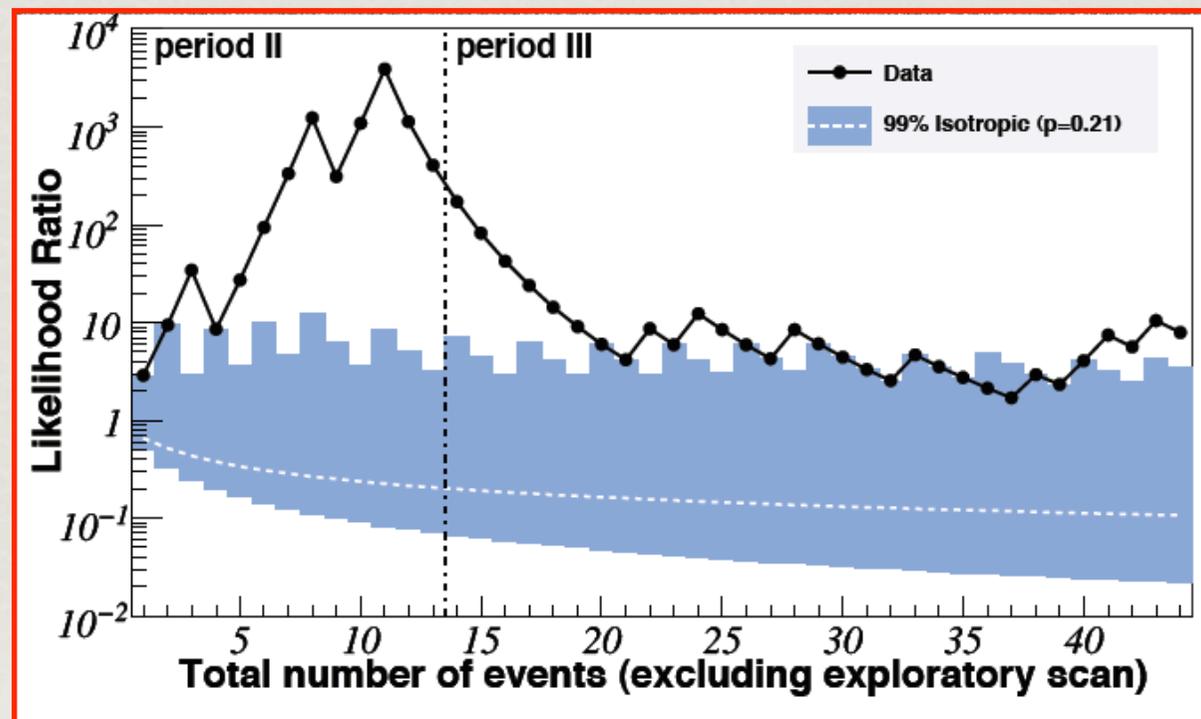
ADDING NEW DATA: 27/5/2006-31/3/2009

- *After-prescription integrated exposure: 12650 km² sr y*
- *Updated event reconstruction: 56 EeV -> 55 EeV*
- *31 new events with E>55 EeV: 44 post-prescription events*
- *A-priori fixed parameters: $E_{th} = 55 \text{ EeV}$ $\psi = 3.1^\circ$ $z_{max} = 0.018$*

ADDING NEW DATA: 27/5/2006-31/3/2009

$$R = \frac{\int_{p_{\text{iso}}}^1 p^k (1-p)^{N-k} dp}{p_{\text{iso}}^k (1-p_{\text{iso}})^{N-k+1}}$$

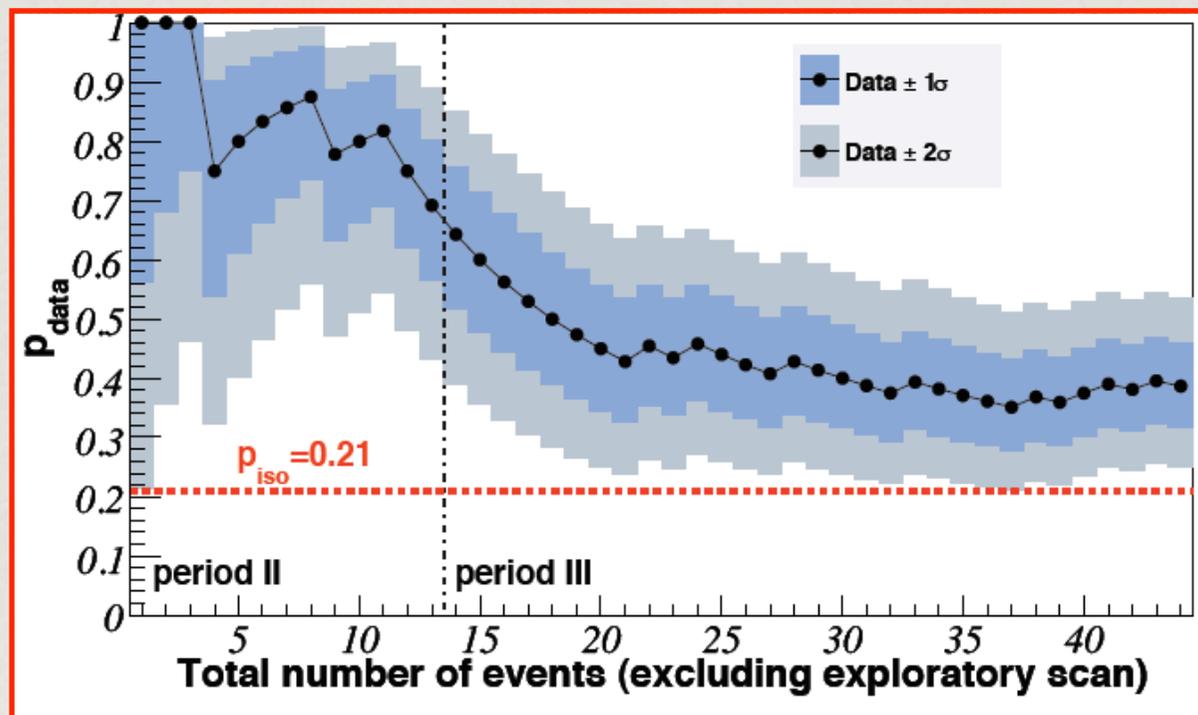
Likelihood ratio: binomial probability of correlation over binomial probability in isotropic case ($p_{\text{iso}}=0.21$)



17/44 EVENTS IN CORRELATION (P=0.006)
ISOTROPY STILL REJECTED AT 99% C.L.

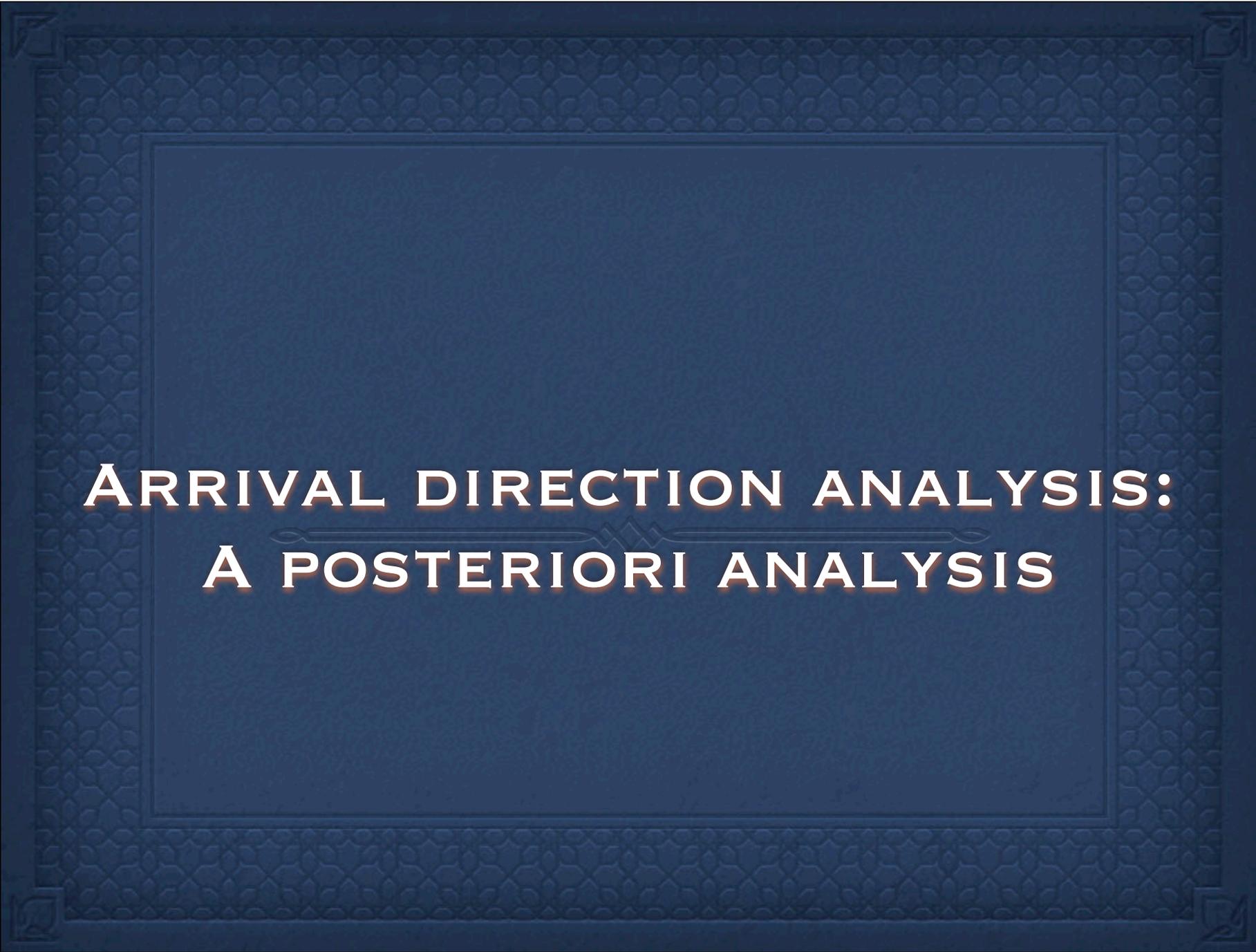
ADDING NEW DATA: 27/5/2006-31/3/2009

Degree of correlation ($p=k/N$) vs total number of time-ordered events



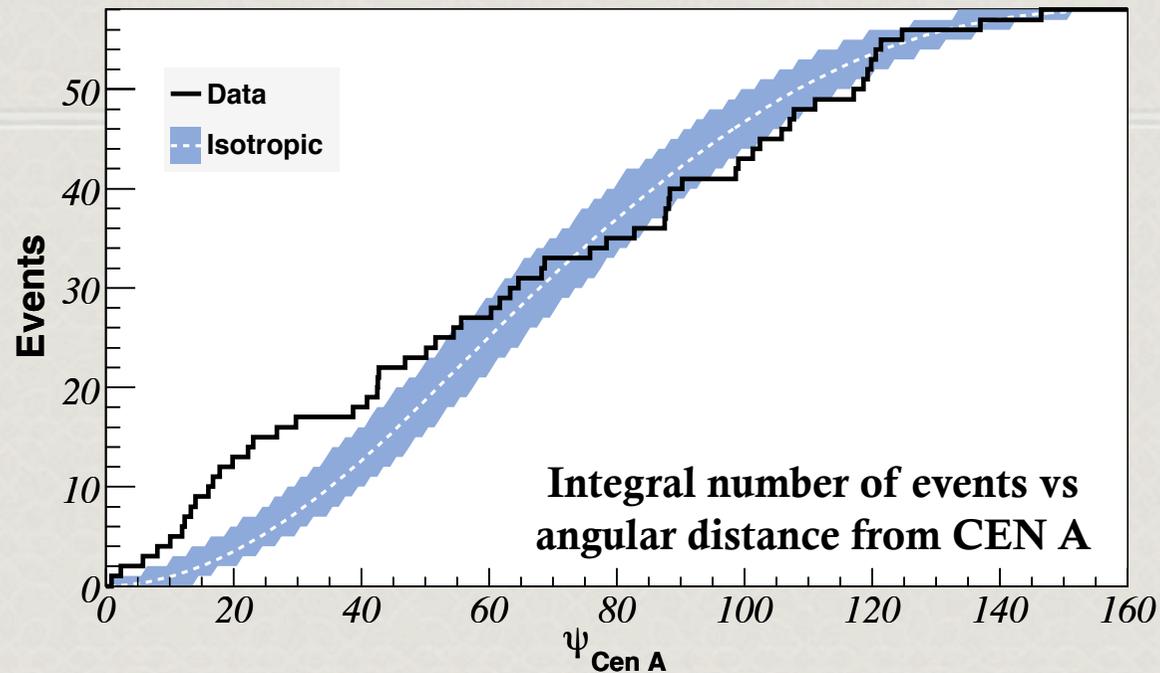
$$P_{\text{DATA}} = 17/44 = 0.38 \pm 0.07$$

**CORRELATION DEGREE DECREASED WRT OUR PREVIOUS REPORT
BUT STILL MORE THAN 2 S.D. FROM ISOTROPY**



**ARRIVAL DIRECTION ANALYSIS:
A POSTERIORI ANALYSIS**

1. CENTAURUS A



KS TEST : 2% OF ISOTROPIC REALIZATIONS HAVE A MAXIMUM DEPARTURE FROM ISOTROPY \geq THE MAXIMUM OBSERVED DEPARTURE

MAXIMUM EXCESS IN CIRCULAR WINDOWS AROUND CEN A CORRESPONDS TO A RADIUS OF 18° : 12 OBSERVED EVENTS VS 2.7 EXPECTED

BY CONTRAST, 0/58 OBSERVED EVENTS IN A 20° CIRCULAR WINDOW AROUND VIRGO (BUT LOW EXPOSURE : 1.2 EXPECTED FROM ISOTROPY)

2. TEST OF ALTERNATIVE SOURCE SCENARIOS

- *Different potential sources:*

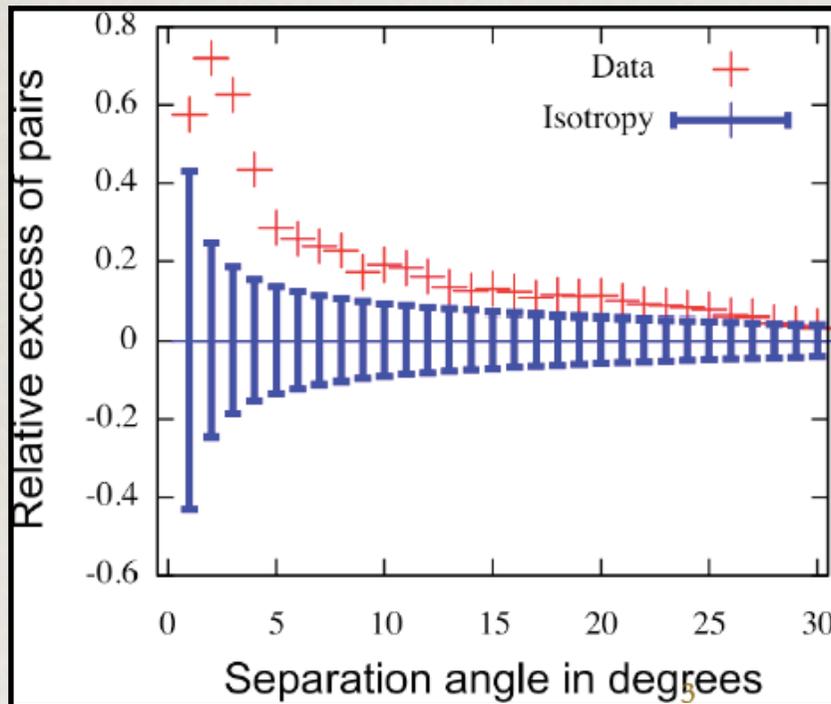
1. *AGNs detected in X-rays in 22-months SWIFT catalogue (261 objects)*
2. *Galaxies in the HIPASS survey (3058 galaxies, radio, flux-limited)*
3. *HIPASS-HL: sub-sample of HIPASS (the 765 most luminous galaxies)*
4. *Galaxies in the 2MRS compilation ($|b| > 10^\circ$, 23000 most luminous galaxies from 2MASS, full-sky, IR)*

- *Different methods:*

- I. *Cross-correlation*
- II. *Log-likelihood*
- III. *2-fold correlation*

I. CROSS-CORRELATION

E.G.: VOLUME SELECTED GALAXIES
($D < 200$ MPC) FROM 2MRS (1940 OBJ)

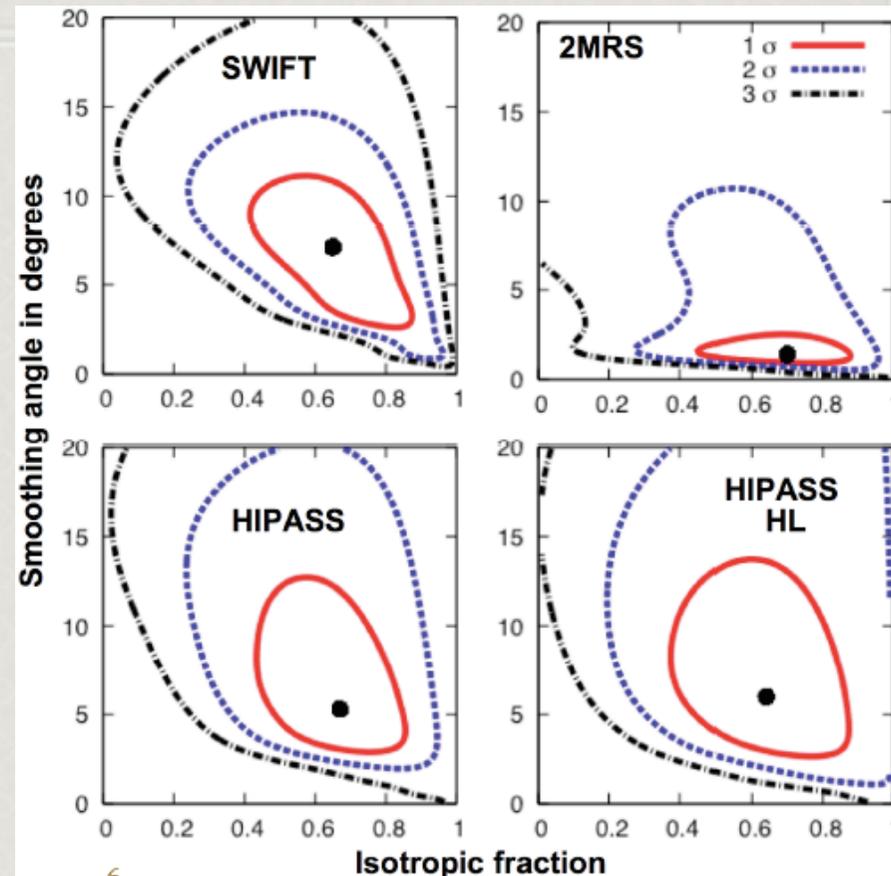


- *Measures the excess of pairs within a given angular separation wrt isotropy (departures are larger if CRs correlate with denser regions of the catalogues)*
- *No weight by distance or luminosity (equal contribution to CR flux from each source)*
- *Departures from isotropy against all 4 classes of objects*
- *Indication that UHECRs are correlated with local matter*

PRIOR TO LL AND 2-FOLD TESTS: BUILDING CATALOGUES SMOOTHED MAPS

- *For each catalogue: build smoothed probability maps of arrival directions*
- *Weight catalogue sources by flux \times GZK attenuation*
- *2 free parameters: smoothing angle σ and isotropic background (catalogue incompleteness)*
- *$F_c(n)$ =density map value in the direction n*
- *Use data to find the best values of (σ, f_{iso}) by maximizing the LL*

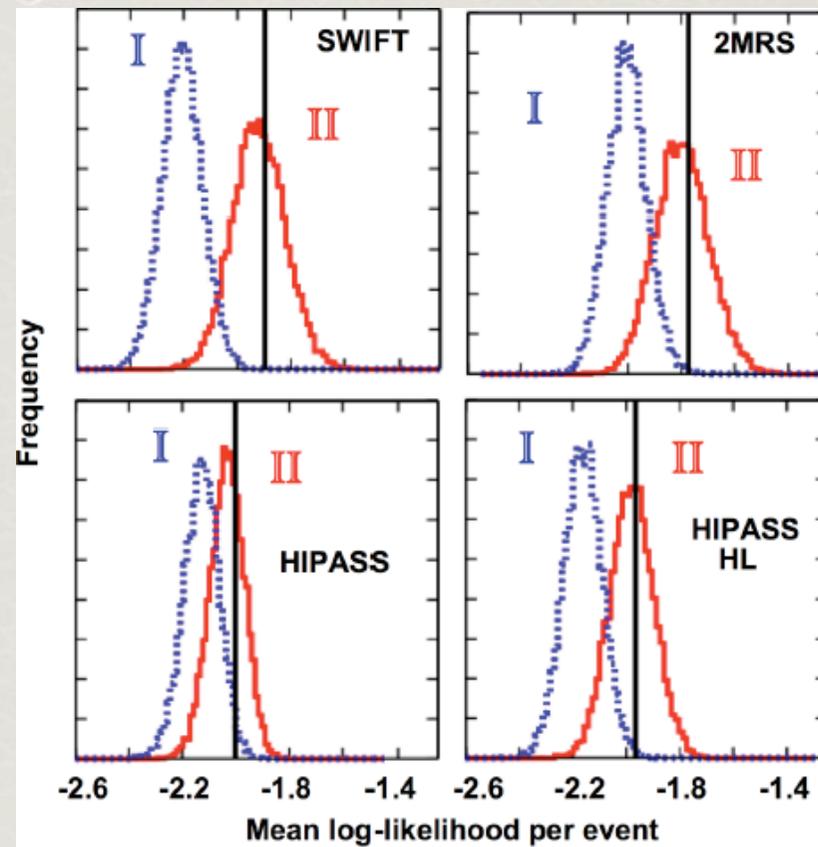
$$\mathcal{LL} = \sum_{k=1}^{N_{\text{data}}} \ln F_c(\mathbf{n}_k)$$



PARAMETERS NOT STRONGLY CONSTRAINED

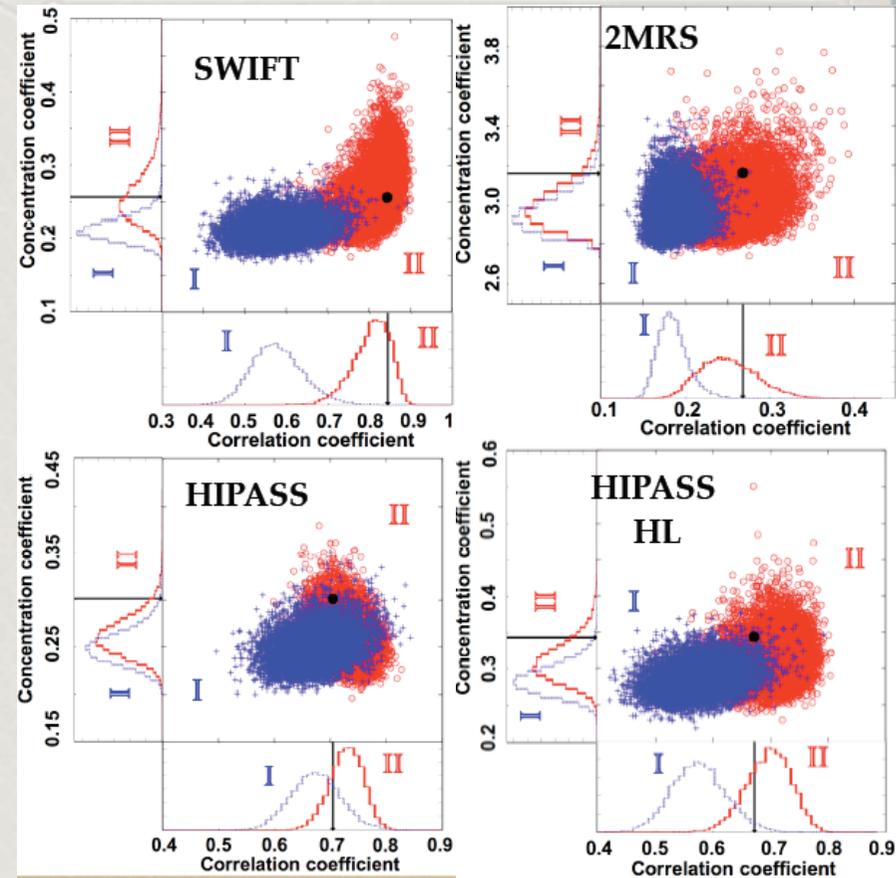
II. LIKELIHOOD TEST

- Simulate 10^4 samples with the same number of data as in the real set
- Draw events accordingly to *catalogue density map* or *isotropically*
- Compare the likelihood distributions with the value obtained from data
- *Good agreement with all the models*
- *LL only sensitive to data points lying or not in high density catalogue regions*



III. 2-FOLD CORRELATION METHOD

- *Complementary method to test overall proportionality between models and data*
- *Based on the computation of two coefficients: correlation (test match between models and data) and concentration (test clustering properties of data)*
- *Data compatible with all the models*
- *The map based on SWIFT gives the most discriminant test against isotropy*



CONCLUSIONS

- *Auger exposure grown to $\approx 17000 \text{ km}^2 \text{ sr y}$ (twice wrt previous report)*
- *58 detected CRs with $E > 55 \text{ EeV}$*
- *On their arrival directions:*
 - *Update on the correlation with VCV objects (a-priori analysis)*
 - *Isotropy still rejected at 99% c.l. (but its evidence not strengthened)*
 - *Degree of correlation lower than in earlier data*
 - *A-posteriori analysis:*
 - *Excess of events close to direction of radio source CEN A*
 - *Distribution of arrival directions compatible with several models for their origin, based on the distribution of nearby extra-galactic matter*
 - *X-rays AGNs (ex-SWIFT) constitute an interesting class of objects*
- *More statistics needed to discriminate possible source scenarios*
- **BE PATIENT: we “only” collect $\approx 2 \text{ UHECR/month}$, $\approx 500 \text{ km}^2 \text{ sr y/month}$. But, we do so for the next 10 y...**