Search for a correlation between the UHECRs measured by the Pierre Auger Observatory and the Telescope Array and the neutrino candidate events from IceCube

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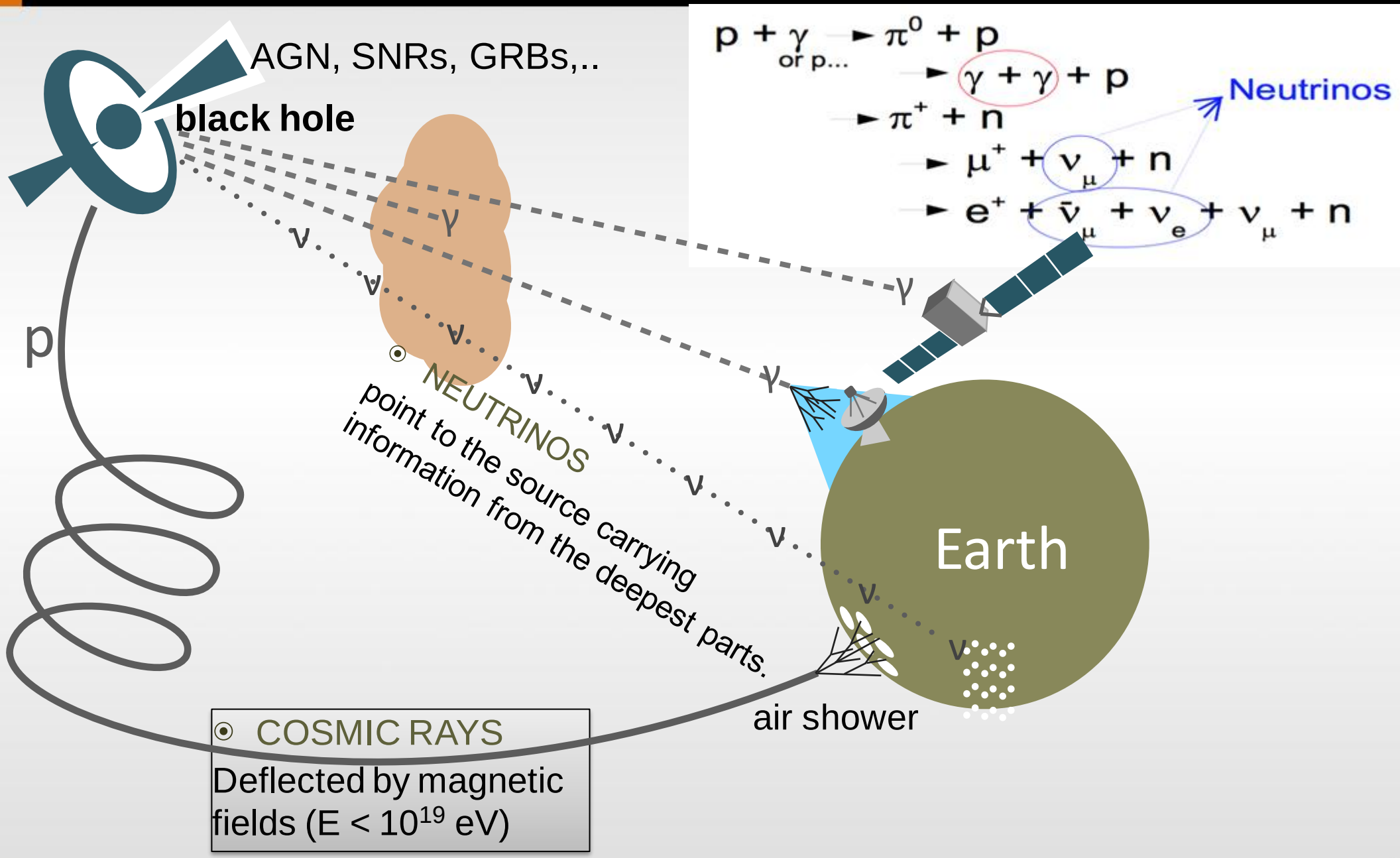
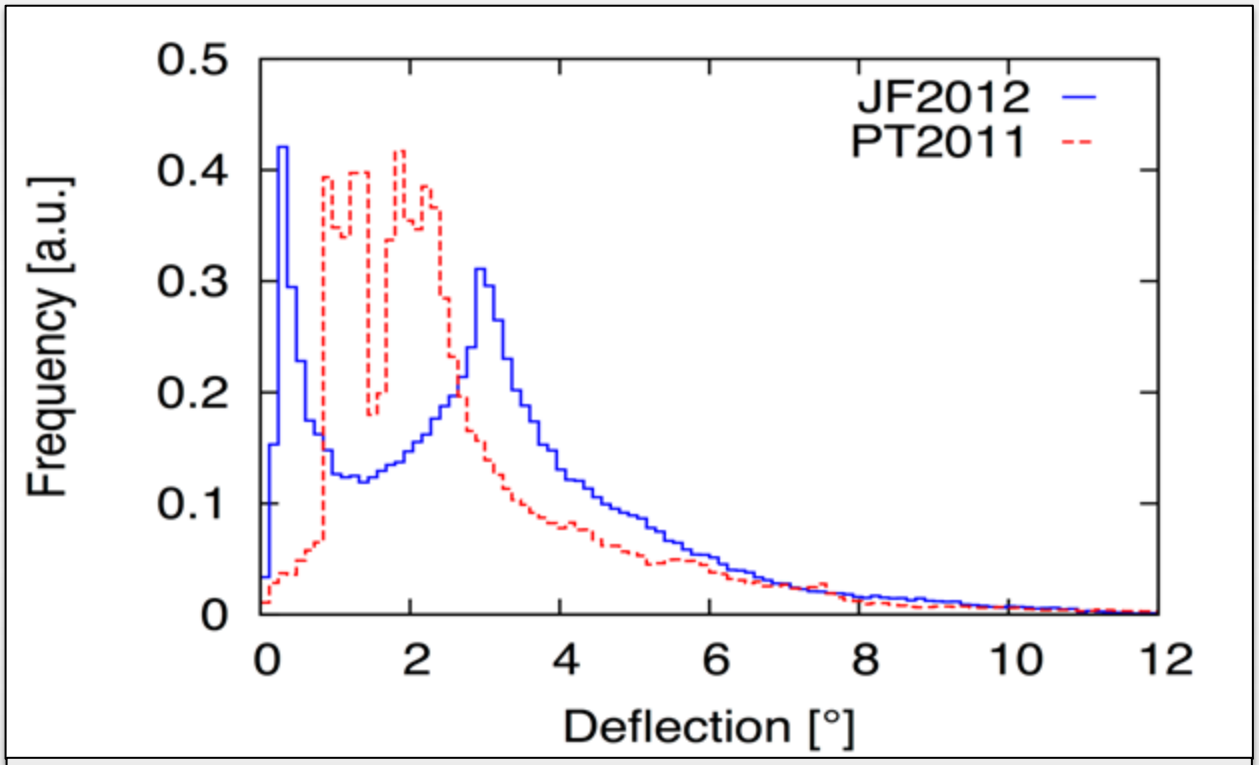
Multi-messenger approach



UHECR magnetic deflections

For E=100 EeV, Z=1: the magnetic deflections due to the regular component of the GMF in 2 different models:



PT2011: Pshirkov, Tinyakov, Kronberg, Newton-McGee, Astrophys. J. 738 (2011) 192.
JF 2012: Jansson, Farrar, Astrophys. J. 757 (2012) 14.

The median is for both models ~2.7° 100 EeV/E_{CR}. This does not include the turbulent component of the GMF.

We will assume the following values for the deflection:

σ_{MD}= D x 100 EeV/E_{CR},
D=3°,6°, (9°).

These may also account for cosmic rays heavier than protons or stronger magnetic fields.

Three correlation analyses

- For UHECRs the magnetic deflections do not erase the information about the origin.
- Neutrinos point back to the production site.

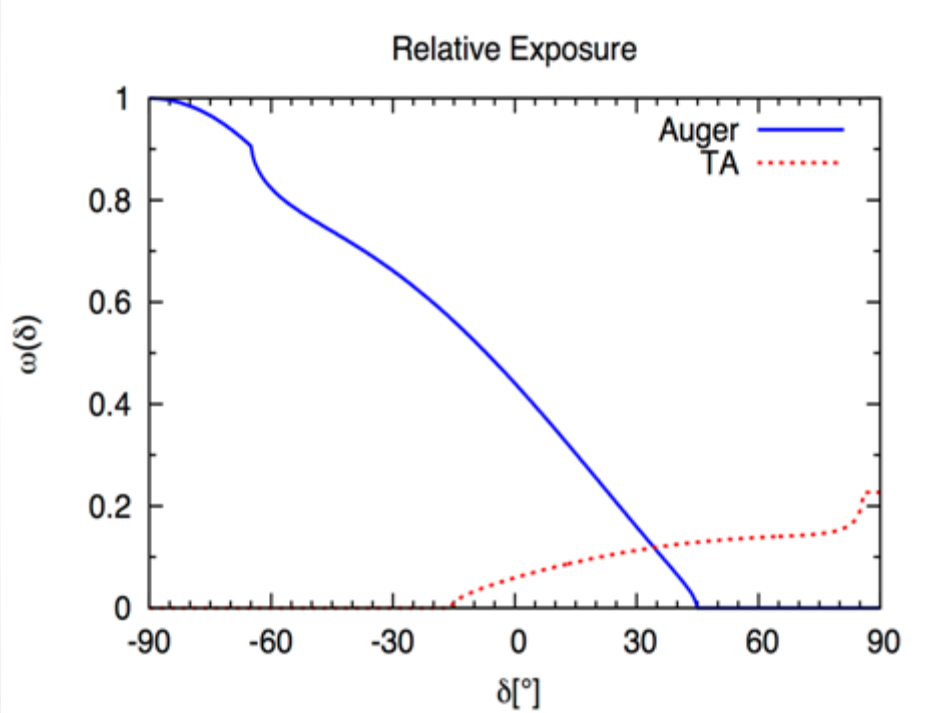
Combine the measurements of Pierre Auger Observatory and the Telescope Array with the neutrino candidate events from IceCube

- **Cross-correlation analysis**
- **Likelihood method stacking the high-energy cascades and high-energy tracks**
- **Likelihood method stacking the UHECRs using the neutrino PS sample**

The UHECR samples used

Period: 01/01/2004 to 31/03/2014
231 events above 52 EeV
Maximum zenith angle = 80°
Angular resolution: 0.9°

Period: 11/05/2008 to 01/05/2014
87 events above 57 EeV
Maximum zenith angle= 55°
Angular resolution: 1.5°

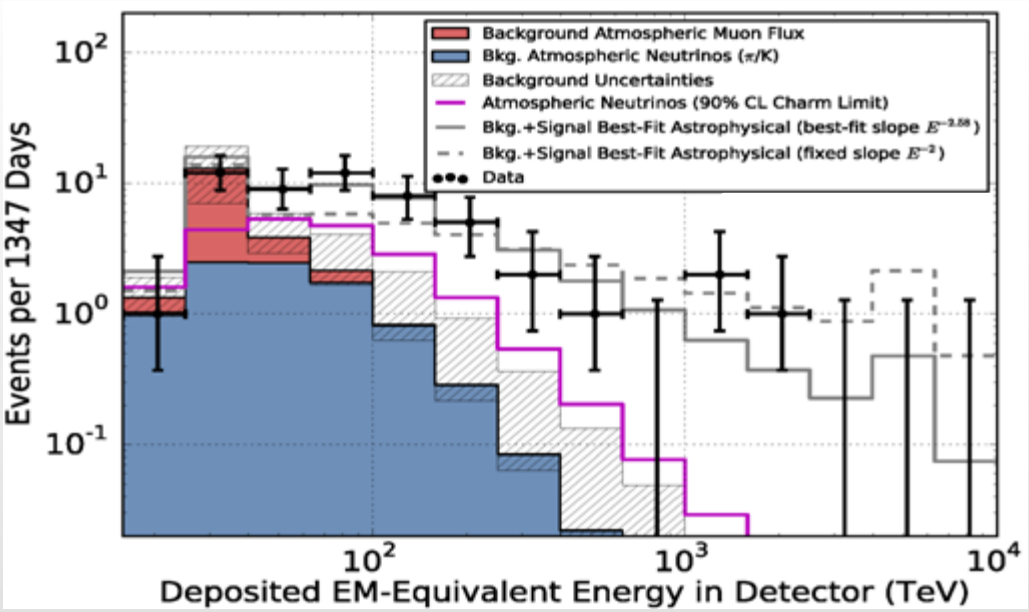


The Pierre Auger Collaboration, Astrophys. J. 804 (2015) 1 and PoS(ICRC2015)310.
The Telescope Array Collaboration, Astrophys. J. Lett. 790 (2014) L21.

High energy IceCube samples used

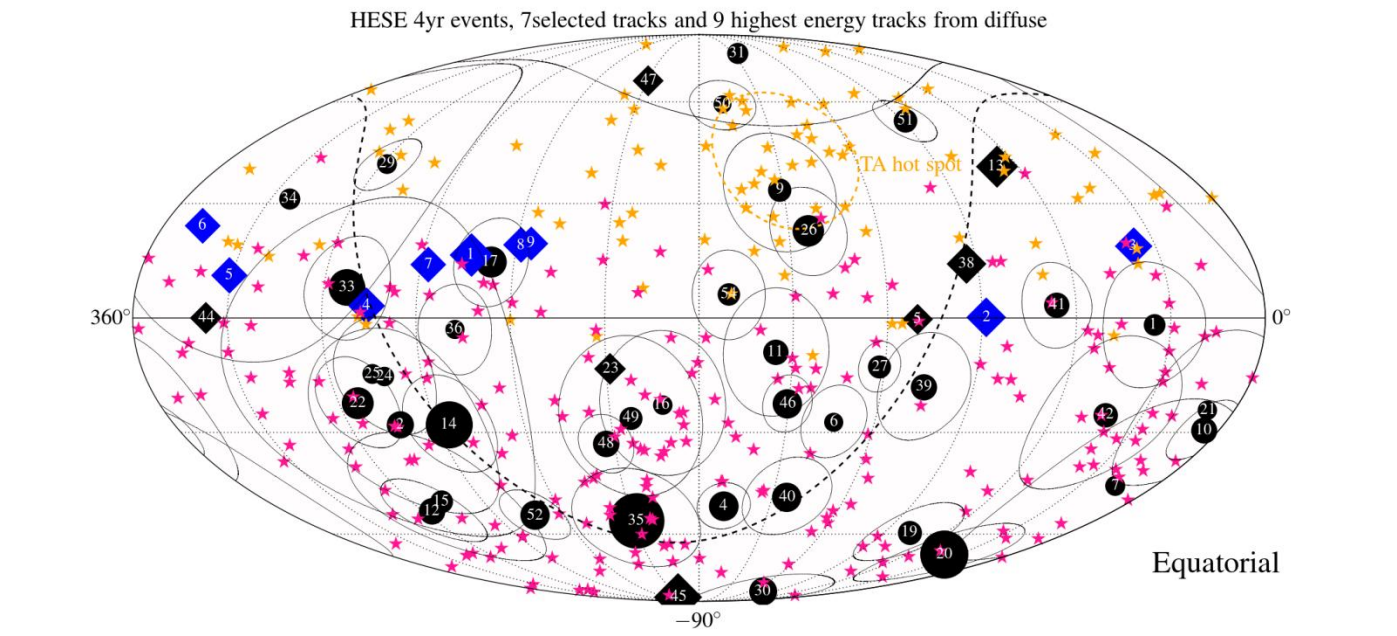
- High-energy cascades: 4-year HESE (High Energy Starting Events)
  - 39 events
  - Bad angular resolution

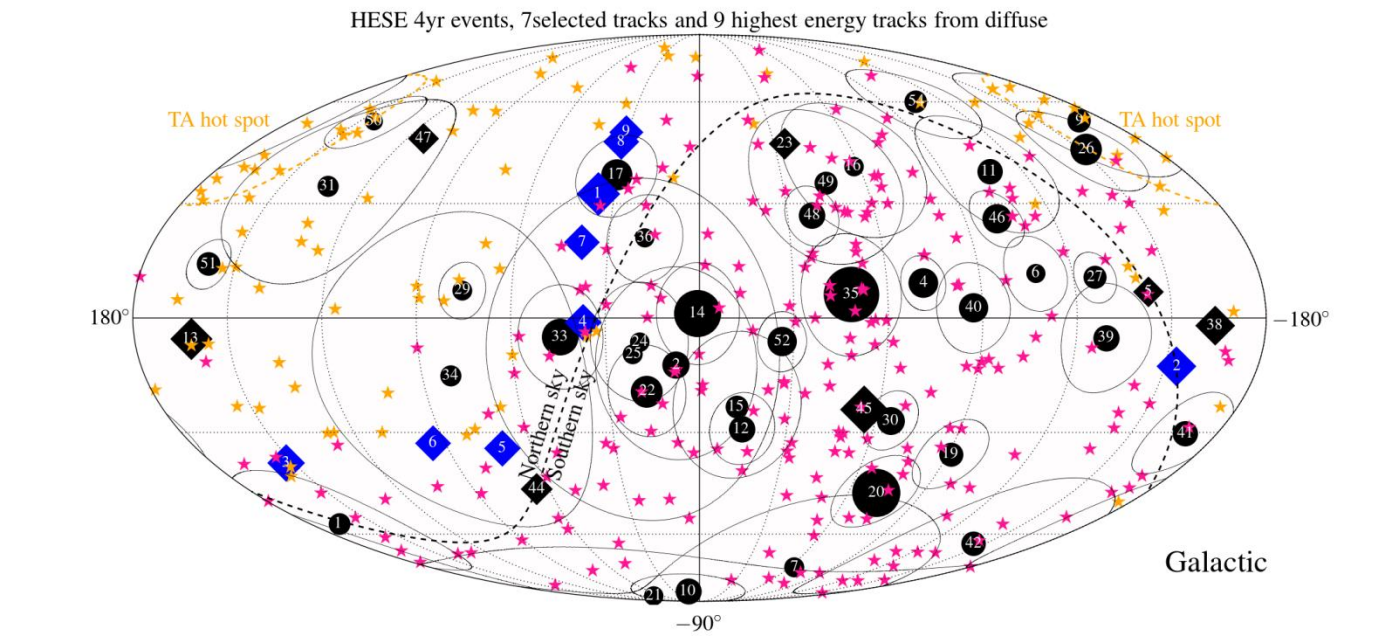
- High-energy tracks: 7 of the HESE tracks plus 9 events with muon energy proxy > 100 TeV from diffuse up-going analysis
  - 16 events
  - Good angular resolution



The IceCube Collaboration, PoS (ICRC2015) 1081.

Sky maps of the Events





Orange stars: TA UHECR

Magenta stars: Auger UHECR

Black dot and circle around it:
HESE Cascades

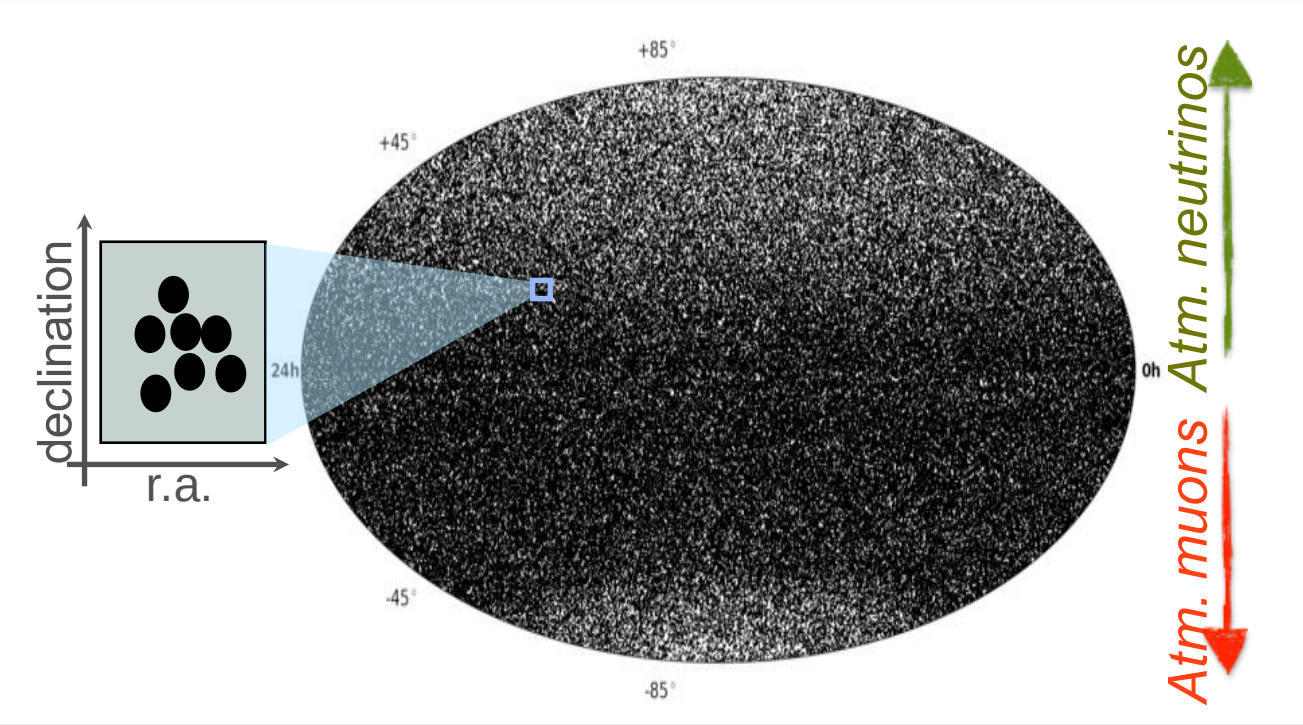
- Energy ~ size of the dot
- Circle ~ Angular uncertainty
- Number ~ HESE event num.

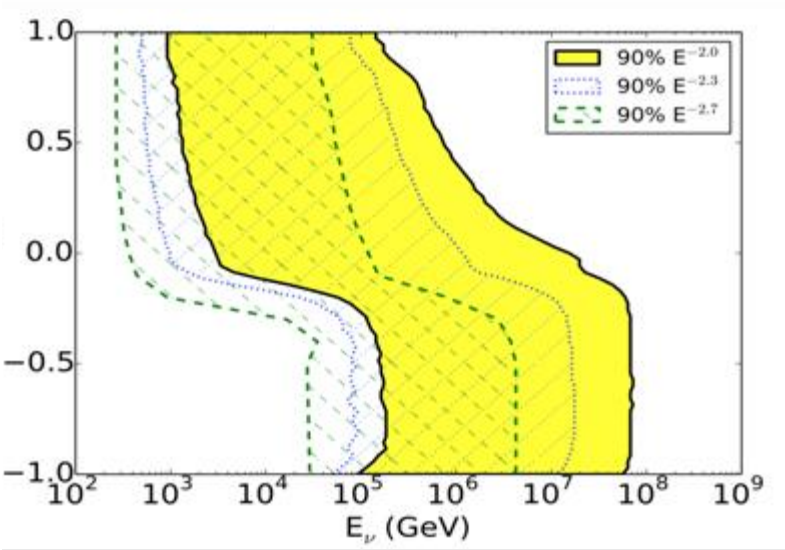
Diamonds:
High Energy Tracks

- Black → selected HESE tracks
- Blue → Diffuse ana. Tracks
- Energy ~ size of the diamond

IceCube Point source sample used

4 yr sample of well reconstructed, through-going muons that could be associated with charged-current muon neutrino interactions (394,000 events)

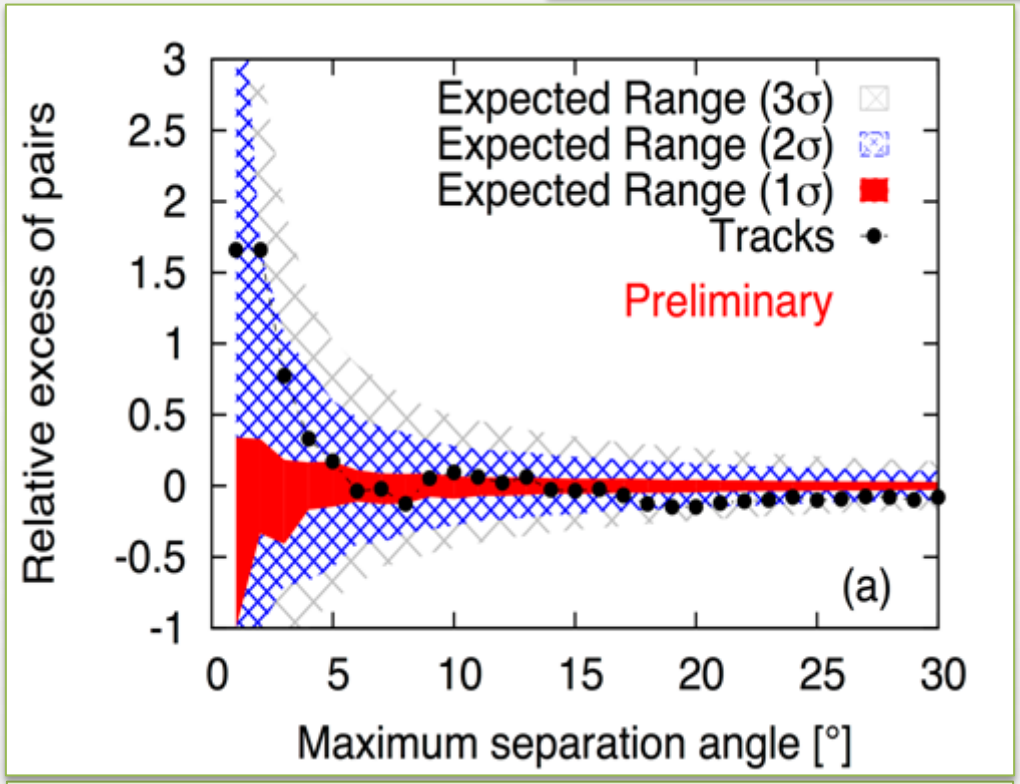


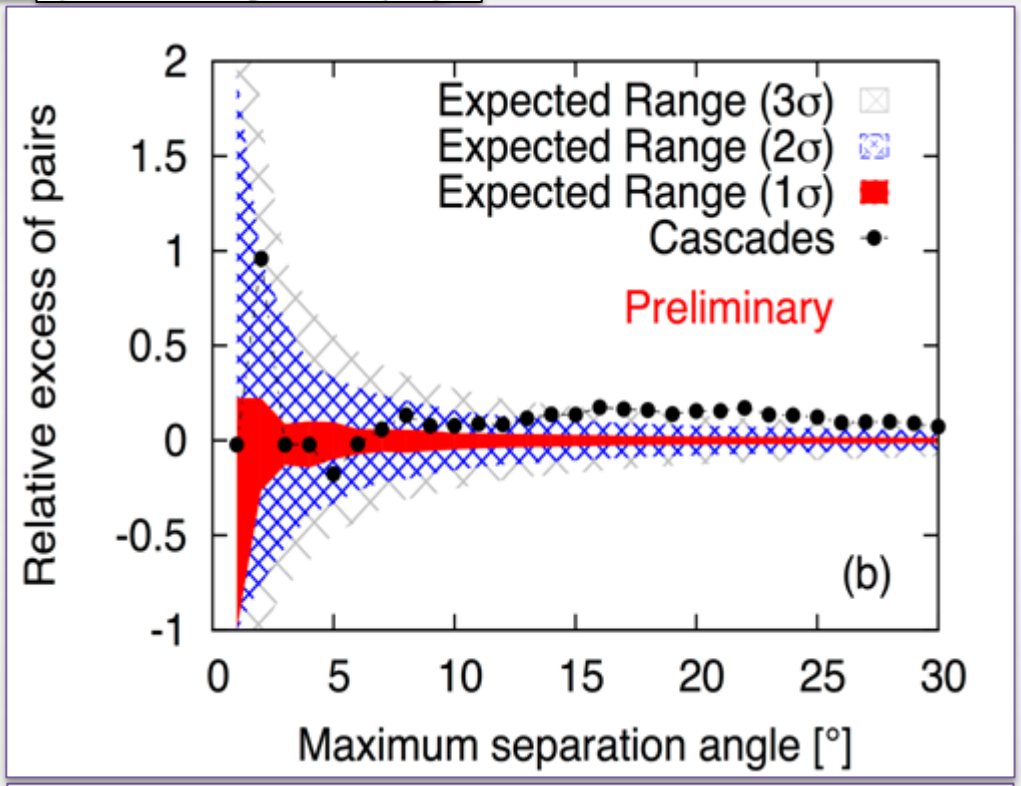


Cross-correlation analysis

Compute the number of UHECR-neutrino pairs as a function of the angular separation in the data and we compare it with expectations from an isotropic distribution of UHECRs.

Relative excess of pairs: $[n_p(\alpha)/\langle n_p^{iso}(\alpha)\rangle] - 1$





Tracks

minimum at 2^0, n_p=4, $\langle n_p^{iso}\rangle$= 1.5,
post-trial p-value=0.34
with respect to an isotropic flux of CRs.

Cascades

minimum at 22^0, n_p=575, $\langle n_p^{iso}\rangle$= 490.3,
post-trial p-value=5 x 10^{-4}
with respect to an isotropic flux of CRs.

Cross-correlation analysis

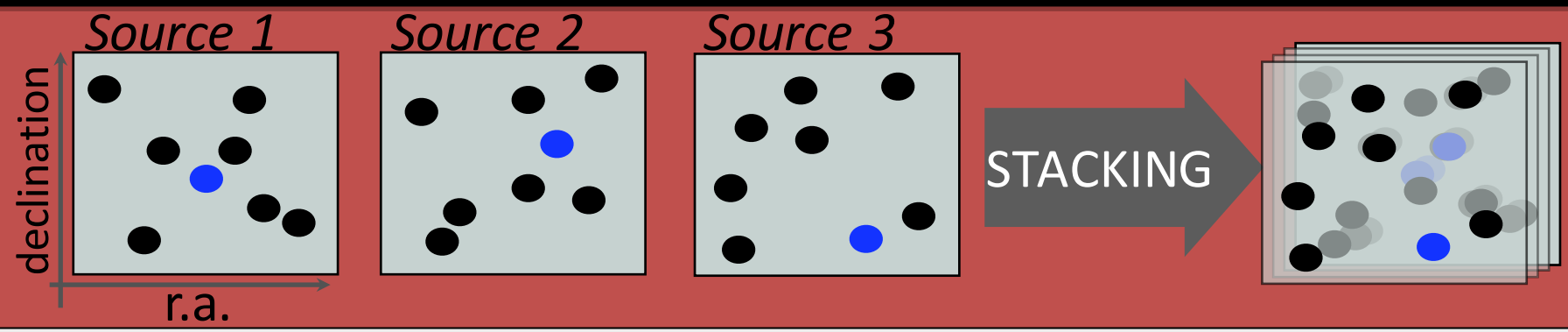
The excess of pairs in the case of the cascades is due to the fact that there are cascades in regions with large densities of UHECRs, i.e. near the Super-Galactic plane and at the TA "hot spot".

A posteriori cross-correlation test:

- separating the data of Auger and TA
  - TA: p-value of 9.3×10^{-4} @ 22^0 (post-trial)
  - Auger: p-value of 4.1×10^{-4} @ 22^0 (post-trial)
  - Hence, both results reinforce each other when considering the entire UHECR data set.

We also evaluated the significance under the hypothesis of an isotropic distribution of neutrinos (note that this alternative hypothesis preserves the degree of anisotropy in the arrival directions of CRs that is suggested by the TA hot spot or the excess around Cen A). The obtained value for the analysis with the cascades is: post-trial p-value= 8.5×10^{-3}, which is potentially interesting and will be monitored in the future.

Likelihood stacking the high-energy cascades and high-energy tracks



The neutrino positions will be the "stacked sources", and we will compare the result to an isotropic distribution of CRs.

$$\ln \mathcal{L} = \sum_{i=1}^{N_{\mathrm{Auger}}} \ln\left(\frac{n_{s_{CR}}}{N_{\mathrm{tot}}} S_i^{\mathrm{Auger}} + \frac{N_{\mathrm{tot}} - n_{s_{CR}}}{N_{\mathrm{tot}}} B_i^{\mathrm{Auger}}\right) + \sum_{i=1}^{N_{\mathrm{TA}}} \ln\left(\frac{n_{s_{CR}}}{N_{\mathrm{tot}}} S_i^{\mathrm{TA}} + \frac{N_{\mathrm{tot}} - n_{s_{CR}}}{N_{\mathrm{tot}}} B_i^{\mathrm{TA}}\right)$$

Signal PDF: the magnetic deflection plus the neutrino spatial PDFs have to be accounted for:

Background PDF: geometric exposure

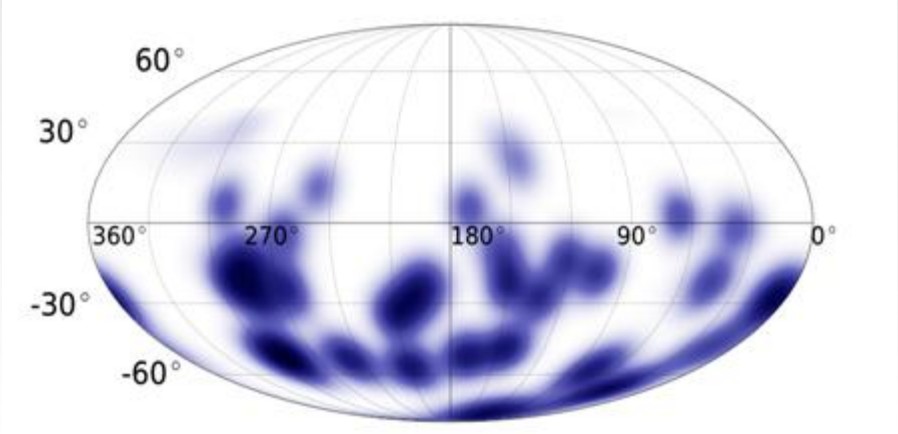
$$N_{\mathrm{tot}} = N_{\mathrm{Auger}} + N_{\mathrm{TA}}$$

$$S_i = \sum_{j=1}^{N_\nu} \omega(\delta_i) S_i^j(ra_i, \delta_i, \sigma_{MD}(E_i))$$

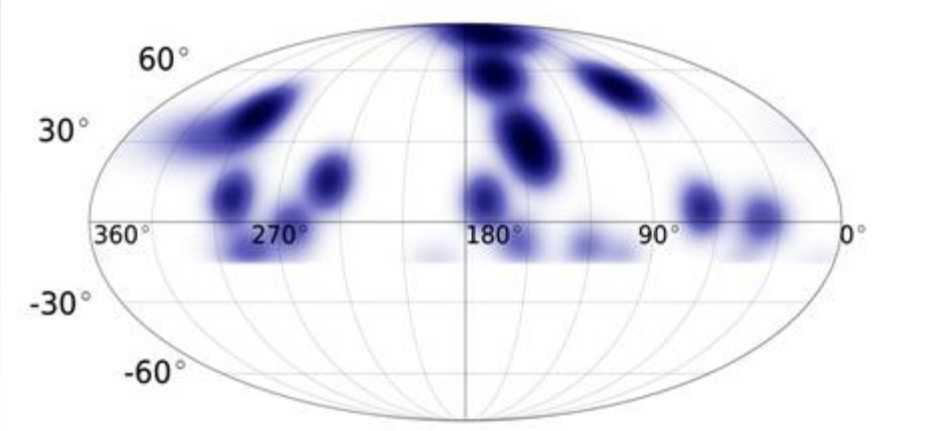
A PDF for a single CR and a single neutrino: takes into account the neutrino map and the magnetic deflection

Neutrino maps

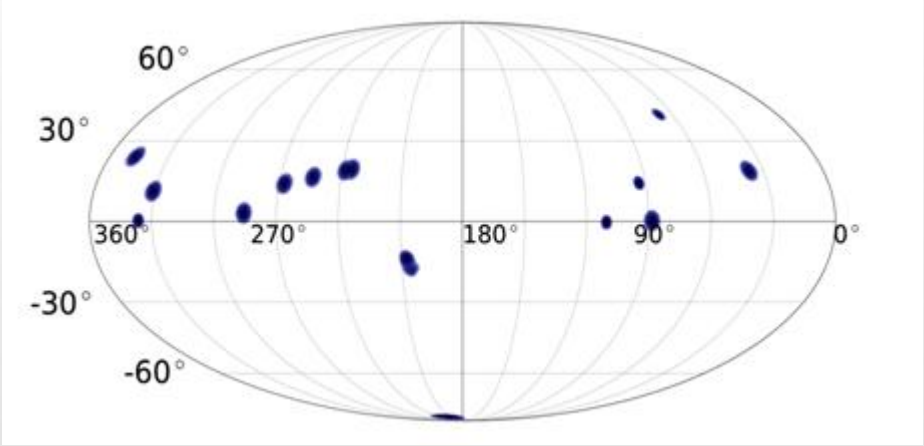
Auger exposure, high-energy cascades



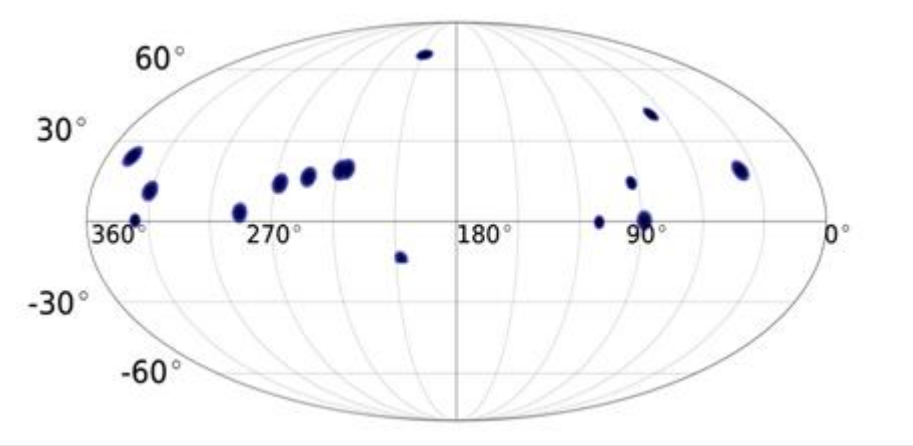
TA exposure, high-energy cascades



Auger exposure, high-energy tracks



TA exposure, high-energy tracks



Signal PDFs taking into account the exposure of the CR observatories, in equatorial coordinates.

Likelihood stacking the high-energy cascades and high-energy tracks

D	Tracks		Cascades	
	$n_{s_{CR}}$	pre-trial p-value	$n_{s_{CR}}$	pre-trial p-value
3°	4.3	0.22	53.7	2.1×10^{-3}
6°	0.5	0.48	85.7	2.7×10^{-4}
9°	-	under-fluctuation	106.1	3.8×10^{-4}

Cascades, D=6°:

post-trial p-value = 8×10^{-4}

with respect to an isotropic flux of CRs.

Cascades - a posteriori test: significance under the hypothesis of an isotropic distribution of neutrinos: post-trial p-value 1.3×10^{-3}

- potentially interesting and will be monitored in the future.

Likelihood method stacking the UHECRs using the neutrino PS sample

Stacked sources : The UHECR positions.

Maximize: γ (neutrino spectral index) and $n_{s\nu}$ (number of signal events)

$$\mathcal{L}(n_{s_\nu}, \gamma) = \prod_{i=1}^{N_\nu} \left(\frac{n_{s_\nu}}{N_\nu} S_i(\gamma, E_i) + \left(1 - \frac{n_{s_\nu}}{N_\nu}\right) B_i \right)$$

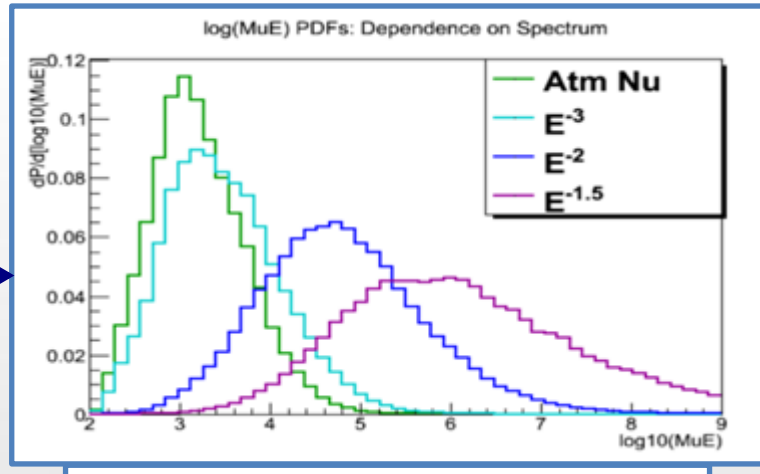
$$B_i = B(\theta_i) P_{atm}(E_i)$$

$$S_i = \sum_{j=1}^{N_{CR}} R_{\mathrm{IC}}(\delta_j, \gamma) S_i^j \Big/ \sum_{j=1}^{N_{CR}} R_{\mathrm{IC}}(\delta_j, \gamma)$$

IceCube acceptance

$$S_i^j = \frac{1}{2\pi(\sigma_i^2 + \sigma_j^2)} e^{-r_{ij}^2/2(\sigma_i^2+\sigma_j^2)} P(E_i|\gamma)$$

$$\sigma_j = \sqrt{\sigma_{\mathrm{MD}}^2 + \sigma_{\mathrm{exp}}^2}$$

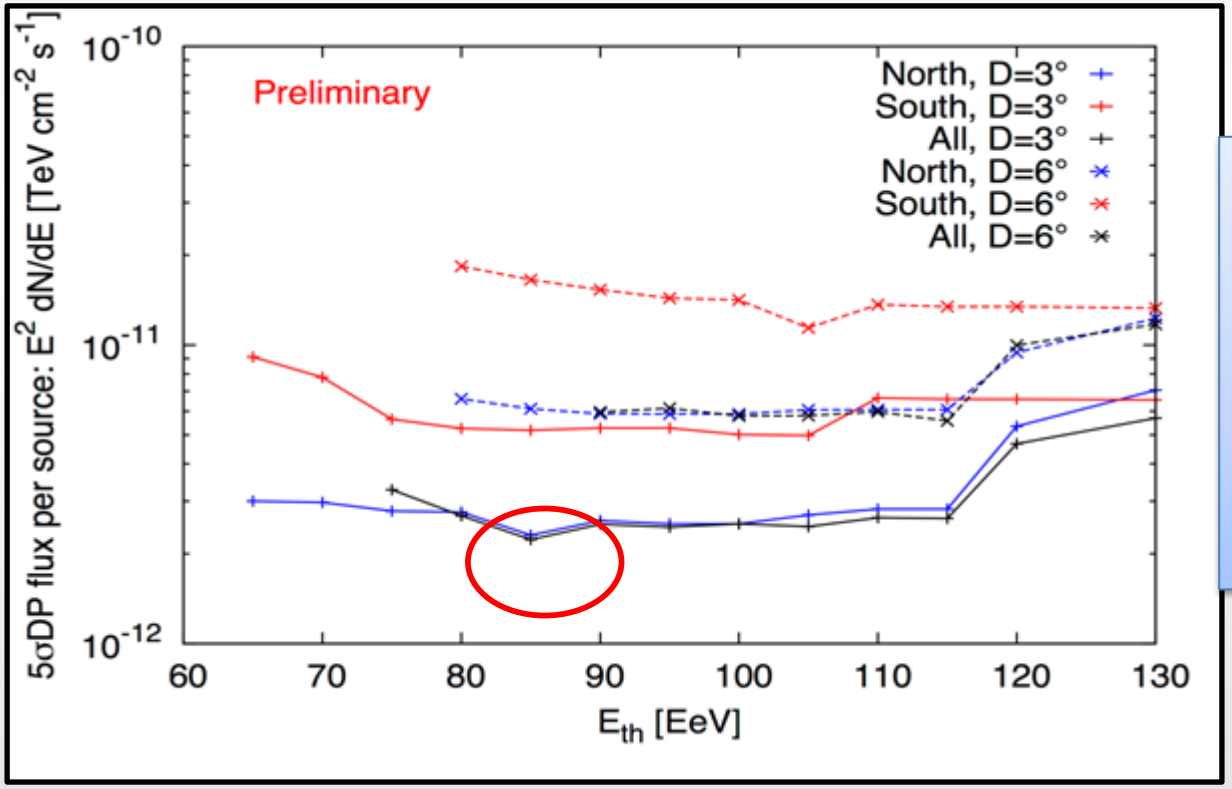


Energy PDF

Likelihood method stacking the UHECRs using the neutrino PS sample

The 318 UHECRs smeared on few degrees would cover large fraction of the sky

- To enhance sensitivity we select only those above a certain energy threshold



The discovery potential shows a minimum at E_{th} = 85 EeV considering the whole sky (N+S).

Likelihood method stacking the UHECRs using the neutrino PS sample

Results:

D	Fitted $n_{s\nu}$	Fitted γ	pre-trial p-value
3°	123.3	3.24	17.1%
6°	$\sim$0	-	$>$ 50%

Post-trial p-value=25%

Conclusions

- All correlations found have less than 3.3 sigma significance.
- There is a potentially interesting result in the analyses with high-energy cascades - if we assume an isotropic flux of neutrinos (fixing the directions of the UHECRs) to assess the effect of the presence of anisotropies in the CR arrival directions (such as TA hot spot), the significance is ~2.4 sigma.
- These results were obtained with relatively few events and we will update these analyses in the future with more statistics.