ANTARES-IceCube combined point-source analysis

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ANTARES
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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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- ANTARES-IceCube combined analysis
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     2. Results using different spectra / E_{cutoff}
  4. Full sky and Candidate List searches
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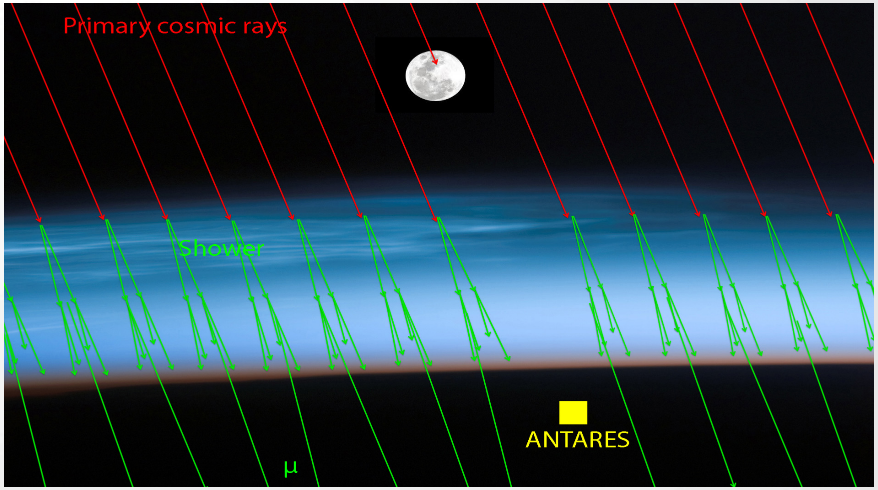
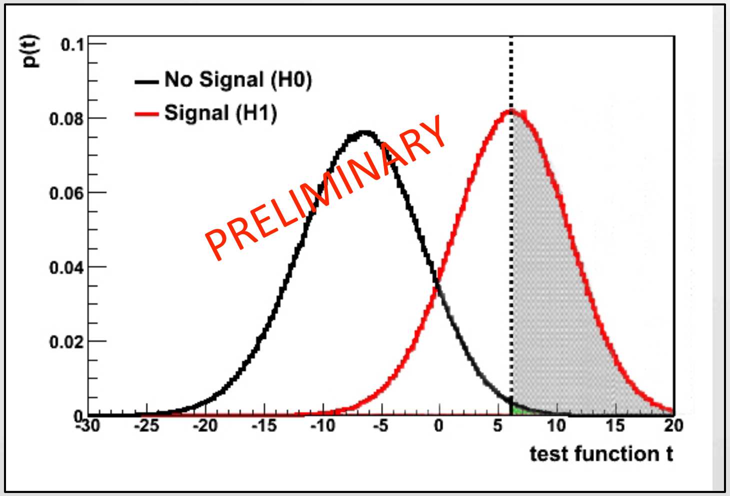
2008-2012 Moon shadow analysis

Test of ANTARES absolute pointing and angular resolution



TEST STATISTIC FUNCTION DISTRIBUTION

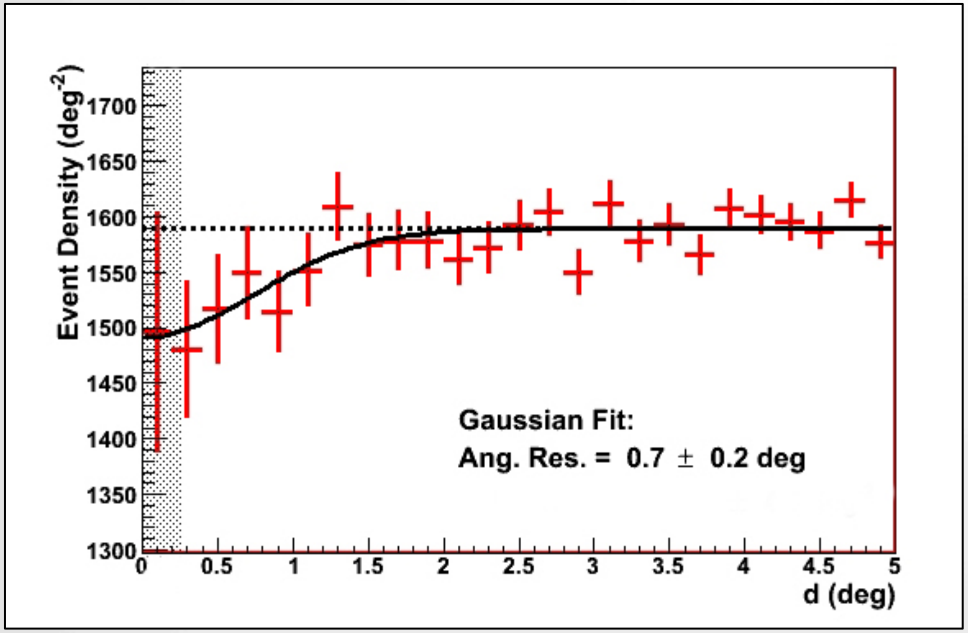


Test statistic reference value = 6.15
Expected significance (MC)= 2.93 σ

Test statistic value (DATA) = 7.12
Moon shadow significance = 3.06 σ

Analysis by Matteo Sanguineti

2008-2012 Moon shadow analysis



GAUSSIAN FIT OF MOON SHADOW

"Moon shadow" angular resolution from MC= 0.6 ± 0.1

"Moon shadow" angular resolution from data = 0.7 ± 0.2

- No relevant systematic effect
- Results are binning independent

Analysis by Matteo Sanguineti

Combined Antares-IceCube analysis status

- Agreement between IC and ANTARES collaboration to do a combined analysis in the Southern Hemisphere.

- Analysis with IC40+59 and ANTARES sample presented between June-July to both collaborations.
  - Agreement: Extension to IC79

- An analysis with IC79 included is now presented
  - Unblinding?

Combined Antares-IceCube analysis status

- Combined point source analysis for the **southern sky only**.

- Samples used:
  - **IC 40 lines:** 375 days, 22796 events
  - **IC 59 lines:** 348 days, 64240 events
  - **IC 79 lines:** 316 days, 59009 events
    - **Azimuth and event times of each event are not included.**

  April 2008 - May 2011 (Official data sets, provided by Chad Finley).

  - **ANTARES 2007-2012:** 1338 days, 4136 events
  - All these samples have already been used for point-source analysis in their respective collaborations.

- More events in the IC samples than the ANTARES one.
  - However, this doesn't mean the expected number of signal events are higher in the IC samples!

Acceptance

- Definition of the acceptance:

$$A(\delta) = \Phi_0^{-1} \iint dE\,dt\,A_{eff}(E,\delta)\frac{d\Phi}{dE}$$

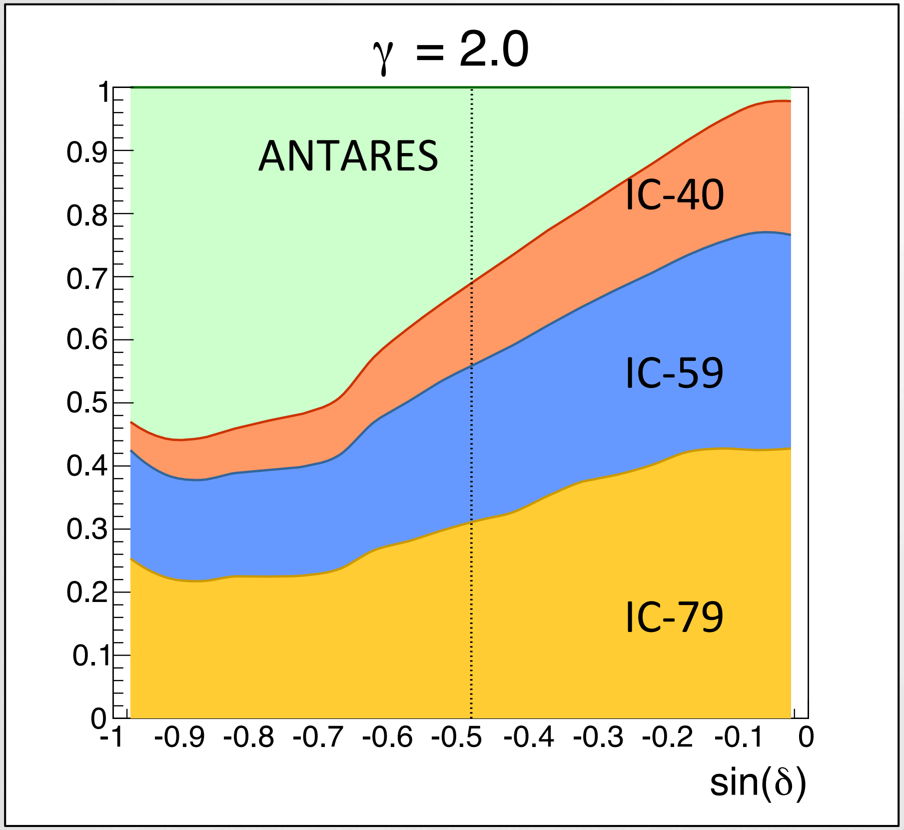
where:

- $A_{eff}(E, \delta)$: Effective area
- Φ_0: Flux normalisation

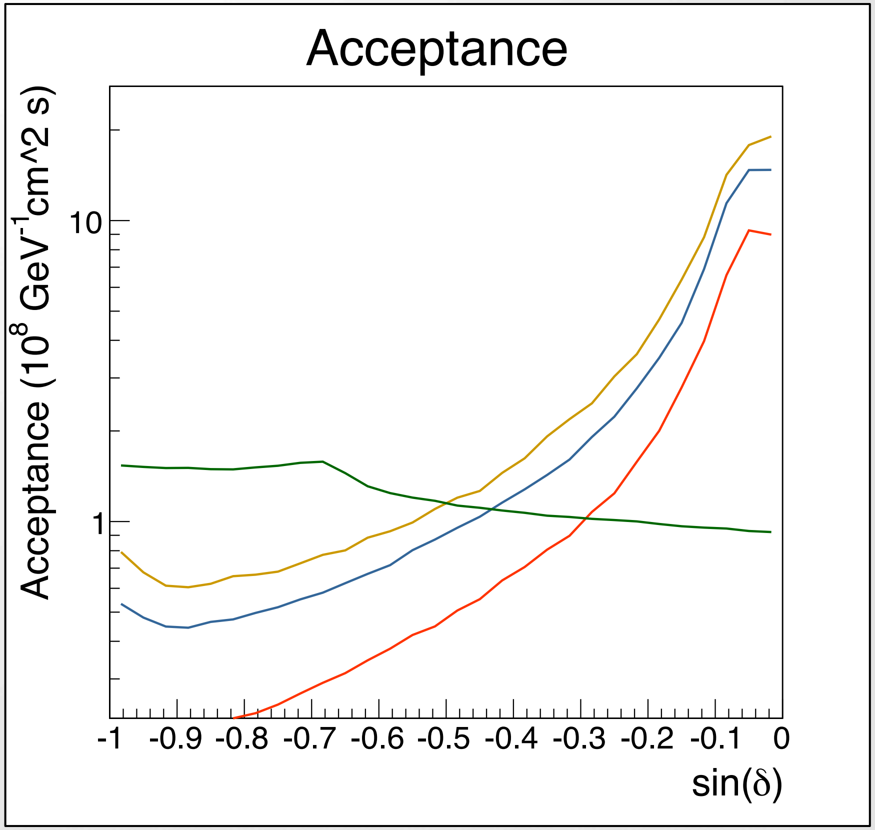
- ~ to indicate the performance of your detector at a given signal.
- Different flux assumptions:
  - Different energy spectra (E^{-2}, $E^{-2.5}$, E^{-3})
  - Energy cutoffs (30 TeV, 100 TeV, 300 TeV, 1 PeV). →

$$\frac{d\Phi}{dE} = \Phi_0 E^{-2} e^{-\sqrt{\frac{E}{E_{cutoff}}}}$$

Relative contribution / Acceptance for E^{-2}

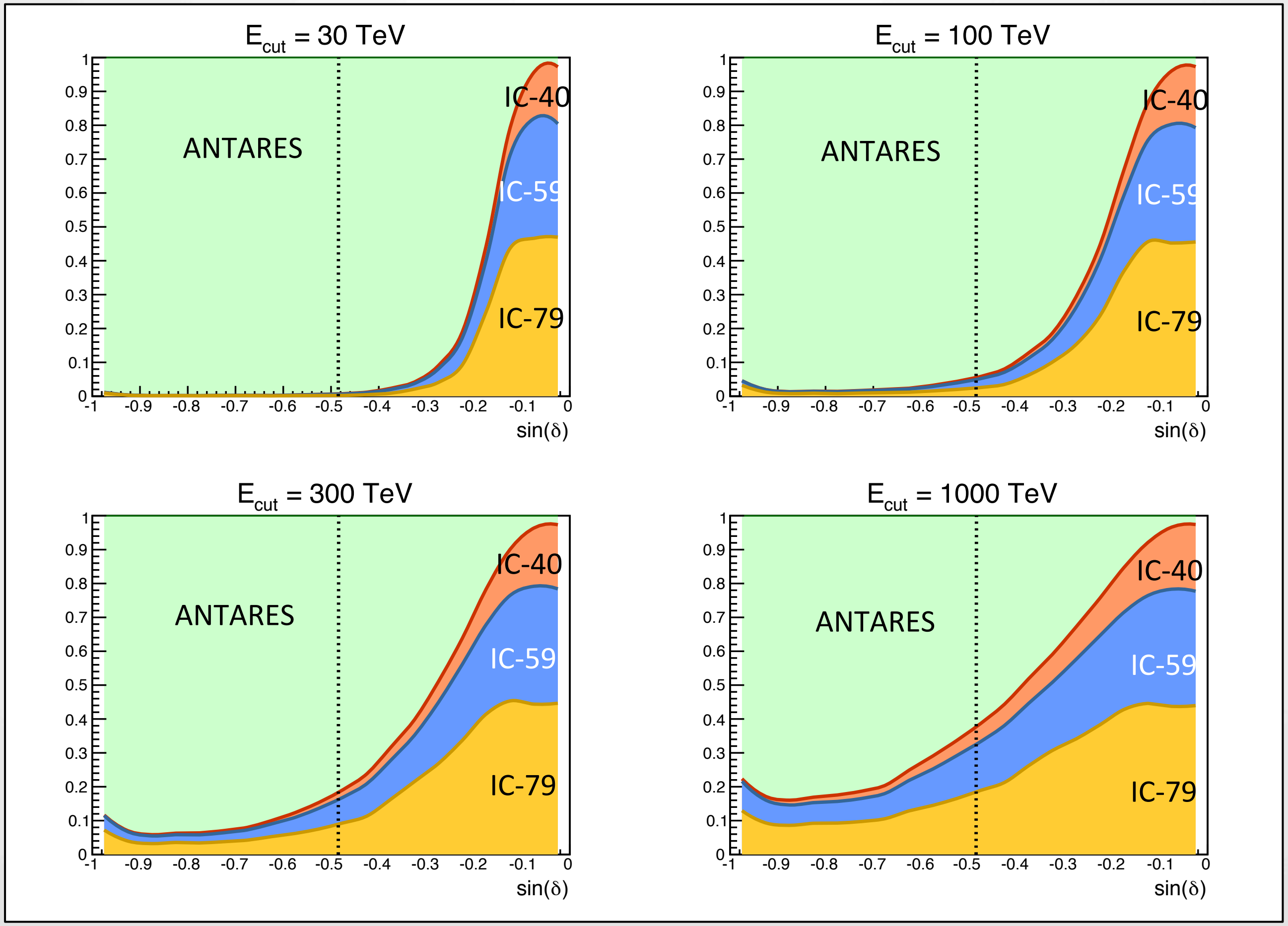


Probability for a signal event to be detected per each experiment. Used to sort the signal events simulated in each pex. Dotted black line indicates the declination of the Galactic Centre.



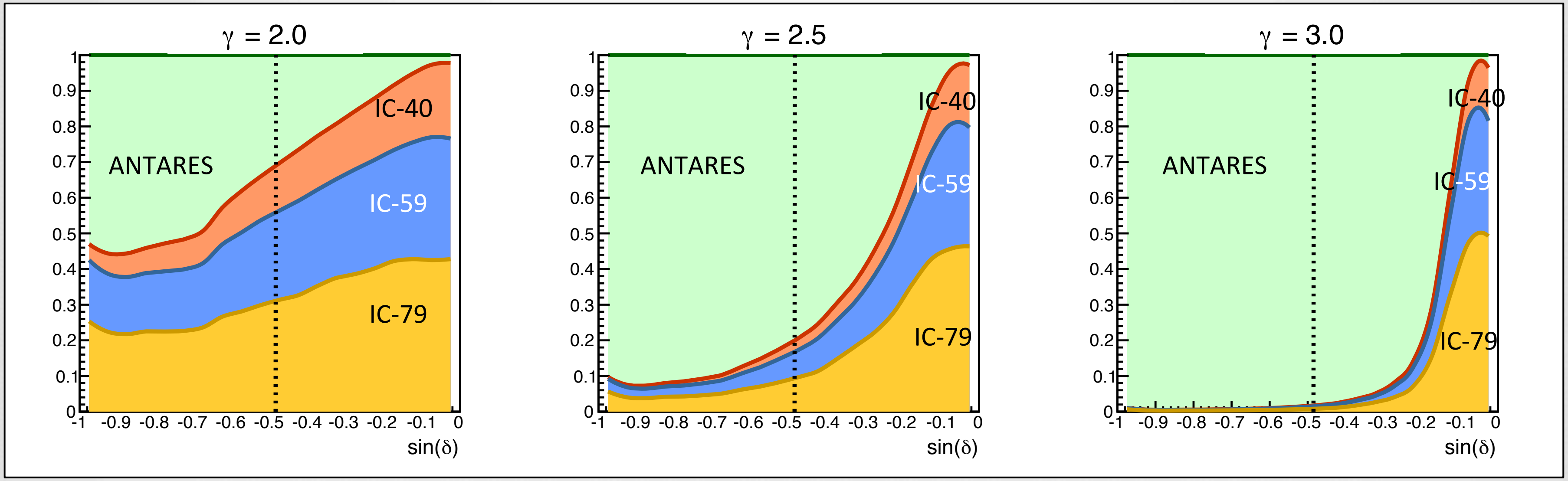
Acceptance for ANTARES, IC-40, IC-59 and IC-79.

Relative contribution: Different $E_{cutoffs}$



Relative acceptances for different energy cutoffs: IC40, IC59, IC-79 and ANTARES. Smaller energy cutoffs result in a higher ANTARES contribution (IC events are more energetic). Dotted-black line indicates the declination of the Galactic Centre.

Relative contribution: Different spectra



Relative acceptances for different energy spectra: IC40, IC59, IC-79 and ANTARES.
The higher the spectrum, the lesser the IC contribution (IC events are more energetic). Black dotted line indicates the declination of the Galactic Centre.

Likelihood

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i\in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

n^j_s related to each sample with the relative contribution of each experiment:

$$n_s^j = C^j(\delta) n_s$$

IceCube signal PDF

$$S_i^{IC} = \frac{1}{2\pi\sigma_i^2} e^{\frac{-|x_s - x_i|^2}{2\sigma_i^2}} P_s(E_i, \sigma_i \mid \delta_i)$$

ANTARES signal PDF

$$S_i^{ANT} = \frac{1}{2\pi\beta_i^2} e^{\frac{-|x_s - x_i|^2}{2\beta_i^2}} P_s(E_i, \beta_i)$$

IceCube background PDF

$$B_i^{IC} = B^j(\delta_i)\varepsilon^j(E_i, \sigma_i \mid \delta_i)$$

ANTARES background PDF

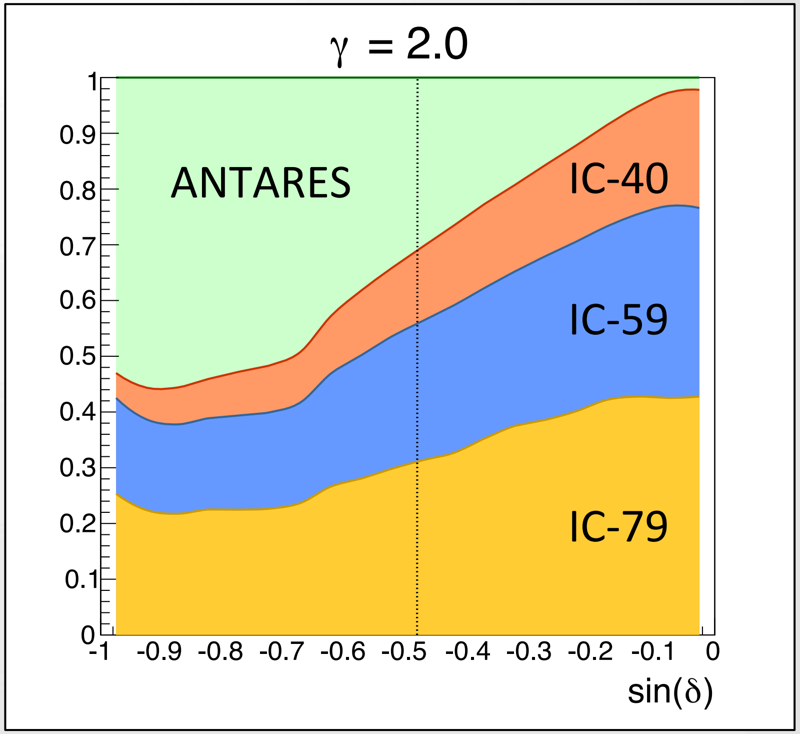
$$B_i^{ANT} = B(\delta_i) P_b(E_i, \beta_i)$$

[See arXiv:physics/0401045v1 for the justification on the use of P(E, beta)]

Procedure: Fixed source analysis

- 10^4 pseudoexperiments per each considered declination and number of source events.
  - Declination range: [-85º, -5º] in steps of 5º.
  - 0 to 30 signal events.

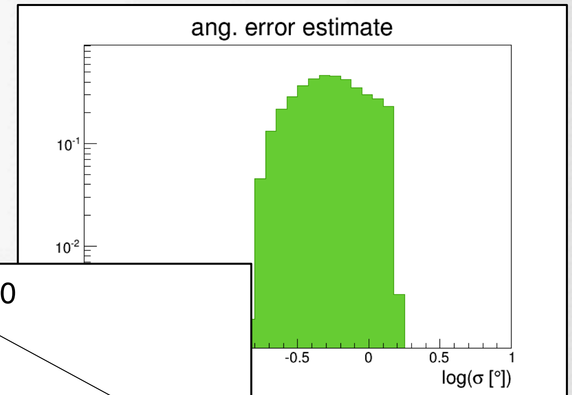
- Sorting of signal events according to the contribution of each sample.

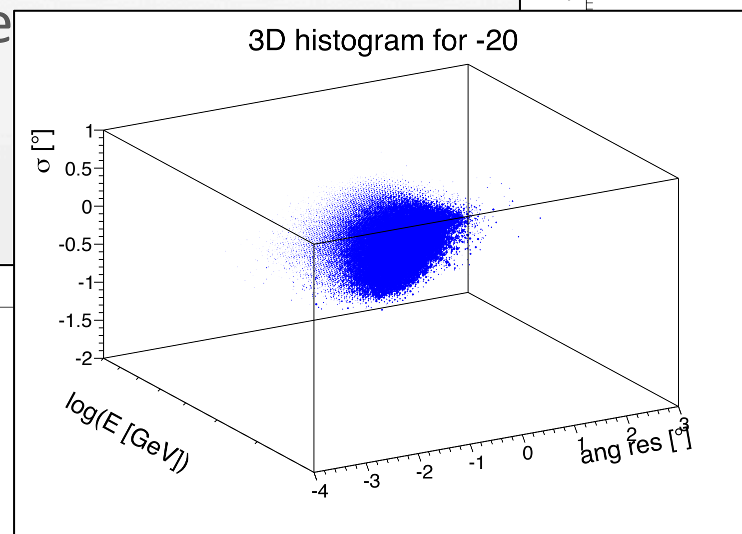


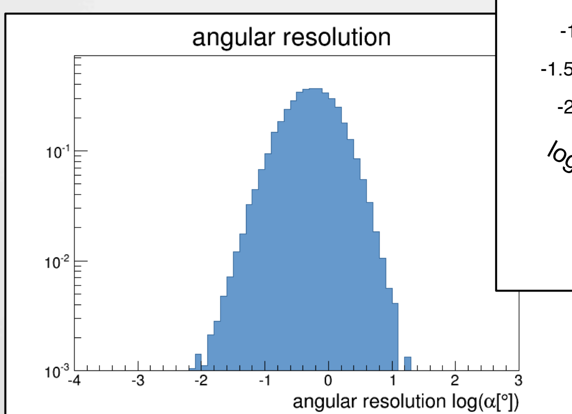
Probability for a signal event to be detected per each experiment. Used to sort the signal events simulated in each pex.

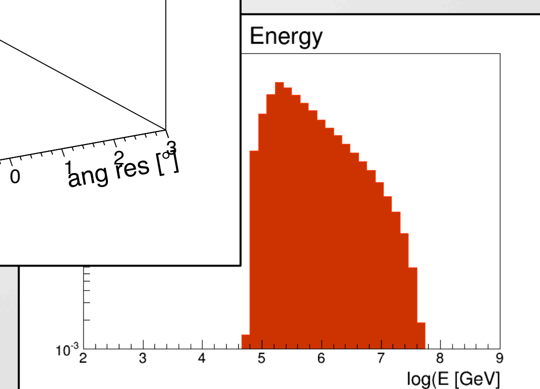
Signal generation

- 3D histogram which contains angular resolution, angular error estimate (σ/β) and the energy estimator.





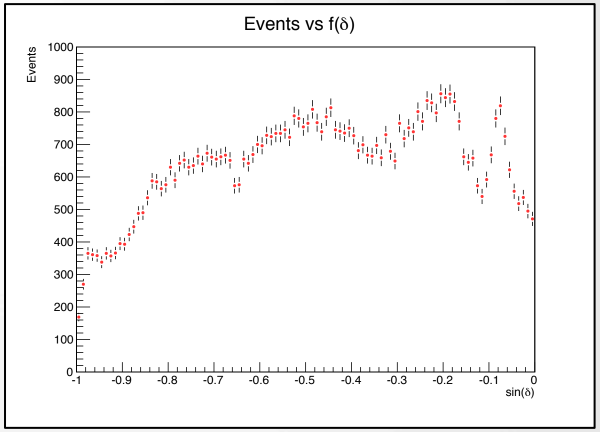




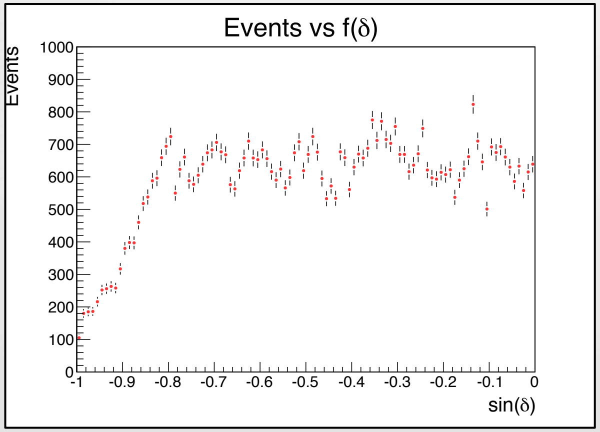
Background generation

- Declination generated through a parametrisation of the data. Right ascension assumed to be uniform.

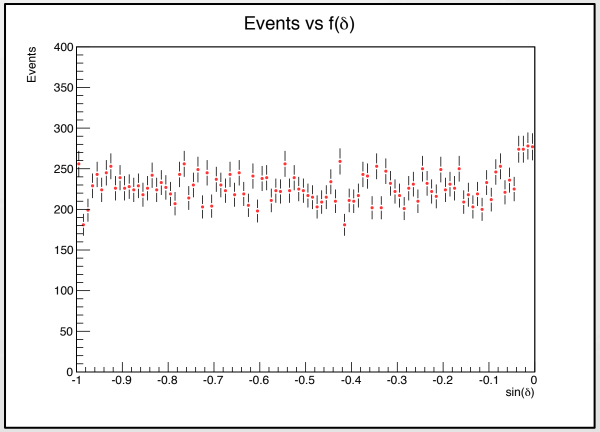
- Energy and angular error estimate obtained from 2D histograms using data events.



Bg parametrisation for IC59.

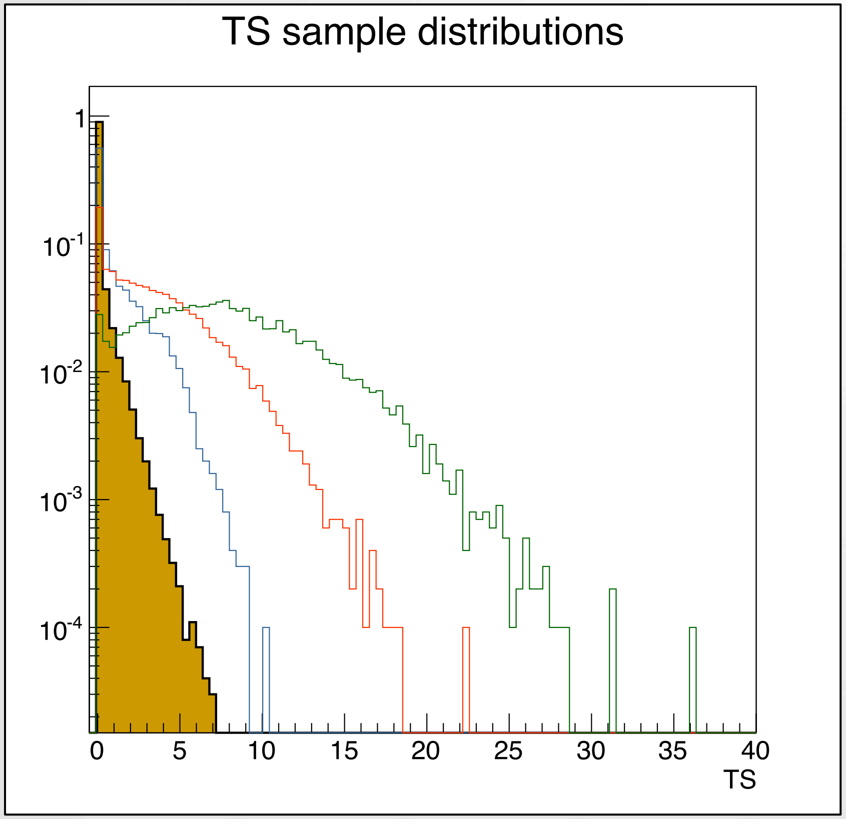


Bg parametrisation for IC79.

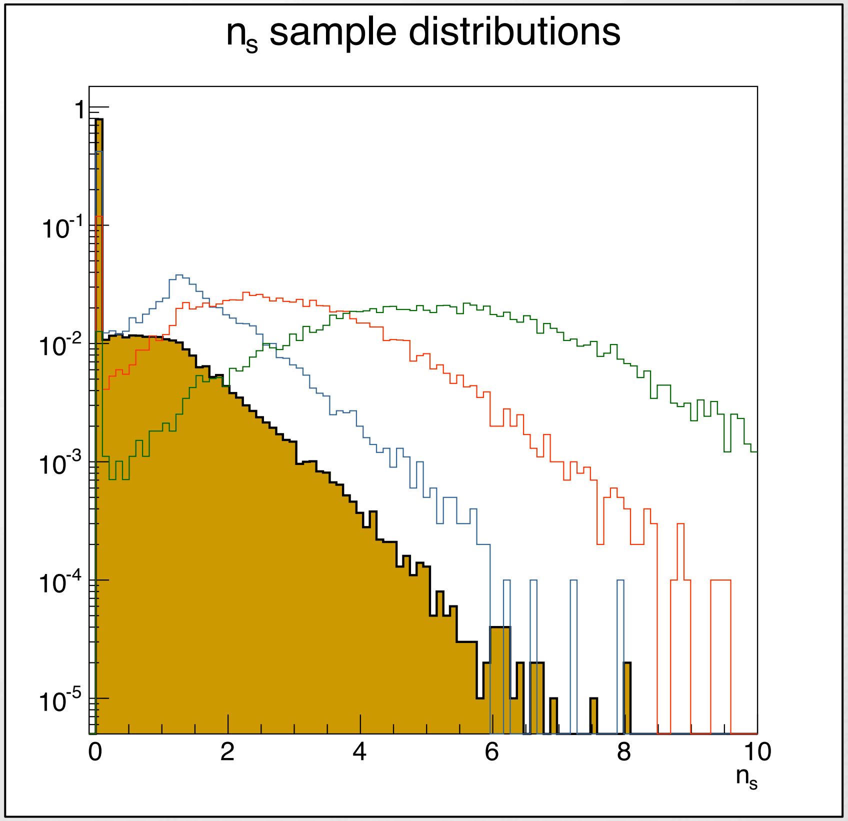


Bg parametrisation for IC40.

TS distributions comparison

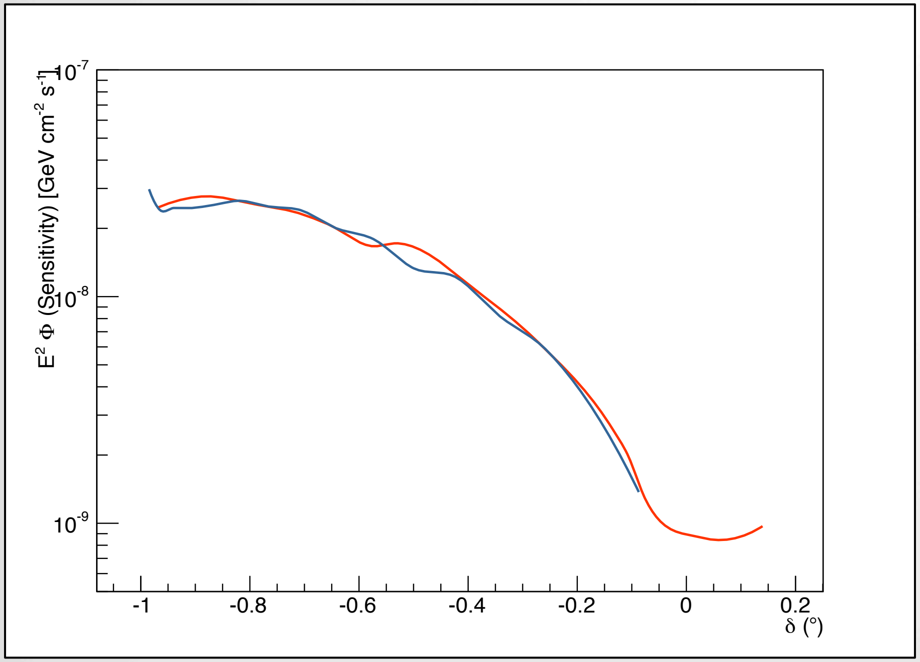


Combined TS sample distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

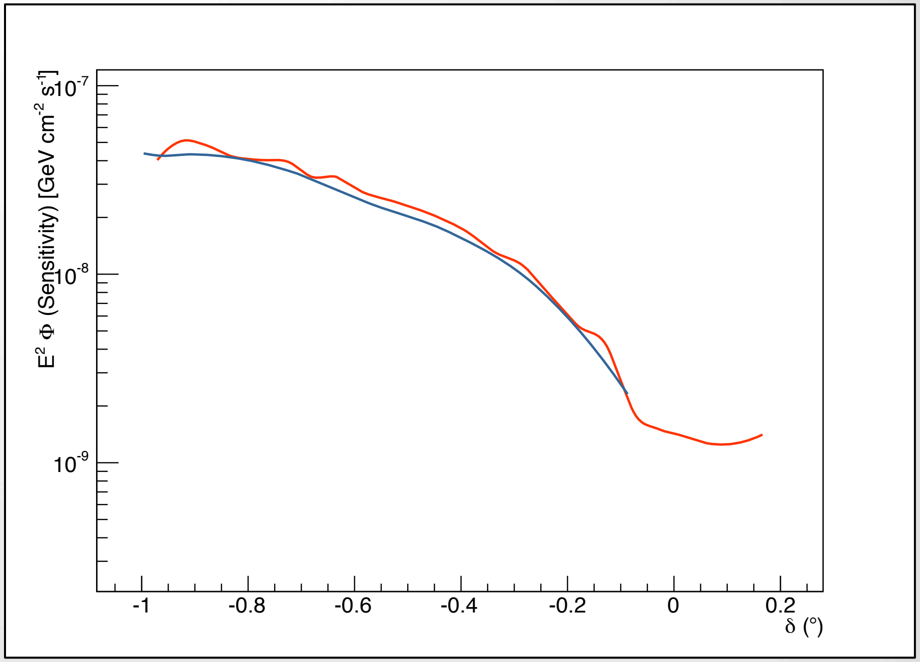


Combined n_s sample distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

IC40+59+79 and IC40+59 sensitivities for a E^{-2} spectrum

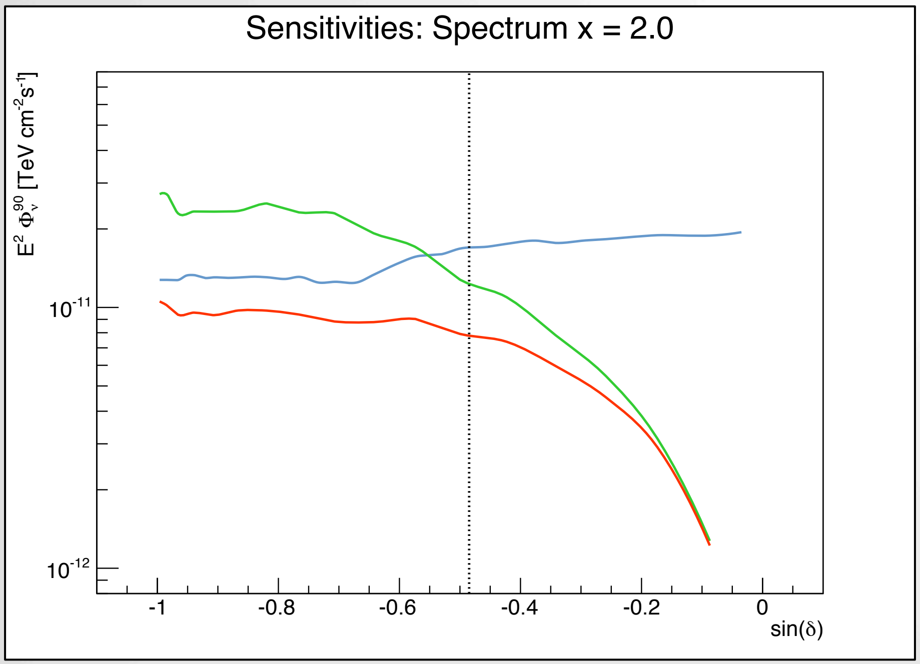


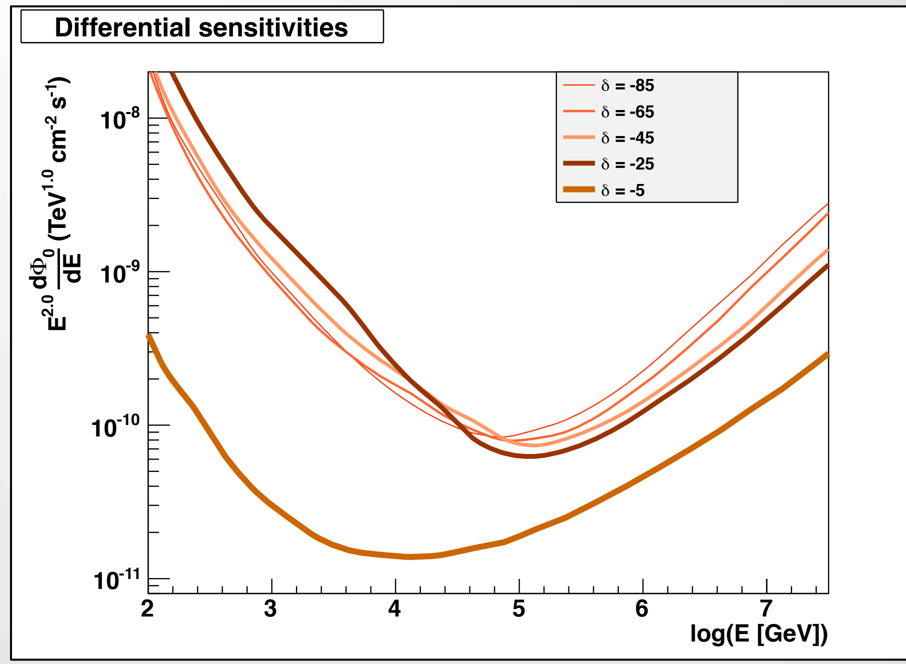
90% CL sensitivity for the IC40+59+79 sample assuming an E^{-2} spectrum (Neyman limit). RED: IceCube official results (arXiv:1012.2137) Blue: Results using our pseudoexperiments.



90% CL sensitivity for the IC40+59 samples assuming an E^{-2} spectrum (Neyman limit). RED: IceCube official results (arXiv:1210.4195) Blue: Results using our pseudoexperiments.

ANTARES+IC40+59+79 sensitivities (γ=2.0)

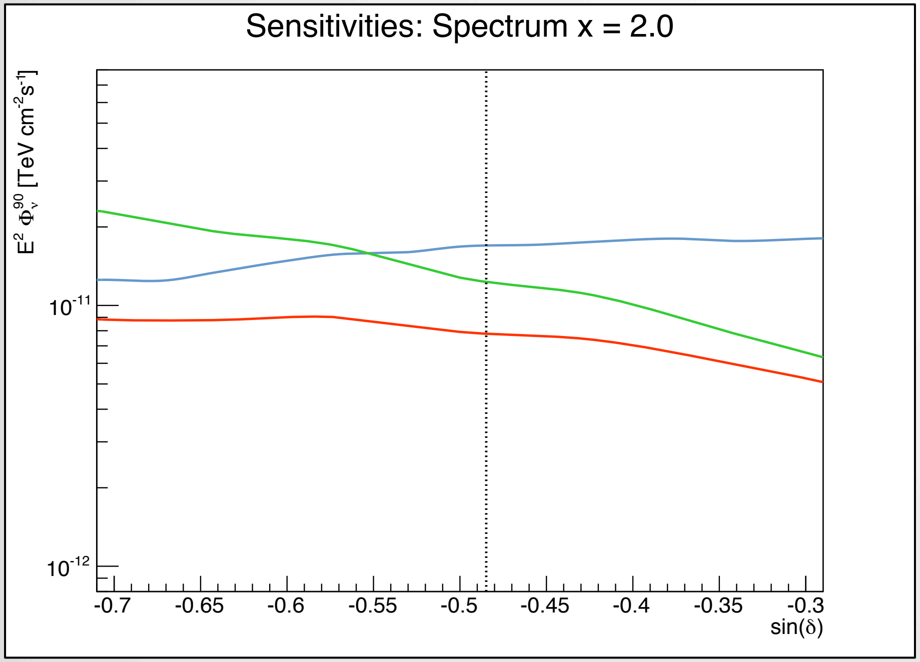




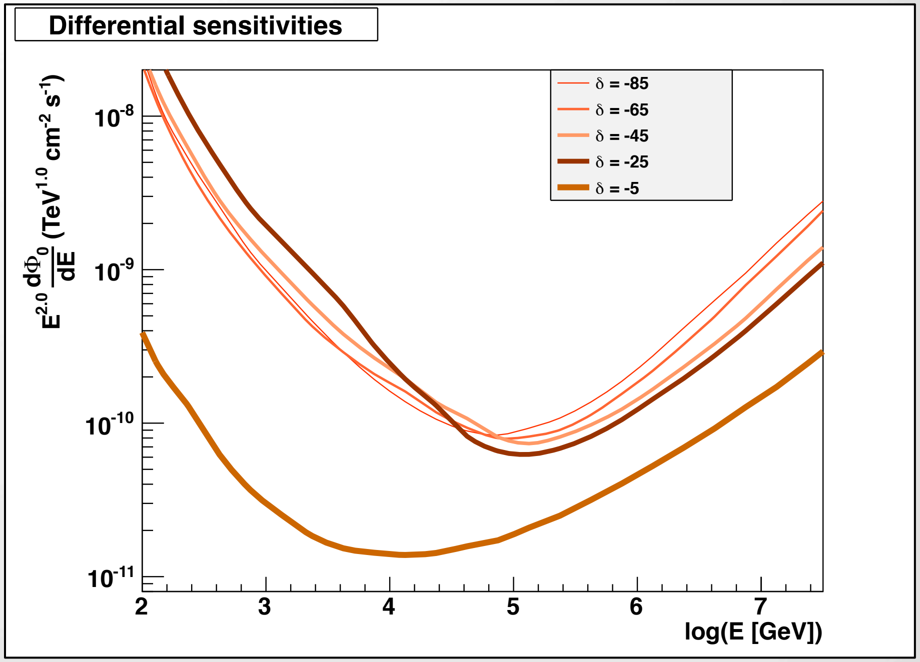
Sensitivities for an E^{-2} spectrum:
Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.

Differential sensitivities for the combined ANTARES and IC40+59+79 sample.

ANTARES+IC40+59+79 sensitivities (γ=2.0)



Sensitivities for an E^{-2} spectrum (zoom around GC): Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79. Black dotted line: GC position.

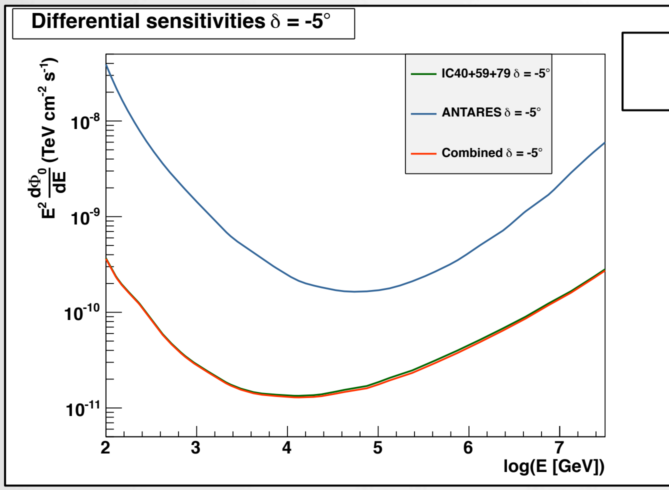


Differential sensitivities for the combined ANTARES and IC40+59+79 sample.

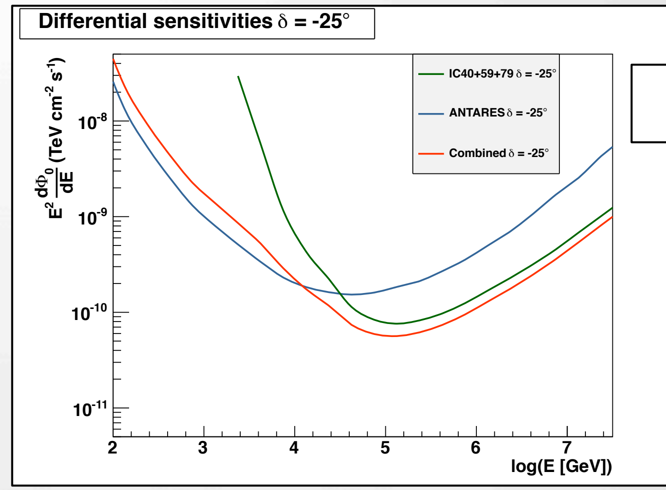
Diferential sensitivities

Differential sensitivities for different declinations:

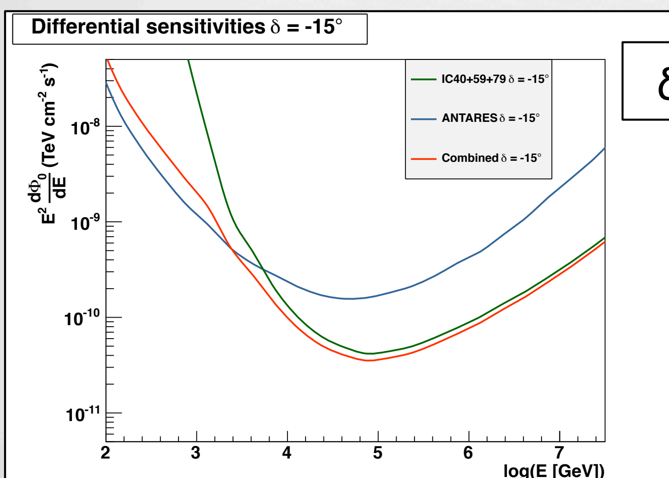
Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.



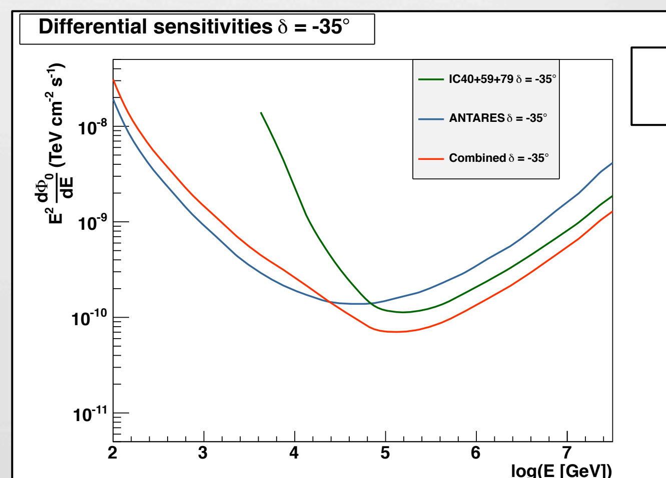
δ=-5º



δ=-25º



δ=-15º

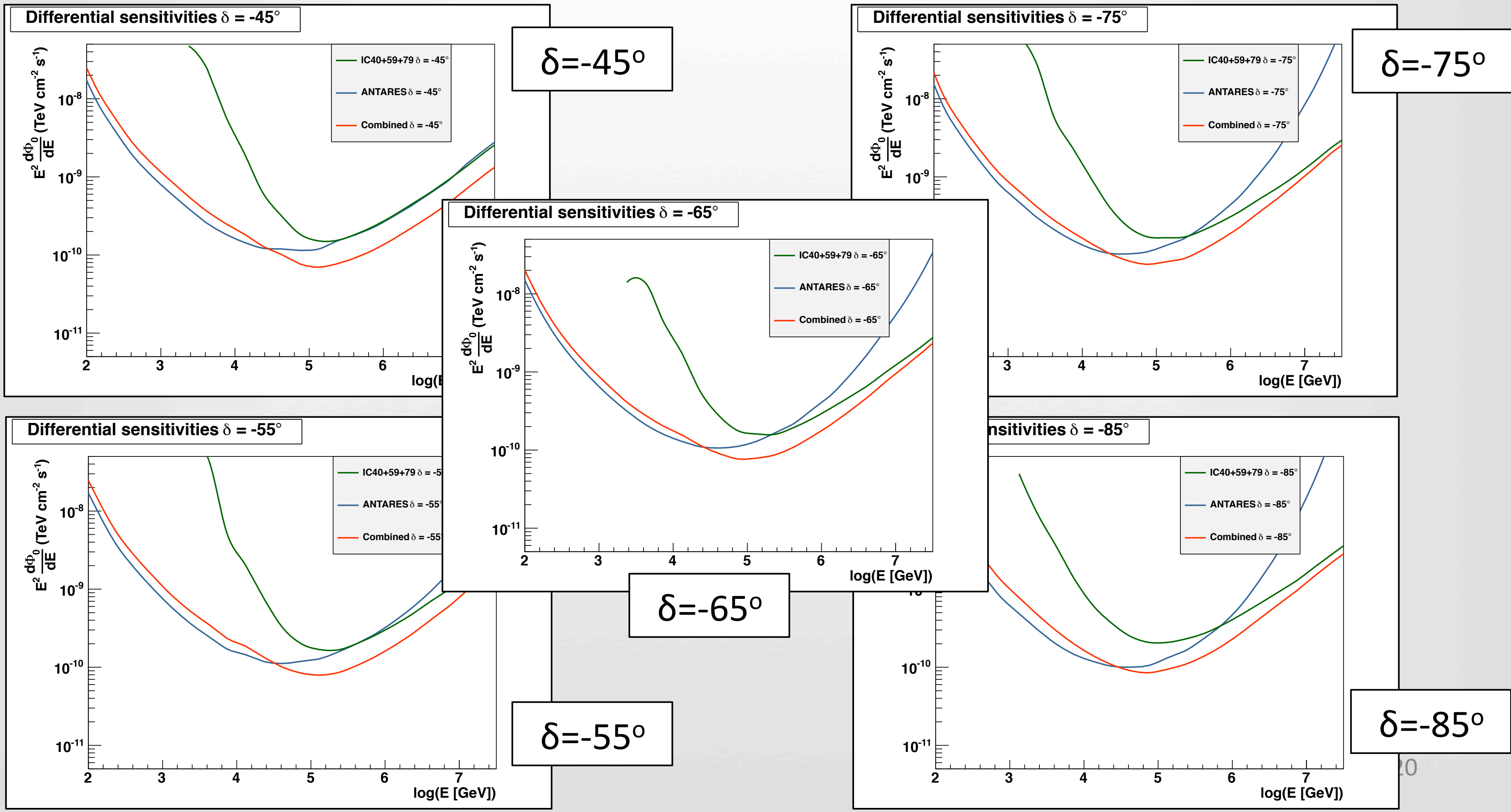


δ=-35º

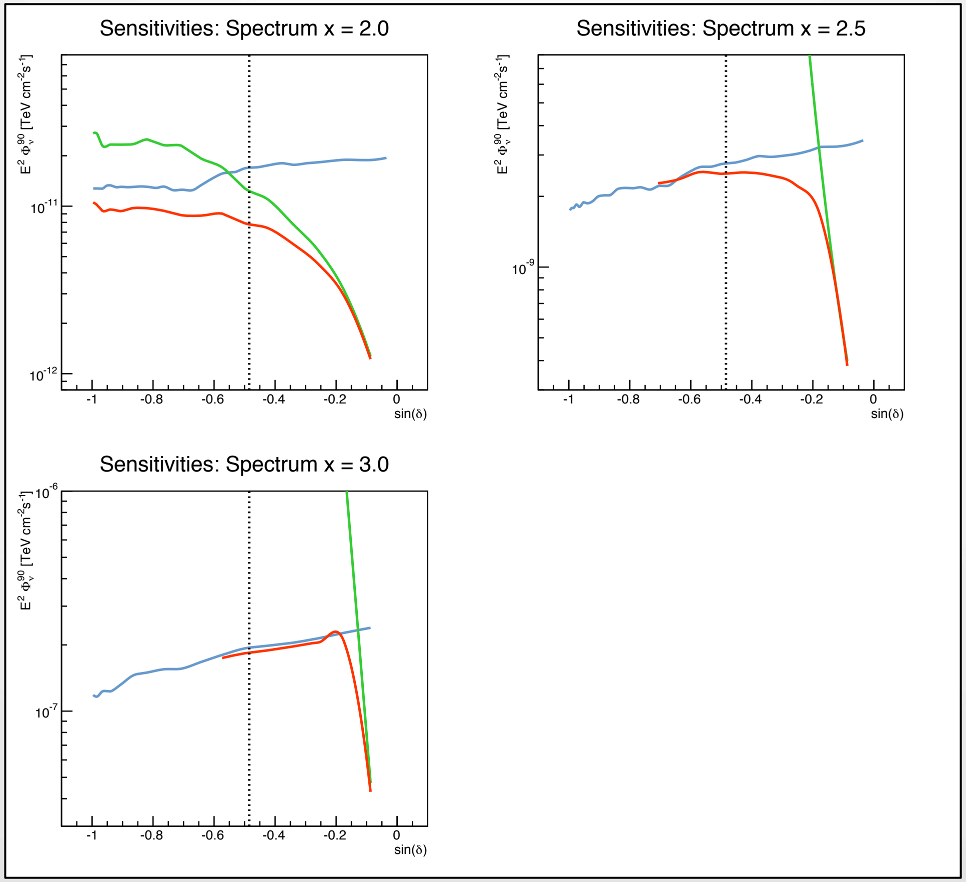
Diferential sensitivities

Differential sensitivities for different declinations:

Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.

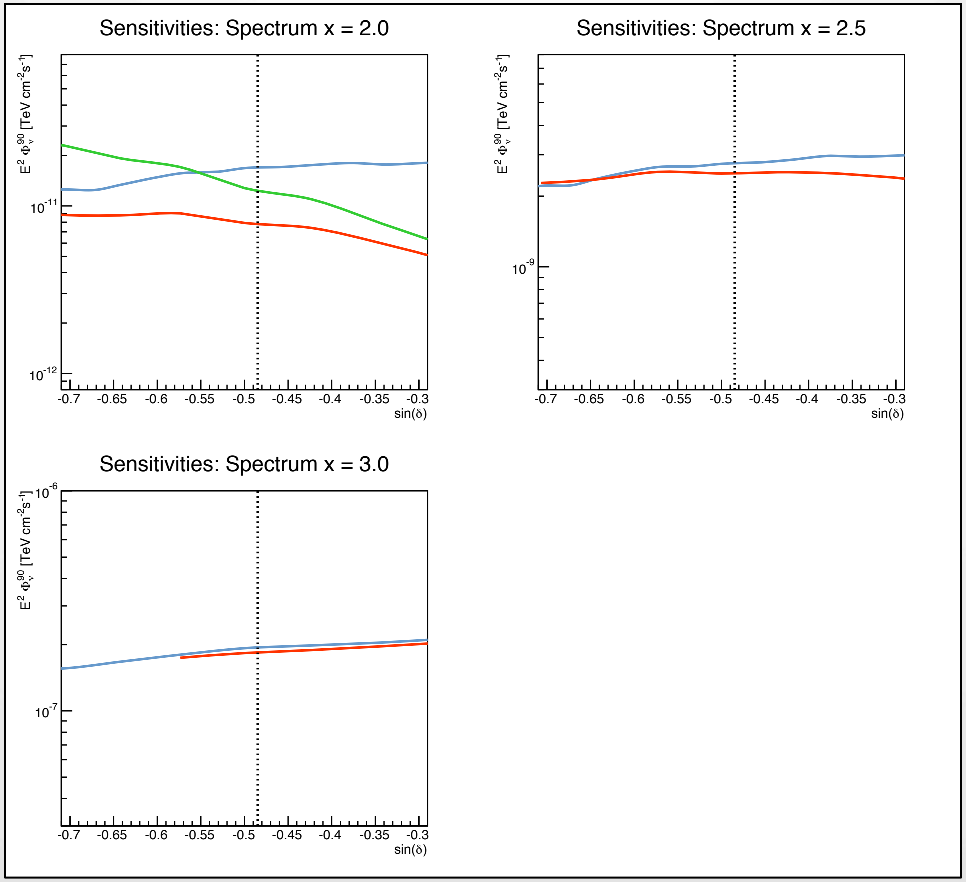


ANTARES+IC40+59+79 sensitivities



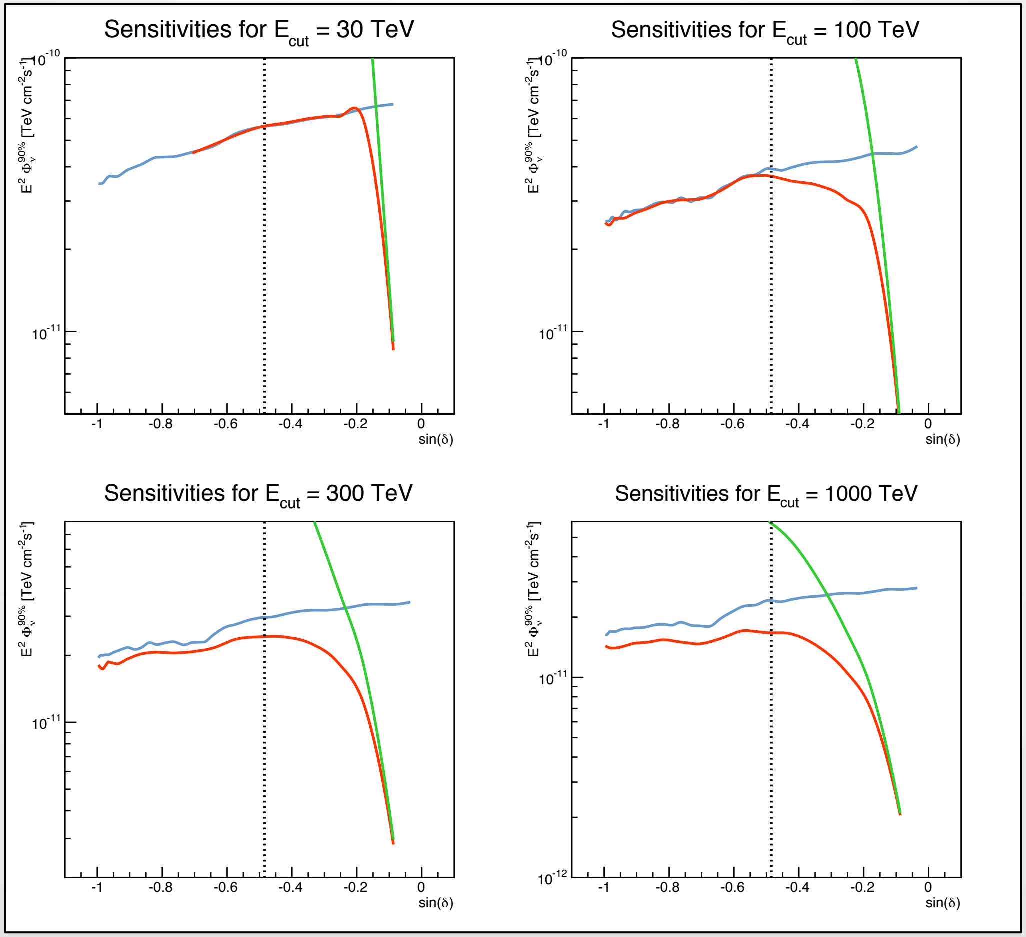
Sensitivities for different energy cutoffs:
Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.

ANTARES+IC40+59+79 sensitivities



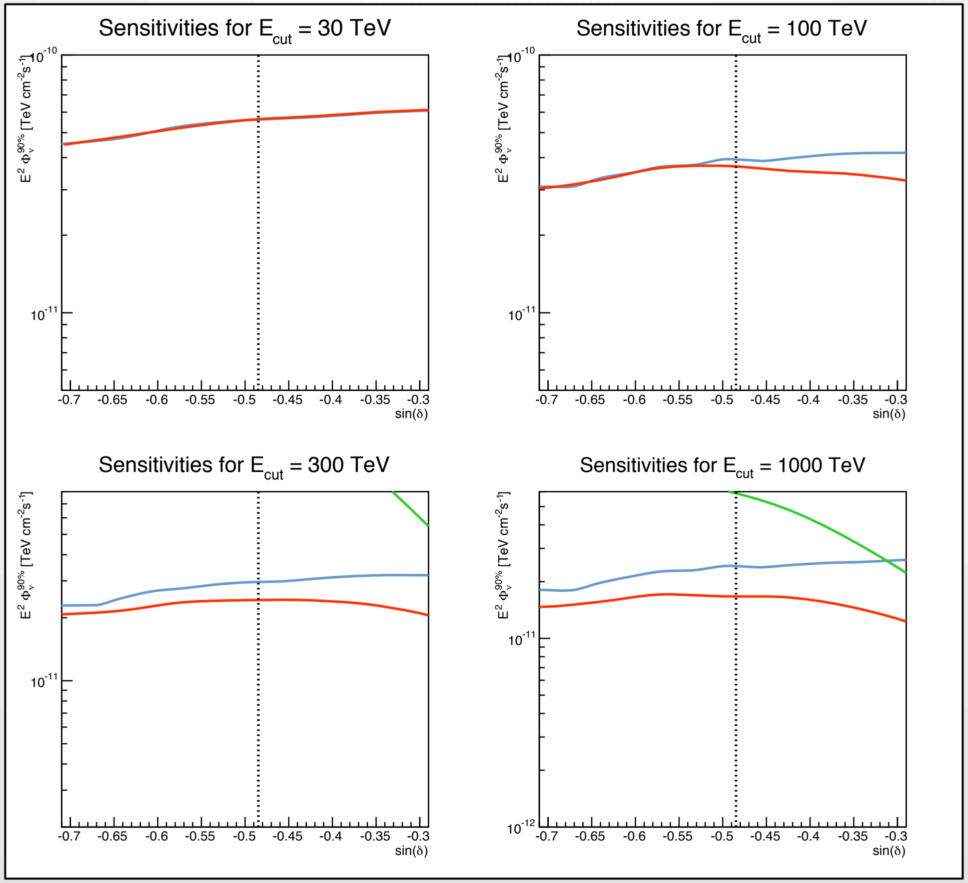
Sensitivities for different energy cutoffs (zoom over GC):
Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.

ANTARES+IC40+59+79 sensitivities



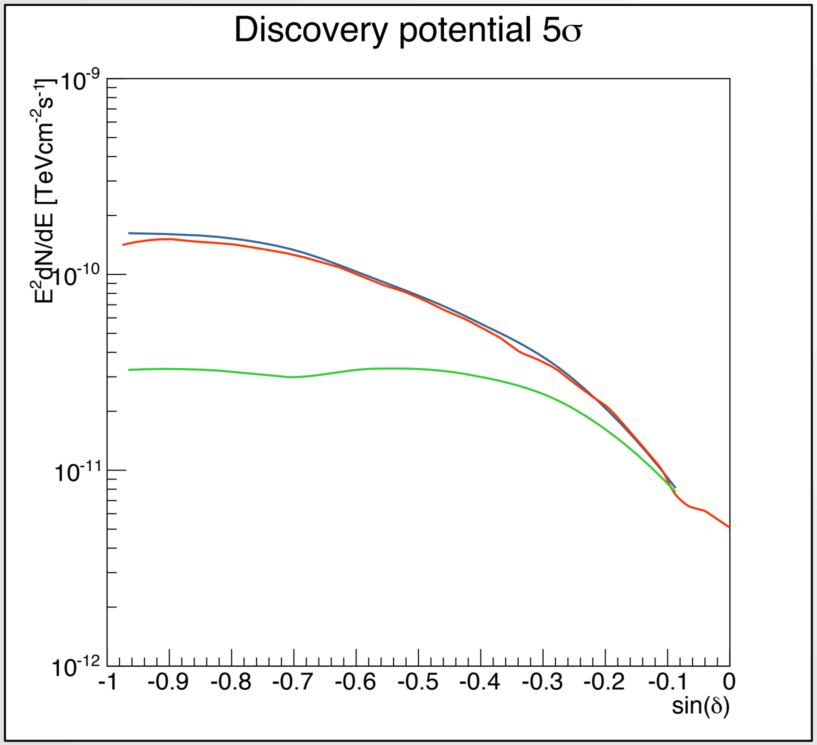
Sensitivities for different energy cutoffs:
Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.

ANTARES+IC40+59+79 sensitivities

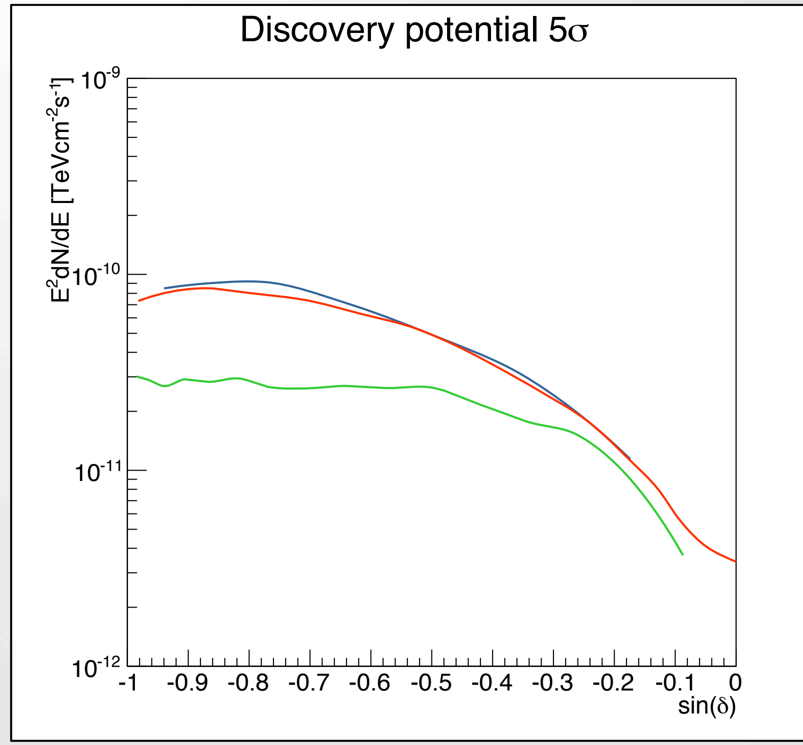


Sensitivities for different energy cutoffs (zoom over GC):
Combined ANTARES and IC40+59+79, ANTARES and IC40+59+79.

5 σ discovery fluxes



5σ discovery fluxes for the combined ANTARES+IC samples and the IC40+59 samples. RED: Official IC results. BLUE: Obtained from my pex.



5σ discovery fluxes for the combined ANTARES+IC samples and the IC40+59+79 sample. RED: Official IC results. BLUE: Discovery flux obtained from my pex.

Candidate list and full sky search

- Full sky search performed for the Southern Hemisphere (implementation details in back-up slides).

- Logical OR of the source lists which had been used so far in ANT & IC point-source publications
  - Same Southern Hemisphere sources as in the IC 3-year high energy paper (http://arxiv.org/abs/1405.5303).
  - Sources in back-up slides.

Conclusions

- The IC40+59+79 and ANTARES samples can be combined to improve the results over the Southern hemisphere.
- Fixed source analysis: Different crossover regions depending on the assumed spectra/cutoff
  - For Υ=3.0 or E_{cutoff} < 100 TeV → Significantly smaller region ($\sin(\delta) > -0.2$)
- Full sky search for Southern Hemisphere, merge of IC and ANTARES candidate source lists.
- Request for unblinding of the data.
- Wiki with more details: http://antares.in2p3.fr/users/jabamar/IceCubeANTARESWiki/
- Layout for paper.

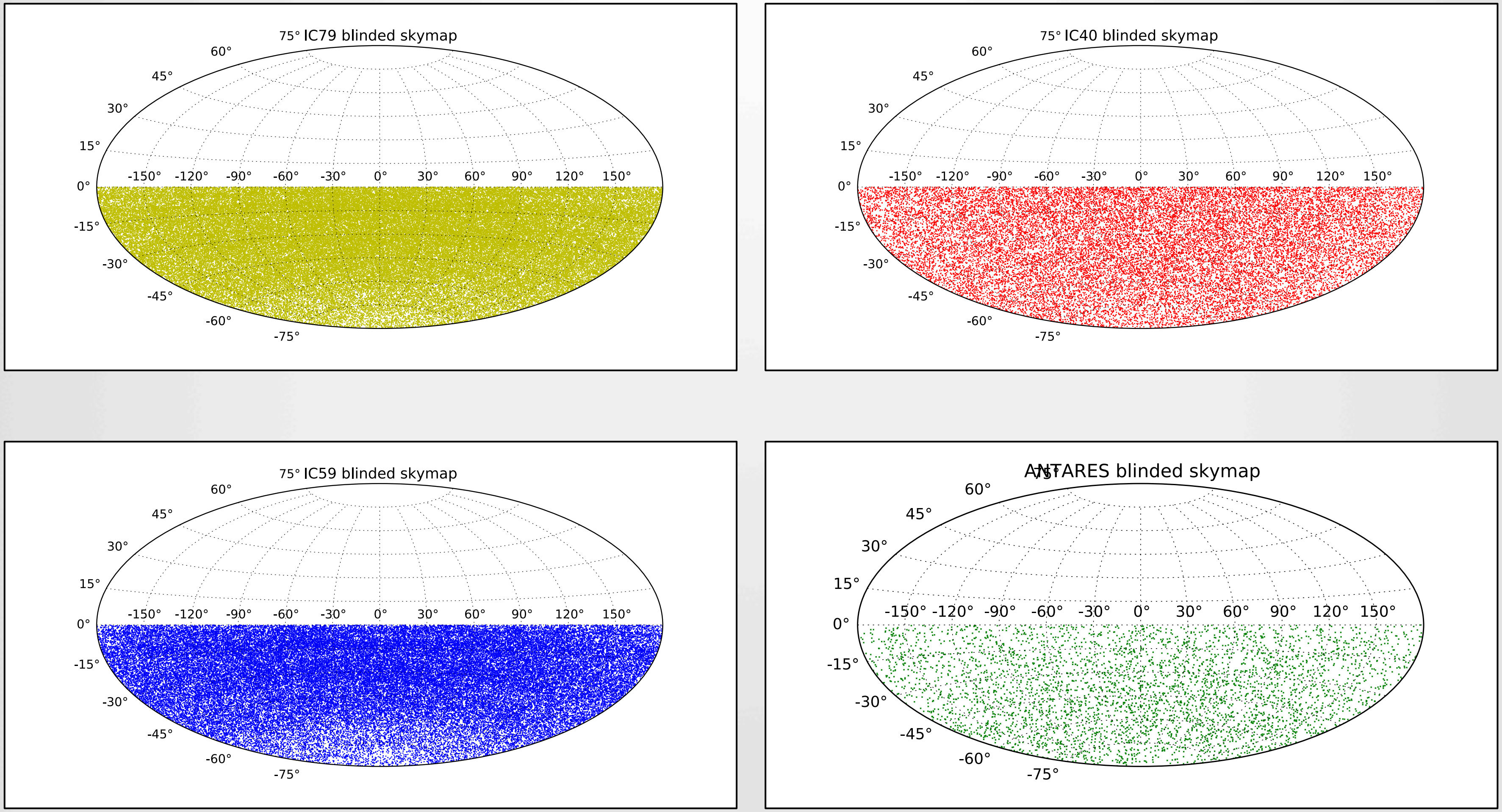
Conclusions

Search for point-like neutrino sources over the Southern Hemisphere with the IceCube and ANTARES neutrino telescopes

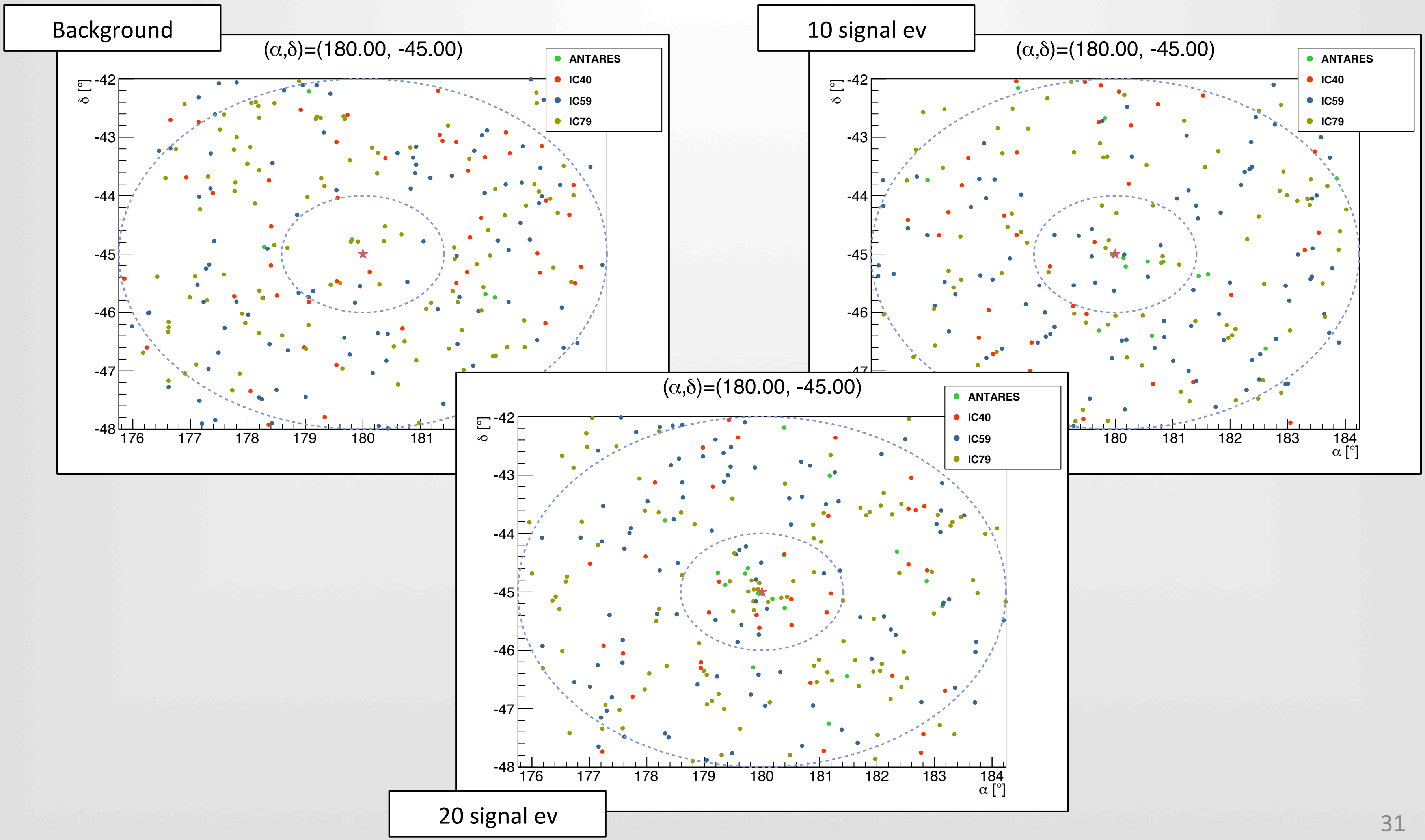
The ANTARES and IceCube collaborations

Back-up slides

(Blinded) Skymaps

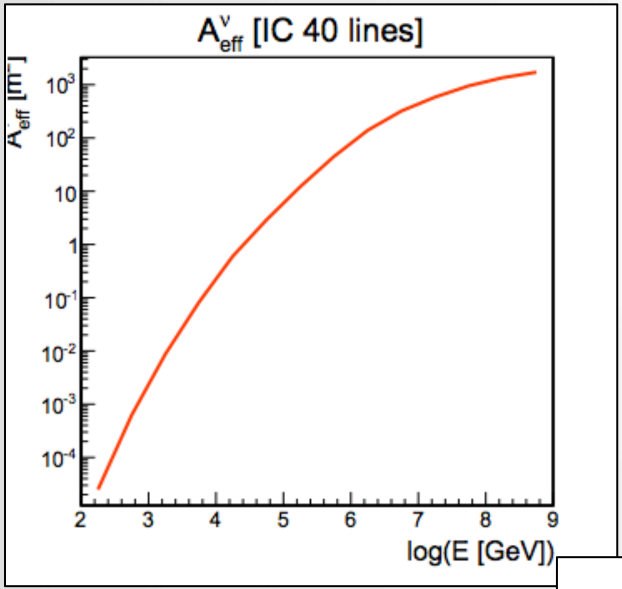


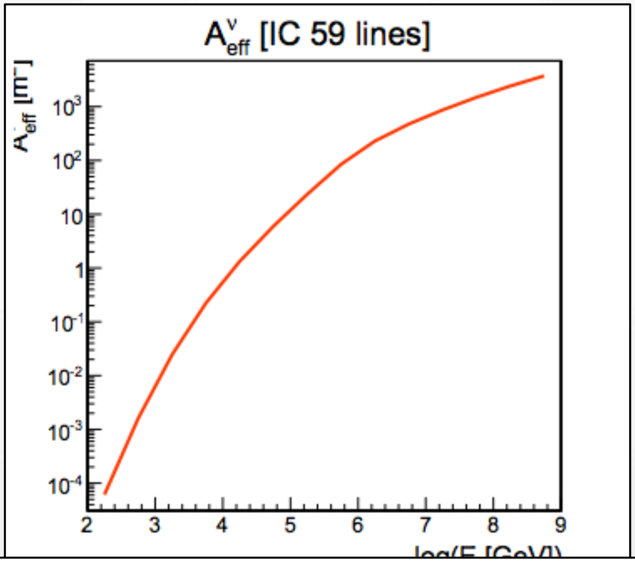
(Blinded) Skymaps

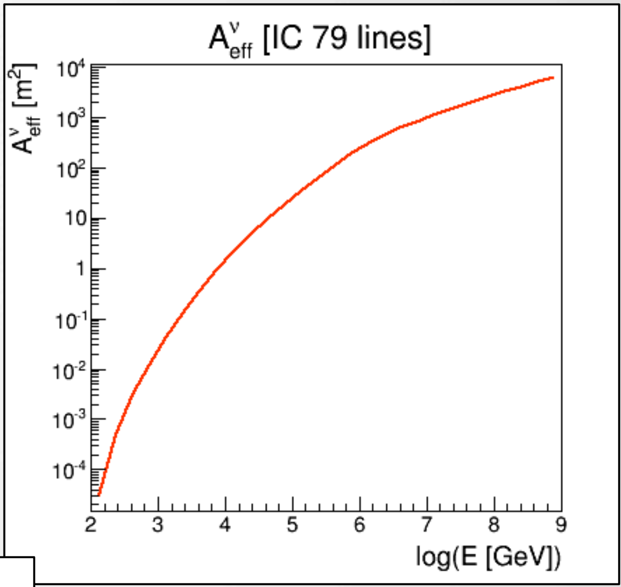


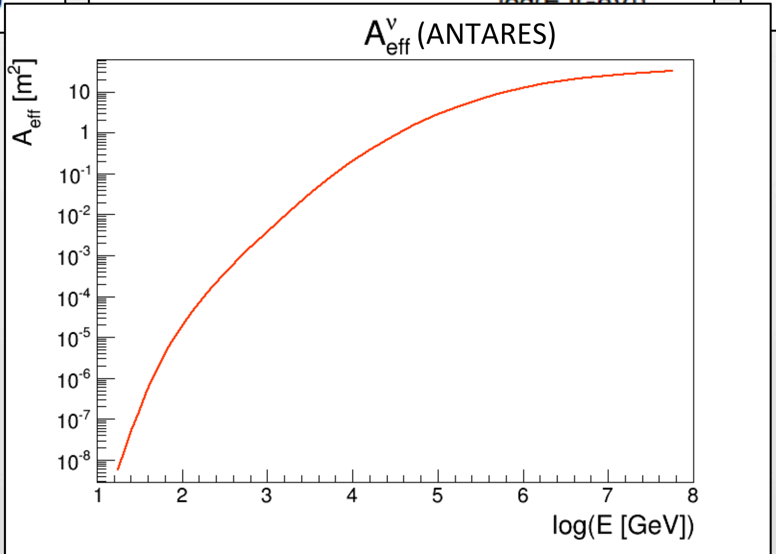
Effective areas

Effective Areas

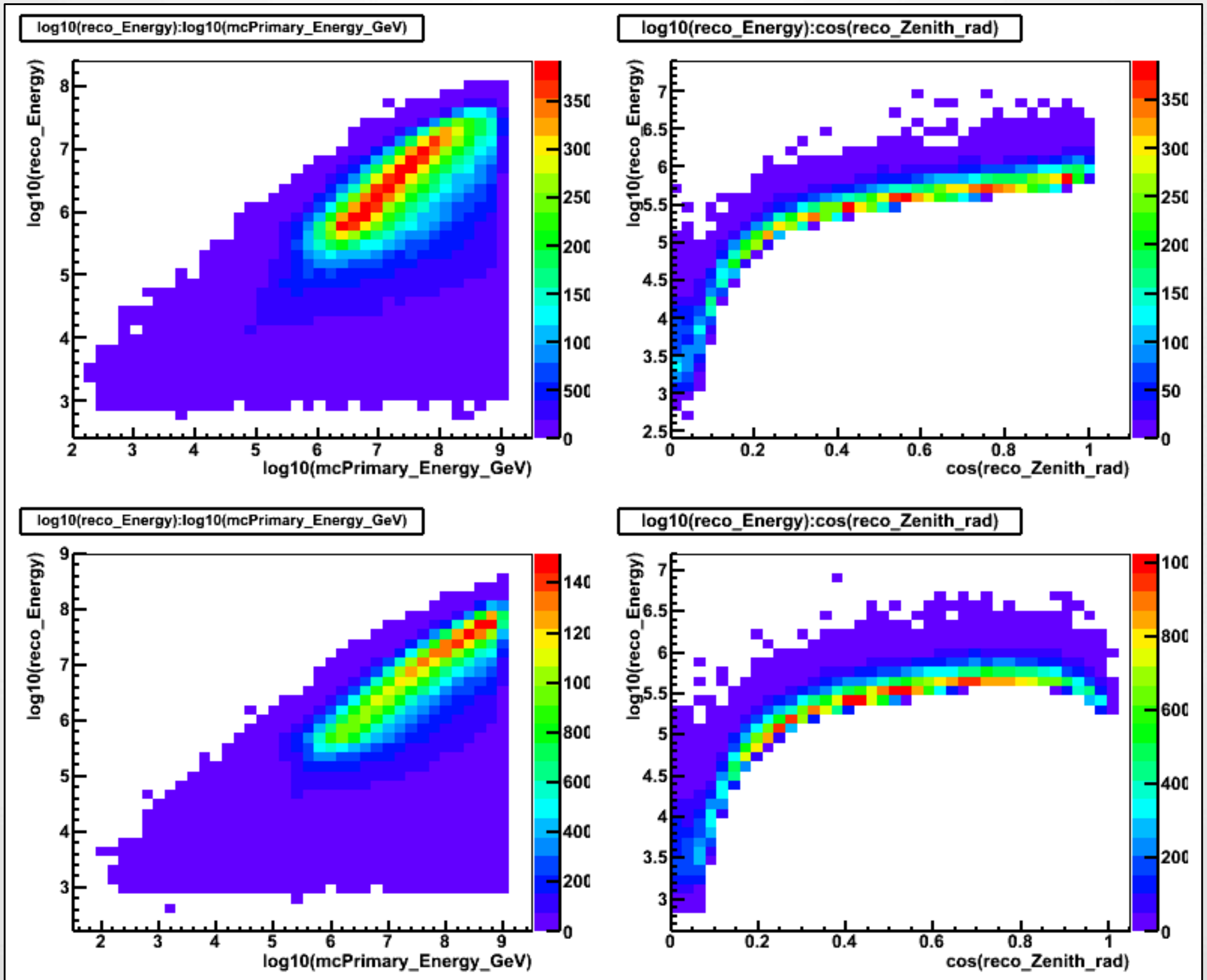








Effective areas



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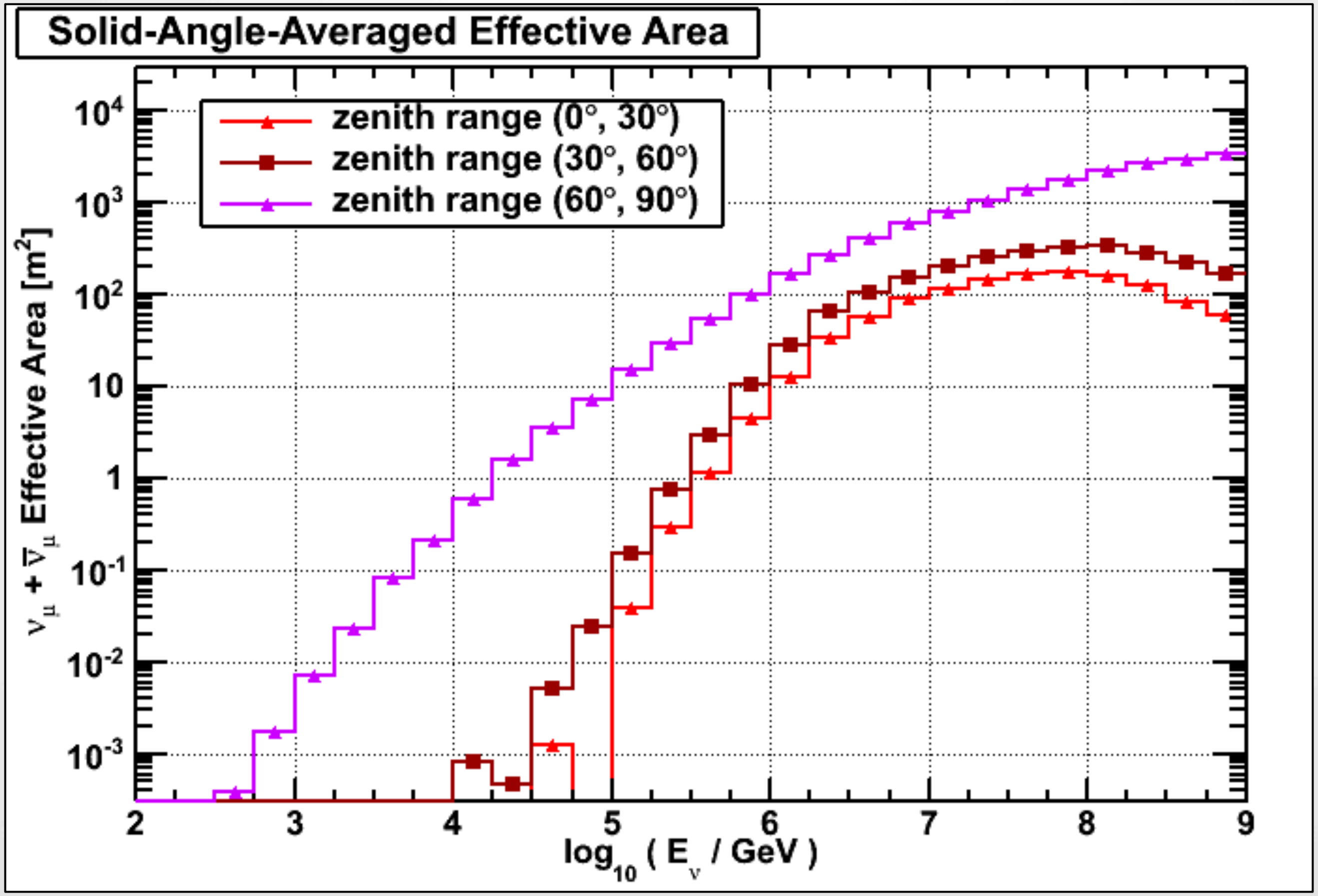

Likelihood

Likelihood (as used by IceCube)

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

- Very similar likelihood to the one used in the IceCube PS analysis and the ANTARES 2007-12 one:
  - j : Sample (IC40, IC59, Antares).

IceCube signal PDF

$$S_i^{IC} = \frac{1}{2\pi\sigma_i^2} e^{\frac{-|x_s - x_i|^2}{2\sigma_i^2}} \varepsilon^j(E_i | \delta_i)$$

ANTARES signal PDF

$$S_i^{ANT} = \frac{1}{2\pi\beta_i^2} e^{\frac{-|x_s - x_i|^2}{2\beta_i^2}} P_s(E_i)$$

Likelihood (as used by IceCube)

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

- Very similar likelihood to the one used in the IceCube PS analysis and the ANTARES 2007-12 one:
  - j : Sample (IC40, IC59, Antares).

IceCube background PDF

$$B_i^{IC} = B^{IC}(\delta_i)\,\varepsilon_{bg}^{IC}(E_i \mid \delta_i)$$

ANTARES background PDF

$$B_i^{ANT} = B^{ANT}(\delta_i)\,\varepsilon_{bg}^{ANT}(E_i)$$

Likelihood (as used in this analysis)

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

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IceCube signal PDF

$$S_i^{IC} = \frac{1}{2\pi\sigma_i^2} e^{\frac{-|x_s - x_i|^2}{2\sigma_i^2}} P_{sg}^{IC}(E_i, \sigma_i \mid \delta_i)$$

ANTARES signal PDF

$$S_i^{ANT} = \frac{1}{2\pi\beta_i^2} e^{\frac{-|x_s - x_i|^2}{2\beta_i^2}} P_{sg}^{ANT}(E_i, \beta_i)$$

[See arXiv:physics/0401045v1 for the justification on the use of P(E, beta)]

Likelihood (as used in this analysis)

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i \in j} \left[\frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

- Very similar likelihood to the one used in the IceCube PS analysis and the ANTARES 2007-12 one:
  - j : Sample (IC40, IC59, Antares).

IceCube background PDF

$$B_i^{IC} = B^{IC}(\delta_i) P_{bg}^{IC}(E_i, \sigma_i \mid \delta_i)$$

ANTARES background PDF

$$B_i^{ANT} = B^{ANT}(\delta_i) P_{bg}^{ANT}(E_i, \beta_i)$$

[See arXiv:physics/0401045v1 for the justification on the use of P(E, beta)]

Likelihood maximisation

- Expressed as log likelihood:

$$\log\left[L\left(n_s\right)\right] = \sum_j \log\left[L^j\left(n_s^j\right)\right]$$

- n^j_s related to each sample with the relative contribution of each experiment:

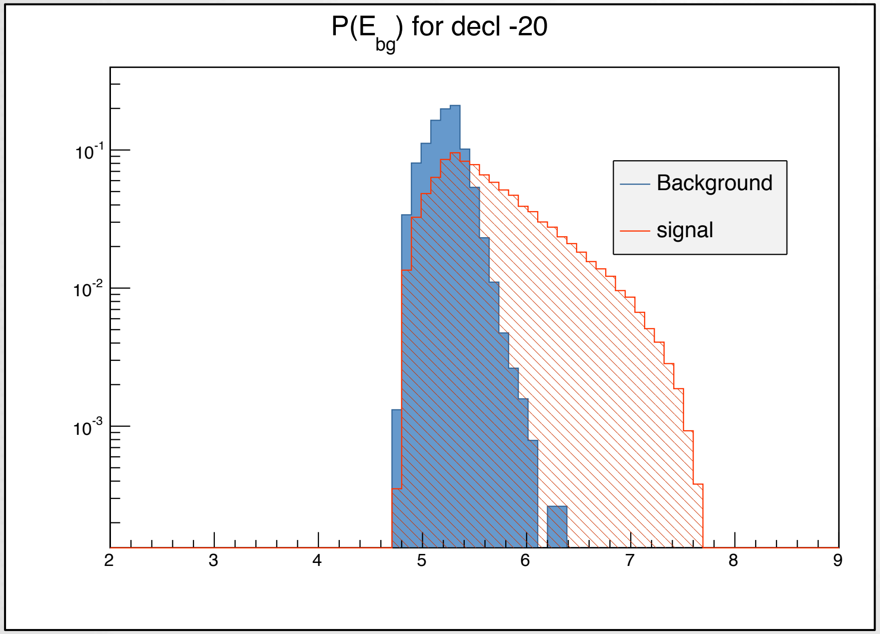
$$n_s^j = C^j(\delta) n_s$$

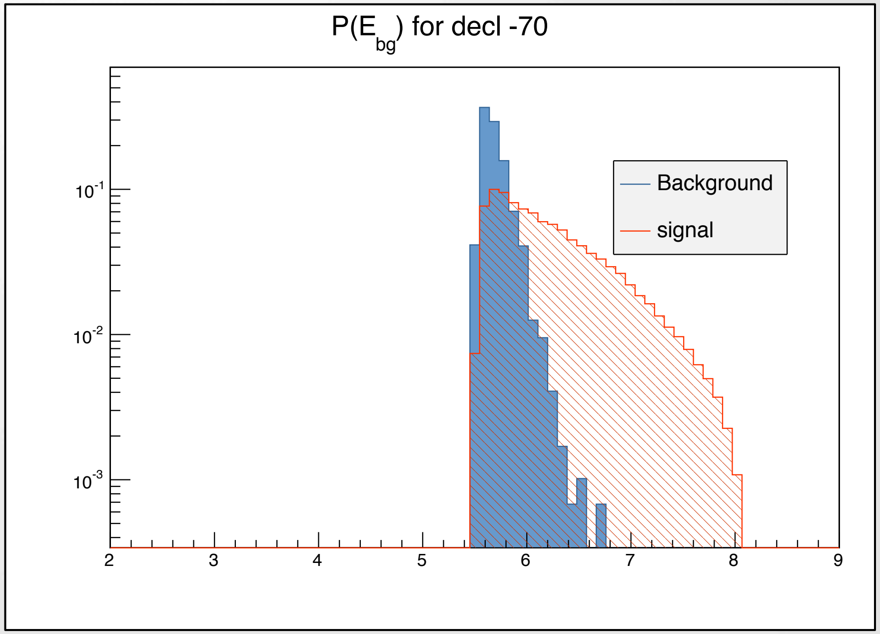
- Fixed source search: Maximisation done with one free parameter (n_s)
- Full sky search: Maximisation done with three free parameters (n_s, α_s, δ_s)
- Test statistic defined as:

$$TS = \log[L_{MAX}] - \log[L_{bg}]$$

- NOTE: All events outside 5º cone from source position are assumed to have $S_i = 0$.

Ingredients: P(Energy|δ)

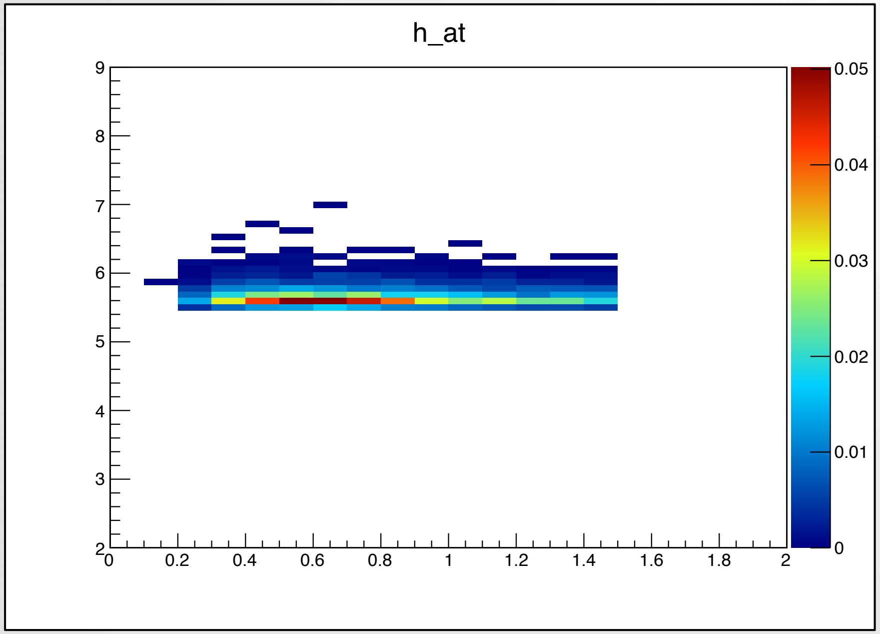




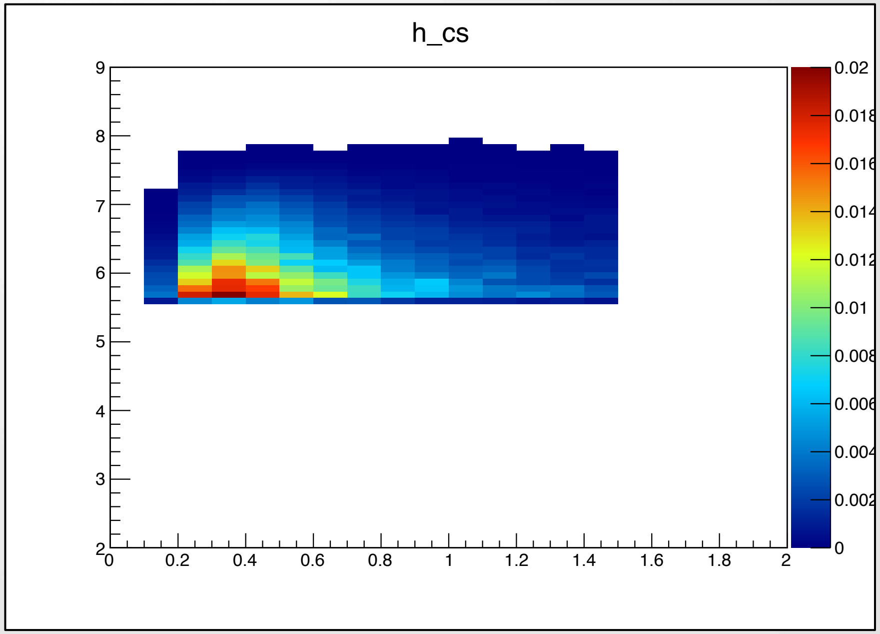
P(E) for signal (red) and background (blue) at = -20º (IC40 lines).

P(E) for signal (red) and background (blue) at = 70º (IC 59 lines).

Ingredients: P(Energy, beta|δ)



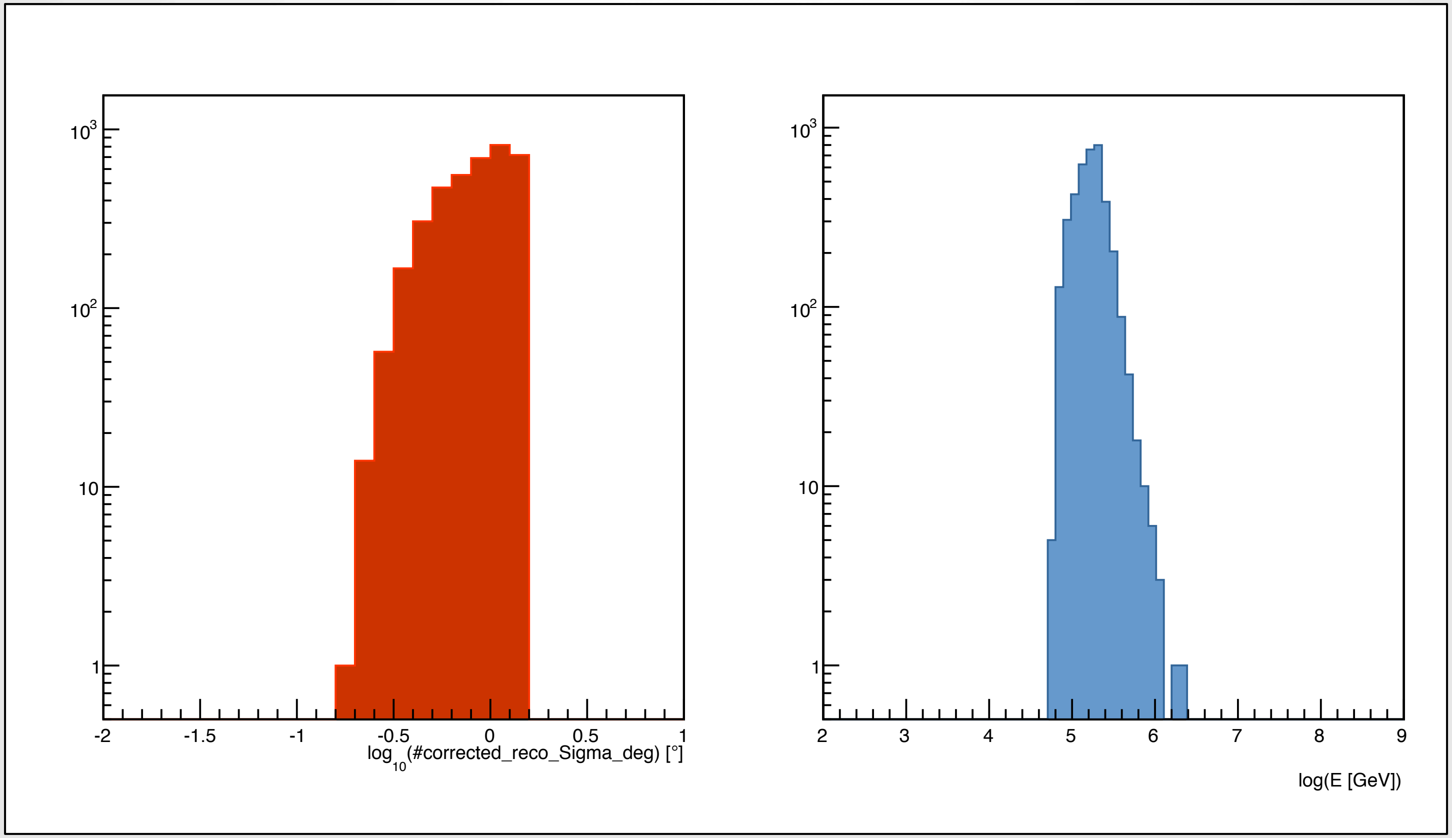
P(E, beta) for bg events at dec = -50º (IC 40 lines)



P(E, beta) for sg events at dec = -50º (IC 40 lines)

Procedure

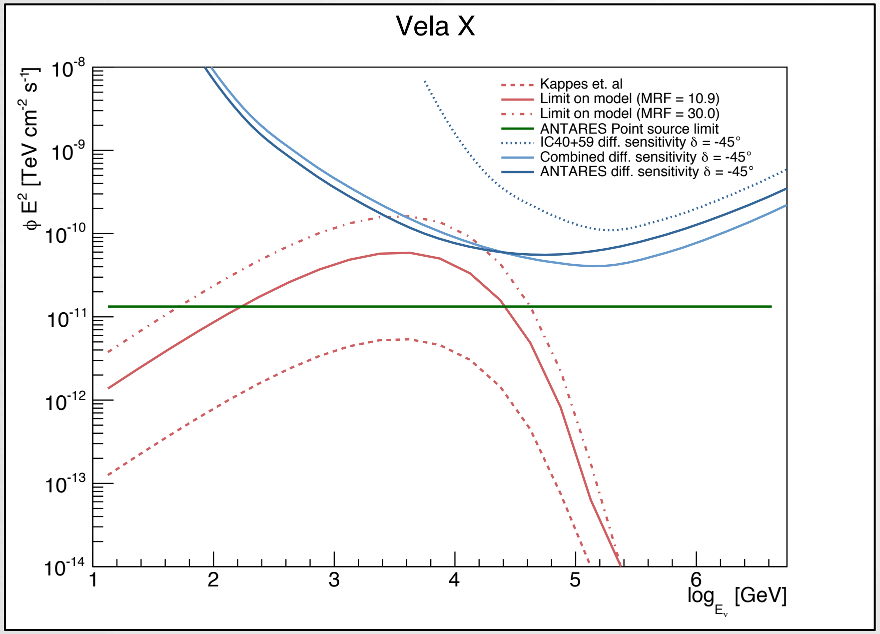
Ingredients: Generation of bg events

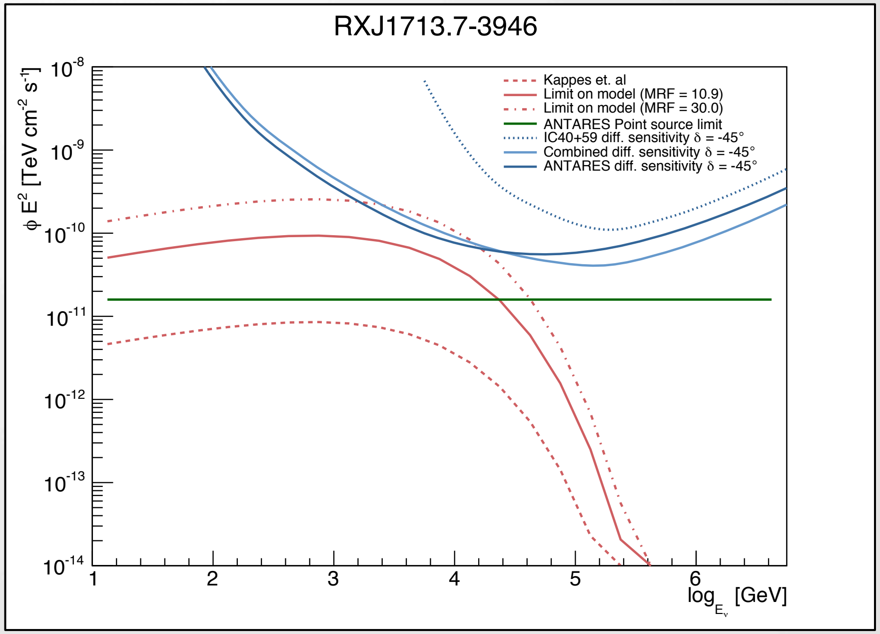


Projection of the angular error estimate (left) and energy (right).

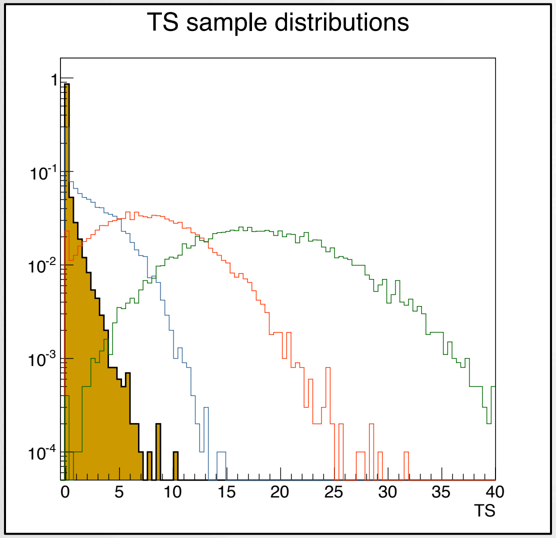
Back-up results

MRF for special sources

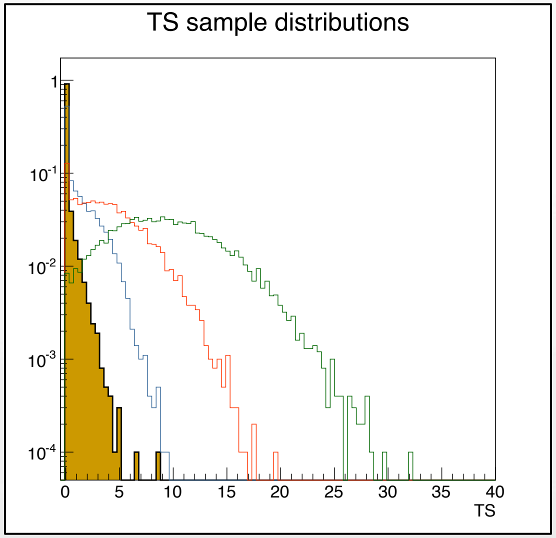




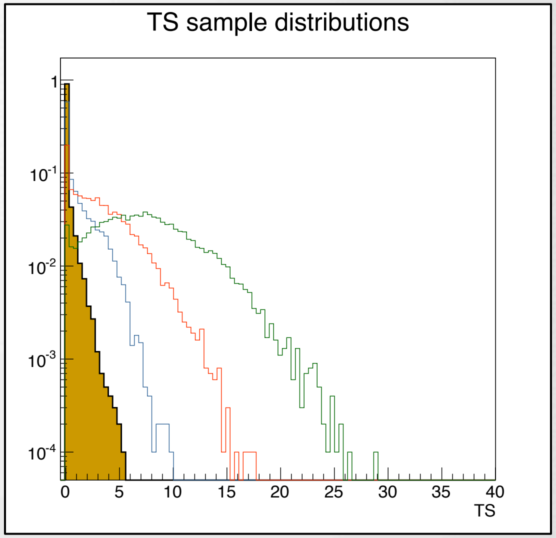
TS distributions comparison



Sample TS ANTARES distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

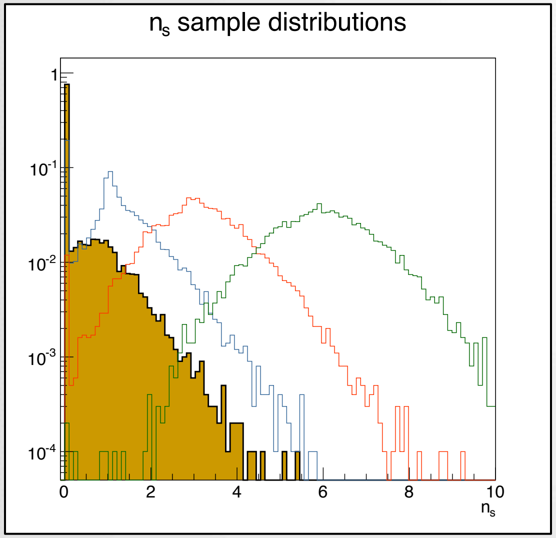


Sample TS IC40 distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

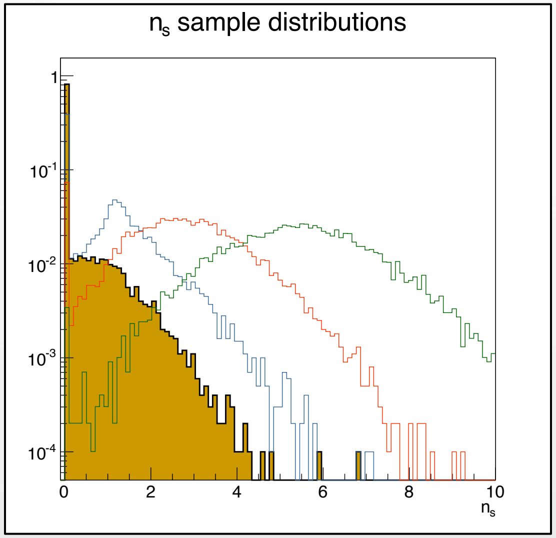


Sample TS IC59 distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

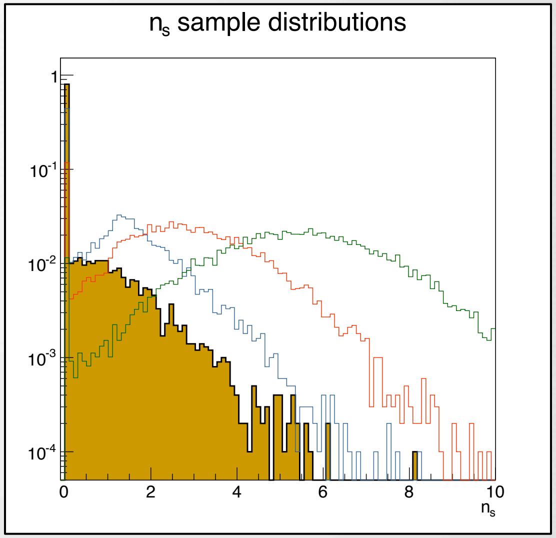
n_s distributions comparison



Sample n_s ANTARES distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

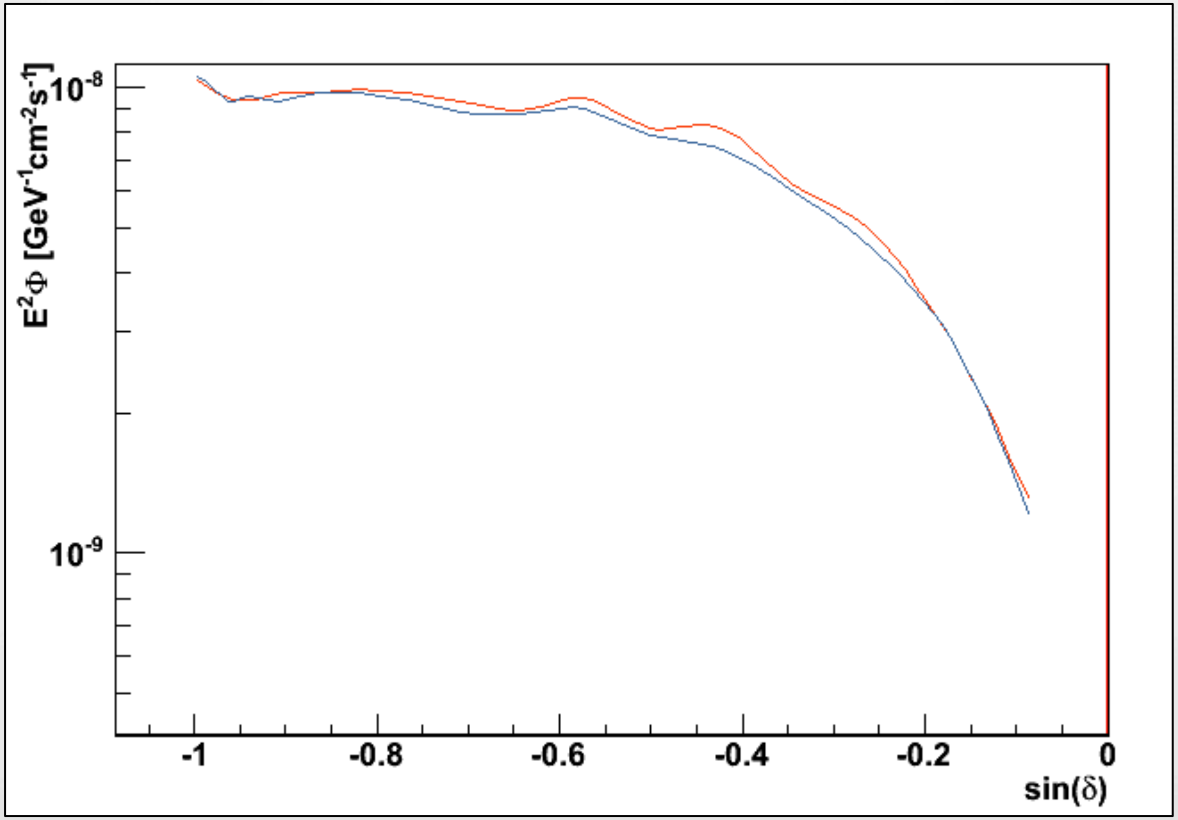


Sample n_s IC40 distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º



Sample n_s IC59 distribution for background, 1 source event, 3 source events and 6 source events for a source position of dec = -45º

Use of P(E, β): Sensitivity for E^{-2}



Fixed source search E^{-2} sensitivity for the combined sample.
RED: Using P(E). BLUE: Using P(E, β).

Full sky search

Full sky search: Algorithm

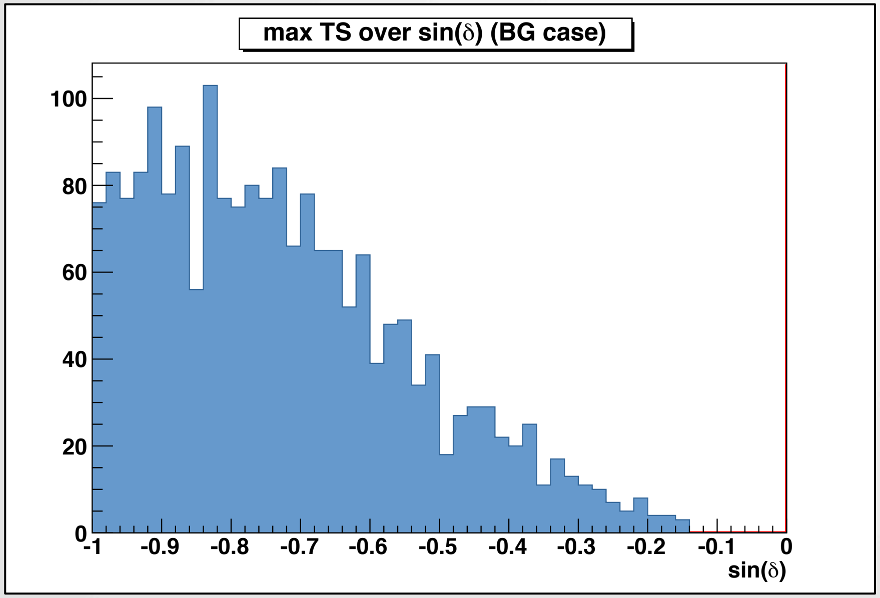
- ANTARES algorithm:
  - Search for all clusters with a minimum of 4 events in a conesize of 3º.
  - Evaluate the TS in these clusters (position: free parameter, range of 2º)
  - Take the largest TS.
  - Problem: Time consumption!

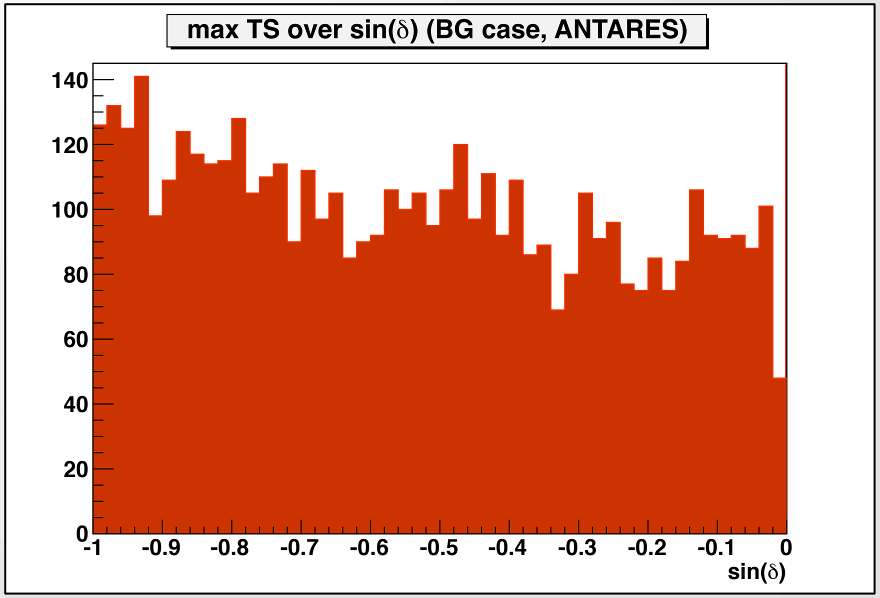
- IceCube algorithm:
  - Evaluate the whole sky in steps of 0.1º x 0.1º.
  - Fixed position in each of these "squares".
  - Take the lowest p-value.
  - Problem: Time consumption.

- Proposed algorithm:
  - Evaluate the whole sky in bigger steps.
  - Position: Free parameter! (range: stepsize)
  - Three different steps used: 0.5º, 1º, 3º.

Full sky search: Max TS vs lowest p-value

- Problem: max TS for the BG case is more probable to be found at lower declinations in the combined sample!

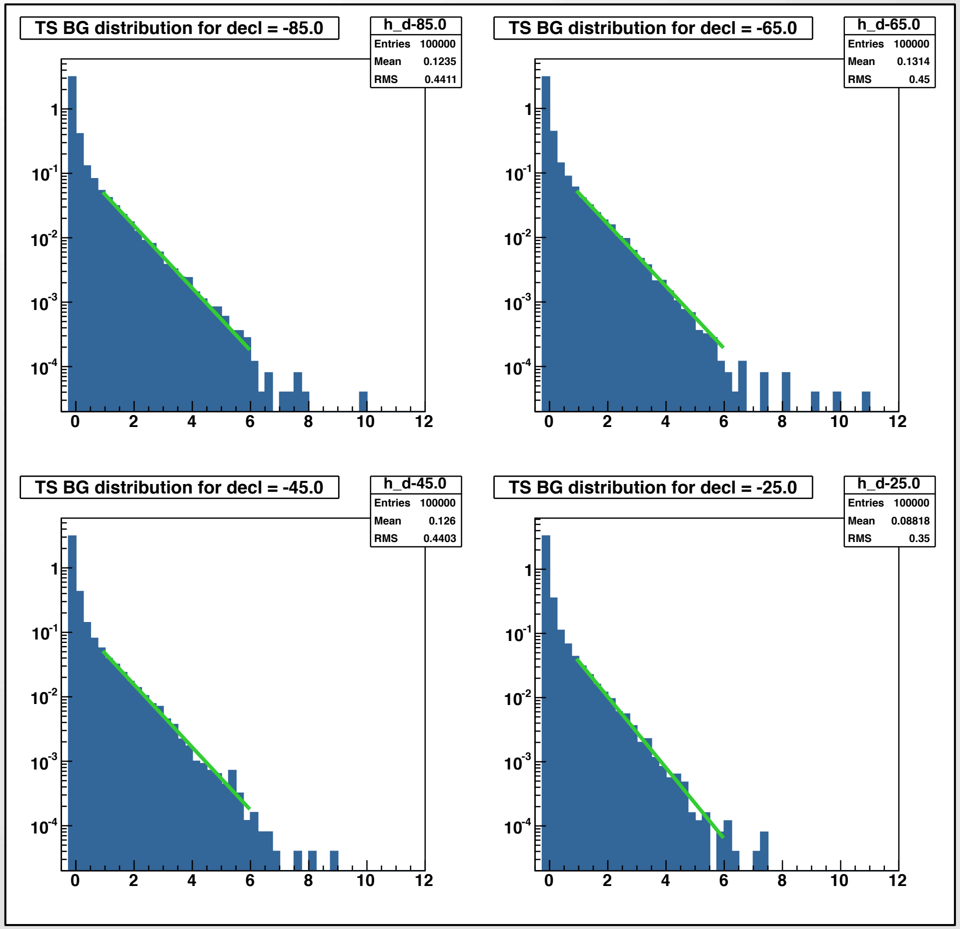




- Idea: Instead of taking the highest TS value, use the lowest p-value!

Full sky search: lowest p-value

- Per each TS value, obtain p-value from TS background distribution from the Fixed Source search.
- Fixed Source TS distributions calculated in steps of 1° in declination.
  - Number of pex per case: 100000
- Approximation: Fit exponential decay in the tail of the distribution.

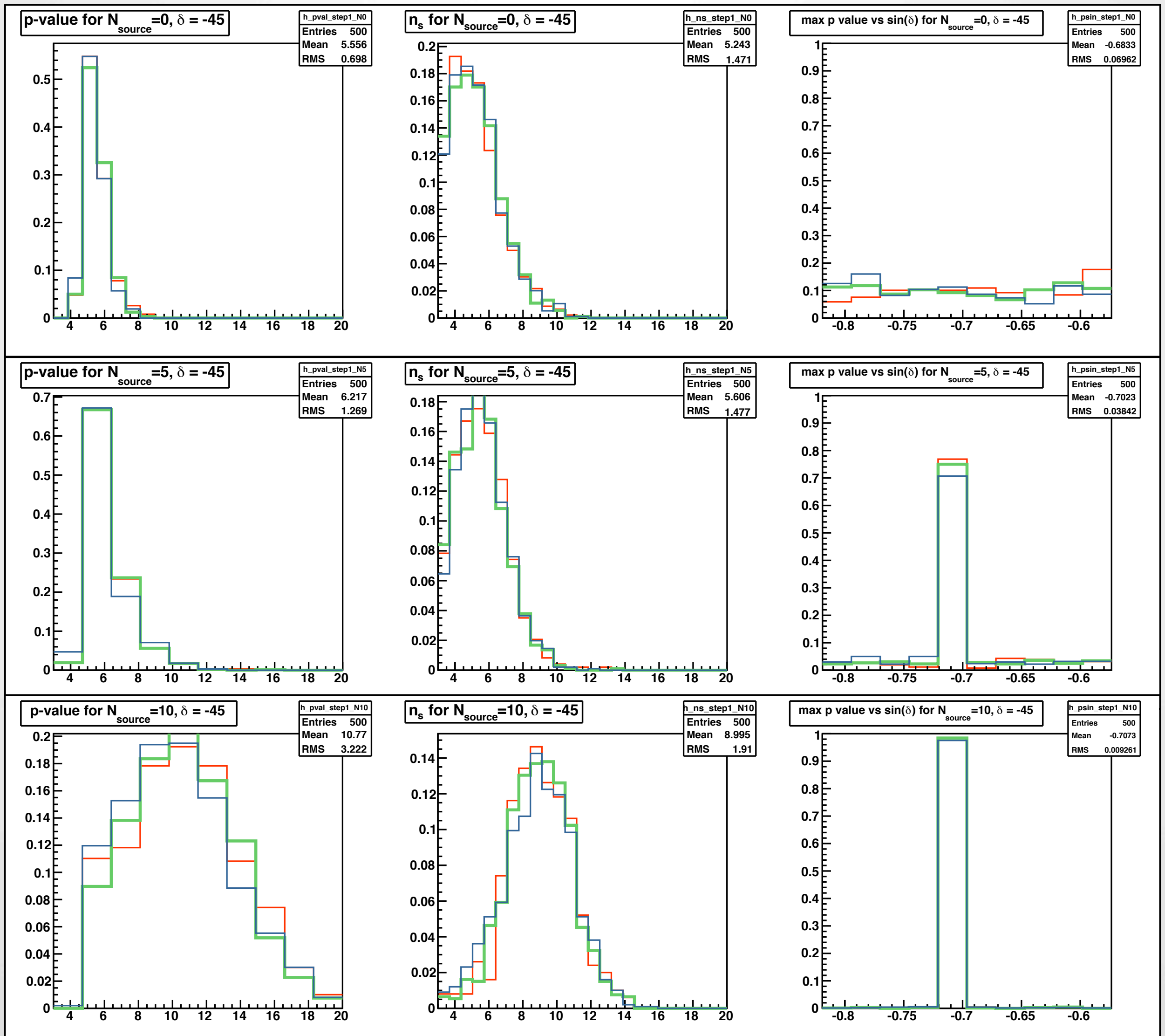


Full sky search: stepsize tests (δ_s=-45º)

$N_s = 0$

$N_s = 5$

$N_s = 10$



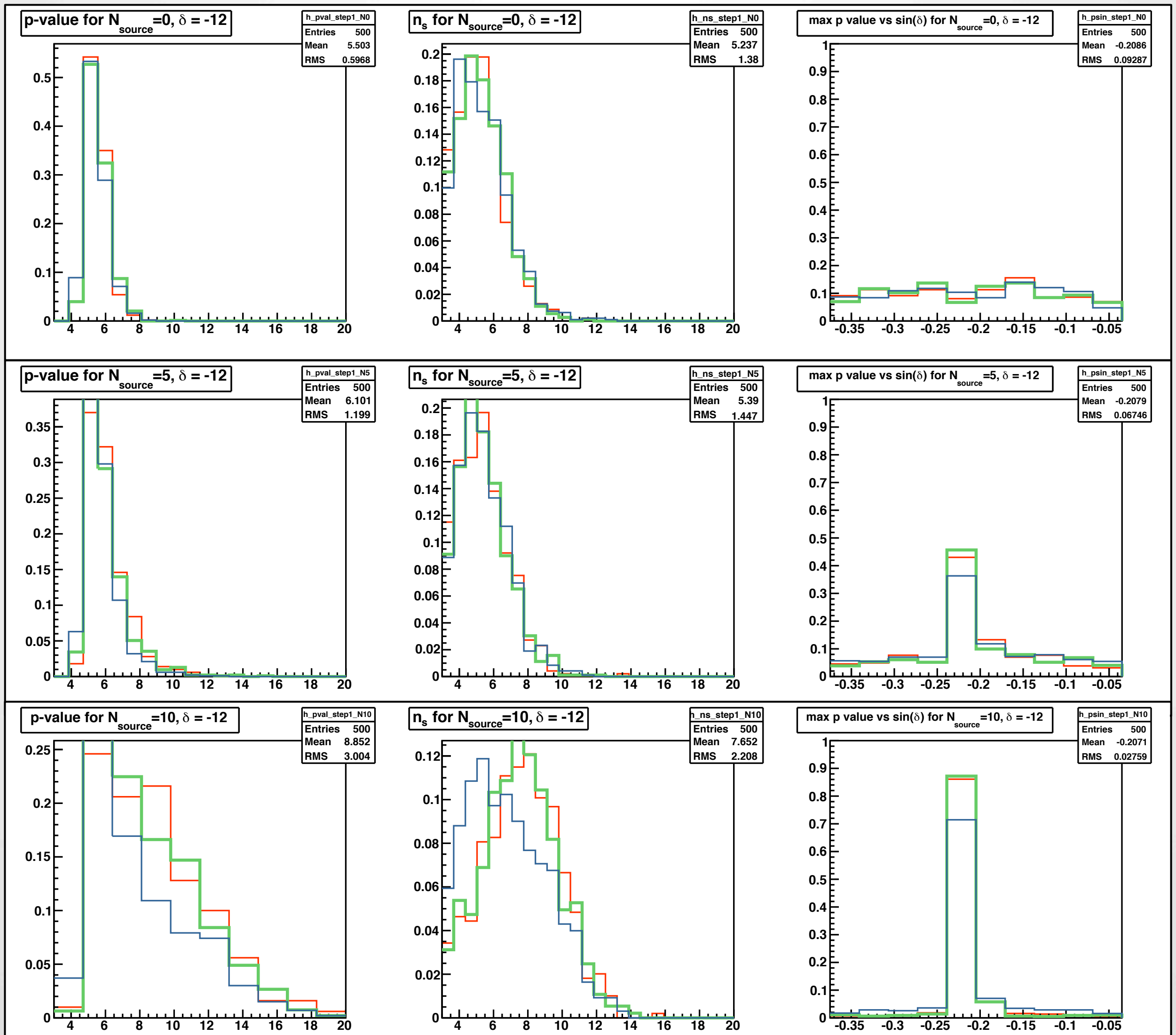
Step 0.5º
Step 1º
Step 3º

Full sky search: stepsize tests (δ_s=-12º)

$N_s = 0$

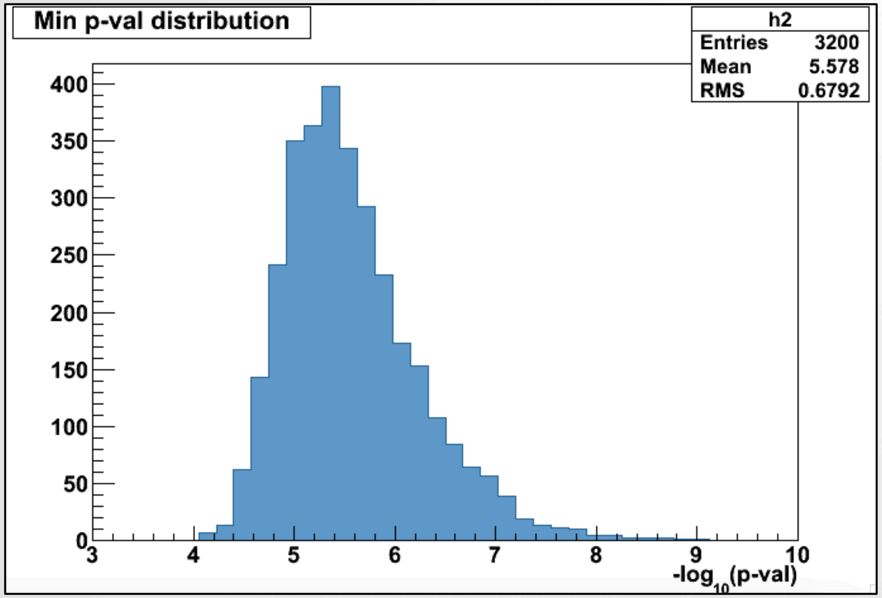
$N_s = 5$

$N_s = 10$

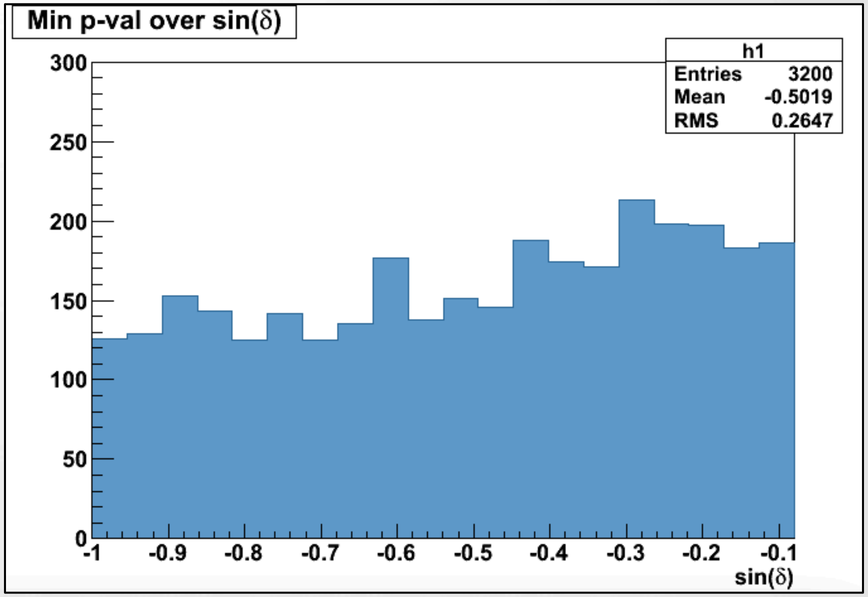


Step 0.5º
Step 1º
Step 3º

Full sky search



Background p-value distribution for the combined sample.



Position of the minimum p-value for each pseudoexperiment (BG case).

Candidate list

Candidate list: Galactic sources

- Long list from ANTARES -> IceCube has only the Galactic Centre

Galactic cente	266.42	-29.01	8.5 kpc	unid
HESSJ1632-478	-111.96	-47.82		PWN
HESSJ1356-645	-151.00	-64.50	2.4 kpc	PWN
HESSJ1616-508	-116.03	-50.97	6.5 kpc	PWN
Vela X	128.75	-45.60	0.29 kpc	PWN
HESSJ1303-631	-164.23	-63.20	6.6 kpc	PWN
LS5039	-83.44	-14.83	2.5 kpc	PWN
W28	-89.57	-23.34	2 kpc	SNR
RXJ0852.0-4622	133.00	-46.37	0.2 kpc	Shell
RCW86	-139.32	-62.48	2.5 kpc	Shell
RXJ1713.7-3946	-101.75	-39.75	1 kpc	Shell
PSRB1259-63	-164.30	-63.83	1.5kpc	BINARY
HESSJ1023-575	155.83	-57.76	8 kpc	WR /MSC
HESSJ1503-582	-133.54	-58.74		DARK
HESSJ1614-518	-116.42	-51.82	6.5 kpc	cluster
HESSJ1741-302	-94.75	-30.20		unid
ESO139-G12	-95.59	-59.94		unid
CirX-1	-129.83	-57.17		unid
GX339-4	-104.30	-48.79	5.6 kpc	HMXB
HESSJ1837-069	-80.59	-6.95		unid
HESSJ1834-087	-81.31	-8.76	4kpc	unid
HESSJ1507-622	-133.28	-62.34		unid

CG (Sgr A*)	266.42	-29.01	8.5 kpc	CG

Candidate list: Extragalactic sources

- We take all the extragalactic sources from both lists (logical OR)

ANTARES

Cen A	-158.64	-43.02	0.00183	Radio Galaxie
MSH15-52	-131.47	-59.16	0,218	PWN
PKS0548-322	87.67	-32.27	0.069	HBL
1ES0347-121	57.35	-11.99	0.188	HBL
PKS2155-304	-30.28	-30.22	0.116	HBL
H2356-309	-0.22	-30.63	0.129	HBL
PKS0454-234	74.27	-23.43	0.186	HBL
PKS0537-441	84.71	-44.08	0.896	BL lac
PKS1454-354	-135.64	-35.67	1.42	FSRQ
3C279	-165.95	-5.79	0.5362	FSRQ
PKS0727-11	112.58	-11.70	2,807	Radio Galaxie
PKS0426-380	67.17	-37.93	1,1	Radio Galaxie

IceCube

Cen A	201.37	-43.02	0,00183	Radio Galaxie
PKS 2155-304	329.72	-30.23	1.116	BL Lac
PKS 0537-441	84.71	-44.09	0.892	BL Lac
PKS 1454-354	224.36	-35.65	1.42	FSRQ
3C 279	194.05	-5.79	0.5362	FSRQ
QSO 2022-077	306.42	-7.64	1.39	FSRQ
PKS 1406-076	212.24	-7.87	1.494	FSRQ
QSO 1730-130	263.26	-13.08	0.902	FSRQ
PKS 1622-297	246.53	-29.86	0.815	FSRQ

Moon shadow analysis

Test statistic function

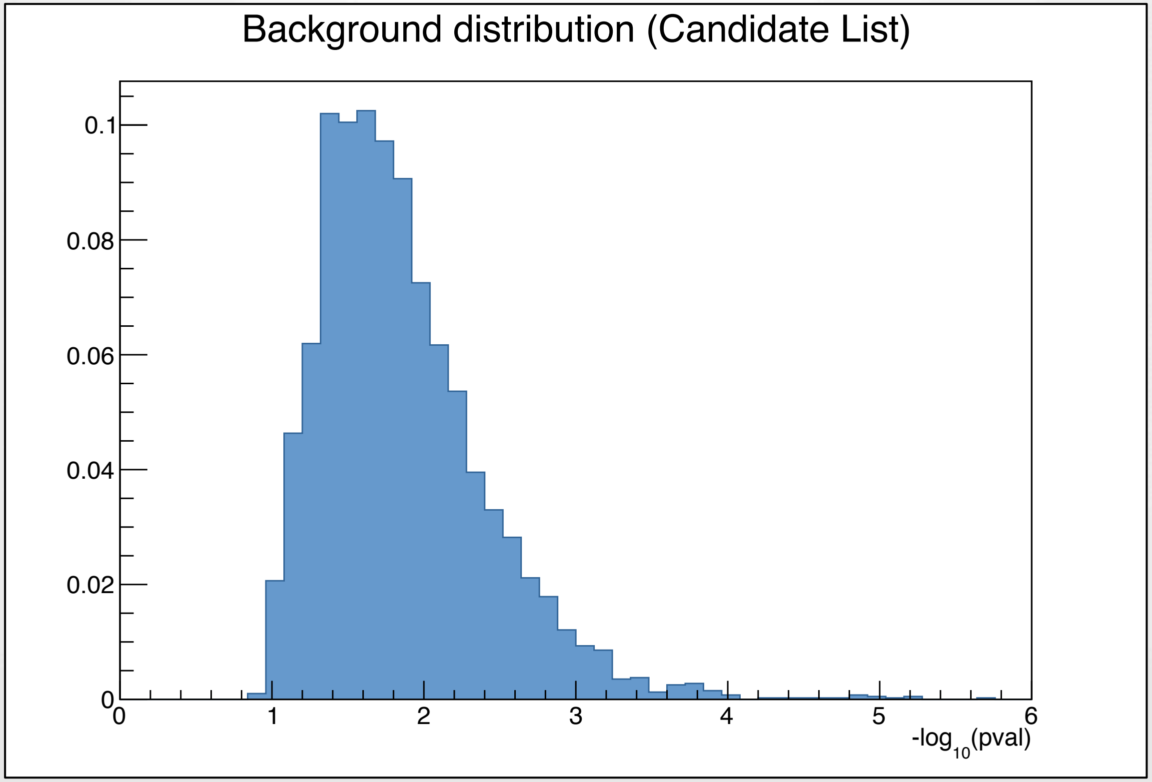
$$t = \sum_{ring} \left(\frac{\left(n_{mes} - n_{\exp,\ NO\ Moon}\right)^2}{n_{\exp,\ NO\ Moon}} - \frac{\left(n_{mes} - n_{\exp,\ Moon}\right)^2}{n_{\exp,\ Moon}} \right)$$

n_{meas}= density of events measured in a ring

$n_{exp, Moon}$= expected density of the ring in "Moon shadow" hypothesis

$n_{exp, NO Moon}$= expected density of the ring in "no Moon shadow" hypothesis

Candidate list bg distribution



Background p-value distribution for the combined sample.