IceCube Moon Shadow

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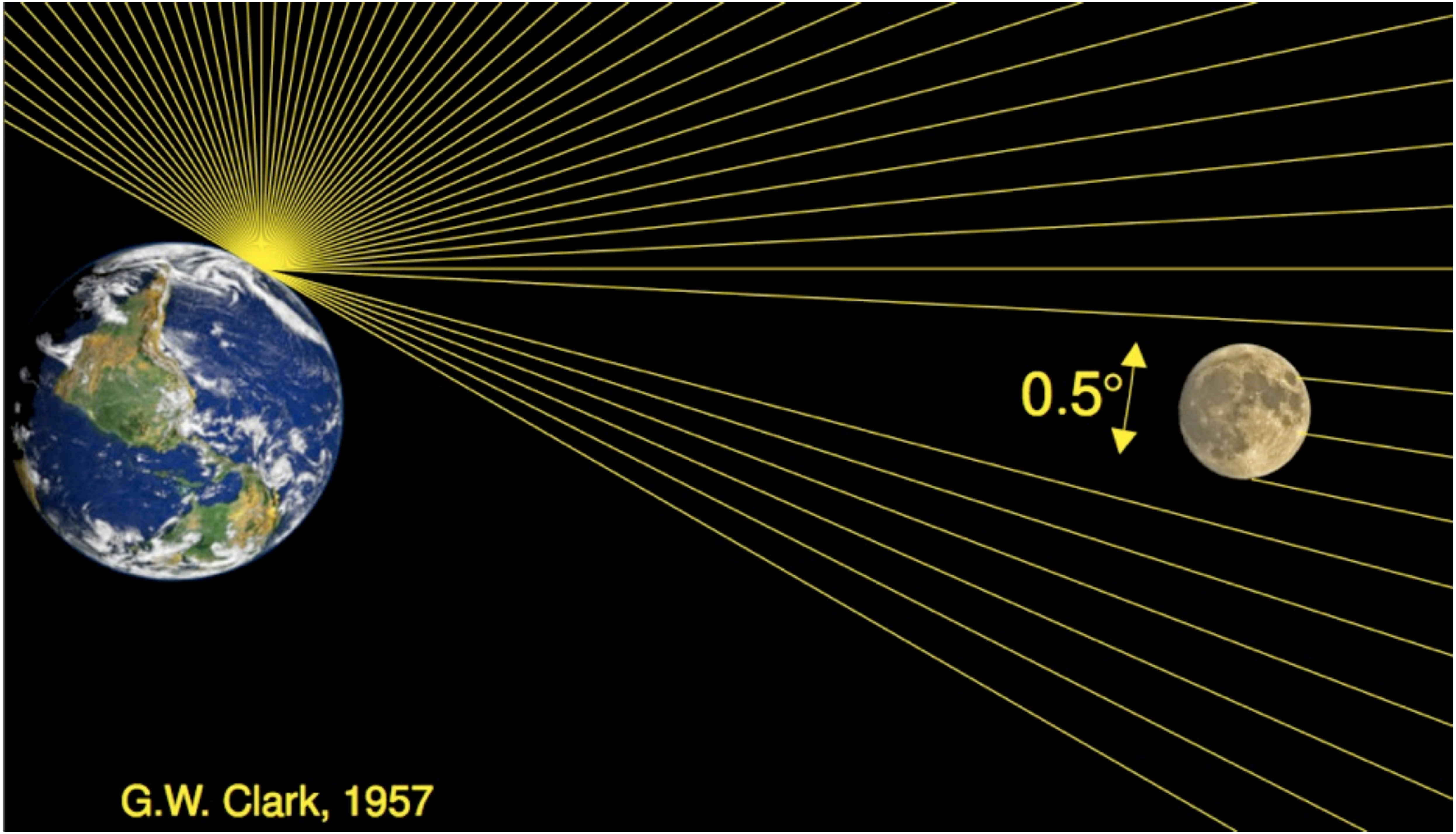
University of Wisconsin, Madison

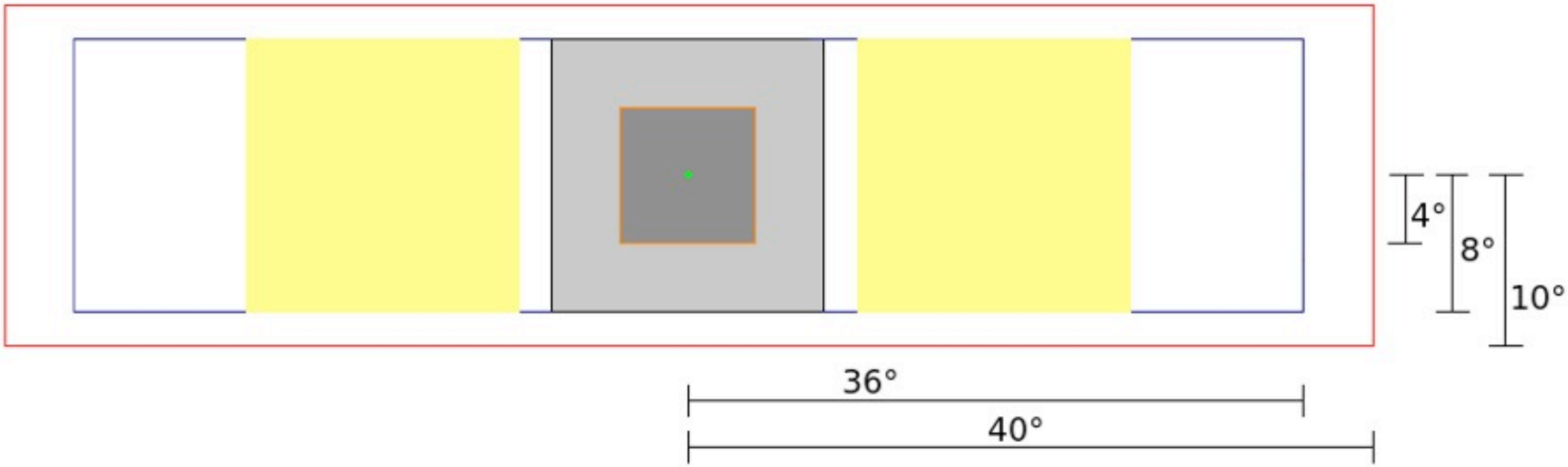
Moriond Electroweak Session
20 March 2011

Shadow is a known signal

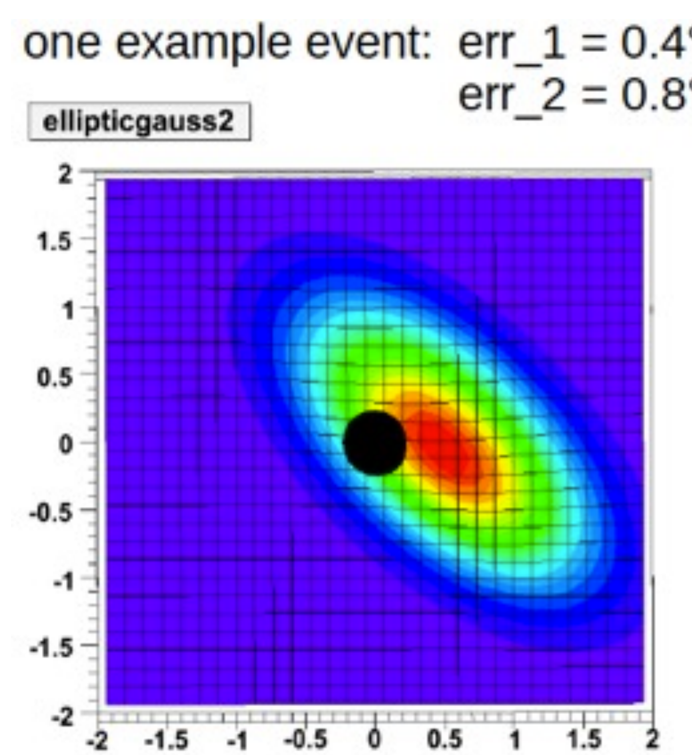


- End-to-end check of systematics and pointing

Data Sample



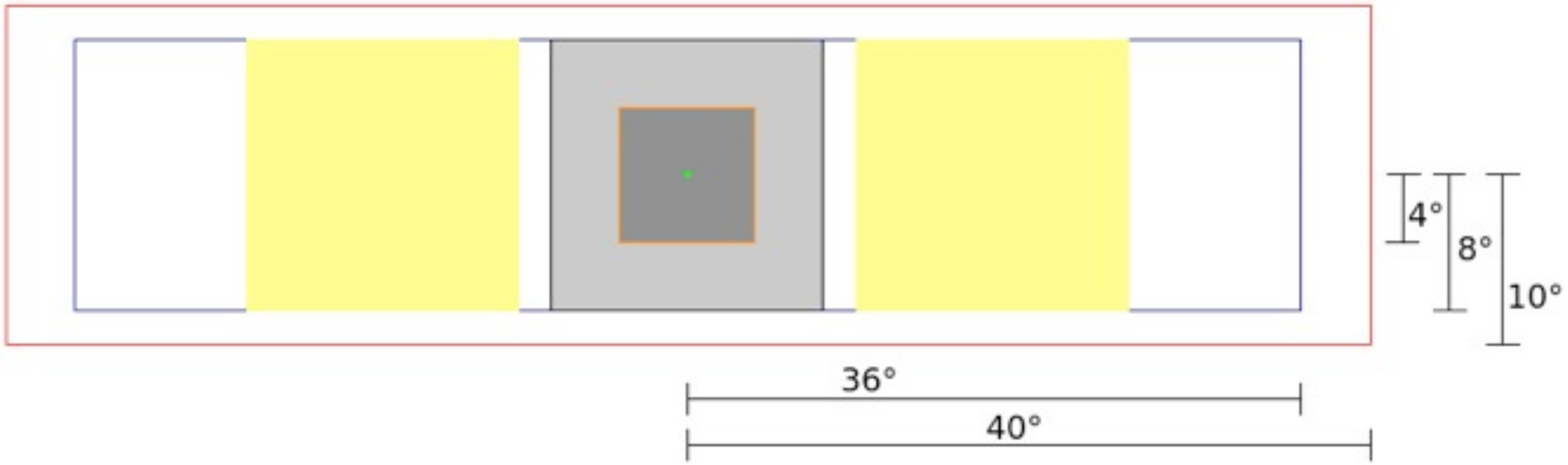
- Use events from a window around the Moon
- Angular resolution is comparable to the size of the Moon



Likelihood Approach

$$L(\vec{x}_s, n_s) = \sum_i^N \log\left(\frac{n_s}{N} S_i + (1 - \frac{n_s}{N} B_i)\right)$$

- Use central signal region and off-source background region
- At each point, vary the number of events blocked by the Moon, n_s
- Maximize likelihood



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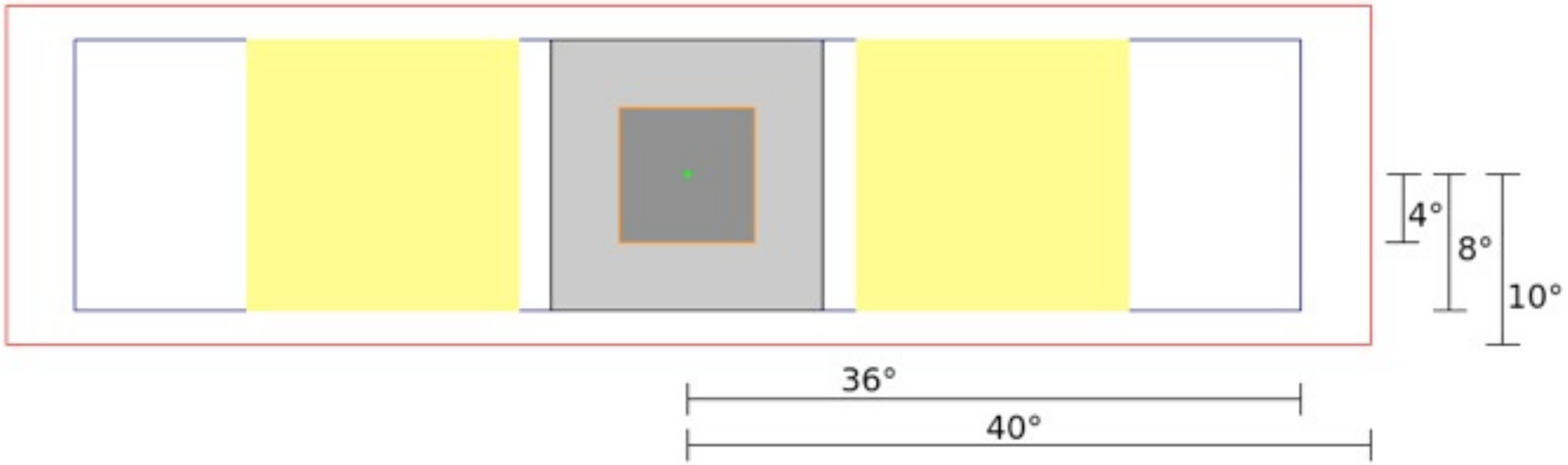
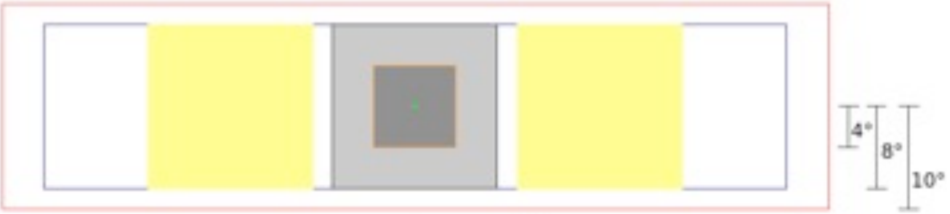
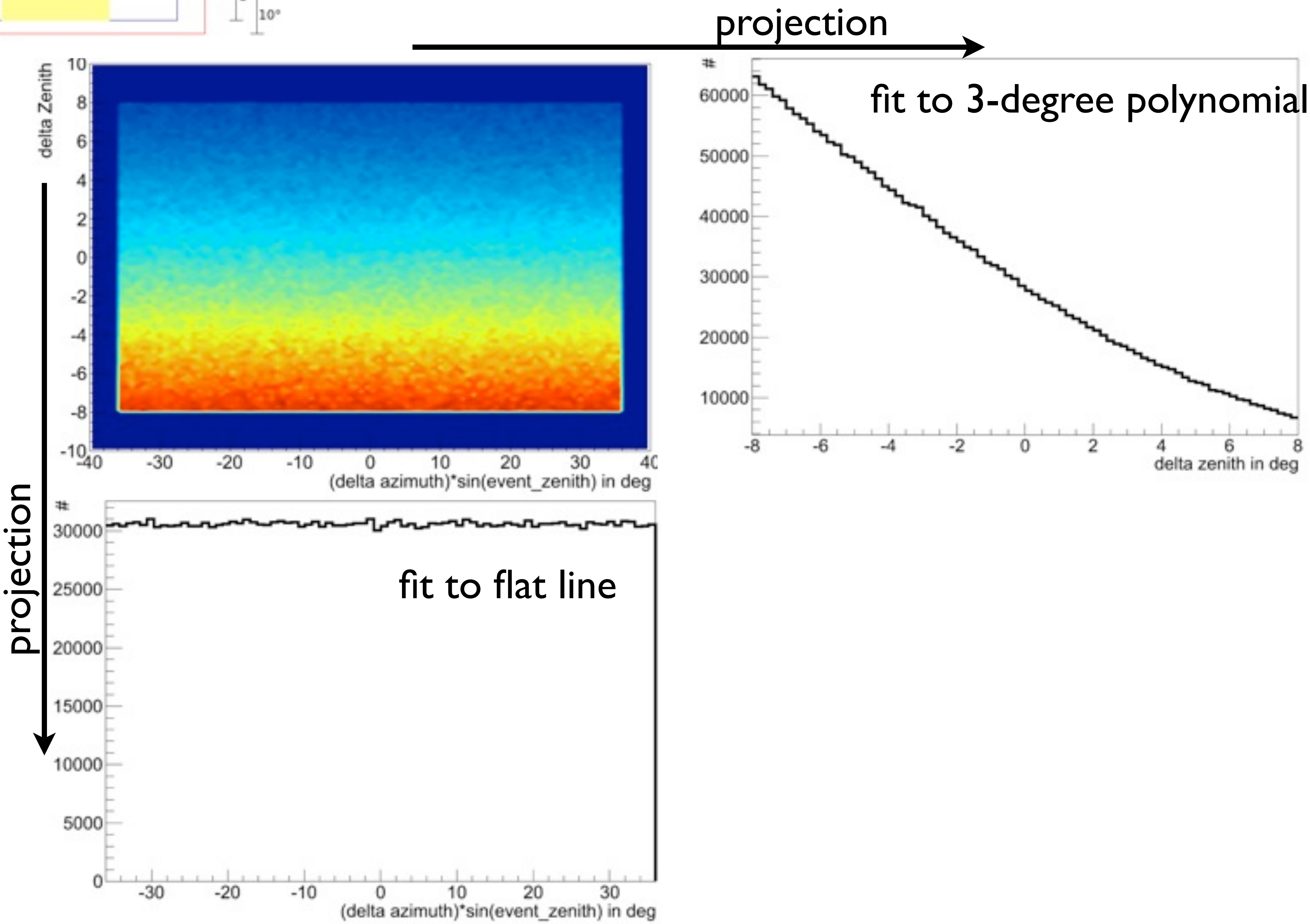
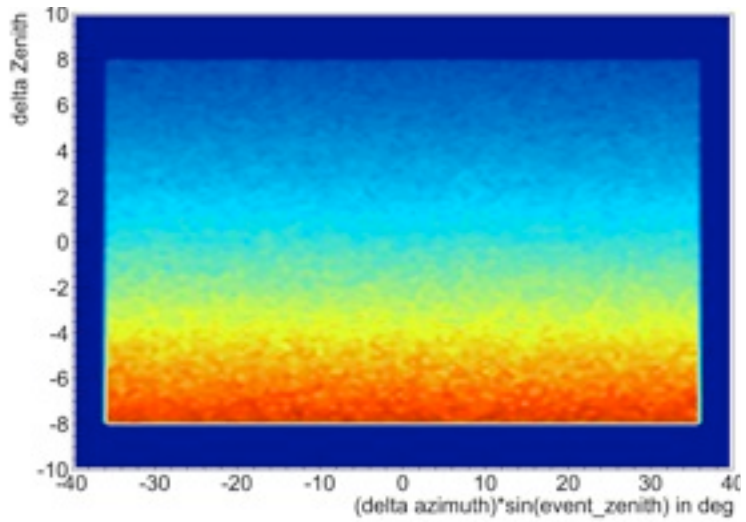


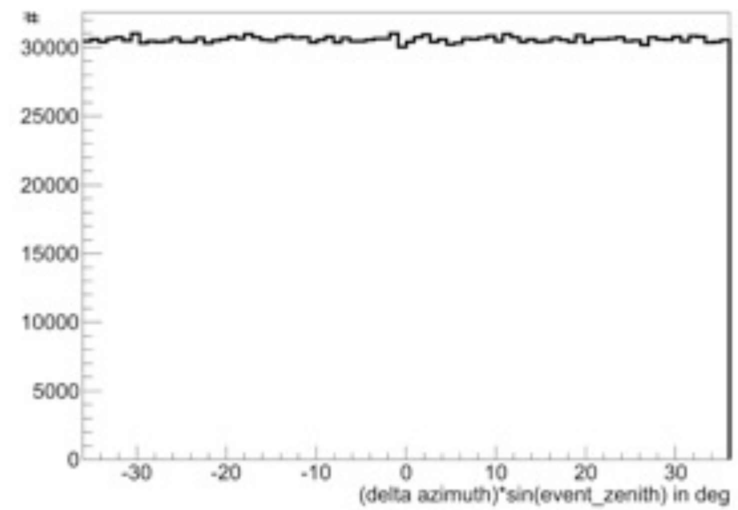
Likelihood: background function

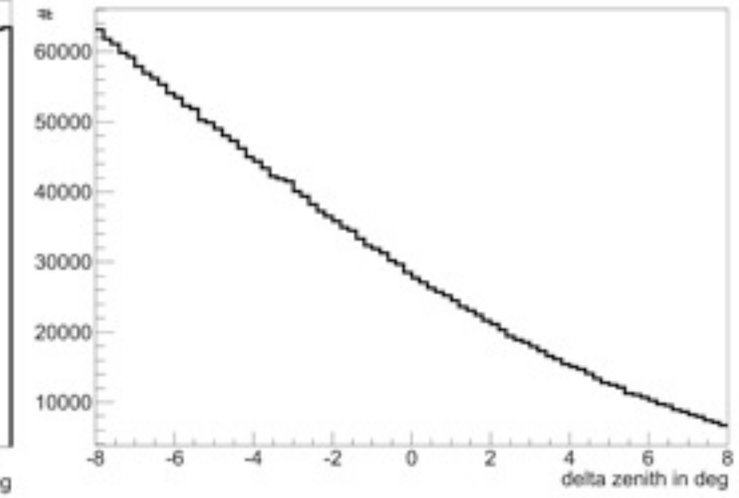




How steady is background







$$L(\vec{x}_s, n_s) = \sum_i^N \log\left(\frac{n_s}{N}S_i + (1 - \frac{n_s}{N}B_i)\right)$$

Null hypothesis fluctuations: look at off-source region as if it were signal

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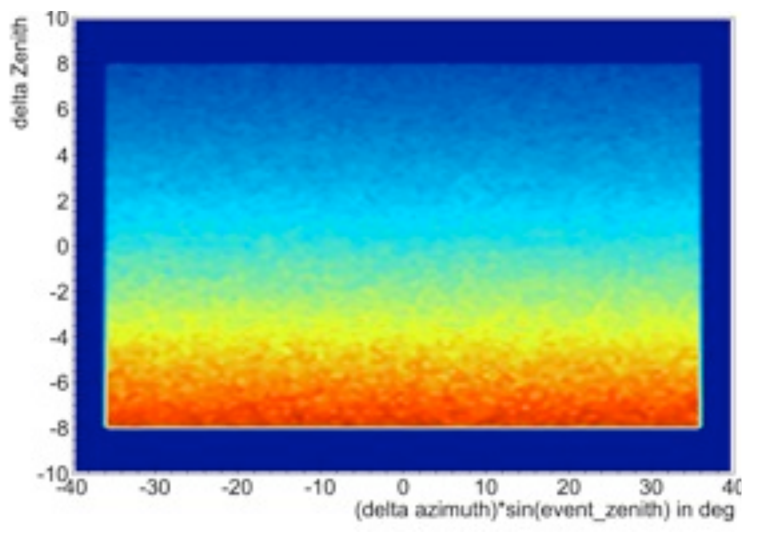

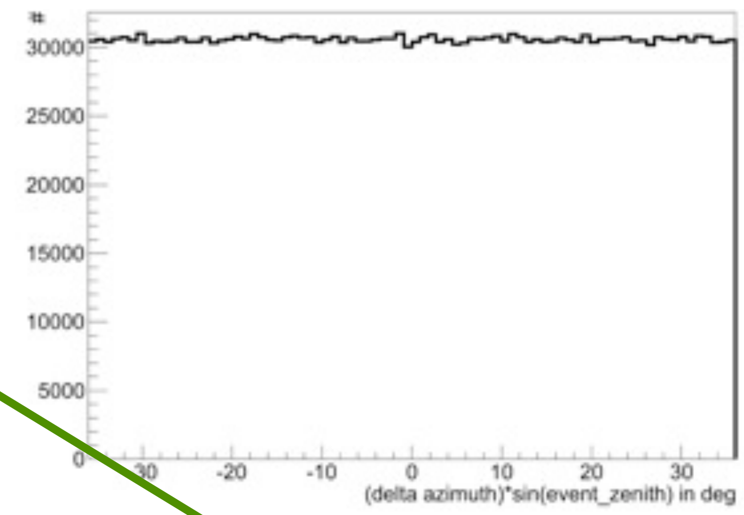

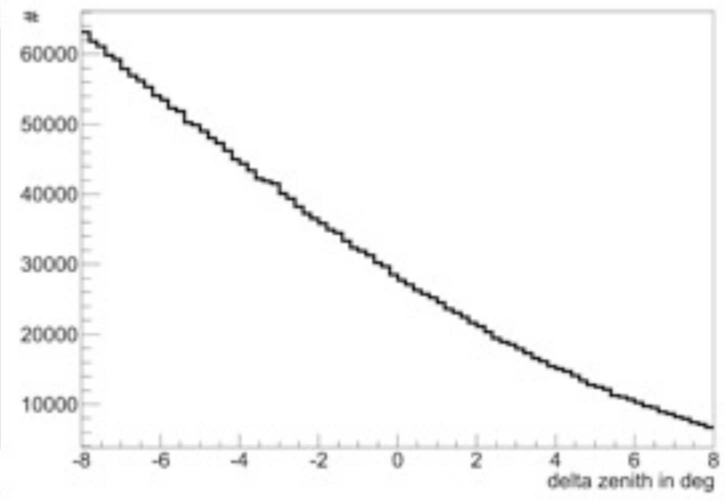

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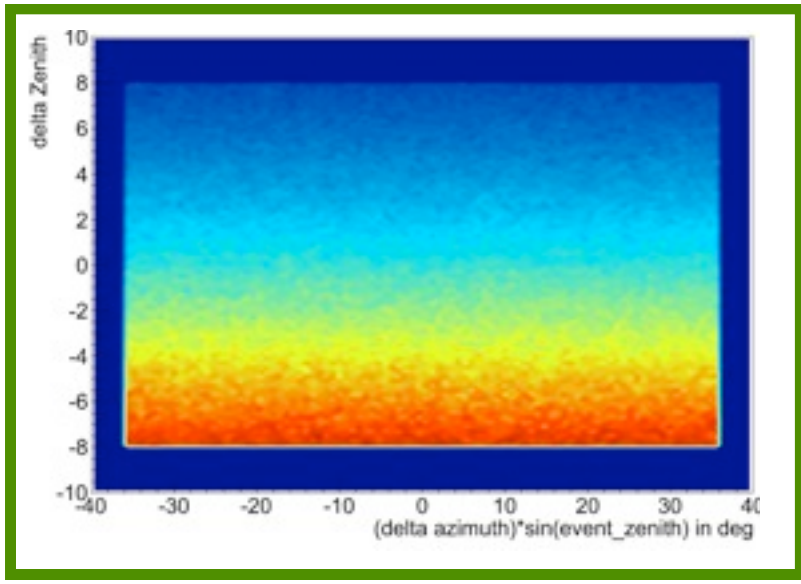

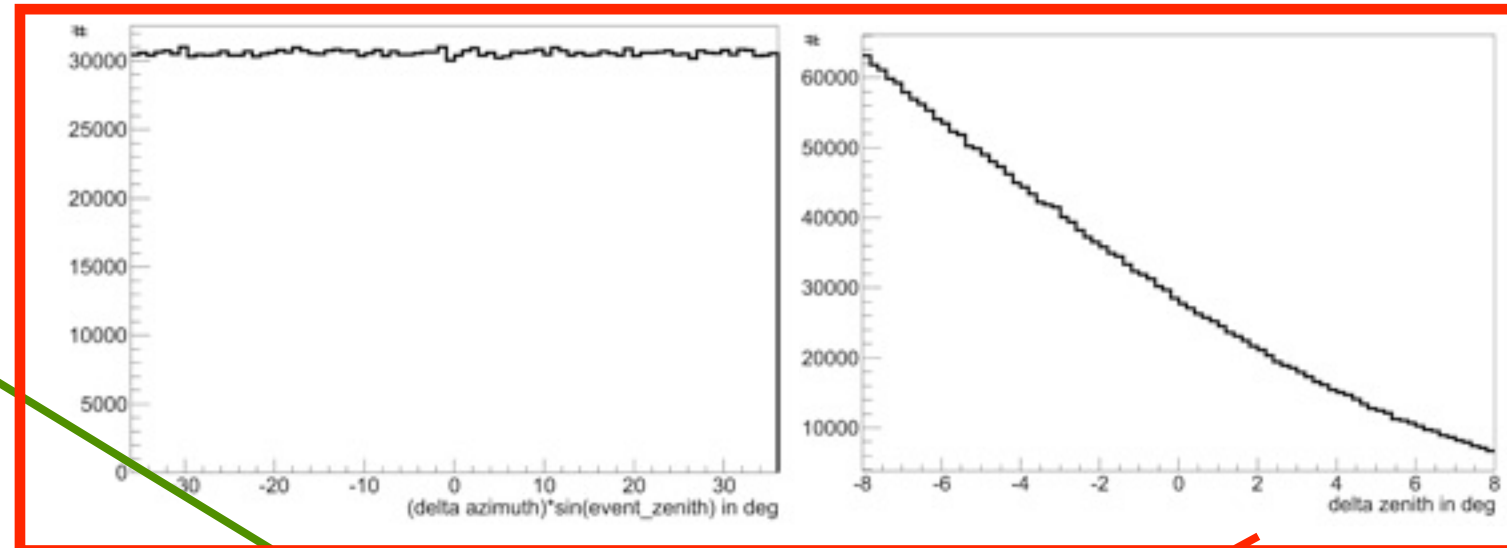

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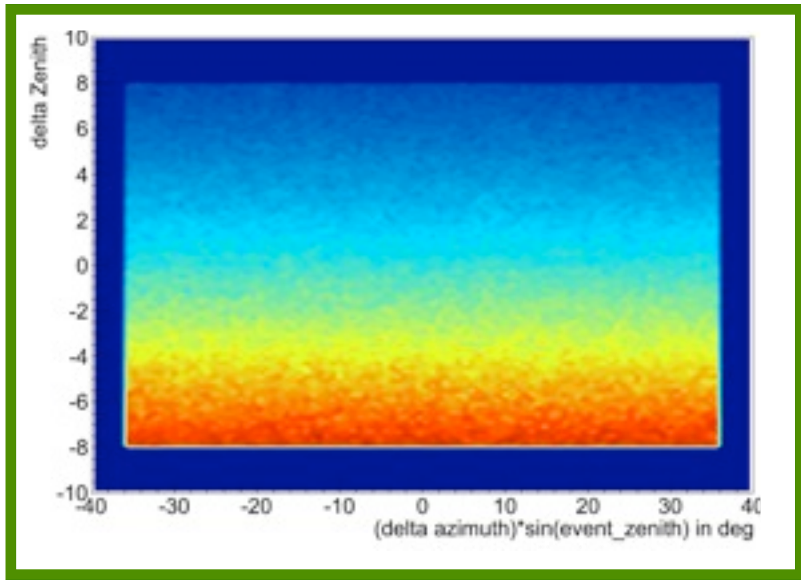

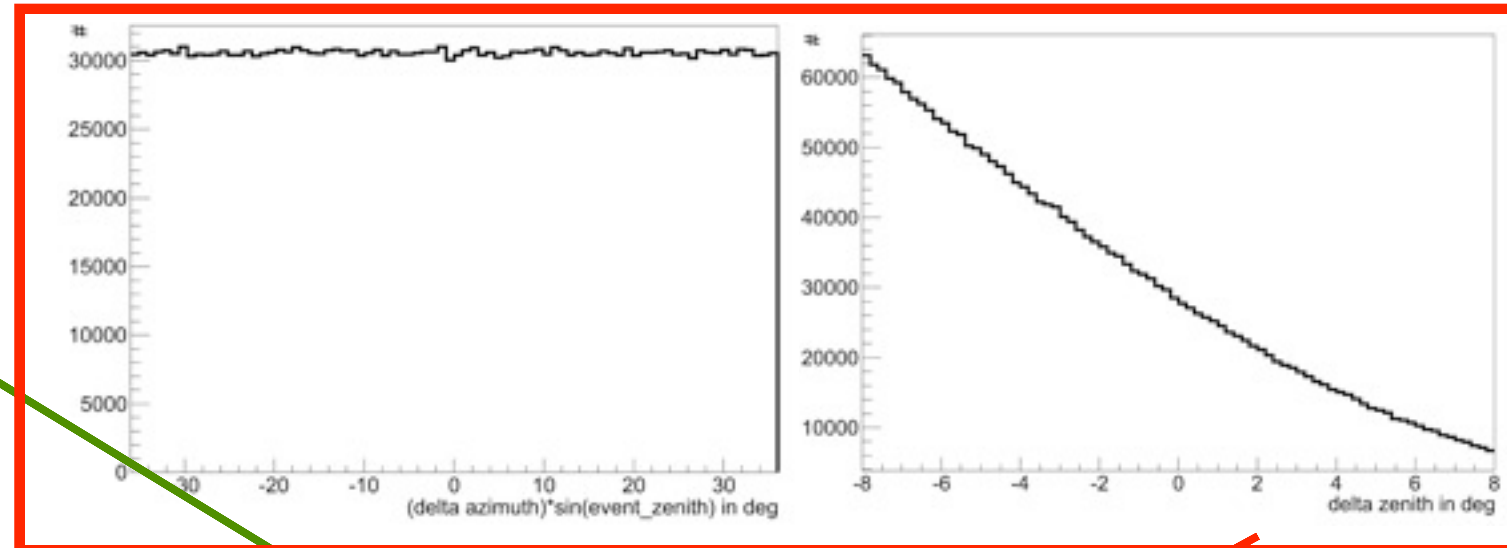

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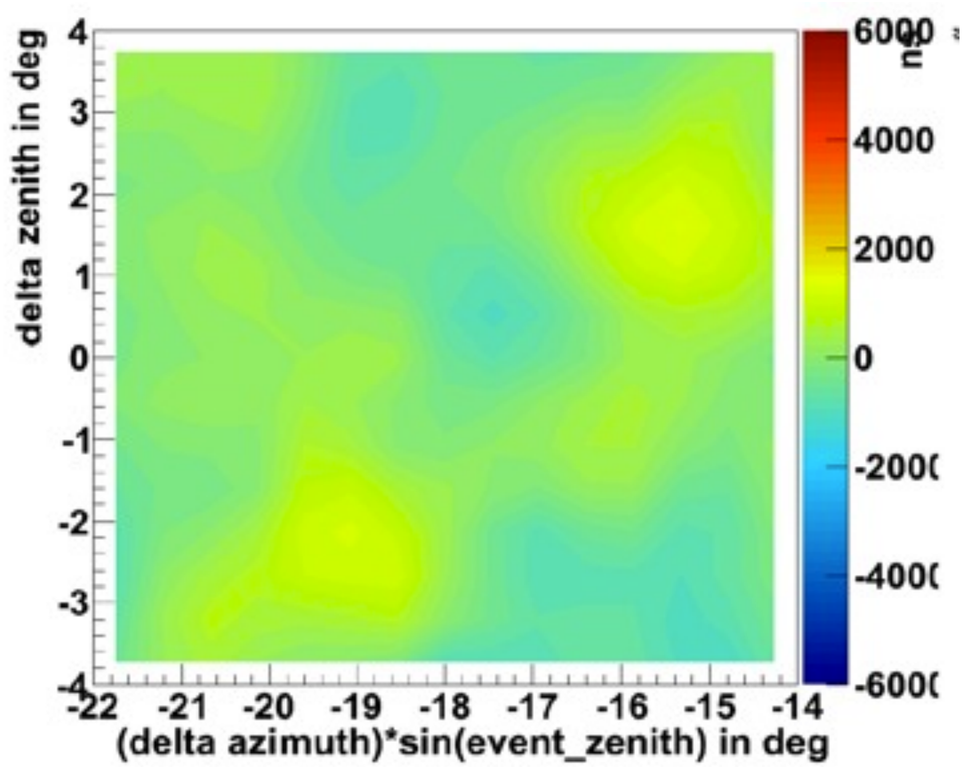

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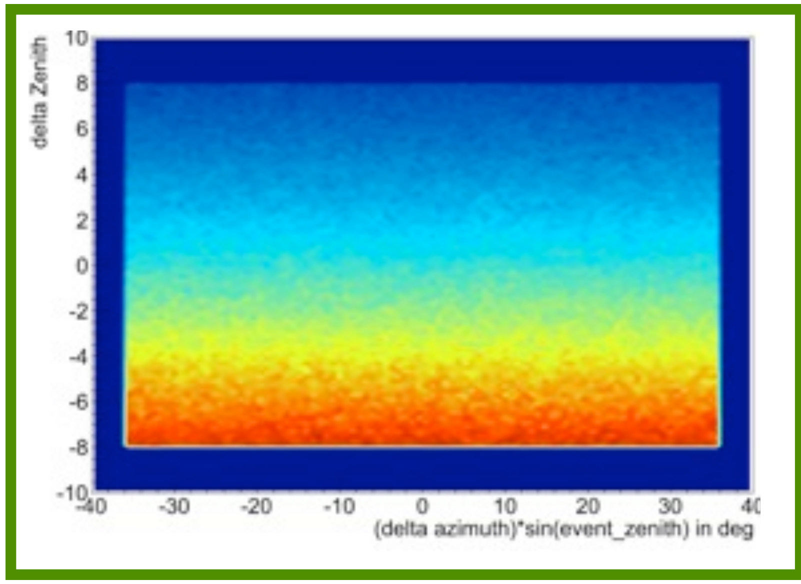

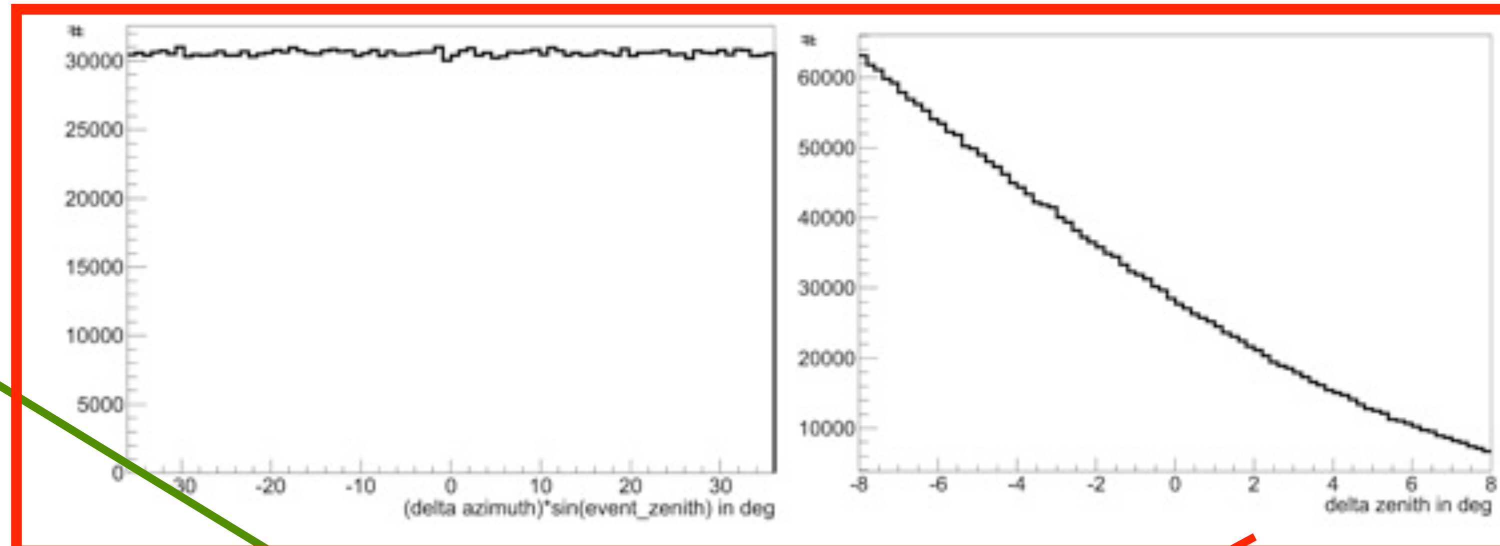

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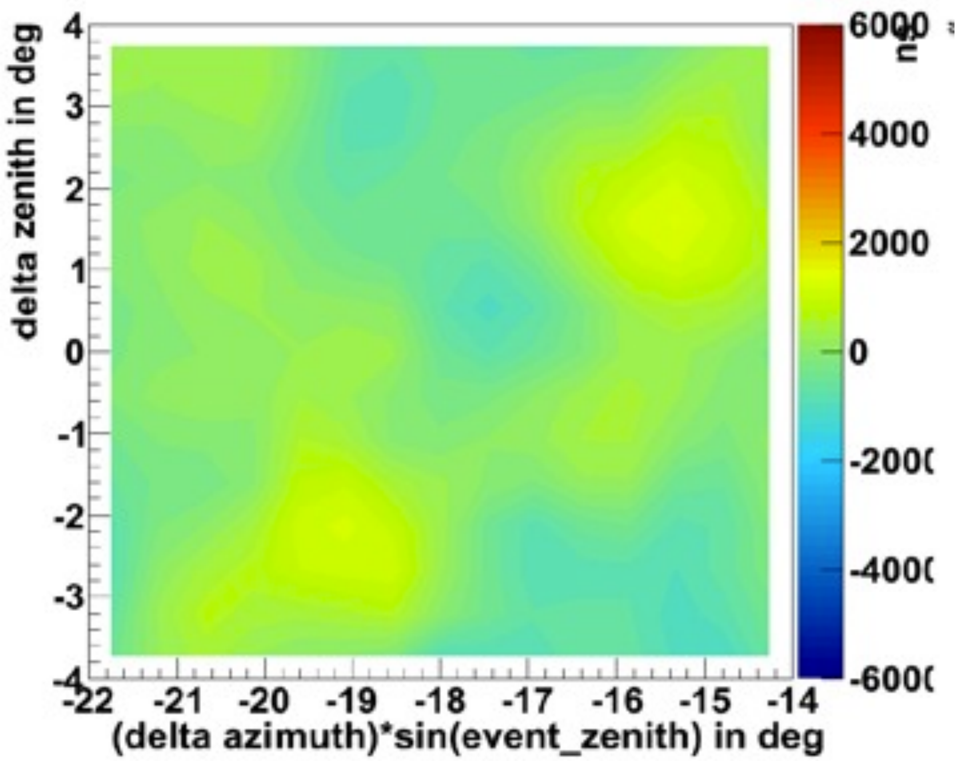

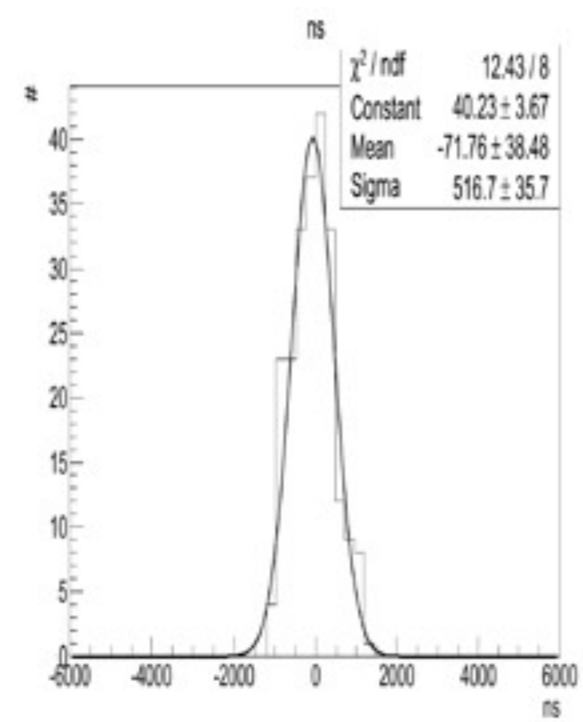

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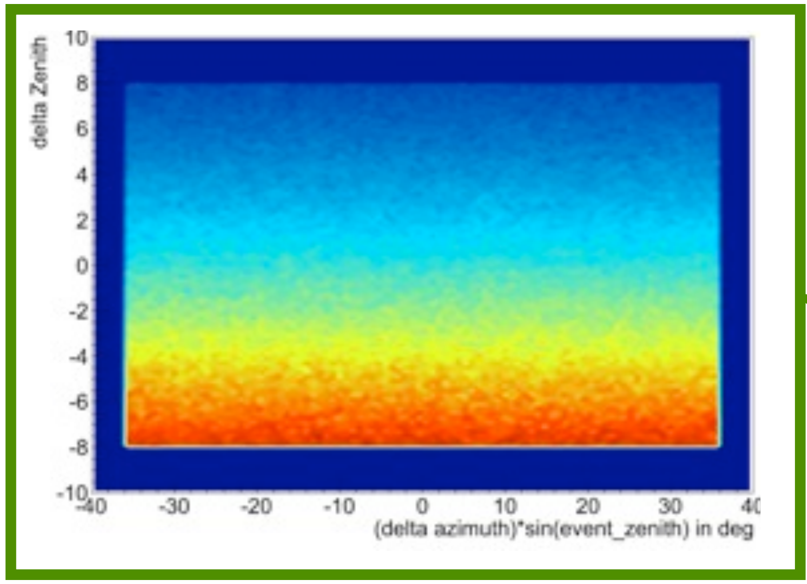

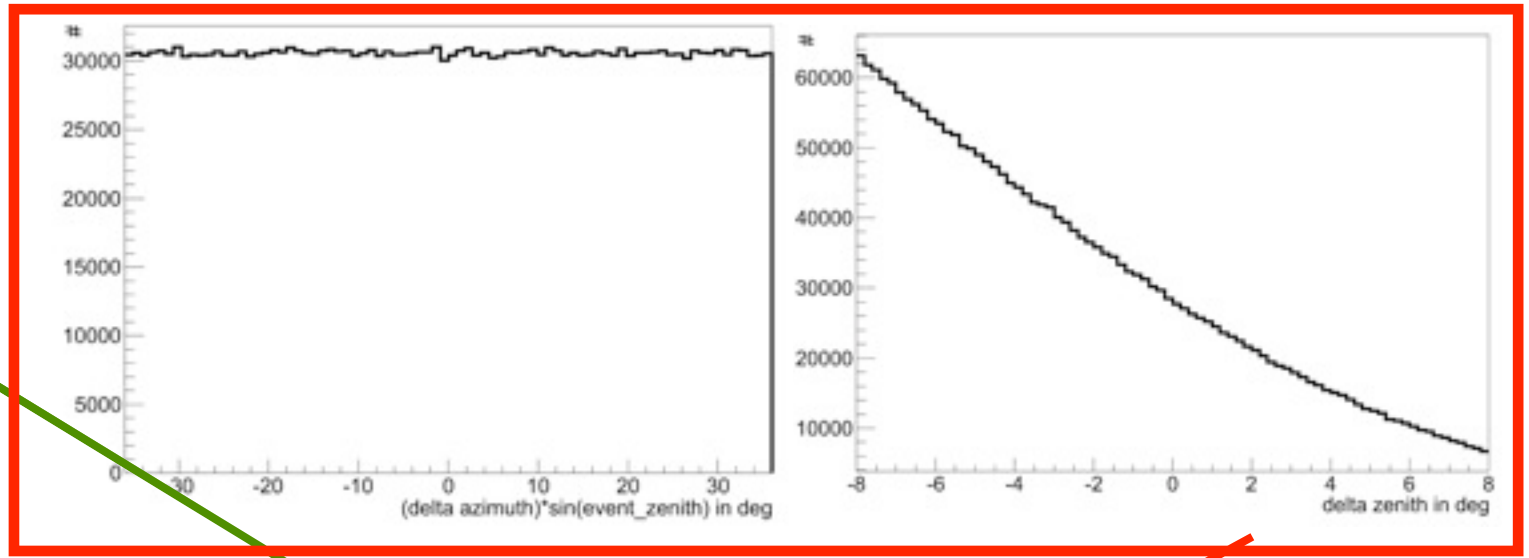

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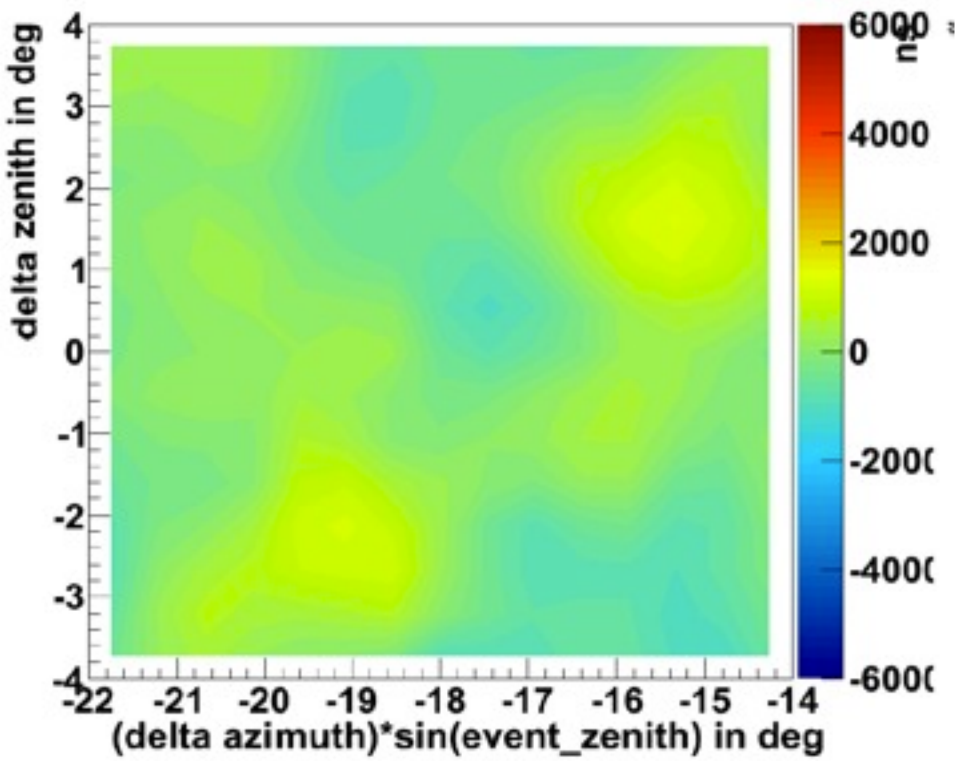
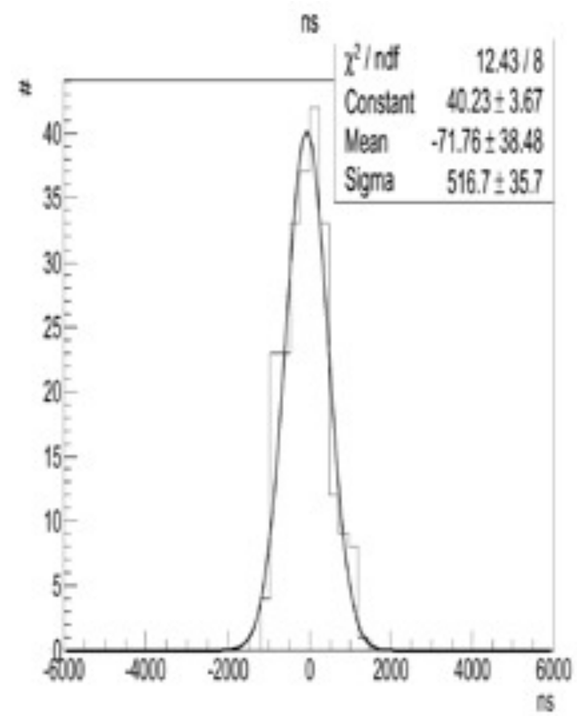
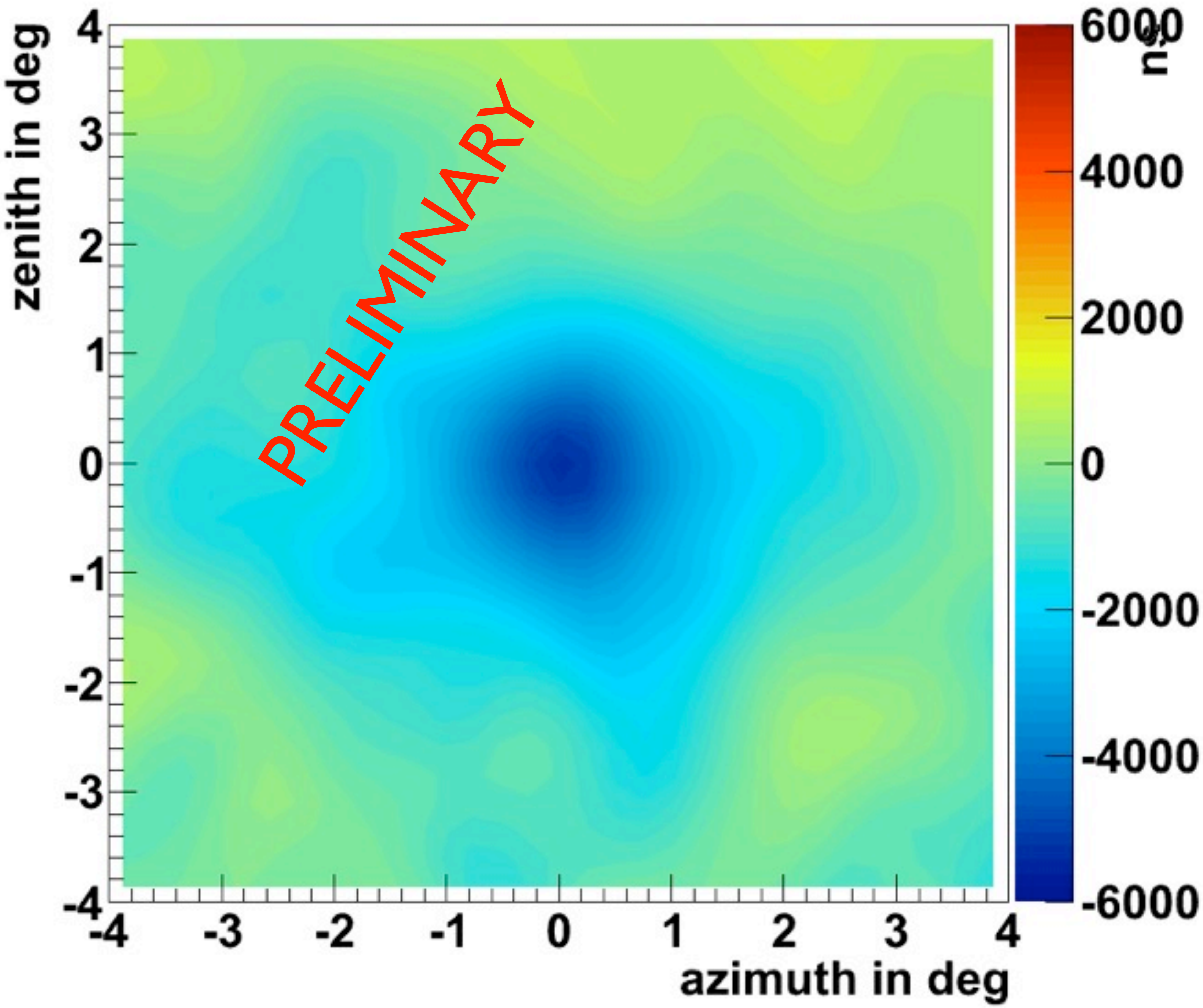




Null hypothesis fluctuations: look at off-source region as if it were signal

Width = 500 events

Likelihood result PRELIMINARY

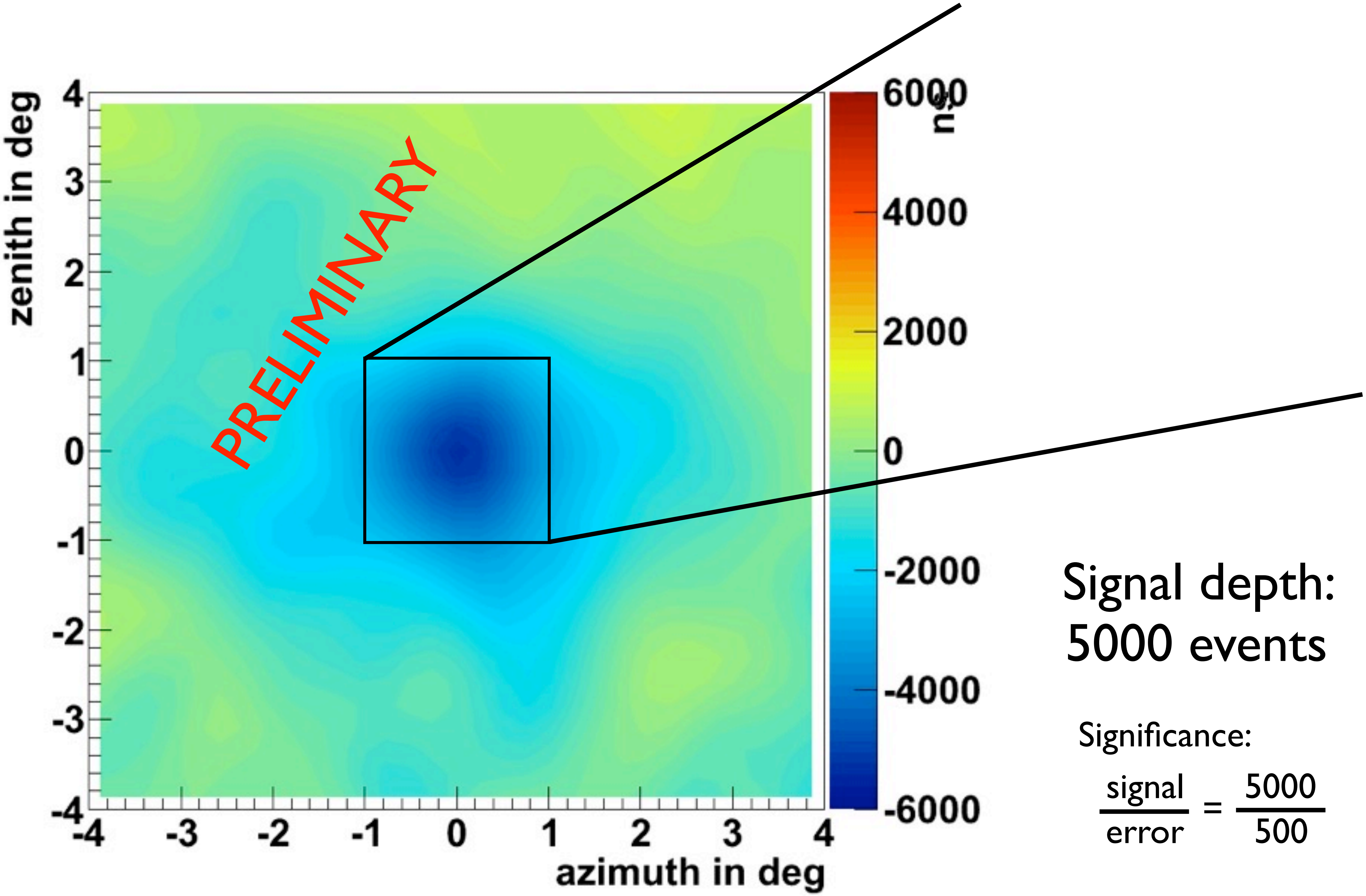


Signal depth:
5000 events

Significance:

$$\frac{\text{signal}}{\text{error}} = \frac{5000}{500}$$

Likelihood result PRELIMINARY



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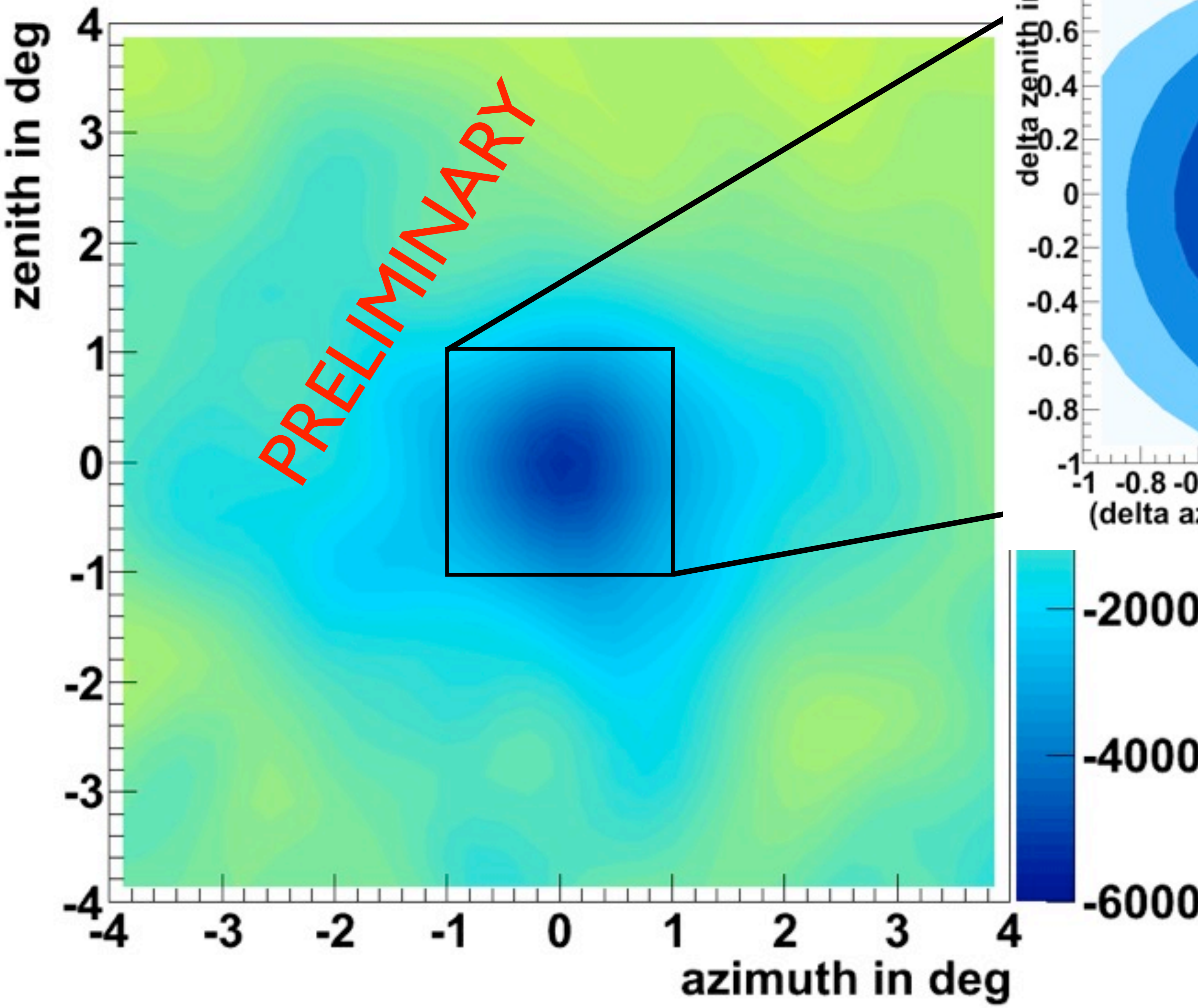

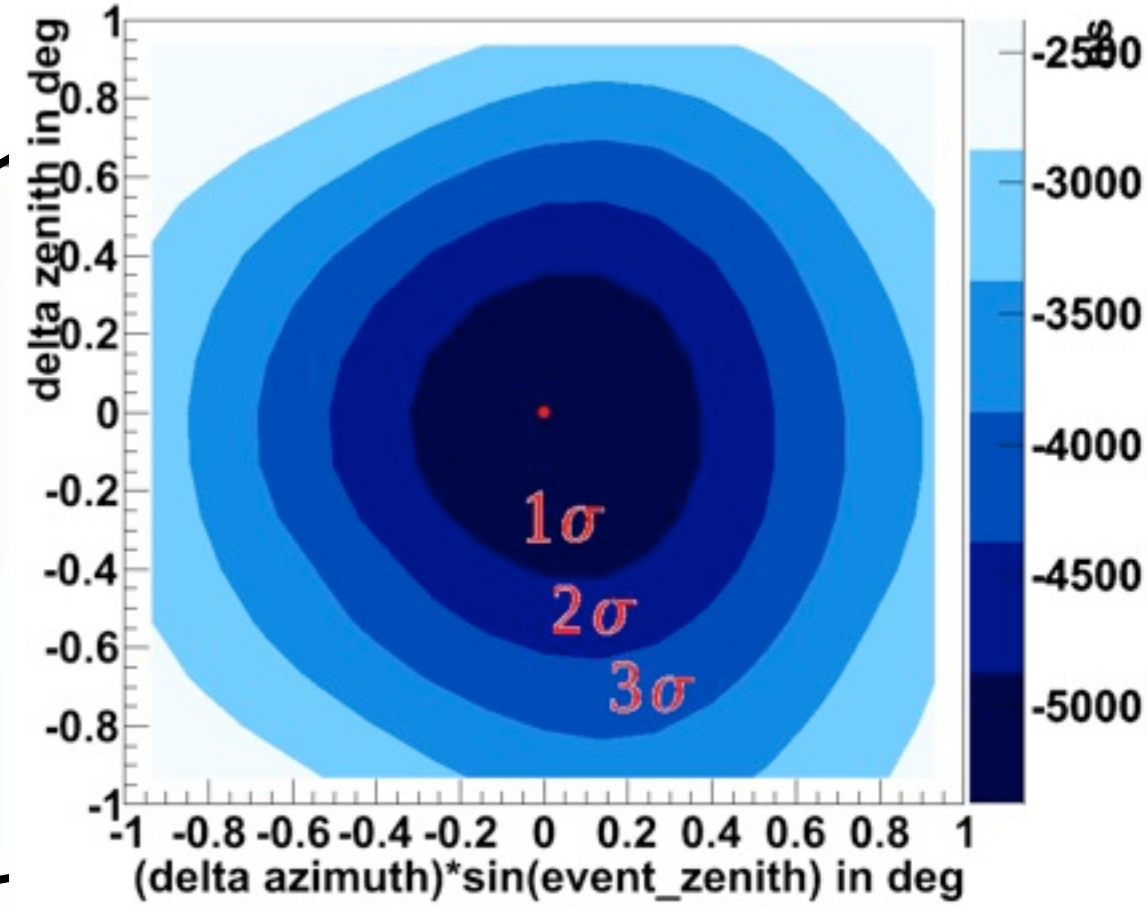

Signal depth:
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Significance:

$$\frac{\text{signal}}{\text{error}} = \frac{5000}{500}$$

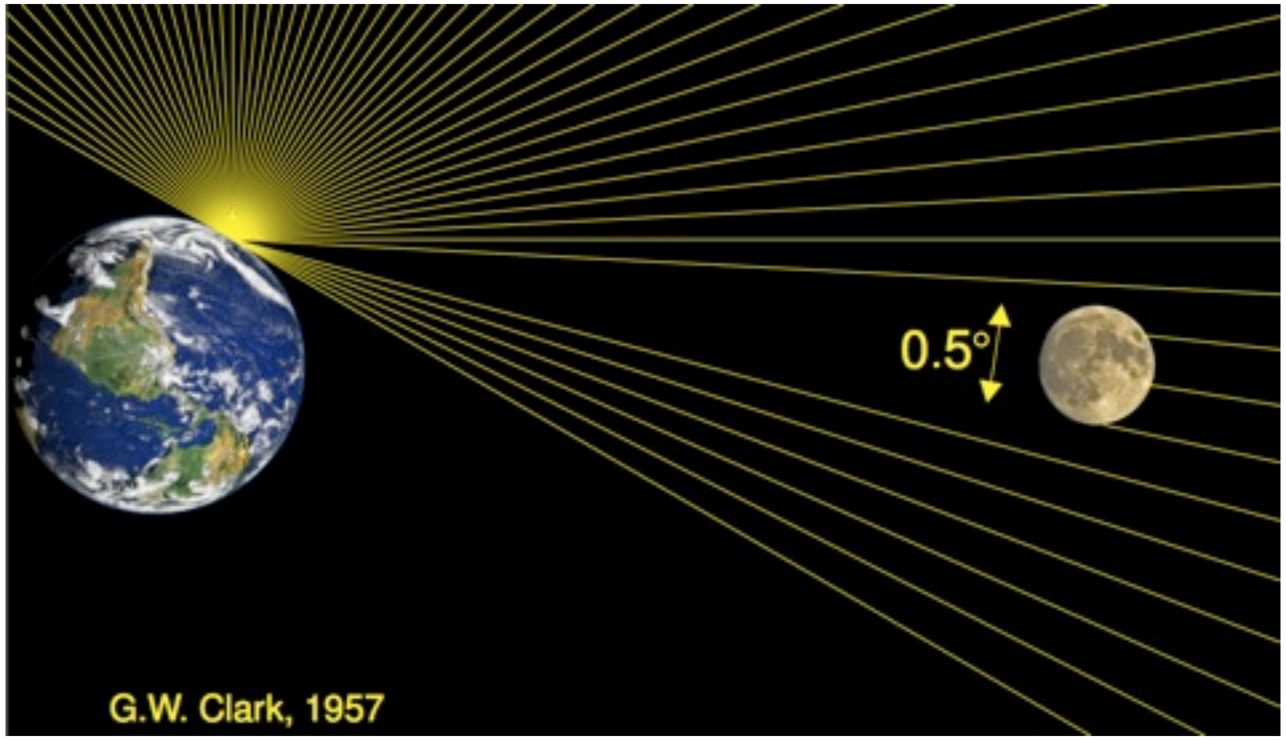
Conclusion:

- IceCube observes the Moon shadow with 10σ, confirming accurate pointing up to $\mathcal{O}(°)$

Thanks to the IceCube Moon group, especially:
David Boersma
Jan Blumenthal
Hugo Stiebel
Marcos Santander

Uses for a known shadow

- End-to-end check of systematics and pointing
  - Monitor monthly to confirm data
- Use the shadow shape to describe the detector point spread function
- Vary fit parameters and observe the effect on shadow strength
  - confirms simulation accuracy



Likelihood: background

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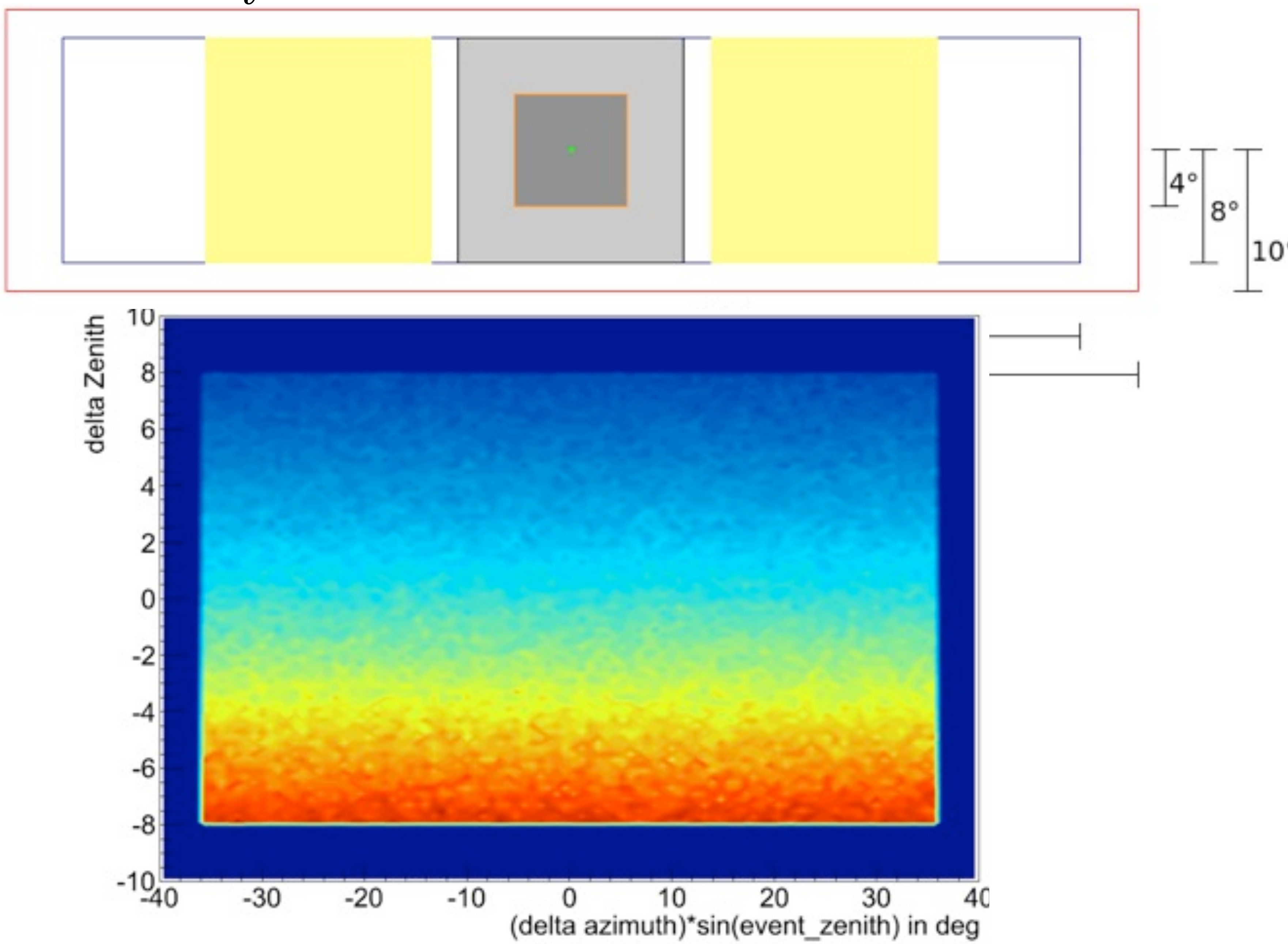
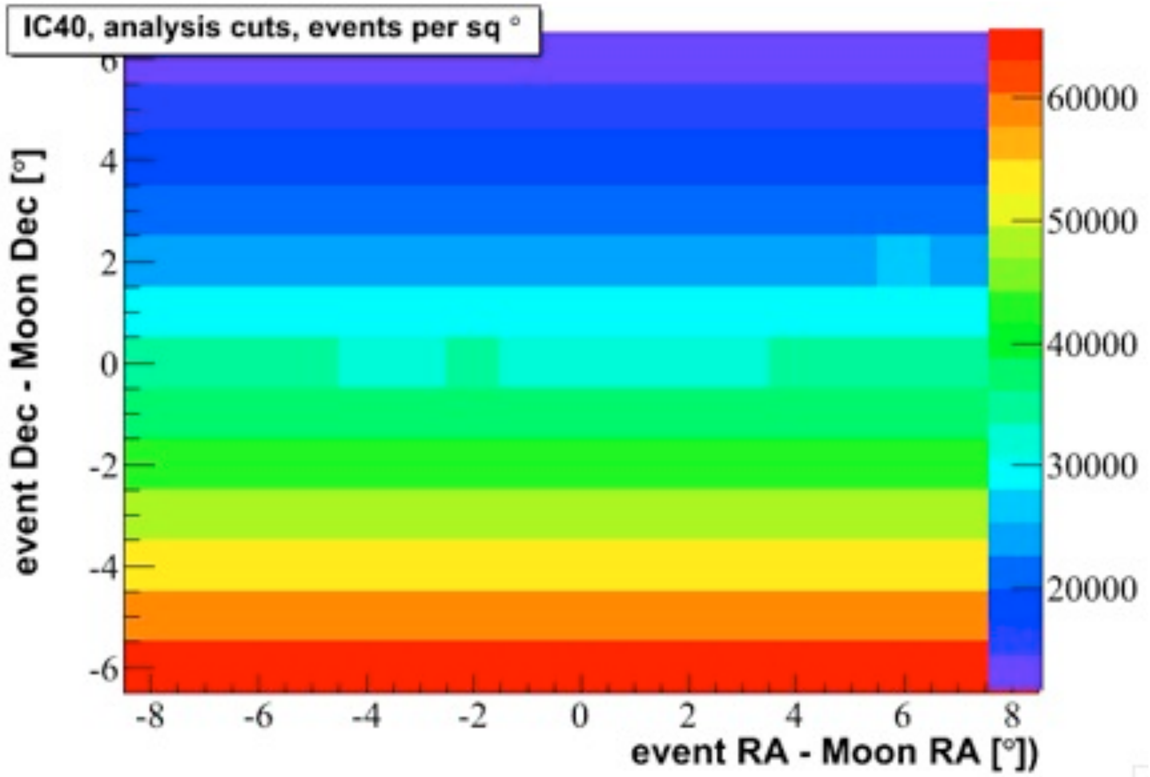
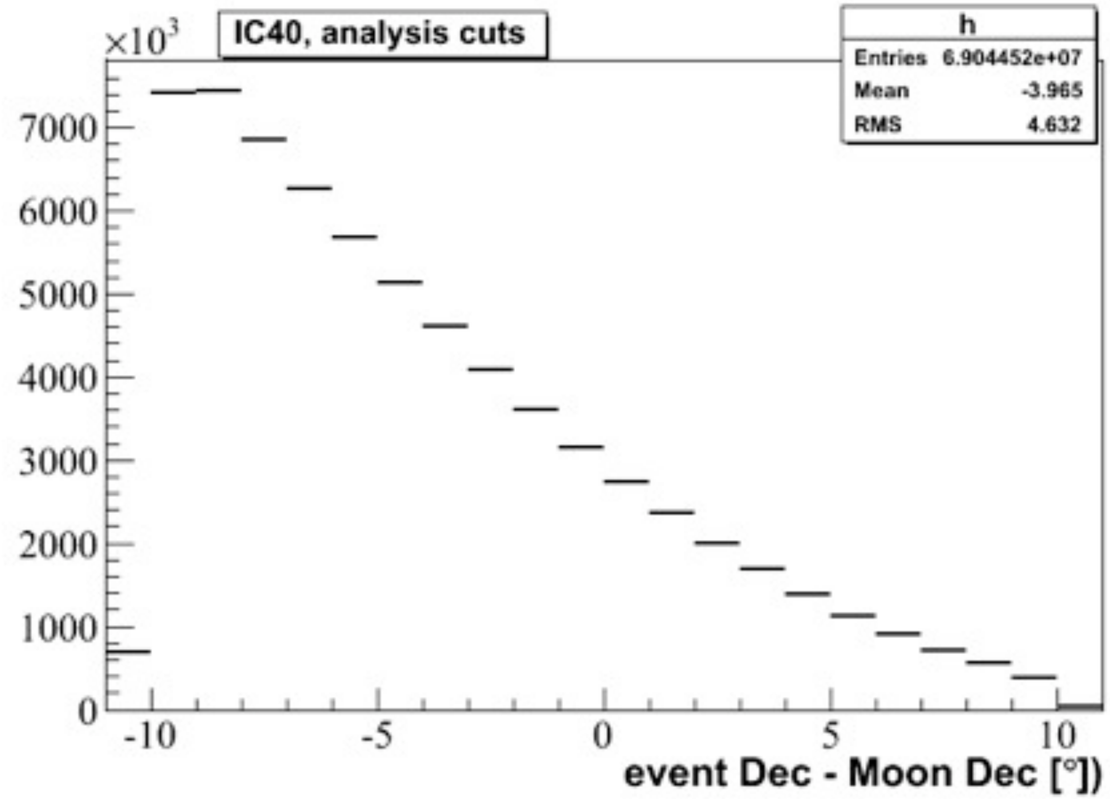
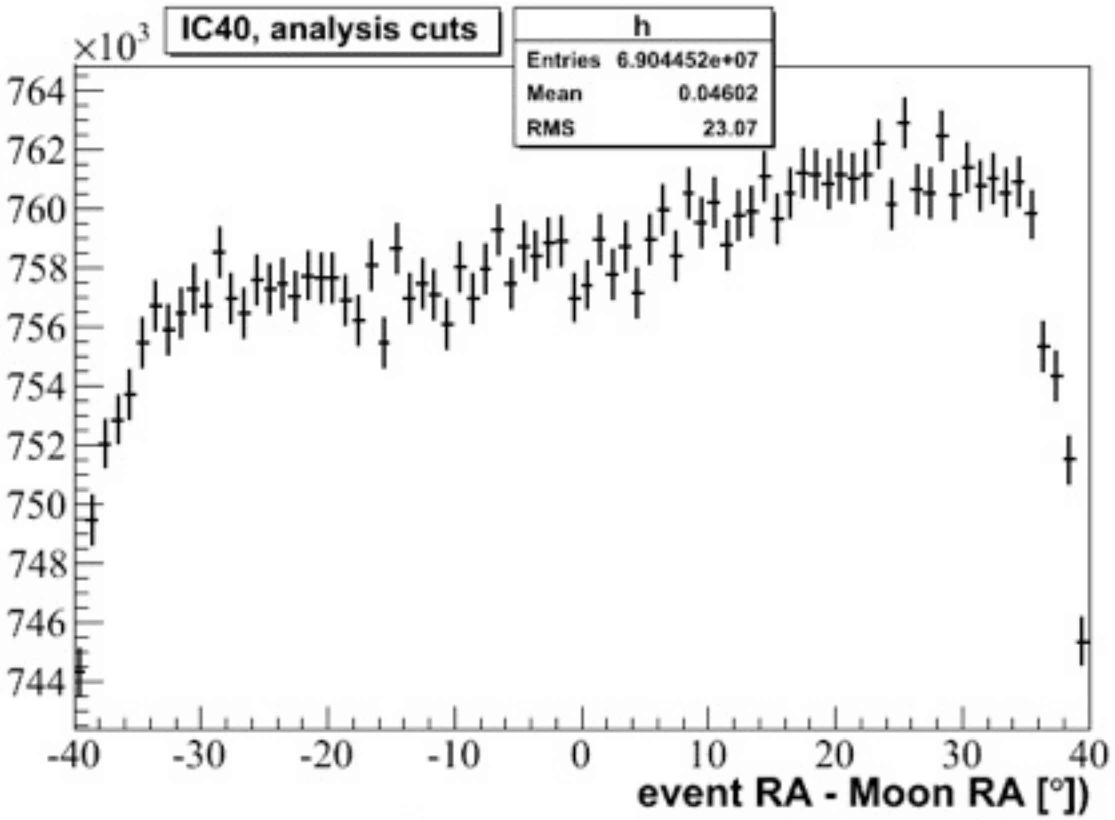
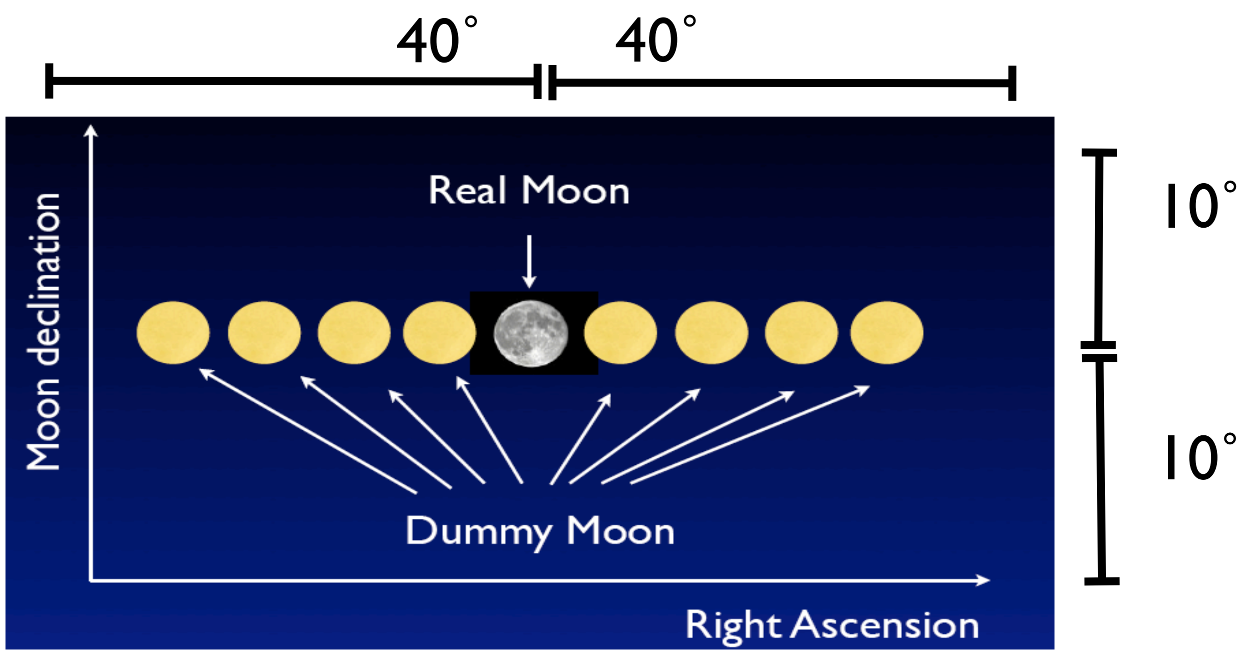


Data set


IC40, analysis cuts, events per sq °
event Dec - Moon Dec [°]
event RA - Moon RA [°])
60000
50000
40000
30000
20000


IC40, analysis cuts
h
Entries 6.904452e+07
Mean -3.965
RMS 4.632
event Dec - Moon Dec [°])


IC40, analysis cuts
h
Entries 6.904452e+07
Mean 0.04602
RMS 23.07
event RA - Moon RA [°])


40°
40°
10°
10°
Real Moon
Moon declination
Dummy Moon
Right Ascension

Data Quality Cuts

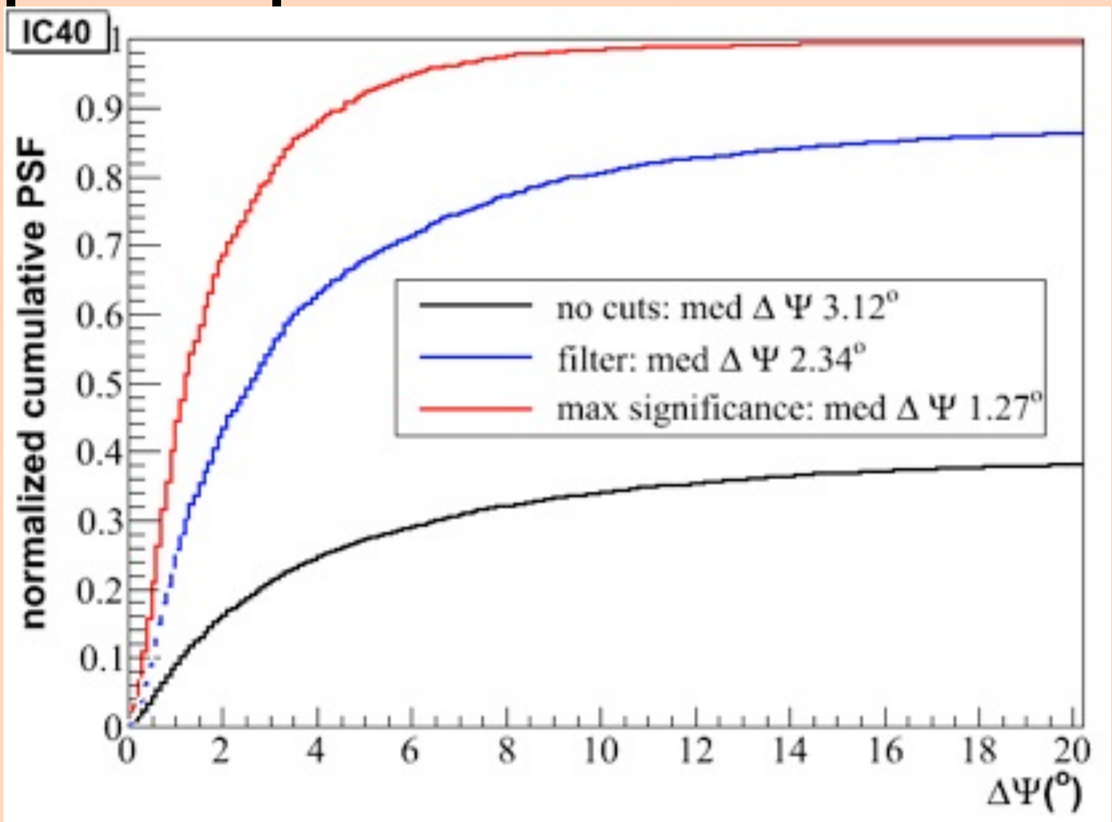
- Filter-level cuts:
  - (number of hit DOMs) ≡ NCh ≥ 12
  - (number of hit strings) ≥ 3
- Analysis-level cuts:
  - estimated angular error of reconstruction ≤ 1.6°
- Resulting sample:
  - 69M events, 53% efficiency from filter
  - median angular resolution: 1.27°
- Search Bin Size: 0.8°

Search bin size optimization

significance ~ $\frac{N_{sig}}{\sqrt{N_{bkgd}}}$

Search bin size optimization

Signal: use simulated point spread function



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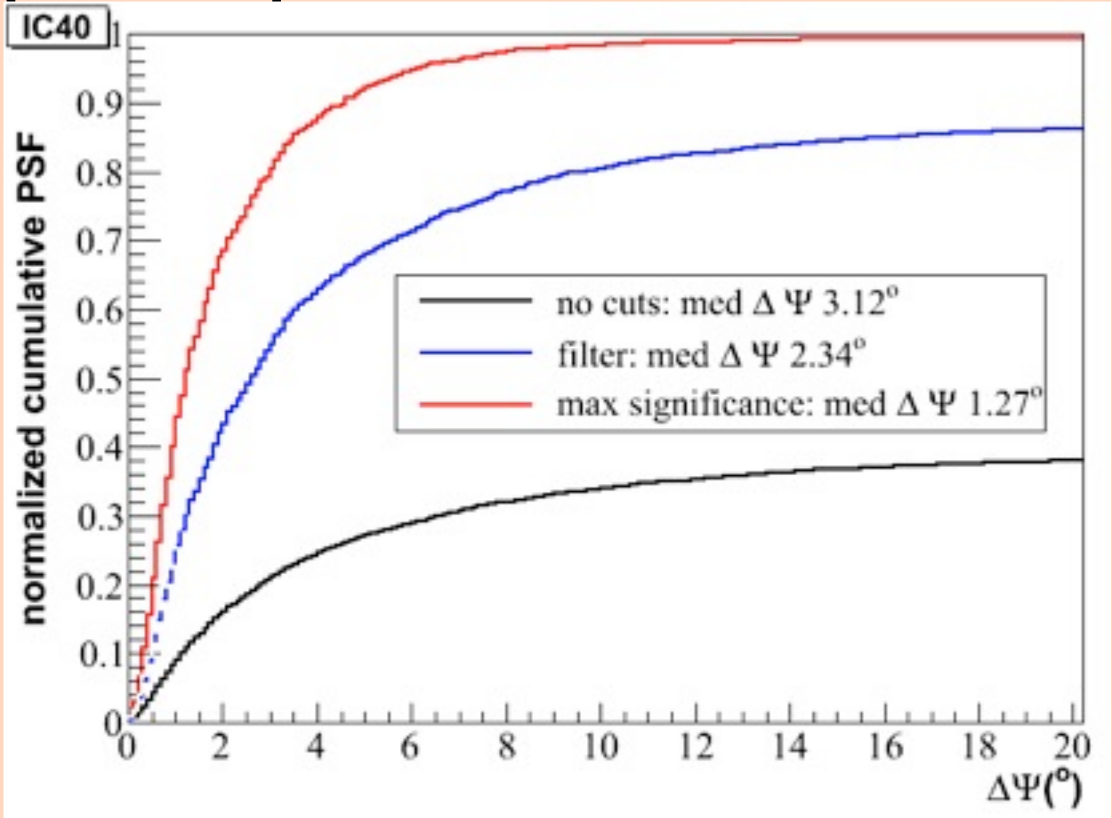


significance ~ $\frac{N_{sig}}{\sqrt{N_{bkgd}}}$

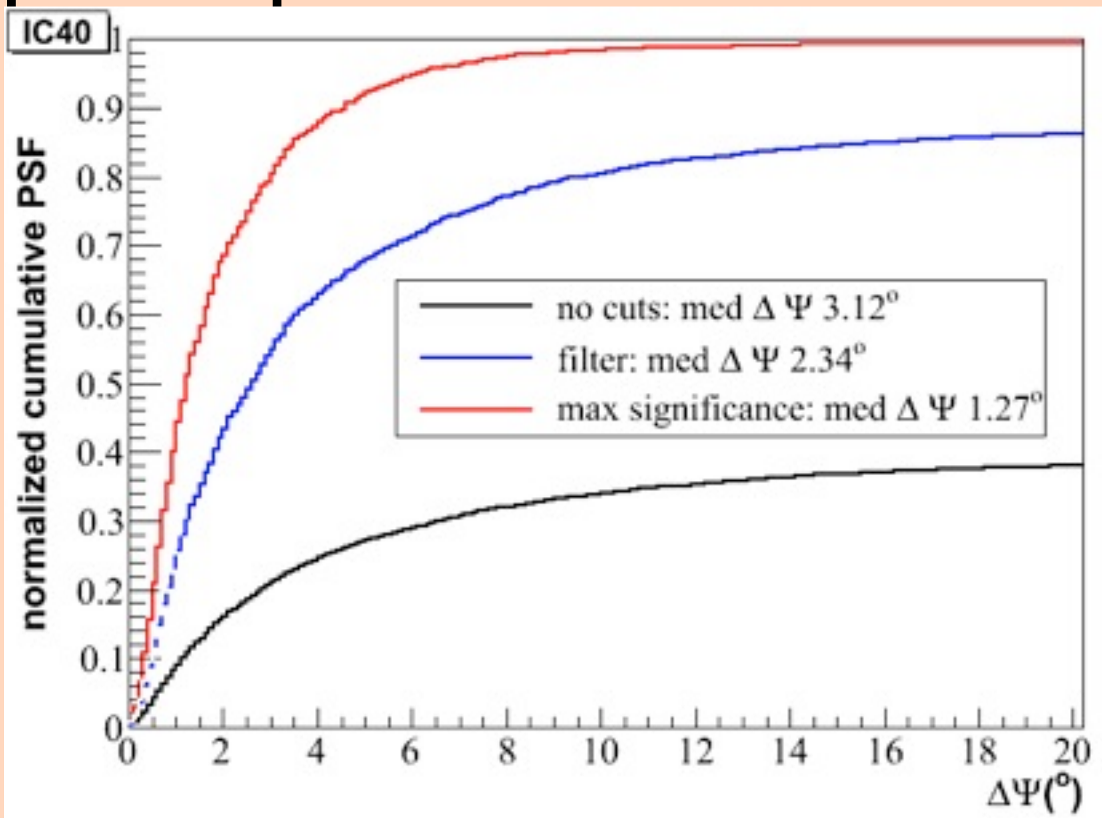
Background: scales with area

$$N_{bkgd} \propto \text{Area} \propto \pi r^2$$

$$\sqrt{N_{bkgd}} \propto r$$

Search bin size optimization

Signal: use simulated point spread function



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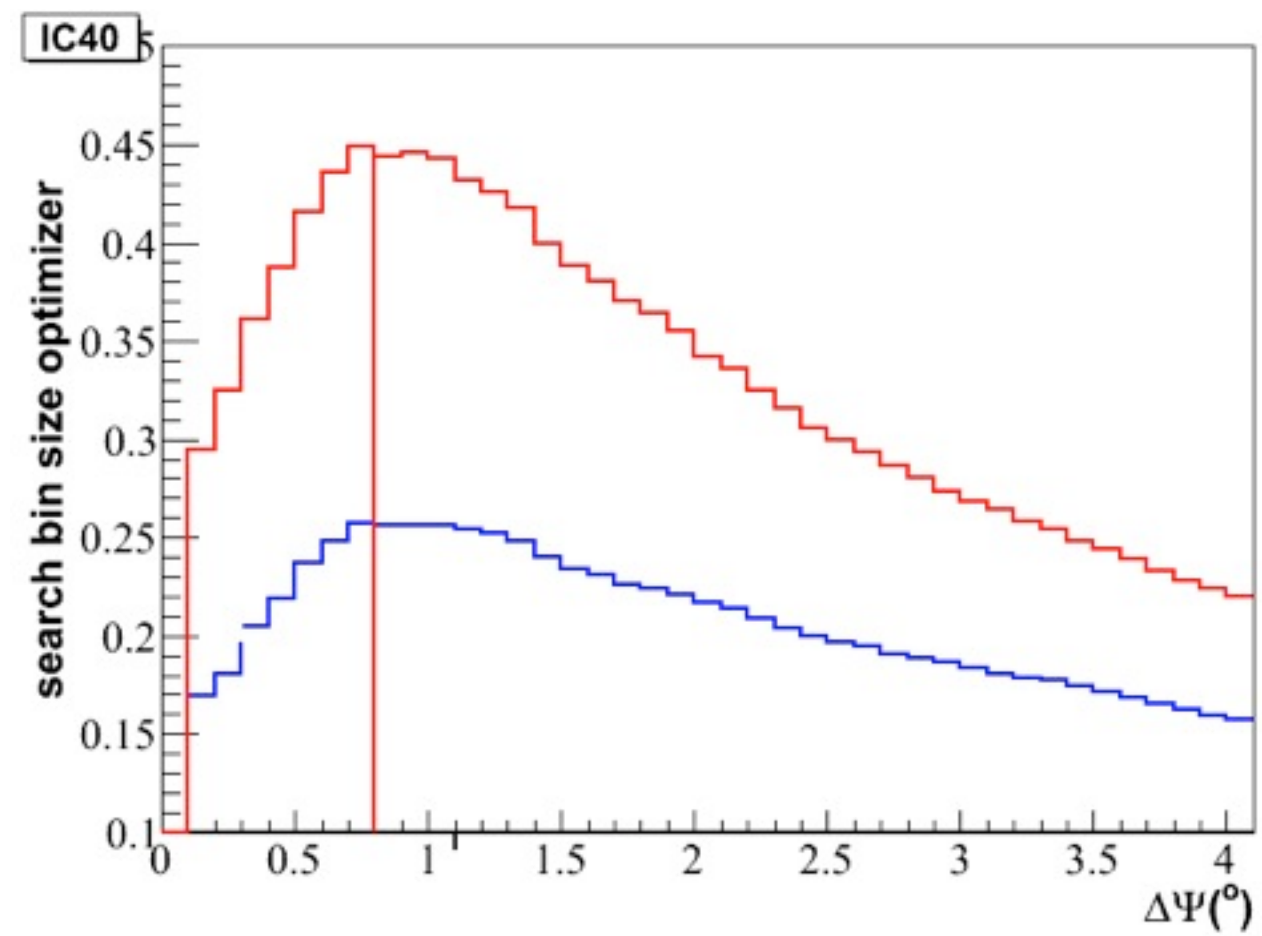
$$\text{significance} \sim \frac{N_{sig}}{\sqrt{N_{bkgd}}}$$



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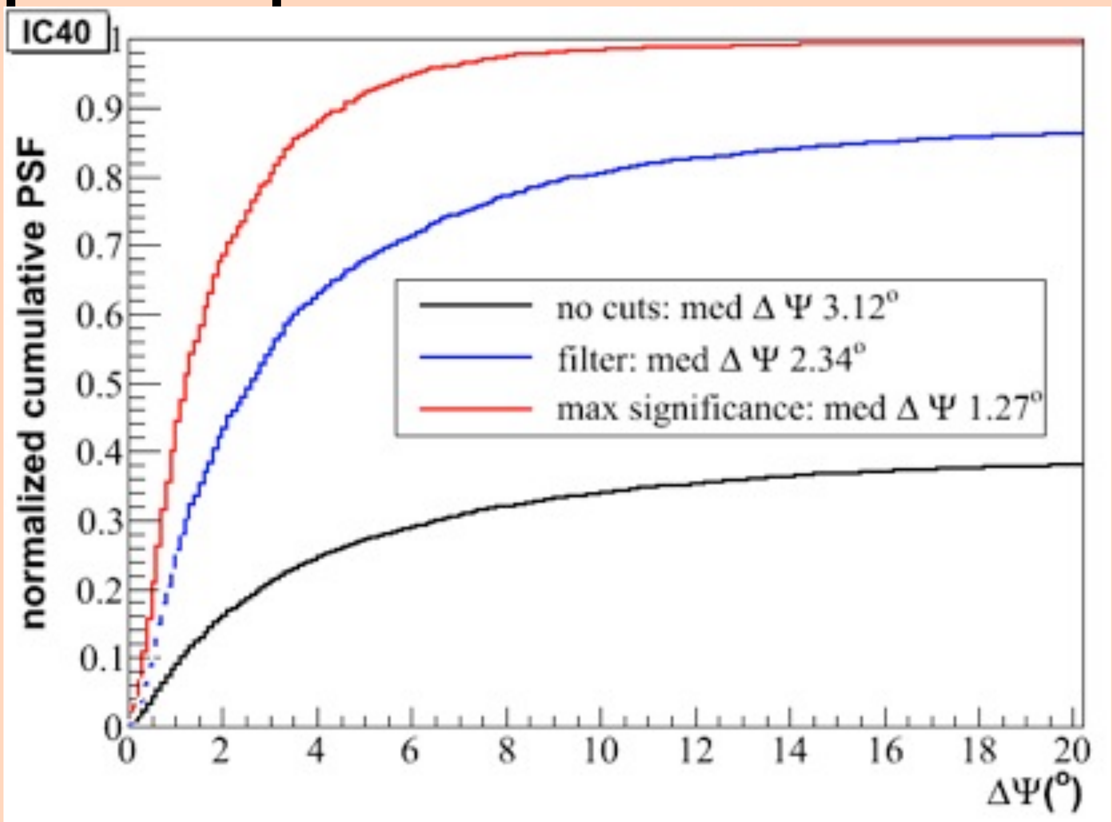

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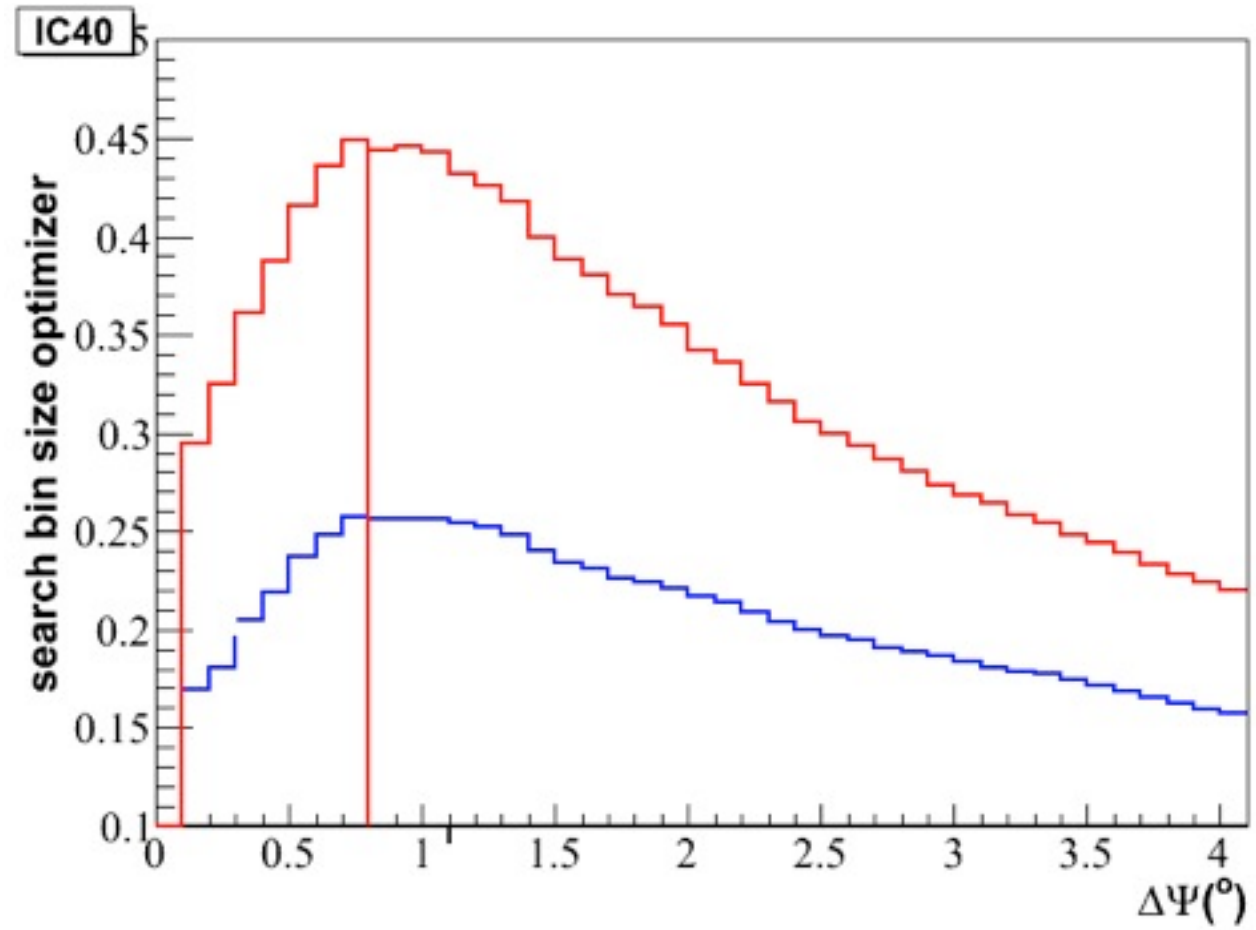
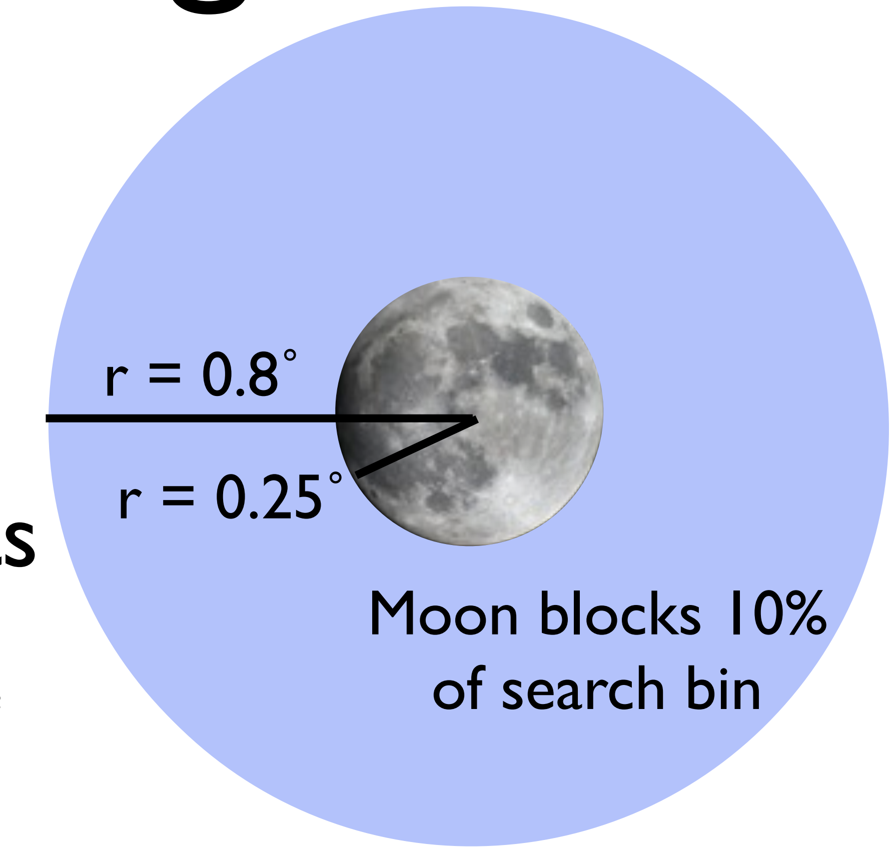


Expect best result with search bin of 0.8°

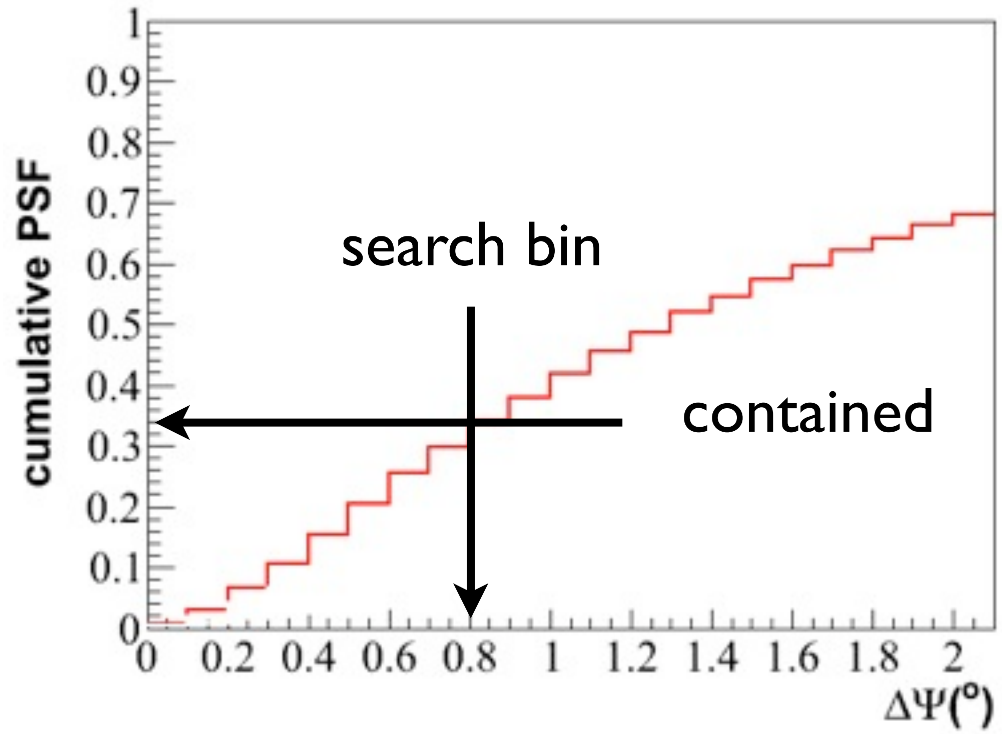
Back-of-the-Envelope Significance

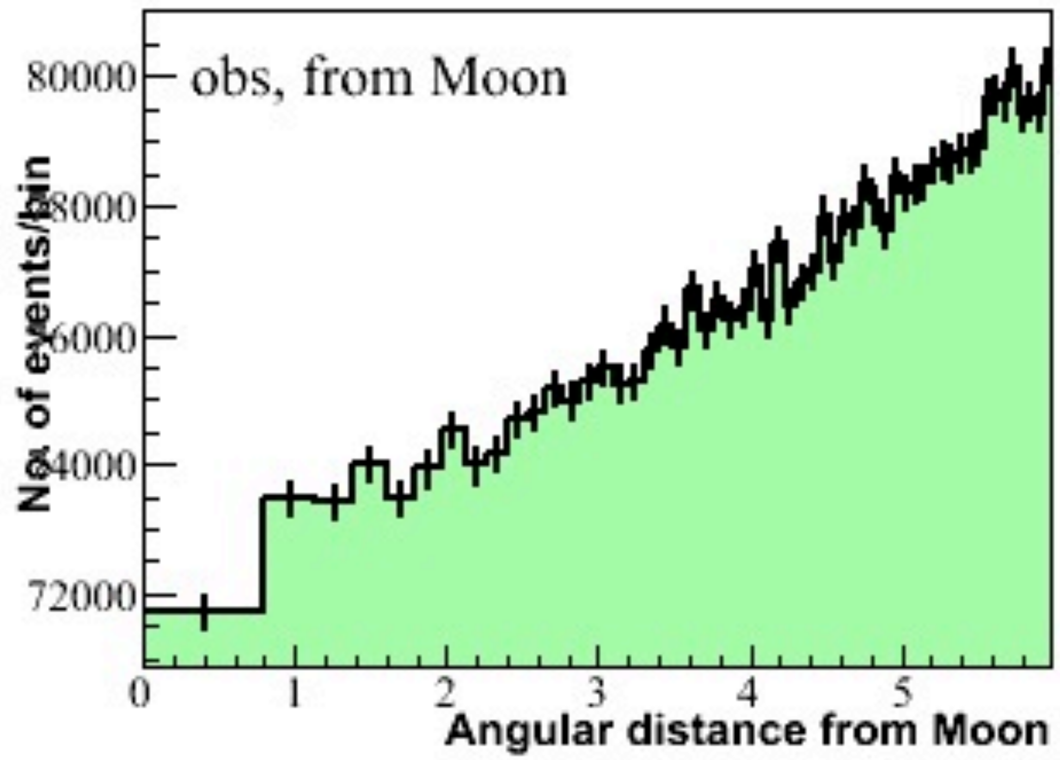
- Observe rate: 35k events/ sq°
  - 70.4k in each background bin
  - 7k events blocked by Moon
- Search bin contains 35% blocked events

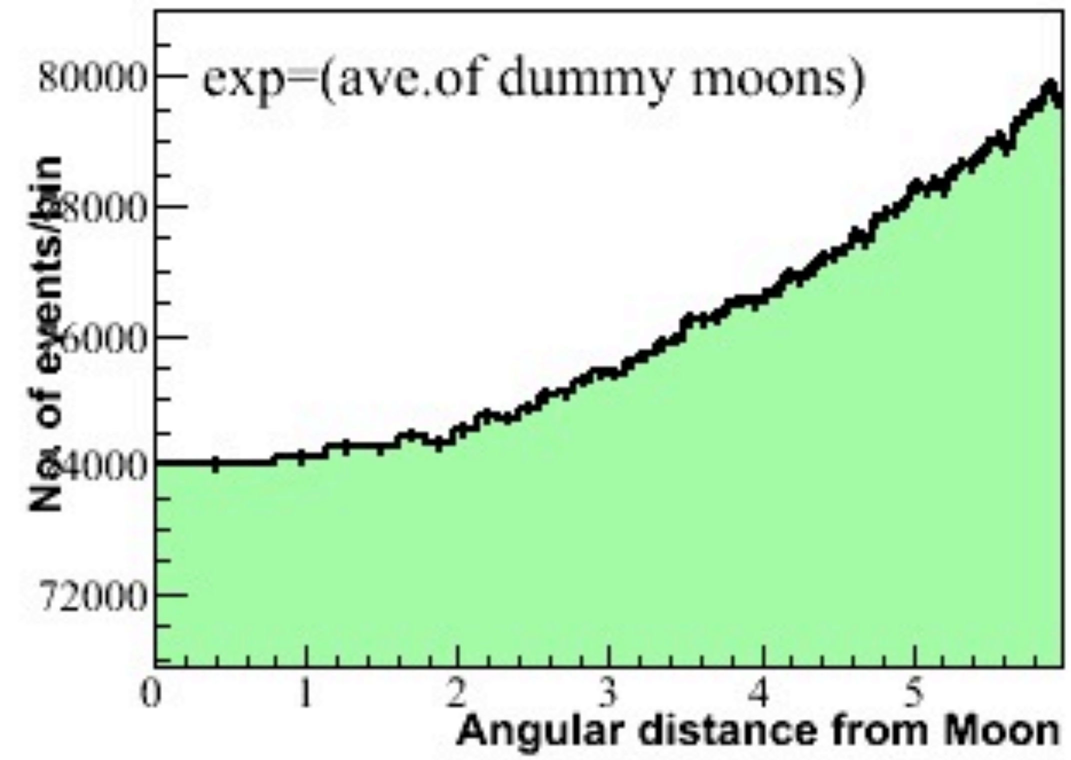


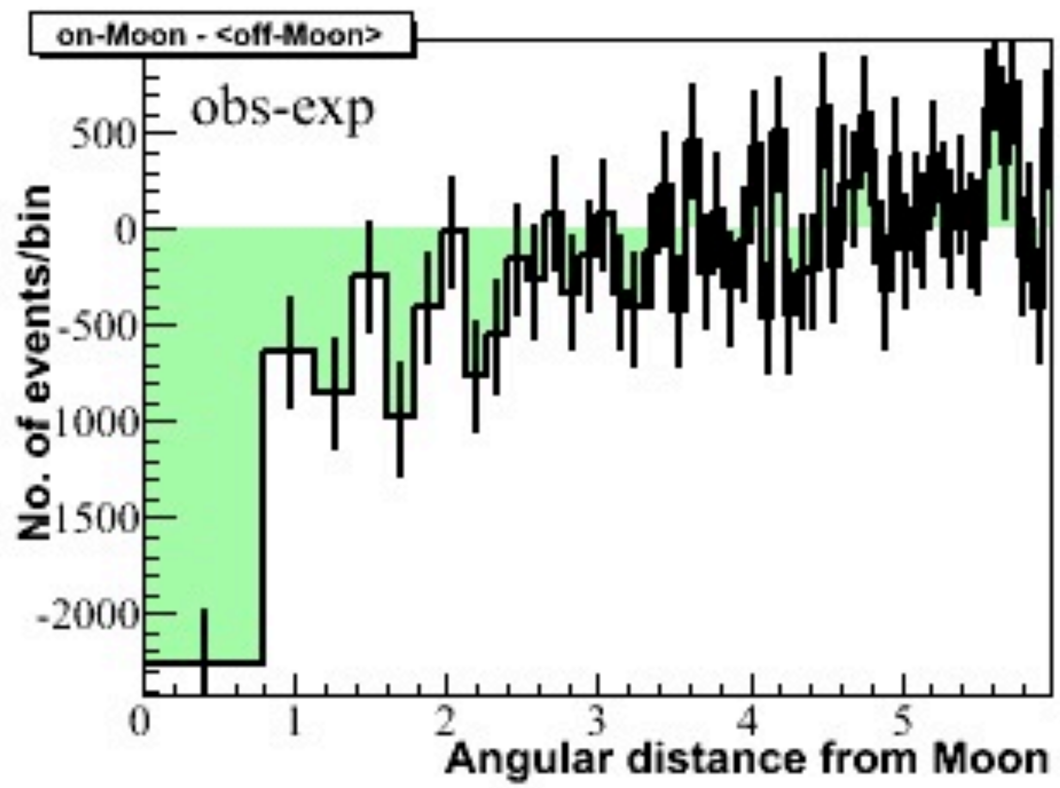
$$S = \sqrt{2}\left\{N_{\text{on}}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right)\right] + N_{\text{off}}\ln\left[(1+\alpha)\left(\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right)\right]\right\}^{1/2}$$

Expect 2500 event deficit: 8.9σ









observed: 7.173e+04 events

expected: 7.4e+04 events

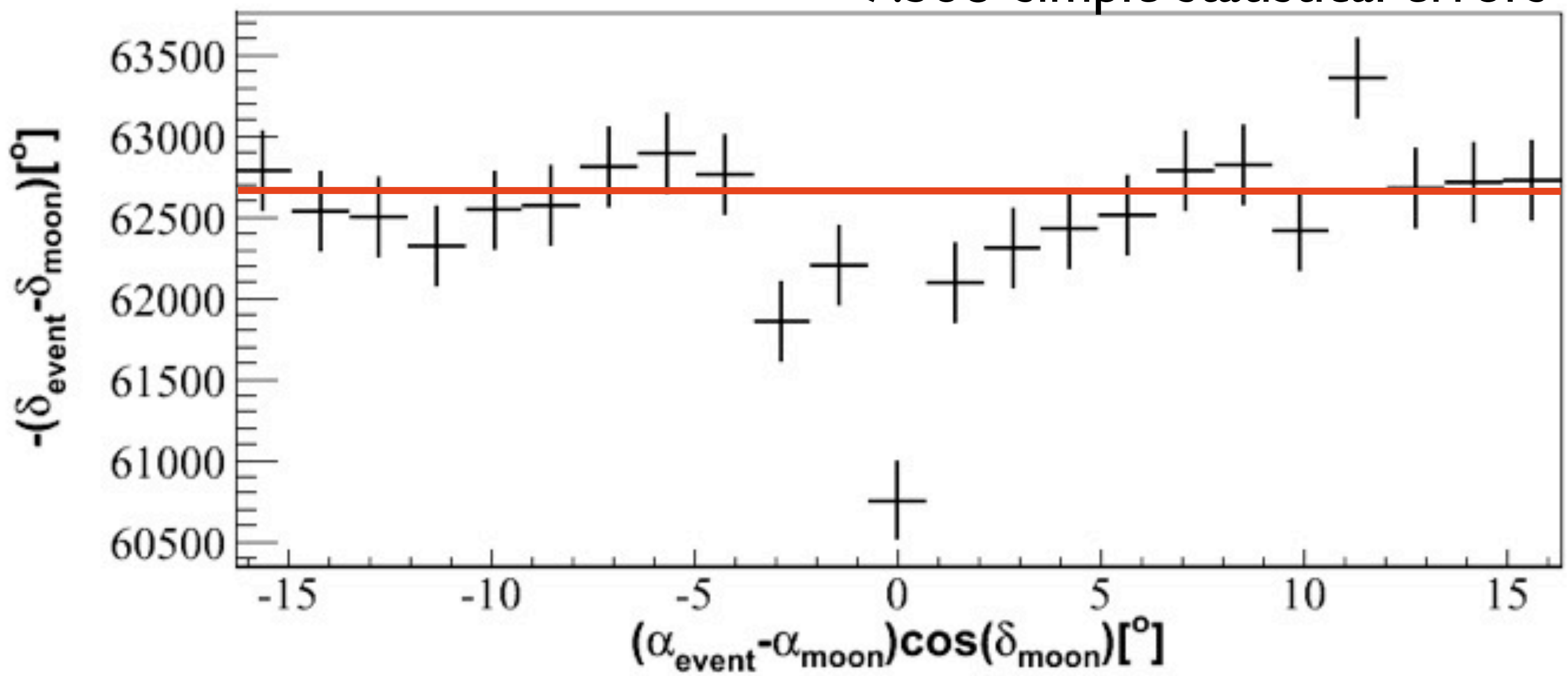
deficit: -2262 events

error: 285 events

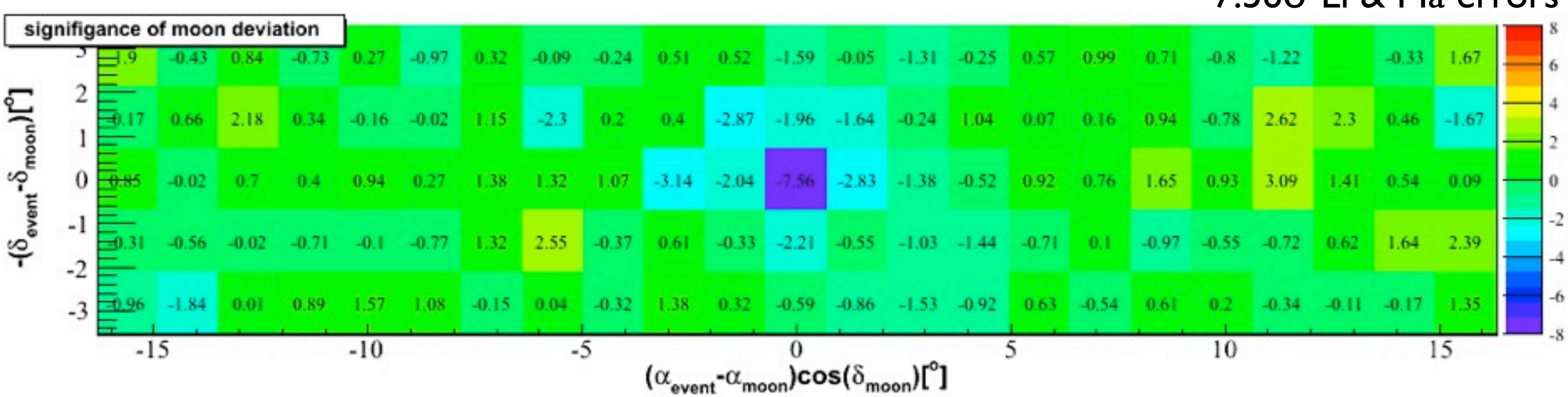
significance: -7.9σ

Once events are reconstructed, this method is fast

7.58σ simple statistical errors

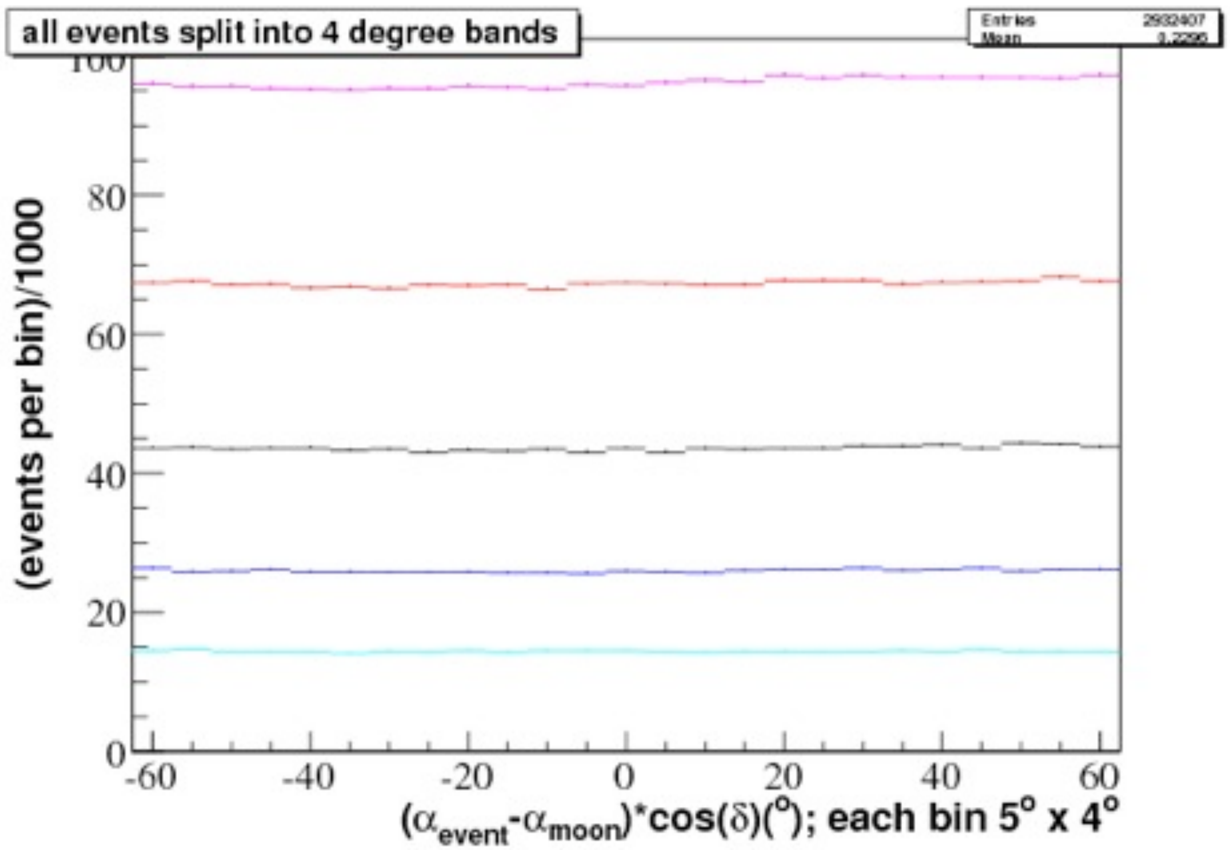


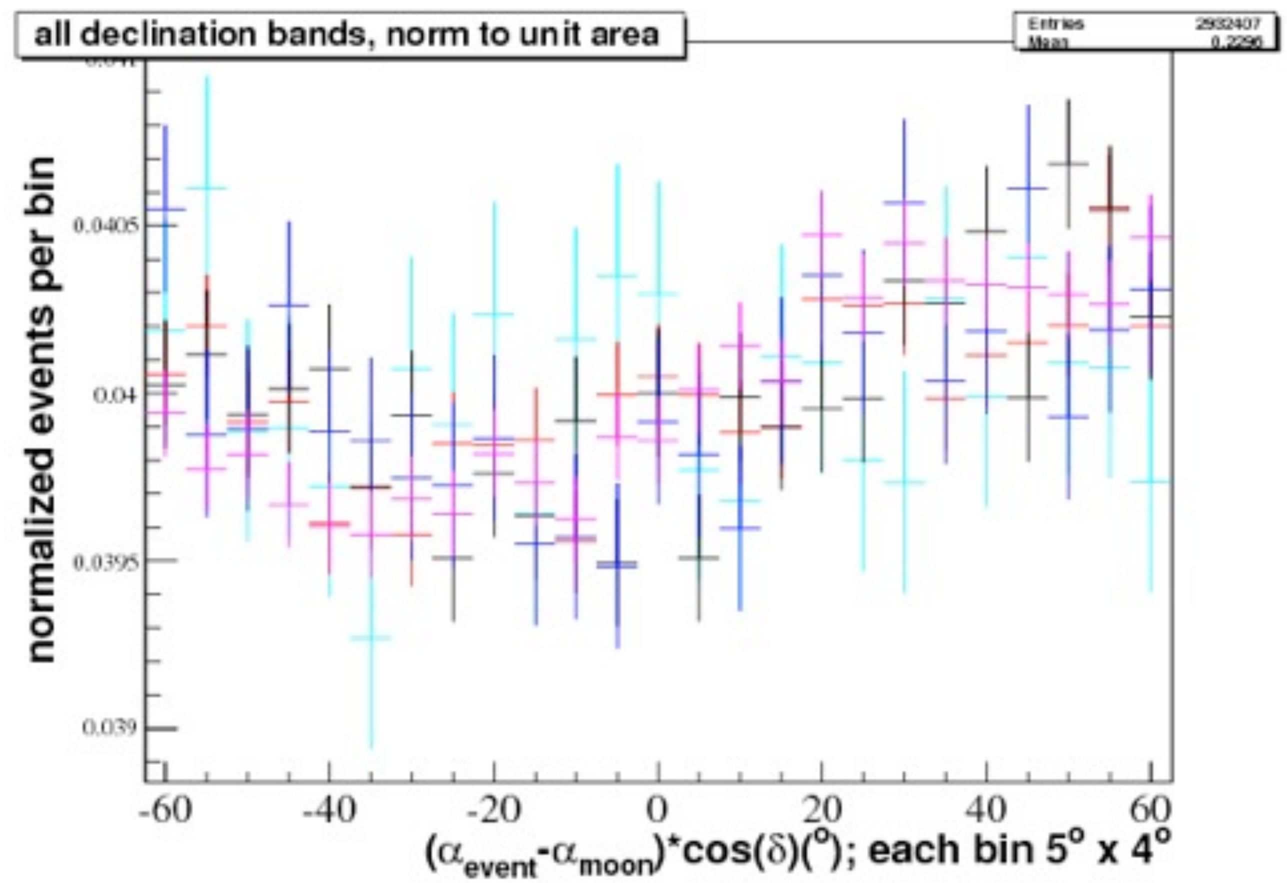
7.56σ Li & Ma errors



Alternate Binned Method

- Consider several declination bands:
- Use off-Moon bands to correct Moon band RA structure
- This was tried on IC22

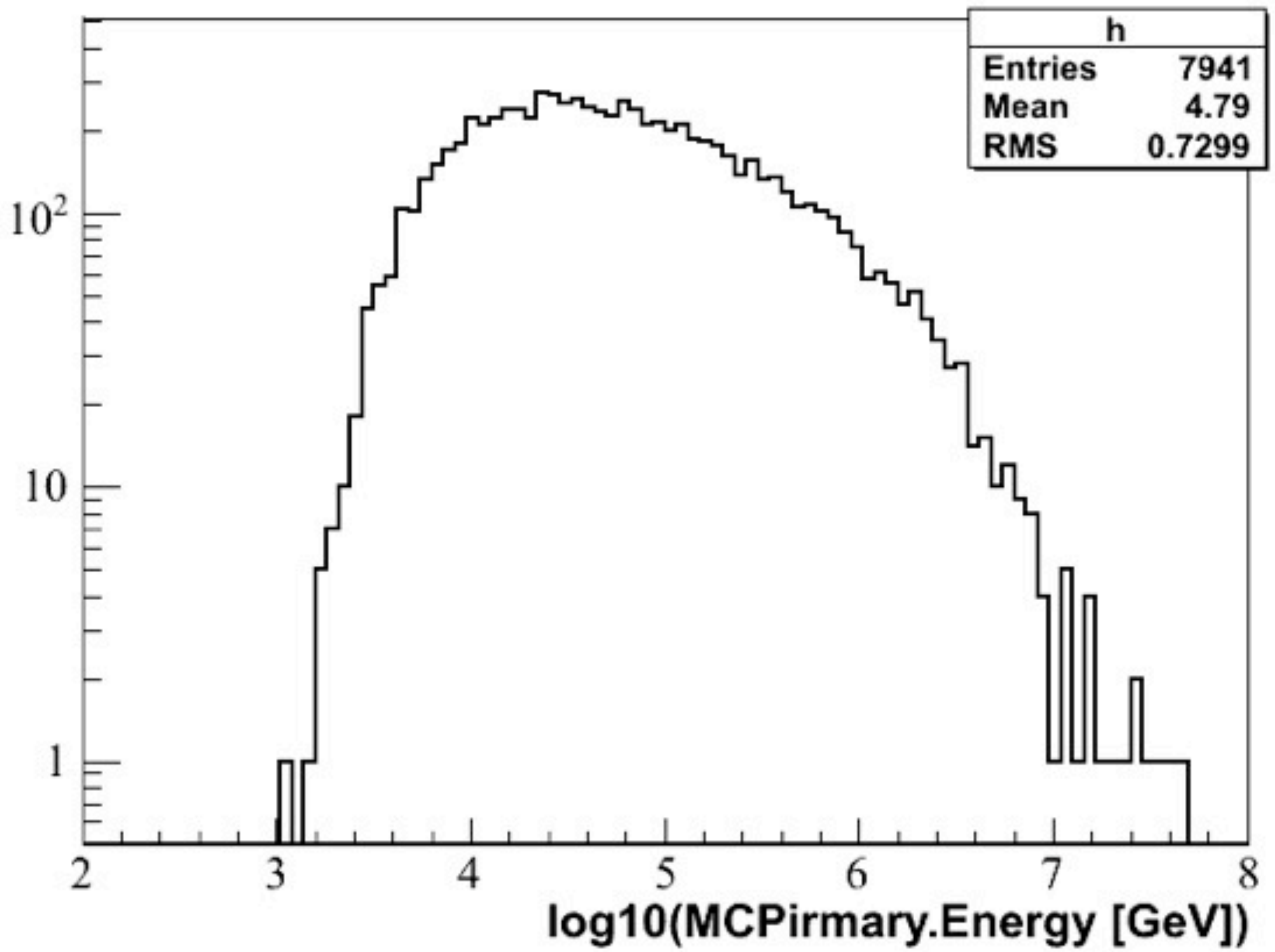


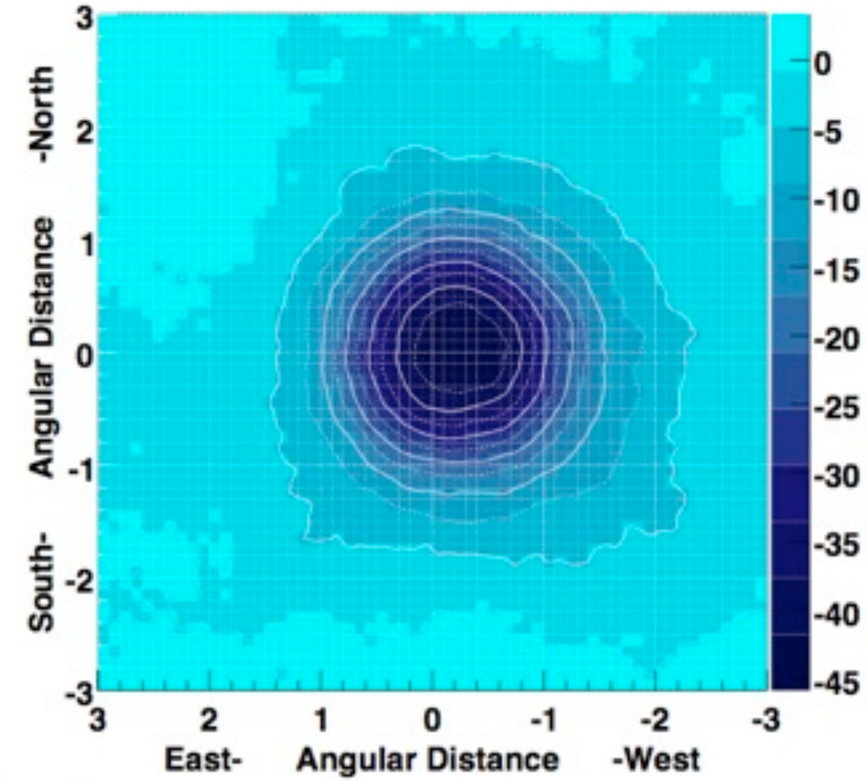


It didn’t work well enough with IC22,
and with IC40 a simpler binned analysis was good enough

Does Geomagnetic field matter?

- filter level cuts, zenith > 50˚





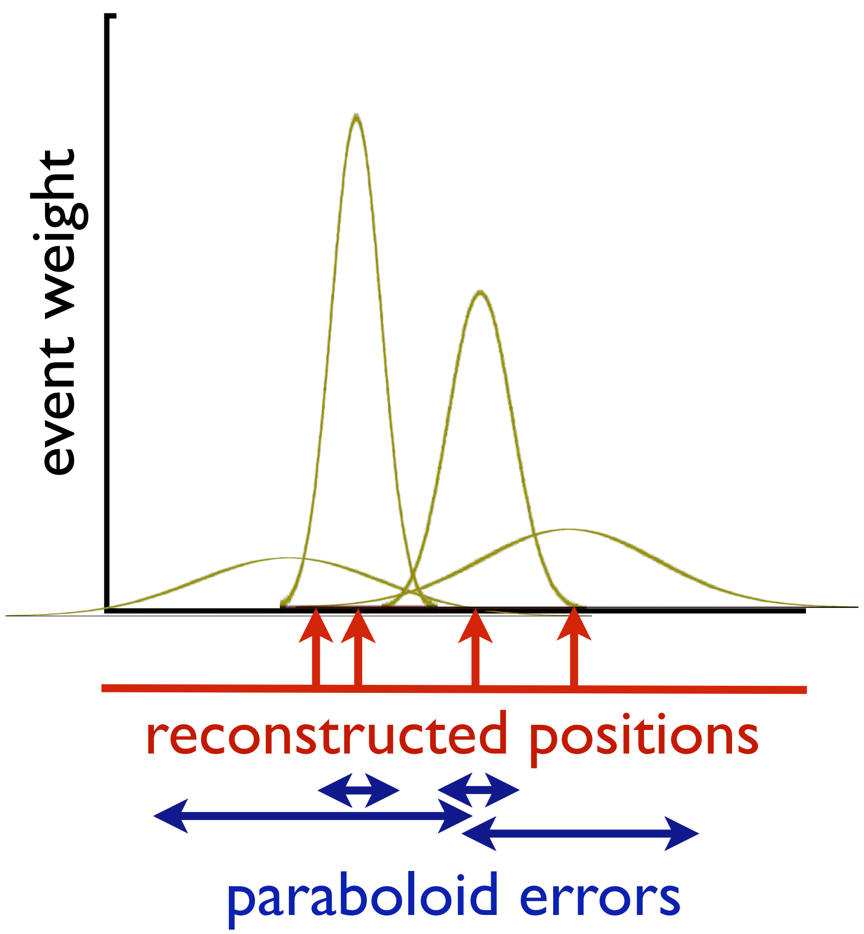
Shift from magnetic fields is negligible
Tibet Air Shower Array
arXiv:0810.3757v1 [astro-ph]
1-40 TeV

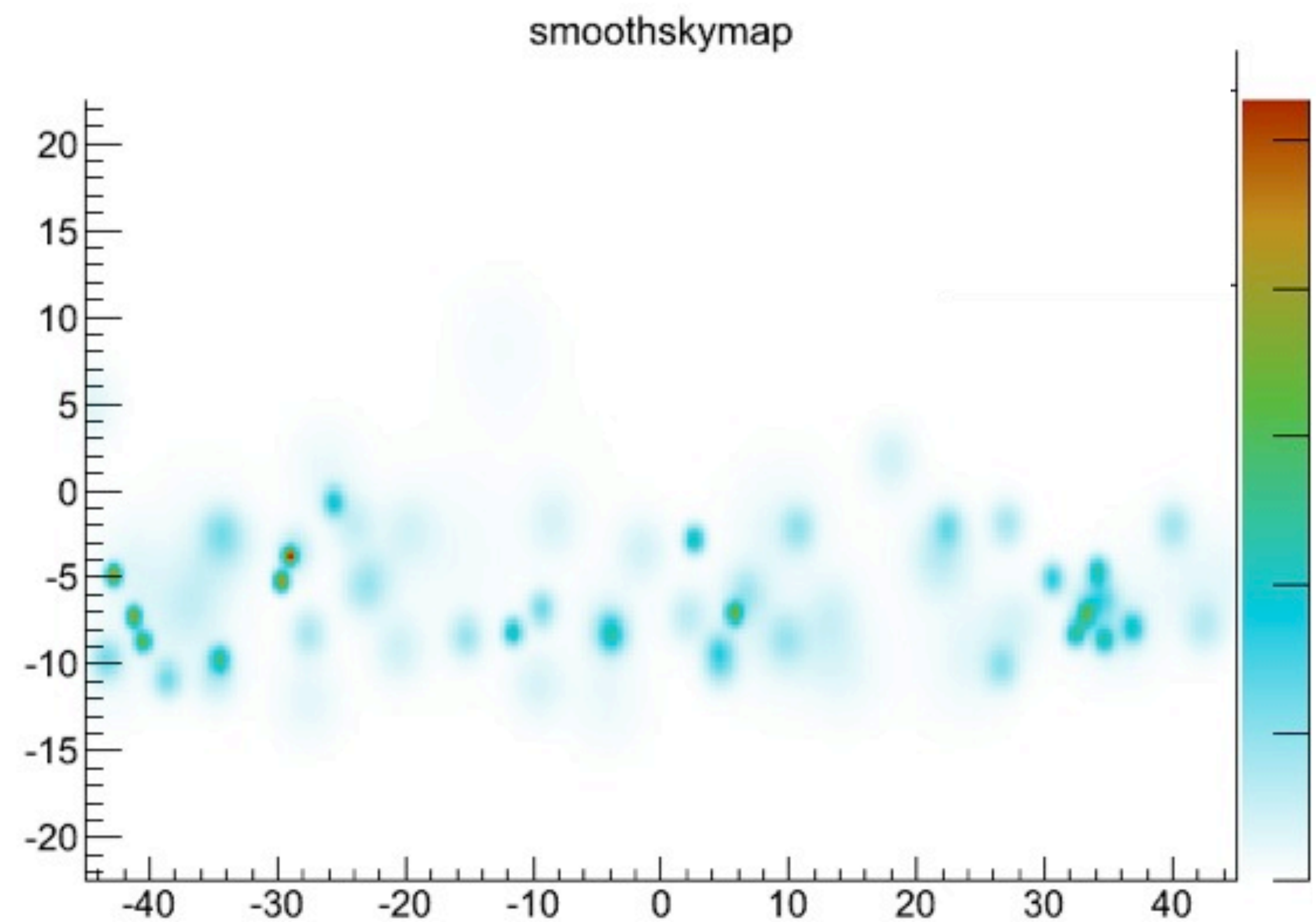
→shift is also negligible in this analysis

Approach II: Unbinned skymap

Smear each event by its paraboloid error

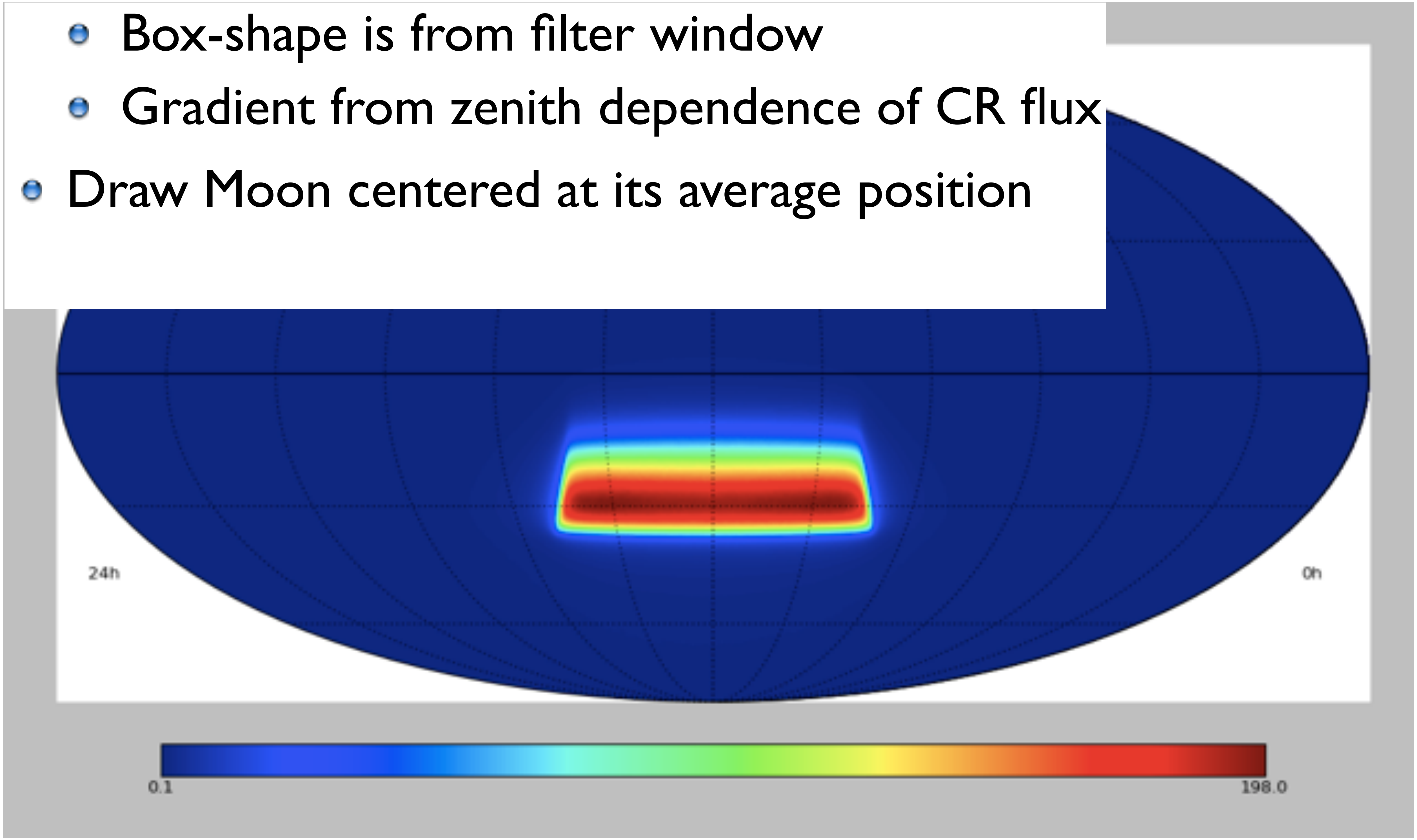
Map the total weighted event sum





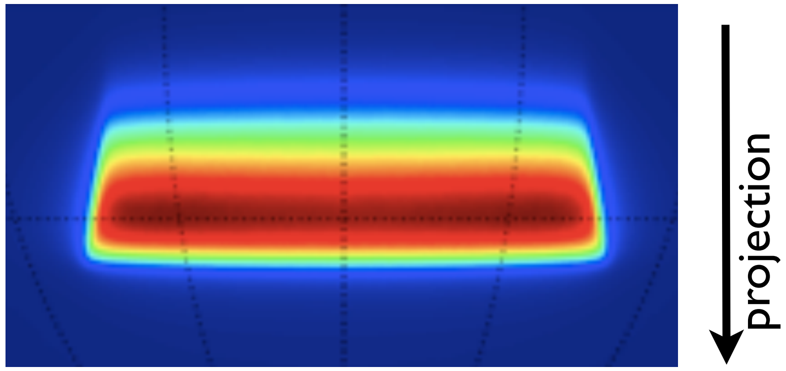
Unbinned Skymap

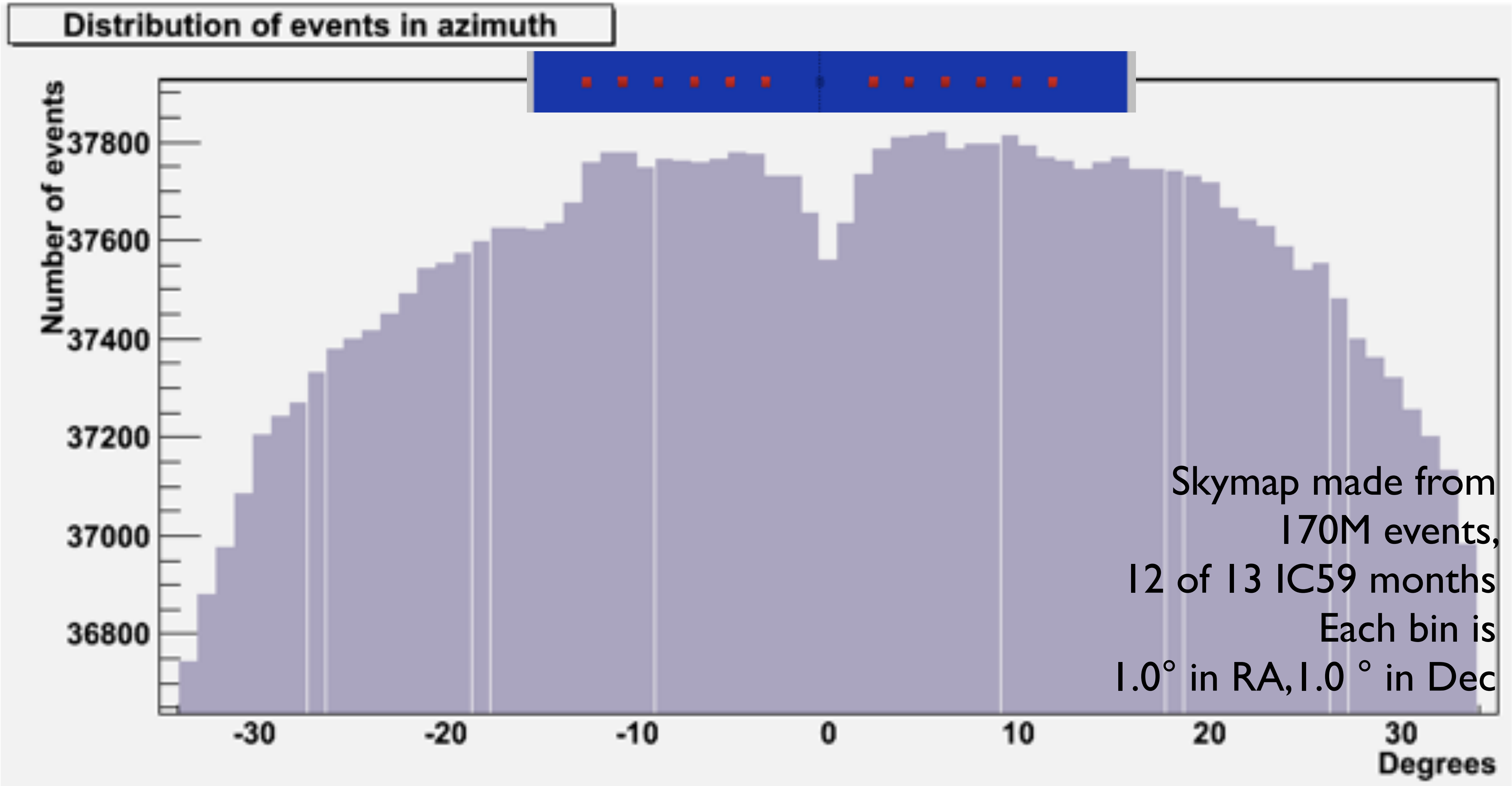
- Healpix: program for skymaps-- uses equal-area bins
  - Box-shape is from filter window
  - Gradient from zenith dependence of CR flux
- Draw Moon centered at its average position



Work in Progress:

- Significance for IC59 skymap:
  - try dummy-moon approach
  - Assumes that RA distribution is flat:





Most-of-IC59 skymap

Skymap made from
170M events,
12 of 13 IC59 months

3° 2° 2°

17°

7.7°

Each bin:
0.01° in RA
0.01° in Dec