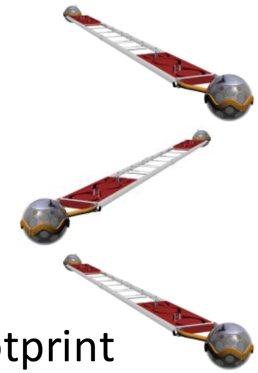
Evaluation of the discovery potential of an underwater Mediterranean neutrino telescope taking into account the estimated directional resolution and energy of the reconstructed track

Apostolos Tsirigotis, Antonis Leisos, Spyros Tzamarias
Physics Laboratory H.O.U

We report on the development of search methods for point-like and extended neutrino sources taking into account the resolution of the neutrino telescope to reconstruct the direction and the energy of the detected muon tracks, on a track by track basis. We present results on the potential of the reference KM3NeT detector to discover neutrino sources as well as of another telescope architecture, based on string structures, containing the same number of OMs and following the same foot print as the reference detector.

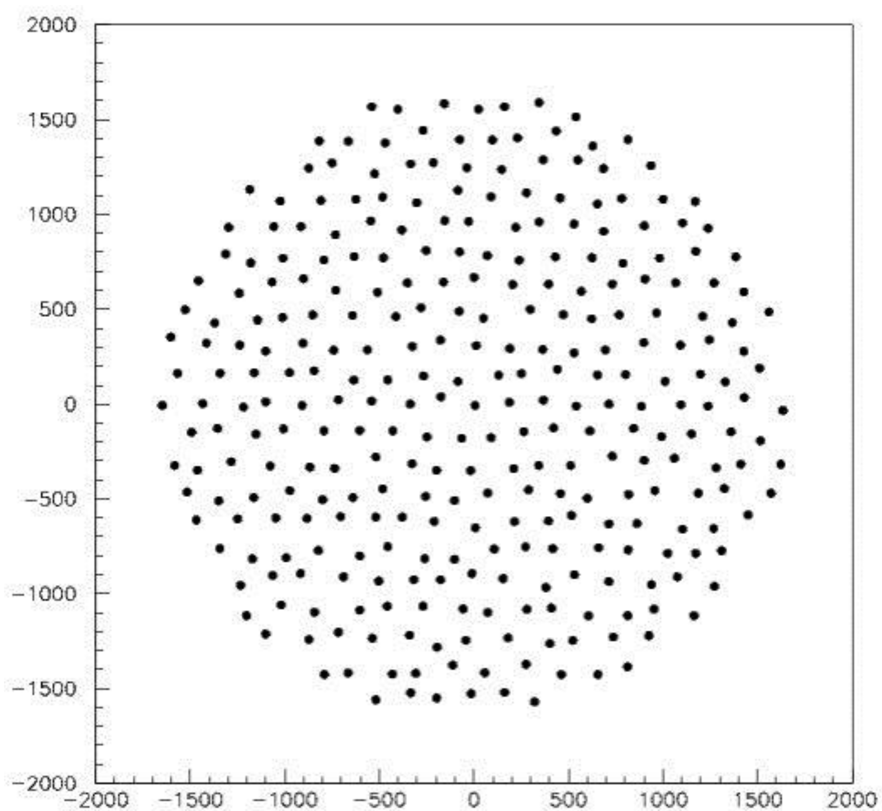
Detector Geometrical Layout

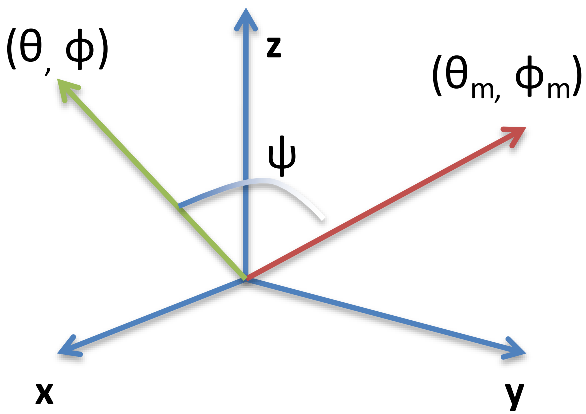
Towers: 154 Towers with 180m inter-tower distance
Each Tower consists of 20 bars, 6m in length and 40m apart
One MultiPMT OM at each end of the bar. 29% QE

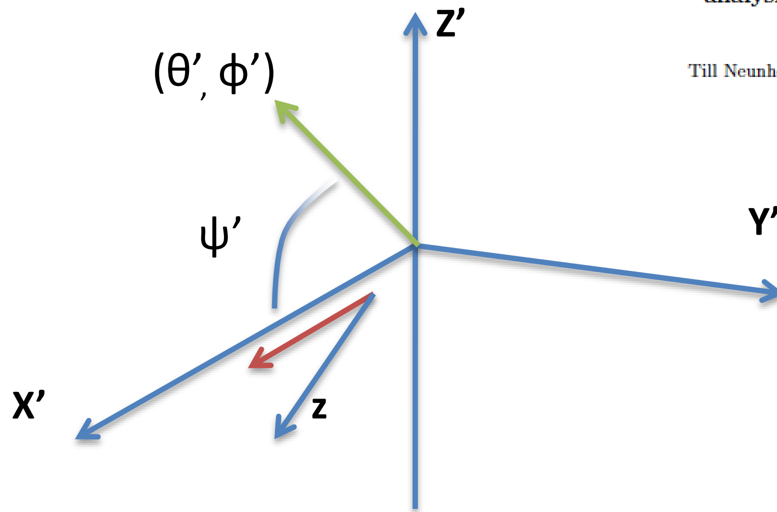


Detectors Footprint

Strings: 308 strings with 180m inter string distance.
Each string comprise 20 Multi PMTs, 40 m apart.







$$\theta^* = \theta' - \pi/2$$

$$\phi^* = \phi' - \pi$$

$$\cos\psi = \cos\psi' = \cos\psi^* \approx \sqrt{(\theta^*)^2 + (\phi^*)^2}$$

$$\begin{pmatrix} V_{\theta\theta} & V_{\theta\phi} \\ V_{\theta\phi} & V_{\phi\phi} \end{pmatrix} \Rightarrow \begin{pmatrix} V_{\theta^*\theta^*} & V_{\theta^*\phi^*} \\ V_{\theta^*\phi^*} & V_{\phi^*\phi^*} \end{pmatrix} = \begin{pmatrix} V_{\theta\theta} & (\sin\theta_m)^2 V_{\theta\phi} \\ (\sin\theta_m)^2 V_{\theta\phi} & \sin\theta_m V_{\phi\phi} \end{pmatrix}$$

$$\left.\begin{aligned} \theta_x &= \theta^* \cos\varepsilon + \phi^* \sin\varepsilon \\ \phi_x &= -\theta^* \sin\varepsilon + \phi^* \cos\varepsilon \\ \tan 2\varepsilon &= \frac{2V_{\theta^*\phi^*}}{V_{\theta^*\theta^*} - V_{\phi^*\phi^*}} \end{aligned}\right\}$$

$$U_{\theta_x\theta_x}, _{\phi_y\phi_y} = \frac{1}{2}\left[\left(V_{\theta^*\theta^*} + V_{\phi^*\phi^*}\right) \pm \sqrt{\left(V_{\theta^*\theta^*} V_{\phi^*\phi^*}\right)^2 + 4\left(V_{\theta^*\phi^*}\right)^2}\right]$$

$$\sigma_x^2 = U_{\theta_x\theta_x}$$

$$\sigma_y^2 = U_{\phi_y\phi_y}$$

$$P^{angle}, P^{energy}$$

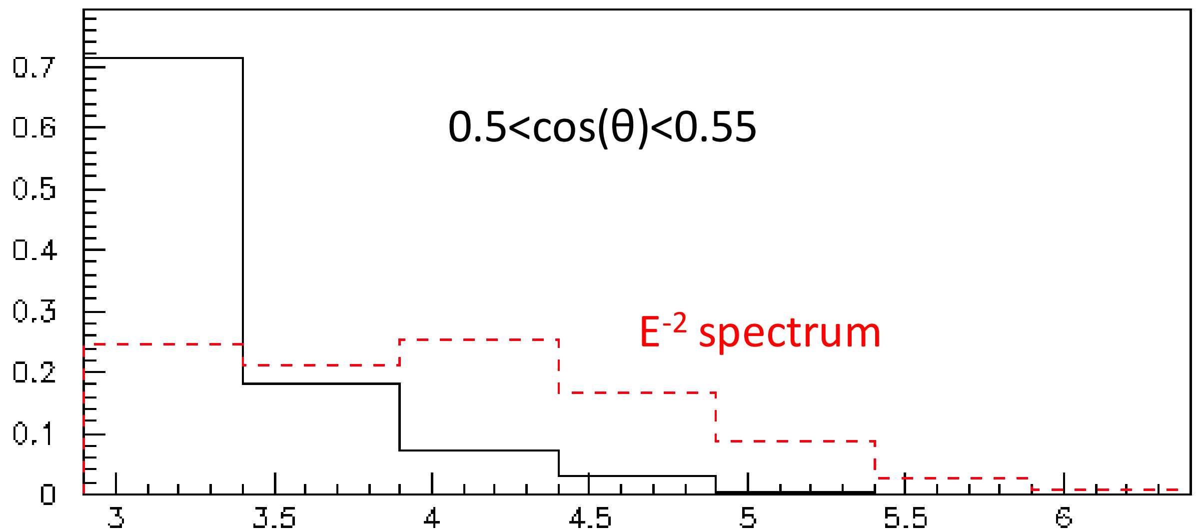
PDF of a reconstructed track to differ by θx and φx from the direction of a point source

$$P^{angle}_{signal}(\theta_x, \phi_y) = \frac{1}{1 - e^{-\frac{R^2{}_{\max}}{s_x^2 + s_y^2}}} \frac{1}{2\pi s_x s_y} e^{-\frac{1}{2}\left(\frac{\theta_x^2}{s_x^2} + \frac{\phi_y^2}{s_y^2}\right)}$$

$$P^{angle}_{bck}(\theta_x, \phi_y) = \frac{1}{\Delta\Omega}$$

Where s_x s_y incorporate the uncertainty of the angle between the ν-μ

Reconstructed Energy Distributions for **Signal (E^{-2} spectrum)** and **Atm. Neutrino Background**



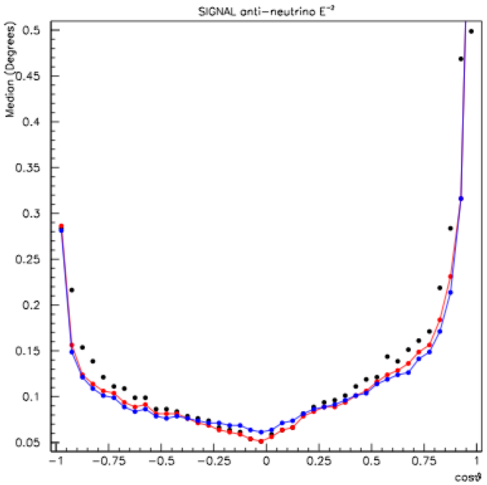
Reconstructed Energy (log of GeV)

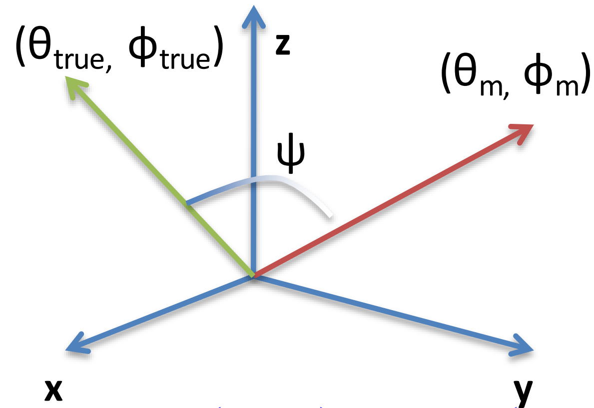
$$P^{energy}_{signal}(E_m, \theta_m; \gamma) = fromMC$$

$$P^{energy}_{bck}(E_m, \theta_m) = fromMC$$

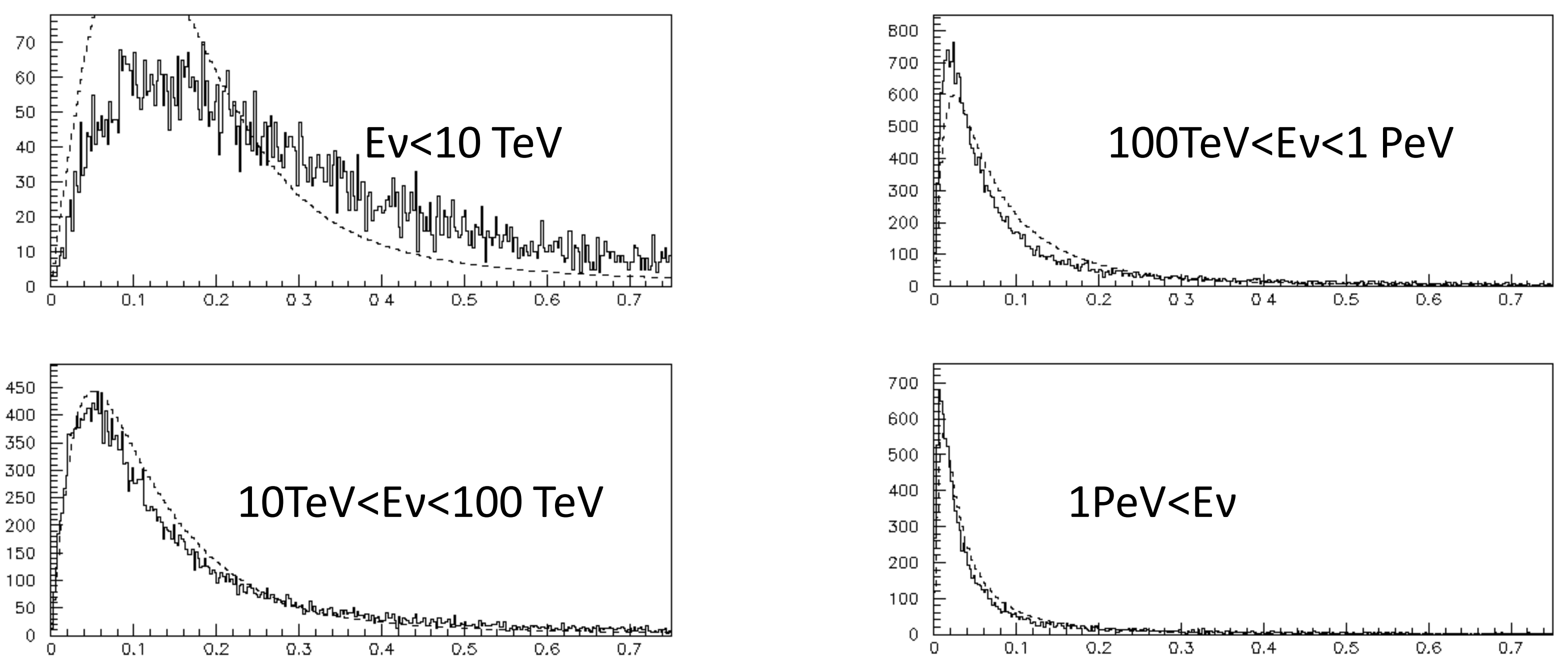
Can we estimate accurately the tracking errors?

Median of Ψ (degrees) vs the cosine of the zenith angle





$$P(\psi)=\frac{\psi}{2\pi s_x s_y}e^{-\frac{1}{2}\psi^2\left(\frac{1}{2s_x^2}+\frac{1}{2s_y^2}\right)}\int_0^{2\pi}e^{-\frac{1}{2}\psi^2\cos w\left(\frac{1}{2s_x^2}-\frac{1}{2s_y^2}\right)}dw$$



Angle (ψ) between reconstructed muon track and parent neutrino (Degrees)

$$P^{angle}_{signal}(\theta_x,\phi_y)=\frac{1}{1-e^{-\frac{R_{\max}}{s_x^2+s_y^2}}}\frac{1}{2\pi\sigma_x\sigma_y}e^{-\frac{1}{2}\left(\frac{\theta_x^2}{s_x^2}+\frac{\phi_y^2}{s_y^2}\right)}$$

$$P^{angle}_{bck}(\theta_x,\phi_y)=\frac{1}{\Delta\Omega}$$

$$P_{signal}\left(\theta_x,\phi_y,E_m,\theta_m;\gamma\right)=P^{angle}_{signal}(\theta_x,\phi_y)\cdot P^{energy}_{signal}(E_m,\theta_m;\gamma)$$

$$P_{bck}\left(\theta_x,\phi_y,E_m,\theta_m\right)=P^{angle}_{bck}(\theta_x,\phi_y)\cdot P^{angle}_{bck}(E_m,\theta_m)$$

$$P_i\left(\theta_x,\phi_y,E_m,\theta_m;\gamma,N_s\right)=\frac{N_s}{N_{total}}\cdot P_{signal}\left(\theta_x,\phi_y,E_m,\theta_m;\gamma\right)+\left(1-\frac{N_s}{N_{total}}\right)P_{bck}\left(\theta_x,\phi_y,E_m,\theta_m\right)$$

$$L(\gamma,N_s)=\frac{(m_B)^{(N_{total}-N_s)}e^{-m_B}}{(N_{total}-N_s)!}\cdot\prod_{i=1}^{N_{total}}P_i\left(\theta_x,\phi_y,E_m,\theta_m;\gamma,N_s\right)$$

$$L(\gamma=2,N_s)=\frac{(\mu_B)^{(N_{total}-N_s)}e^{-\mu_B}}{(N_{total}-N_s)!}\prod_{i=1}^{N_{total}}P_i\left(\theta_x,\phi_y,E_m,\theta_m;\gamma=2,N_s\right)$$

$$L_0(N_s=0)=\frac{(\mu_B)^{(N_{total})}e^{-\mu_B}}{(N_{total})!}\prod_{i=1}^{N_{total}}P_i\left(\theta_x,\phi_y,E_m,\theta_m;N_s=0\right)$$

use extended likelihood

$$\lambda=-2\cdot\ln\frac{L_0(N_s=0)}{L(\gamma=2,\hat{N}_s)}$$

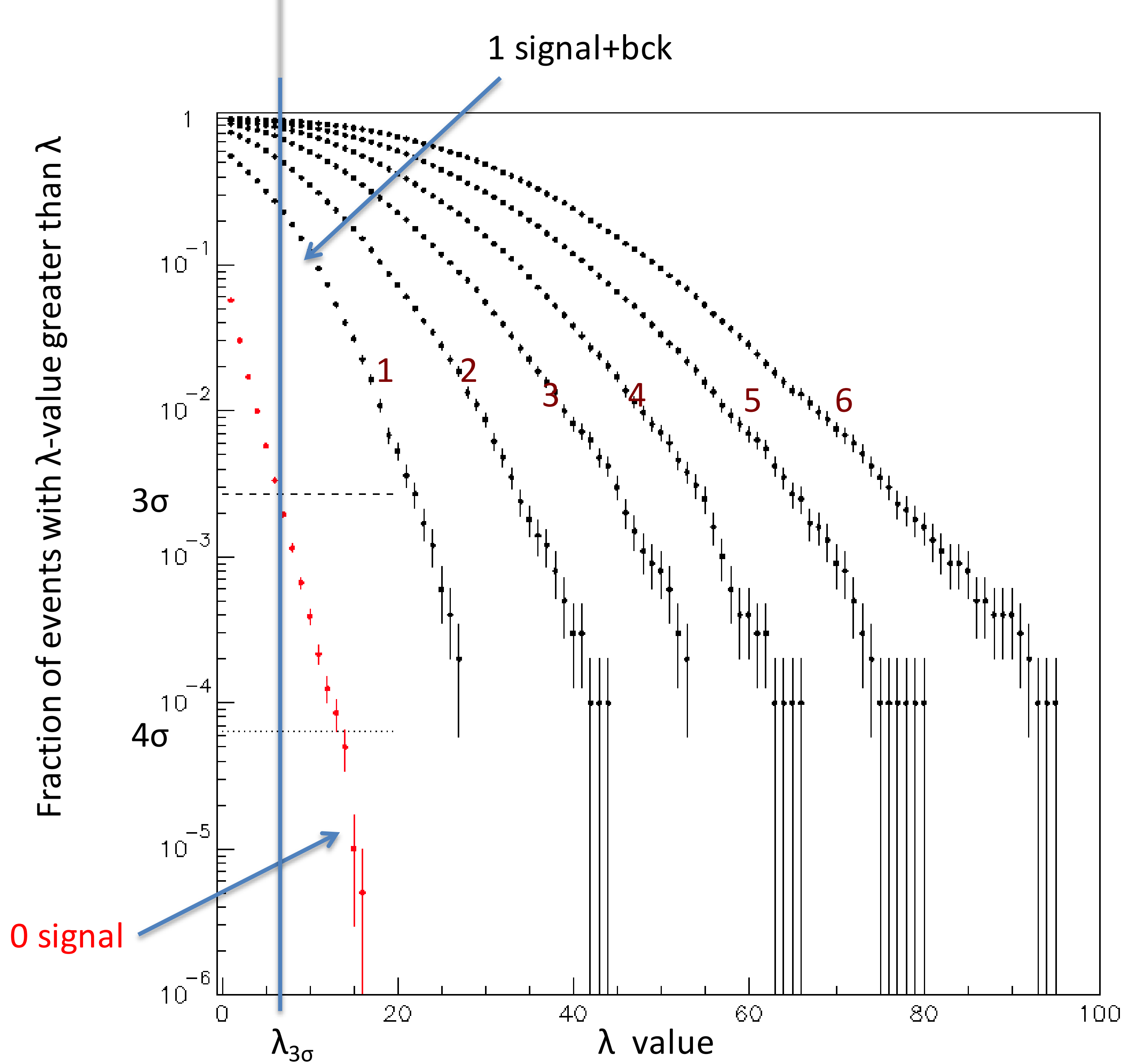
Declination -60°, Background: atmospheric neutrina, R=10xMedian but R<0.6°

Expected Background: 1.52 reconstructed muons/year
(Signal: 1.54 reconstructed muons/year/ reference flux (RF=$10^{-9}E^{-2}GeV^{-1}s^{-1}cm^{-2}$)

Prepare:
1,000,000 sets with back events, each set with n events distributed: a) isotropicaly within the search ring with radius R, b) in θ according to the time the source spends in θ and following Poissonian statistics with total mean 1.52
10,000 sets with 1 signal event distributed in θ according to the time the source spend in θ and n back events as above
10,000 sets with 2 signal events…….
…………….
10,000 sets with 24 signal events

Fit (maximize the likelihood) each set and evaluate for each set the quantity:

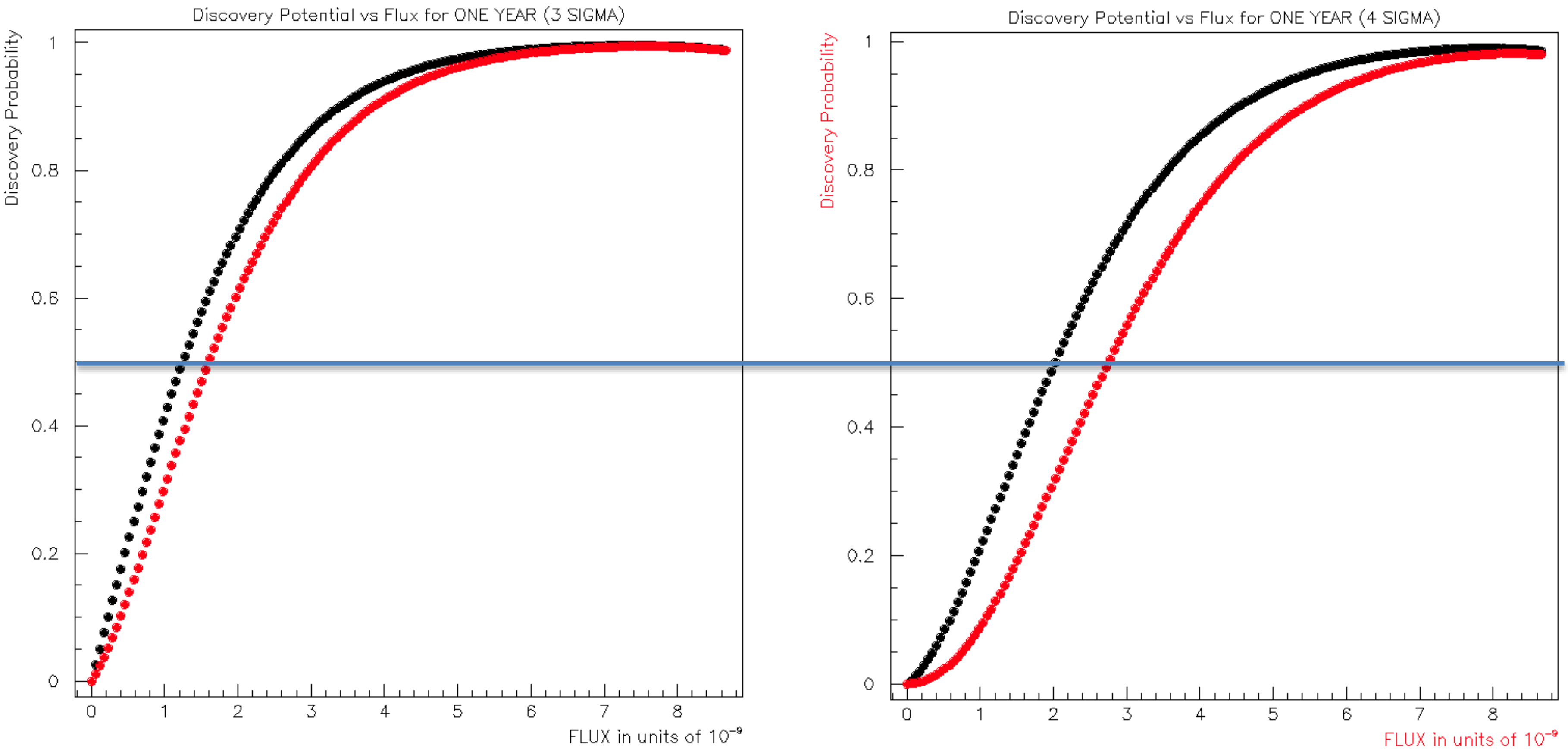
$$\lambda = -2 \cdot \ln \frac{L_0(N_s = 0)}{L(\gamma = 2, \hat{N}_s)}$$



1 signal+bck
Fraction of events with λ-value greater than λ
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
3σ
4σ
0 signal
1
2
3
4
5
6
0
20
40
60
80
100
λ3σ
λ value

Declination -60°, Background: atmospheric neutrina, R=10xMedian but R<0.6°

Point Source Discovery Potential (50% Discovery Probability)



3σ : 1.2×10^{-9} E^{-2} flux for 50% discovery

4σ : 1.8×10^{-9} E^{-2} flux for 50% discovery

5σ : 2.8×10^{-9} E^{-2} flux for 50% discovery

3σ

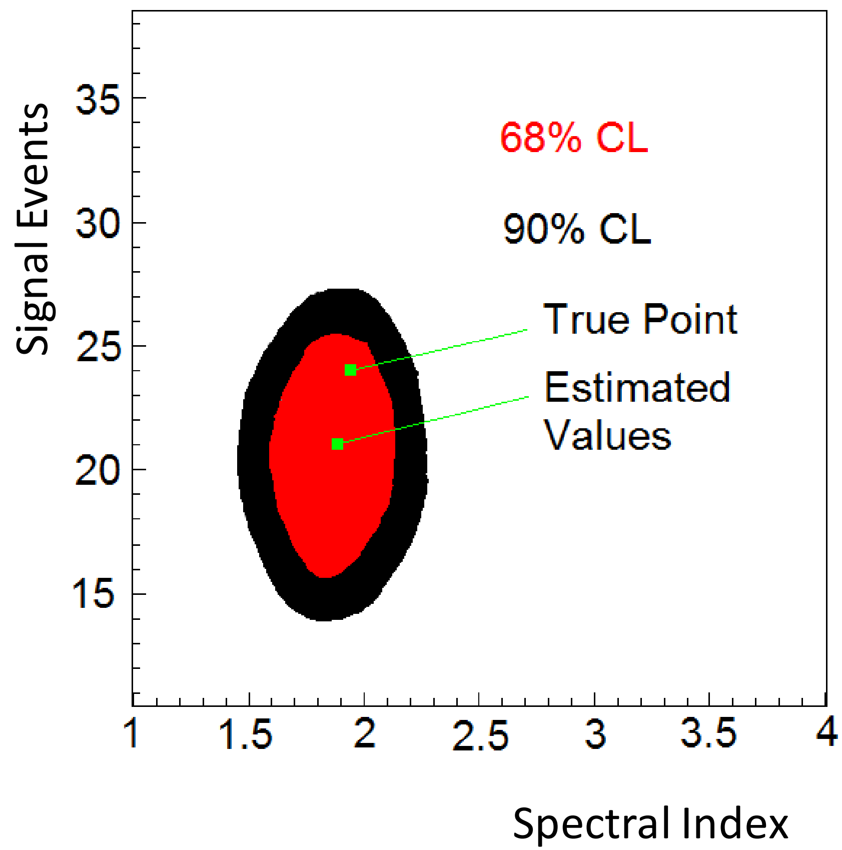
This Method without Energy: 1.6×10^{-9}

Binned method: $>2.4\times10^{-9}$

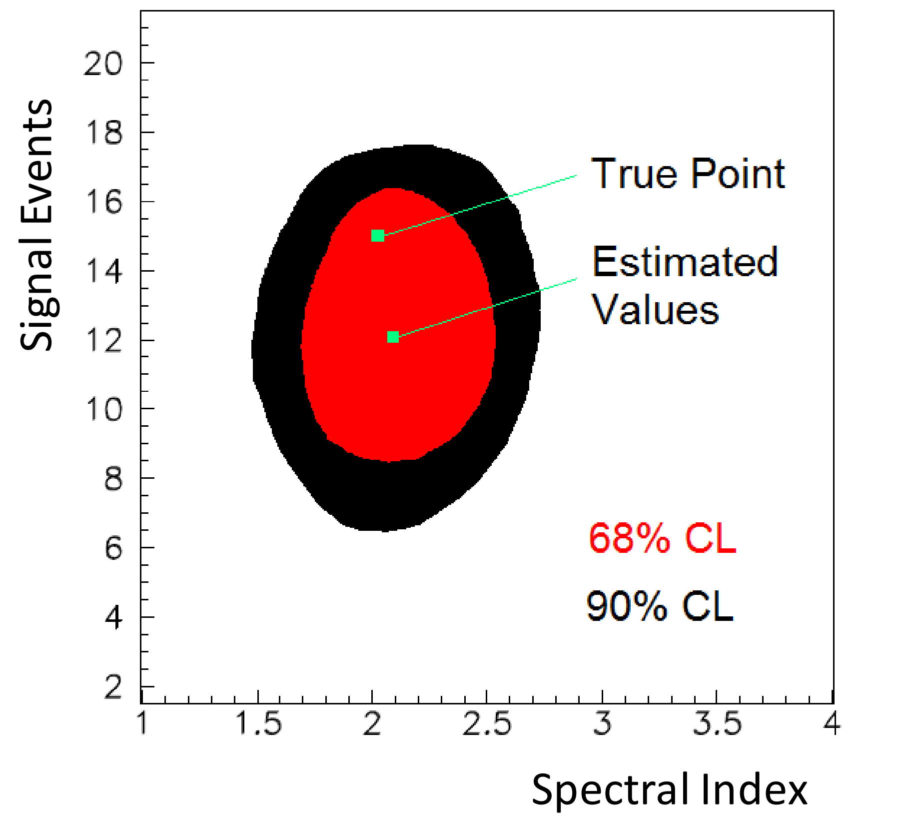
We can maximize the Likelihood simultaneously for Ns and γ

e.g. assuming E^{-2} energy spectrum

24 Signal Events on Top of 14 Background

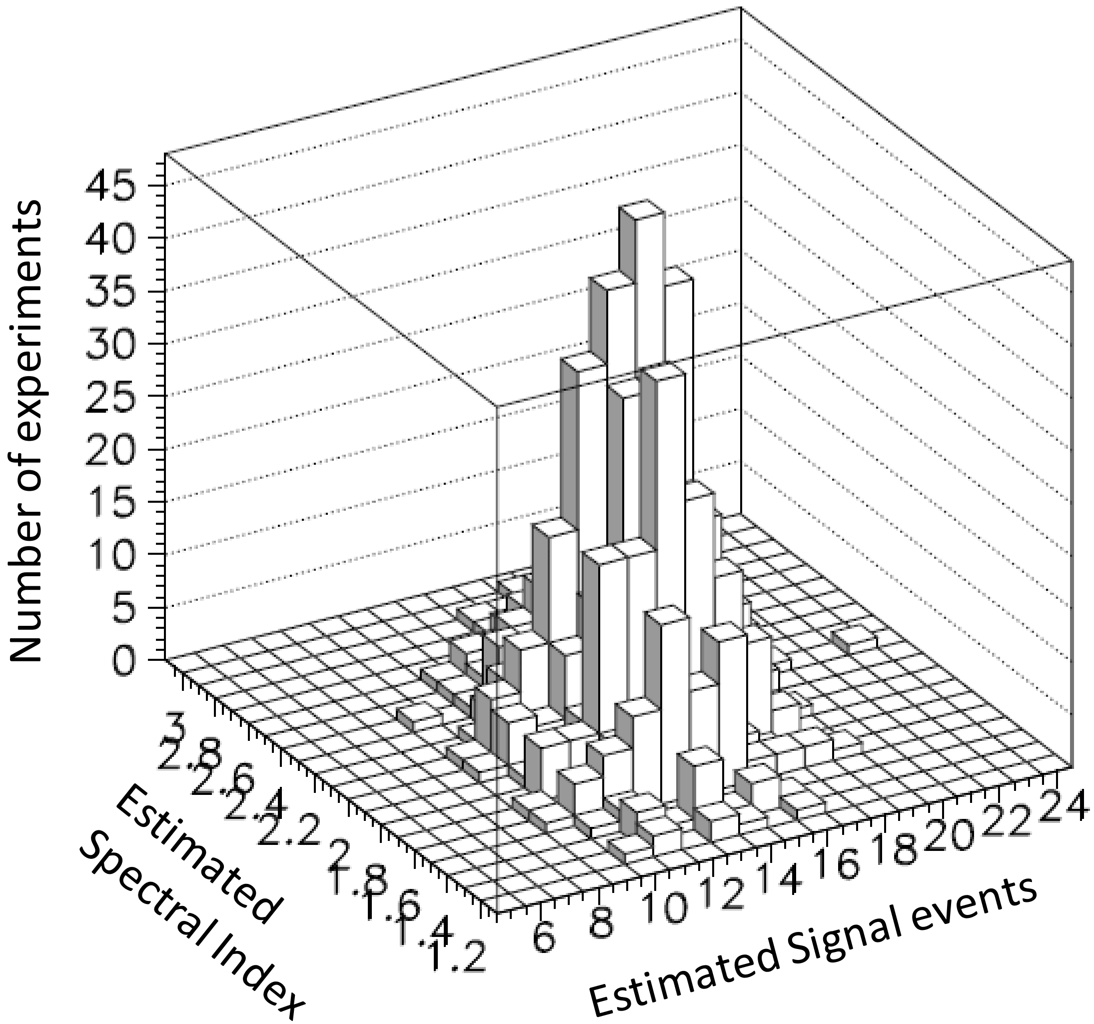


15 Signal Events on Top of 14 Background

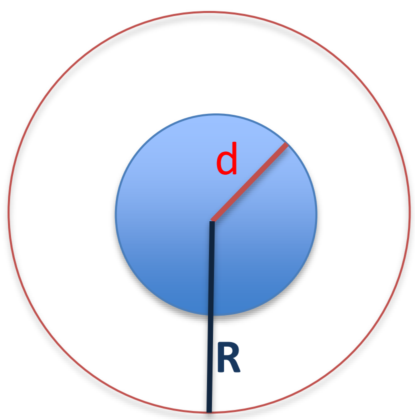


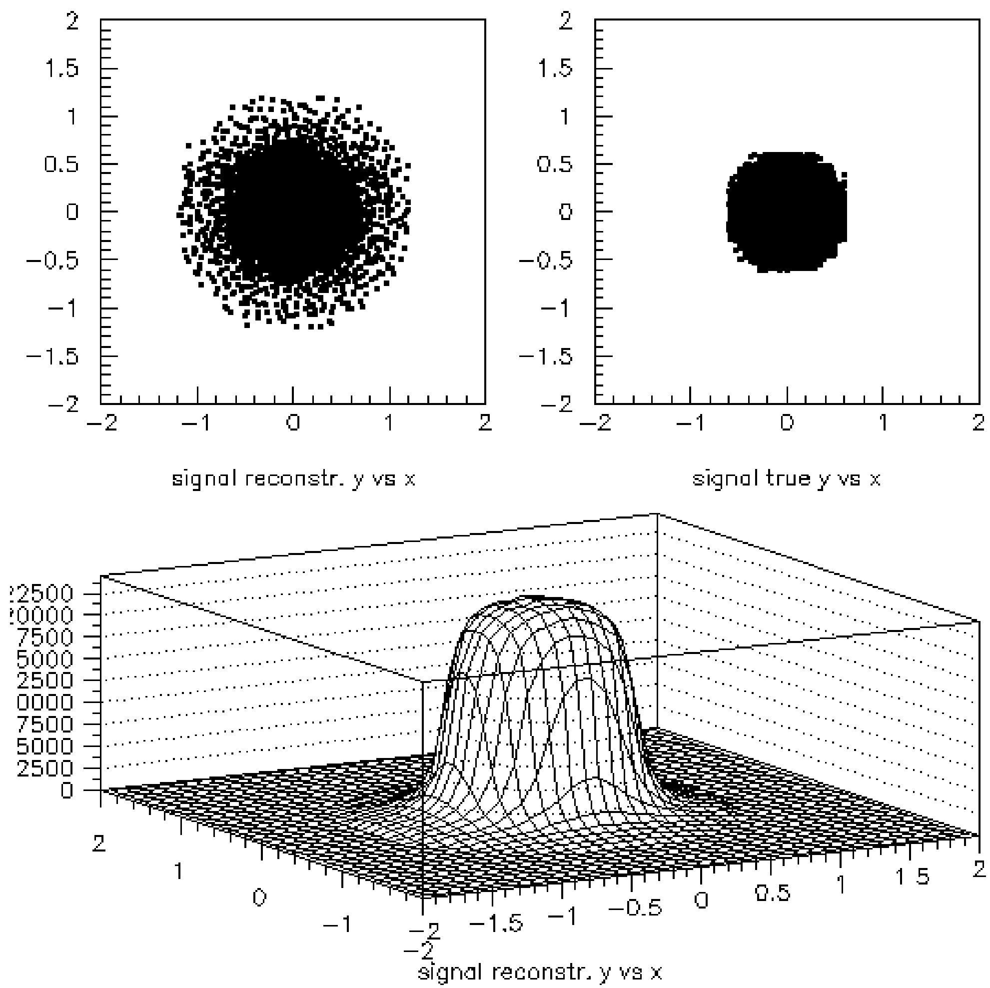
$$L(\gamma, N_s) = \frac{(m_B)^{(N_{total} - N_s)} e^{-m_B}}{(N_{total} - N_s)!} \cdot \prod_{i=1}^{N_{total}} P_i(\theta_x, \phi_y, E_m, \theta_m; \gamma, N_s)$$

True Values: 15 Signal Events on top of 14 Background with γ=2

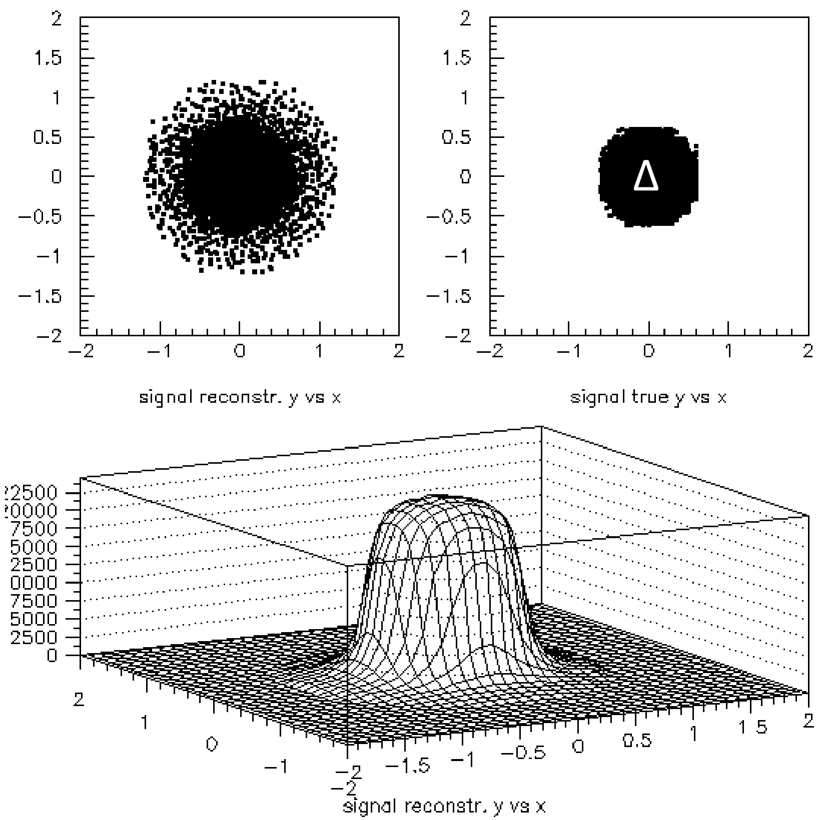


Extended Source: radius d=0.6^o

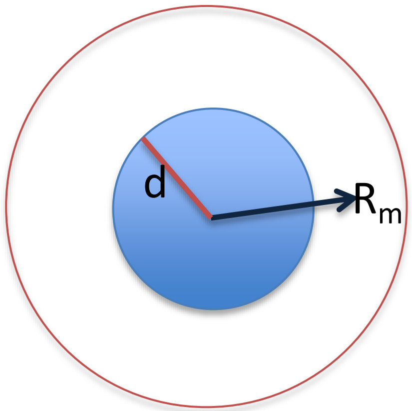


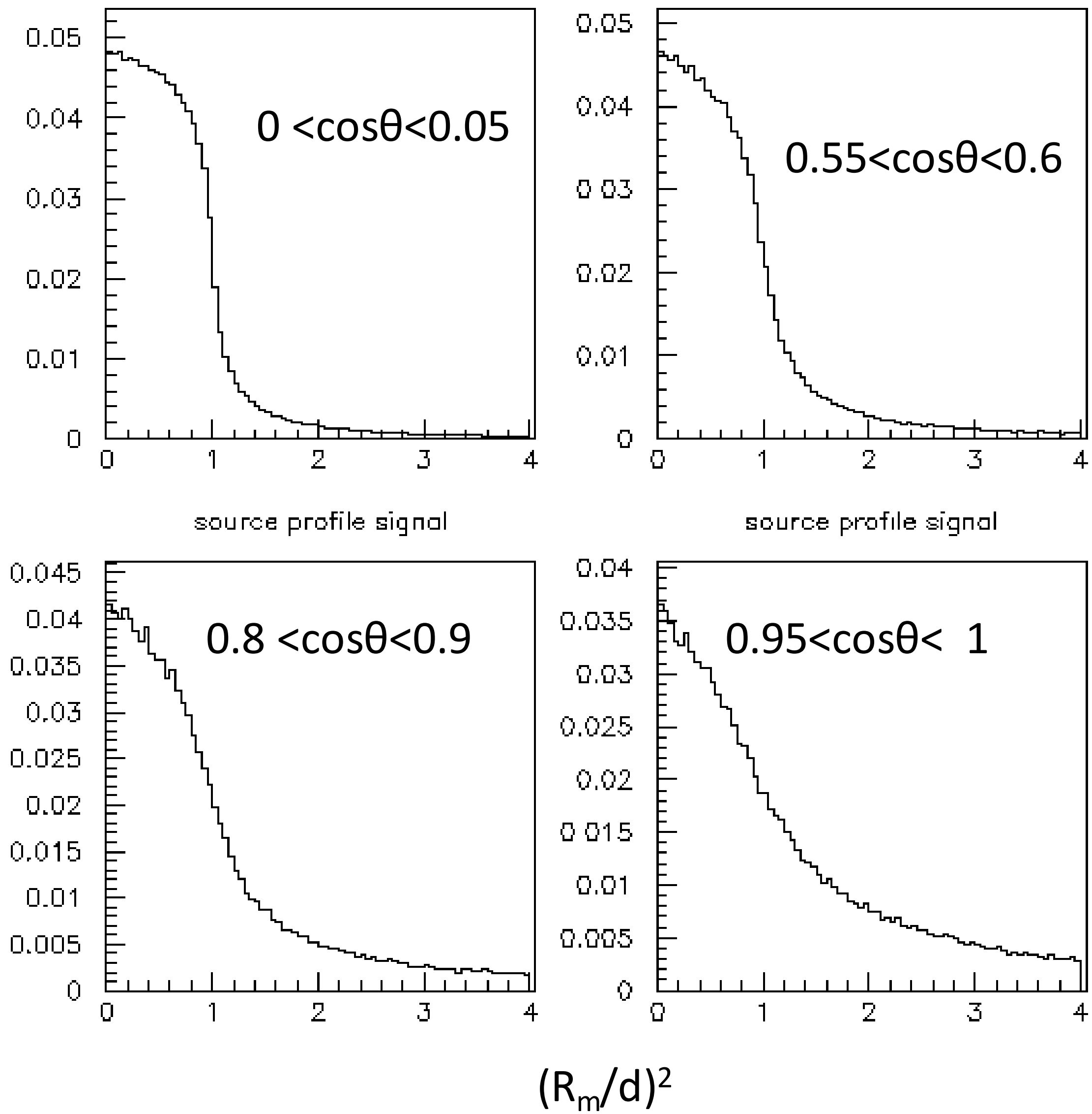


$$P^{angle}_{signal}(\theta_x,\phi_y)=\frac{1}{1-e^{-\frac{R^2}{s_x^2+s_y^2}}}\,\frac{1}{2\pi\sigma_x\sigma_y}\iint\limits_{\Delta} e^{-\frac{1}{2}\left(\frac{(\theta_x-\theta_t)^2}{s_x^2}+\frac{(\phi_y-\varphi_t)^2}{s_y^2}\right)}\,\frac{1}{\pi d^2}\,d\theta_t\,d\phi_t$$



$$P_{signal}^{angle}(\theta_x, \phi_y) \rightarrow P_{signal}^{angle}\left(\left(\frac{R_m}{d}\right)^2, \cos\theta_t\right)$$





E^{-2} Spectrum

Extended Source: d=0.6°
Declination -60°, Background: atmospheric neutrina, R=d+10xMedian but R<0.6°+d

Expected Background: 6.1 reconstructed muons/year
(Signal: 1.67 reconstructed muons/year/$10^{-9}E^{-2}$ flux)

3σ : 1.85x 10^{-9} E^{-2} flux for 50% discovery

4σ : 3.05x 10^{-9} E^{-2} flux for 50% discovery

5σ : 4.65x 10^{-9} E^{-2} flux for 50% discovery

Point Source: d=0.
Declination -60°, Background: atmospheric neutrina, R=10xMedian but R<0.6°

Expected Background: 1.52 reconstructed muons/year
(Signal: 1.54 reconstructed muons/year/$10^{-9}E^{-2}$ flux)

3σ : 1.2x 10^{-9} E^{-2} flux for 50% discovery

4σ : 1.8x 10^{-9} E^{-2} flux for 50% discovery

5σ : 2.8x 10^{-9} E^{-2} flux for 50% discovery

Spectrum with an Energy cutoff ~ 10TeV

$$\Phi(E) = 1.68\ 10^{-14}(E/1[\text{TeV}])^{-1.72} e^{-\left(\sqrt{\frac{E}{2.1[\text{TeV}]}}\right)}\ [\text{GeV}^{-1}\ \text{cm}^{-2}\text{s}^{-1}]$$

Extended Source: RXJ1713.7-3946 d=0.6°
Background: atmospheric neutrina, R=d+10xMedian but R<0.6°+d

Expected Background: 4.73 reconstructed muons/year
(Signal: 1.84 reconstructed muons/year/Reference flux)

3σ : 2.91 x Reference flux for 50% discovery

4σ : 4.05x Reference flux for 50% discovery

5σ : 5.6x Reference flux for 50% discovery

Extended Source: RXJ1713.7-3946 d=0.6°
Background: atmospheric neutrina, R=d+10xMedian but R<0.25°+d

Expected Background: 2.37 reconstructed muons/year
(Signal: 1.61 reconstructed muons/year/Rederence flux)

3σ : 3.0 x Reference flux for 50% discovery

4σ : 4.1x Reference flux for 50% discovery

5σ : 5.6x Reference flux for 50% discovery

Without Energy and Shape

3σ : 3.7 x Reference flux for 50% discovery

4σ : 4.6x Reference flux for 50% discovery

5σ : 7.2x Reference flux for 50% discovery

Towers vs STRINGS (same number of Oms)

Spectrum with an Energy cutoff ~ 10TeV

Extended Source: RXJ1713.7-3946 $d=0.6^o$

Background: atmospheric neutrina, R=d+10xMedian but $R<0.6^o+d$

STRINGS: Expected Background: 1.17 reconstructed muons/year
(Signal: 0.87 reconstructed muons/year/Reference flux)

3σ : 3.9 x Reference flux for 50% discovery

4σ : 5.2x Reference flux for 50% discovery

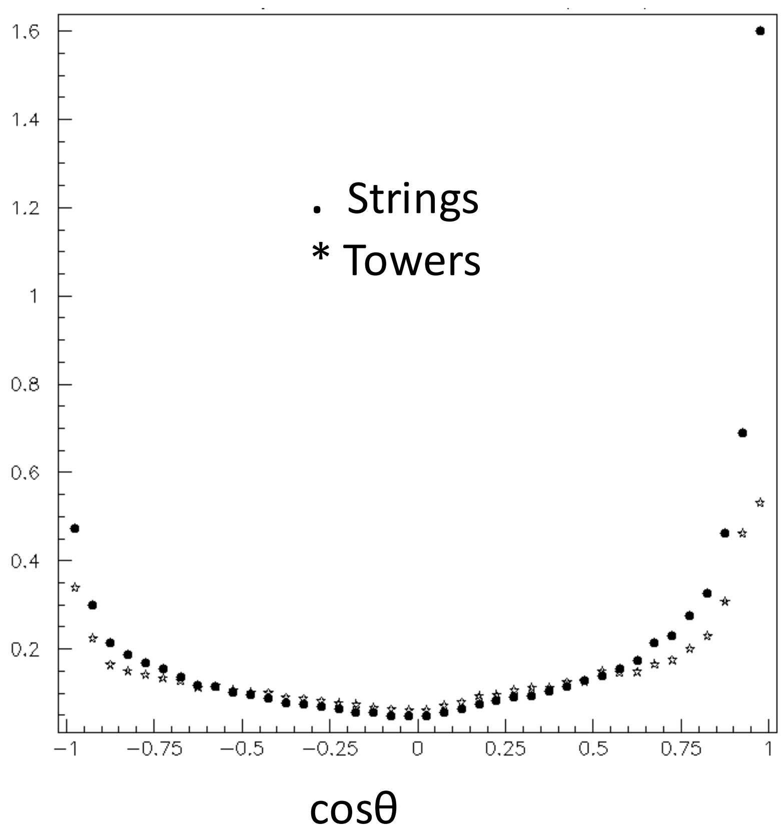
5σ : 8x Reference flux for 50% discovery

Towers: Expected Background: 4.73 reconstructed muons/year
(Signal: 1.84 reconstructed muons/year/Reference flux)

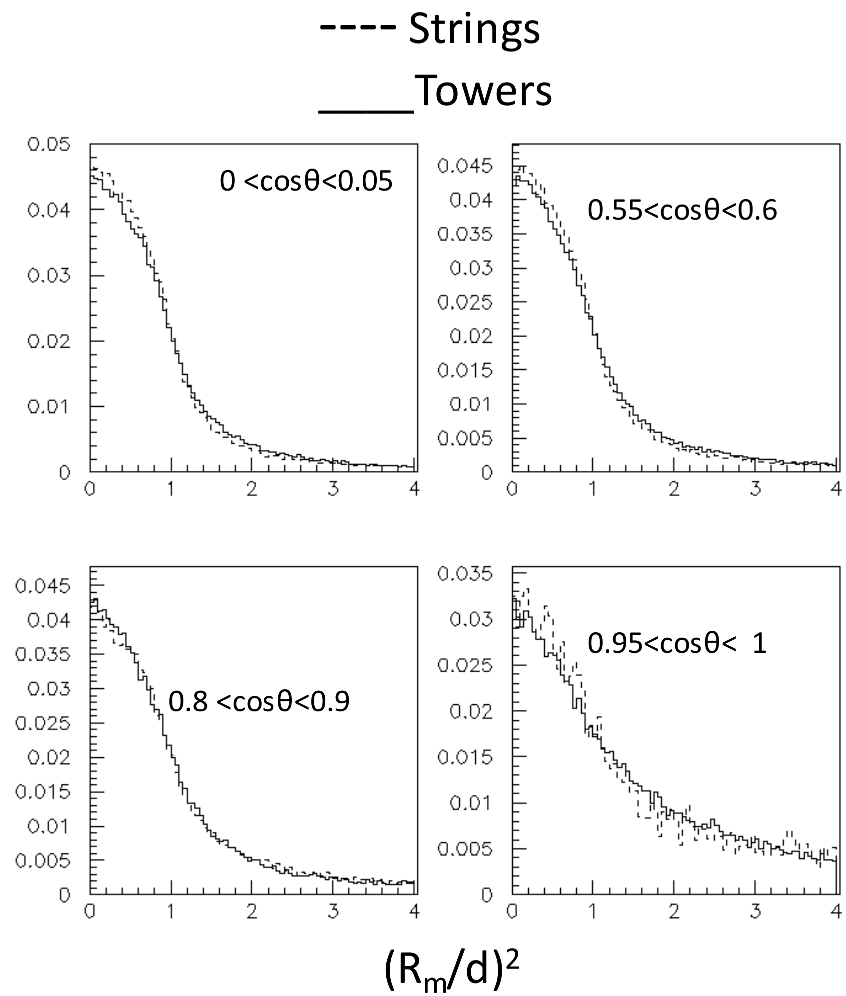
3σ : 2.91 x Reference flux for 50% discovery

4σ : 4.05x Reference flux for 50% discovery

5σ : 5.6x Reference flux for 50% discovery



. Strings
* Towers
cosθ



---- Strings
____Towers
0 <cosθ<0.05
0.55<cosθ<0.6
0.8 <cosθ<0.9
0.95<cosθ< 1
(Rm/d)2

E^{-2} Spectrum

STRINGS Point Source: d=0.

Declination -60°, Background: atmospheric neutrina, R=10xMedian but R<0.6°

Expected Background: 0.46 reconstructed muons/year

(Signal: 1.63reconstructed muons/year/$10^{-9}E^{-2}$ flux)

3σ : 0.75x 10^{-9} E^{-2} flux for 50% discovery

4σ : 1.3x 10^{-9} E^{-2} flux for 50% discovery

5σ : 1.9x 10^{-9} E^{-2} flux for 50% discovery

TOWERS Point Source: d=0.

Declination -60°, Background: atmospheric neutrina, R=10xMedian but R<0.6°

Expected Background: 1.52 reconstructed muons/year

(Signal: 1.54 reconstructed muons/year/$10^{-9}E^{-2}$ flux)

3σ : 1.2x 10^{-9} E^{-2} flux for 50% discovery

4σ : 1.8x 10^{-9} E^{-2} flux for 50% discovery

5σ : 2.8x 10^{-9} E^{-2} flux for 50% discovery

E^{-2} Spectrum

STRINGS: Extended Source: d=0.6°

Declination -60°, Background: atmospheric neutrina, R=d+10xMedian but R<0.6°+d

Expected Background: 1.85 reconstructed muons/year

(Signal: 1.76 reconstructed muons/year/$10^{-9}E^{-2}$ flux)

3σ : 1.5x 10^{-9} E^{-2} flux for 50% discovery

4σ : 2.11x 10^{-9} E^{-2} flux for 50% discovery

5σ : 3.18x 10^{-9} E^{-2} flux for 50% discovery

TOWERS: Extended Source: d=0.6°

Declination -60°, Background: atmospheric neutrina, R=d+10xMedian but R<0.6°+d

Expected Background: 6.1 reconstructed muons/year

(Signal: 1.67 reconstructed muons/year/$10^{-9}E^{-2}$ flux)

3σ : 1.85x 10^{-9} E^{-2} flux for 50% discovery

4σ : 3.05x 10^{-9} E^{-2} flux for 50% discovery

5σ : 4.65x 10^{-9} E^{-2} flux for 50% discovery

Summary

Taking into account the tracking reconstruction error and the ν estimated energy the discovery potential is improved up to a factor of 2:

Point sources- E^{-2} energy spectrum: 1) a factor of 2 improvement, 2) 50% of the improvement is due to the energy spectrum

Extended Sources: The track error is taken into account on statistical basis, up to 30% improvement

Towers vs Strings

A denser detector has a higher tracking efficiency at low energies resulting to a better discovery potential. Each KM3 configuration should be optimized independently.