Sensitivity to New Physics using Atmospheric Neutrinos and AMANDA-II

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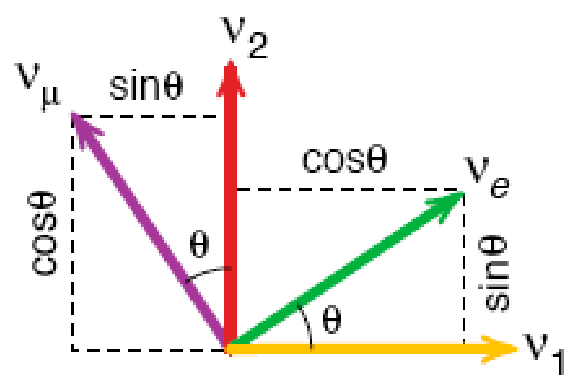
Oscillations: Particle Physics with Atmospheric Neutrinos

- Evidence (SuperK, SNO, KamLAND, MINOS, etc.) that neutrinos oscillate flavors (hep-ex/9807003)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Mass-induced oscillations now the accepted explanation



- Small differences in energy cause large observable effects!

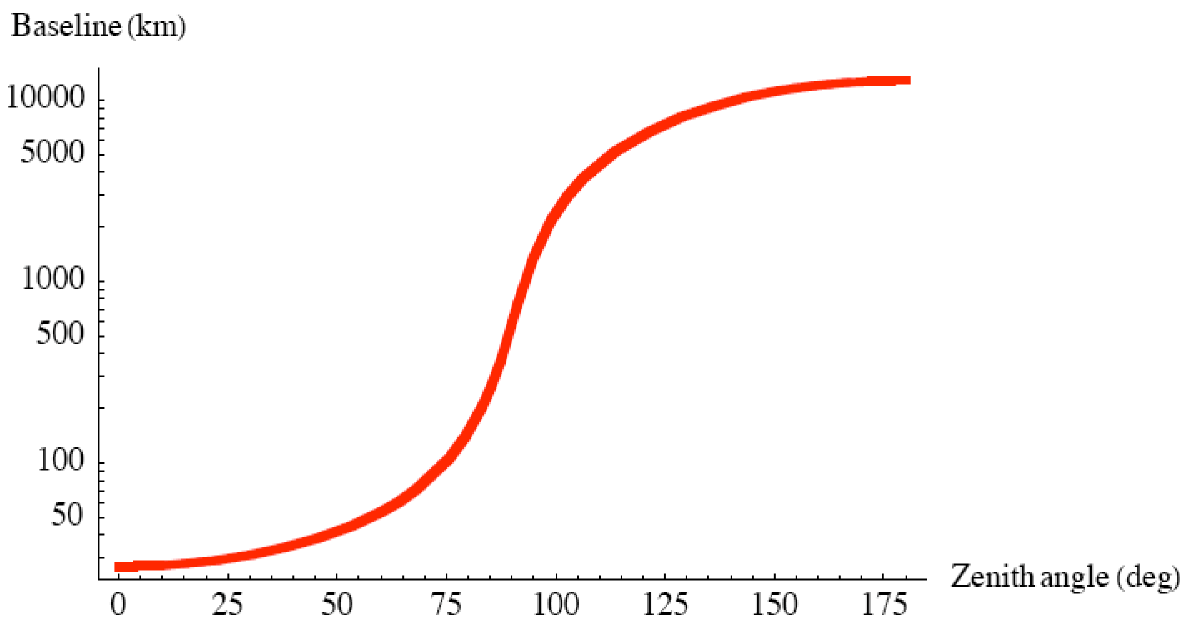
Figures from Los Alamos Science **25** (1997)

Atmospheric Oscillations

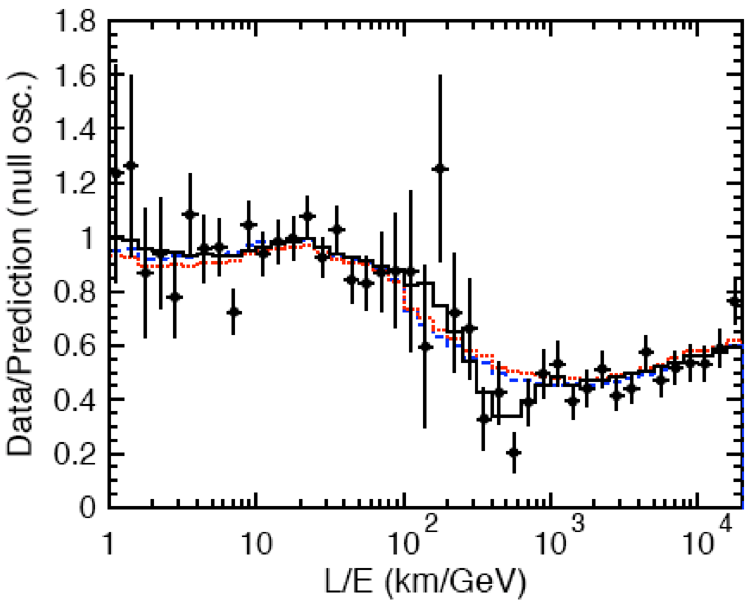
- Direction of neutrino (zenith angle) corresponds to different propagation baselines L

Oscillation probability:

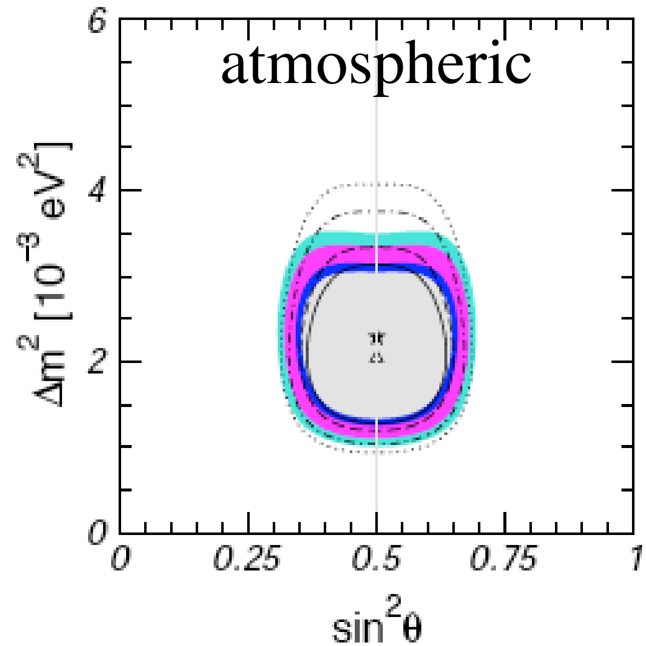
$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \sin^2 2\theta \, \sin^2[1.27 \, \Delta m^2 (L/E)]$$



Experimental Results



SuperK, hep-ex/0404034



$$\sin^2\theta_{\rm SOL} = 0.29\,, \quad \Delta m^2_{\rm SOL} = 7.2\times 10^{-5}\ {\rm eV}^2 \quad \text{(SOL BP04+KAM data)}$$

$$\sin^2\theta_{\rm ATM} = 0.5\,, \quad \Delta m^2_{\rm ATM} = 2.3\times 10^{-3}\ {\rm eV}^2 \quad \text{(ATM+K2K data)}$$

$$\sin^2\theta_{13} \le \begin{cases} 0.068\ (0.12) & \text{(solar+KamLAND)} \\ 0.031\ (0.081) & \text{(CHOOZ+atmospheric)} \\ 0.029\ (0.061) & \text{(global data)} \end{cases}$$

Global oscillation fits
(Maltoni *et al.*, hep-ph/0405172)

Neutrinos as a New Physics Probe

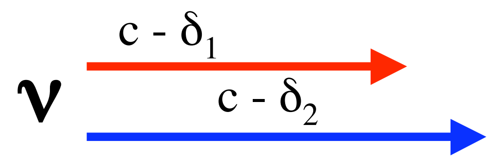
- Neutrinos are already post-Standard Model (massive)
- For $E > 100$ GeV and $m_\nu < 1$ eV*, Lorentz $\gamma > 10^{11}$
- Oscillations are a sensitive quantum-mechanical probe

Eidelman *et al*.: "It would be surprising if further surprises were not in store…"

* From cosmological data, $\Sigma m_i < 0.5$ eV, Goobar *et*. *al*, astro-ph/0602155

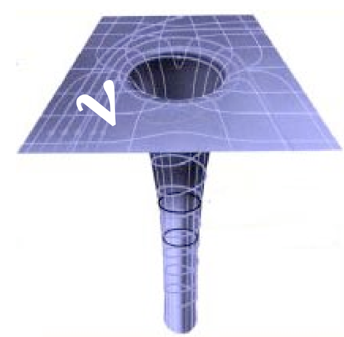
New Physics Effects

- Violation of Lorentz invariance (VLI) in string theory or loop quantum gravity*



- Violations of the equivalence principle (different gravitational coupling)†

- Interaction of particles with space-time foam ⇒ quantum decoherence of pure states‡



* see e.g. Carroll *et al.*, PRL **87** 14 (2001), Colladay and Kostelecký, PRD **58** 116002 (1998)
† see e.g. Gasperini, PRD **39** 3606 (1989)
‡ see e.g. Hawking, Commun. Math. Phys. **87** (1982), Ellis *et al.*, Nucl. Phys. B241 (1984)

VLI Phenomenology

- Modification of dispersion relation*: $E_a^2 = \vec{p}_a^{\,2} c_a^2 + m_a^2 c_a^4.$

- Different maximum attainable velocities c_a (MAVs) for different particles: $\Delta E \sim (\delta c/c)E$

- For neutrinos: MAV eigenstates not necessarily flavor or mass eigenstates

$$\mathrm{H}_{\pm} \equiv \frac{\Delta m^2}{4E} \mathbf{U}_\theta \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_\theta^\dagger + \frac{\Delta\delta_n\, E^n}{2} \mathbf{U}_{\xi_n,\pm\eta_n} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_{\xi_n,\pm\eta_n}^\dagger$$

* Glashow and Coleman, PRD **59** 116008 (1999)

VLI Oscillations

$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{\nu_\mu \to \nu_\tau} = 1 - \sin^2 2\Theta \, \sin^2 \left(\frac{\Delta m^2 L}{4E} \mathcal{R} \right)$$

$$\sin^2 2\Theta = \frac{1}{\mathcal{R}^2} \left(\sin^2 2\theta + R_n^2 \sin^2 2\xi_n + 2R_n \sin 2\theta \sin 2\xi_n \cos \eta_n \right) \; ,$$

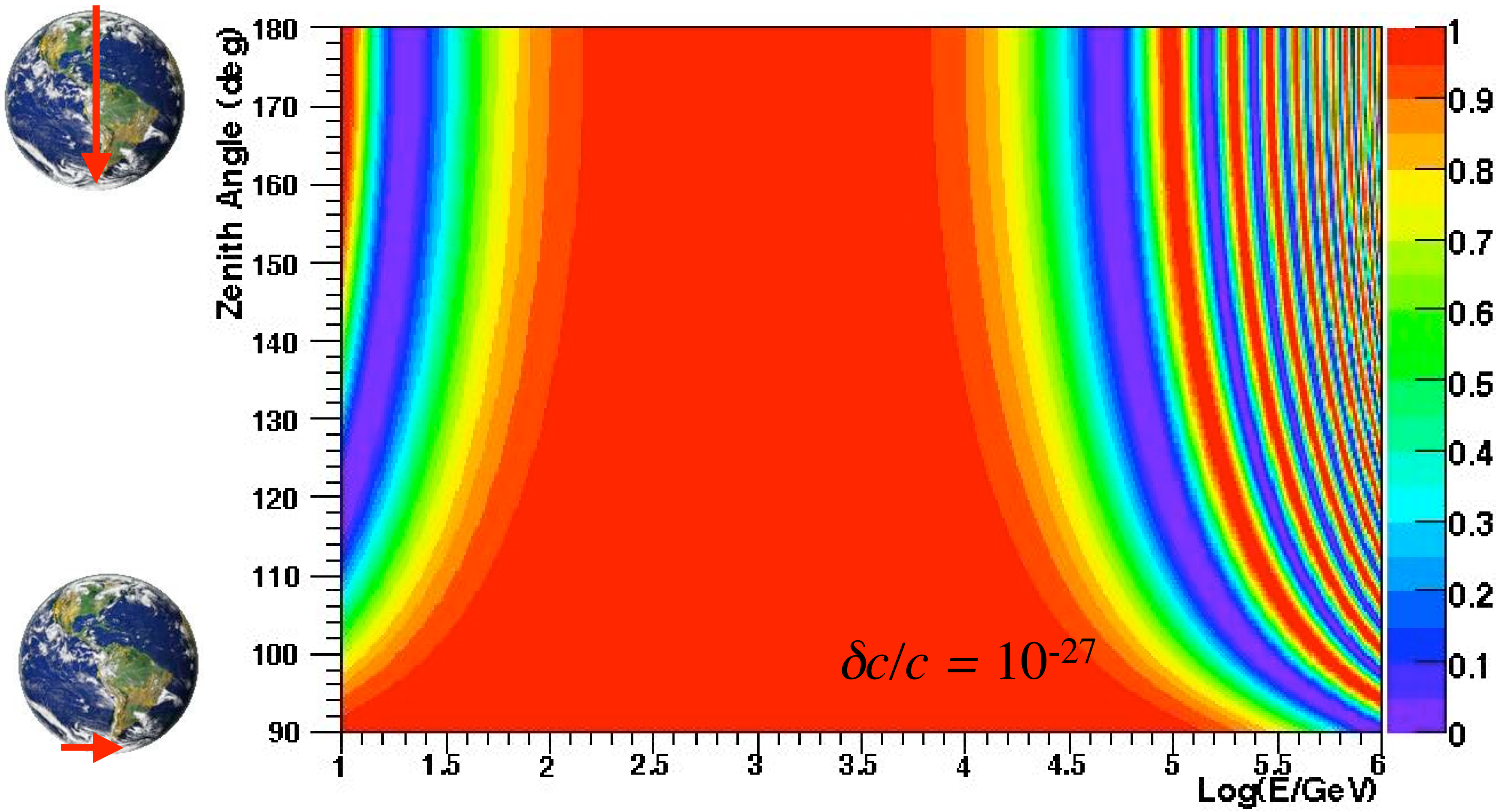
$$\mathcal{R} = \sqrt{1 + R_n^2 + 2R_n \left(\cos 2\theta \cos 2\xi_n + \sin 2\theta \sin 2\xi_n \cos \eta_n \right)} \; ,$$

$$R_n = \sigma_n^+ \frac{\Delta\delta_n E^n}{2} \frac{4E}{\Delta m^2} \, ,$$

Gonzalez-Garcia, Halzen, and Maltoni, hep-ph/0502223

- For atmospheric ν, conventional oscillations turn off above ~50 GeV (*L*/*E* dependence)
- VLI oscillations turn on at high energy (*L E* dependence), depending on size of δ*c*/*c*, and distort the zenith angle / energy spectrum

ν_μ Survival Probability



Quantum Decoherence Phenomenology

- Modify propagation through density matrix formalism:

dissipative term

$$\dot{\rho} = -i[H, \rho] + \not{\delta} H \rho.$$

- Solve DEs for neutrino system, get oscillation probability*:

$$P\left[\nu_\mu \to \nu_\tau\right] = \frac{1}{2}\left\{1 - \cos^2(2\theta) M_{33}(E,L) - \sin^2(2\theta) M_{11}(E,L) - \frac{1}{2}\sin 4\theta \left[M_{13}(E,L) + M_{31}(E,L)\right]\right\},$$

*for more details, please see Morgan *et al.*, astro-ph/0412628

QD Parameters

$$M(E,L) = \exp\left[-2\mathcal{H}(E)L\right], \qquad \mathcal{H}(E) = \begin{pmatrix} a & b - \frac{\Delta m^2}{4E} & d \\ b + \frac{\Delta m^2}{4E} & \alpha & \beta \\ d & \beta & \delta \end{pmatrix}.$$

- Various proposals for how parameters depend on energy:

$$\alpha = \frac{1}{2}\gamma_\alpha, \qquad \alpha = \frac{\mu_\alpha^2}{4E}. \qquad \alpha = \frac{1}{2}\kappa_\alpha E^2$$

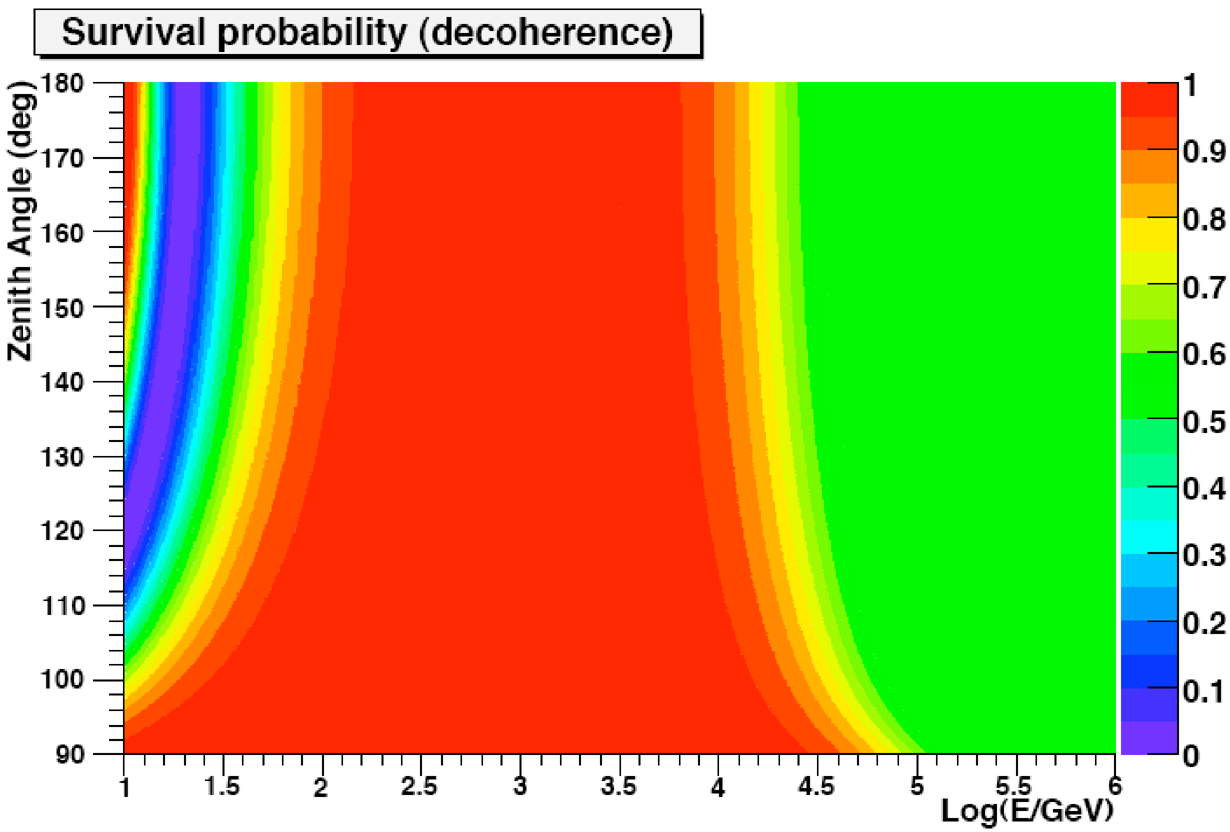
simplest

preserves Lorentz invariance

recoiling D-branes!

ν_μ Survival Probability (κ model)

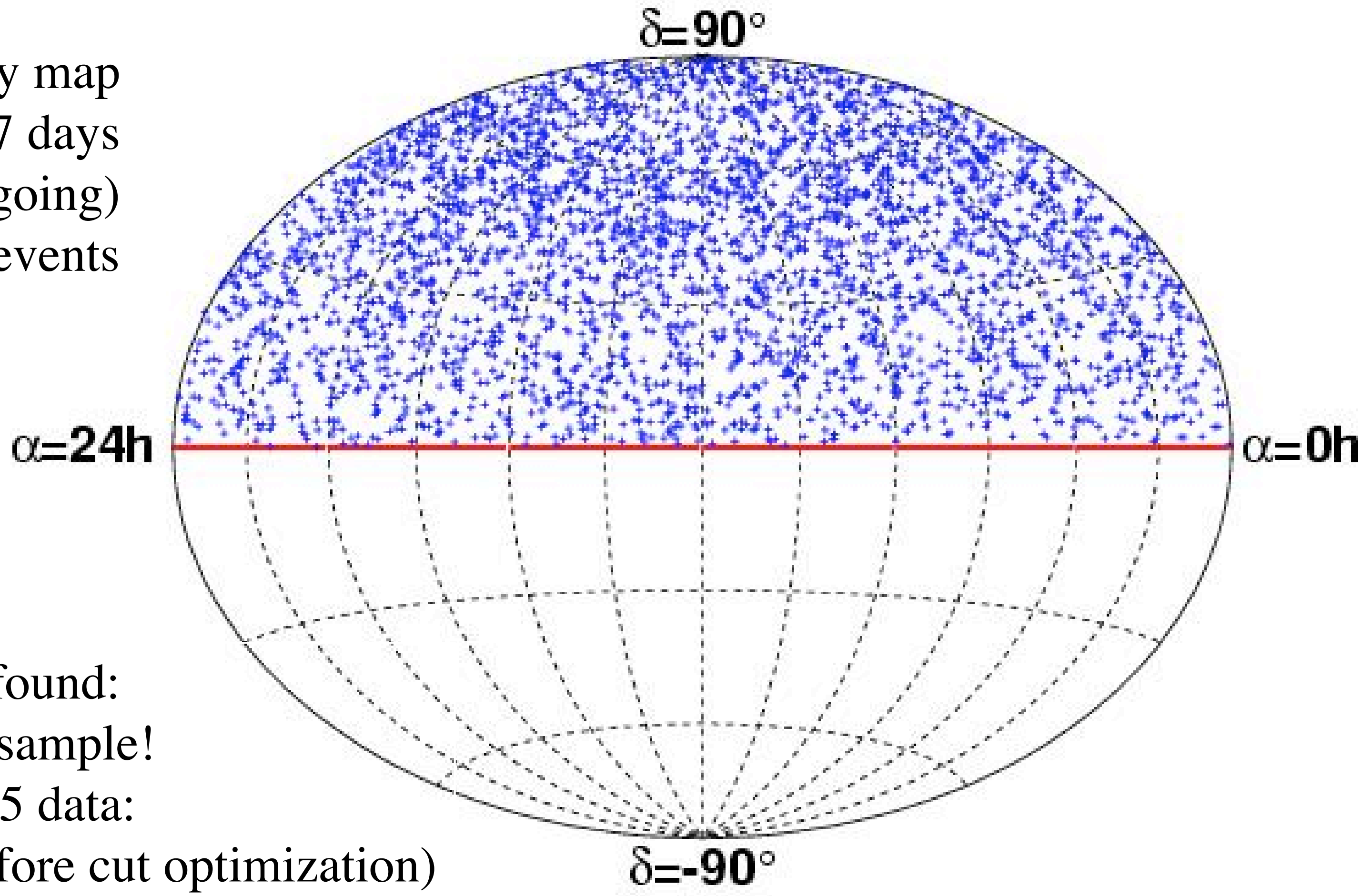
$$P[\nu_\mu \to \nu_\mu] = \frac{1}{2} + e^{-(\alpha+a)L} \cos\left(2\frac{\Delta m^2 L}{4E}\right) \qquad (\sin^2(2\theta) = 1,\ b = \beta = d = \delta = 0)$$



$a = \alpha =$
$4 \times 10^{-32} (E^2 / 2)$

Data Sample

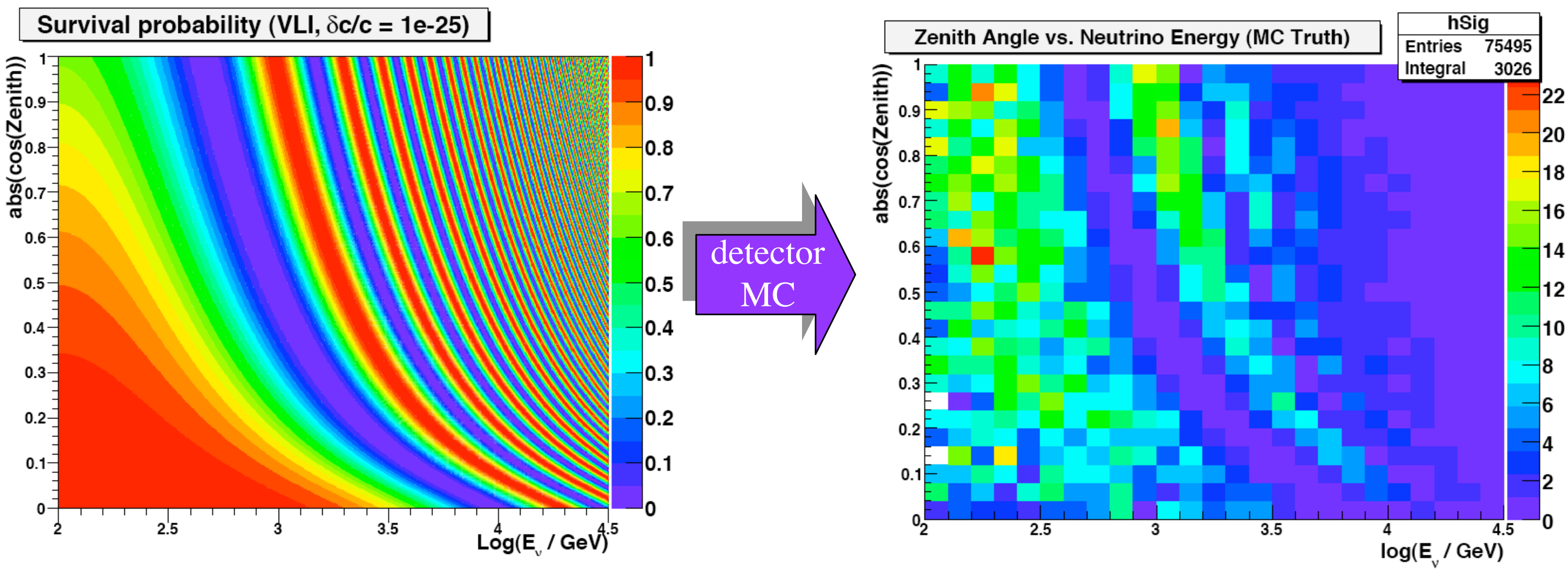
2000-2003 sky map
Livetime: 807 days
3329 events (up-going)
<5% fake events



No point sources found:
pure atmospheric sample!
Adding 2004, 2005 data:
> 5000 events (before cut optimization)

Analysis

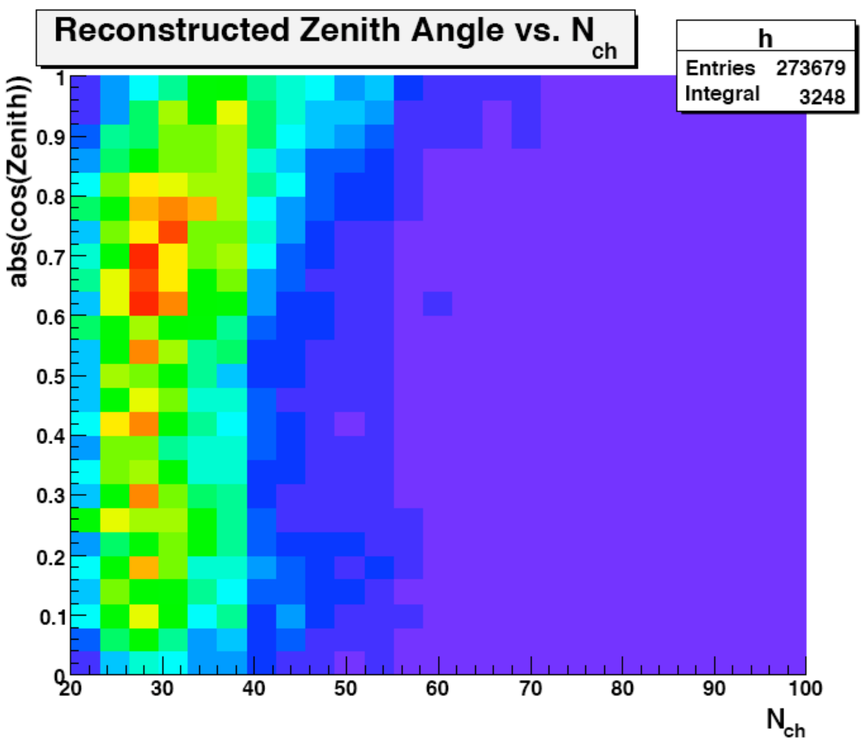
Or, how to extract the physics from the data?



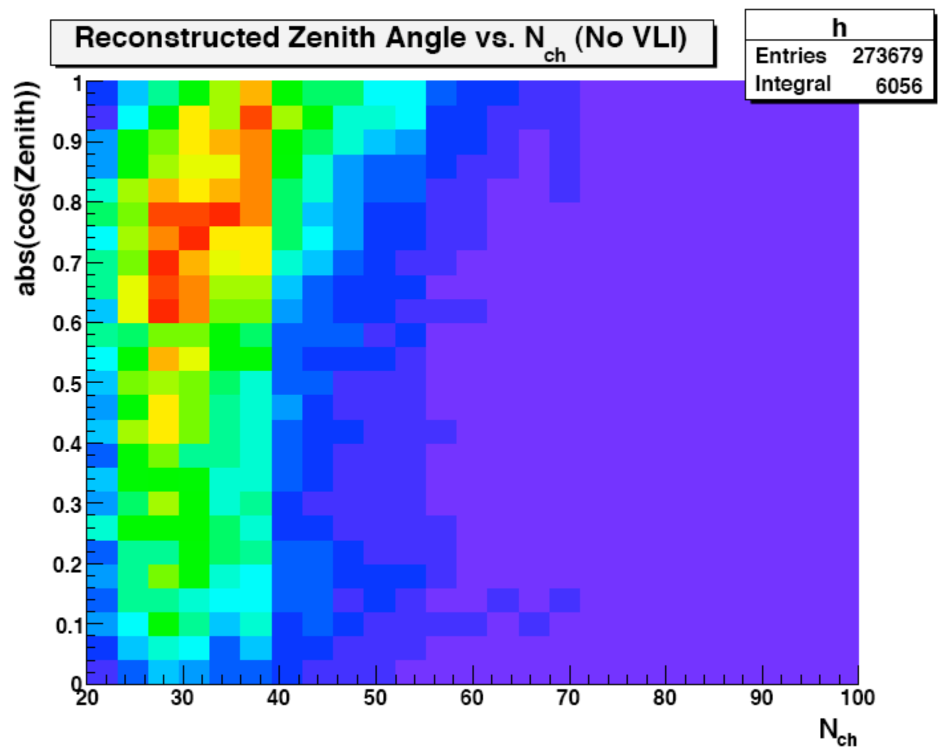
...only in a perfect world!

Observable Space

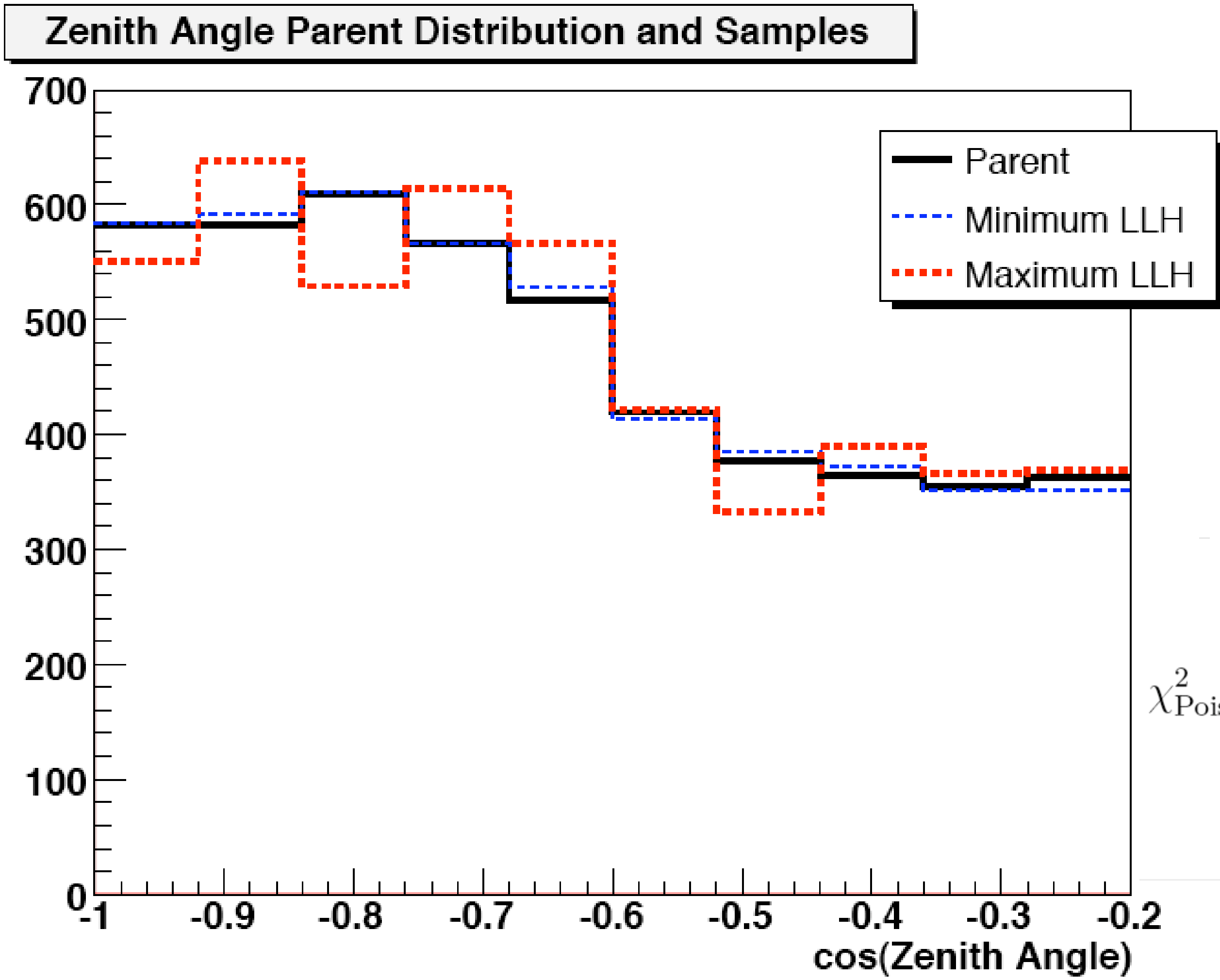
$\delta c/c = 10^{-25}$



No New Physics



Binned Likelihood Test



Poisson probability

$$P(n) = e^{-\mu}\frac{\mu^n}{n!}$$

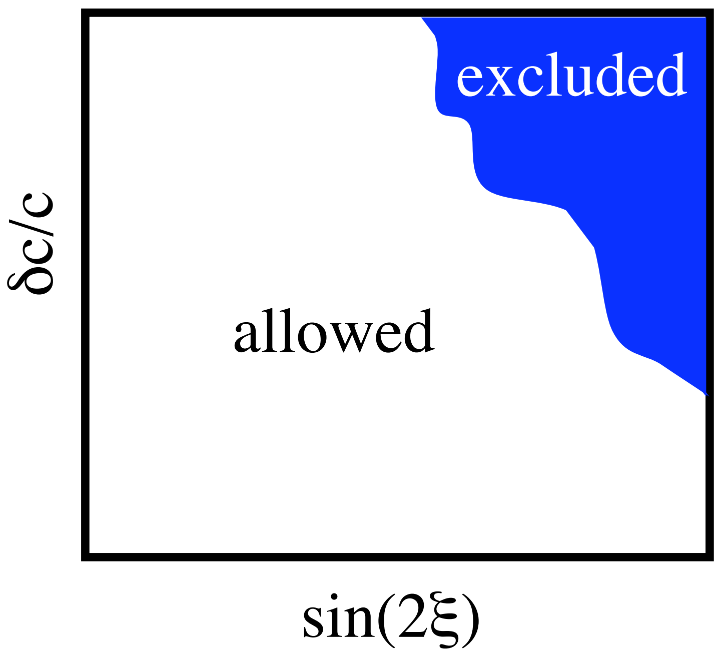
Product over bins

$$P_p(\{n_i\}) = \prod_{i=1}^{N} e^{-\mu_i}\frac{\mu_i^{n_i}}{n_i!}$$

Test Statistic: LLH

$$\begin{aligned}\chi^2_{\text{Poisson}} &= -2\ln P_p(\{n_i\}) \\ &= 2\sum_{i=1}^{N}(\mu_i - n_i \ln \mu_i + \ln n_i!)\end{aligned}$$

Testing the Parameter Space



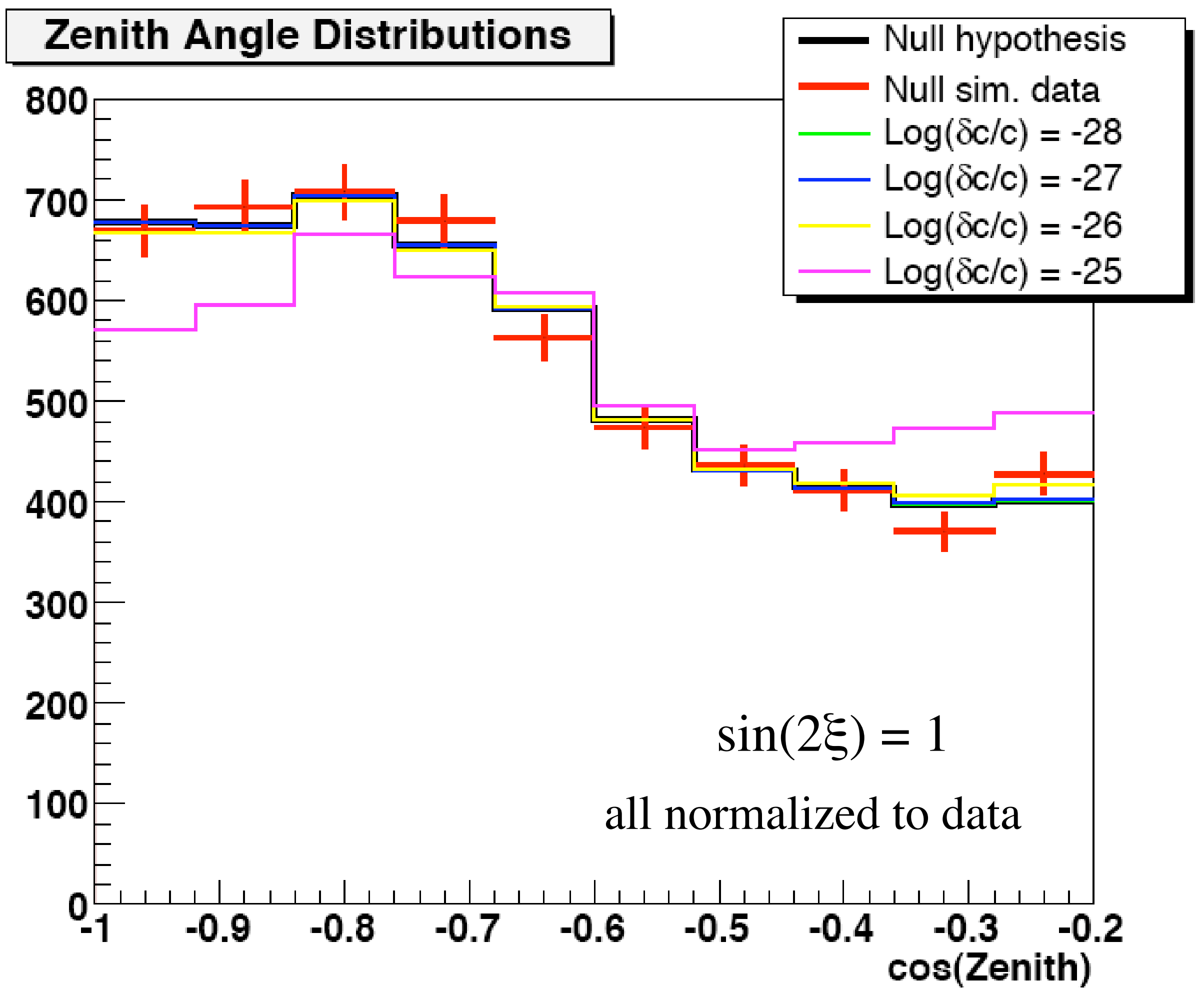
Given a measurement, want to determine values of parameters $\{\theta_i\}$ that are allowed / excluded at some confidence level

Feldman-Cousins Recipe

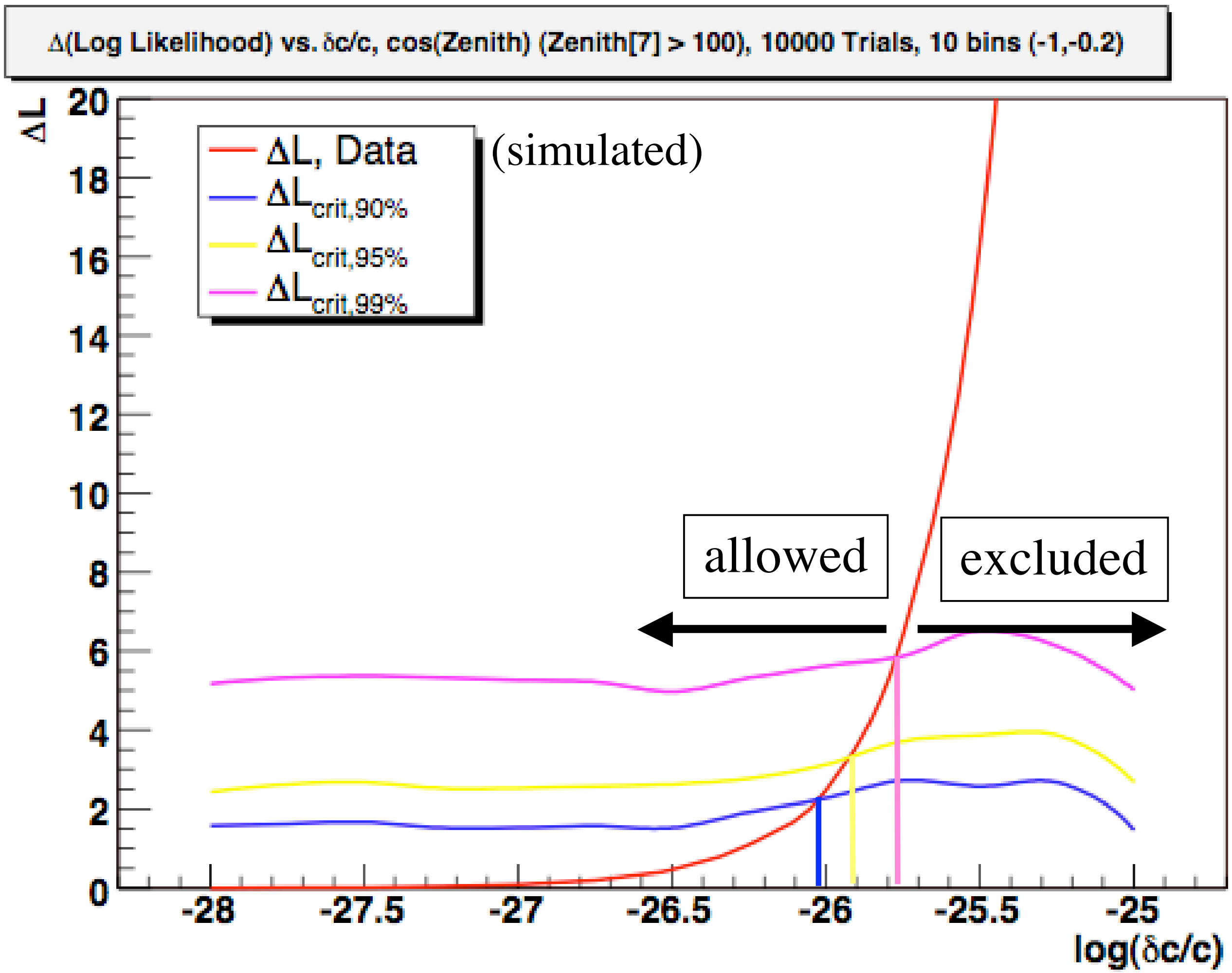
- For each point in parameter space $\{\theta_i\}$, sample many times from parent Monte Carlo distribution (MC "experiments")
- For each MC experiment, calculate likelihood ratio:
  ΔL = LLH at parent $\{\theta_i\}$ - minimum LLH at some $\{\theta_{i,best}\}$
- For each point $\{\theta_i\}$, find ΔL_{crit} at which, say, 90% of the MC experiments have a lower ΔL (FC ordering principle)
- Once you have the data, compare ΔL_{data} to ΔL_{crit} at each point to determine exclusion region
- Primary advantage over χ^2 global scan technique: proper coverage

Feldman & Cousins, PRD **57** 7 (1998)

1-D Examples


Zenith Angle Distributions
Null hypothesis
Null sim. data
Log(δc/c) = -28
Log(δc/c) = -27
Log(δc/c) = -26
Log(δc/c) = -25
800
700
600
500
400
300
200
100
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
cos(Zenith)
sin(2ξ) = 1
all normalized to data

VLI Sensitivity: Zenith Angle



2000-05 livetime simulated

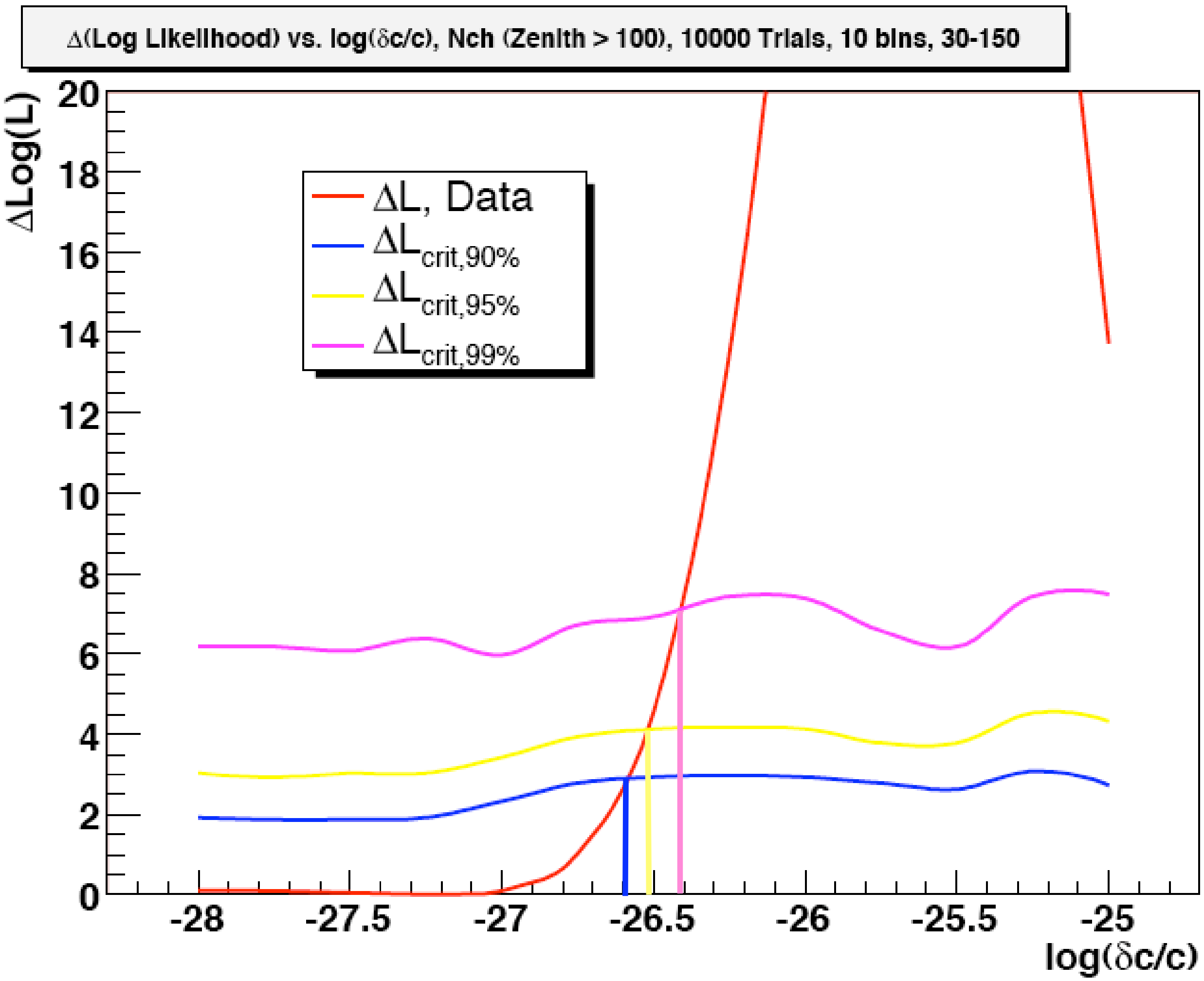
Median Sensitivity
$\delta c/c$ ($\sin(2\xi) = 1$)

- 90%: 1.4×10^{-26}
- 95%: 1.6×10^{-26}
- 99%: 2.1×10^{-26}

MACRO limit*:
2.5×10^{-26} (90%)

*hep-ex/0503015

VLI: Sensitivity using N_{ch}



2000-05 livetime simulated

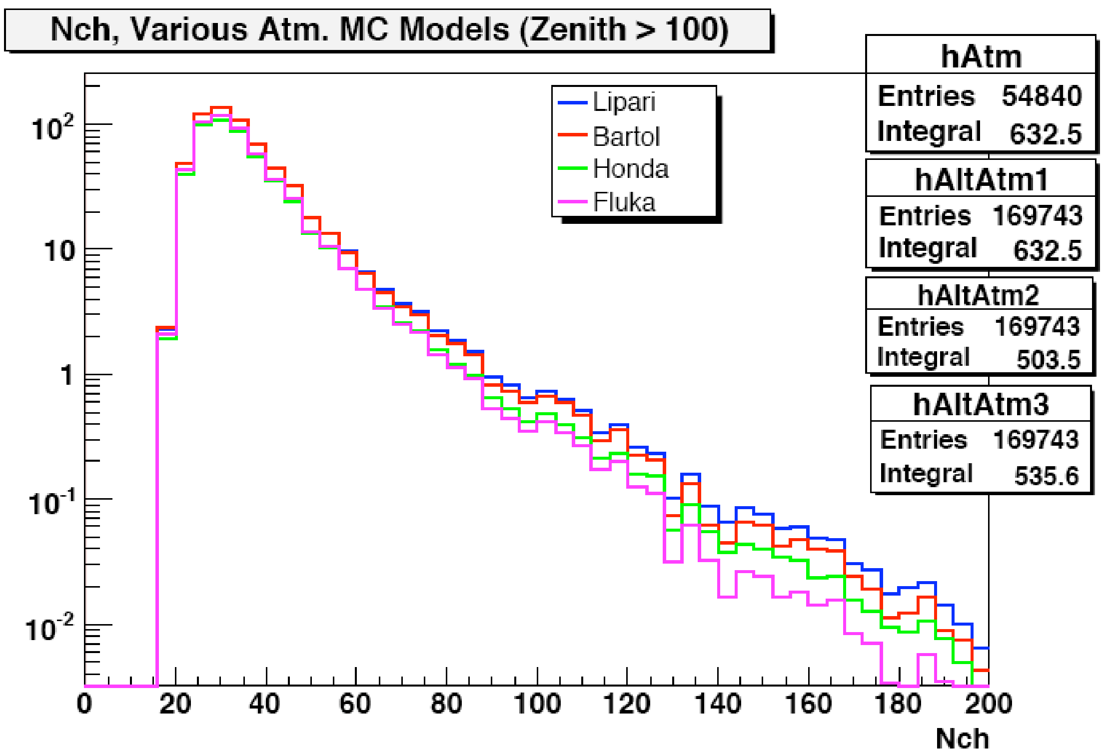
Median Sensitivity

$\delta c/c$ ($\sin(2\Xi) = 1$)

- 90%: 3.2×10^{-27}
- 95%: 3.6×10^{-27}
- 99%: 5.1×10^{-27}

Significantly better than MACRO

Systematic Errors



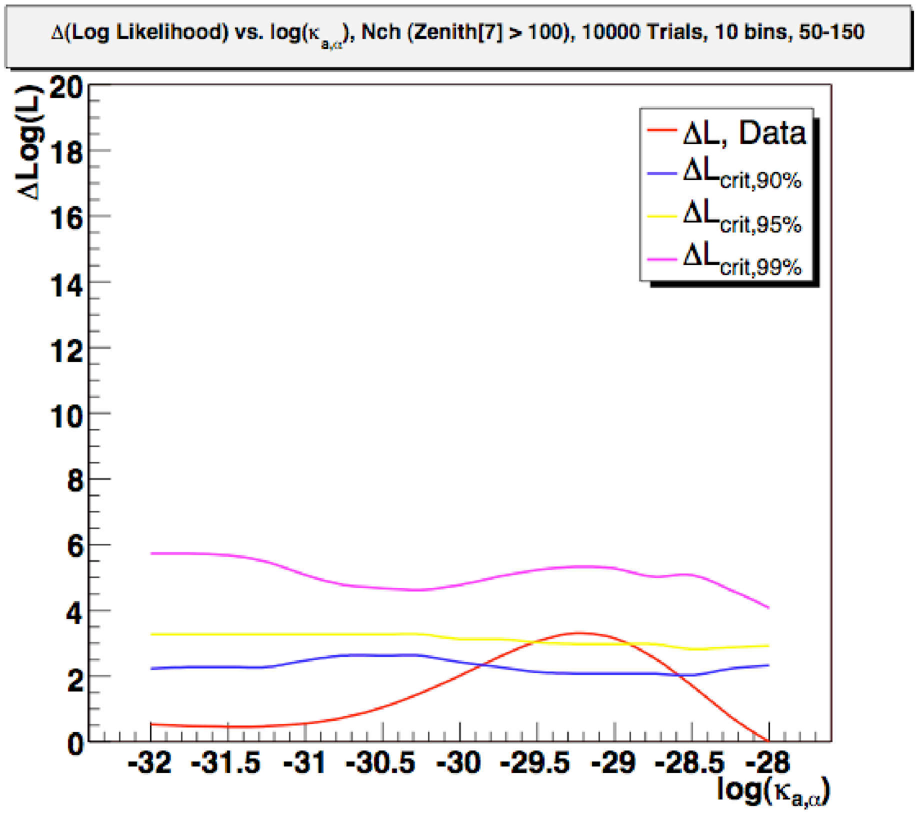
- Atmospheric production uncertainties
- Detector effects (OM sensitivity)
- Ice Properties

Can be treated as nuisance parameters: minimize LLH with respect to them

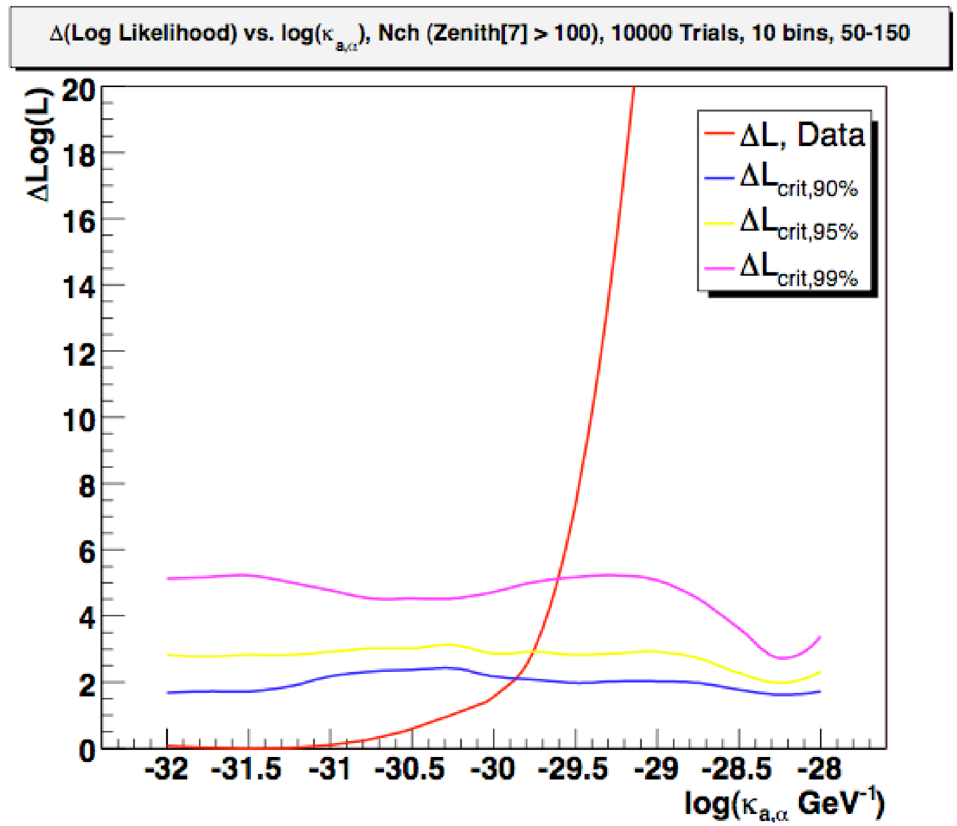
Or, can simulate as fluctuations in MC experiments

Normalization is already included!
(free parameter — could possibly constrain)

Decoherence Sensitivity (Using Nch, κ model)



Normalization free



Norm. constrained ±30%

Decoherence Sensitivity

Median Sensitivity
$\kappa_{a,\alpha}$ (GeV^{-1})

- 90%: 3.7×10^{-31}
- 95%: 5.8×10^{-31}
- 99%: 1.6×10^{-30}

(E^2 energy dependence)

SuperK limit (90%)[‡] : 0.9×10^{-27} GeV^{-1}

ANTARES (3 yr sens, 90%)[*] : 10^{-44} GeV^{-1}

Almost 4 orders of magnitude improvement!

* Morgan *et al*., astro-ph/0412618
‡ Lisi, Marrone, and Montanino, PRL **85** 6 (2000)

To Do List

- 2005 data and Monte Carlo processing
- Improve quality cuts for atmospheric sample
- Extend analysis capabilities
  - better energy estimator?
  - full systematic error treatment
  - multiple dimensions (observable and parameter space)
  - optimize binning

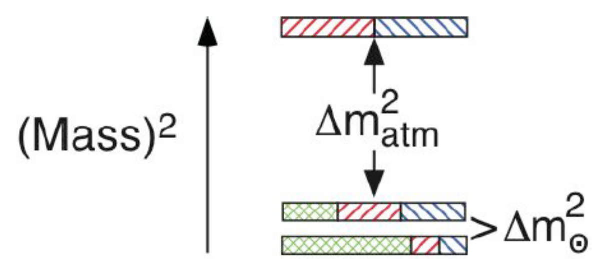
Extra Slides

Three Families?

- *In theory*: mixing is more complicated (3x3 matrix; 3 mixing angles and a CP-violation phase)

- *In practice*: different energies and baselines (and small θ_{13}) mean approximate decoupling again into two families

$$U = \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times \, \mathrm{diag}(e^{i\alpha_1/2}, \ e^{i\,\alpha_2/2}, \ 1) \ .$$

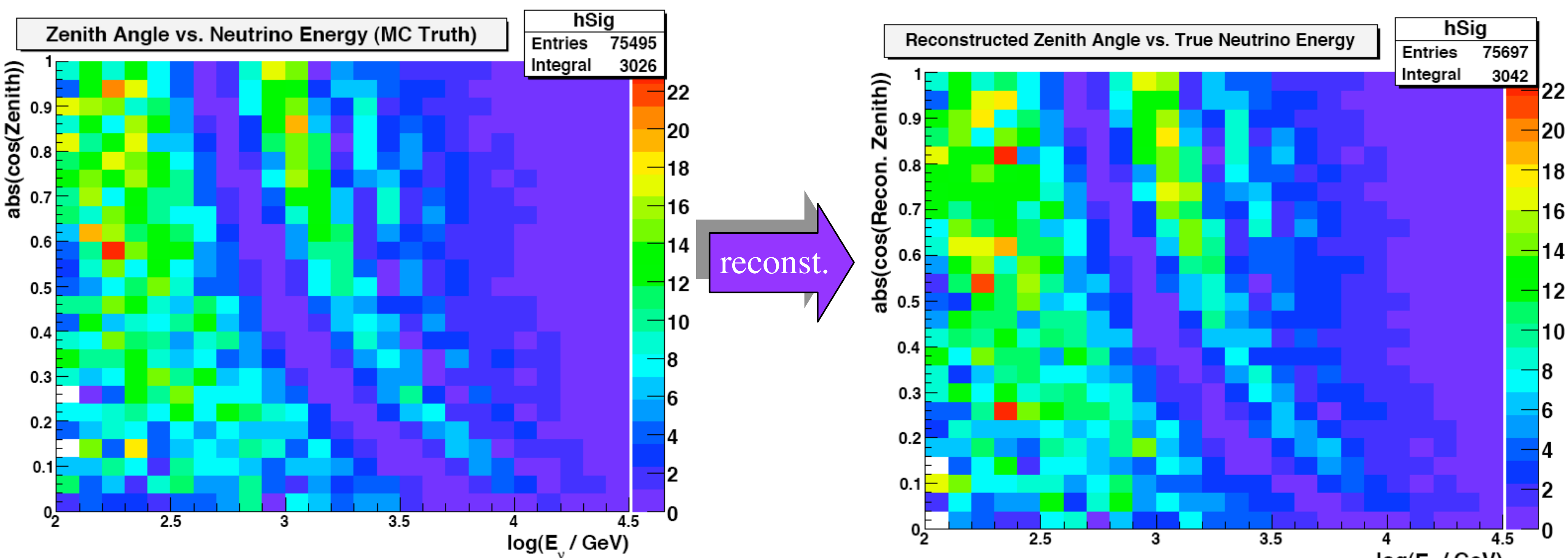


Standard (non-inverted) hierarchy

Atmospheric $\nu_\mu \leftrightarrow \nu_\tau$ is essentially two-family

Closer to Reality

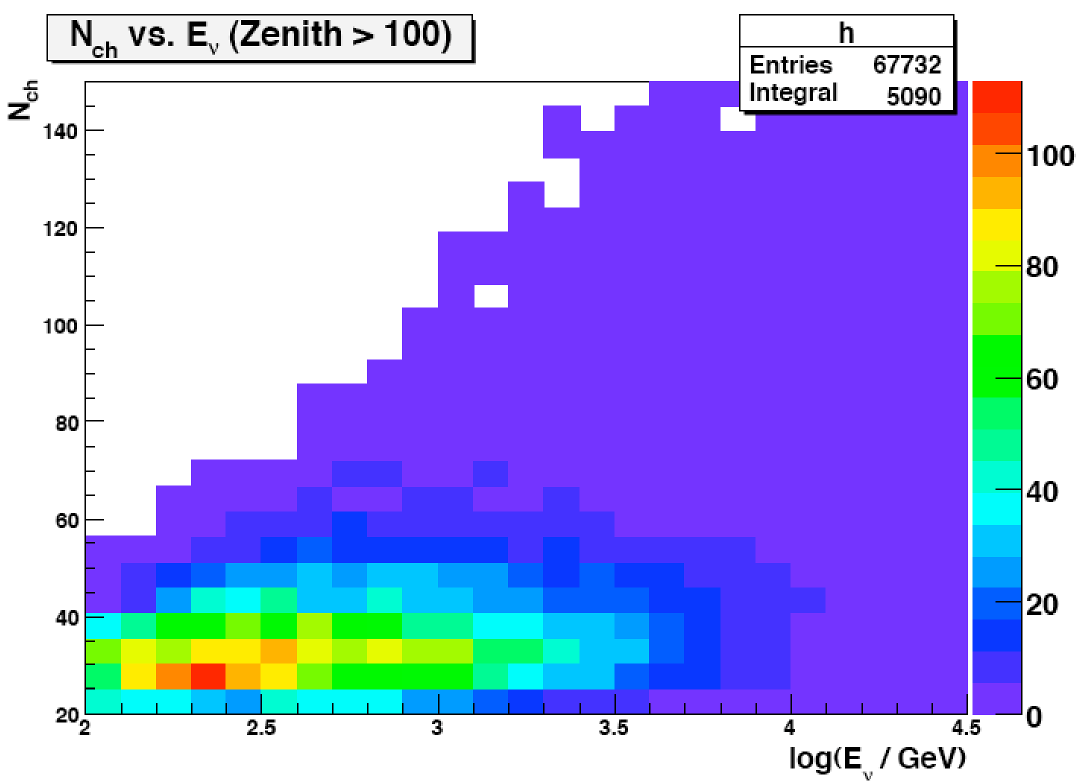
Zenith angle reconstruction — still looks good



The problem is knowing the neutrino energy!

Number of OMs hit

N_{ch} (number of OMs hit): stable observable, but acts more like an energy threshold



Other methods exist: dE/dx estimates, neural networks…