Sensitivity to New Physics using Atmospheric Neutrinos and AMANDA-II

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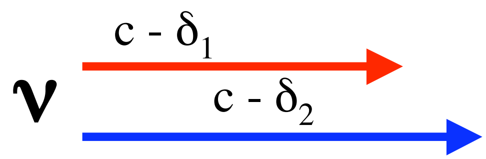
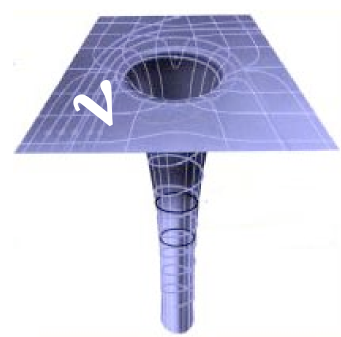
New Physics Effects

- 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 Oscillations

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

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

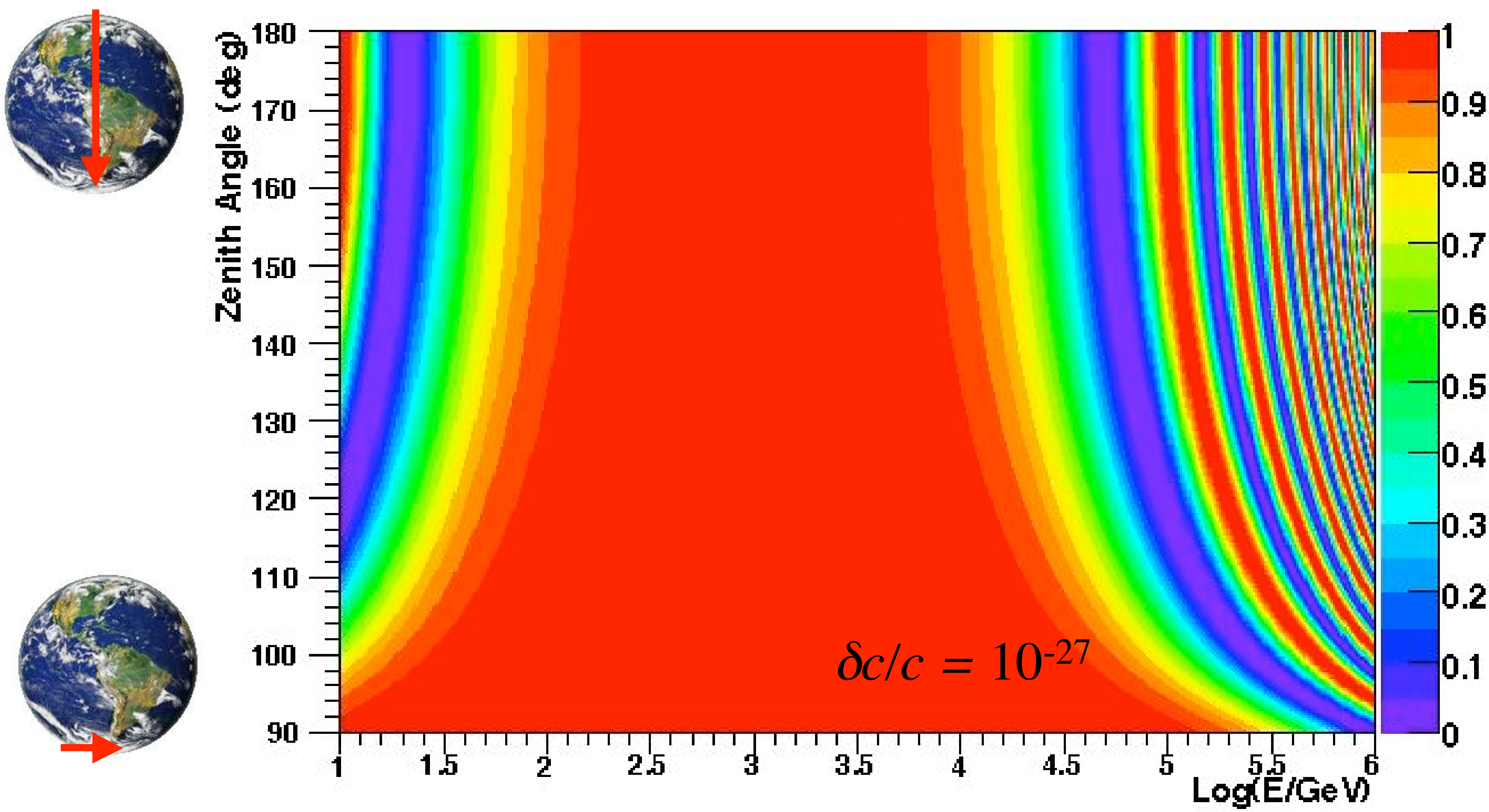
$$\mathcal{R} = \sqrt{1 + R_n^2 + 2R_n \left(\cos 2\theta \cos 2\xi_n + \sin 2\theta \sin 2\xi_n \cos \eta_n \right)} ,$$

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

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

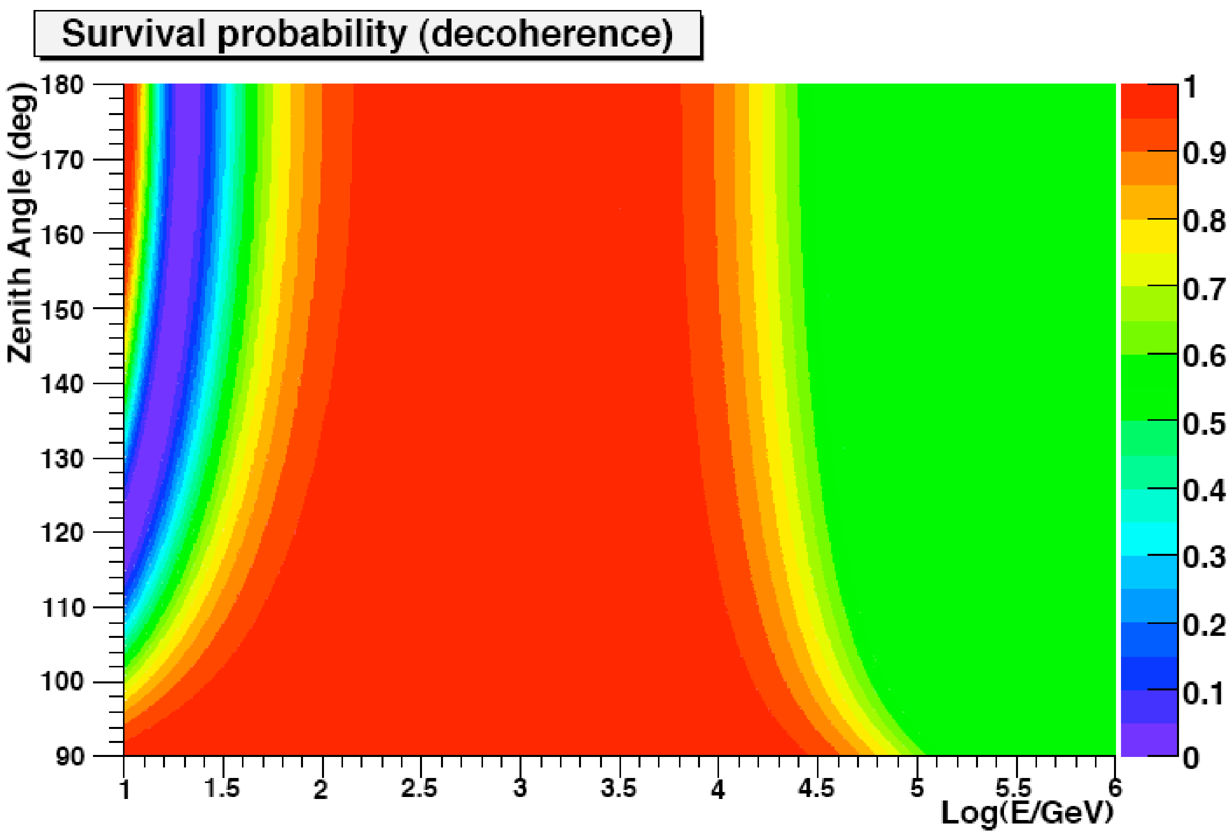
- For atmospheric ν, conventional oscillations turn off above ~50 GeV (*L*/*E* dependence)
- VLI oscillations turn on at high energy (*L E* dependence), depending on size of *δc*/*c*, and distort the zenith angle / energy spectrum

ν_μ Survival Probability (Violation of Lorentz Invariance)



ν_μ Survival Probability (Quantum Decoherence)

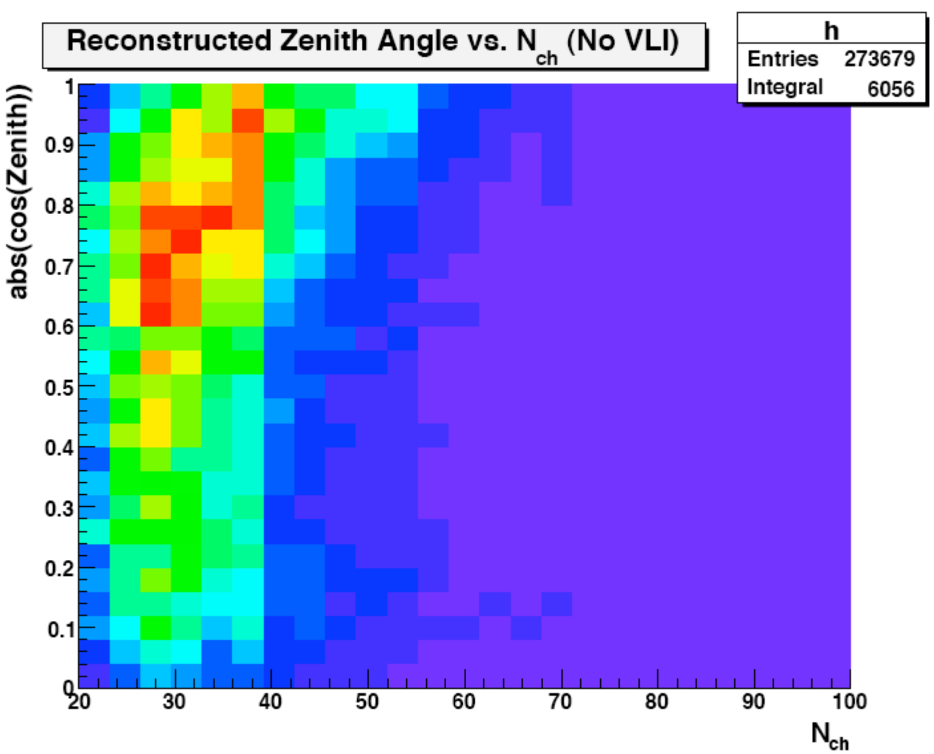
$$P[\nu_\mu \to \nu_\mu] = \frac{1}{2} + e^{-(\alpha+a)L}\cos\left(2\frac{\Delta m^2 L}{4E}\right) \qquad (\sin^2(2\theta) = 1,\ b = \beta = d = \delta = 0)$$



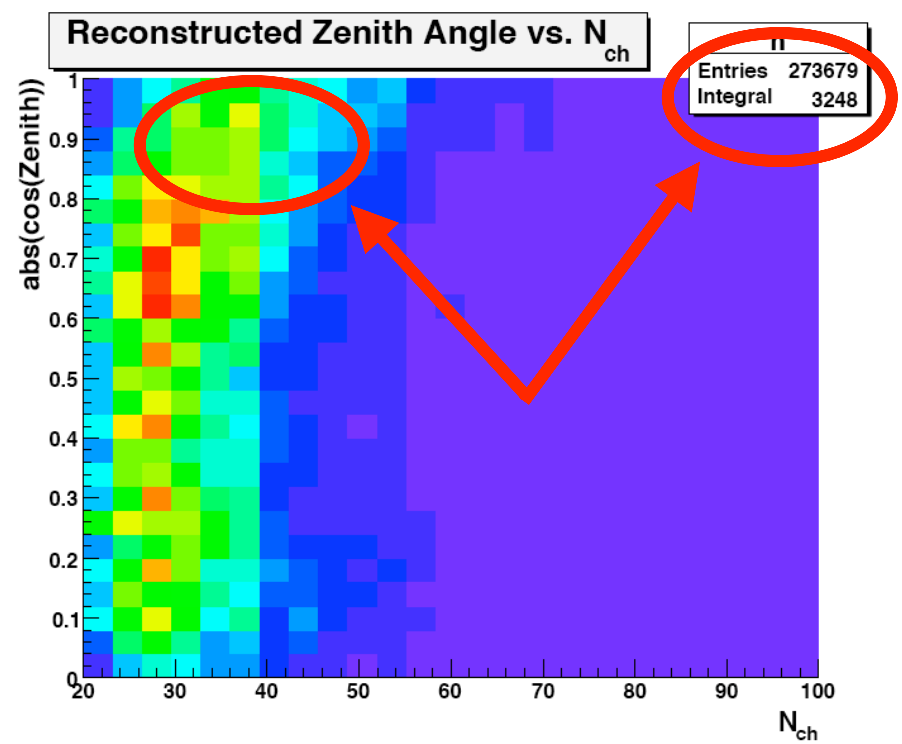
κ model, $a = \alpha = 4 \times 10^{-32} (E^2 / 2)$

Data Analysis

Look for distortions in N_{ch} vs. zenith angle

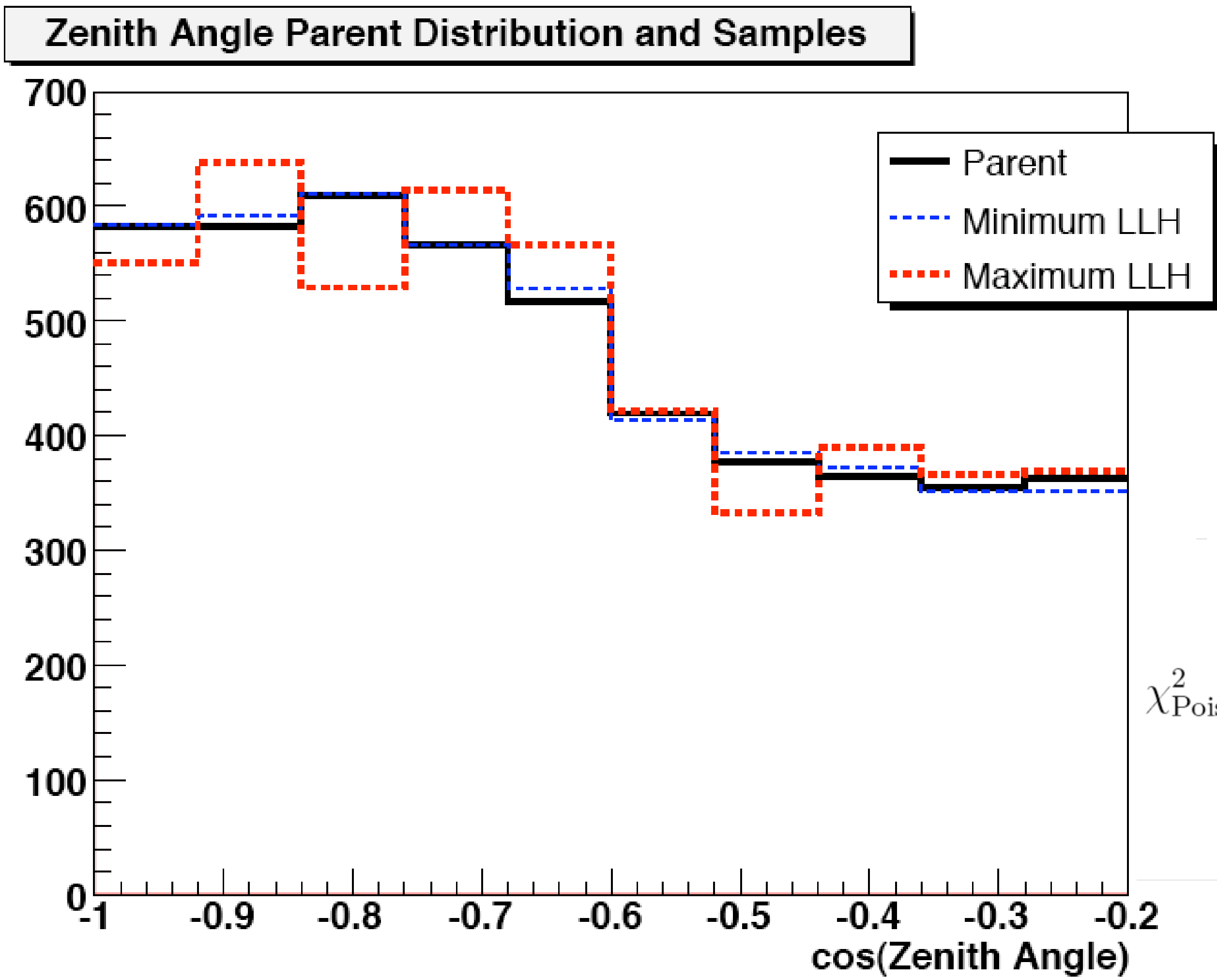


No New Physics



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

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

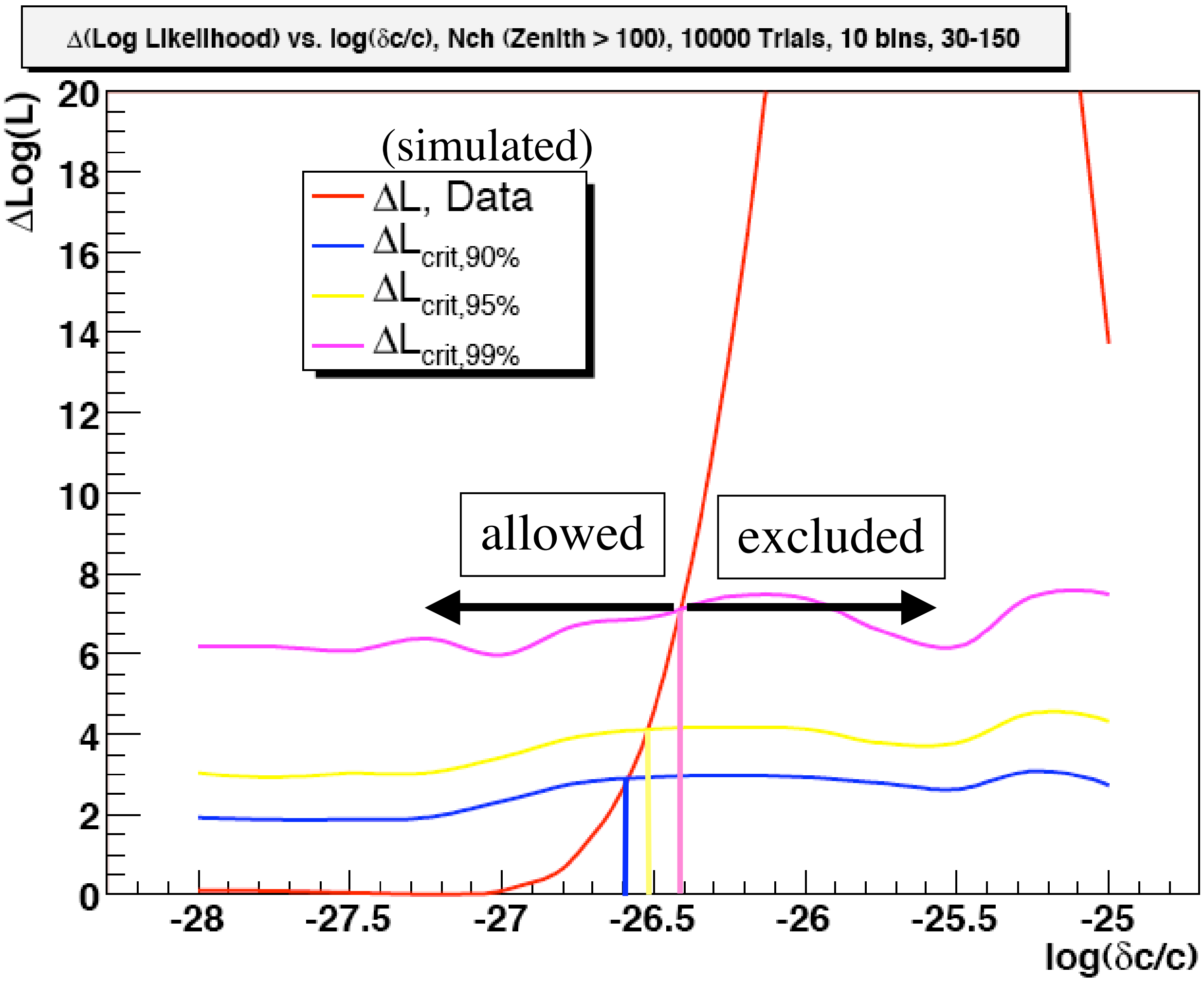
$$\begin{aligned} \chi^2_{\text{Poisson}} &= -2\ln P_p(\{n_i\}) \\ &= 2\sum_{i=1}^{N}(\mu_i - n_i \ln \mu_i + \ln n_i!) \end{aligned}$$

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)

VLI: Sensitivity using only N_{ch}



2000-05 livetime simulated

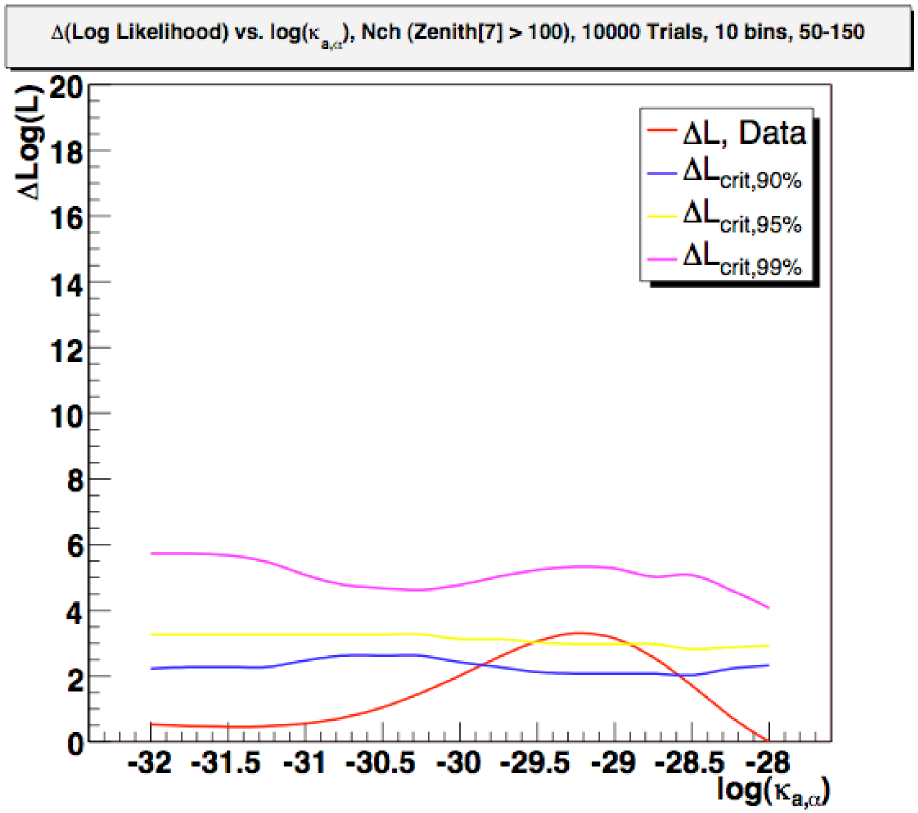
Median Sensitivity
$\delta c/c$ ($\sin(2\Xi) = 1$)

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

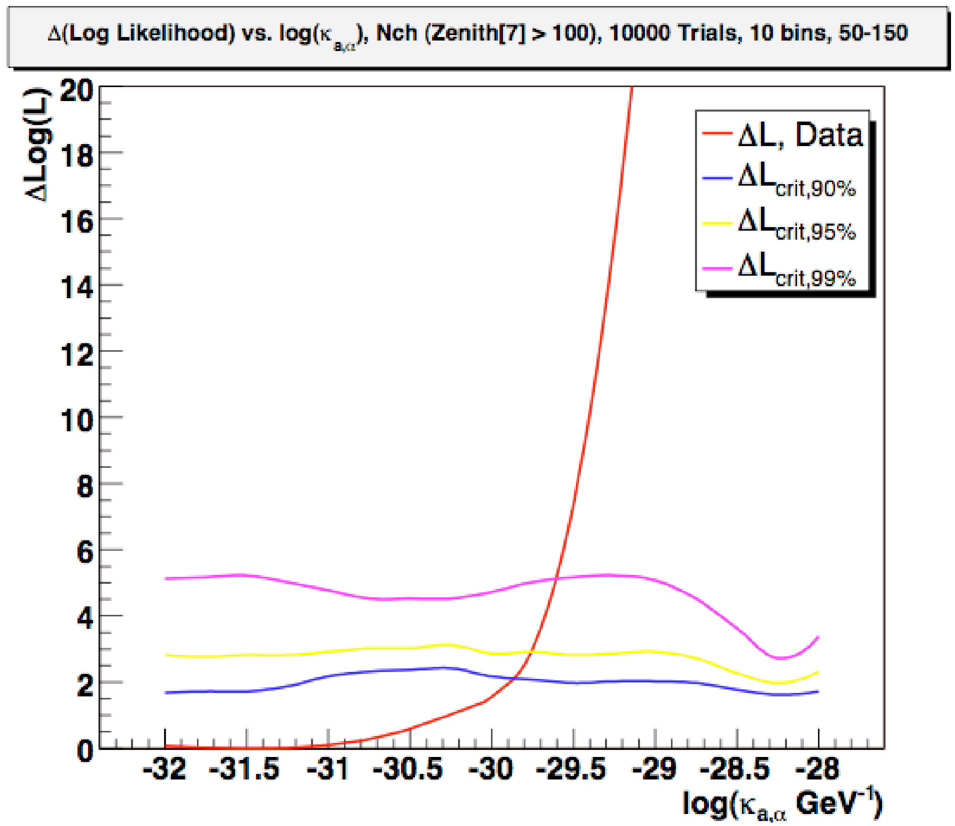
MACRO limit*:
2.5×10^{-26} (90%)

*hep-ex/0503015

Decoherence Sensitivity (Using N_{ch}, κ model)



Normalization free



Norm. constrained ±30%

Decoherence Sensitivity

<u>Median Sensitivity</u>

$\kappa_{a,\alpha}$ (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}

Almost 4 orders of magnitude improvement!

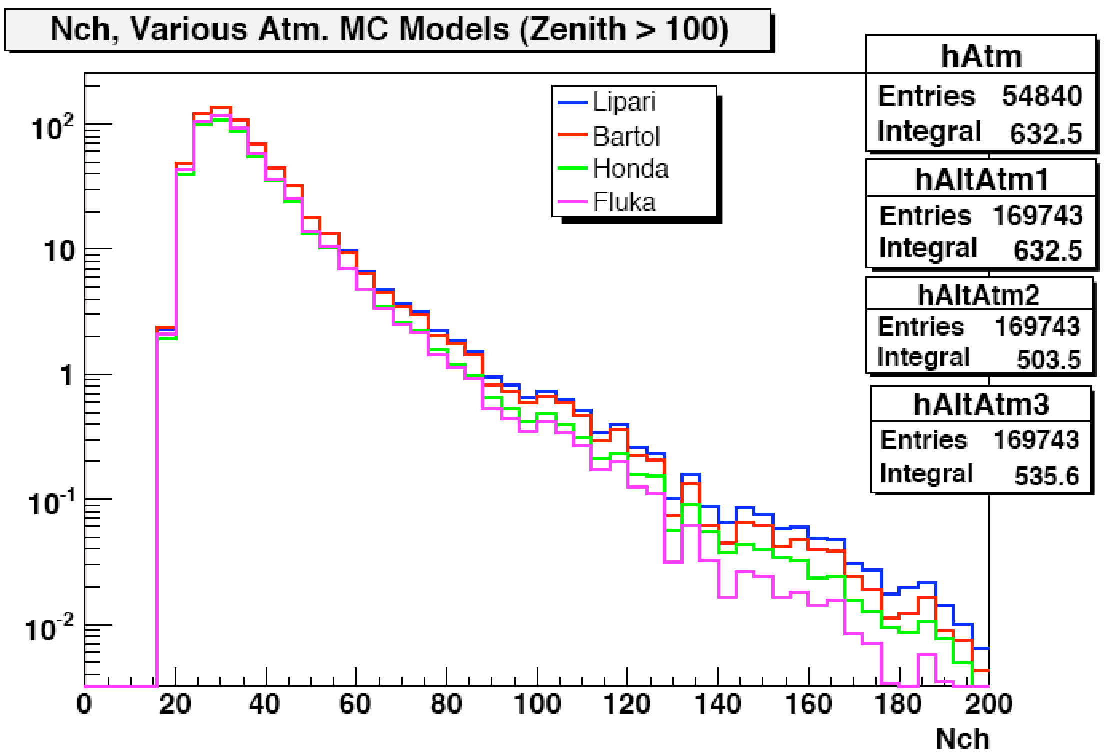
[‡] Lisi, Marrone, and Montanino, PRL **85** 6 (2000)

To Do List

- 2005 data and Monte Carlo (with Photonics) processing underway
- Improve quality cuts for atmospheric sample — leverage work done at Mainz
- Extend analysis capabilities
  - better energy estimator?
  - full systematic error treatment
  - multiple dimensions (observable and parameter space)
  - optimize binning

Extra Slides

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)