Analysis of Atmospheric Neutrinos: AMANDA 2000-2006

John Kelley

April 30, 2008

IceCube Collaboration Meeting

Outline

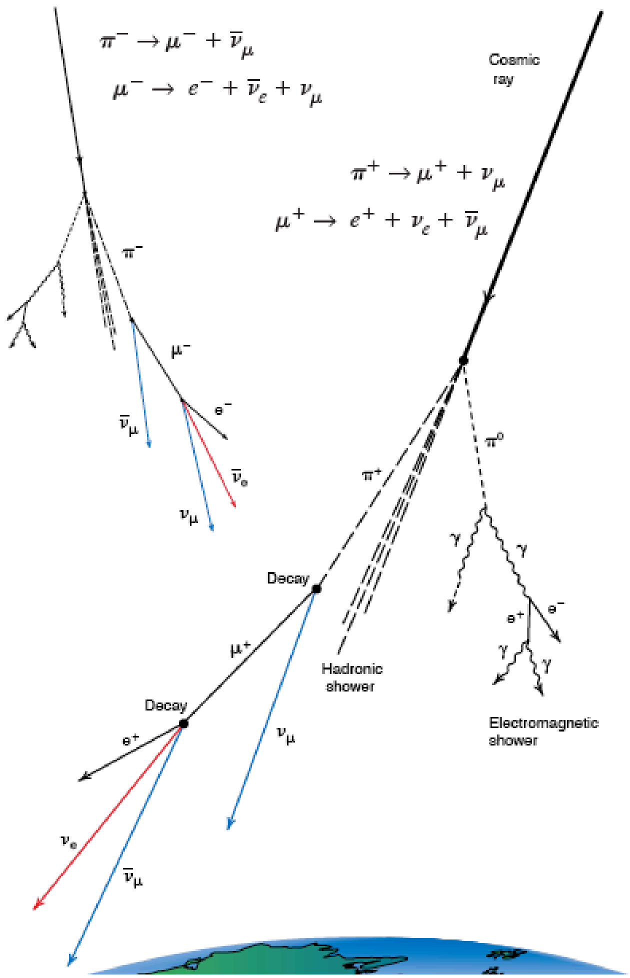


Figure from Los Alamos Science **25** (1997)

- Hypotheses
- Analysis Methodology
- Systematic Errors
- Data Sample
- Sensitivities

Hypotheses

- New physics (high-energy flavor-changing phenomena)
  - violation of Lorentz invariance
  - quantum decoherence

- Conventional theory
  - measure normalization, spectral slope relative to current models (Bartol, Honda 2006)

New Physics

Violation of Lorentz Invariance (VLI)

- occurs naturally in many quantum gravity theories
- phenomenologically modeled via effective field theory: Standard Model Extension (SME)*
- specific form we are interested in: neutrinos have distinct maximum velocity eigenstates $\neq c$, and difference $\delta c/c$ results in oscillations

* Colladay and Kostelecký, PRD **58** 116002 (1998)

VLI + Atmospheric Oscillations

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

$$\sin^2 2\Theta = \frac{1}{\mathcal{R}^2} (\sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos \eta) \; ,$$

$$\mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos \eta)} \; ,$$

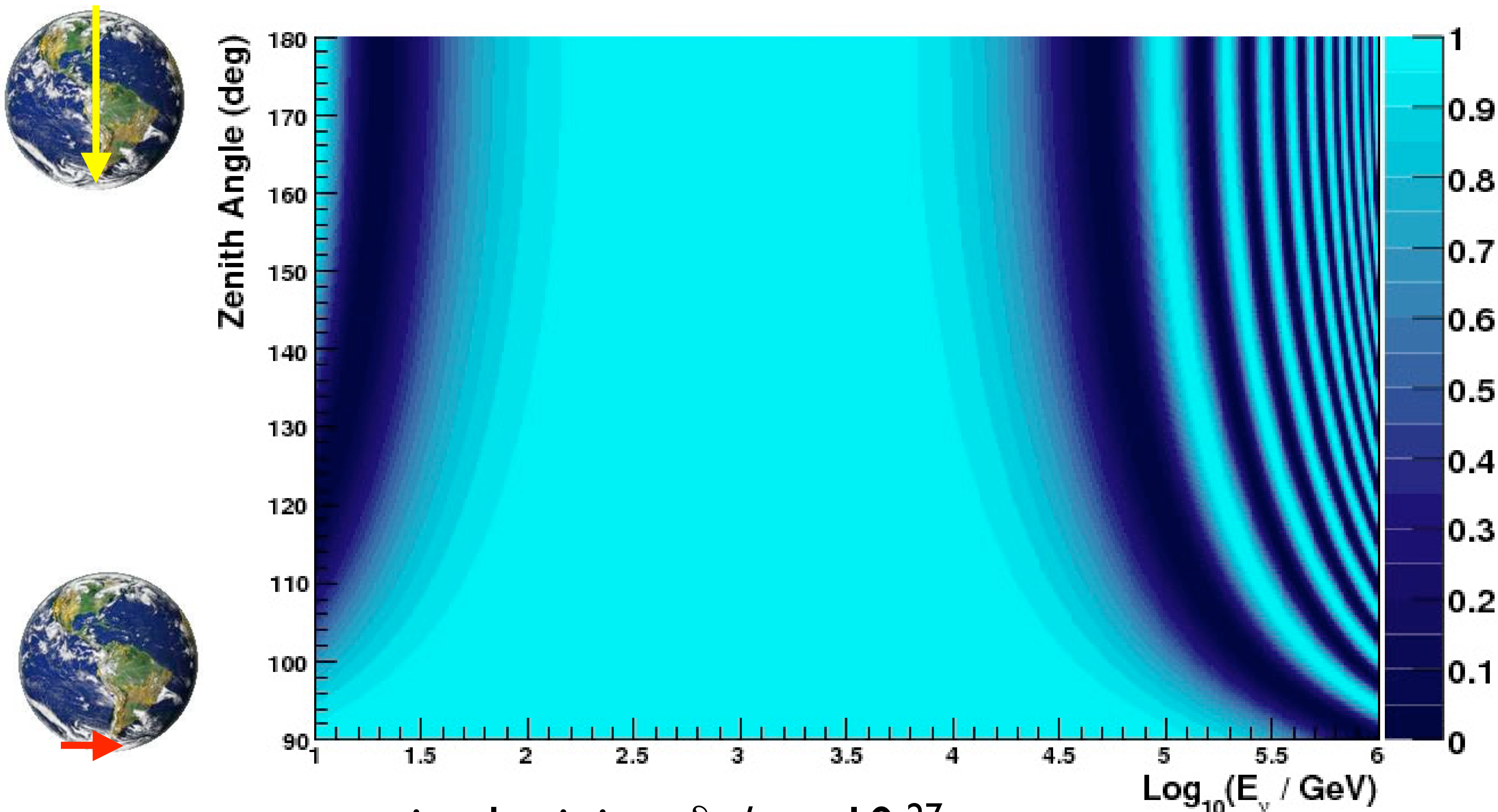
$$R = \frac{\delta c}{c} \frac{E}{2} \frac{4E}{\Delta m^2_{23}}$$

- 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 $\delta c/c$, and distort the zenith angle / energy spectrum (other parameters: mixing angle ξ, phase η)

González-García, Halzen, and Maltoni, hep-ph/0502223

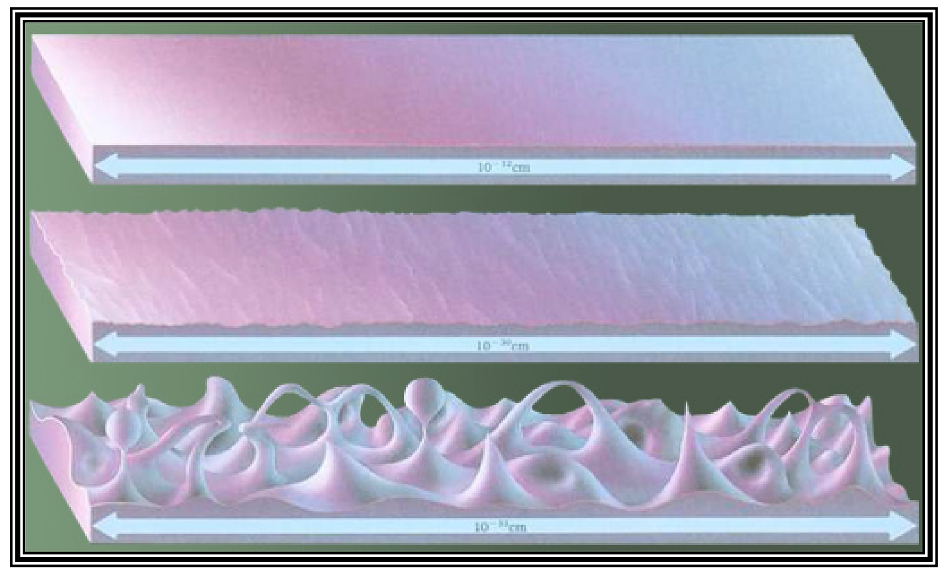
VLI Atmospheric ν_μ Survival Probability



maximal mixing, $\delta c/c = 10^{-27}$

Quantum Decoherence (QD)

- Another possible low-energy signature of quantum gravity: quantum decoherence
- Heuristic picture: foamy structure of space-time (interactions with virtual black holes) may not preserve certain quantum numbers (like ν flavor)
- Pure states interact with environment and decohere to mixed states



Decoherence + Atmospheric Oscillations

characteristic exponential behavior

1:1:1 ratio after decoherence

$$P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{3} + \frac{1}{2}\left(e^{-\gamma_3 L} \cos^4\theta_{23} + \frac{1}{12} e^{-\gamma_8 L}(1 - 3\cos 2\theta_{23})^2 \right.$$
$$+ 4 e^{-\frac{\gamma_6+\gamma_7}{2}L} \cos^2\theta_{23} \sin^2\theta_{23} \left(\cos\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right] \right.$$
$$\left.\left. + \sin\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right] \frac{(\gamma_6-\gamma_7)}{\sqrt{\left|(\gamma_6-\gamma_7)^2 - \left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}} \right)\right)$$

derived from Barenboim, Mavromatos *et al.* (hep-ph/0603028)

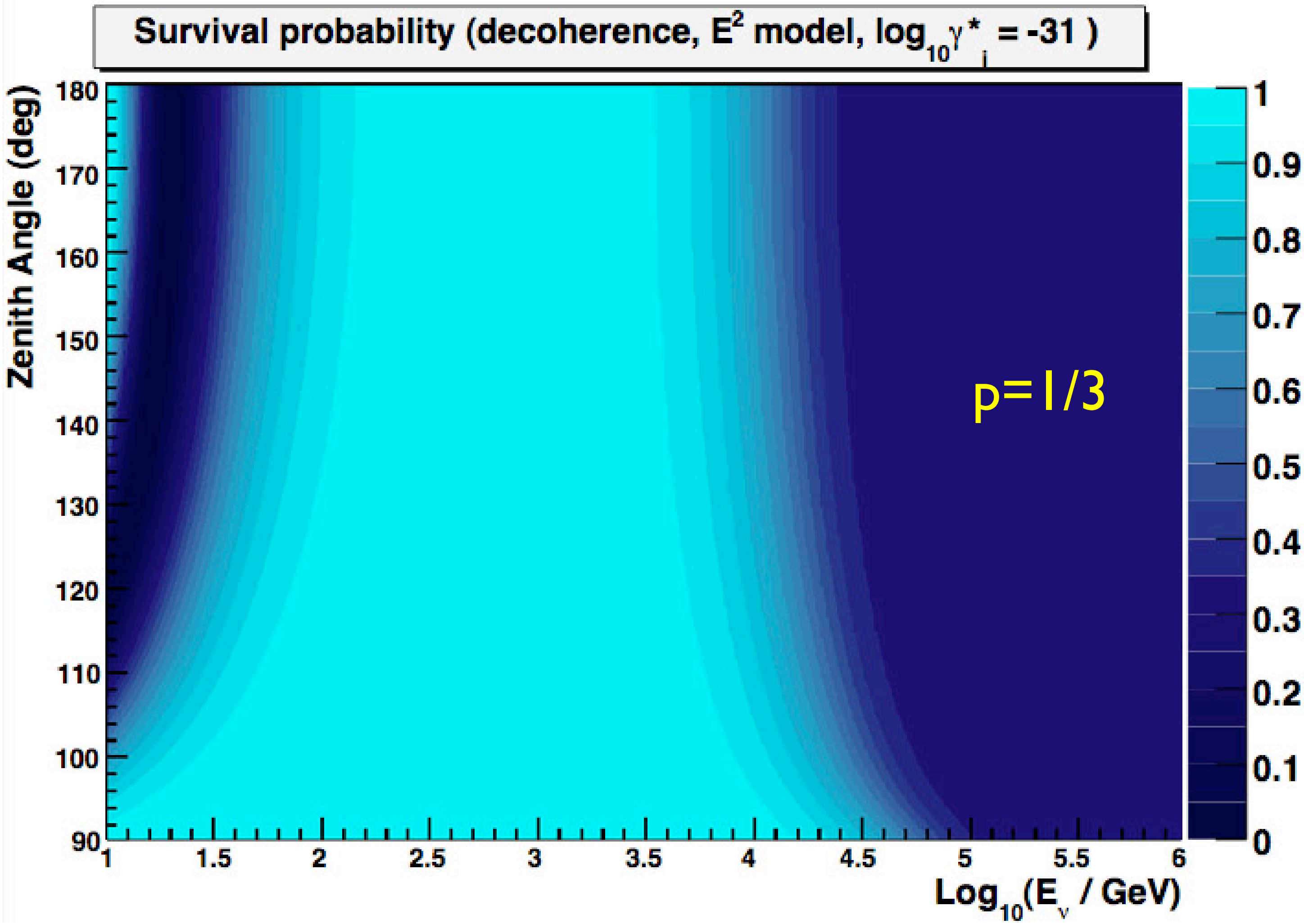
Energy dependence depends on phenomenology: $\gamma_i = \gamma_i^* \; E^n, \quad n \in \{-1, 0, 2, 3\}$

n = -1	*n = 0*	*n = 2*	*n = 3*
preserves Lorentz invariance	simplest	recoiling D-branes*	Planck-suppressed operators‡

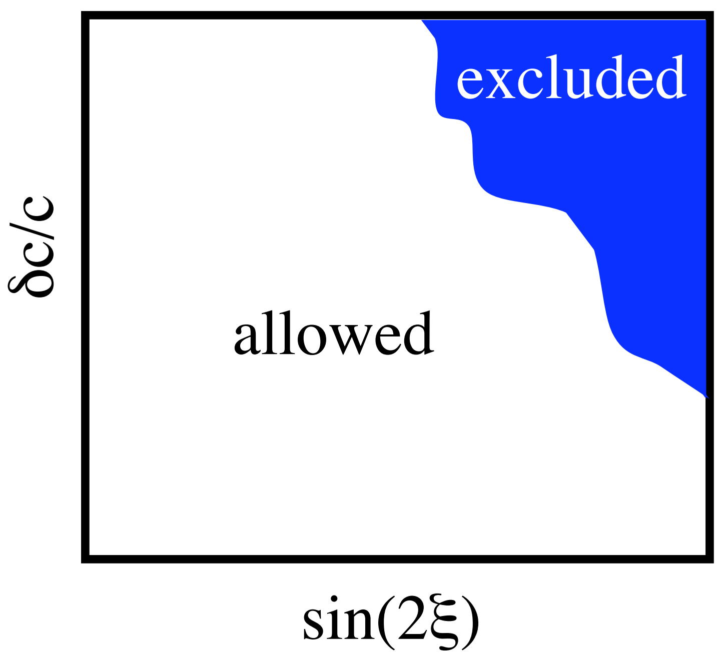
*Ellis *et al.*, hep-th/9704169

‡ Anchordoqui *et al.*, hep-ph/0506168

QD Atmospheric ν_μ Survival Probability



Testing the Parameter Space



Given observables x, want to determine values of parameters $\{\theta_r\}$ that are allowed / excluded at some confidence level

Binned likelihood + Feldman-Cousins

Feldman-Cousins Recipe (frequentist construction)

- For each point in parameter space $\{\theta_r\}$, sample many times from parent Monte Carlo distribution (MC "experiments")

- For each MC experiment, calculate likelihood ratio:
  ΔL = LLH at parent $\{\theta_r\}$ - minimum LLH at some $\{\theta_{r,best}\}$
  (compare hypothesis at this point to best-fit hypothesis)

- For each point $\{\theta_r\}$, find ΔL_{crit} at which, say, 90% of the MC experiments have a lower ΔL

- Once you have the data, compare ΔL_{data} to ΔL_{crit} at each point to determine exclusion region

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

Nuisance Parameters / Systematic Errors

How to include nuisance parameters $\{\theta_s\}$:

– test statistic becomes *profile likelihood*

$$l = \frac{L(x|\theta_{r0}, \hat{\hat{\theta}}_s)}{L(x|\hat{\theta}_r, \hat{\theta}_s)}$$

Variable	Meaning
θ_r	physics parameters
θ_s	nuisance parameters
$\hat{\theta}_r, \hat{\theta}_s$	unconditionally maximize $L(x|\hat{\theta}_r, \hat{\theta}_s)$
$\hat{\hat{\theta}}_s$	conditionally maximize $L(x|\theta_{r0}, \hat{\hat{\theta}}_s)$

– MC experiments use "worst-case" value of nuisance parameters (Feldman's *profile construction* method)

- specifically, for each θ_r, generate experiments fixing n.p. to data's $\hat{\hat{\theta}}_s$, then re-calculate profile likelihood as above

Specifics of the Analysis

- Observables (*x*)
  - cos(Zenith$_{Pandel}$), [-1, 0], 10 bins
  - N_{ch}, [20, 120], 10 bins
- Physics: parameters of interest (θ_r)
  - VLI: $\delta c/c$, sin 2ξ, cos η
  - QD: γ_3 and γ_8, γ_6 and γ_7
- Nuisance parameters (θ_s) … time for systematics study
  - must try and limit dimensionality (already 2- or 3-dimensional space to search)
  - still want to account for shape effects on zenith, N_{ch} — not just normalization

Atmospheric Systematics

- Separate systematic errors into four classes, depending on effect on observables:
  - normalization
    - e.g. atm. flux normalization
  - slope: change in primary spectrum
    - e.g. primary CR slope
  - tilt: tilts zenith angle distribution
    - e.g. π/K ratio
  - OM sensitivity (large, complicated effects)

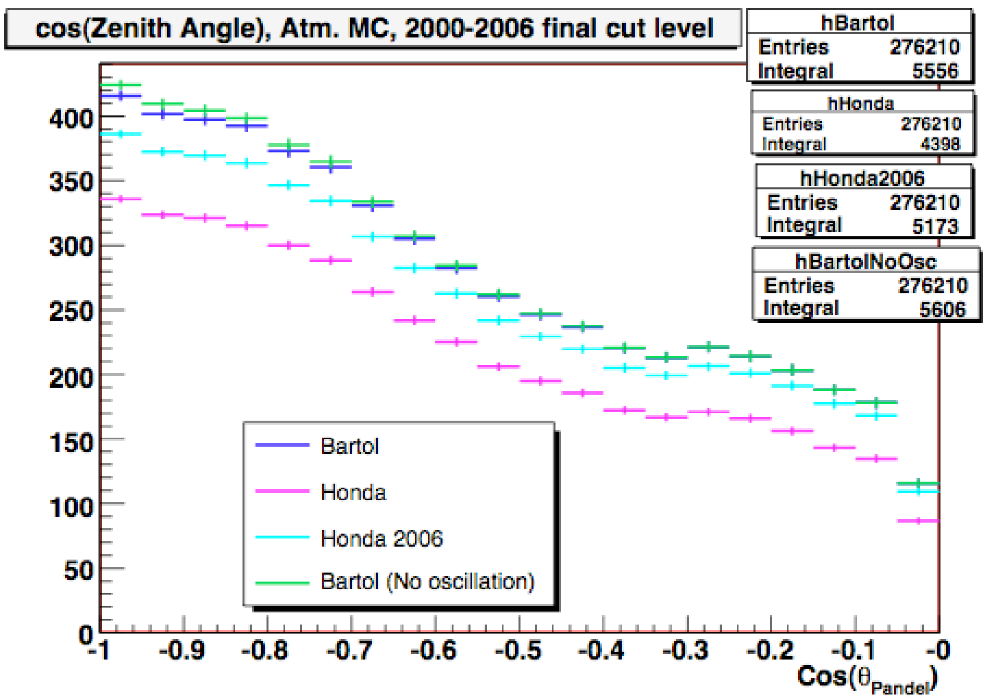
Systematics List

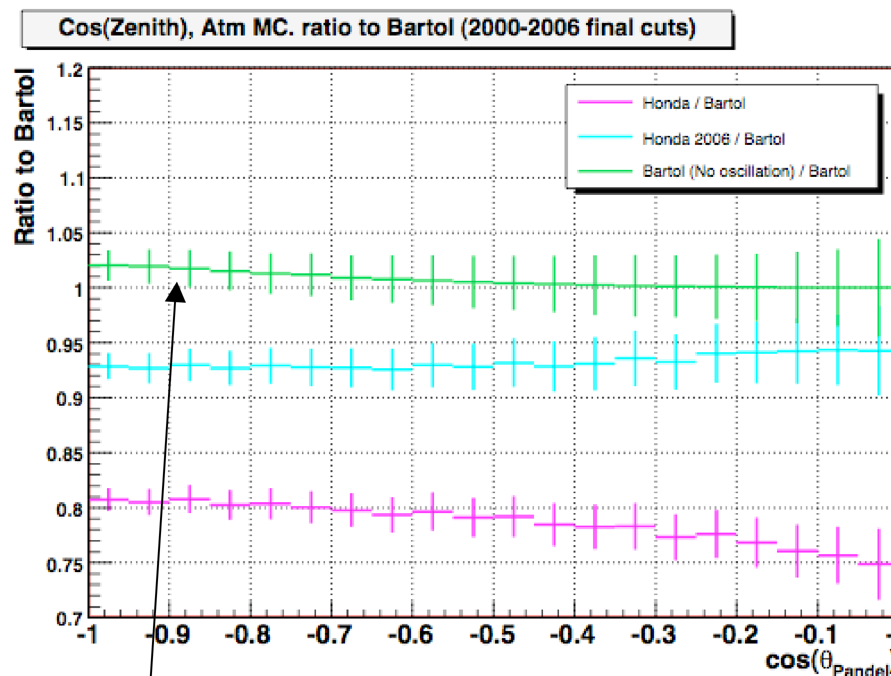
error	type	size	method
atm. ν flux model	norm.	±18%	MC study
σ_ν, ν-μ scattering angle	norm.	±8%	MC study
reconstruction bias	norm.	-4%	MC study
ν_τ-induced muons	norm.	+2%	MC study
charm contribution	norm.	+1%	MC study
timing residuals	norm.	±2%	5-year paper
μ energy loss	norm.	±1%	5-year paper
rock density	norm.	<1%	MC study
primary CR slope (incl. He)	slope	$\Delta\gamma$ = ±0.03	Gaisser *et al.*
charm (slope)	slope	$\Delta\gamma$ = +0.05	MC study
π/K ratio	tilt	tilt +1/-3%	MC study
charm (tilt)	tilt	tilt -3%	MC study
OM sensitivity, ice	OM sens.	sens. ±10%	MC, downgoing μ

Atmospheric Flux Models

Norm. difference between Bartol, Honda2006: -7%

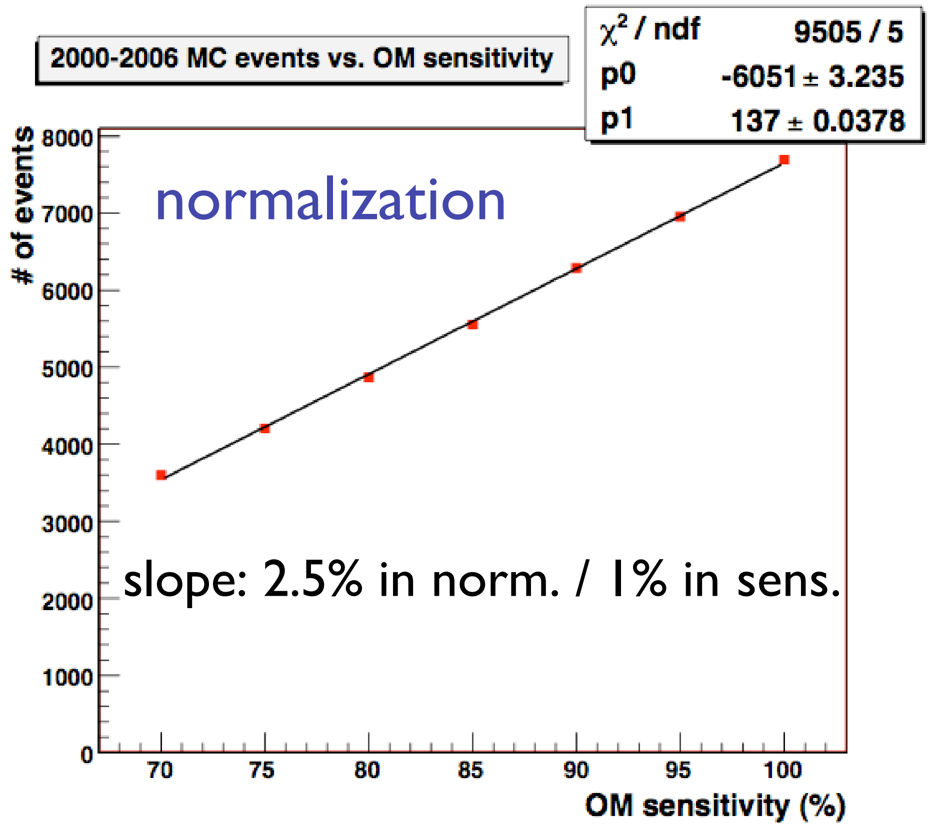
But difference in ν_μ: -18%; 1/3 ν_μ-bar: +11%

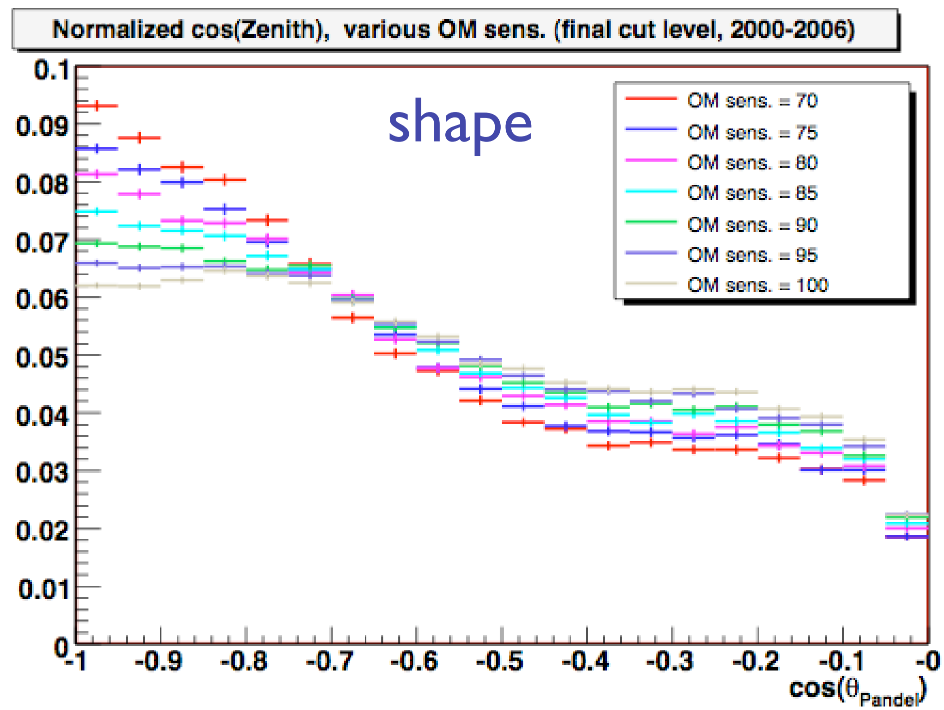




side note: effect of mass-induced neutrino oscillations is O(1%)

OM Sensitivity





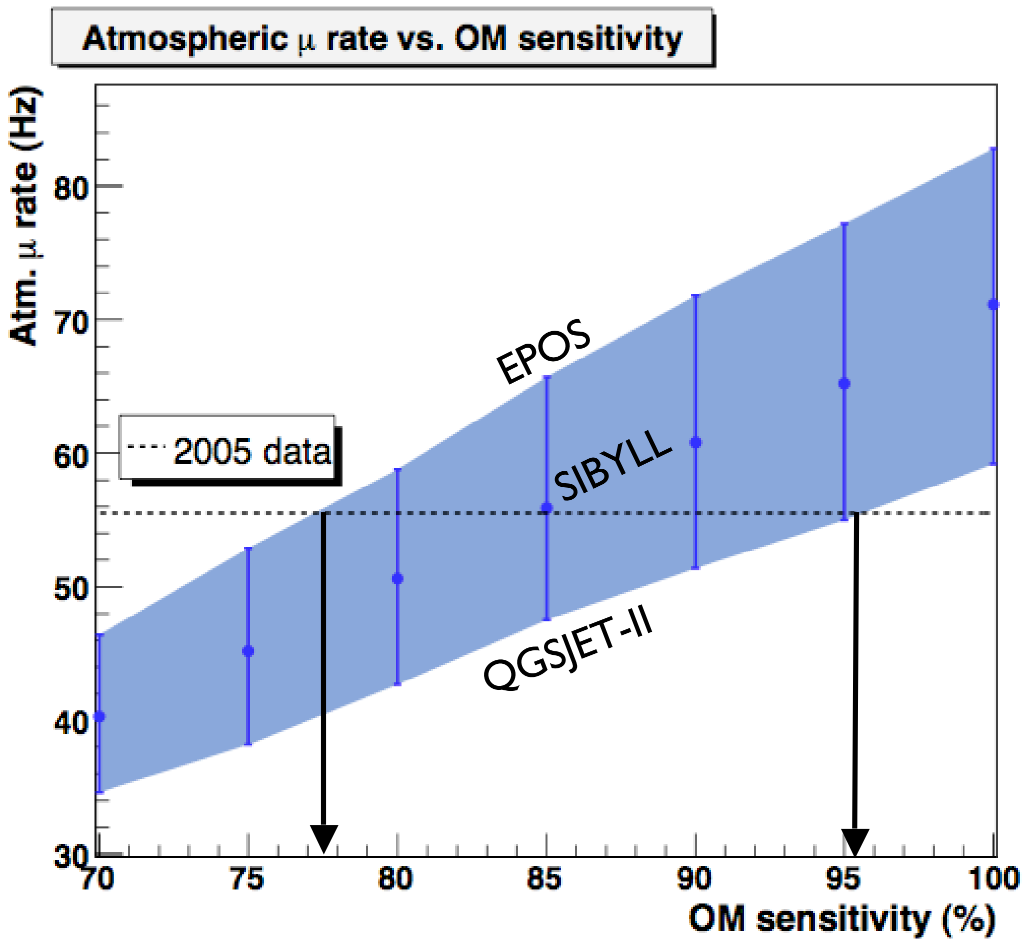
Unfortunately not possible to parametrize all effects on observables (I tried)

⇒ new simulation for every year + sensitivity (above right plot is 63 sets)!

Study with atmospheric muons

- Compare muon rate in data (trigger level + cleaning) with AHA simulation at various OM sensitivities
- Error band on normalization from spread in hadronic models (EPOS, QGSJET-II, and Sibyll)
- Pull out a range of allowed OM sensitivities and a mean for this ice model

Estimated Error



OM sensitivity (AHA)

85% +10%/-7%

- Zeuthen estimate using atm. ν zenith angle shape: 100% +3%/-10% (PTD/MAM)
- Error spread is close via two methods (17% here vs. 13% Zeuthen)
- Difference in mean is from ice model

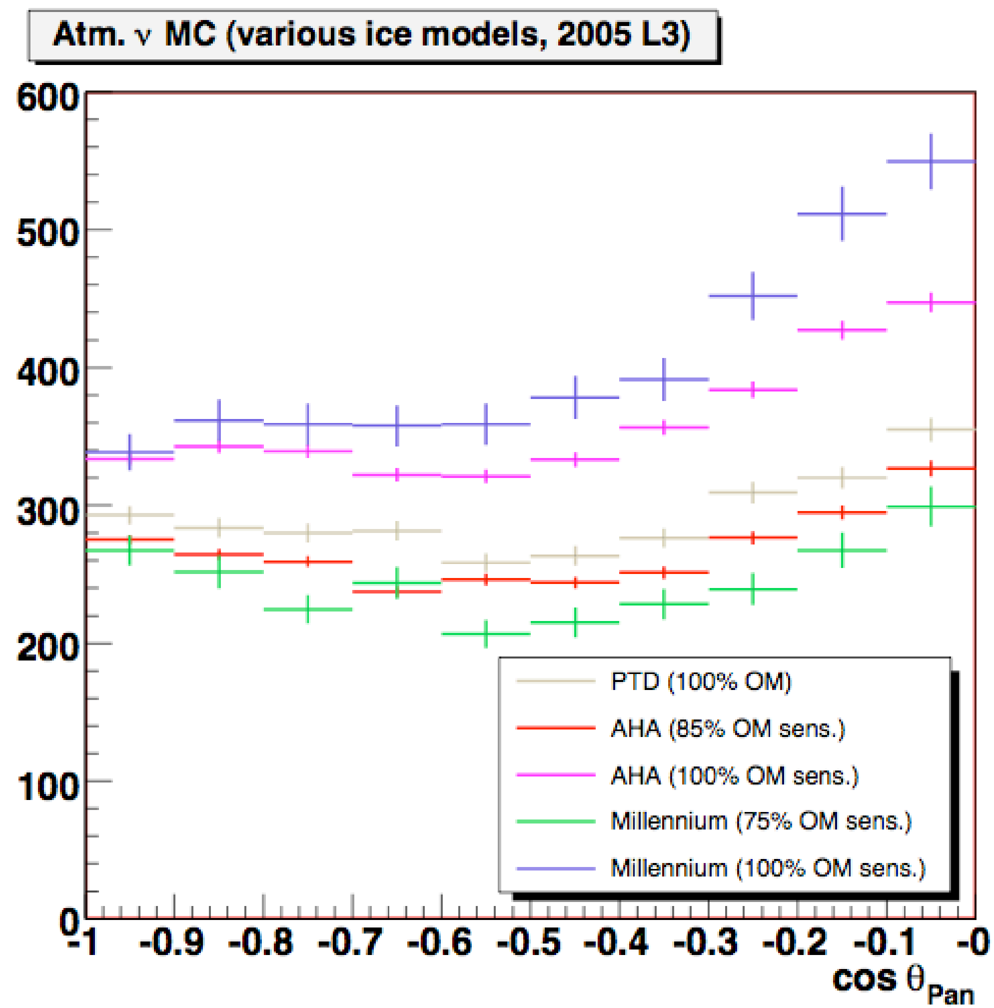
Ice Models

- Millennium + 100% OM,
  AHA + 100% OM:
  both have too much light (at least with v1.54-caustic)

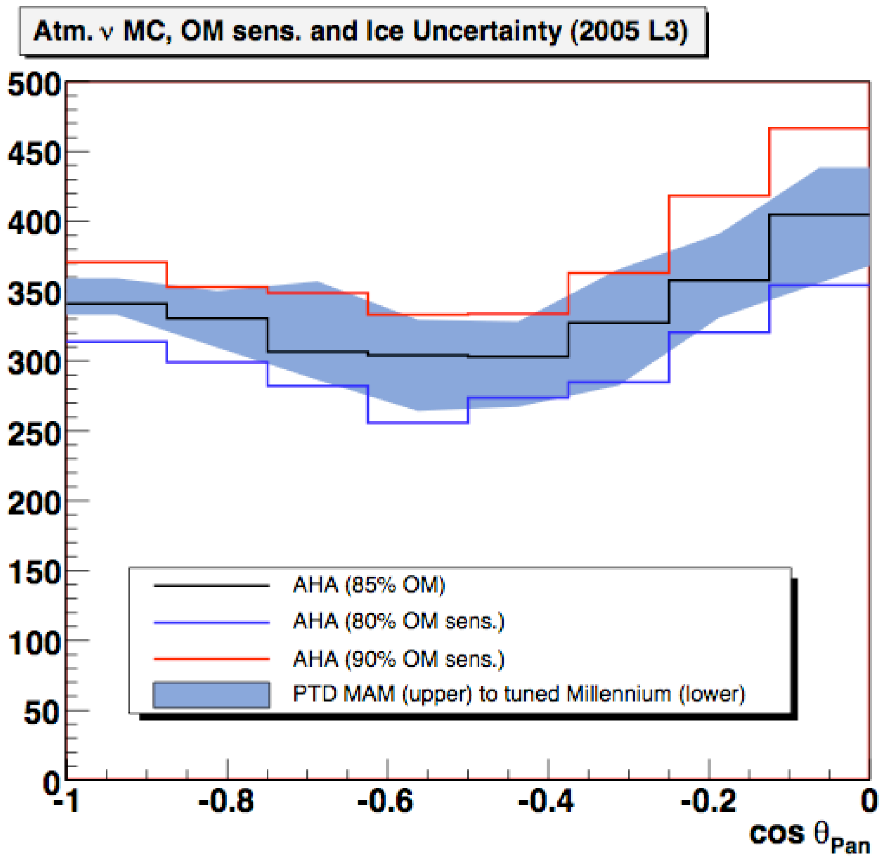
- Turn down OM sensitivity to correct muon rate (also fixes neutrino simulation), combine ice + OM errors

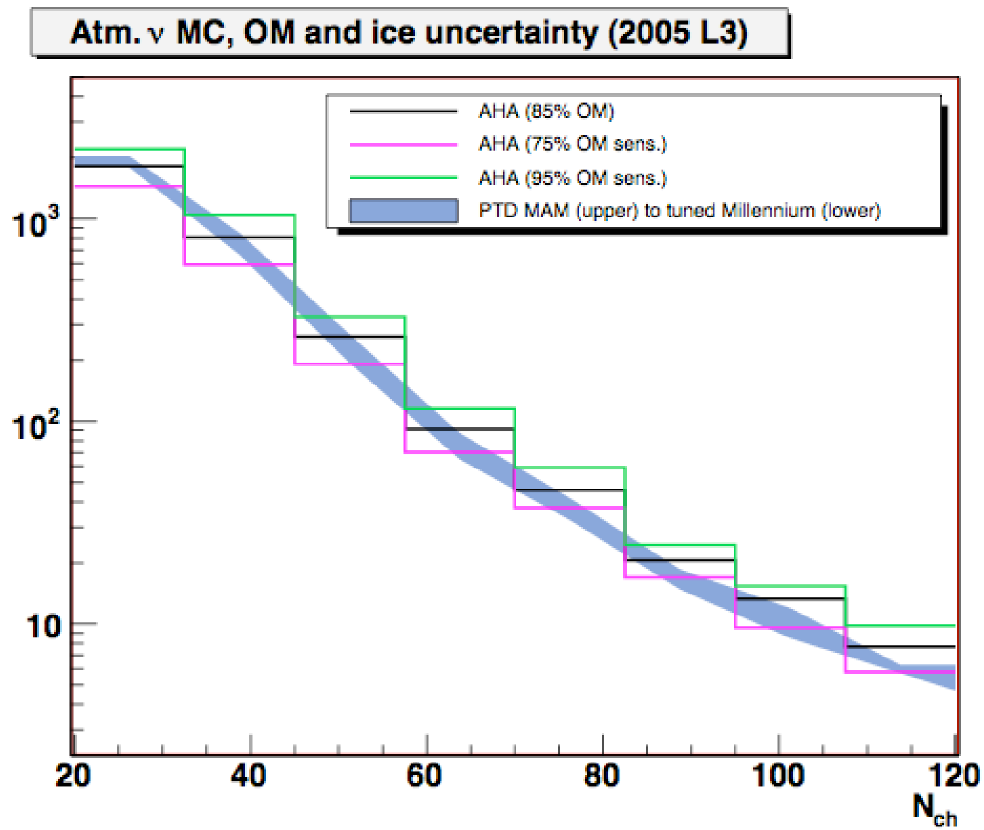
Atm. ν vs. PTD/MAM:

Millennium	+39%
AHA	+23%
AHA (85% OMs)	-8%



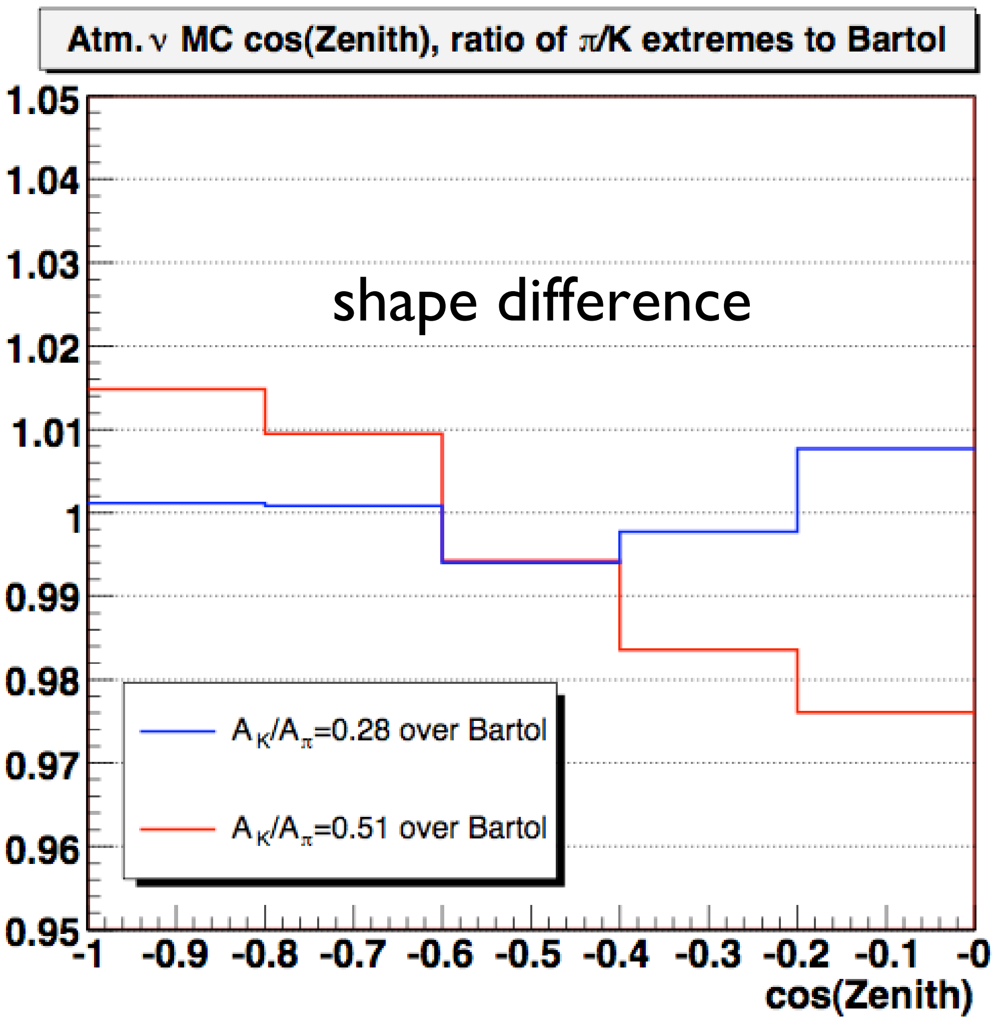
Ice Model Uncertainty



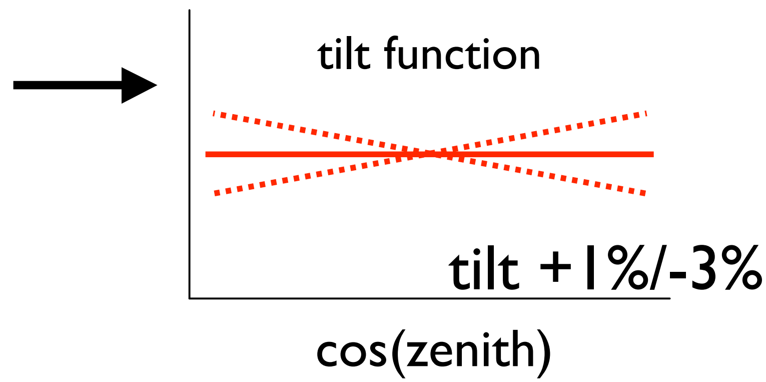


Covered by ±10% in OM sensitivity (roughly same uncertainty as muon analysis)

Pion/Kaon Ratio

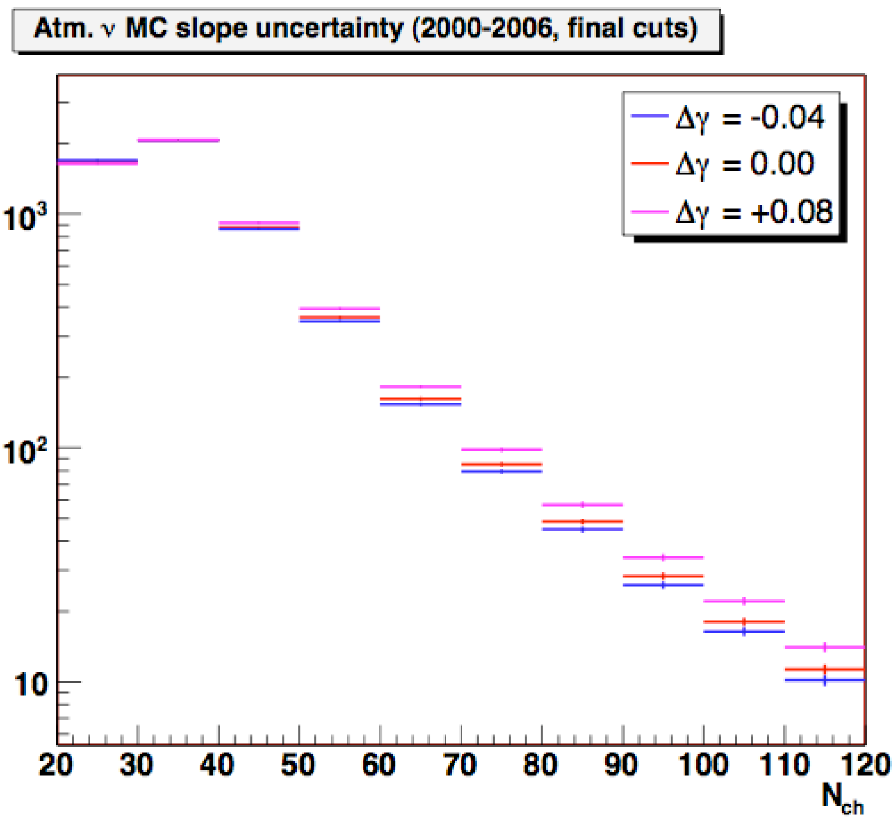


Change π/K ratio using Gaisser formulation: uncertainty in $Z_{N\pi}$, Z_{NK}*: $A_K/A_\pi \in [0.28, 0.51]$



*Agrawal *et al.*, PRD **53** (1996)

Spectral Slope



- Uncertainty in primary CR slope dominated by He: $\Delta\gamma_{He} = \pm 0.07^{*}$

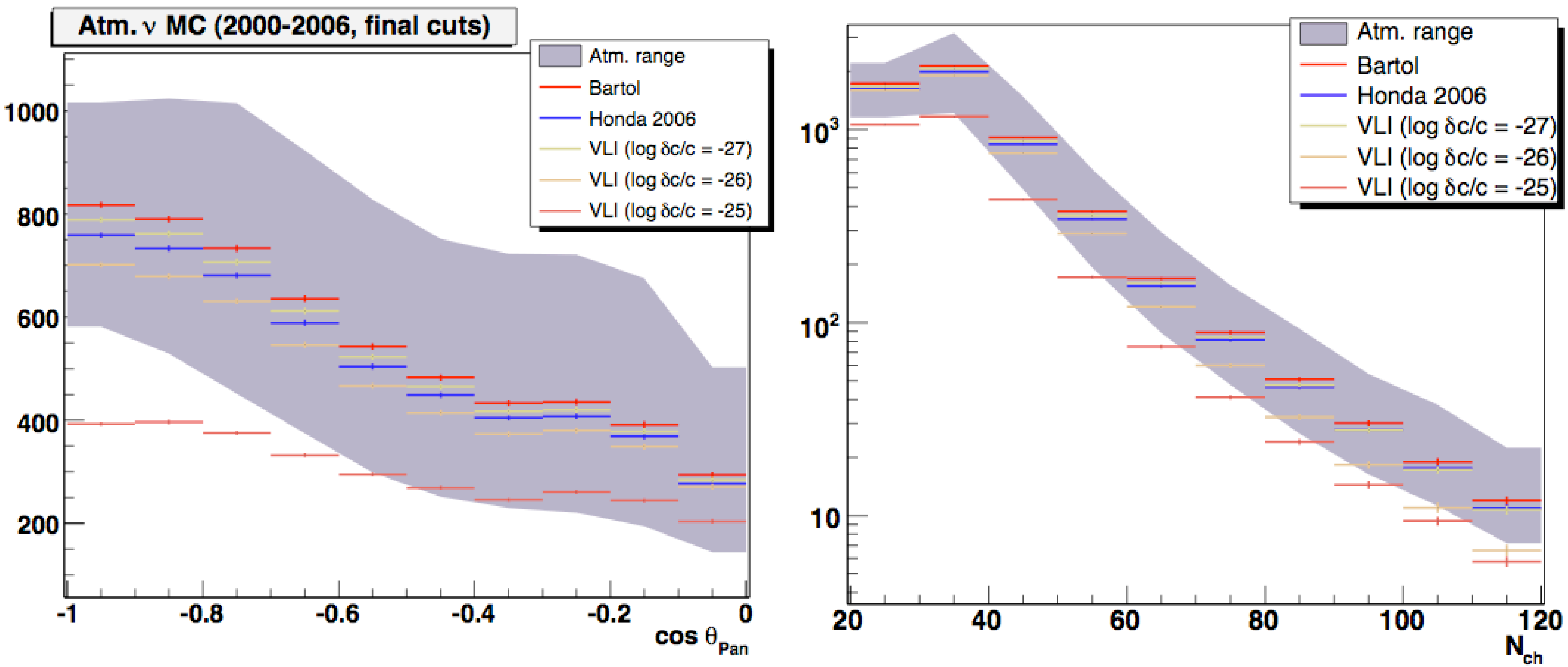
  to first order:
  $\Delta\gamma \approx \Delta\gamma_p + f_{He}\,\Delta\gamma_{He} = \pm 0.03$

- Tweak atmospheric model by $(E/E_{median})^{\Delta\gamma}$, $E_{median} = 630$ GeV

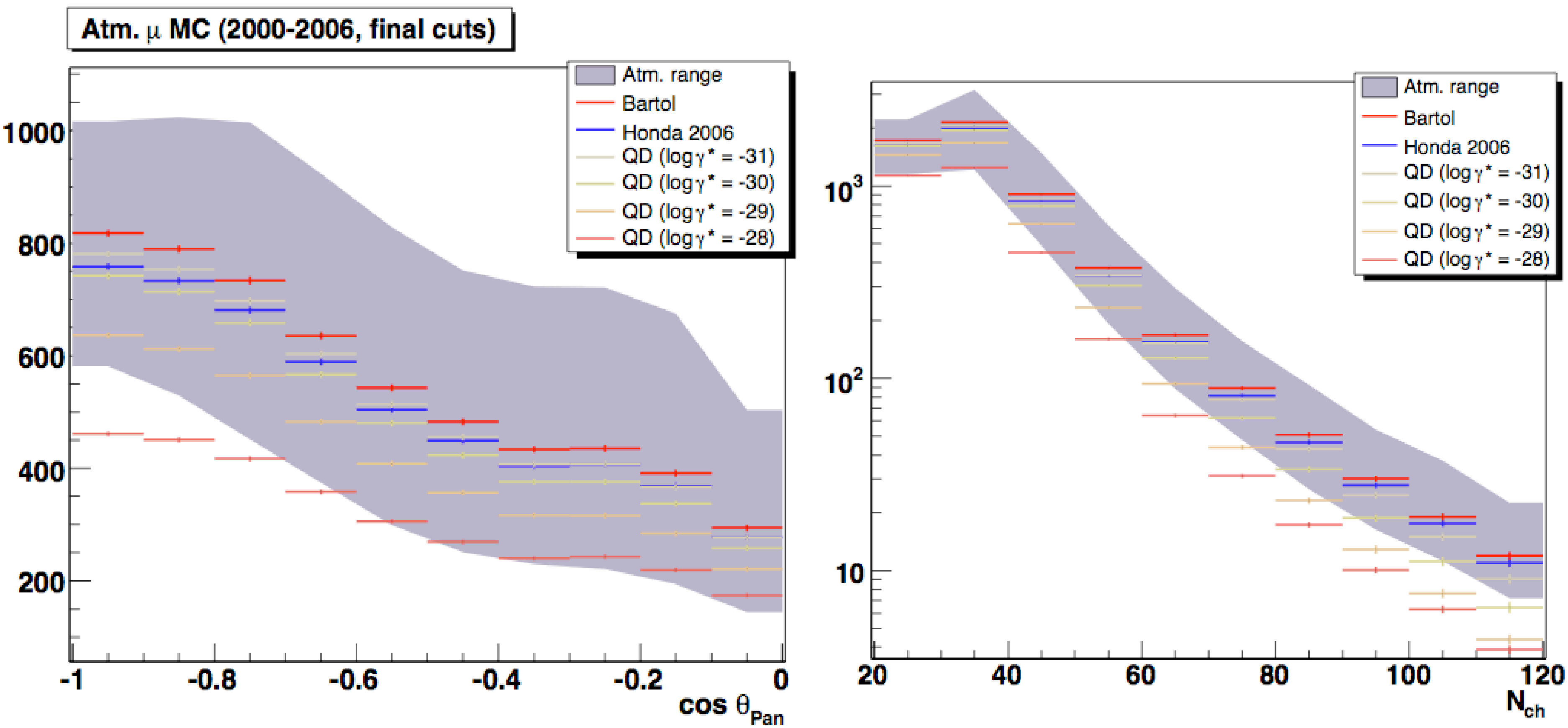
- Other uncertainties (charm) increase range of $\Delta\gamma$

*Gaisser, Honda *et al.*, 2001 ICRC

VLI + All Systematics Band



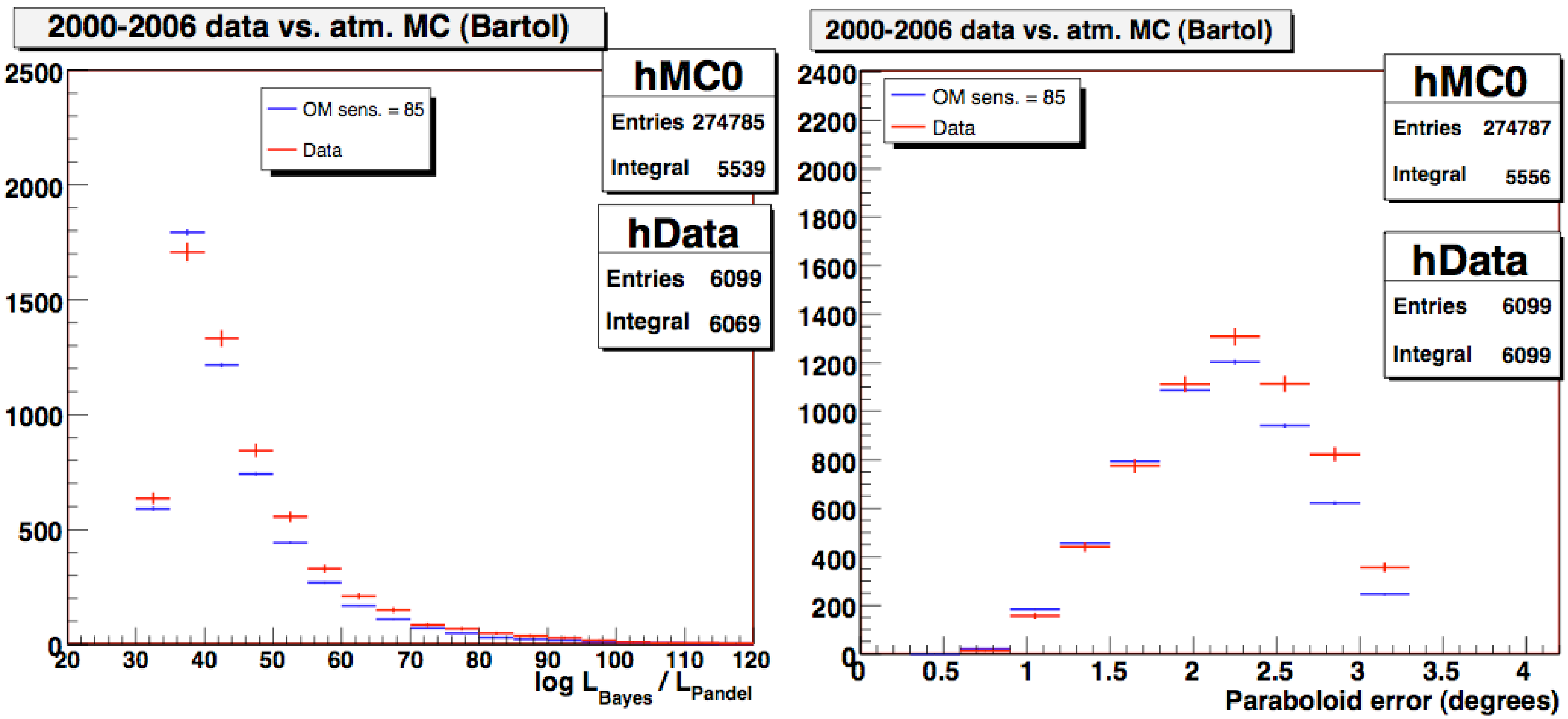
QD + All Systematics Band



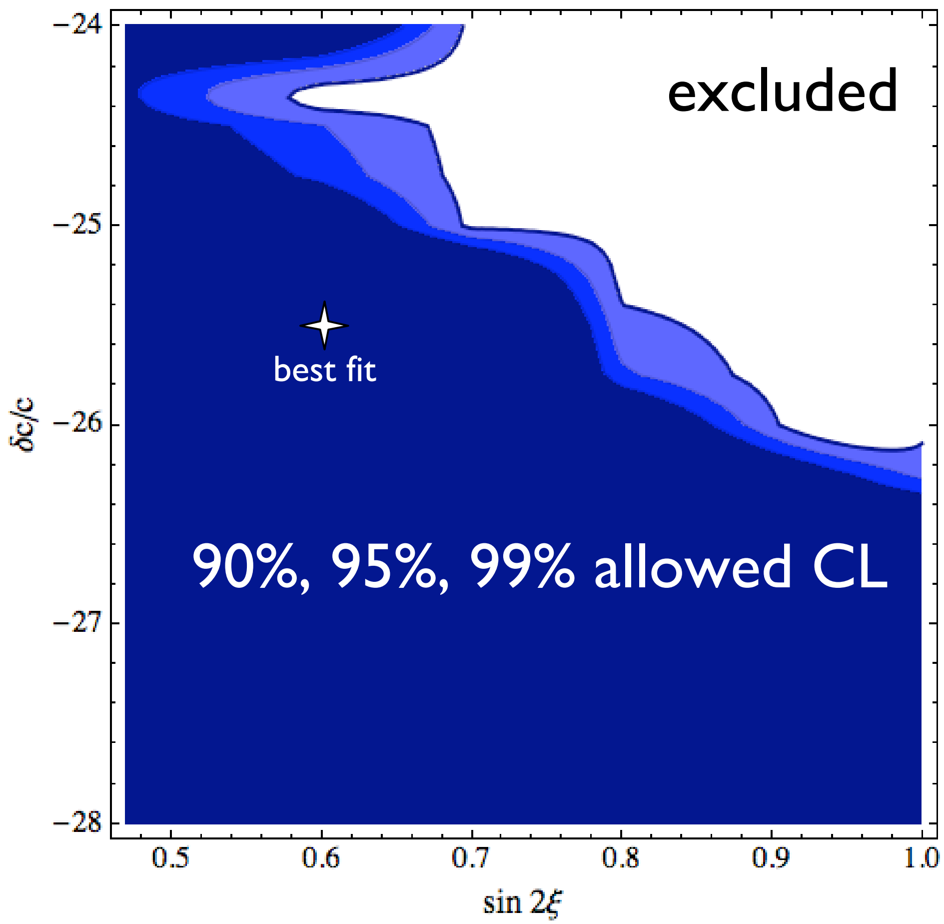
7-year Data Sample

- 2000-2006 data
  - 2000-04: Zeuthen combined filtering
  - 2005-06: Madison filtering
  - 1387 days livetime
- Zeuthen final cuts
  - purity is important (small unsimulated b.g.)
  - not specifically optimized for high energy
  - after cuts: 6099 events below horizon (4.4/day)
  - rate similar to 4-year Mainz sample (4.2/day)
- N_{ch}, zenith angle removed from files until unblinding

Data vs. MC Sample Plots



VLI Sensitivity



- 2000-03 analysis (Ahrens):

  $\delta c/c < 5.3 \times 10^{-27}$ (90%CL)

- Median sensitivity (χ^2 approx.):

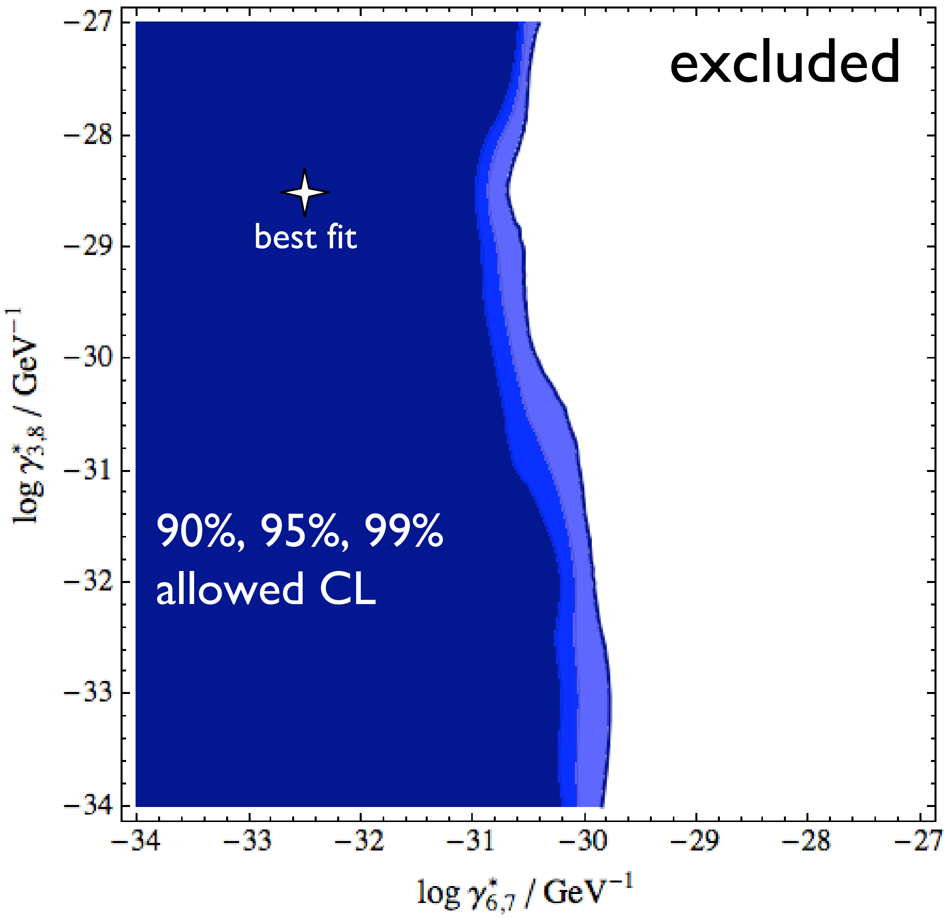
  $\delta c/c < 4.3 \times 10^{-27}$ (90%CL)

- Sample sensitivity (1 MC experiment, full construction):

  $\delta c/c < 4.5 \times 10^{-27}$ (90%CL)

(maximal mixing, $\cos \eta = 0$)

QD Sensitivity



- ANTARES sensitivity (3 years)*:

  $\gamma^* < 2 \times 10^{-30}$ GeV^{-1} (2-flavor)

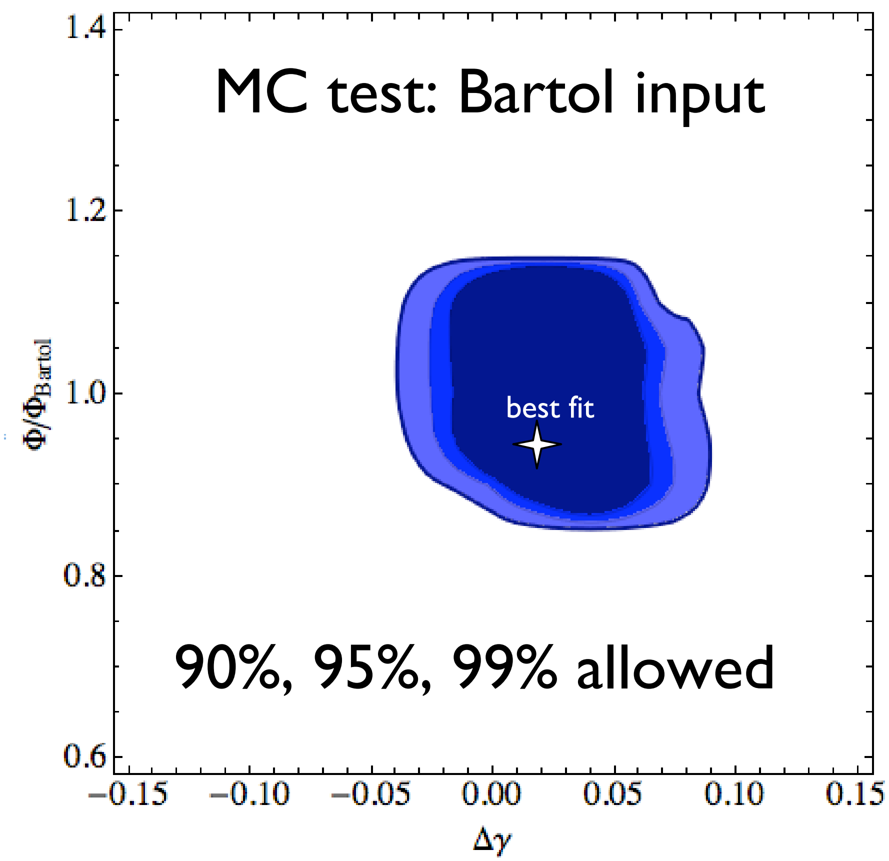
- This analysis (1 MC experiment, full construction):

  $\gamma^* < 2.0 \times 10^{-31}$ GeV^{-1}

  (E^2 model, $\gamma_3 = \gamma_8 = \gamma_6 = \gamma_7$)

* Morgan *et al.*, astro-ph/0412618

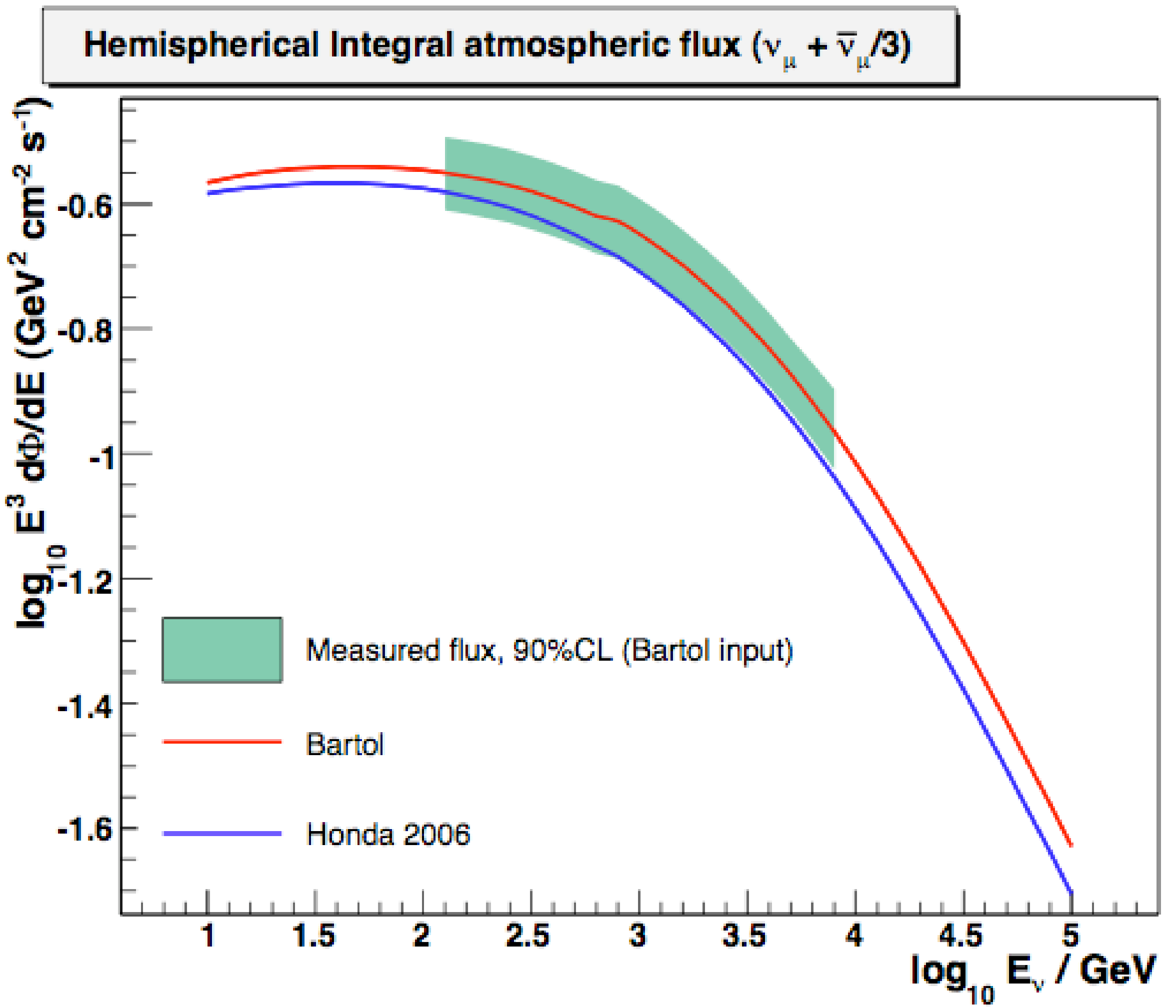
Conventional Analysis



- Parameters of interest: normalization, slope change $\Delta\gamma$
- Nuisance parameters: remove atm. flux norm. and slope uncertainty, keep others
- Sensitivity: roughly ±15% in normalization, ±0.07 in slope

Energy Spectrum

- Allowed band: range of parameters from previous plot
- Energy range: intersection of 5-95% regions, MC final cut level, various OM sens.
- With data: will use both Bartol and Honda as reference shapes, allowed regions should be similar

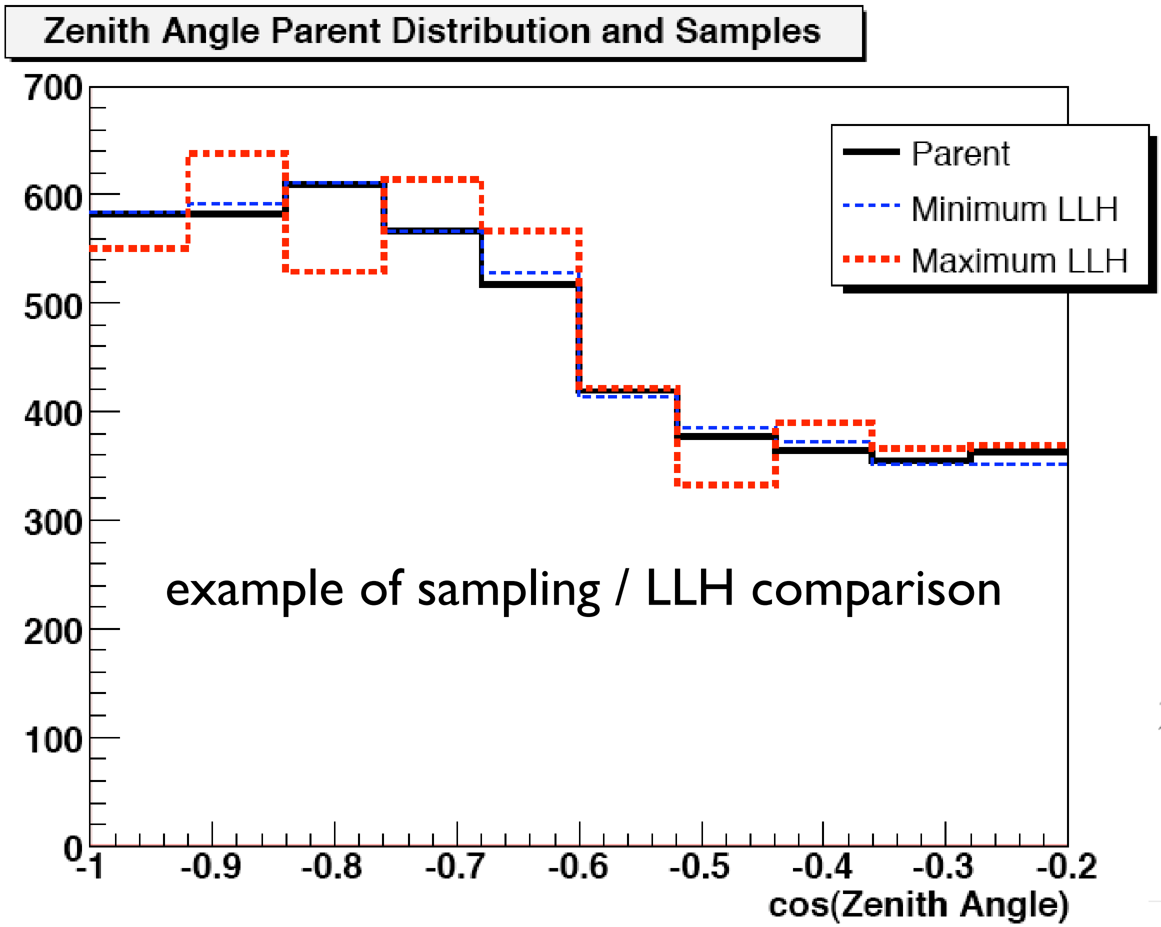


On the Docket

- May add E^3 decoherence, E^2 VLI
  - analysis procedure the same, just computation time
- Possible mid-to-high-N_{ch} excess in data
  - discussion violates blindness, but excess would be inconsistent with any proposed new physics hypothesis
  - will design two-step unblinding procedure to address any serious contamination
- Unblinding request out to working group very shortly!

Extra Slides

Analysis Methodology: Binned Likelihood Test



Poisson probability

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

Product over bins

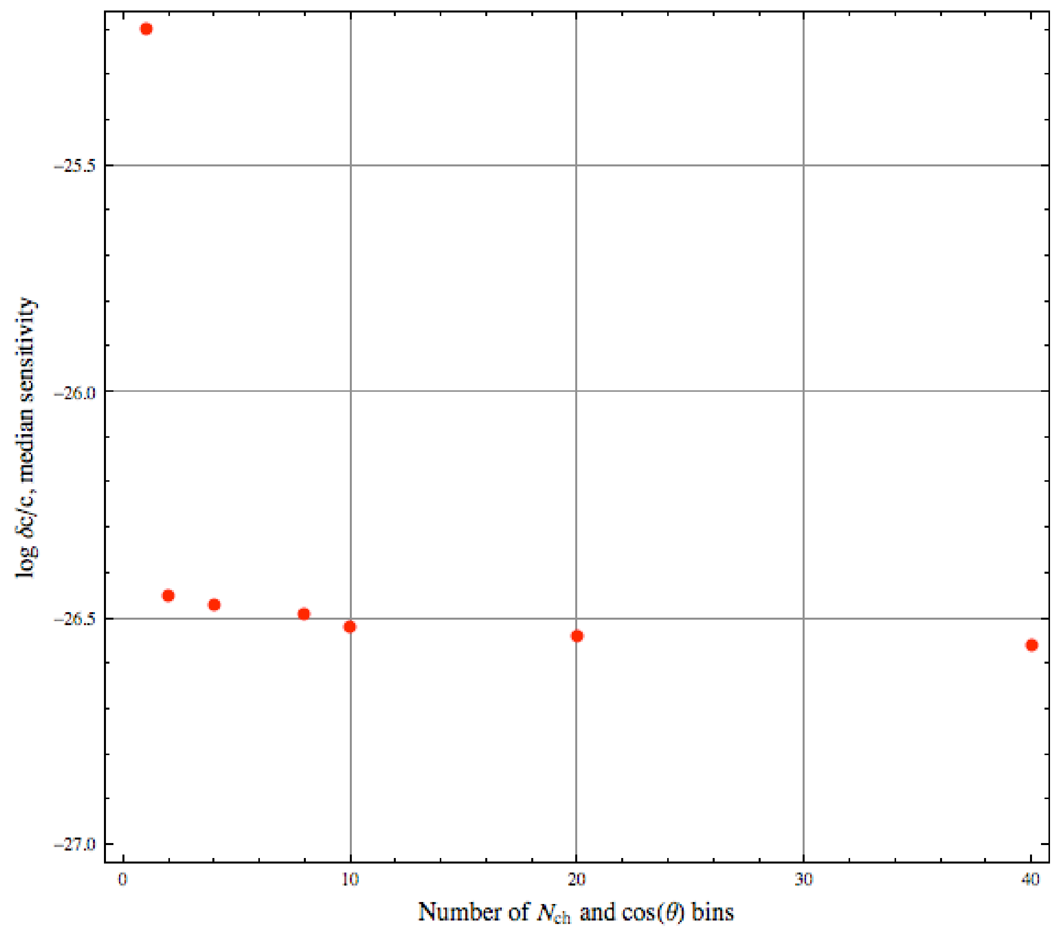
$$P_p(\{n_i\}) = \prod_{i=1}^{N} e^{-\mu_i}\frac{\mu_i^{n_i}}{n_i!}$$

Test Statistic: LLH

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

Optimal Binning

- In general: finer binning is always better for LLH analysis
- But gain after a certain point is nominal, could run into data/MC artifacts
- Use 10 bins in each observable



Computational Details

- Weighted MC observable histograms precomputed on a grid in $\{\theta_r, \theta_s\}$ space (θ_r more finely binned)
  - ~2min./histogram x 16k-32k points/hypothesis = 1 CPU-month / hypothesis
- 1000 MC experiments per point in $\{\theta_r\}$ space
  - likelihood minimization over $\{\theta_r, \theta_s\}$ exhaustive search because of discrete parameter space
  - construction: about 12h / hypothesis (still manageable)
- Recording confidence level at each point (instead of just yes/no at a CL) allows some contour interpolation

MC Sample(s)

- nusim: zenith range (80,180) with γ=1.5
- Amasim Aluminum-opt5 + AHA ice (v1) + Photonics 1.54-caustic
- (9 periods) x (7 OM sens.) = 63 MC sets
  - everything else via weighting
- For atm. neutrinos: ~60 years of effective livetime at each OM sensitivity

$$L\frac{n_{\mathrm{eff}}}{T} = \frac{L\ \sum w_i}{\sum w_i^2} = L_{\mathrm{eff}}$$