Analysis of neutrino-induced upward-going muons with Super-Kamiokande

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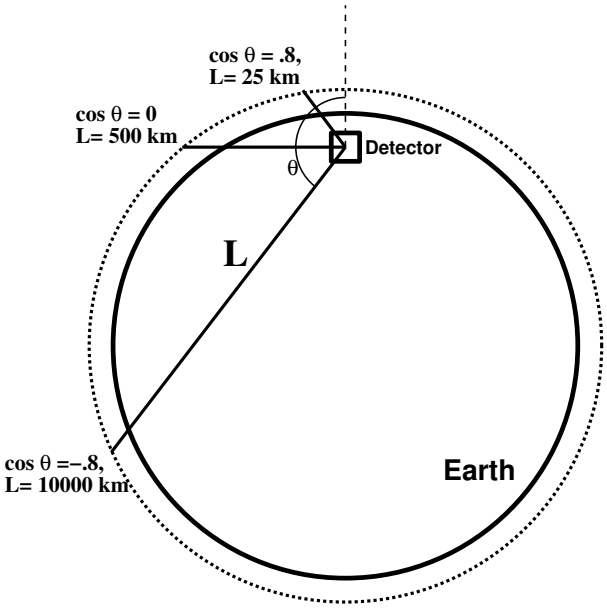
Abstract:

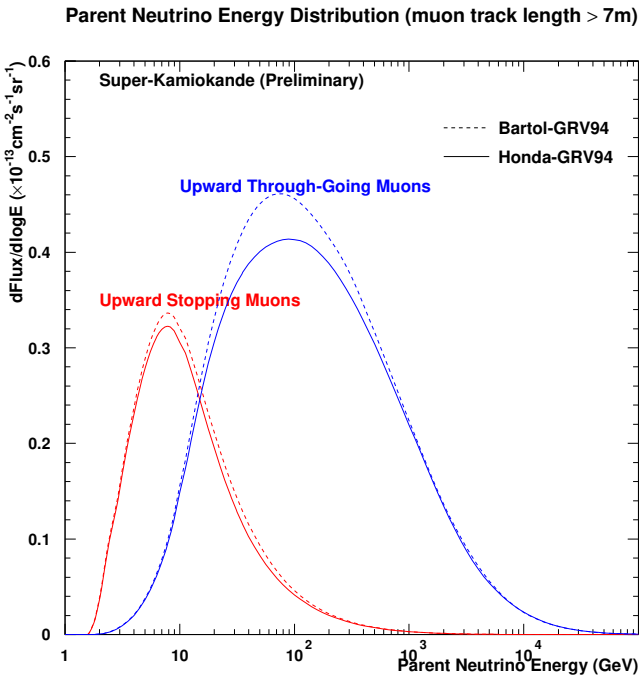
We have analyzed more than 500 days of Super-Kamiokande data and obtained both the upward stopping and upward through-going neutrino-induced muon fluxes. Both the shape of the through-going zenith angle distribution and the ratio of stopping to through-going fluxes are not consistent with expectations, unless those expectations are recalculated under the assumption of $\nu_\mu \rightarrow \nu_\tau$ oscillations. We have used these measurements to test which values of $sin^2(2\theta)$ and Δm^2 best match the observed zenith angle distribution and stopping/through-going flux ratio. This allowed region is consistent with the parameters measured using the fully contained Super-K atmospheric neutrino dataset.

Up-going μ's in Super-K

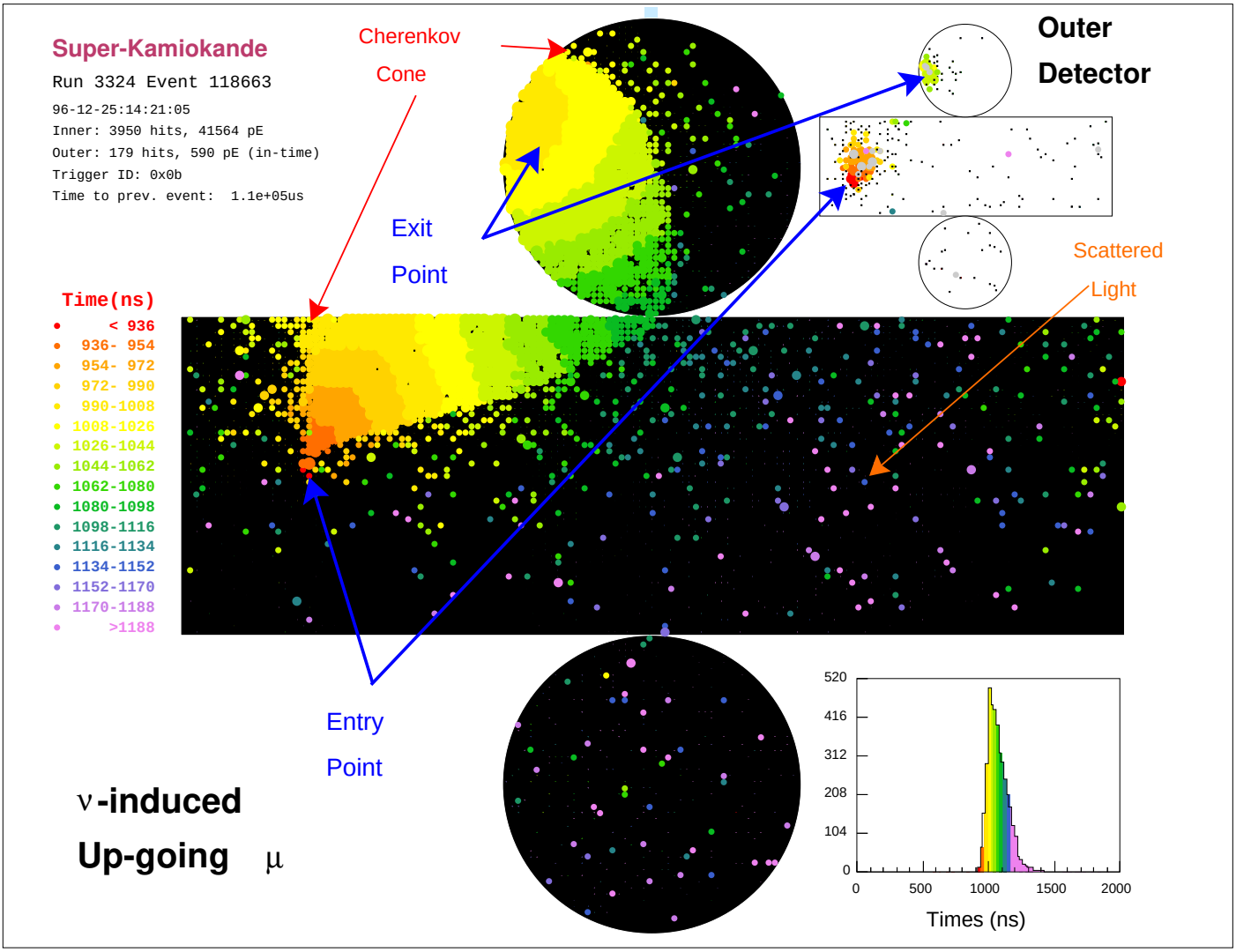
μ's headed upwards in an underground detector come from ν_μ interactions in the rock below. The primary ν origin is in cosmic-ray induced air-showers.



Lower energy ν's produce lower energy μ's, which might range out inside the detector - called "stopping up-μ's".



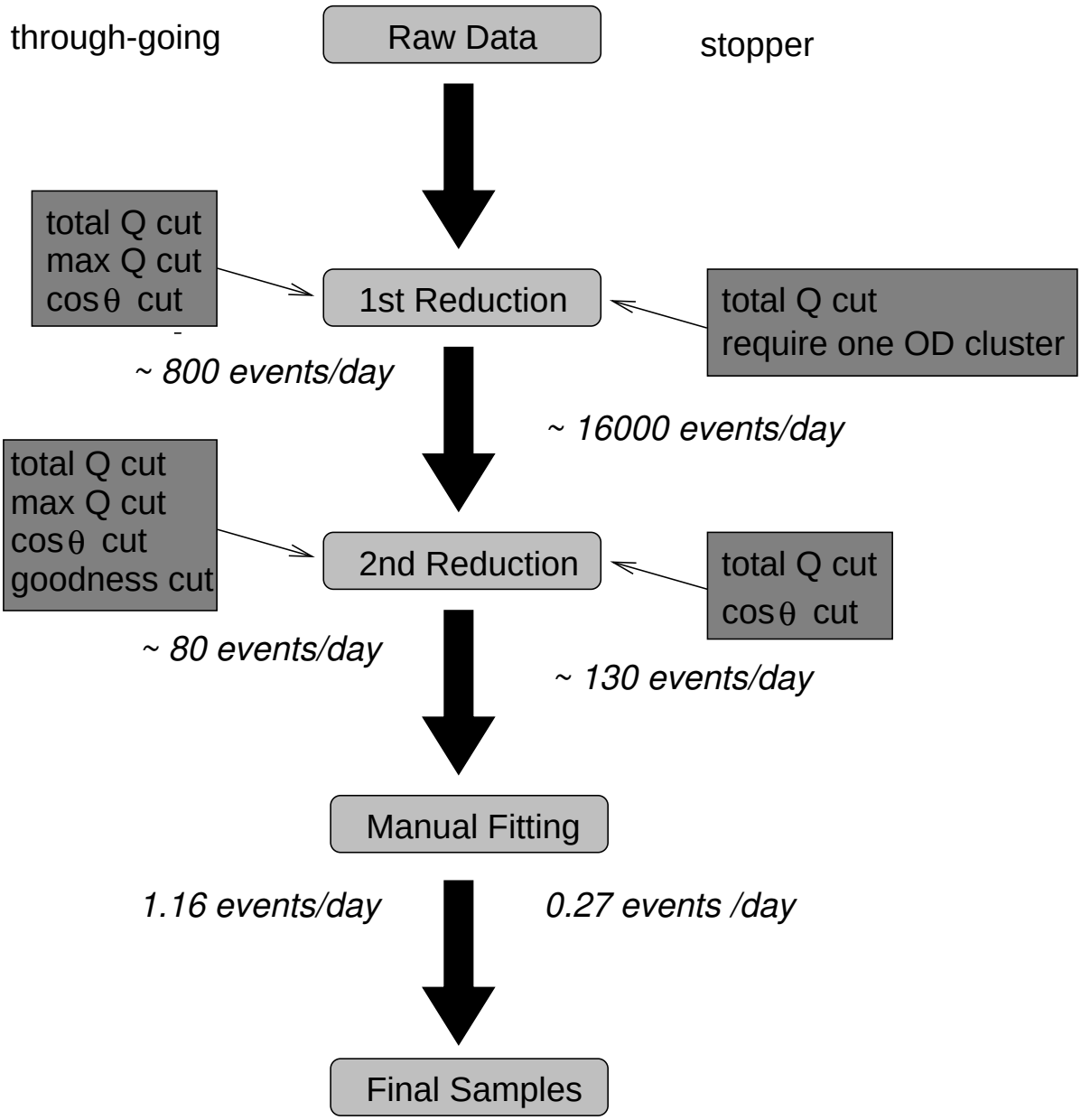
An up-μ as seen in Super-K



This is an "unrolled" view of a Super-K up-μ. Imagine the Super-K cylinder cut open and flattened like a tin can. Colored dots are hit phototubes. They are colored in time, with red being the earliest hits, green being later, and purple being last.

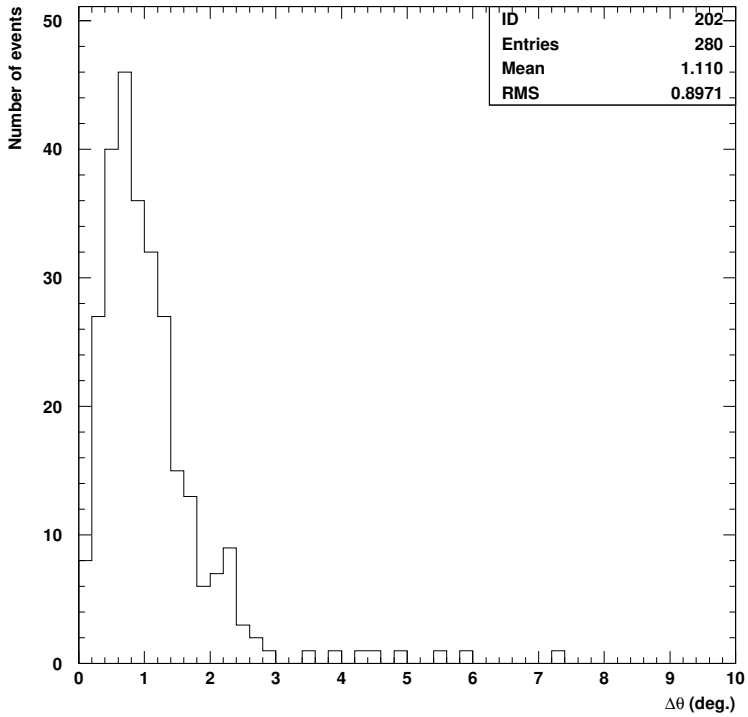
The progression of time along the Cherenkov cone of the μ identifies this μ as going upwards.

Data Reduction

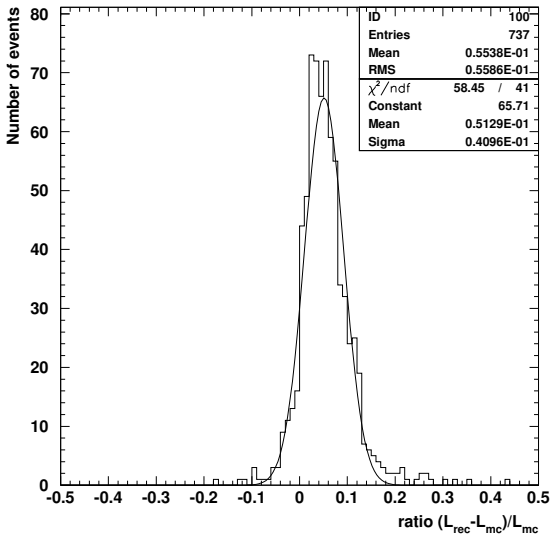


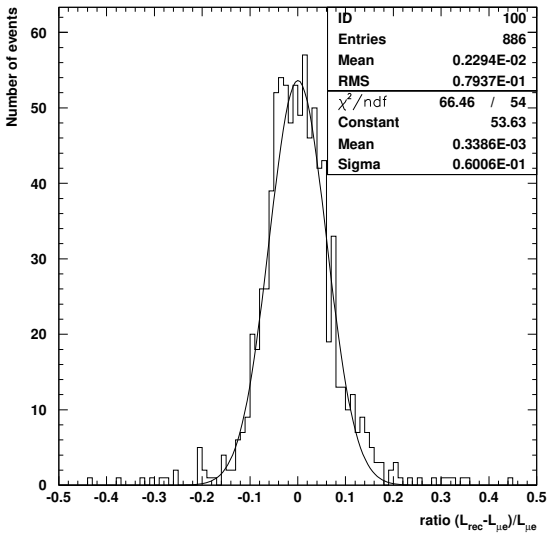
Fitting Resolution

$\Delta\theta$ in direction between fit value and MC direction.

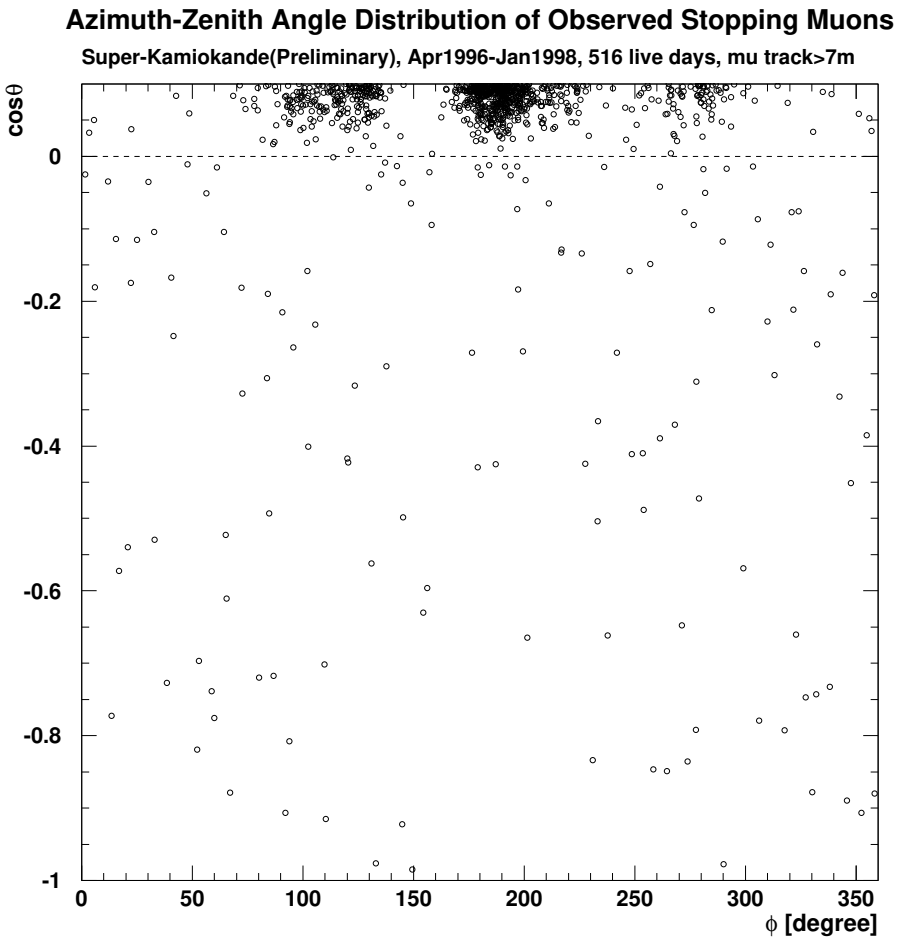


Track length estimation compared to MC stopping point (left) and decay e^- vertex (right).





Background Subtraction

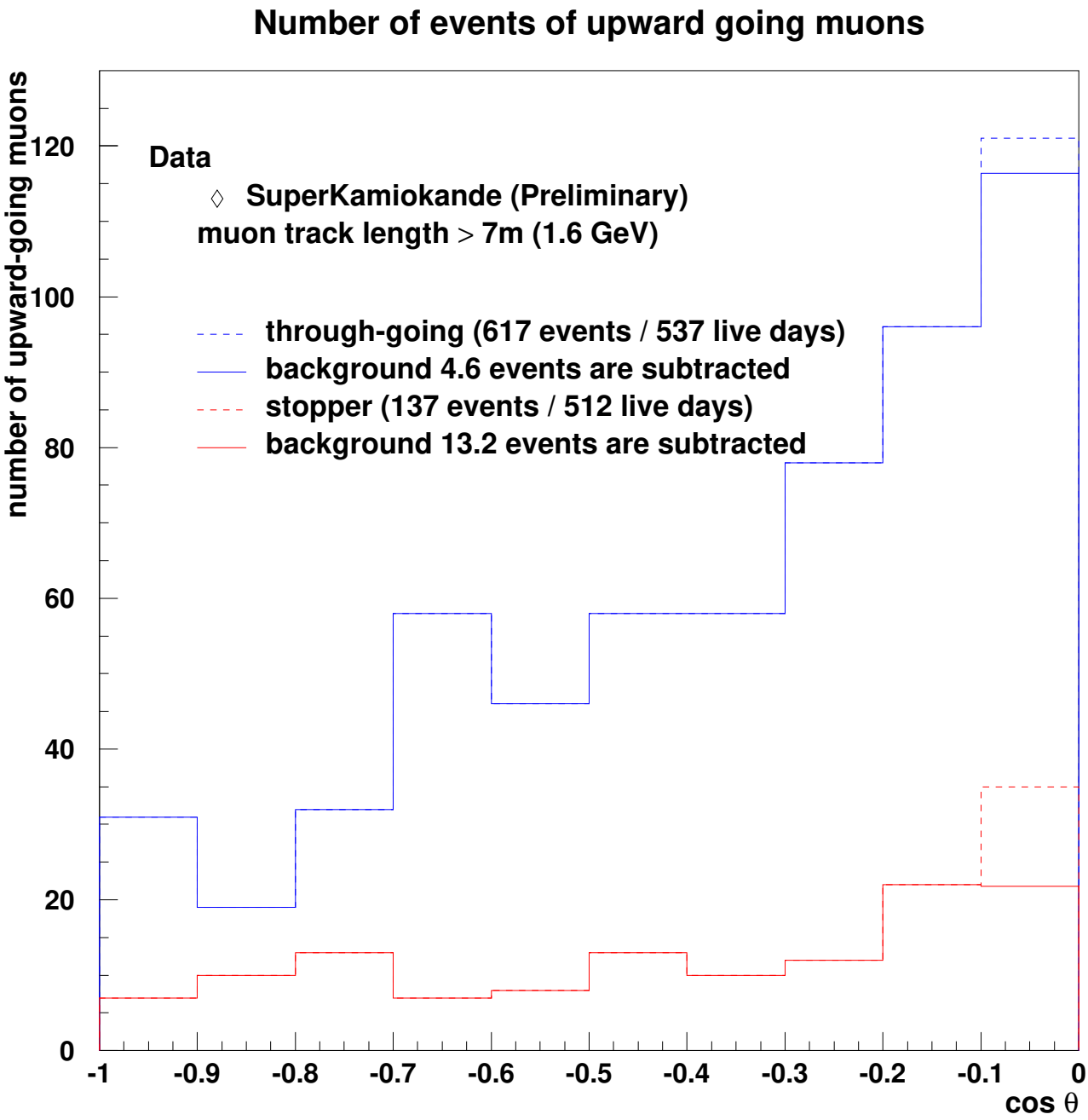


The spatial distribution of stopping-μ events near the horizon. Note the clusters of down-going events where the mountain is thin.

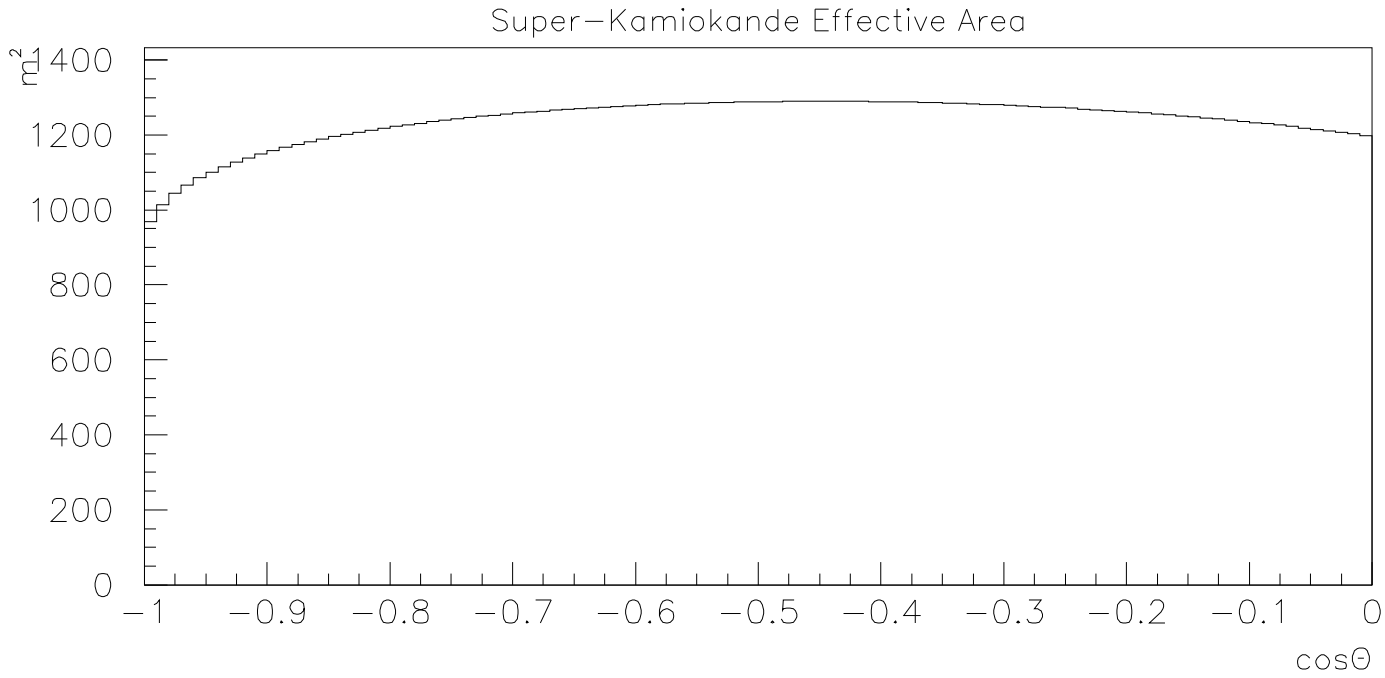
A fit to this distribution was done to estimate the number of cosmic-ray up-μs.

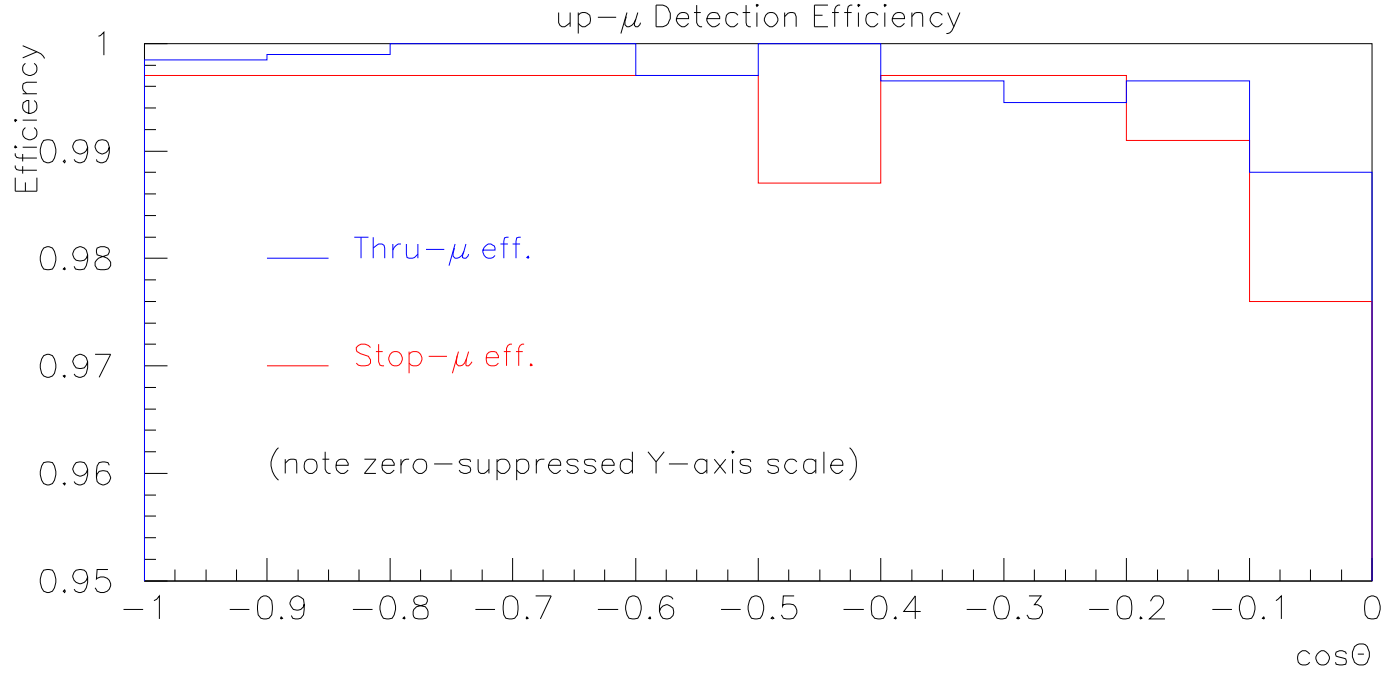
This yields a background of 4.59 through-μ's and 13.2 stop-μ's in the $-0.1 \leq \cos\Theta \leq 0.0$ bin.

Data vs. Zenith Angle



SK's up-μ Acceptance





Data Summary

Through-going up-μ's:

- 617 events in 537 live-days.
- BG: 4.59 events in the $-0.1 \leq \cos\Theta \leq 0.0$ bin.
- A total flux of: $\Phi_p =$ $1.75 \pm 0.07(stat) \pm 0.08(syst) \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$
- Honda'95 plus GRV94 PDF-DIS, QE, Multi-π, etc. predicts: $\Phi_p = 1.88 \pm 0.38 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

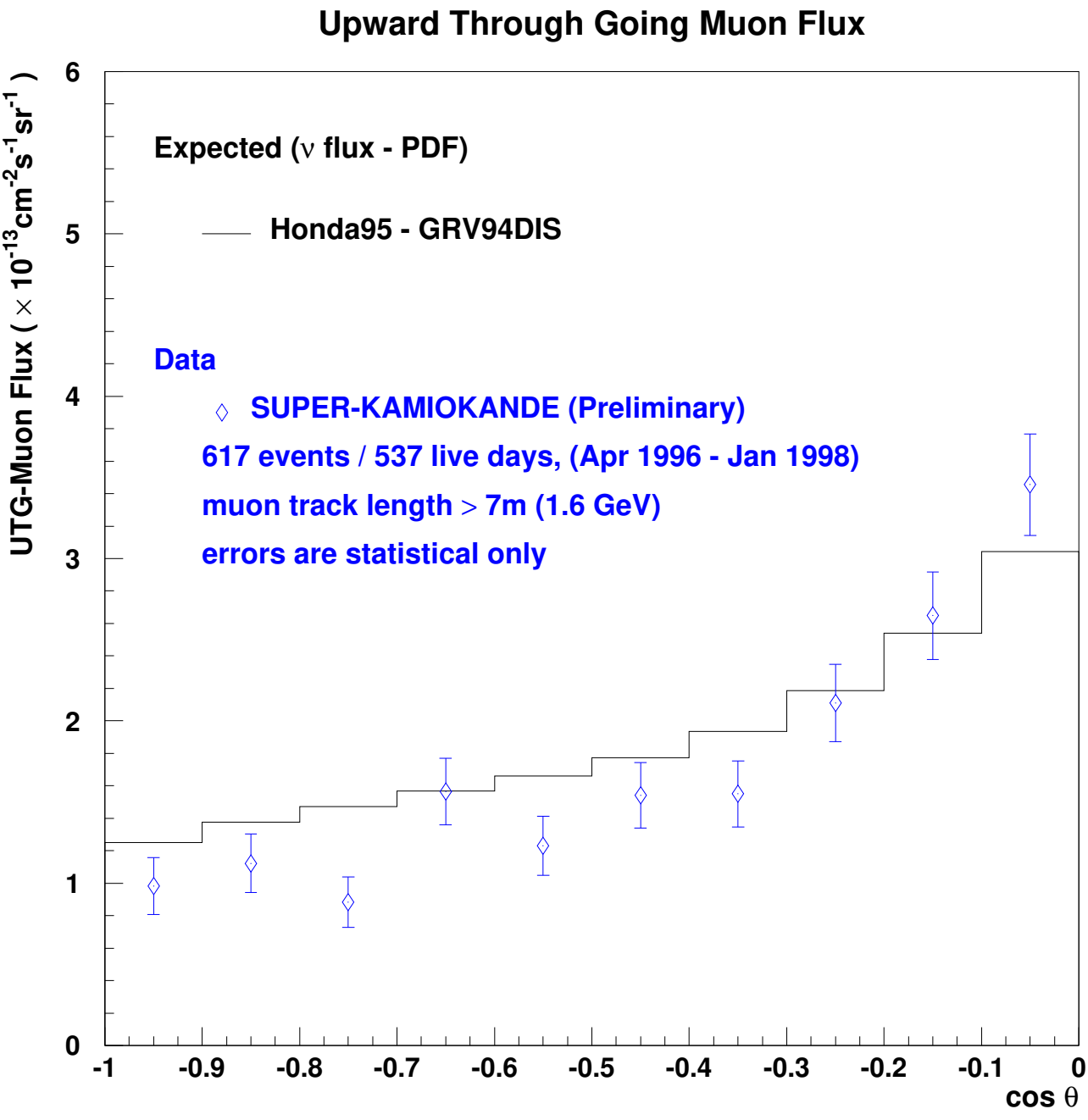
Stopping up-μ's:

- 137 events in 512 live-days.
- BG: 13.2 events in the $-0.1 \leq \cos\Theta \leq 0.0$ bin.
- A total flux of: $\Phi_s =$ $0.38 \pm 0.04(stat)^{+0.03}_{-0.02}(syst) \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$
- Honda'95 plus GRV94-DIS, QE, Multi-π, etc. predicts $\Phi_s = 0.73 \pm 0.15 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

The stop/through up-μ ratio:

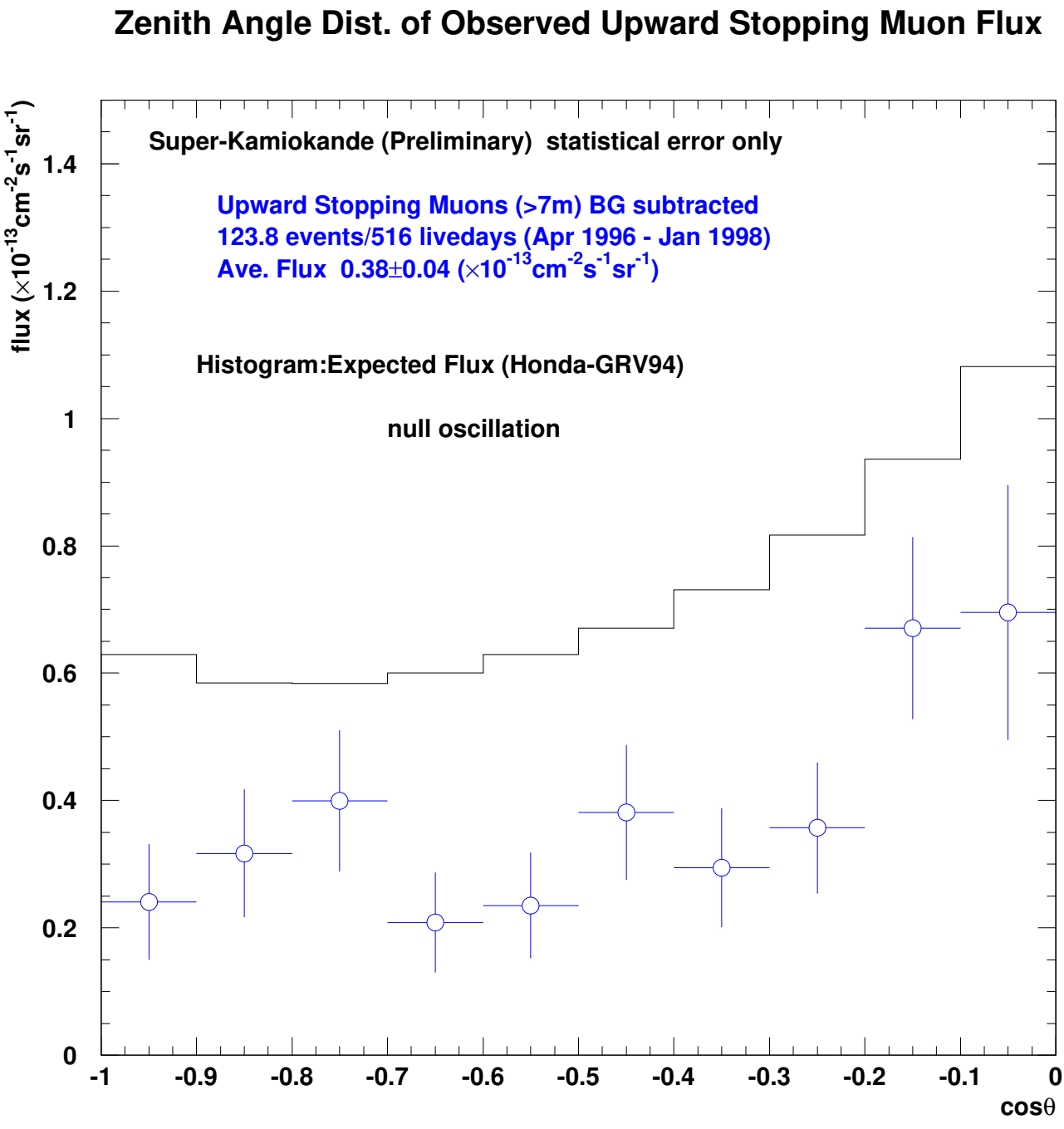
- $\Re = \Phi_s/\Phi_p = 0.217 \pm 0.023(stat)^{+0.014}_{-0.013}(syst)$
- Predicted $\Re = 0.388^{+0.052}_{-0.047}$

Through-going up-μ Flux



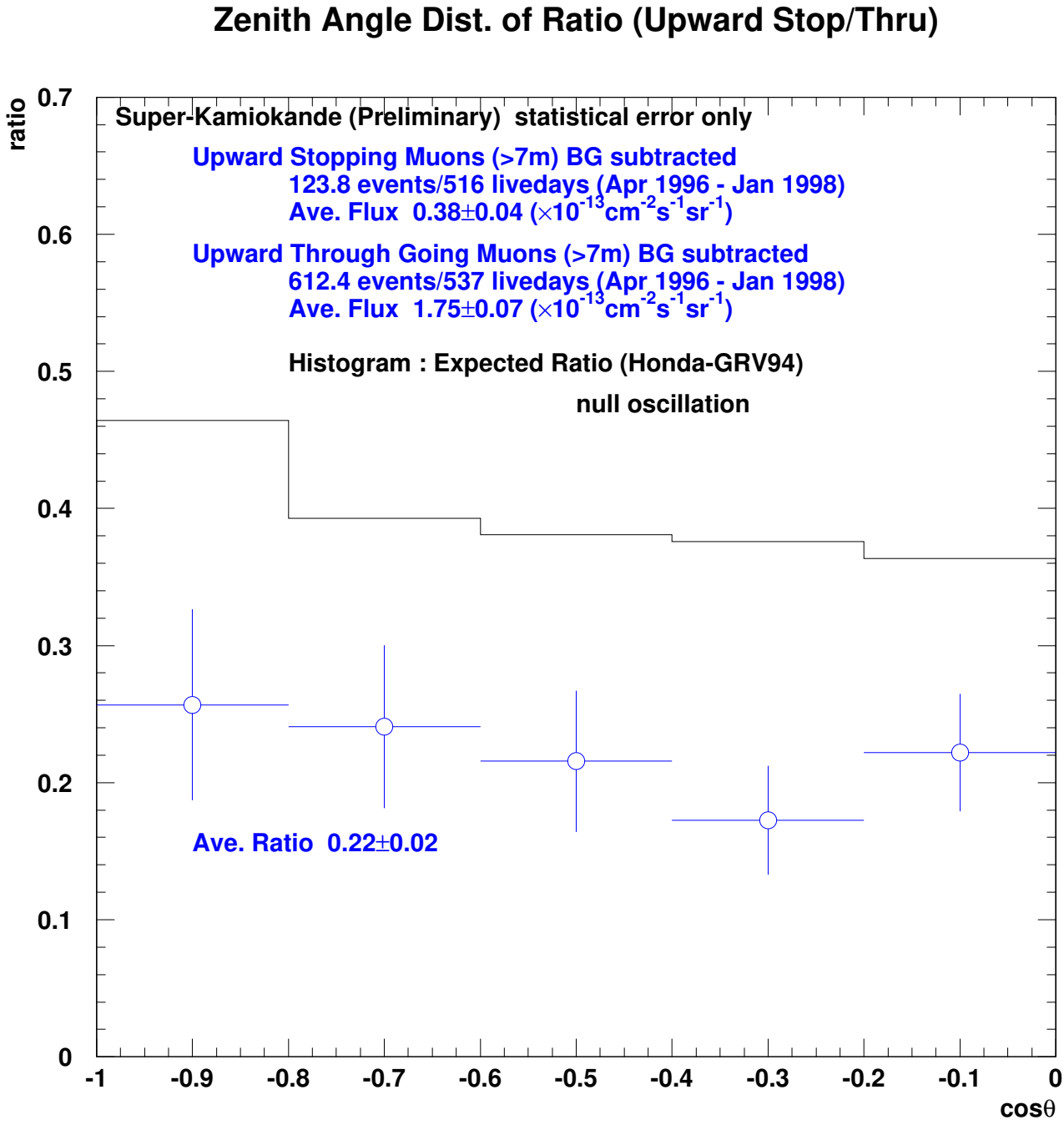
The theoretical absolute flux is uncertain by $\sim$20%, but the zenith angle shape is known to $\sim$5%.

Stopping up-μ Flux



The theoretical absolute flux is uncertain by $\sim$20%.

Stopping/Through-going Ratio



Much of the systematic error in the absolute flux cancels out in this ratio. The resulting error on the ratio is $\sim 14\%$, and is due mostly to the uncertainty in the cosmic ray spectral index.

ν Flavor Oscillations

Non-zero ν mass results in flavor oscillations. ν-induced up-going μ's are sensitive to this. The probability P of a ν_μ oscillating away is :

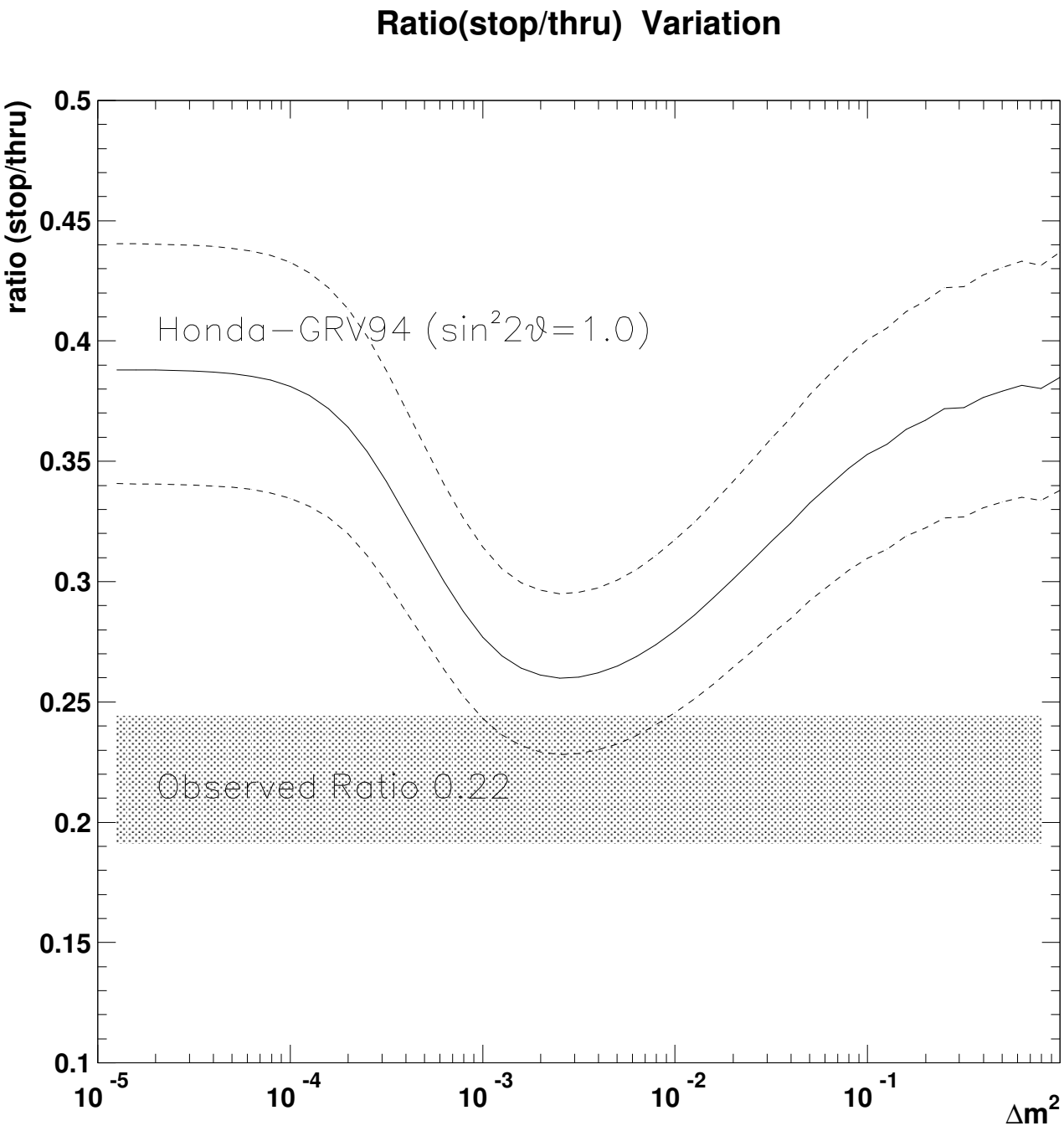
$$P_{\nu_\nu \to \nu_\tau} = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E_\nu} \right)$$

(L in km, E_ν in GeV, Δm^2 between flavors in eV^2).

Baseline L decreases with increasing up-μ zenith angle, so ν_μ near the nadir have a higher P to oscillate, producing a distortion in the shape of the zenith angle distribution.

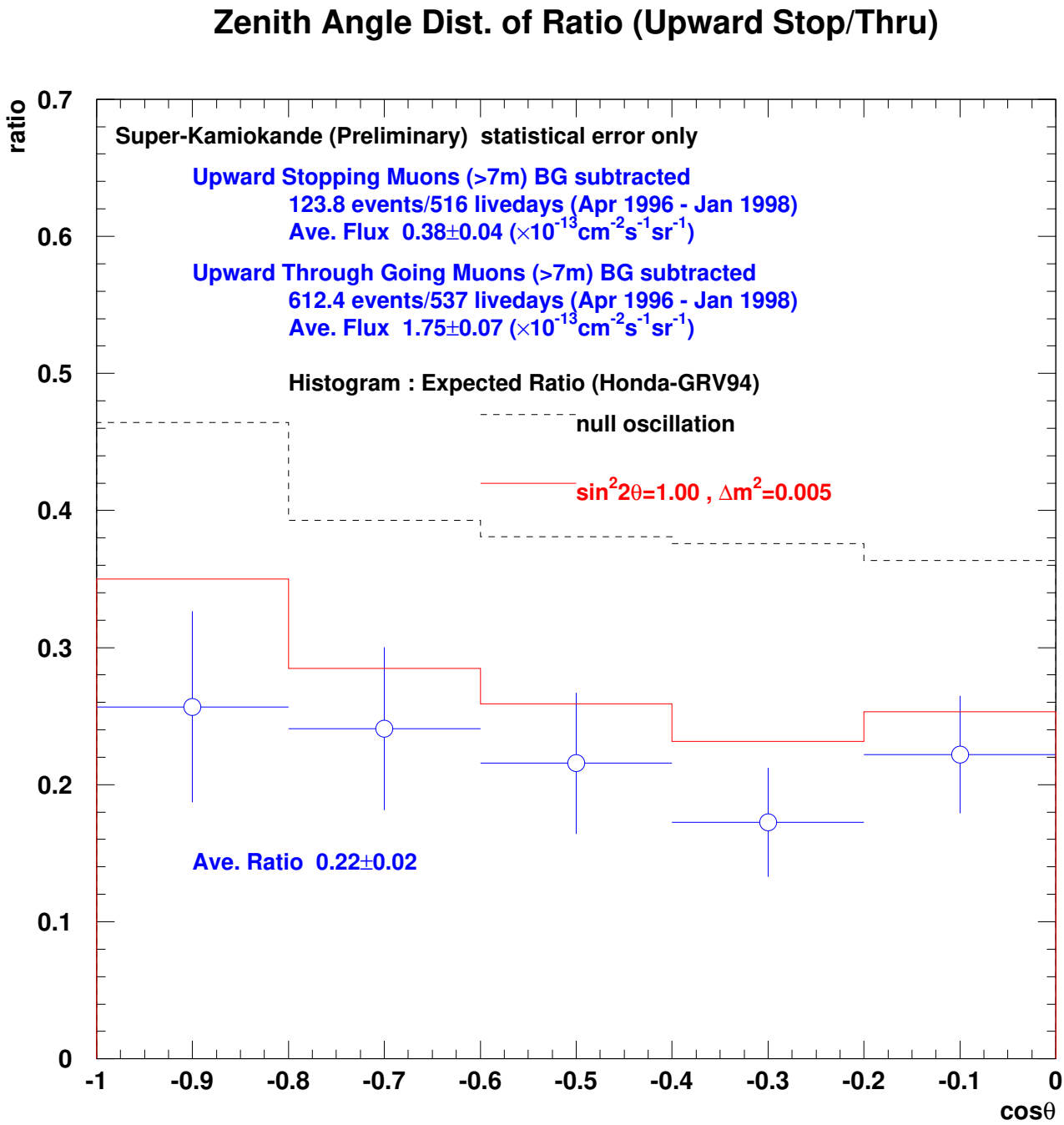
Stopping up-μ's are produced on average by lower energy ν's, so have a higher P than through-going up-μ's. The ratio of stop/through fluxes decreases in the presence of flavor oscillations.

Osc. Effect on Stop/Through Ratio

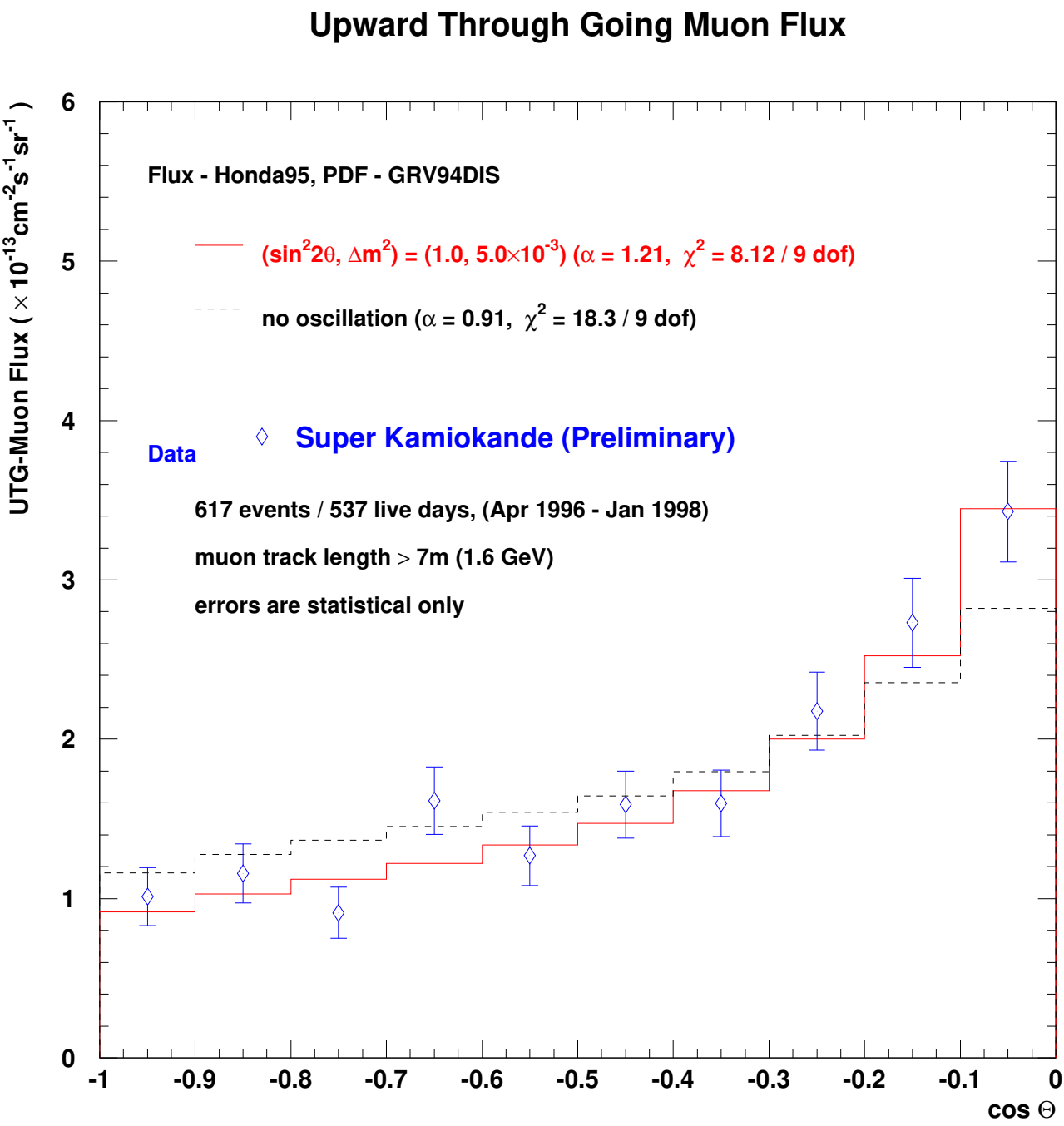


This figure shows the effect of ν oscillations on the stop/through ratio. Δm^2 varies along the X axis, and $\sin^2(2\theta) = 1$ is fixed.

Stop/Through Ratio vs. Oscillations



Through-going up-μ Flux vs. Oscillations



Data vs. predictions for no osc. and at a maximal mixing test point. α is the best fit absolute flux normalization.

χ^2 Definition

The form of the χ^2 used for these calculations is:

- Through-going zenith angle shape and normalization:

$$\chi^2 = \sum_{bin=1}^{10} \left(\frac{\Phi_{data}(bin) - \alpha\ \Phi_{theo}(bin)}{\sigma_{data}(bin)} \right)^2 + \left(\frac{1-\alpha}{\sigma_\alpha} \right)^2$$

  where α is the absolute flux normalization. $\sigma_\alpha = 20\%$.

- Stop/through ratio shape and normalization:

$$\chi^2 = \sum_{bin=1}^{5} \left(\frac{\Re_{data}(bin) - \eta\ \Re_{theo}(bin)}{\sigma_{data}(bin)} \right)^2 + \left(\frac{1-\eta}{\sigma_\eta} \right)^2$$

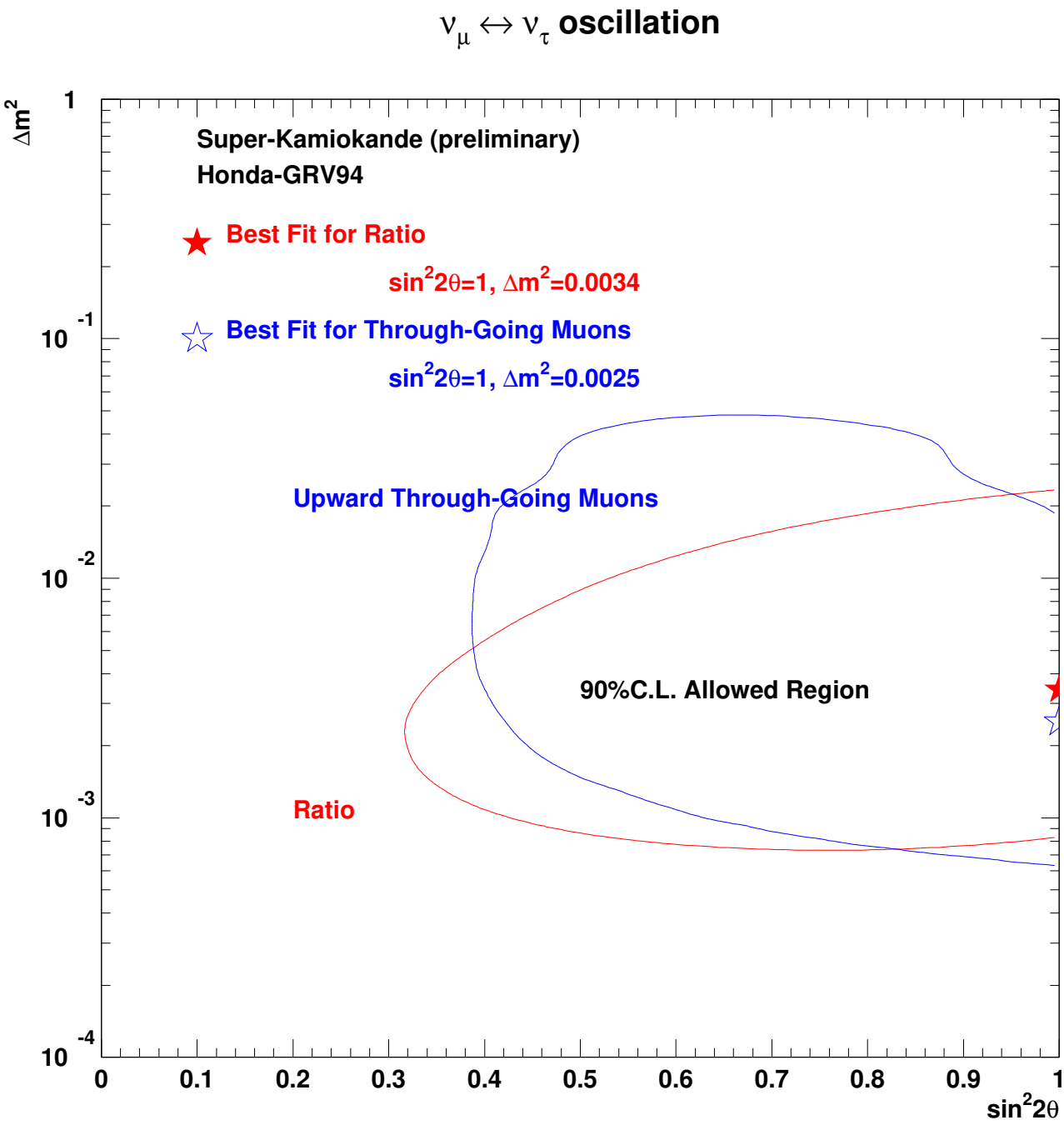
  where η is the $\Re$ normalization. $\sigma_\eta \simeq 14\%$.

α and η are minimized at each point in parameter space. The unphysical region has been taken into account when calculating the probability contours.

The Case for ν Oscillations

- The through-going up-μ flux shape is unlikely to be a fluctuation from a no-oscillation prediction ($\chi^2 = 18.3$ for 9 dof, a probability of $\sim 2\%$).
- The Stop/Through ratio for the no-oscillation case is also improbable ($\Re_{data}$ differs from $\Re_{theo}$ by 3.2σ, a probability of $< 1\%$).
- However, parameter estimation in $\sin^2(2\theta)$, Δm^2 space shows that $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing and Δm^2 in the range of $\sim 7 \times 10^{-4}$ eV^2 to $\sim 2 \times 10^{-2}$ eV^2 are consistent with the observed data.
- This observation is consistent with the Super-K contained and partially-contained event data presented at this conference.

Allowed Oscillation Parameter Space



ν-induced Up-μ Conclusions

Super-Kamiokande Observes an upward through-going ν-induced μ flux of
$1.75 \pm 0.07(stat) \pm 0.09(syst) \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$ and an upward-stopping ν-induced μ flux of
$0.38 \pm 0.04(stat)^{+0.03}_{-0.02}(syst) \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$.

The zenith angle distribution of the up-through-μ flux is consistent with the no-oscillation prediction only at the $\sim 2\%$ level.

The ratio of stop/through flux is consistent with the no-oscillation prediction only at the $< 1\%$ level.

A study of the best way to combine the shape and the ratio into a full oscillation analysis is underway.

$\nu_\mu \rightarrow \nu_\tau$ flavor oscillations, however, predict a zenith angle distribution shape and a stop/through ratio which is in agreement with our data. The allowed range of the $sin^2 2\theta$ and Δm^2 parameters is consistent with that measured by the Super-K contained and partially contained ν interaction analysis.