Measurements of the atmospheric neutrino by Super-Kamiokande: energy spectrum, geomagnetic effects, and solar modulation

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Introduction

Atmospheric Neutrinos

- Secondary cosmic ray showers create neutrinos by e.g.

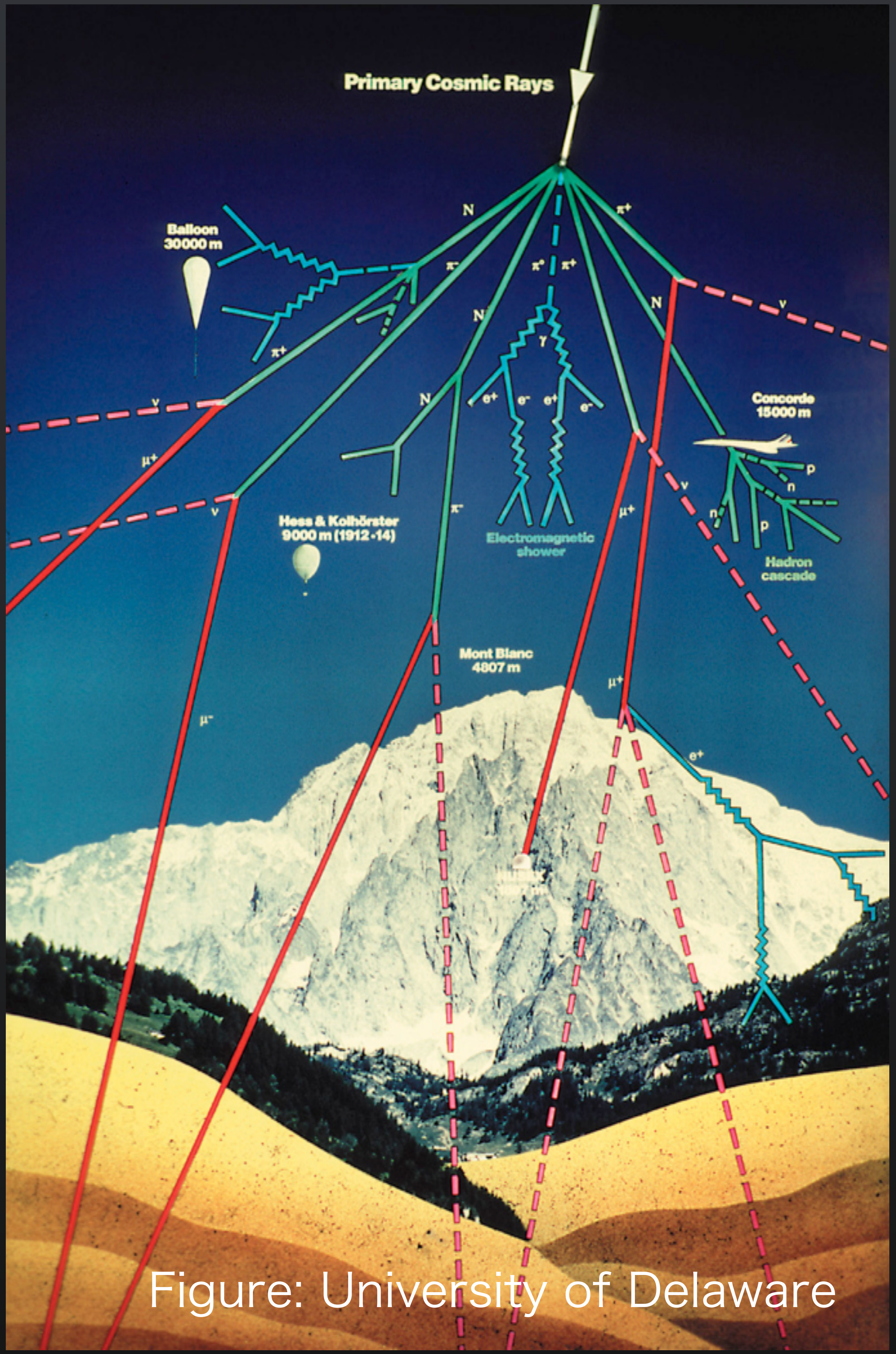

Figure: University of Delaware

Atmospheric Neutrinos

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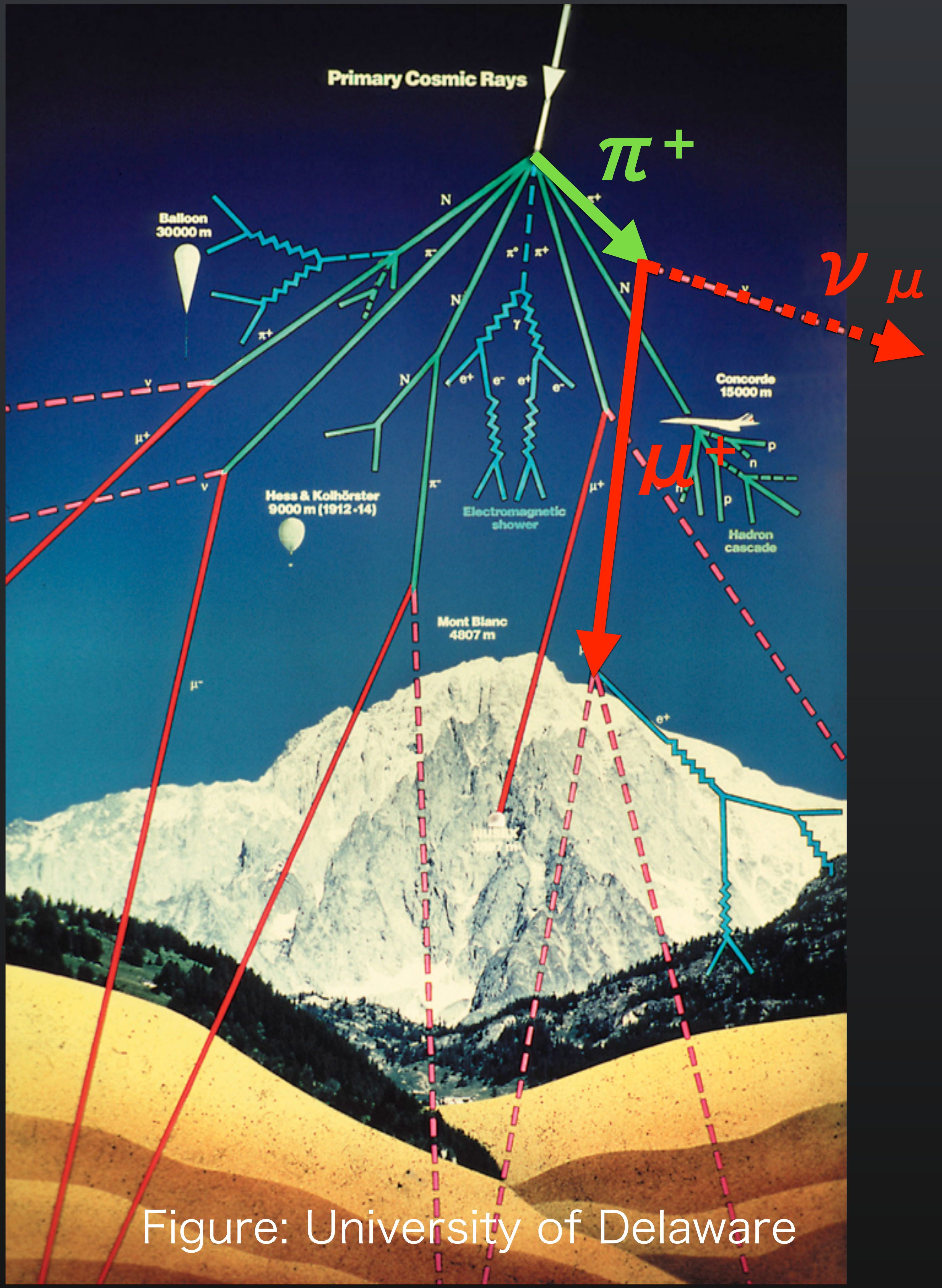
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$



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Atmospheric Neutrinos

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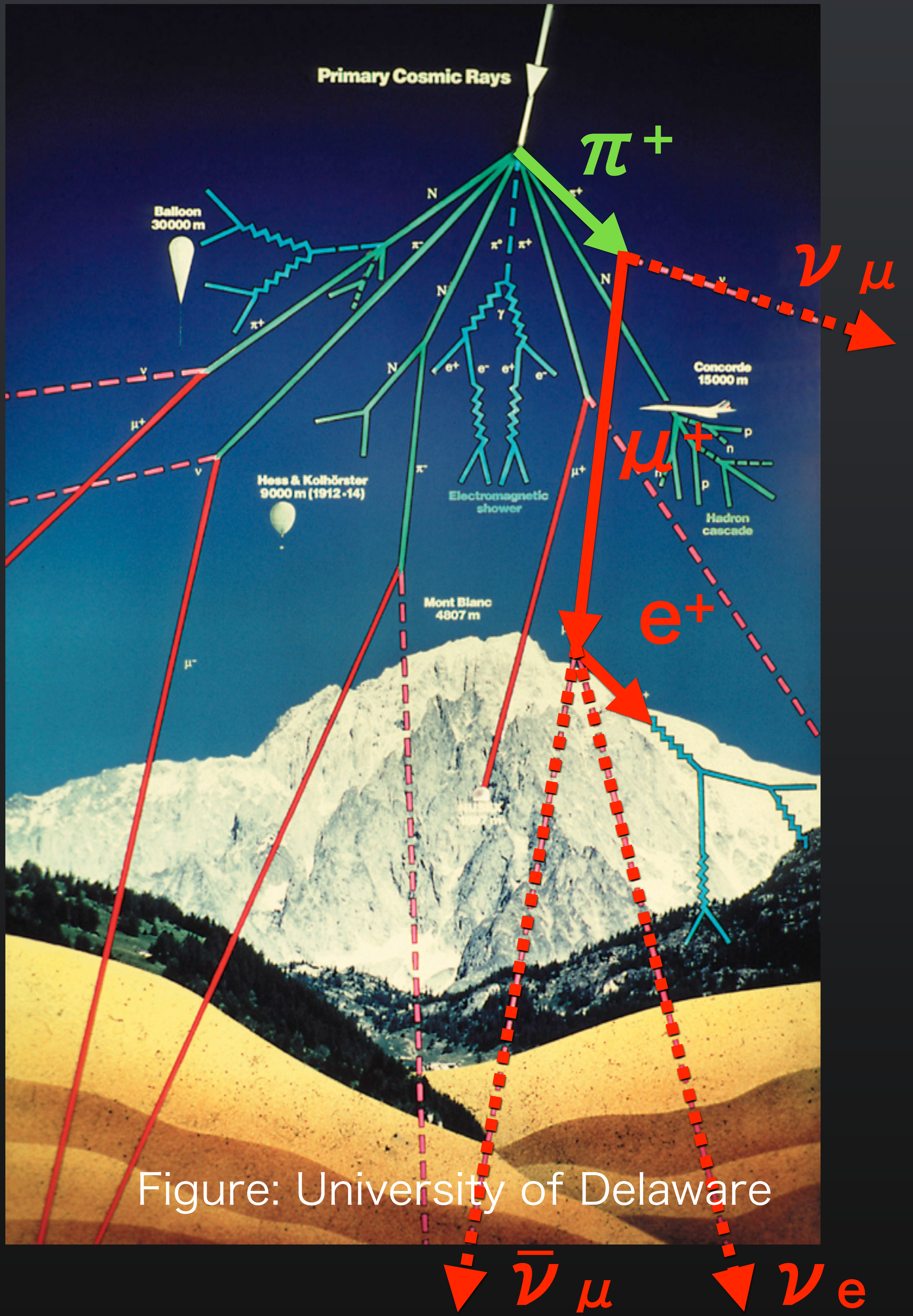
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$



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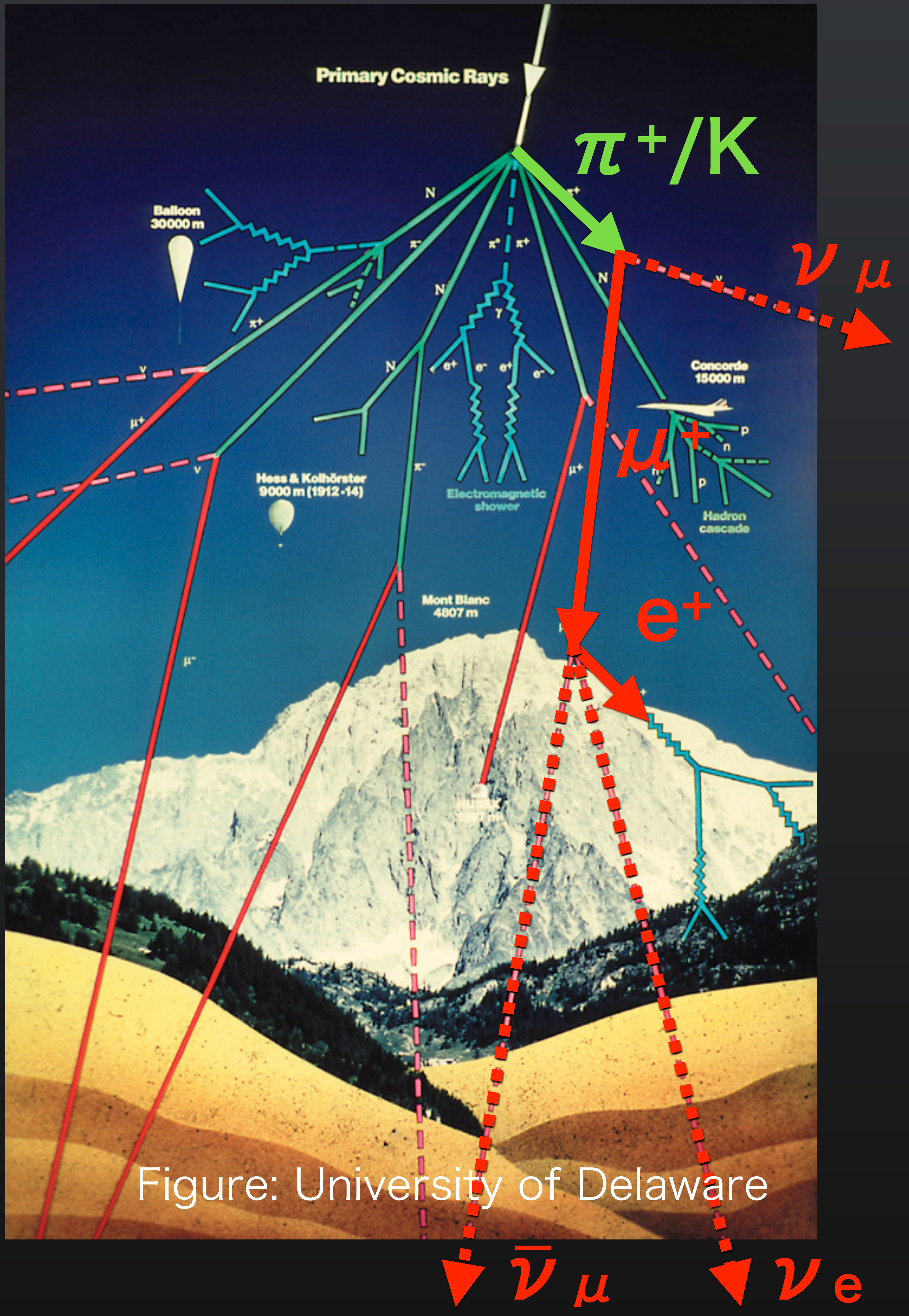
$K \rightarrow$ same (or pions)



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Atmospheric Neutrinos

- Secondary cosmic ray showers create neutrinos by e.g.

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$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

$$K \rightarrow \text{same (or pions)}$$

- These can be termed “conventional” neutrinos.
- Also, higher energy charm components (“prompt” neutrinos, due to the short lifetime of charmed hadrons).

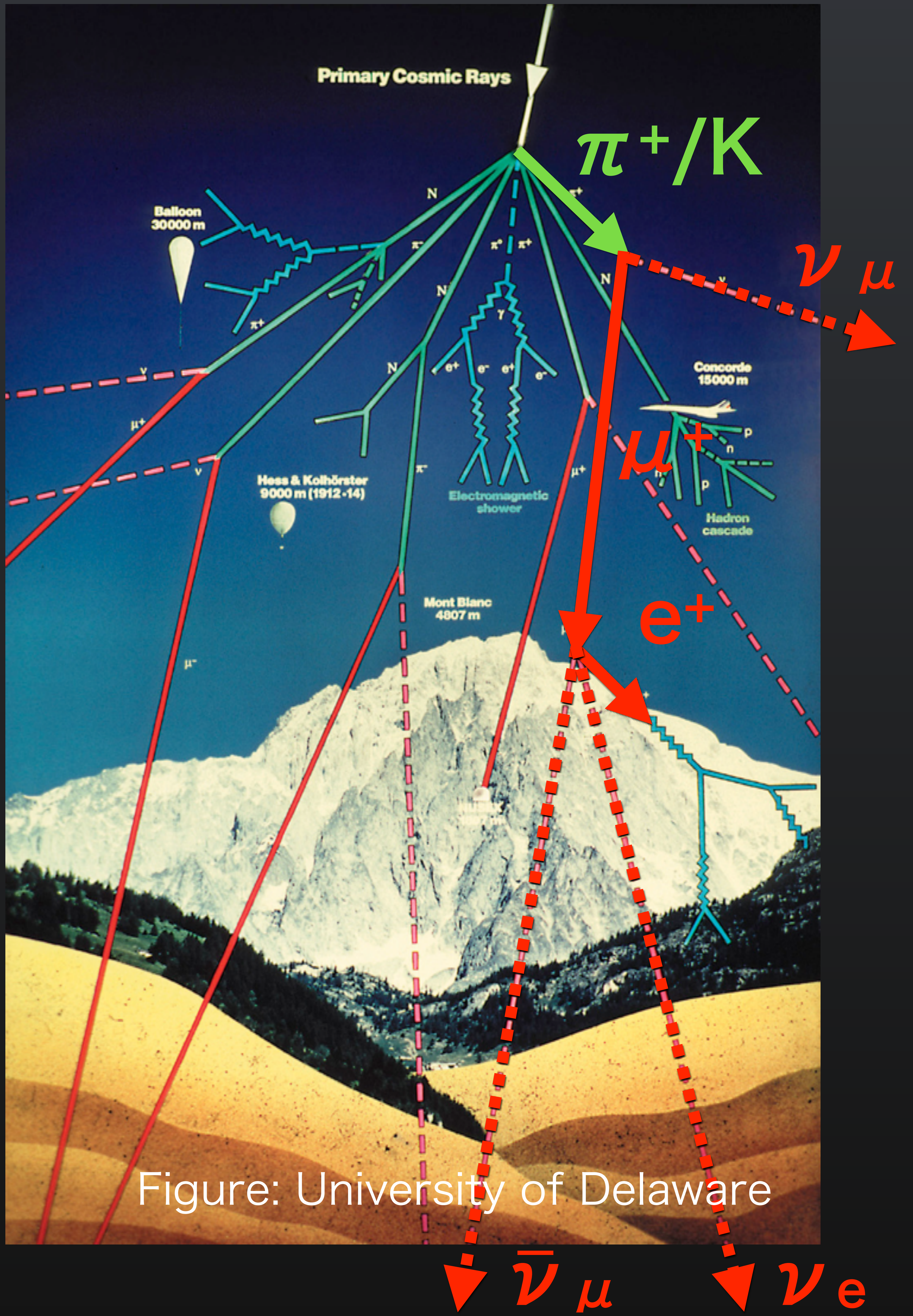
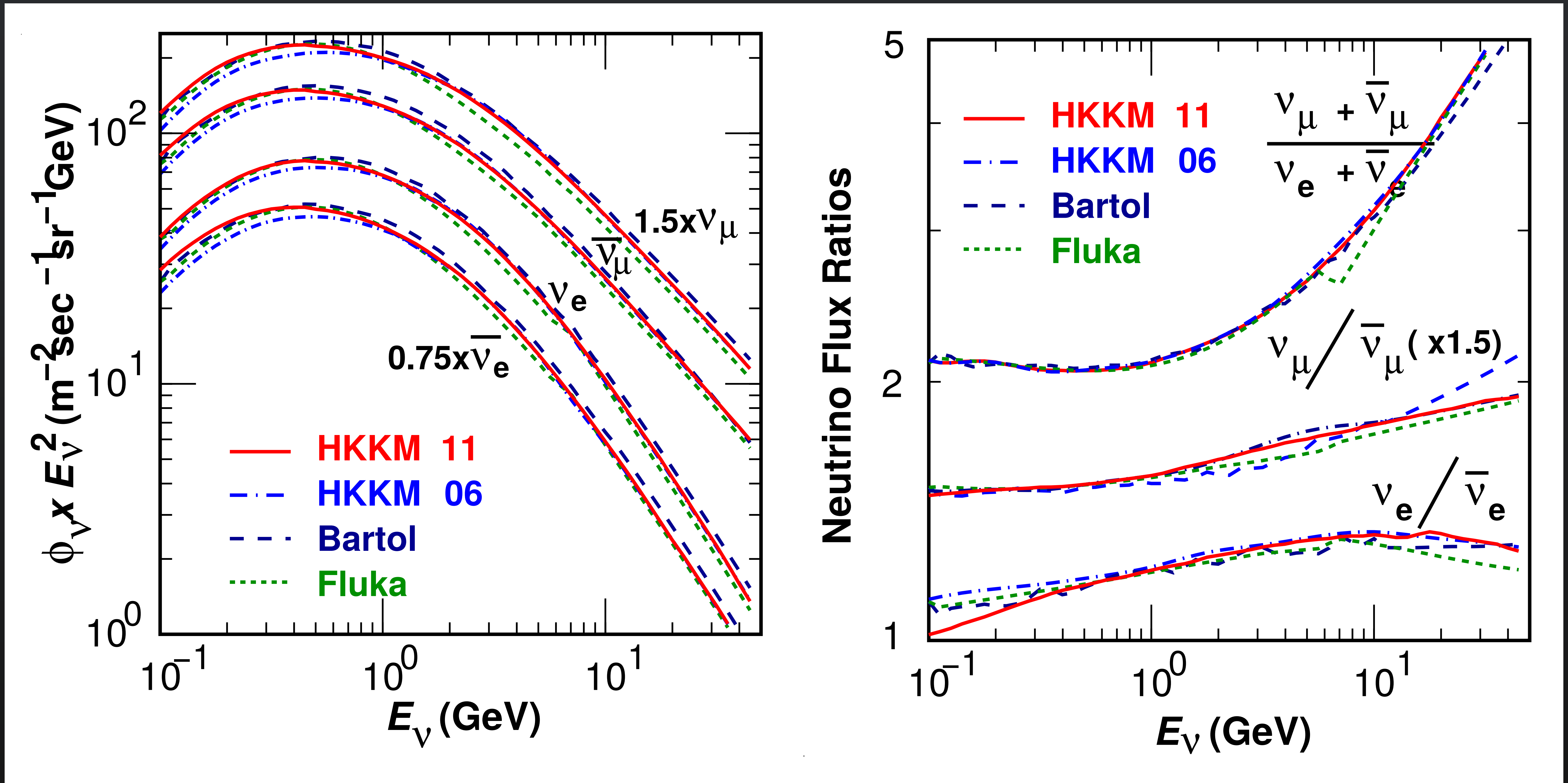


Figure: University of Delaware

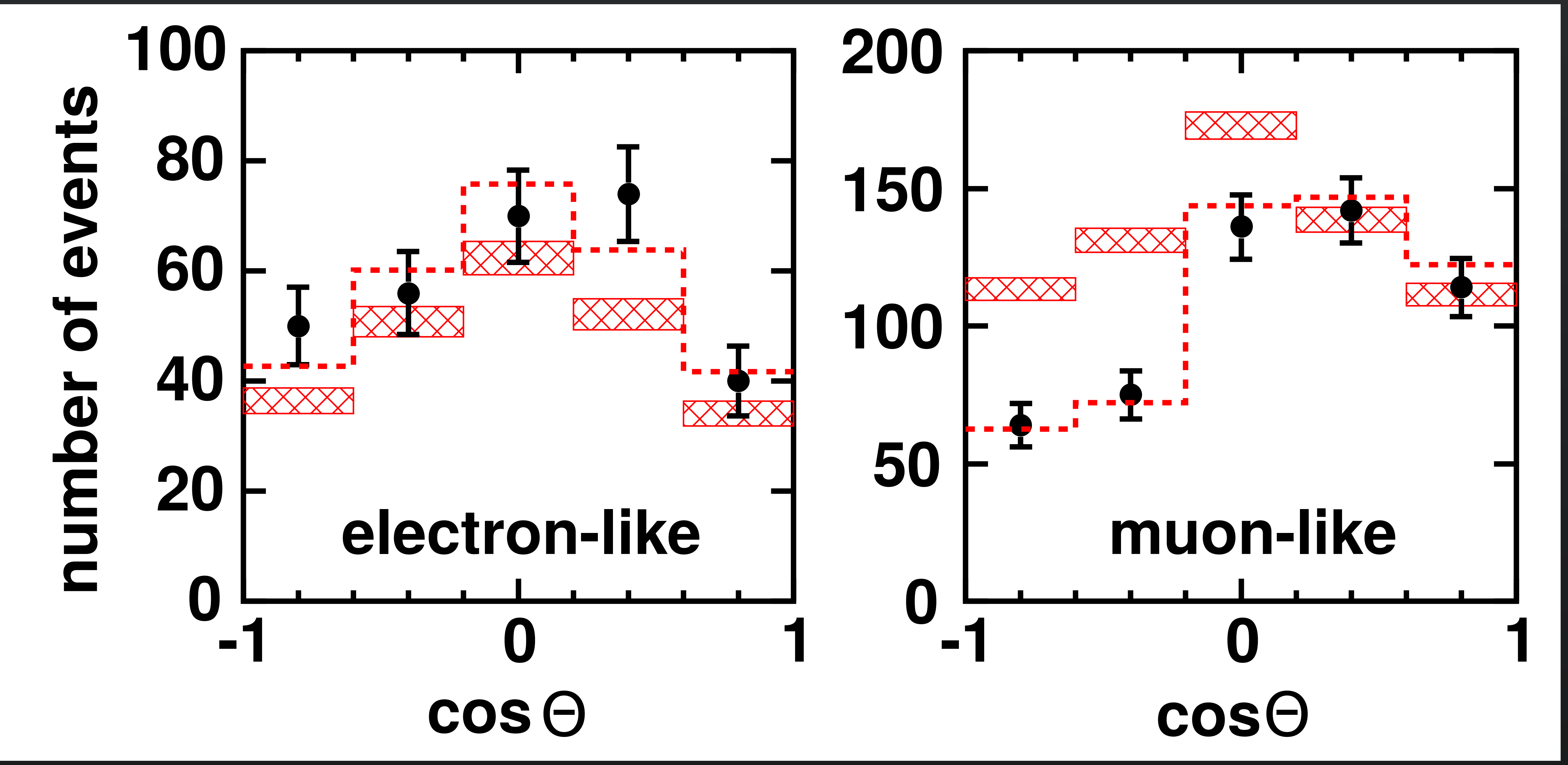
Atmospheric Neutrino Flux Models

- Flux MCs propagate primaries and secondaries according to geomagnetic and atmospheric models, and track neutrinos arriving at a given location on Earth. Several models are available:

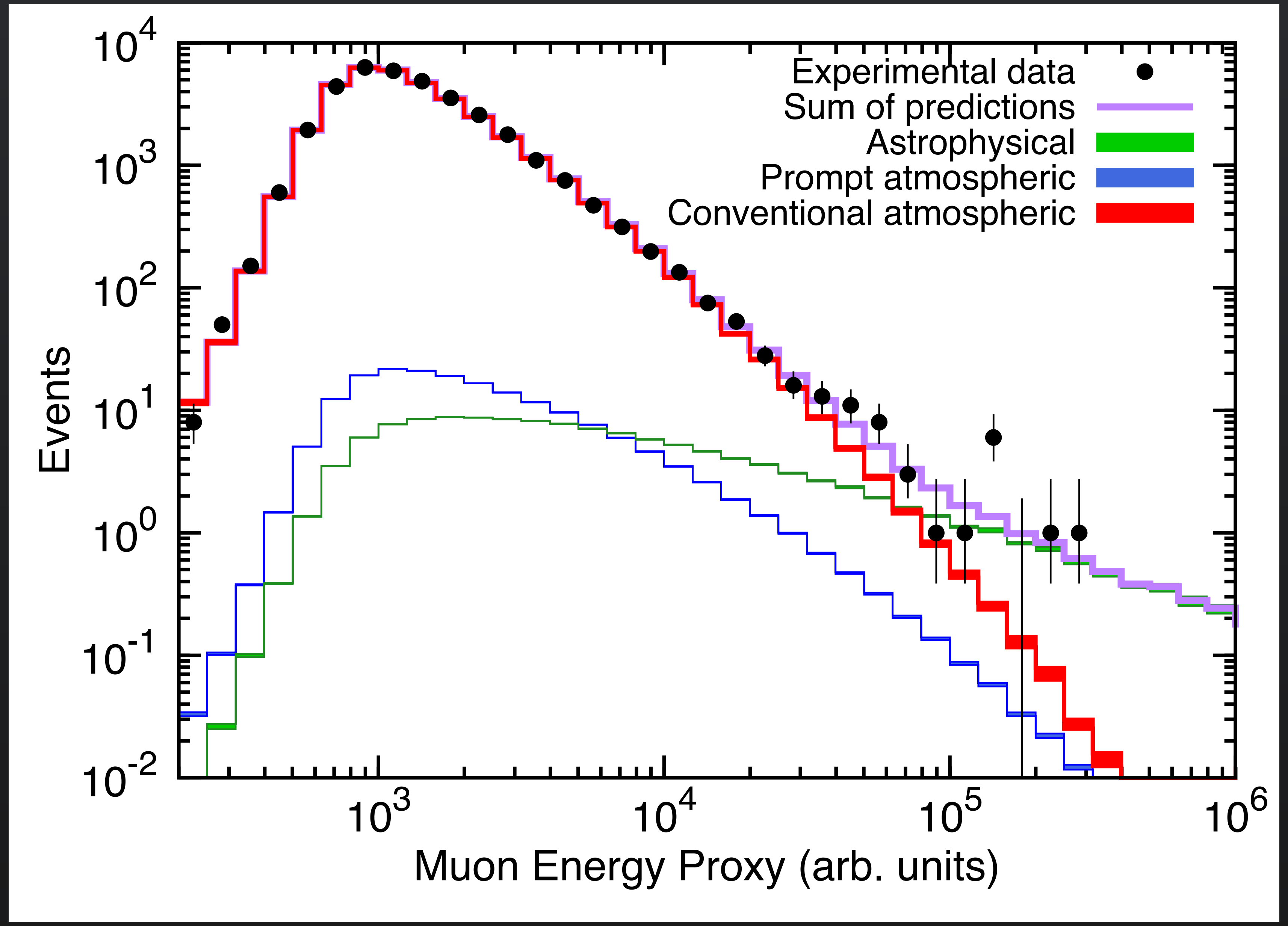


Motivations for Direct Measurements

- Accurate flux prediction necessary for any study of the atmospheric neutrino as a signal (e.g. oscillation studies) or as a background (e.g. proton decay, dark matter, astrophysical neutrinos).



Discovery of neutrino oscillation

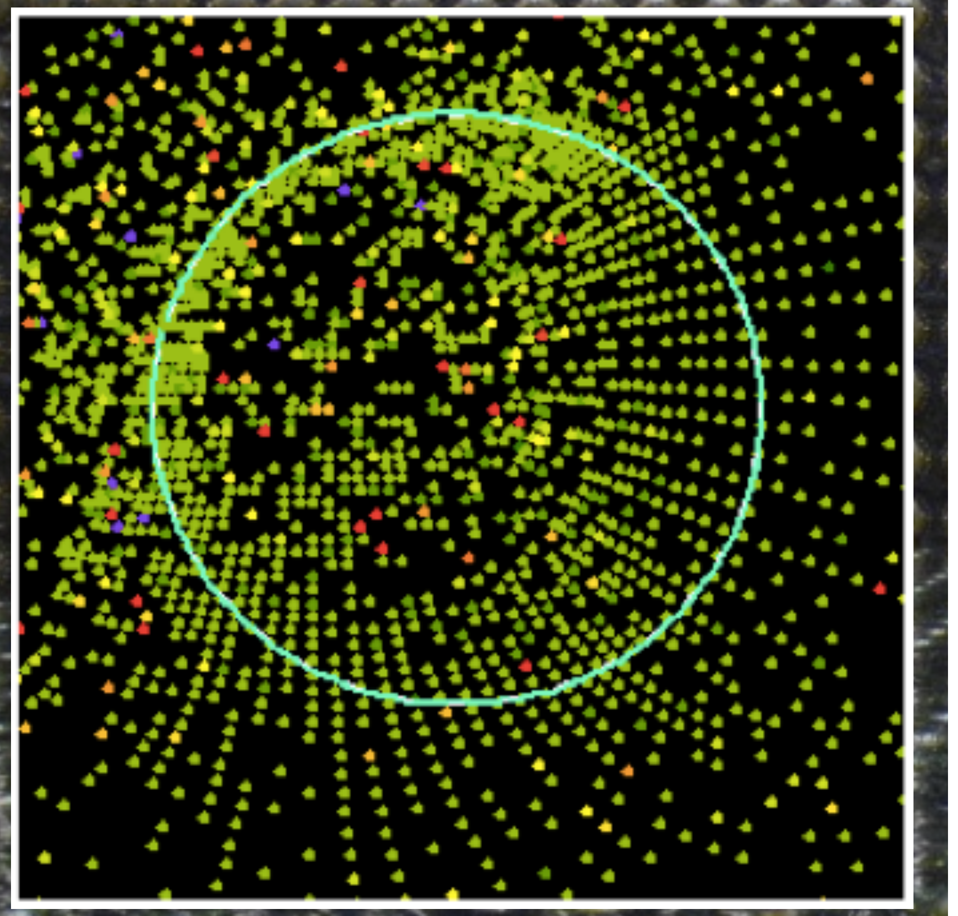


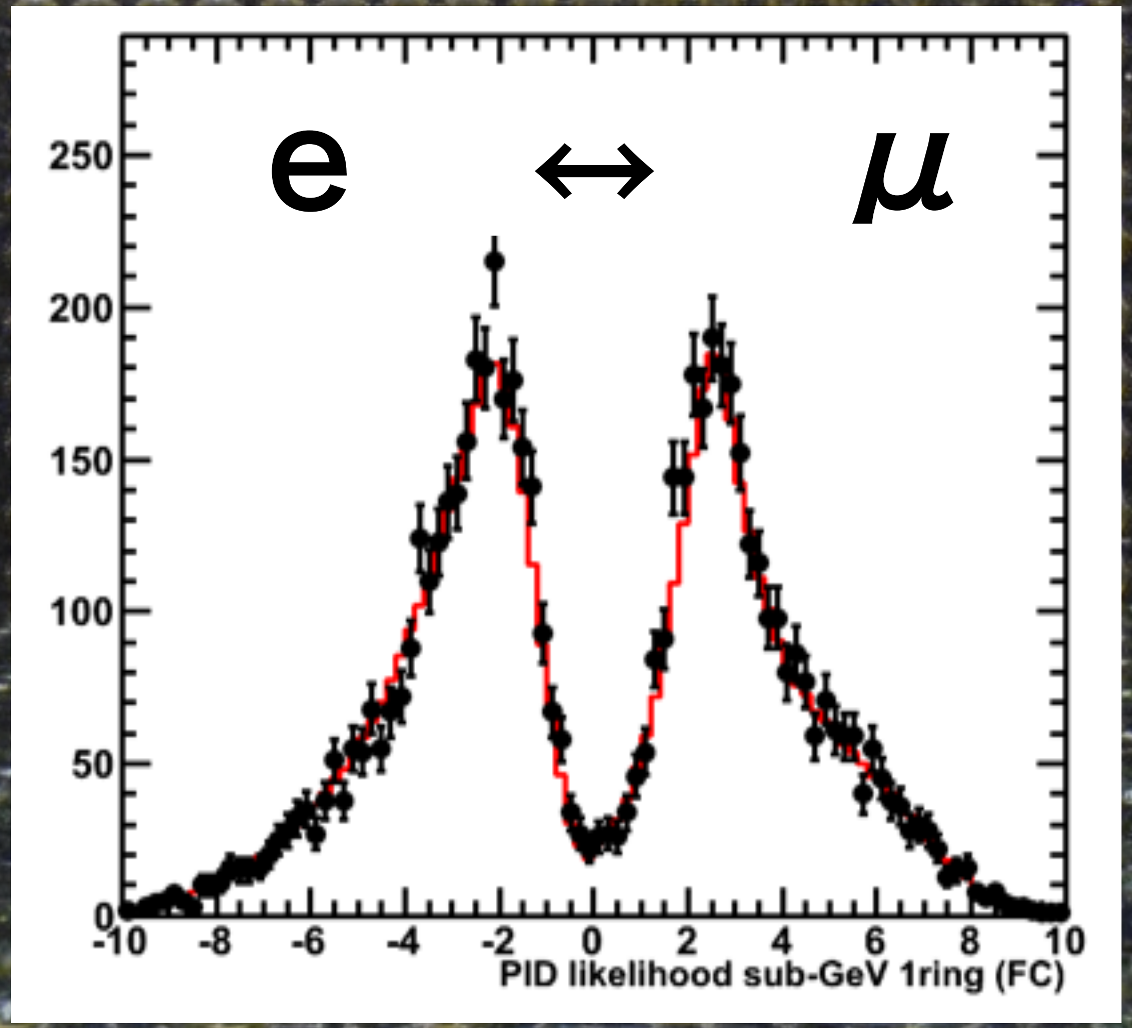
Search for astrophysical neutrinos

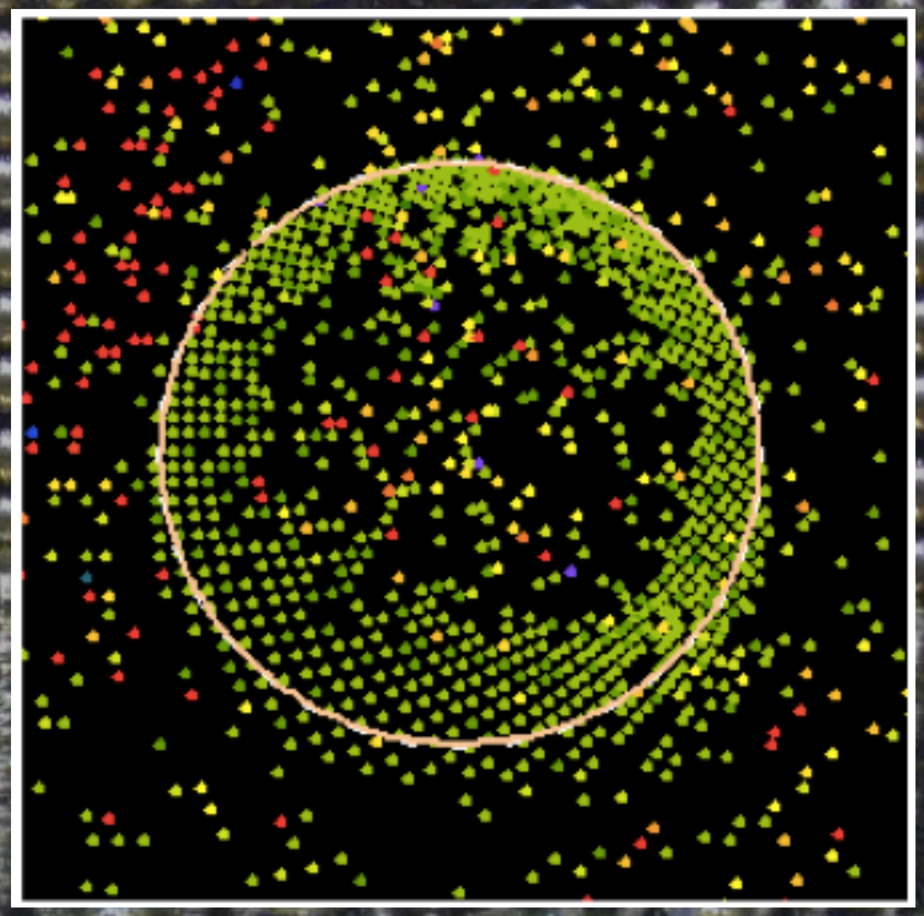
Figure: IceCube Collaboration

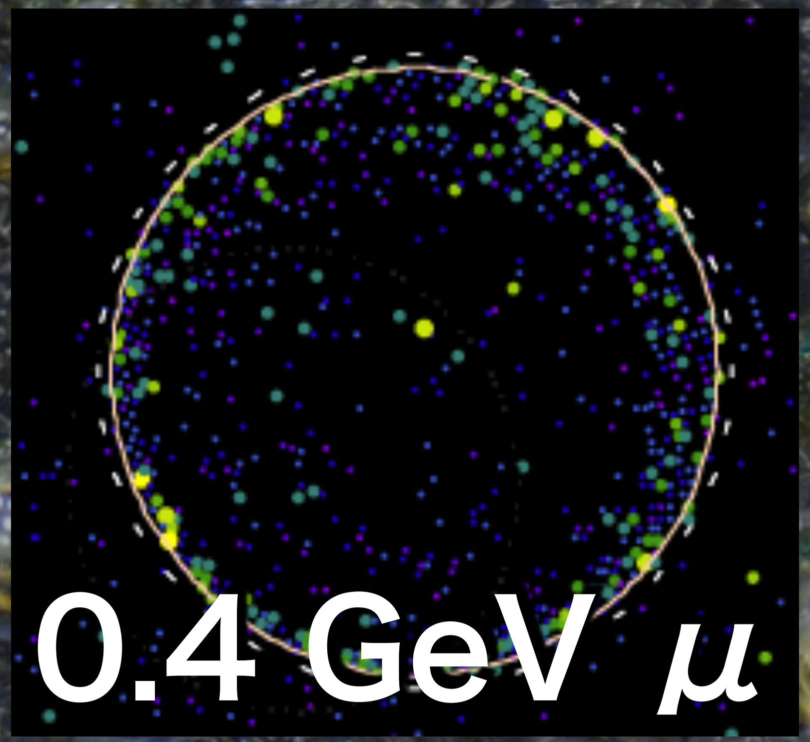
Super-Kamiokande

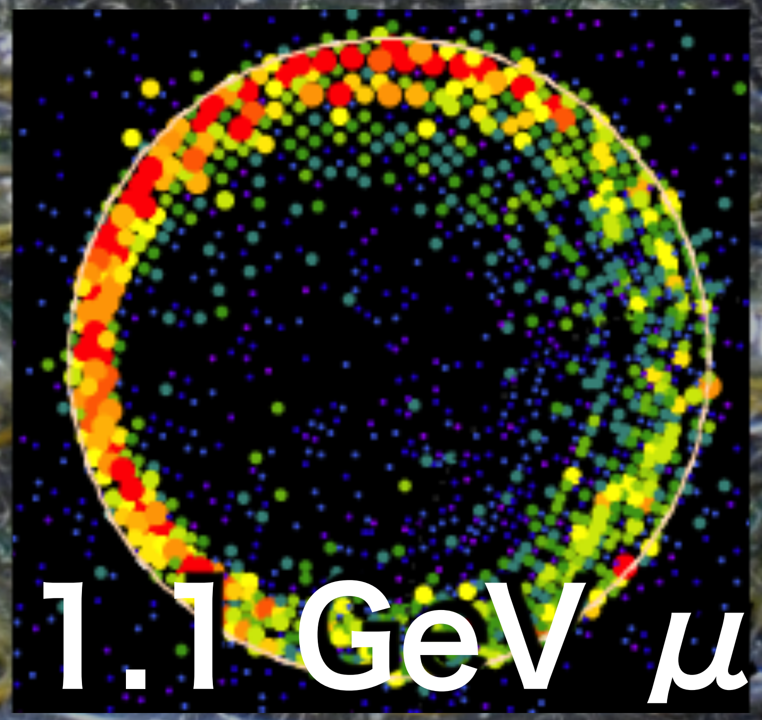
- PID and energy classification by Cherenkov light pattern.
- ~20 years of operation.

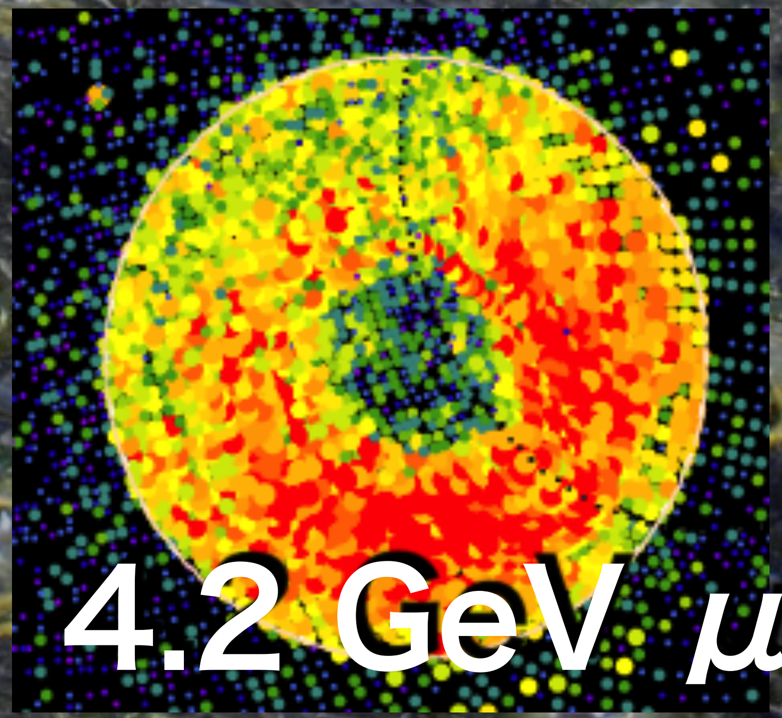






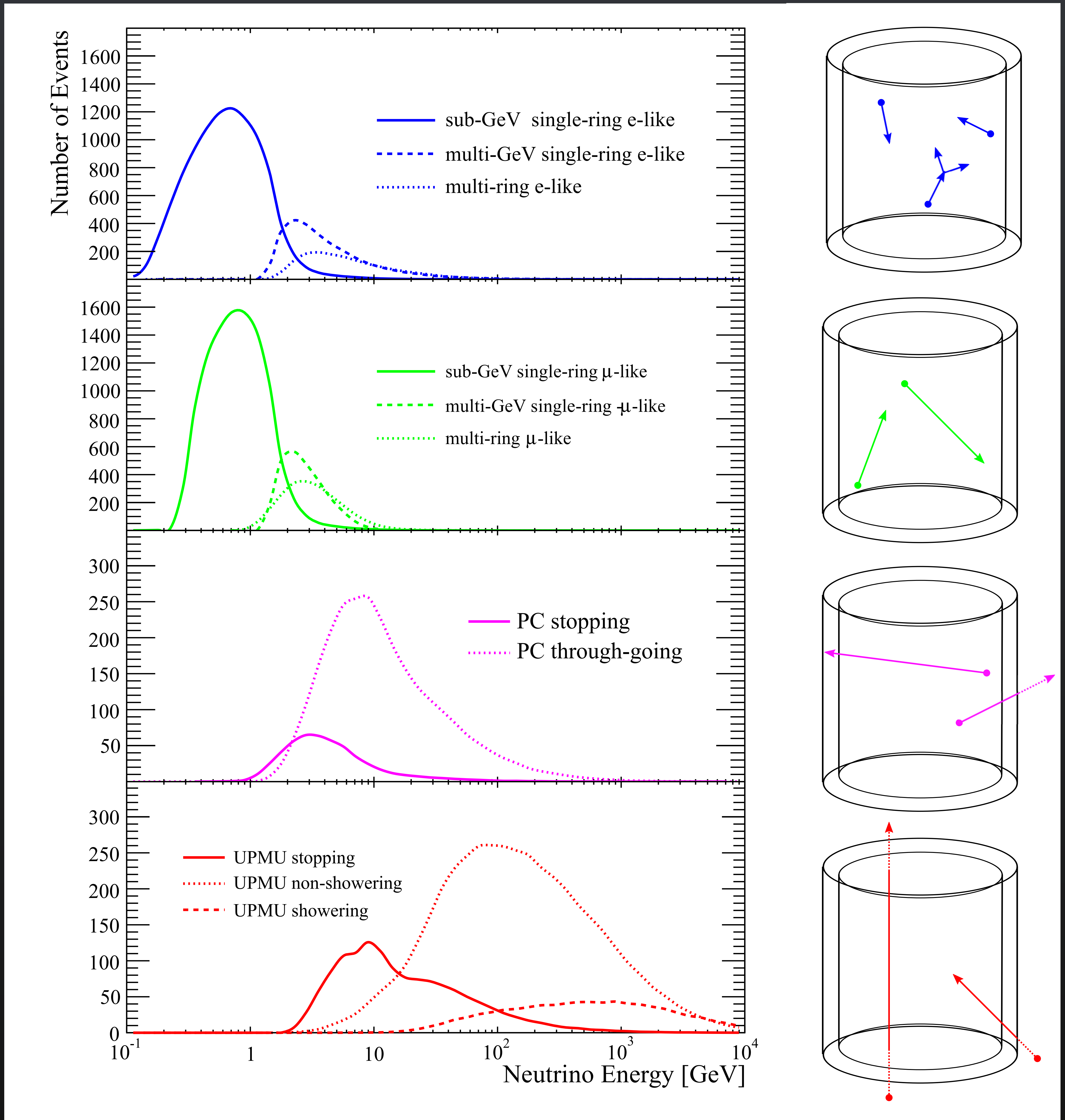






Event Classification

- Events divided by topology, defining sub-samples with different energy resolution and neutrino flavour purity.
  - Fully Contained (FC, ν_e or ν_μ by PID)
  - Partially Contained (PC, ν_μ only)
  - Upwards-Going Muons (UPMU, ν_μ only)



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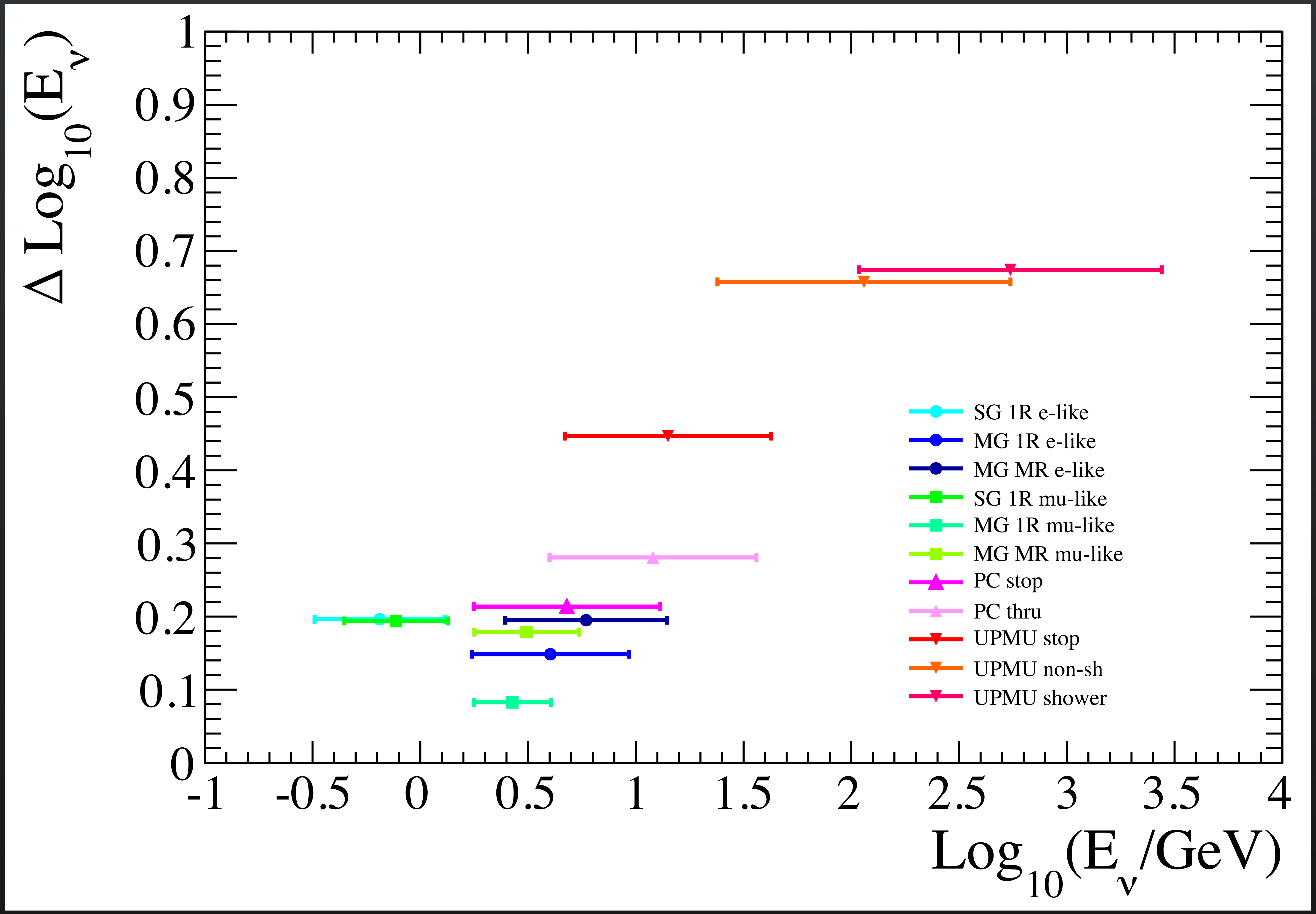

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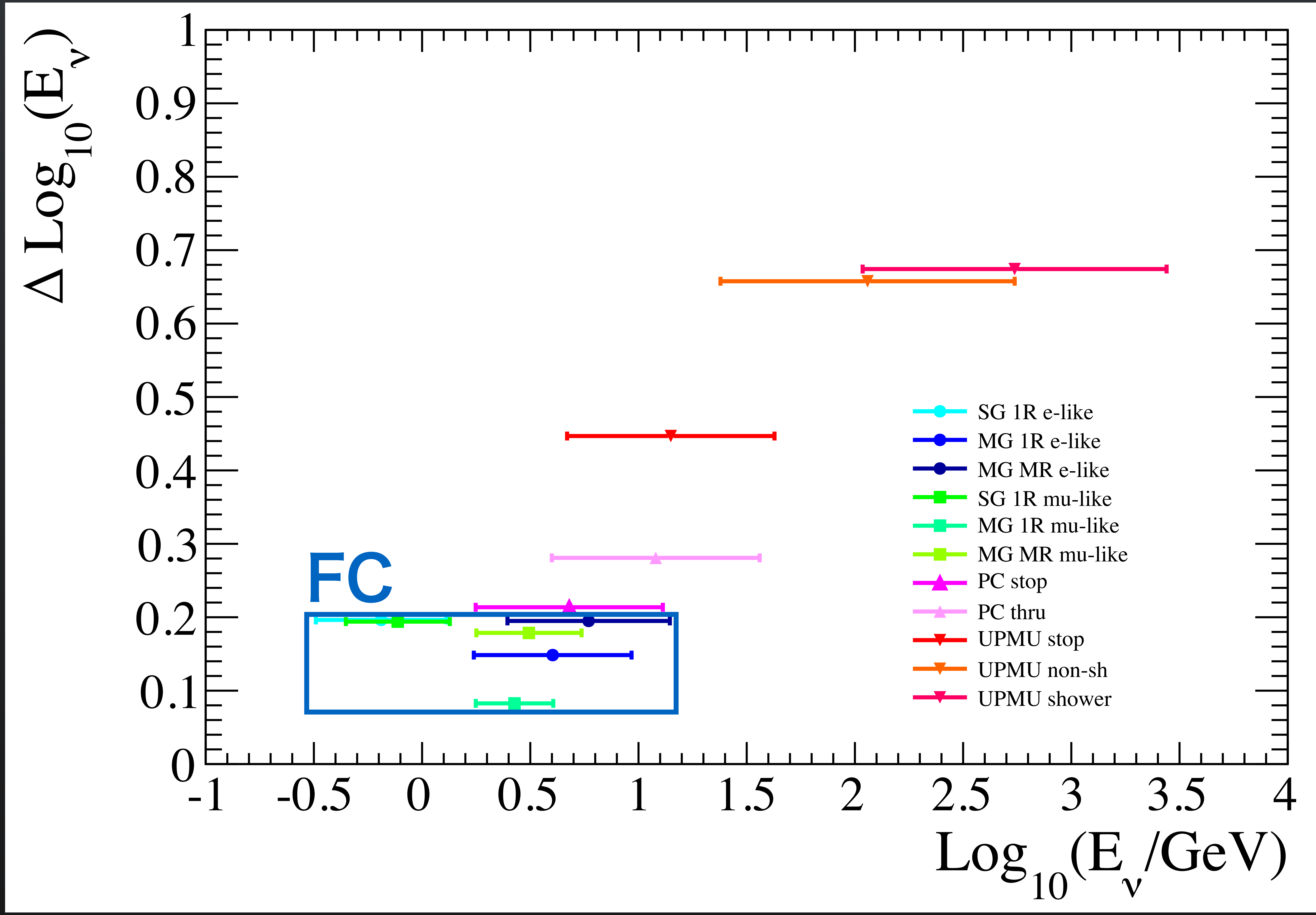

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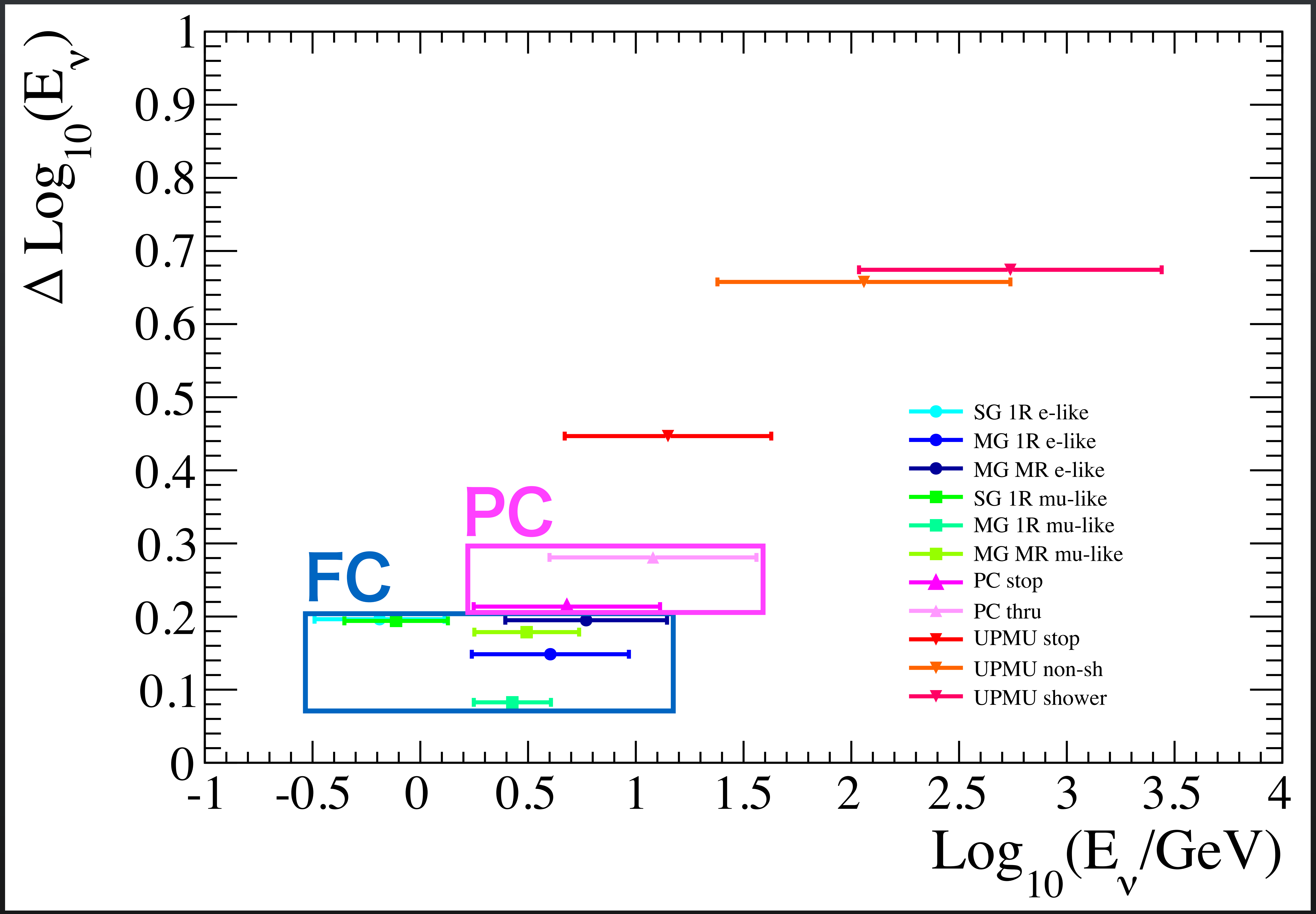

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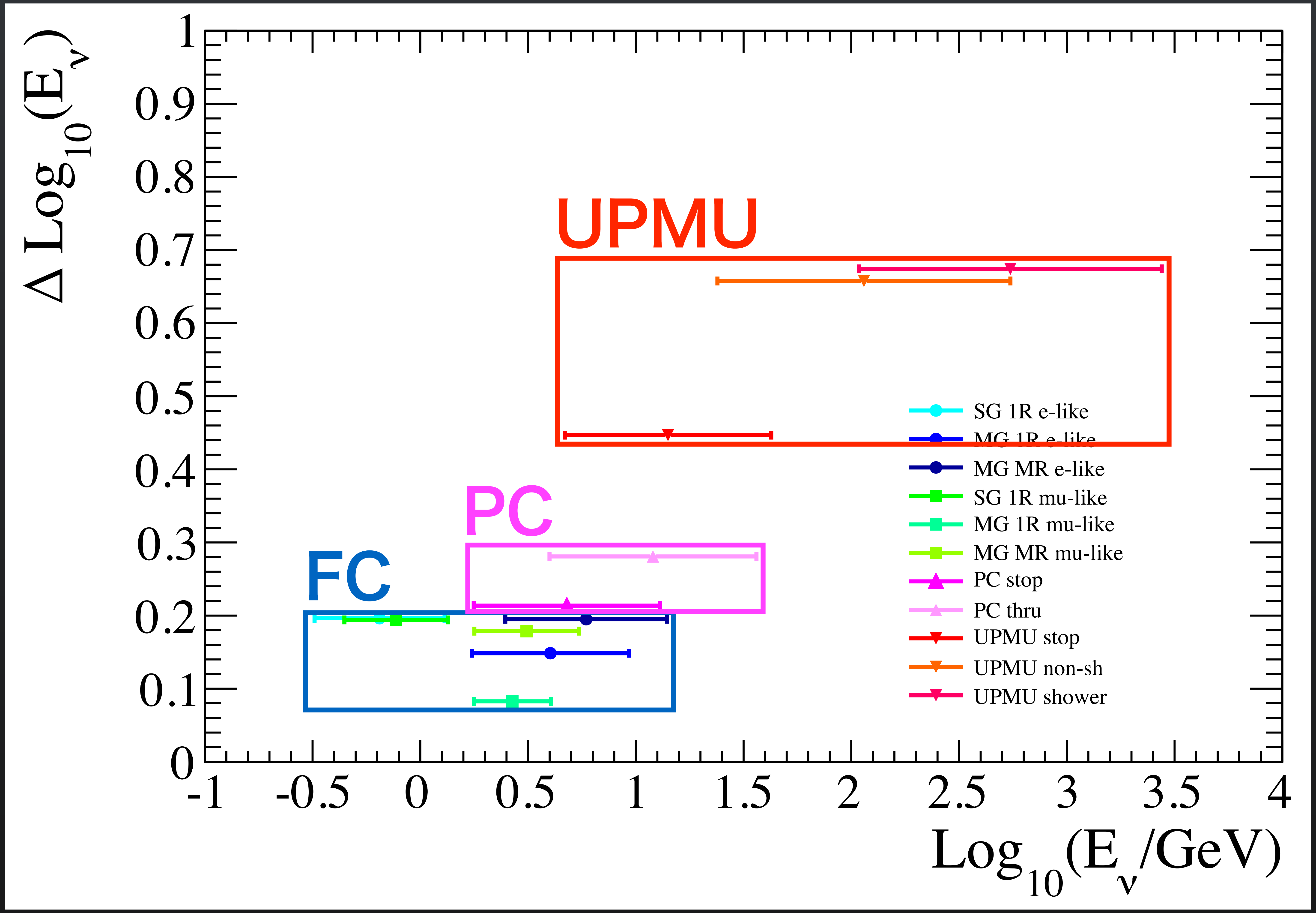
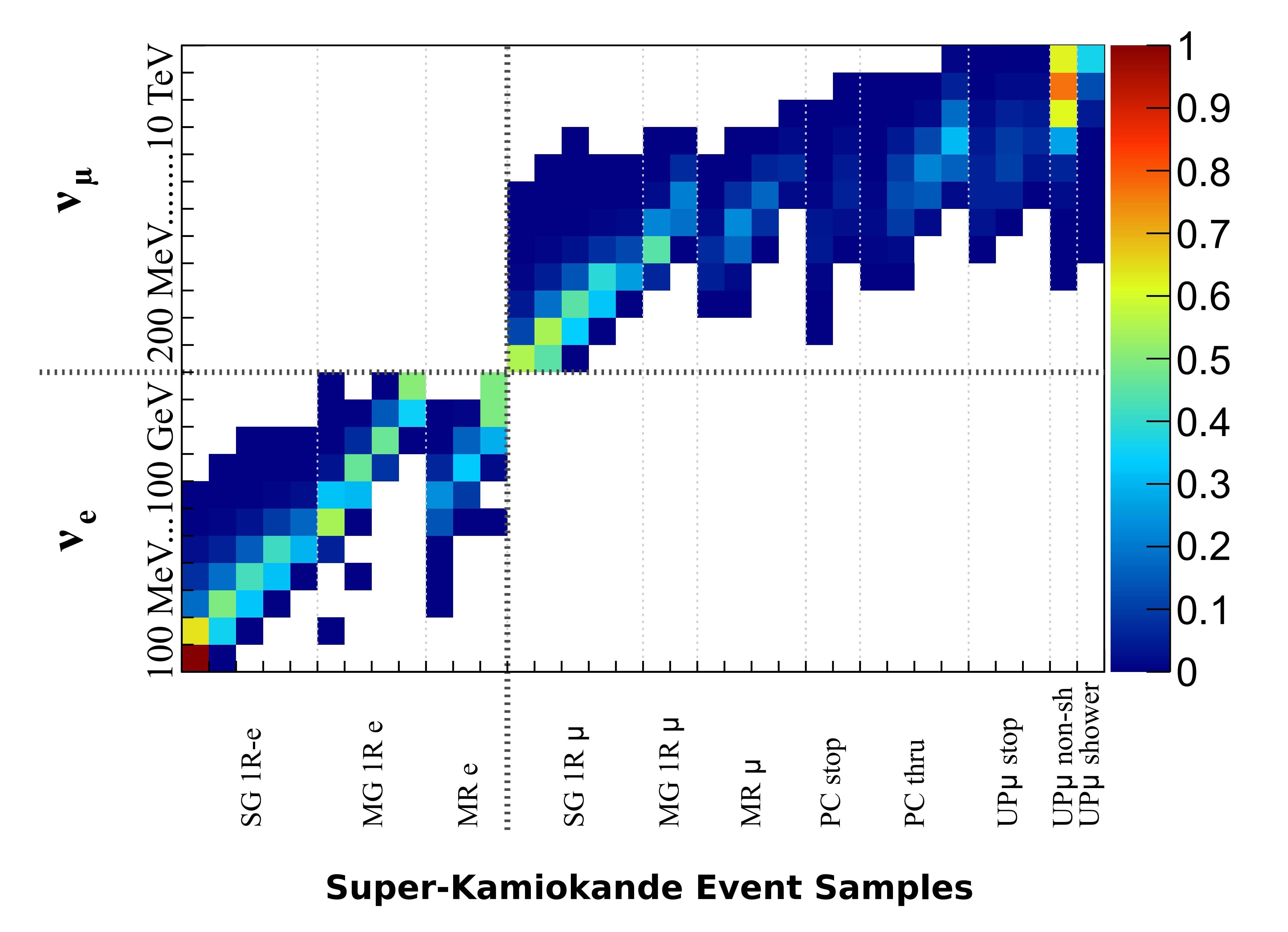


Energy Spectra

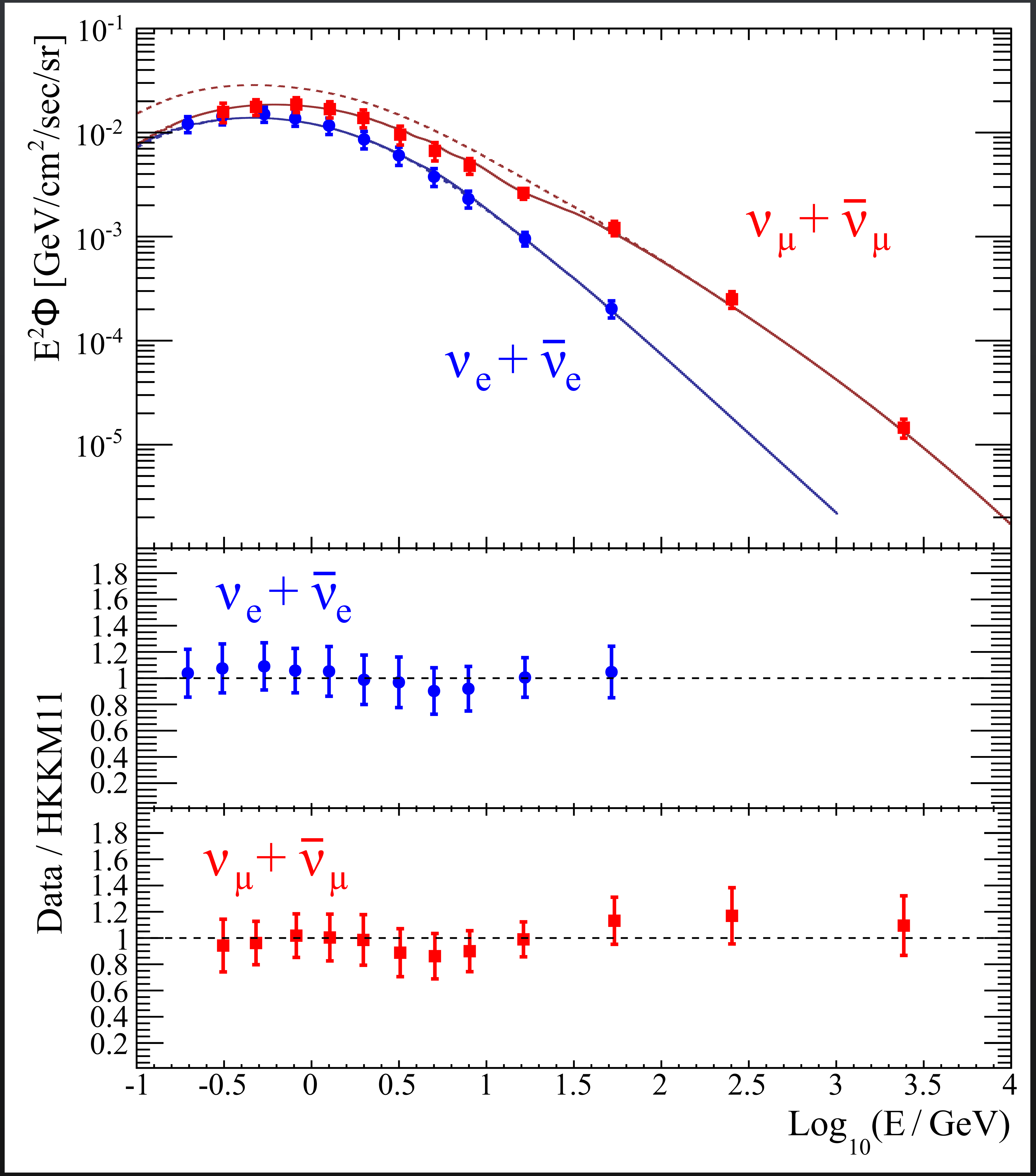
Energy Spectrum Unfolding

- Aim to reconstruct the true $\nu_e + \bar{\nu}_e$ and $\nu_\mu + \bar{\nu}_\mu$ fluxes at the detector position (model-independent measurement).
- Detector response matrix is first estimated by MC, then an iterative Bayesian method is applied. Reliable result with accurately estimated unfolding related uncertainties.



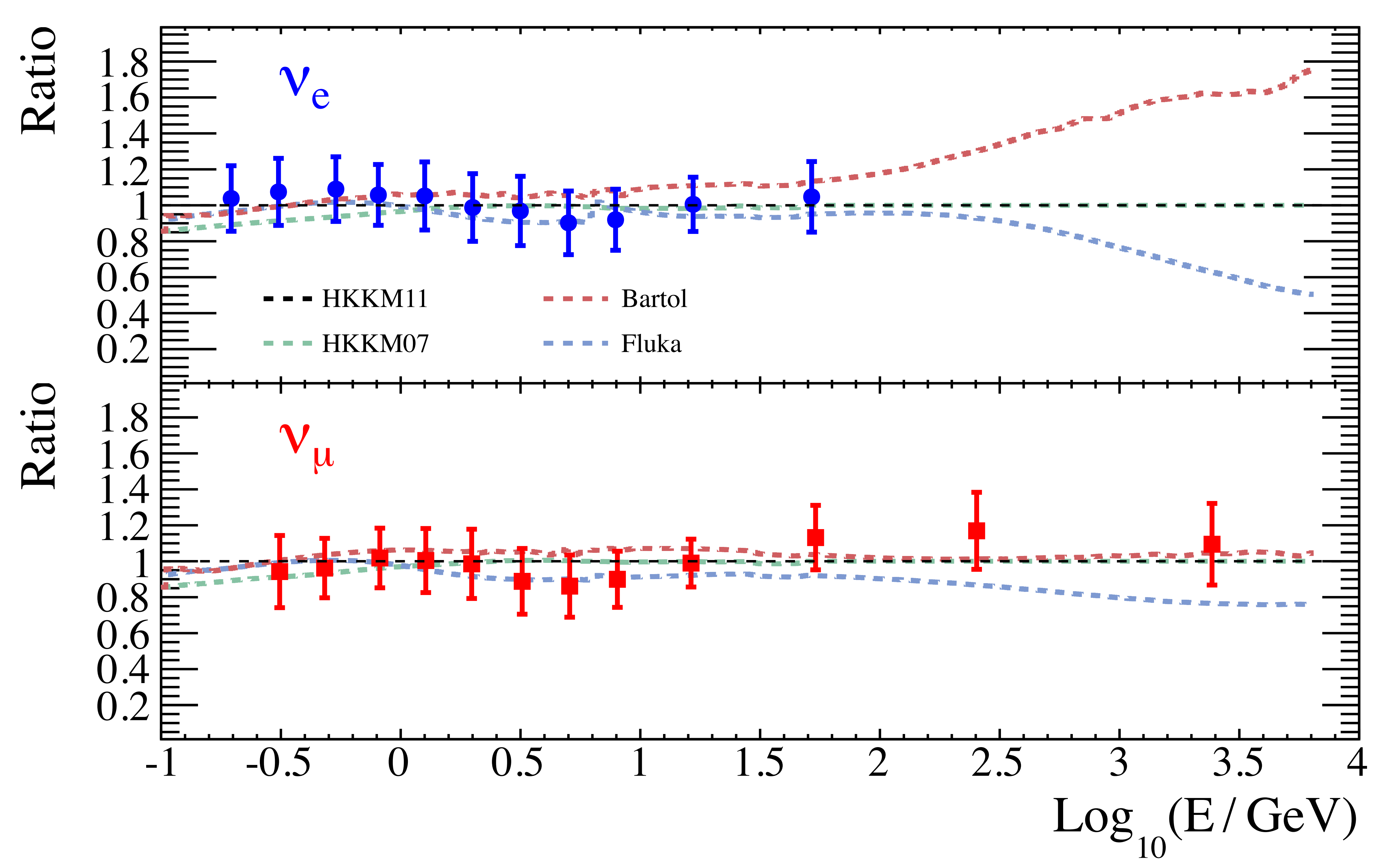
Measured Flux

- Plotted against the HKKM11 flux model (dashed line shows unoscillated prediction).
- Error bars include the effects of all statistical and systematic uncertainties (cross-sections, detector reconstruction, oscillation, and regularization) as estimated by toy MC.



Flux Model Comparisons

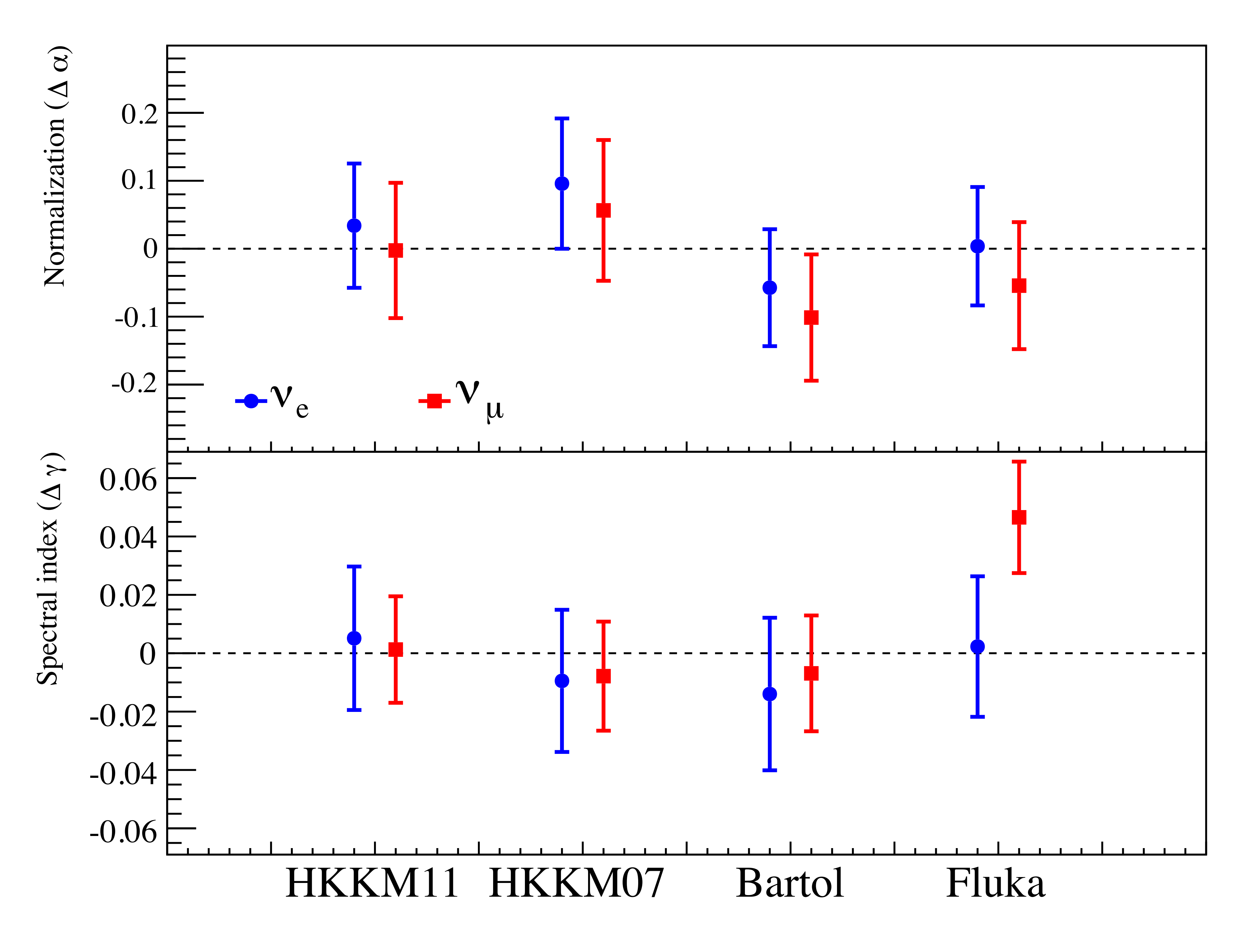
- Compare against current flux models by χ^2 test (accounting for error covariance matrix).
- No models are strongly inconsistent (for the $\nu_\mu + \nu_e$ test, p=32% for Fluka and 13% for Bartol).



χ^2	$\nu_e + \nu_\mu$	ν_e	ν_μ
HKKM11	**21.8**	8.5	19.5
HKKM07	**22.2**	15.4	21.7
Bartol	**30.7**	10.9	28.8
Fluka	**25.6**	9.0	18.7
DOF	**23**	11	12

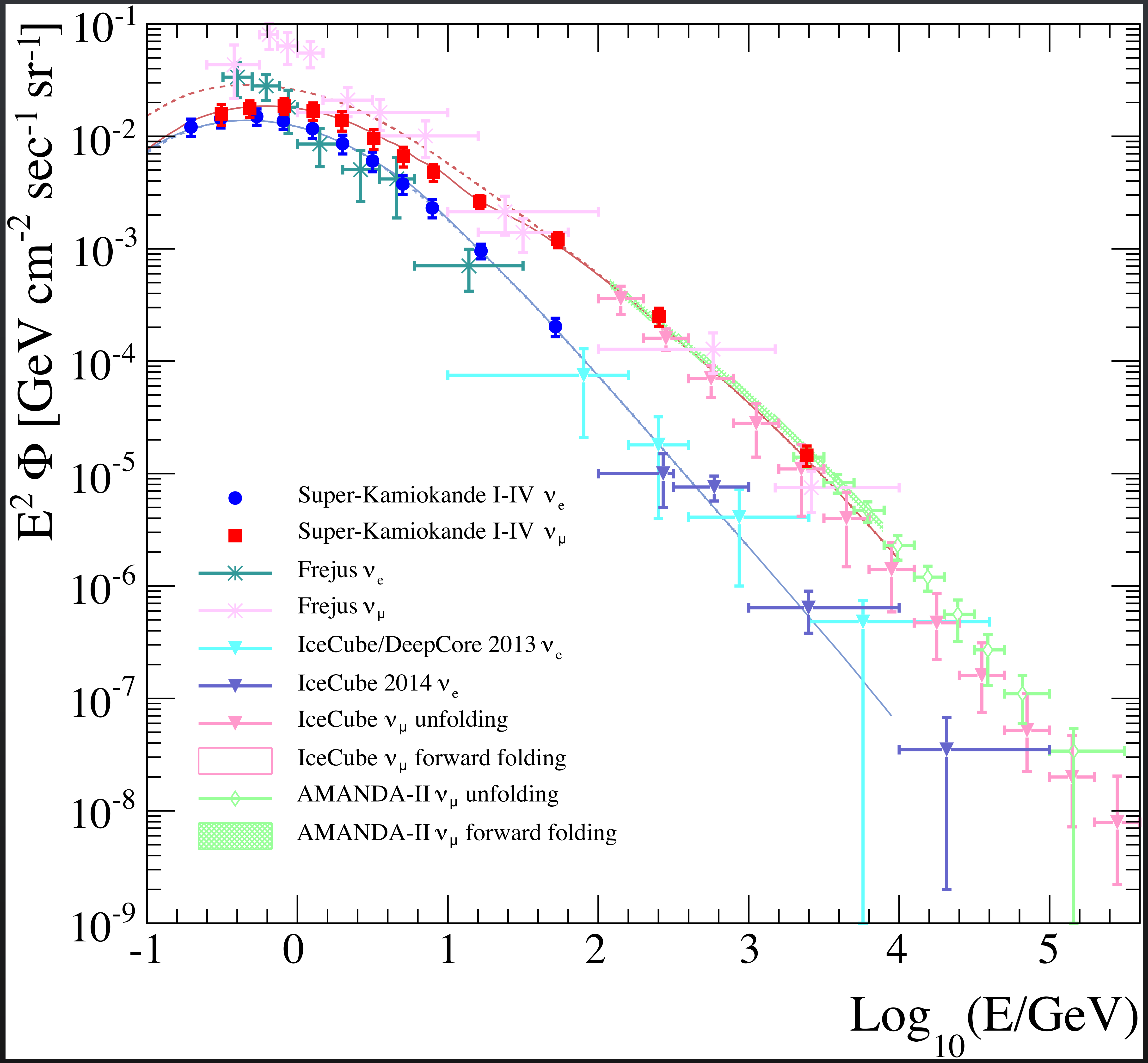
Flux Model Comparisons

- Also check the normalization and spectral index of the flux models.
- Generally consistent, some disagreement with the spectral index of Fluka ν_μ.



Comparison to Other Measurements

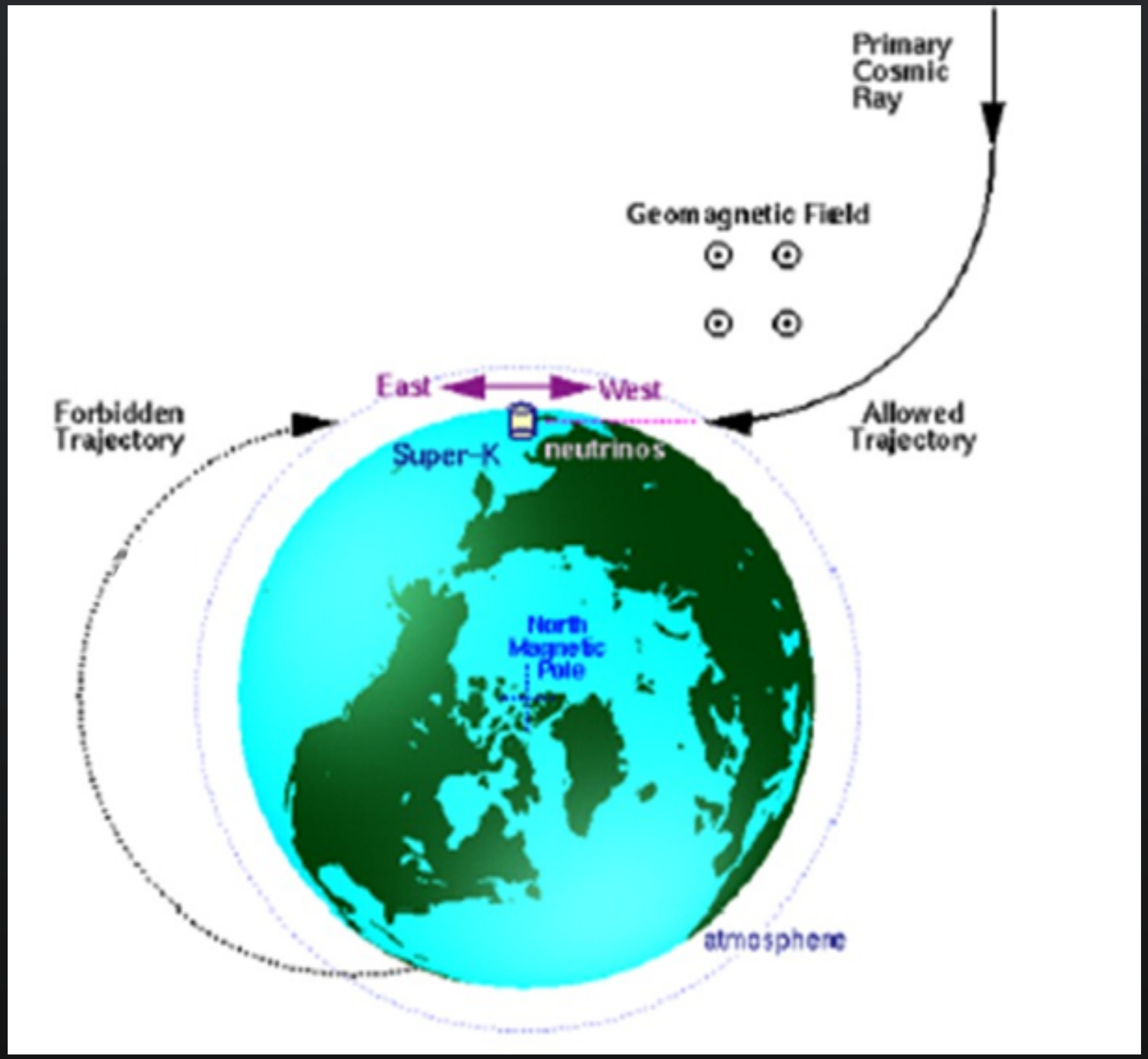
- Our data provide improved precision, extending up to 100 GeV for ν_e and 10 TeV for ν_μ, and the first data below 320 MeV.
- Overlap with km^3 detectors allows our data to provide extended constraints.
  - In particular, should be helpful to measure more accurately the astrophysical neutrino flux.

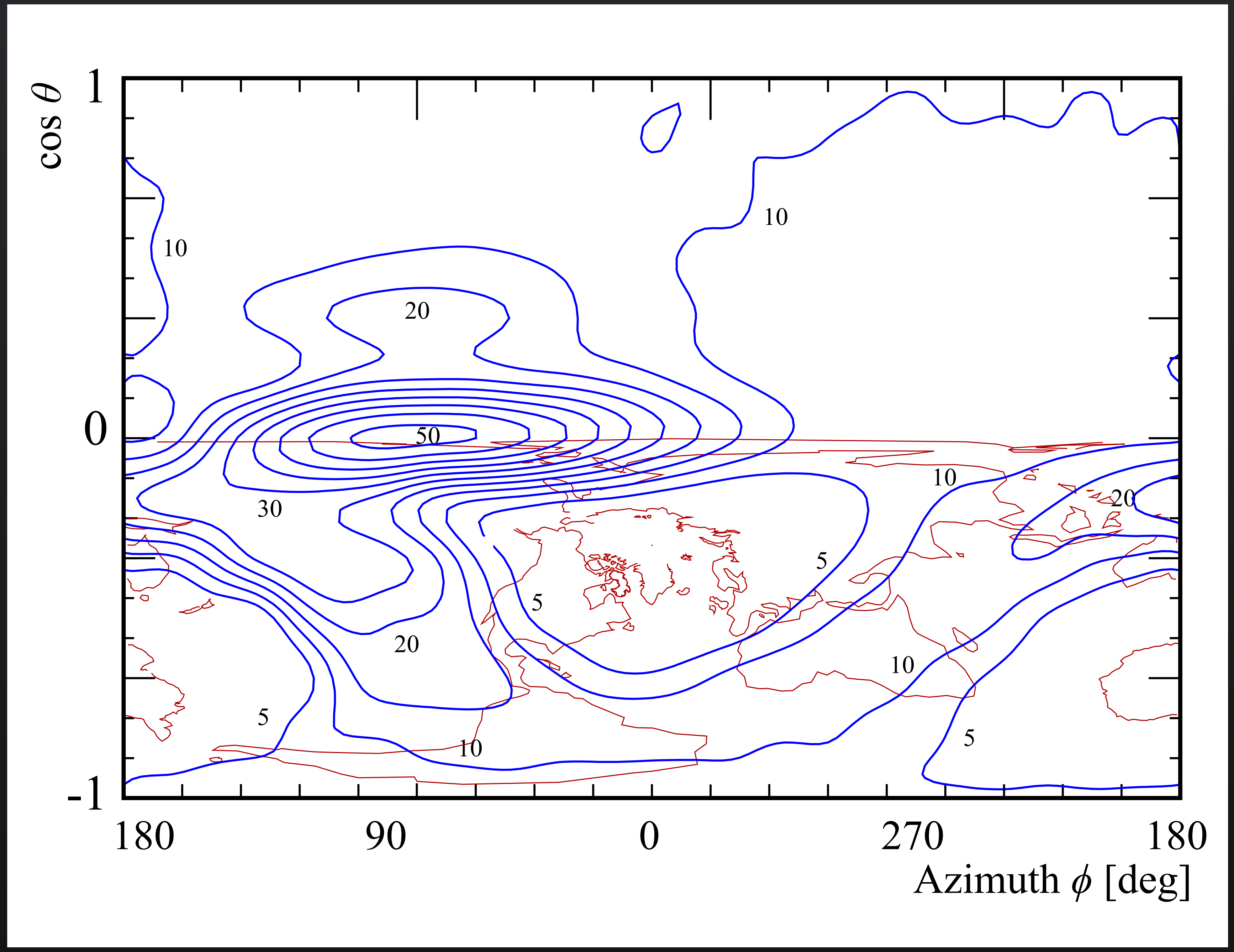


Geomagnetic Effects

Geomagnetic Effects

- The rigidity cutoff due to the geomagnetic field is a function of position and direction at the Earth's surface.
- There are well-known effects on the primary and secondary CR flux, such as the "east-west effect" dipole asymmetry.
- We test for any asymmetries in the neutrino flux, primarily by the azimuthal distributions.

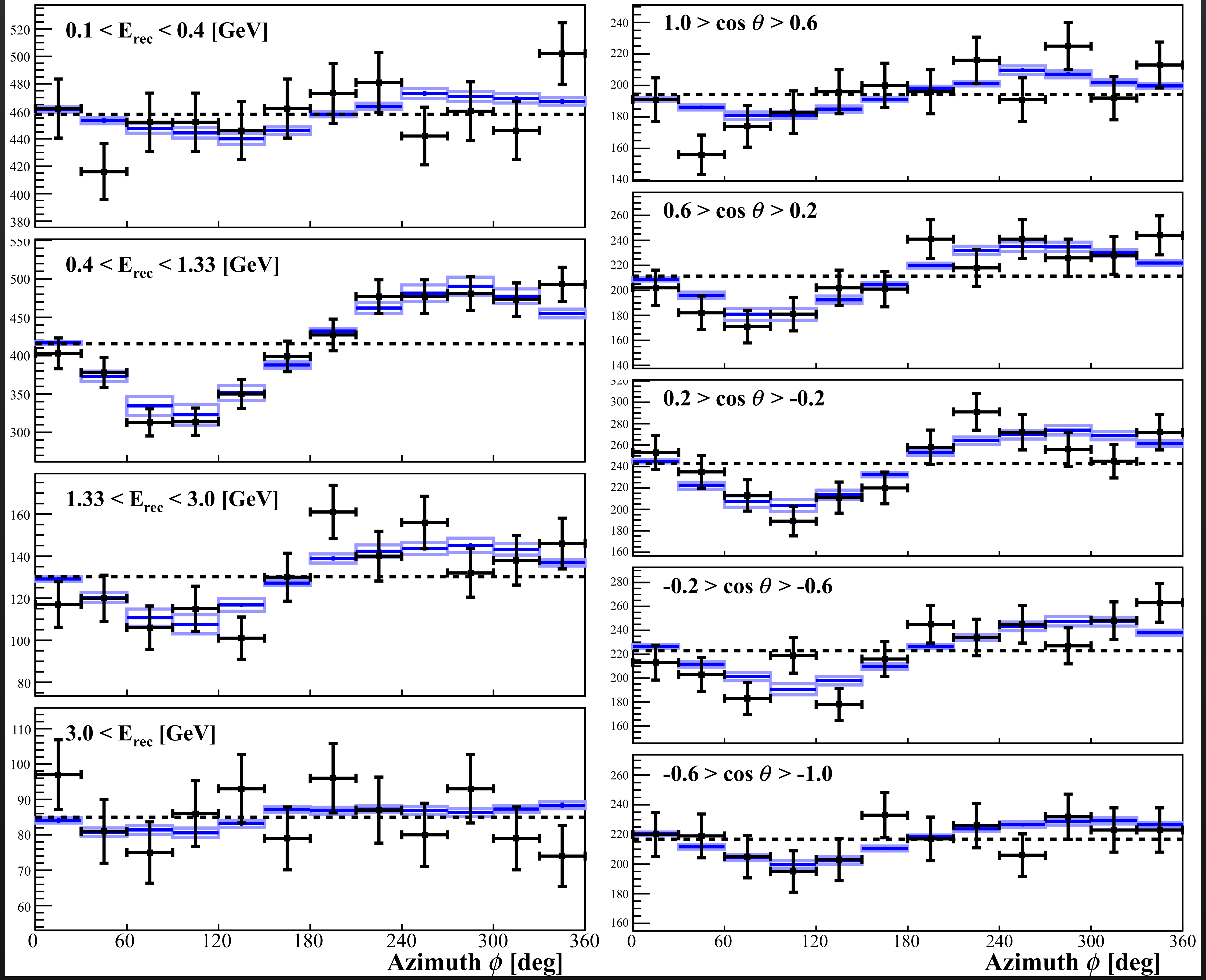




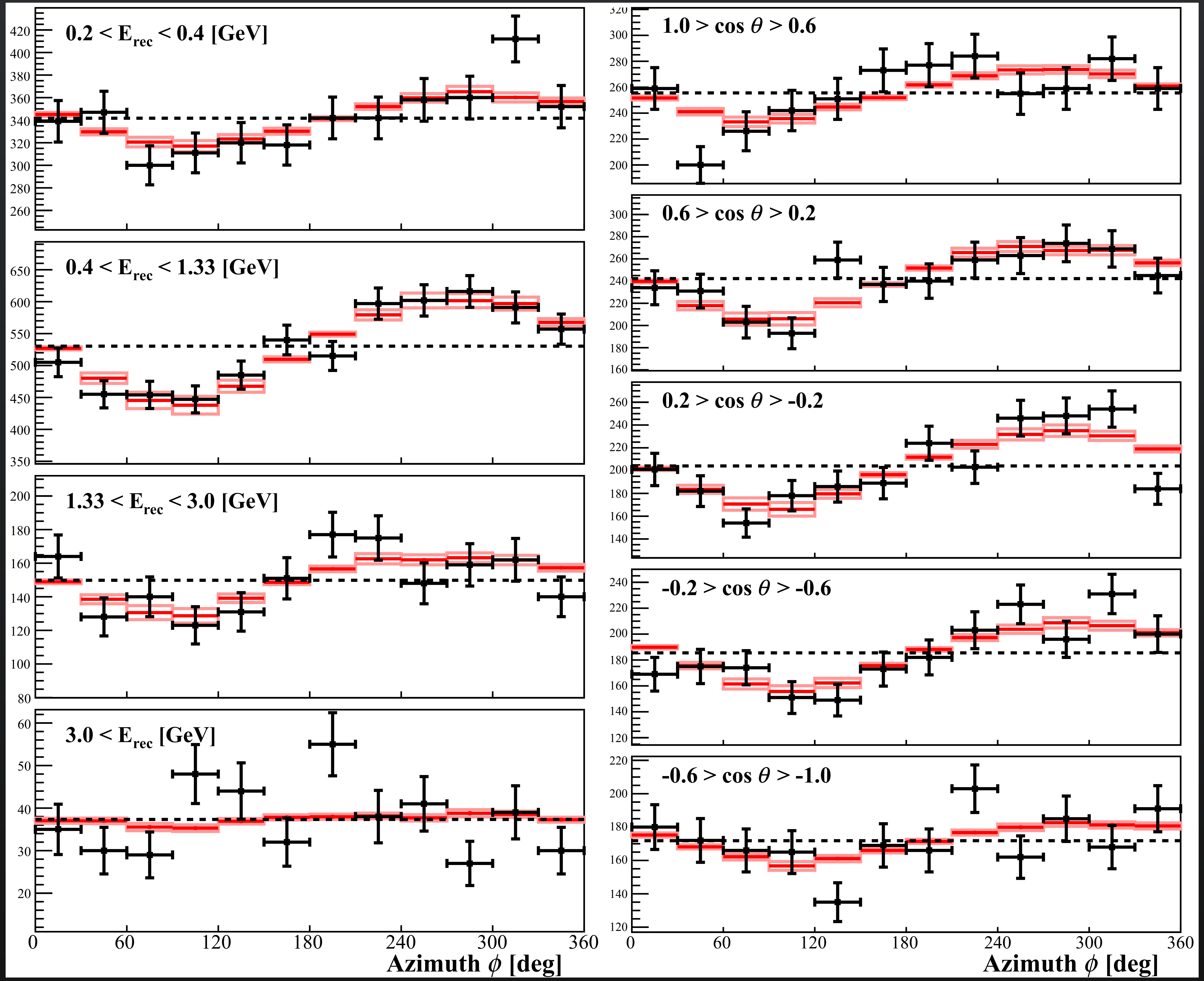
Azimuthal Distributions

- Showing various energy and zenith ranges. Testing against the HKKM11 model, which uses the IGRF-10 magnetic field model.

ν_e sample



ν_μ sample

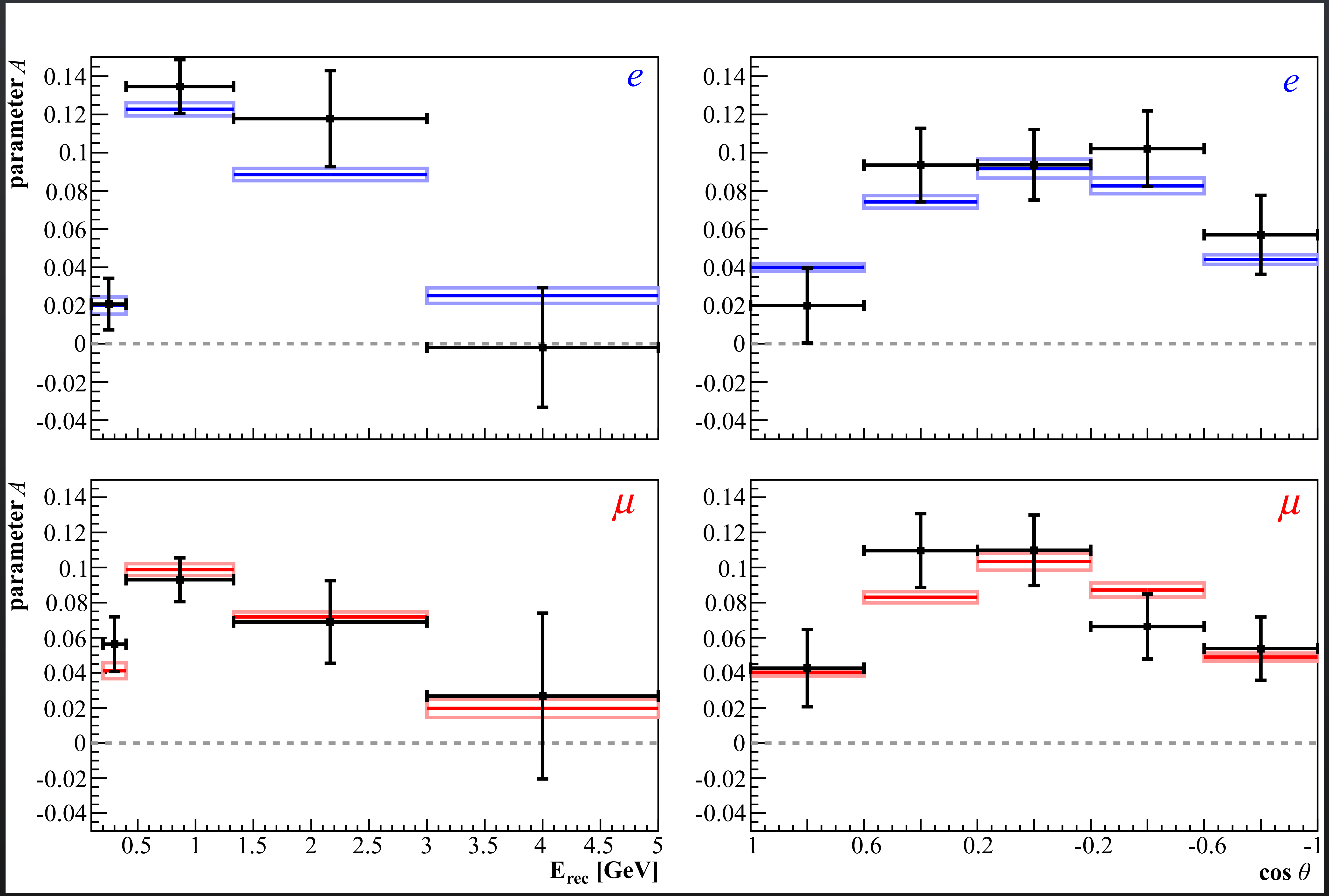


East-West Dipole Asymmetry

- Test for the dipole asymmetry in each plot, by the parameter

$$A = (n_w + n_e) / (n_w - n_e)$$

where n_e (n_w) are the number of east (west) going events.



East-West Dipole Asymmetry

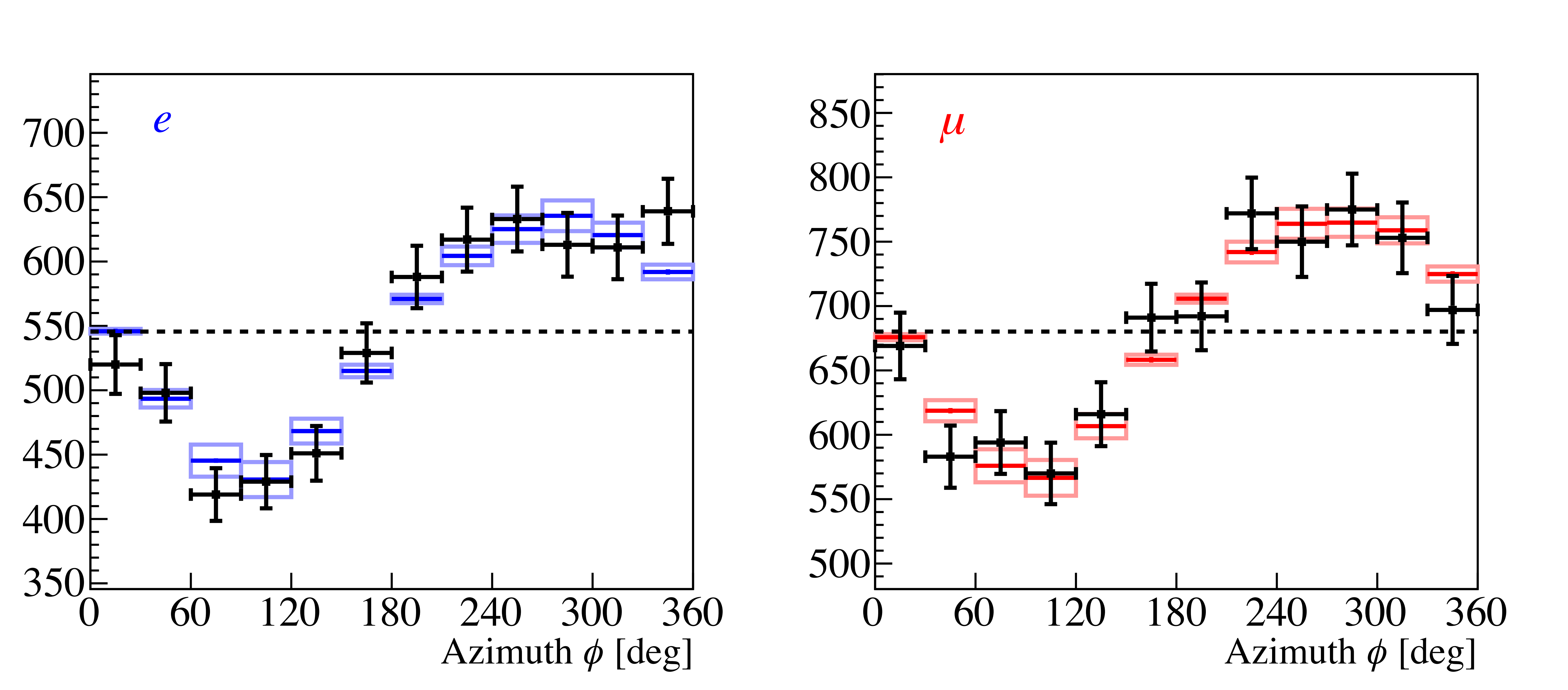
- Selecting a sub-sample of events by zenith angle

  $|\cos(\theta)| < 0.6$

  and reconstructed energy

  $400 < E_{rec} < 1330$ MeV

  optimizes for the sample with strongest predicted dipole asymmetry.



- Significance of a nonzero asymmetry is improved from previous measurements[1] by $4.9 \rightarrow 8.0\sigma$ ($2.2 \rightarrow 6.0\ \sigma$) in the ν_e (ν_μ) sample.

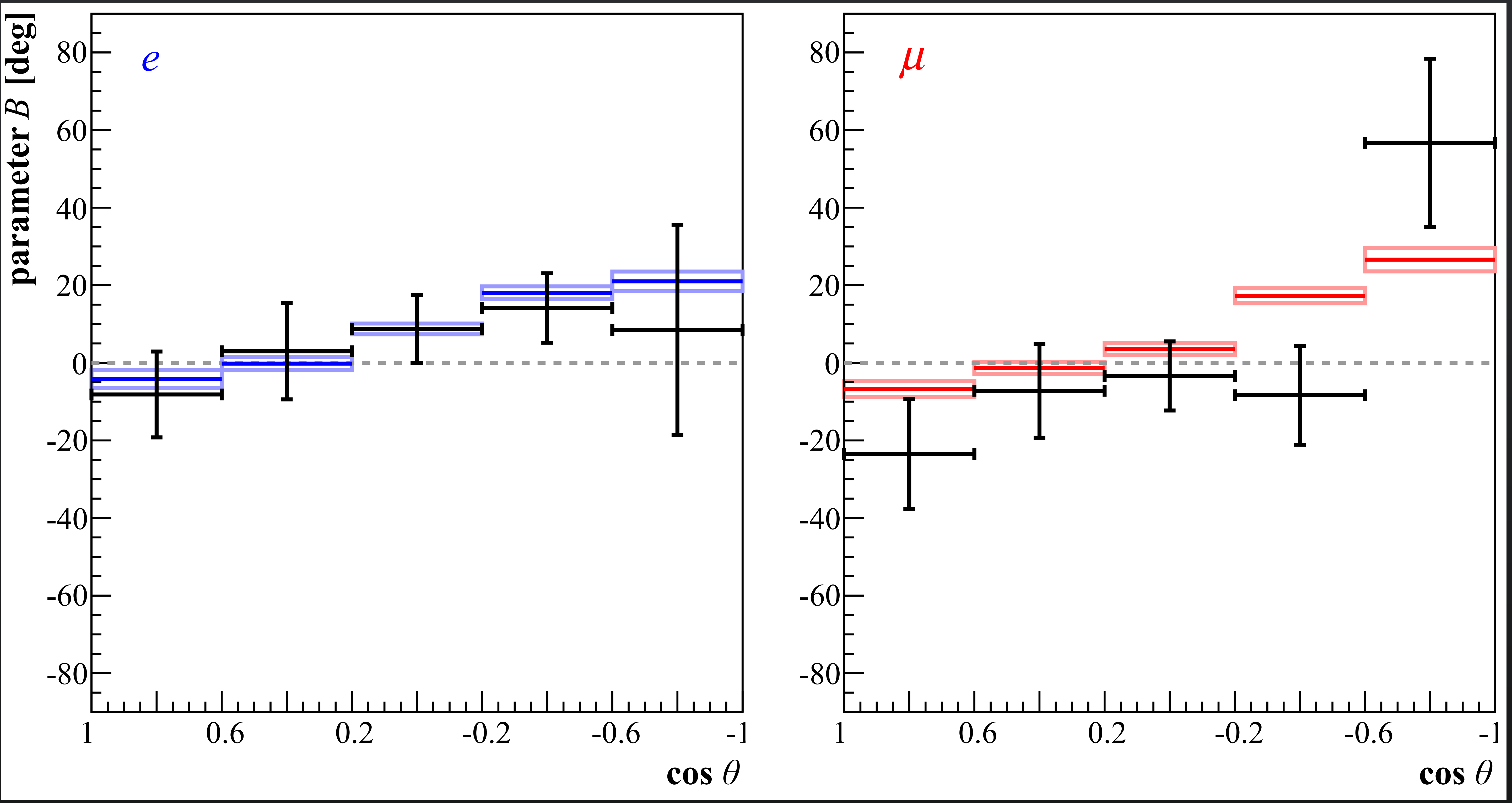
1. Phys. Rev. Lett. 82, 5194 (1999)

Zenith Dependency of Dipole Asymmetry

- Check zenith dependency of dipole asymmetry angle by fitting the azimuthal distribution in each zenith bin by

  $k_1 * \sin(\phi + B) + k_2$

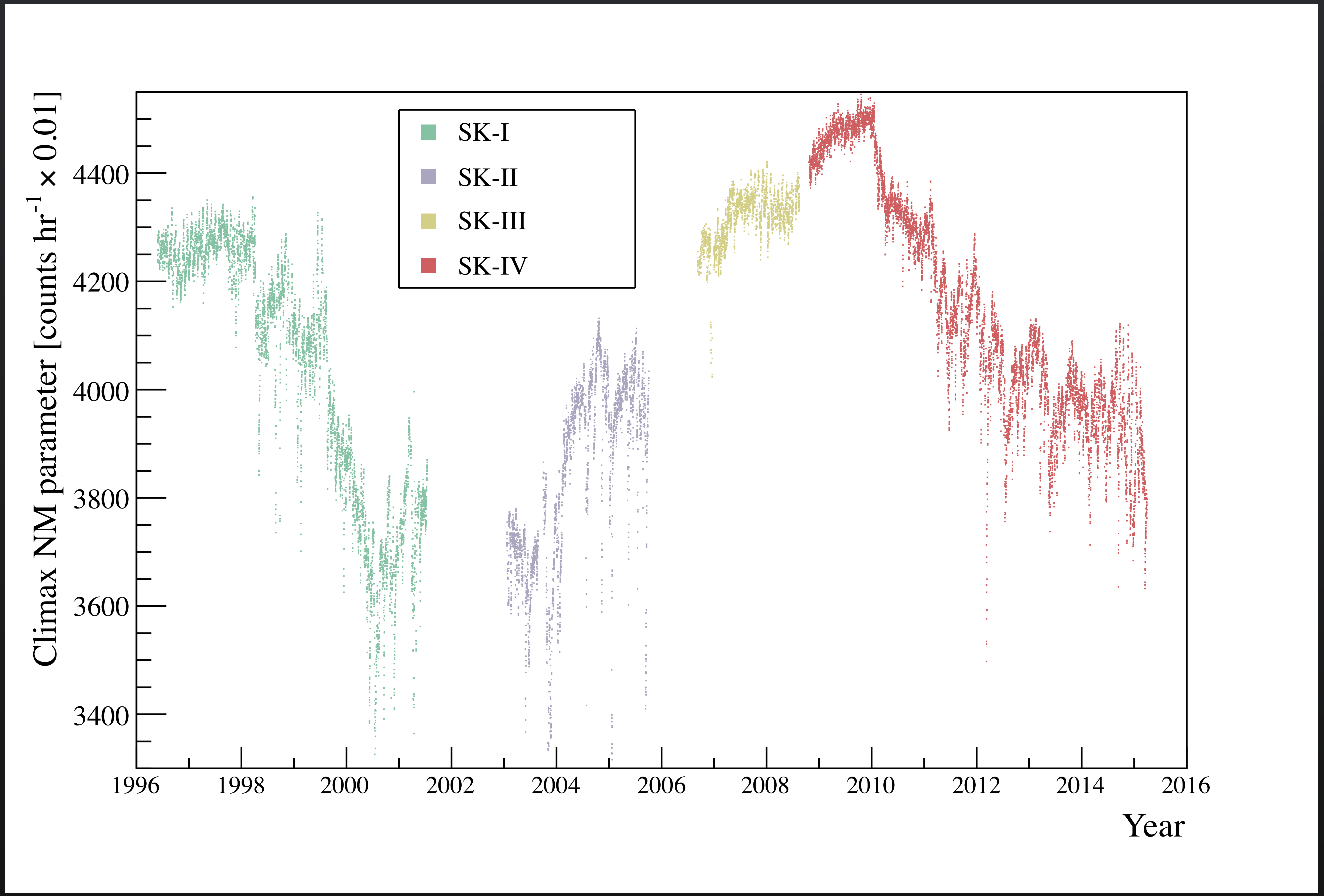
- 2.2 σ significance of a non-zero dependency.
- First measurement to explore beyond simple east-west asymmetry.



Solar Modulation

Solar Cycle and Neutron Monitors

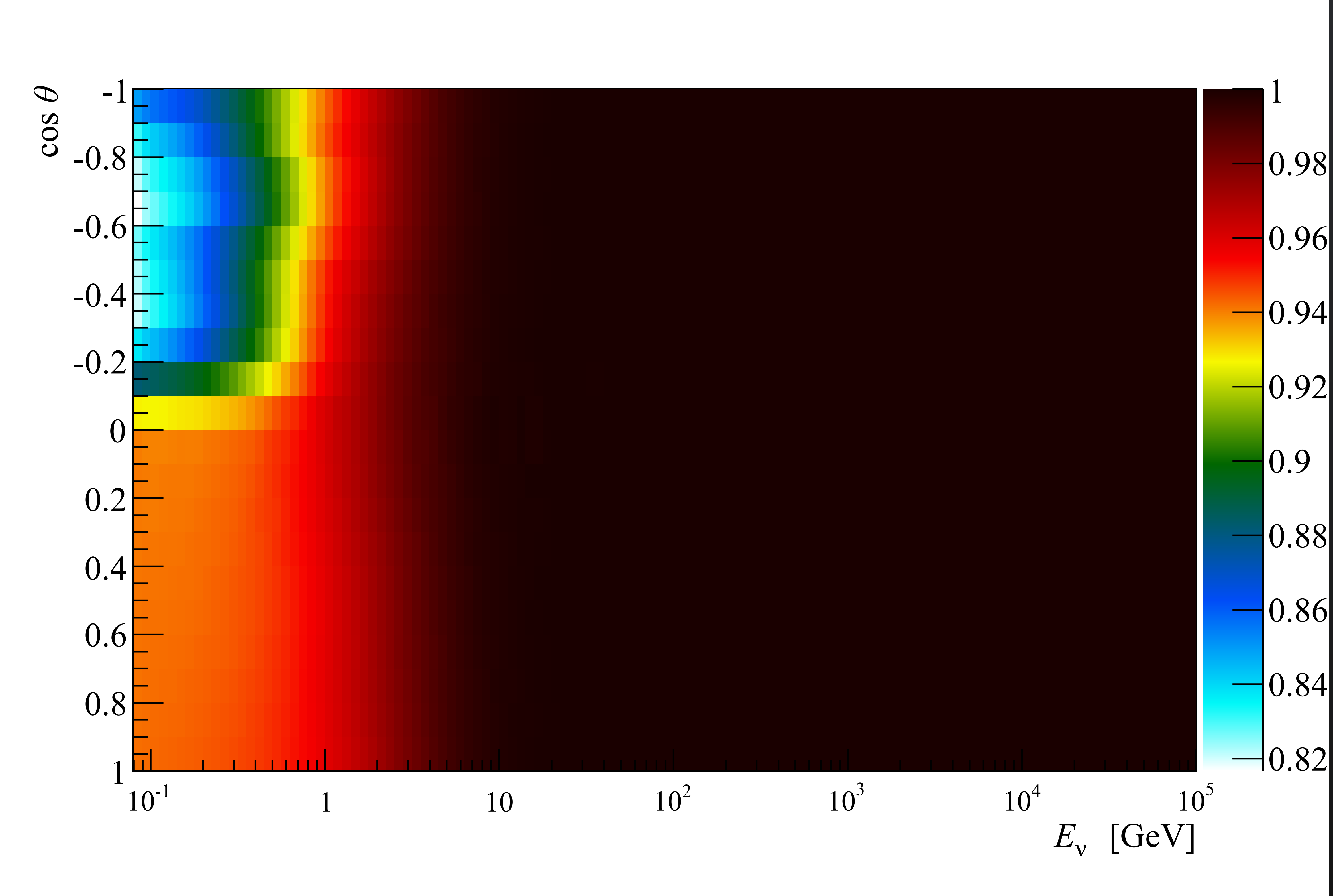
- The solar cycle is an 11-year modulation of the solar structure, and emitted plasma flux, well known to affect CRs approaching the Earth.
- Test to see if the neutrino flux is similarly correlated.
- We compare the neutrino flux to the neutron flux at ground level on the Earth.
  - Constantly and accurately measured, with no delay of plasma flux propagation, and expected to be well correlated to the primary CR flux.



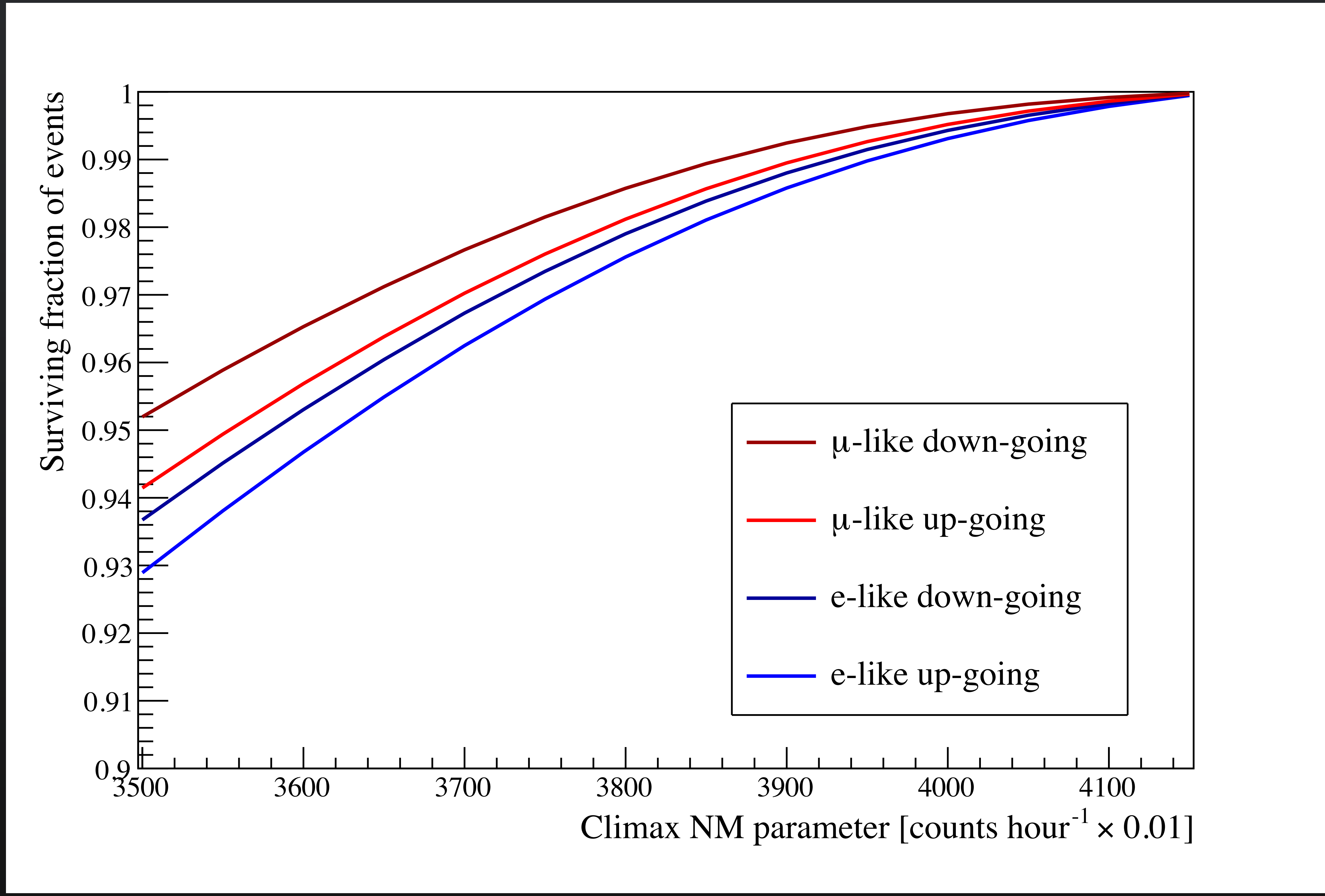
Effects on the Super-K Data

- Test for the correlation as predicted by the HKKM group.
  - Use SK samples with 100 < E_{rec} < 1330 MeV.

True ν_e flux prediction

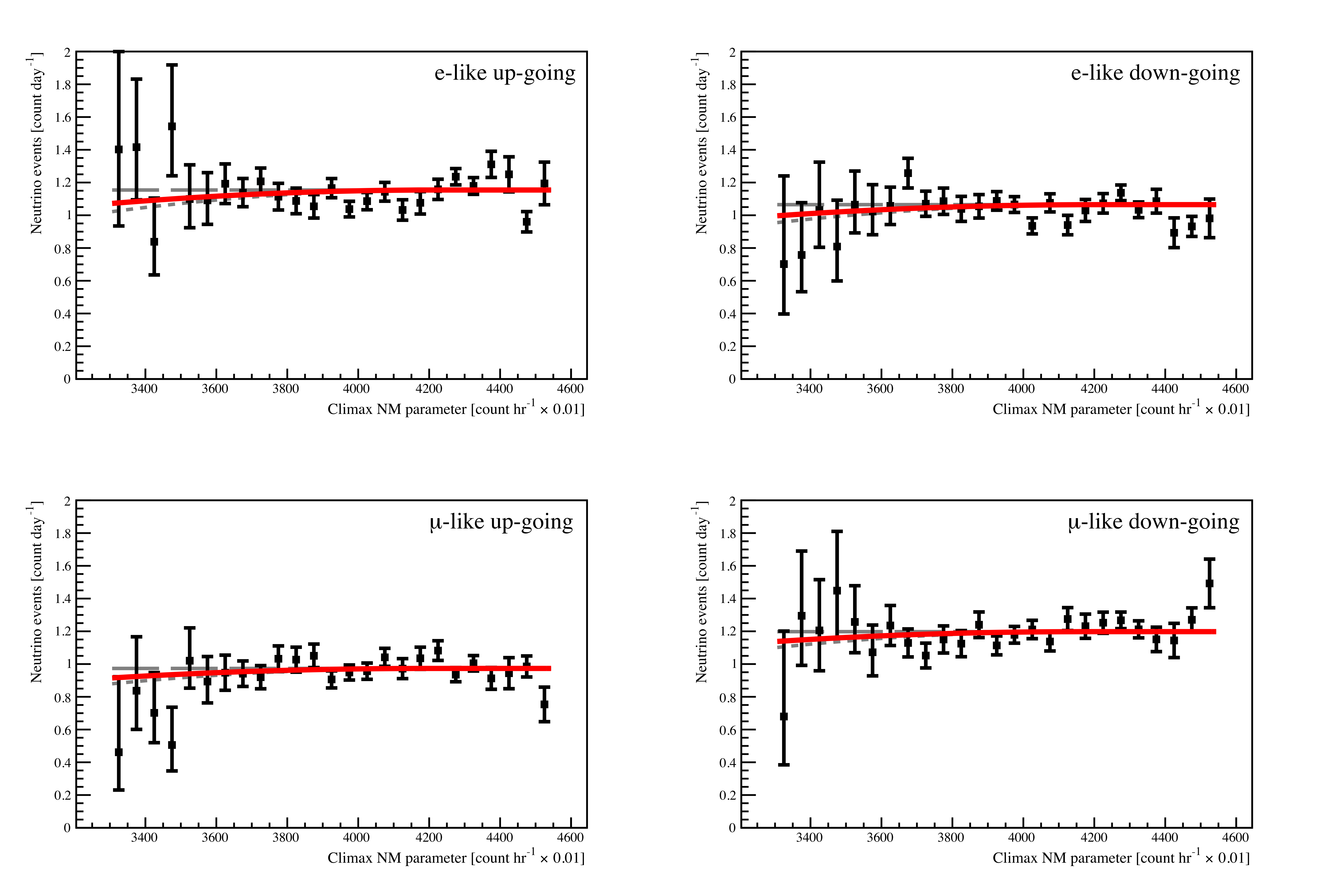


SK data prediction



Results - Long Term Search

- Bin events by NM count, and fit the four samples simultaneously across ~20 years of SK data.
- Fitted by continuous parameter α, where α=0 is no correlation and α=1 is the predicted correlation.
  - Best fit α = 0.62 ± 0.58
  - Significance of a nonzero correlation = 1.1σ (expected sensitivity 1.8σ)



Results - Forbrush Decreases

- For very high solar activity (NM count < 330,000 hr^{-1}) no prediction is available, but we have 7.1 days of detector uptime.

Start	End	Hours
15 Jul. 2000	17 Jul. 2000	50
11 Apr. 2001	13 Apr. 2001	38
29 Oct. 2003	01 Nov. 2003	61
02 Nov. 2003	04 Nov. 2003	67
19 Jan. 2005	19 Jan. 2005	13
Total		229

- Expect 32.80 ± 0.17 events (in four samples), but only 20 observed.
  - P-value to observe 20 or less events p = 0.017
  - 98.3% (2.38 σ) rejection of no-correlation hypothesis.

Summary

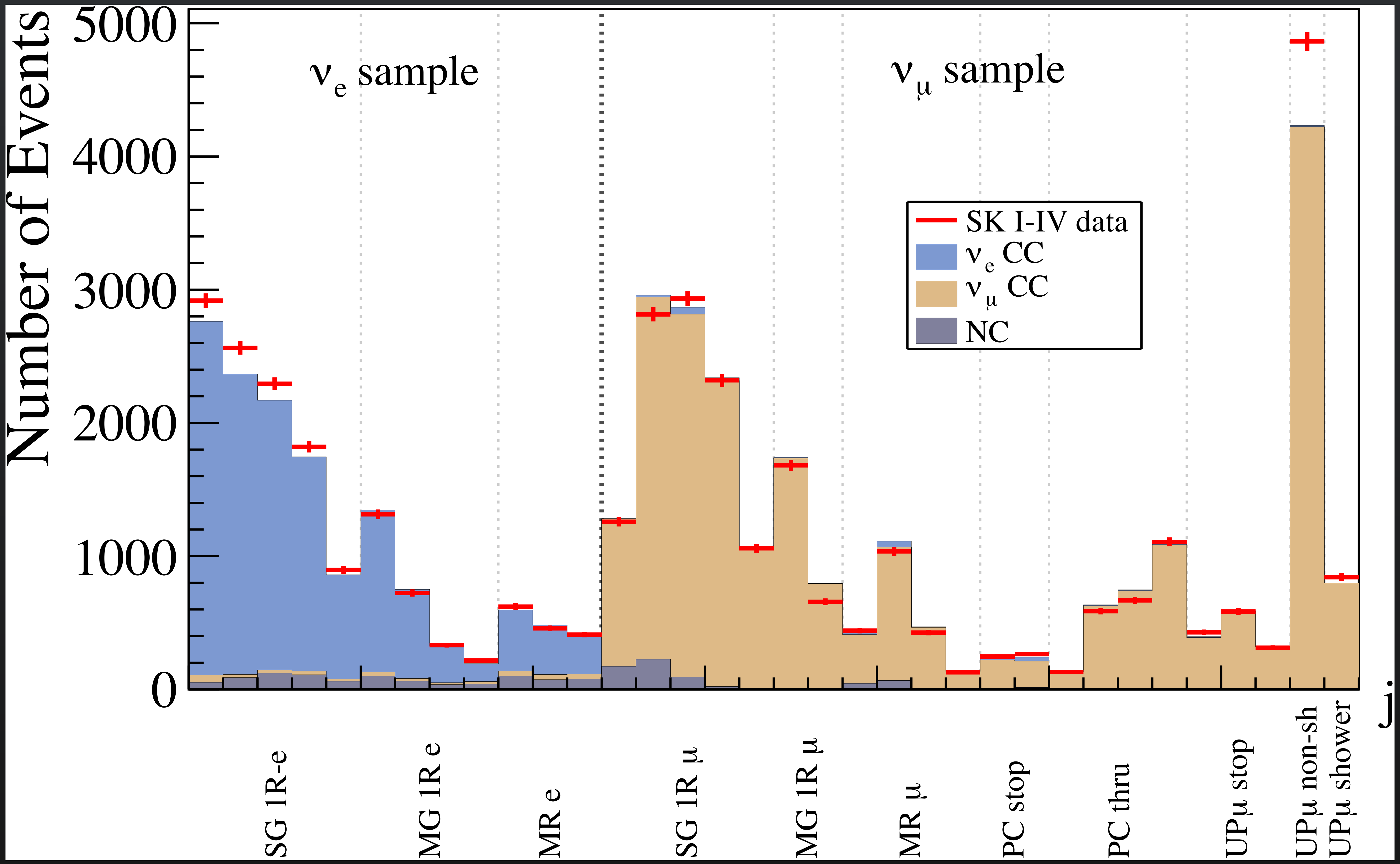
Summary

- The **energy spectrum** of the $\nu_e+\bar{\nu}_e$ and $\nu_\mu+\bar{\nu}_\mu$ fluxes were measured at SK over 100 MeV to 10 TeV, with the current best accuracy up to ~100 GeV.
  - Overlaps with the IceCube measurements (which are ≳100 GeV).
  - Consistent with current flux models (HKKM11, Fluka, Bartol) with some preference for HKKM11 as the best fit.
- The **azimuthal spectra** were compared with the HKKM11 model using IGRF-10.
  - The east-west dipole asymmetry was seen at 6σ (8σ) for the ν_μ (ν_e) sample.
  - Indication of an azimuthal dependence of the dipole at 2.2σ.
- A correlation with the **solar cycle** over 20 years of data was seen with only a weak preference (1.1σ compared to expected 1.8σ sensitivity).
  - Considering more extreme solar activity (7.1 separate days of data), some correlation was seen at 2.4σ.

Backup

Energy Unfolding - Data

- Raw data, and MC with estimated purities.



Energy Unfolding - Iterative Bayesian Method

- If N^{CC}_i is the true energy spectrum (bins i), and M_j is the reconstructed energy spectrum (bins j), then define priors

$$P_0(i) = \frac{N^{CC}_{MC,i}}{\sum_k N^{CC}_{MC,k}},$$

and state Bayes' theorem

$$P(i|j) = \frac{P(j|i)P_0(i)}{P_0(j)} \qquad P_0(j) = \sum_i P(j|i)P_0(i).$$

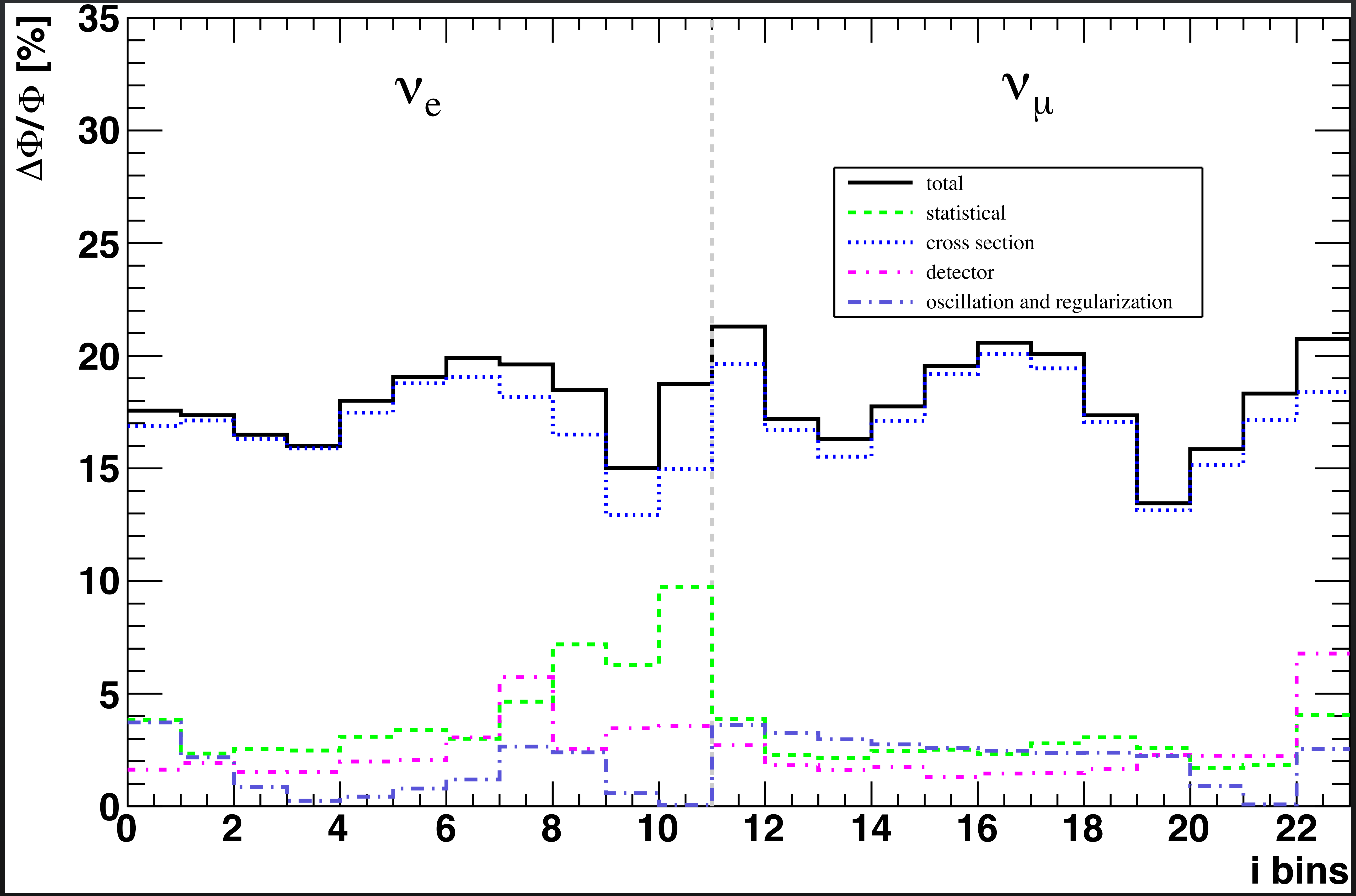
then make estimation based on the data

$$\hat{N}^{CC}_i = \sum_j P(i|j)M_j.$$

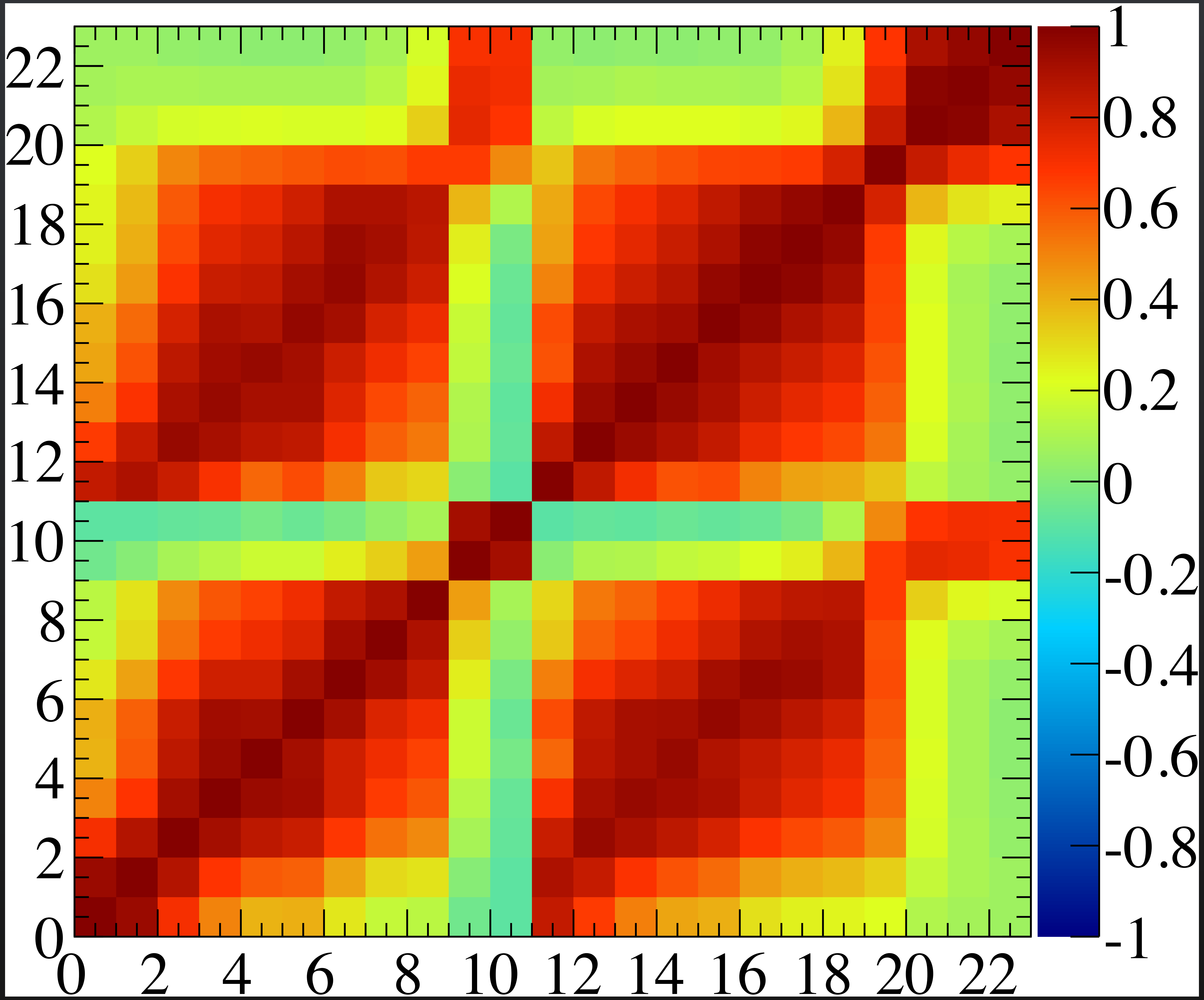
and take the result as new priors, to proceed iteratively. Background events are considered as a possible cause.

Energy Unfolding - Systematic Errors

- Detailed systematic error analysis for neutrino cross-sections, reconstruction, and oscillation parameter related uncertainties.

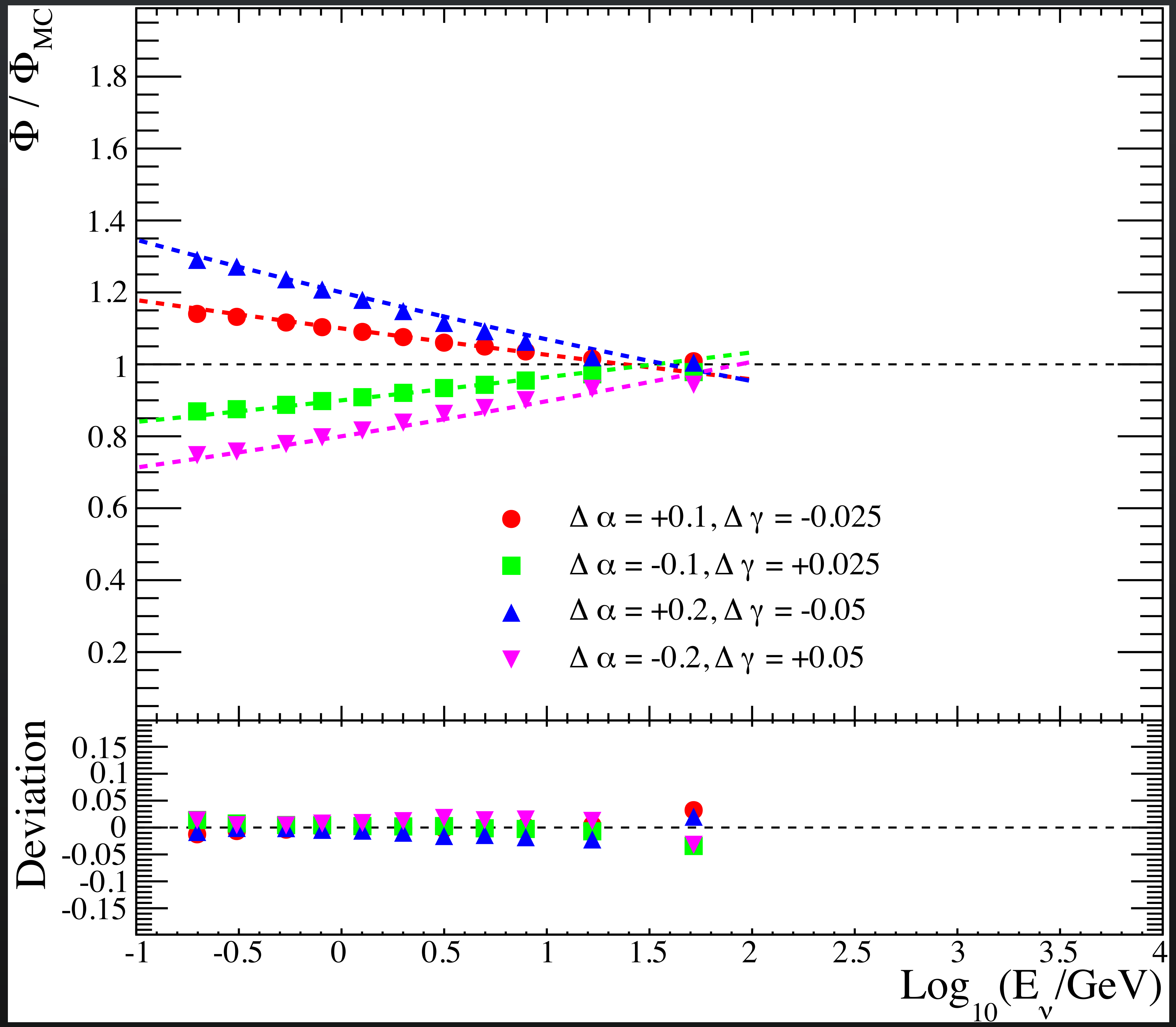


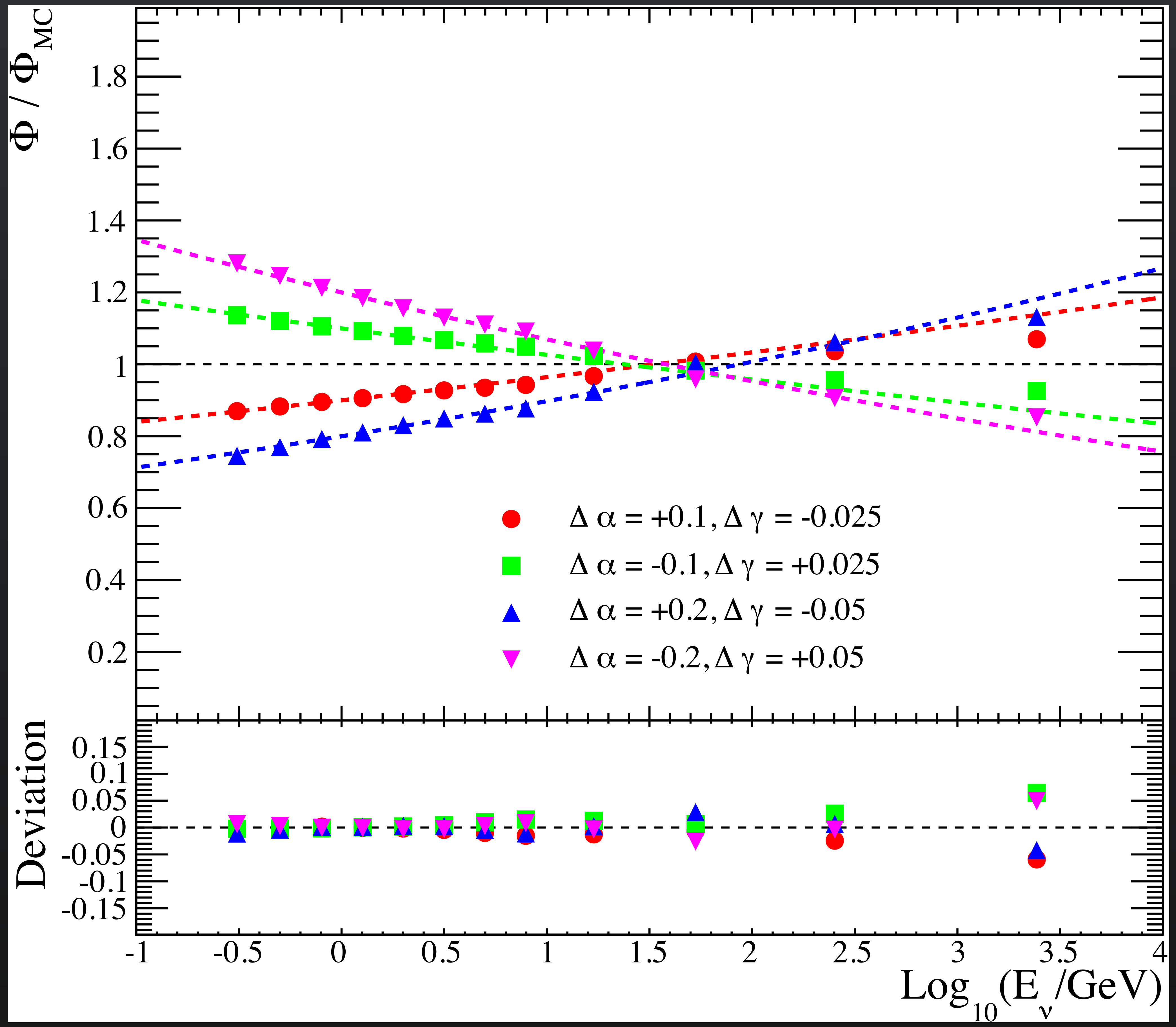
Energy Unfolding - Error Matrix



Energy Unfolding - Bias Check

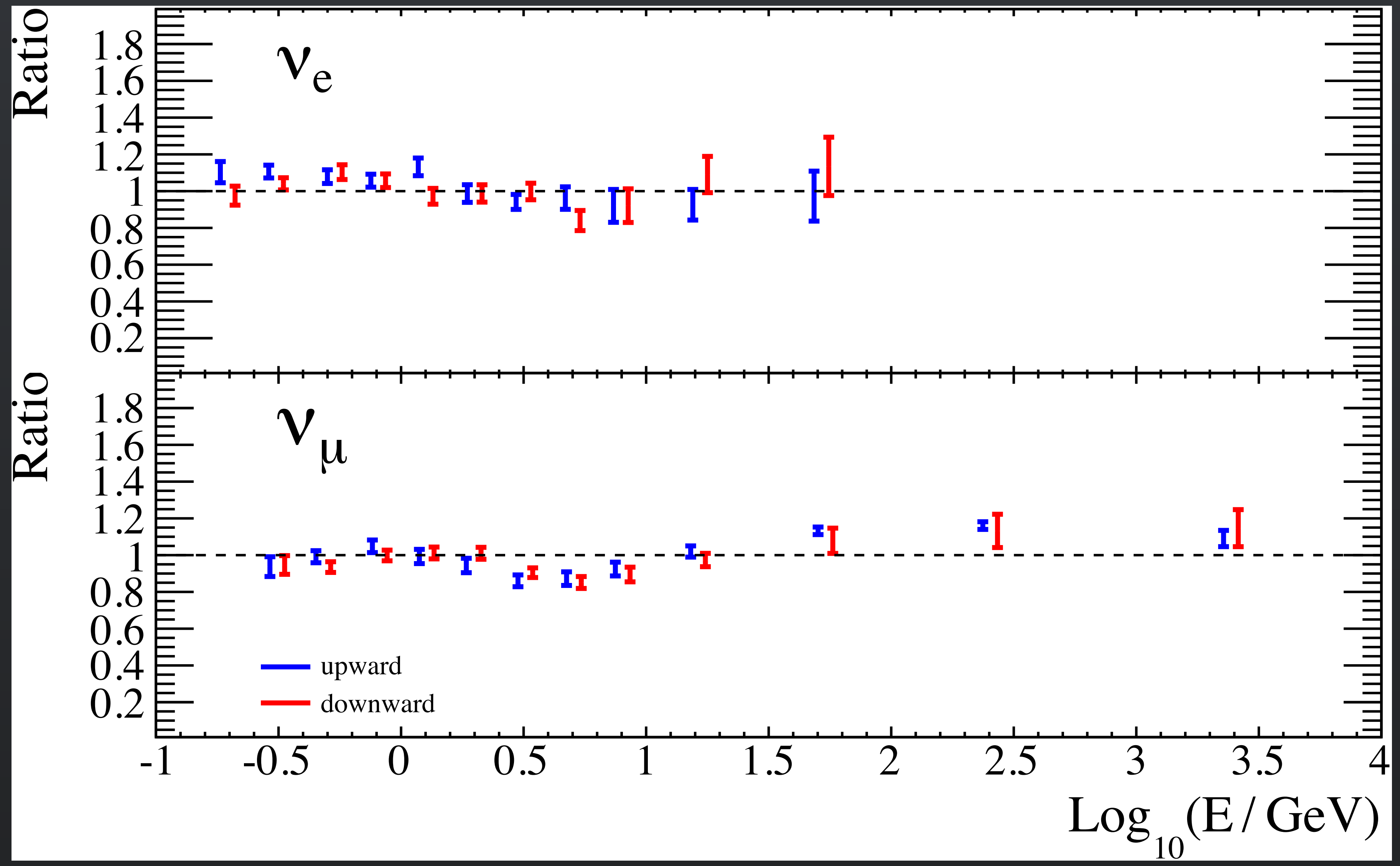
- Unfold toy spectra with modified normalization α and spectral index γ, to estimate any bias coming from the initial MC expectations.



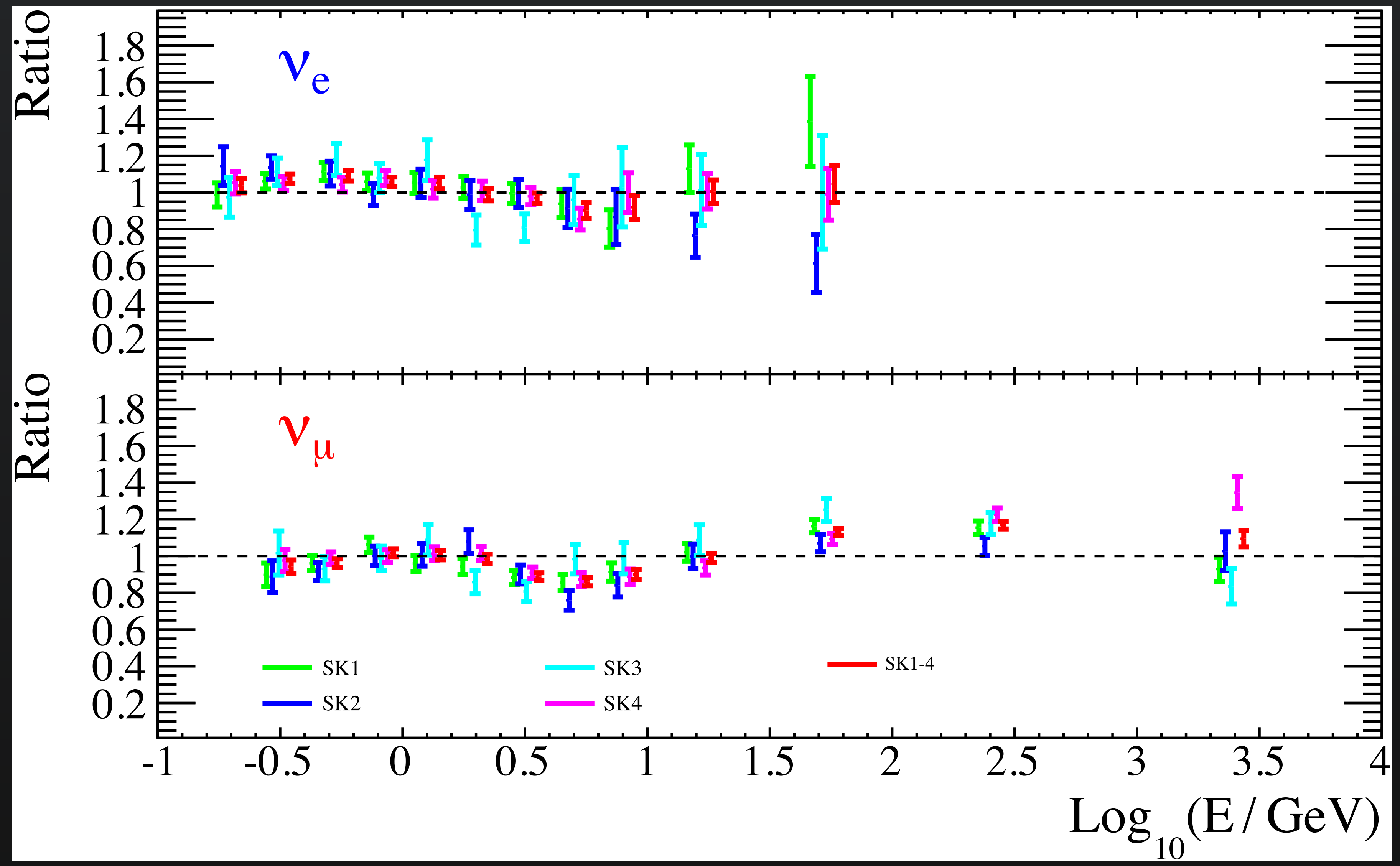


Energy Unfolding - Other Checks

- Unfolding by up / down fluxes separately (UPMU is upwards only).

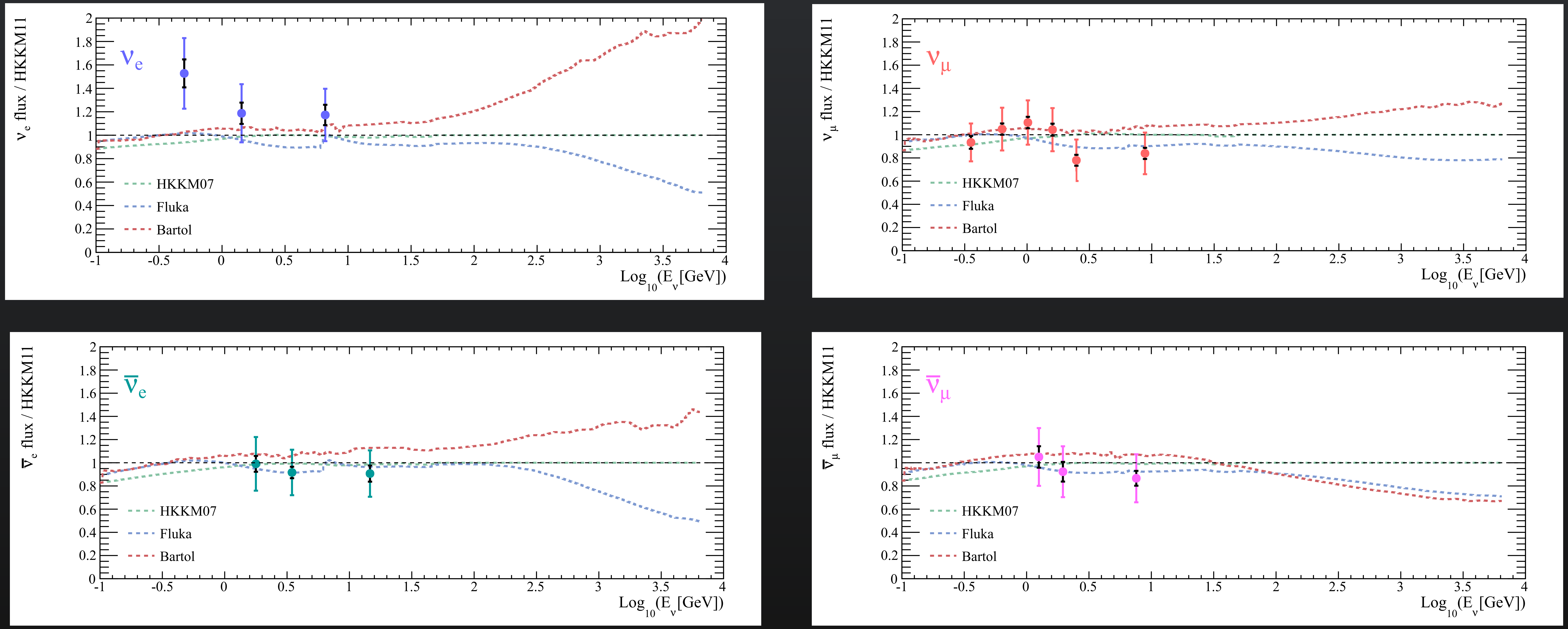


- Unfolding by each SK period (showing statistical errors only).



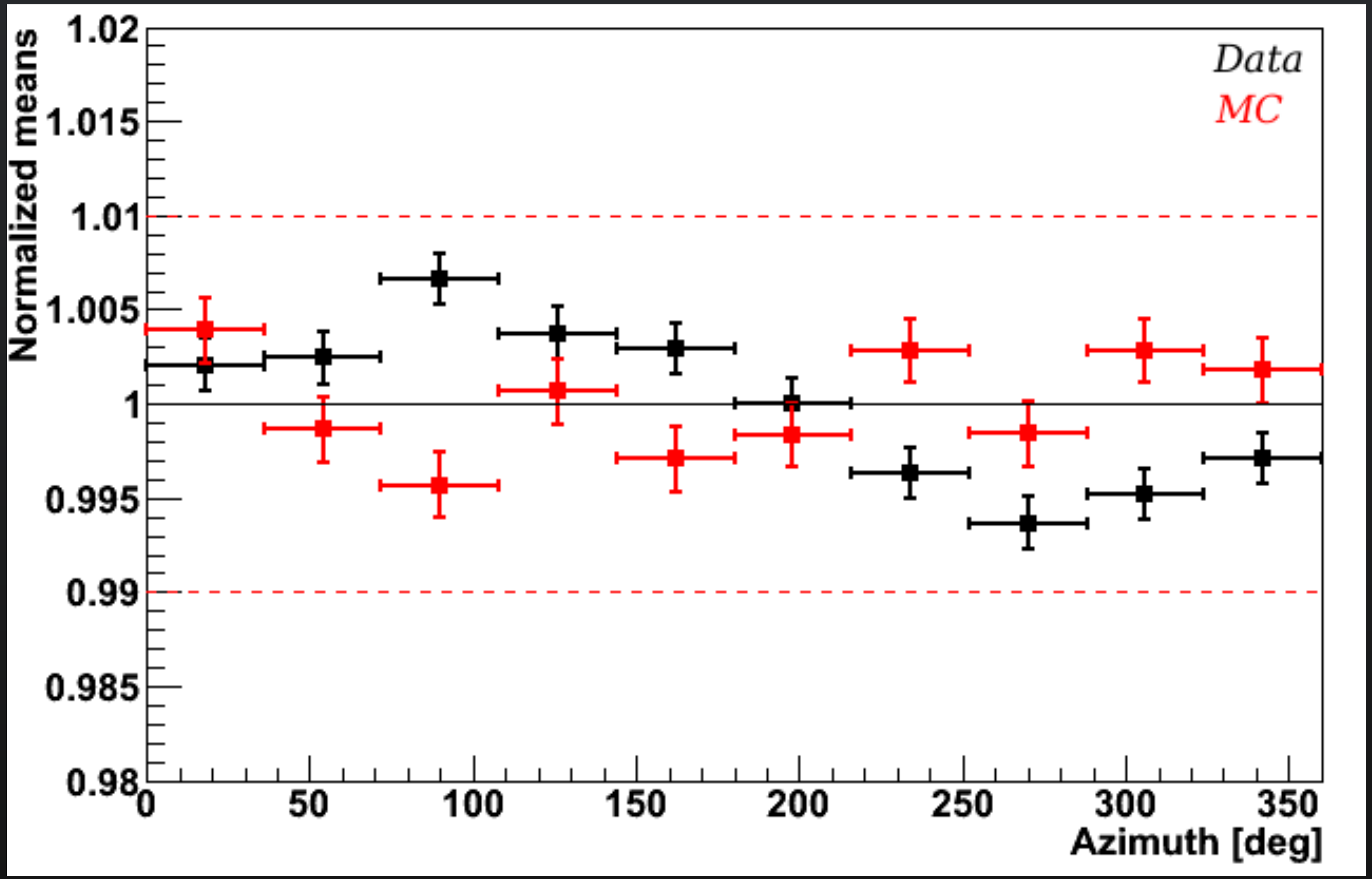
ν / $\bar{\nu}$ Separated Energy Unfolding

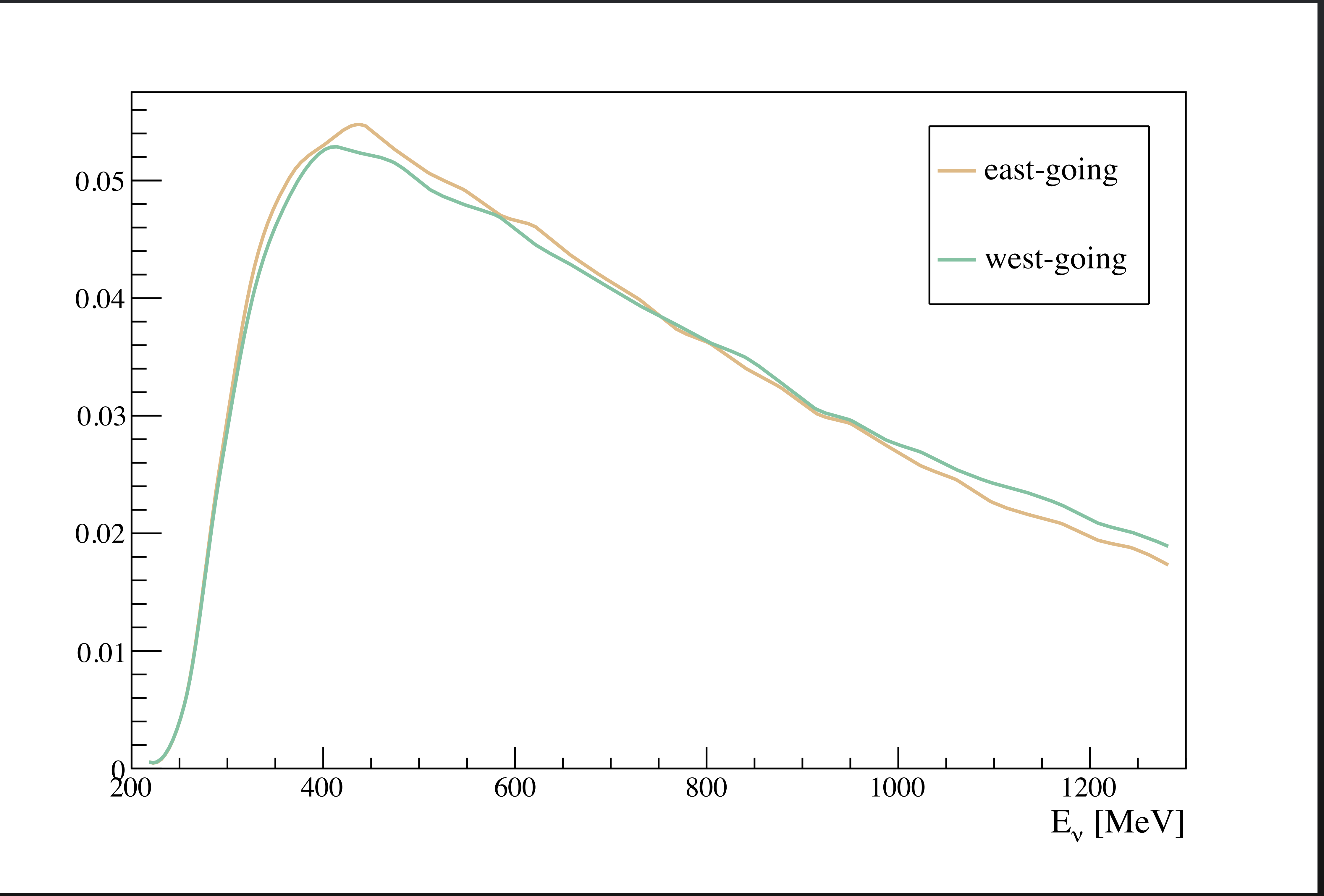
- Using kinematics (no charge separation by electric field possible in Super-K), some separation power between ν and $\bar{\nu}$ — though results have meaning only in a comparative sense (**preliminary**).



Azimuthal Systematics

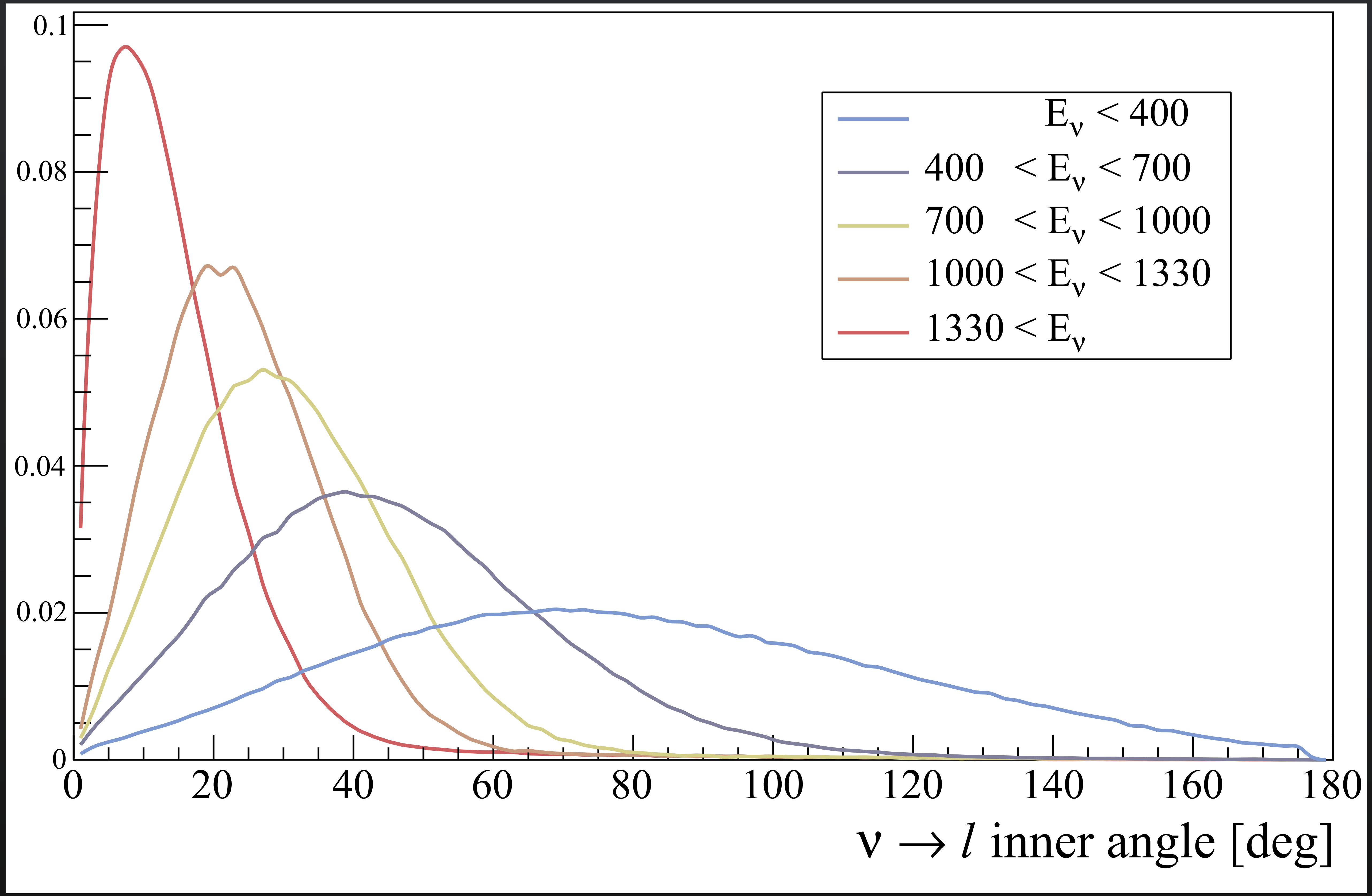
- SK detector is highly azimuthally symmetric, although some energy systematic may exist at the <1% level.
- Other systematics (such as differences in the east and west going energy spectra) can contribute in second-order.





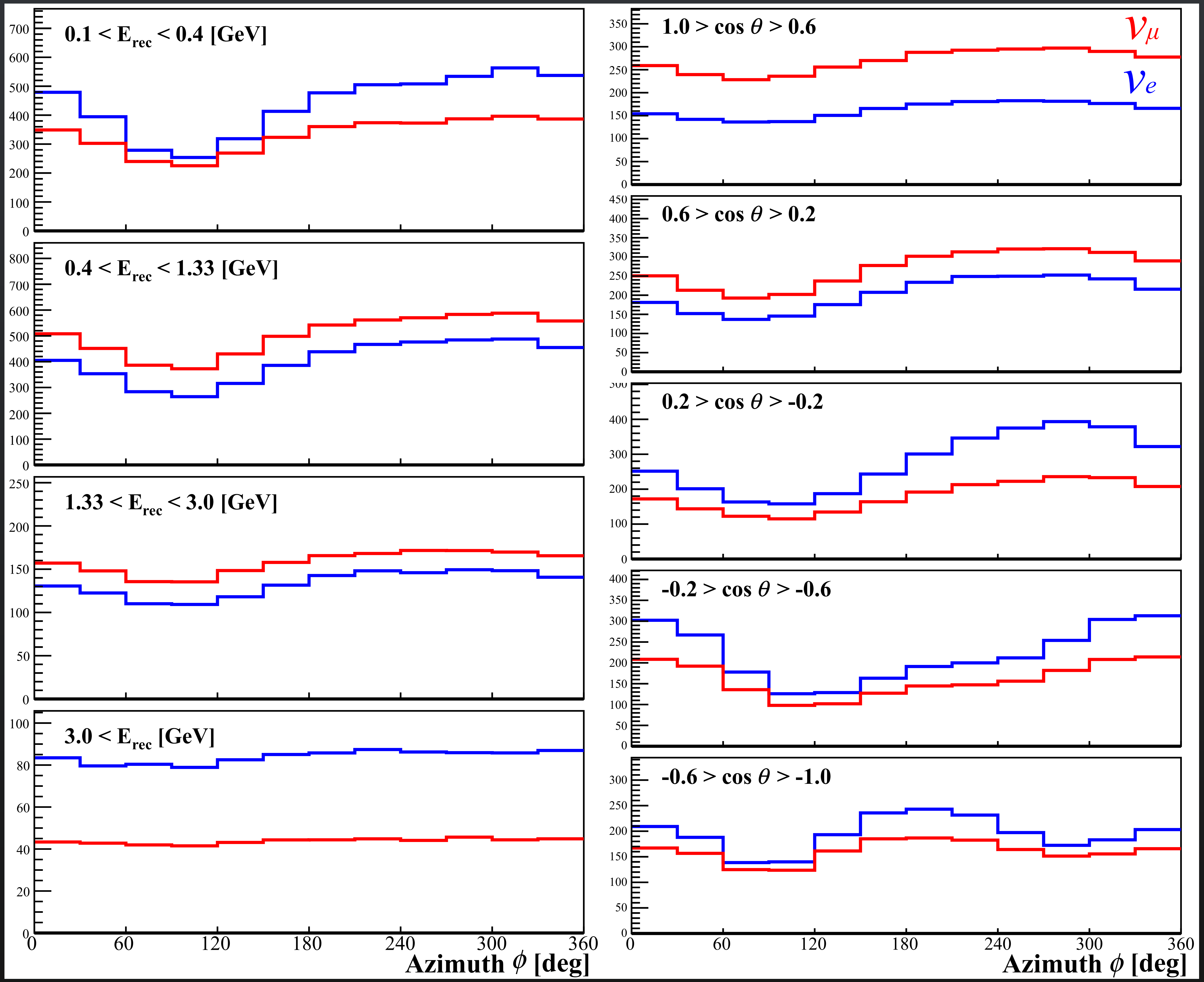
Lepton → Neutrino Directional Correlation

- Dominant uncertainty in reconstructing the neutrino direction in CCQE events comes from the poor correlation with the emitted charged lepton direction (worse at lower energies).



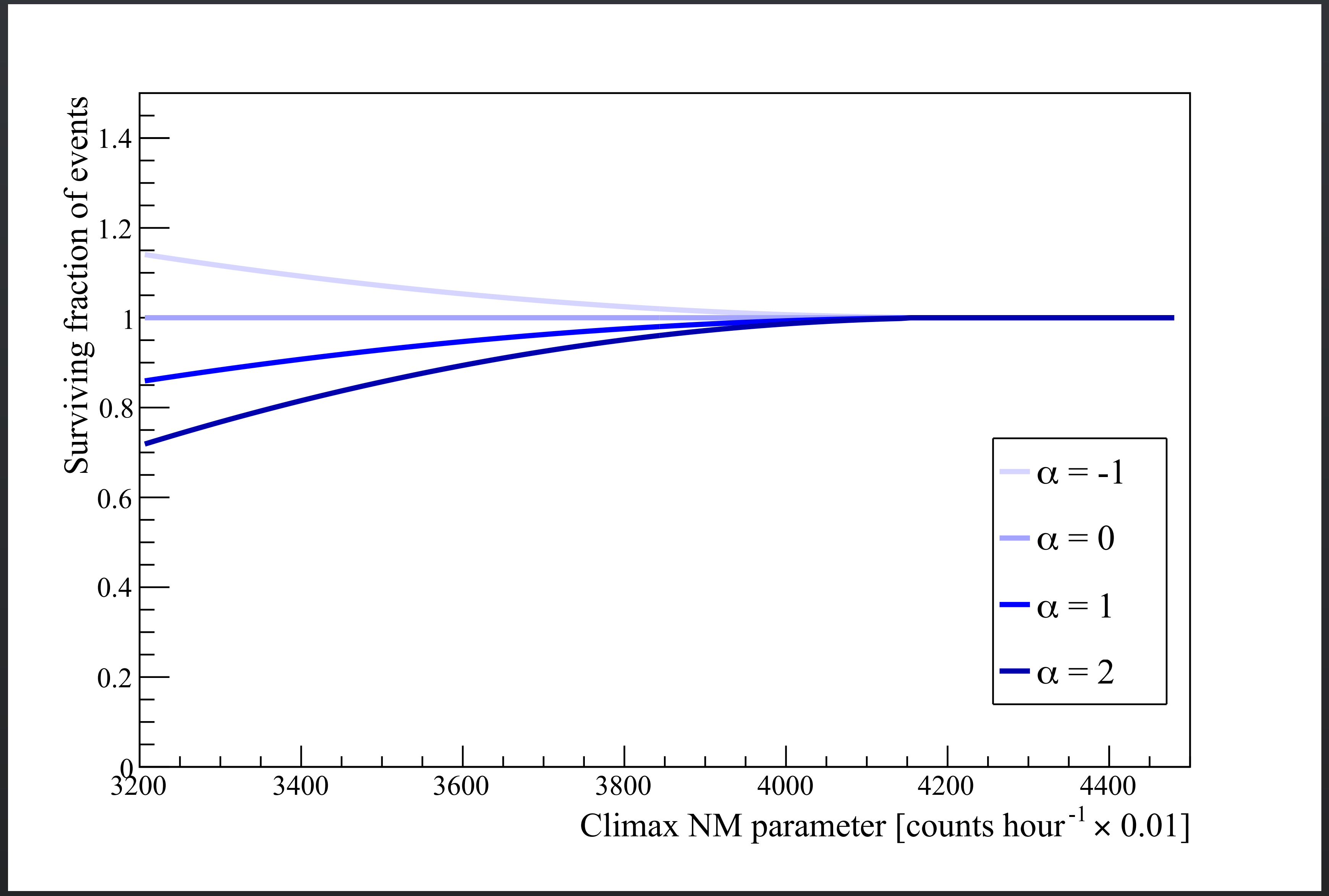
Azimuthal MC Truth Distributions

- The same events as shown in the reconstructed plots, but rebinned using the true lepton direction and momentum.

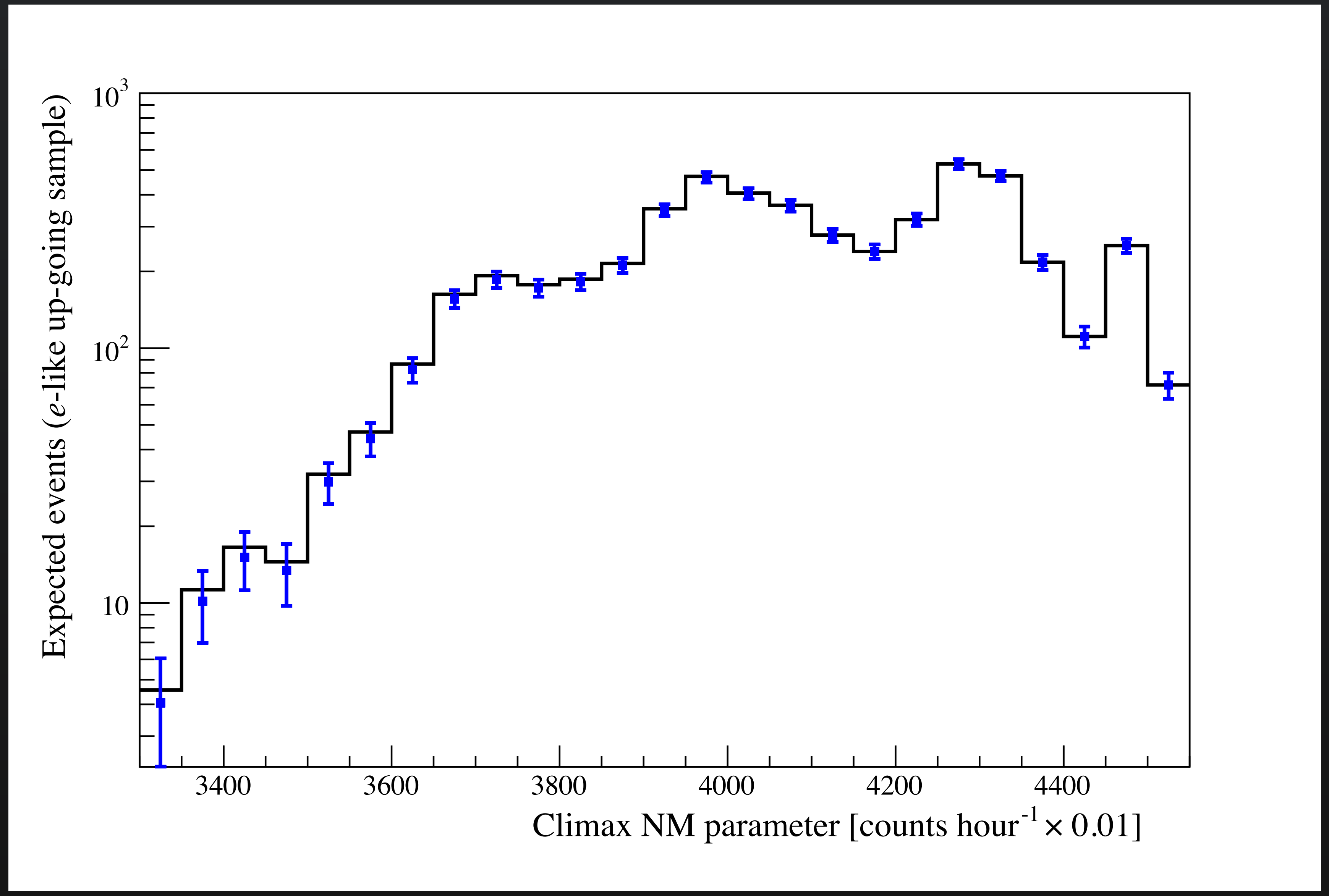


Solar Modulation - Hypothesis Test

- Hypotheses for expected number of events based on the scaleable parameter α, in turn based on the HKKM prediction.



- Black line has α = 0, blue data points have α = 1.



Solar Modulation - Hypothesis Test

- If $N_{s,i}$ are our data and $H'_{s,i}$ is our hypothesis (in data sample s and bin i) then define the log-likelihood as

$$\ln L(N|H) = \sum_s \sum_i \ln \left(\frac{{H'}_{s,i}^{N_{s,i}} e^{-H'_{s,i}}}{N_{s,i}!} \right) + \epsilon^2$$

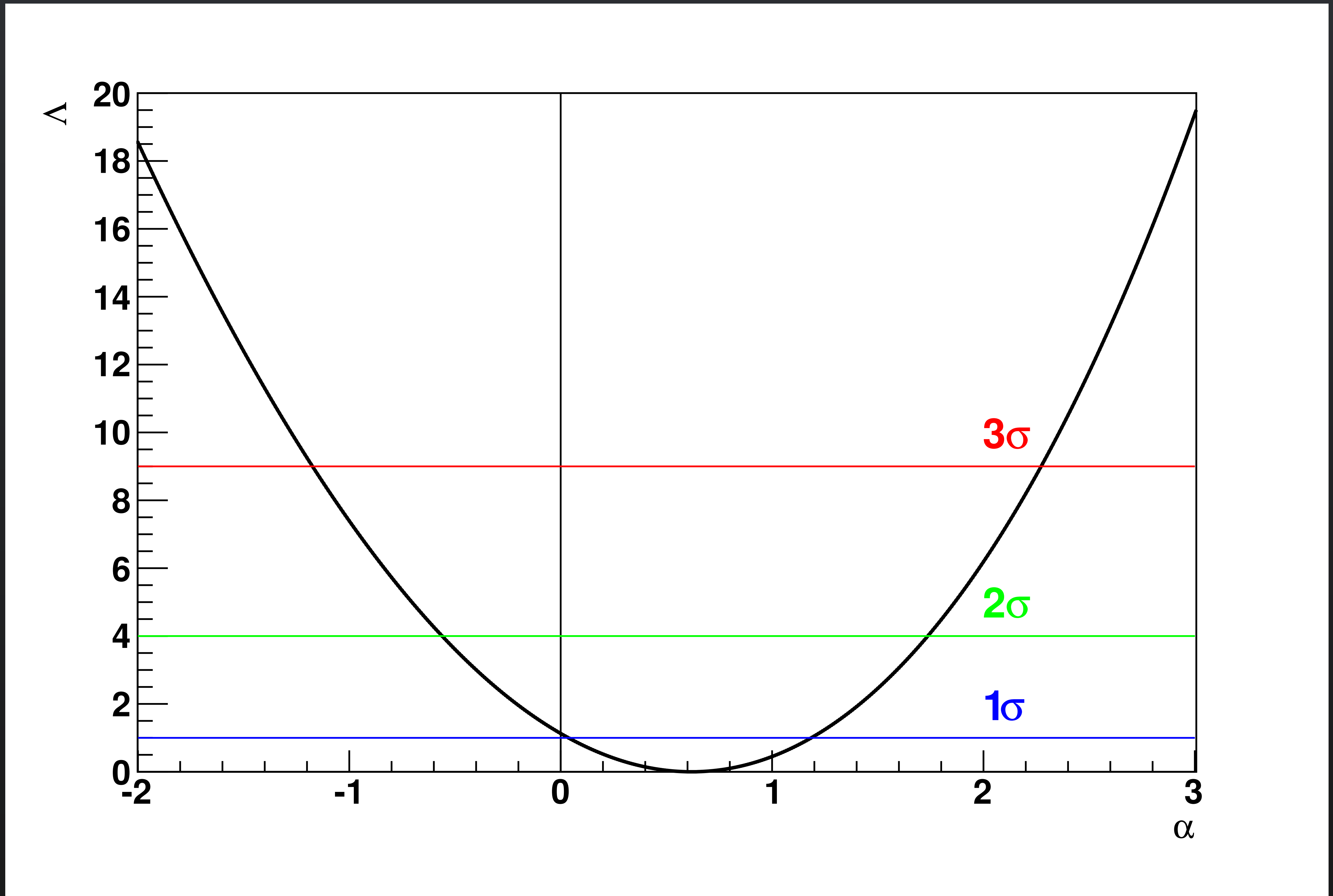
where ε is a penalty term from systematic error pulls, where the hypothesis has been modified appropriately. Then, our statistic is

$$\Lambda = 2 \ln \frac{L_M\left(N|H'\right)}{L_M\left(N|H'(\alpha=0)\right)},$$

where $_M$ denotes minimization over systematic errors and α (except in the demoninator where α is fixed).

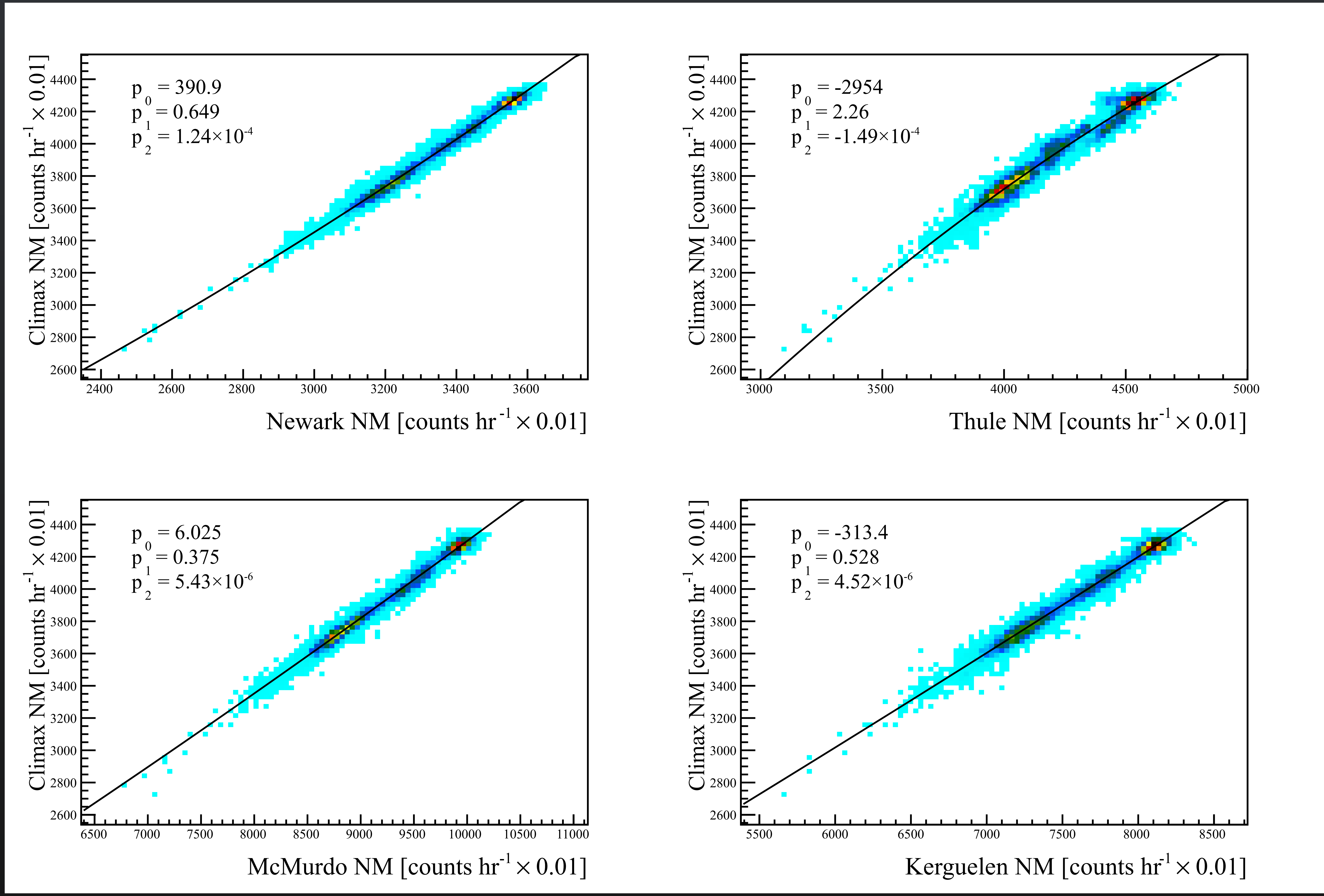
Solar Modulation - Hypothesis Test

- Final significance parameter.



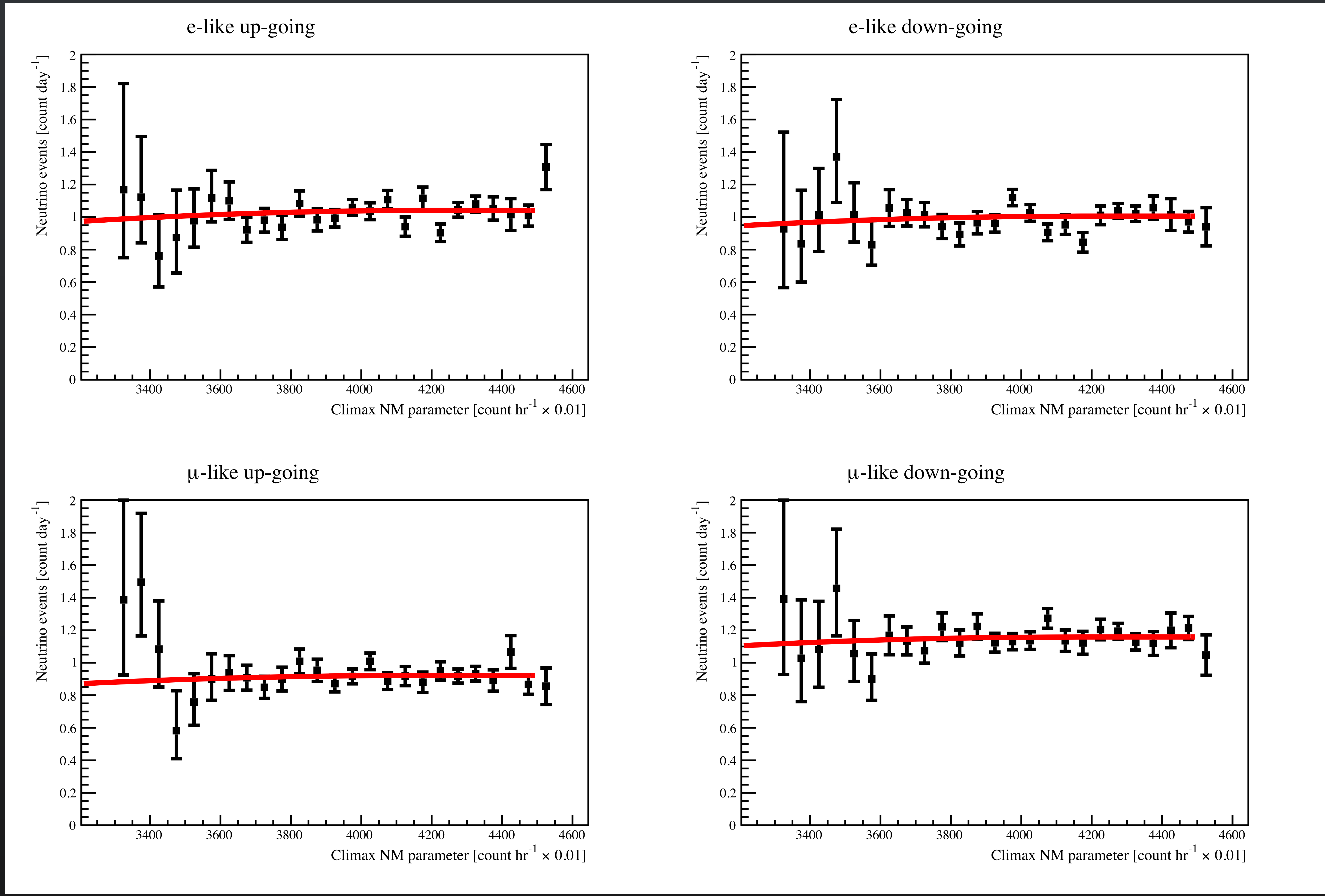
Solar Modulation - NM Correlations

- Conversion factor between the four NMs we use, and the Climax NM



Solar Modulation - Toy MCs

- Toy MC example datset.
- 1000 toy MCs used to confirm the test statistic is distributed as expected, unbiased, etc.
- Expected sensitivity to the effect (assuming $\alpha=1$) is 1.75σ.



Solar Modulation - Results By Sample

- Fit for α independently, first by SK period, then by sample type.
- Somewhat interestingly, ν_e prefers no correlation while ν_μ prefers the expected correlation, although statistical power is low.