HK Atmospheric Neutrino Tools

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Introduction

- Current charge:
  - Introduce the software and analysis tools, as well as systematic error assumptions, that are used to estimate Hyper-Kamiokande's sensitivity.
  - Also mention something about the future of these studies

- The Master summary:

- Atmospheric Neutrinos
  - Neutrino interactions are simulated using the NEUT interaction generator
  - The Flux model is that of Honda et. al 2011
  - Oscillations are studied using a binned likelihood ratio with systematic error effects incorporated via the “pull” method
  - Discuss impact of systematic errors

- Proton Decay (not many details today)
  - Atmospheric neutrino background is taken from the above
  - Signal simulation is done mode-by-mode with an independent generator
  - Final limits and discovery potentials are calculated based on a Poisson likelihood

At Present

- The study of atmospheric neutrinos and proton decay for Hyper-Kamiokande is based entirely on tools developed for and used by Super-Kamiokande
  - The production of dedicated Hyper-K tools are in development, but are not assumed in any of the following

- For the most part the analyses are statistical scaling to the Hyper-K exposure to account for changes in the detector volume and effective area for rock-induced muons (Upward-going μ)

- So far no assumptions are made about improvements (or degradation) relative to the systematic errors used in the Super-K analyses

- However, the proton decay analyses at Hyper-K use modified versions of the Super-K detector simulation to account for
  - the expected increase in photon yield and faster timing of Hyper-K's photosensors
  - the loss of light across the larger Hyper-K volume
  - (These effects have limited impact on neutrino oscillations and have not been included yet)

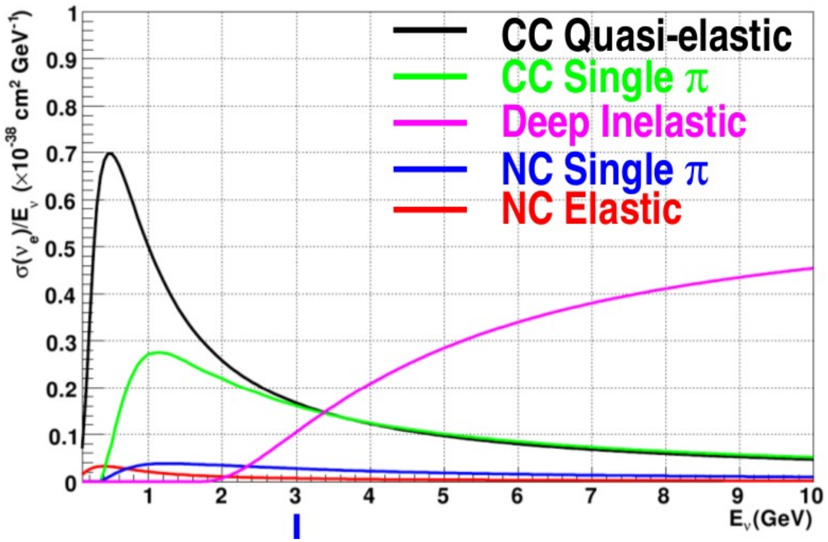
Neutrino Interactions with NEUT

- NEUT is an effectively open source piece of software that simulates the interaction of neutrinos with nucleons and the propagation of secondaries through their parent nuclei
  - "effectively" mean it is available upon request, but little manpower for support
  - Project leader is Yoshinari Hayato (ICRR), but there have been significant contributions to the code from Super-K and T2K collaborators

- The current Hyper-K atmospheric neutrino MC is based on NEUT 5.1.4
  - (Current stable NEUT version is 5.3.6, not adopted for HK yet)

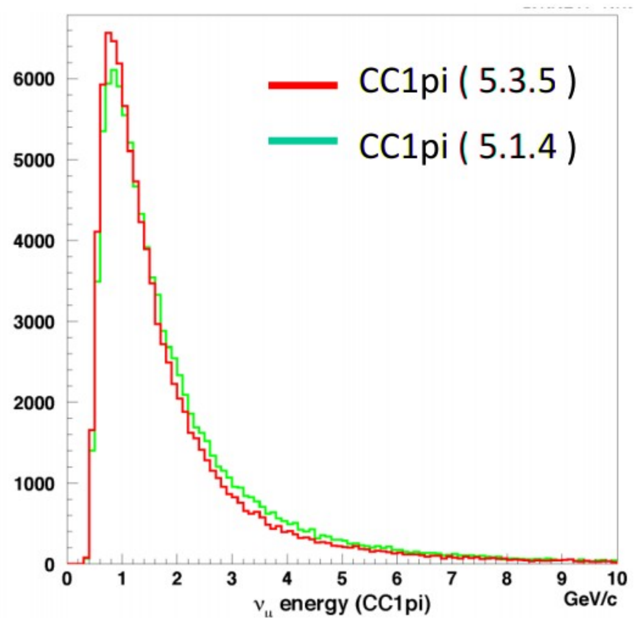
- Highlights:

- Quasi-elastic scattering
  - Smith and Moniz, simple Fermi-Gas (Global)
  - Vector form factor (dipole)
  - Axial form factor (dipole) with $M_A = 1.2\ GeV/c^2$



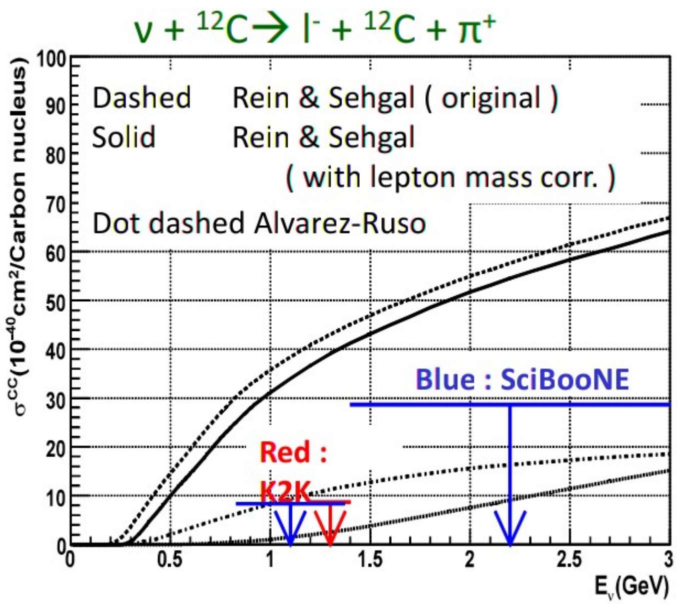
Neutrino Interactions with NEUT (2)

- Single Pion Production
  - Based on Rein-Segal model
  - Original form factors and lepton mass corrections
- Intranuclear propagation effects included
  - Pauli-blocking (<3% effect)
  - Pion-less delta decays (20%)
    - NB. 2p-2h (MEC) models not included until recent NEUT 5.3.+
  - Pion FSI tuned to external data



- Coherent Pion production
  - Rein-Segal model
- Deep inelastic scattering

	W < 2GeV	W > 2GeV
# of π = 1	Rein & Sehgal	PDF + Custom kinematics (Bodek & Yang Corr.)
# of π > 1	Use PDF + PYTHIA (Bodek & Yang Corr.)	Use PDF + PYTHIA (Bodek & Yang Corr.)



The Honda Flux

- Atmospheric neutrinos are simulated using the “Honda Flux” otherwise known as the “HKKM” model from 2011
  - Lead author is Morihiro Honda (ICRR), but developed by a few-man collaboration
  - Effectively open source code, available upon request
  - Data tables are completely public

- In practice Hyper-K uses these flux tables an an input to the NEUT simulation for generating neutrino interactions
  - Currently we do not run the simulation ourselves, but are working with the authors to improve the calculation and its use in the analysis
  - The following few slides are a short overview of how the calculation proceeds

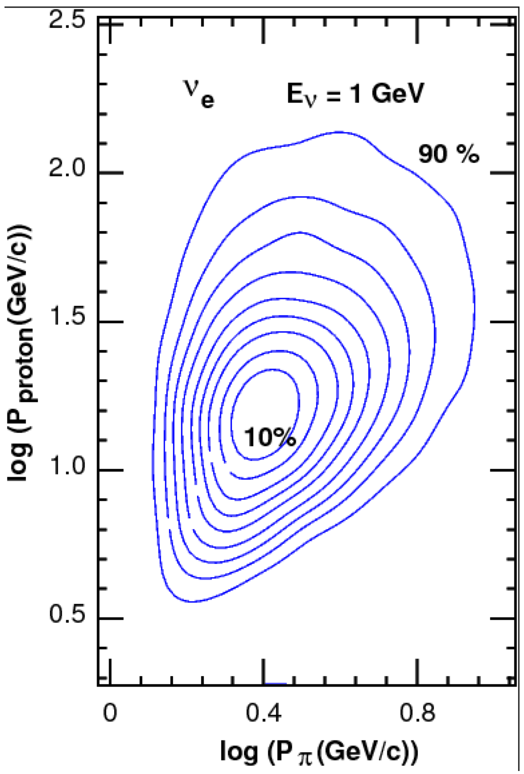
The Honda Flux Calculation

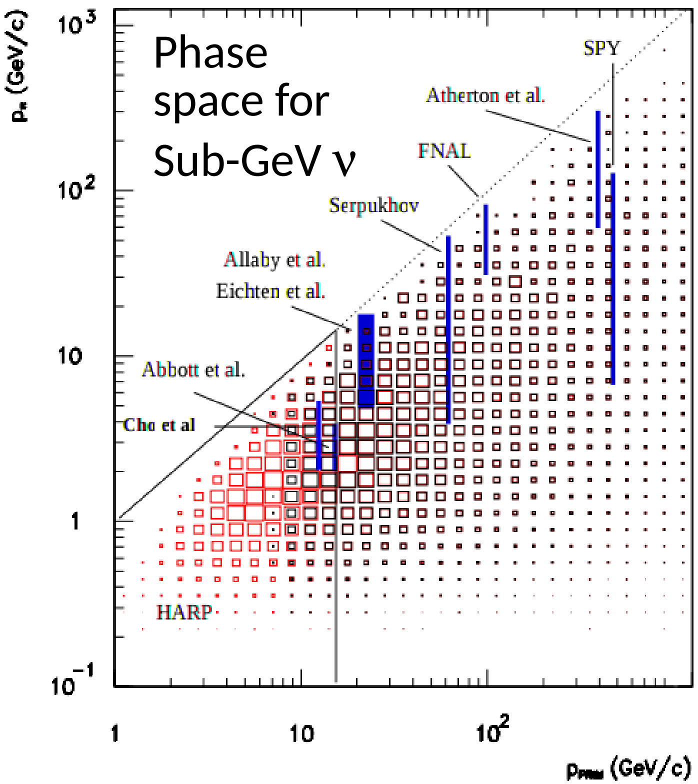
- Atmospheric neutrinos are produced by the collision of primary cosmic rays with air nuclei:

$$p + A \rightarrow N + \pi + \; + x$$

$$\Rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

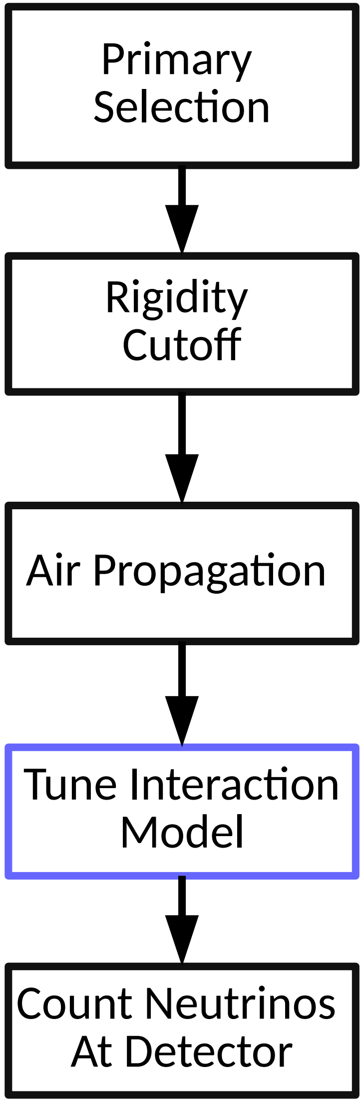
- Idea behind the Honda flux calculation:
  - constrain the neutrino flux using measurements of atmospheric muons





The Honda Flux Calculation

- 3-Dimensional Monte Carlo simulation incorporating primary cosmic ray data, hadron production models, atmospheric air profiles, geomagnetic field, detector overburden to determine neutrino flux at a particular location



Sample from from primary cosmic ray distribution and inject at the top of the atmosphere : h = +100 km

Propagate particle backwards in time accounting for the geomagnetic field to determine if its a **feasible** trajectory
Reject particles with insufficient rigidity

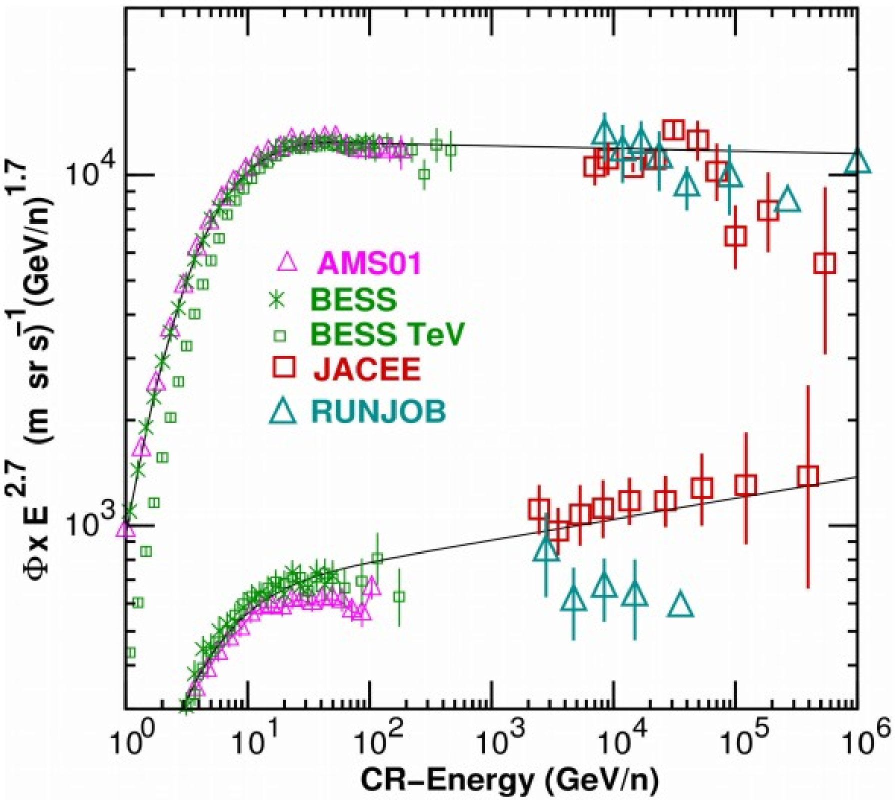
Simulate interaction of primary with air nuclei and propagate all secondaries through the atmosphere

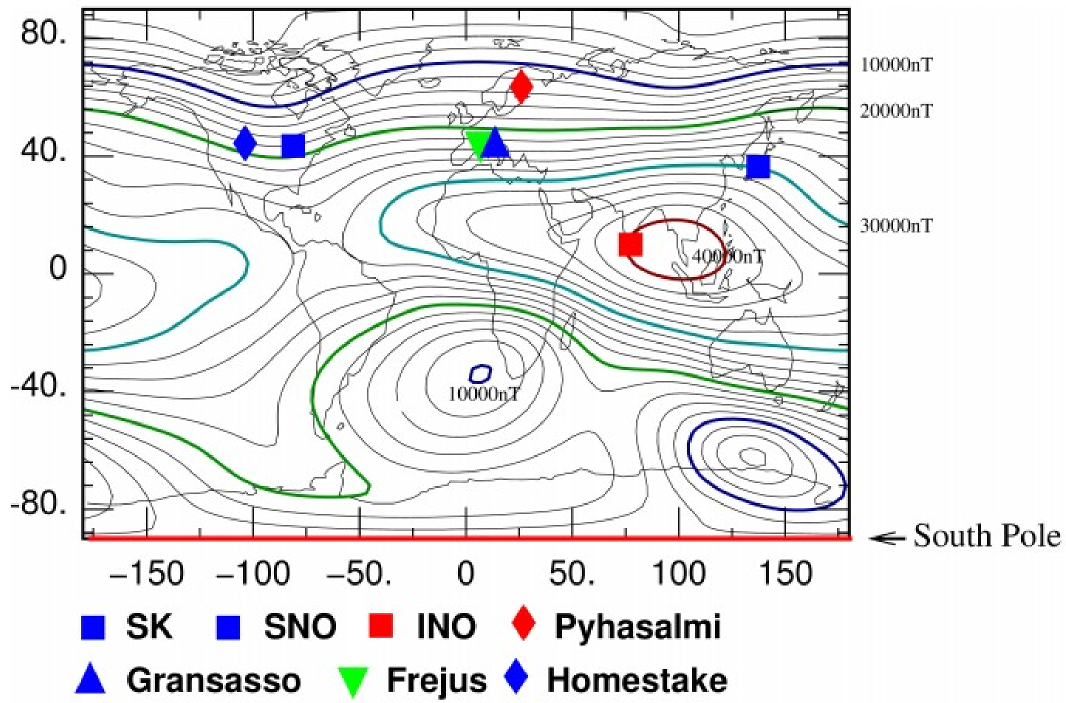
+ reinteractions and travel through the geomagnetic field
+ Non-neutrino particles striking the ground are discarded

Match the calculated muon spectrum with measurements from balloon and ground-based experiments

Any neutrino passing through a disk of radius 1000 km around the detector is used in the flux calculation

The Honda Flux Calculation: Inputs

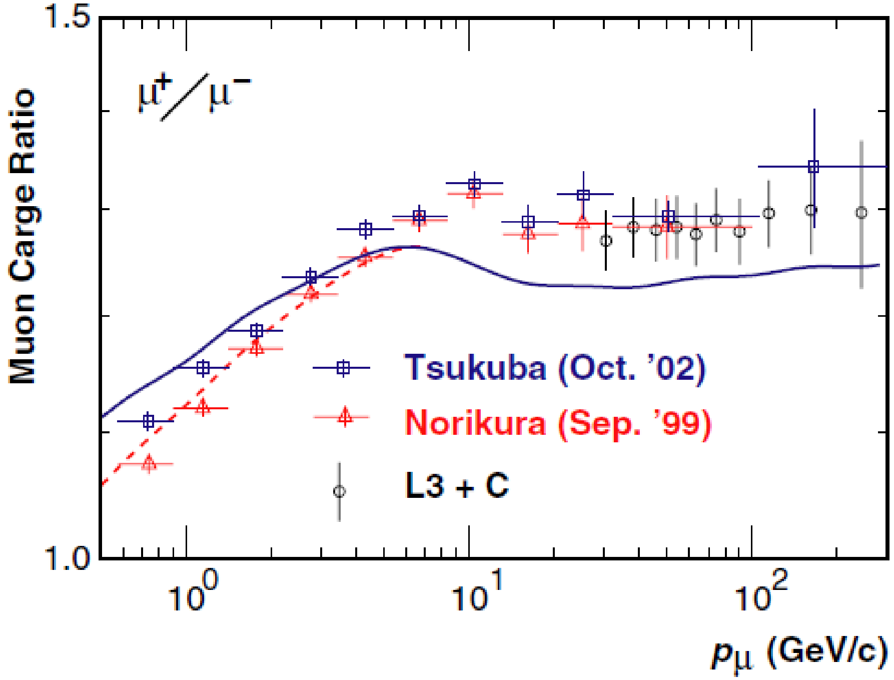




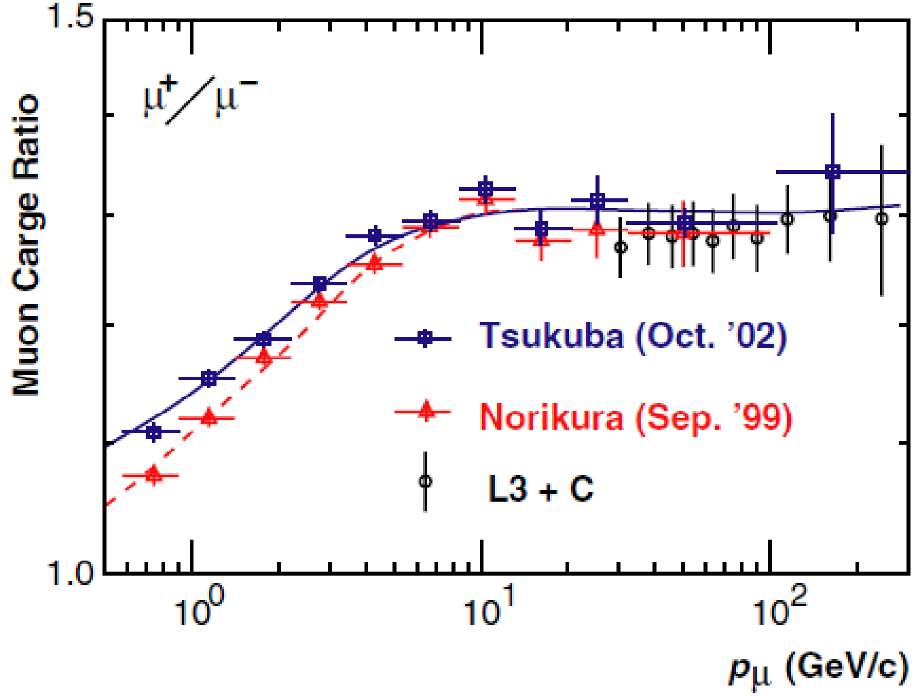
- Primary cosmic ray spectrum taken from AMS and BESS data with a power law scaling to connect with measurements at high energy (>1 TeV / n)
- With detailed information of the primary cosmic ray spectrum the muon flux measurement is sufficient to constrain the hadronic interaction models

The Honda Flux : Interaction model tuning

Nominal



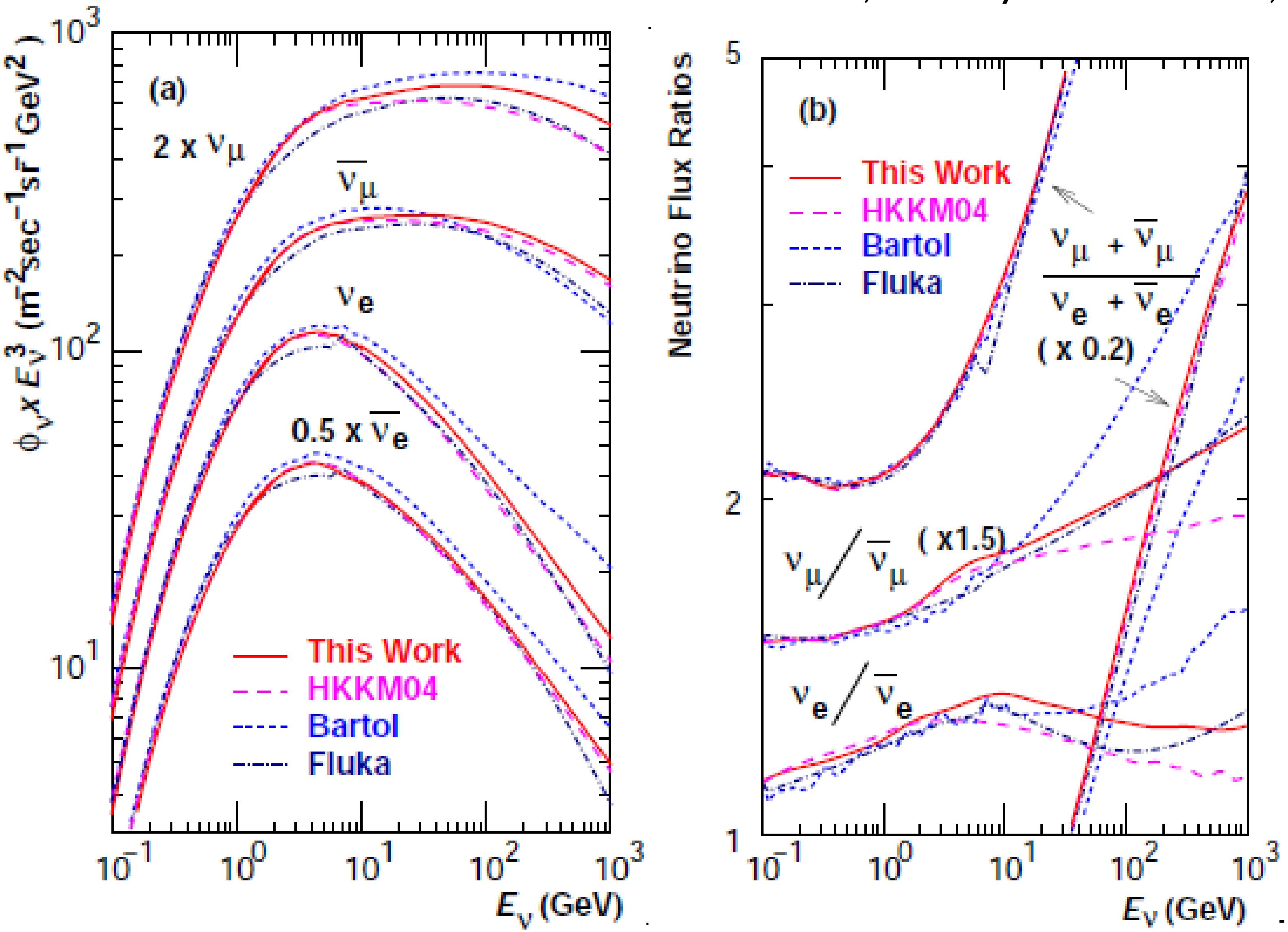
Tuned



- HKKM uses DPMJET-III (> 32GeV) and JAM interaction (< 32 GeV) codes to model the production of hadrons and their secondaries as well as their subsequent interactions
  - Nominal codes do not reproduce muon distributions at the surface well (better at altitude)
- Average energies of mesons and hadrons are tuned at the quark level to the vertical muon flux at the surface
  - This is repeated for several interaction models for validation and systematic error determination

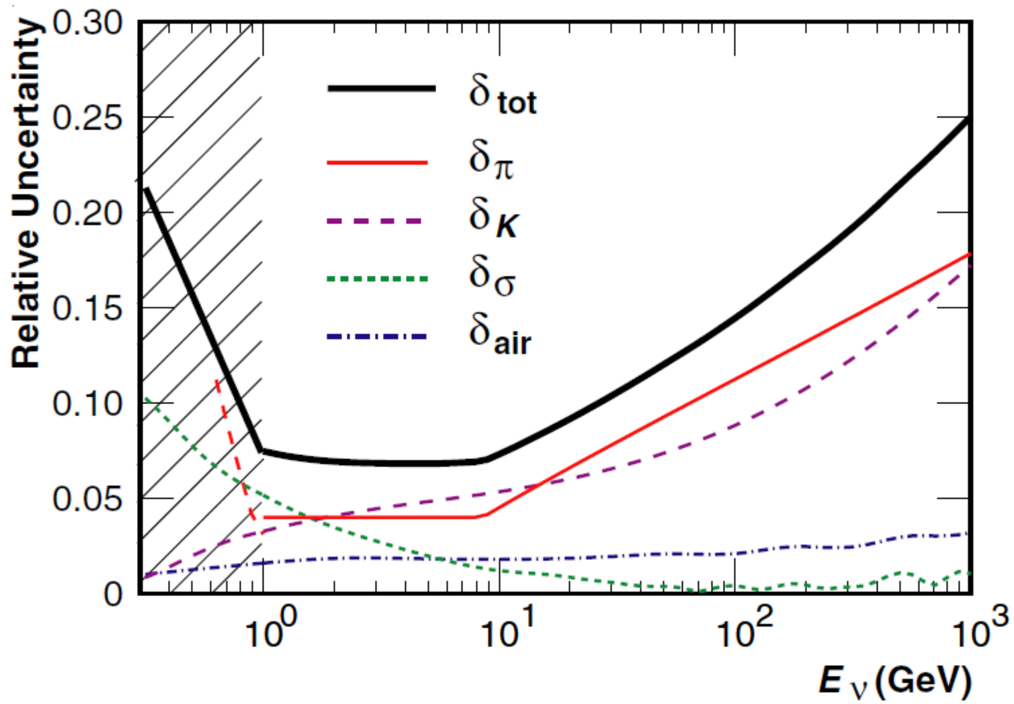
Atmospheric Neutrino Fluxes

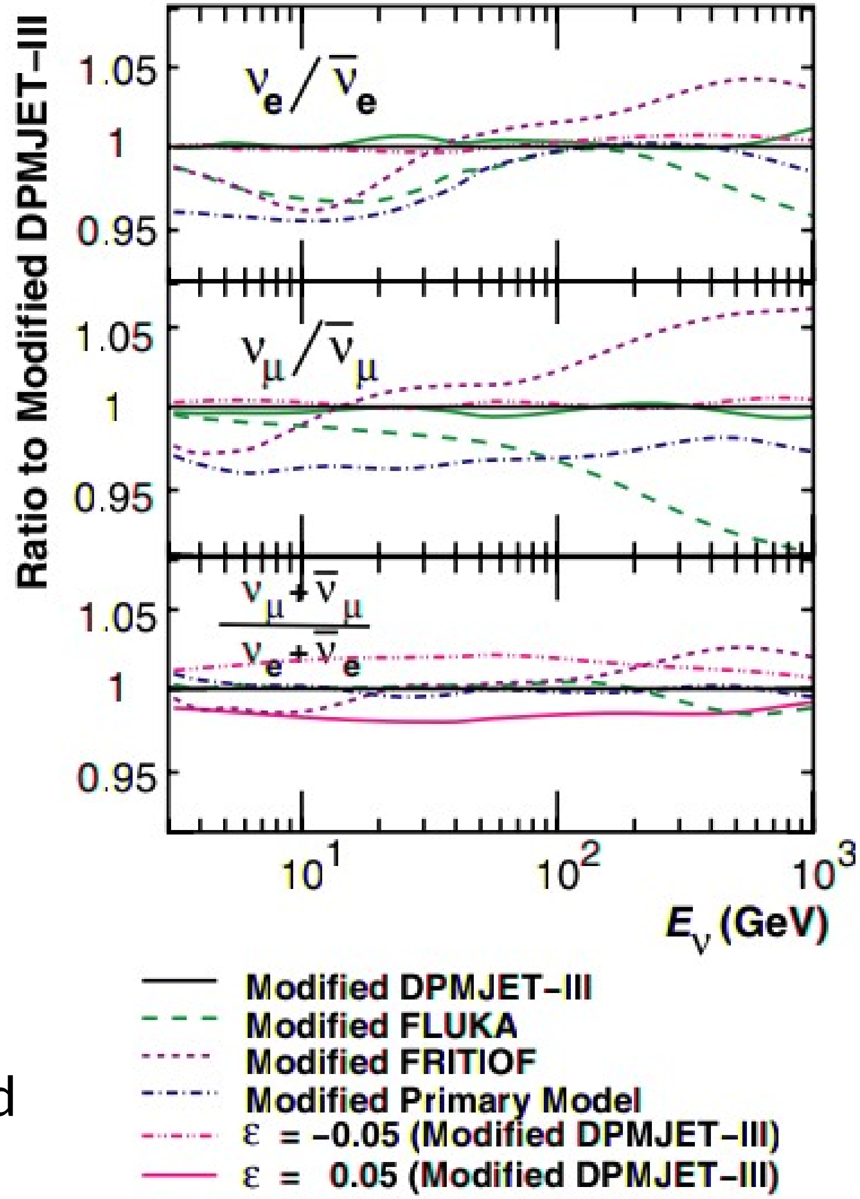
M. Honda, et. Al Phys.Rev.D75:043006,2007



- Flux is available at several detector cites in bins of zenith and azimuth

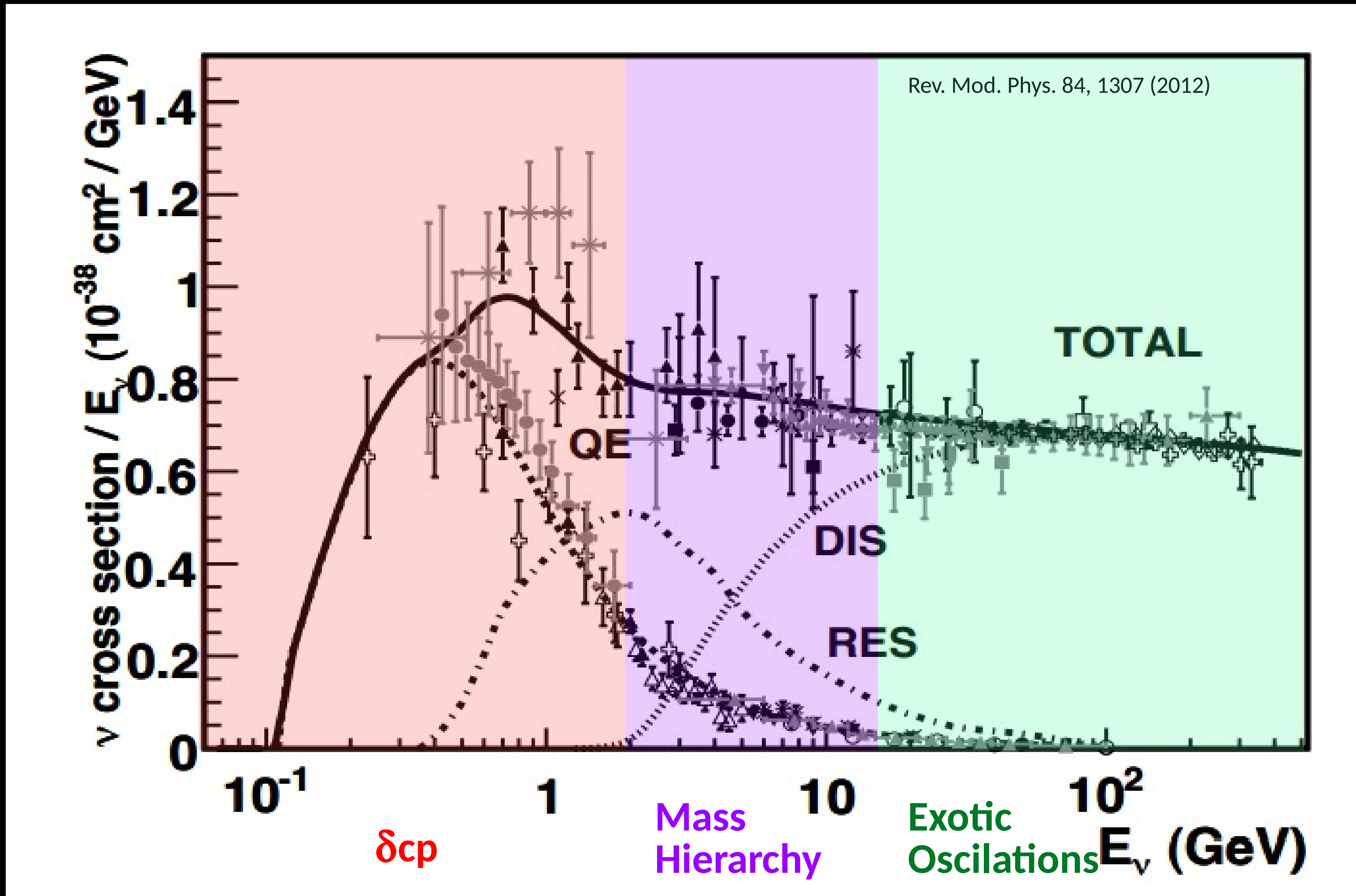
The Honda Flux : Systematic Errors





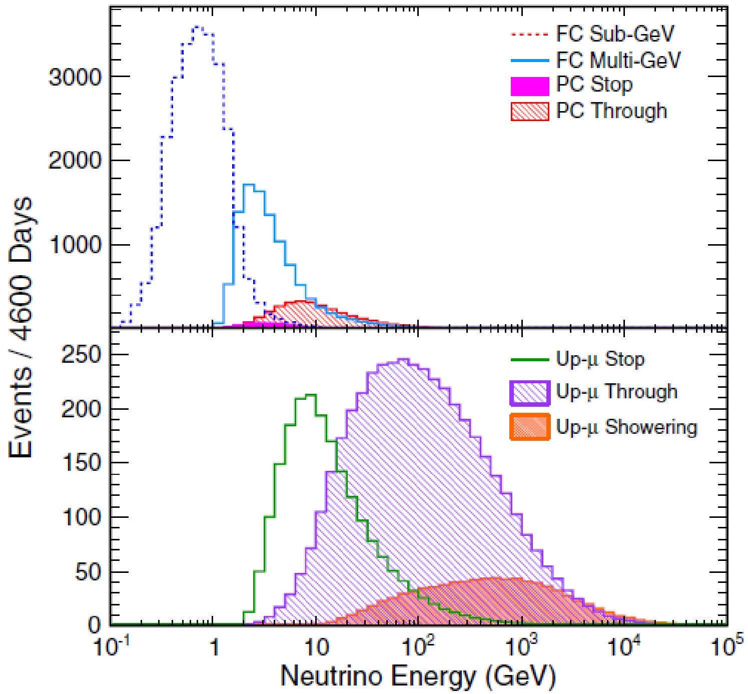
- HKKM also releases systematic error information which is currently used directly in the atmospheric neutrino analysis
  - Absolute uncertainty is based on residual data/MC differences after muon tuning procedure
  - Ratio systematics are formed from the spread in alternative interaction models under the same tuning procedure

Neutrino Interactions Relevant for Atmospheric Neutrinos

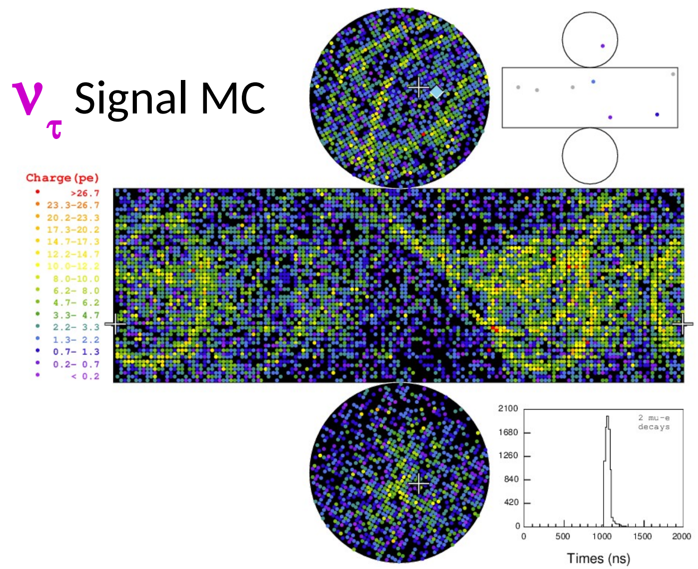


Atmospheric Neutrino Oscillation Analysis Overview

- Generate a set of interaction vectors based on the Honda11 flux and NEUT 5.1.4 (no oscillation weights)
  - Current production uses a 500year exposure of the Super-K detector or roughly 30 years of Hyper-K
  - MC energies and directions are recycled in places but this adds considerable computation time
  - The primary neutrino flux is completely simulated, and $\nu\tau$ events with the $\nu\mu$ spectrum are also generated for the $\nu\mu \rightarrow \nu\tau$ appearance channel

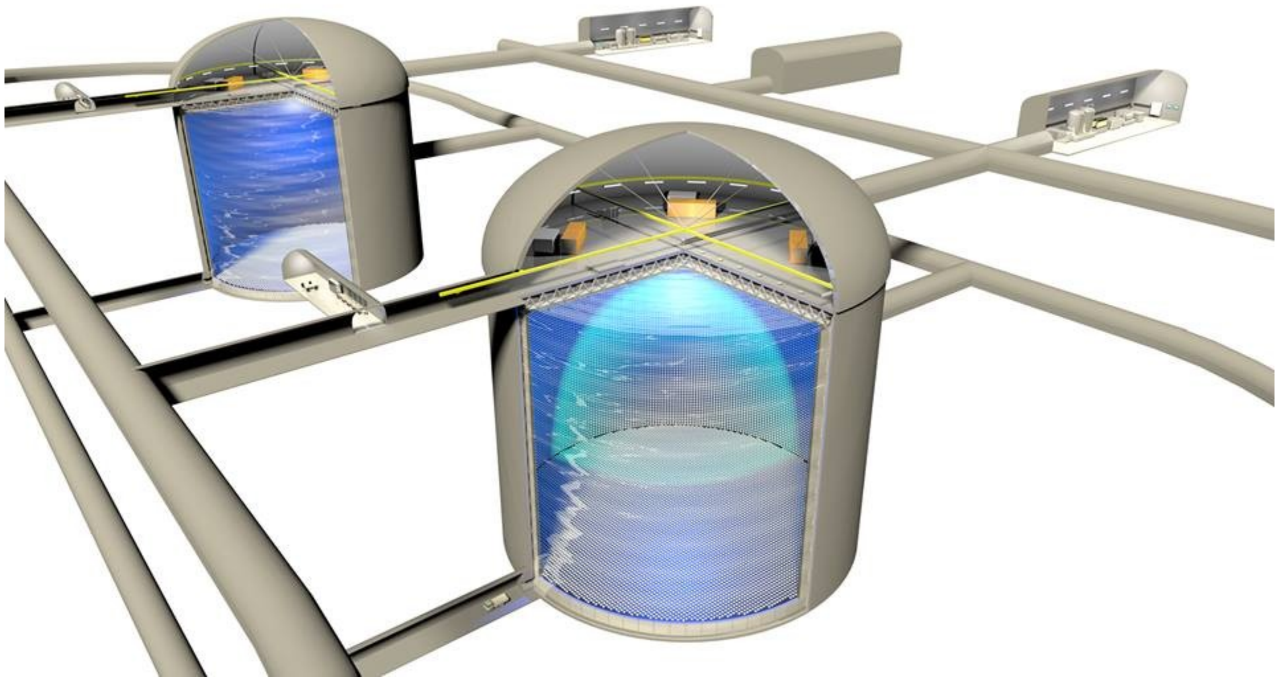


- Events are then passed to the detector simulation (GEANT3-based) secondary interactions use the same NEUT FSI as the vector generator



- Output is processed with the "APFit" reconstruction algorithm (charge-pattern based)
  - Staged likelihood-based reconstruction for counting visible cherenkov rings. PID and kinematics are identified ring-by-ring

Hyper-Kamiokande: Introduction

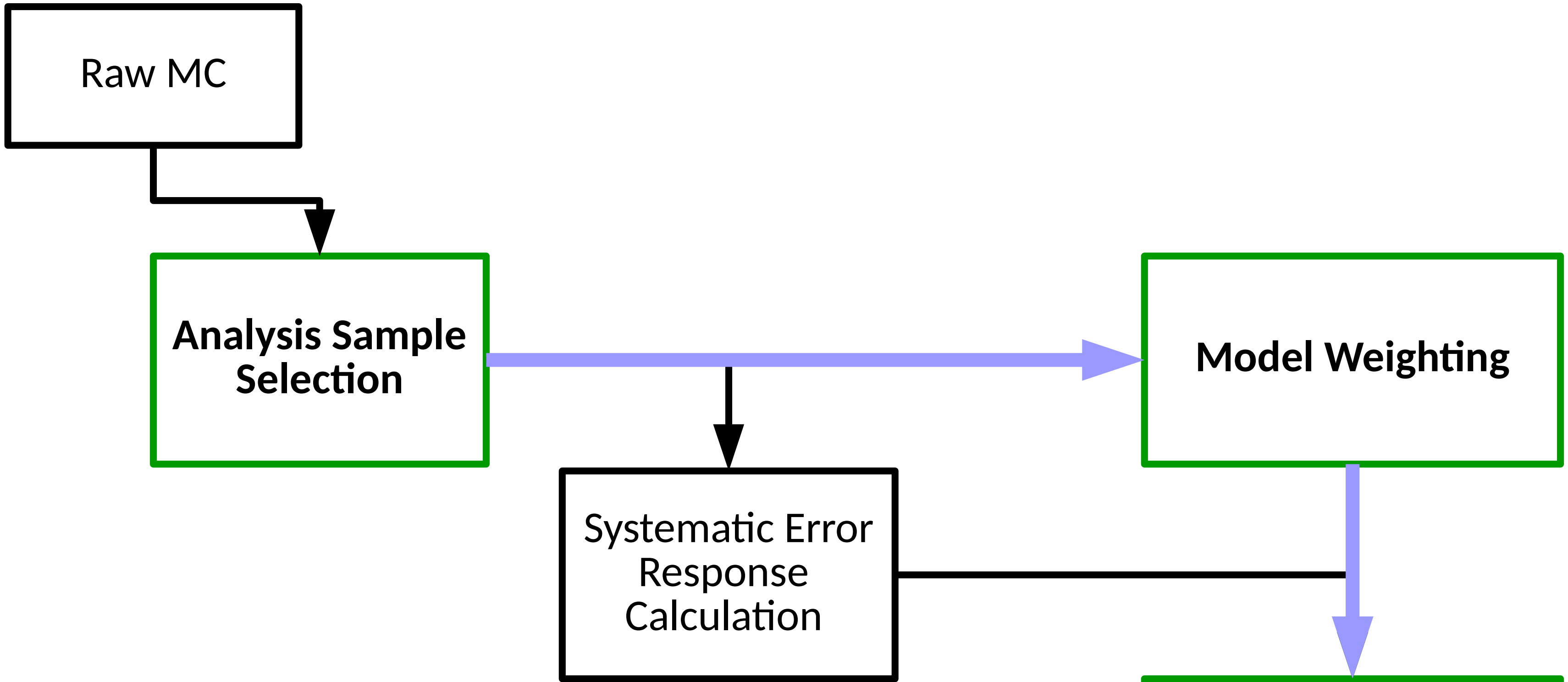


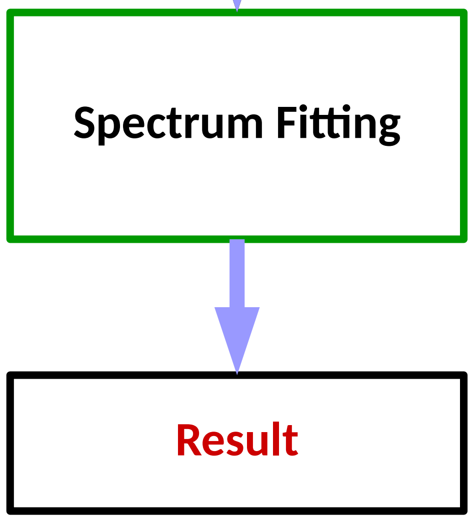
apfit

Atm ν	Hyper-K
σ_{mom} e / μ	5.6% /3.6%
σ_{dir} e / μ	3.0° / 1.8°
ν CC Purity :	
FC e-like	94.2 %
FC μ-like	95.7 %
PC μ-like	98.7 %
Neutron Tag efficiency	73.0 %

- Present studies are performed assuming
  - 187 + 187 kton fiducial volume (10 years, staging)
  - Equivalent detector performance for SK
- No additional improvements relative to Super-K analyses
  - Ie, expected improvements in event reconstruction with upcoming reconstruction algorithms have <u>not</u> yet been included
- Similarly no extrapolation of flux and cross section systematics

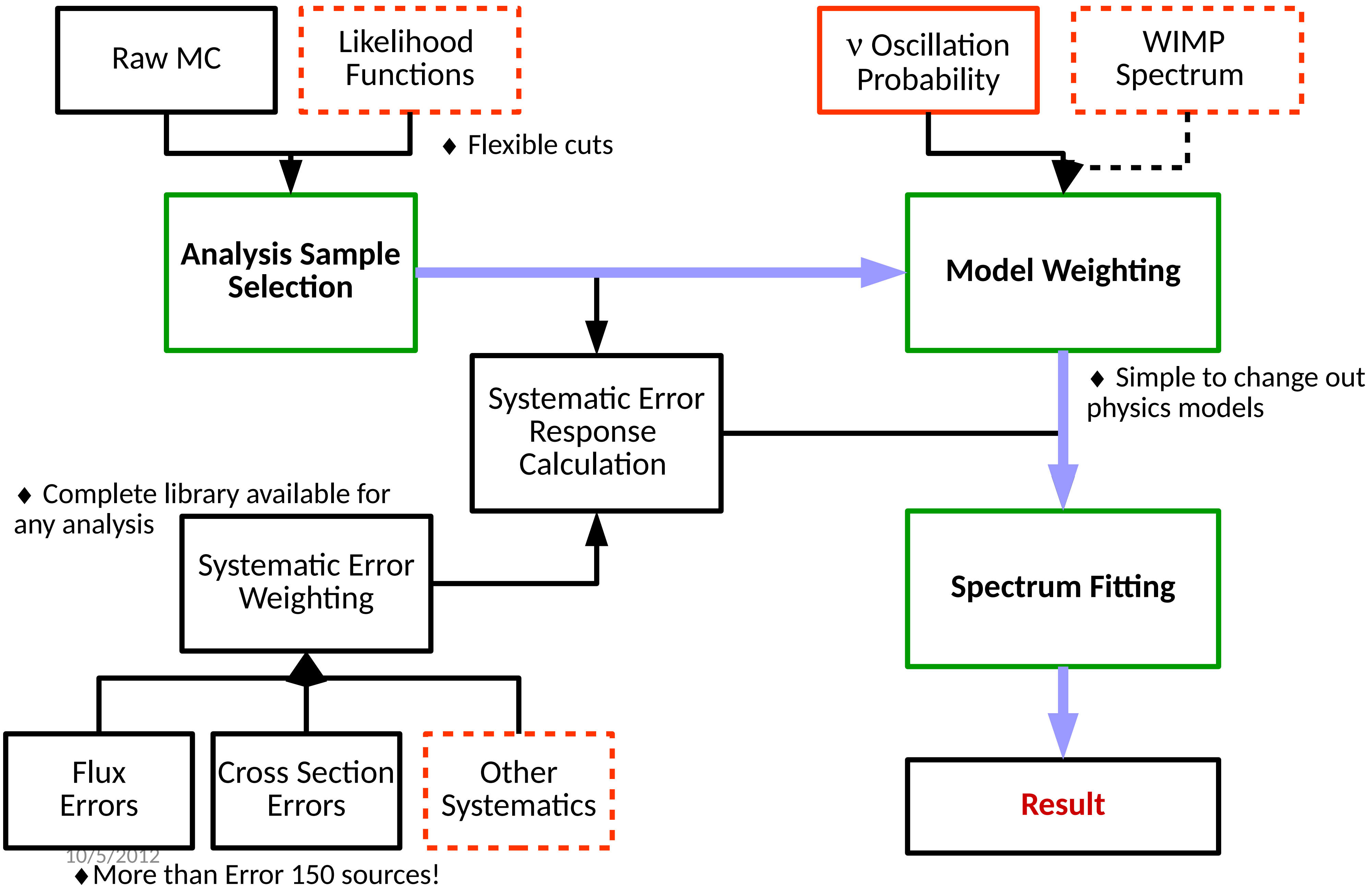
Basic Atmospheric Analysis Structure at Hyper-K





- However Hyper-Kamiokande data are expected to cover a large range of energies and event topologies
  - Possible to explore many physics topics
- A unified framework exists to allow systematic error and event resources to be efficiently shared between similar analyses
  - The HK spectrum fit for Dark Matter uses flux weighting for a signal spectrum, but is otherwise the same fit as the oscillation analysis

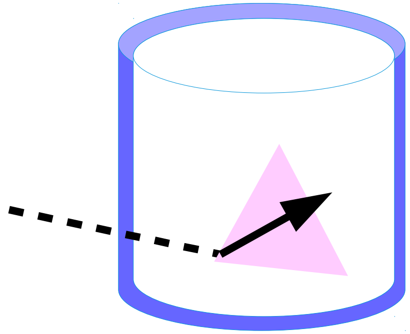
Basic Atmospheric Analysis Structure at Hyper-K



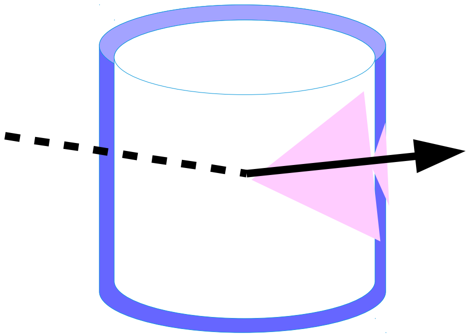
Super-K Atmospheric ν Analysis Samples

6 Mton year

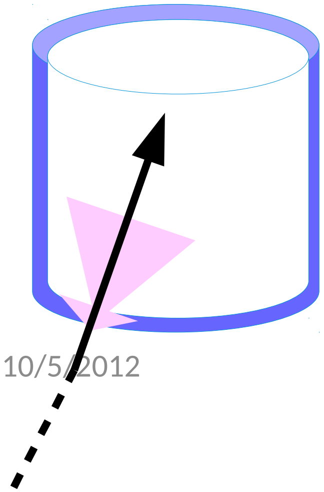
Fully Contained (FC)

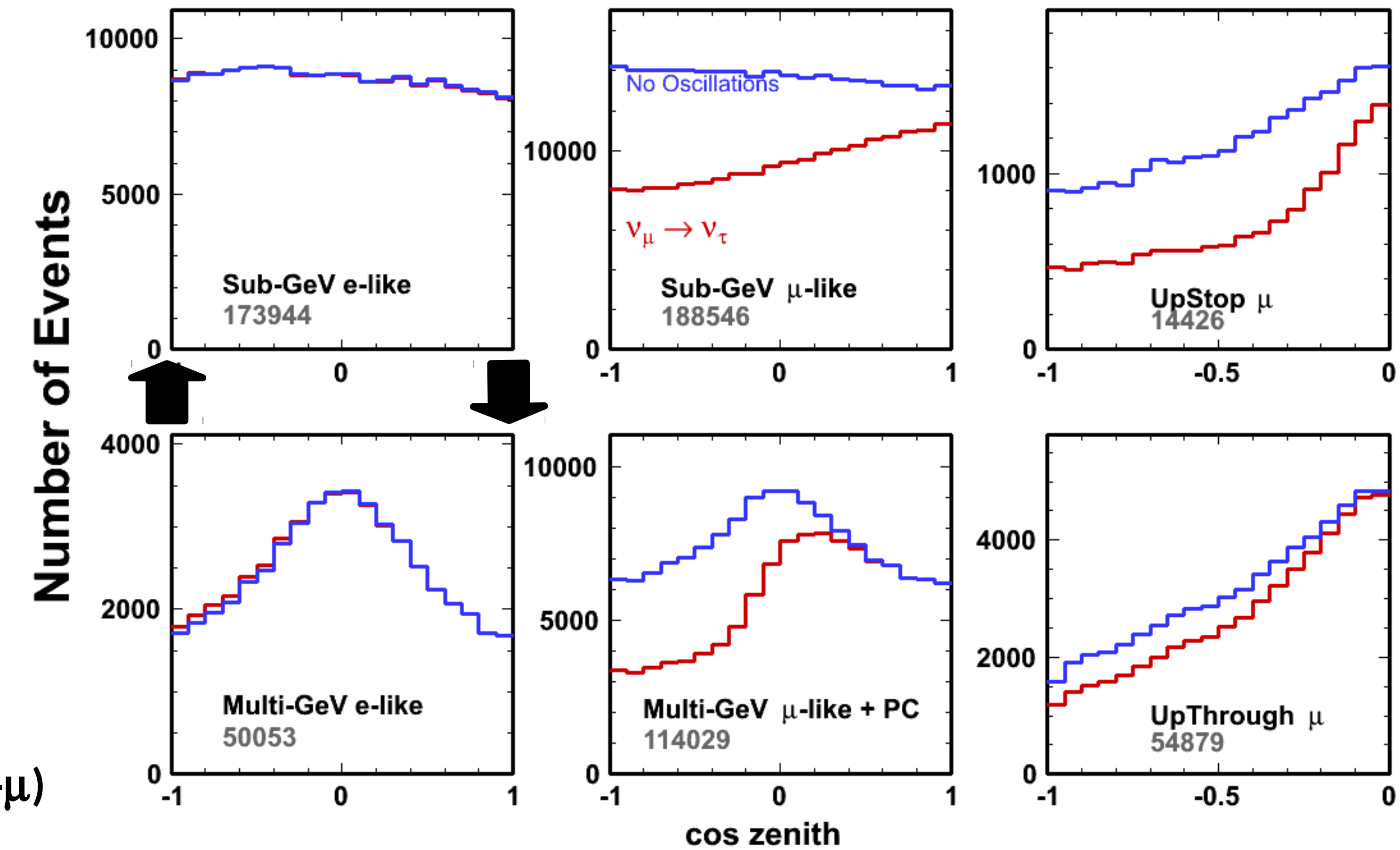


Partially Contained (PC)



Upward-going Muons (Up-μ)



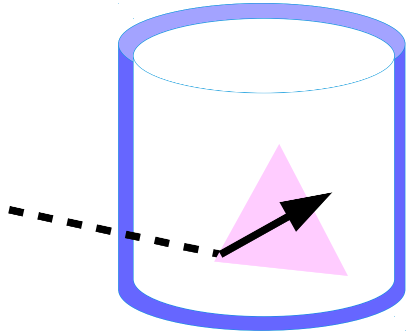


- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like subsamples (100 MeV ~ O(10) TeV)
- Dominated by ν_μ->ν_τ oscillations
  - We thus expect (and find) ντ interaction to appear somewhere in the data at energies above the τ threshold

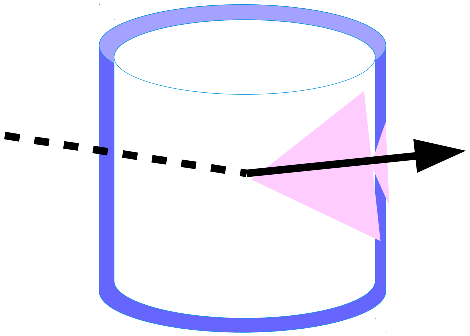
Super-K Atmospheric ν Analysis Samples

6 Mton year

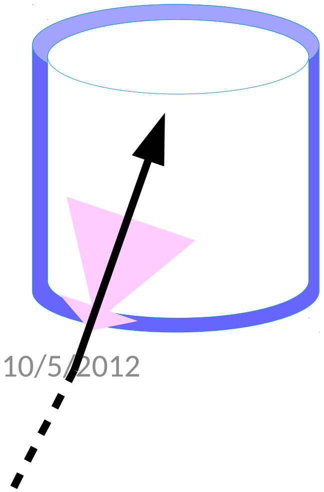
Fully Contained (FC)

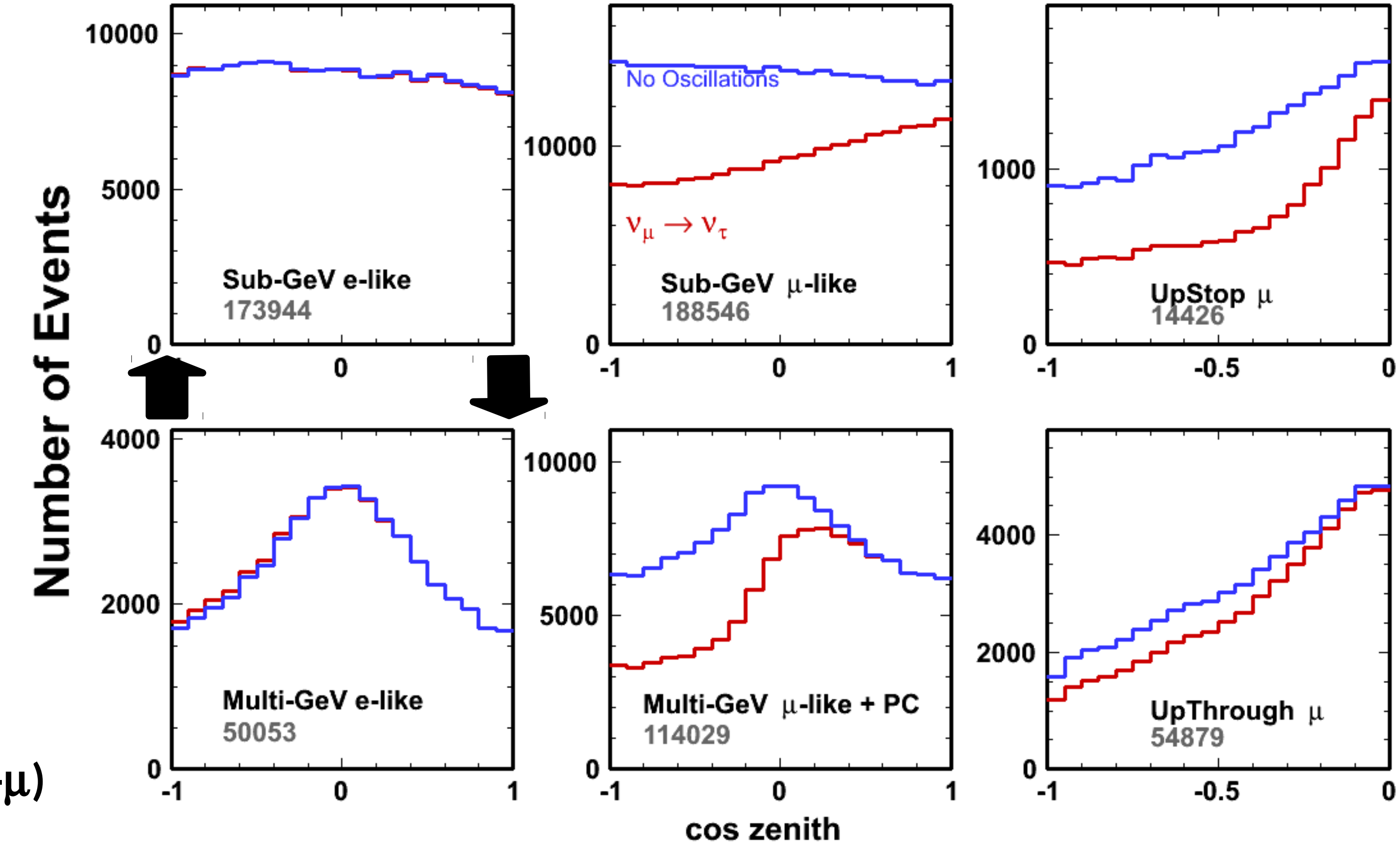


Partially Contained (PC)



Upward-going Muons (Up-μ)





- Generally the data themselves off several ways of constraining uncertainties:
  - 4-π detector, constrain Up/Down (0.1~2%) Horizontal/Vertical ratio (0.3~3%) systematics
  - Several “Sidebands” : NC π^0, DIS-enhanced samples

The Spectrum Fit

- Based on a "pulled" method and a grid search

$$\chi^2 = 2\sum_n \left(\underline{E_n(1+\sum_i f_n^i \epsilon_i)} - \mathcal{O}_n + \mathcal{O}_n \ln \frac{\mathcal{O}_n}{E_n(1+\sum_i f_n^i \epsilon_i)} \right) + \sum_i \left(\frac{\epsilon_i}{\sigma_i}\right)^2$$

  - This is a system of equations in epsilons (error parameters) , which can be solved with matrix inversion (fast!)
  - Do this at every point on grid to find global best fit
  - Final contours based on frequentist intervals

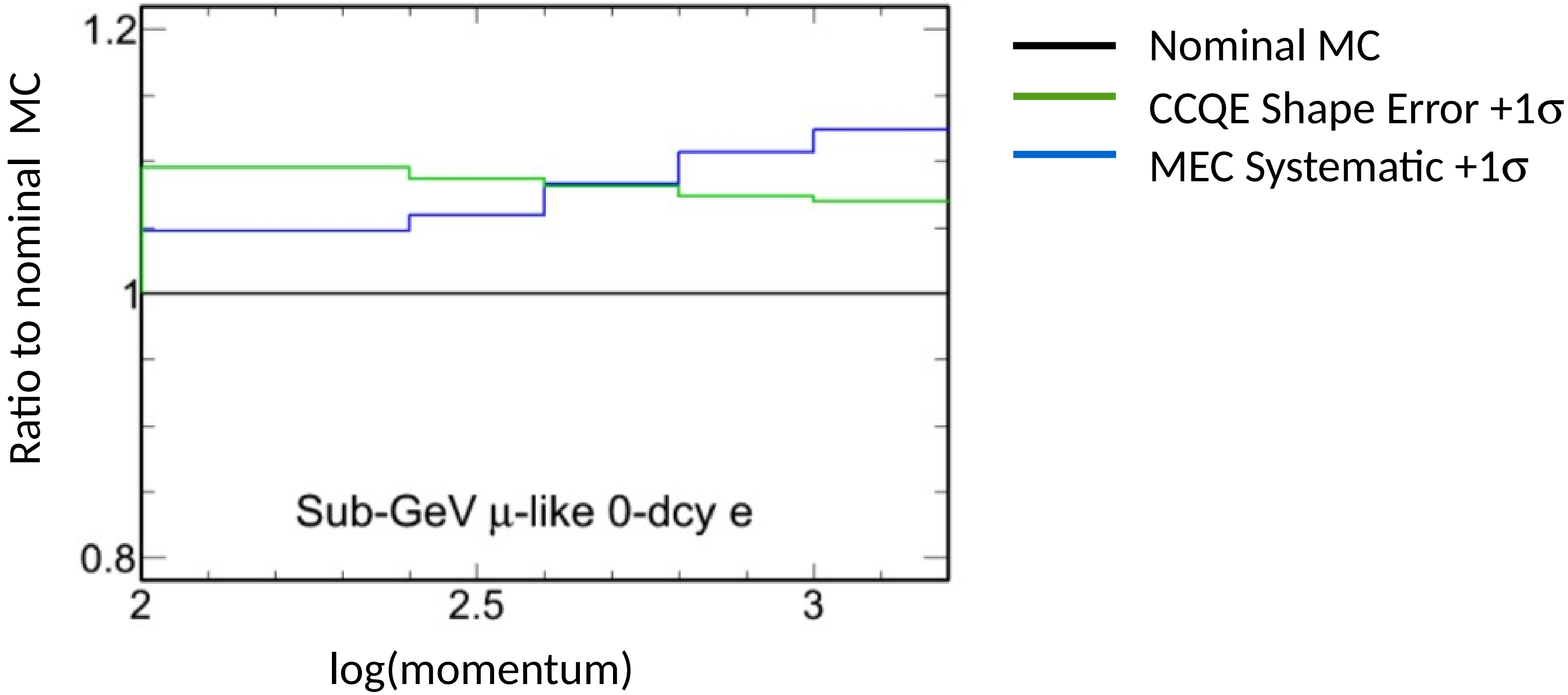
$$E_n(1+\sum_i f_n^i \epsilon_i)$$

***i*th Fitting Parameter**

Oscillated MC in bin "n"

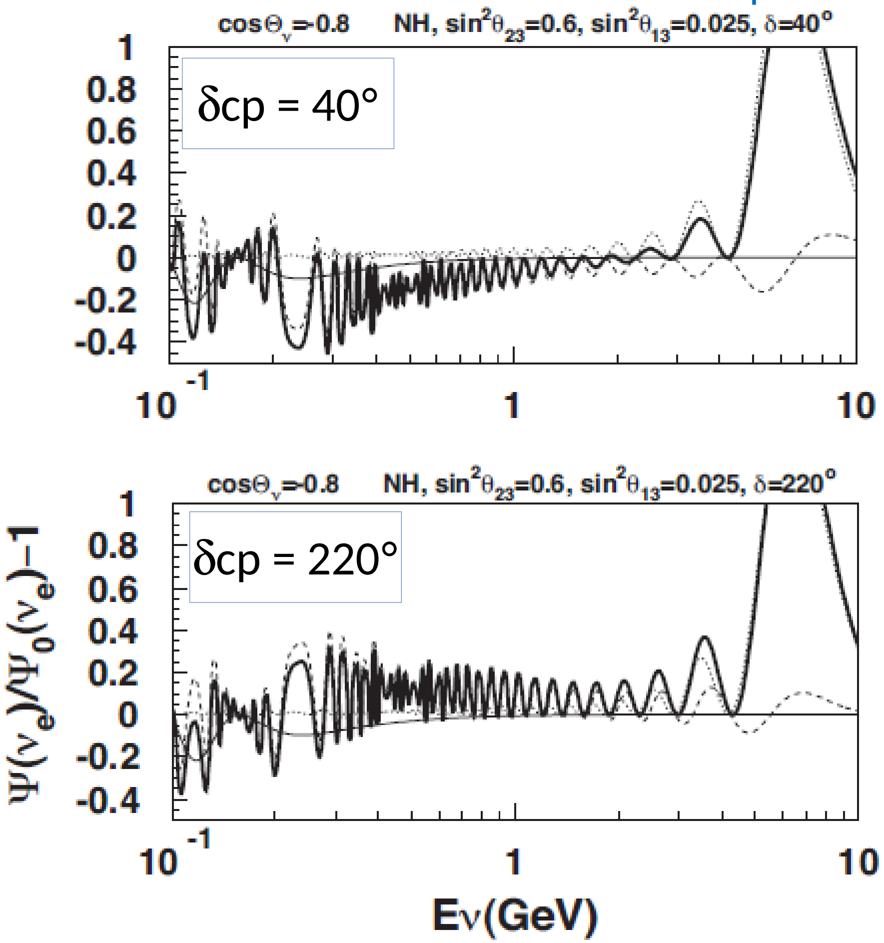
Linear response Coefficient:

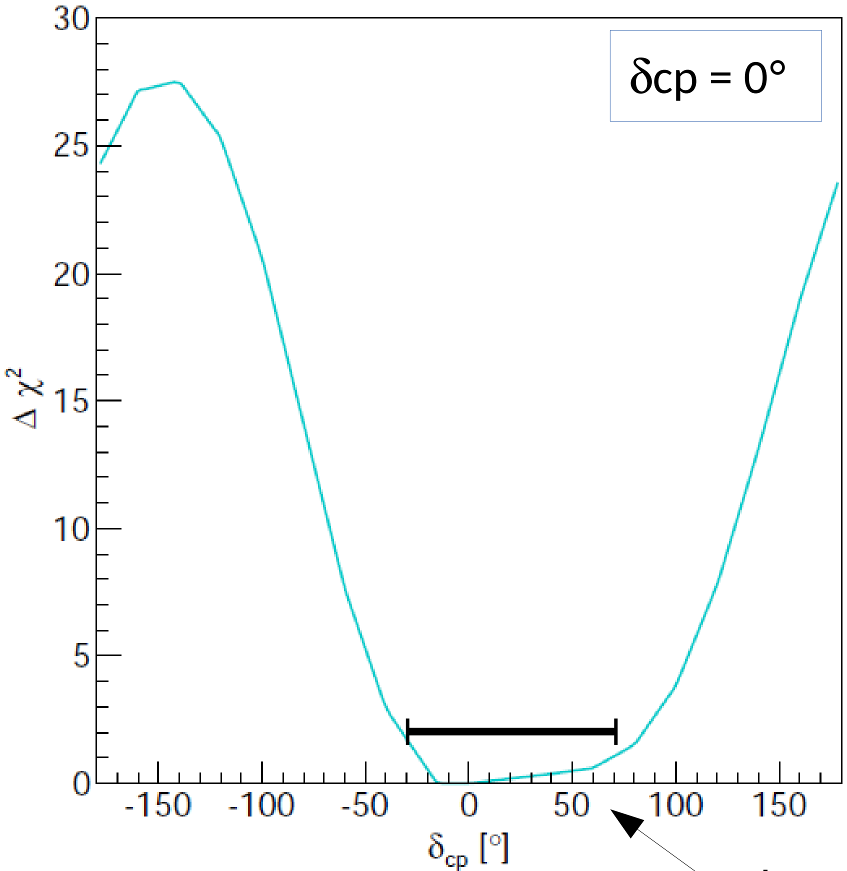
The Spectrum Fit : Example Systematic Error



- Systematic errors are applied "bin-by-bin"
  - The size of each is computed in advance and their effect on each bin is calculated using MC and parameterized as a **linear** response function
    - At +2σ, the blue and green lines would increase by double
  - Error sources are uncorelated *a priori* (by definition) with correlations naturally induced by competing error effects in each bin
- At present a complete and computationally efficient method of implementing highly correlated constraints from HK near detector measurements is lacking

Hyper-K's Sensitivity to δ_{cp} Atmospheric neutrinos (5.6 Mton yr)

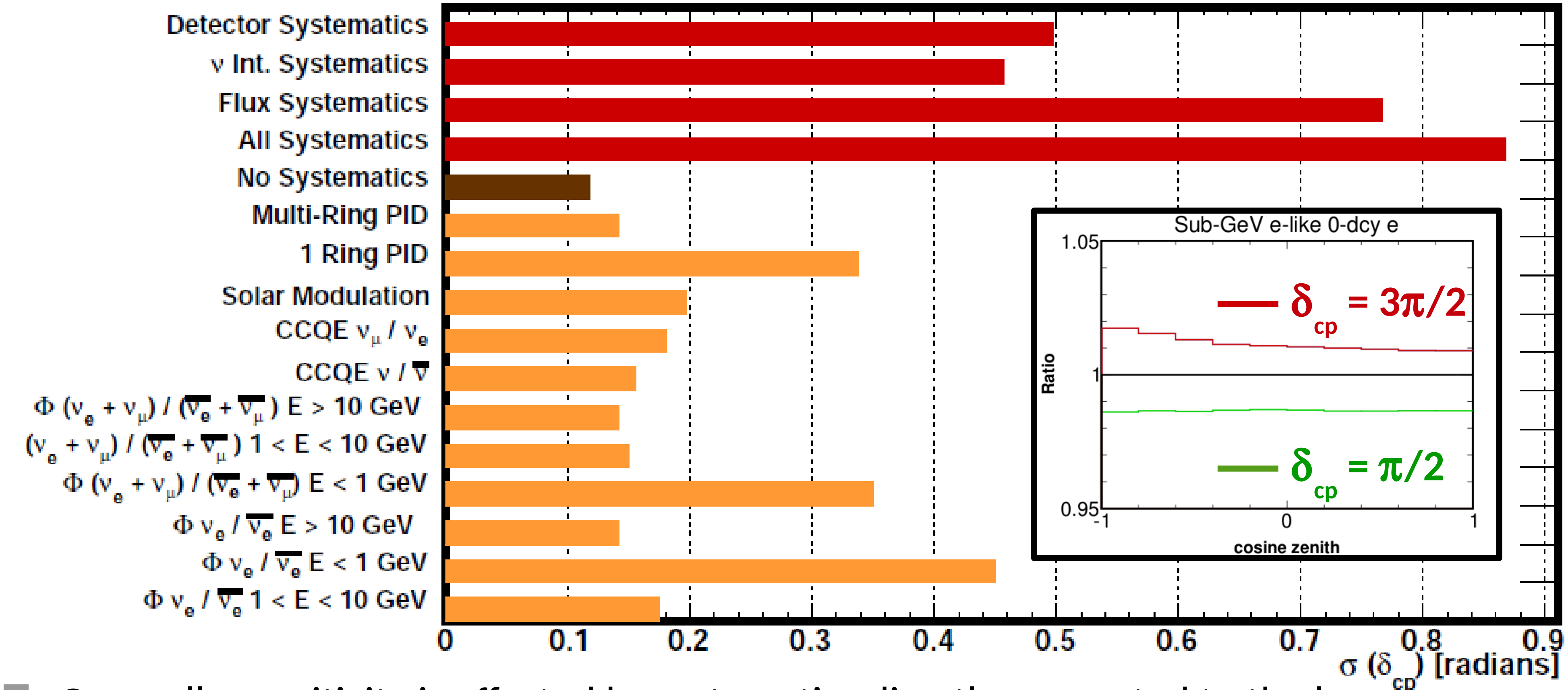




1 σ error on dcp reported next page

- Sensitivity to δcp is mostly through νe ↔νμ oscillations below 1 GeV
  - Though mostly QE interactions, lack of pointing and systematic errors problematic
  - Improved separation between neutrino and antineutrino components desired
  - Working to introduce neutron tagging at low energies, ideas for flux uncertainties

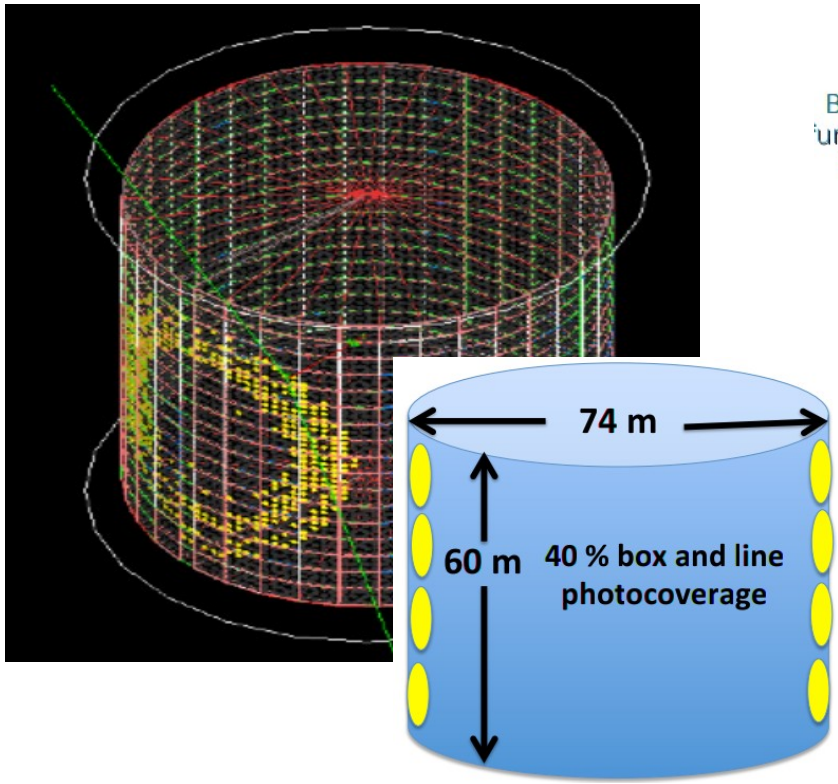
Hyper-K's Sensitivity to δ_{cp} with Atmospheric neutrinos



- Generally sensitivity is affected by systematics directly connected to the low energy neutrino flux
  - To a lesser extent the low energy interaction model:
    - CCQE $\nu/\bar{\nu}$: 5~15% below 500 MeV, CCQE $\nu\mu$ /νe : 2~10% below 500 MeV
    - Improved measurements will help
- Note that the detector performance also becomes important
  - Single ring mis-PID uncertainty is 1~2% below 1330 MeV

A word about the Future

WCSim



FiTQun

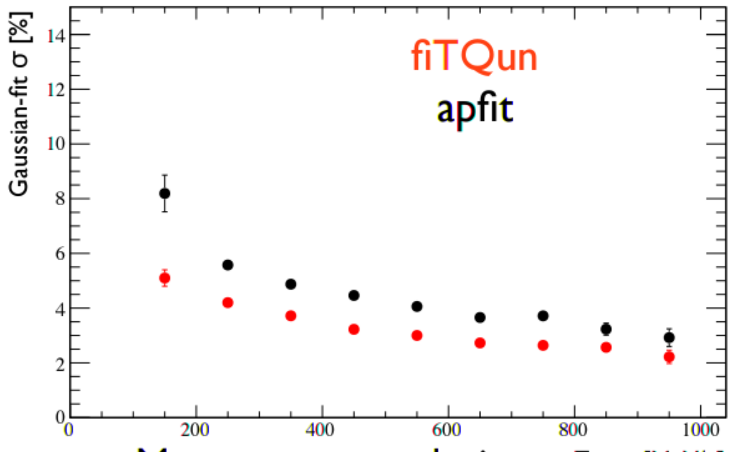
Use information from sensors both with and without registered hits in the event

$$L(\mathbf{x}) = \prod_{i_{unhit}} \mathrm{P}(i_{unhit}|\mathbf{x}) \prod_{i_{hit}} \mathrm{P}(i_{hit}|\mathbf{x}) f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x})$$

Build likelihood function for event hypothesis **x**

For hit photosensors:

Compare observed charge to prediction and Compare hit time to prediction



Momentum resolution

- WCSim - Detector Simulation Upgrade
  - GEANT4 based detector model, with flexible geometry and Hyper-K photosensors implemented
- fiTQun – a maximum likelihood fitter developed for T2K/SK
  - Includes both time and charge PDFs, shows improved performance in PID, and momentum and direction resolution
  - Now being tailored for use with Hyper-K/WCSim

Summary

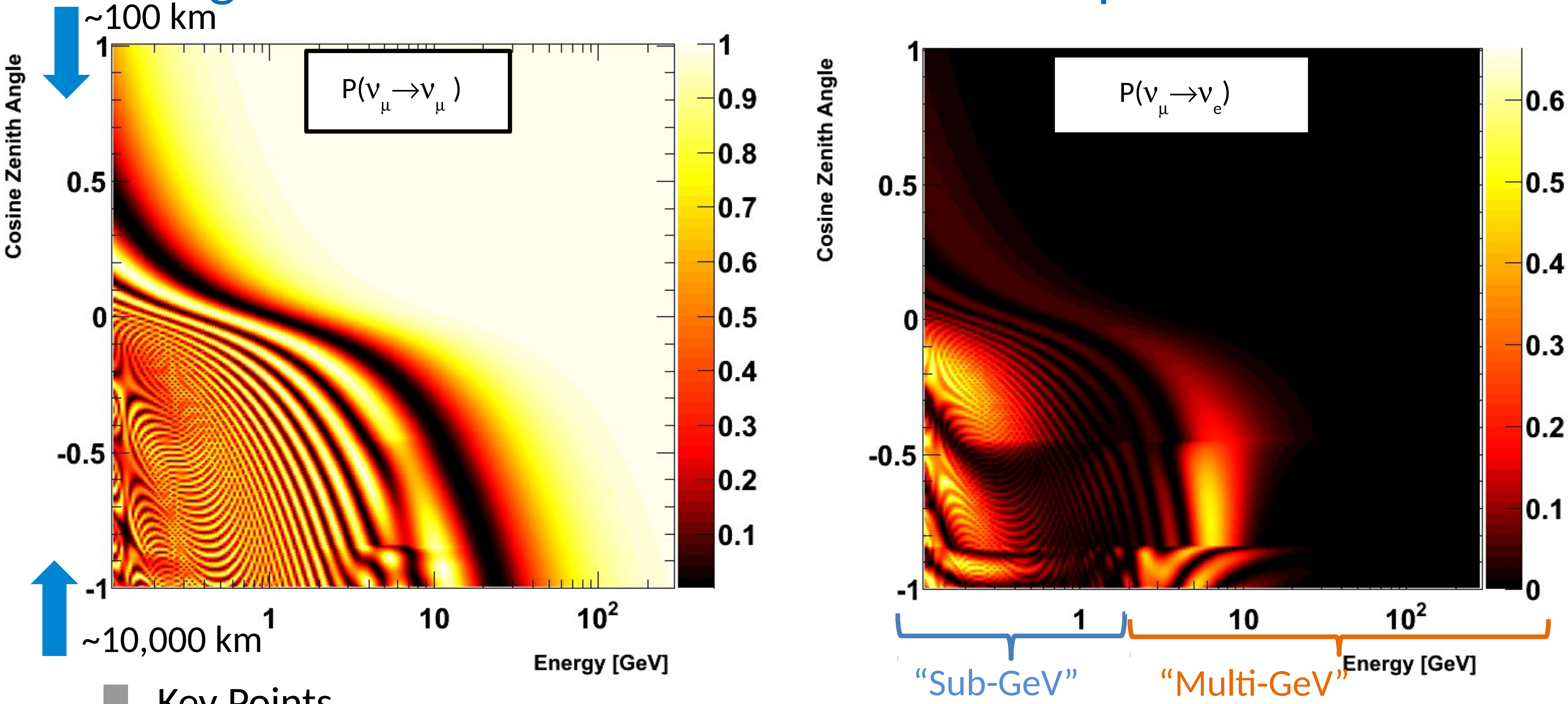
- Hyper-K is currently using a variety of tools developed for Super-K atmospheric neutrino and proton decay analysis

- Many of these are effectively open source and available upon request
  - Used freely within the Hyper-K collaboration

- Dedicated Hyper-K software is currently being developed to improve on existing methods
  - New ideas and techniques are certainly welcome

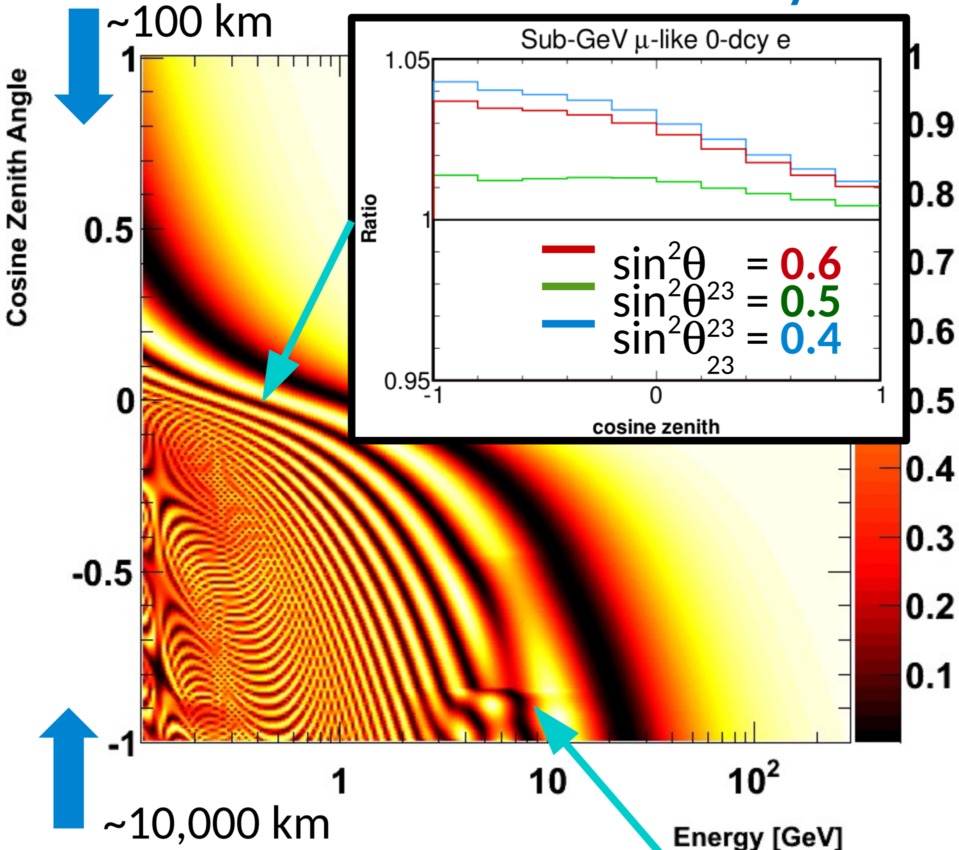
Supplements

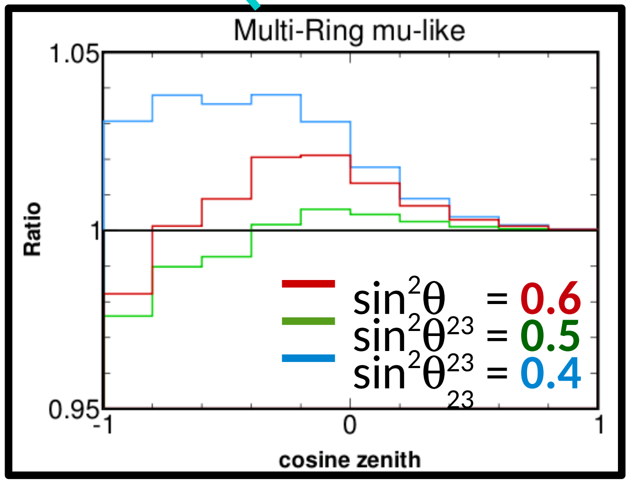
Searching for Three-Flavor Effects: Oscillation probabilities

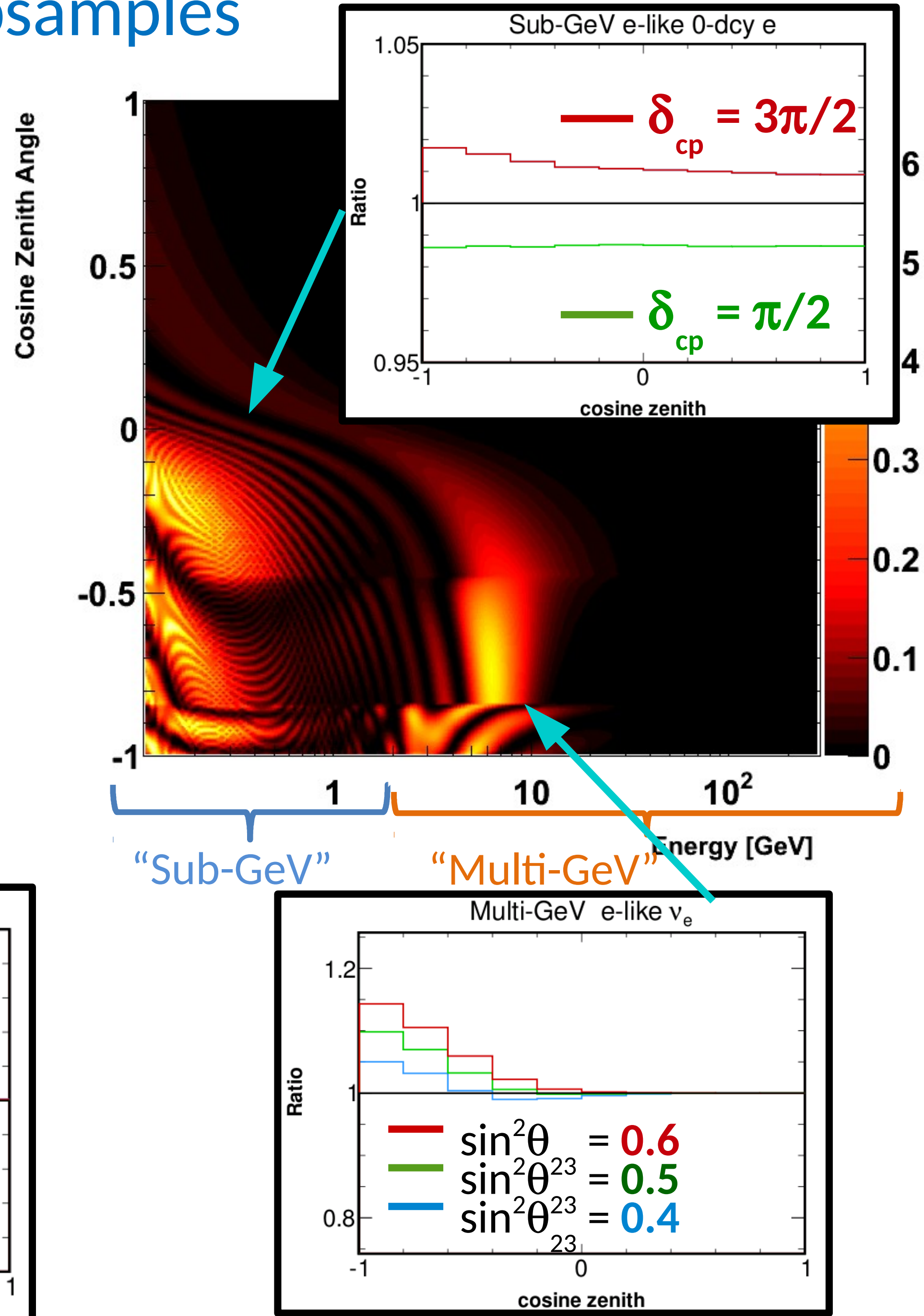


- Key Points
  - No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest in upward-going ν_e

Oscillation Effects on Analysis Subsamples







Ratio to two-flavor oscillations

Appearance effects are halved in the IH

$$r_i = m_\mu^2/m_i^2 \text{ for } i = (\pi, K)$$

$$\frac{dN_\nu}{dE_\nu} = \frac{\phi_N(E_\nu)}{(1 - Z_{NN})(\gamma + 1)} \left\{ \left[\frac{Z_{N\pi}(1 - r_\pi)^\gamma}{1 + B_{\pi\nu} \cos\theta E_\nu/\epsilon_\pi} \right] + 0.635 \left[\frac{Z_{NK}(1 - r_K)^\gamma}{1 + B_{K\nu} \cos\theta E_\nu/\epsilon_K} \right] \right\},$$

$$\phi(E_0) = \frac{dN}{dE_0} = A \times E_0^{-(\gamma+1)}$$

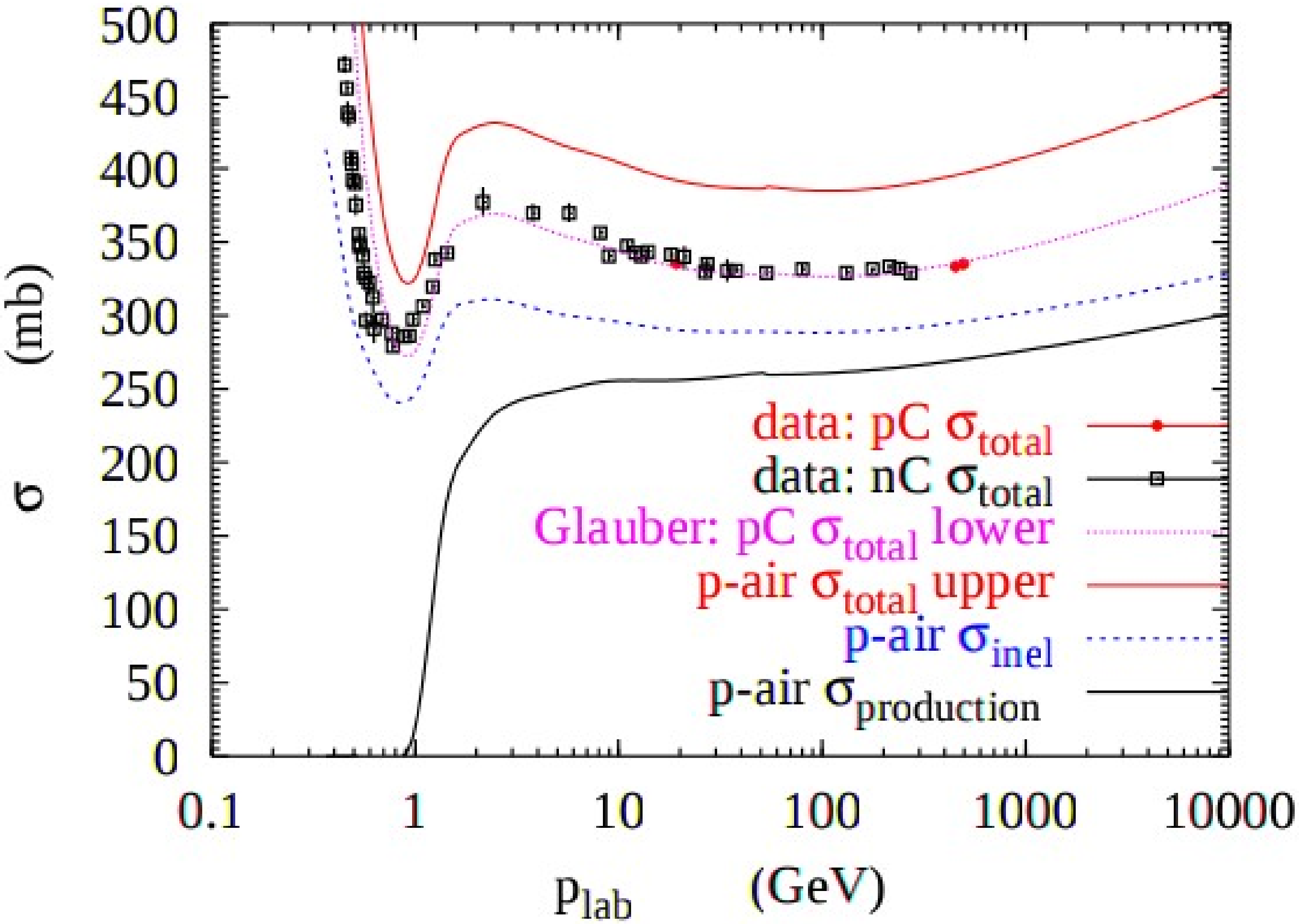
$$Z_{N\to\pi(K)} = \int_0^1 dx\,(x)^{\gamma-1} F_{N\to\pi(K)}(x)$$

$$F_{N\pi}(E_\pi, E_N) = \frac{E_\pi}{\sigma_N} \frac{d\sigma(E_\pi, E_N)}{dE_\pi}$$

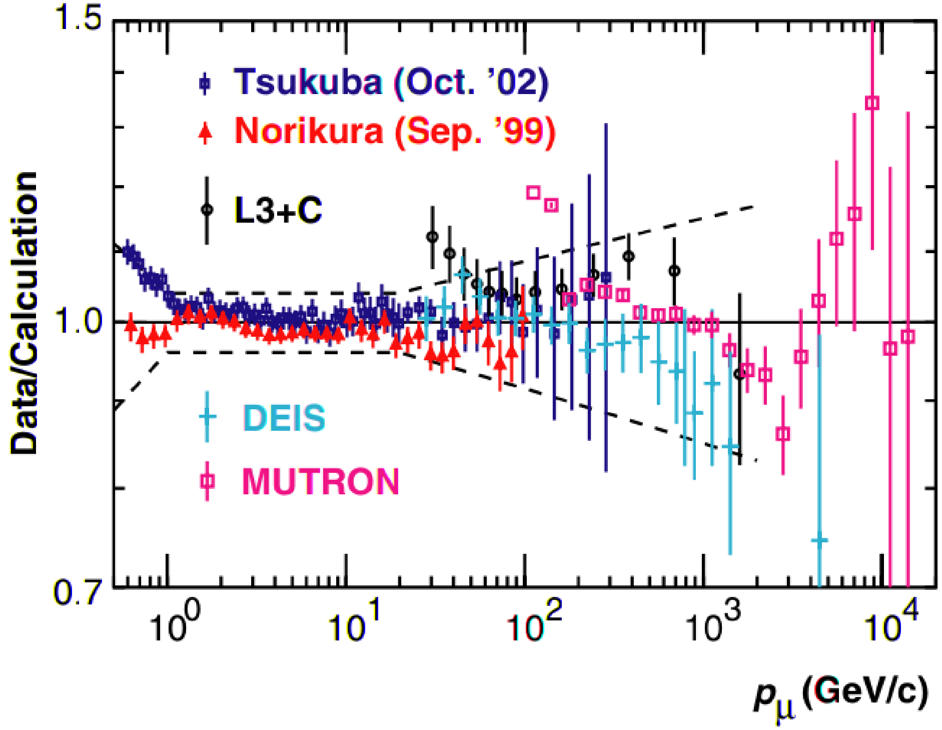
normalized inclusive cross section for $N + \text{air} \rightarrow \pi^\pm + X$

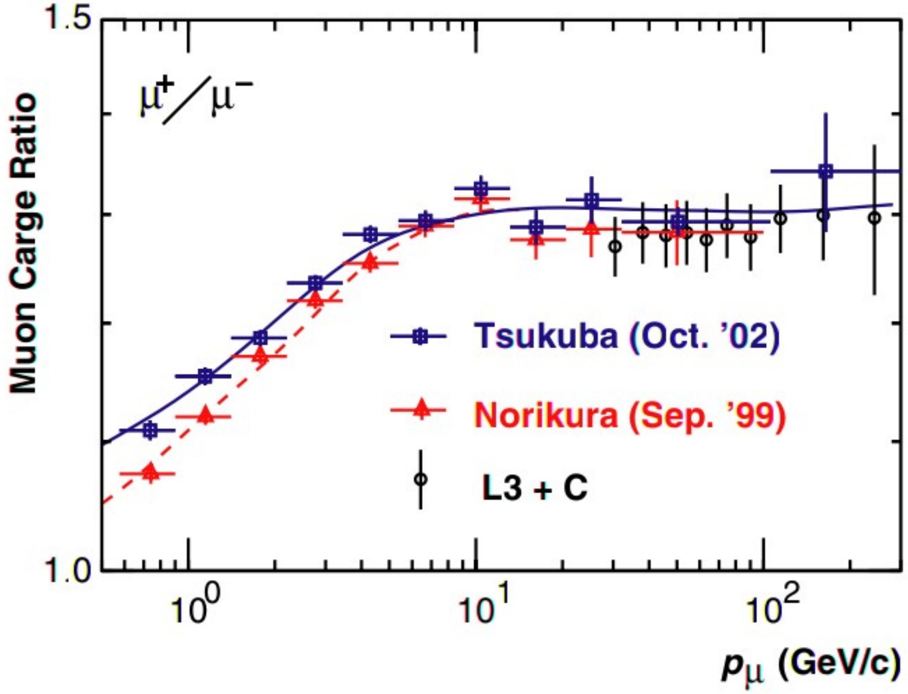
Table 1: Parameters for atmospheric $\nu_\mu + \bar{\nu}_\mu$ from π,K-decay

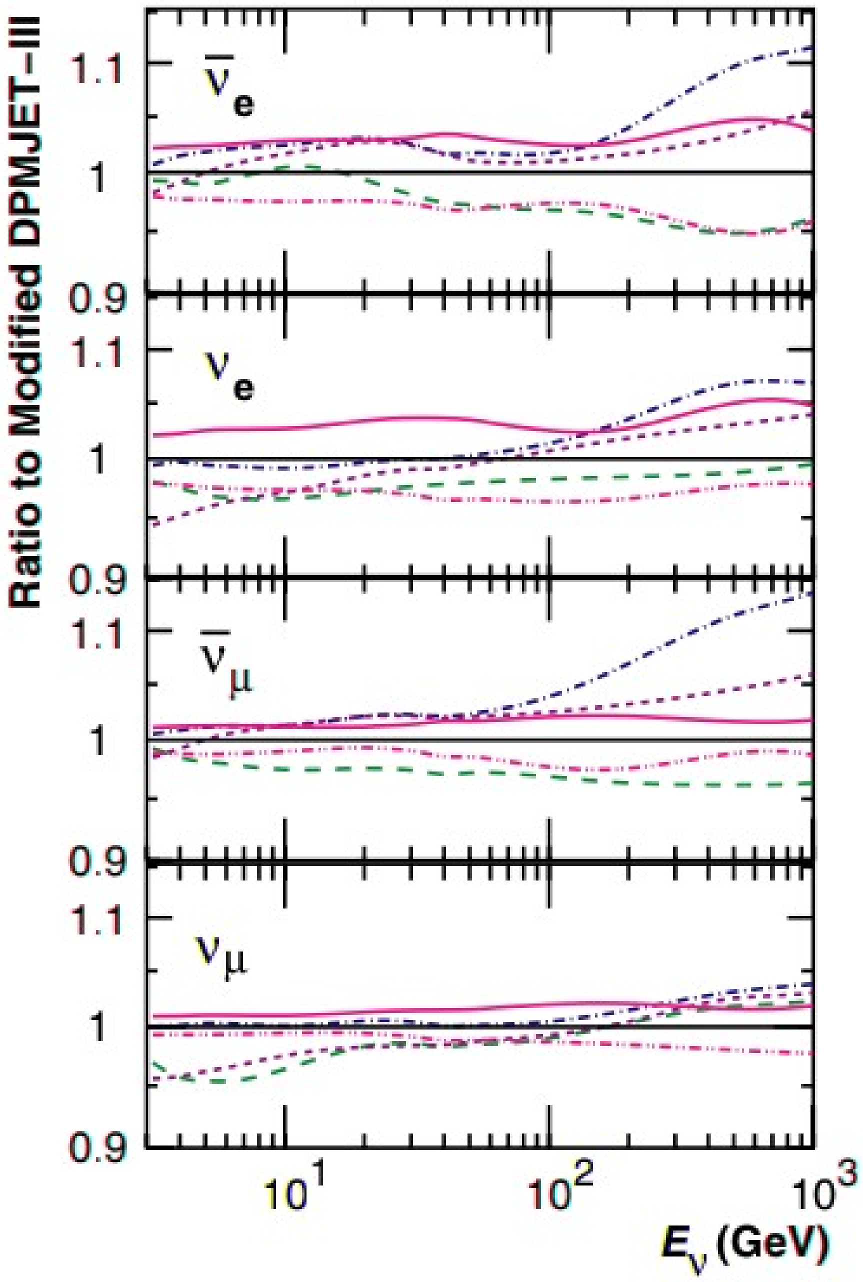
Mass-square ratios	r_π	r_K	B_π	B_K
& B-factors:	0.573	.046	2.77	1.18
Characteristic E_{decay}:	ϵ_π	ϵ_K	ϵ_{charm}	
	115 GeV	850 GeV	$\sim 5 \times 10^7$ GeV	
Z-factors:	Z_N	Z_π	Z_K	
	0.30	0.079	0.0118	



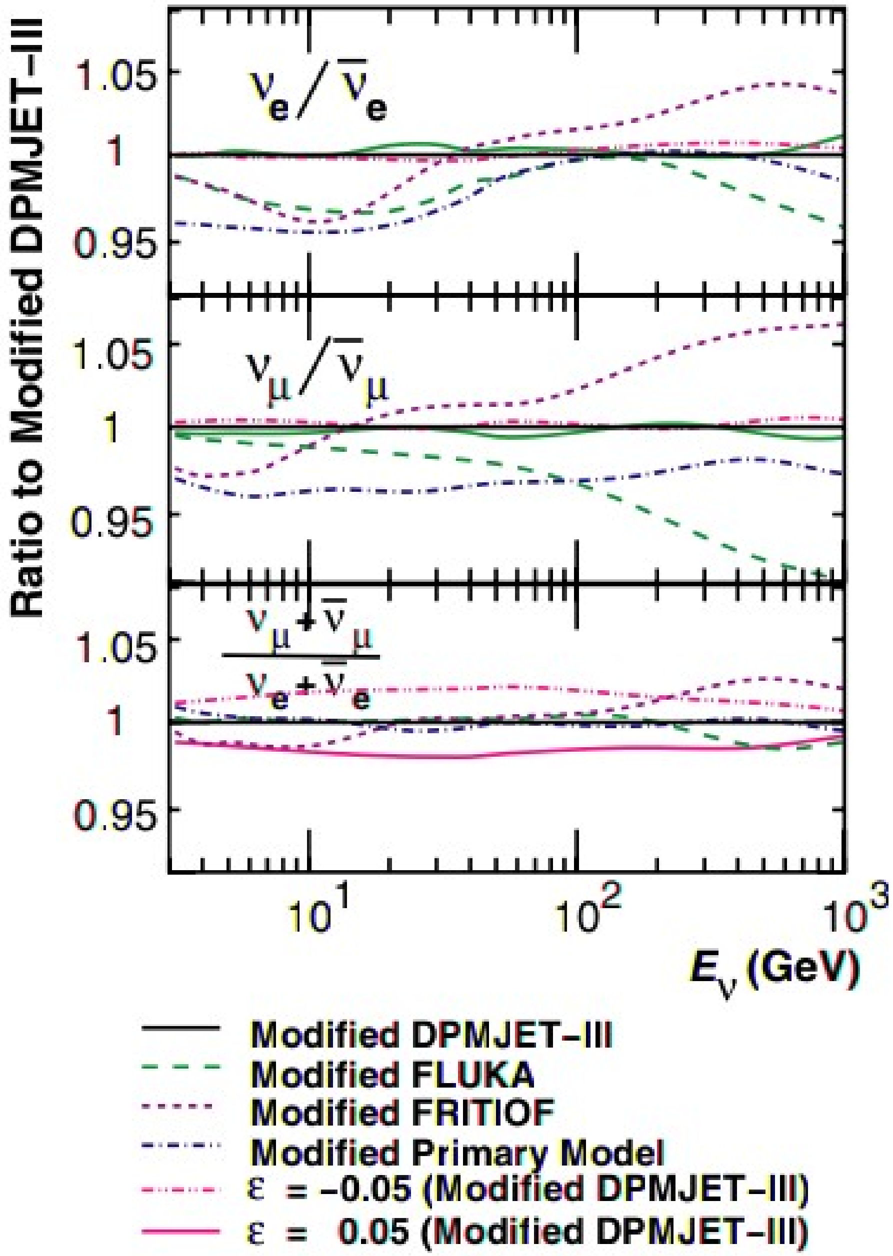
500
450
400
350
300
250
200
150
100
50
0
σ (mb)
0.1
1
10
100
1000
10000
p_lab (GeV)
data: pC σ_total
data: nC σ_total
Glauber: pC σ_total lower
p-air σ_total upper
p-air σ_inel
p-air σ_production


Data/Calculation
1.5
1.0
0.7
Tsukuba (Oct. '02)
Norikura (Sep. '99)
L3+C
DEIS
MUTRON
10^0
10^1
10^2
10^3
10^4
pμ (GeV/c)


Muon Carge Ratio
1.5
1.0
μ+/μ−
Tsukuba (Oct. '02)
Norikura (Sep. '99)
L3 + C
10^0
10^1
10^2
pμ (GeV/c)



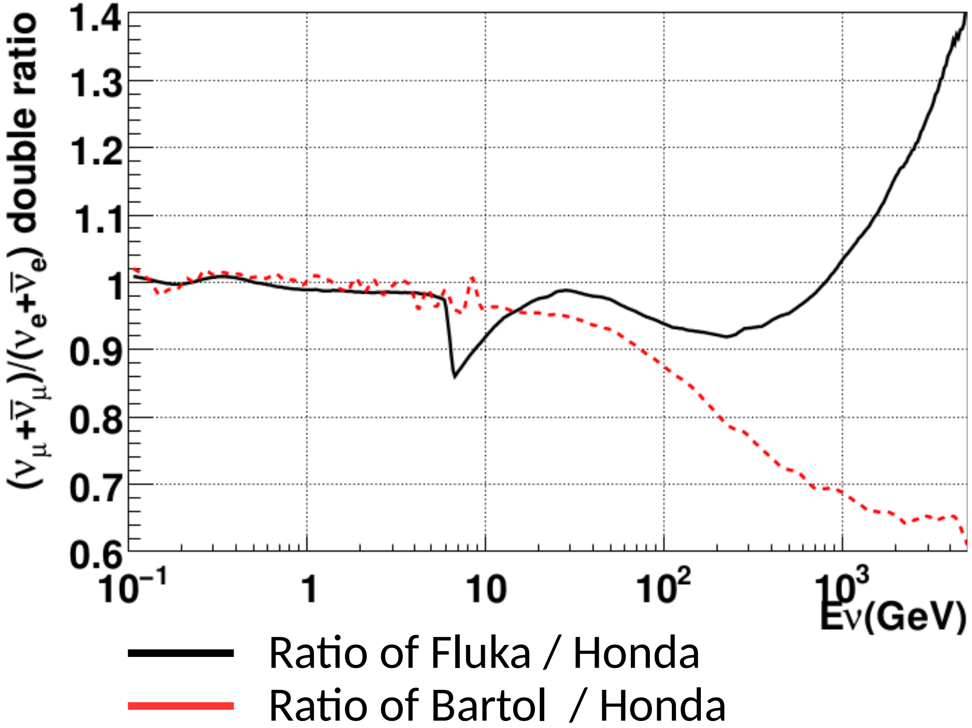
Ratio to Modified DPMJET-III
$\bar{\nu}_e$
ν_e
$\bar{\nu}_\mu$
ν_μ
1.1
1
0.9
10^1
10^2
10^3
E_ν (GeV)



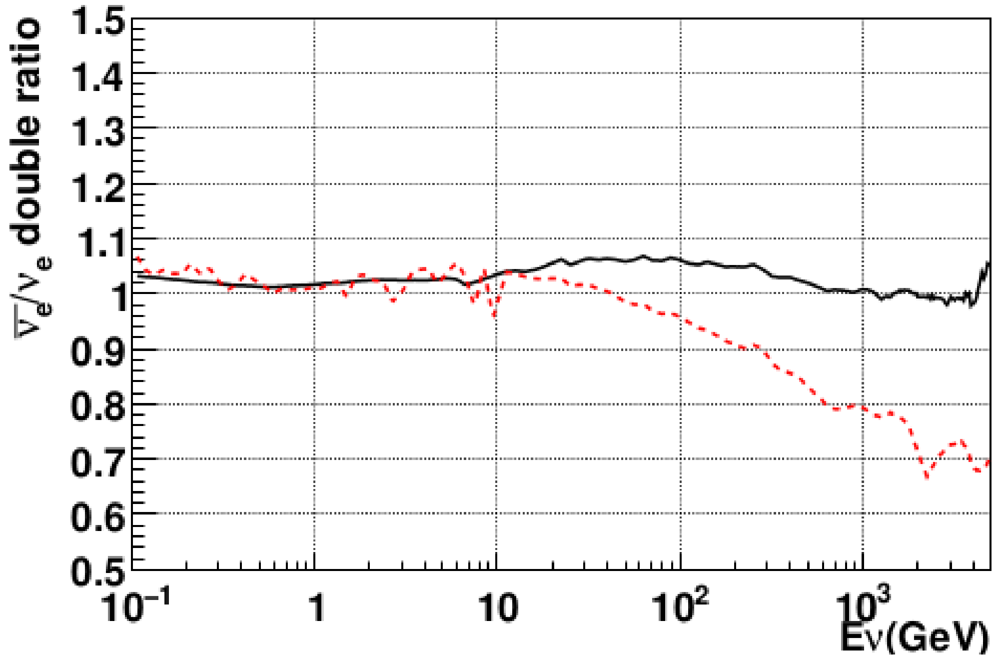
Ratio to Modified DPMJET-III
$\nu_e / \bar{\nu}_e$
$\nu_\mu / \bar{\nu}_\mu$
$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$
1.05
1
0.95
10^1
10^2
10^3
E_ν (GeV)
Modified DPMJET-III
Modified FLUKA
Modified FRITIOF
Modified Primary Model
ε = -0.05 (Modified DPMJET-III)
ε = 0.05 (Modified DPMJET-III)

Atmospheric Neutrino Flux Uncertainties (Honda 2011)

Flavor Ratio Comparison



Electron to Antielectron Neurino Ratio



- Systematic Errors on the Neutrino flux at Super-K (Hyper-K) are based on both direct estimates from the authors of the Honda 2011 Flux and by comparisons with other models
  - Flavor Ratio uncertainty is 2% below 1 GeV
  - Electron ratio uncertainty is 5% below 10 GeV
- Changes in solar activity affect the low energy neutrino flux, but the exact magnitude depends on the real experimental run
  - Here 10% uncertainty is assumed on a run with 35% (65%) 'high' ('low') activity

Comparison to Current Super-K Exposure

	Hyper-K HD	SK-IV
Fiducial Vol.	**186 kton**	22.5 kton
Eff. Area	**6,430 m^2**	1500 m^2
Protons	**6.0×10^{34}**	7.5×10^{33}
Neutrons	**5.0×10^{34}**	6.0×10^{33}
Fully Contained μ-/e-like	**246,600**	41,000
Partially Contained μ-like	**21,300**	3,100
Upward-Going μ	**24,300**	7,400

- Hyper-K sensitivity studies are based on Super-K simulation and reconstruction
  - Analyses exposures have been adjusted to account for difference in fiducial volume and effective area between Hyper-K and Super-K
- Event rates compare 10 years of Hyper-K and 12.8 years of SK

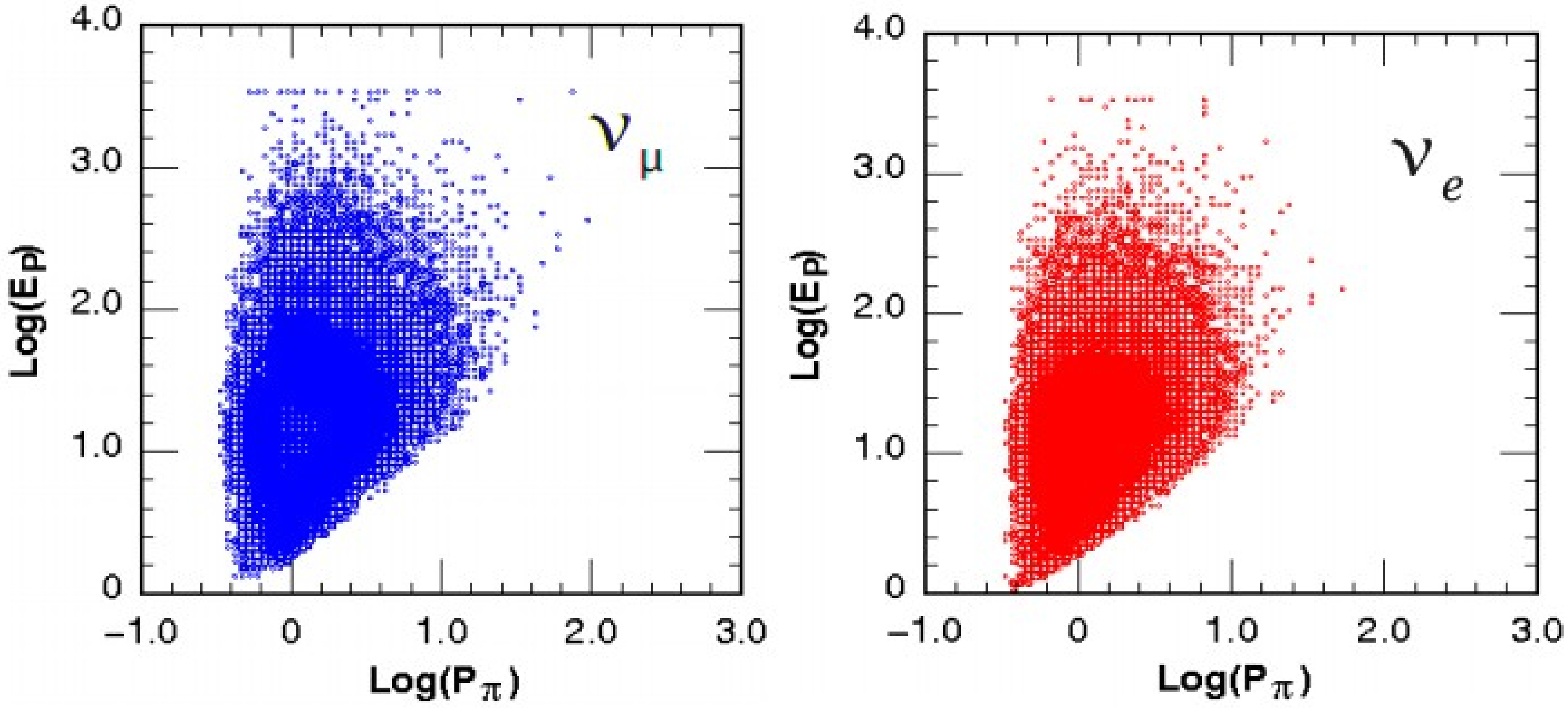
Components of the Calculation

- Primary Cosmic Rays Model
  AMS01 and BESS observation for < 100 GeV
  JACEE and RUNJOB for > 3 TeV and the interpolations

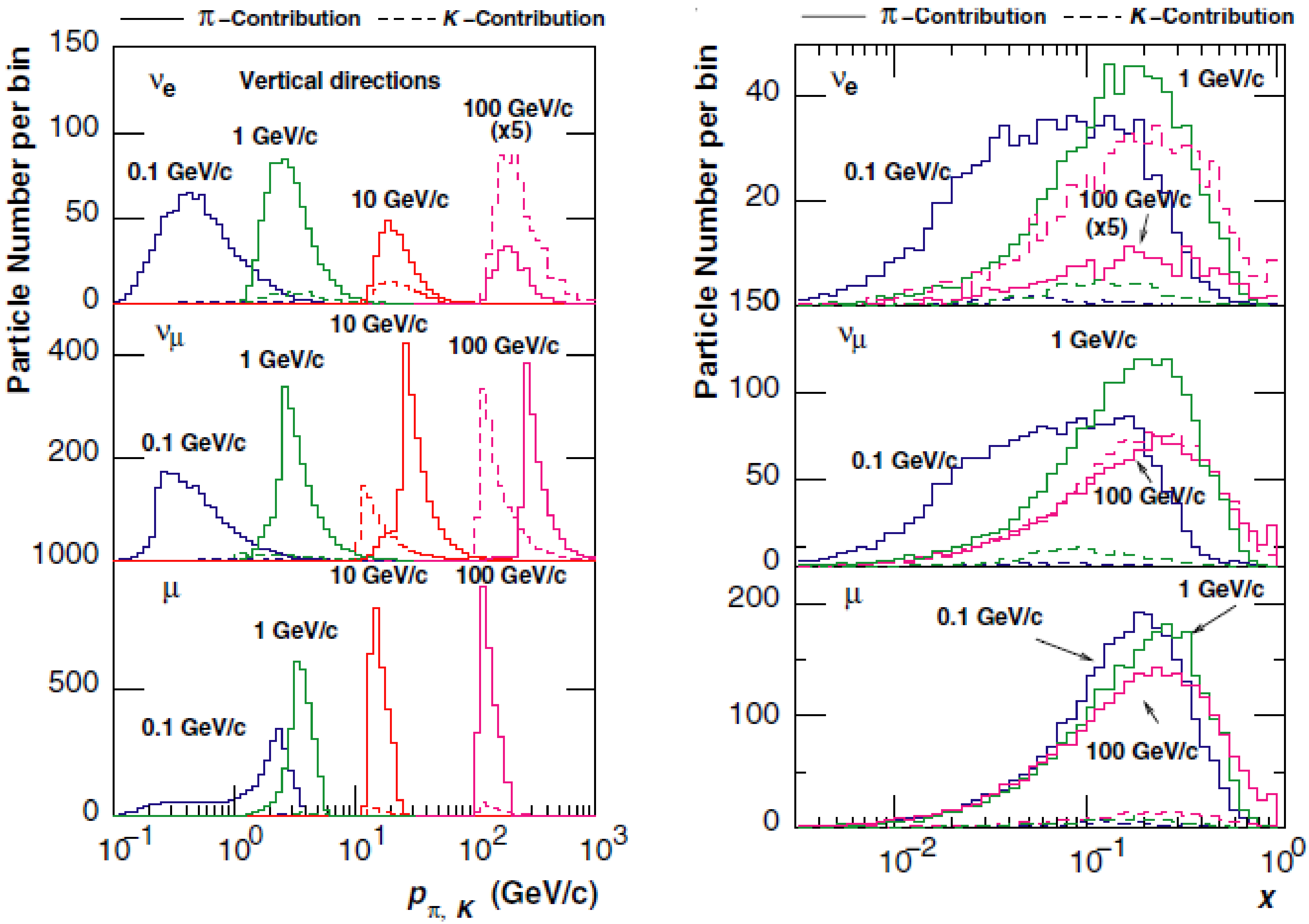
- Hadronic interaction Models
  DPMJET-III (>5GeV) and NUCRIN (<5GeV) in
  HKKM04 and HKKMS07.
  DPMJET-III (>32GeV) and JAM (<32GeV) in
  HKKM11 and HAKKM15.
  They are modified in the Muon Calibration

- Atmosphere Model
  US-starndard'76 before HAKKM15
  NRLMSISE-00 in HAKKM15

- Geomagnetic Model
  IGRF00 (HKKM04) ～ IGRF10 (HAKKM15)

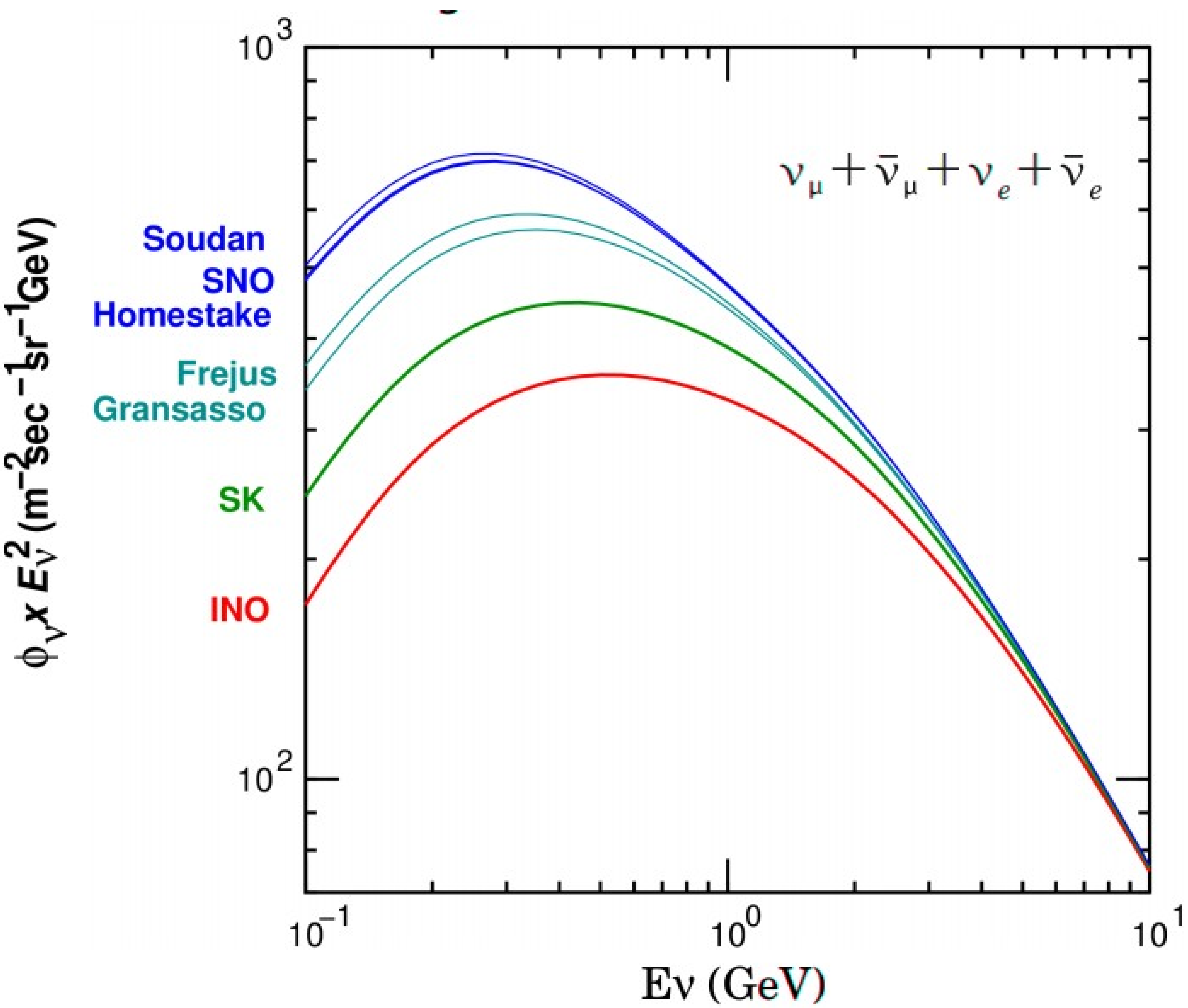


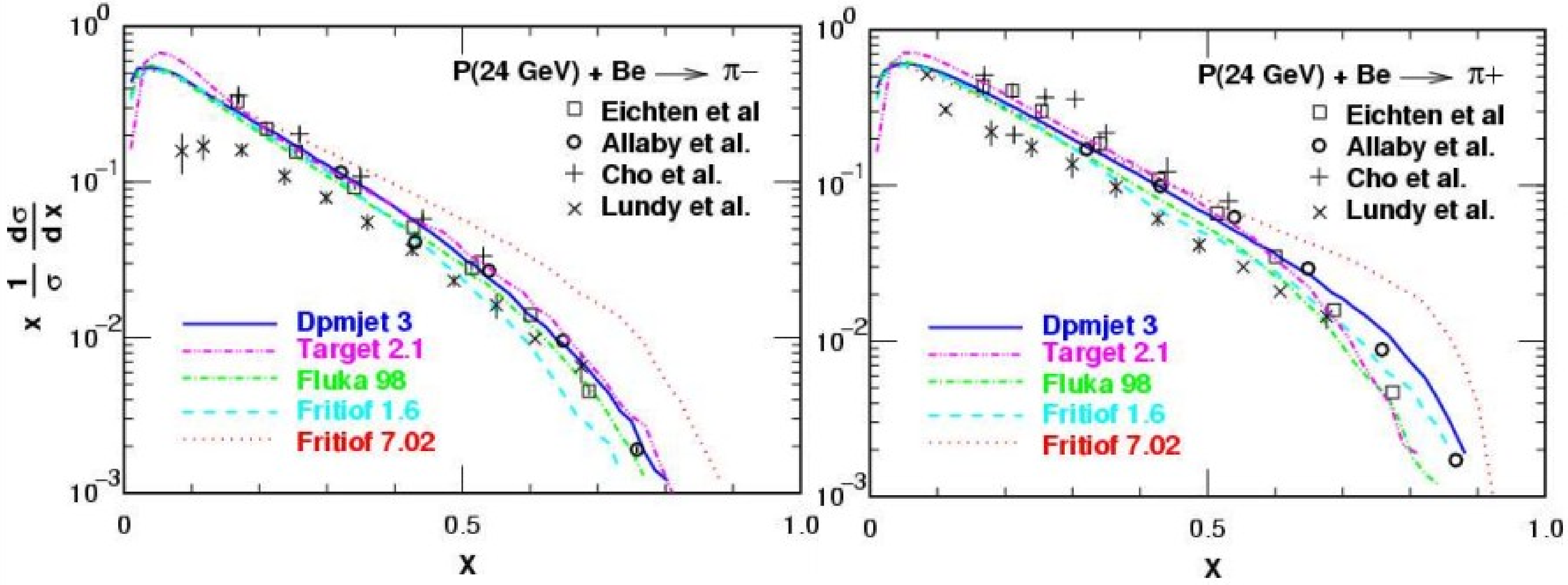
Phase space of $p + N(air) \rightarrow \pi + X$ for 0.32 GeV neutrinos.



π – Contribution
K – Contribution
Particle Number per bin
νe
Vertical directions
100 GeV/c (x5)
1 GeV/c
0.1 GeV/c
10 GeV/c
νμ
100 GeV/c
μ
$p_{\pi, K}$ (GeV/c)
x

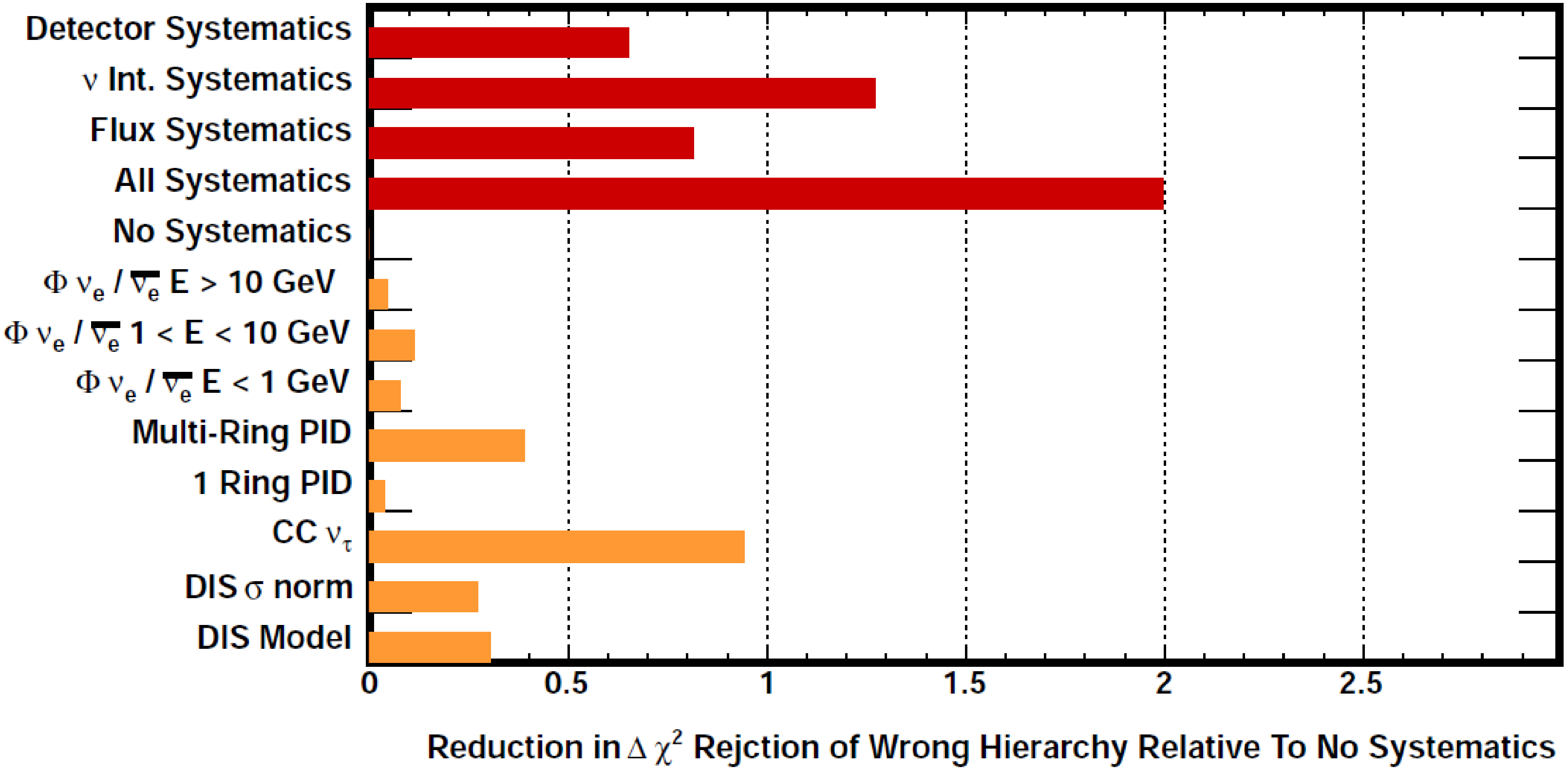
The Honda Flux





P(24 GeV) + Be → π−
Eichten et al
Allaby et al.
Cho et al.
Lundy et al.
Dpmjet 3
Target 2.1
Fluka 98
Fritiof 1.6
Fritiof 7.02
x (1/σ) dσ/dx
X
P(24 GeV) + Be → π+

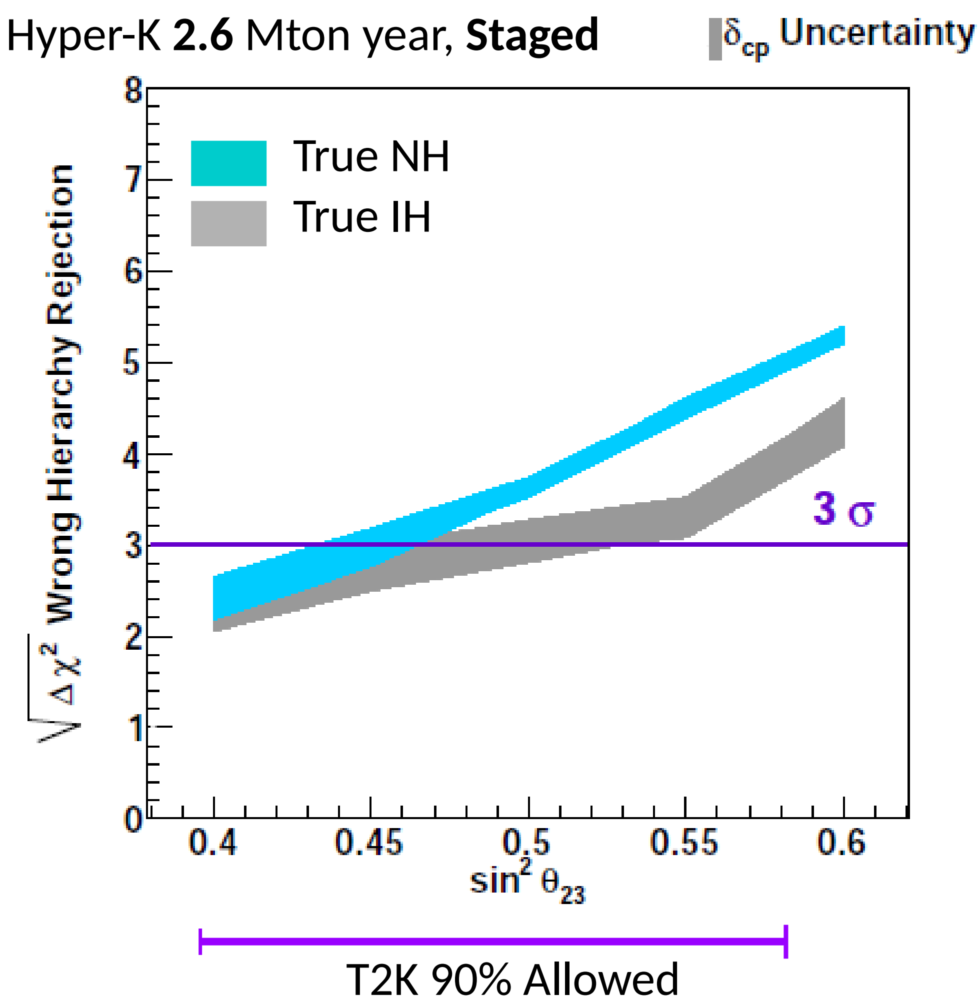
Systematic Effect on Hierarchy Sensitivity at Super-K

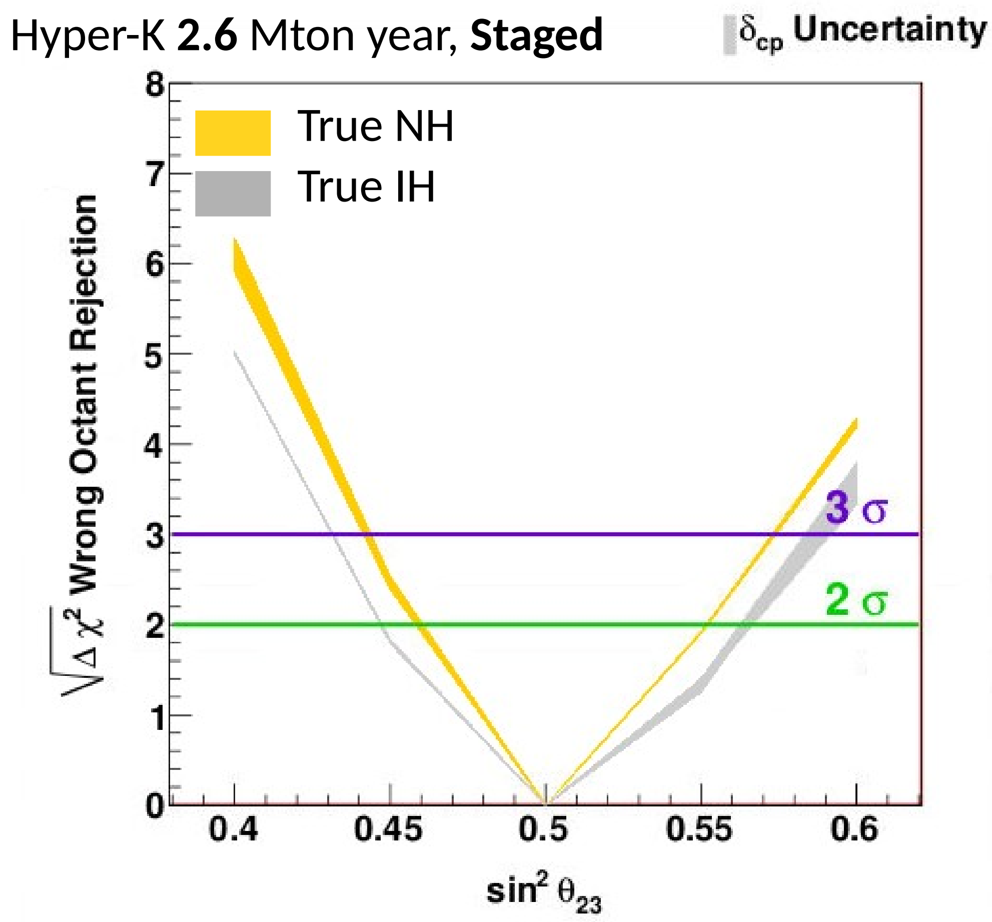


- Sensitivity to the hierarchy is largely affected by uncertainties interaction of high energy neutrinos
  - particularly the CC $\nu\tau$ background component
- The situation is compounded at Hyper-K

$\Delta\chi2$, $\theta23$	0.40	0.60
No Syst.	0.81	4.7
Full Syst.	0.59	2.7

Hyper-K Sensitivity 10 Years, Staging Scenario



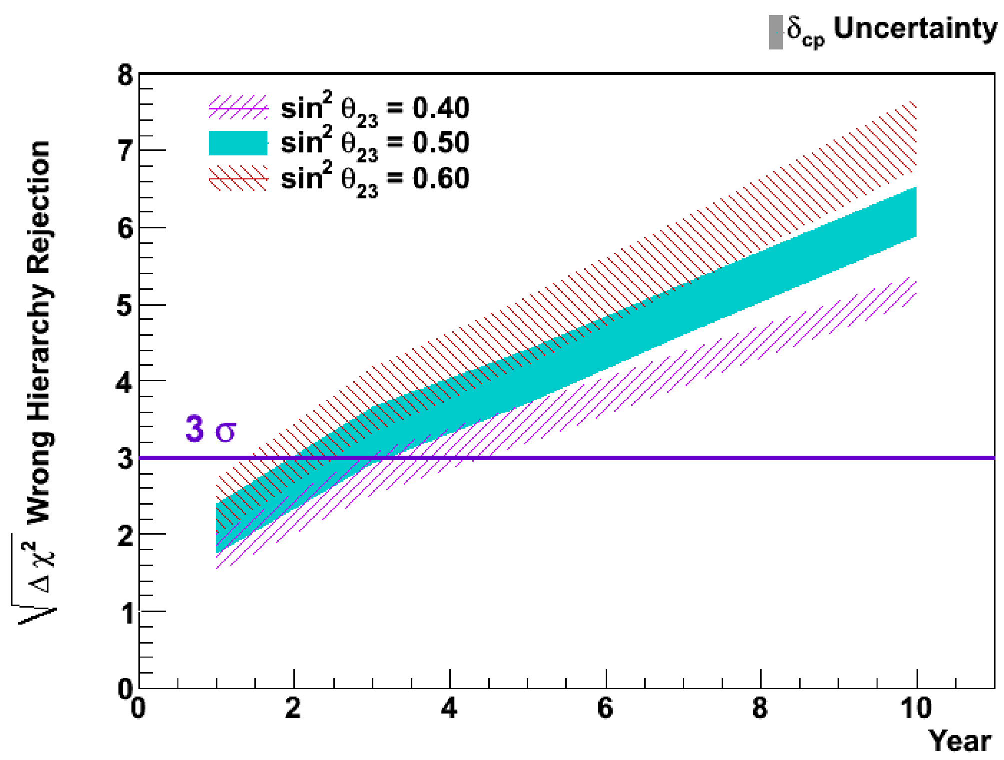


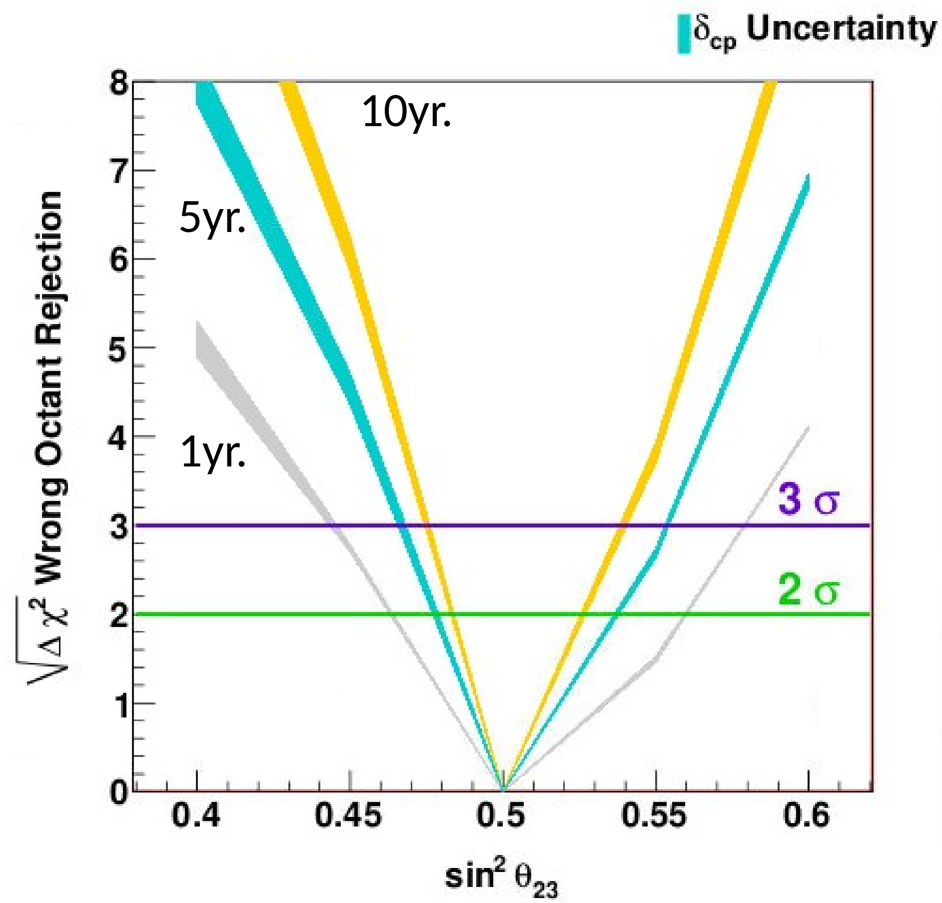
- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 4°$

Combination of Beam and Atmospheric Neutrinos

- Beam neutrinos provide tight constraints on mixing parameters that weaken the sensitivity of the (statistics limited) atmospheric neutrino sample to the mass hierarchy for instance
- Sensitivity of the two samples to the CP parameter is largely complementary, such that combined measurement yields better precision.

Combination with Beam Neutrinos : Hierarchy and Octant





- For the optimal (worst) set of parameters the combined measurement can determine the mass hierarchy with ~1.5 (4.0) years of data
- Here the beam exposure after 10 years is assumed to be 2.7×10^{22} POT , divided in a 1:3 ratio between neutrinos and antineutrinos
  - POT have been scaled evenly for shorter run periods
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 3°$

Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_e like	1R	60.2	10.6	13.5	14.8
	MR	57.5	17.4	10.7	13.7
Anti-ν_e like	1R	55.7	36.6	1.1	6.4
	MR	51.9	20.7	8.2	19.7

Composition (%)		CC ν_e	CC anti-ν_e	CC ν_μ+anti-ν_μ	NC
ν_μ like	1R	0.2	0.08	98.8	0.2
	MR	2.5	0.3	91.7	4.4

- This is a partial listing of things relevant to three-flavor issues

Error Source	Uncertainty
ν_e vs. anti-ν_e sample selection	7%
Charged-Neutral Pion Production	40%
Tau Production Cross section	25%
DIS Cross Section	5-10%
NC / CC Ratio	20%
Single-Pion Production	20%
Flux Normalization above 1 GeV	7%
Flux Ratio ν to ν bar above 1 GeV	5-8%