Impact of Hadron Production Measurements on Atmospheric Neutrino Oscillation Measurements

Roger Wendell
Kyoto University
2016.10.04
Hadron Production Workshop
Nagoya University

Introductory Remarks

- Hadron production measurements are important for atmospheric neutrino oscillation measurements in two (broad ways)

- Used in estimation of hadron yields from primary cosmic ray interaction
  - Mesons produced in the decays/interactions of create the atmospheric neutrino flux. Hadron production uncertainties translate (directly) into errors on the (absolute) neutrino flux

- Used in the calculation of products and rate of interaction of particles escaping the primary neutrino vertex
  - Secondary interactions in an atmospheric neutrino detector change the visible topology of an event, introducing uncertainties in oscillation parameter measurements

- In this talk:
  - Take "hadron production" to mean *all* hadrons
  - Super-K = 306 kton yr exposure
  - Hyper-K = 5.6 Mton yr exposure of SK detector

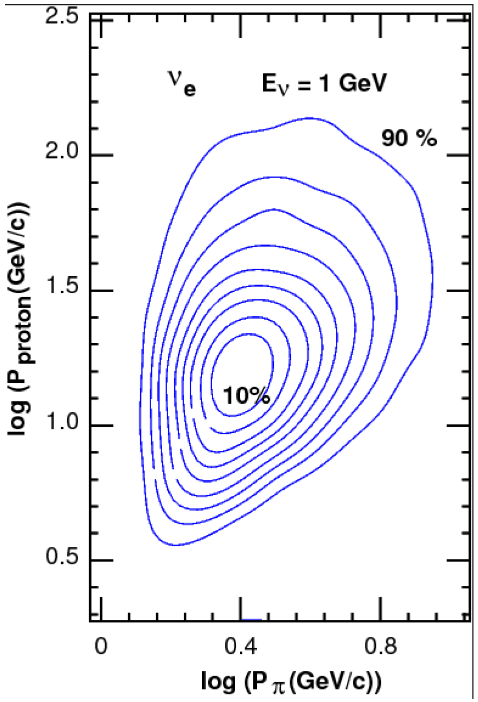
Atmospheric Neutrino Flux Calculations

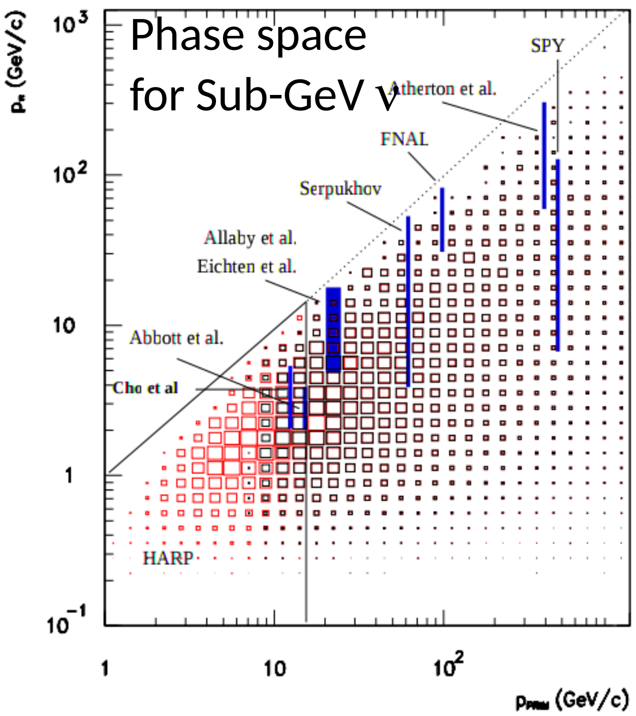
- Atmospheric neutrinos are produced by the collision of primary cosmic rays with air nuclei:

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

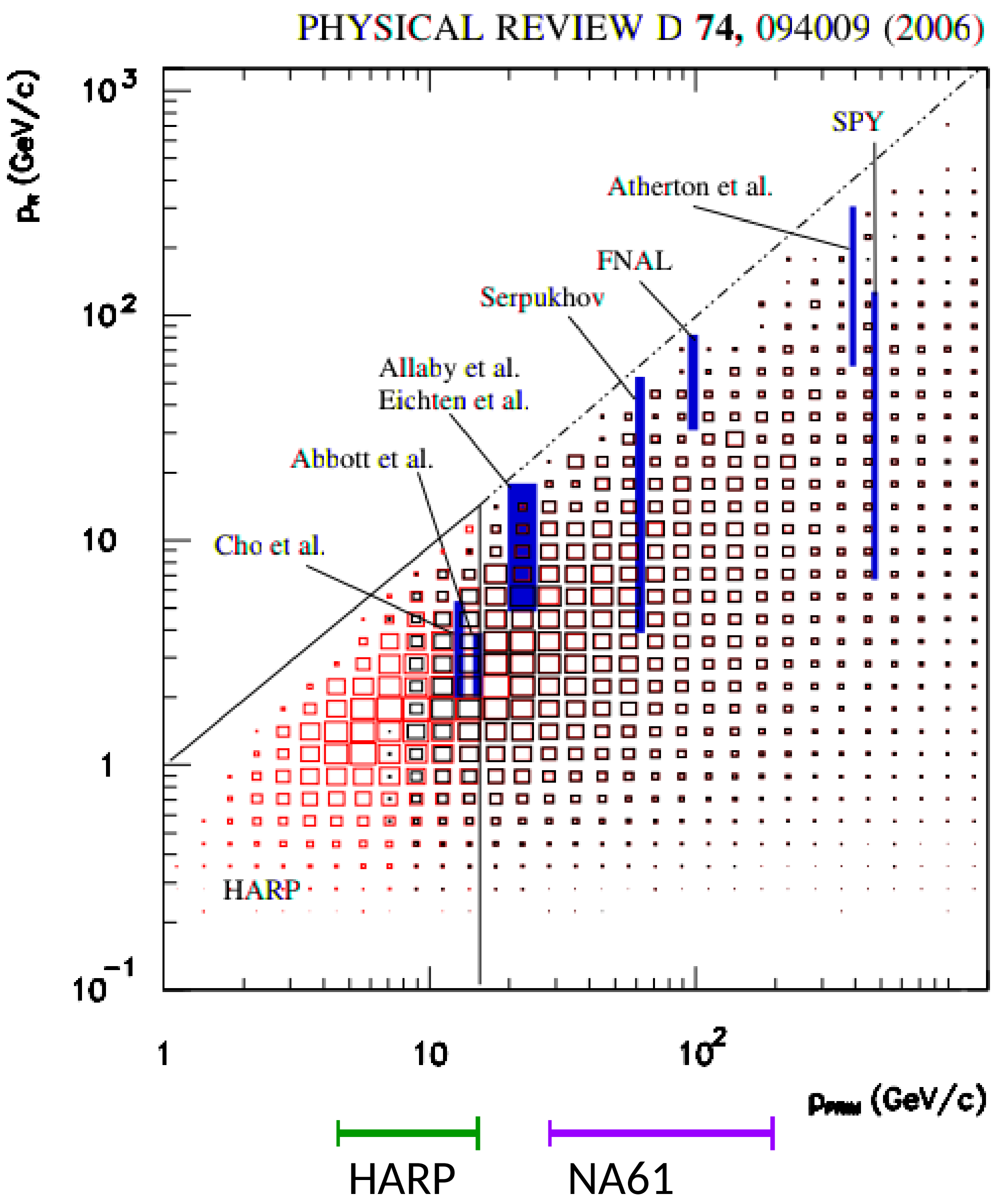
$$\Rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

- Leading models either
  - constrain the neutrino flux using measurements of atmospheric muons to tune hadronic model of the shower (Honda)
  - Appeal directly hadron production codes (Bartol)





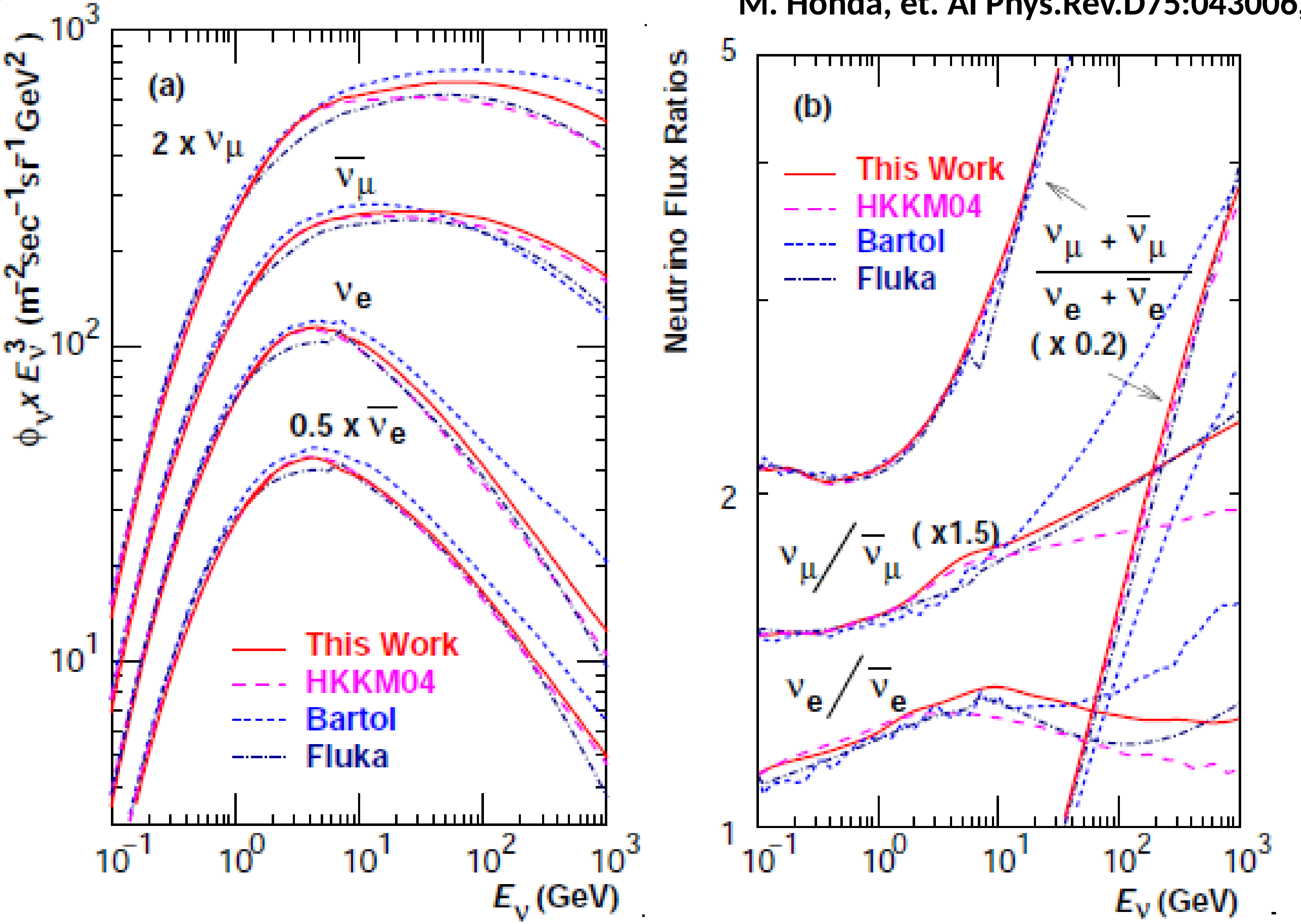
Hadron Production



- Phase space for generating ***contained*** neutrino interactions
  - E_n ($\nu\mu$) < 1 GeV
- Red : high geomagnetic latitude
- Black: low geomagnetic latitude
- Existing hadron production measurements use C, Be, Al, B
- However atmosphere is composed of O and N, so some extrapolation is required
- Improved phase space coverage by recent experiments not (yet!) included in models

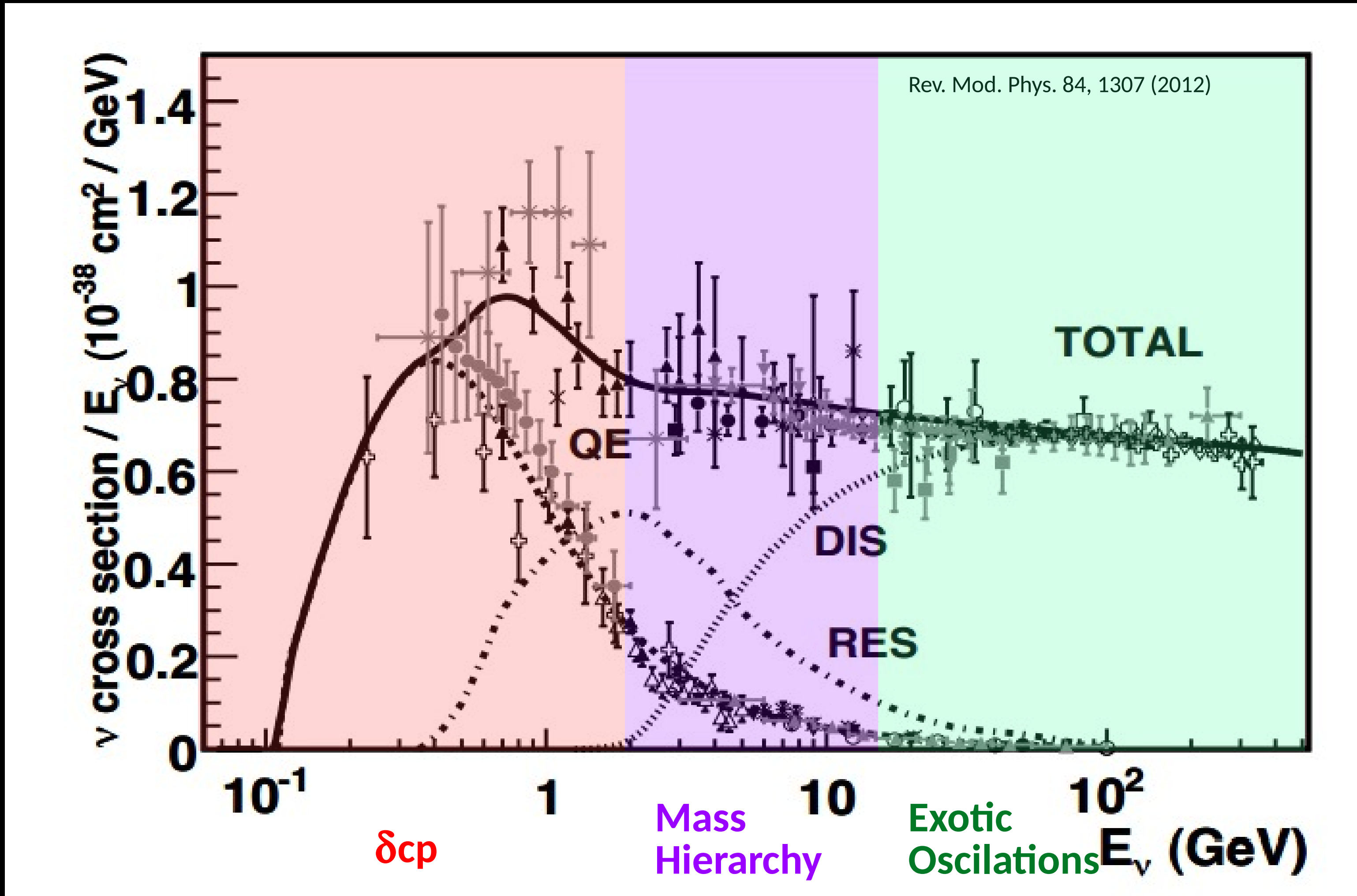
Atmospheric Neutrino Fluxes

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

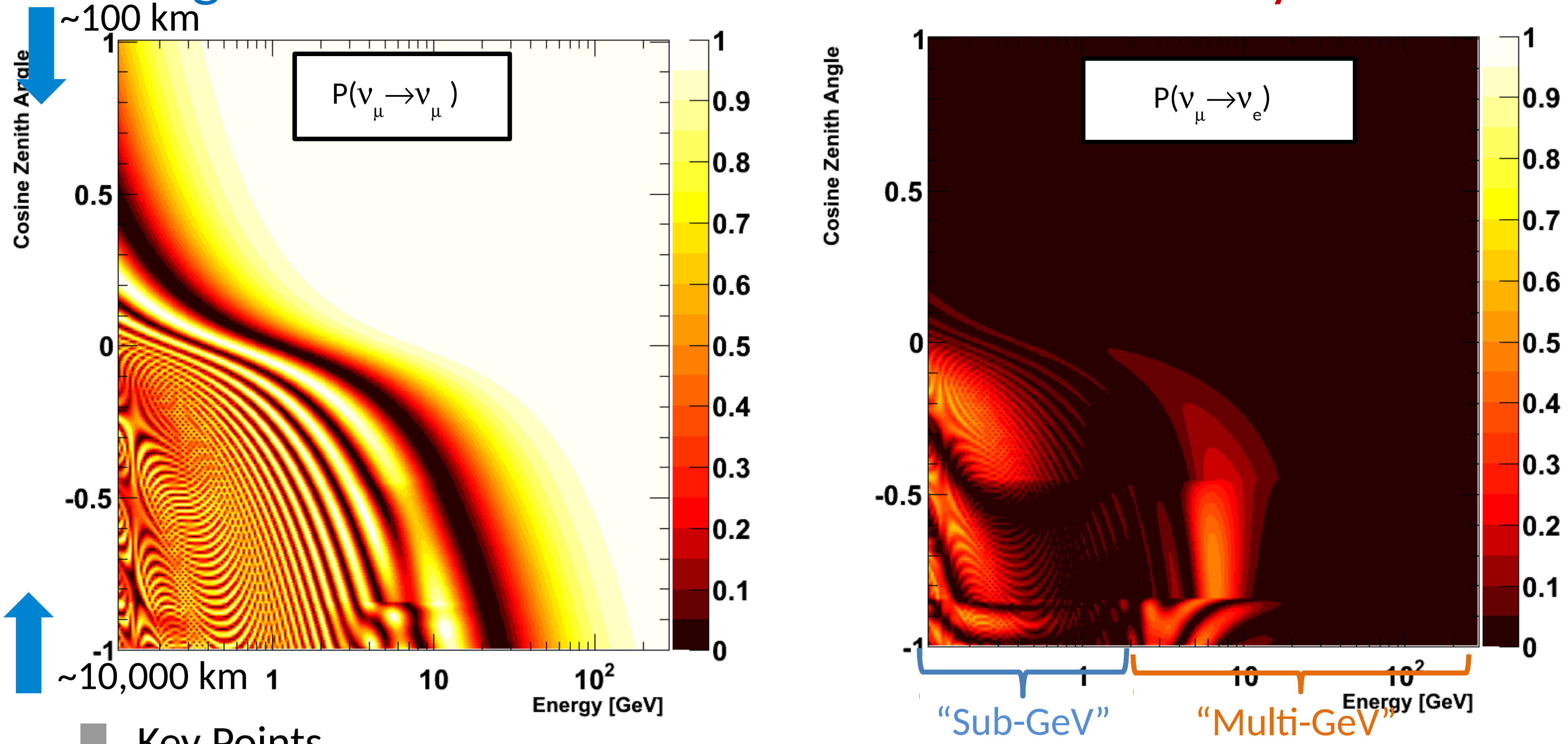


- Estimation of flux is complicated by the wide range of primary cosmic ray energies and the inability of any one (balloon, hadron production, etc.) experiment to cover the phase space of resulting secondaries

Neutrino Interactions Relevant for Atmospheric Neutrinos

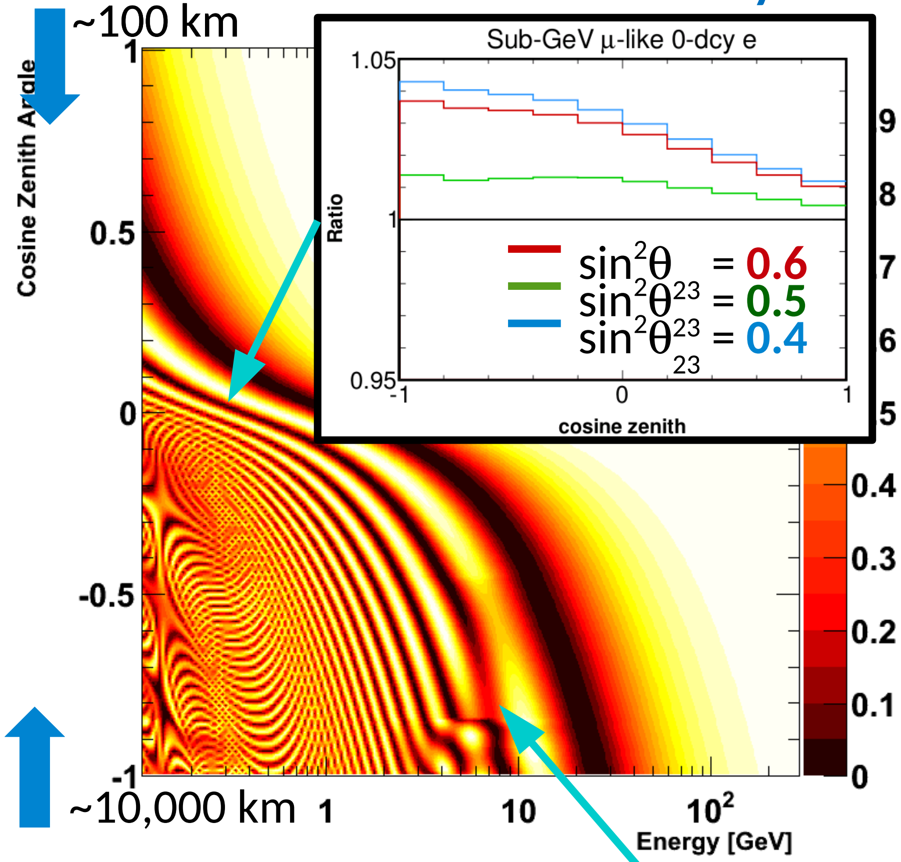


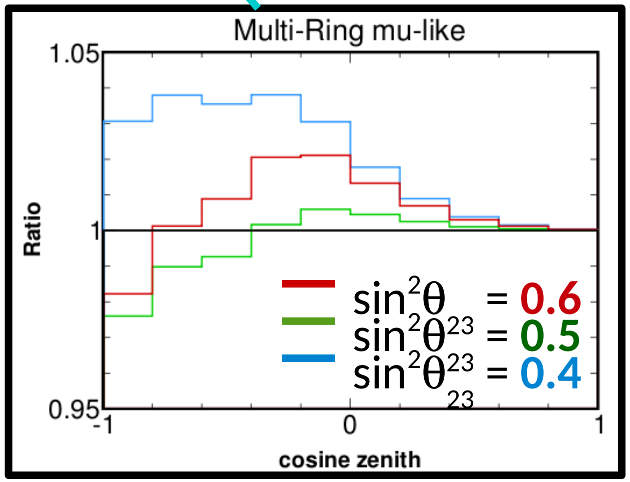
Searching for Three-Flavor Effects: Normal Hierarchy

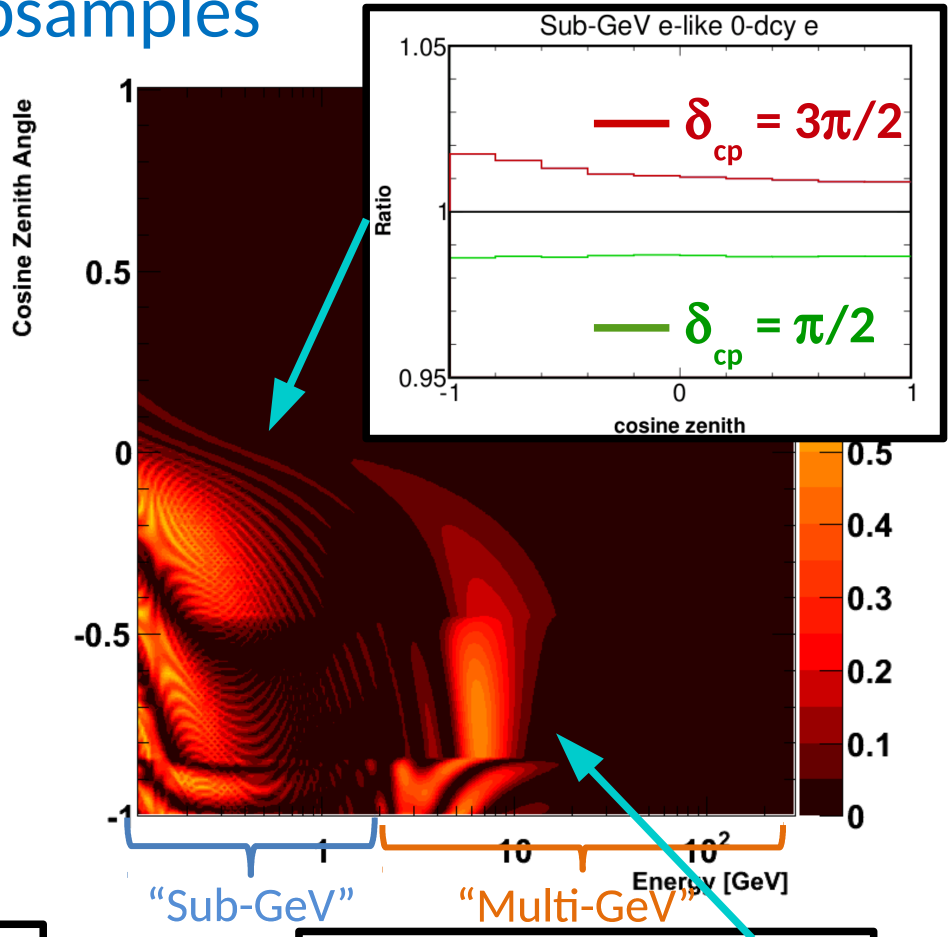


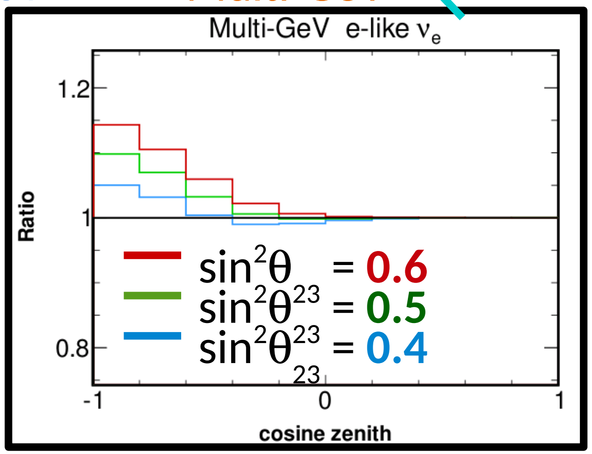
- Key Points
  - No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - No oscillations above 200 GeV
  - No oscillations from downward-going neutrinos above ~5 GeV
  - Expect effects in most analysis samples, largest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

Oscillation Effects on Analysis Subsamples





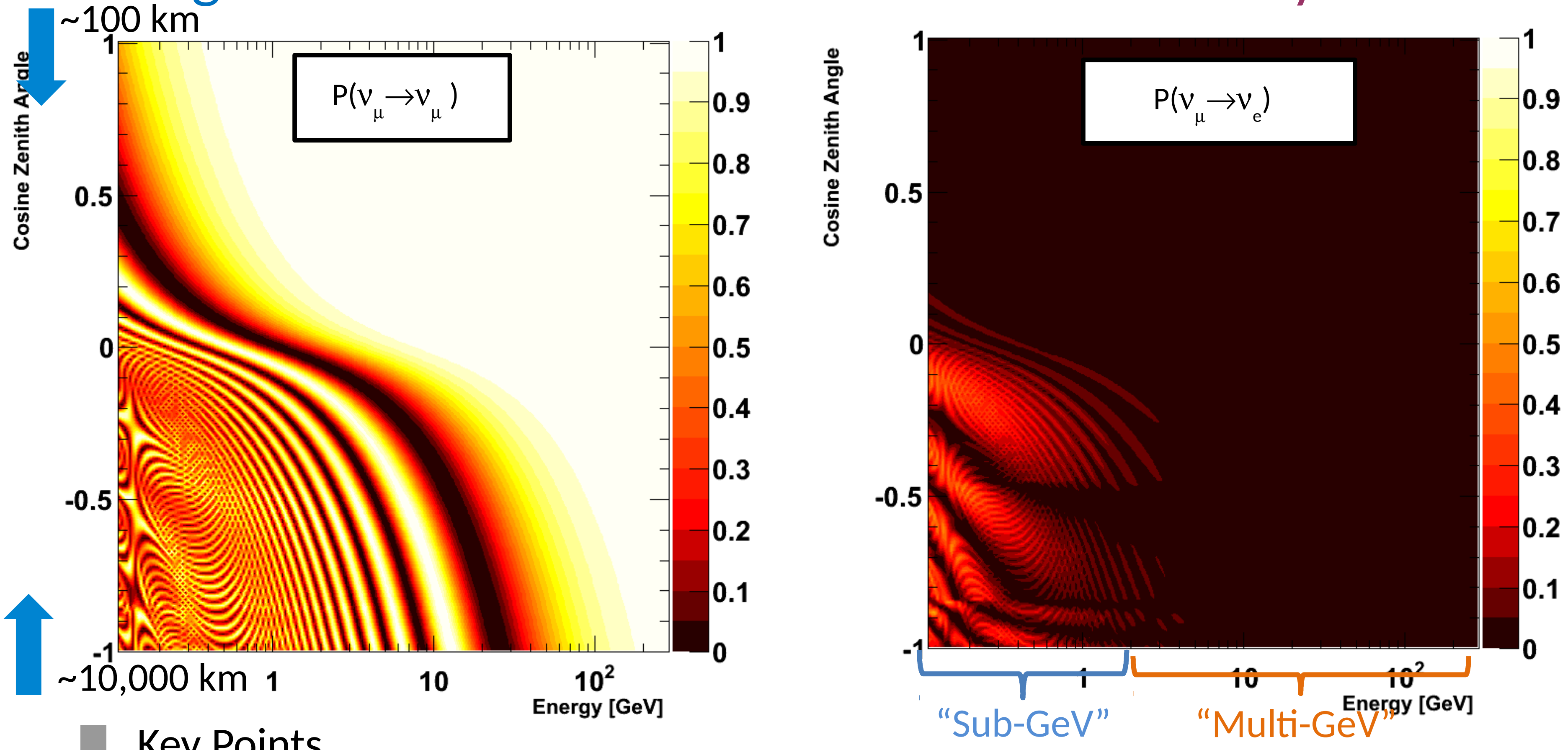




Ratio to two-flavor oscillations

Appearance effects are halved in the IH

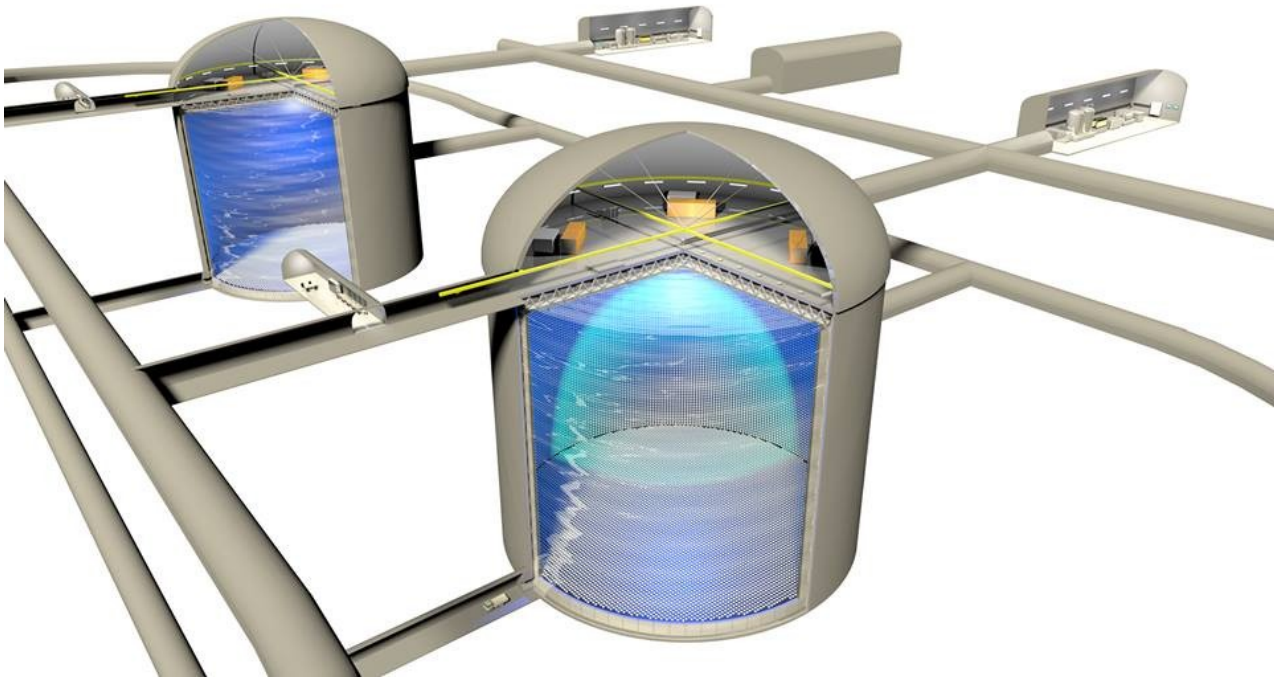
Searching for Three-Flavor Effects: Inverted Hierarchy



- Key Points
  - No $\nu_\mu \to \nu_e$ 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

Hyper-Kamiokande's Sensitivity to δcp

Hyper-Kamiokande: Introduction

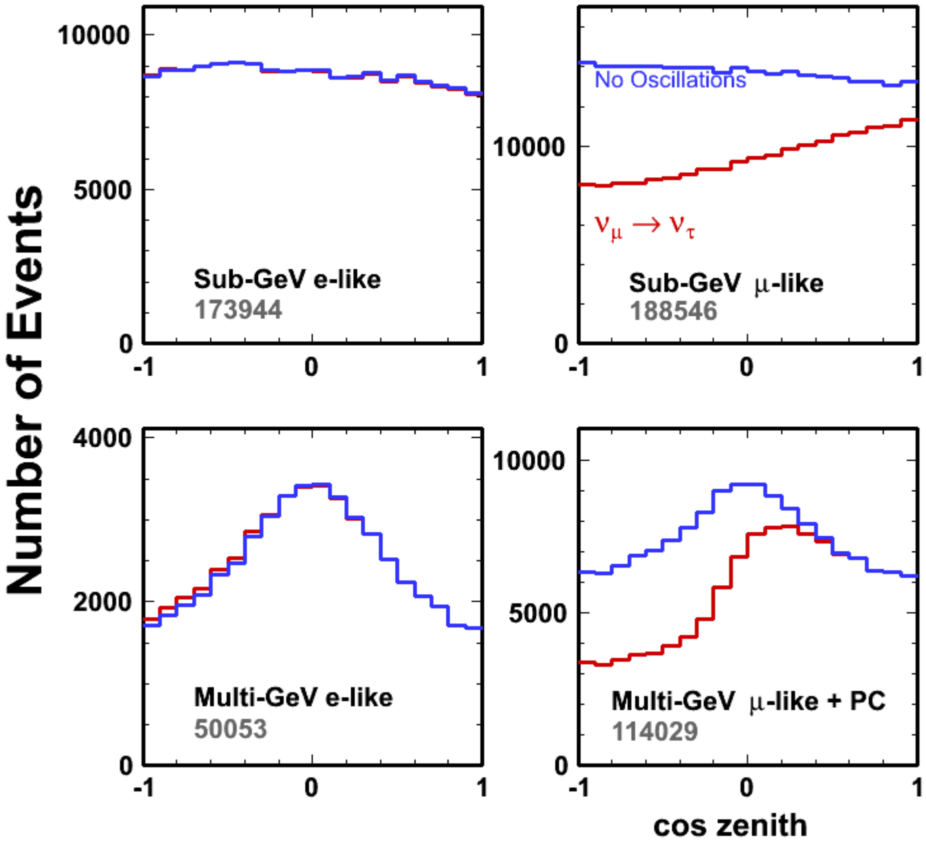


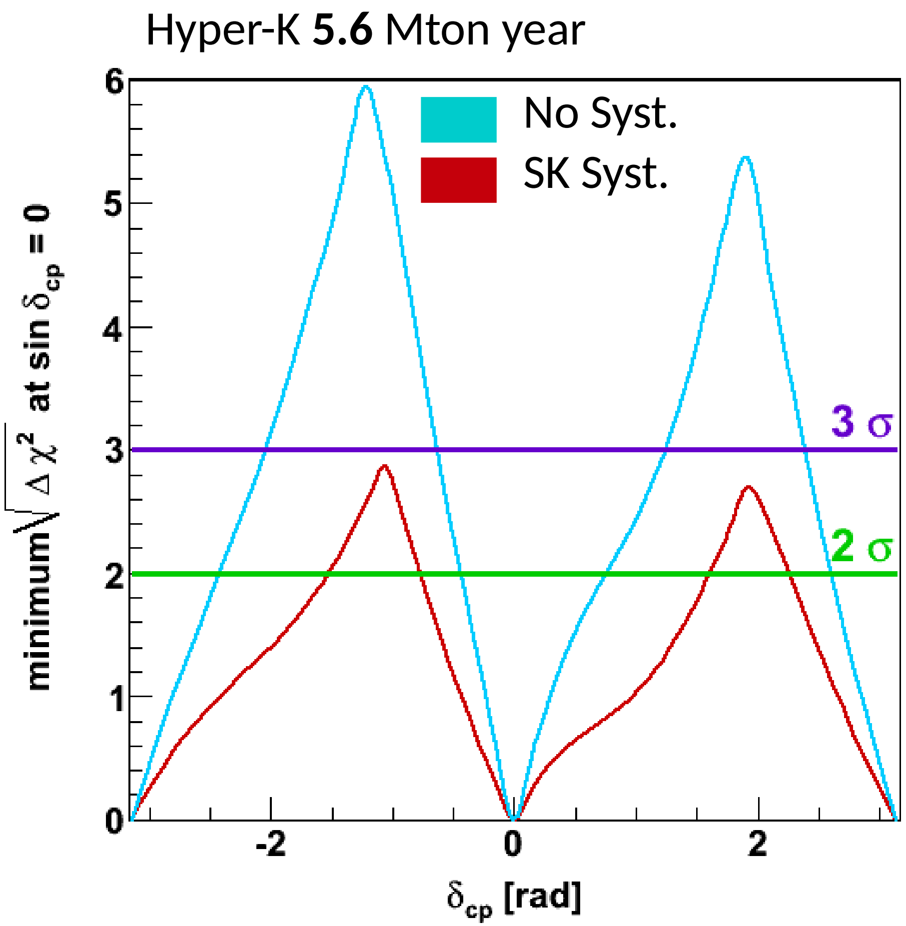
apfit

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 not yet been included
- Similarly no extrapolation of flux and cross section systematics

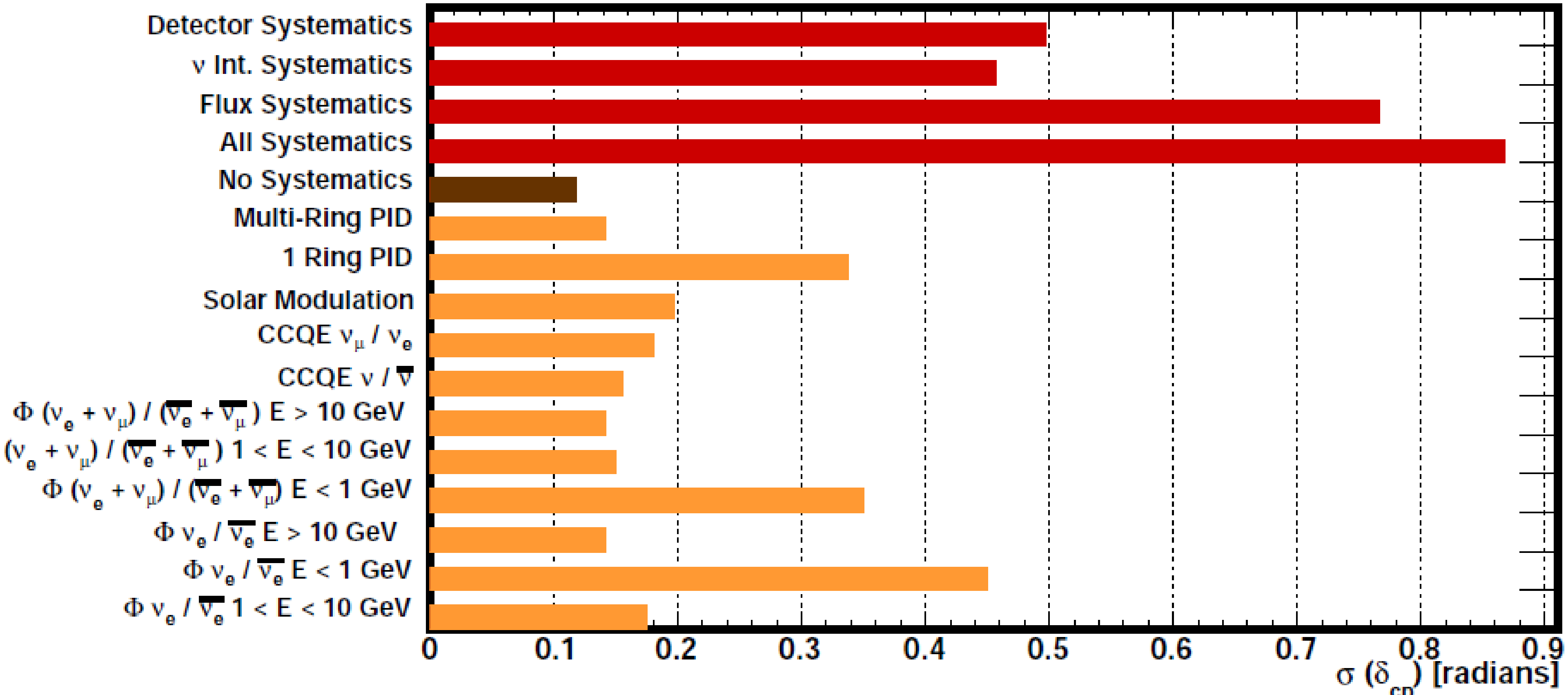
Hyper-K: CP Violation Sensitivity





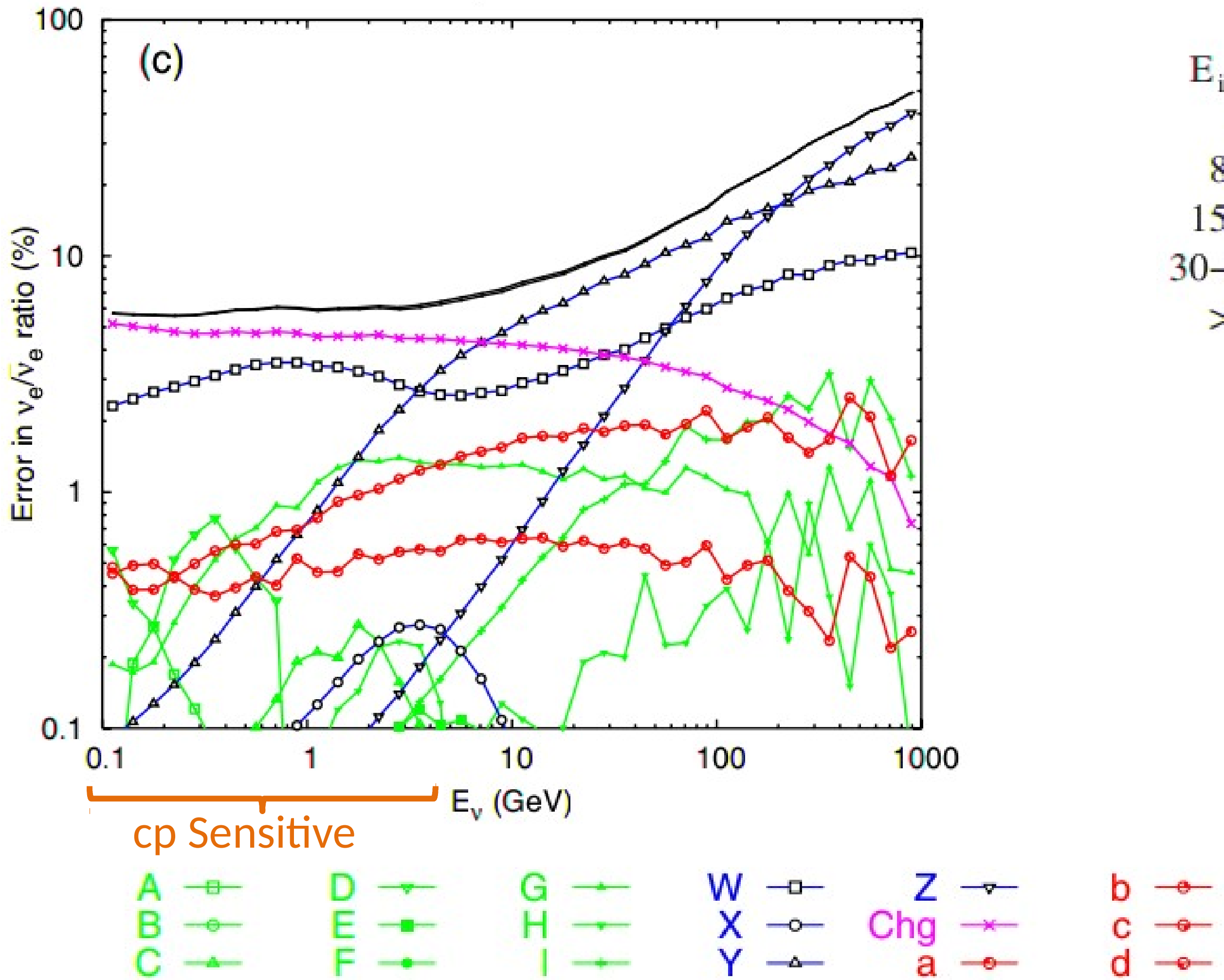
- Despite ample statistics in sensitive samples, limited sensitivity to CP-violation with atmospheric ν alone
- Impact of systematic errors is large
  - Poor angular resolution of low energy neutrinos also problematic

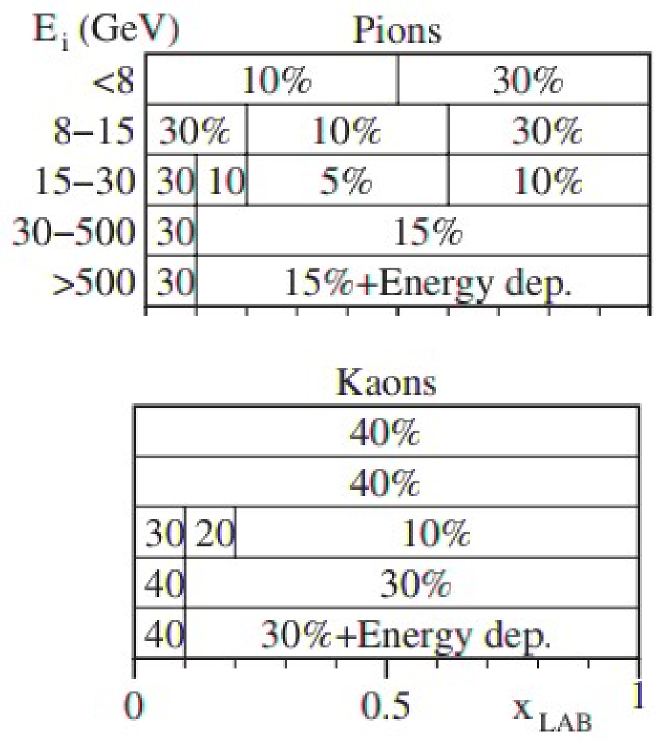
Hyper-K's Sensitivity to δ_{cp} with Atmospheric neutrinos



- 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
- Note that the detector performance also becomes important
  - Single ring mis-PID uncertainty is 1~2% below 1330 MeV

Systematic Error's In the Bartol Flux Model :



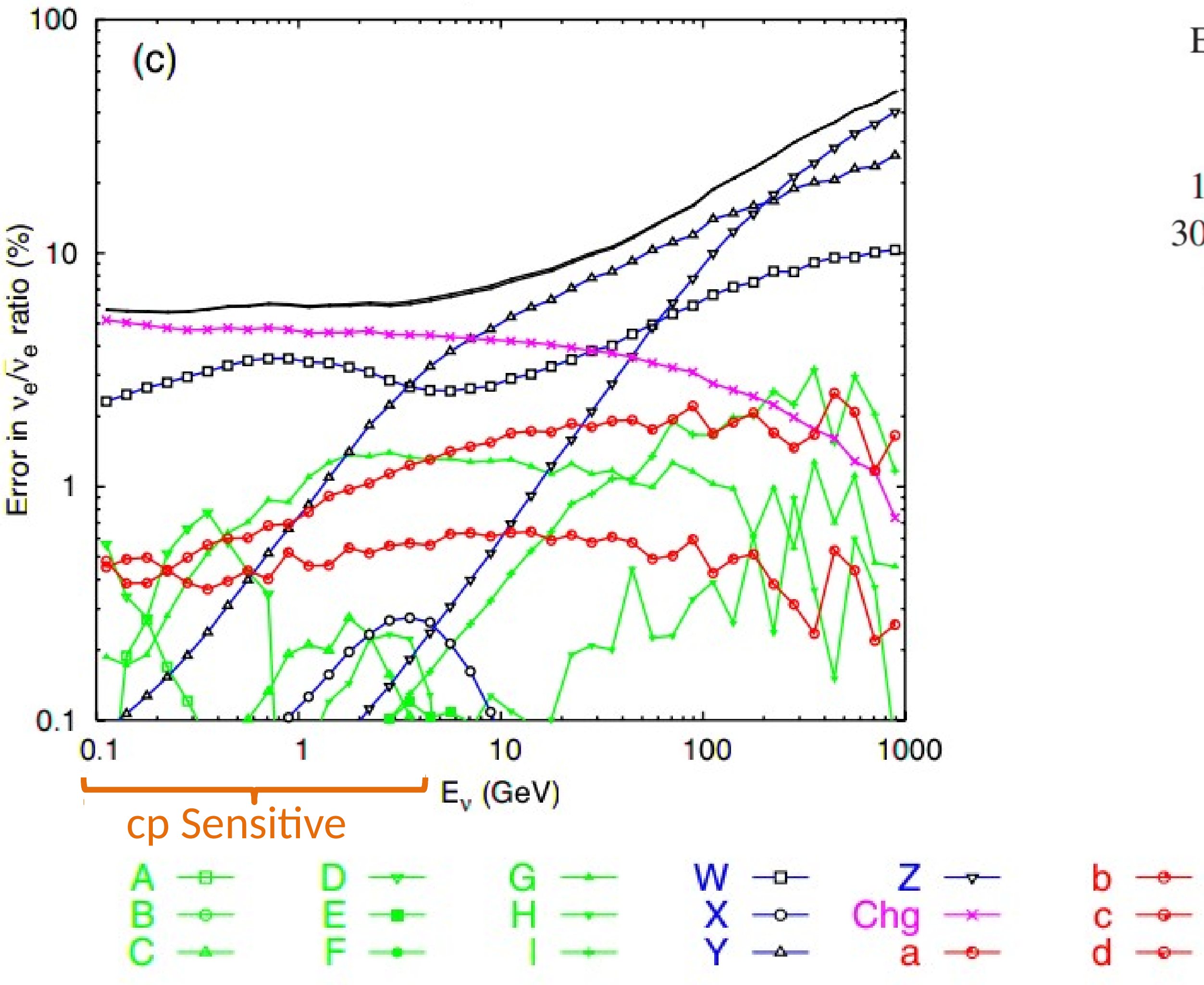


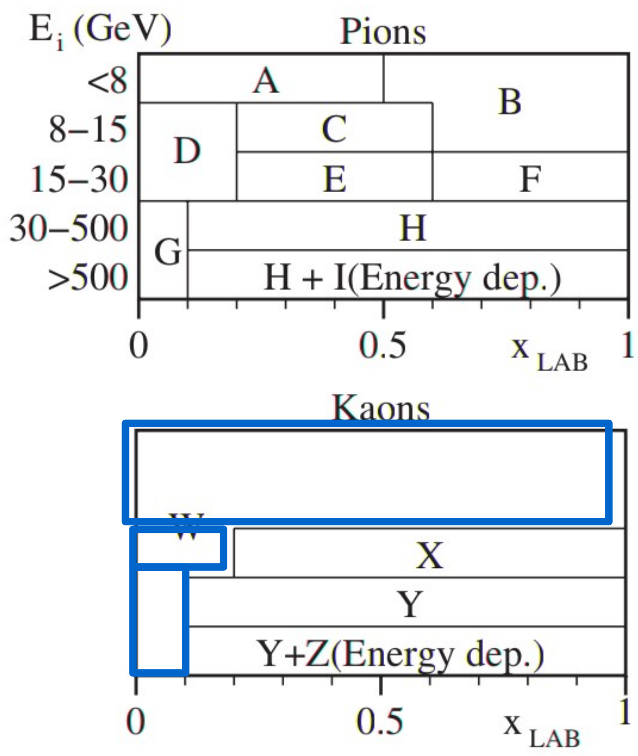
E_i : $E_{primary}$

x_{LAB} : $E_{secondary}$ / E_i

- At low energies the uncertainty is dominated
  - Kaon production uncertainty at modest projectile energies (Ei)
  - Uncertainty in the charged pion ratio uncertainty

Systematic Error's In the Bartol Flux Model :



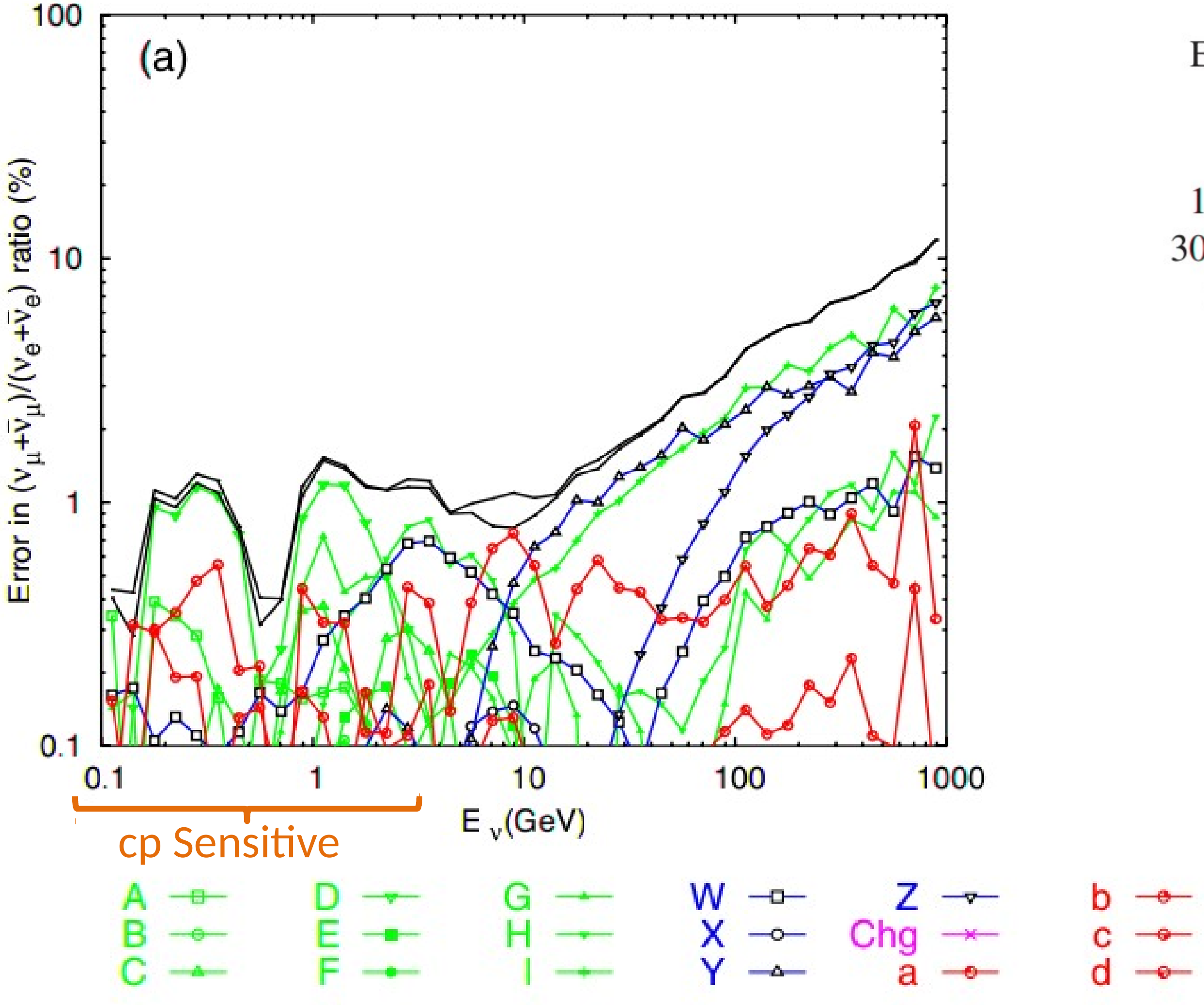


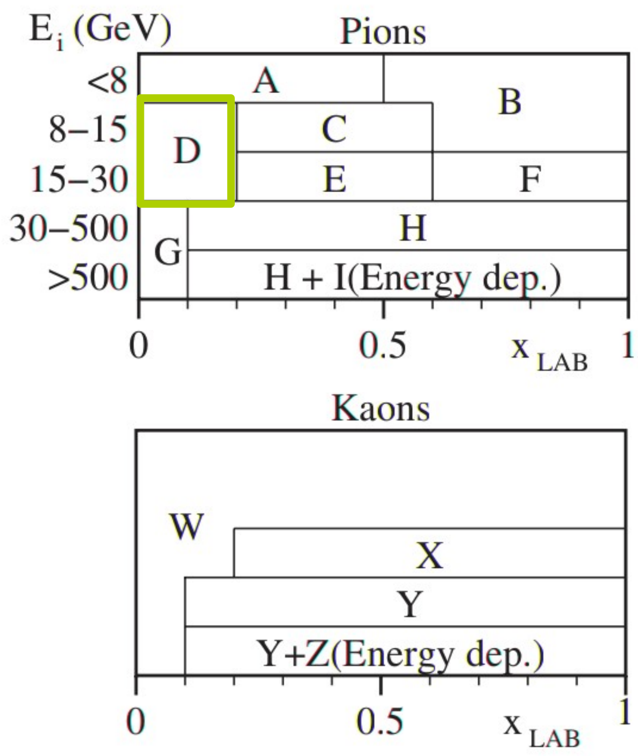
E_i : $E_{primary}$

x_{LAB} : $E_{secondary} / E_i$

- At low energies the uncertainty is dominated
  - Kaon production uncertainty at modest projectile energies (Ei)
  - Uncertainty in the charged pion ratio uncertainty

Systematic Error's In the Bartol Flux Model :



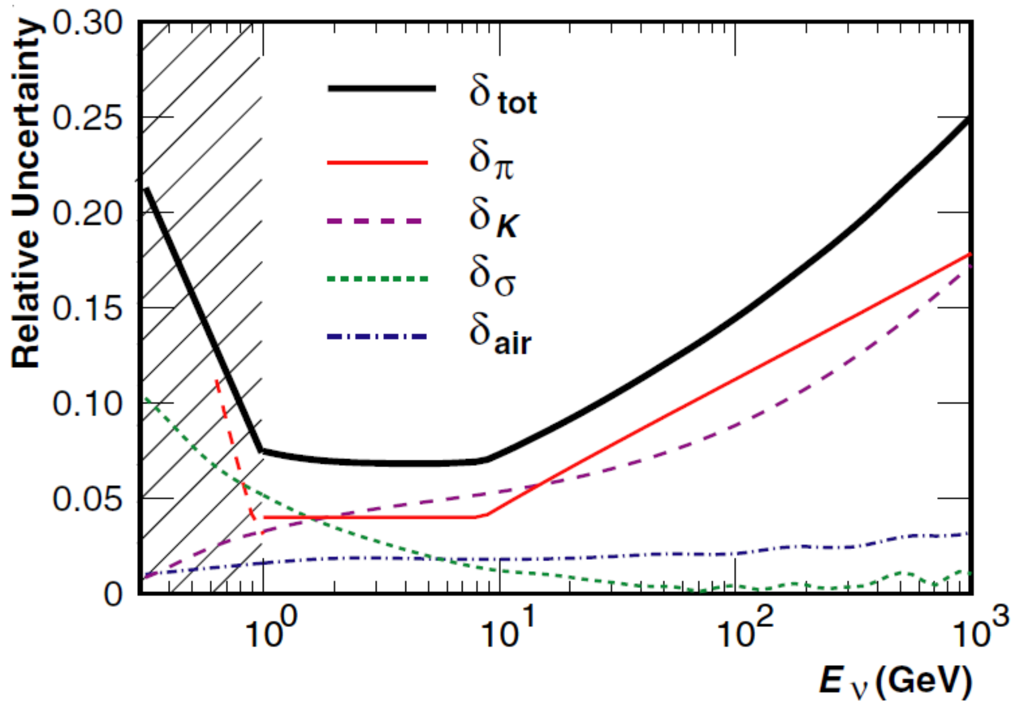


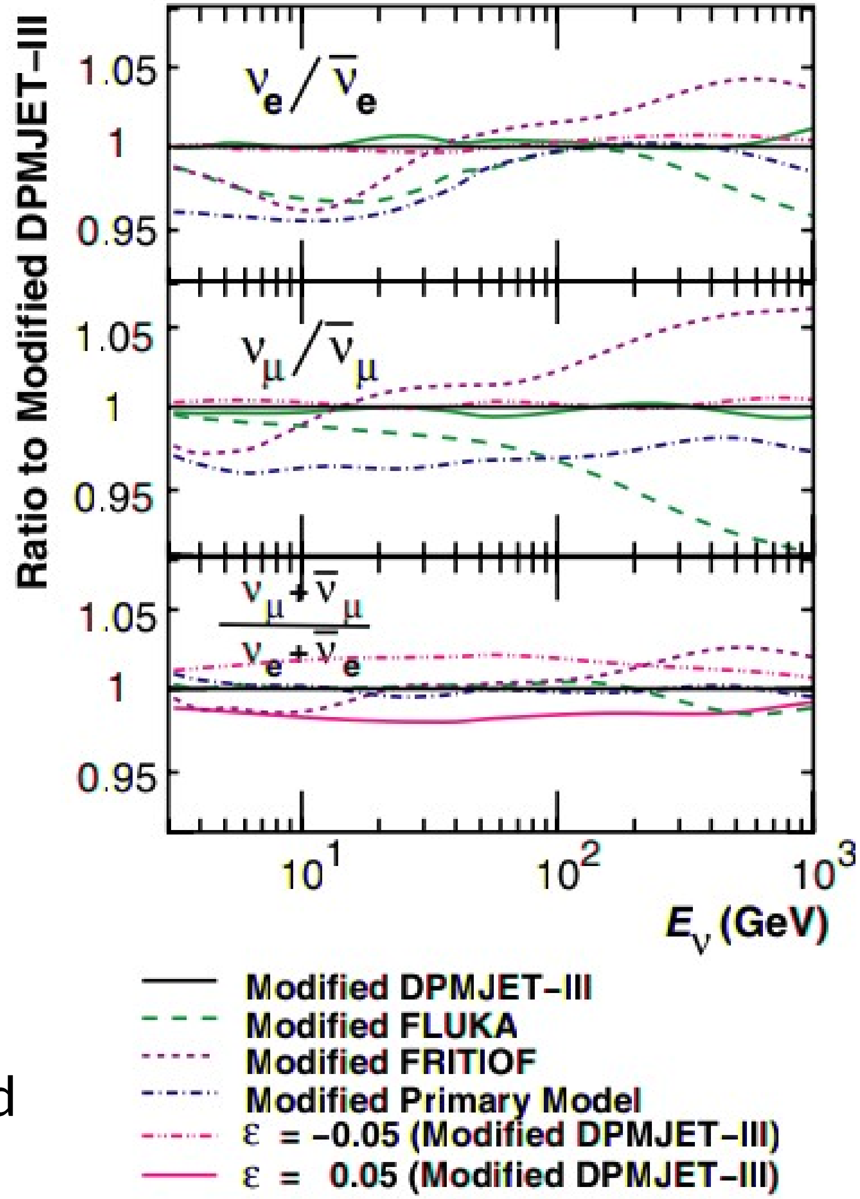
E_i : $E_{primary}$

x_{LAB} : $E_{secondary}$ / E_i

- At low energies the uncertainty is dominated
  - Pion production at low energies **D**: 10-30%
- Better cancellation of systematics

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

Higher Energy Neutrinos

Sterile Neutrino Oscillations in Atmospheric Neutrinos

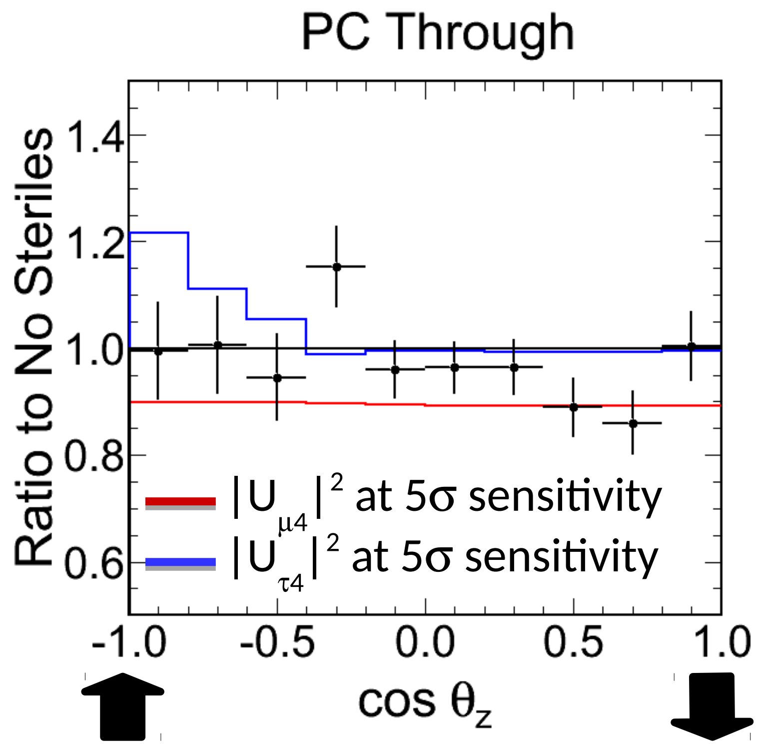
- Sterile Neutrino searches at SK are independent of the sterile Δm^2 and the number sterile neutrinos
  - 3+1 and 3+N models have the same signatures in atmospheric neutrinos
  - For $\Delta m_s^2 \sim 1$ eV^2 oscillations appear fast:

    $< \sin^2 \Delta m^2 L/E > \sim 0.5$

MNS Sterile

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

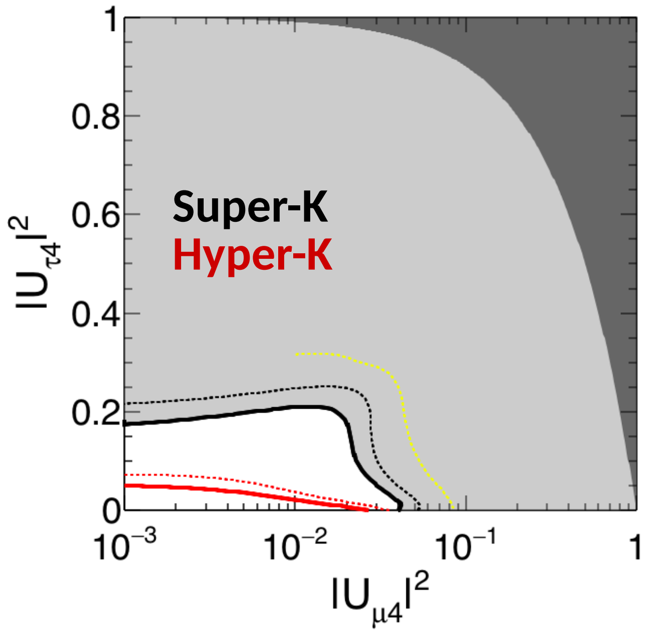
- $| U_{\mu 4} |^2$
  - Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $| U_{\tau 4} |^2$
  - Shape distortion of angular distribution of higher energy μ-like data



Hyper-K's sensitivity to Sterile Neutrino Mixing

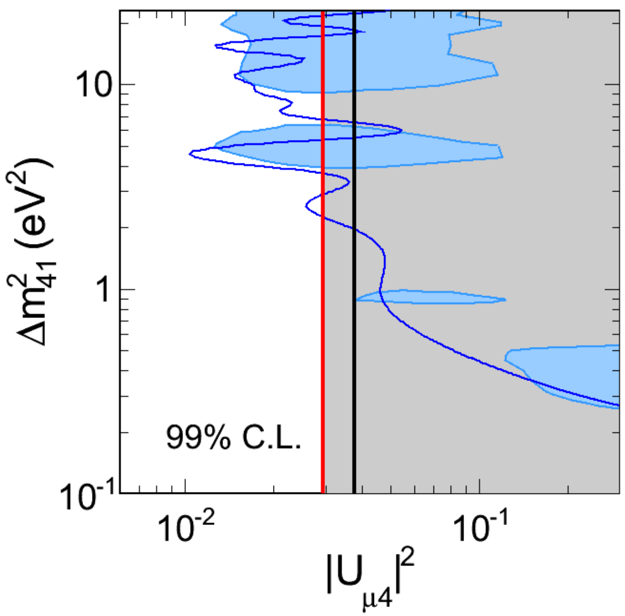
- Sensitivity gains are limited by
  - flux and cross section errors
  - Better knowledge during actual hyper-K running can improve these constraints

	Hyper-K	SK-IV
$\lvert U_{\mu 4}\rvert^2$	**0.029**	0.038
$\lvert U_{\tau 4}\rvert^2$	**0.066**	0.164

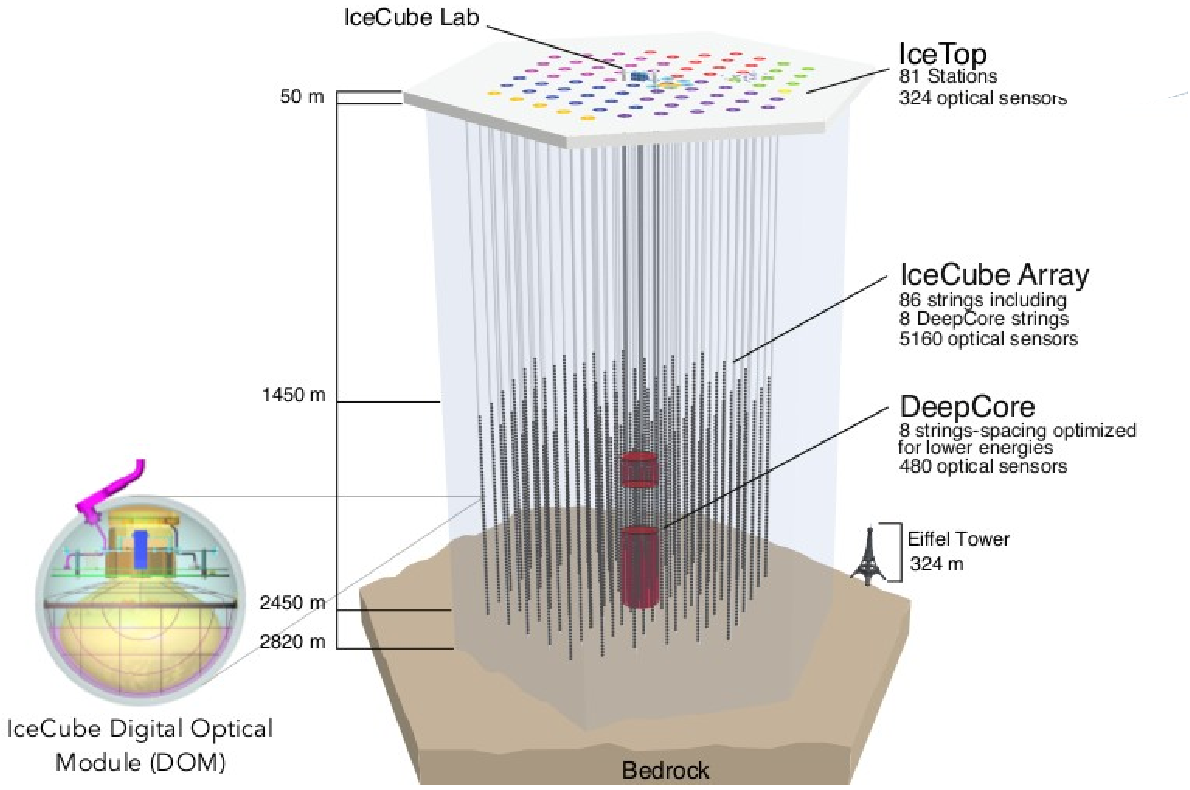


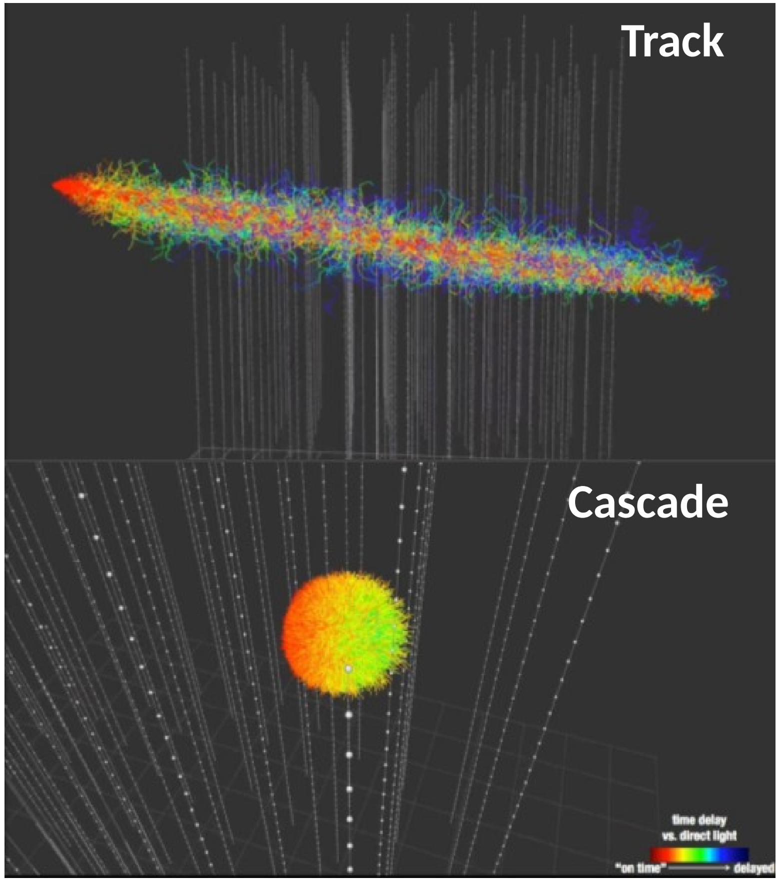
- Sensitivity to Um4 depends on understanding of muon rate in the detector
  - Absolute flux uncertainty is large
  - Constraint is achieved by coupling to νe flux, but limited by uncertainty in the ratio

Systematic uncertainty	No steriles (σ)	Best fit (σ)
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, < 1 GeV	−0.49	−0.13
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$, 1–10 GeV	−0.50	−0.09
CCQE ν_μ/ν_e	0.36	0.01



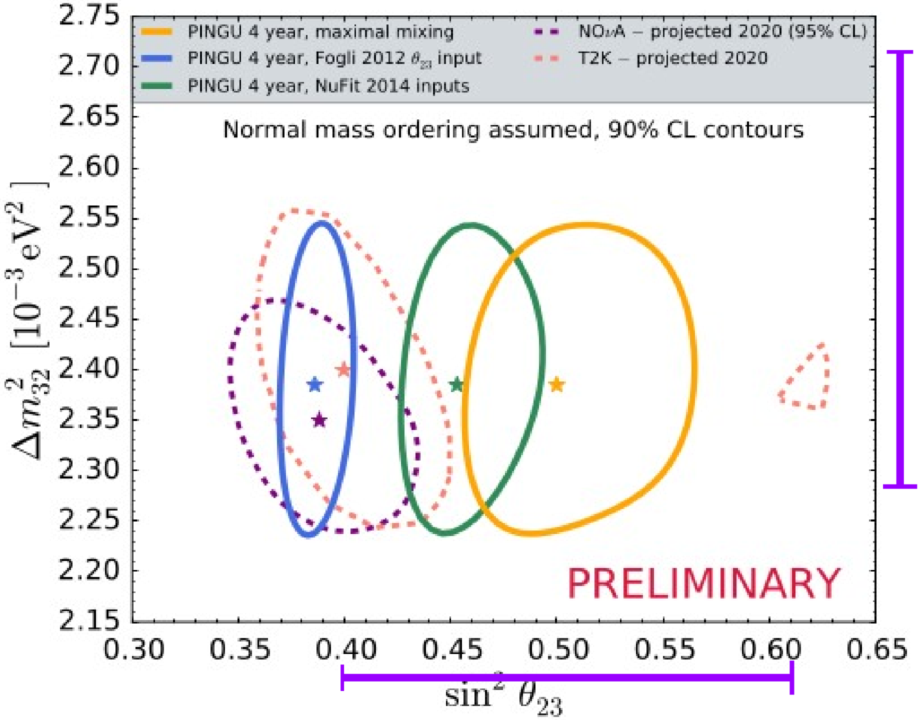
What about other atmospheric neutrino experiments?

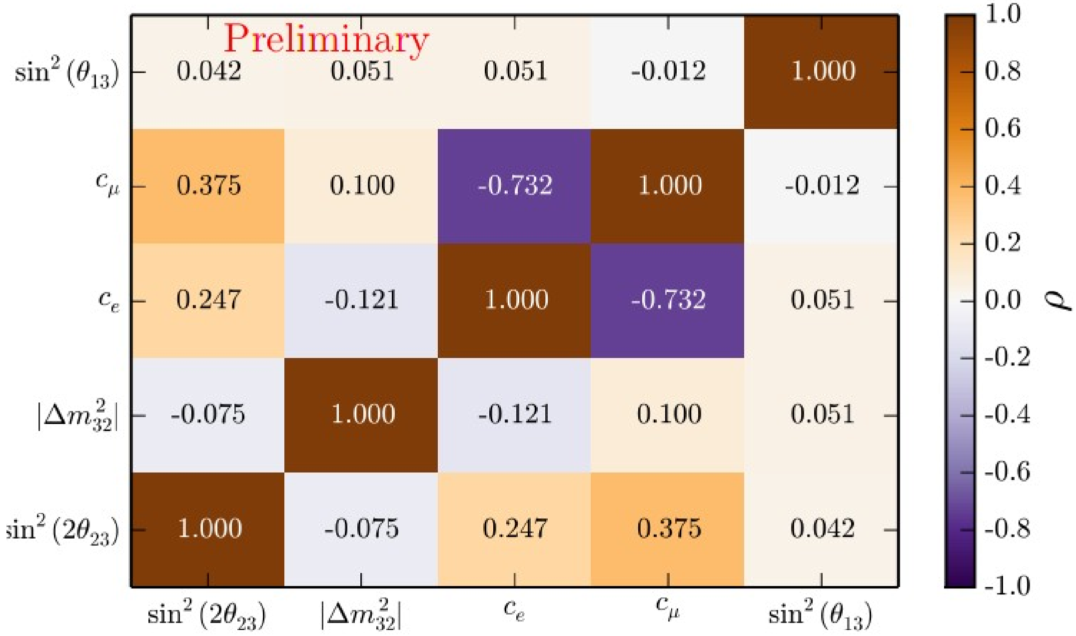




- Use IceCube/DeepCore/PINGU as a proxy for all neutrino telescopes
- Tracks ($\nu\mu$) – good pointing, and good energy resolution if contained
- Cascades – poor pointing, good energy resolution, PID is marginal
  - DeepCore ~ 40% CC $\nu\mu$

PINGU: What About Atmospheric Mixing Parameters?

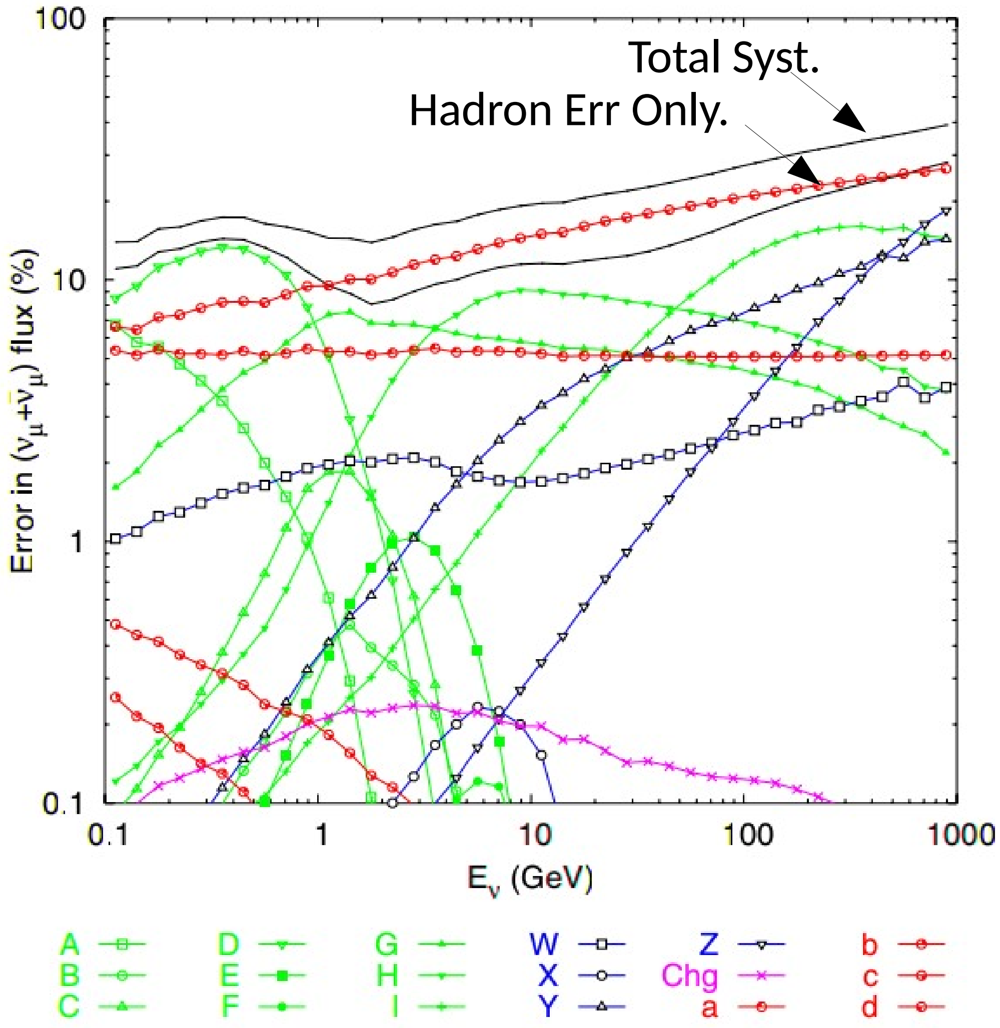


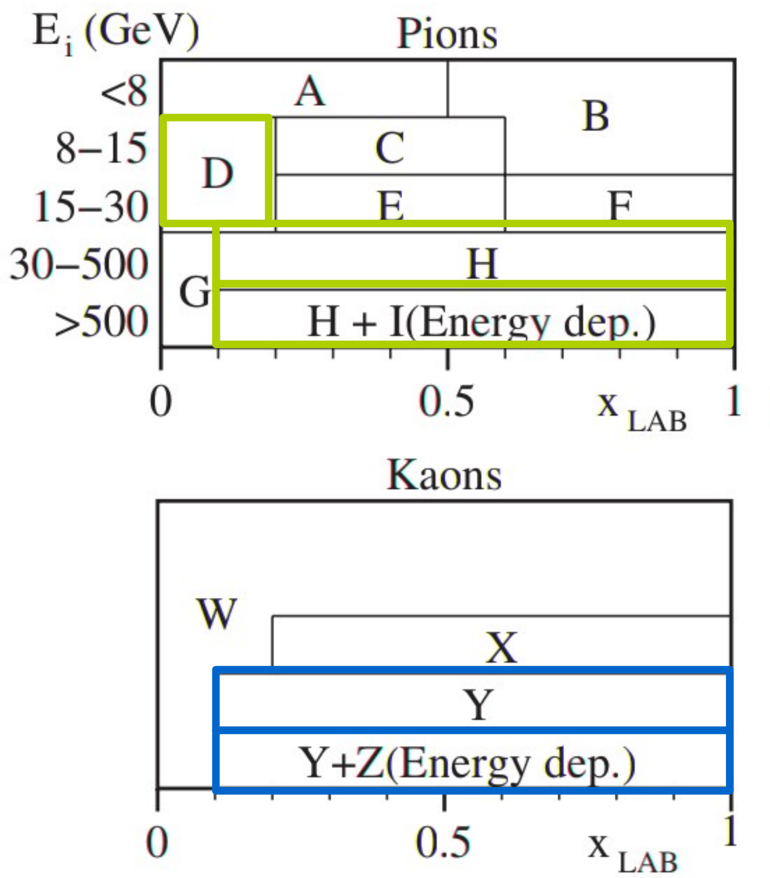


- Absolute flux uncertainty more of an issue for PINGU/DeepCore IceCube due (ostensibly) to inability to simultaneously constrain nm and ne fluxes
  - “Cascade” sample is a mixture of CC ne, CC nt, and NC events

- (2014 disappearance result was most effected by normalizion of the horizontal flux - pull: 1σ)

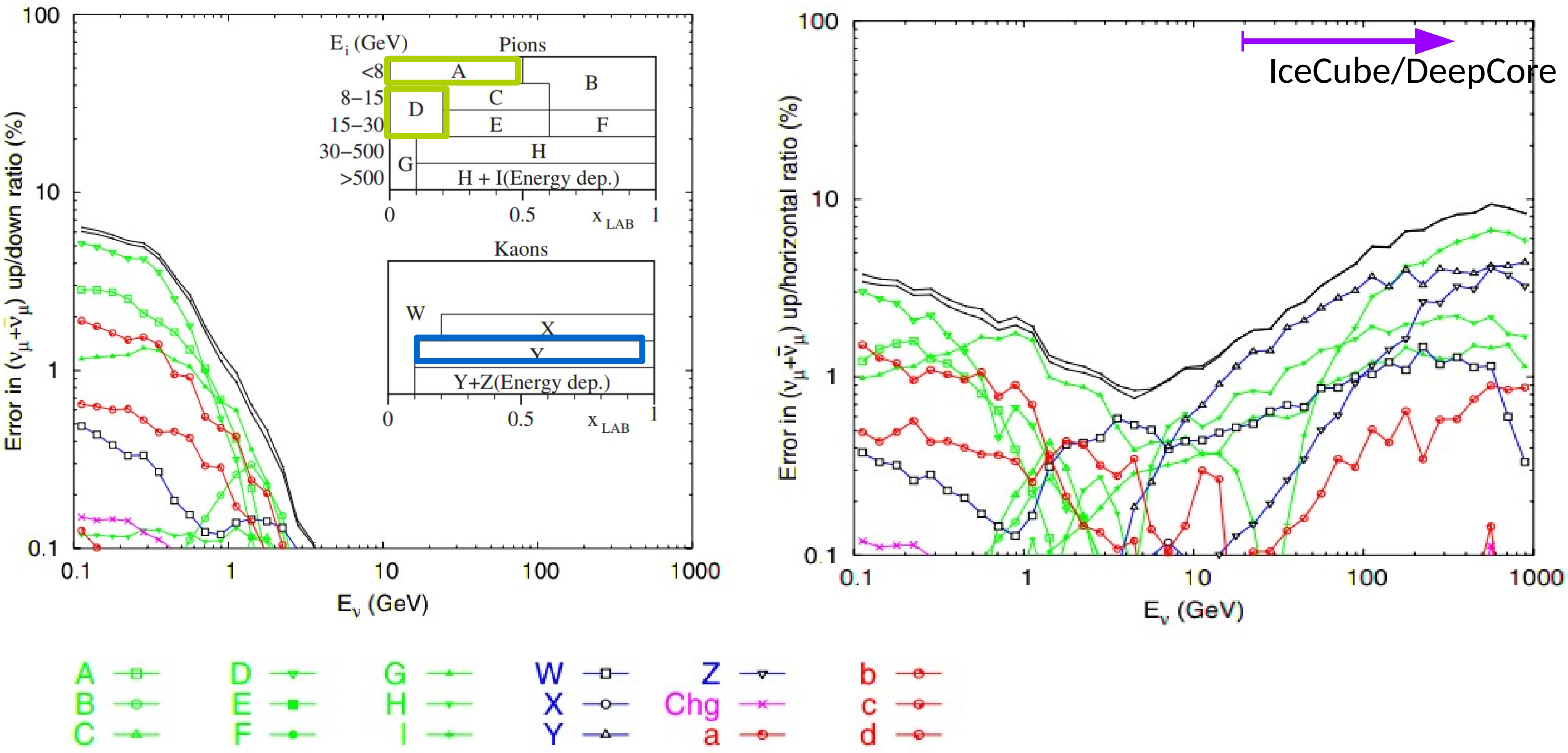
Systematic Error's In the Bartol Flux Model :





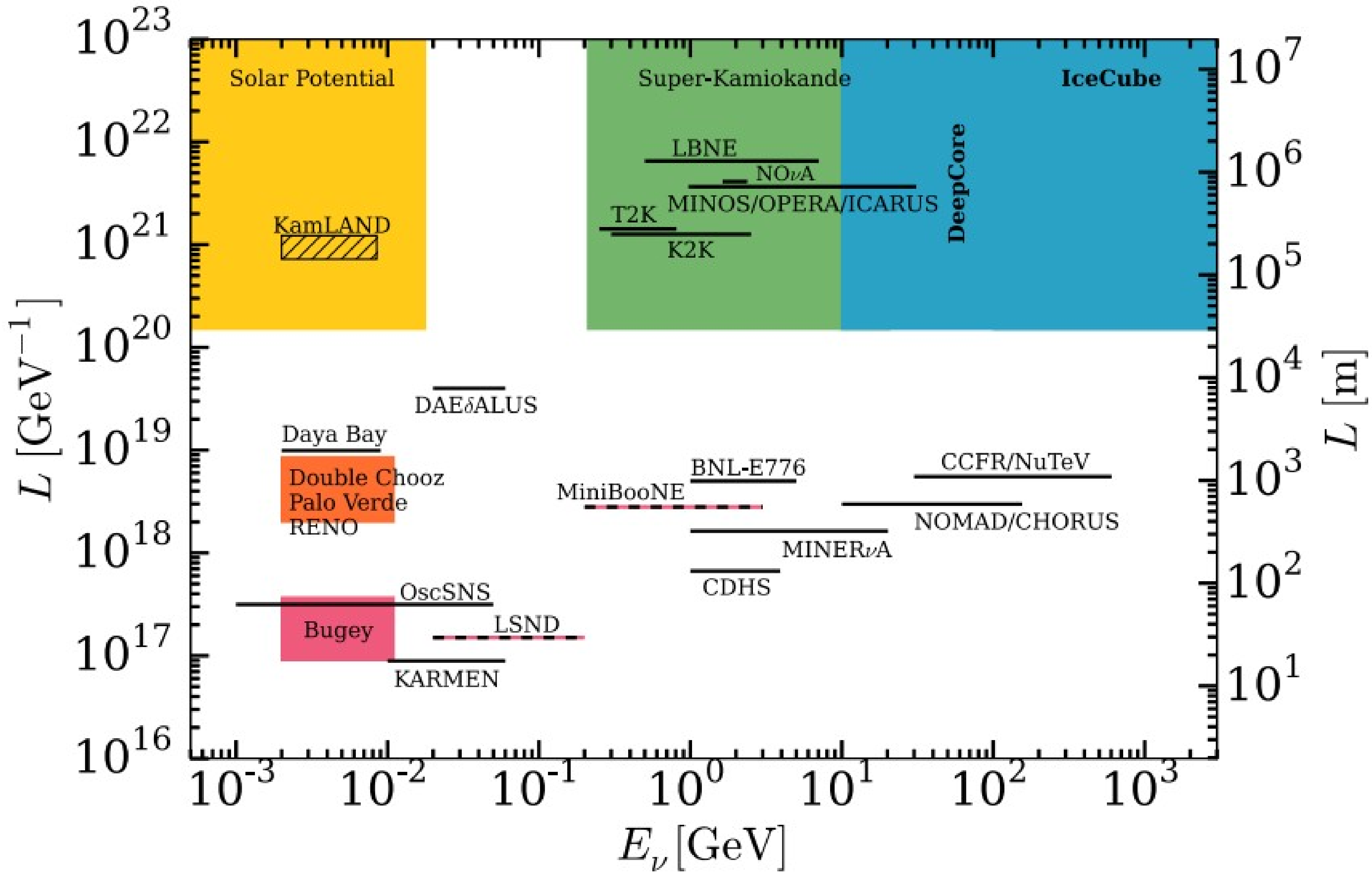
- Uncertainty is dominated by
  - At low energies: pion production at low energies D: 10-30%
  - Mid-to-high energies H: 15%
  - Highest energies kaons from Y, Z : 30%

Systematic Error's In the Bartol Flux Model :



- Octant measurement for a SK-like detector can be improved with better constraints from regions “A” and “D”, (Pions)
- Large cherenkove telescopes benefit from measurements around “Y” (Kaons)

Comments

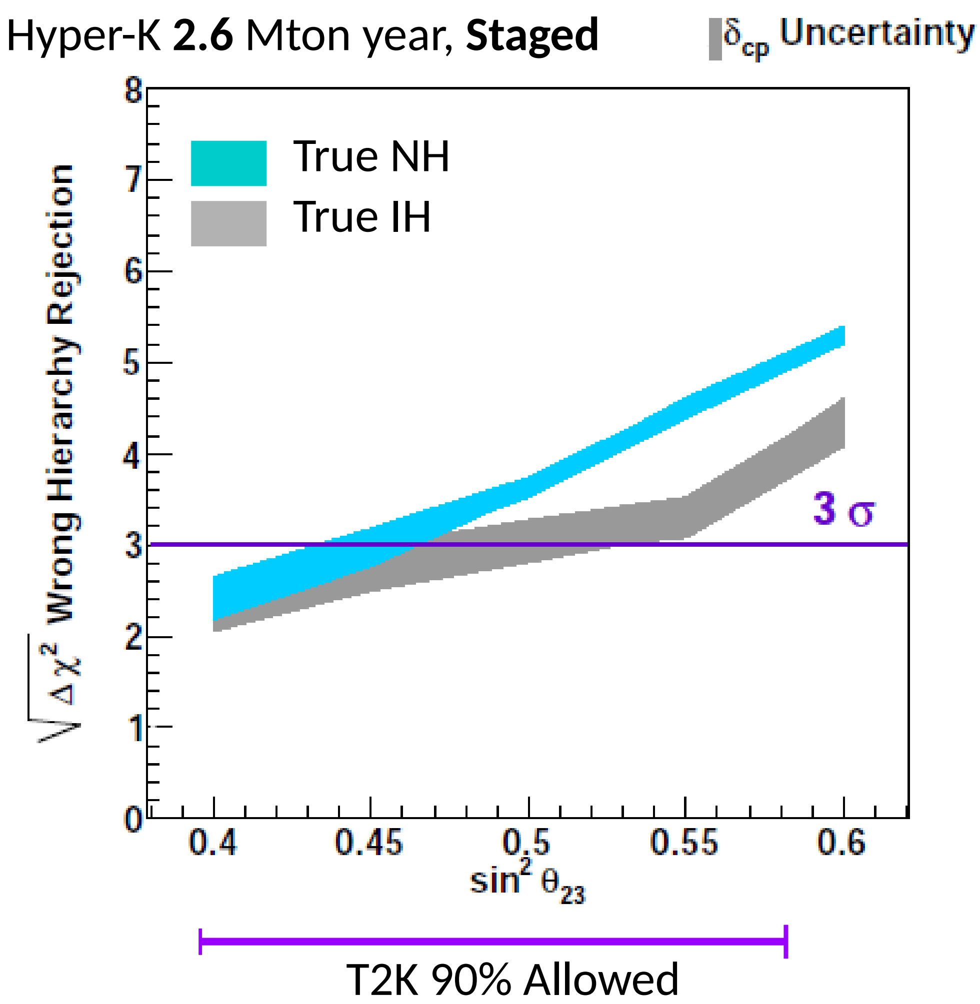


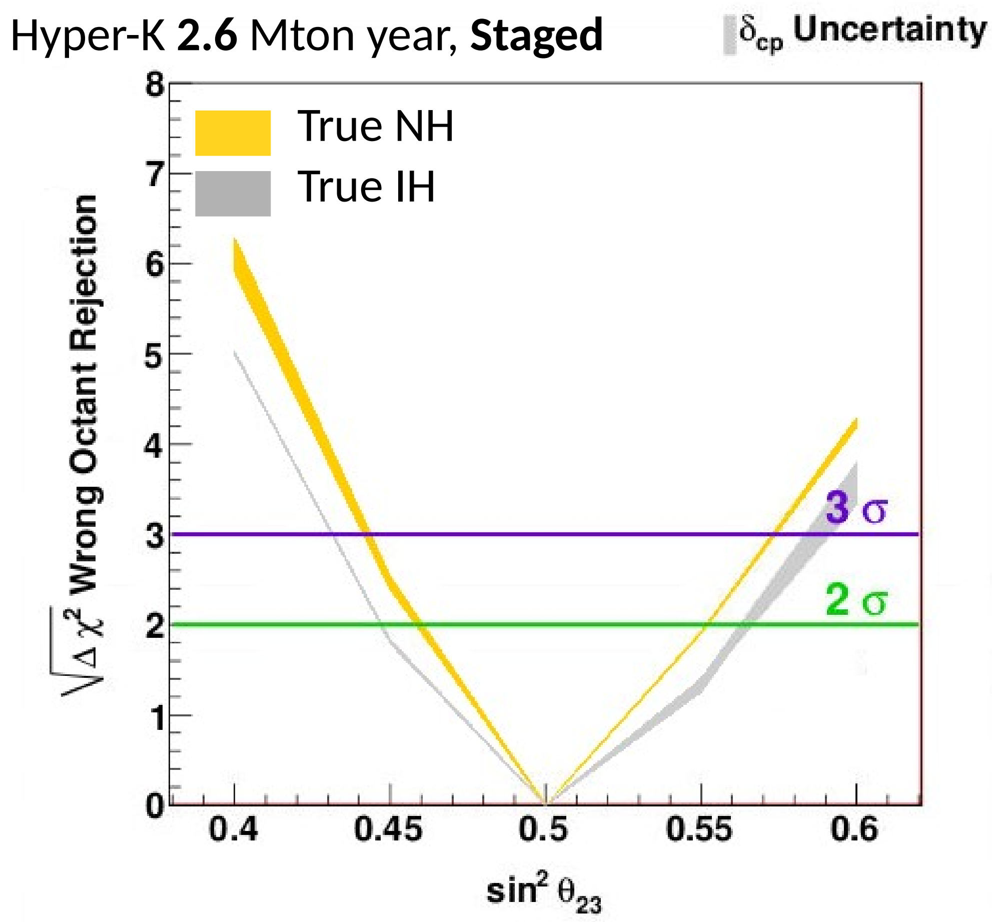
Solar Potential
KamLAND
Super-Kamiokande
IceCube
DeepCore
LBNE
NOνA
MINOS/OPERA/ICARUS
T2K
K2K
DAEδALUS
Daya Bay
Double Chooz
Palo Verde
RENO
MiniBooNE
BNL-E776
CCFR/NuTeV
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
Bugey
LSND
KARMEN
$L\ [\mathrm{GeV}^{-1}]$
$L\ [\mathrm{m}]$
$E_\nu\ [\mathrm{GeV}]$
10^{23} 10^{22} 10^{21} 10^{20} 10^{19} 10^{18} 10^{17} 10^{16}
10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1}
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}

Sensitivity to the Neutrino Mass Hierarchy:

Recall: separation of neutrinos and antineutrinos is essential

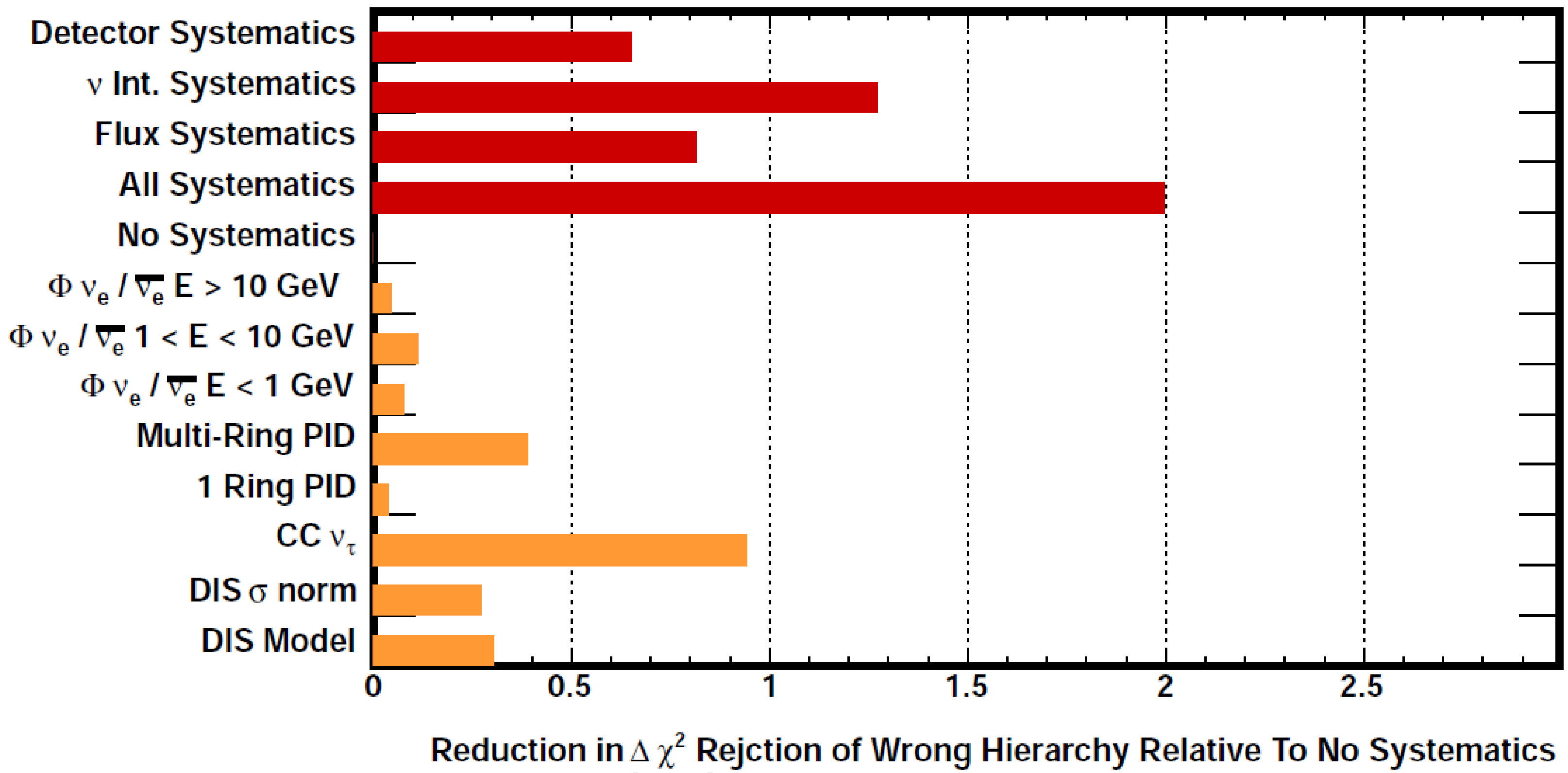
Hyper-K Sensitivity 10 Years, Staging Scenario





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

Systematic Effect on Hierarchy Sensitivity at Super-K



- Largest uncertainties are stat. and other oscillation parameters
- Sensitivity to the hierarchy is largely affected by uncertainties interaction of high energy neutrinos
  - particularly the CC ντ background component
- The situation is compounded at Hyper-K

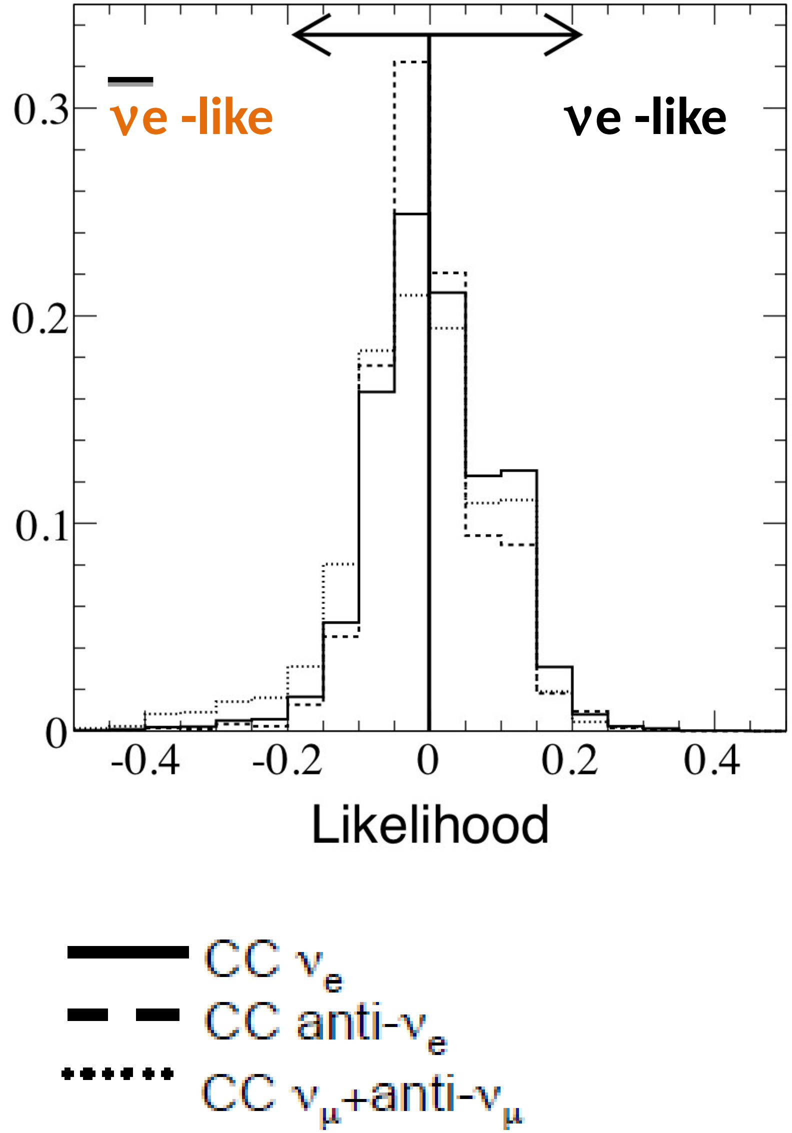
Δχ2, θ23	0.40	0.60
No Syst.	0.81	4.7
Full Syst.	0.59	2.7

- Hadron production has an indirect effect on these measurements

Super-K (Hyper-K) Analysis Samples

Sample	Energy bins	$\cos\theta_z$ bins	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	CC ν_τ	NC
Fully Contained (FC) Sub-GeV							
e-like, Single-ring							
0 decay-e	5 $e^\pm$ momentum	10 in $[-1, 1]$	0.717	0.248	0.002	0.000	0.033
1 decay-e	5 $e^\pm$ momentum		0.805	0.019	0.108	0.001	0.067
μ-like, Single-ring							
0 decay-e	5 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.041	0.013	0.759	0.001	0.186
1 decay-e	5 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.001	0.000	0.972	0.000	0.026
2 decay-e	5 $\mu^\pm$ momentum		0.000	0.000	0.979	0.001	0.019
π^0-like							
Single-ring	5 $e^\pm$ momentum		0.096	0.033	0.015	0.000	0.856
Two-ring	5 π^0 momentum		0.067	0.025	0.011	0.000	0.897
Fully Contained (FC) Multi-GeV							
Single-ring							
ν_e-like	4 $e^\pm$ momentum	10 in $[-1, 1]$	0.621	0.090	0.100	0.033	0.156
$\bar{\nu}_e$-like	4 $e^\pm$ momentum	10 in $[-1, 1]$	0.546	0.372	0.009	0.010	0.063
μ-like	2 $\mu^\pm$ momentum	10 in $[-1, 1]$	0.003	0.001	0.992	0.003	0.002
Multi-ring							
ν_e-like	3 visible energy	10 in $[-1, 1]$	0.557	0.103	0.117	0.040	0.184
$\bar{\nu}_e$-like	3 visible energy	10 in $[-1, 1]$	0.531	0.270	0.041	0.023	0.136
μ-like	4 visible energy	10 in $[-1, 1]$	0.027	0.004	0.913	0.005	0.051
Other	4 visible energy	10 in $[-1, 1]$	0.275	0.029	0.348	0.049	0.299

SK Sample Selection : Multi-GeV Multi-Ring anti-νe and νe -like

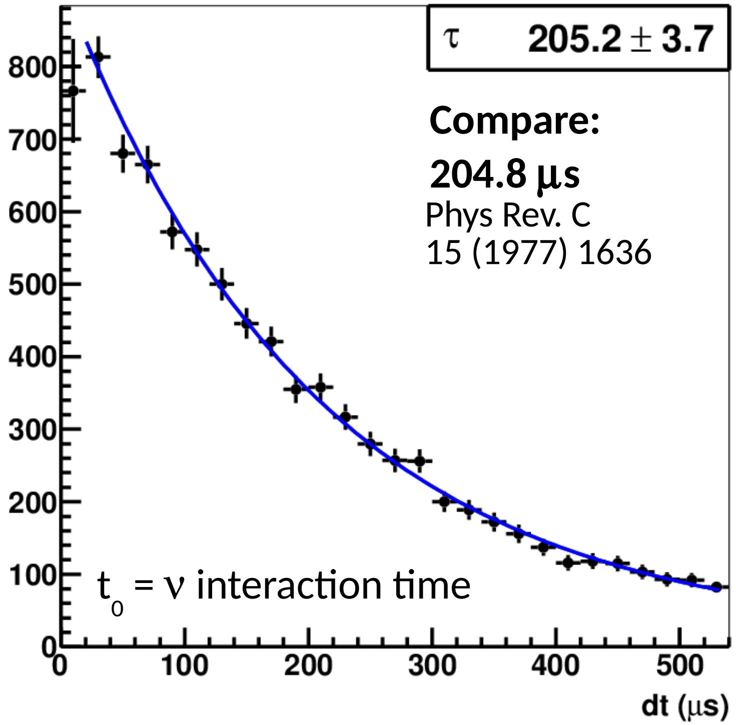


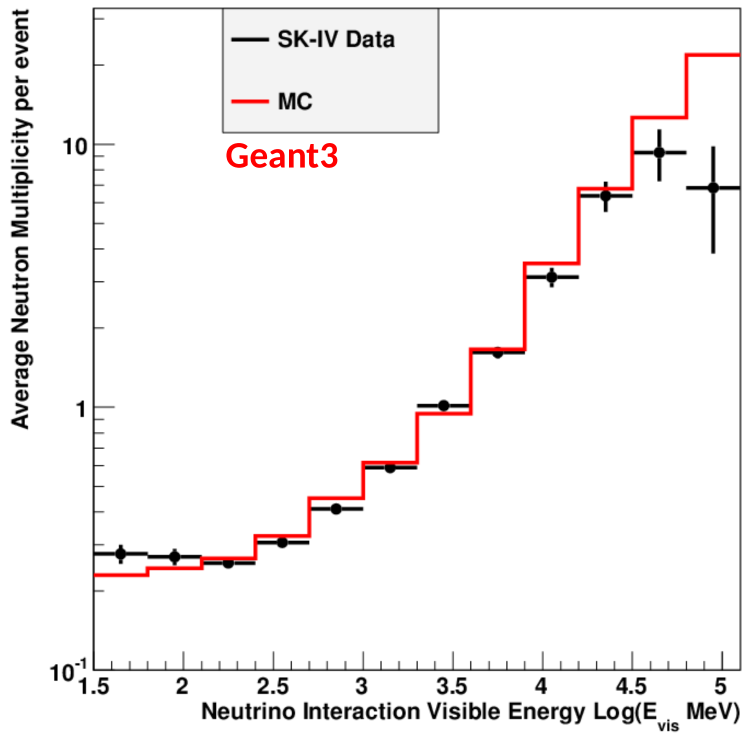
- Multi-ring events are complicated
  - Many outgoing particles from DIS or multi-π interactions
  - Plus their subsequent interactions
- Likelihood function built on four variables
  - Number of decay electrons
  - Number of Cherenkov rings found
  - Transverse momentum
- Essentially counting number of charged pions (+lepton)

Variable	CC ne	CC anti-ne
N Rings	More	Fewer
N Decay e	More	Fewer
Transverse P	Larger	Smaller

Neutron Tagging

Preliminary

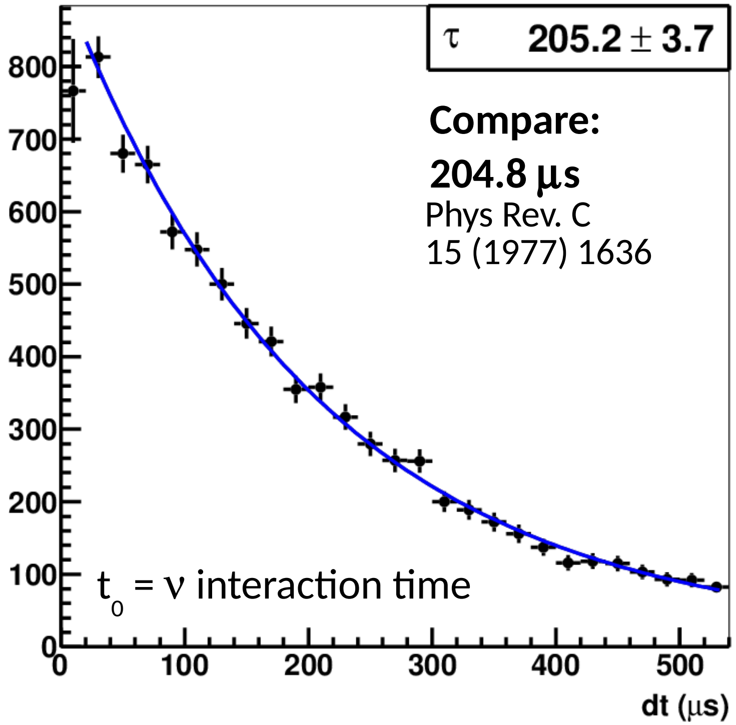




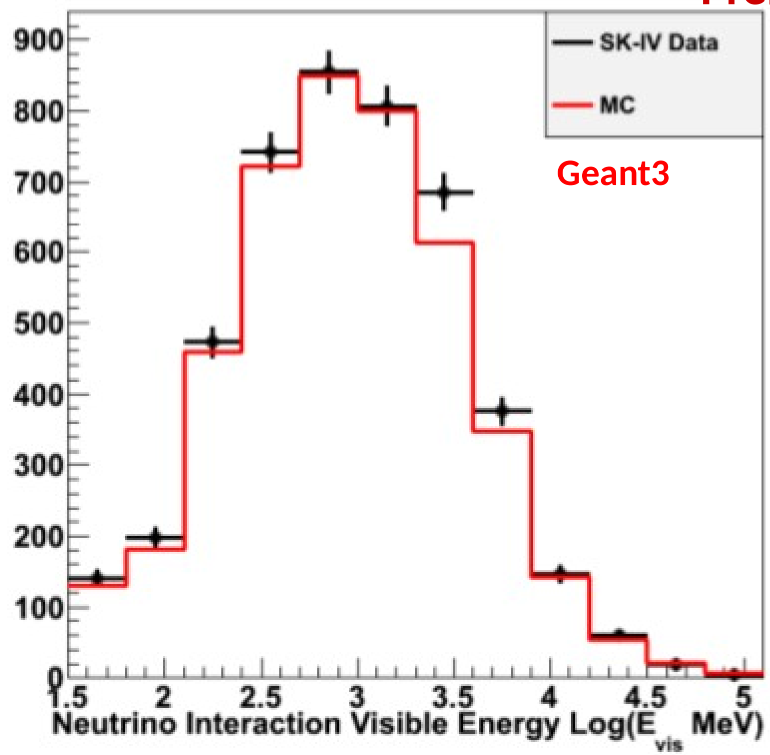
- Upgraded detector electronics in SK-IV store all PMT hits in a 500 μsec window after a physics trigger
  - Search for the 2.2 MeV gamma from p(n,γ)d
- Search is performed using a neural network built from 16 variables
  - Data and MC show good agreement on atmospheric neutrino sample
- **Future**: Implement neutron tagging to help distinguish $\nu/\bar{\nu}$ interactions and to reduce proton decay backgrounds

2.2 MeV γ Selection	
Efficiency	**20.5%**
Background / Event	**0.018**

Neutron Tagging



Preliminary



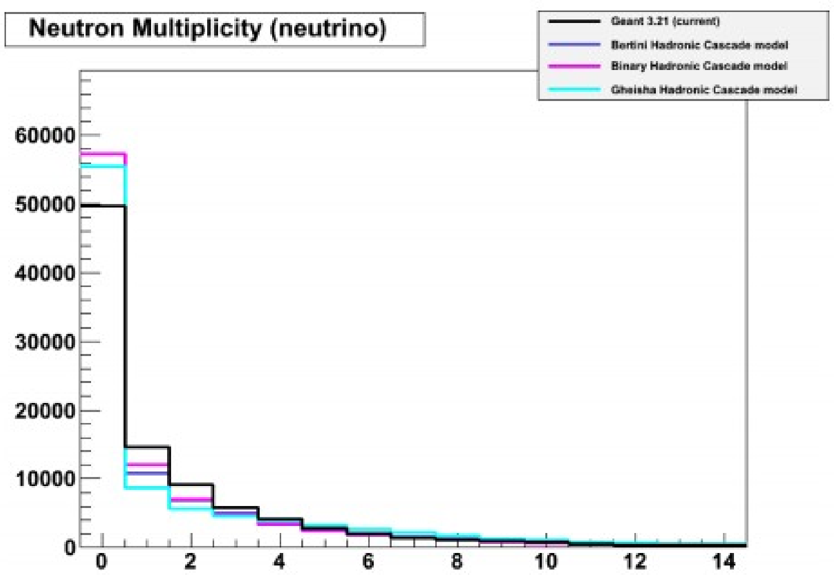
- Upgraded detector electronics in SK-IV store all PMT hits in a 500 μsec window after a physics trigger
  - Search for the 2.2 MeV gamma from p(n,γ)d
- Search is performed using a neural network built from 16 variables
  - Data and MC show good agreement on atmospheric neutrino sample
- **Future**: Implement neutron tagging to help distinguish $\nu/\bar{\nu}$ interactions and to reduce proton decay backgrounds

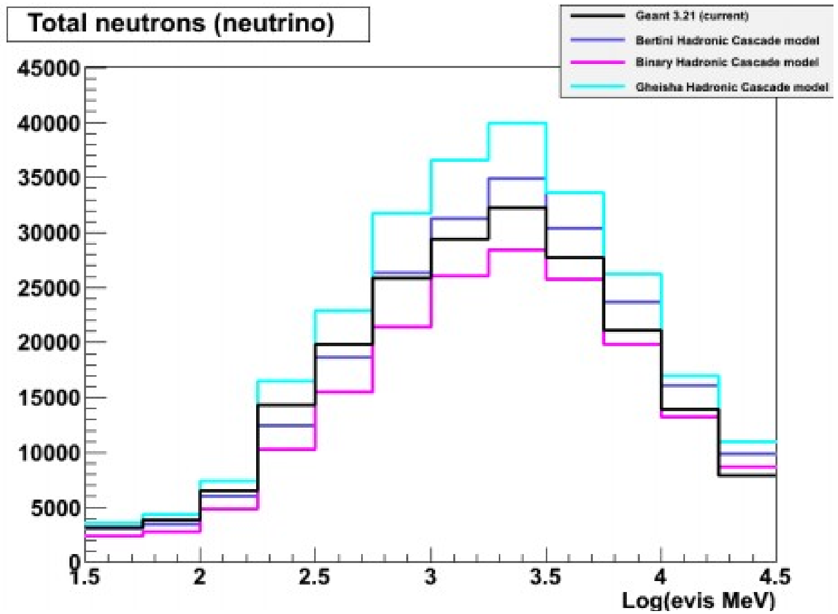
2.2 MeV γ Selection	
Efficiency	**20.5%**
Background / Event	**0.018**

Neutron Tagging for Mass Hierarchy: Neutrinos

T.Irvine

	Geant 3	Bertini	Binary	Gheisha
All	277021	297378	243614	337463
Neutrino	**205976**	**216192**	**179280**	**250849**
Anti-Neutrino	71045	81186	64334	86614



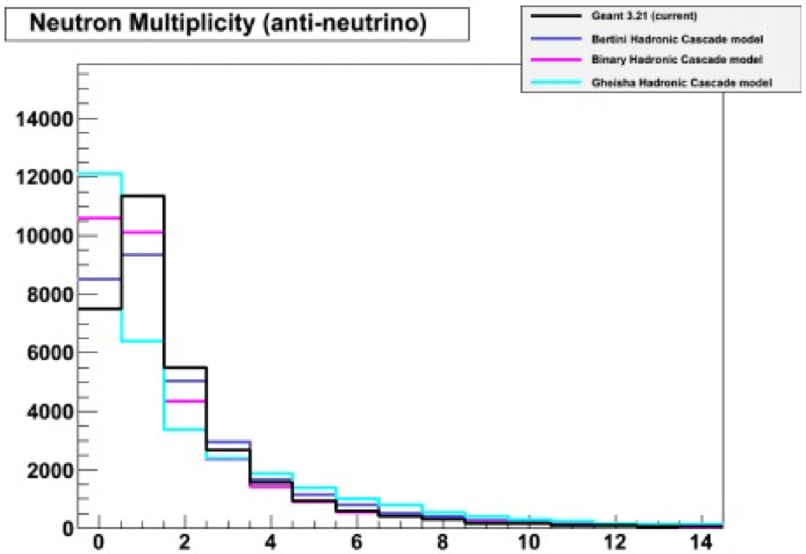


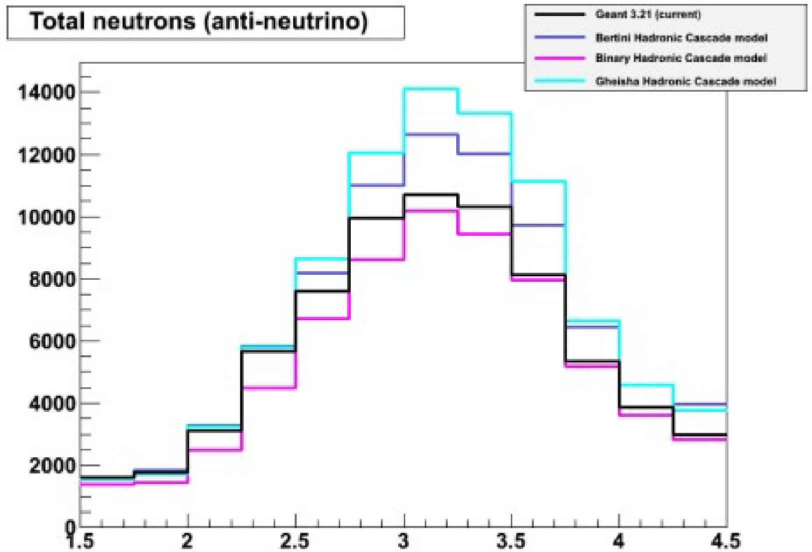
- Neutron tagging can be used to further enhance neutrino and antineutrino separation, in principle
- These plots show number of neutrons after the initial neutrino interaction for a variety of hadron propagation codes
- Currently SK data agree best with GEANT3 model in the total number of neutrons:
  - Whether this remains true after CP separation, is unknown -> systematics

Antineutrinos

T.Irvine

	Geant 3	Bertini	Binary	Gheisha
All	277021	297378	243614	337463
Neutrino	205976	216192	179280	250849
Anti-Neutrino	**71045**	**81186**	**64334**	**86614**





- Neutron tagging can be used to further enhance neutrino and antineutrino separation, in principle
- These plots show number of neutrons after the initial neutrino interaction for a variety of hadron propagation codes
- Currently SK data agree best with GEANT3 model in the total number of neutrons:
  - Whether this remains true after CP separation, is unknown -> systematics

Summary

- Improved hadron production measurements will have immediate impacts on atmospheric neutrino oscillation measurements by providing more accurate descriptions of the primary flux and its associated uncertainties

- Pion production from primaries with about O(10) GeV can be expected to improve constraints on the low energy flux and thereby improve measurements of CP violation with ~1 GeV neutrinos
  - Some improvement to octant sensitivity expected with lower energy primaries

- Better knowledge of the higher energy neutrino flux (abs norm) produced from Kaon parents will improve sensitivity to standard and exotic oscillations in neutrino telescopes

- Hierarchy sensitivity can be improved with:
  - better neutron production modeling for low threshold experiments
  - (also break away from isospin constraints in primary flux?)

Supplements