Atmospheric Neutrino Oscillations at Super-K and Hyper-K

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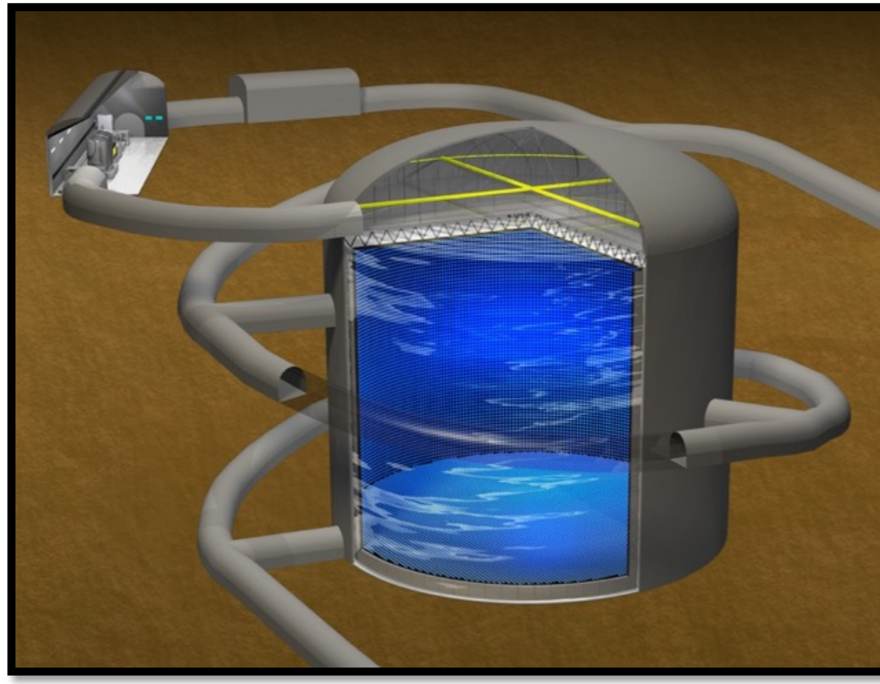
2019.03.22

Introductory Remarks

- Generically discuss Super-K and Hyper-K atmospheric neutrinos
- Here the latter is just a larger version of the former with slightly better timing and energy reconstruction
  - SK: Atm ν, ~8/day neutron eff. ~20%
  - HK Atm ν: ~80/day neutron eff. >40%
  - Nonetheless, statistics are the dominant error for most analyses
  - Additionally Hyper-K analyses use neutrinos from J-PARC beam with effective statistics about 20 times that of T2K



- Focus on atmospheric neutrino oscillations, with some comments on beam + atmospheric neutrino data and impact of flux uncertainties
- Currently using an error model with ~70 systematic errors in these categories
  - 20 Flux-related (Primary model is Honda 2011)
  - 22 Neutrino interaction (NEUT)
  - 26 Detector response (GEANT3)
  - Miscellaneous, osc. parm errors, etc.)

Status of Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric

Capozzi 1804.09678

Solar

- Three mixing angles, two independent mass differences (Δm^2_{21}, Δm^2_{32}), and a CP violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain

Parameter	Ordering	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51
	IO	7.34	7.20 – 7.51
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18
	IO	3.03	2.90 – 3.17
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23
	IO	2.18	2.11 – 2.26
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.455	2.423 – 2.490
	IO	2.441	2.406 – 2.474
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70
	IO	5.57	5.33 – 5.74
δ/π	NO	1.32	1.14 – 1.55
	IO	1.52	1.37 – 1.66

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Atmospheric

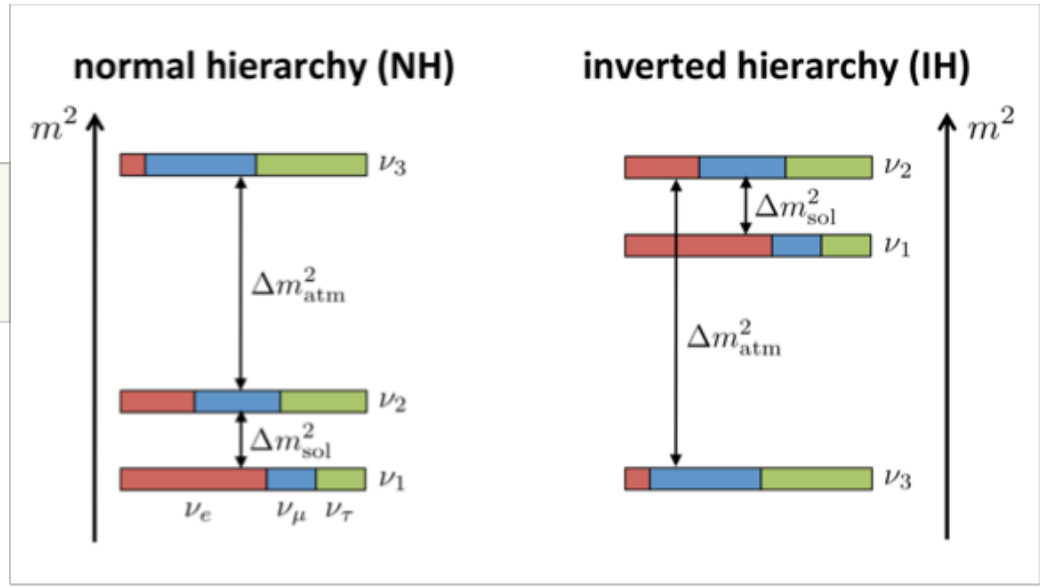
Capozzi 1804.09678

Solar

Mass Ordering is Unknown

★ Are the electron-rich states ν_1 & ν_2 **heavier or lighter** than ν_3 ?

- Important implications for
  - GUT Models
  - Neutrinoless double beta decay
  - …



$\Delta m^2_{32} > 0$ $\Delta m^2_{32} < 0$

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Atmospheric

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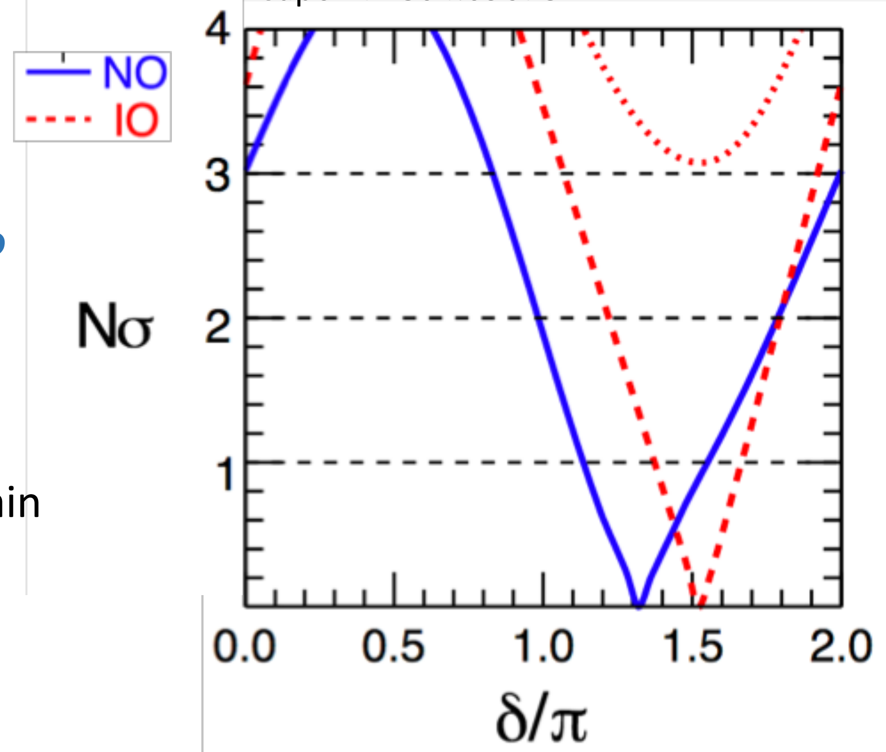
Capozzi 1804.09678



Do neutrino oscillations violate CP?

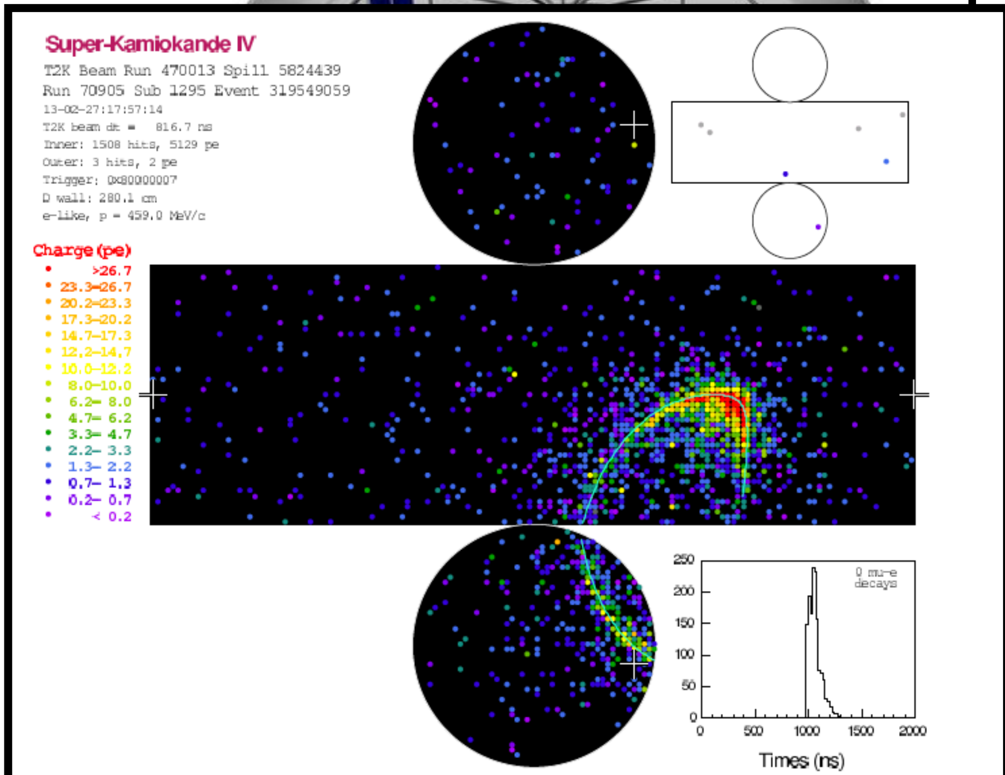
(sin δ ≠ 0 ?)

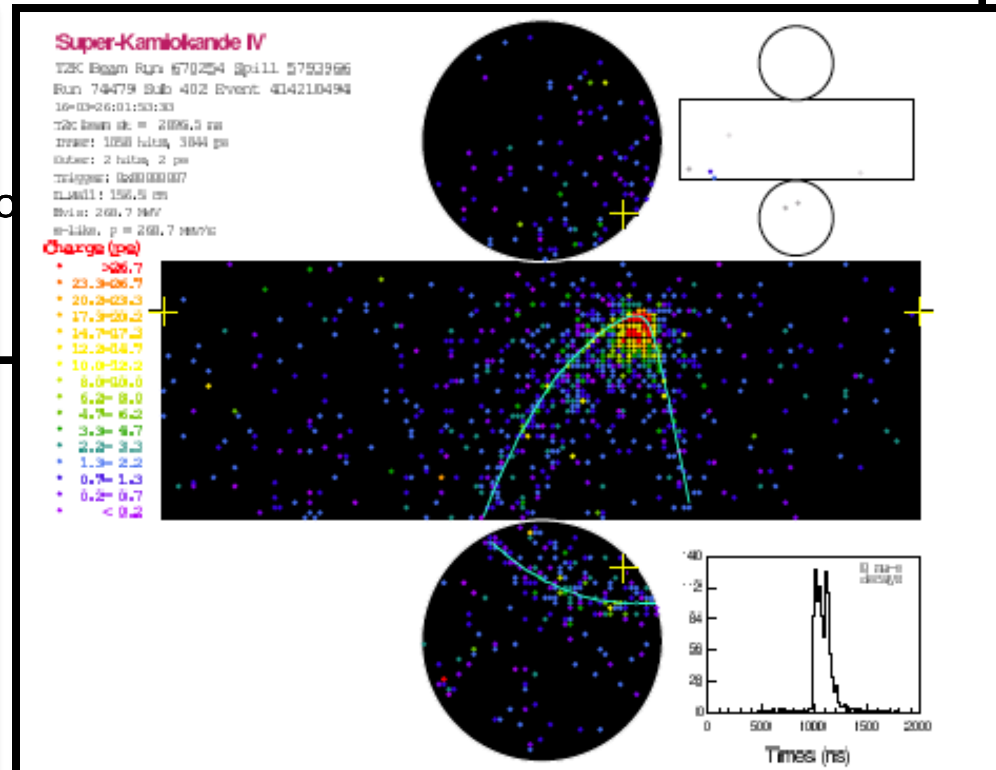
- New sources of CP violation needed to explain matter dominant universe
- Allowed within νSM

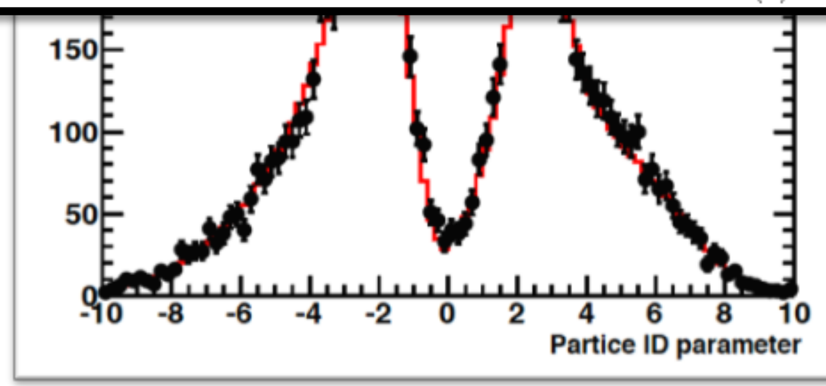
Super-Kamiokande: Introduction

Neutrino, Antineutrino?

20” PMTs







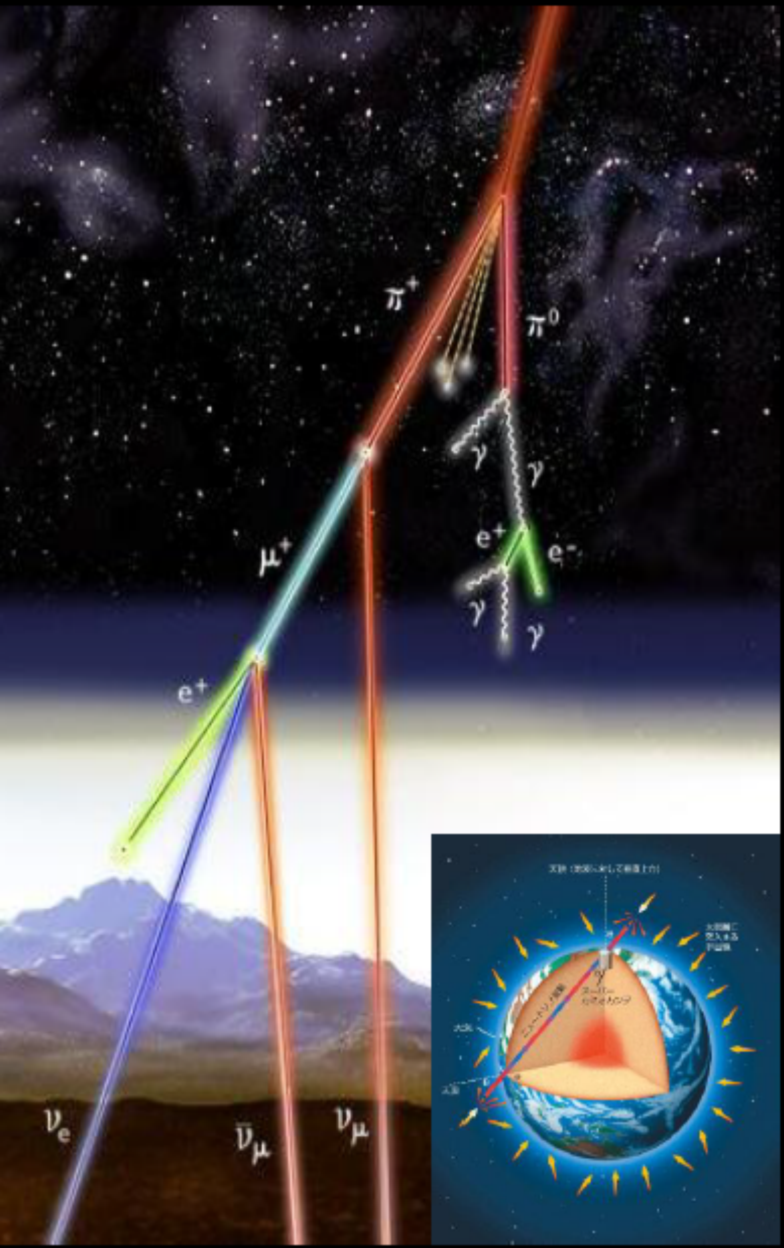
Four Run Periods:

SK-I (1996-2001) SK-II (2003-2005)

SK-III (2005-2008) SK-IV (2008-2018)

Upgrade Complete Now operating as SK-V !!

About the Atmospheric Neutrino Flux



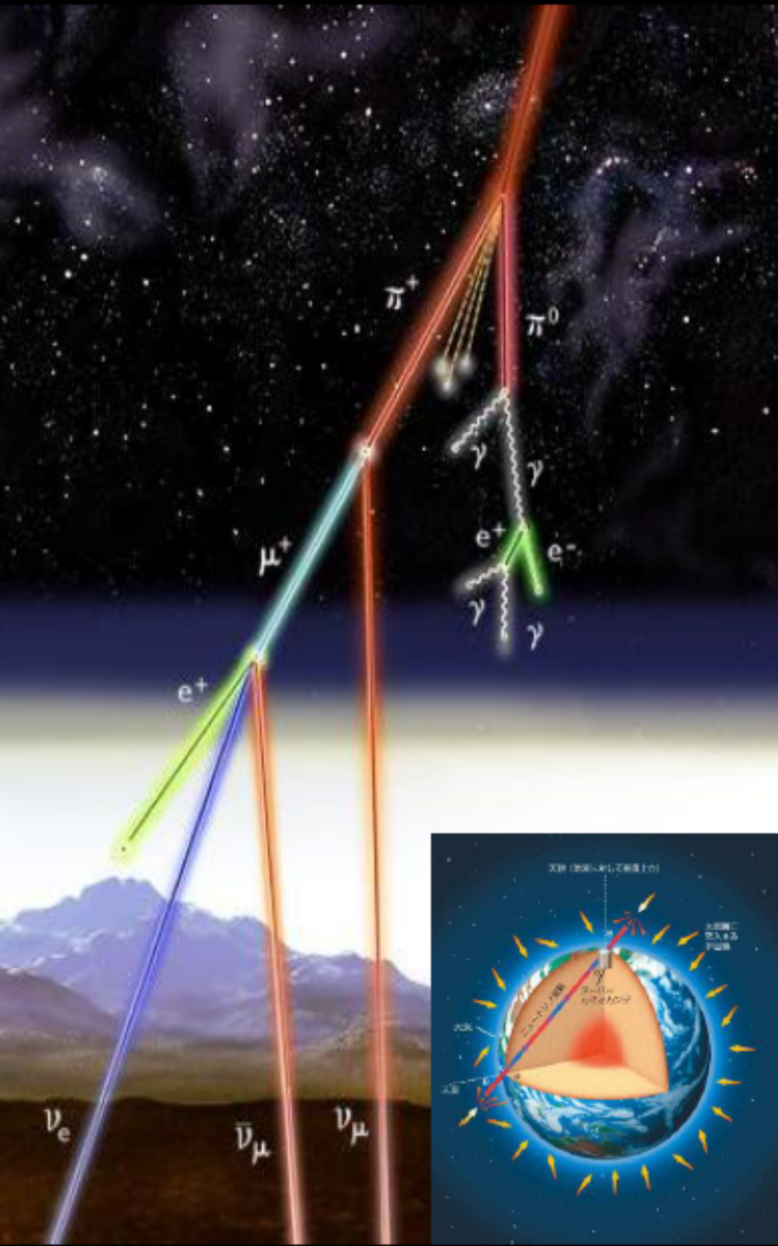
- Cosmic rays strike air nuclei and the decays of the out-going hadrons produce neutrinos

$$P + A \rightarrow N + \pi^+ + x$$

$$\hookrightarrow \mu^+ + \boxed{\nu_\mu} \rightarrow e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu}$$

- Isotropic about the Earth
  - Path length to the detector spans 10 – 10,000 km
- Spans many decades in energy ~100 MeV – PeV$^+$

About the Atmospheric Neutrino Flux



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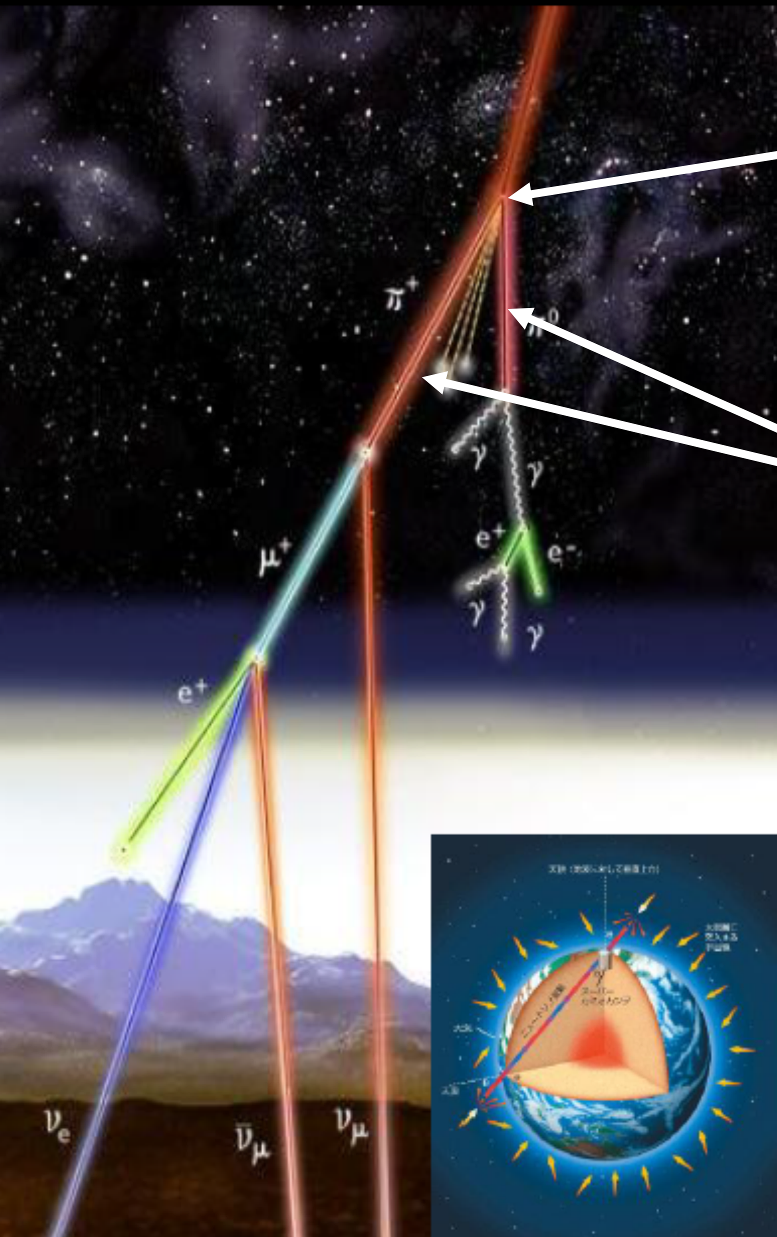


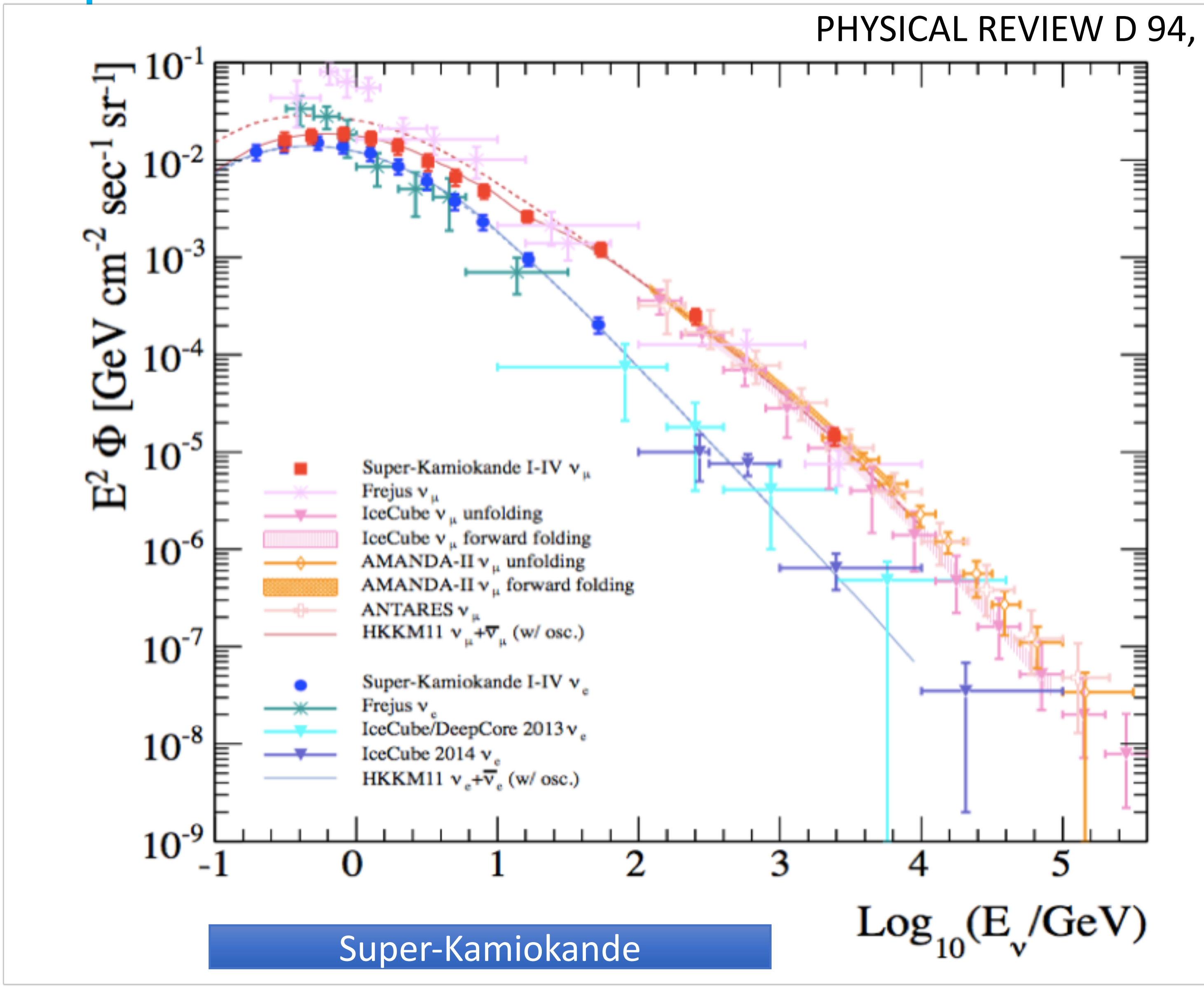
Hadron production data for primary interaction:
p + O, p + N, …

Hadron reinteraction and subsequent production processes possible
π + O, π + N, …

Hadron and muon interaction data valuable for constraining flux (energy, direction, flavor content)

Atmospheric Neutrino Flux:

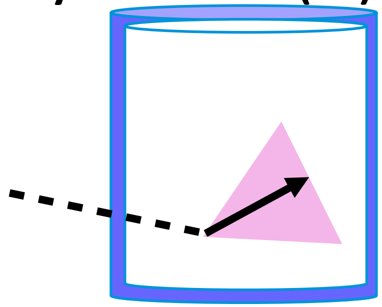
PHYSICAL REVIEW D 94, 052001 (2016)



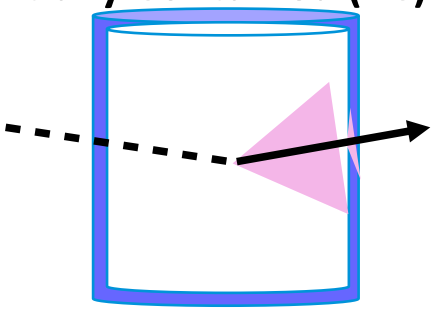
IceCube/DeepCore

Super-K Atmospheric ν Analysis Samples

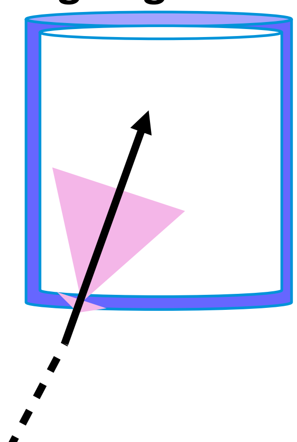
Fully Contained (FC)

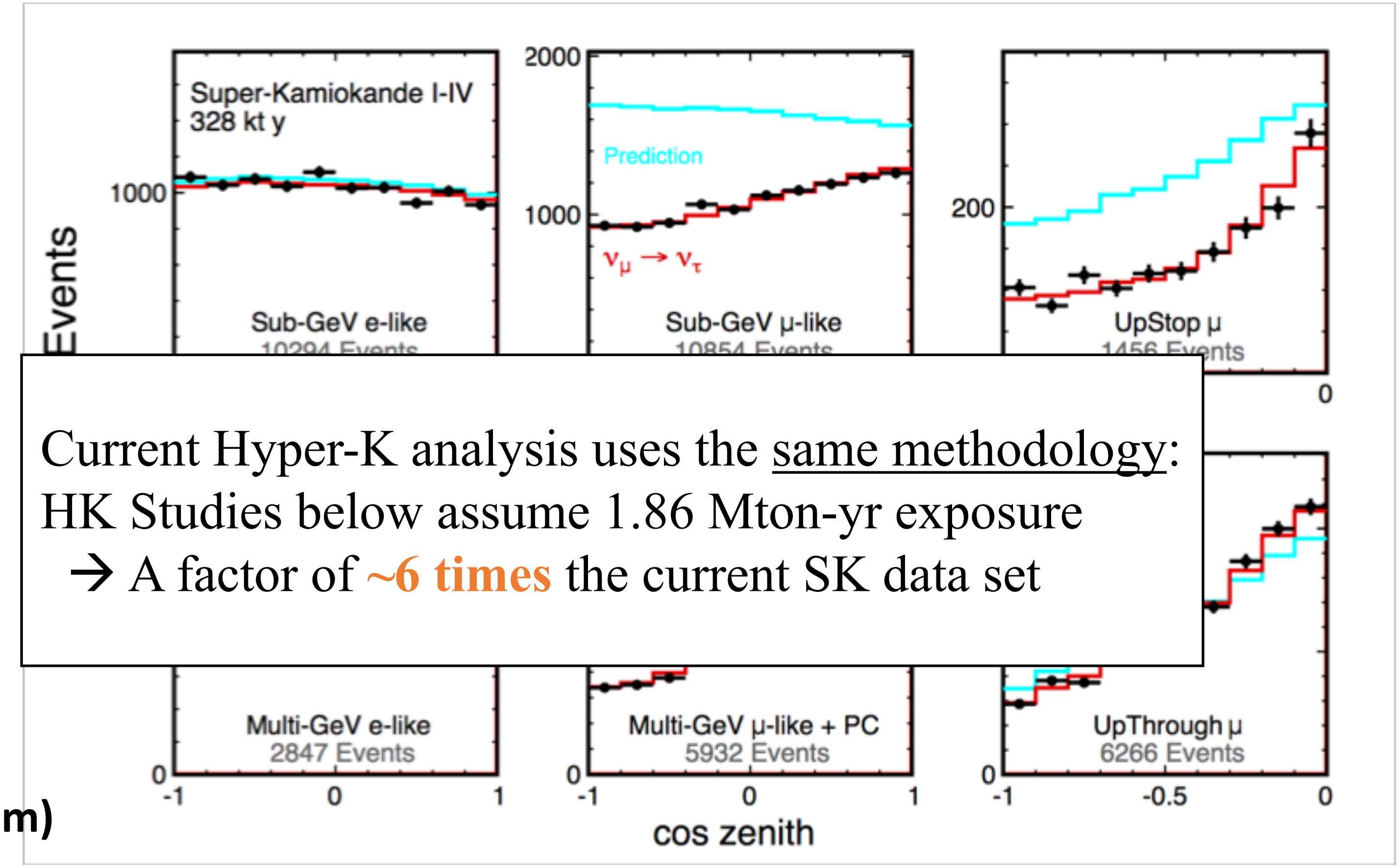


Partially Contained (PC)



Upward-going Muons (Up-m)

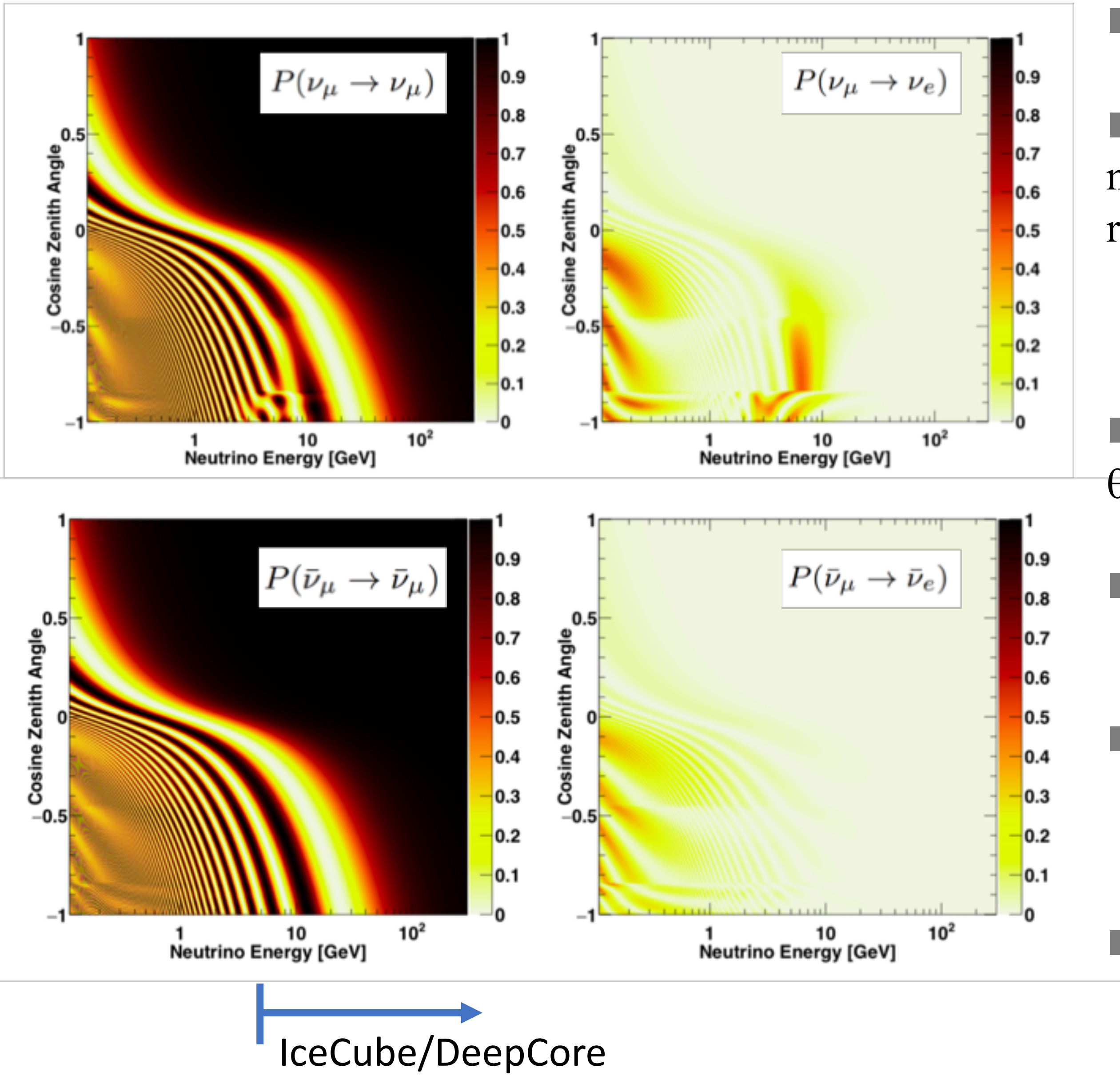




Current Hyper-K analysis uses the <u>same methodology</u>:
HK Studies below assume 1.86 Mton-yr exposure
→ A factor of **~6 times** the current SK data set

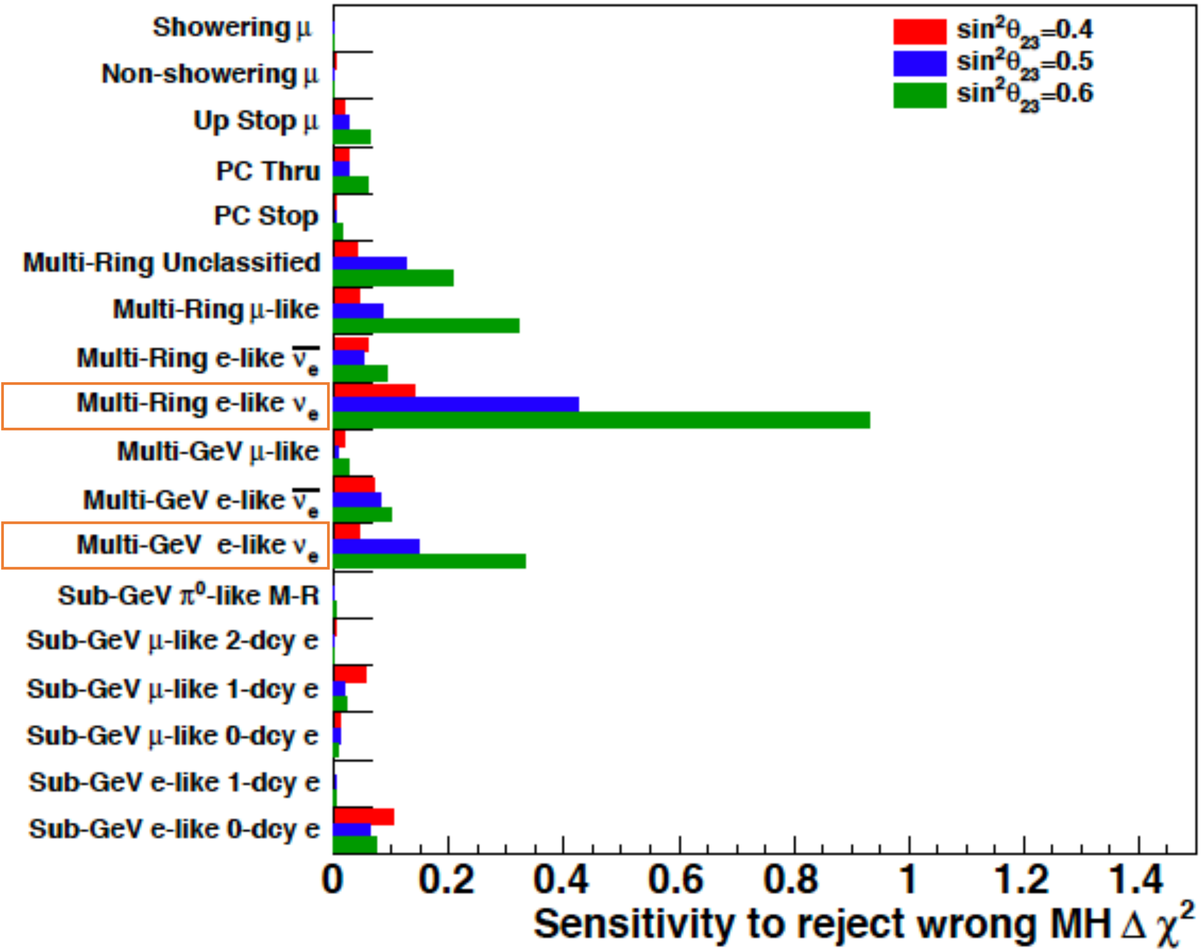
- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and ν-bar-like subsamples (p, cos θ) binning
- 5,300 days (328 kton-yr) data set
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.

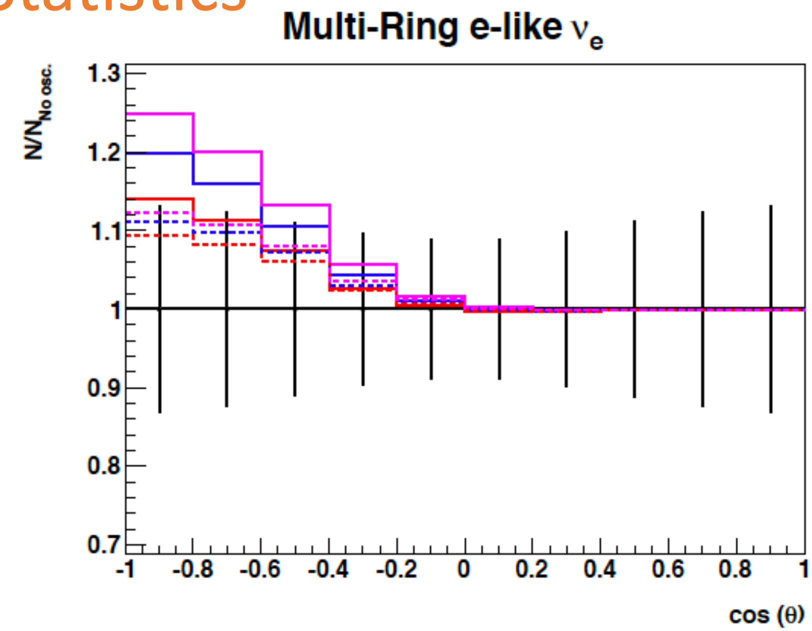
Atmospheric Neutrino Oscillations :

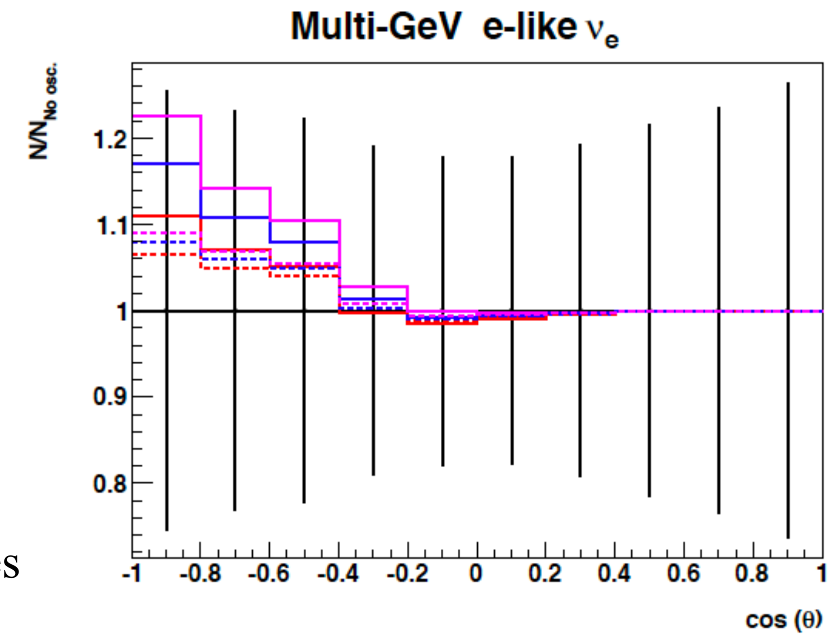


- Plots assume the Normal Hierarchy
- Under the inverted hierarchy the neutrino and antineutrino plots reverse roles
  - Resonance effects in the antineutrino channels
- Size of matter effects depends on θ_{13}, θ_{23}, δ_{CP} (in order of importance)
- Mass hierarchy sensitivity:
  - 2 ~ 10 GeV
- CP sensitivity
  - Below 2 GeV , strongest effects (400~600 MeV)
- *Exotic* Scenarios
  - Lorentz-Invariance: > 5 GeV
  - Sterile Neutrinos > 1 GeV

Mass Hierarchy Sensitivity : Super-K IV Statistics





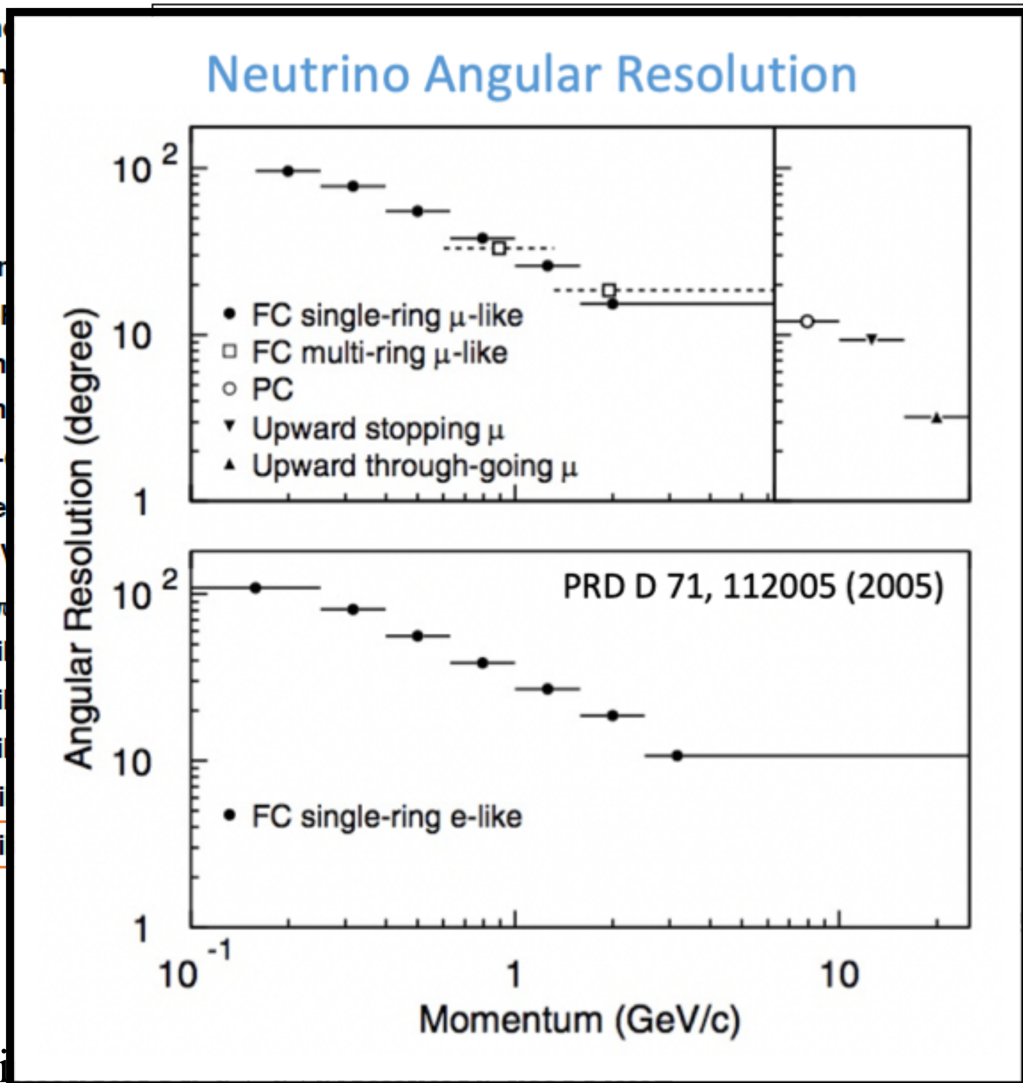


- Most influenced by systematics affecting
  - Ratio of Upward- and Downward-going events
  - Relative fraction of neutrino and antineutrino species

* Bars show statistical error

Sensitivity to δcp : Super-K IV Statistics

Sh
Non-sh
Multi-Ring Ur
Multi-I
Multi-Rin
Multi-Rin
Multi-
Multi-Ge
Multi-GeV
Sub-GeV π
Sub-GeV μ-li
Sub-GeV μ-li
Sub-GeV μ-li
Sub-GeV e-li
Sub-GeV e-li



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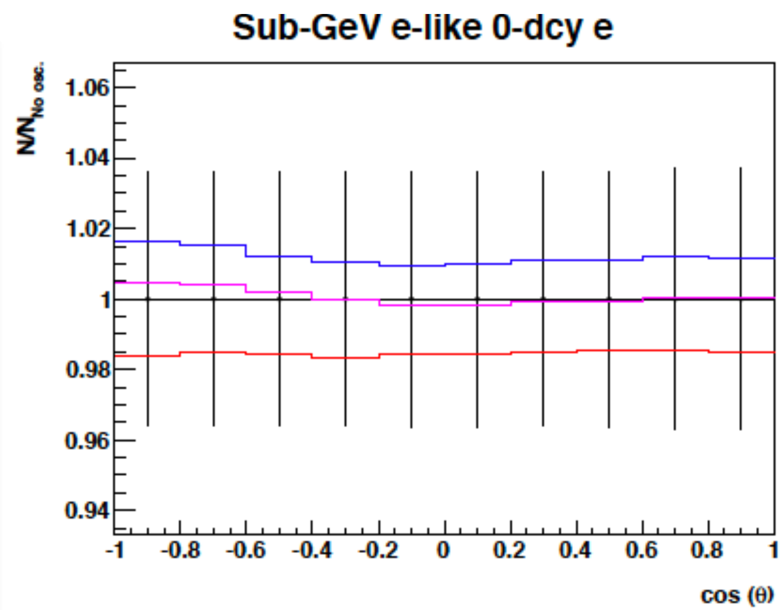
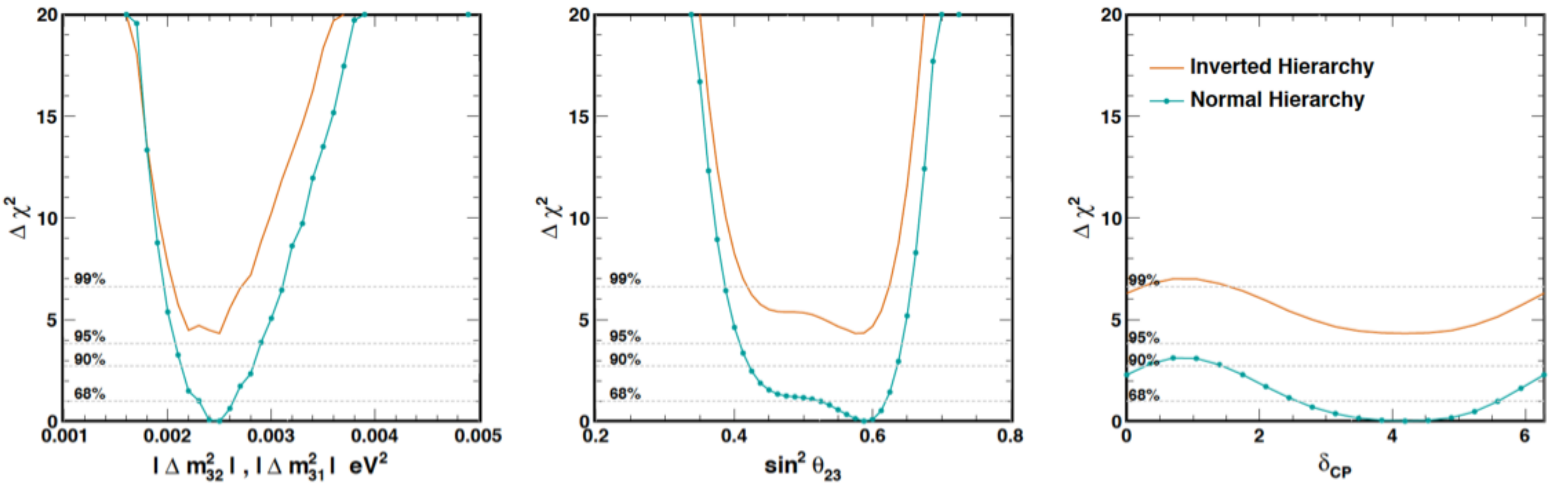


* Bars show statistical error

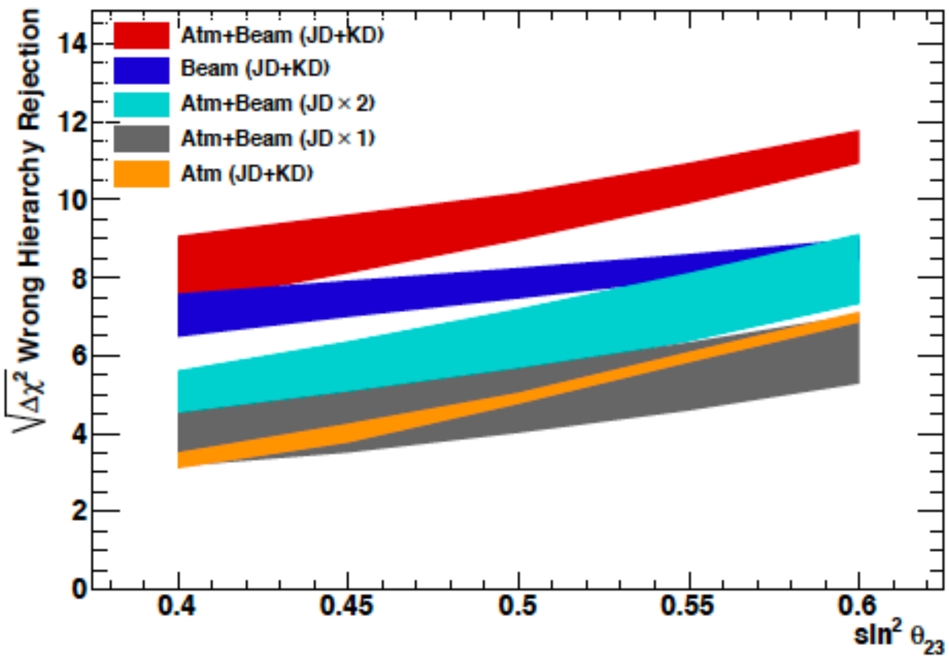
- Most i
  - Absolute flux and cross section normalizations (Pointing is a problem)
  - Relative fraction of neutrino and antineutrino species

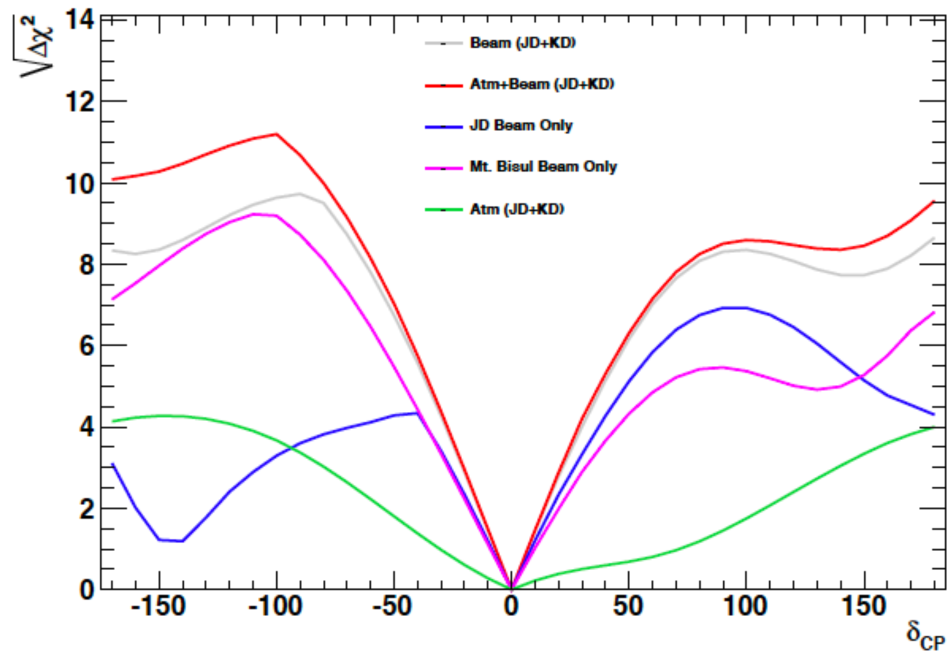
Atmospheric Mixing + δ_{cp}: Super-K (only)



Hierarchy Significance			
NH Preference	**Lower Oct.**	**Best Fit**	**Upper Oct.**
SK Only	82.9%	93.0%	96.7%
SK+T2K Model	91.9%	92.5%	94.4%

Hyper-Kamiokande Sensitivity after 10 Years



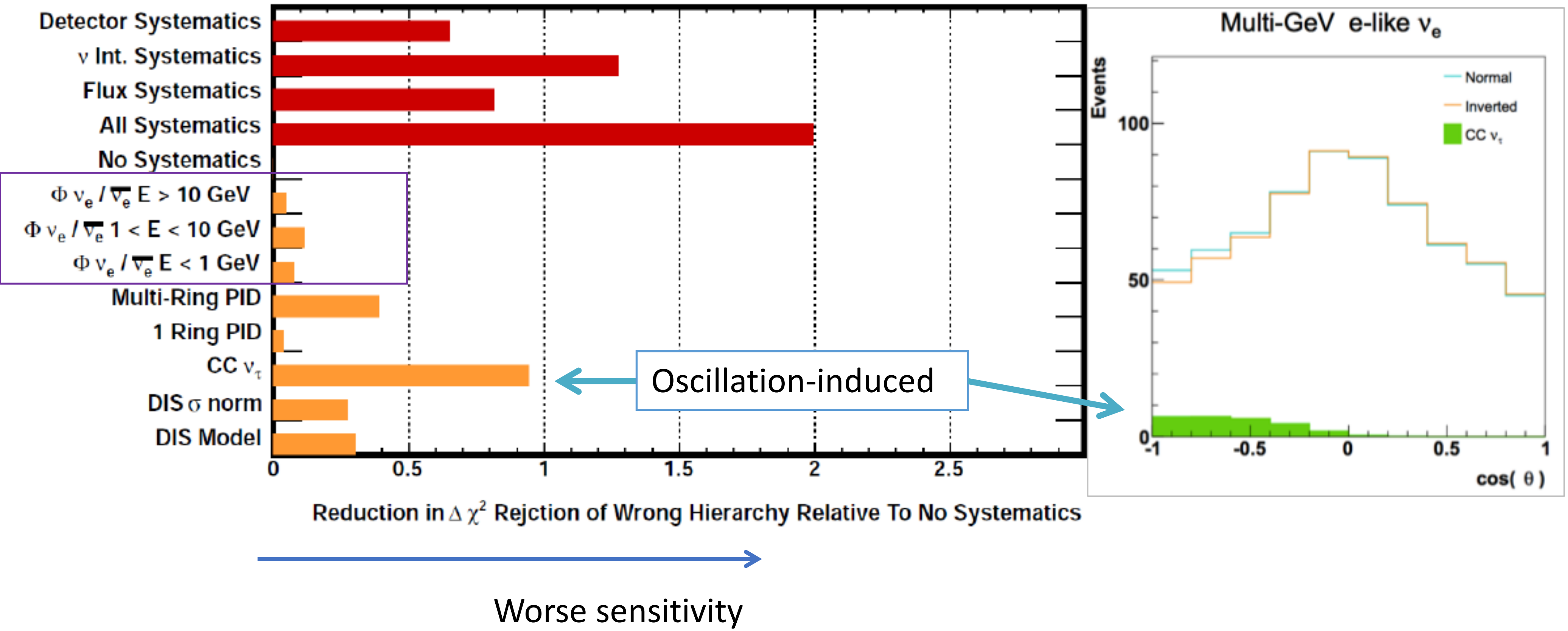


- Even at Hyper-K exposures, statistical uncertainties will hamper hierarchy sensitivity
- Sensitivity will be improved by combining beam and atmospheric measurements

- Measurement of δ_{CP} is dominated by beam neutrino sample, some improvement in combination with atmospheric sample
  - However sensitivity is complementary, $\rightarrow \cos(\delta_{CP})$, useful for breaking parameter degeneracies

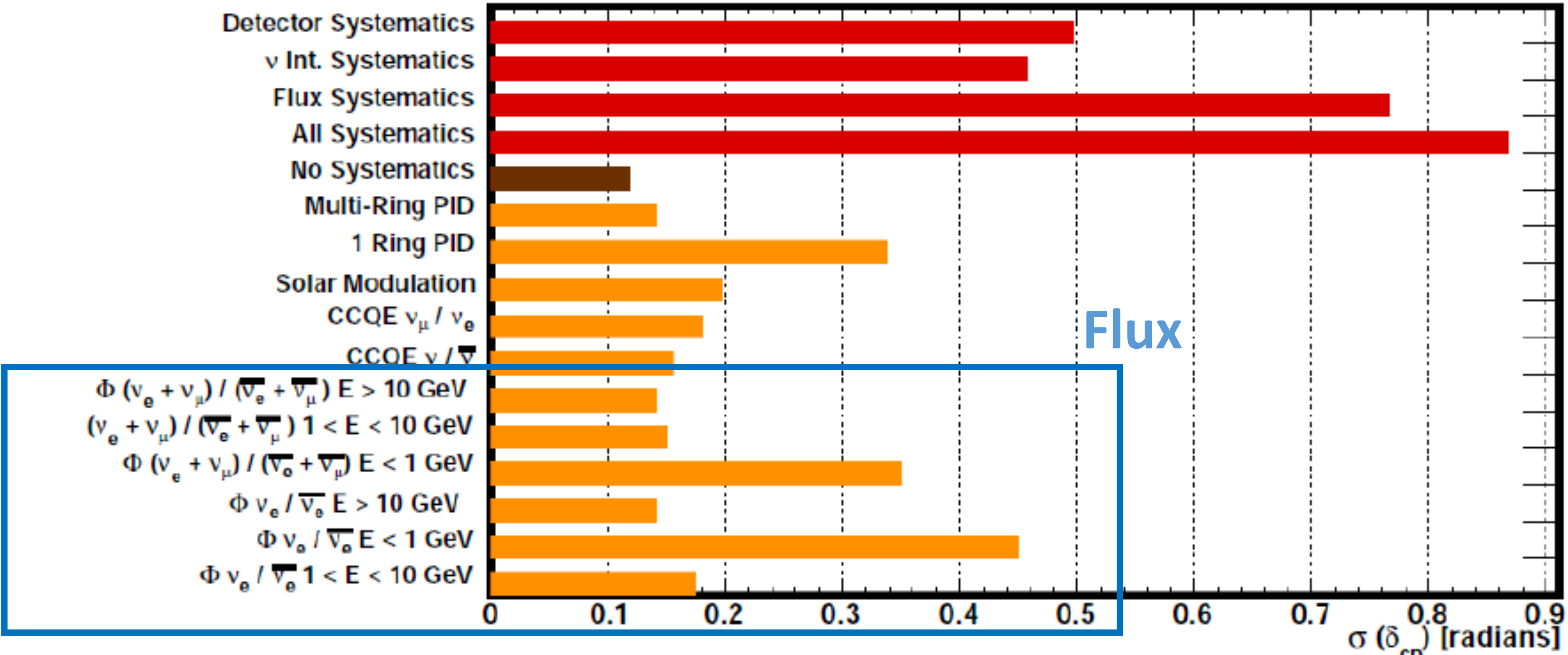
Impact of Hadron Production Uncertainties (ie, Flux uncertainty)

Super-K : Mass Hierarchy Systematics



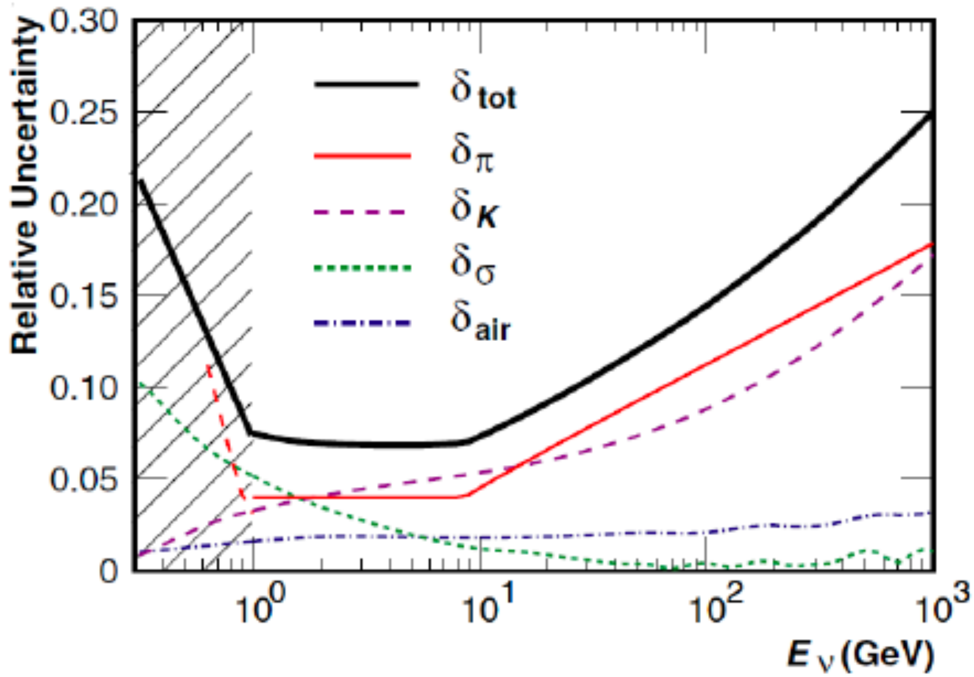
- Largest uncertainties are statistical and osc. parms (not shown)
- Mass hierarchy sensitivity is largely affected by uncertainties in high energy neutrinos, particularly ν_τ background events
- Need to observe, understand, and constrain such background events

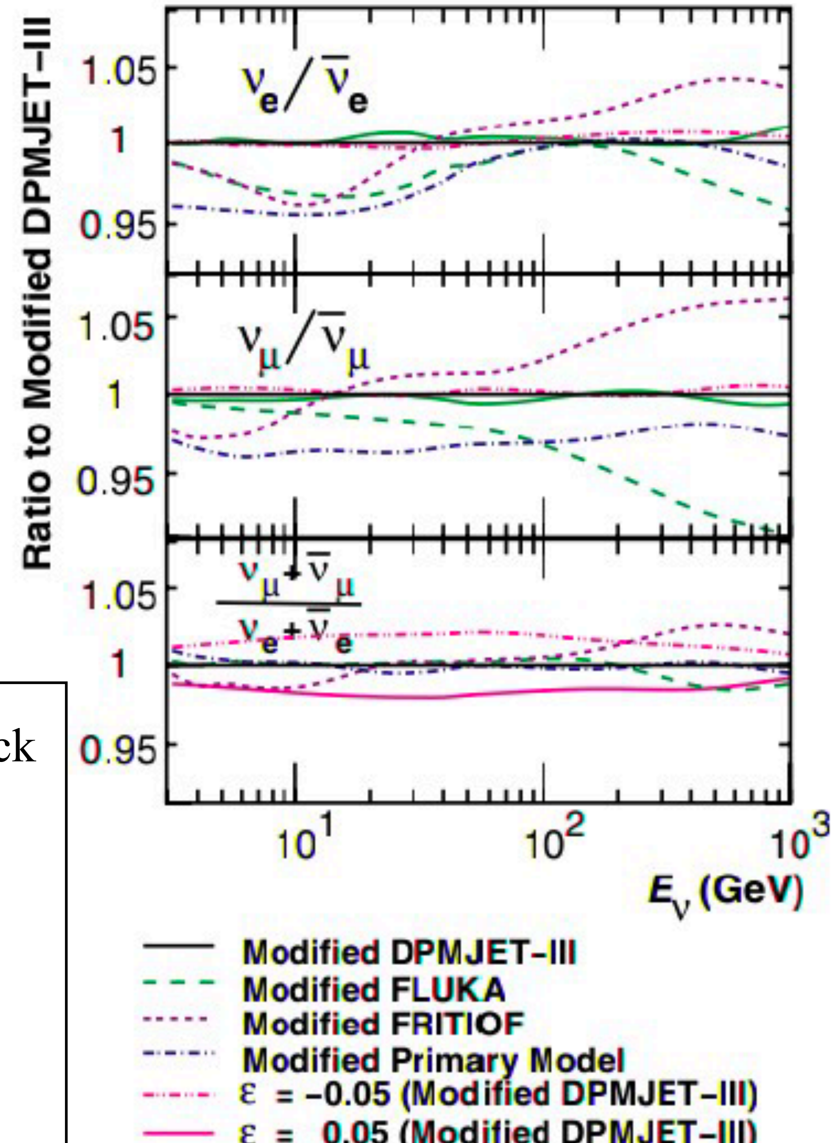
Systematics on δ_{CP} Sensitivity



- 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

The Honda Flux : Systematic Errors

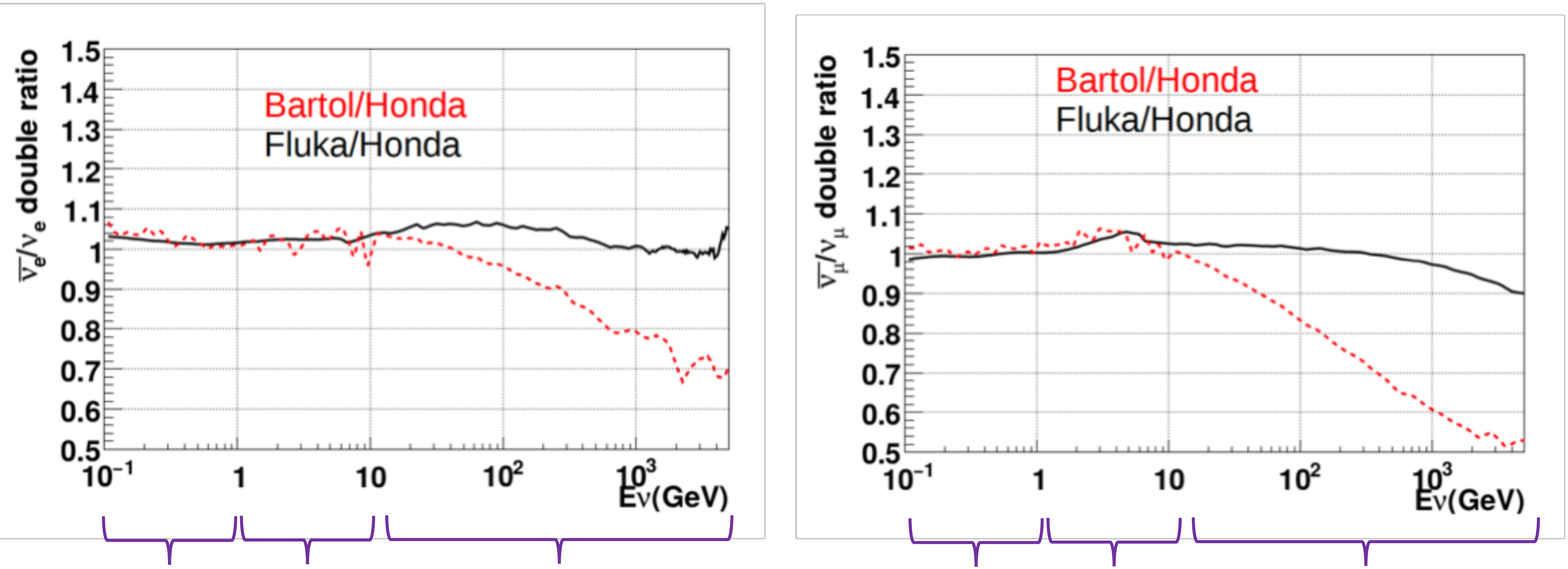




- Super-K's absolute flux uncertainty is taken from the black line, divided into to independent parameters (left)
  - one for sub-GeV and another for Multi-GeV

- Flavor / species ratio errors within Honda model are provided based on comparisons of the calculation result using different hadronic interaction codes (right)
  - SK Systematic errors are a bit more conservative …

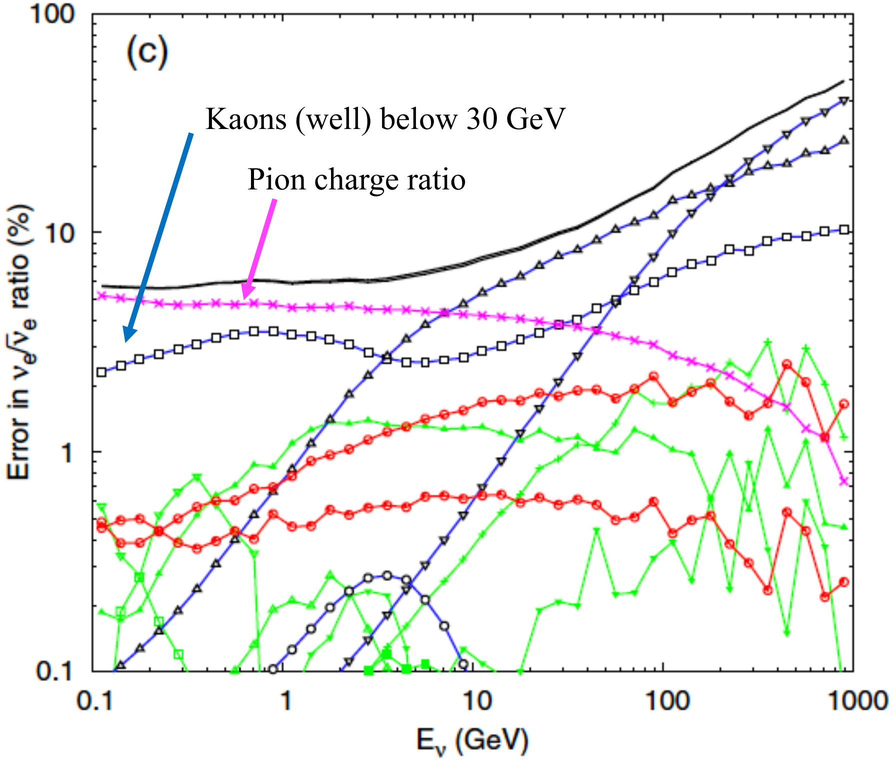
Systematic Limitations on Atmospheric ν Sensitivity

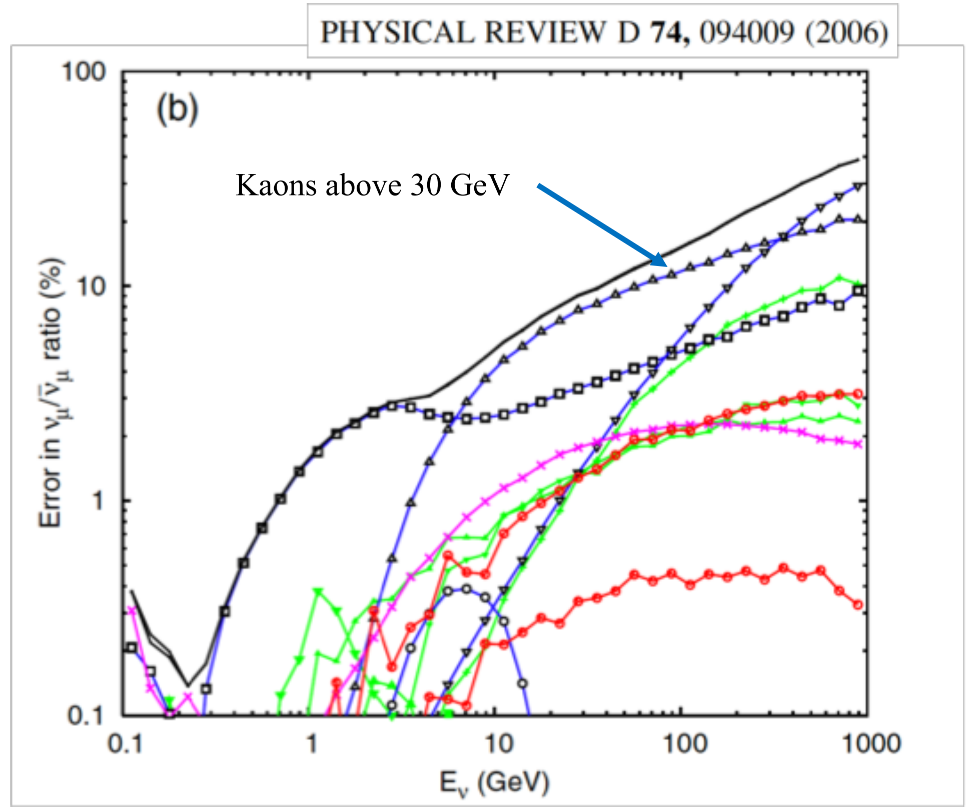


5% 5% Red Line 2% 6% Red Line

- Current systematic errors are taken from difference between Honda and other models (Fluka in this picture)
- Three independent error parameters are assigned for each source (nu/number, numu/nue, etc.)
- Conservative?

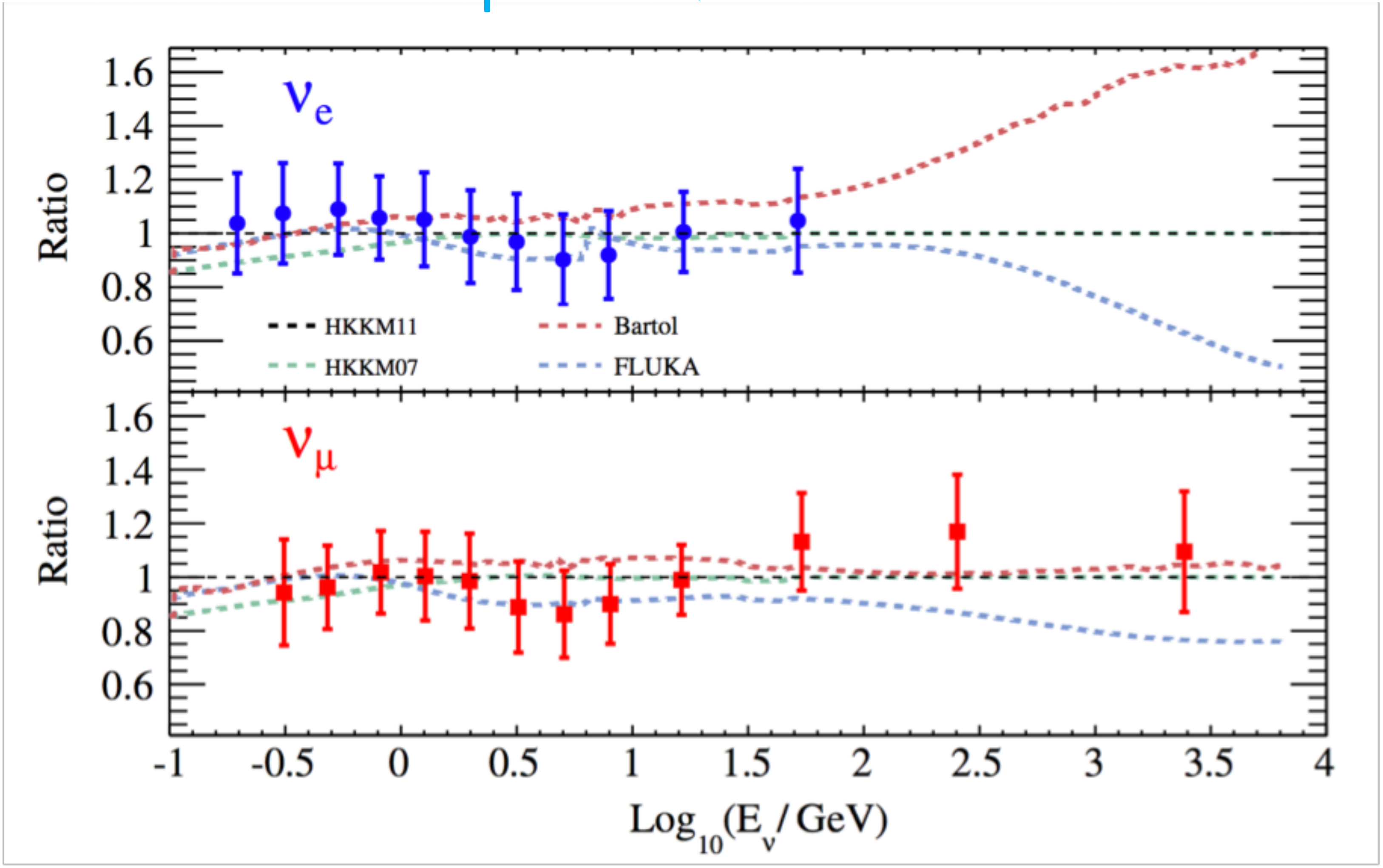
Compared to Bartol Systematics





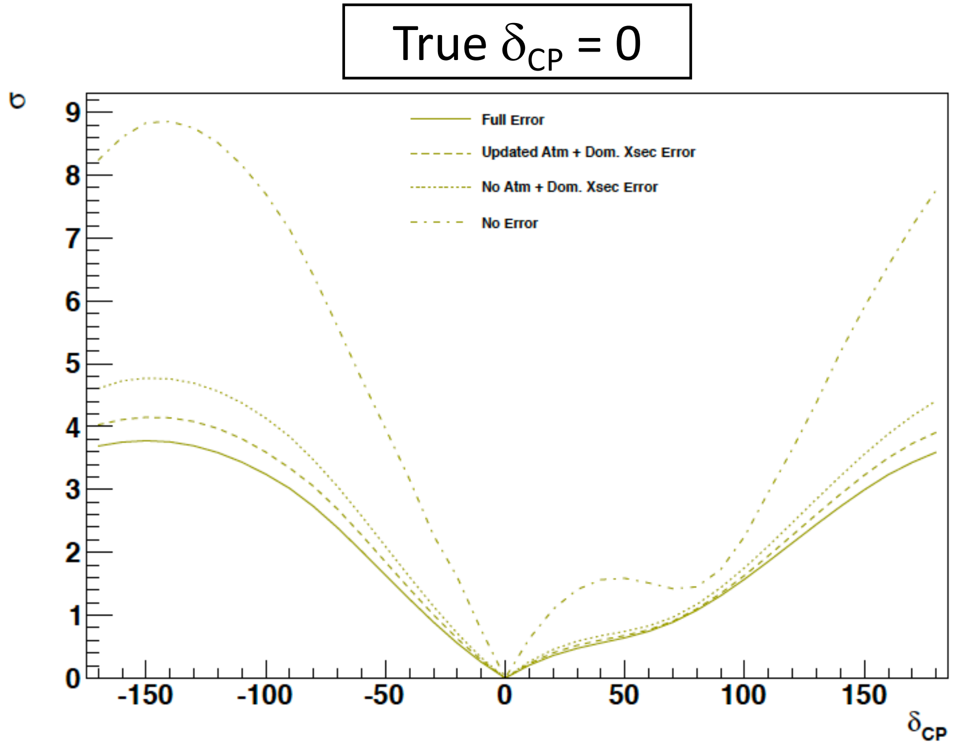
- Some similarities between uncertainties taken by Honda, SK, and Bartol
  - Some differences as well…
- Currently revisiting the SK error parameterization

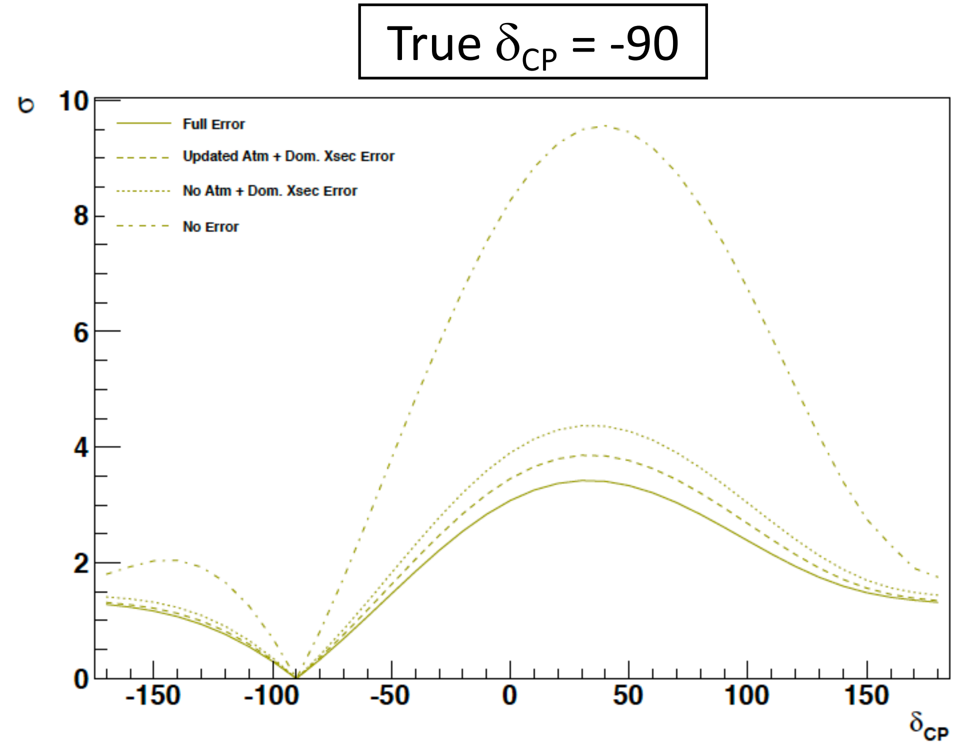
A brief aside : Atmospheric ν Flux Measurements



- Direct flux measurements are hampered by neutrino interaction modeling or statistics (Error bars show 1total error)
- Smaller flux uncertainties (via better hadron production and cosmic ray muon data) essential

Impact of Various Systematic Error Sources: δ_{CP} Measurement





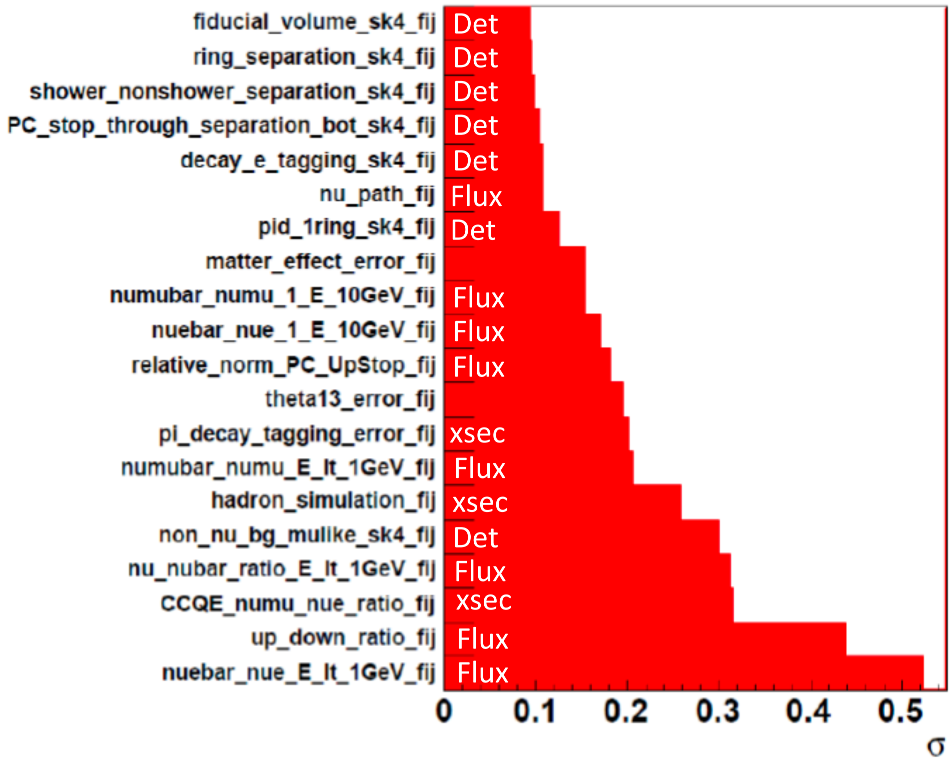
- Plots are for Hyper-K statistics assuming NH
- Legend Explanation:
  - Full error – Current SK errors
  - No Atm. + Dom. X sec – Assume atmospheric flux and dominant xsec errors are zero
  - Updated - Assume 50% reduction in uncertainty (via hadron prod. measurements)

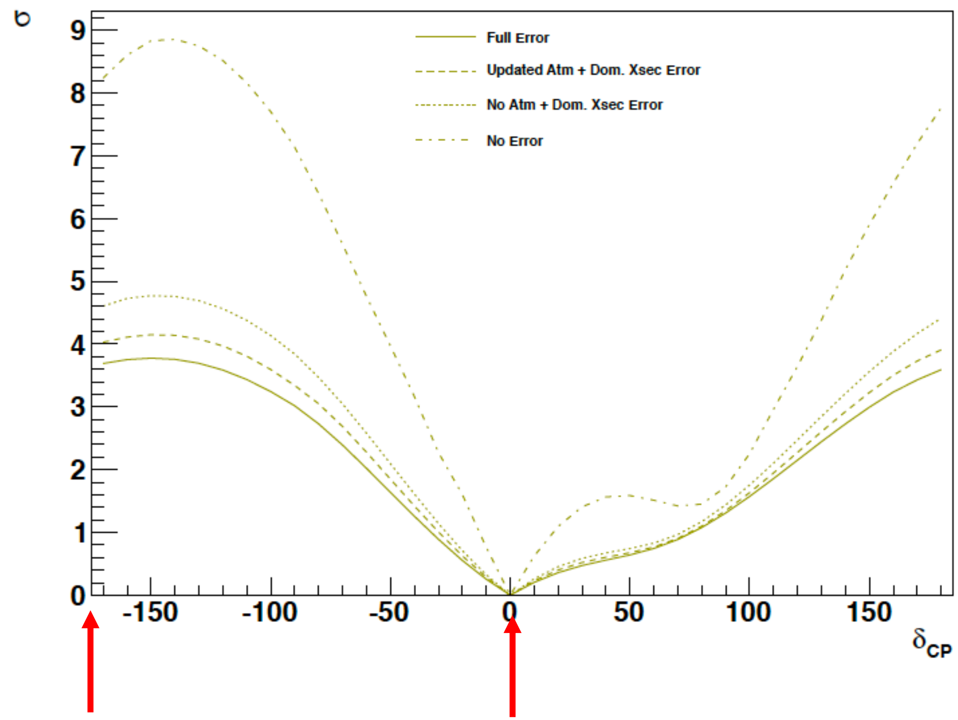
- Flux improvements appear to have little impact due to suppression of by other errors

Impact of Various Systematic Error Sources: δ_{CP} Measurement

All Error

True δ_{CP} = 0

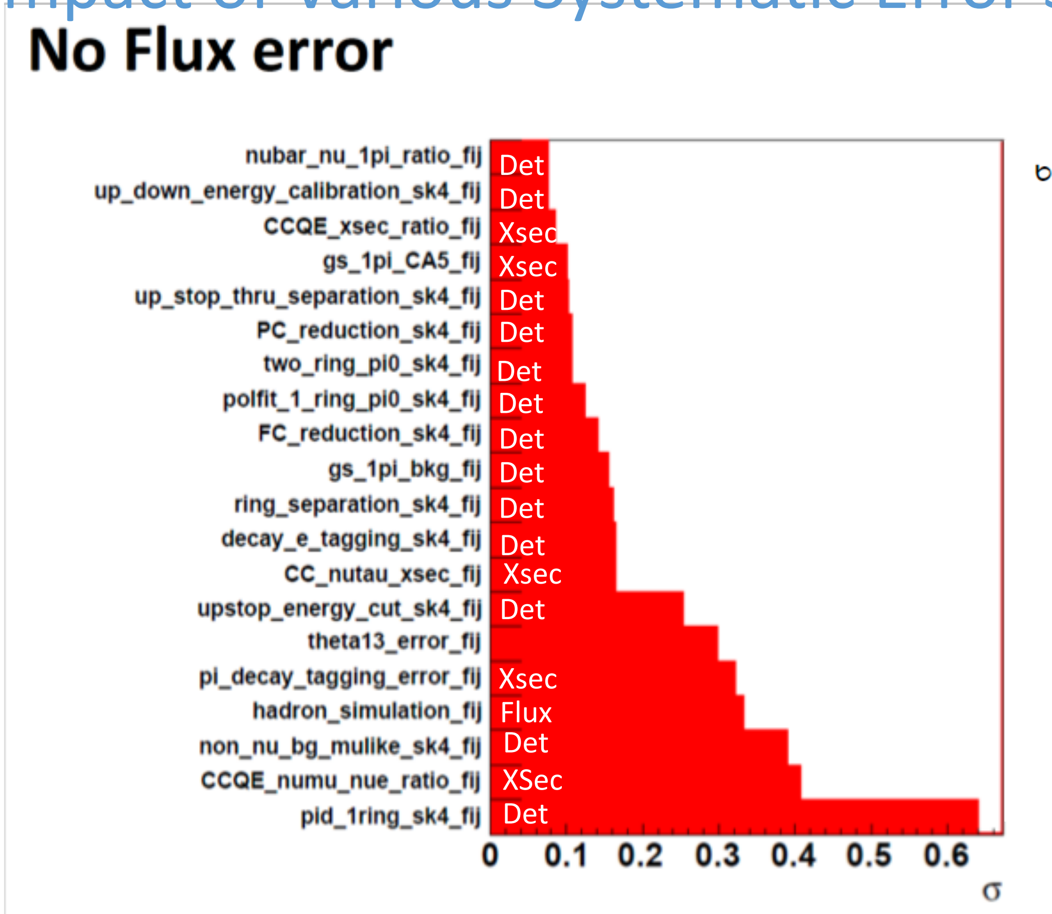


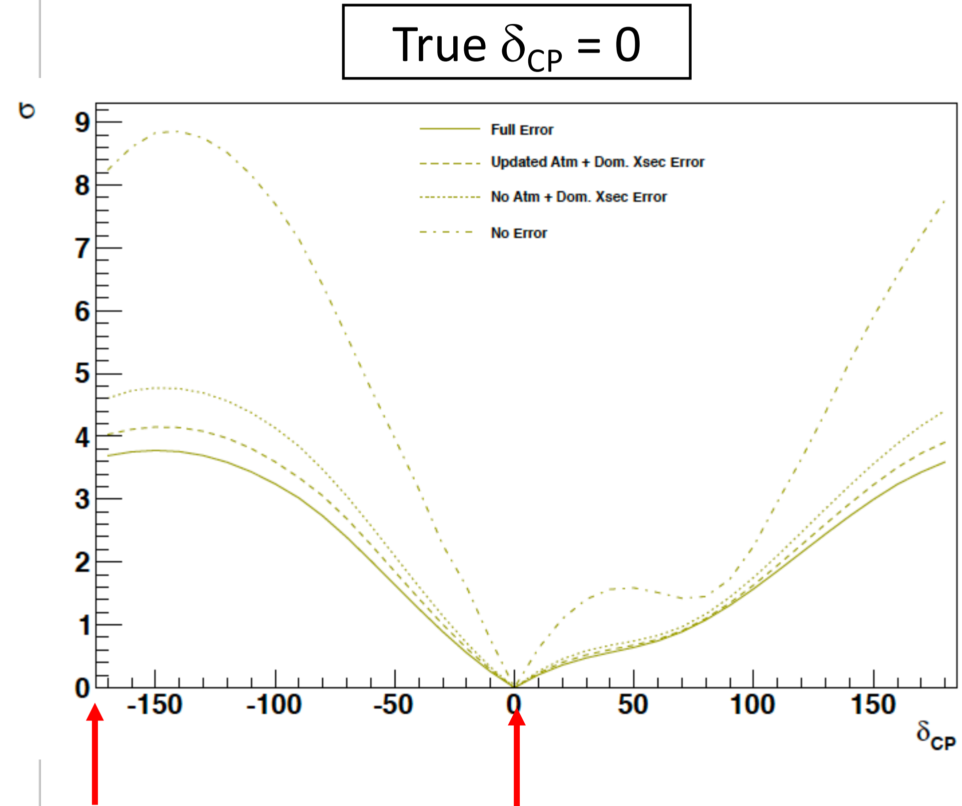


Difference in systematic pulls here

- Left plot shows size of systematic error pulls between two CP points
- Error Categories
  - Flux – Atmospheric neutrino flux-related
  - Xsec – ν Interaction and pion FSI/SI systematics
  - Det – Event reconstruction related
  - Unlabelled – other

Impact of Various Systematic Error Sources: δ_{CP} Measurement





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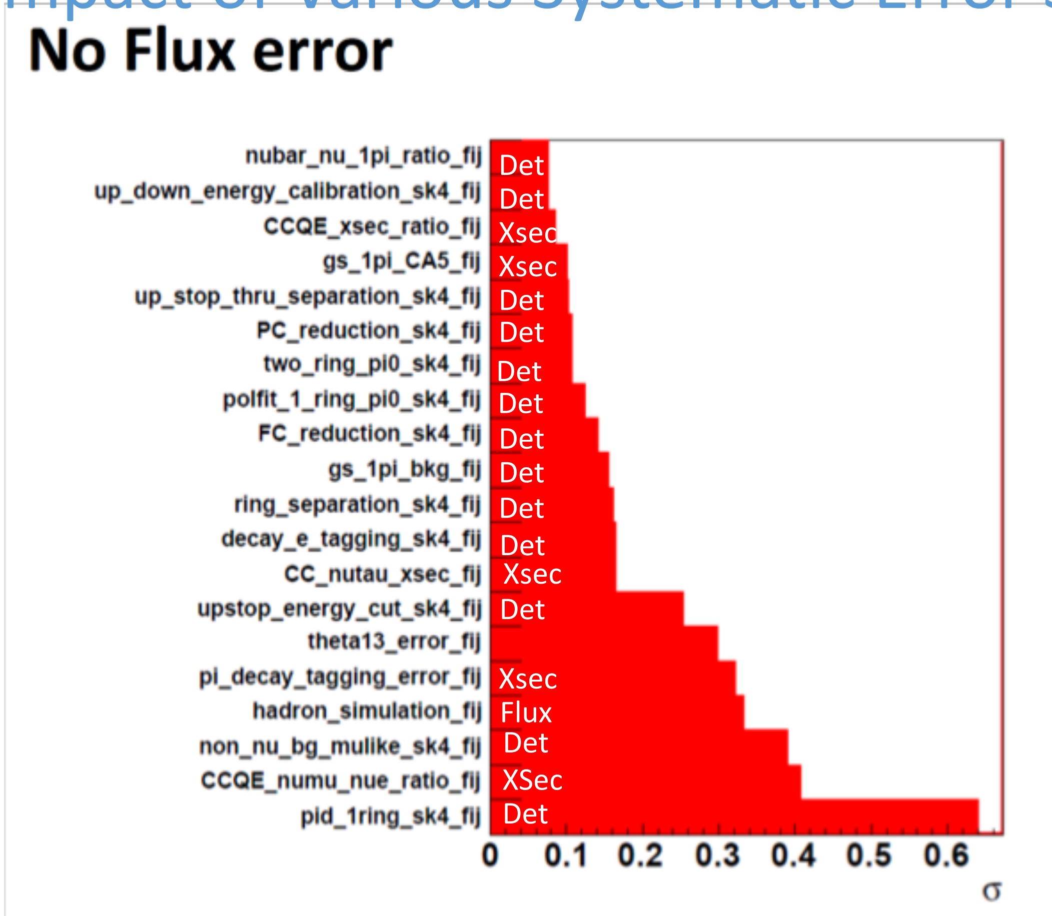

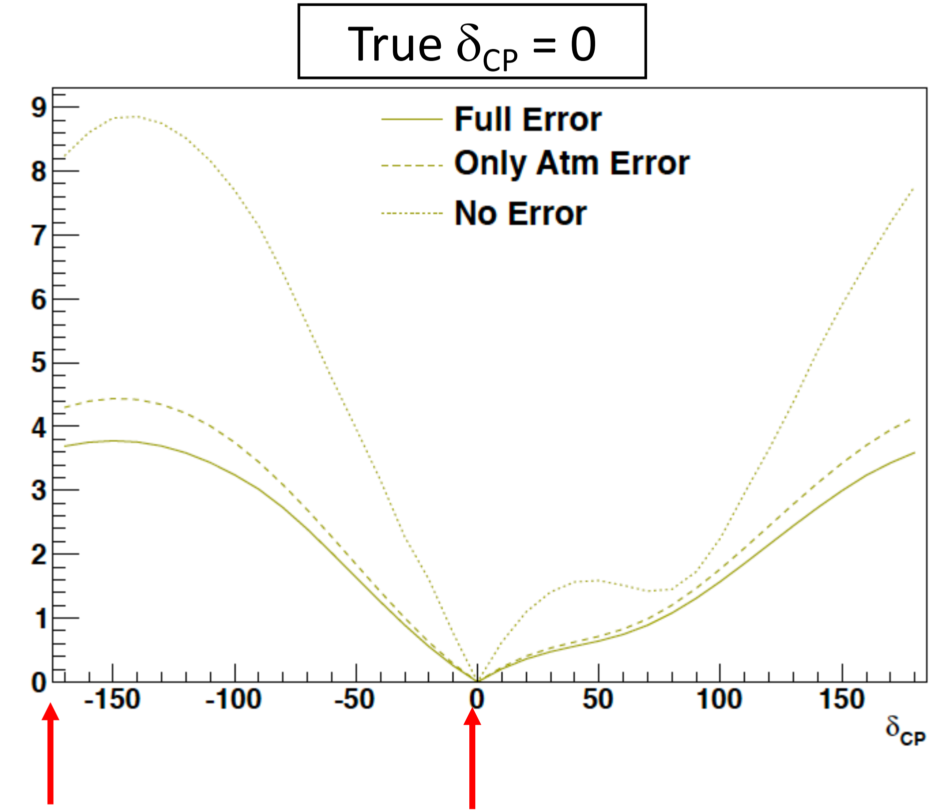

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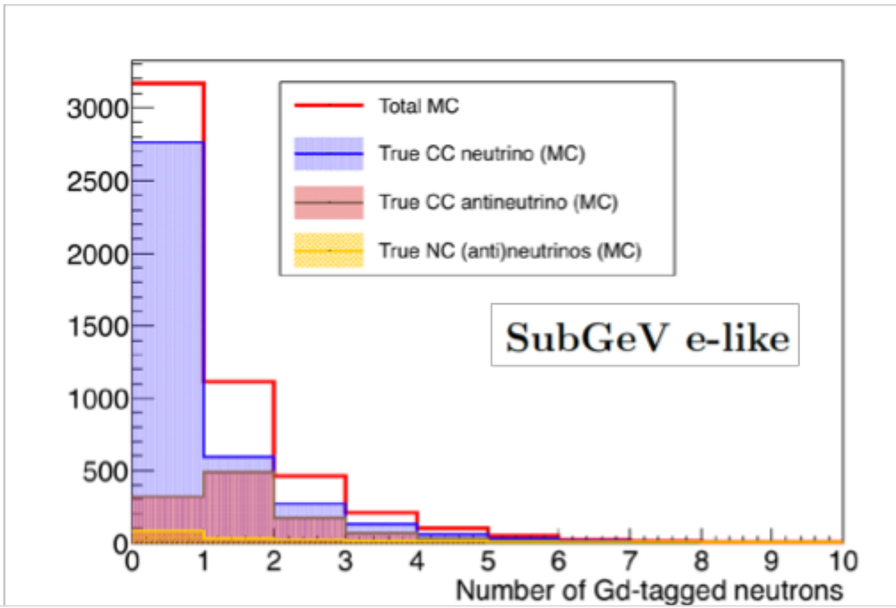
Perhaps not as impressive as one would hope, but…

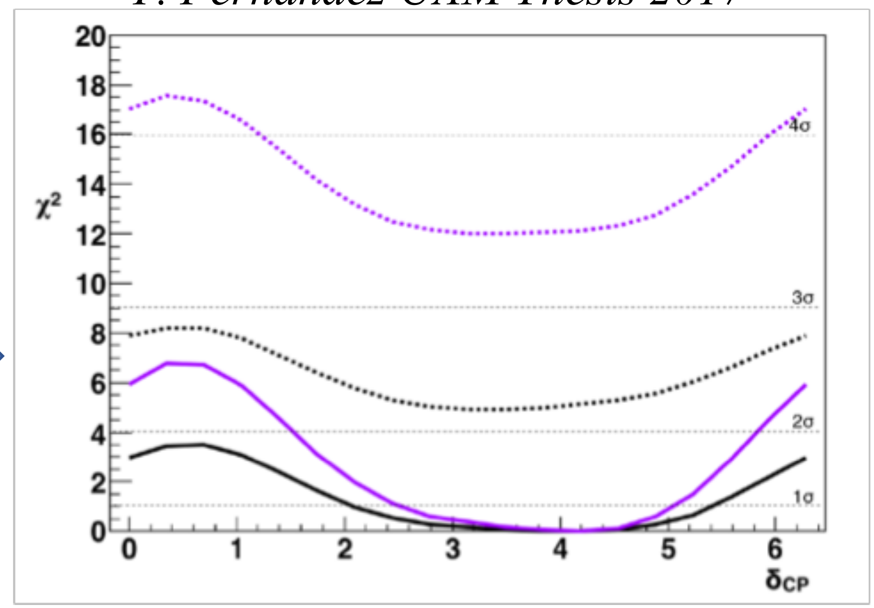
- Direction resolution problem can be partially ameliorated by separation of neutrinos and antineutrinos with neutron tagging

- Benefit from better pointing of antineutrino events as well as separating CP sensitive components

P. Fernandez UAM Thesis 2017

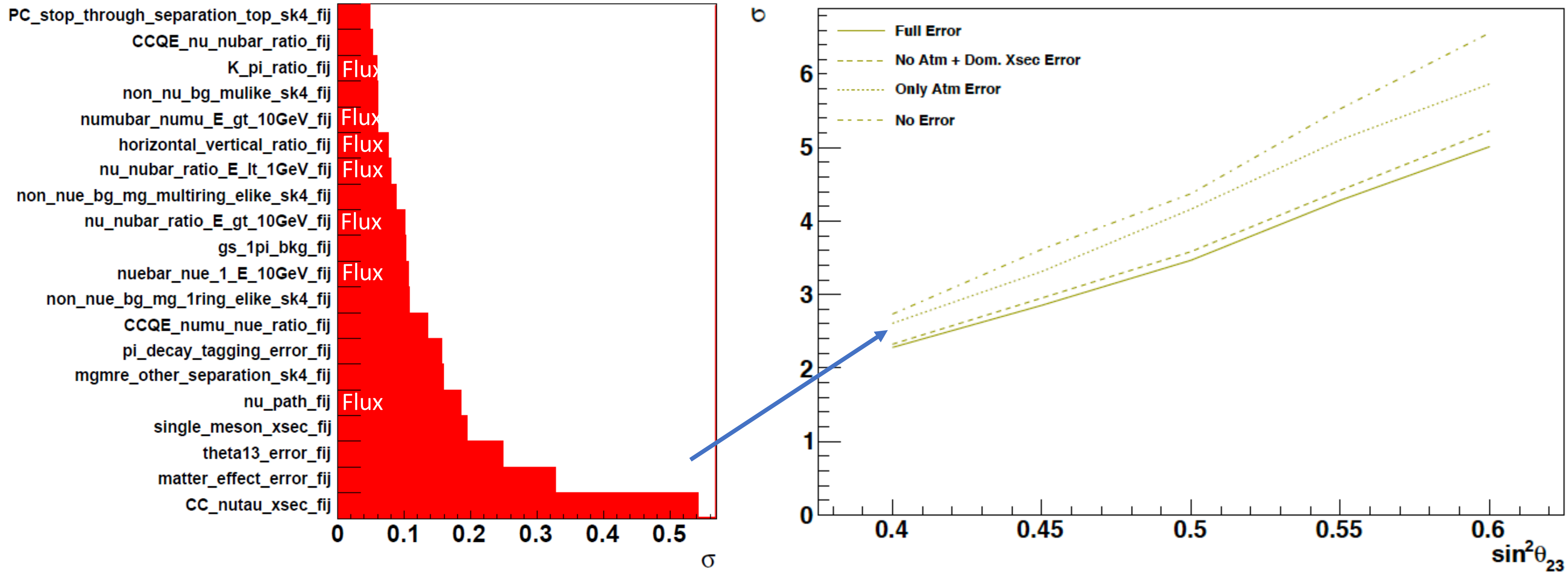


		Samples		
		ν_e-like (dcy-e>0)	$\nu_e + \overline{\nu}_e$-like (dcy-e=0 & neutrons=0)	$\overline{\nu}_e$-like (dcy-e=0 & neutrons>0)
MC true ν	CC ν_e	77.1%	85.8%	51.9%
	CC $\overline{\nu}_e$	1.7%	11.1%	43.9%
	CC ν_μ	11.6%	0.3%	0.3%
	CC $\overline{\nu}_\mu$	3.3%	0.0%	0.0%
	NC ν	6.3%	2.8%	3.9%



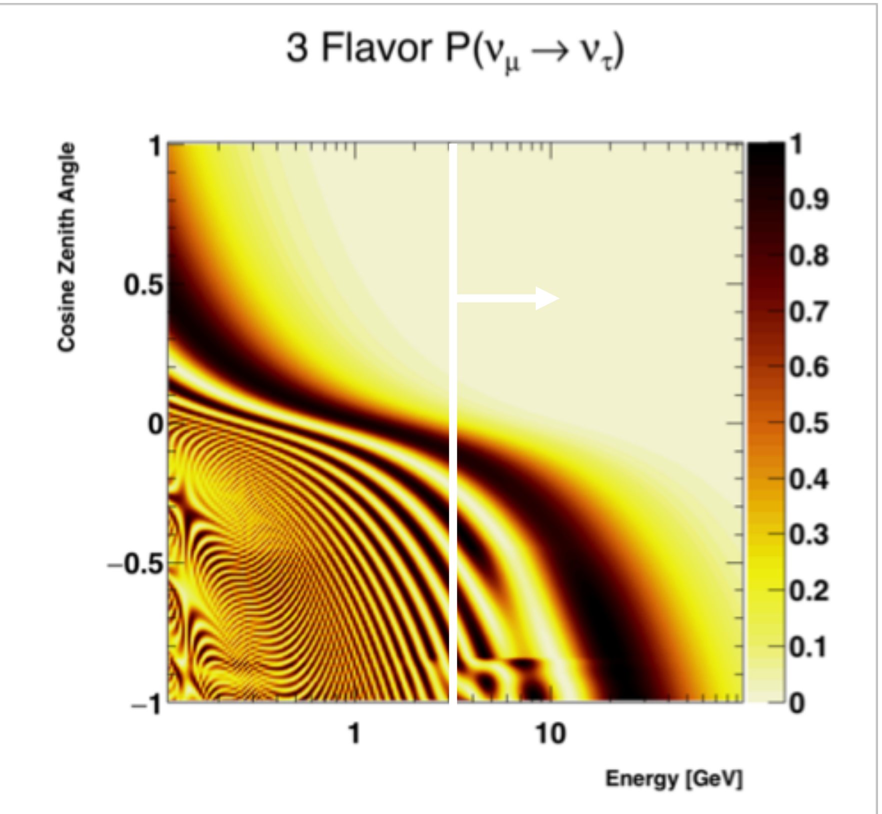
Black : Std HK Analysis
Purple : With 70% eff. Neutron tagging

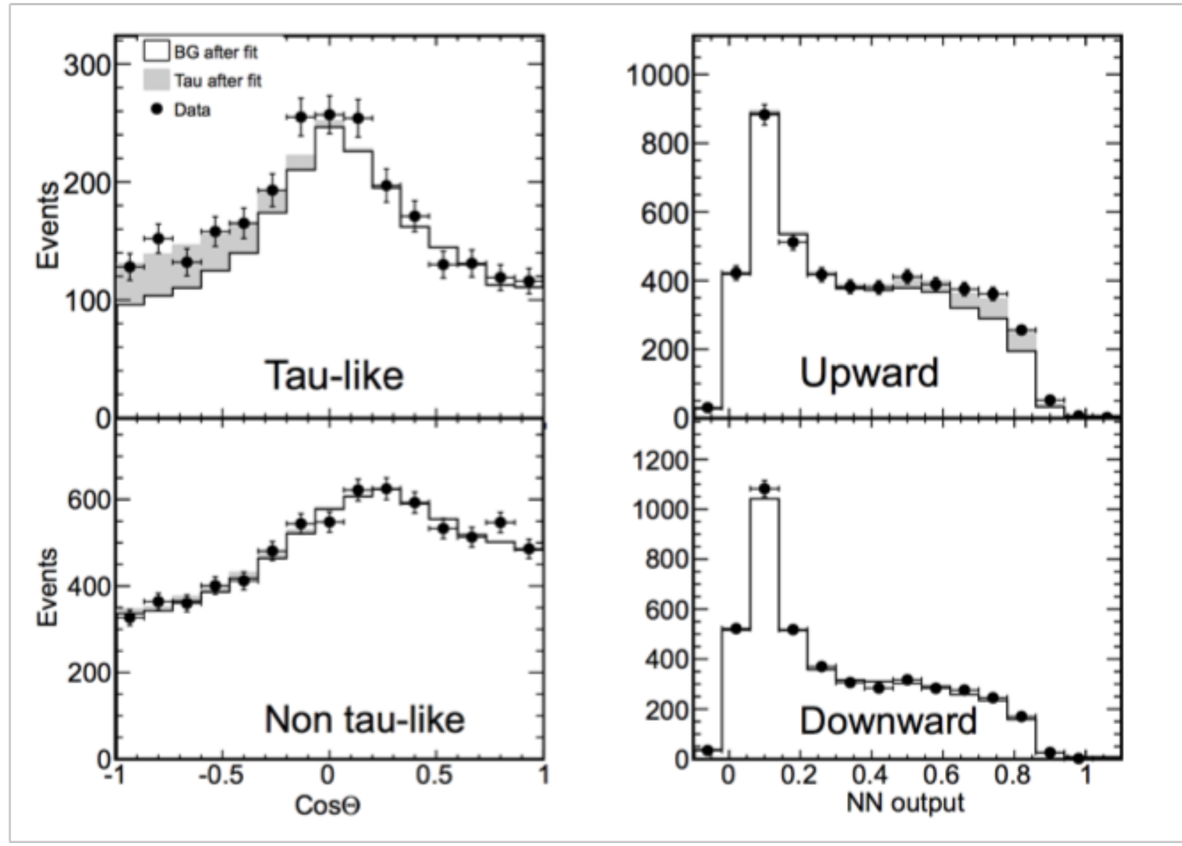
Impact of Various Systematic Error Sources: Mass Hierarchy



- Uncertainties -not- related to the flux are the biggest issue for MH determination
- Until tau neutrino interaction cross section is known better, flux improvements will be of limited impact

Search for Tau Neutrinos at SK





- Tau neutrinos do not exist in the primary atmospheric flux below 10^5 GeV but can be induced by oscillations
  - Important for ν_τ cross section studies, tests of unitarity, background to hierarchy search, etc.
- Complicated event topologies due to hadronic tau decay, search using neural network-based method

Systematic Errors in Search for Tau Neutrinos

Phys. Rev. D 98, 052006 (2018)

- Tau appearance seen in SK at 4.6 σ
- Flux-averaged cross section

$$\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$$

$$= (0.94 \pm 0.20) \times 10^{-38}\ \text{cm}^2$$

Stat+Syst.

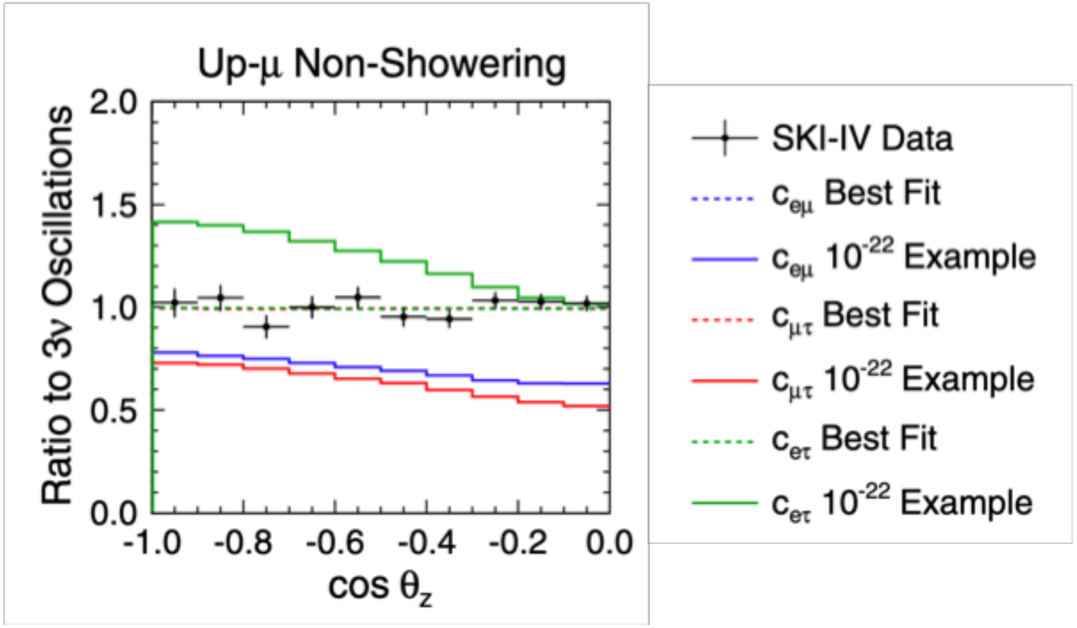
- Dominant systematics are cross section related but flux systematics are also relevant

Ordered in decreasing order of impact

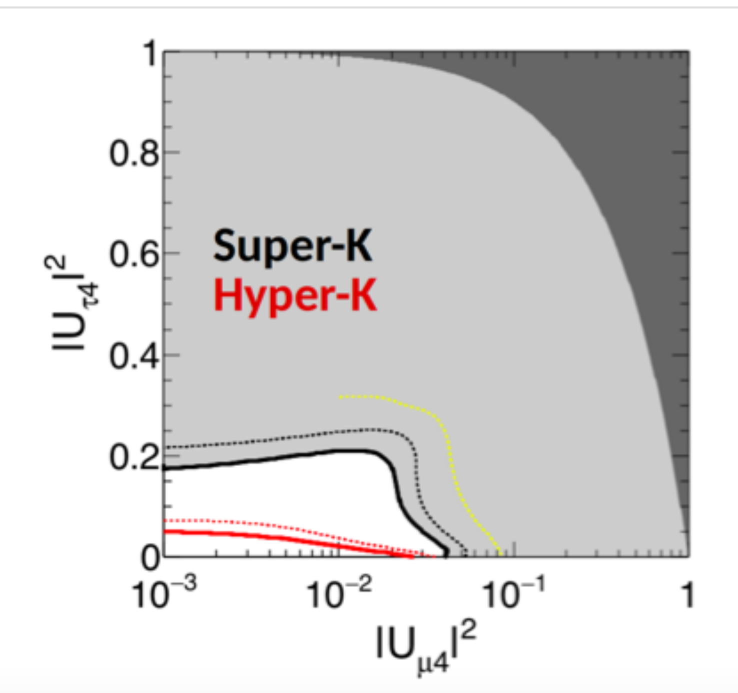
Systematic error		σ (%)
NC/CC ratio	20%	20
DIS q^2 dependence for low W	15%	10
Meson exchange current		10
1π axial coupling		10
DIS q^2 dependence for high W		10
Coherent π cross section		100
Flux normalization ($E_\nu > 1$GeV)	11%	15
1π background scale factor		10
1π axial form factor		10
CCQE cross section		10
Single pion $\pi^0/\pi^\pm$ ratio		40
$\bar{\nu}_\mu/\nu_\mu$ ratio ($E_\nu > 10$ GeV)	5.6%	15
$\nu/\bar{\nu}$ ratio ($E_\nu > 10$ GeV)	5.3%	5
DIS cross section ($E_\nu < 10$ GeV)		10
FC multi-GeV normalization		5
$\bar{\nu}_e/\nu_e$ ratio ($E_\nu > 10$GeV)	4.6%	8
K/π ratio	4.5%	10
Single meson cross section		20
Single-pion $\bar{\nu}/\nu$ ratio		10
Horizontal/vertical ratio	3%	1
CCQE $\nu/\bar{\nu}$ ratio		10
DIS cross section		5
Matter effect		6.8
Neutrino path length		10

* Numbers in red are maximum impact on analysis bins

A word about *Exotic* Oscillation Scenarios



- Lorentz invariance-violating oscillation effects are strongest at high energies
- E > 30 GeV flux uncertainties limit (already impressive sensitivity cur. Lim ~ $10^{-23,-28}$)



- Sterile neutrino oscillation sensitivity limited by uncertainties in flux (and cross section) around 1 GeV
- Particularly $U_{\mu 4}$

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

Thoughts

- There is considerable motivation to make the most of current (Super-K, T2K, their combination) and future (Hyper-K) and therefor systematic error reduction across the board should be expected

- Assuming the errors discussed above are reduced, then the impact of atmospheric flux uncertainties will become a more serious issue

- Hadron production measurements can be expected to help reduce flux uncertainties
  - Either *directly* as in the Bartol Model …or…
  - *Indirectly* via better tunes of the generators used in the Honda Model

- Similarly improved muon measurements can improve flux predictions and cross checks of models

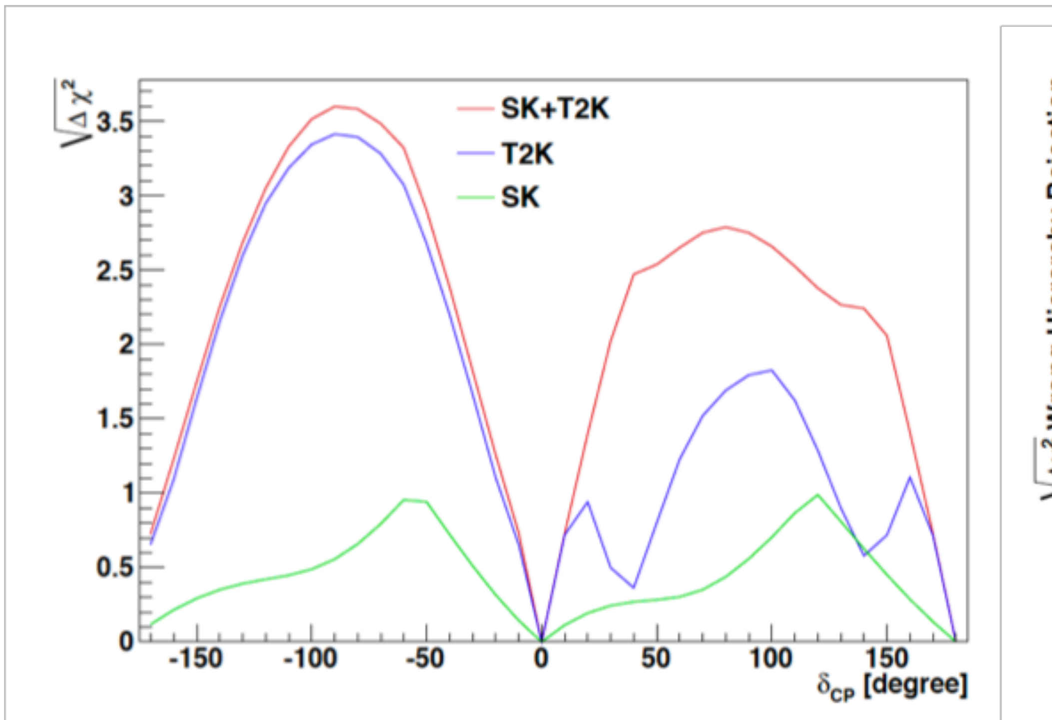
- In addition: Hadron production measurements are essential for neutrino interaction cross section measurements, which typically suffer from large flux systematic errors (which themselves derive from hadron production data)
  - Atmospheric neutrino measurements will indirectly benefit as a result of improved cross section understanding

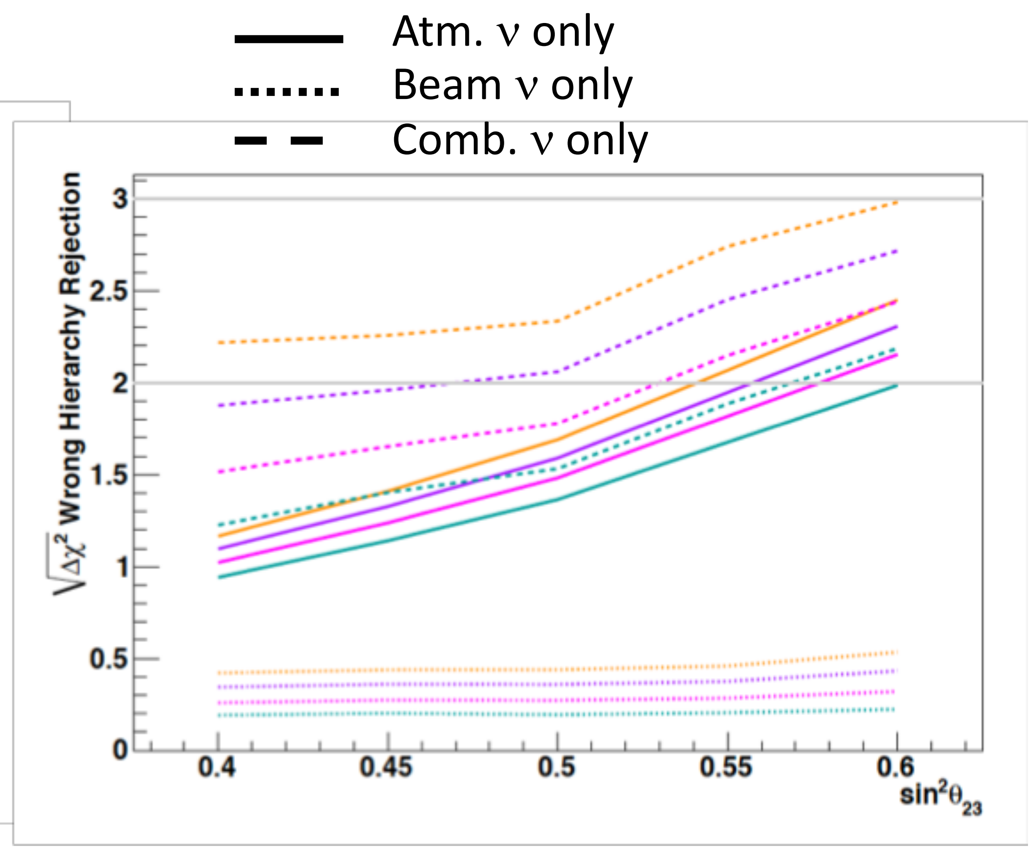
Thoughts* About: Common Treatment of Hadron Production Systematics

* Rather speculative.

Motivations for Considering Common Flux Systematics

- There are several possible "combined" fits that could benefit from unified flux systematics
  - Super-K + T2K : Beam + Atmospheric ν oscillation constraints
  - Super-K + IceCube : Atmospheric ν flux or oscillation measurements
  - T2K + NOvA : Beam oscillation constraints
  - … all of the above …





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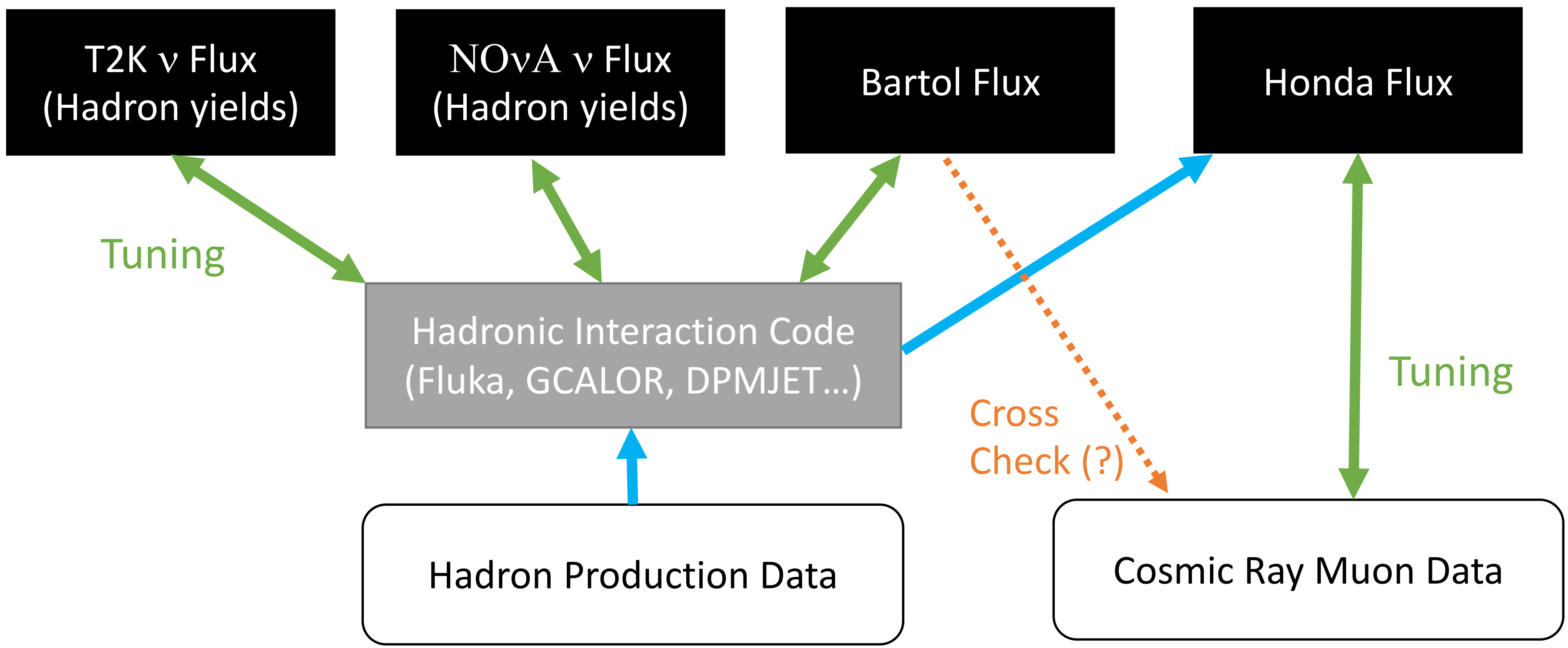
  - … all of the above …

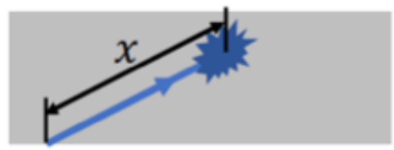
- Models are built or tuned from similar hadron production data sets, so are in principle correlated (though not everyone uses the same generators, and production targets are different)



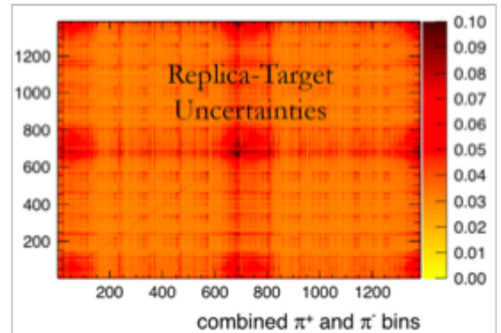
For Combined SK and T2K

- Atmospheric neutrino flux model is tuned to some central value either with hadron production data (*pion*, kaon) or cosmic ray muon data, with some uncertainties

- T2K flux model is also tuned to a central value with uncertainties based on the uncertainties in the available hadron production data (*pion*, kaon reweighting)



$$weight(x) = \frac{\sigma_{data}}{\sigma_{MC}} e^{-\rho(\sigma_{data} - \sigma_{MC})x}$$



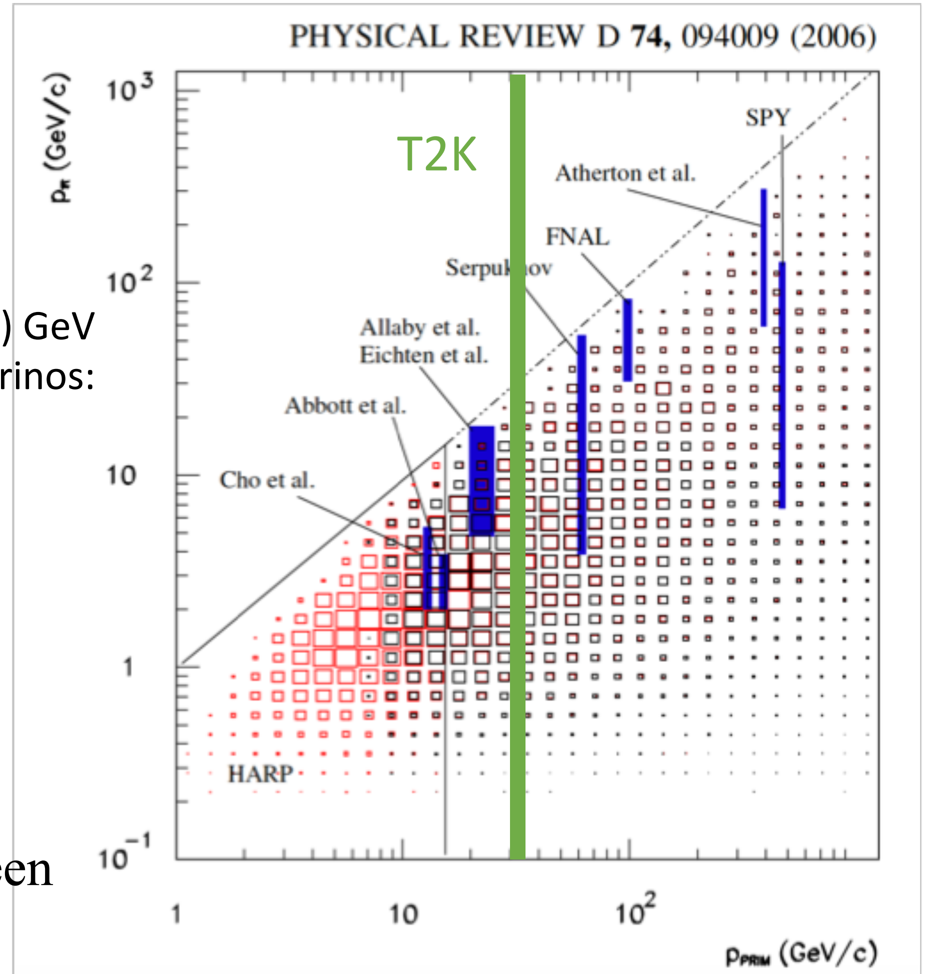
- Near detector *neutrino* data is then fit to constrain both interaction uncertainty and flux uncertainty
  - Since neutrinos come from *hadronic* parents, this can alternatively be viewed as an additional constraint on those parents (now correlated with neutrino cross section model)
- If SK (atmospheric ν) and T2K use the same neutrino interaction model, then *in principle* part of the atmospheric neutrino flux can be constrained as well

- Of course it sounds straight-forward…

For Combined SK and T2K: Difficulties

- Hadron production phase space for atmospheric neutrinos and accelerator neutrinos different
  - Model dependence

Phase space for producing E < O(1) GeV atmospheric neutrinos:



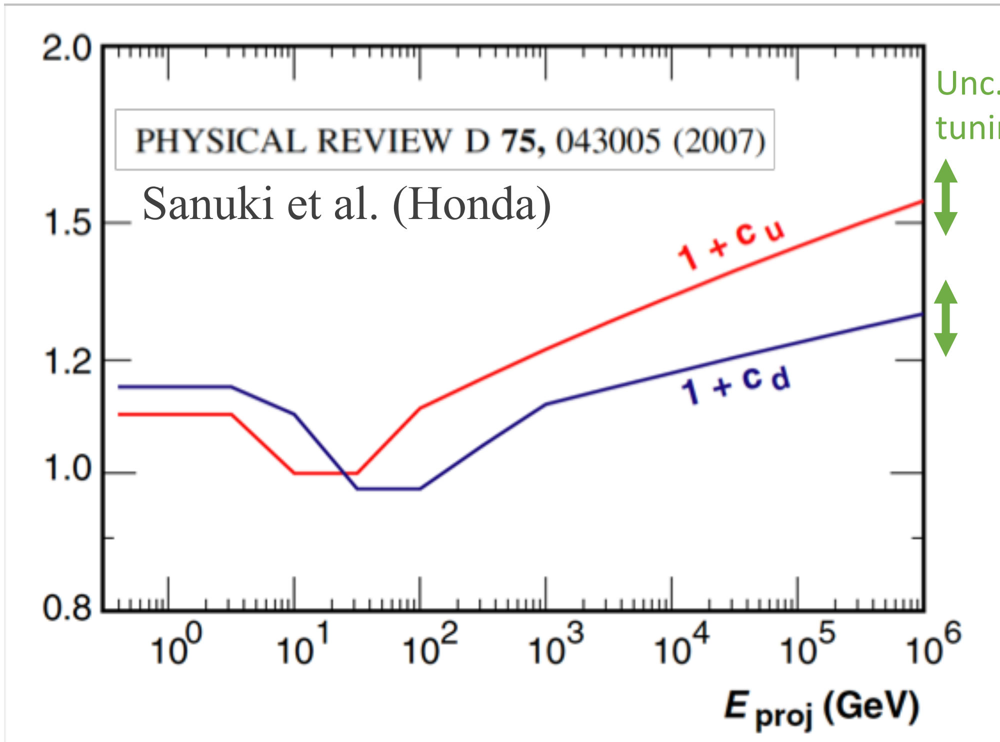
- Production targets and interaction environment are different
  - Carbon vs. Nitrogen / Oxygen
  - Fe, Al, Ti vs. Nitrogen / Oxygen
  - Model dependence

- Not exactly clear how to draw correlations between the models
  - …. Needs more thought (rough ideas next page)

- Not obvious that its wise to try and use the same hadronic codes in both beam flux prediction and and atmospheric neutrino models

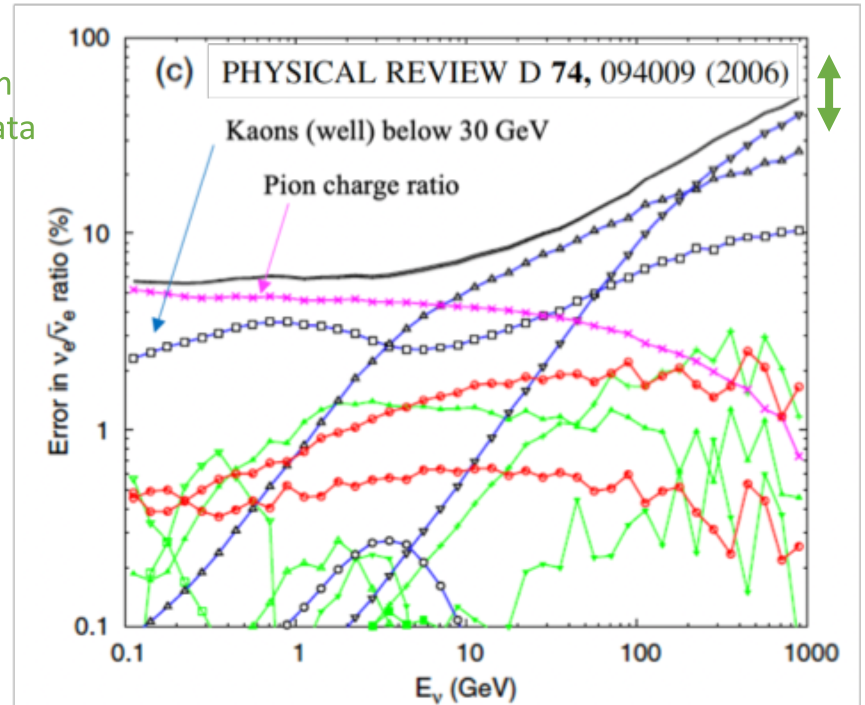
Possible Approaches: Tier 1

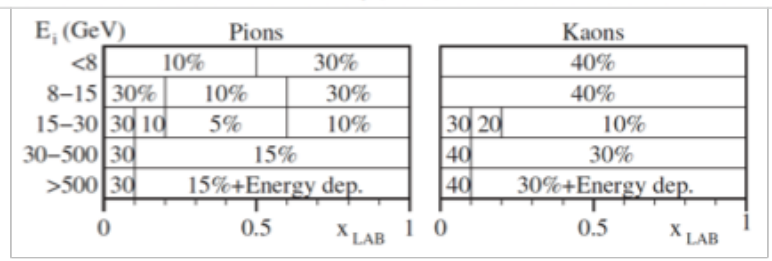
- If experiments (or combinations of experiments) are interested in forming correlated flux predictions would want to know how atmospheric flux changes as a function of the systematic errors assigned to underlying hadron production data
- Ie, "response functions" for neutrino flux for model parameters with some prior
  - Experiments can try to connect to their choice of hadron simulation



Unc. from tuning data

$$\langle E_{\pi^+}\rangle = (1 + c_u)\langle E^0_{\pi^+}\rangle \qquad (u\bar{d})$$
$$\langle E_{\pi^-}\rangle = (1 + c_d)\langle E^0_{\pi^-}\rangle \qquad (d\bar{u})$$
$$\langle E_{\pi^0}\rangle = (1 + (c_u + c_d)/2)\langle E^0_{\pi^0}\rangle \qquad ((u\bar{u} - d\bar{d})/2)$$

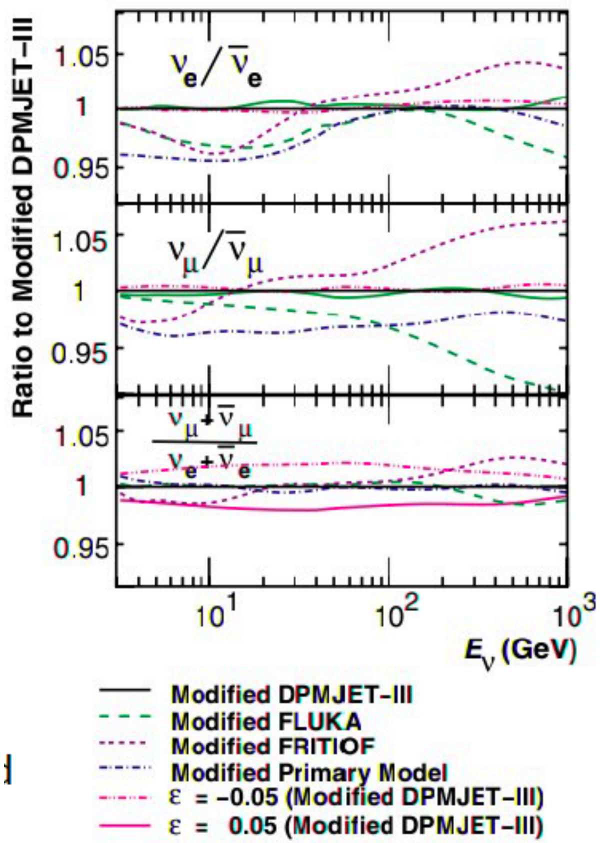




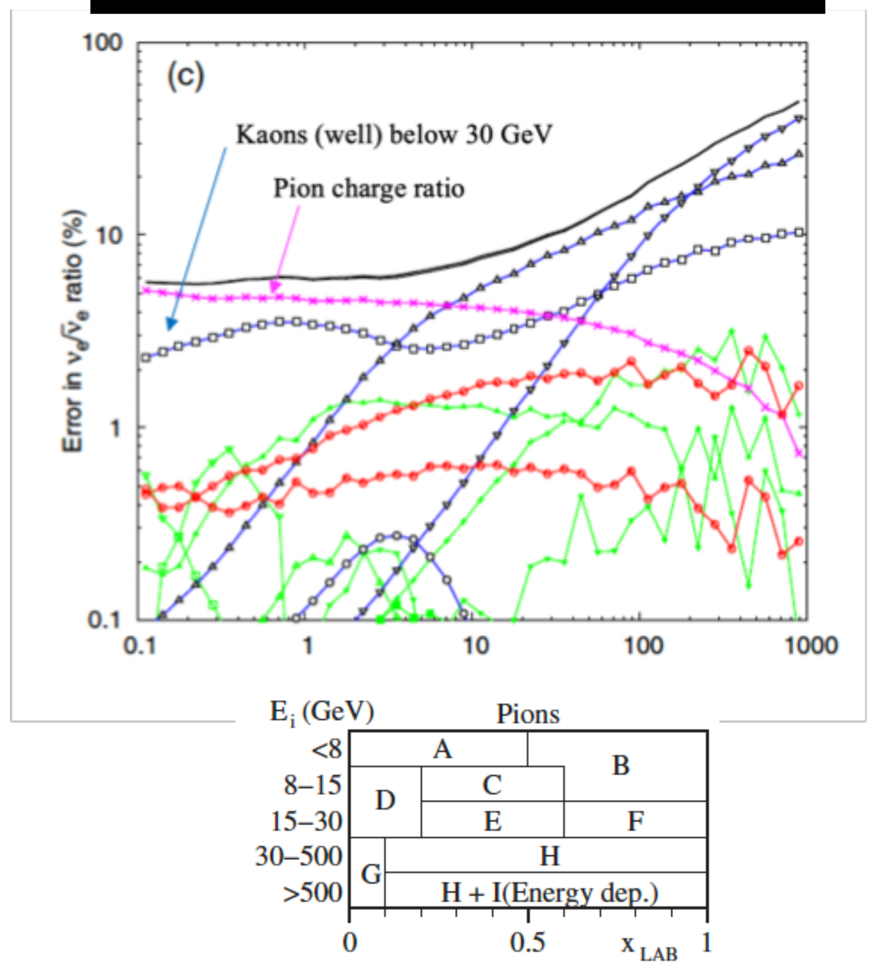
Possible Approaches: Tier 2

- Can imaging atmospheric neutrino flux models providing uncertainties and their parameters by swapping in different hadronic interaction codes
  - … a kind of a hybrid approach between Honda and Bartol methods
  - Naïve understanding is that both codes have this ability

Honda: Several Models

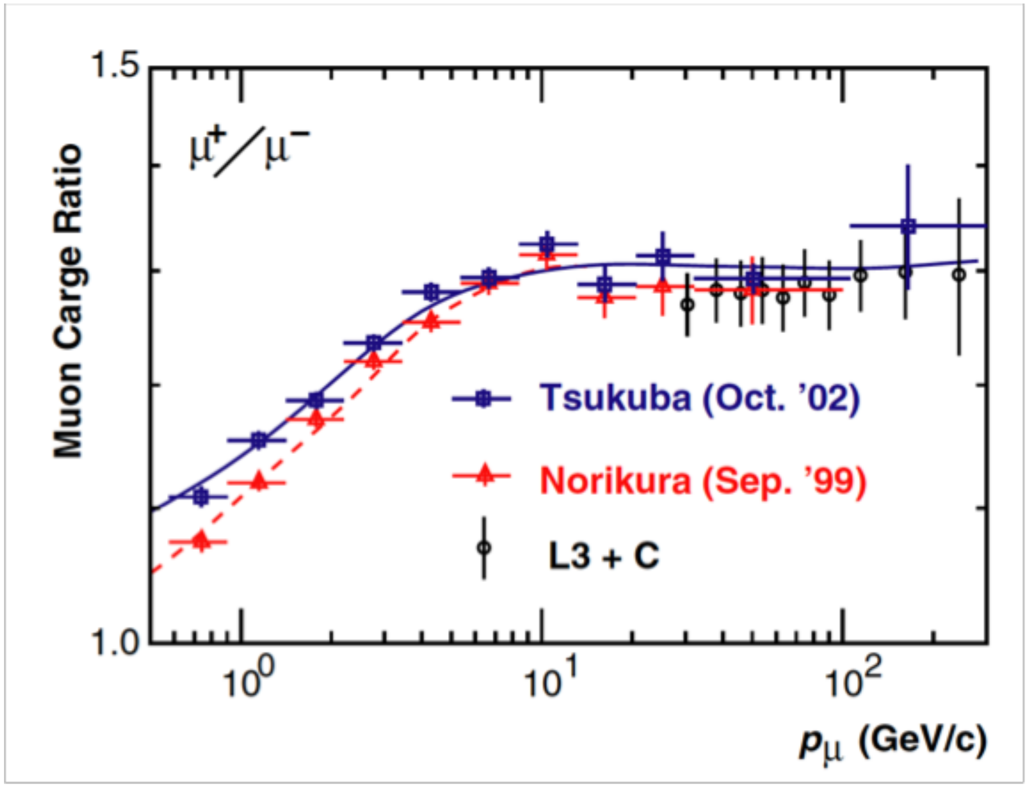


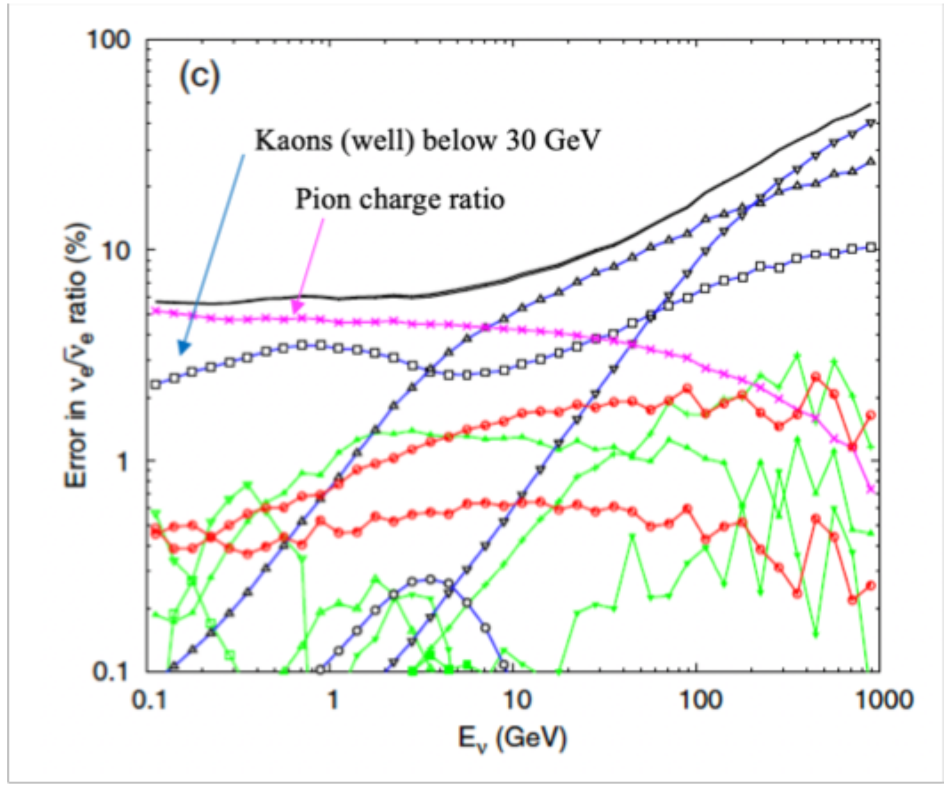
Bartol: One Model, several dials



Speaking of merged methods…

- Is there any extra benefit of trying to over constrain the atmospheric neutrino flux calculations by tuning with both cosmic ray muon and hadron production data sets?

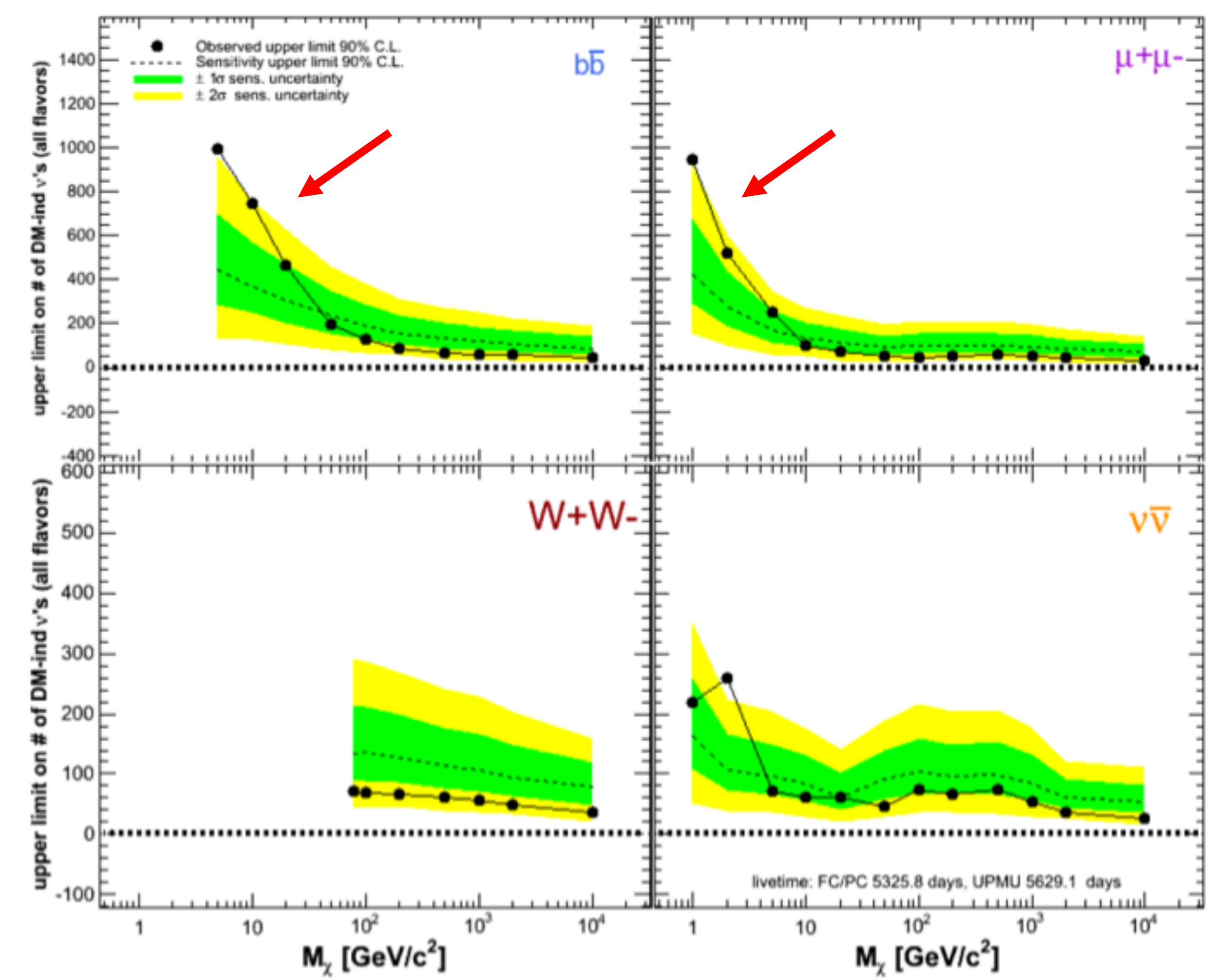




Flux Uncertainty's Impact on non-Oscillation Physics

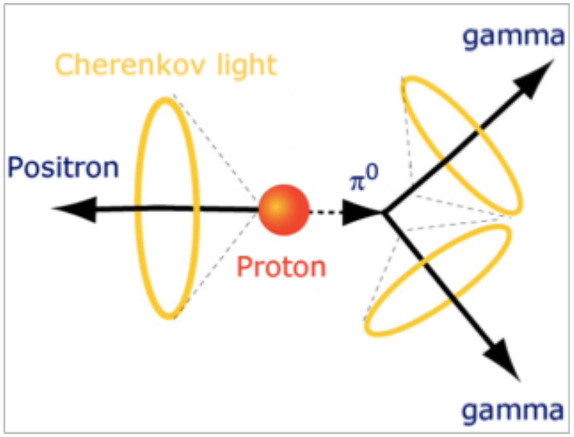
Other Areas of Impact: Indirect Dark Matter Searches

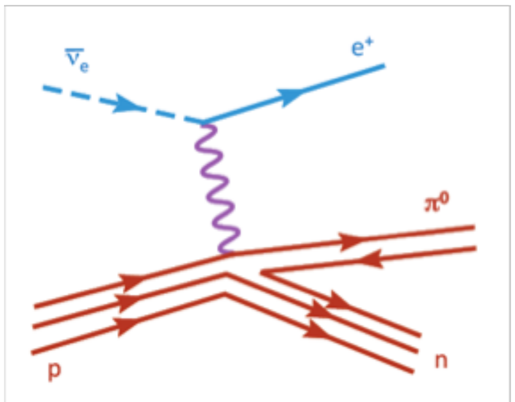
- Atmospheric neutrinos are the dominant background to indirect searches for dark matter
- Low energy flux is the largest uncertainty in the search for low mass WIMPs
  - Normalization in particular!
- Super-K data show a weak excess of low energy data, consistent with the no-WIMP hypothesis, but uncertainties are large



Plots show search for $\chi\chi$ annihilation in the galactic center for various assumed branching modes

Other Areas of Impact: Searches for Proton Decay





		$p \to e^+\pi^0$ low P_{tot}	$p \to e^+\pi^0$ high P_{tot}
Efficiency			
	π-FSI	2.8	10.6
	Correlated decay	1.9	9.1
	Fermi momentum	8.5	9.3
	Reconstruction	4.6	5.6
	Total	10.2	17.7
Background			
	Flux	7.0	6.9
	Cross section	14.5	10.4
	π-FSI	15.4	15.4
	Reconstruction	21.7	21.7
	(neutron tag)	10	10
	Total (I/II/III)	31.2	29.4
	(IV)	32.7	31.1
Exposure		1.0	1.0

- Flux systematic errors are sub-dominant at current exposures, but may become more important in future

In Summary

- In some sense there is a ‘chicken-and-egg’ problem with atmospheric neutrino measurements:
  - Oscillation parameter measurements improve with better cross section measurements which improve with better flux constraints
  - Seems reasonable to start trying to improve everything at once

- The biggest impact of reduced flux uncertainties would come manifest as improved constraints on δ_{CP} and perhaps also exotic scenarios
  - Knock-on benefit to non-oscillation physics and MH
  - Expect further benefit with reduction of other (xsec and detector) errors

- In principle all fluxes based on hadron production should be correlated at some level
  - It *may* be beneficial to define and exploit those correlations for future combined measurements
  - Likely easier for atmospheric-only combinations than for beam+atmospheric studies

Backups