Cross-sections for atmospheric neutrino studies

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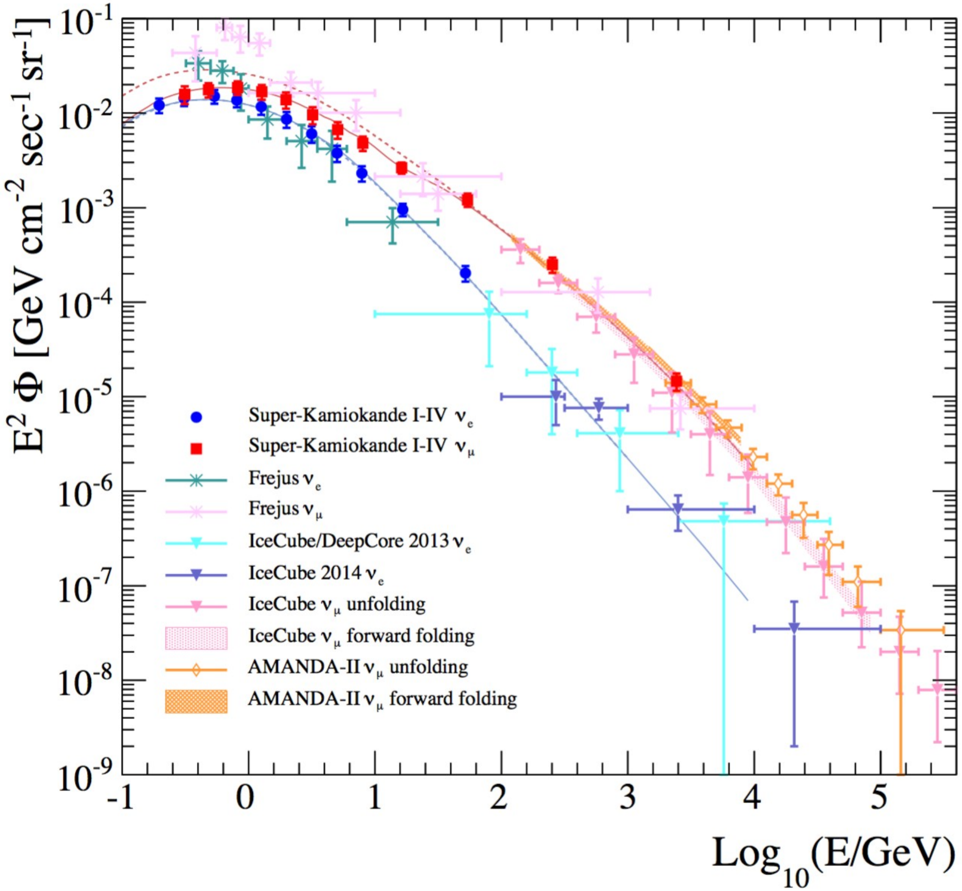
2019-12-12

Introduction

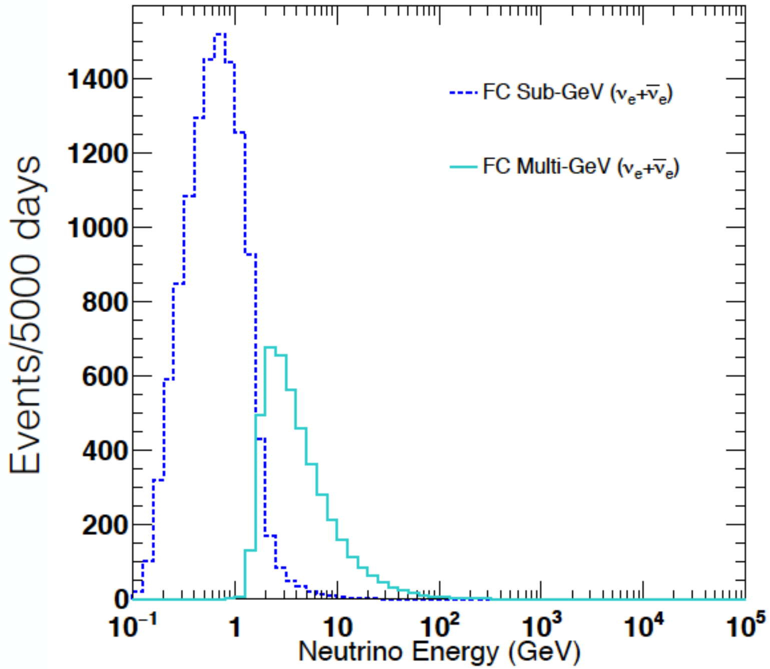
- In this presentation, I will be covering the case of Super-Kamiokande (which extends naturally to Hyper-Kamiokande), needs of other experiments like IceCube or KM3NET could be a bit different

- Focusing on what I think are the main neutrino interaction related issues for the study of atmospheric neutrino oscillations. See talks I gave at the NuSTEC SIS/DIS and Pion production in the resonance region workshops for more details and other issues.

Atmospheric flux covers a large energy range, and different interaction modes dominate in different regions



Super-Kamiokande samples



In Super-K, divide between low ("sub-GeV") and high energy ("multi-GeV") samples

Schematically:

Sub-GeV

- Sensitive to δ_{CP}
- Dominated by CCQE and 2p2h interactions

→ Lot of studies in recent years for beam experiments

→ No additional needs compared to those experiments

Multi-GeV

- Sensitive to mass hierarchy
- Dominated by resonant and DIS interactions

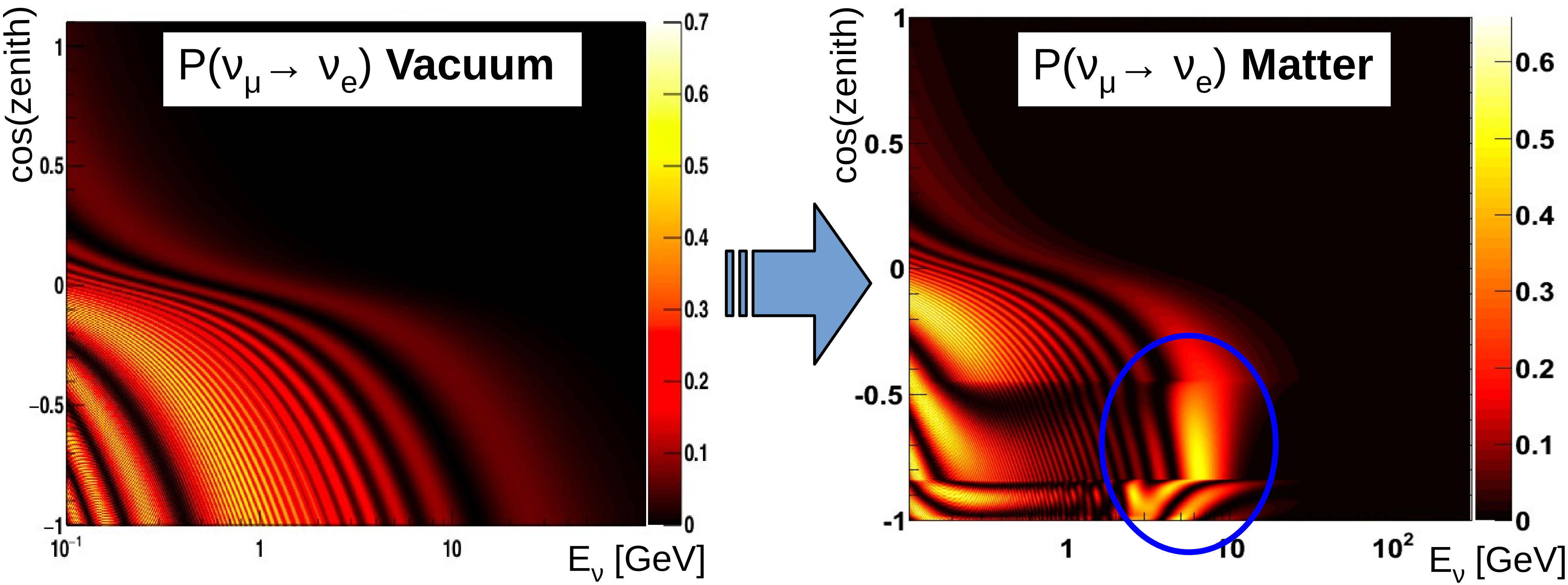
→ Not as intensely studied recently, in particular for DIS

→ Where we would benefit from some developments

Mass hierarchy with atmospheric neutrinos

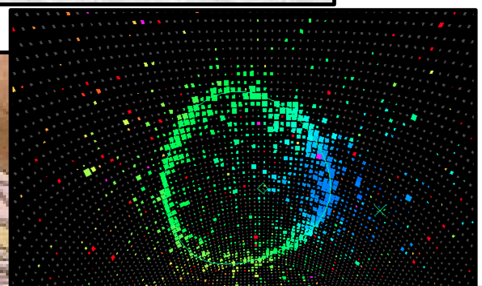
- Order of neutrino mass eigenstates is not fully known
- Propagation in matter modifies oscillation probabilities compared to vacuum, in different ways depending on MH
- In particular resonance in muon to electron flavor oscillation

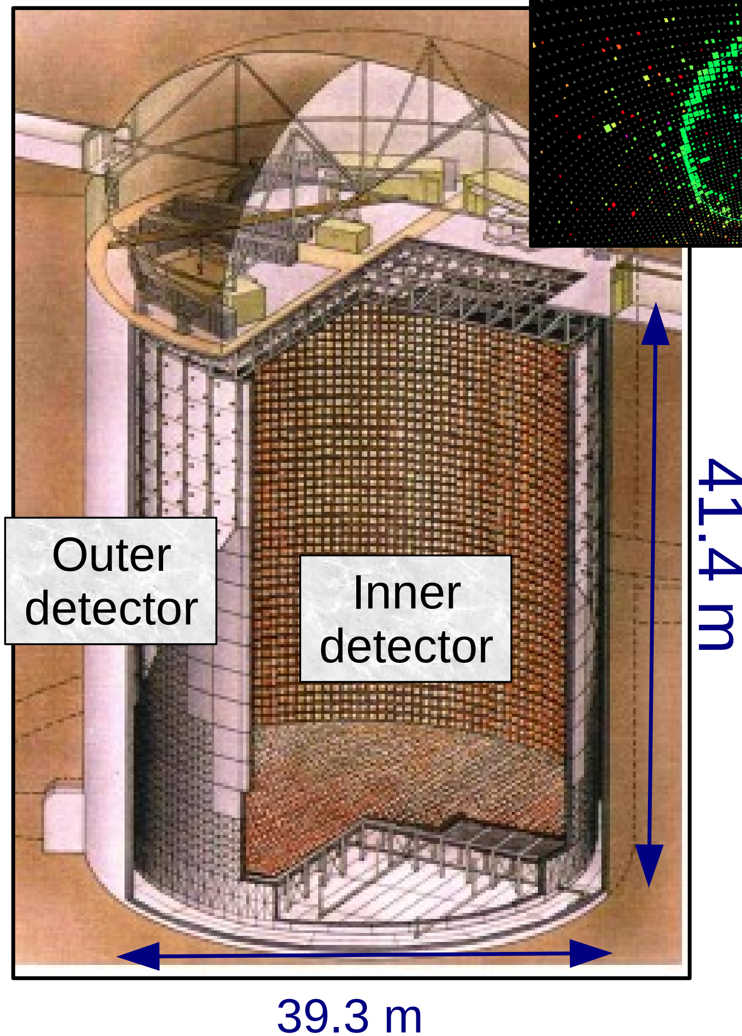
NH: ν only - IH: $\bar{\nu}$ only



Super-Kamiokande Detector

- 50 kt (22.5 kt fiducial) water Cherenkov detector
- 1000m overburden
- Operational since 1996



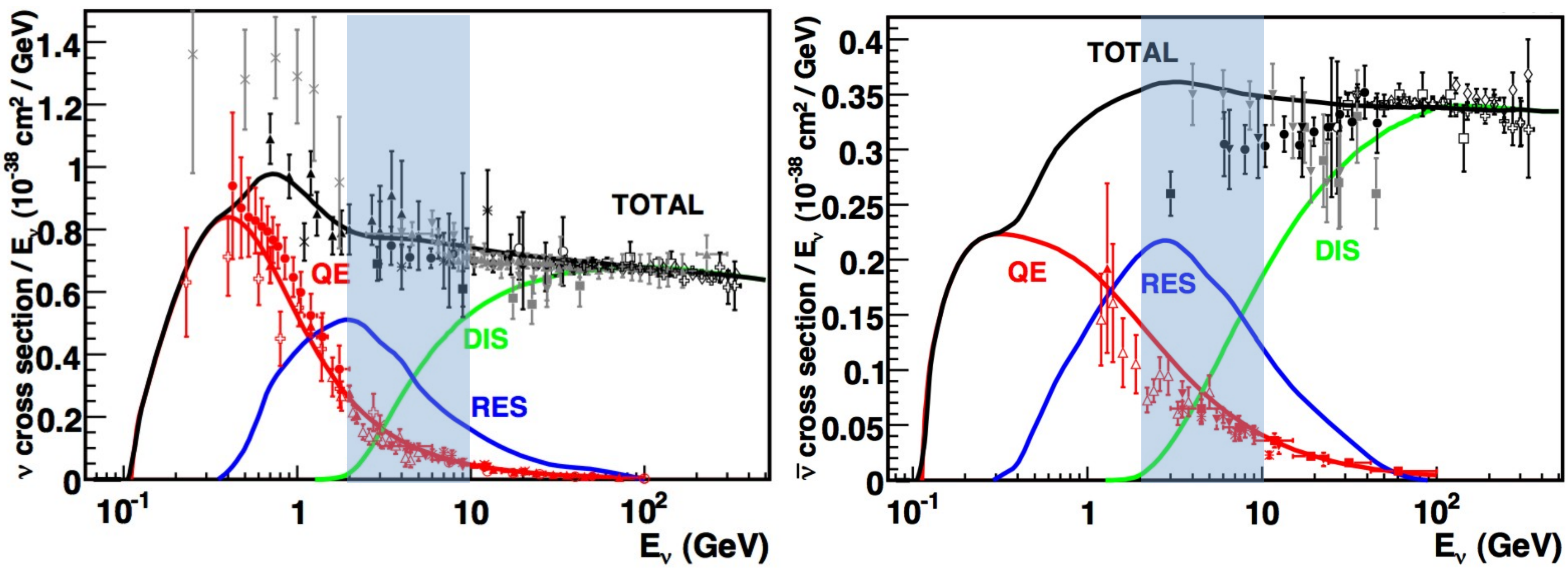


Wide physics program:
- ✓ **Atmospheric neutrinos**
- ✓ Solar neutrinos
- ✓ Supernova neutrinos
- ✓ Proton decay
- ✓ Dark matter indirect detection

- Good separation between $\mu^{\pm}$ and $e^{\pm}$ (**separate ν_{μ} and ν_{e} CC interactions**)
  → Less than 1% mis-PID at 1 GeV
- No magnetic field: **cannot separate ν and $\bar{\nu}$ on an event by event basis**
- **Only detects charged particles above Cerenkov threshold and photons**
  → limitation for energy and directional reconstruction

Neutrino interactions in the resonance region

- Resonance expected to occur in the region 2-10 GeV
- This is essentially the "transition region" from resonant to DIS
- As a result, need good:
  - resonant model
  - DIS model, in particular at low W
  - way to move from one type of model to the other



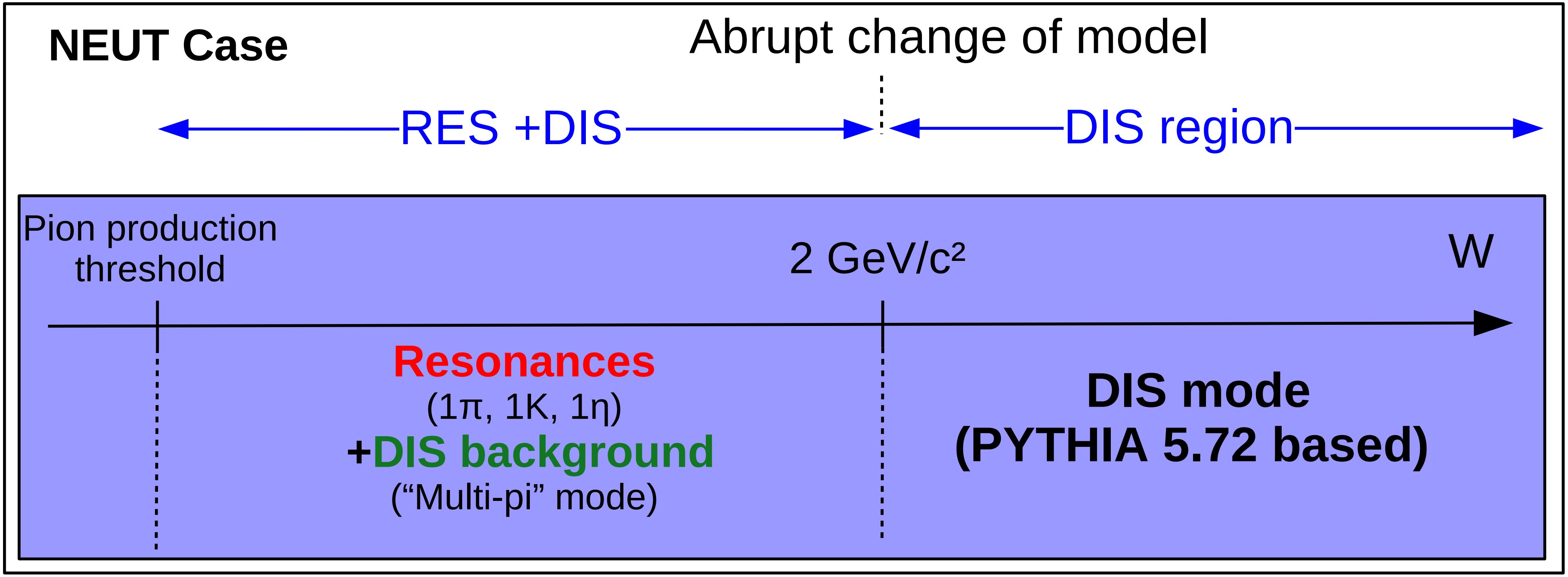
Plots from Hewett, J.L. et al. arXiv:1205.2671 [hep-ex]

Transition between RES and DIS regions

- Duality suggests to use resonant parameterization at low W and DIS parameterization at high W, but no clear guidance on how to transition and deal with overlap

- In practice generators use schemes based on number of particle produced at low W:
  - use resonant model for single and sometimes 2 mesons production
  - custom DIS model for events with more particle produced
  - subtract part of the DIS cross section that corresponds to what is handled by the resonant

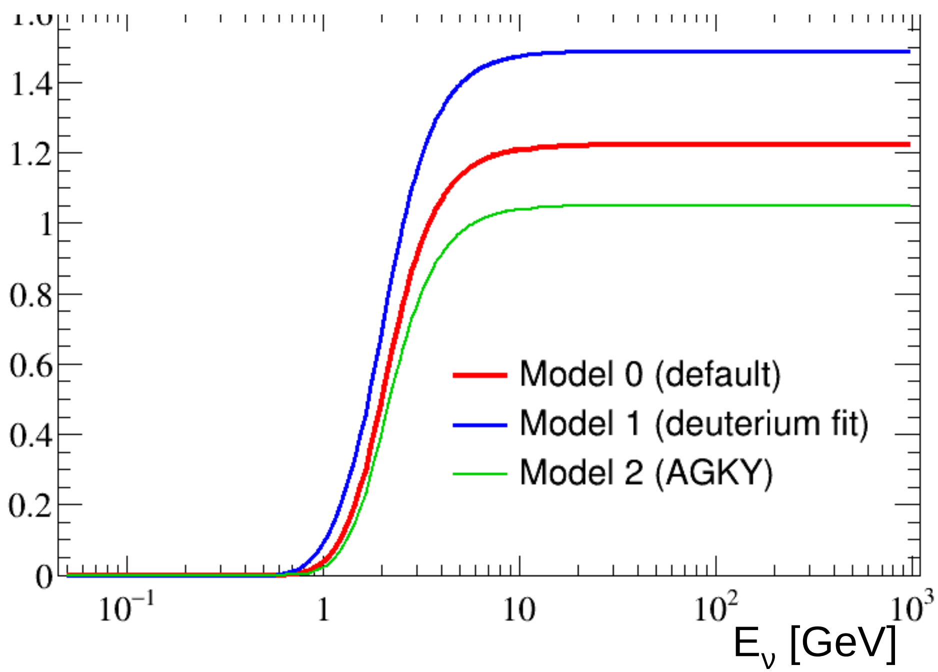
- Above a certain W, use full DIS model based on PYTHIA

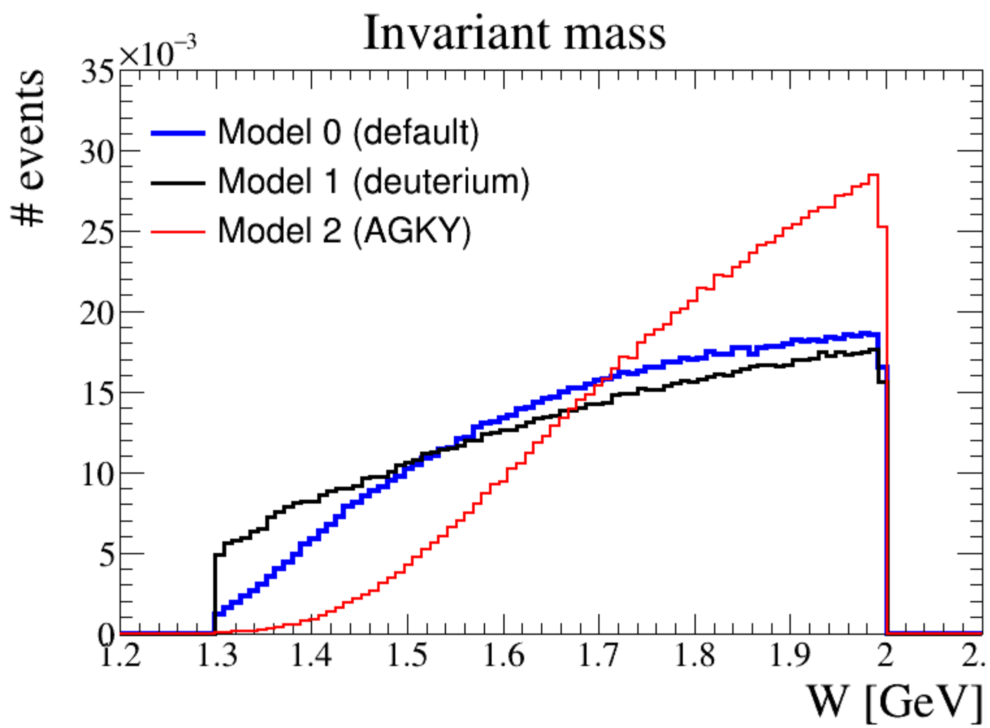


Transition between RES and DIS regions Problem(s)

- Main issue is that to subtract part of the DIS cross-section at low W model, need to use multiplicity model to determine which fraction of the DIS events correspond to 2 hadrons, 3 hadrons and so on

- No reliable model for this, and as a result total and differential cross-section for DIS mode in this region depend on the model chosen





- Could potentially make a good multiplicity model with new multiplicity data on hydrogen and deuterium
- But might be better to have a model which has the transition and overlap built in

PYTHIA at low W

At last year's NuSTEC workshop on SIS/DIS region, one of the PYTHIA author warned us about using PYTHIA at "low" W

"I would not trust PYTHIA for anything with less than 6 pions"

Physics assumptions/limitations:

Always want to confine previously deconfined color.

Target-m not really present in x-section or q/g kinematics.

Only tested for $W > 4$ GeV, small W in $e^+e^- \to h$ only, last global overview in 1987?

"Jet joining" not well-understood for low hadron multiplicity.

Strong isospin not traced in string.

Strings are traditionally non-interaction.

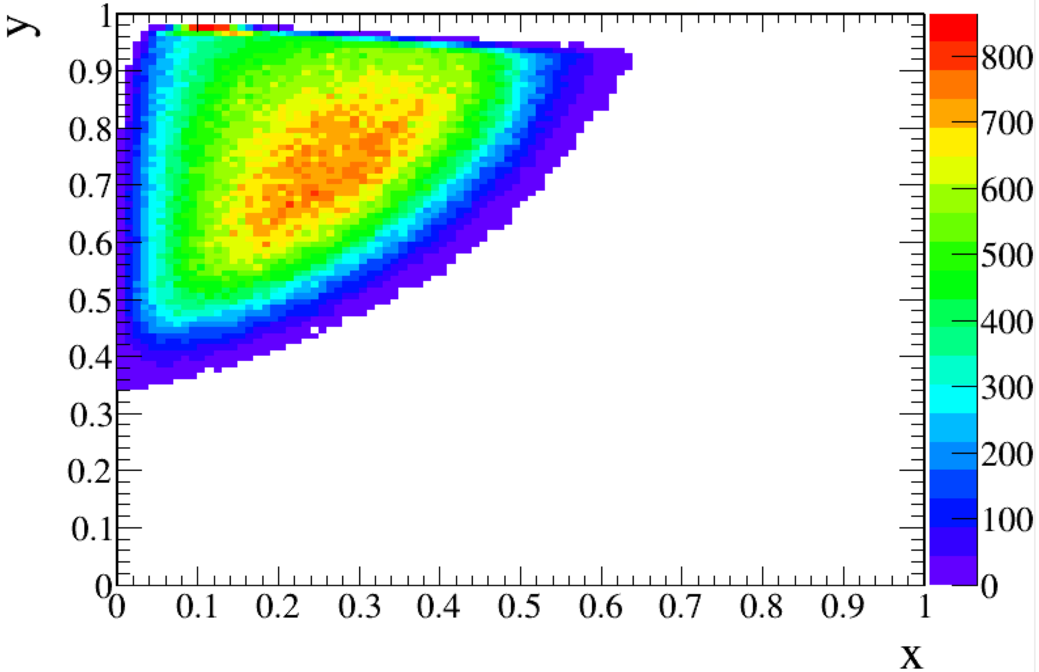
S. Prestel, "The LUND hadronization model"

Unfortunately we use it from W=2 GeV in NEUT
(a bit higher W for GENIE)

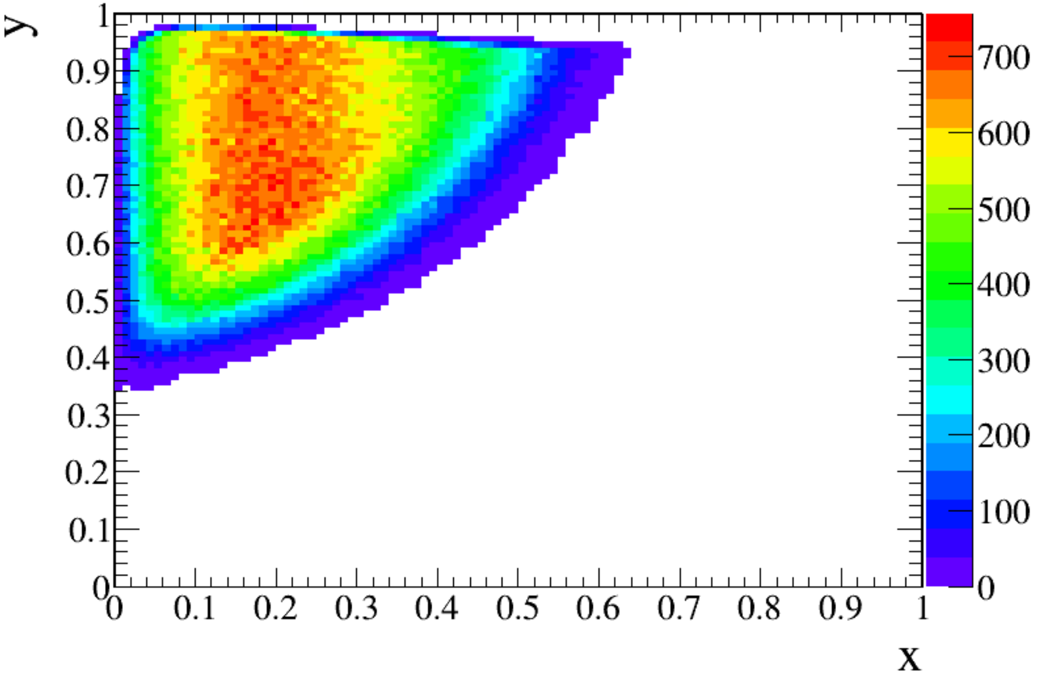
PYTHIA at low W
There might really be a problem

- In NEUT, only pass the neutrino and target nucleon type and energies to PYTHIA and let it generate the event
- When looking at the obtained (x,y) distribution, it does not match the prediction from the double differential cross-section formula

From Pythia 5.72



From d²σ/dxdy formula



4 GeV ν_μ on H_2O target

PYTHIA at low W: use it differently?

- GENIE and NuWRO use PYTHIA 6, who can't generate the event. So they decide of the properties of the event (from $d^2n/dxdy$) and use PYTHIA fragmentation routines only
- Need to pass hit quark, spectator diquark and W to Pythia
- Problem is for interaction on a sea quark: not a hit quark + diquark spectator system

Driving PYTHIA6 from GENIE

Some amount of monkey business in making **quark** + **diquark** assignments most certainly due to our own unfamiliarity with PYTHIA. Luckily, overall generation outcomes not sensitive to choices made.

Init state	Hit quark	Leading quark	Remnant system	PYTHIA6 assignment		Weirdness level
ν + p CC	d valence	(d $\rightarrow$) u	uu	u	uu	
ν + p CC	d sea	(d $\rightarrow$) u	$\bar{d}$ + uud	u	uu	*
ν + p CC	s sea	(s $\rightarrow$) u	$\bar{s}$ + uud	u	uu	**
ν + p CC	$\bar{u}$ sea	($\bar{u}$ $\rightarrow$) $\bar{d}$	u + uud	u	uu	***
ν + n CC	d valence	(d $\rightarrow$) u	ud	u	ud	
ν + n CC	d sea	(d $\rightarrow$) u	$\bar{d}$ + udd	u	ud	*
ν + n CC	s sea	(s $\rightarrow$) u	$\bar{s}$ + udd	u	ud	**
ν + n CC	$\bar{u}$ sea	($\bar{u}$ $\rightarrow$) $\bar{d}$	u + uud	u	ud	***
...	...	...	...	...	...	...
...	...	...	...	...	...	...

C.Andreopoulos (Liverpo

C. Andreopoulos at NuSTEC SIS/DIS workshop

Solves the problem of the (x,y) distribution, but not of PYTHIA not properly doing hadronization at low W (especially with diquark endpoint according to PYTHIA author)

DIS model and systematics

- DIS Model used in Super-Kamiokande is based on NEUT as described on slide 6, with a custom low W model and PYTHIA at higher W
- Now considering possible limitation of the models and systematic uncertainties based on their importance for the study of the mass hierarchy

Currently 4 DIS related systematics in the atmospheric analysis

- "**DIS model**": comparison between NEUT and CKMT model
  1 parameter with a E_ν dependant effect

- "**DIS low Q^2**": Bodek and Yang on/off comparisons
  2 parameters with Q^2 dependant effects

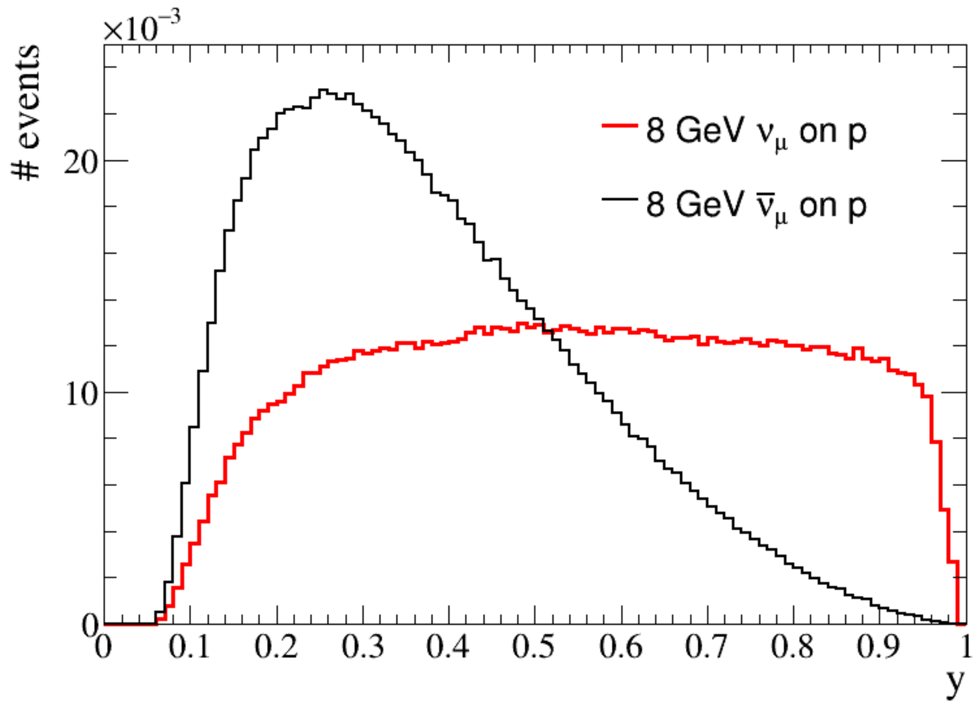
- "**DIS xsec**": difference between NEUT and PDG CC inclusive cross-section
  1 normalization parameter, effect of different size on ν and $\bar{\nu}$

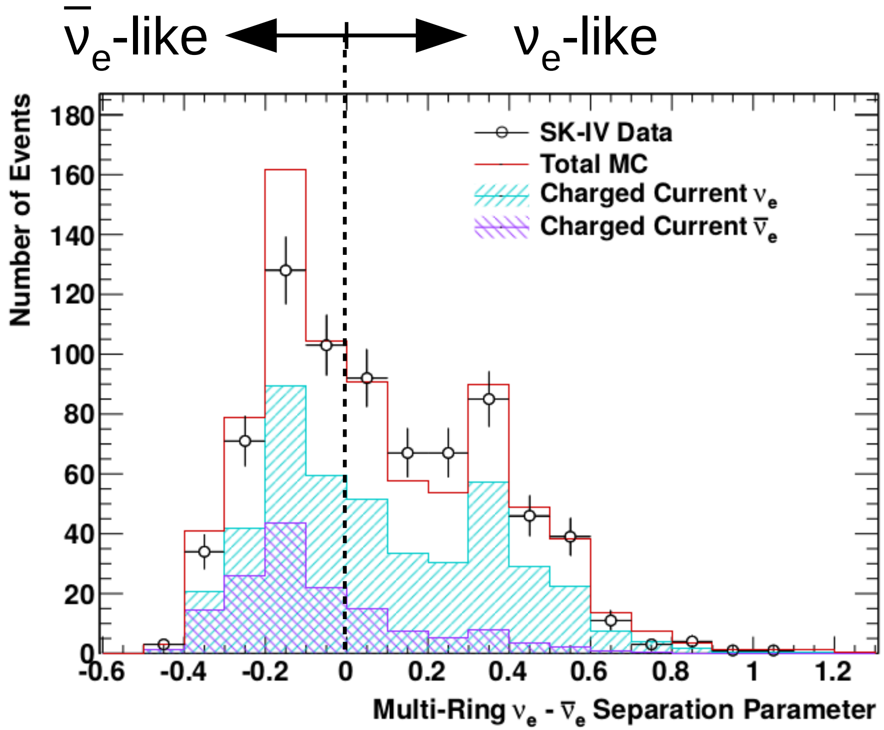
- "**DIS hadron multiplicity**": comparison between NEUT and AGKY model for hadron multiplicity in multi-pion events.
  1 parameter with a E_ν dependant effect for low W DIS mode events
  Should have a second, shape-like, parameter in the future

Those parameters have essentially an impact on the overall normalization for DIS events, and we found that did not seem to have a strong effect on the mass hierarchy sensitivity

Statistical separation of ν_e and $\bar{\nu}_e$

- Super-K cannot separate neutrino and anti-neutrino events on an event by event basis
- Make "enriched samples" to increase the sensitivity to the mass hierarchy
- For multi-ring events, likelihood separation based on differences between DIS interactions of neutrinos and anti-neutrinos

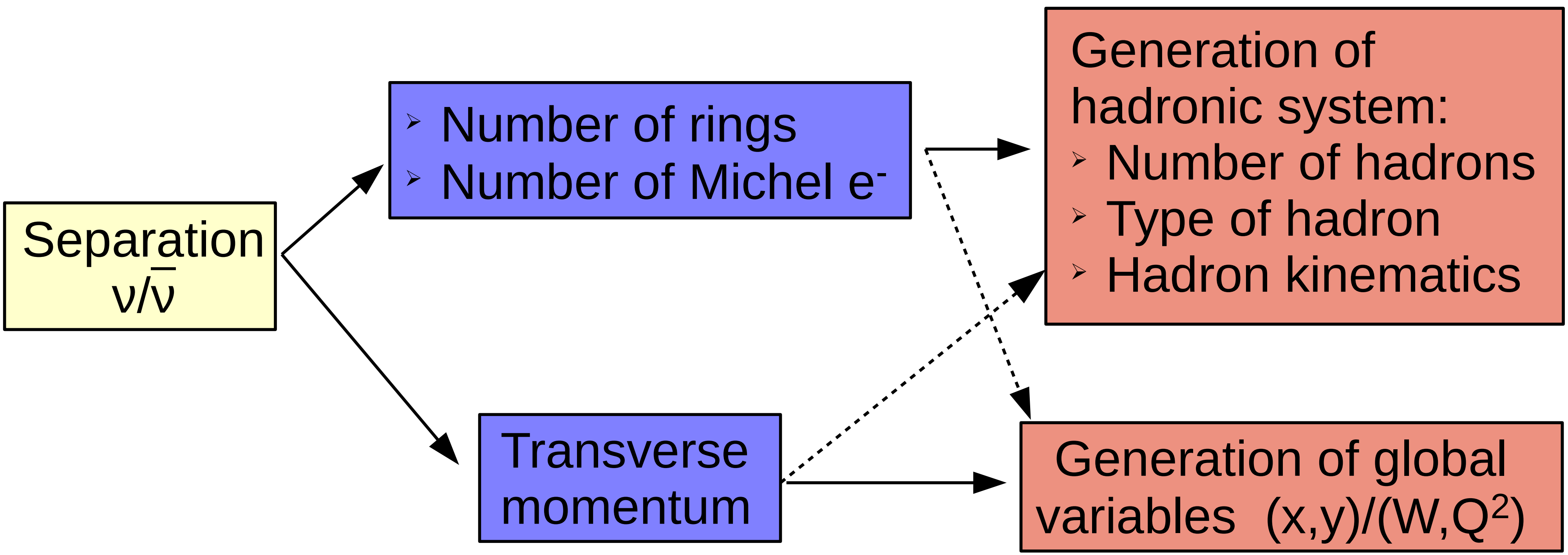




	Neutrino	Anti-neutrino
Nb of rings	More	Less
Nb of Michel e-	More	Less
Transverse momentum	Larger	smaller

Hadronic system

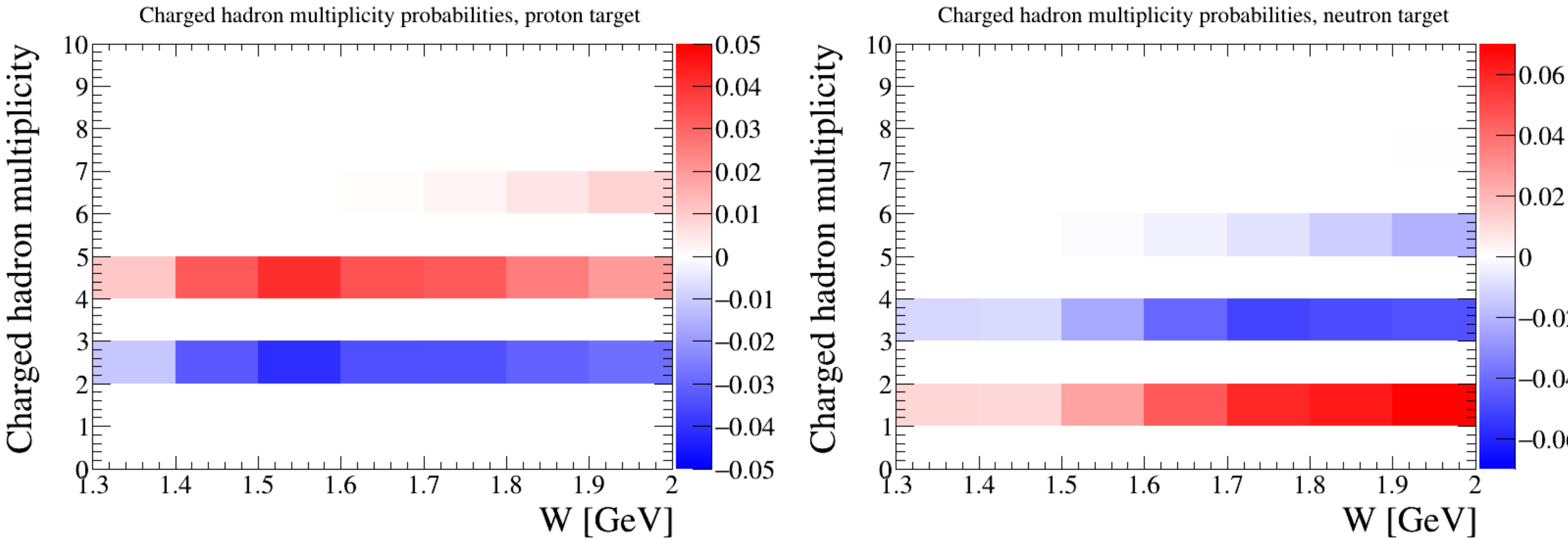
- No clear guidance to build the hadronic system for low W DIS model, nor tests of the hadronic systems used with PYTHIA in this region
- Multiplicity model, particle content and their kinematics could matter for the likelihood from previous slide



Hadronic system
Multiplicities for low W model

- As mentionned before, the hadron multiplicity models are not currently very reliable, and building a proper one would require new data on H/^{2}H
- For now can try to build systematics based on difference between models
- Having a resonant model fully describing 2 pion productions (including non resonant contribution) would reduce the problem by limiting this low W model to 3 pion and more events

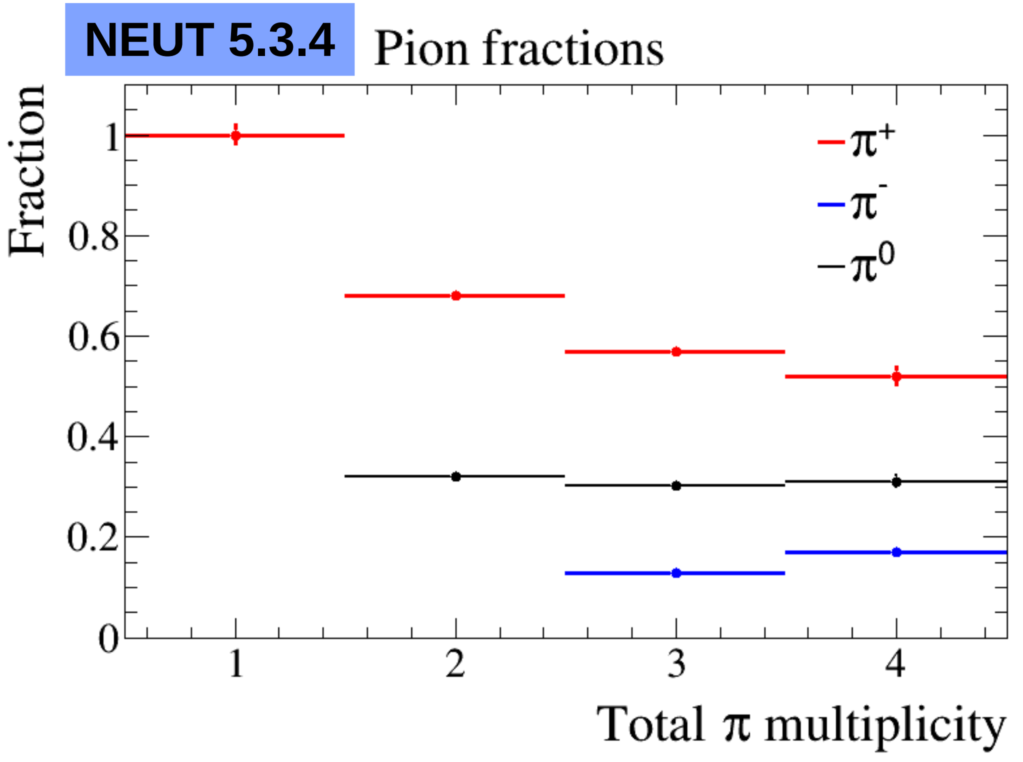
Difference of probability to produce a certain number of charged hadrons for a given value of W between NEUT nominal model and AGKY model

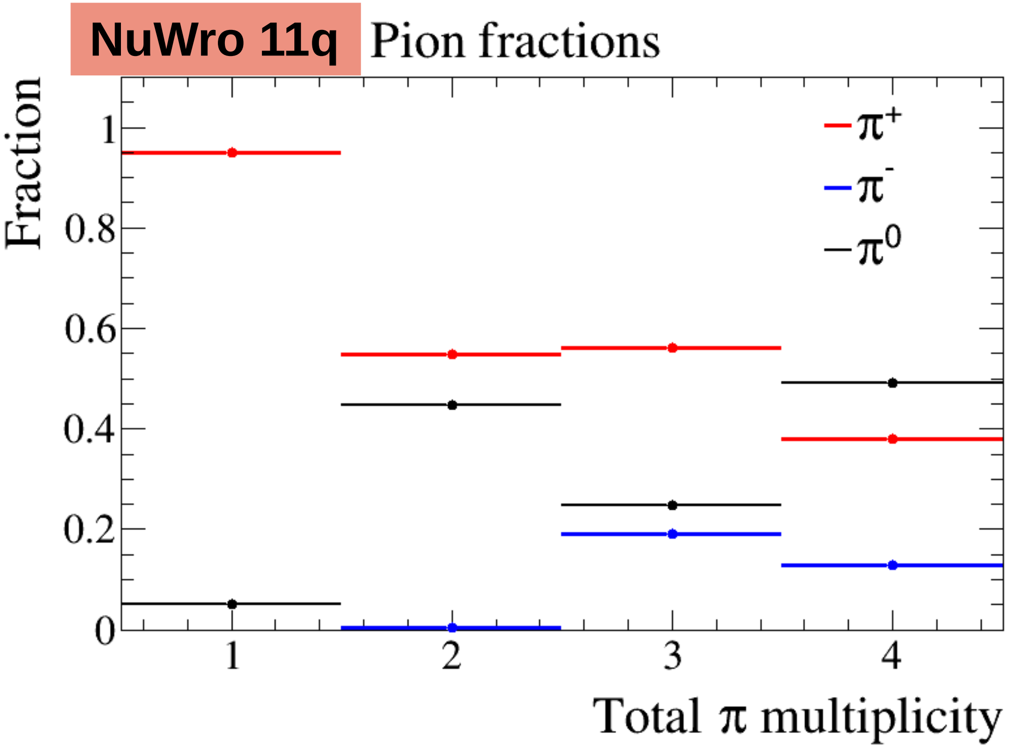


5 GeV free protons and neutrons, multi-pion mode

Hadronic system
Particle content for low W DIS model

- Another possible source of uncertainty is the type of particle produced
- Different type of pions would have a different signature in terms of number of rings and decay electrons in the detector
- Not particularly well constrained. For example NuWro and NEUT don't necessary agree

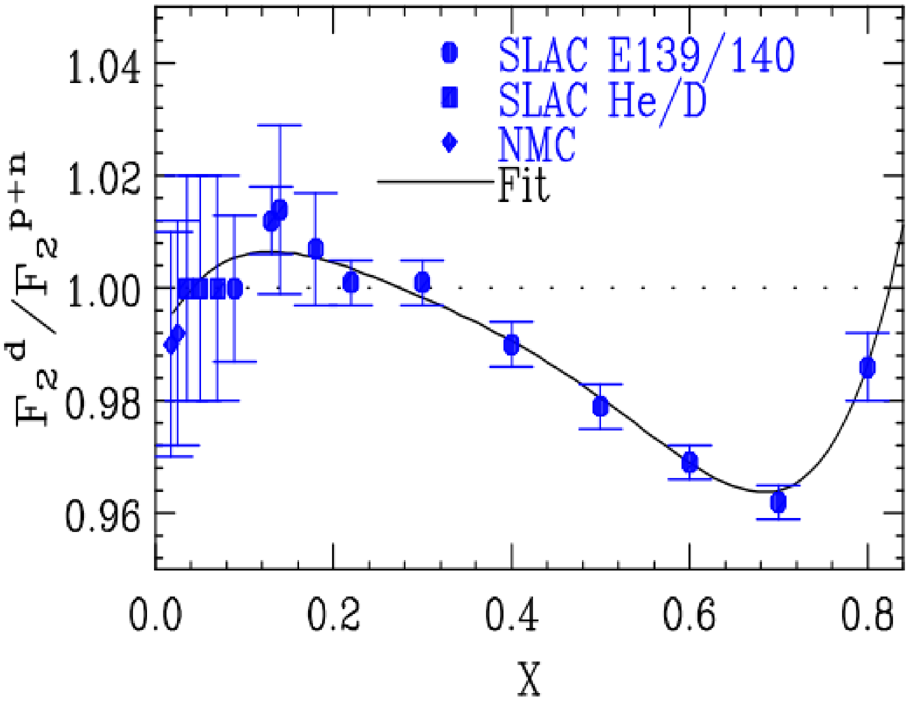


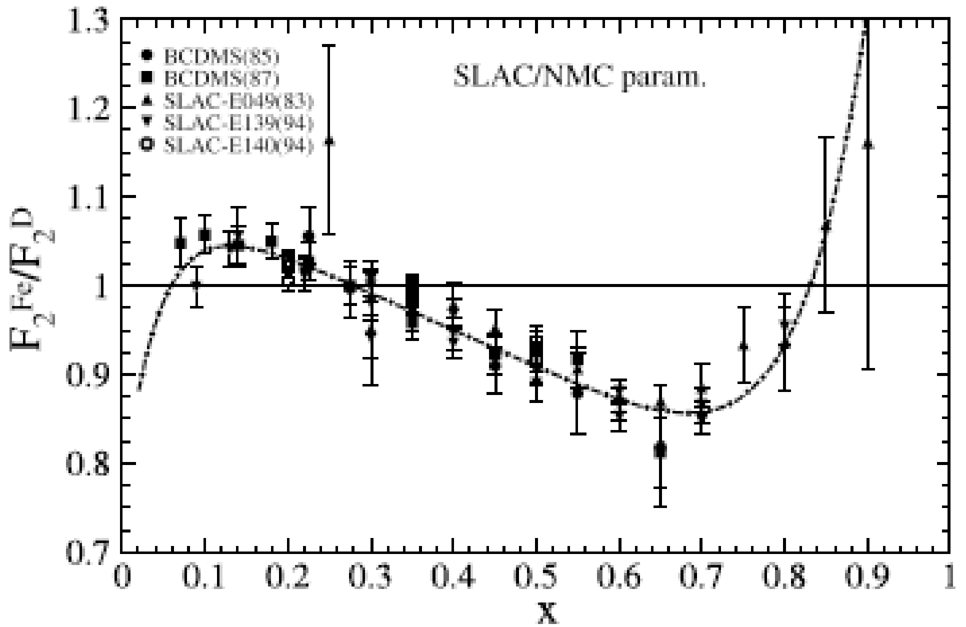


<u>Old</u> comparison (from NuINT 2015), ν_μ on free protons, no FSI, 1.7<W<2.0 GeV

Possible other issue
Nuclear modifications

- Nuclear effects seen to modify the structure functions
- Not clear if there are proper models to describe this
- Some empirical modifications available for deuterium and iso-scalar iron (implemented in GENIE).
- Not sure if there is something that can be done for oxygen and how much it matters





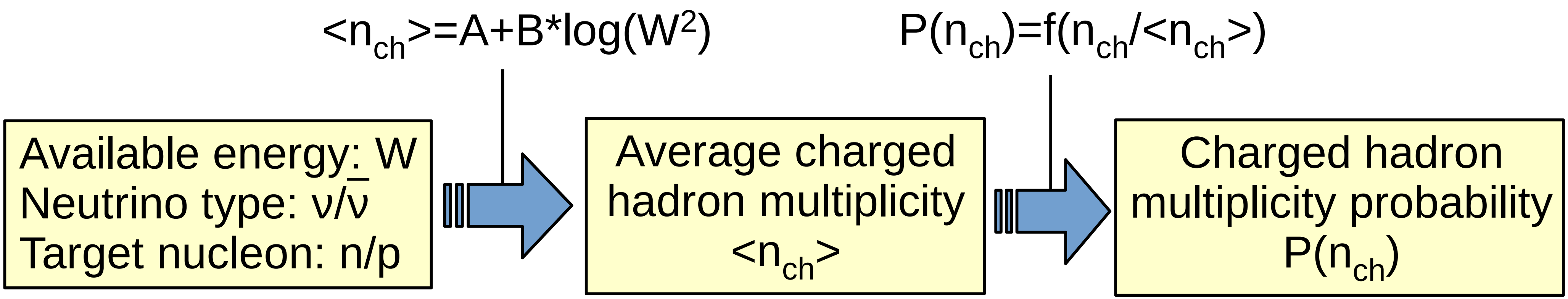
Summary

- Atmospheric neutrinos cover a wide energy range, and different energy regions allow to study different questions on neutrino oscillations
- Sub-GeV events allow to study CP symmetry, and have similar interactions as a beam experiment like T2K. No specific additional need for Super-K there.
- Multi-GeV events allow to study the mass hierarchy, and are mainly composed of resonant and DIS events.
- 3 main topics on which development would benefit the analysis:
  - → Modelization of the transition region
  - → Use of PYTHIA at low (but not too low) W
  - → Modelization of the hadronic system in DIS events

BACKUP

Multiplicity models (Hadronization for low W mode)

- Multiplicity models give the probability to produce a given number of hadrons for a given value of W
- Based on KNO scaling: the distribution of $P(n_{ch})=f(n_{ch}/\langle n_{ch}\rangle)$ is independent of W
- Average charged hadron multiplicity observed to be a linear fonction of $\log(W^2)$ in bubble chamber data
  (K. Kuzmin and V. Naumov argue for a quadratic function at low W in PRC 88, 065501 (2013))



3 or 4 parameters for each couple of neutrino type and target nucleon depending on choice of f

Multi-pion mode
Uncertainty on multiplicity model

- Use data from bubble chamber experiments to measure free parameters
- To decorrelate from final state interaction modelisation, use data from hydrogen and deuterium experiments

Author(s), experiment, publ. date	Ref.	Target	W^2 range	Kinematic cuts	Intercept a	Slope b
			$\nu_\mu p \to \mu^- X^{++}$			
Coffin *et al.*, FNAL E45, 1975	[21]	H	4–200		1.0 ± 0.3	1.1 ± 0.1
Chapman *et al.*, FNAL E45, 1976	[22]	H	4–200		1.09 ± 0.38	1.09 ± 0.03
Bell *et al.*, FNAL E45, 1979	[23]	H	4–100	$Q^2 = 2 - 64\ \text{GeV}^2$		1.35 ± 0.15
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	1–100		0.80 ± 0.10	1.25 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	4–225		0.50 ± 0.08	1.42 ± 0.03
Saarikko *et al.*, CERN WA21, 1979	[28]	H	3–200		0.68 ± 0.04	1.29 ± 0.02
Schmitz, CERN WA21, 1979	[29]	H	4–140		0.38 ± 0.07	1.38 ± 0.03
Allen *et al.*, CERN WA21, 1981	[30]	H	4–200		0.37 ± 0.02	1.33 ± 0.02
Grässler *et al.*, CERN WA21, 1983	[32]	H	11–121		-0.05 ± 0.11	1.43 ± 0.04
Jones *et al.*, CERN WA21, 1990	[33]	H	16–196		0.911 ± 0.224	1.131 ± 0.086
Jones *et al.*, CERN WA21, 1992	[34]	H	9–200		0.40 ± 0.13	1.25 ± 0.04
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	2–60		1.07 ± 0.27	1.31 ± 0.11
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \text{GeV}^2$	0.13 ± 0.18	1.44 ± 0.06
			$\overline{\nu}_\mu p \to \mu^+ X^0$			
Derrick *et al.*, FNAL E31, 1976	[14]	H	4–100	$y > 0.1$	0.04 ± 0.37	1.27 ± 0.17
Singer, FNAL E31, 1977	[15]	H	4–100	$y > 0.1$	0.78 ± 0.15	1.03 ± 0.08
Derrick *et al.*, FNAL E31, 1978	[16]	H	1–50		0.06 ± 0.06	1.22 ± 0.03
Derrick *et al.*, FNAL E31, 1982	[20]	H	4–100	$0.1 < y < 0.8$	-0.44 ± 0.13	1.48 ± 0.06
Grässler *et al.*, CERN WA21, 1983	[32]	H	11–121		-0.56 ± 0.25	1.42 ± 0.08
Jones *et al.*, CERN WA21, 1990	[33]	H	16–144		0.222 ± 0.362	1.117 ± 0.141
Jones *et al.*, CERN WA21, 1992	[34]	H	9–200		-0.44 ± 0.20	1.30 ± 0.06
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	7–50		0.55 ± 0.29	1.15 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	6–140		0.18 ± 0.20	1.23 ± 0.07
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	6–140		0.02 ± 0.20	1.28 ± 0.08
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \text{GeV}^2$	-0.29 ± 0.16	1.37 ± 0.06
			$\nu_\mu n \to \mu^- X^+$			
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	1–100		0.21 ± 0.10	1.21 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	4–225		-0.20 ± 0.07	1.42 ± 0.03
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	2–60		0.28 ± 0.16	1.29 ± 0.07
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \text{GeV}^2$	1.75 ± 0.12	1.31 ± 0.04
			$\overline{\nu}_\mu n \to \mu^+ X^-$			
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	7–50		0.10 ± 0.28	1.16 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	4–140		0.79 ± 0.09	0.93 ± 0.04
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	2–140		0.80 ± 0.09	0.95 ± 0.04
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	8–144	$Q^2 > 1\ \text{GeV}^2$	0.22 ± 0.21	1.08 ± 0.06

Phys. Rev. C 88, 065501

<u>Many problems:</u>

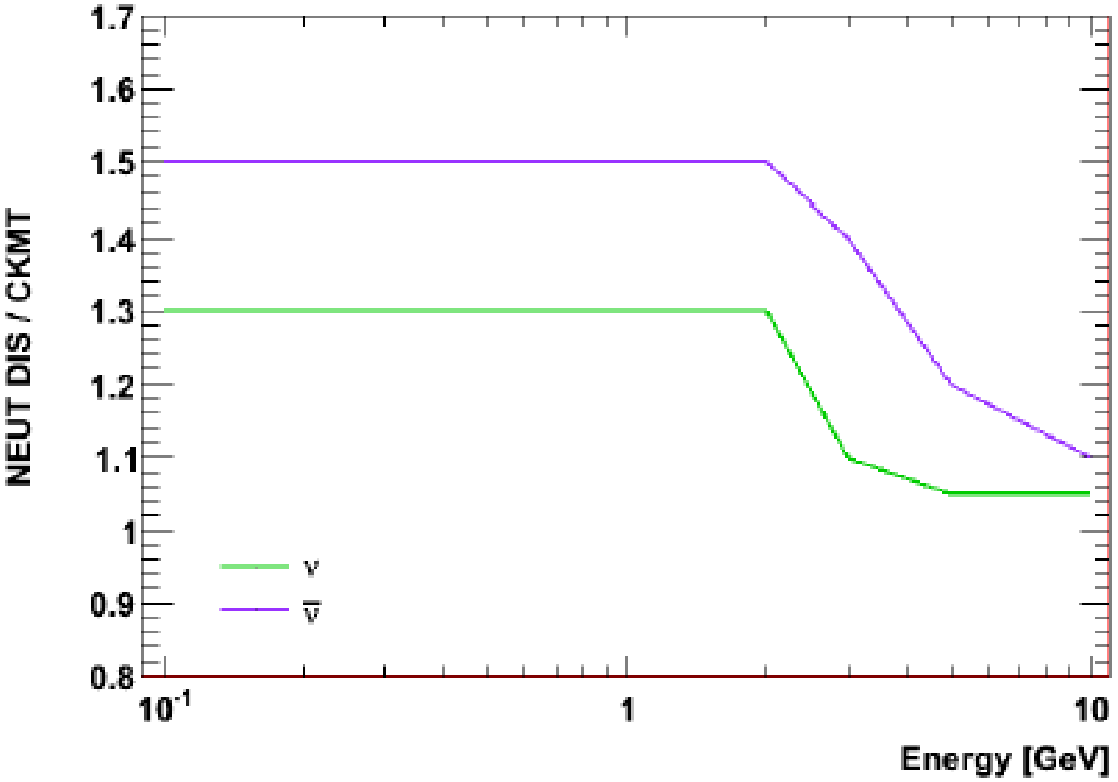
- ✗ inconsistent results between datasets
- ✗ actual data hard to find
- ✗ no systematic uncertainties most of the time

- NEUT model 0 uses [16] ($\overline{\nu}$-p) for all types
- GENIE uses [27] for ν and [37] for $\overline{\nu}$, and symmetry νp ↔ νn for some parameters

$\langle n_{ch} \rangle = a + b\, x \log(W^2)$

DIS Model systematic

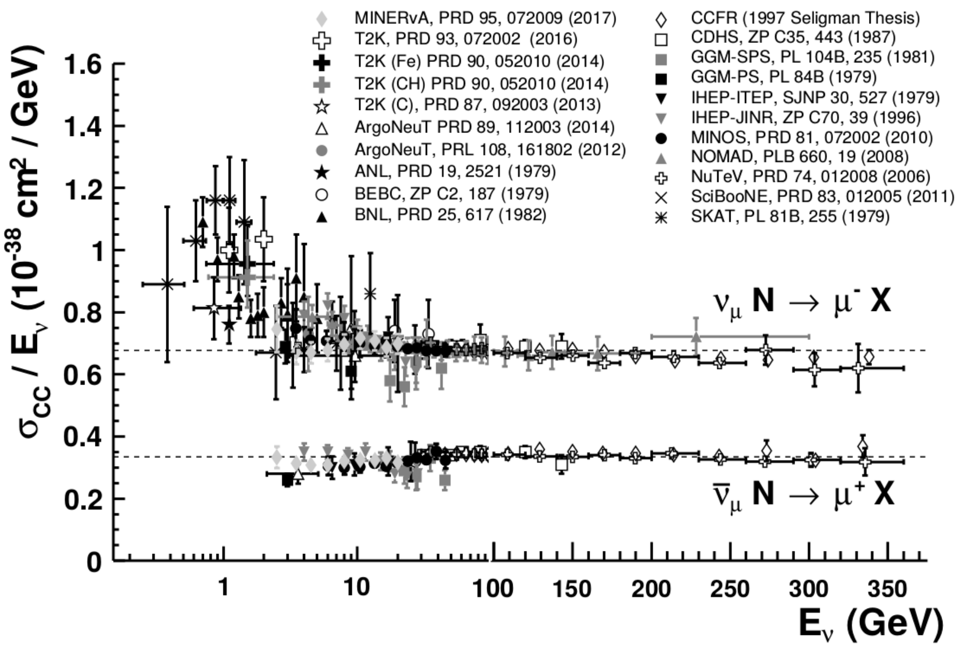
- Current Super-Kamiokande analysis has a "DIS model uncertainty"
- Computed as ratio of cross-section obtained with alternative model to NEUT predictions below 10 GeV
- Alternative model: CKMT (Physics Letters B 337 (1994) 358-366)



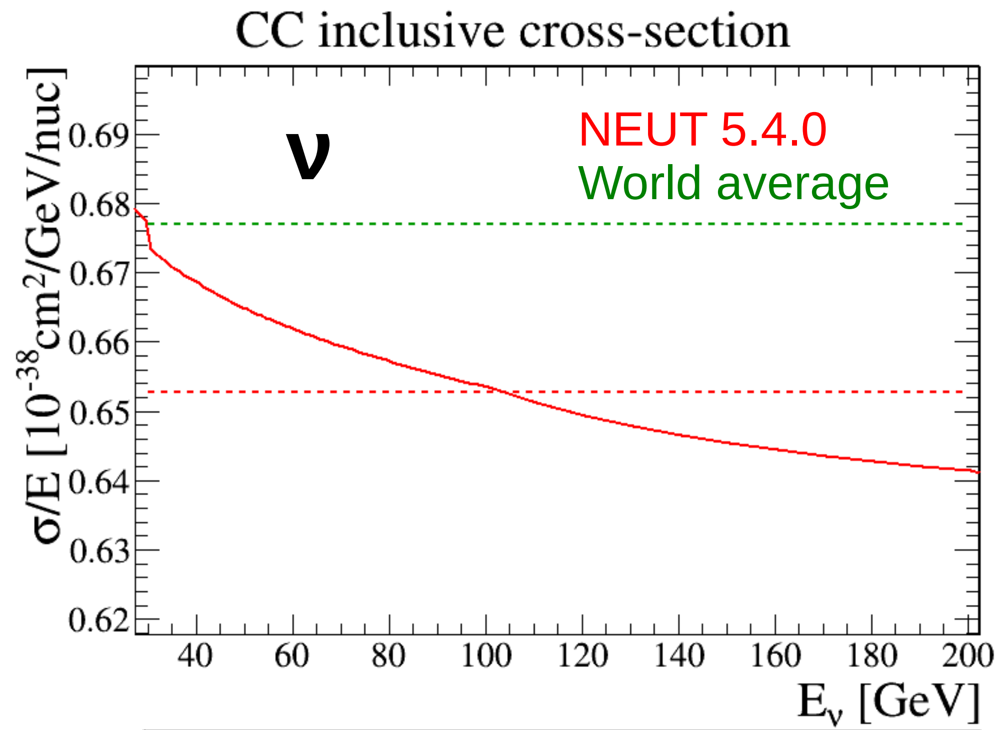
- CKMT model does not seem to be used anymore
- Considering replacing this with comparison to CTEQ PDFs for $Q^2 > Q_0$
- Not sure what to do for $Q^2 < Q_0$

DIS additional cross-section uncertainty

Additional systematic uncertainty from difference between NEUT predictions and world average CC inclusive cross-section



PDG 2017
Dashed lines are average on 30-200 GeV

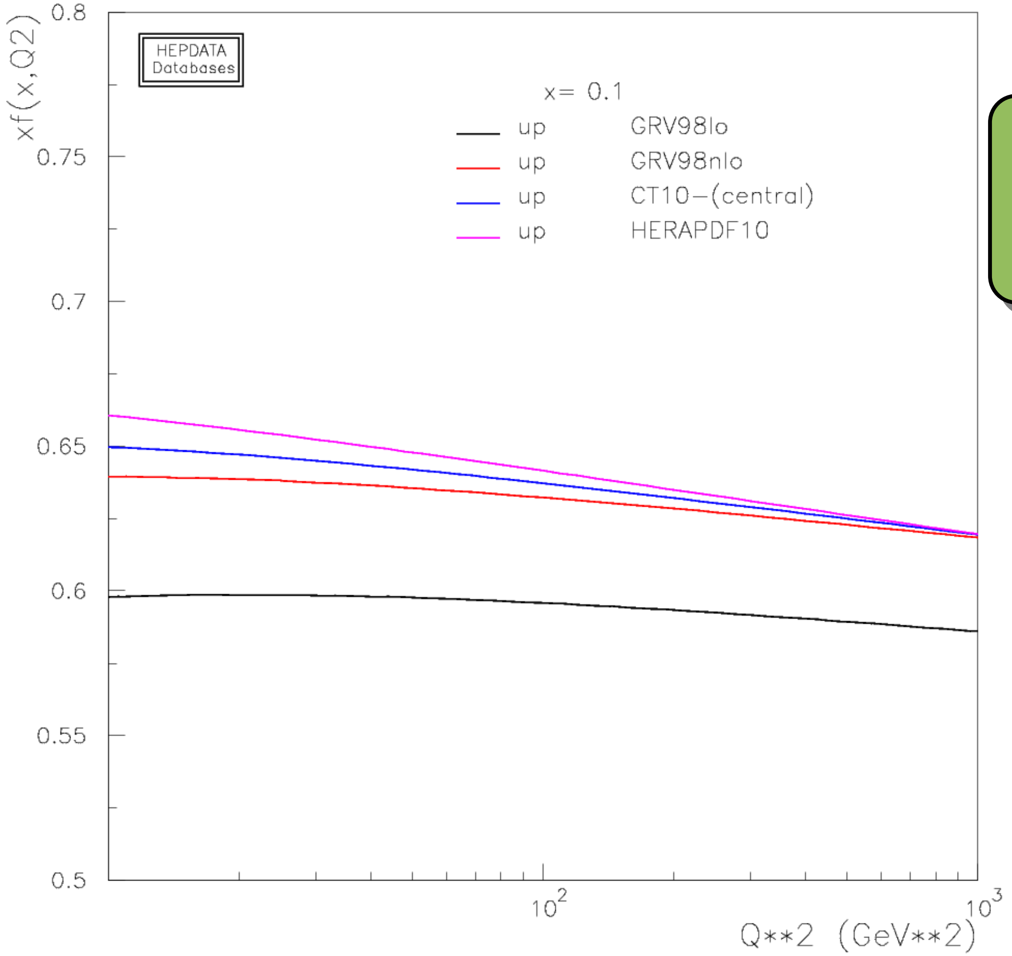


Found that NEUT 5.4.0 under-predicts this average by:

- 3.5% for neutrinos
- 6.5% for anti-neutrinos

Cross section calculation
Choice of PDF

- PDFs can be computed in QCD with free parameters determined by a fit to data
- Only works for $Q^2 > Q_0^2$(typically ~1 GeV)



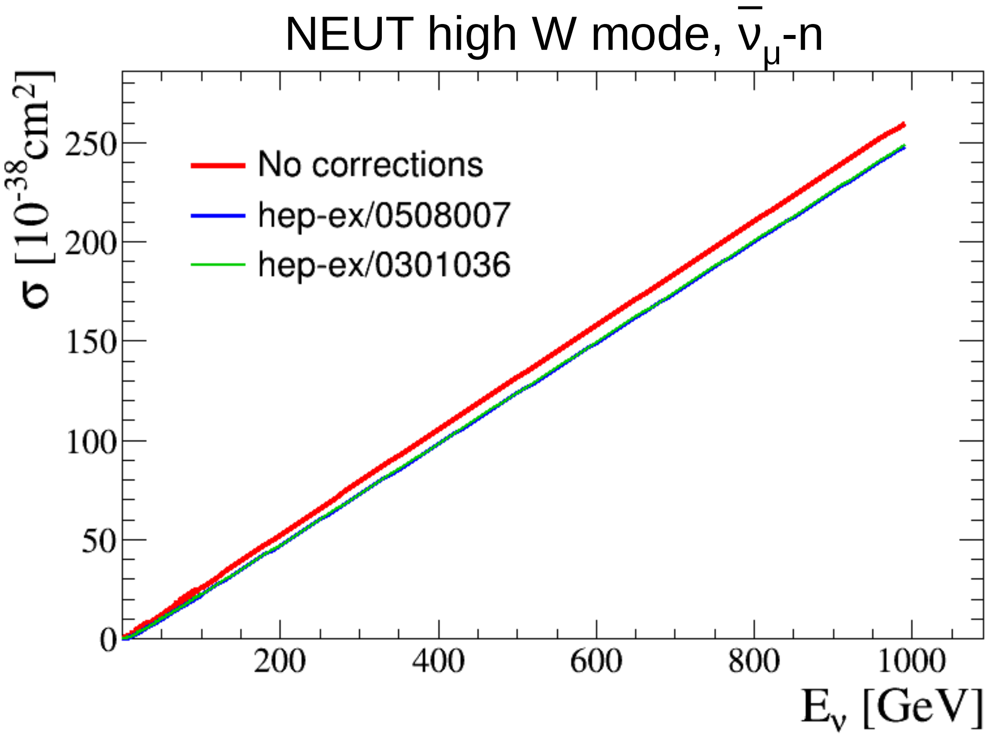
Bodek and Yang have produced a set of corrections to go below Q_0 but is only available for GRV98 leading order PDFs

Using GRV98 leading order in generators, although it disagrees with more recent PDFs

Cross section calculation
Bodek-Yang model

- Model with free parameters, determined by a fit of electron scattering and photo-production data
- Different versions, latest ones not implemented in generators
- Errors on parameters not given for version implemented in NEUT and GENIE
- Values of the parameters can change significantly between two versions, but similar predictions

Parameter	hep-ex/0301036	hep-ph/0508007
A	0.419	0.538
B	0.223	0.305
C_{val1}^{d}	0.544	0.202
C_{val1}^{u}	0.544	0.291
C_{val2}^{d}	0.431	0.255
C_{val2}^{u}	0.413	0.189
C_{sea}^{d}	0.380	0.621
C_{sea}^{u}	0.380	0.363



Cross section calculation
Bodek-Yang model

Broadly speaking, 2 different approaches to do systematic uncertainties on BY corrections:
- on/off as 1 sigma error
- use error on the different parameters

GENIE includes errors, based on Debdatta Bhattacharya PhD's thesis.

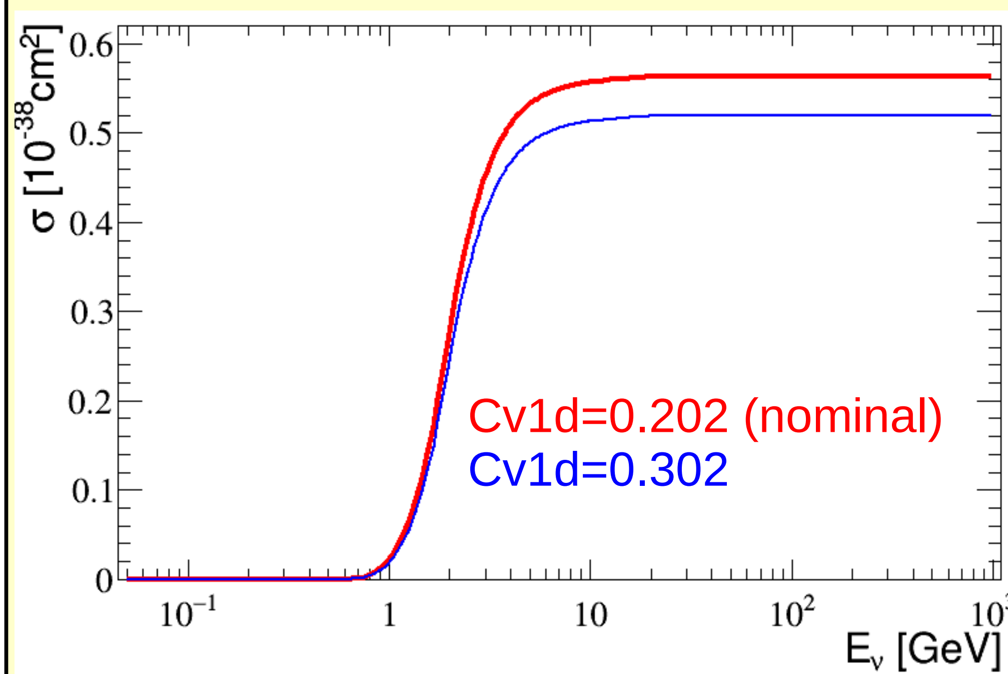
"The uncertainty in the DIS model parameters is determined by varying each parameter in the model [5] and studying the effect on the reduced χ^2 of the fit to the charged-lepton data"

But:

- no correlations of the errors between parameters

- no error on some of the parameters

"Cv1d , Cv2d and Cs have very small effect on the χ^2 and hence have been neglected" D. Bhattacharya PhD's thesis



Cross section calculation
Bodek-Yang model – plans for next SK analysis

- Concluded that more studies were required to be able to use errors on parameters, and defaulted to on/off type of systematic
- 2 different parameters (uncorrelated): one for each NEUT mode (low and high W)

- Implemented as a function of Q^2 by interpolation on histograms
- Considered range 0-100 GeV^2
- Different histograms for nu/nubar and the three neutrino flavors