NuSTEC workshop on Shallow- and Deep-Inelastic Scattering

SIS/DIS interactions and uncertainties in atmospheric oscillation analysis

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Introduction

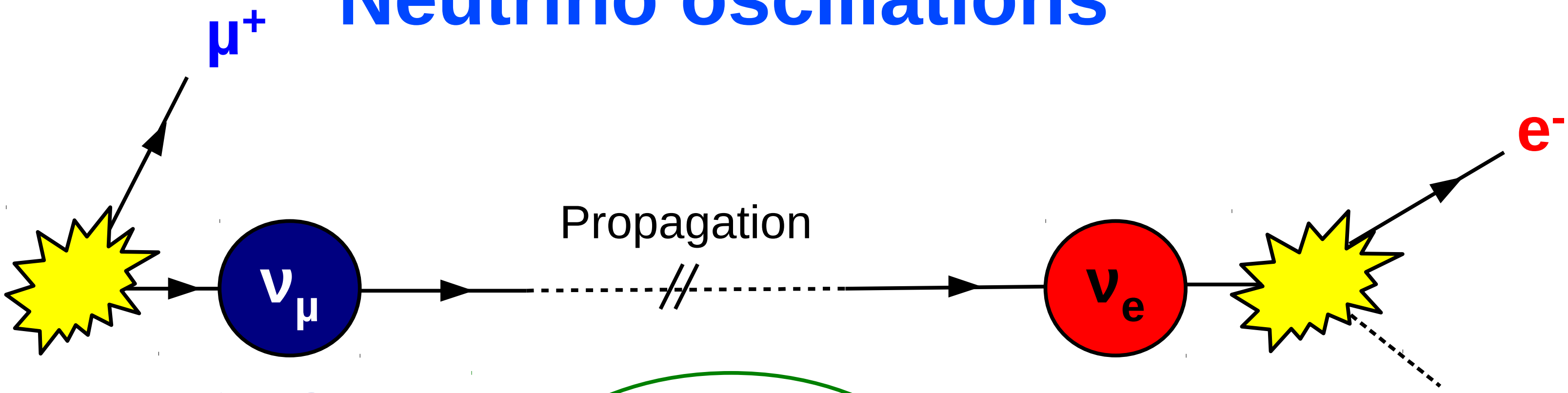
- Will look at the importance of the modelization of DIS interactions for atmospheric neutrino oscillations with the example of the mass hierarchy determination in Super-Kamiokande

- Other atmospheric experiments (KM3NET, IceCube) are at higher energy and use different reconstruction methods: not everything shown here will be relevant for those experiments

- Current Super-K analysis is statistically limited, but modelization of the systematics will be important for Hyper-Kamiokande era.

- Outline:
  - determination of the mass hierarchy with atmospheric neutrinos
  - approach used in Super-Kamiokande
  - observables of DIS interactions to model
  - sources of uncertainties and modelization of systematic uncertainties

Neutrino oscillations



Flavor eigenstates
(interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
(propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

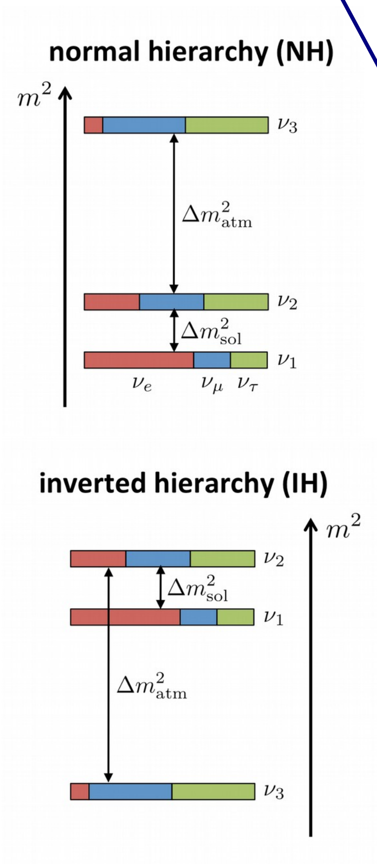
$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino

- Amplitude of oscillations depends on the mixing matrix U
- Phase of the oscillation depends on energy and difference of mass squared: $\mathbf{\Delta m^2_{ij} L/E}$

$(\Delta m^2_{ij} = m^2_i - m^2_j)$

Neutrino oscillation
Main current physics goals

Mass hierarchy:
$m_3 > m_2, m_1$?



PDG 2017 summary table

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Octant of θ_{23}:
$\theta_{23} > \pi/4$?
$\theta_{23} < \pi/4$?

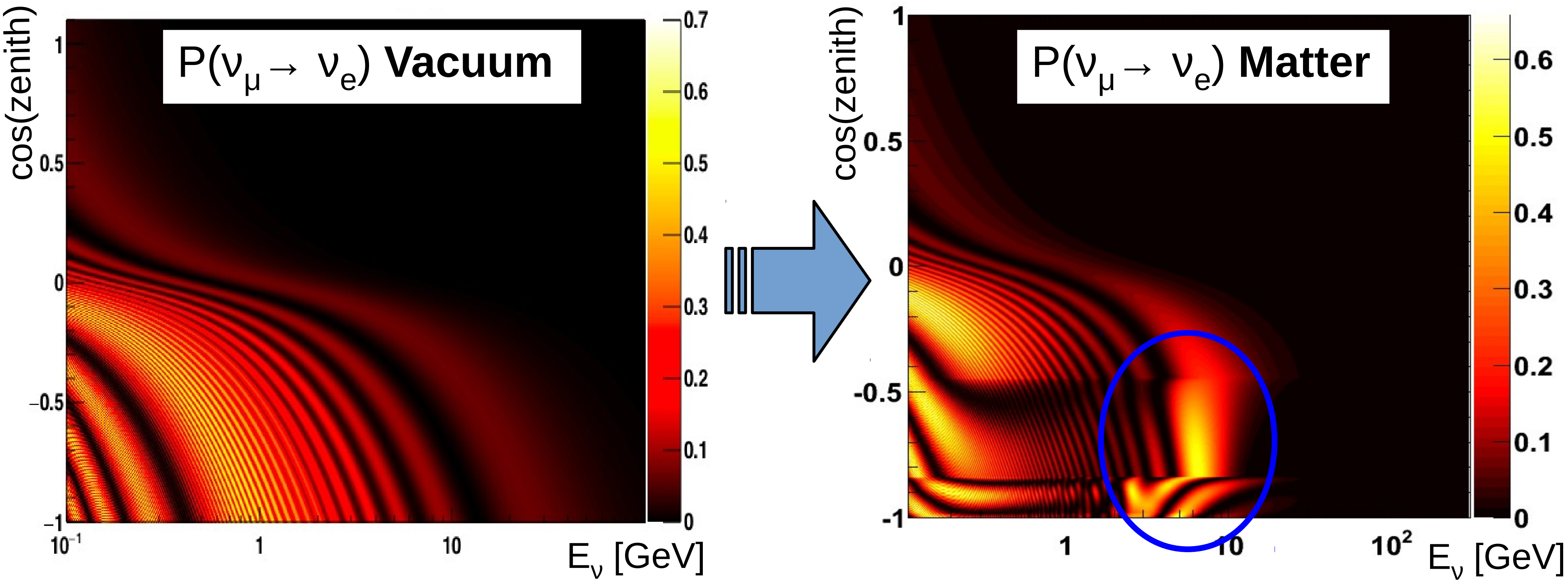
Violation of CP symmetry in neutrino oscillations?

Degeneracies between those 3 questions

Mass hierarchy with atmospheric neutrinos

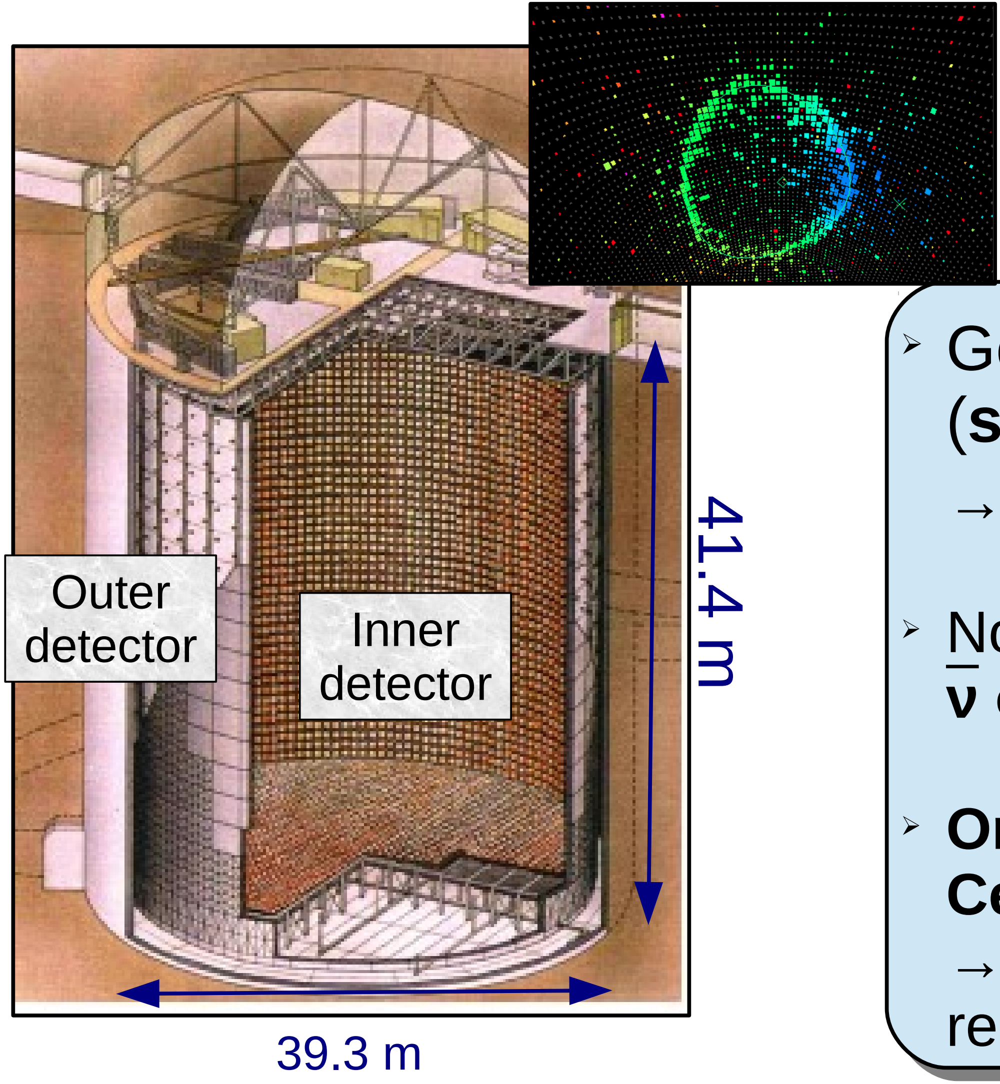
- Order of neutrino mass eigenstates is not fully known
- Propagation in matter modifies oscillation probabilities compared to vacuum, in different ways depending on MH
- In particular resonance in muon to electron flavor oscillation

NH: ν only - IH: $\bar{\nu}$ only



Super-Kamiokande Detector

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



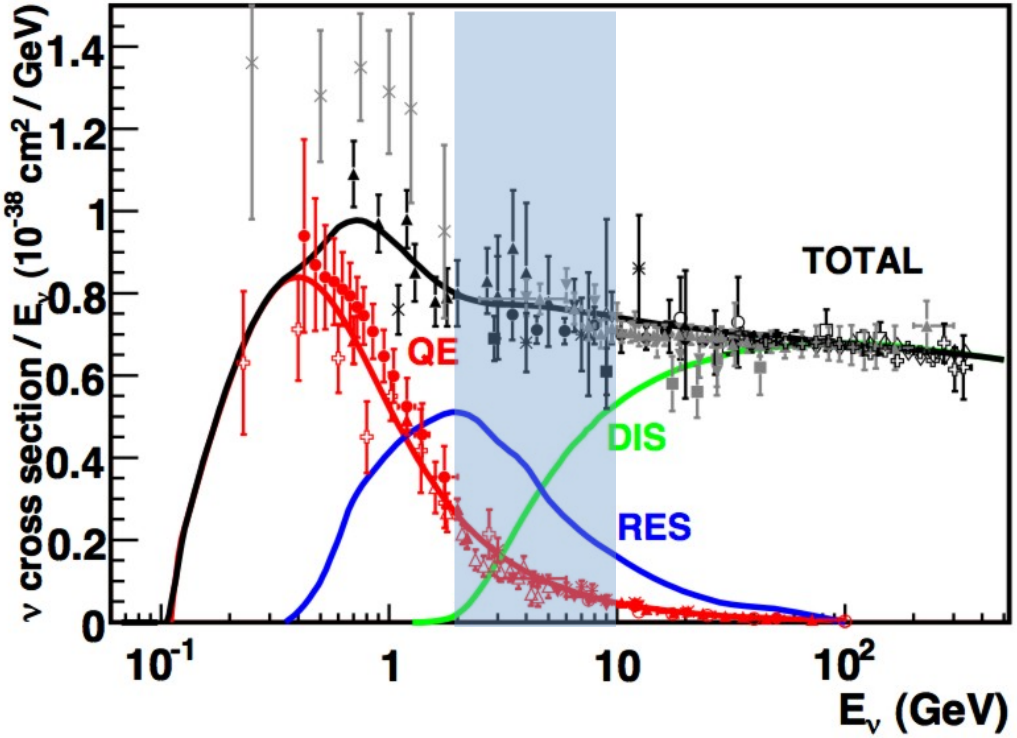
Wide physics program:

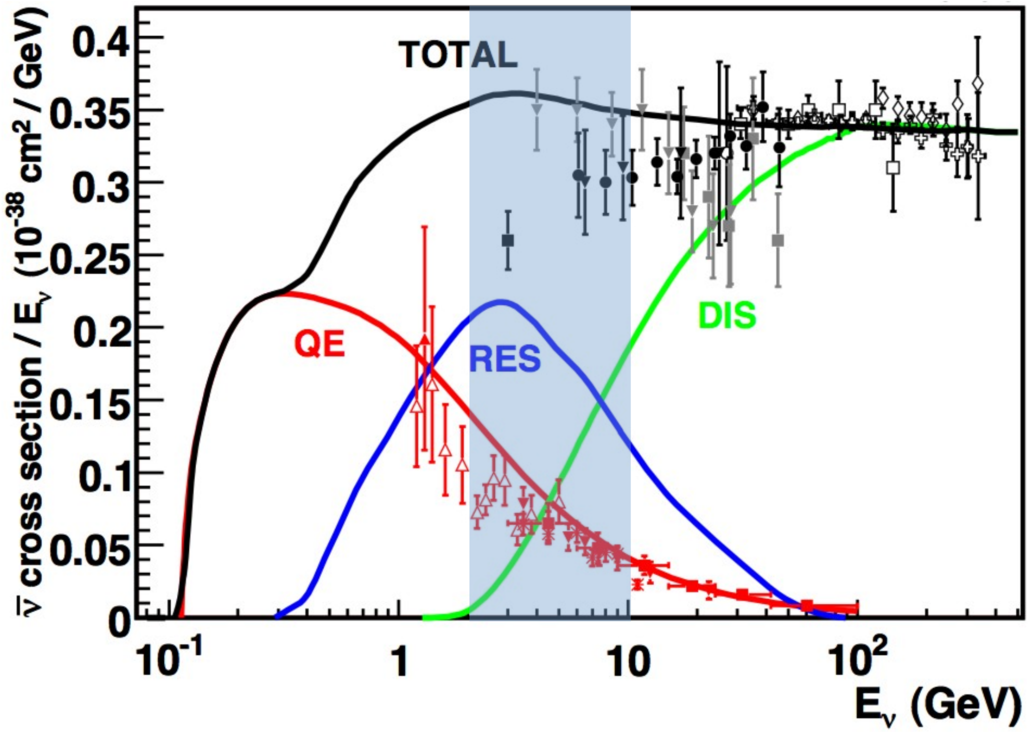
- ✓ **Atmospheric neutrinos**
- ✓ Solar neutrinos
- ✓ Supernova neutrinos
- ✓ Proton decay
- ✓ Dark matter indirect detection

- 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

Mass hierarchy with atmospheric neutrinos
Water Cerenkov detector

- Water Cerenkov detectors cannot distinguish on an event by event basis between ν and $\bar{\nu}$
- Two handles to study MH:
  - flux and cross sections of ν larger than those of $\bar{\nu}$
  - differences between interactions of ν and $\bar{\nu}$ allow to do statistical separation (“enriched samples”)
- Resonance expected to occur in the region 2-10 GeV

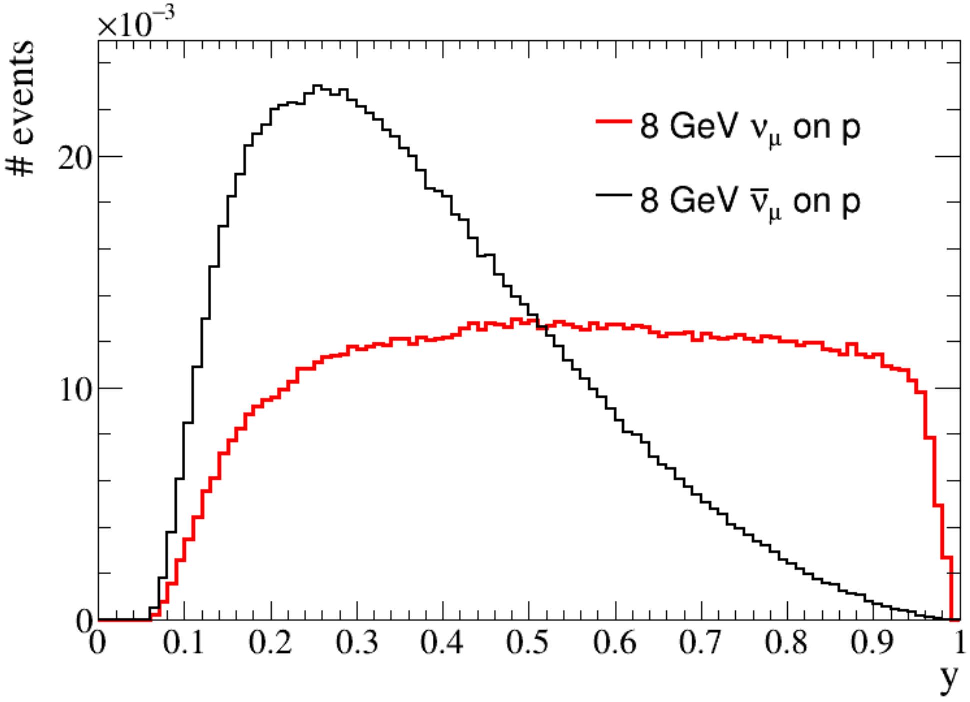




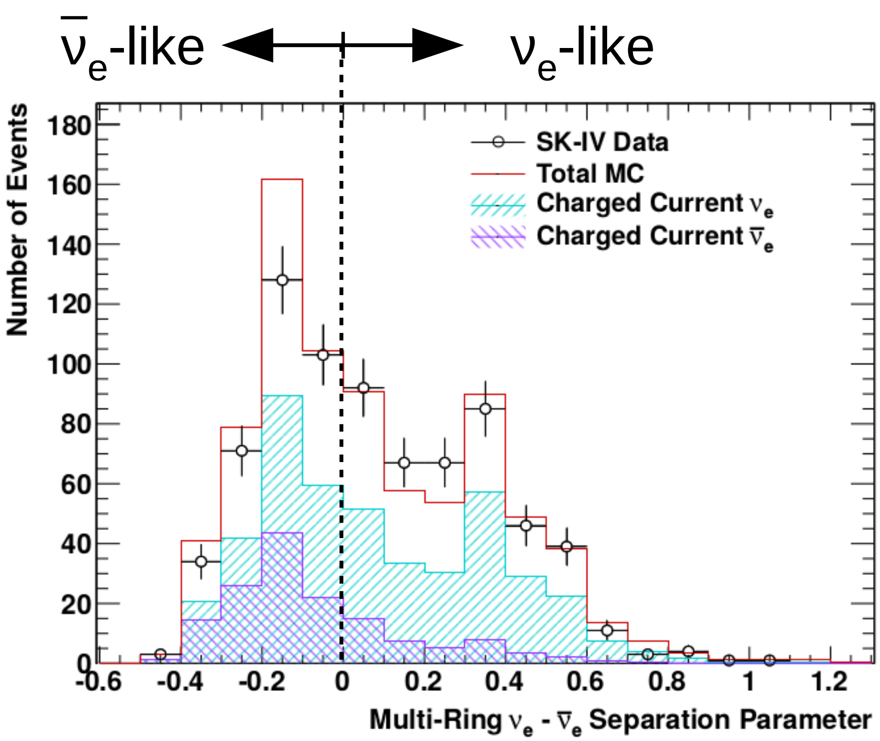
Plots from Hewett, J.L. et al. arXiv:1205.2671 [hep-ex]

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

Likelihood separation based on differences between DIS interactions of neutrinos and anti-neutrinos



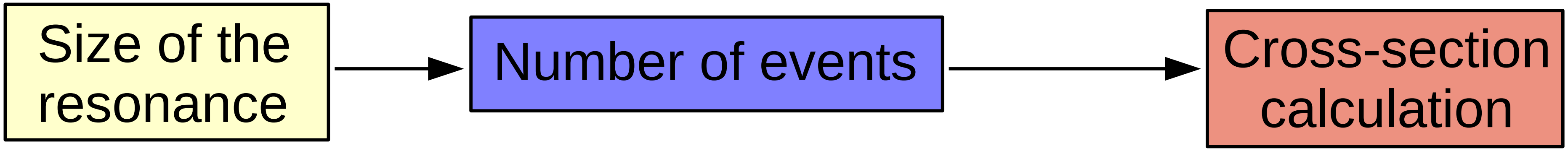
	Neutrino	Anti-neutrino
Nb of rings	More	Less
Nb of Michel e-	More	Less
Transverse momentum	Larger	smaller



	Efficiency (signal)	Purity
ν_e-like	52.9%	58.4%
$\bar{\nu}_e$-like	71%	27.5%

Phys. Rev. D 97, 072001 (2018)

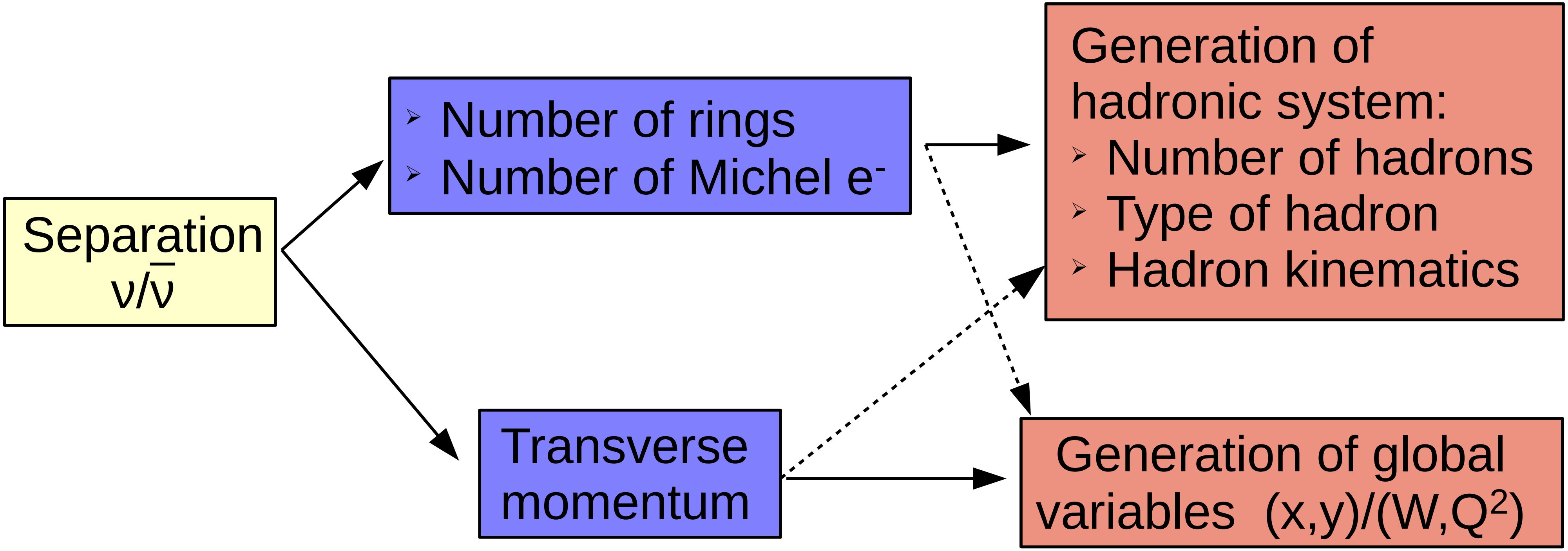
DIS related uncertainties



Size of the resonance

Number of events

Cross-section calculation



Separation $\nu/\bar{\nu}$

- Number of rings
- Number of Michel e^-

Transverse momentum

Generation of hadronic system:

- Number of hadrons
- Type of hadron
- Hadron kinematics

Generation of global variables (x,y)/(W,Q^2)

Differences between neutrinos and anti-neutrinos are of particular importance

Cross section calculation

Calculated by integrating d²σ/dxdy over possible values of x and y
Bjorken x ≈ fraction of the nucleon momentum carried by the struck quark
Bjorken y: fraction of the neutrino energy transferred to the hadronic system

d²σ/dxdy parametrized in terms of structure functions $F_1, \ldots, F_5$

$$\frac{d^2\sigma}{dxdy} \propto \sum_{i=1}^{5} \alpha_i \times F_i(x, Q^2)$$

- Use modified Calland-Gross and Albright-Jarlskog relations to relate F_1, F_4, F_5 to F_2 and xF_3

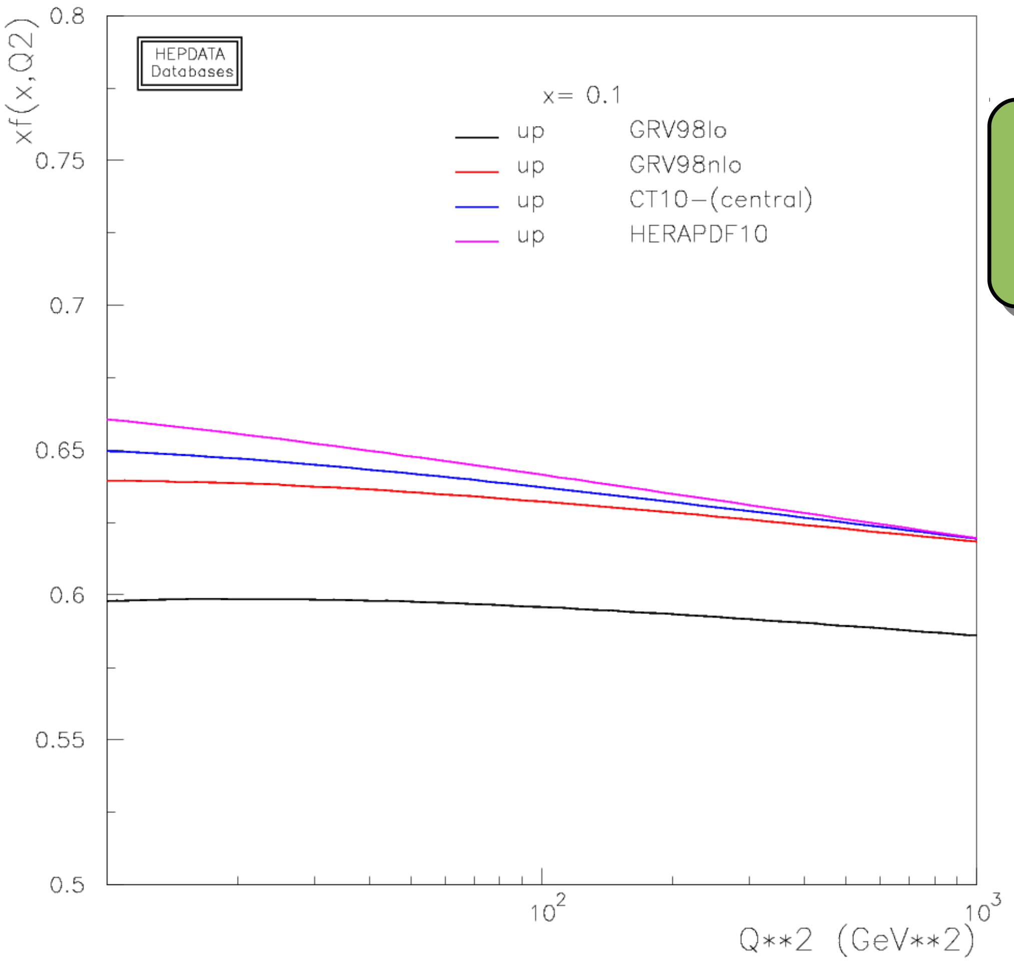
$$F_1(x,Q^2) = \frac{1}{2x} F_2(x,Q^2) \times \left(\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)} \right) \qquad F_4(x,Q^2) = 0 \qquad F_5(x,Q^2) = \frac{F_2(x,Q^2)}{x}$$

- Finally use quark-parton model to compute F_2 and xF_3 from Parton Distribution Functions

Main source of uncertainty on the cross-sections are the PDFs (then relations between structure functions)

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)

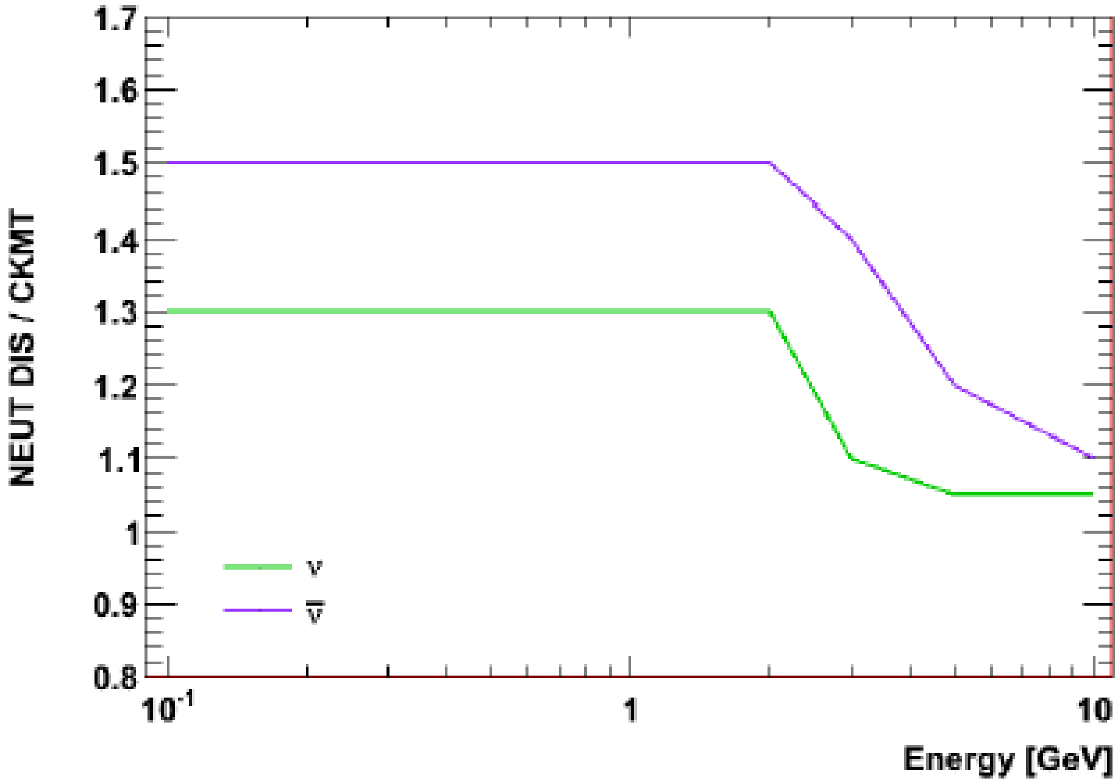


Bodek and Yang have produced a set of corrections to go below Q_0 but is only available for GRV98 leading order PDFs

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

Cross section calculation
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)



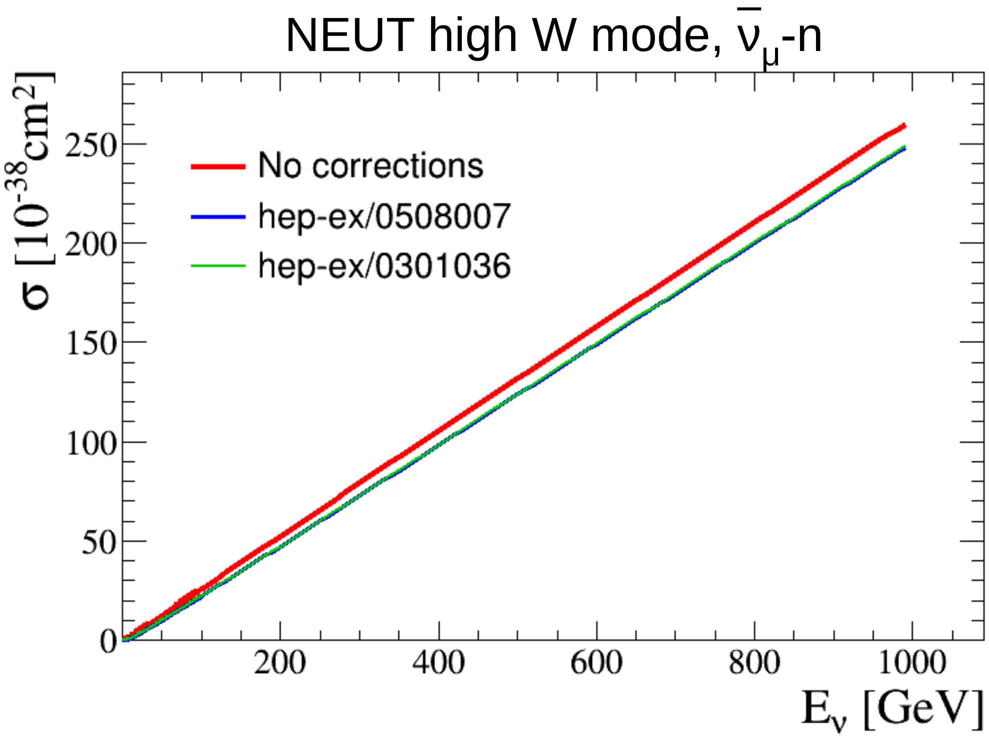
- CKMT model does not seem to be used anymore
- Considering replacing this with comparison to CTEQ PDFs for $Q^2 > Q_0$
- Not sure what to do for $Q^2 < Q_0$

Cross section calculation
Bodek-Yang model

Caveat: written before seeing U-K Yang's presentation

- 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.

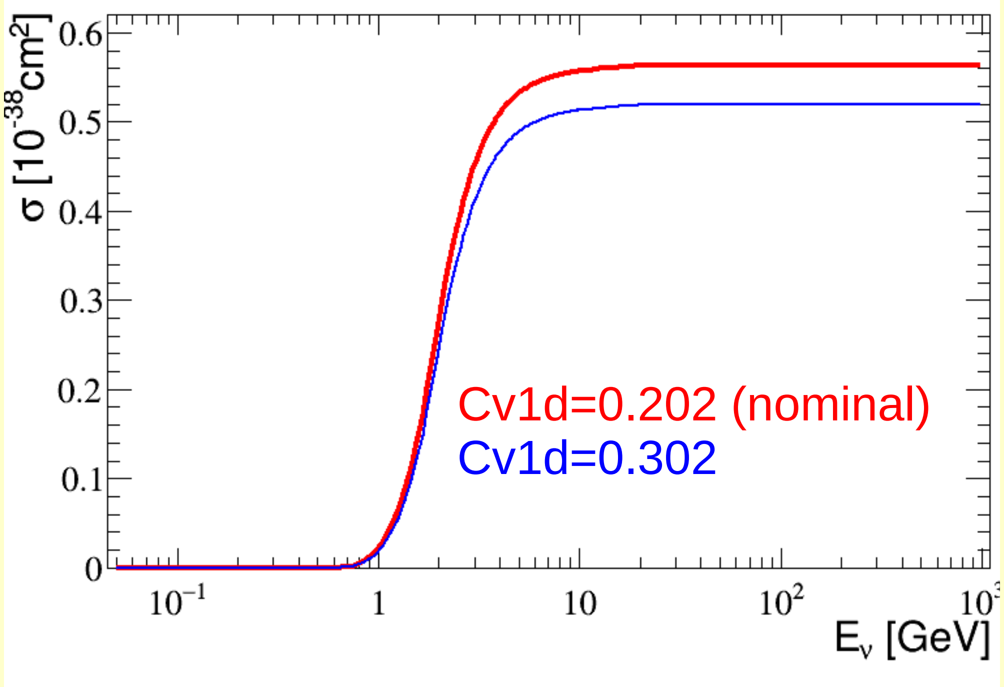
“The uncertainty in the DIS model parameters is determined by varying each parameter in the model [5] and studying the effect on the reduced χ^2 of the fit to the charged-lepton data”

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

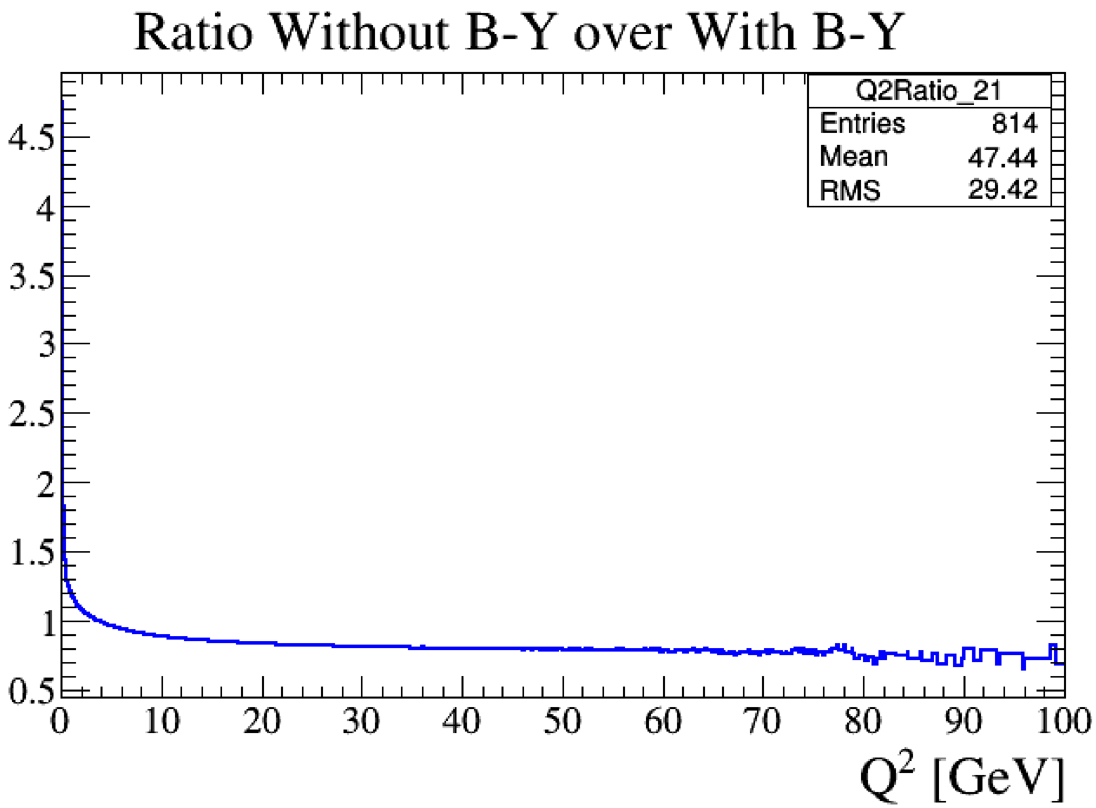


Cross section calculation Bodek-Yang model – plans for next SK analysis

Caveat: written before seeing U-K Yang's presentation

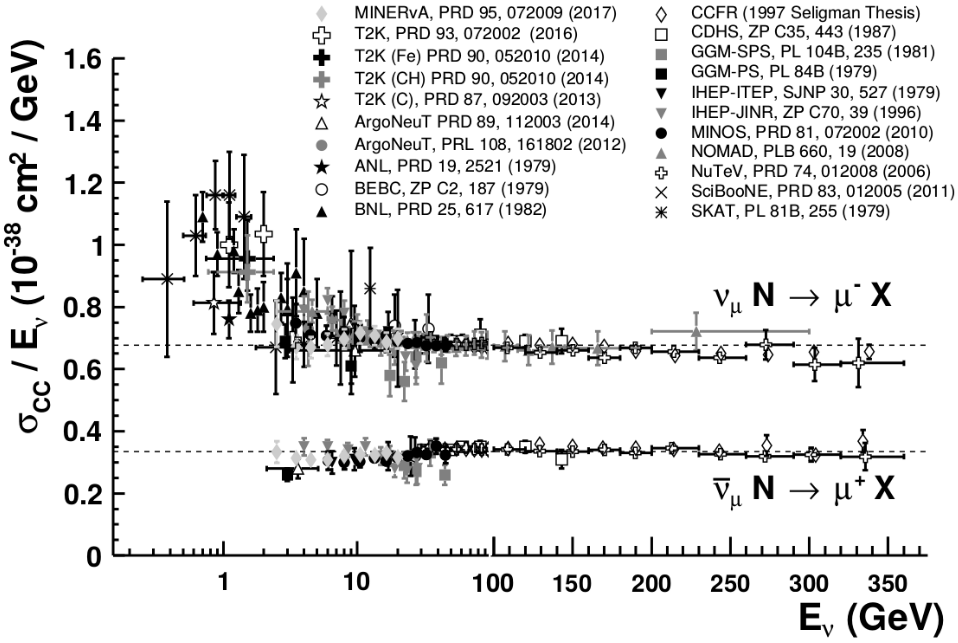
- Concluded that more studies were required to be able to use errors on parameters, and defaulted to on/off type of systematic
- 2 different parameters (uncorrelated): one for each NEUT mode (low and high W)

- 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

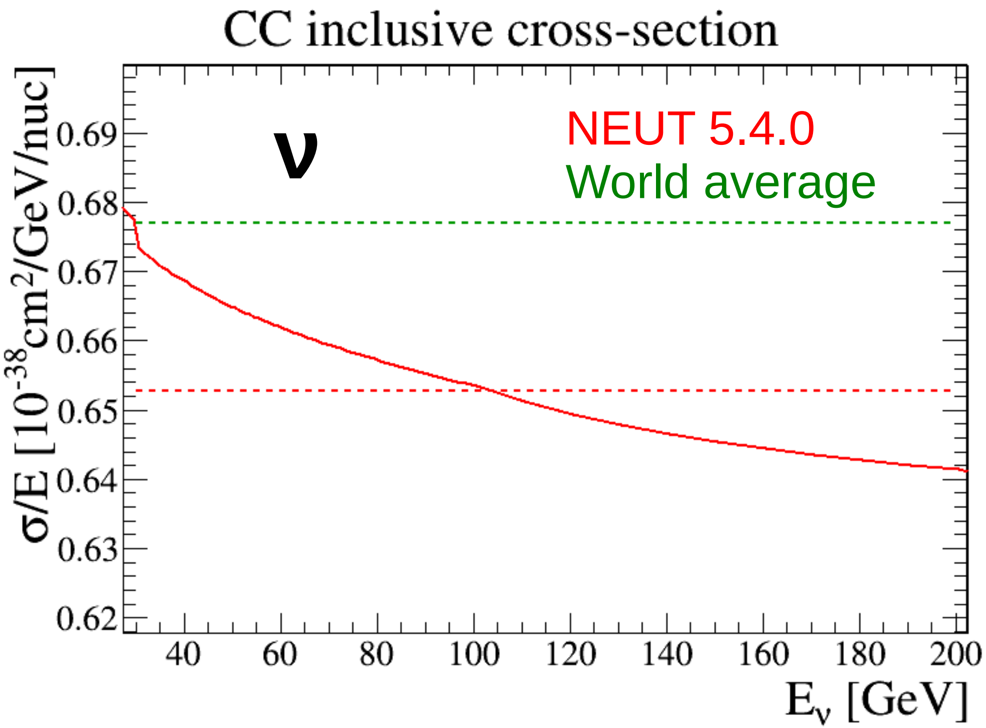


Cross section calculation
Additional cross-section uncertainty

In SK analysis, 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

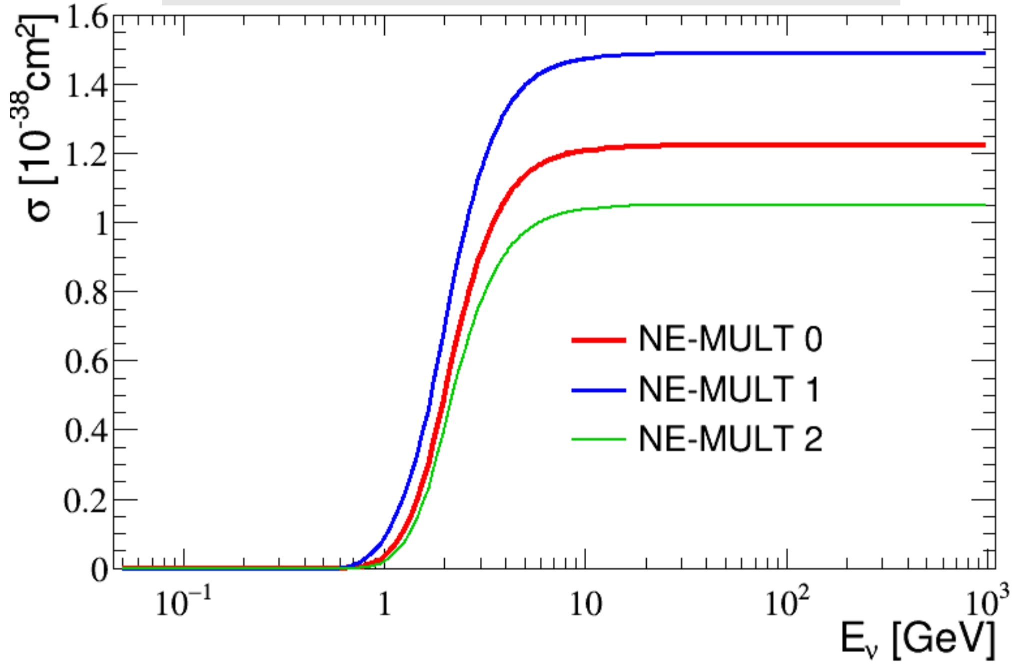
Cross section calculation
Avoiding double counting with RES

When generators use combination of resonant and DIS modes, need to avoid double counting
→ subtract from DIS cross-section fraction handled by resonant modes

- In practice, done as a function of number of particles in the DIS events
- e.g: NEUT only keep DIS events with ≥ 2 pions for low W model

Cross section depends on multiplicity model, which is not well constrained

NEUT low W DIS ν-n xsec

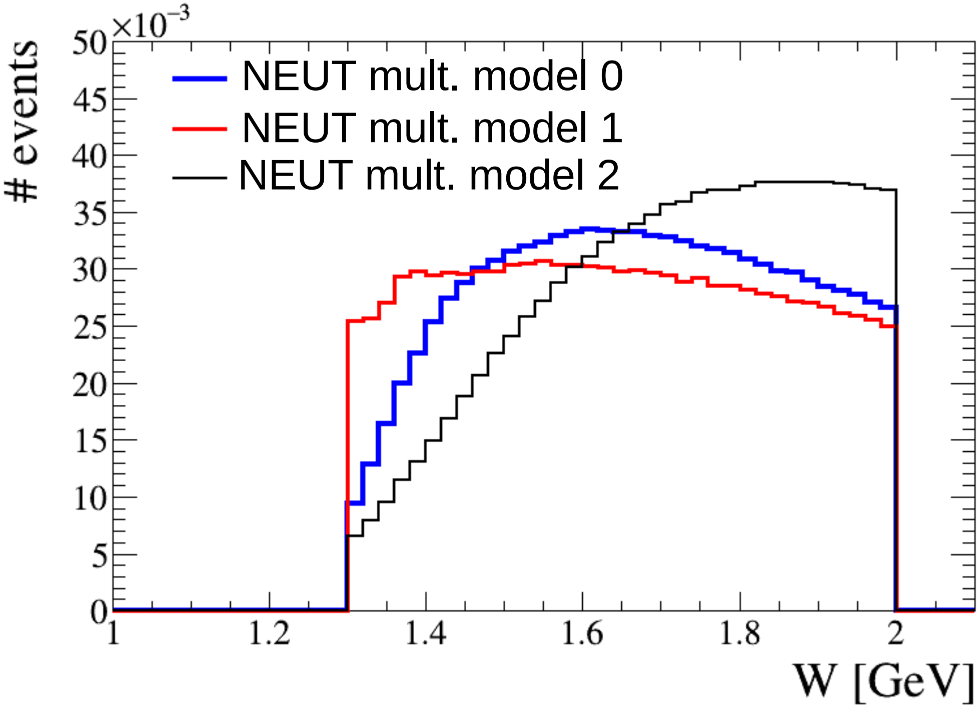


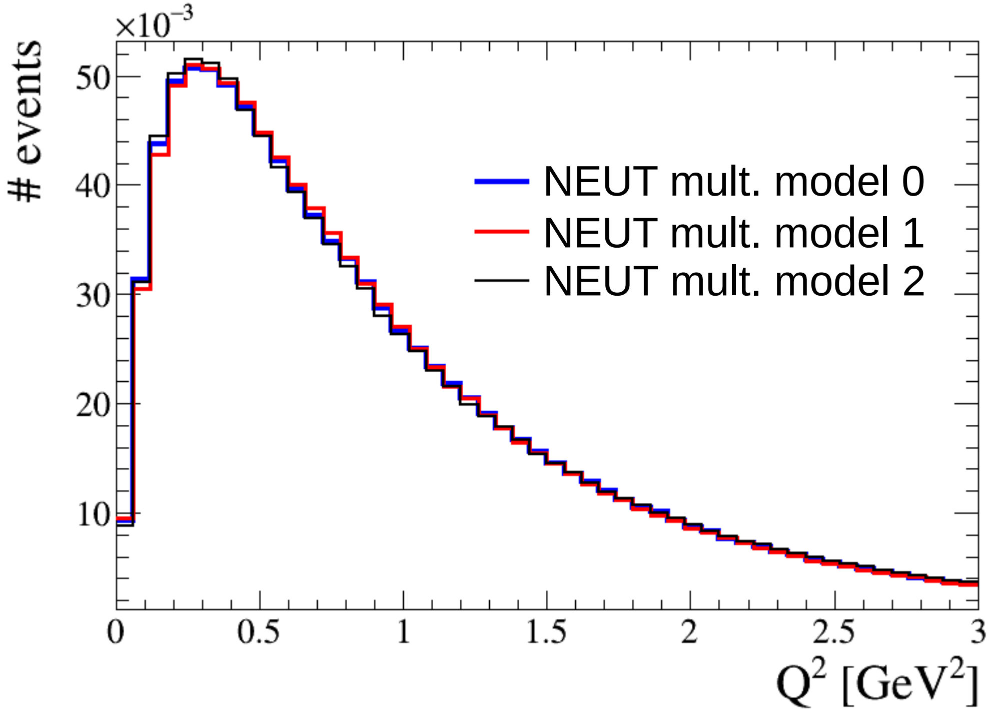
Is there a better way to constrain DIS cross section as a function of (W,Q²) for the low W models?

Global kinematics (W,Q^2)
Low W mode

- For the low W mode, need to use the scheme to avoid double counting with resonant events
- Rejection as a function of number of particle produced
- In multiplicity models, multiplicity probability depends of W

→ strong dependence on multiplicity model for W

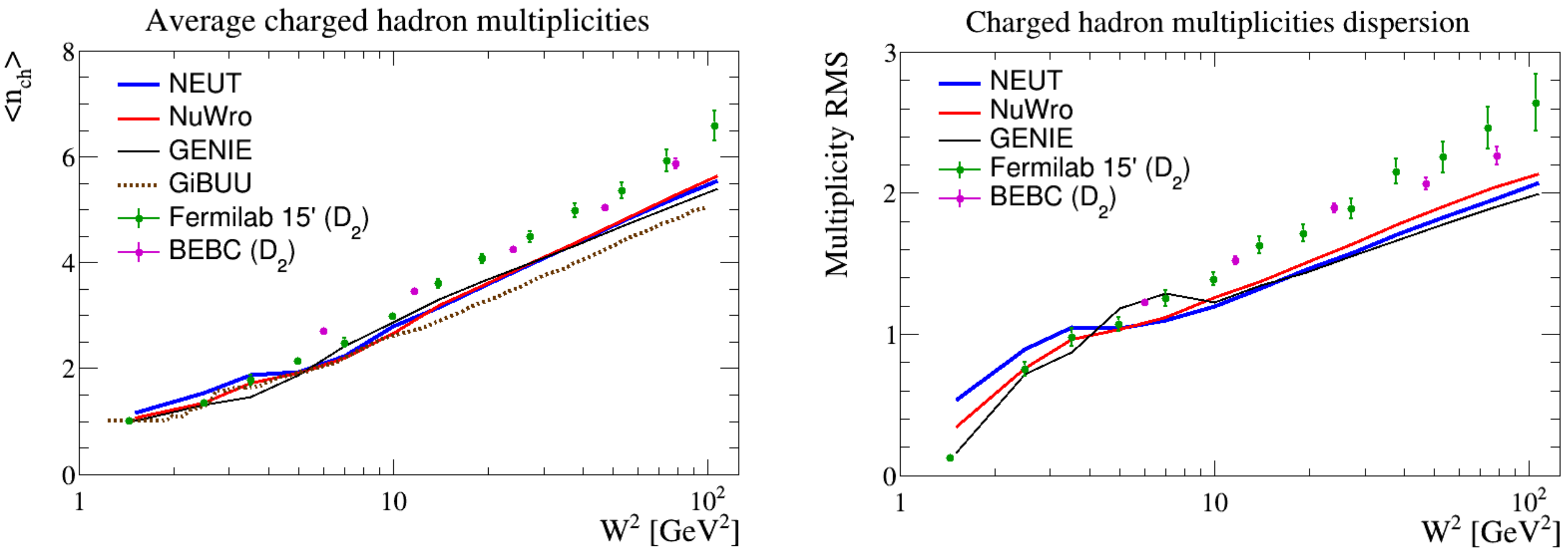




(T2K near detector flux, area normalized, low W mode W<2 GeV, $n_\pi \geq 2$)

Hadronization
Comparison to data

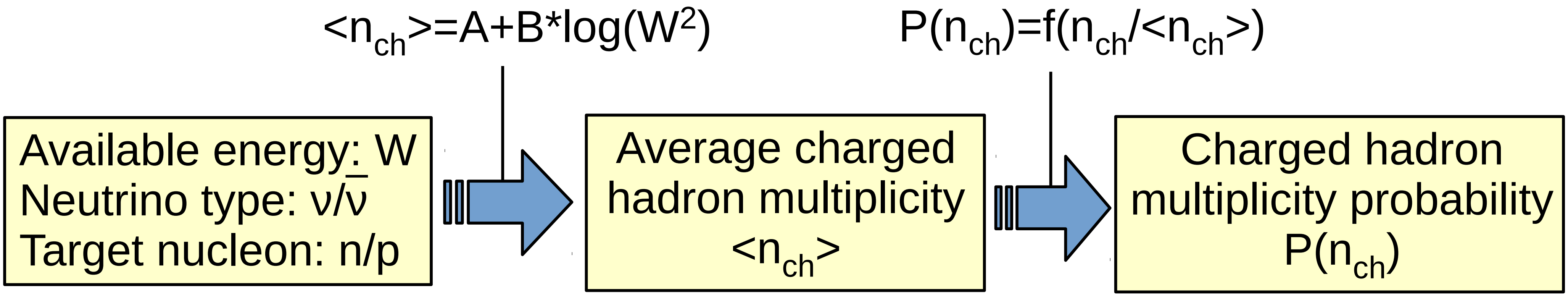
- Generators convert the available W into particles
- Bubble chamber experiments measured the **charged** hadron multiplicities in DIS interactions in the 70’s and 80's
- Generators found to underestimate mean value and dispersion of those multiplicities



caveats:
- plots from NuINT 2015, older version of the generators
- comparing events generated for free neutrons to data of ν-n interactions in deuterium

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 $P(n_{ch})=f(n_{ch}/<n_{ch}>)$ 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))



$<n_{ch}>=A+B*\log(W^2)$

$P(n_{ch})=f(n_{ch}/<n_{ch}>)$

Available energy: W
Neutrino type: ν/ν
Target nucleon: n/p

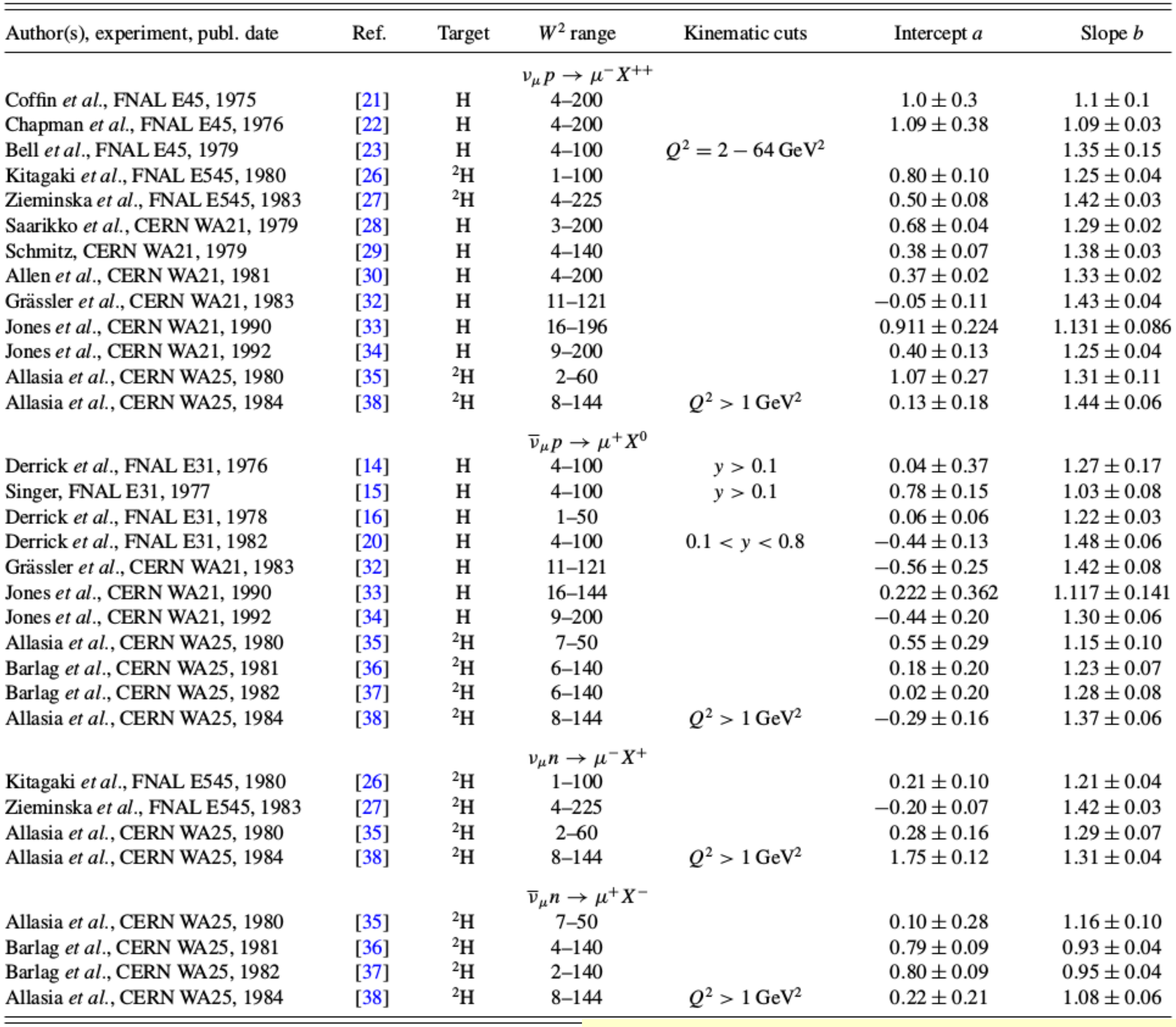
Average charged hadron multiplicity $<n_{ch}>$

Charged hadron multiplicity probability $P(n_{ch})$

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

Low W multiplicity models

- 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
$\bar{\nu}_\mu p \to \mu^+ X^0$						
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
$\nu_\mu n \to \mu^- X^+$						
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$\bar{\nu}_\mu n \to \mu^+ X^-$						
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 (2013)

<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] ($\bar{\nu}$-p) for all types
- GENIE uses [27] for ν and [37] for $\bar{\nu}$, and symmetry νp ↔ νn for some parameters

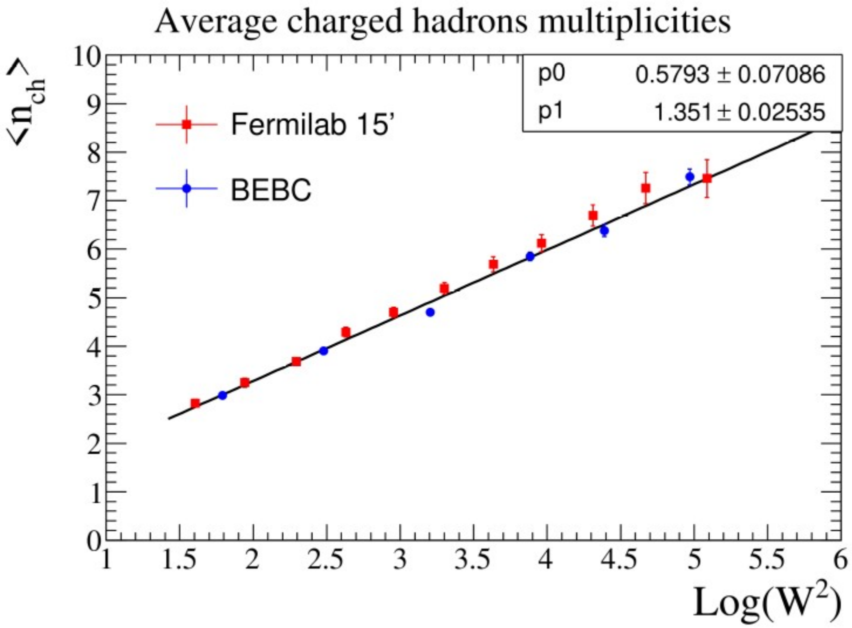
CB, M. Hartz
arXiv:1607.06558 [hep-ph]

Deuterium fits

Tried to make an improved multiplicity model using bubble chamber data on deuterium, assumed to be free neutrons and protons:
- Use all deuterium datasets considered valid in Phys. Rev. C 88, 065501 (2013)
- Fit all parameters for all combinations of ν/ν̄ on p/n

Average multiplicity $<n_{ch}>$ at this W

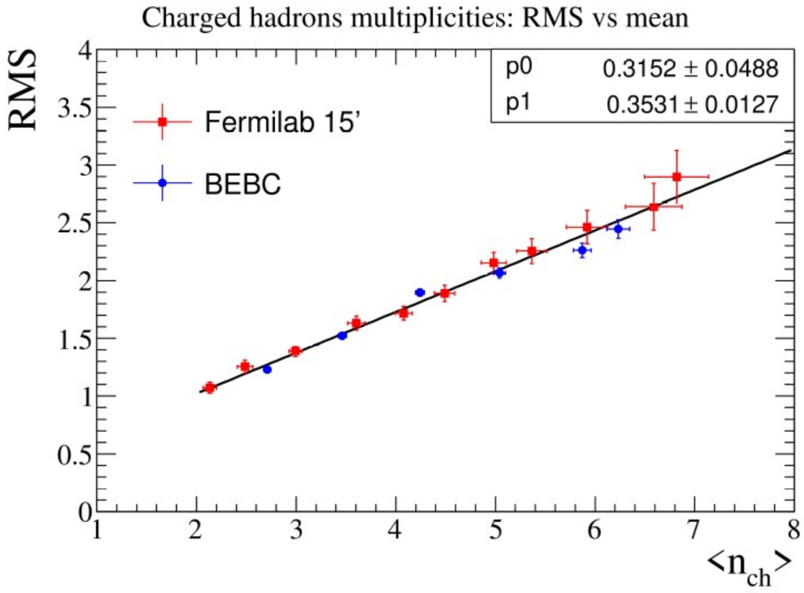
$$< n_{ch} > (W) = A + B \times ln(W^2)$$



2 parameters **A** and **B** obtained by fitting $<n_{ch}>=f(W)$ in bubble chambers data

Deduce the probability of n_{ch} at this W

$$P(n_{ch}, W) = \frac{1}{< n_{ch} > -\alpha} \times f\left(\frac{n_{ch} - \alpha}{< n_{ch} > -\alpha}, C\right)$$



2 parameters **C** and **α**, obtained by fitting the RMS versus the mean of the multiplicity distributions for the different W bins.

- Use for f the 'Levy function' used in the AGKY model (Eur. Phys. J. C **63** ,1-10 (2009))
- Compared to standard KNO scaling, use an additional parameter α as defined in Z. Phys. C **21**, 189 (1984)

Low W Multiplicity models Status

- Different multiplicity models allow to see the effect of those models on generation of DIS event
- Would be better to have a definite model with systematic uncertainties
- Model from deuterium fit would need a bit more work to take into account deuterium FSI, and evaluate systematic uncertainties

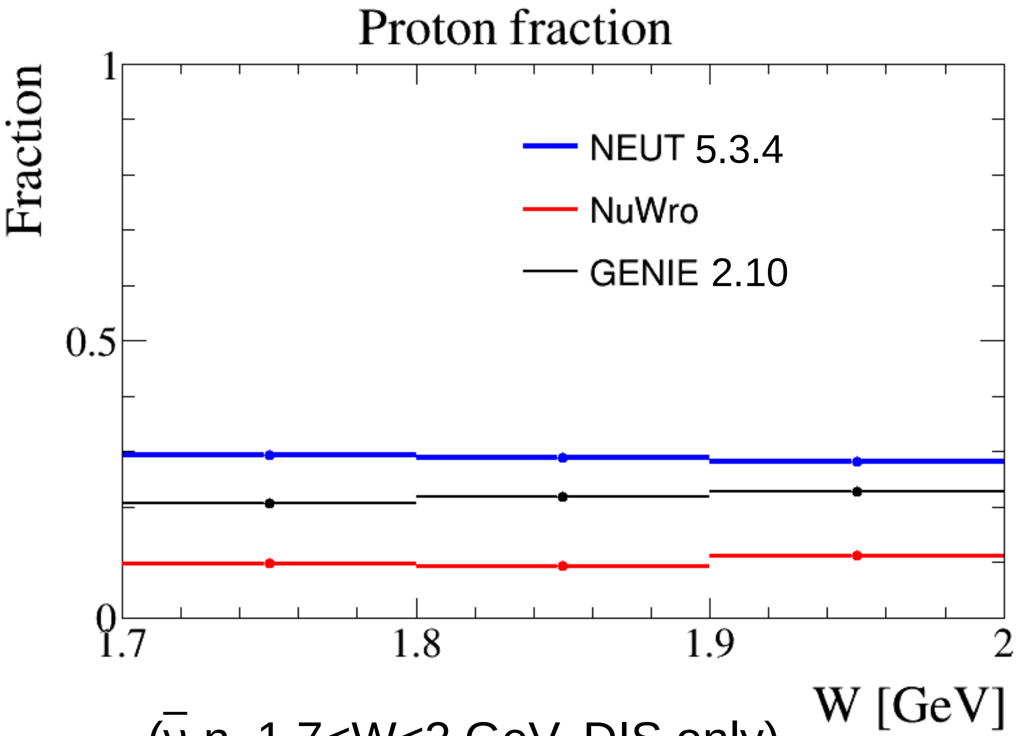
3 multiplicity models in NEUT 5.4.0:

- ✓ Model 0: previous NEUT model, based on M. Derrick et al., PRD 17 (1978)
- ✓ Model 1: deuterium fits (arXiv:1607.06558 [hep-ph])
- ✓ Model 2: AGKY model (Eur. Phys. J. C 63 ,1-10 (2009))) used in GENIE

For low W models need $n_{ch} \rightarrow n_{had}$.

Requires additional assumptions:

- → relation between $n(\pi^{\pm})$ and $n(\pi^{0})$
- → fraction of outgoing nucleons that are protons



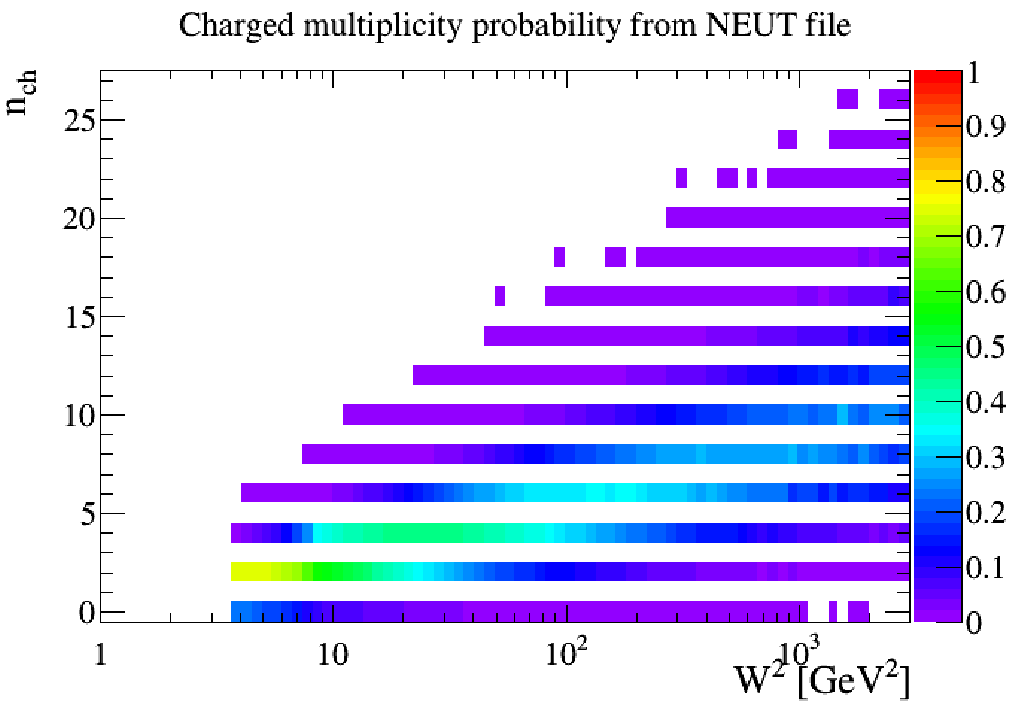
($\bar{\nu}$-n, 1.7<W<2 GeV, DIS only)

Low W Multiplicity models
Considerations for next SK analysis

Until model from deuterium fit is ready:

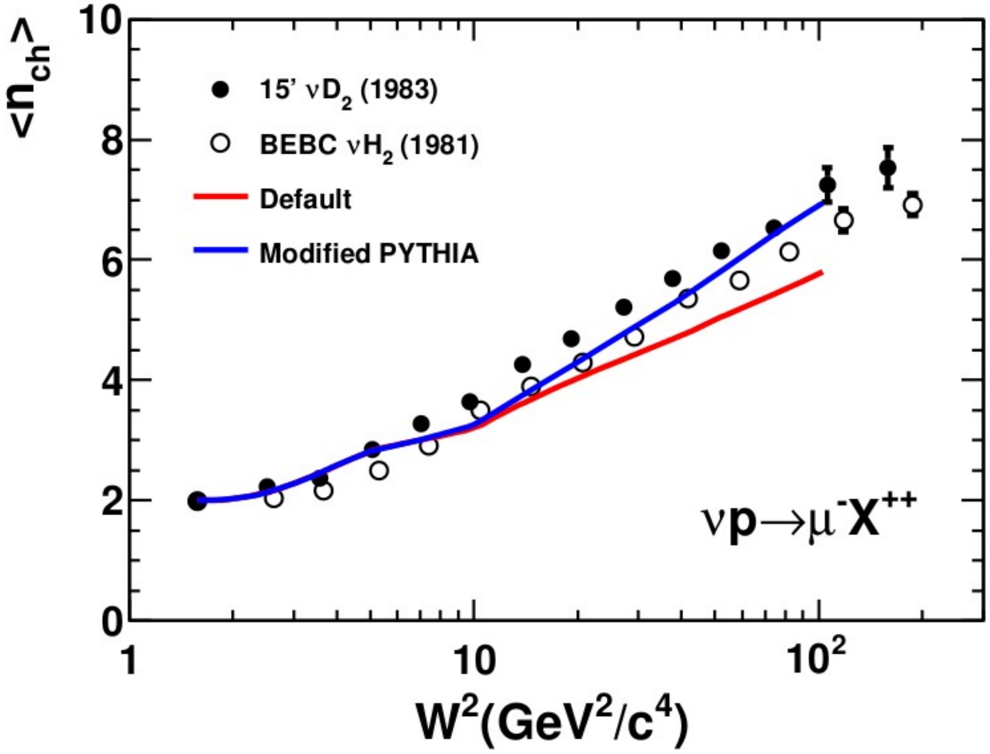
- Keep old NEUT model (model 0) as default model
- Make systematic uncertainties by comparing this default model to AGKY one
- 2 uncorrelated systematic parameters:
  - cross-section (normalization) for multi-pi mode
  - shape: W and multiplicity distribution for a given W

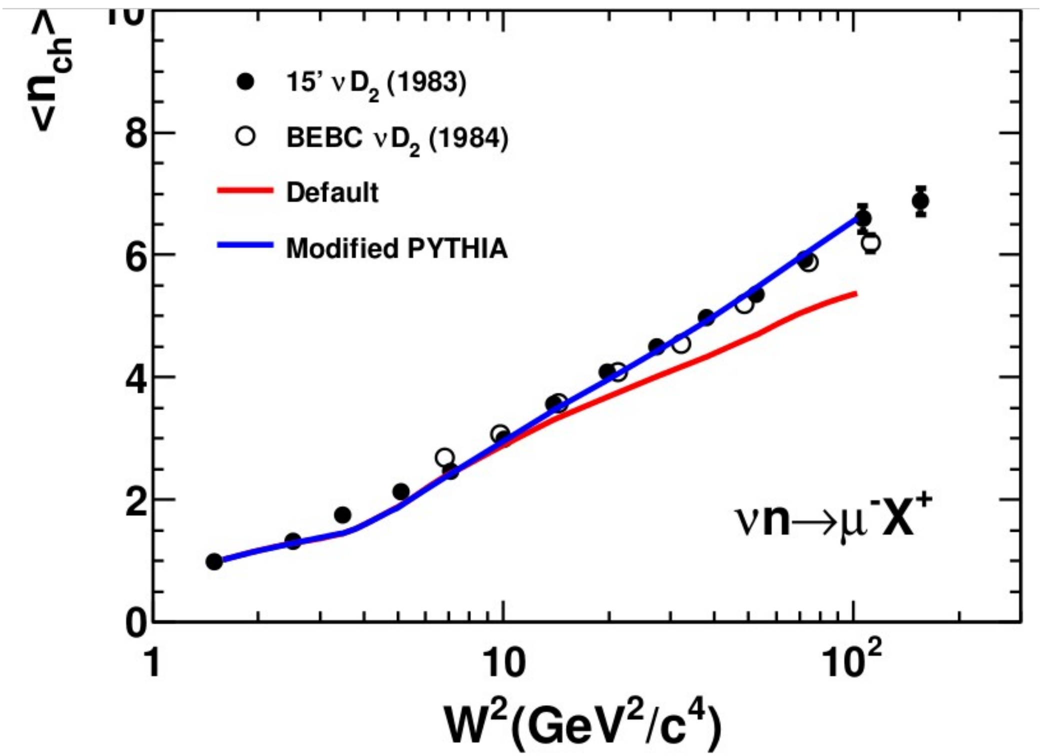
Rational:
- avoid using deuterium fits until understood
- Provides freedom in the fit on interesting quantities while still having some physics motivation
- keep shape and normalization separate, as there are many underlying parameters so don’t want to tie shape to a fit on number of events



Multiplicity models
High W modes - PYTHIA

- At high W, fragmentation handled by PYTHIA
- Also disagrees with bubble chamber data
- Attempts to tune PYTHIA by T. Katori and S. Mandalia (arxiv: 1412.4301v3)



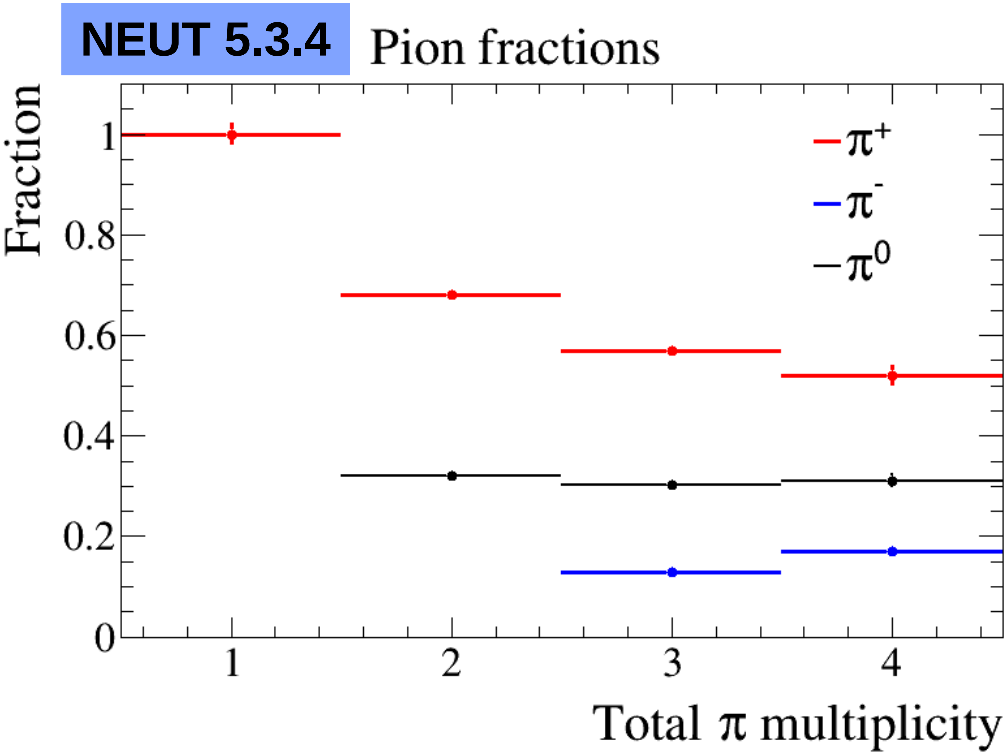


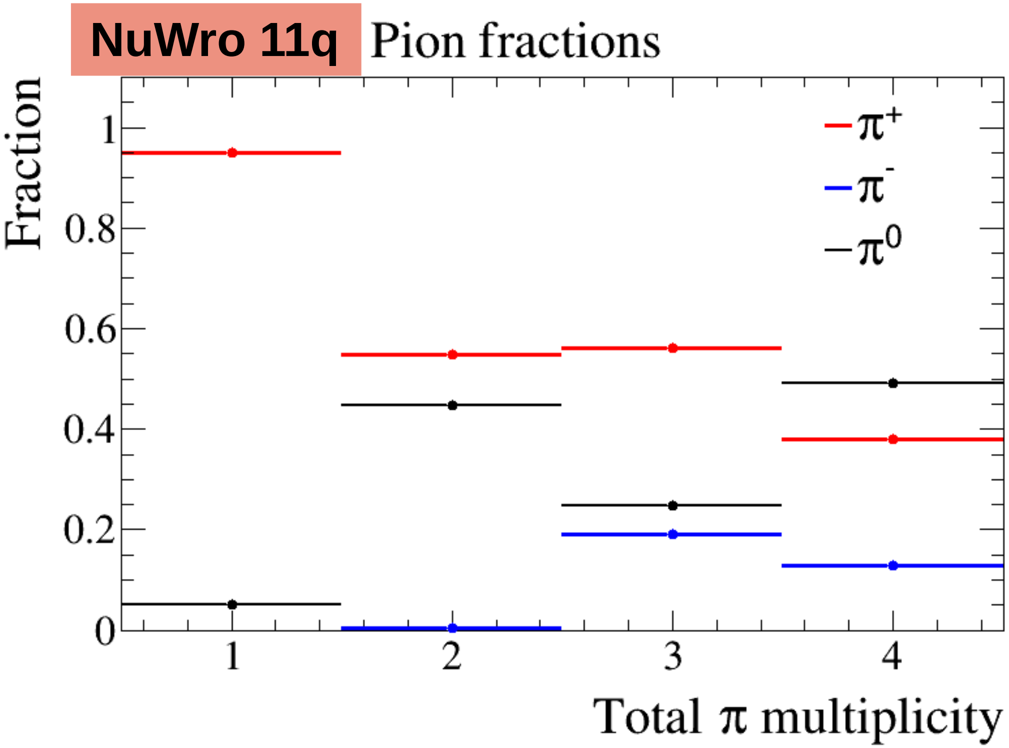
Found some difficulties:
- dispersion of the charged hadron multiplicities
- neutral hadron multiplicities

"Further tuning is ongoing"

Hadron types – Low W mode

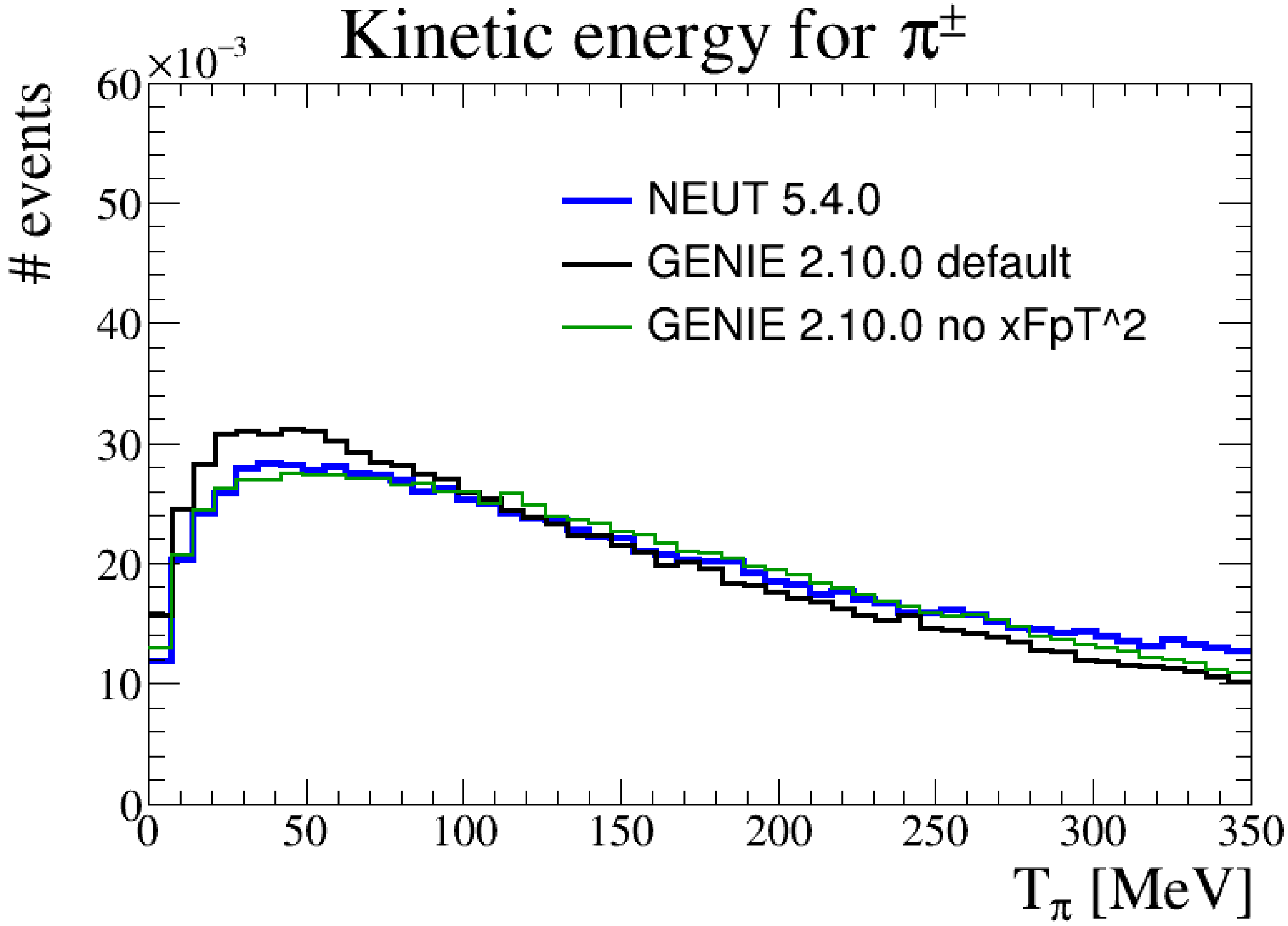
- Different kind of hadrons have very different signatures in a detector like Super-K (nb of rings, ring type, threshold, Michel electron)
  → will have an impact on $\bar{\nu}/\nu$ separation
- Currently no systematic uncertainties on this
- Particle content seems different for NEUT low W mode and PYTHIA, as can be seen in comparison with NuWro





Hadron kinematics – Low W mode

- Hadron kinematics matter for observables in water Cerenkov: depending on its momentum, a $\pi^{\pm}$ will appear as a ring or a Michel electron
- Differences seen in NEUT and GENIE low W modes could maybe provide a first systematic uncertainty on this



(No FSI, see talk on generator comparisons for settings)

Summary

- Super-Kamiokande can study the mass hierarchy by trying to determine if a resonance in the oscillation probabilities happen for neutrinos or anti-neutrinos

- SK cannot distinguish between the interaction of and on an event-by-event basis: use differences in DIS interactions of the two to make statistical separations

- Important quantities to model are cross-section, and properties of the hadronic system (number, type and kinematics of the hadrons produced)

- Uncertainties come from the PDFs, the parameters of the Bodek-Yang models and scheme to transition from resonant to DIS regions for the cross-section

- For the hadronic system at low W, multiplicity model has a large impact. Trying to make a model with uncertainties to take this into account

- Focused mainly on the low W region for the hadronic system, but higher W region handled by PYTHIA should be studied as well

BACKUP

Bodek-Yang corrections

GRV98 PDFs used by the generators to compute structure functions are valid for Q^2>0.8 GeV
The Bodek-Yang corrections allow to go to lower Q^2
Different modifications are applied:

1) Change the scaling variable used to compute the PDFs

$$x \rightarrow \xi = \frac{2x\left(Q^2 + m_f^2 + B\right)}{Q^2\left[1+\sqrt{1+\frac{(2Mx)^2}{Q^2}}\right]+2Ax}$$

- m_f is the final quark mass, and is neglected except for charm production
- B takes into account the initial quark p_T, and the final state quark mass from multi-gluon emission
- A is there to enhance the target mass effects to account for higher QCD and higher twist corrections

Bodek-Yang corrections

2) Freeze the evolution of the PDFs at a given Q^2 (0.8 for GRV98)
Below that value, the PDFs at 0.8 are used, and the variations with Q^2 come only from correction factors

3) Use multiplicative correction factors K for the PDFs
(used for all Q^2)

$$K_{val}=(1-G_D^2)\frac{Q^2+C_{v2}}{Q^2+C_{v1}} \qquad K_{sea}=\frac{Q^2}{Q^2+C_s}$$

In later versions of the corrections, different K factors for up and down quarks.
G_D is the proton elastic form factor, the C_i are parameters, which values were obtained by a fit.

4) Correct the ratio of up and down quarks for the valence quarks

$$corr=-0.00817+0.0560\,x+0.0798\,x^2$$

$$u'=\frac{u}{1+corr\times\frac{u}{u+d}} \qquad d'=\frac{d+u\times corr}{1+corr\times\frac{u}{u+d}}$$

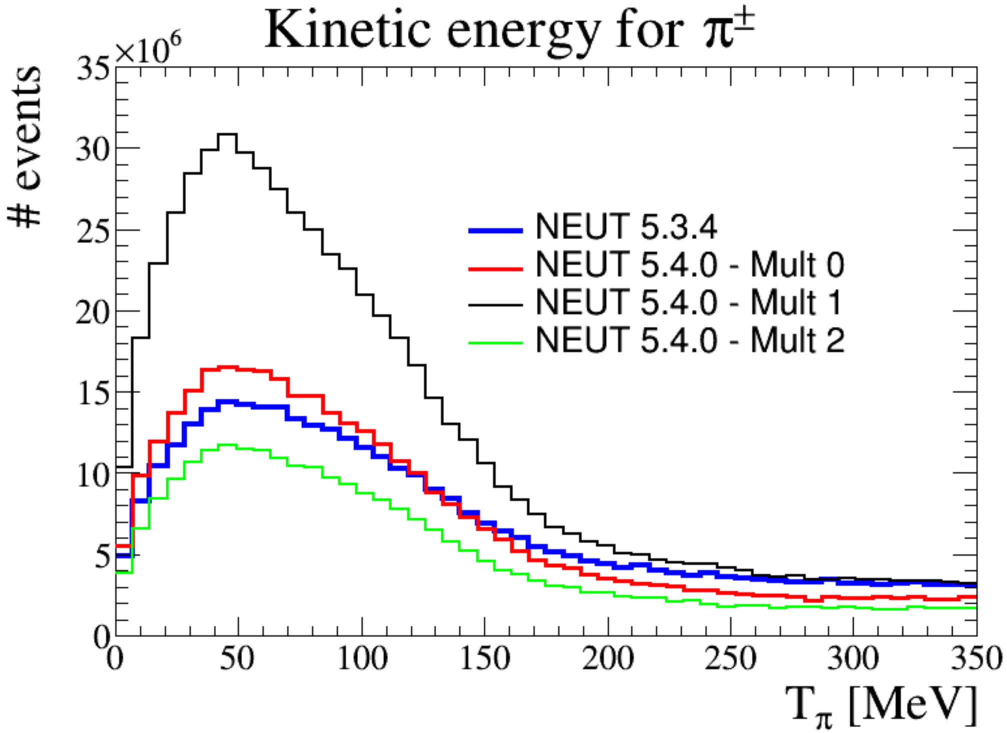
Deuterium fits
Limits

- Those fits represent an improvement compared to other models, which just used one dataset for all targets and neutrinos (NEUT), or one dataset for each when available and symmetry $\nu p \leftrightarrow \bar{\nu} n$ else (AGKY)
- Goal was to then have systematic uncertainties on this model, to make a systematic uncertainty to propagate for physics analysis.
- Found however that some additional work was needed on this model

Deuterium FSI

- Main issue is that I assumed deuterium= free n and p
- Several papers mentionned that nu-n samples should be rather pure, but not nu-p due to FSI
- Solution would be to use hydrogen data for nu-p, and difference H/He in nu-p to correct for FSI in nu-n

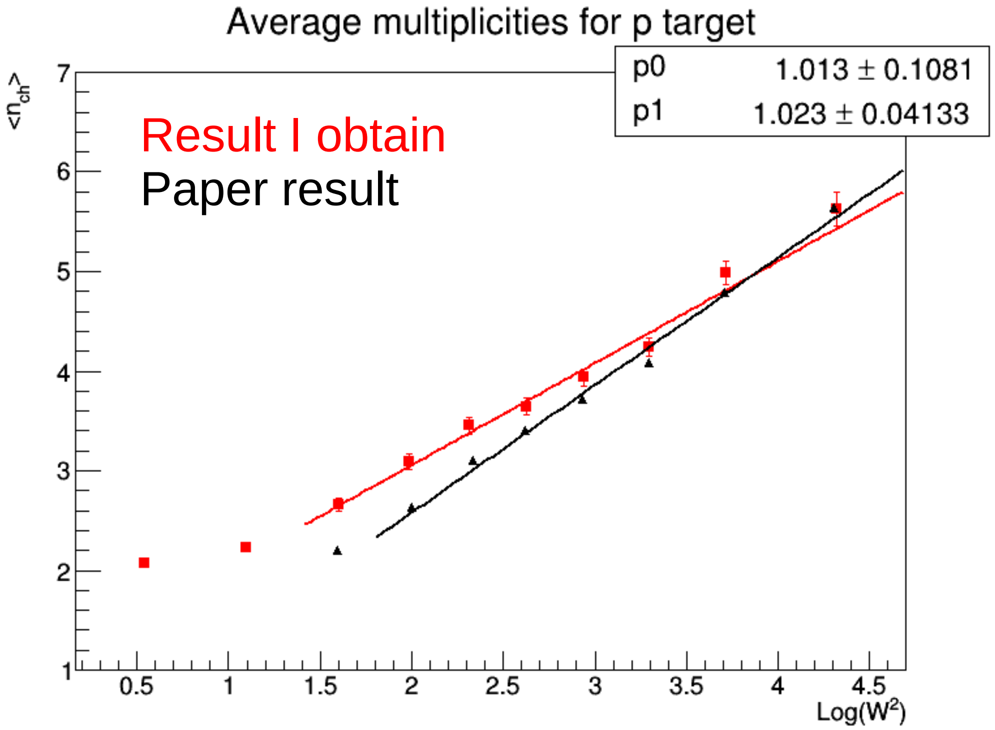
Also has a large impact on normalization for some distributions



Multiplicity models
Systematic uncertainties

Ultimately, want to have errors on the model:
- Error on A, B, C, α from fit with correlations
- FSI effect from difference H/He for ν-p
- Additional systematics for multi-pion modes: $n_{ch} \rightarrow n_{had}$
  - fraction of outgoing baryon that is a proton
  - relation between $\pi^{\pm}$ and π^{0} multiplicities

A bit harder to do then expected:
- many datasets disagree (use pGOF?)
- most paper don't give systematic uncertainties
- data are usually provided corrected by MC
- a number of paper don't give the data. Have to be digitalised from hand made log plots, probably need a "scanning" systematic
- sometimes hard to reproduce paper results using obtained numbers...



Generating hadronic system
Particle content – Low W modes

- Different kind of hadrons have very different signatures in a detector like Super-K (nb of rings, ring type, threshold, Michel electron)
- For NEUT and GENIE, based on the idea that all pion types are as probable, so generate randomly
- Charge conservation and available energy put constraint on what can be produced

NuWro

Use PYTHIA fragmentation routines extended to low W

NEUT

- 1 nucleon, than only pions
- All pion types same probability
- Rethrow until combination which respects charge is obtained

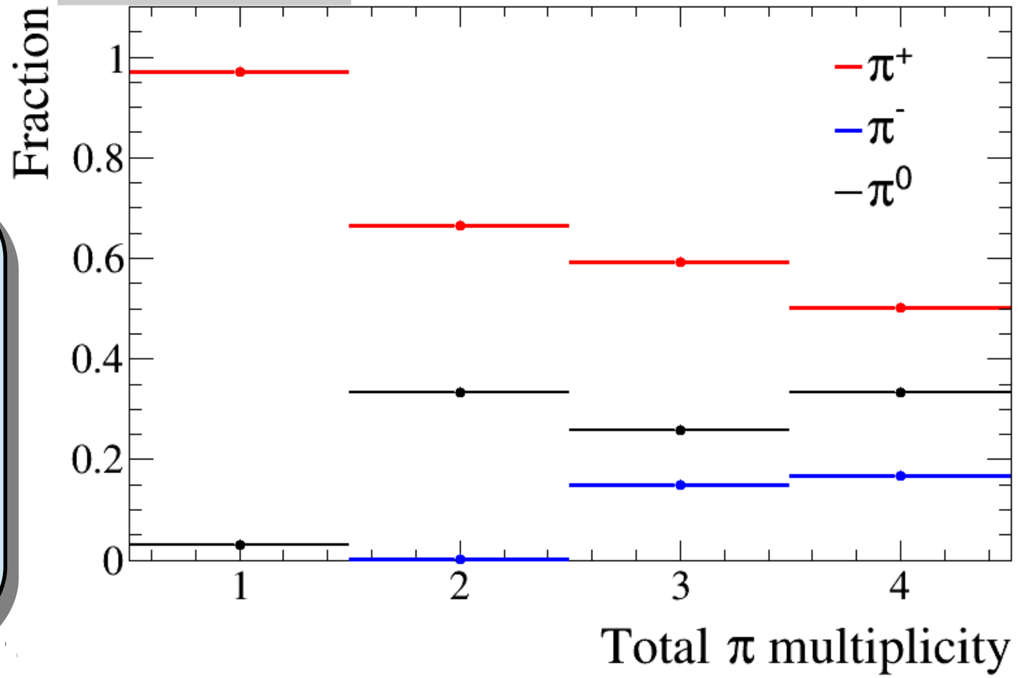
GENIE

- 1 nucleon, than pions and kaons
- Balance charge, than add neutral particles or pairs.
- $P(\pi^+, \pi^-)=2*P(\pi^0,\pi^0)$
- P(strange meson pair)=6%

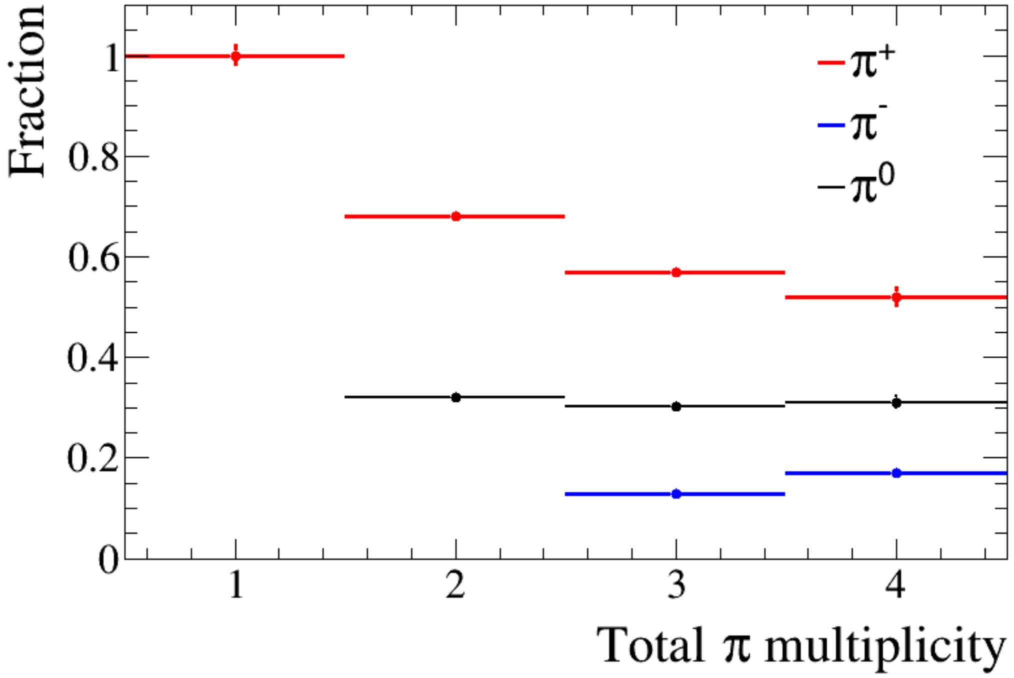
Particle content - Pions
Low W modes

- Similar pattern between GENIE and NEUT
- More differences with PYTHIA, in particular for π^0
- Exemple of interations of **neutrinos on free protons**

GENIE 2.10 Pion fractions



NEUT 5.3.4 Pion fractions



NuWro 11q Pion fractions