Workshop on Neutrino-nucleus interaction in a few GeV region

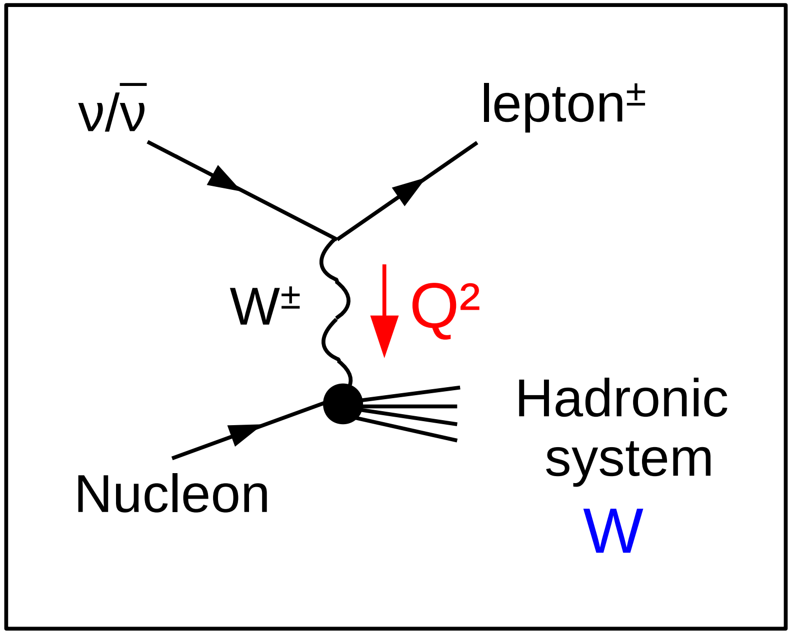
Modelisation of neutrino deep inelastic interactions for simulations

Christophe Bronner
2017-11-19

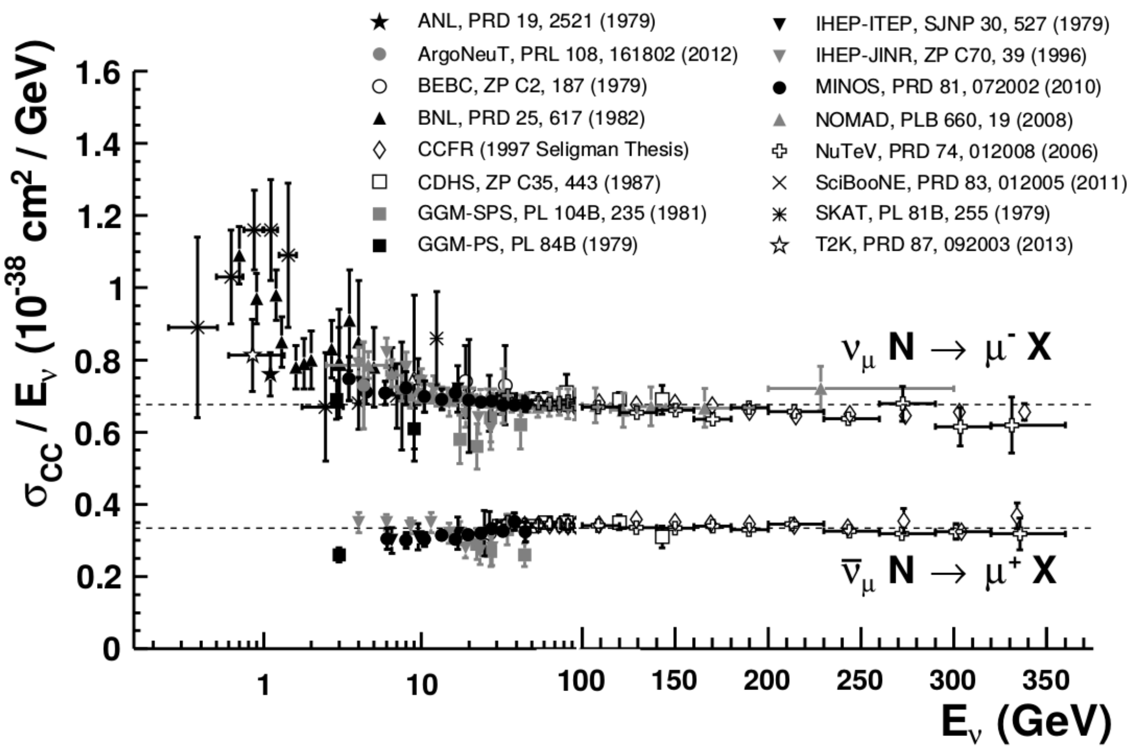
KAMIOKA OBSERVATORY

Introduction

- DIS interactions generally considered to be better understood than CCQE or resonant pion production
- However difficulties in practice for experimentalists trying to construct MC and model systematic uncertainties
- Looking at the case of mass hierarchy with atmospheric neutrinos



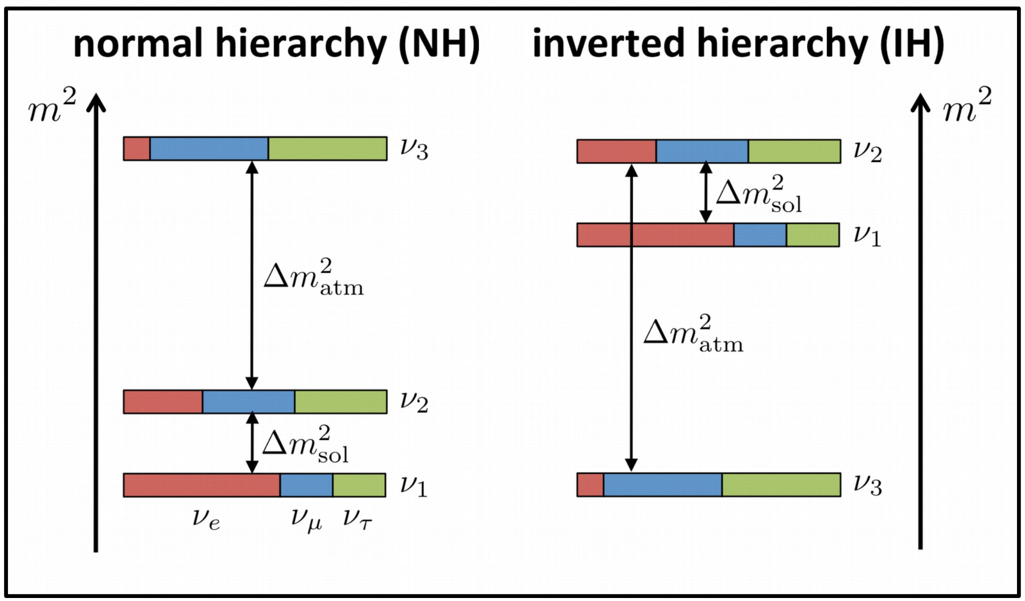
From PDG 2015

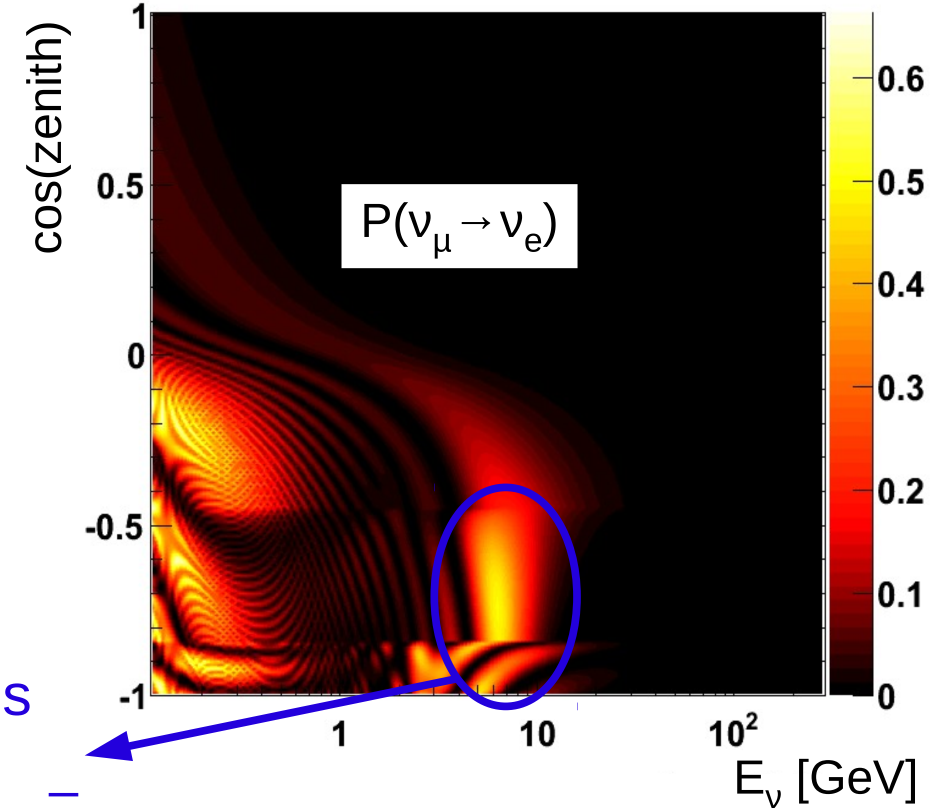


Mass hierarchy with atmospheric neutrinos

- Order of neutrino mass eigenstates is not fully known
- Propagation in vacuum 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

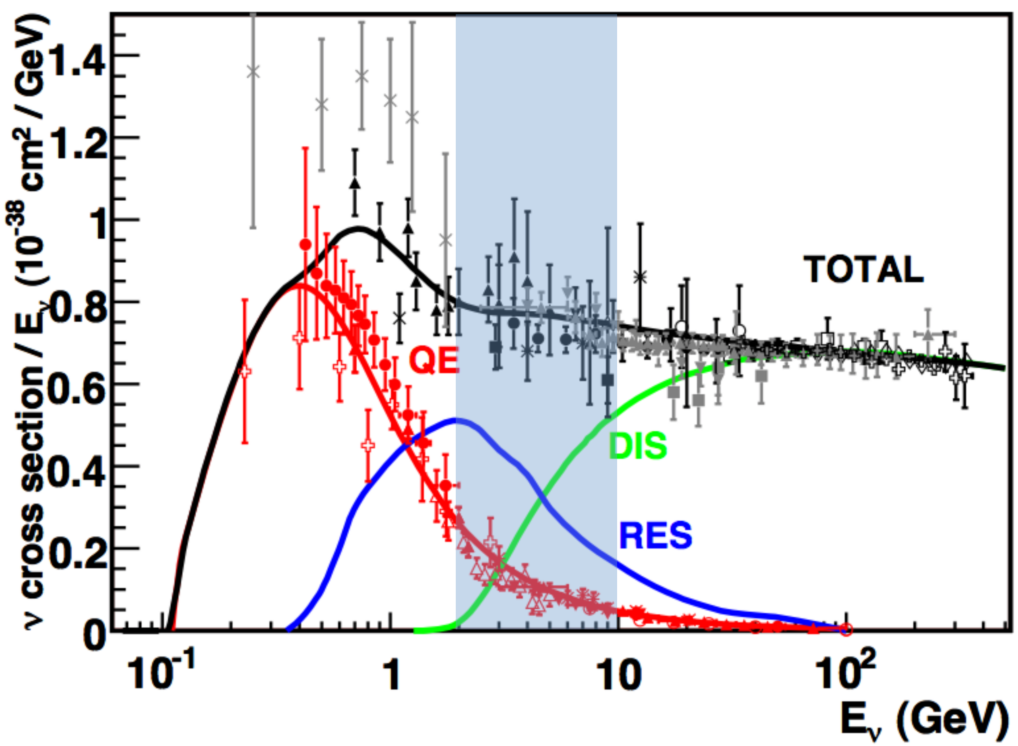




Determine if this enhancement happens for ν or $\bar{\nu}$

Mass hierarchy with atmospheric neutrinos
Water Cerenkov detector

- Water Cerenkov detectors cannot distinguish on an event by event basis between ν and ν
- 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”)

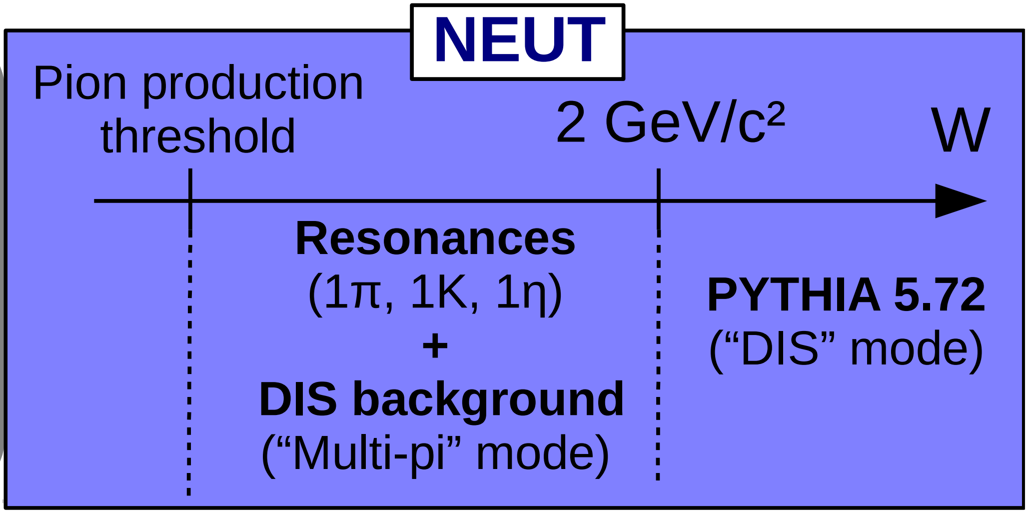


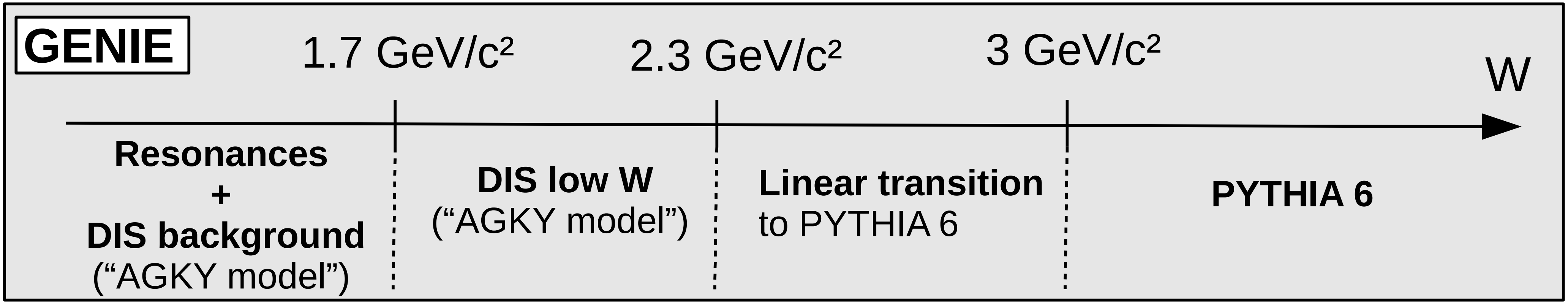
<u>Need to know precisely:</u>

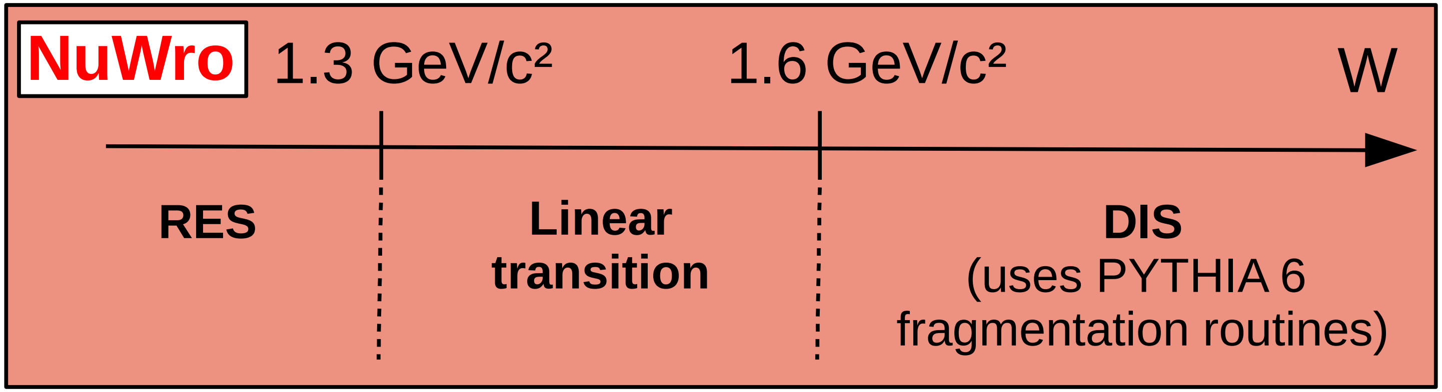
- cross-section (expected size of the resonance in each MH)
- topology of the interactions in the detector
  - number of pions
  - energy transfer
  - kinematics of the hadronic system
- In particular the differences between ν and ν for those

Transition region in interaction generators

- Different models as a function of W
- Combination of resonances and DIS continuous parametrization
- No clear prescription about how to do transition and which resonances to consider

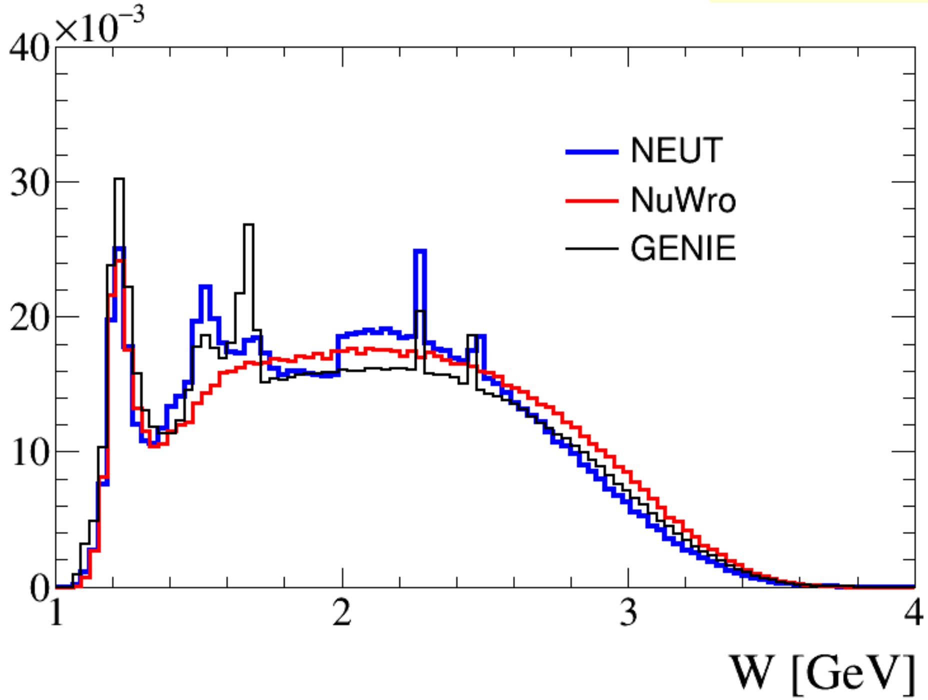


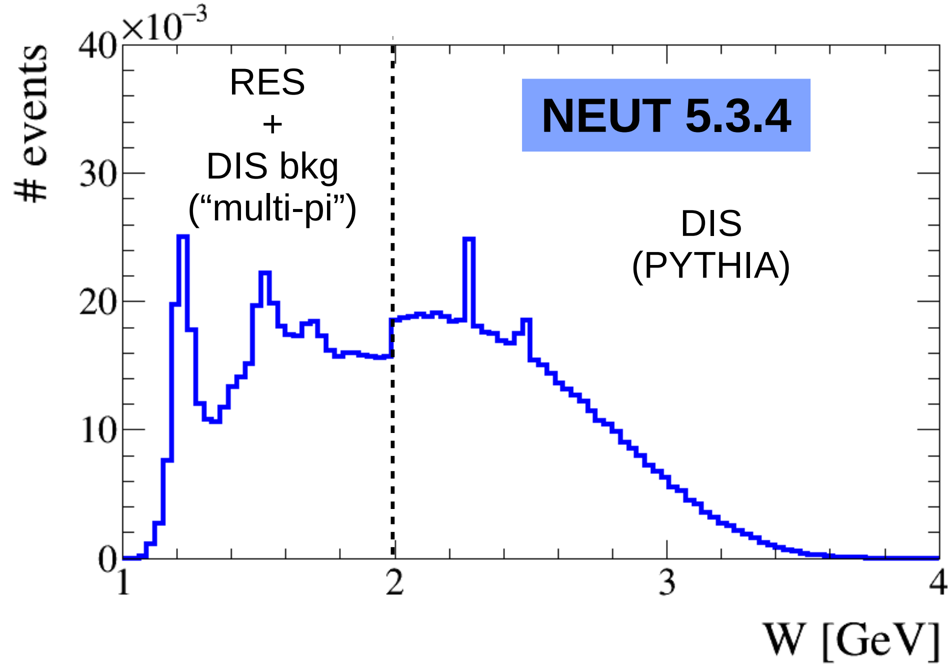


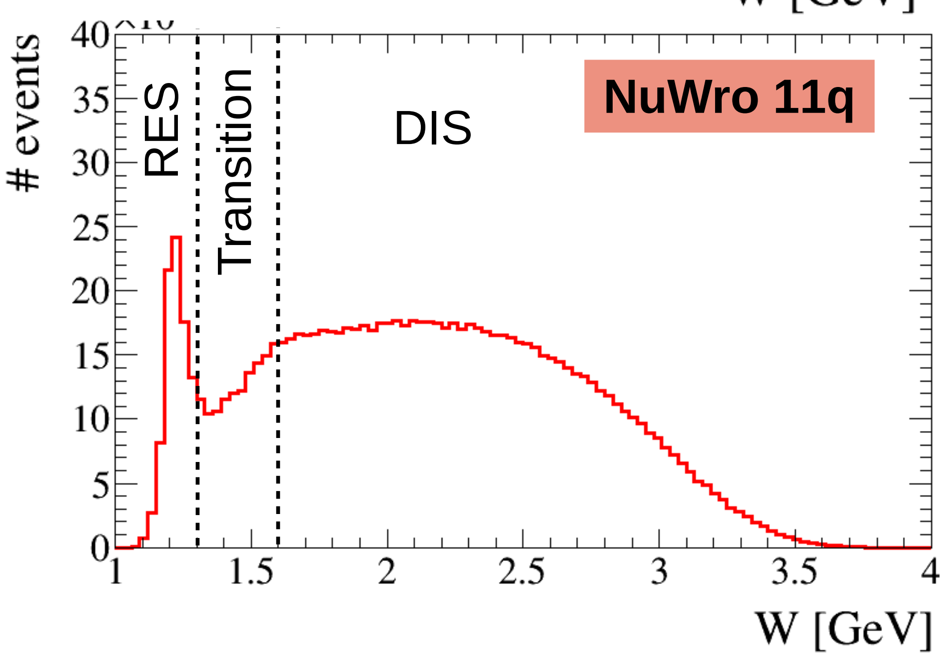


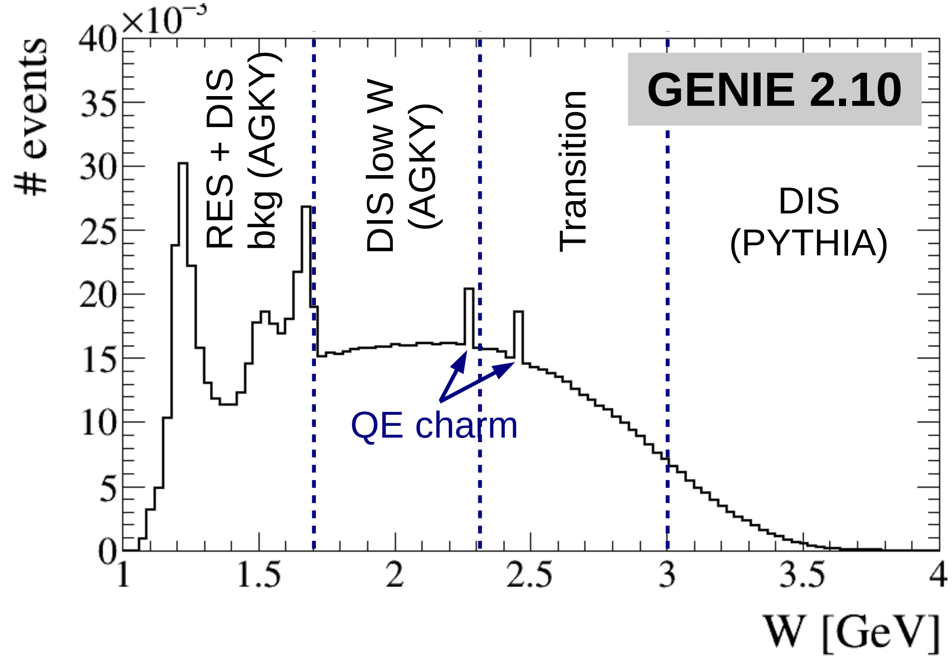
Transition region in interaction generators

6 GeV ν_μ on Fe target









DIS events in interaction generators

3 main operations to simulate DIS events in neutrino interaction generators

Calculate cross-section → Number of events to generate

Determine global kinematics (W,Q^2) →
- Lepton kinematics
- Energy available to build hadronic system (W)

Generate hadronic system
- Low W: Custom models
- High W: PYTHIA generator

→
- Number of hadrons
- Type of hadrons
- Kinematics of each hadron

Remark: in NEUT, global kinematics is actually determined by PYTHIA 5 for high W mode

Cross section calculation

Calculated by integrating $d^2\sigma/dxdy$ 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

$d^2\sigma/dxdy$ 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

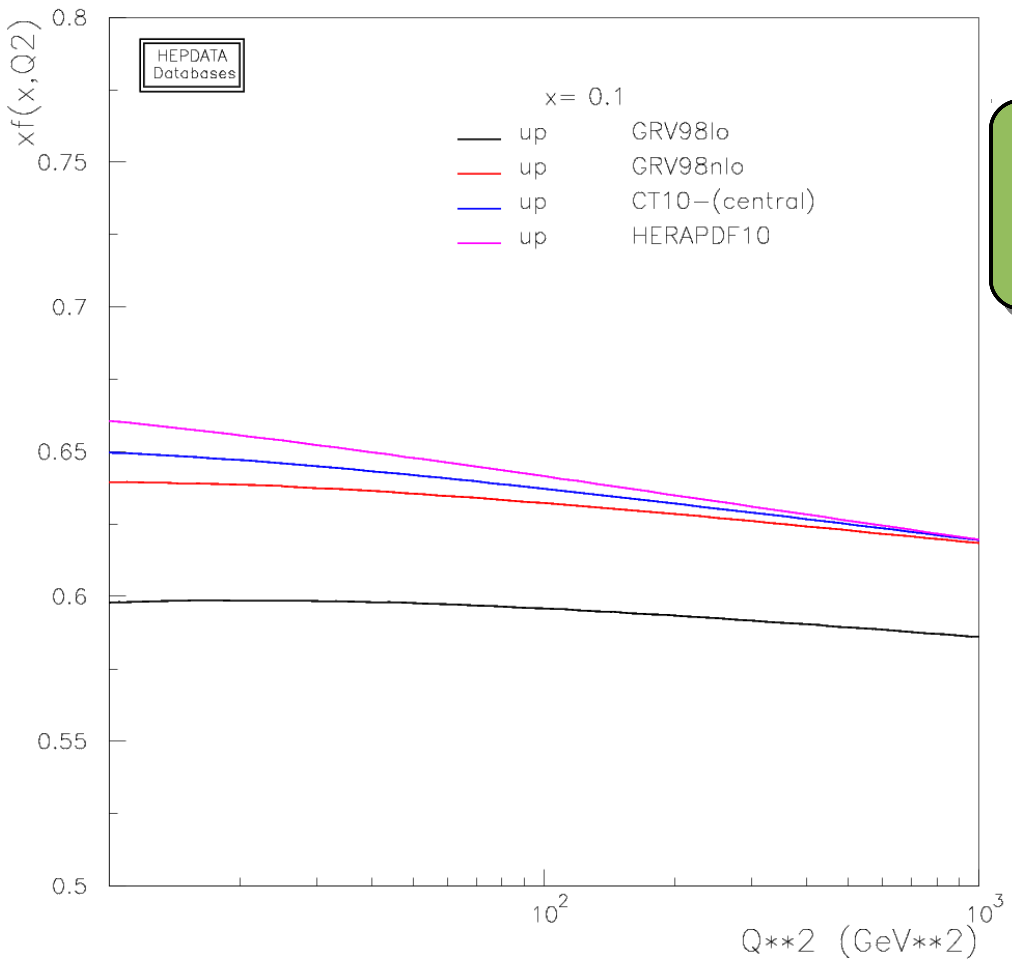
$$F_1(x,Q^2) = \frac{1}{2x} F_2(x,Q^2) \times \left(\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)} \right) \qquad F_4(x,Q^2)=0 \qquad F_5(x,Q^2) = \frac{F_2(x,Q^2)}{x}$$

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

Inputs (and source of uncertainty) on the cross-sections are the PDFs

Cross section calculation
Parton Distribution functions

- PDFs can be computed in QCD using perturbative expansion, 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

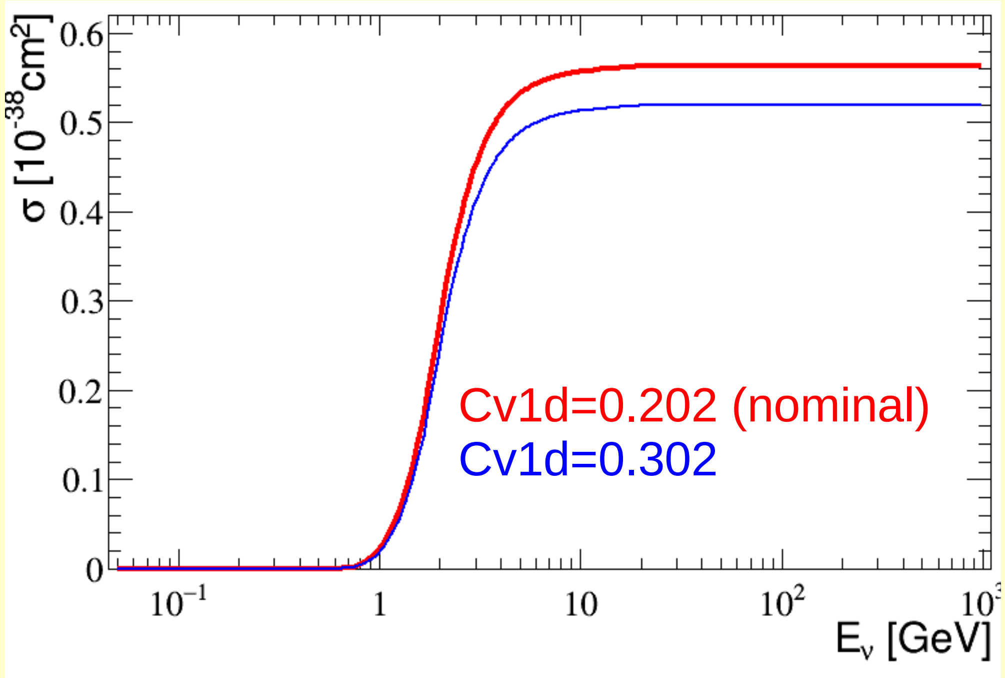
Using GRV98 leading order in generators, although it disagrees with more recent PDFs

Cross section calculation
Corrections by Bodek and Yang

- Model with free parameters, determined by a fit of electron scattering and photo-production data
- Many different versions, latest ones difficult to implement in generators
- No errors given on some of the parameters as they don't seem to change the result of the fit of lepton scattering data, although they affect cross sections
- Use difference with / without corrections as systematic uncertainty?

Parameter	hep-ex/0301036	hep-ex/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

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



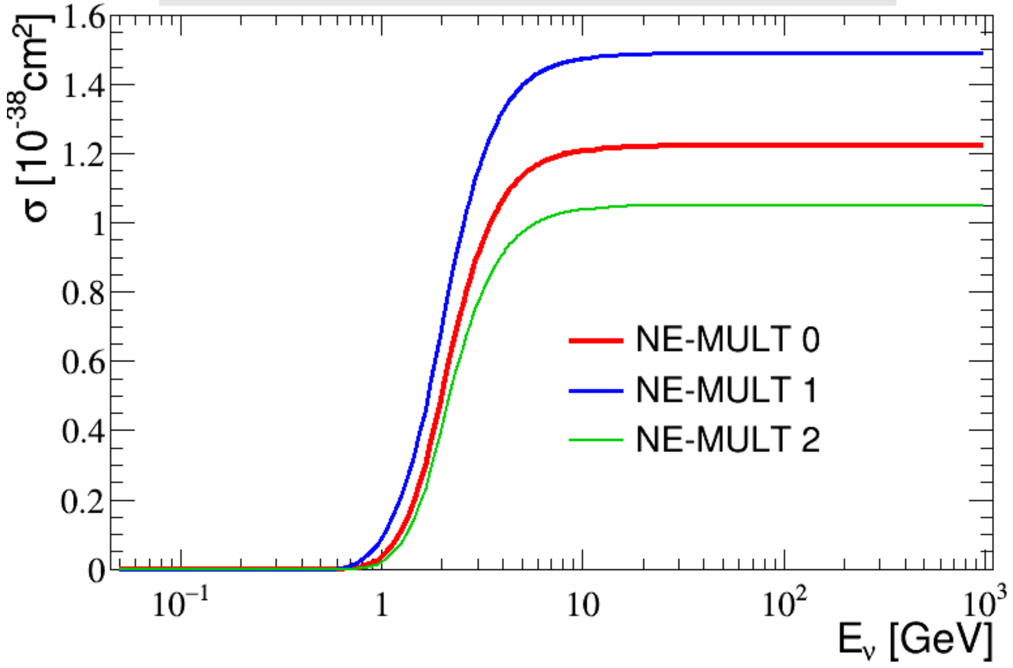
Cross section calculation
Avoiding double counting with RES

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

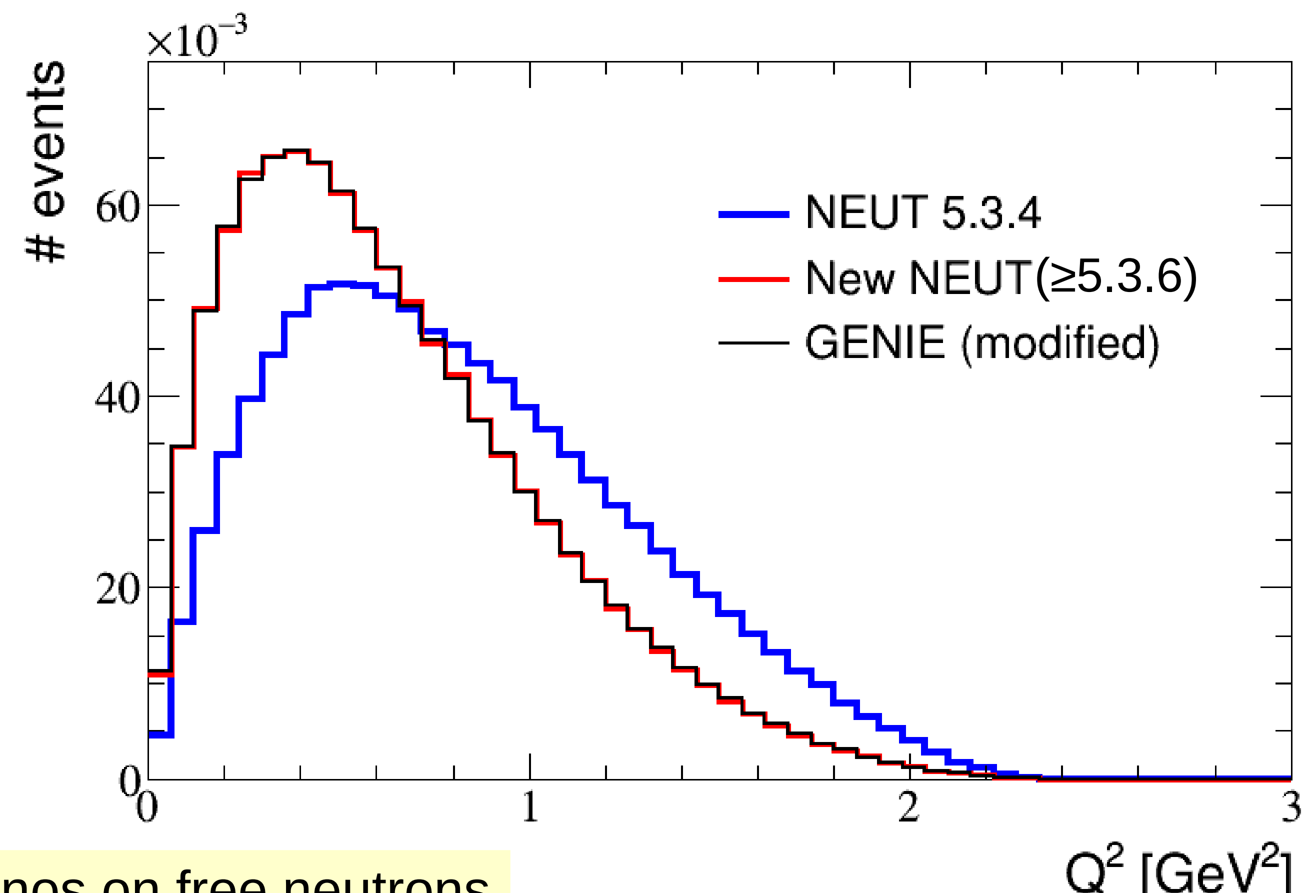
NEUT low W DIS ν-n xsec



Is there a better way to constrain DIS cross section as a function of (W,Q^2) for the low W models?

Global kinematics (W,Q²)

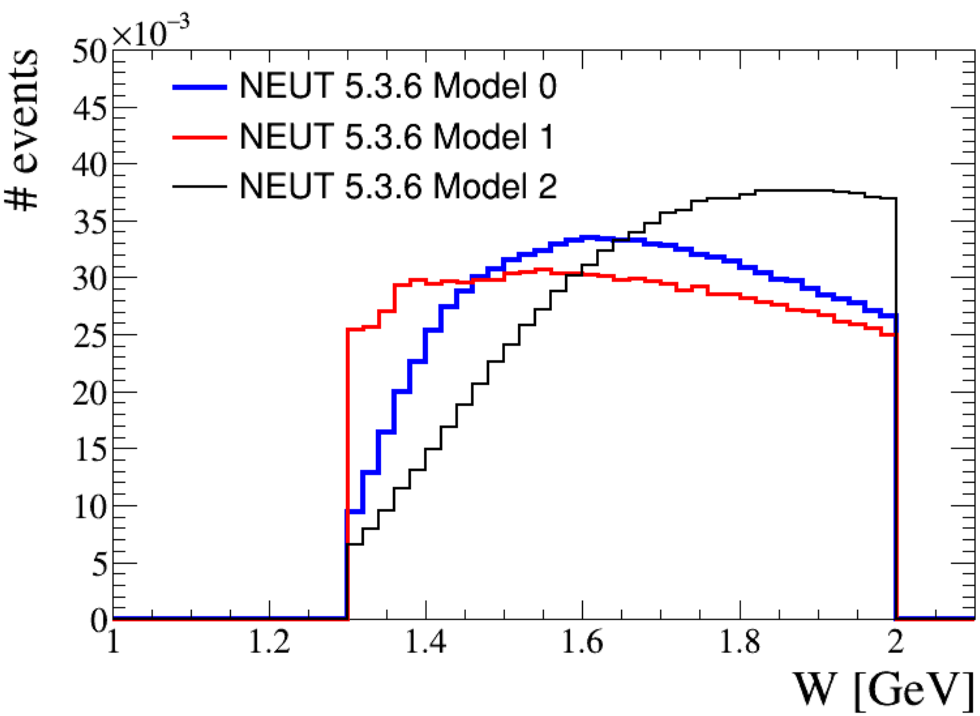
- (x,y) are generated using acceptance-rejection method on $d^2\sigma/dxdy$
- As a result, uncertainties coming from PDF and Bodek-Yang corrections
- Can compute (W,Q^2) directly from (x,y)
- In the past, saw disagreements between GENIE and NEUT for this step, now fixed

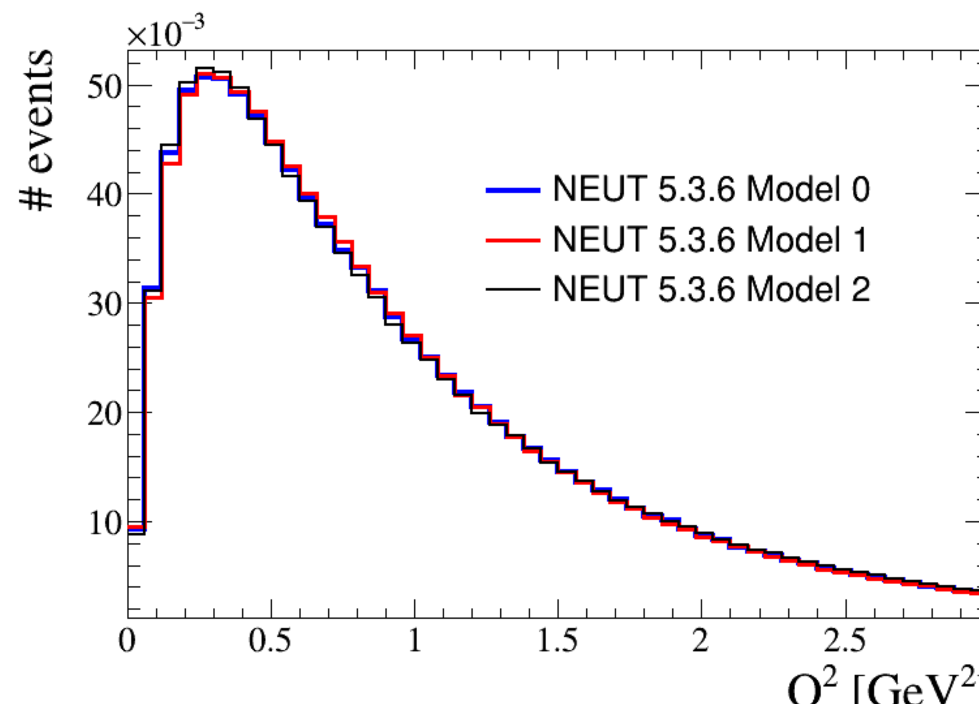


2 GeV neutrinos on free neutrons
Low W modes (W<2 GeV, $n_\pi \geq 2$)

Global kinematics (W,Q²)
Low W modes

- For the low W modes, 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

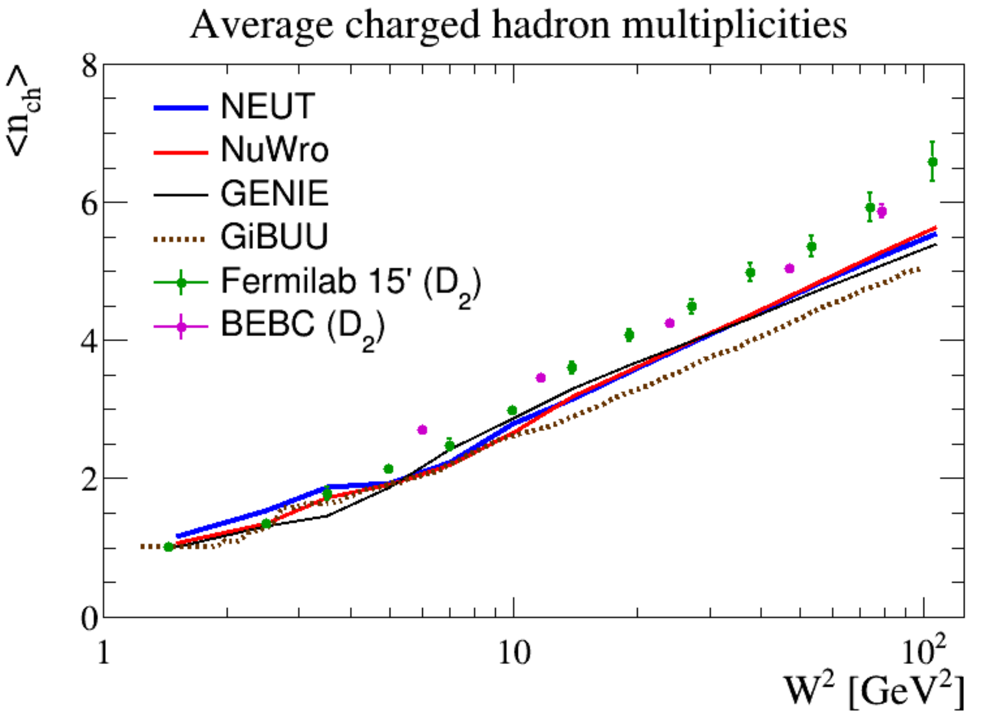


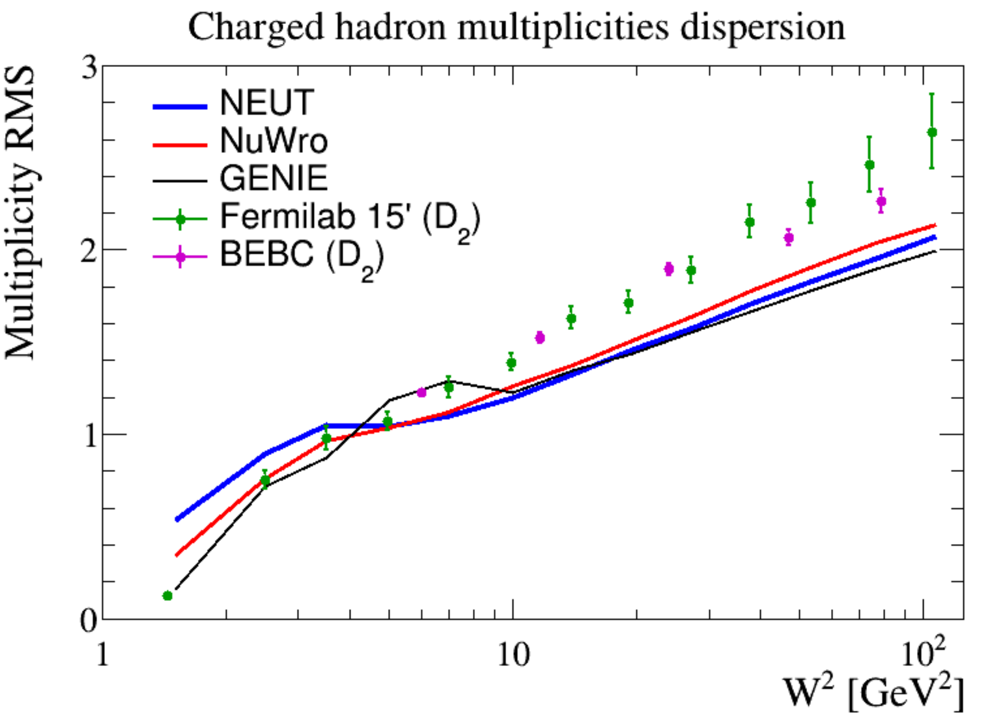


(area normalized, low W mode W<2 GeV, $n_\pi \geq 2$)

Generating hadronic system Multiplicities

- 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





(caveat: events generated on free neutrons vs deuterium data)

Multiplicity models

- 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))

$\langle n_{ch}\rangle = A + B*\log(W^2)$ $\qquad$ $P(n_{ch})=f(n_{ch}/\langle n_{ch}\rangle)$

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

→ Average charged hadron multiplicity $\langle n_{ch}\rangle$

→ 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

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	$Q^2 = 2 - 64\,\mathrm{GeV}^2$		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	$Q^2 > 1\,\mathrm{GeV}^2$	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	$Q^2 > 1\,\mathrm{GeV}^2$	-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	$Q^2 > 1\,\mathrm{GeV}^2$	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	$Q^2 > 1\,\mathrm{GeV}^2$	0.22 ± 0.21	1.08 ± 0.06

Phys. Rev. C 88, 065501 (2013)

Many problems:

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

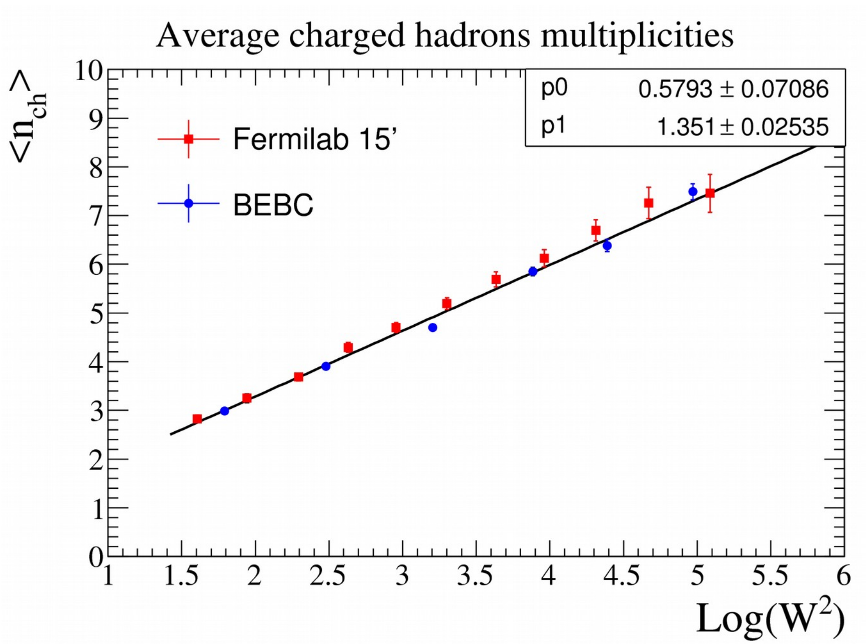
- NEUT was using [16] (ν-p) for all types
- GENIE uses [27] for ν and [37] for $\bar{\nu}$

Multiplicity models
Deuterium fits

- Tried to make a new multiplicity model, with all deuterium datasets judged acceptable in the review in Phys. Rev. C 88, 065501 (2013)
- Use same function f as in AGKY model used in GENIE (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)

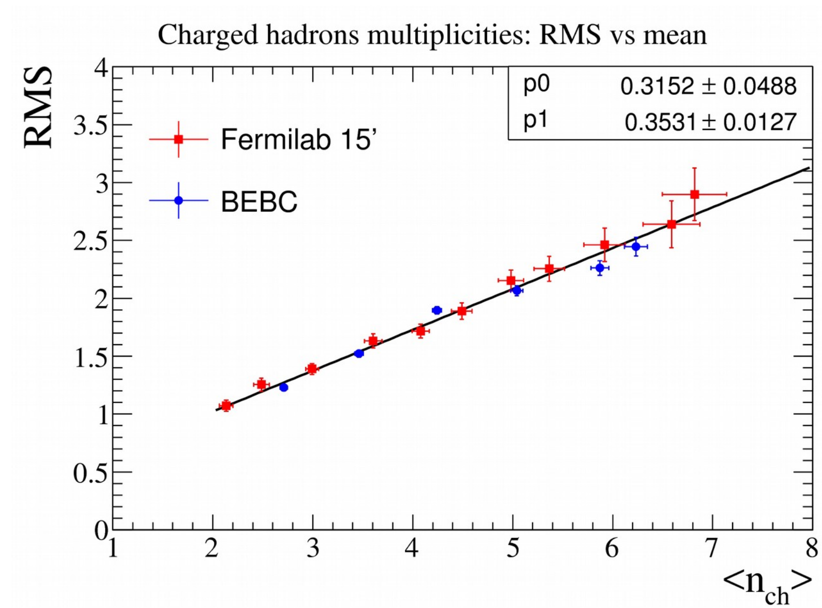
Compute the average multiplicity $<n_{ch}>$ at this W

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



Deduce the probability of n_{ch} at this W

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



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

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

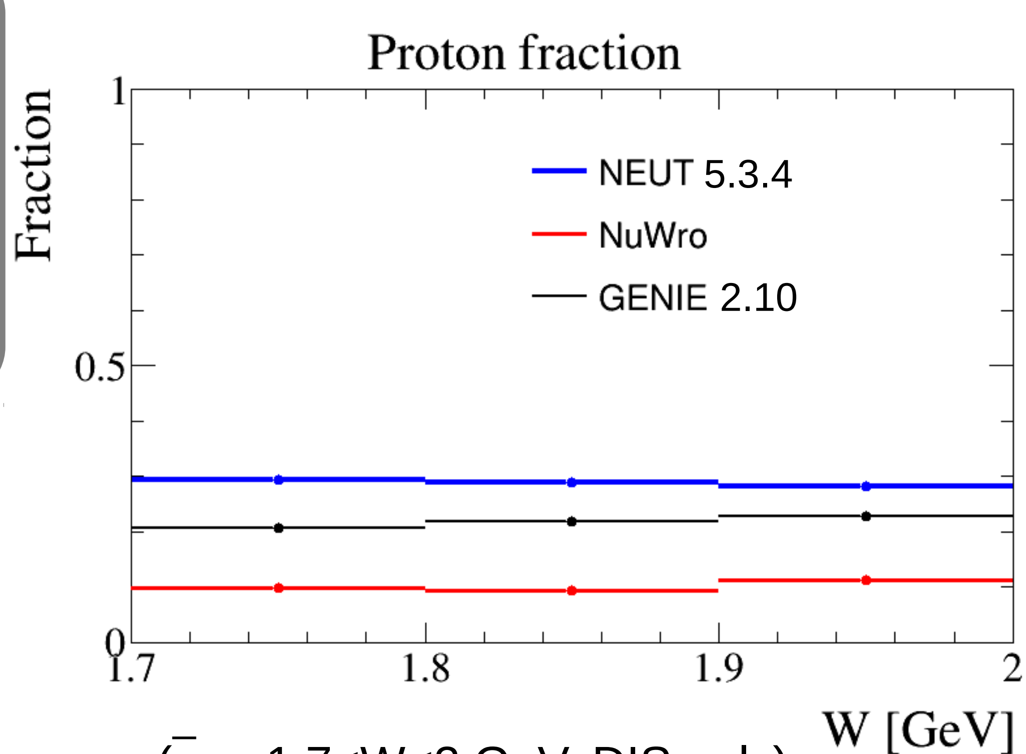
3 multiplicity models in NEUT 5.3.6:

- 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:

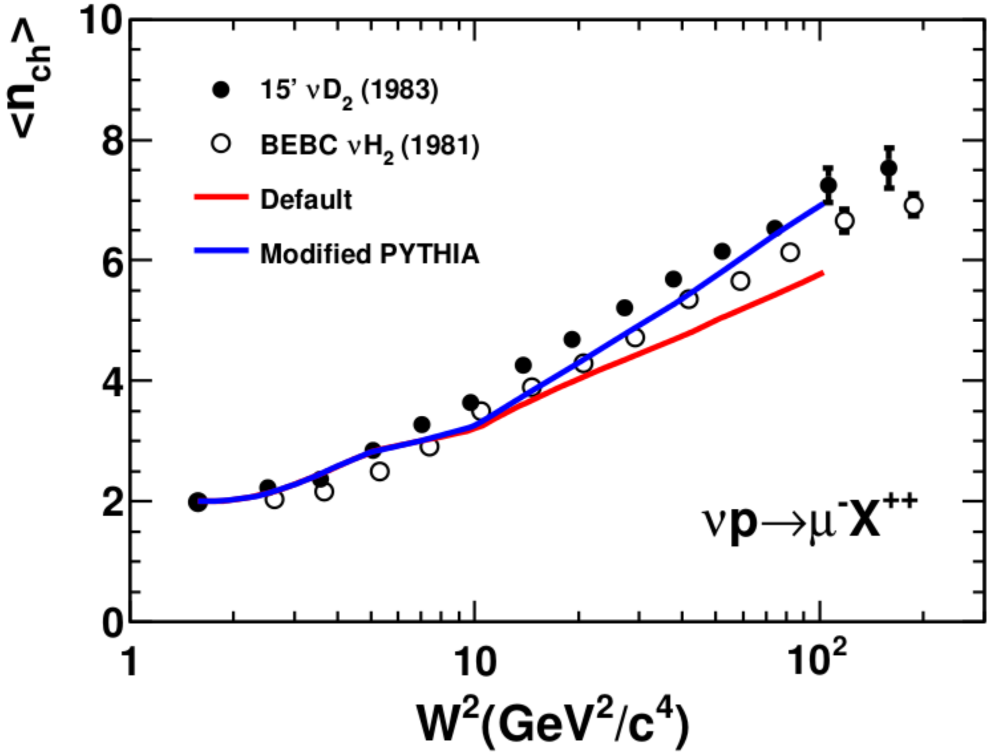
- relation between $n(\pi^{\pm})$ and $n(\pi^{0})$
- fraction of outgoing nucleons that are protons

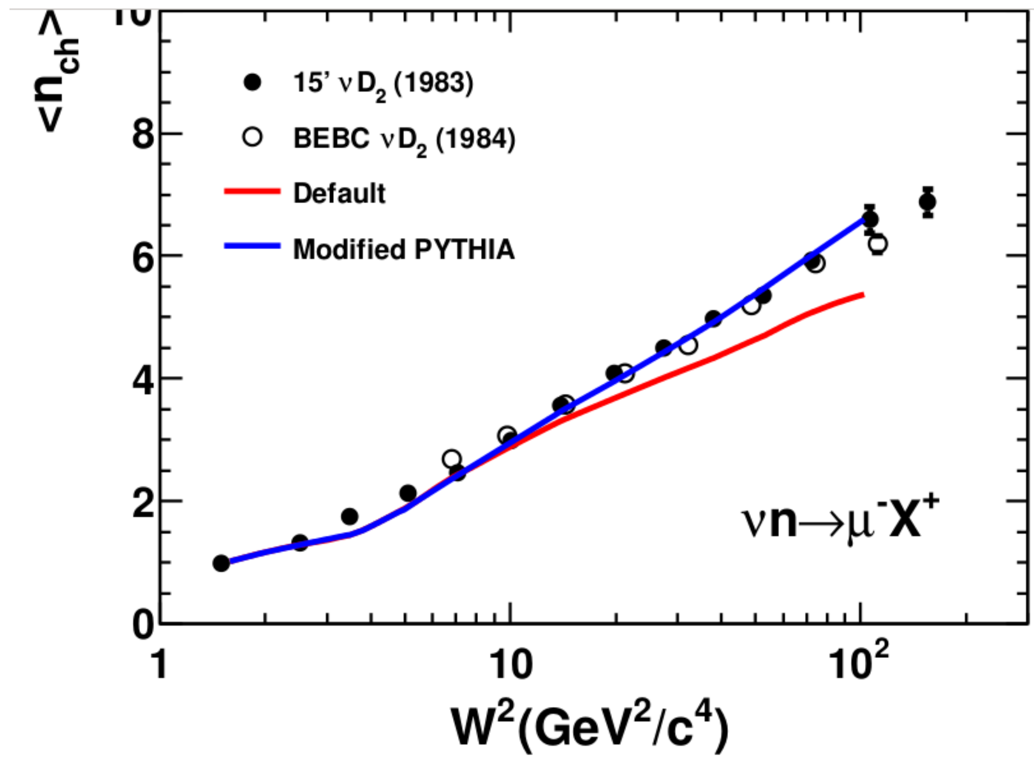


($\bar{\nu}$-n, 1.7<W<2 GeV, DIS only)

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)





<u>Found some difficulties:</u>

→ dispersion of the charged hadron multiplicities

→ neutral hadron multiplicities

"Further tuning is ongoing"

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

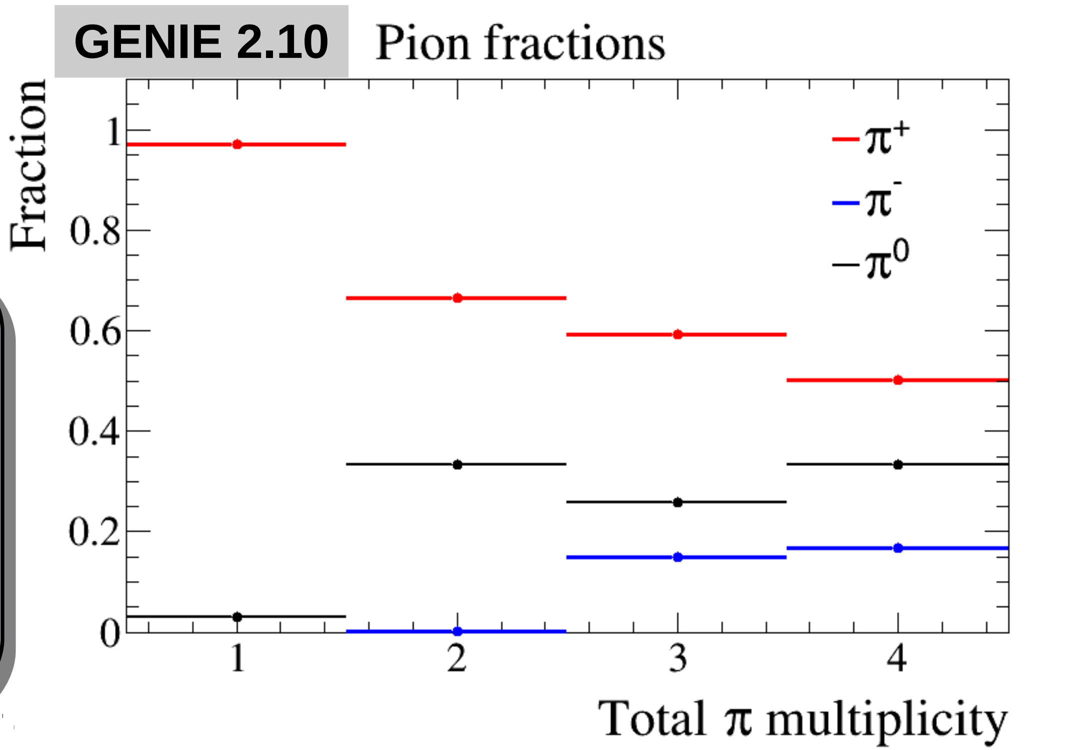
- 1 nucleon, than only pions
- All pion types same probability
- Rethrow until combination which respects charge is obtained

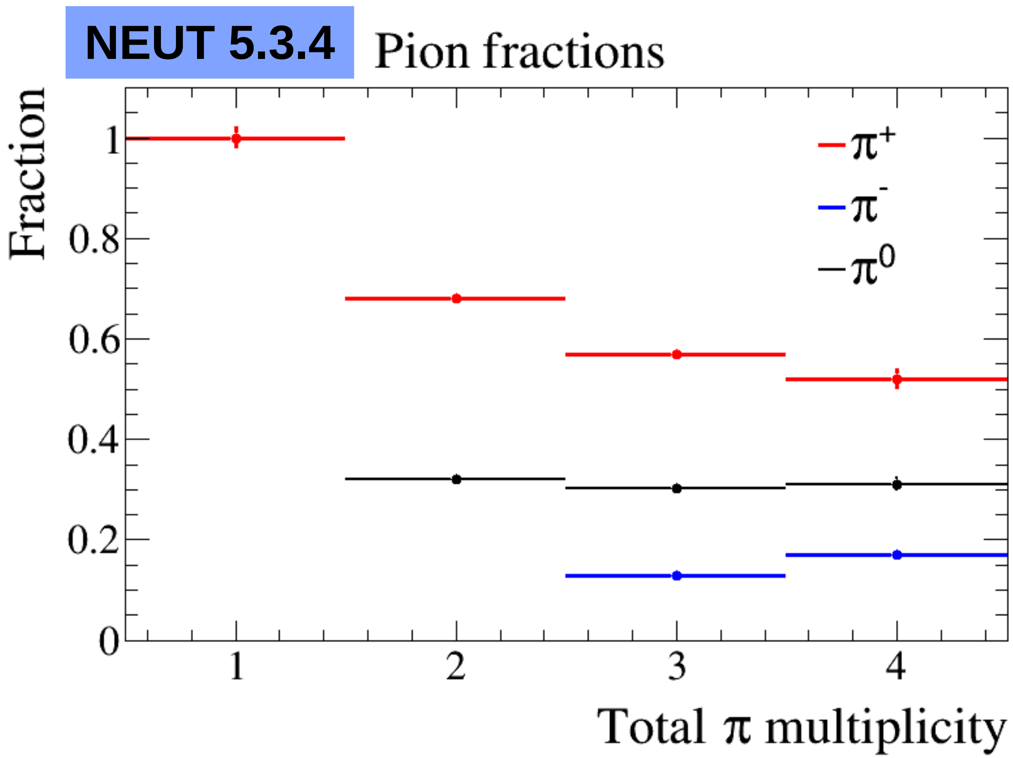
GENIE

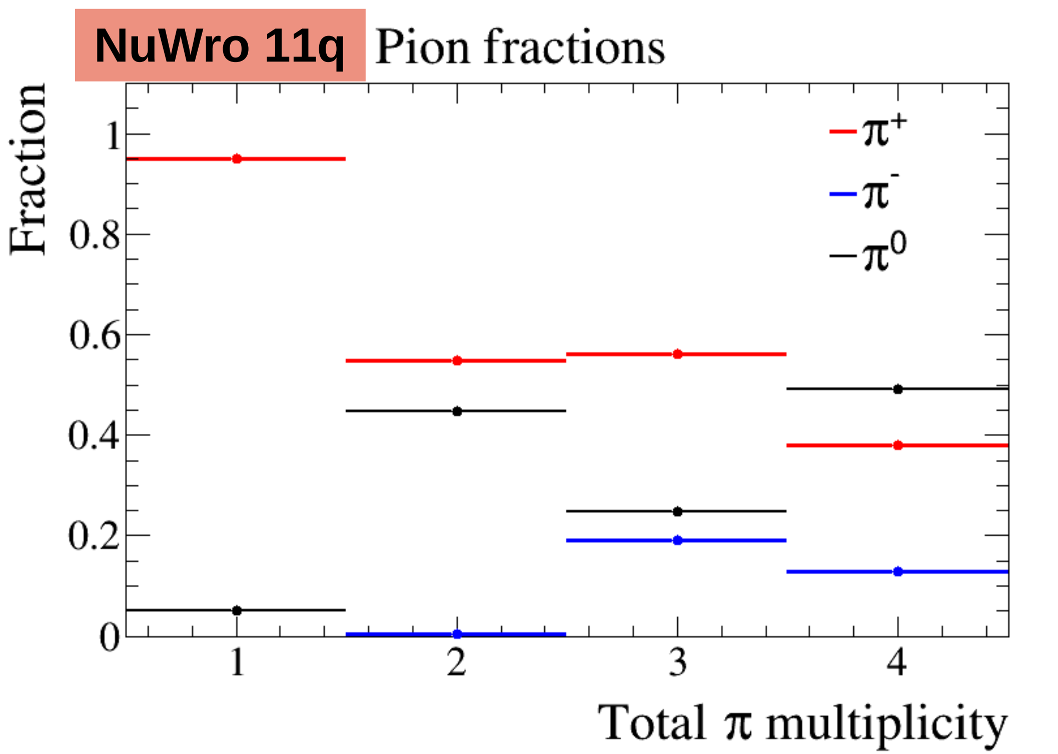
- 1 nucleon, than pions and kaons
- Balance charge, than add neutral particles or pairs.
- $P(\pi^+, \pi^-)=2*P(\pi^0,\pi^0)$
- P(strange meson pair)=6%

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**





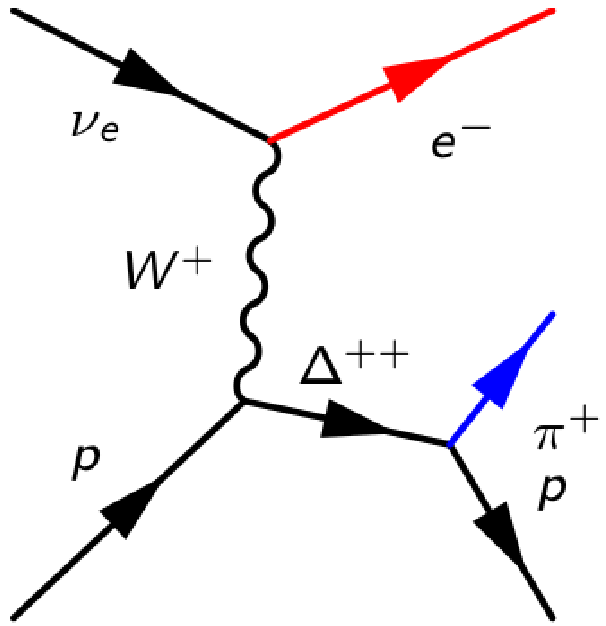


Generating hadronic system
Hadron kinematics – Low W modes

- Last step is to assign momentum to each hadron
- Important for Super-K: threshold to see charged hadrons
- In particular for $\pi^{\pm}$: energy determines if it appears as a ring or a Michel electron

T2K new CC1π sample

1 e^- ring + 1 'decay e^-' from π^+

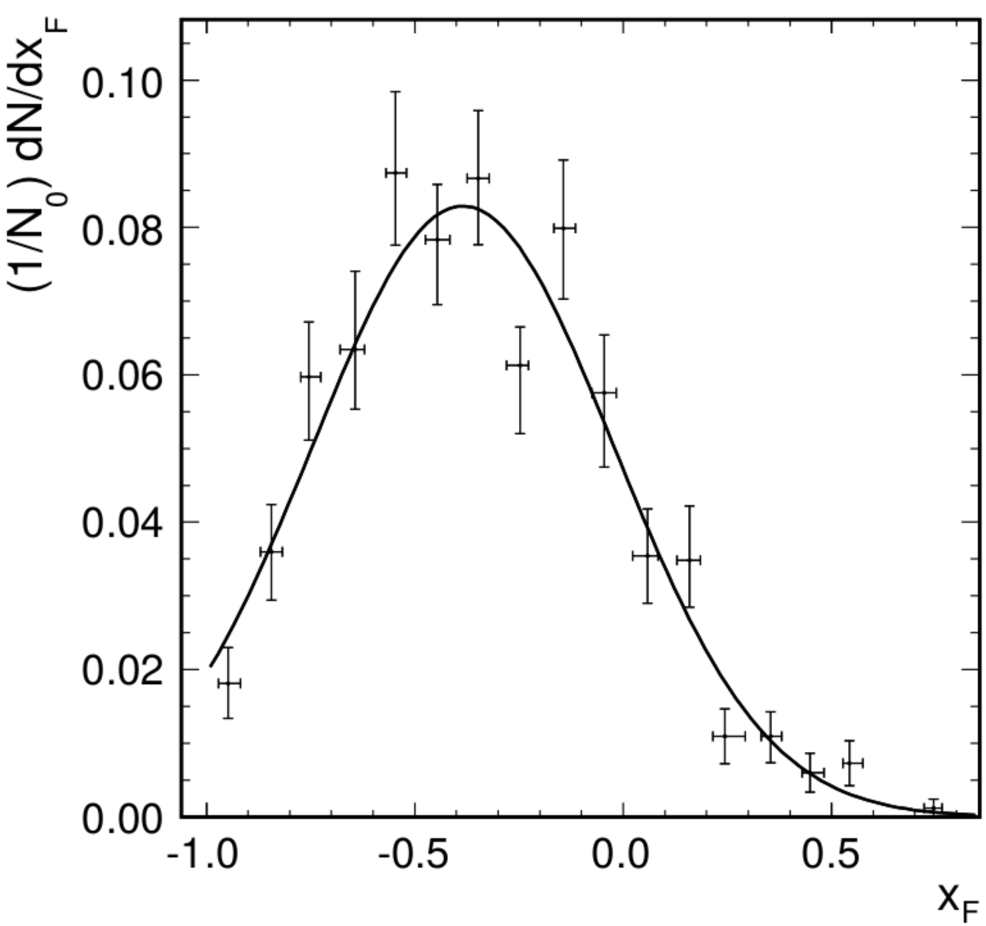


T2K appearance samples summer 2017

Sample	δ=-π/2 MC	Observed
ν-mode 1Re	73.51	74
$\bar{\nu}$-mode 1Re	7.921	7
ν-mode CC1π	**6.923**	**15**

Generating hadronic system Hadron kinematics – Low W modes

- For low W DIS events, NEUT and GENIE use “phase space decayer”
- NEUT uses this for all hadrons
- GENIE uses experimental data for outgoing nucleon, phase space decay for other hadrons



From neutrino82 proceedings, ref. for the plot is “G. Gerbier (WA24 draft in preparation)”, could not find actual paper

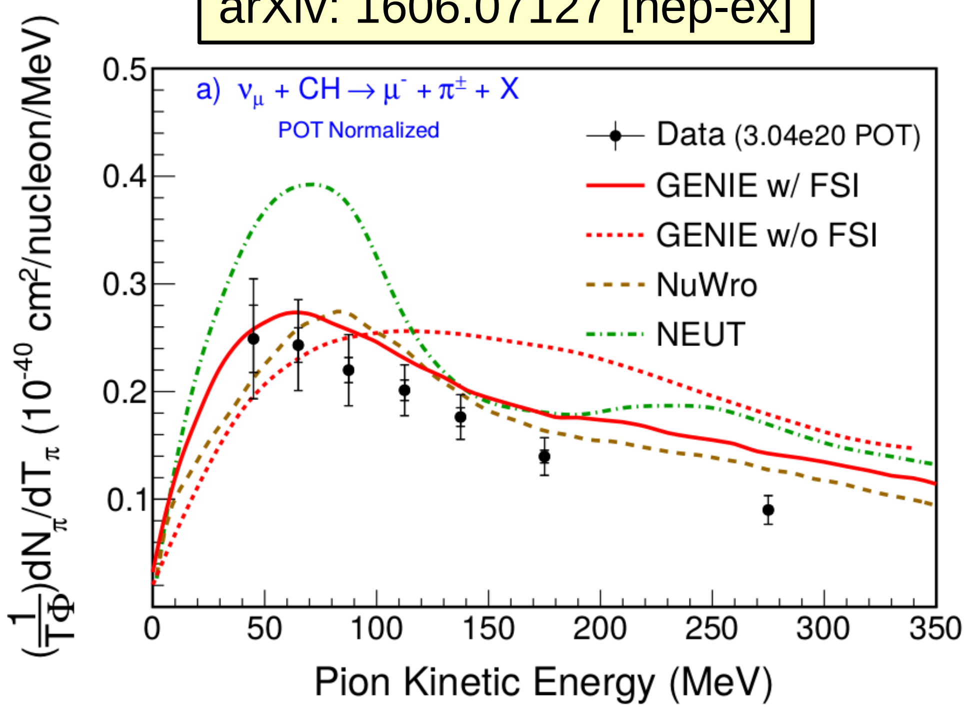
“The separation of the target and current fragments experimentally is non trivial. Usually we assume that hadrons for which $x_F>0$ (<0) i.e. forward (backward) in the hadron c.m. are current (target) fragments. **This separation does not make sense when the rapidity distribution is narrow, as it is for low W events**. W>4 GeV is necessary before any forward/backward separation is visible in the data”

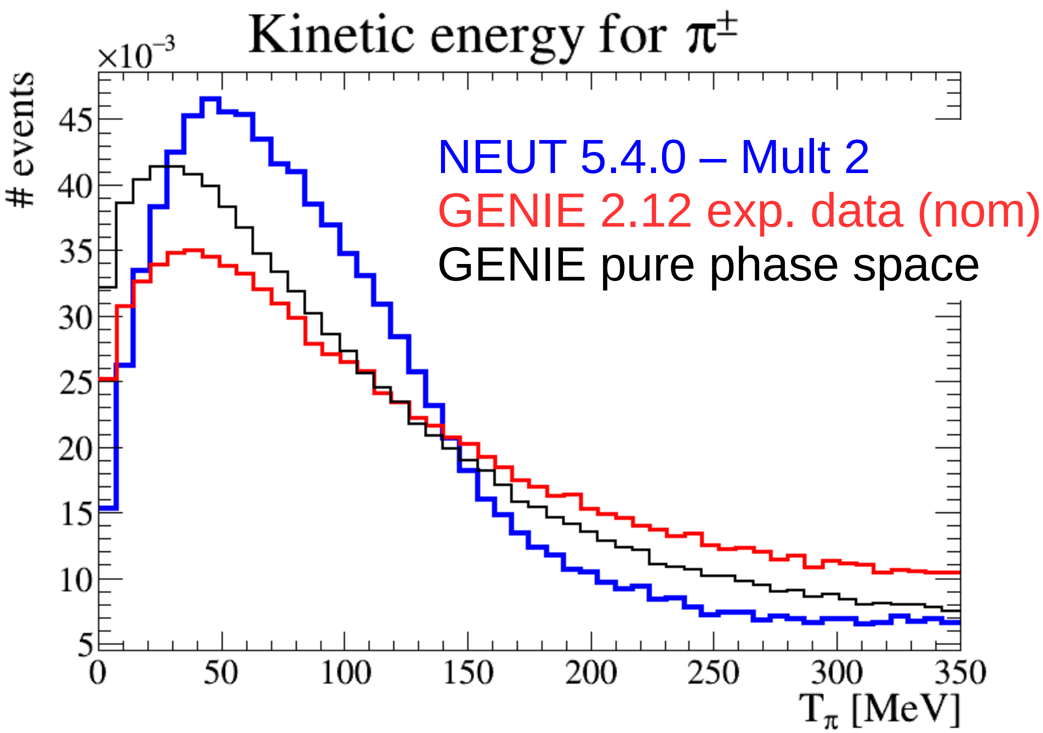
Not used in NEUT

Generating hadronic system
Hadron kinematics – Low W modes

- Whether those data are used or not for kinematics will influence pion kinematics as well
- For example, studies to understand Minerva CC(π^+) $d\sigma/dT_\pi$ results

arXiv: 1606.07127 [hep-ex]





1.5 GeV < E_ν < 10 GeV, W<1.8 GeV

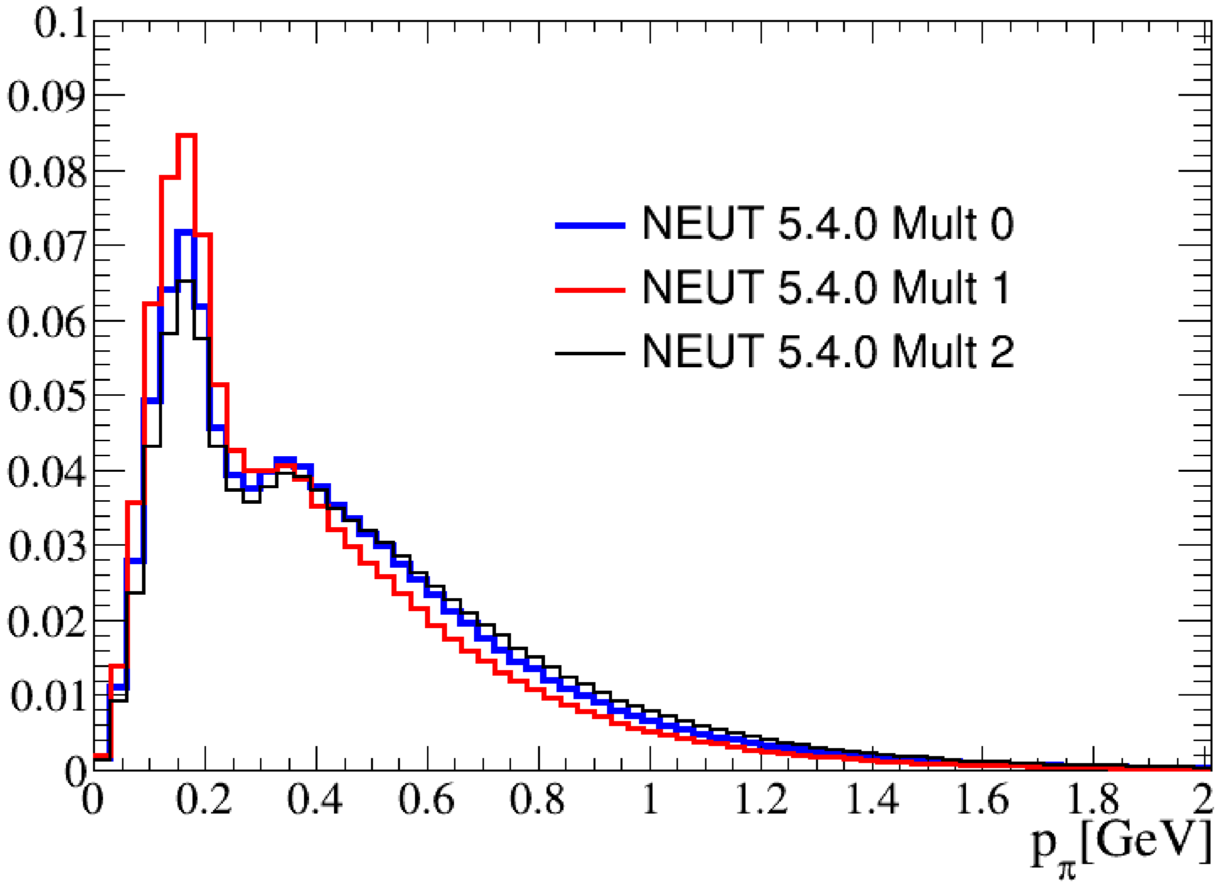
Multi-pi mode (NEUT) and low W DIS (GENIE) events only

GENIE mode modified to behave like NEUT (1.3<W<2, n_π≥2)

Shape only comparison (**area normalized**)

Hadron kinematics – Low W modes
Multiplicity model

For a given W, average available energy for each hadron depends on the number of hadrons
→ Multiplicity model also affects the hadron kinematics



Leading pion momentum
NEUT low W DIS mode
ν_μ with T2K ND flux
Area normalized

Summary

- Need to be able to simulate properly neutrino DIS interaction in the region 2 to 10 GeV to determine the mass hierarchy using atmospheric neutrinos in Super-K/Hyper-K

- Of particular interests are:
  - cross-sections
  - lepton kinematics
  - hadronic system: multiplicity, particle content and kinematics

- Difficulties coming from uncertainty on:
  - transition from resonances to DIS model
  - Parton Distribution Functions at low Q^2
  - multiplicity model for the hadronic system

  and lack of model to detemine particle content and kinematics at low W where PYTHIA cannot be used

Additional slides