13th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region

Deep inelastic interactions in NEUT

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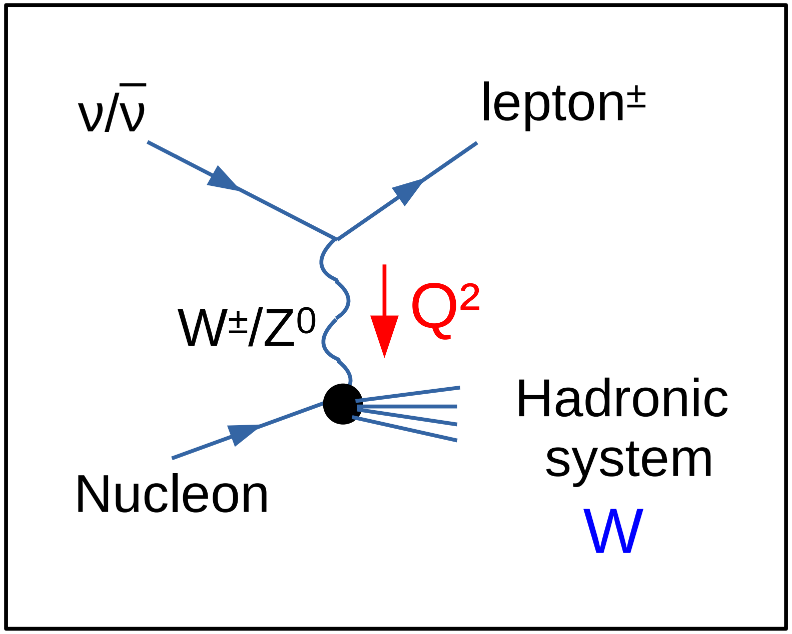
Introduction

- NEUT relies on different models to simulate neutrino interactions
- Will cover here the ones describing DIS interactions
  - Main updates since last presented to the community (NEUT 5.4.0, 2018 pre-NuINT SIS/DIS workshop)
  - Implementation and effect of the new Bodek-Yang model
  - Updated comparisons with other generators

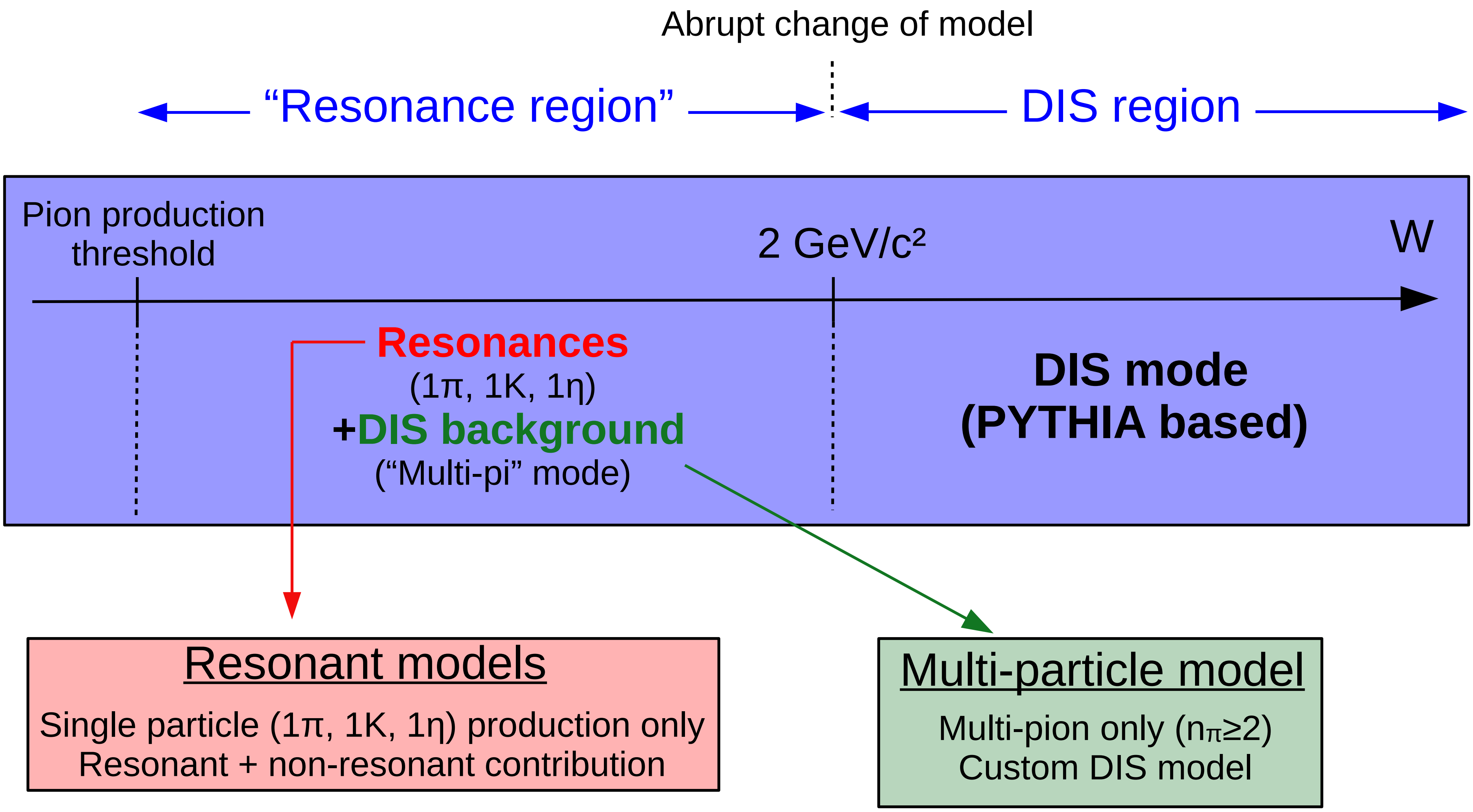


In NEUT:

$Q^2 \leftrightarrow$ lepton kinematics

$W \leftrightarrow \begin{cases} \text{Choice of model} \\ \text{Hadronic system} \end{cases}$

Inelastic region in NEUT



Abrupt change of model

“Resonance region”

DIS region

Pion production threshold

2 GeV/c^2

W

Resonances

(1π, 1K, 1η)

+DIS background

(“Multi-pi” mode)

DIS mode

(PYTHIA based)

Resonant models

Single particle (1π, 1K, 1η) production only

Resonant + non-resonant contribution

Multi-particle model

Multi-pion only ($n_\pi \geq 2$)

Custom DIS model

- No 2π/3π resonances
- No DIS contribution to single particle production below W<2 GeV
- 2 separate DIS models: low and high W

Low W DIS model

- Multi-pion mode describes the multiparticle ($n_{had} \geq 3$) component in the region 1.3 GeV/c^2 < W < 2GeV/c^2

- Custom deep-inelastic model with the component $n_{had}=2$ removed (both in generated events and total cross-section) to avoid double counting with resonant modes

- Relies on two main inputs:
  - cross-section ($d^2\sigma/dxdy$) for global kinematics (W/Q^2)
  - hadron multiplicity model

- Assumes that all the events have:
  - one outgoing lepton
  - one outgoing baryon
  - n outgoing pions (n>1)
  - no kaons, η (only resonant production for W<2 GeV/c^2)

High W DIS model

- Pure DIS mode for $W>2$ GeV/c^2 based on PYTHIA generator
- Recent version of PYTHIA do not allow generation of events at the low energies relevant for T2K/Super-Kamiokande
  → use older version [1] (found in CERNLIB based on JetSet 5.72)
- Cross-section calculated by integrating $d^2\sigma/dxdy$ (as for multi-pion mode)
- PYTHIA used only for the actual event generation:
  - input E_ν and nucleon four-momentum (from simple RFG model)
  - Loop over PYTHIA event generation until $W>2$ GeV and right NC/CC type

[1]:T. Sjöstrand, Computer Physics Commun. 82 (1994) 74

$d^2\sigma/dxdy$

A central part of those models:
- ➔ integrate over x and y to get total cross-section
- ➔ Underlying probability to generate (x,y) → (Q^2,W)

$d^2\sigma/dxdy$ 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

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

$$F_4(x,Q^2) = 0$$

$$F_5(x,Q^2) = \frac{F_2(x,Q^2)}{x}$$

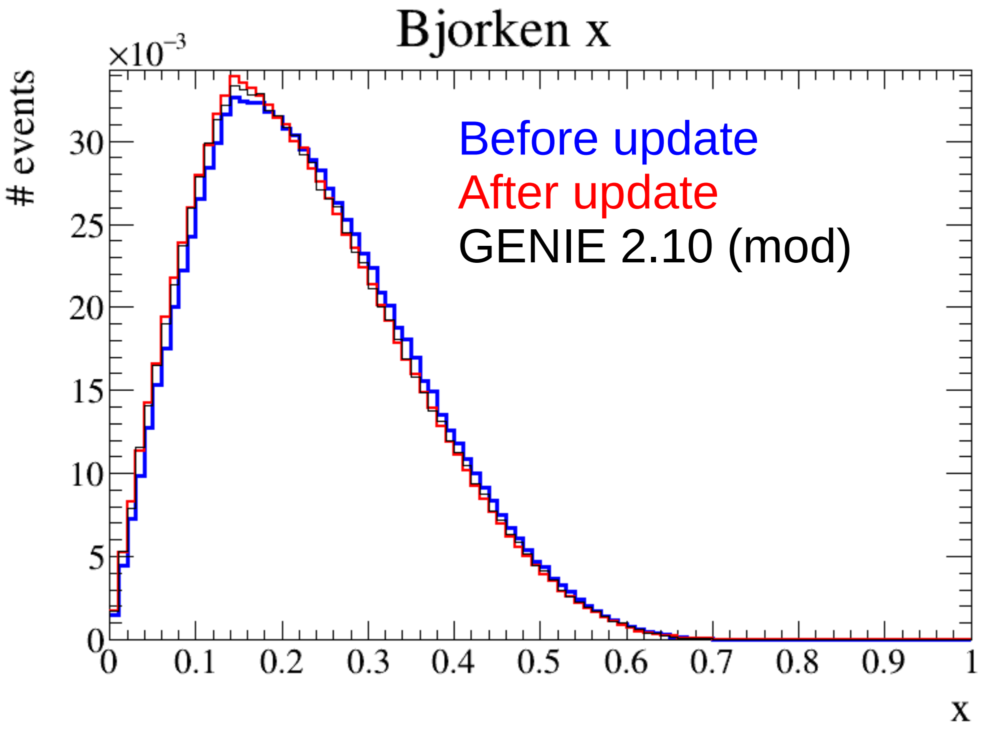
- Finally use quark-parton model to compute F_2 and xF_3 from Parton Distribution Functions

PDFs not valid at low Q^2 => use Bodek-Yang model
(see talk by U-K Yang for details)

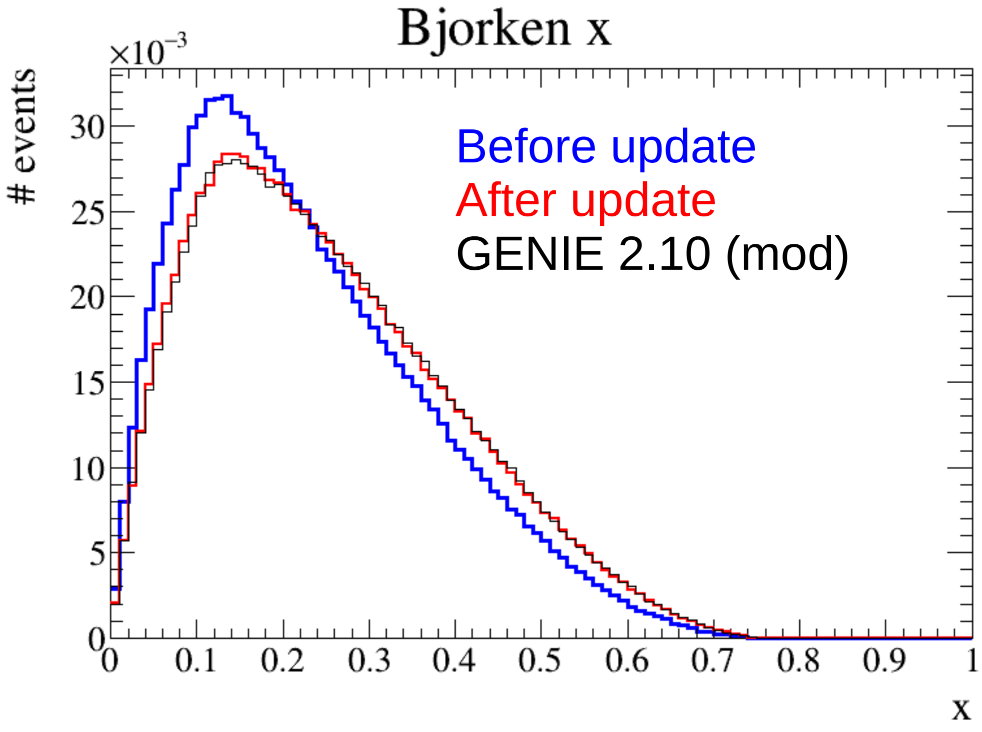
Neutral current DIS events
Structure functions

- NC DIS was very approximate in NEUT 5.4.0 for low W mode and cross-section calculations
- Was essentially the CC model with a different outgoing lepton mass. Fixed this:
  - use Z^0 propagator instead of W for NC
  - use proper structure functions (eq 16.18 of PDG2011)
- After those updates, difference in scaling variables seen with GENIE disappeared

2 GeV numu on free n



2 GeV numubar on free n

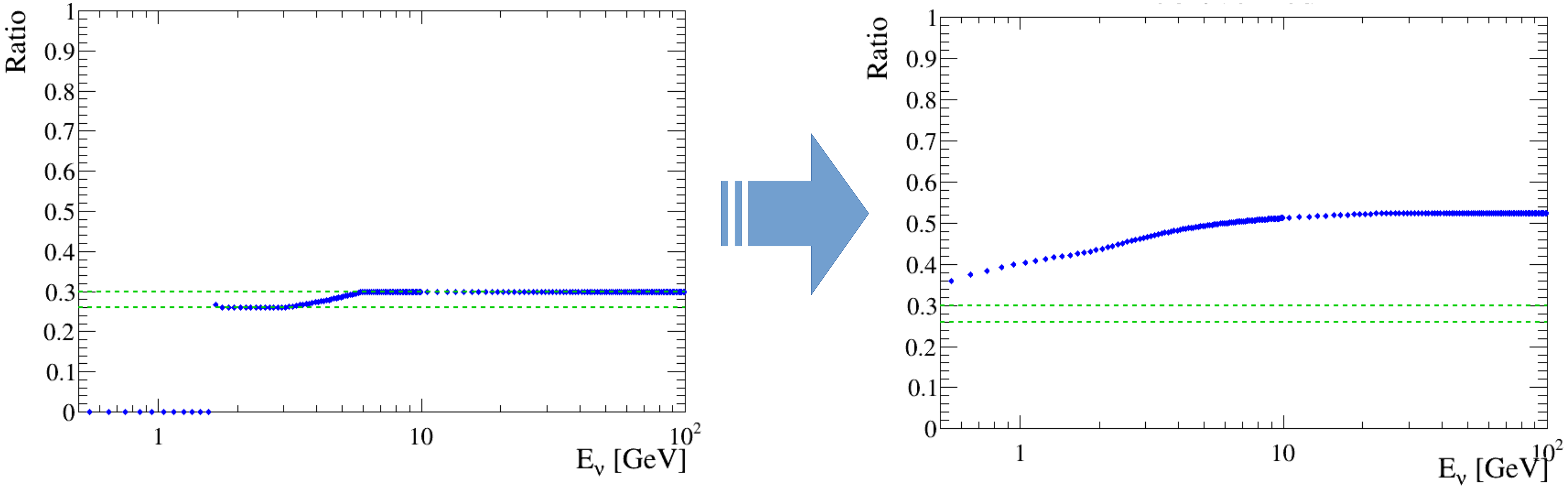


GENIE 2.10 with modifications (cut on number of pions, W,…) to make it comparable to NEUT multi-pi mode

Neutral current DIS events Cross-section

- Similarly NC DIS cross-sections were not explicitly computed in NEUT 5.4.0
- Applied a factor to CC ones from Rev. Mod. Phys. 53, 211 (1981)
- Now computing them by integrating d²σ/dxdy
- Significant changes of NC DIS cross-section for certain channels

<u>Example</u>: ratio σ_{NC}/σ_{CC} for interactions of ν_e on protons, low W DIS mode

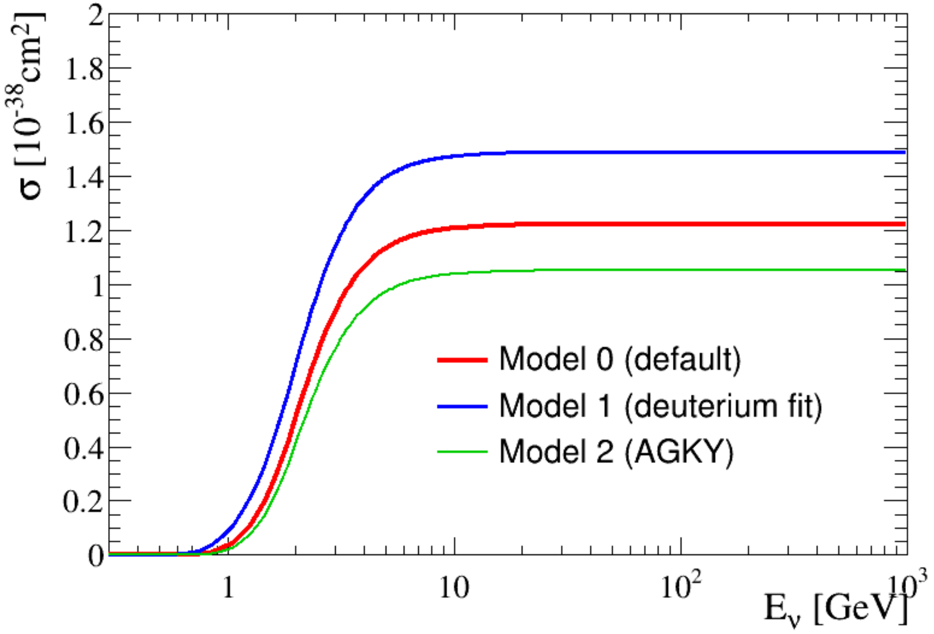


Hadron multiplicity model

- For low W mode, events with only 2 hadrons produced are rejected to avoid double counting with resonant modes
- As a result, hadron multiplicity model has a significant impact on cross-section and W distribution for this mode
- NEUT 5.4.0 had 3 different multiplicity models for event generation
- Now also implemented effect on low W mode cross-section

3 hadron multiplicity models:

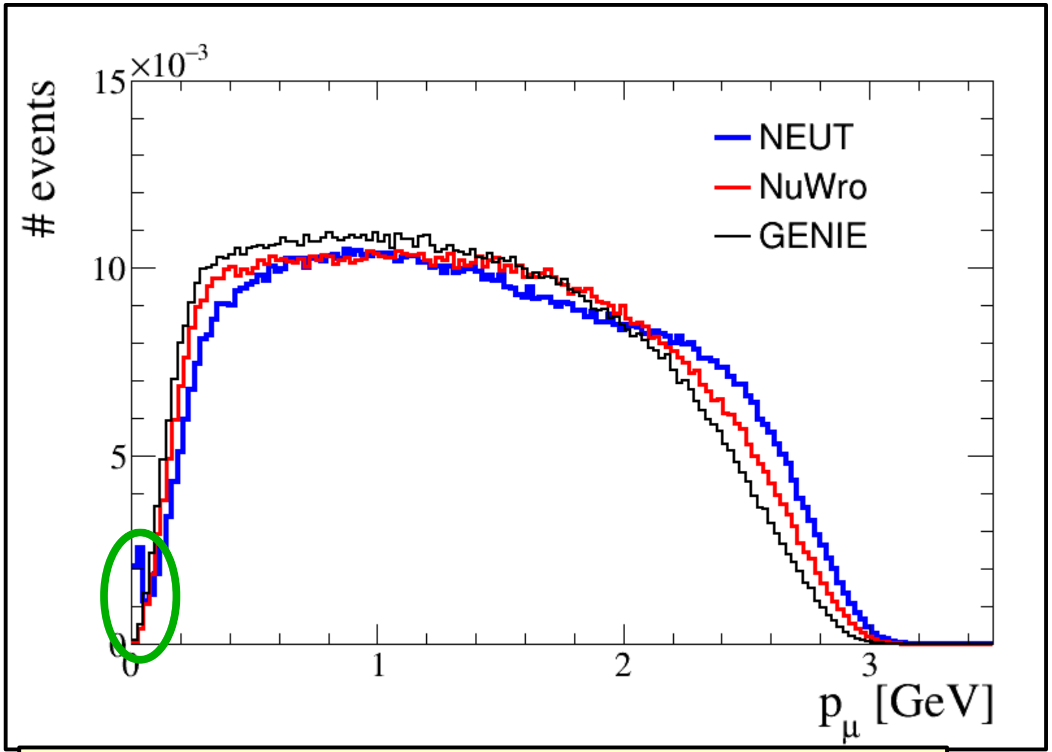
- NE-MULT=0: NEUT default
- NE-MULT=1: from deuterium bubble chamber fits (CB, hep-ph:1607.06558)
- NE-MULT=2: AGKY model (GENIE model, hep-ph:0904.4043)



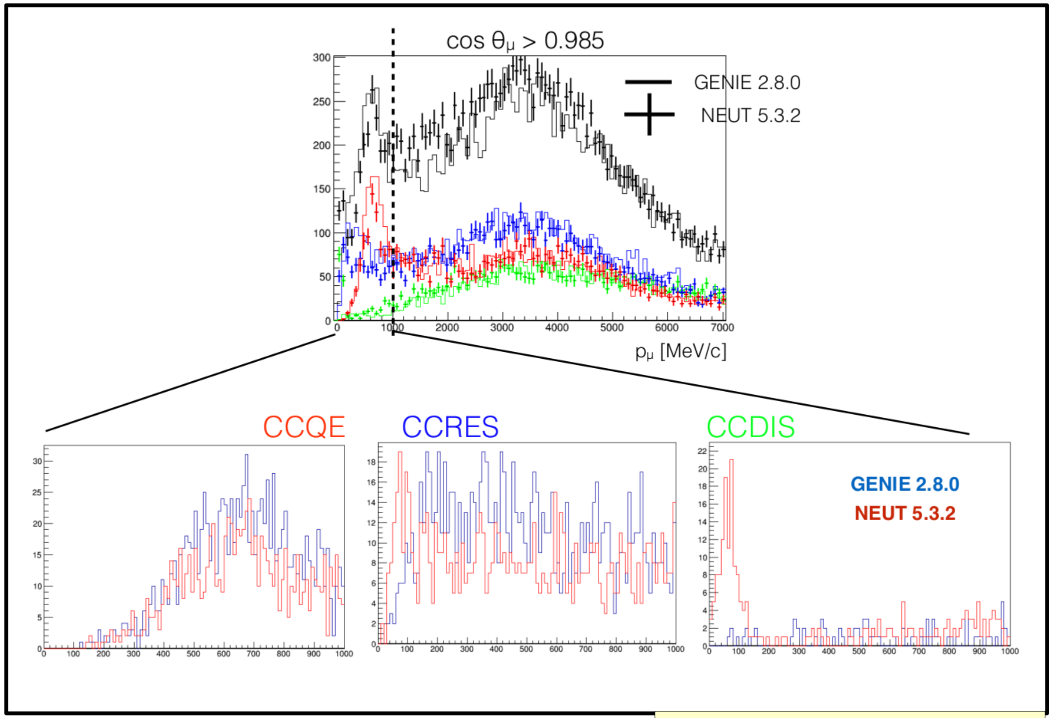
Low W mode cross-section
ν_μ on neutrons

“Feature” in PYTHIA events

- Previous versions of NEUT were showing a strange peak at low p_{lep}
- Particularly visible in the forward region
- Was found to be from events generated by PYTHIA in high W DIS mode



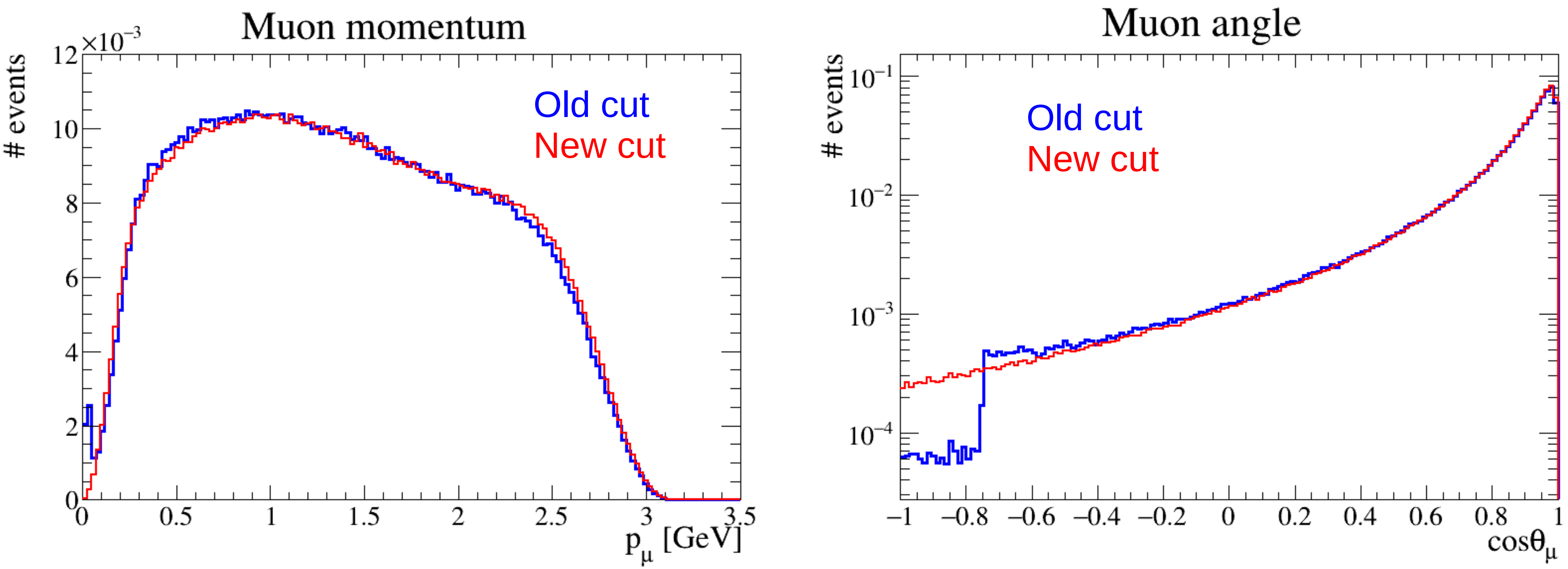
CB @ NuSTEC SIS/DIS workshop (2018)



A. Garcia (2017)

“Feature” in PYTHIA events

- NEUT is using PYTHIA to generate events entirely, not just fragmentation routines like NuWro and GENIE
- In PYTHIA, most $2 \rightarrow 2$ processes have divergent cross-section for $z=\cos(\theta_{RF}) \rightarrow \pm 1$
- In colliders, addressed by requiring pT>pT_min, but we’re at too low energy to do this
- A cut $|\cos(\theta_{RF})|>0.999$ removes problematic features better than previous $\cos(\theta_{lab})>-0.75$ cut



New Bodek-Yang model

- NEUT 5.4.0 was using Bodek-Yang model from hep-ph:0508007 (“Previous model”)

- Have been trying for some time to implement new version, with in particular separation between axial and vector part of F_2
  (expected to have an effect at low Q2 mainly)

- Started with a preliminary version of the new model provided by authors, and found that:
  - when assuming vector=axial (“Type I”), new model was giving predictions relatively close to previous one
  - separation of axial and vector part of F_2 (“Type II”) had limited effect on cross-section

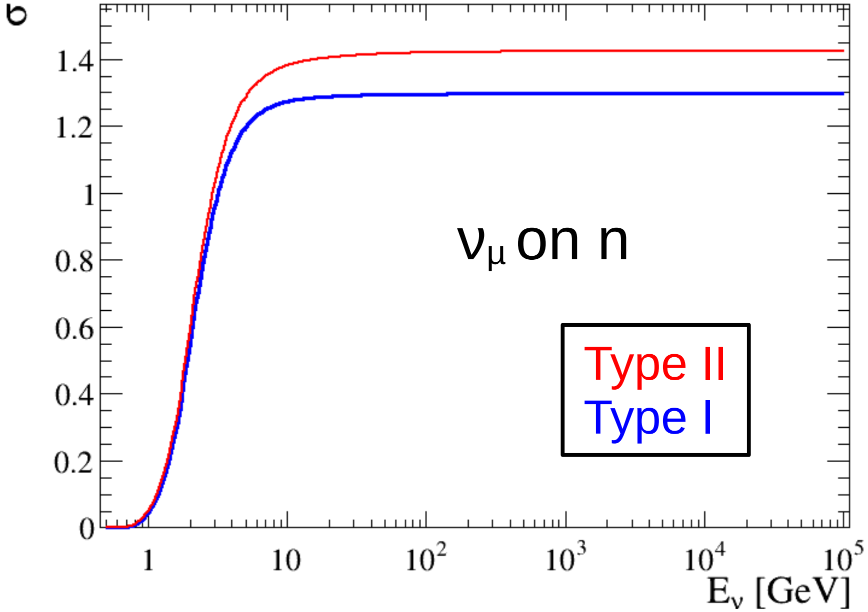
- A new version is now available on arXiv: hep-ph:2108.09240v2
  (Changes: value of K^{axial}_{val}, introduction of K_{LW}^{ax}, increase sea quark and antiquark contributions)

- Updated implementation to this new version, and saw a very different picture

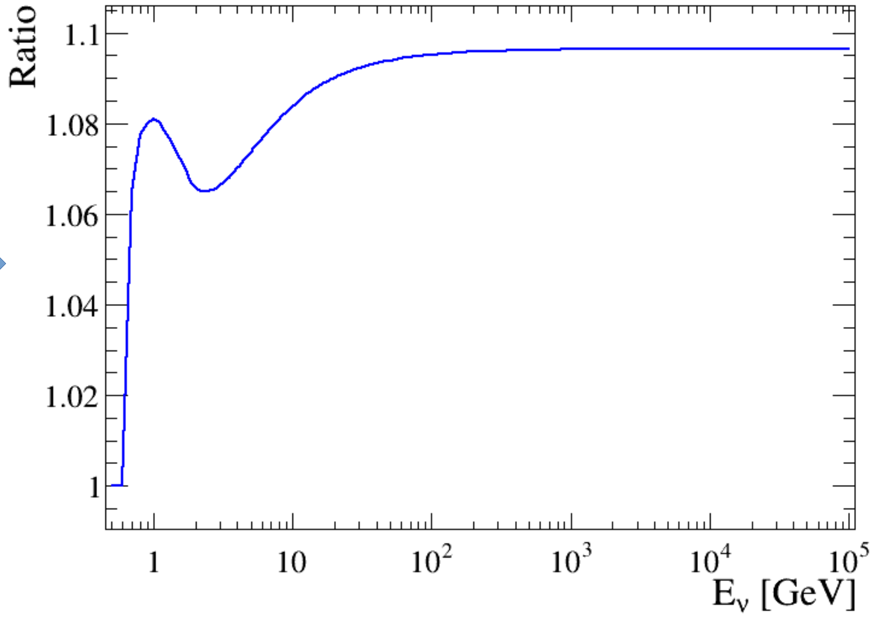
- Note: could only fully implement new model for low W mode, problems to separate axial and vector part of F2 in PYTHIA

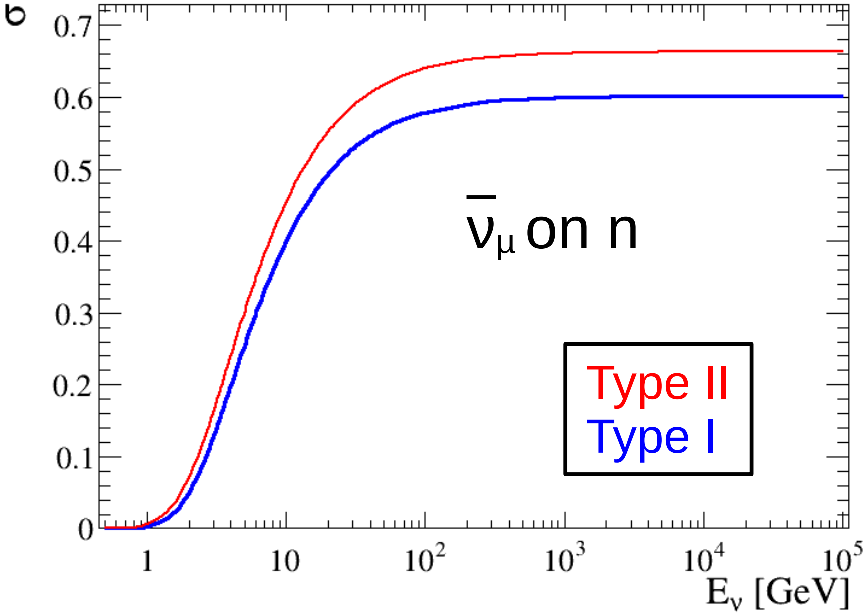
New Bodek-Yang model
Separation of axial and vector F2

Now see significant effect of axial/vector separation on **low W mode** cross-section



Ratio II/I





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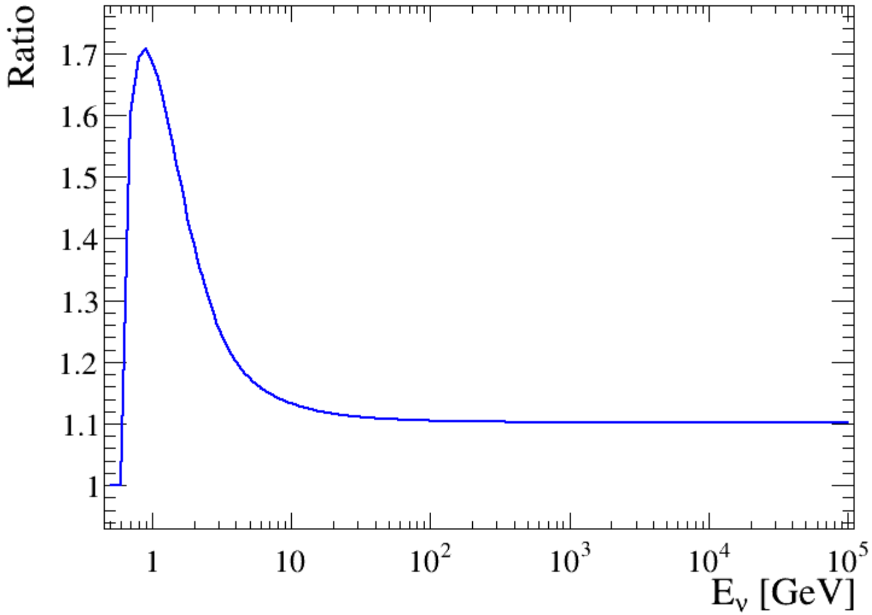
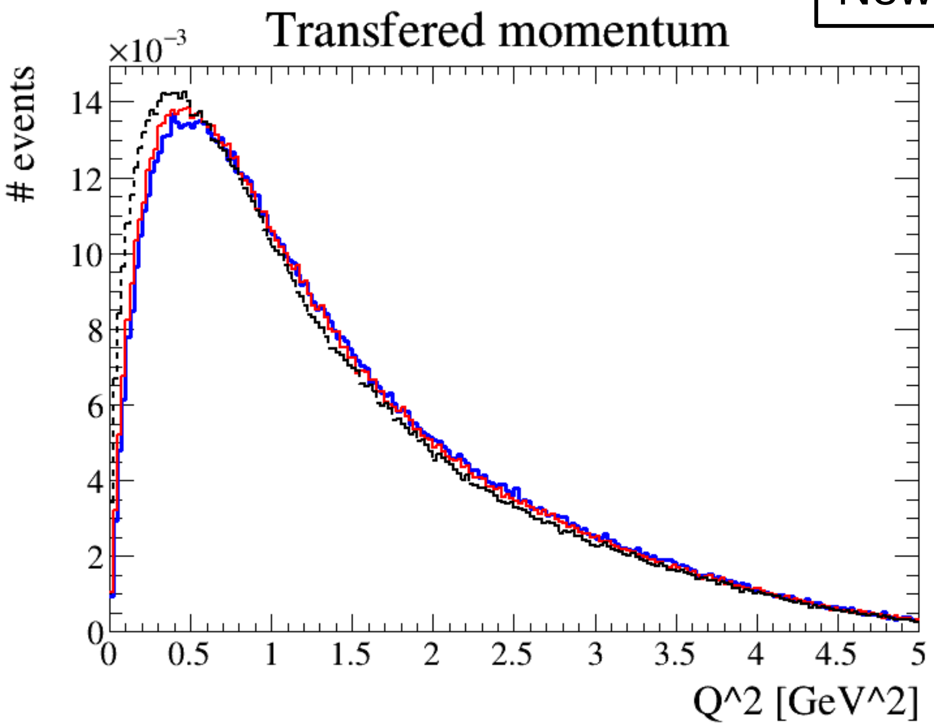
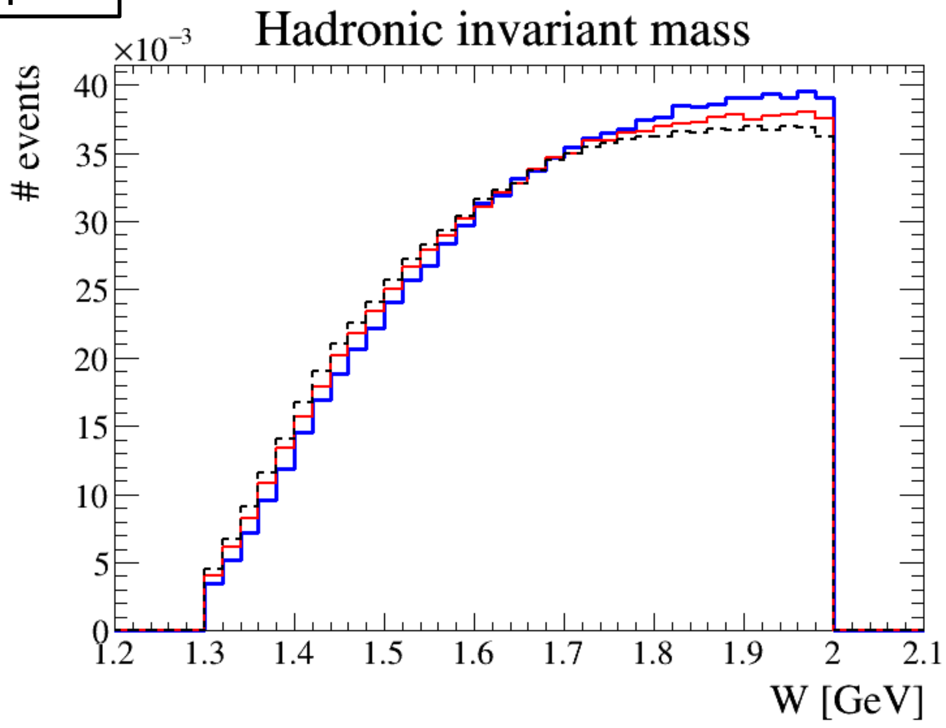


New Bodek-Yang model
Separation of axial and vector F2

- 4 GeV ν_μ on water, low W mode (W<2 and n_{had}>2)
- Type II allows lower Q^2, and shifts W distribution to lower values (probably explains increase of xsec at low W)

Previous BY
New BY Type I
New BY Type II

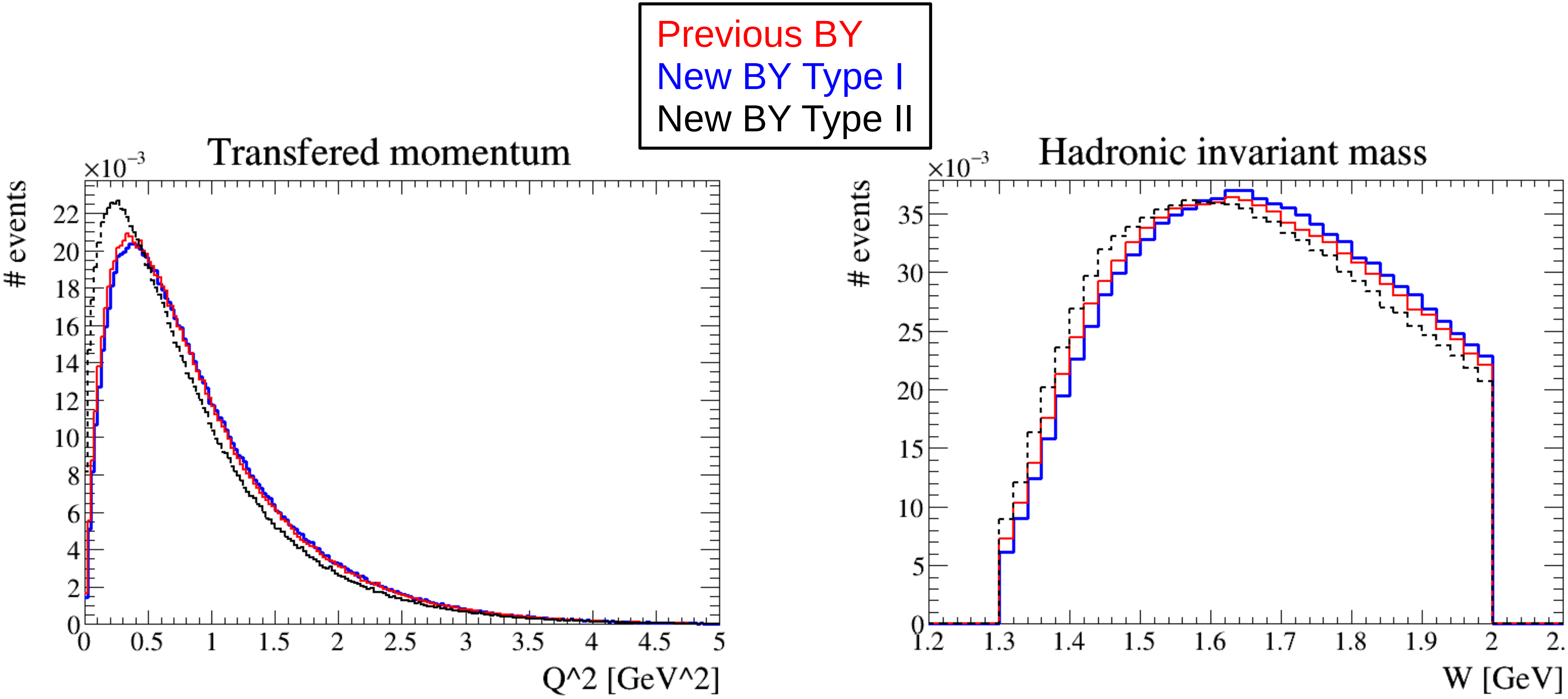




(normalized histograms)

New Bodek-Yang model
Separation of axial and vector F2

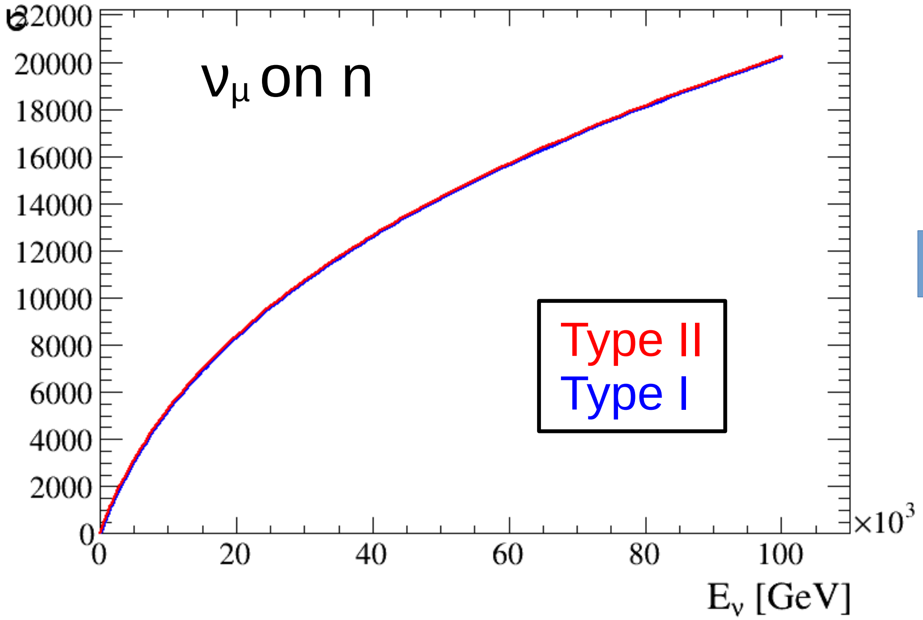
- 4 GeV $\bar{\nu}_\mu$ on water, low W mode (W<2 GeV and $n_{had}>2$)
- Enhancement at low W is really strong for antineutrinos



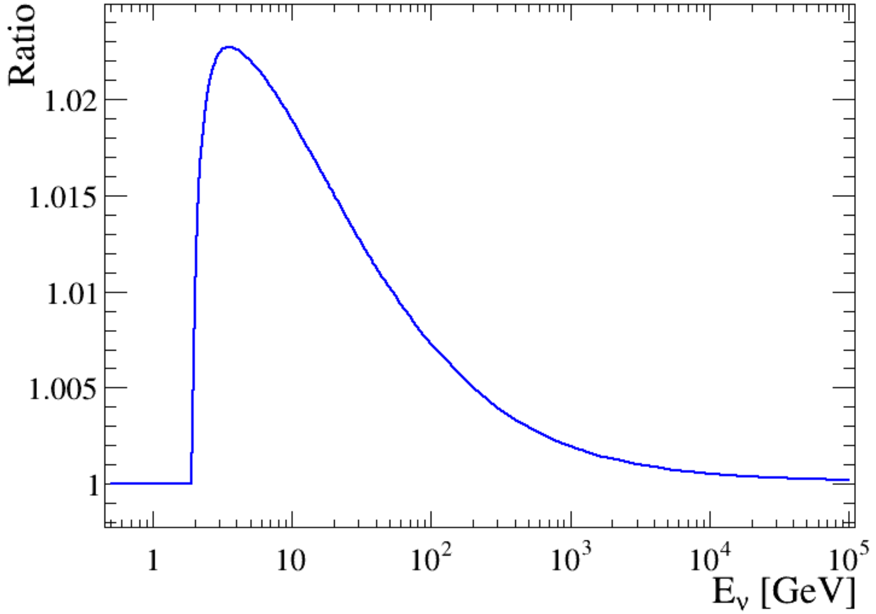
(normalized histograms)

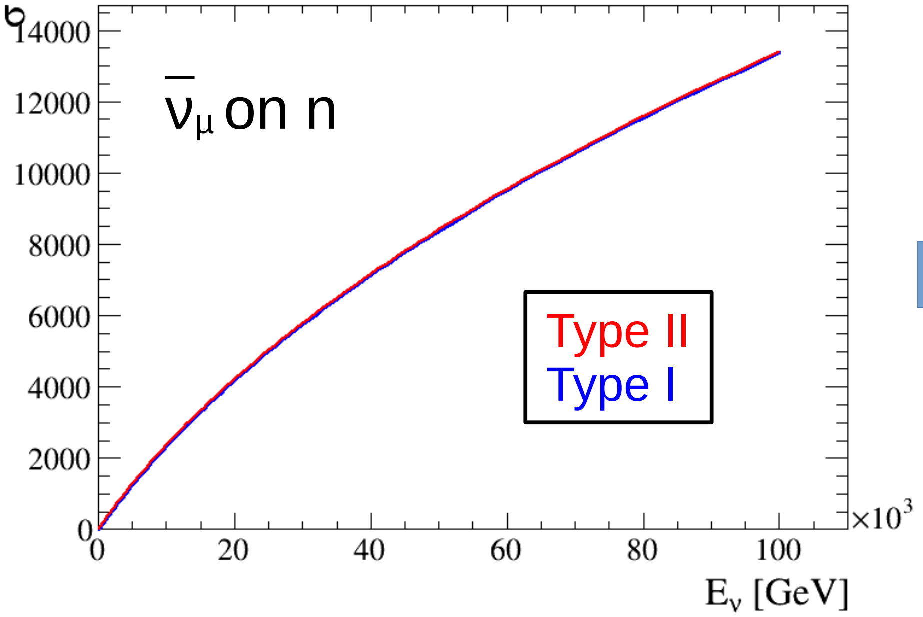
New Bodek-Yang model
Separation of axial and vector F2

For high W mode (W>2GeV), effect is more limited but still visible at low energy, in particular for $\bar{\nu}$

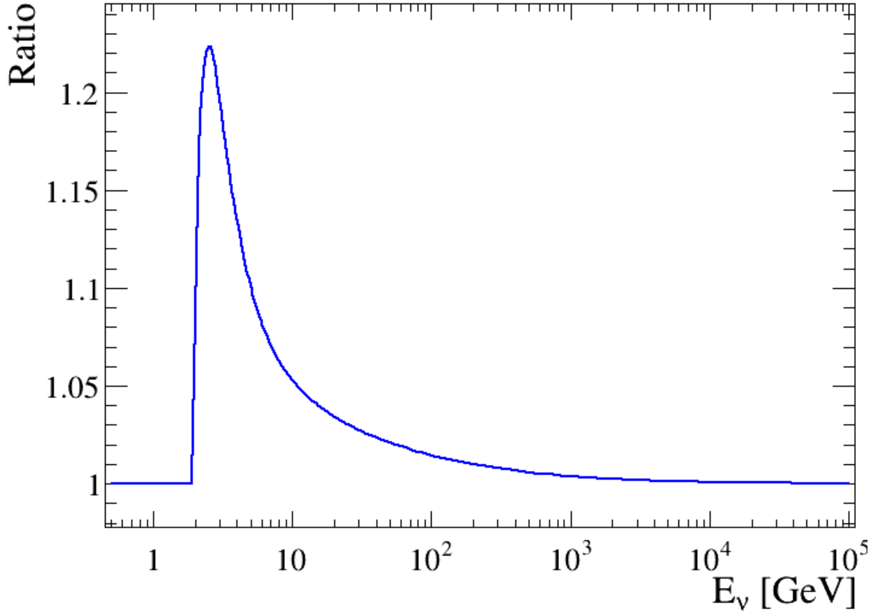


Ratio II/I



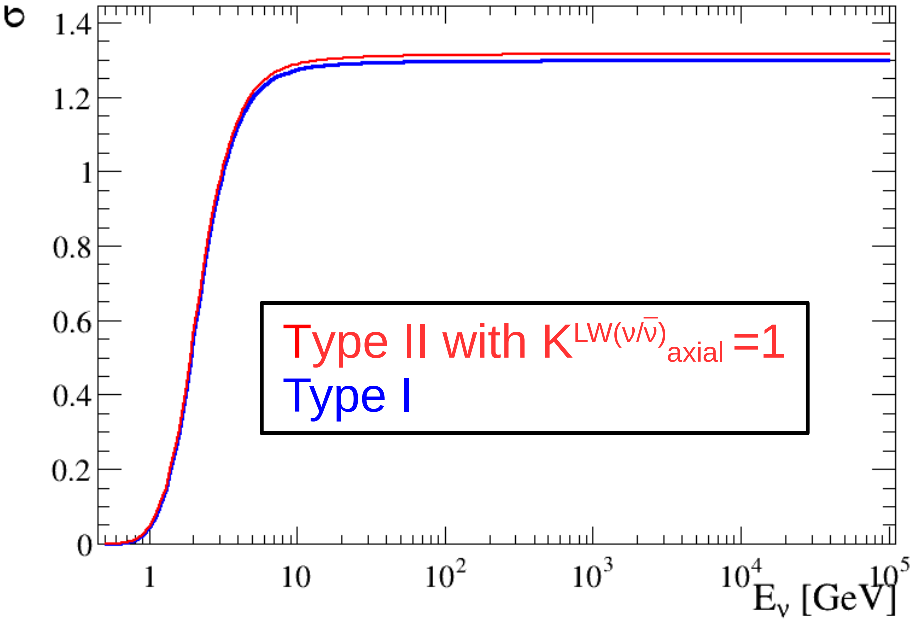


Ratio II/I

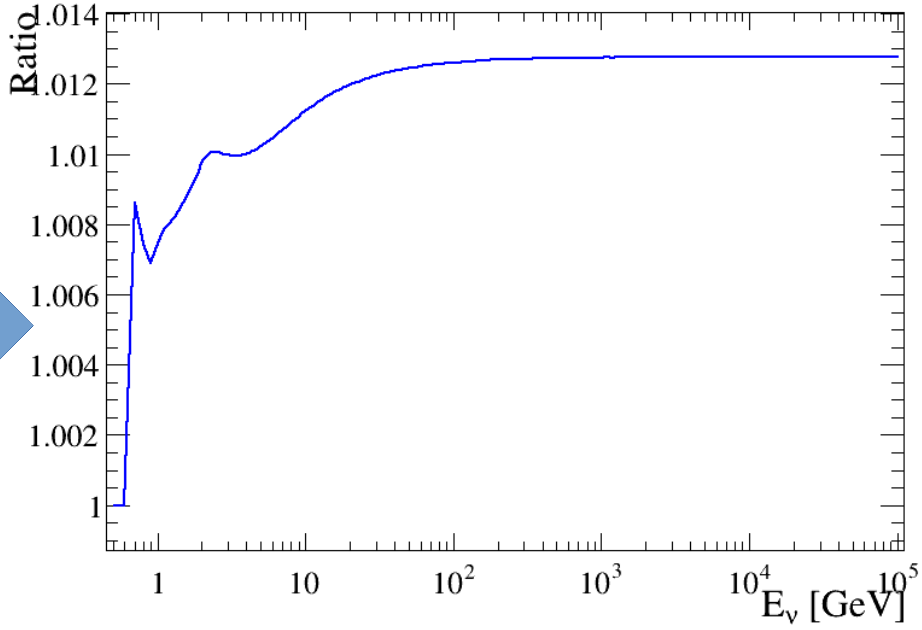


New Bodek-Yang model
Separation of axial and vector F2

- Most of the effect on the cross-section for **low W mode** come from new $K^{LW(\nu/\bar{\nu})}_{axial}$ factors
- Introduced in new update of the model “to better describe the low energy neutrino and antineutrino total cross sections”
- Setting them to 1 reduce significantly difference of cross section
- For muon neutrinos on neutrons, effect decreases from ~10% to ~1%



Ratio II/I



Comparison to other generators

- Compared predictions of updated NEUT to other generators for W and lepton kinematics
  (update of comparisons shown at NuINT2015 and 2018 NuSTEC SIS/DIS workshop)

- CC DIS and RES modes only (+QE charm for GENIE)

- Additional cut W>1.7 GeV for lepton kinematics plots

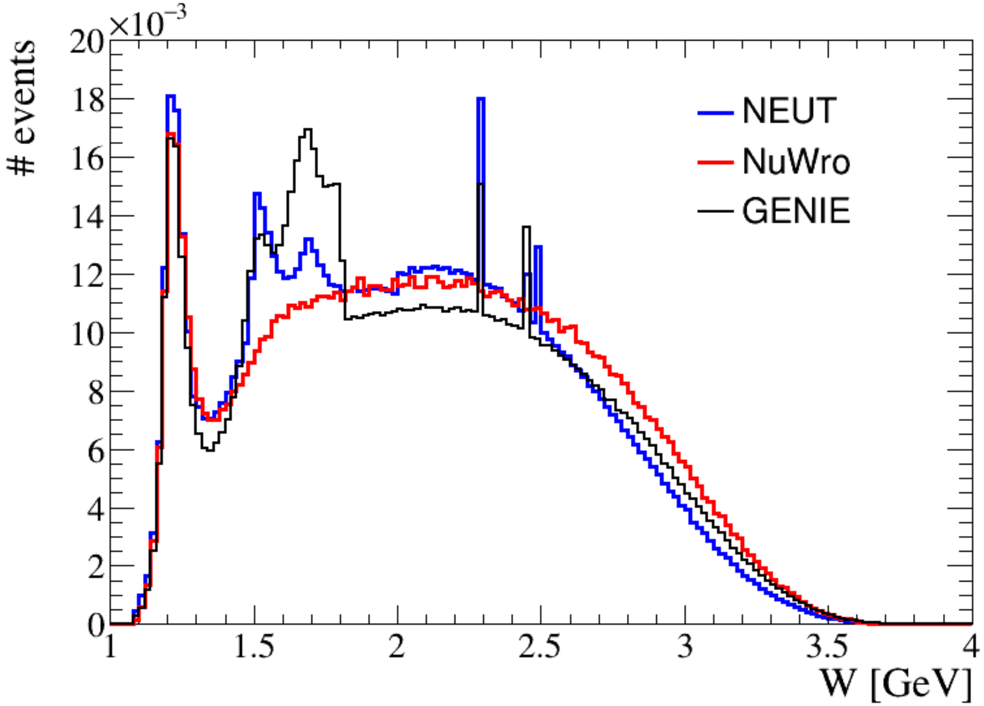
- Compared following 3 generators:
  - **NEUT**: version with updates presented here, in particular new Type II Bodek-Yang model (not released yet)
  - **NuWro** 21.09.2
  - **GENIE** 3.02.00 with tune G18_02b_02_11b (includes cross-section model re-tune published in Phys. Rev. D 104, 072009 (2021))

- Plots are normalized by area: shape comparison only

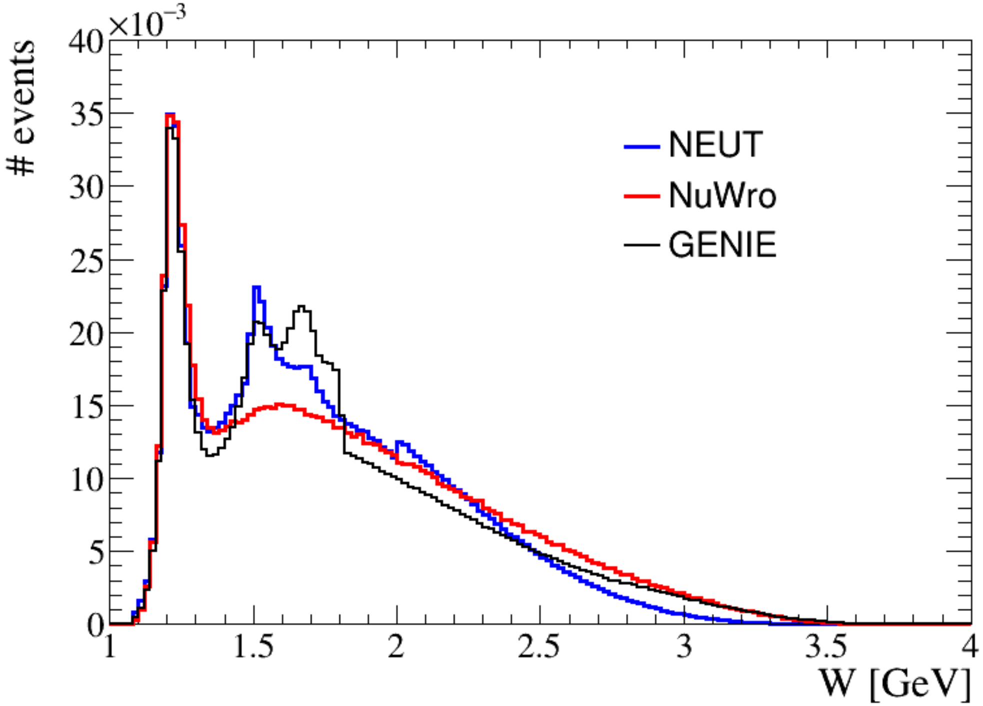
Comparison to other generators
Hadronic invariant mass

- **6 GeV $\nu_\mu/\bar{\nu}_\mu$ on Fe**
- Clear differences coming from resonances included and position of the transition RES → DIS
- Additional differences from versions of GRV PDFs and Bodek-Yang models used

Neutrino



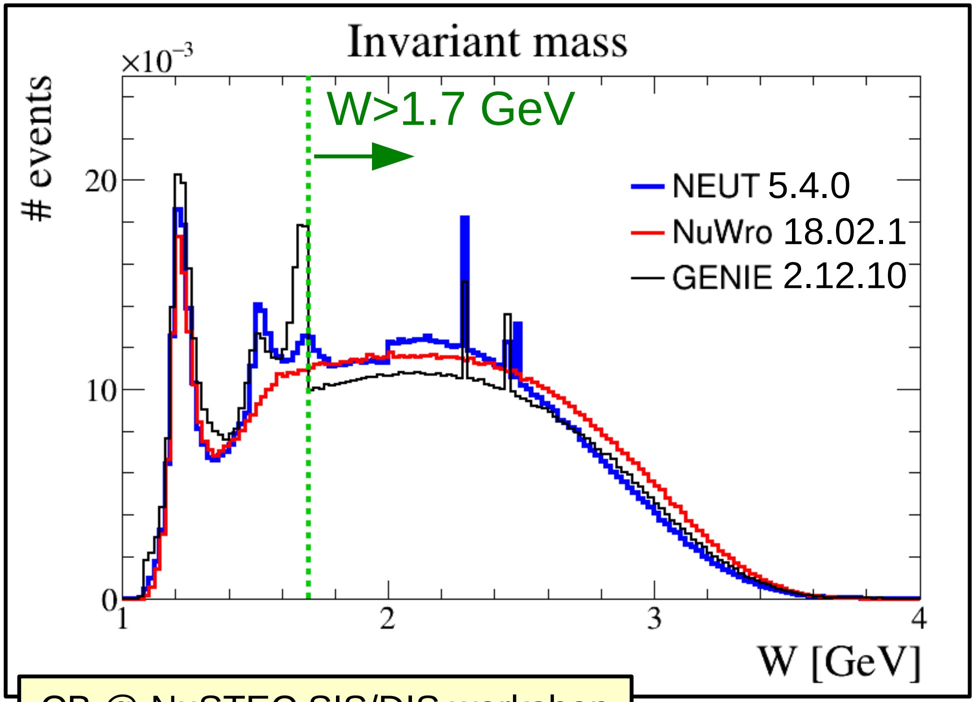
Anti-neutrino



Comparison to other generators
Hadronic invariant mass

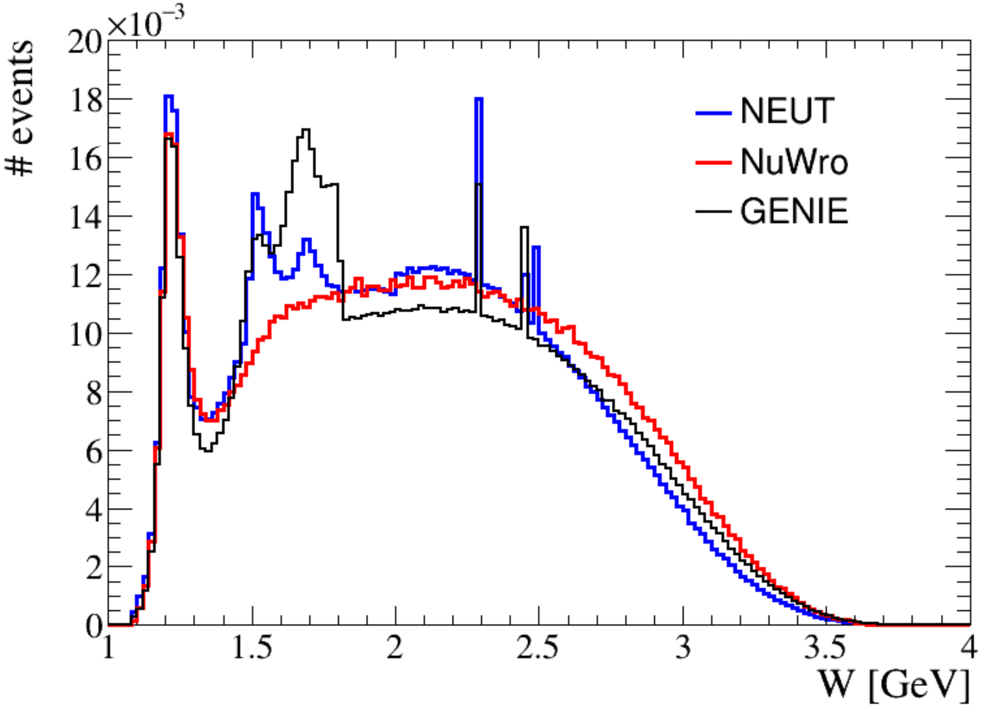
- Evolution from 2018: significant changes only for GENIE
- NEUT has some small change of the relative normalizations of the different regions

2018 version



CB @ NuSTEC SIS/DIS workshop

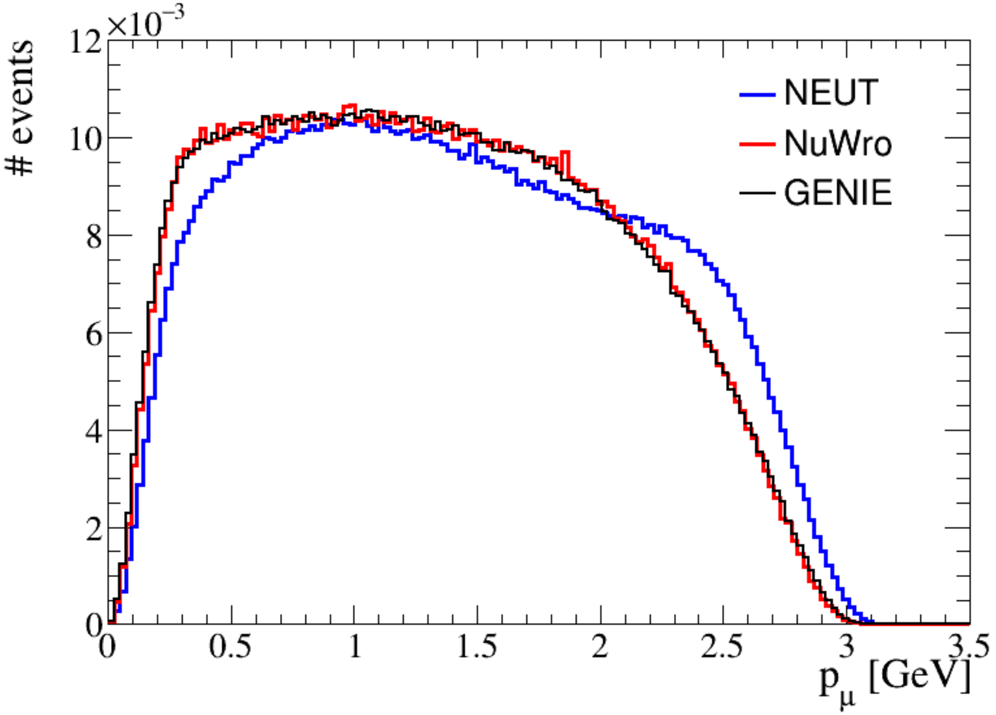
2022 version



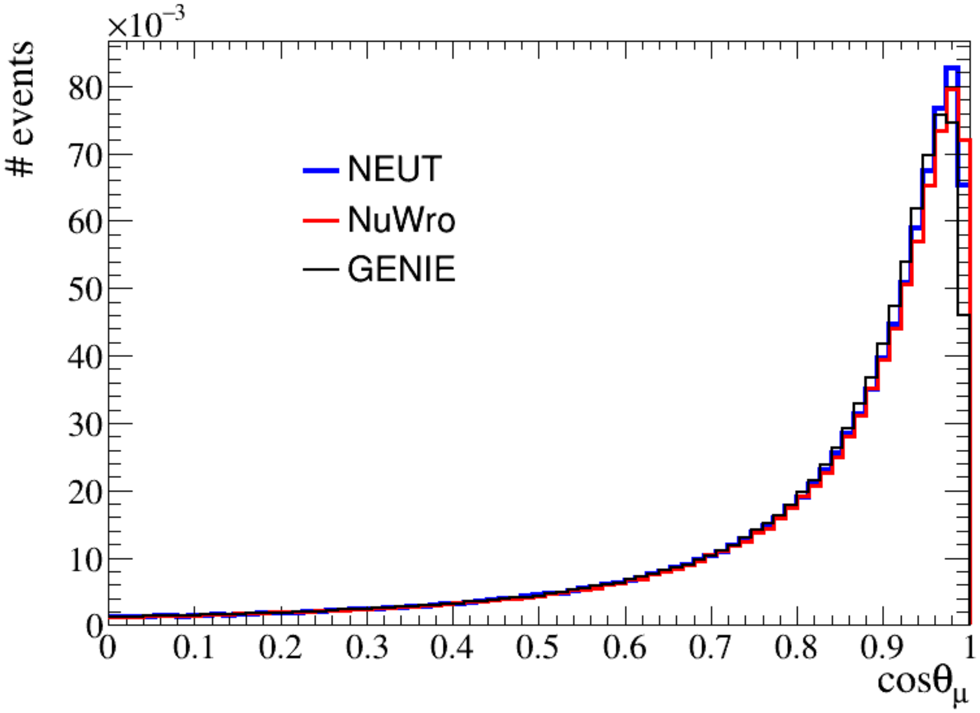
Comparison to other generators
Lepton kinematics

- **4 GeV ν_μ on water**, W>1.7 GeV
- Good agreement GENIE/NuWro for lepton momentum, NEUT visibly different
  A result of using PYTHIA for full event generation vs just fragmentation routines?
- Events in GENIE look a bit less forward

Lepton momentum



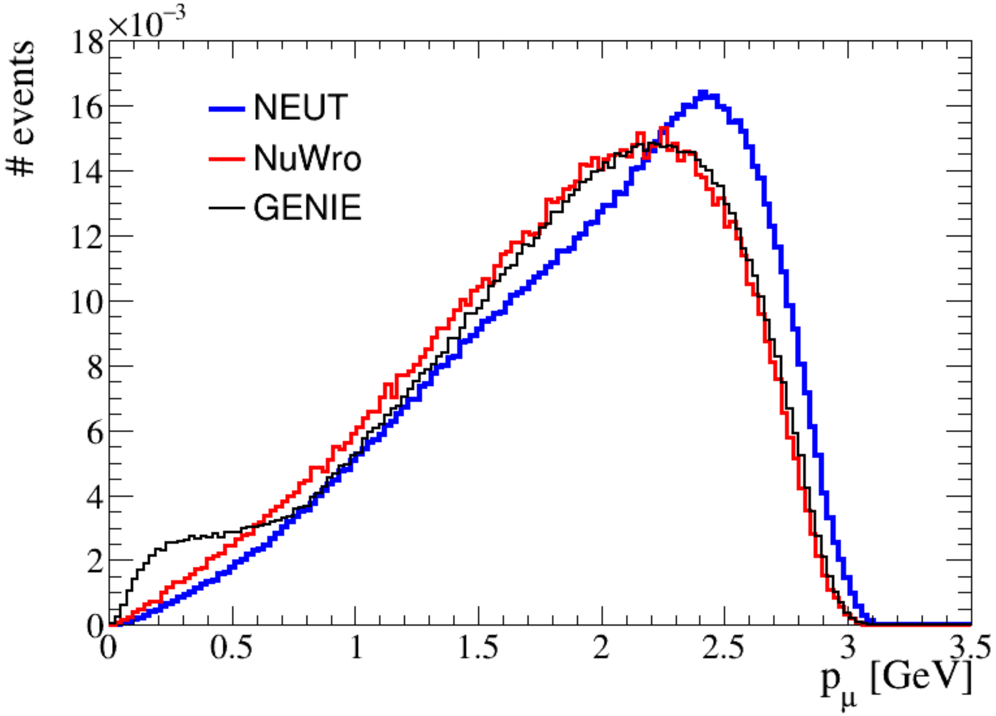
Lepton angle



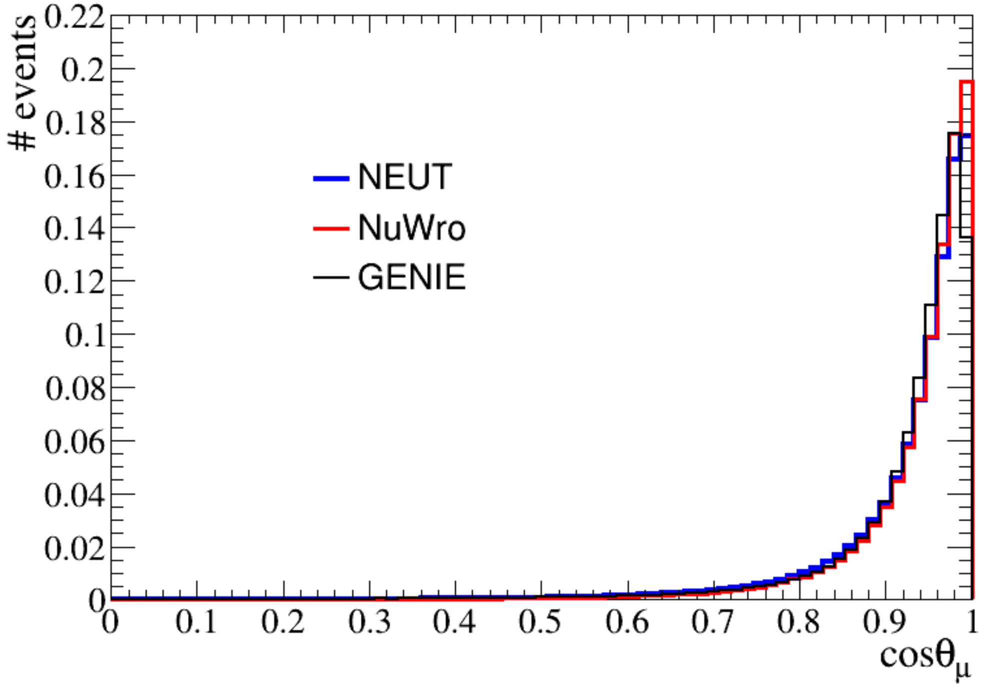
Comparison to other generators
Lepton kinematics

- **4 GeV $\bar{\nu}_\mu$ on water**, W>1.7 GeV
- Good agreement NuWro/GENIE for lepton momentum from 1.7 GeV, strange peak for GENIE at low momentum. Was already there in 2018
- Visible differences in how forward events are

Lepton momentum



Lepton angle



Summary

- 2 deep inelastic models in NEUT:
  - low W mode (W<2GeV): custom model for multi-particle background on top of resonant modes
  - high W mode (W>2GeV): uses PYTHIA for event generation

- Since NEUT 5.4.0:
  - improved simulation of neutral current DIS events
  - fixed a number of problems, including strange feature in lepton kinematics for events generated with PYTHIA

- Implemented new version of Bodek-Yang model: see significant effect of separation axial and vector part of F2 for corrections.

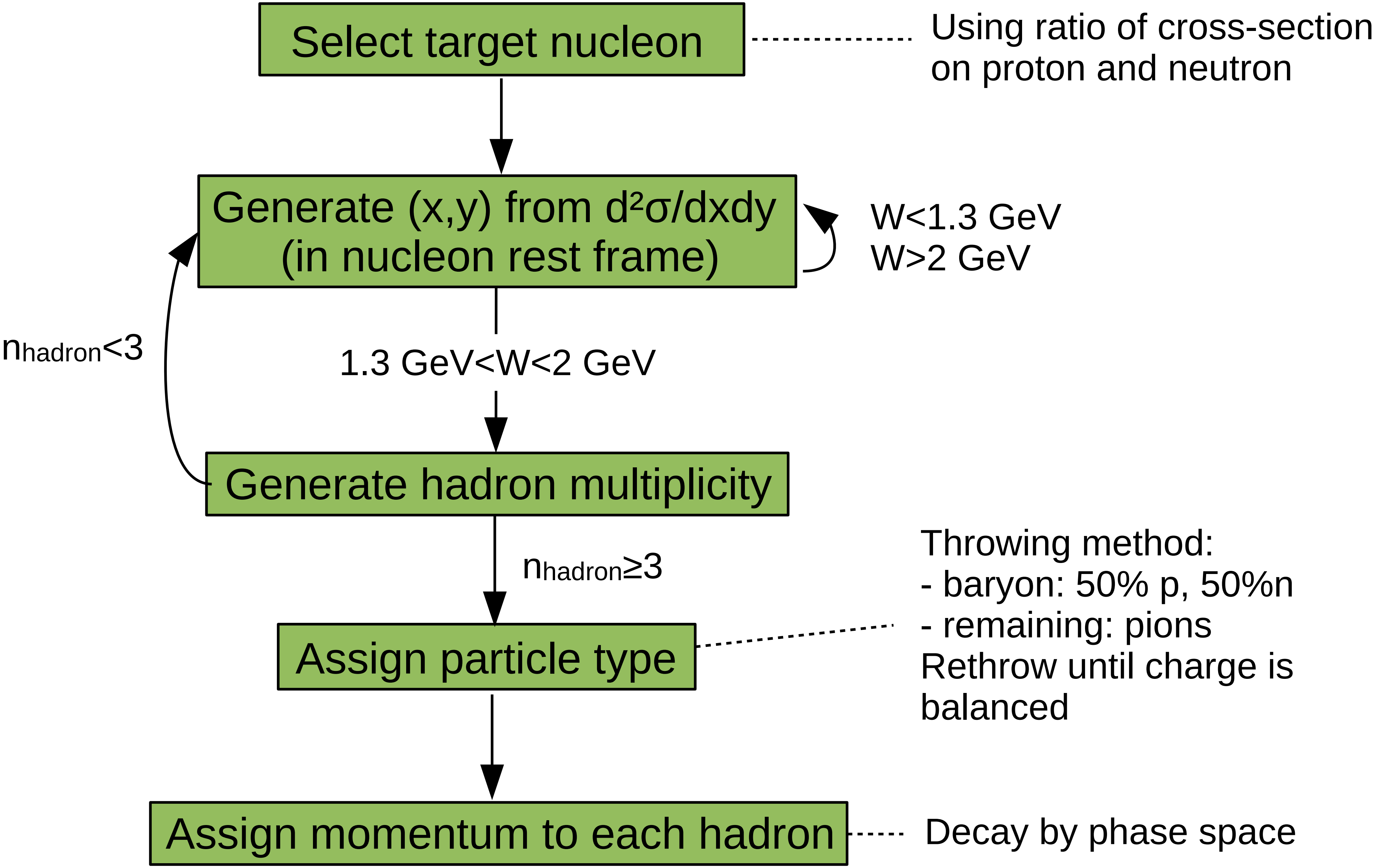
- Updated comparisons to GENIE and NuWro: still significant differences in the way generators treat the transition region

- Planning to continue working on the use of PYTHIA:
  - implementation of separation axial/vector F2 for BY model
  - difference in (x,y) compared to expectations from d2σ/dxdy

- Another important missing part is nuclear effects

BACKUP

Multi-pion model Flow



Select target nucleon

Using ratio of cross-section on proton and neutron

Generate (x,y) from $d^2\sigma/dxdy$ (in nucleon rest frame)

W<1.3 GeV
W>2 GeV

1.3 GeV<W<2 GeV

Generate hadron multiplicity

$n_{hadron}<3$

$n_{hadron}\geq 3$

Assign particle type

Throwing method:
- baryon: 50% p, 50%n
- remaining: pions

Rethrow until charge is balanced

Assign momentum to each hadron

Decay by phase space

DIS region

- Pure DIS mode for $W>2$ GeV/c^2 based on PYTHIA/JETSET 5.72
- Cross-section calculated by integrating $d^2\sigma/dxdy$ (as for multi-pion mode)
- PYTHIA used for the actual event generation:
  - input E_ν and nucleon four-momentum (from simple RFG model)
  - Loop over PYTHIA event generation until $W>2$ GeV and right NC/CC type

Modified parameters in PYTHIA

```
*     Lower edge of allowed sqrt{s} [GeV]
      CKIN(1)     = 0.001
*     Lower cut-off on p_t [GeV/c]
      CKIN(5)     = 0.0001
*     Lower CM energy [GeV]
      PARP(2)     = 0.001
*     Switch to be allowed to decay or not
      MDCY(LUCOMP(111),1) = 0
      MDCY(LUCOMP(221),1) = 0
      MDCY(LUCOMP(311),1) = 0
      MDCY(LUCOMP(223),1) = 0
      MDCY(LUCOMP(130),1) = 0
      MDCY(LUCOMP(310),1) = 0
      MDCY(LUCOMP(331),1) = 1
**** without tau decay(decay at tauola)
      IF(ITAUFLGCORE.eq.1) THEN
        MDCY(LUCOMP(15),1) = 0
      ENDIF
```

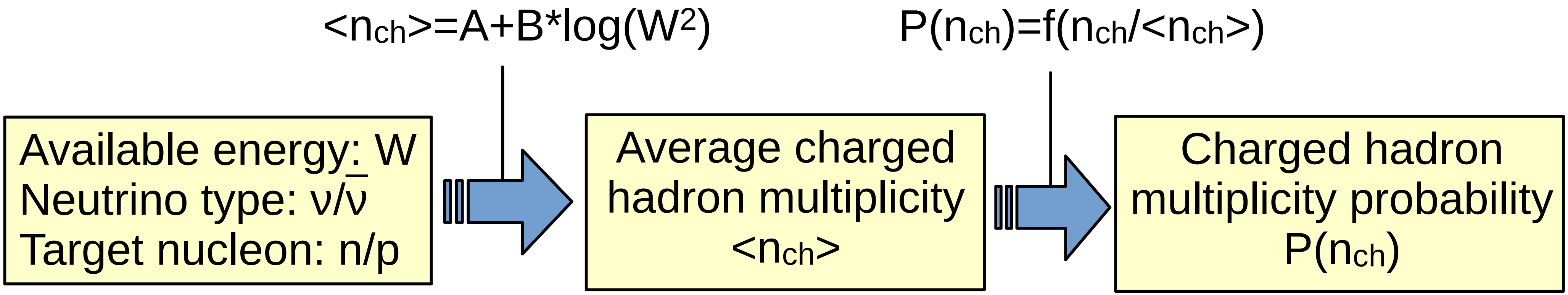
Don’t do decays of π^0, η, K^0, ω and τ
Decay η’

Other changes since 5.4.0

- Improved calculation of cross-section for low W mode, to make it more stable at high energy
- As a result, now use calculation up to 2.5 TeV instead of 25 GeV
- Add extra normalization of GRV98 PDFs when using Bodek-Yang model
- Rewriting of code used to compute and load DIS cross-sections, to make it easier to include additional models
- Fix bug in kinematics cut for the high W mode: cuts on Q2 due to validity of PDFs were mistakenly passed to PYTHIA as cuts on W

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

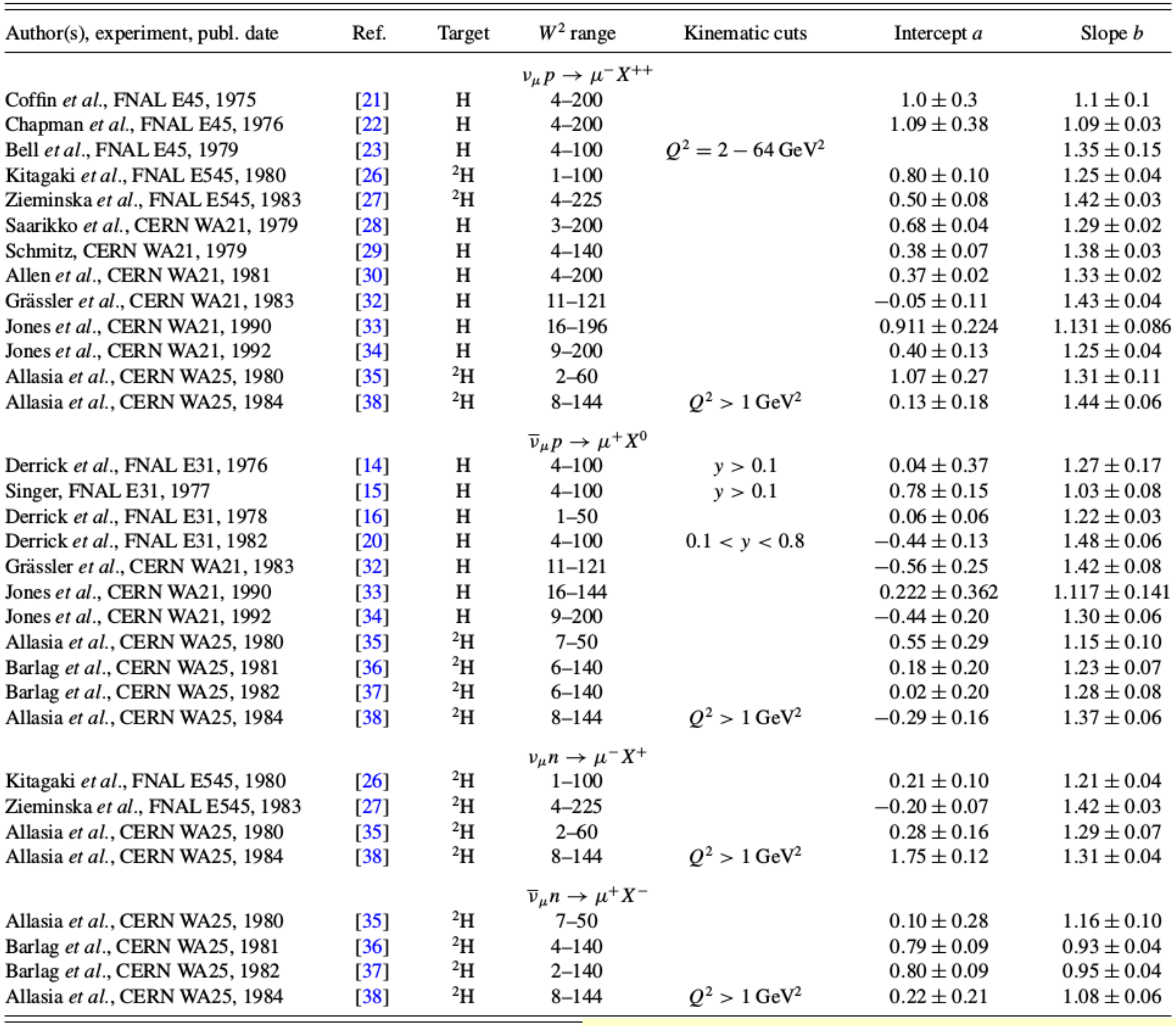
Average charged hadron multiplicity $<n_{ch}>$

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
$\overline{\nu}_\mu p \to \mu^+ X^0$						
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 (2013)

Many problems:

- ✗ 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

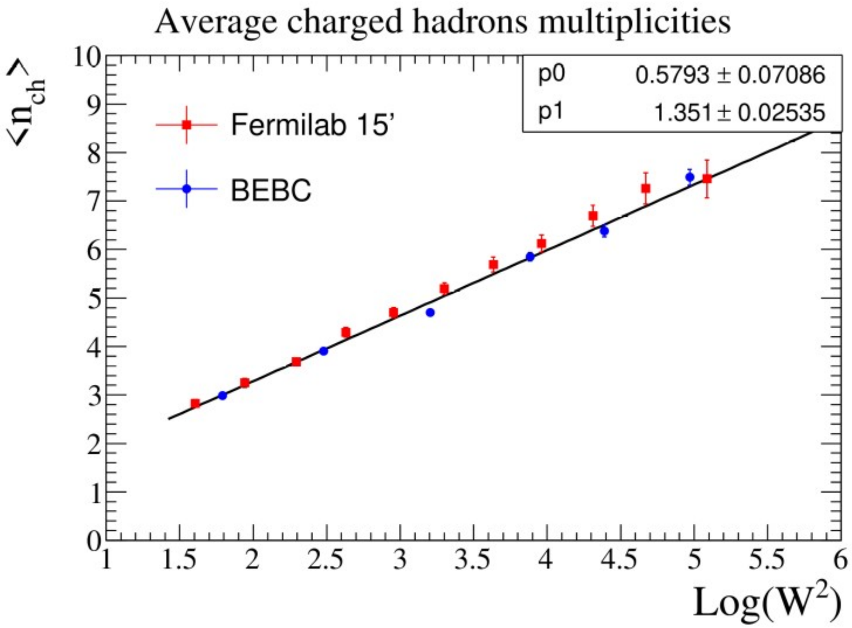
CB, M. Hartz
arXiv:1607.06558 [hep-ph]

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 $\nu/\bar{\nu}$ on p/n

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

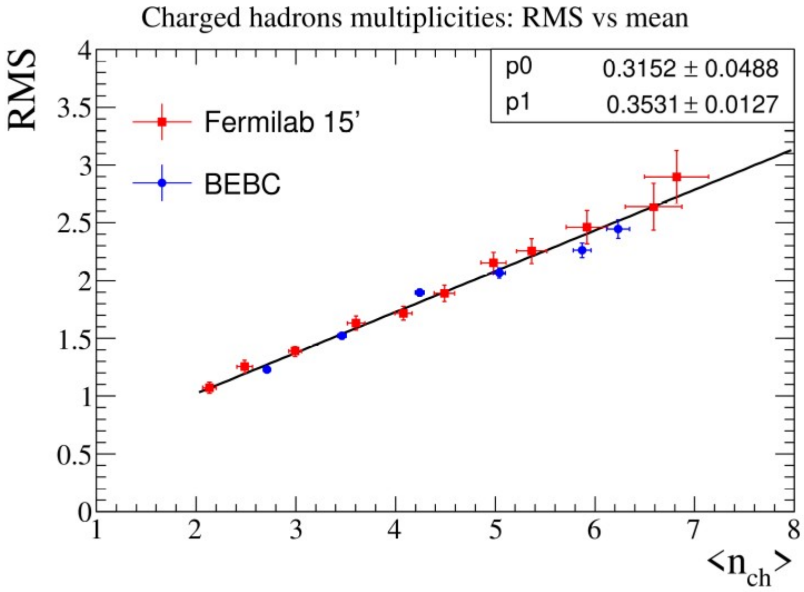
$$< n_{ch} > (W) = A + B \times ln(W^2)$$



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.

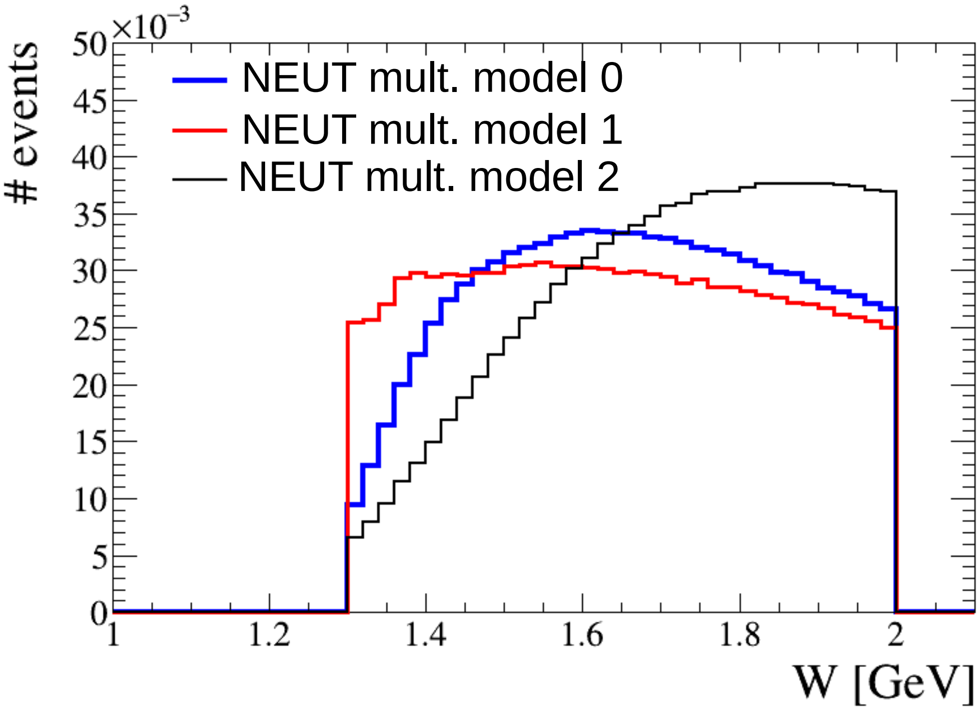
- Use for f the 'Levy function' used in the AGKY model (Eur. Phys. J. C **63** ,1-10 (2009))
- Compared to standard KNO scaling, use an additional parameter α as defined in Z. Phys. C **21**, 189 (1984)

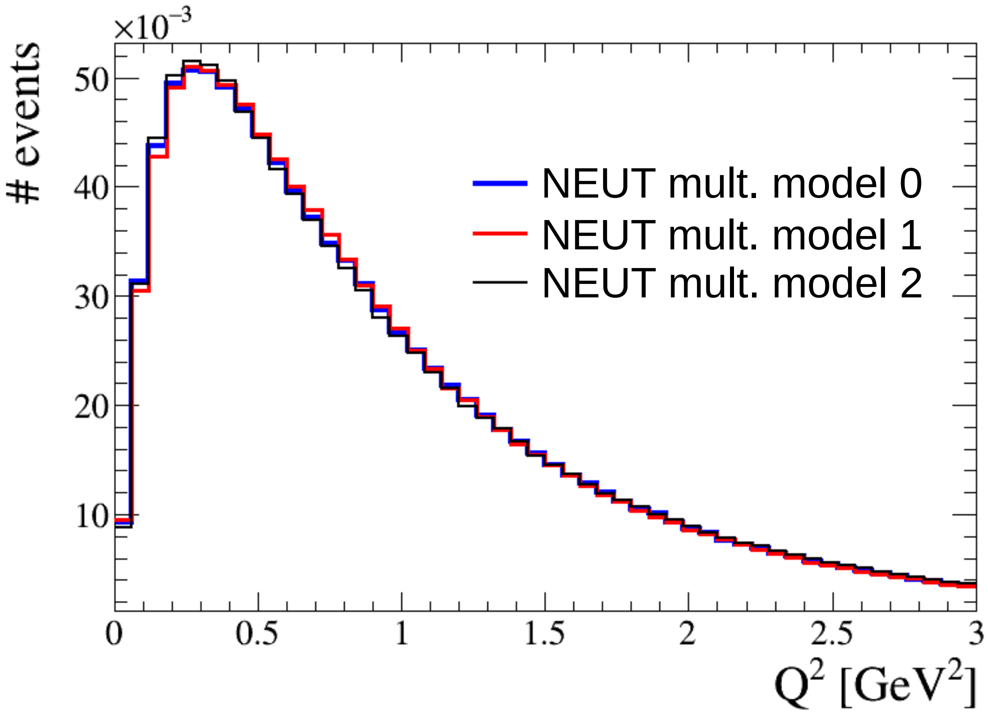
Multi-pion mode
Uncertainty on W distribution

- Generate (x,y) based on throwing method, keeping only events with $n_{had} \geq 3$
- In multiplicity models, multiplicity probability depends of W

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

- Shape of W distribution of the multi-pion component is uncertain as a result of uncertainty on a and b





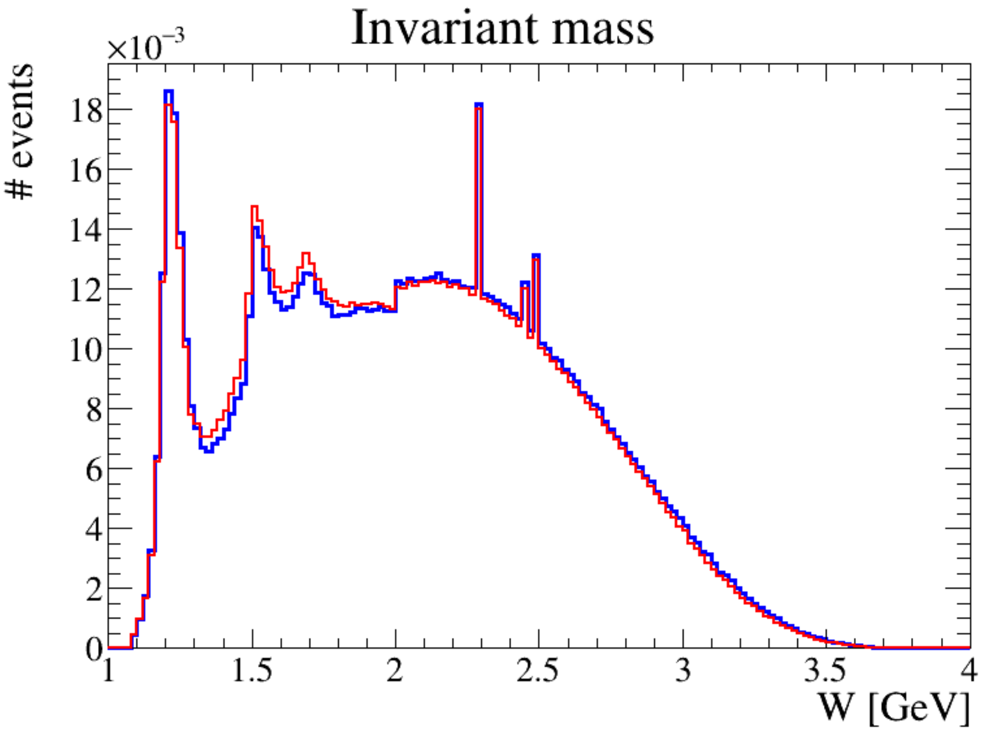
(T2K near detector flux, area normalized, low W mode W<2 GeV, $n_\pi \geq 2$. NEUT 5.4.0)

NEUT invariant mass

- Limited changes for NEUT
- Main feature is the slightly lower contribution of delta peak. Could be because the low W DIS background in the region after it has increased as a result of the increase of xsec for multi-pion mode

NEUT 5.4.0
New NEUT (BY Type II)

Neutrino



Anti-neutrino