NuSTEC workshop on Shallow- and Deep-Inelastic Scattering

Generator comparisons SIS/DIS region

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Introduction

- Generator comparison: run the different generators and compare the ouputs, and try to understand what causes the differences

- Focus on **charged current interactions**
  Assume SIS/DIS region = **W>1.7 GeV**
  All interactions from **muon neutrinos and anti-neutrinos**

- Only consider CC resonant and DIS modes (no QE, 2p2h)

- Comparisons on kinematical variables (W, Q2, muon momentum and angle) and multiplicities (charged hadrons and pions)

- **Plots normalized by area** in comparisons
  (shape comparison only, no cross-section comparison)

Generators

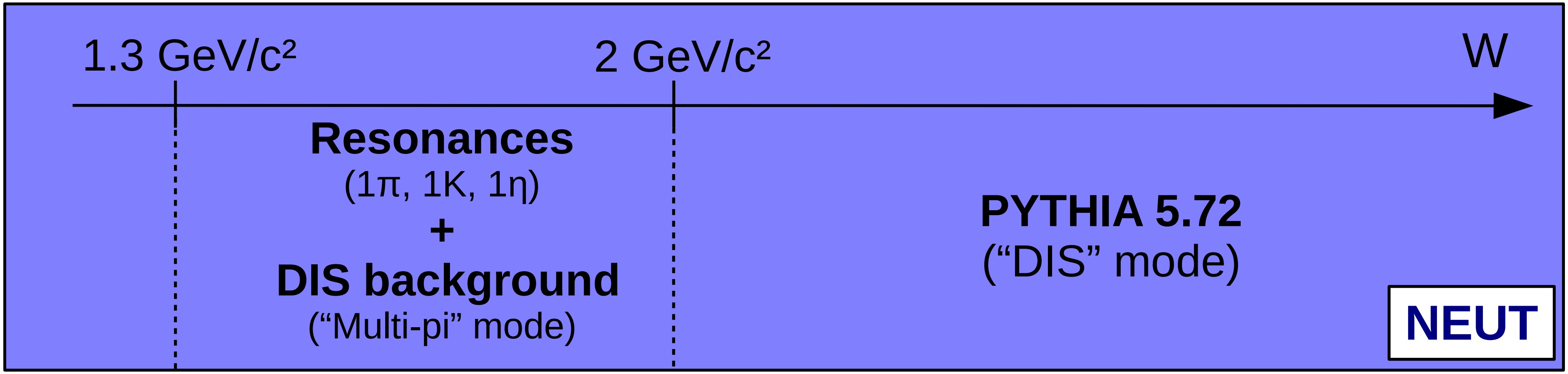
Compared the following 3 generators:

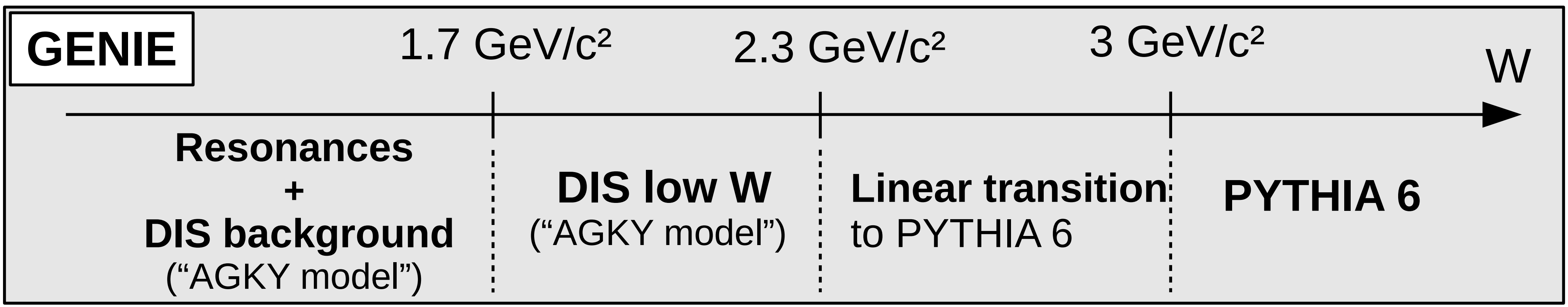
- ➔ **NEUT 5.4.0**
- ➔ **GENIE 2.12.10**
- ➔ **NuWro 18.02.1**

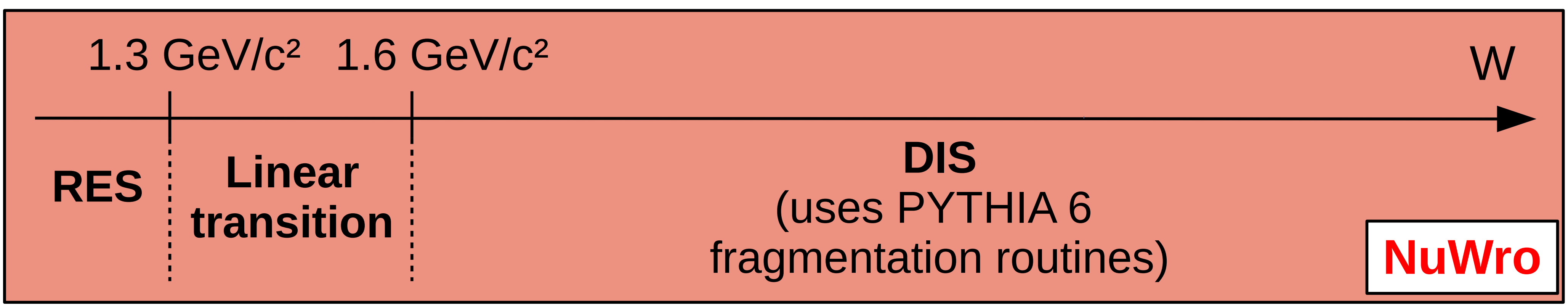
} CC DIS and RES modes only (+QE charm for GENIE)

Except when stated otherwise, generators ran with their default settings

SIS/DIS region in the generators

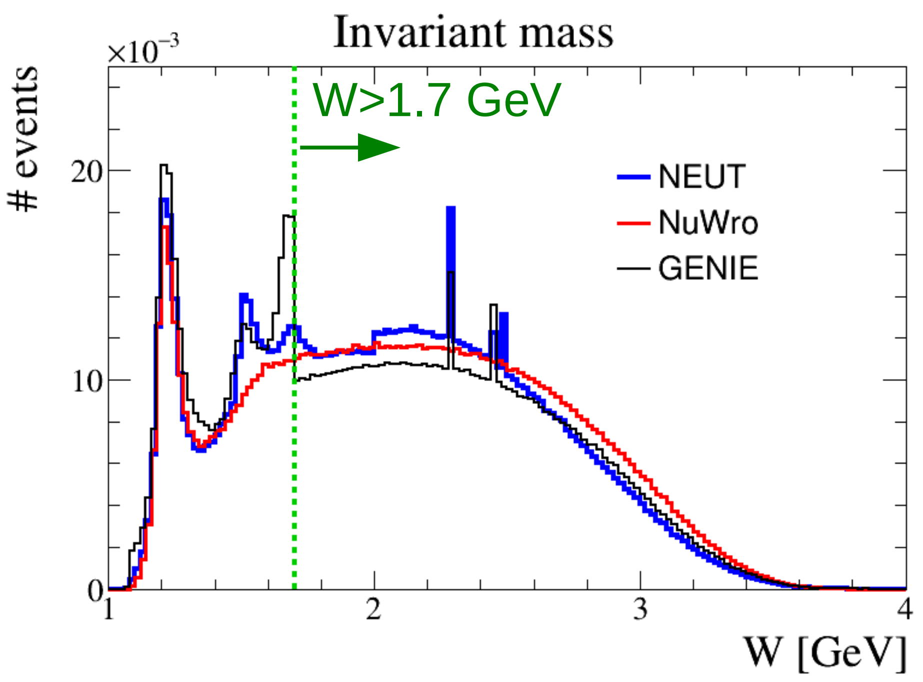


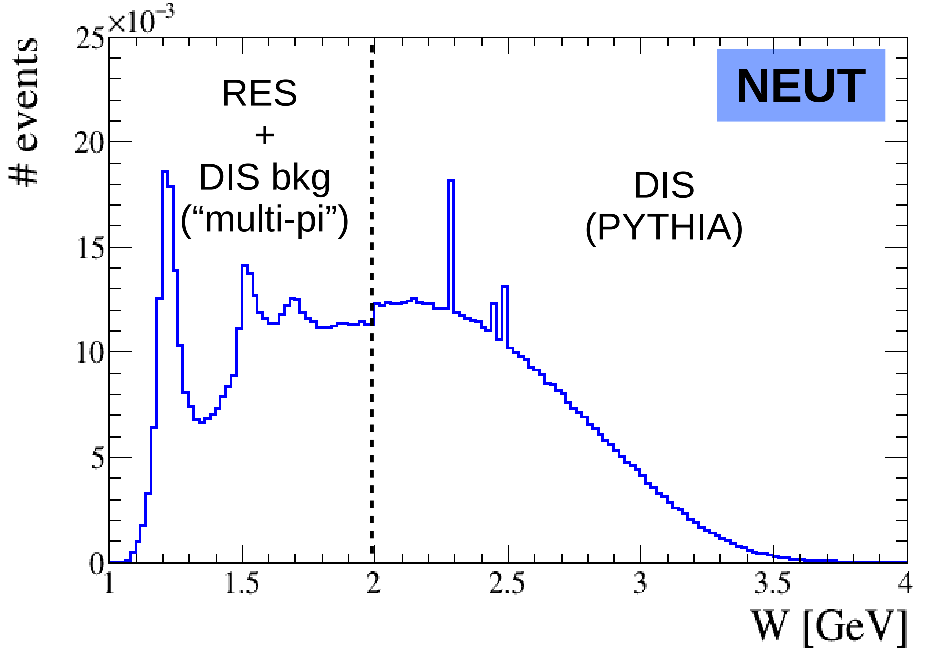


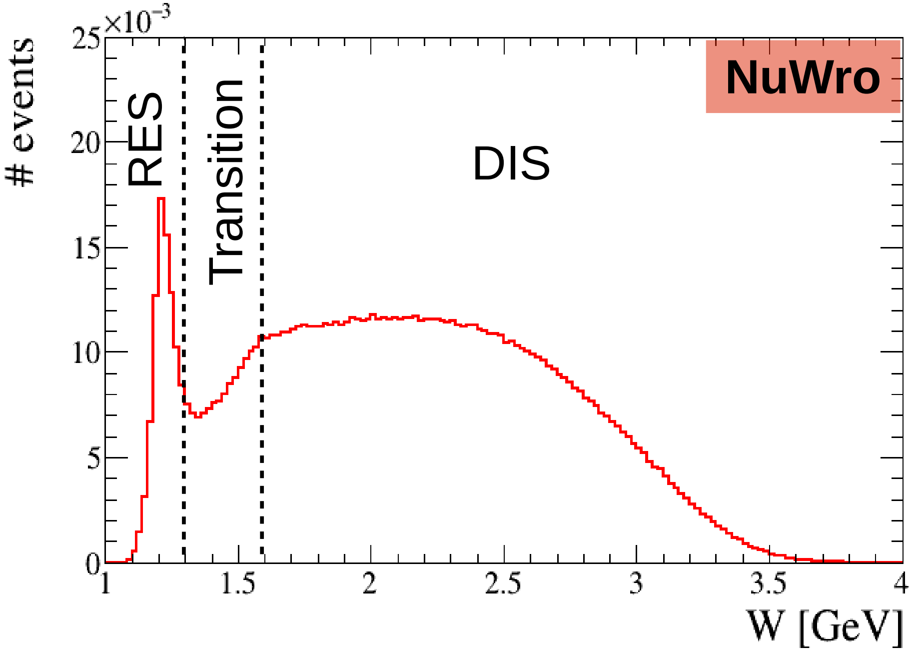


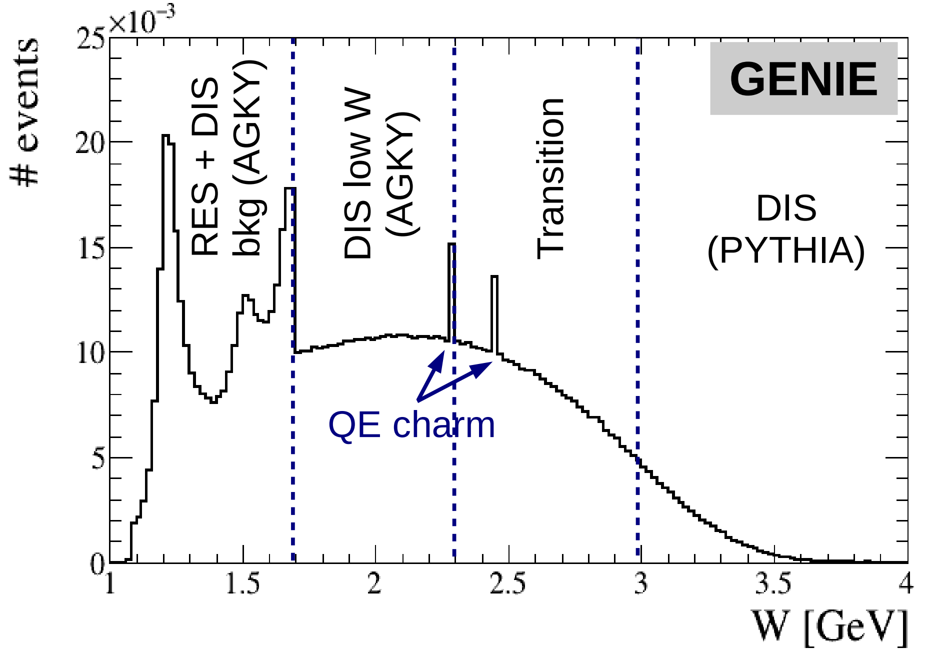
Invariant mass distribution

ν_μ on Fe, E_ν=6.0 GeV







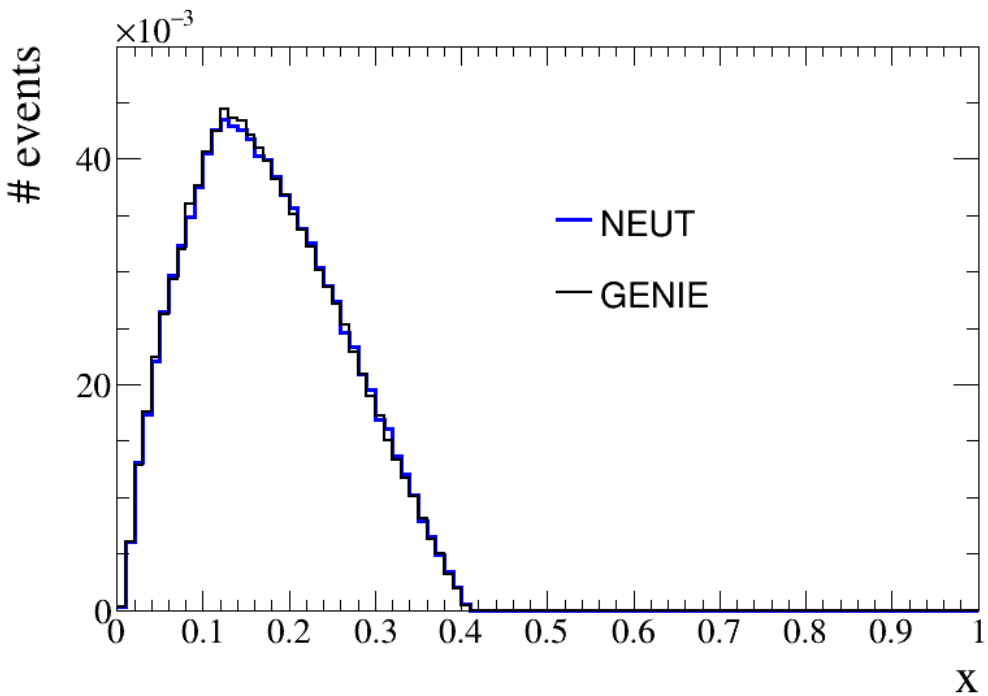


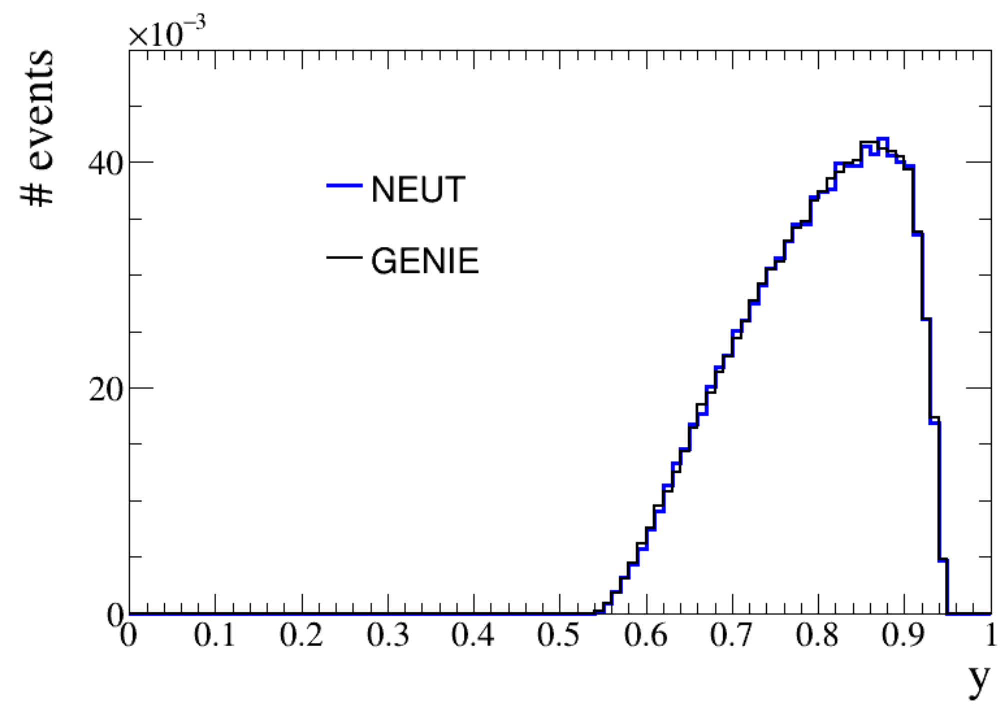
Global kinematics comparison

- Compare the different parts of the DIS models between generators
- Consider two regions where generators use the same kind of models:
  - “high W”: all the generators use PYTHIA: W > 3 GeV
  - “low W”: generators use their custom DIS model: 1.7 GeV < W< 2 GeV
- In comparisons of interactions on nuclear targets, many nuclear effects can add differences between predictions of the generators:
  - Final state interactions
  - nuclear corrections to PDF
  - model used for nucleon momentum
- Start by looking at interactions on free nucleons to look at the nucleon level differences between the generators

Low W models

The predictions for Bjorken x and y are similar for the low W models of GENIE and NEUT if used in the same way
(DIS only, 1.7 GeV < W < 2 GeV, at least 2 pions)





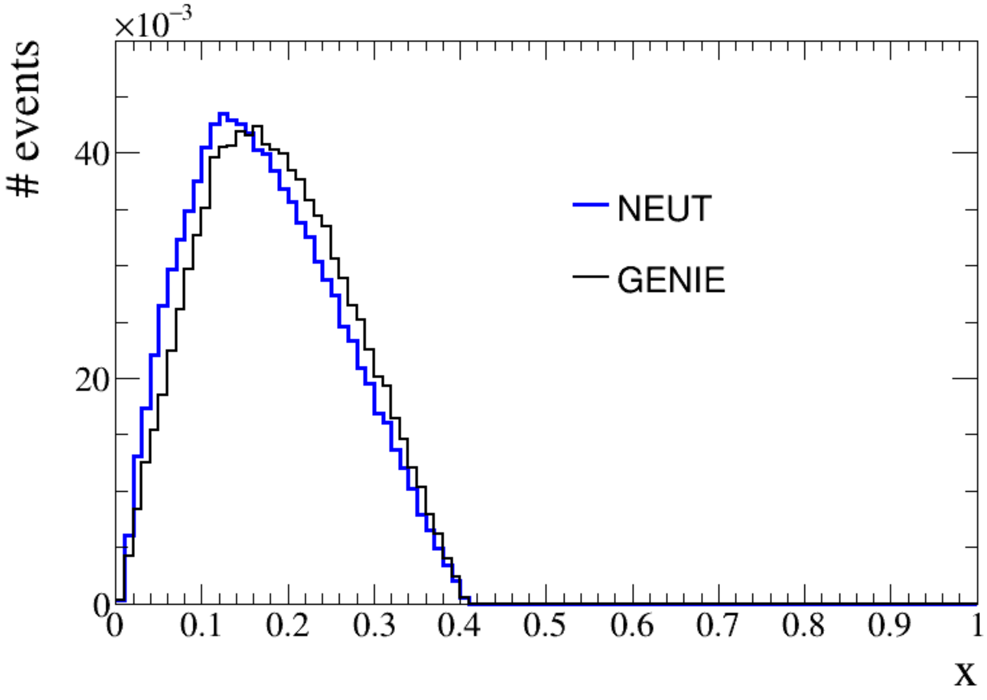
<u>NEUT settings:</u>
- default

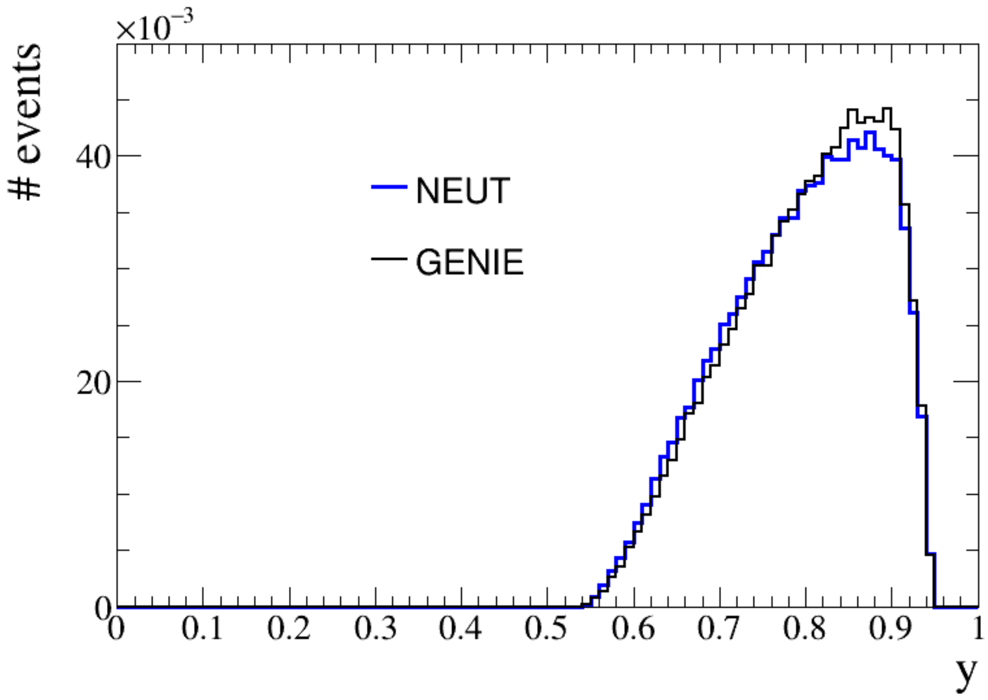
<u>GENIE settings:</u>
- DISSF-Use2016Corrections false → true
- DISSF-LowQ2CutoffF1F2 0.8 → 0.0

2 GeV ν_μ on free protons, $n_\pi \geq 2$

Low W models
Scaling variables

In default GENIE settings, corrections for the scaling variable used and freezing of Q^2 in the relation between structure function is not enabled.





<u>NEUT settings:</u>
- default

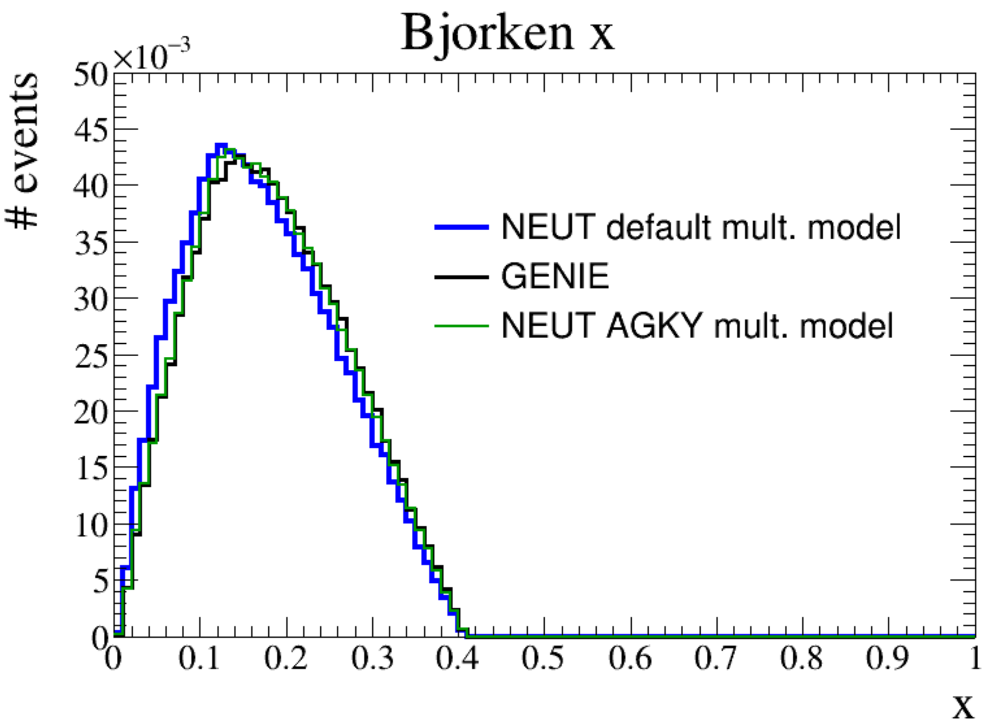
<u>GENIE settings:</u>
- default

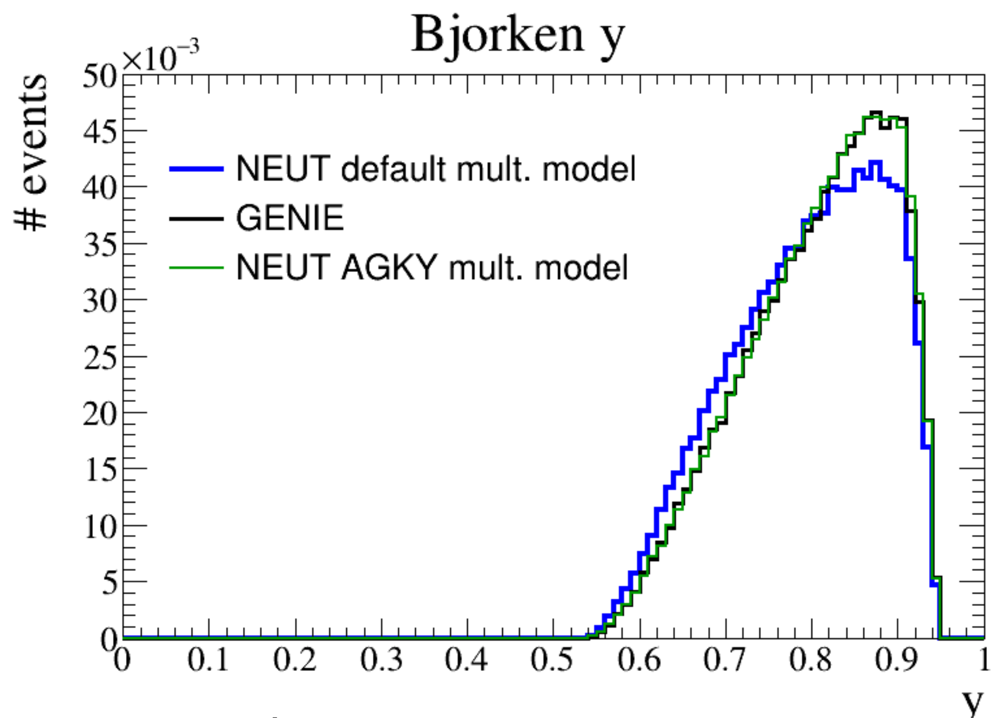
2 GeV ν_μ on free protons

(DIS only, 1.7 GeV < W < 2 GeV, $n_\pi \geq 2$)

Low W models
Multiplicity model

For combinations of ν/$\bar{\nu}$ and target nucleons for which NEUT nominal multiplicity model is different from GENIE's ones, this creates differences in x,y (so in W/Q^2)





<u>NEUT settings:</u>
- default

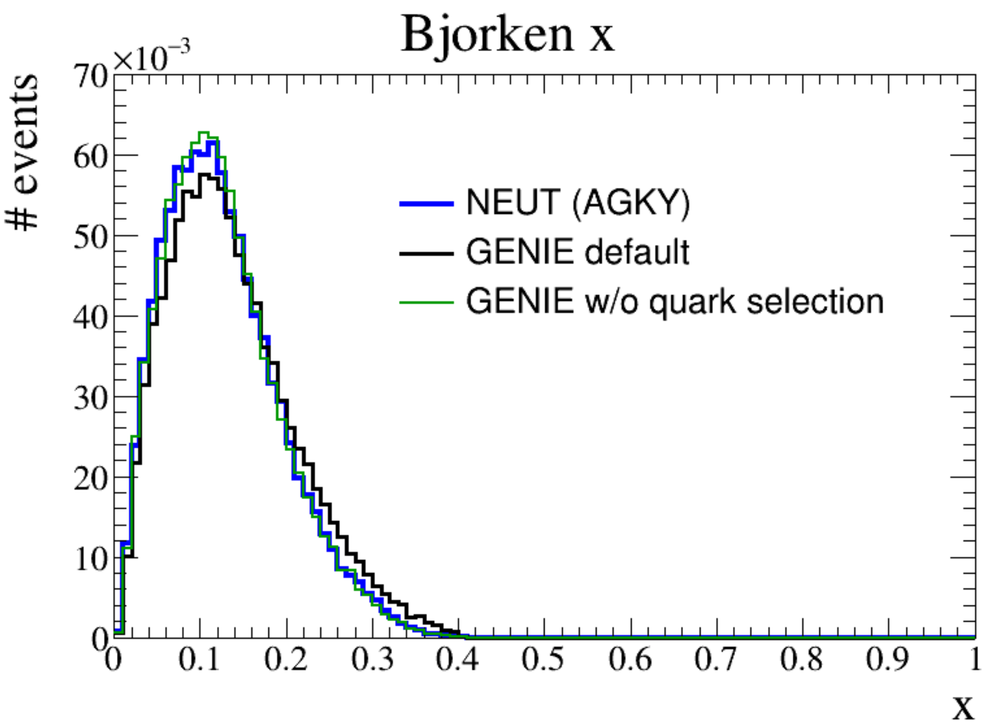
<u>GENIE settings:</u>
- DISSF-Use2016Corrections false → true
- DISSF-LowQ2CutoffF1F2 0.8 → 0.0

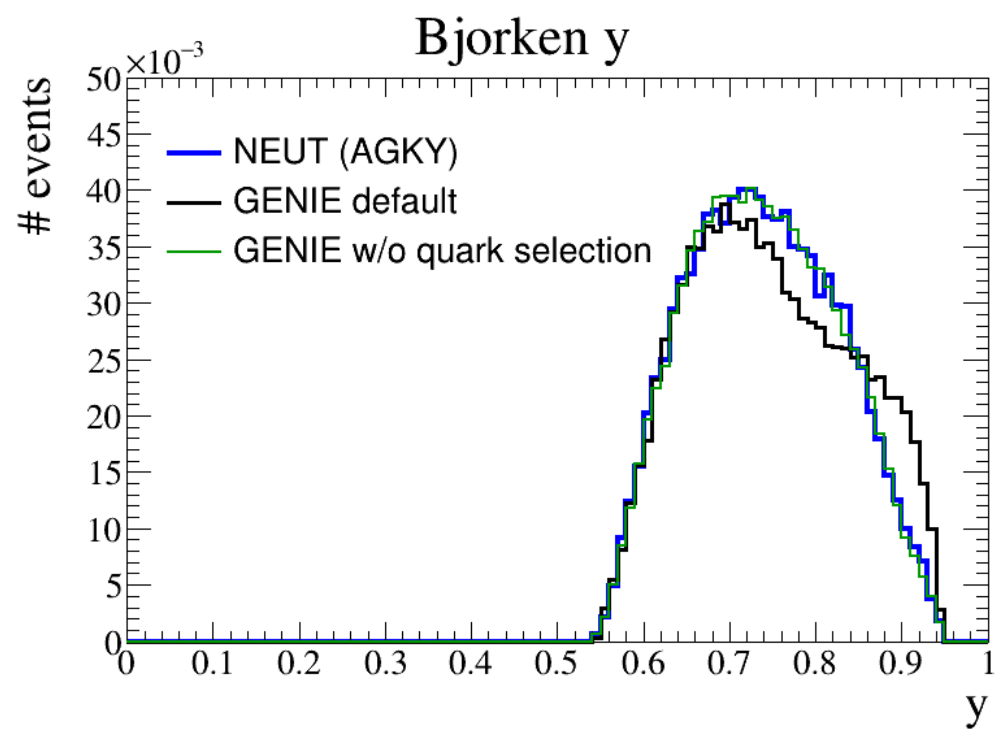
2 GeV ν_μ on free **neutrons**

(DIS only, 1.7 GeV < W < 2 GeV, $n_\pi \geq 2$)

Low W models
Anti-neutrinos

By default, GENIE computes cross-section for reactions on each type of quark, and then generates (x,y) using only the contribution of this type of quark in structure functions.
It creates a difference for anti-neutrinos.





<u>NEUT settings:</u>
- AGKY multiplicity model

<u>GENIE settings:</u>
- DISSF-Use2016Corrections false → true
- DISSF-LowQ2CutoffF1F2 0.8 → 0.0

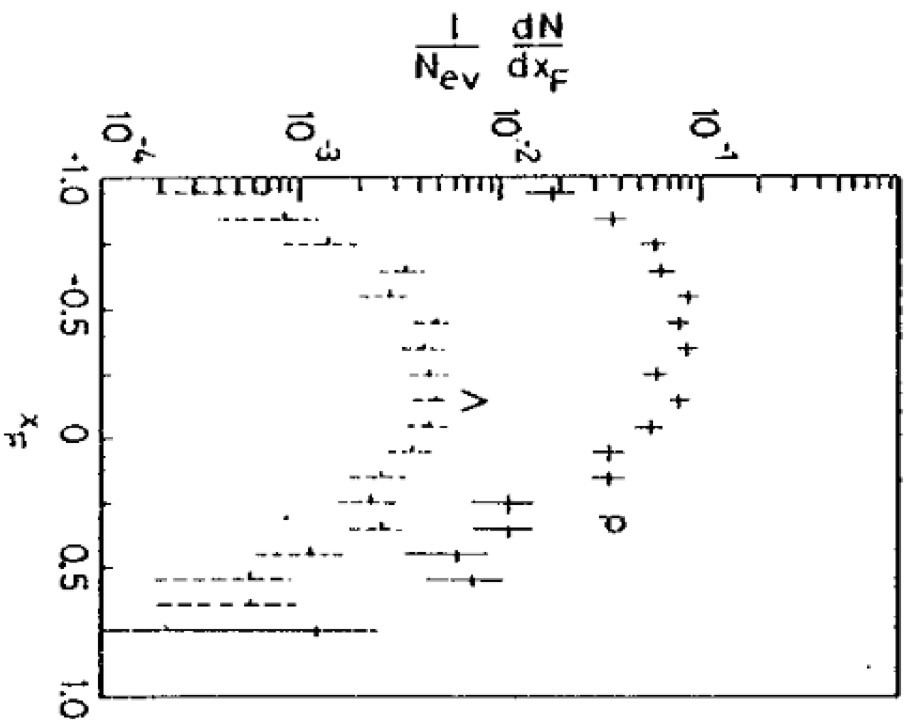
2 GeV $\bar{\nu}_\mu$ on free neutrons

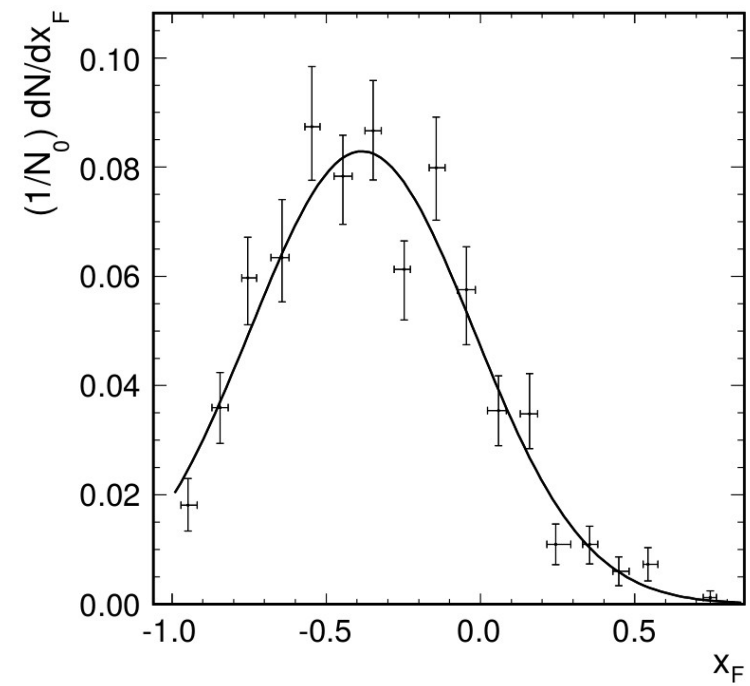
(DIS only, 1.7 GeV < W < 2 GeV, $n_\pi \geq 2$)

Low W models
Hadron kinematics

Differences in hadron kinematics coming from several differences:

- different multiplicity models:
  different nb of hadrons → available energy per hadron is different
- Differences on how momentum is attributed:
  - GENIE uses experimental distributions of x_F and p_T^2 for the baryon, remaining hadrons generated using phase space decay
  - in NEUT, all hadrons generated using phase space decay
- Differences in FSI models

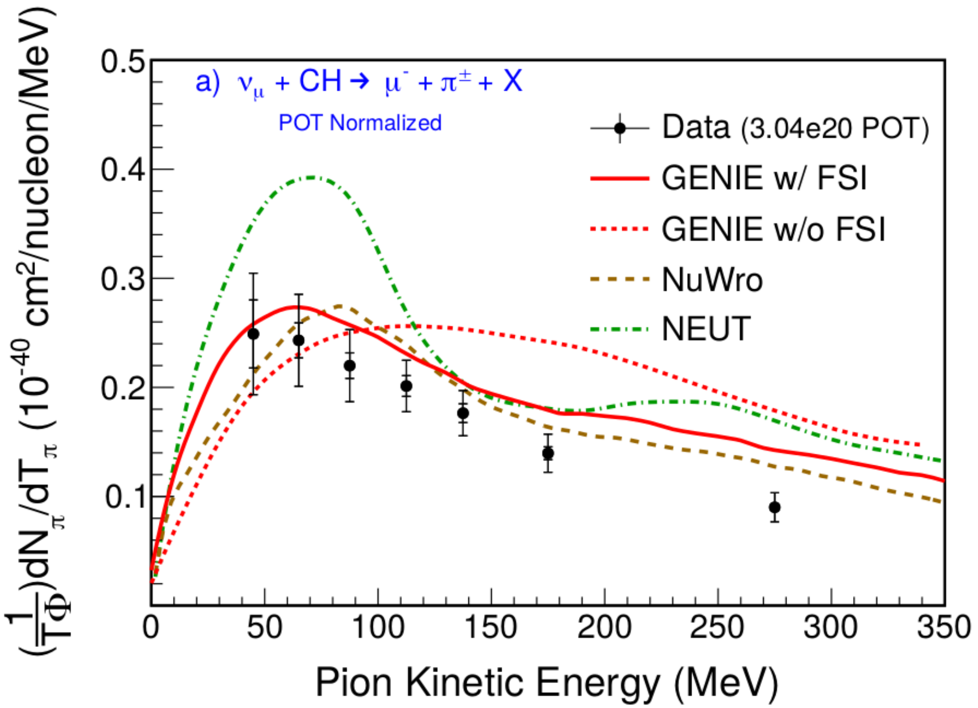




Taken from A. M. Cooper-Sarkar @Neutrino82

Low W models
Hadron kinematics

MINERνA CC1$\pi^{\pm}$ differential cross section
Phys. Rev. D 94, 052005 (2016)



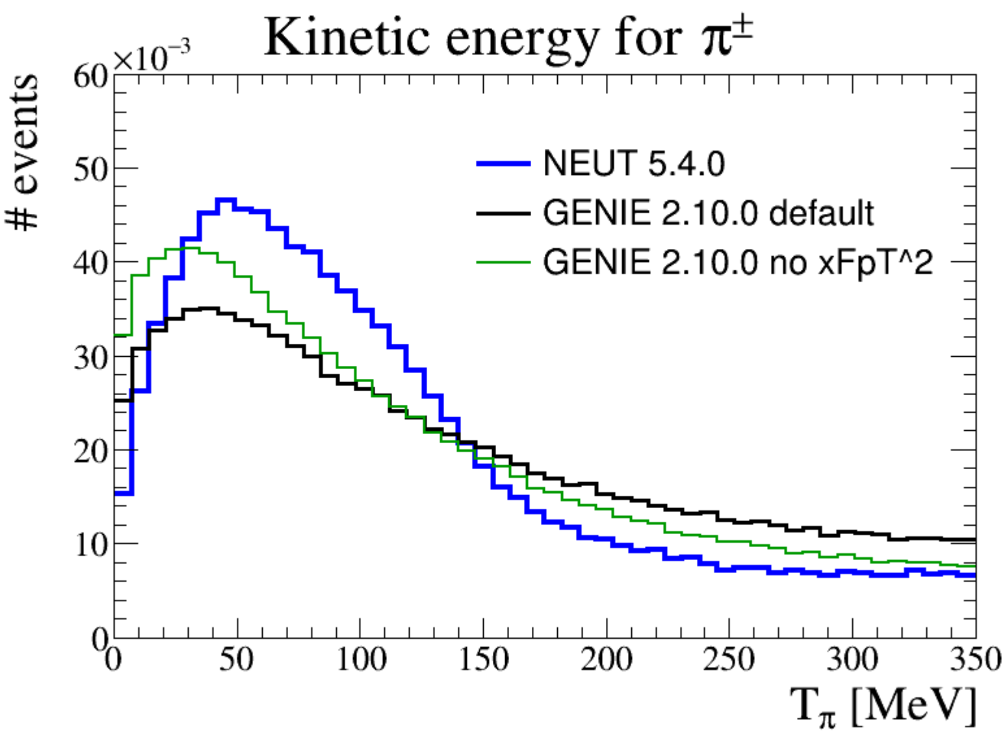
Tried to understand shape difference:

- NEUT 5.4.0 vs GENIE 2.10.0
  - AGKY multiplicity model for NEUT
  - use “2016 corrections” for GENIE
  - keep only events with $n_\pi \geq 2$
  - CC DIS events only
- Interactions on CH
- Flux: Minerva numu FHC
- Cuts: W<1.8 GeV
  1.5 Gev<E<10 GeV

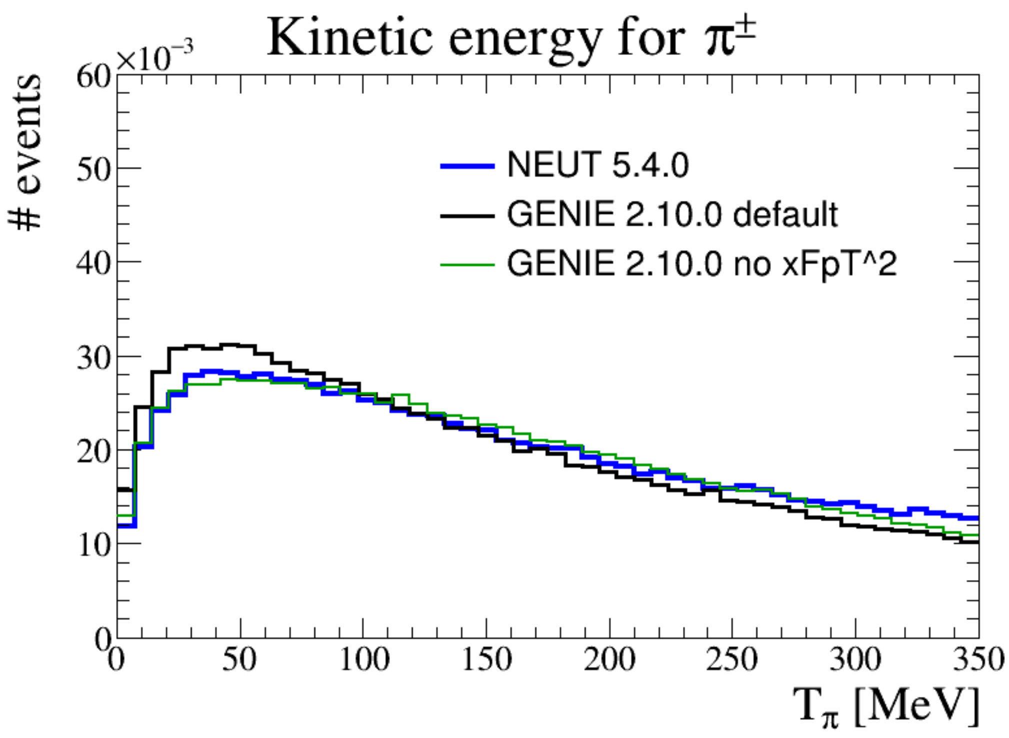
Low W models
Hadron kinematics

Main difference found to be coming from FSI model.
Use of xF/pT² PDF for the baryon adds some smaller difference

With FSI

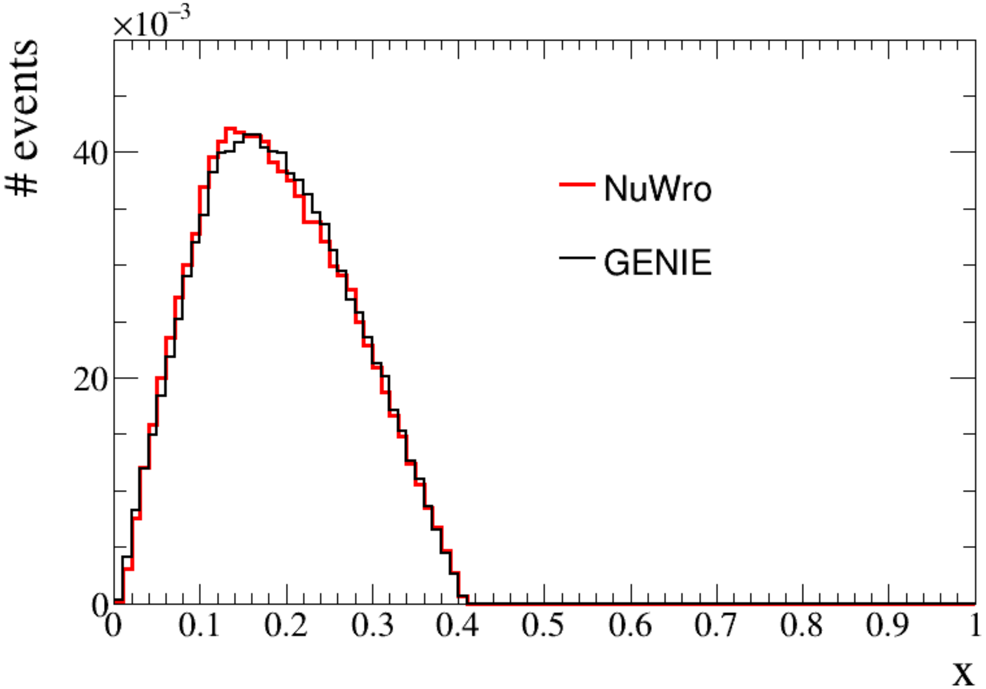


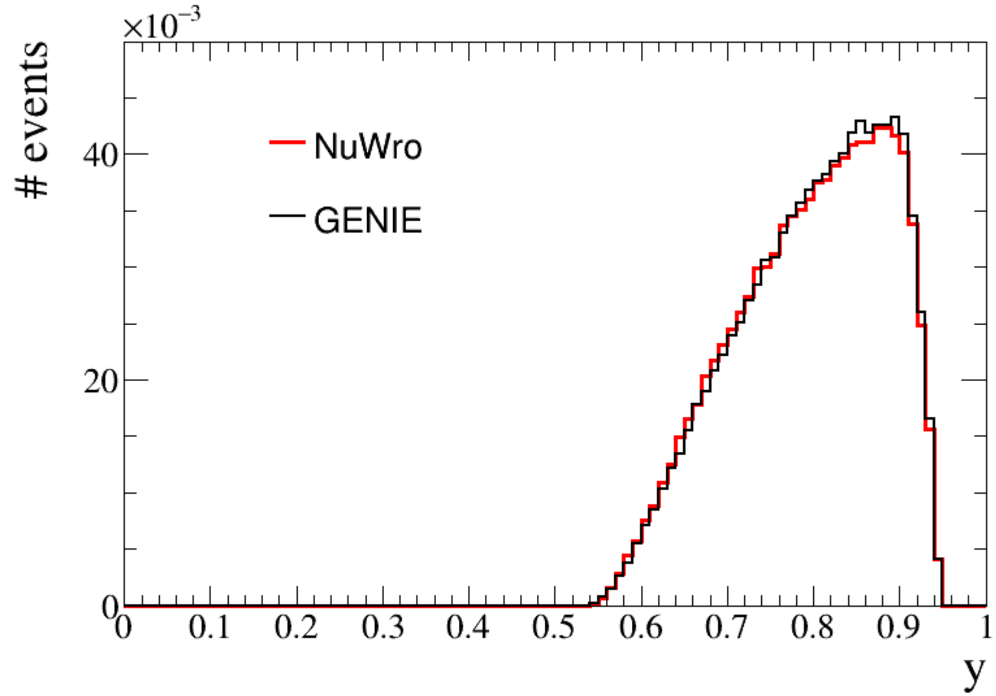
Without FSI



Low W models
NuWro

- NuWro does not have separate low and high W DIS models
- Generates (x,y) and select hit quark then uses PYTHIA fragmentation routines to produce the event





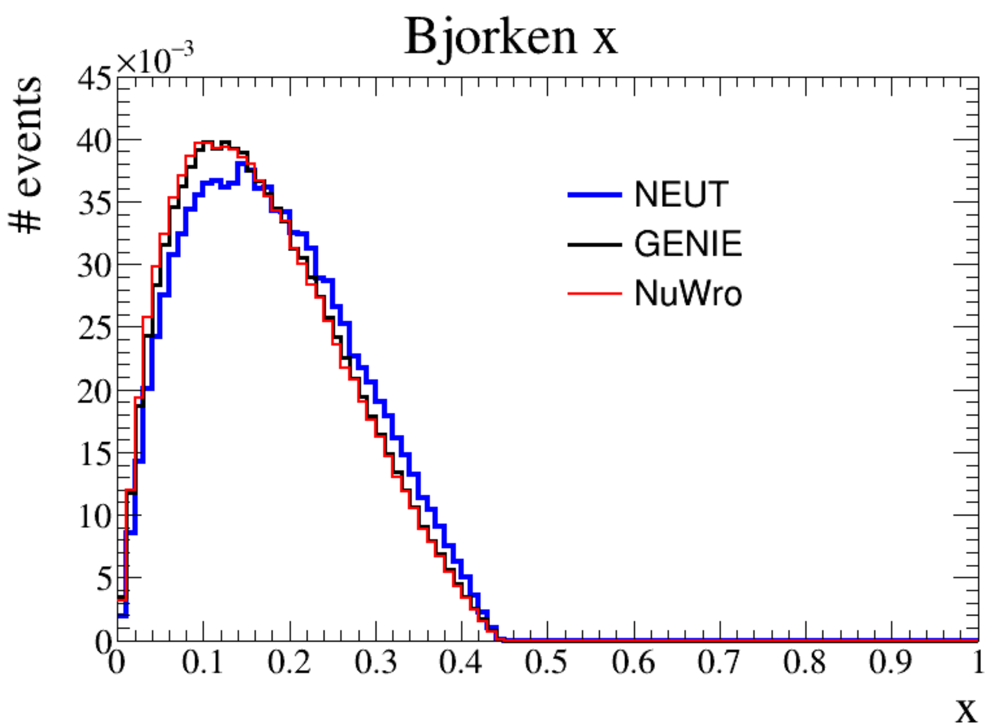
Obtained (x,y) very similar to default GENIE in this region, although NuWro uses GRV94 and GENIE GRV98

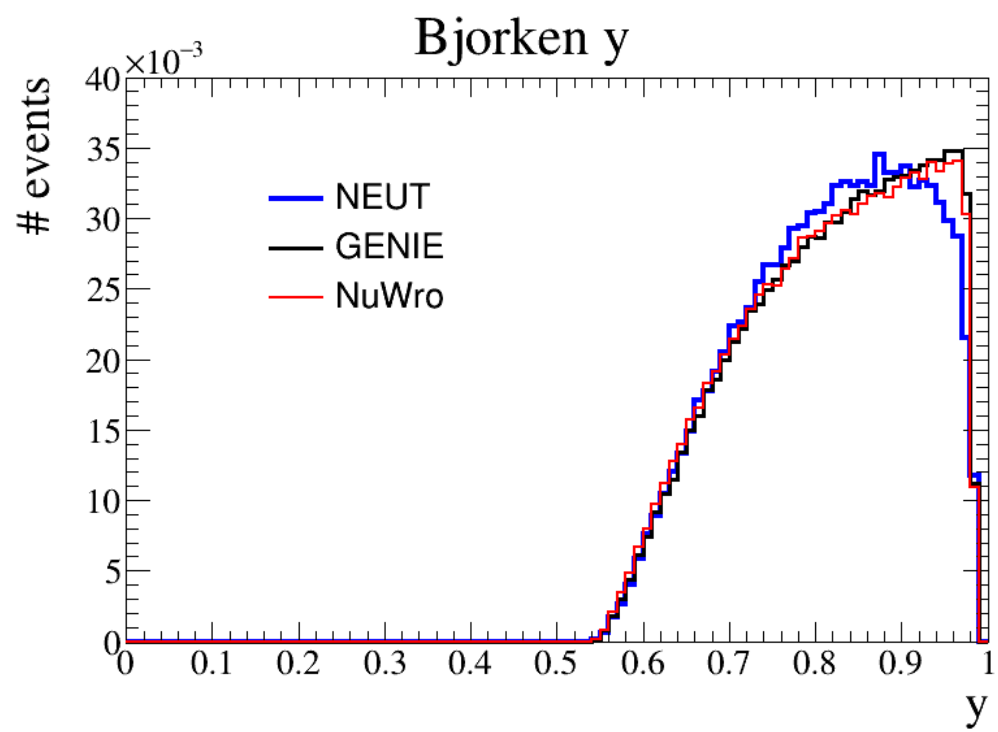
2 GeV ν_μ on free protons, 1.7<W<2 GeV

High W models

At high W, all generators use PYTHIA

- NEUT uses PYTHIA 5, GENIE and NuWro PYTHIA6
- In NEUT, event is fully generated by PYTHIA
- GENIE and NuWro generate (x,y), select target quark and use PYTHIA fragmentation routines
- NEUT and GENIE use GRV98, NuWro uses GRV94





8 GeV ν_μ on free protons, W>3 GeV

Comparisons on nuclear targets

Comparing predictions for different targets and fixed energies

- **H_2O at 4 GeV** (8 bound protons, 8 bound neutrons, 2 free protons)

In backup slides:

- **CH at 2 GeV** (6 bound protons, 6 bound neutrons, 1 free proton)
- **Ar at 2.5 GeV** (18 bound protons, 22 bound neutrons, 0 free protons)
- **Fe at 6 GeV** (26 bound protons, 30 bound neutrons, 0 free protons)

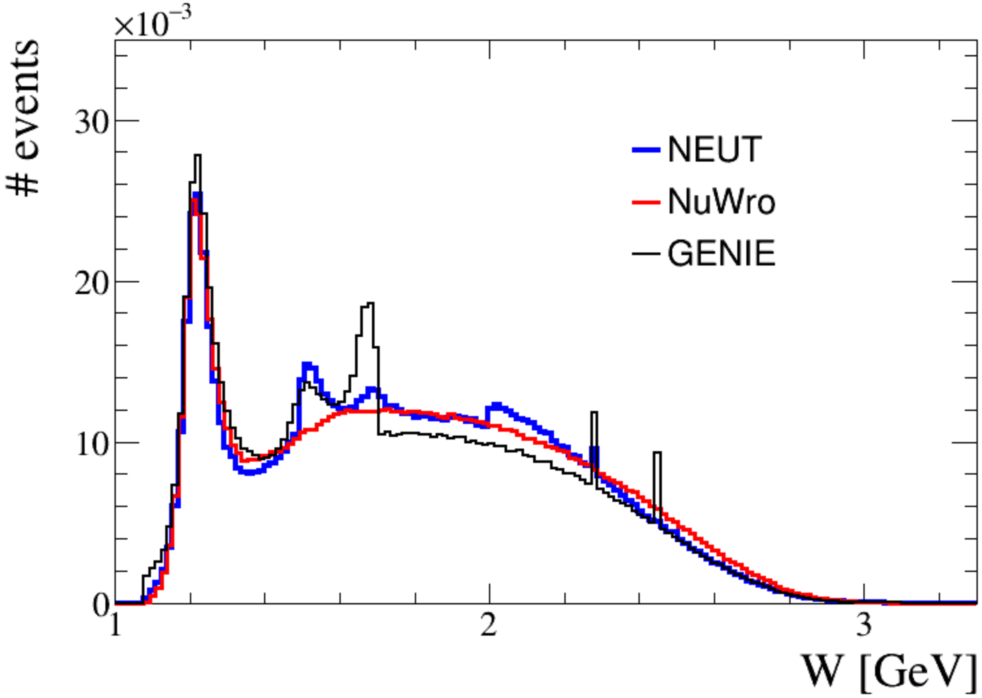
7 different comparisons for each:

- **W** distribution - computed as $W^2=(P_\nu+P_{nuc}-P_\mu)^2$
- **Q^2** distribution - computed as $Q^2=(P_\nu-P_\mu)^2$
- **p_μ**: lepton momentum
- **$\cos(\theta_\mu)$**: lepton angle
- **n_{ch}**: charged hadron multiplicities
- **n_π**: pion (charged + neutral) multiplicities
- **$n_{\pi 0}$**: neutral pion multiplicities

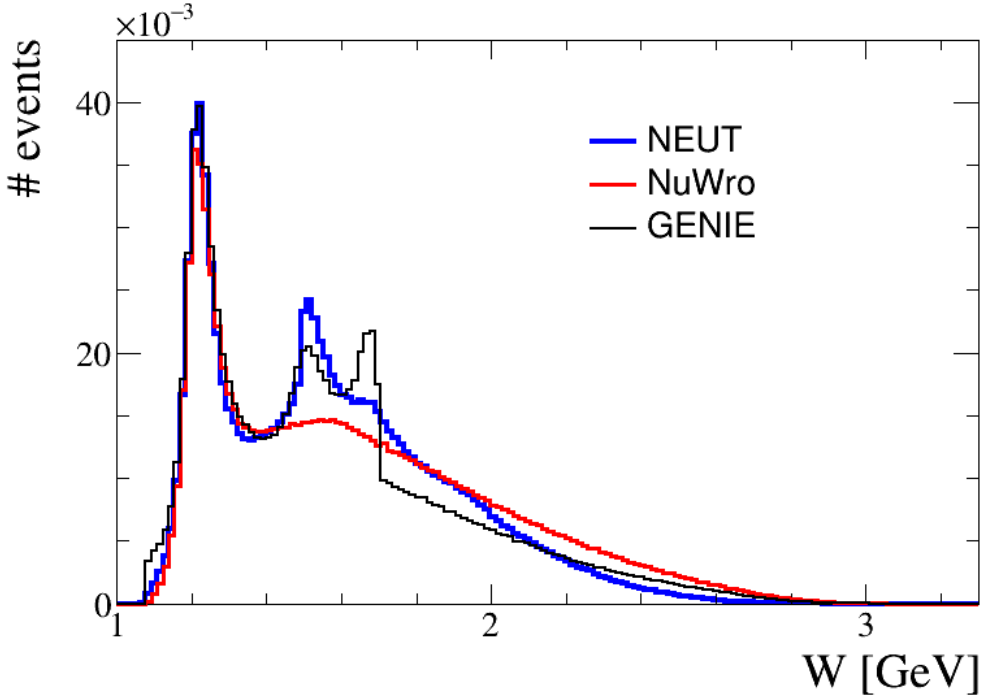
> - **CC DIS+Res only**
> - **W>1.7 GeV cut**
> - **Normalized by area**

W distributions
H_2O, E_ν=4.0 GeV

Neutrino

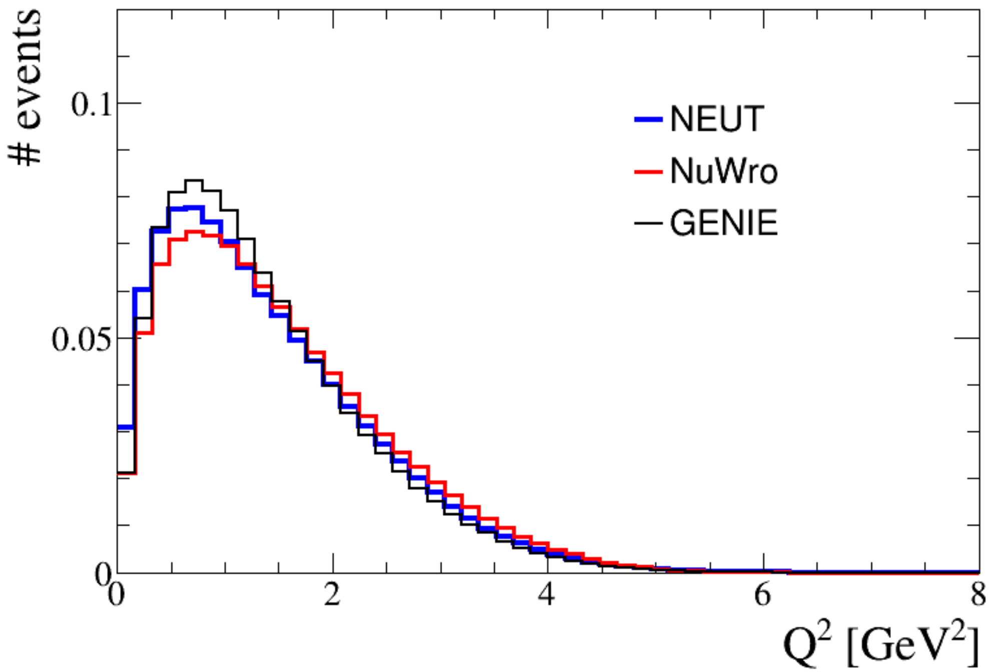


Anti-neutrino

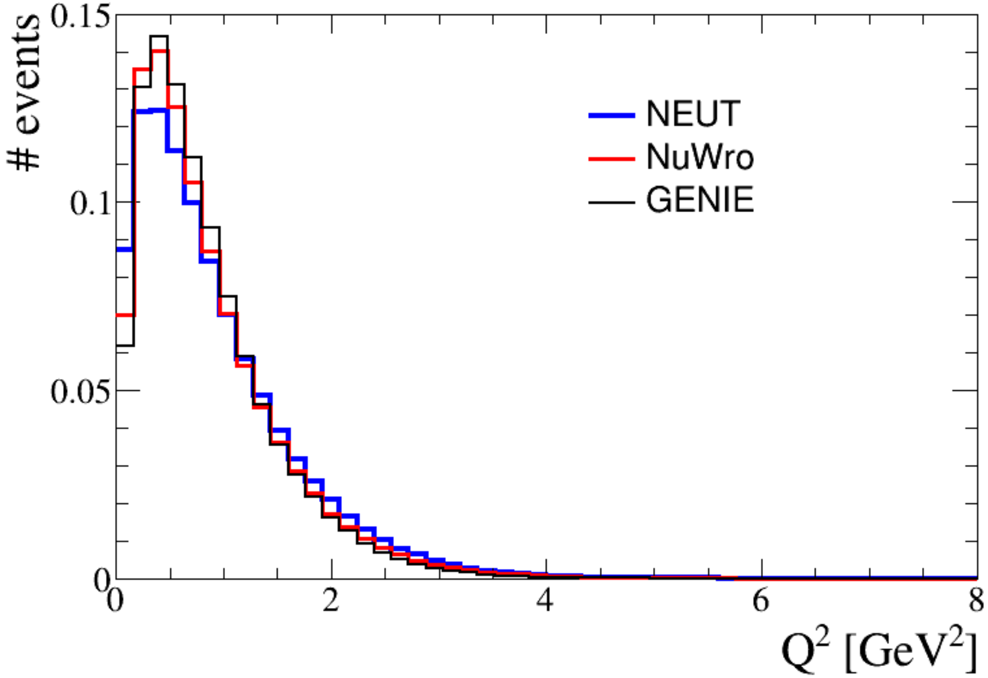


Q^2 distributions
H_2O, E_ν=4.0 GeV

Neutrino

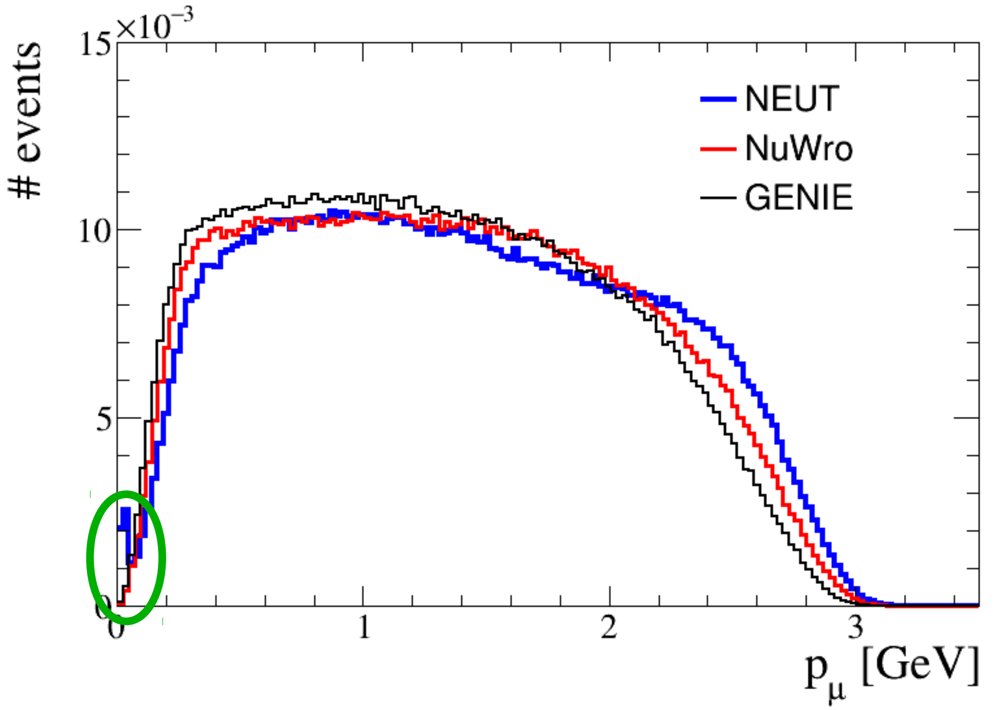


Anti-neutrino

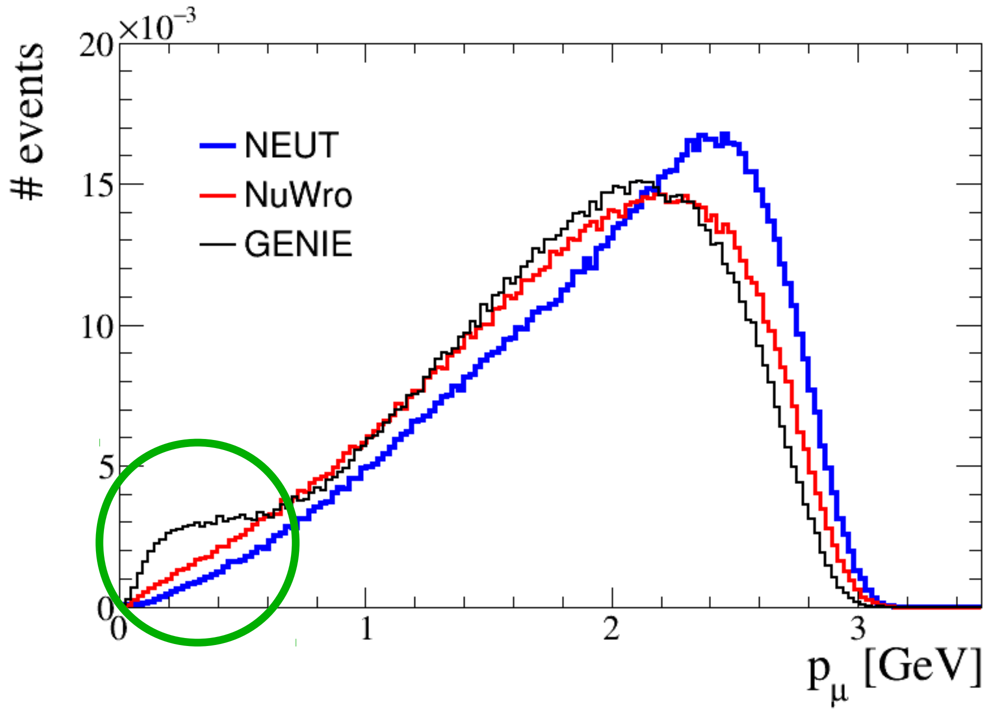


Lepton momentum
H_2O, E_ν=4.0 GeV

Neutrino

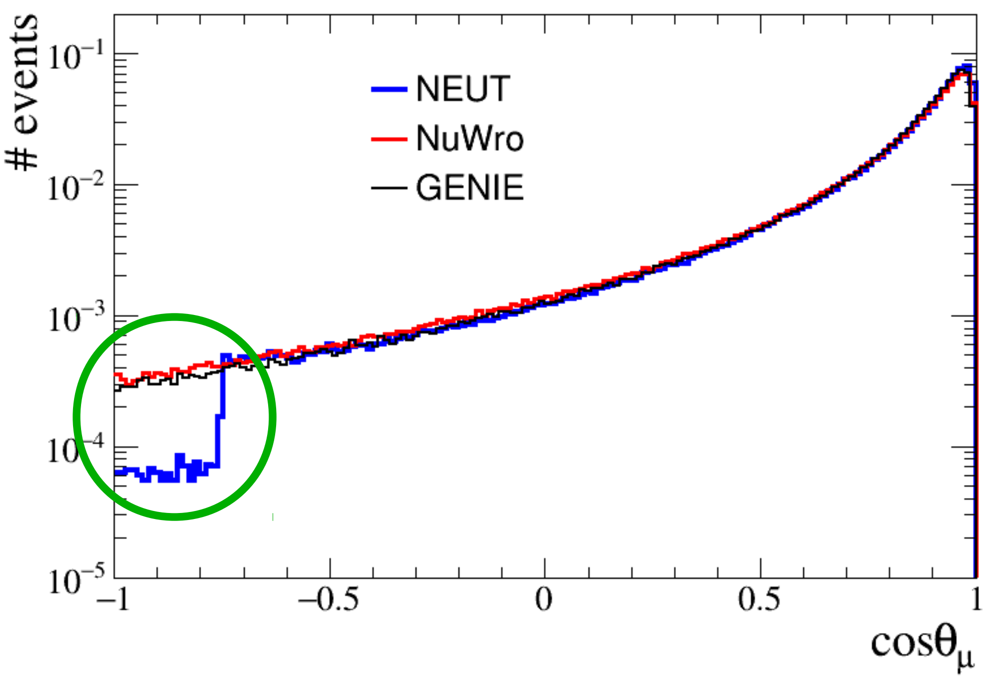


Anti-neutrino

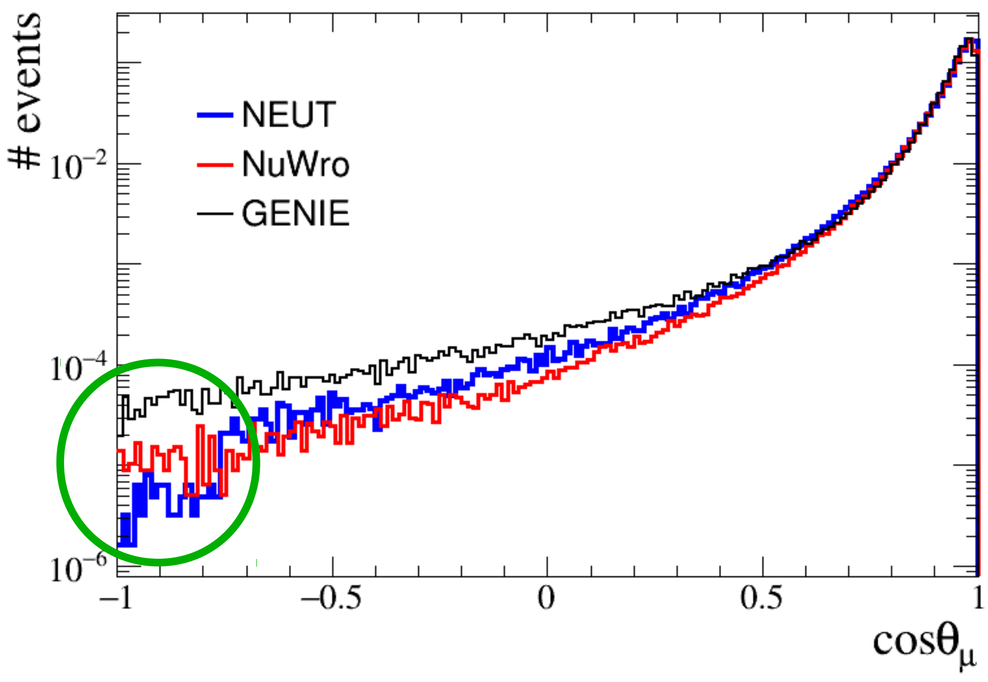


Lepton angle
H_2O, E_ν=4.0 GeV

Neutrino

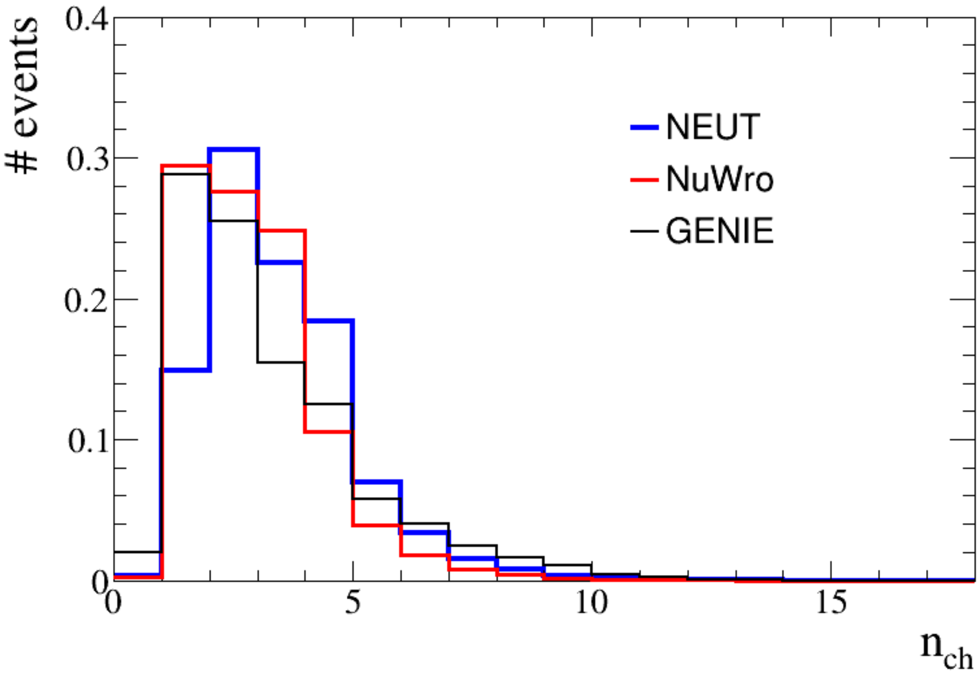


Anti-neutrino



Charged hadron multiplicities
H_2O, E_ν=4.0 GeV

Neutrino



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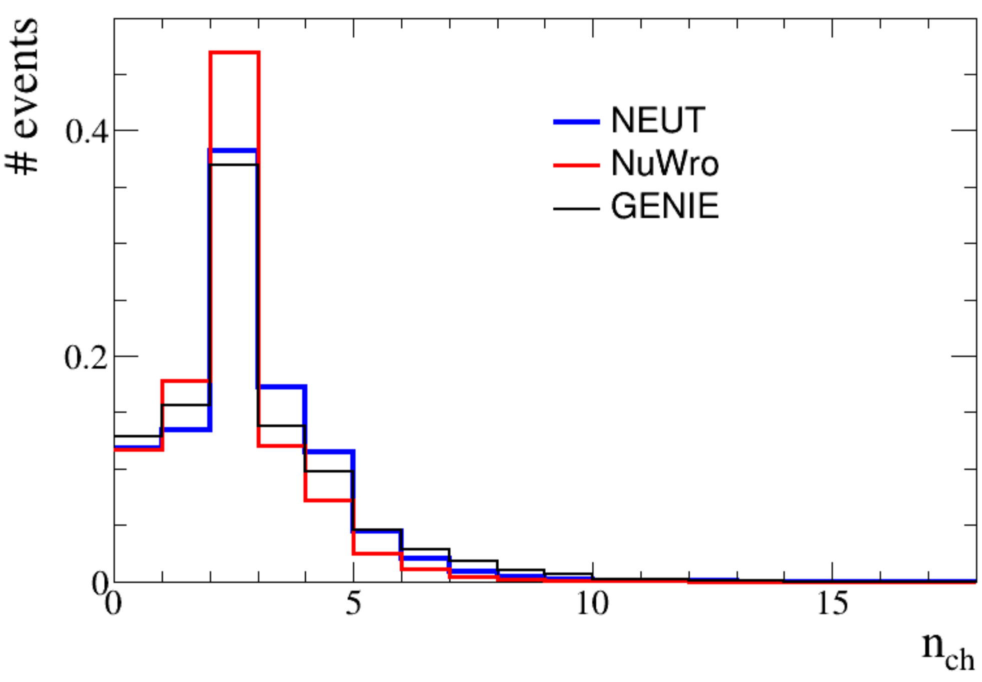
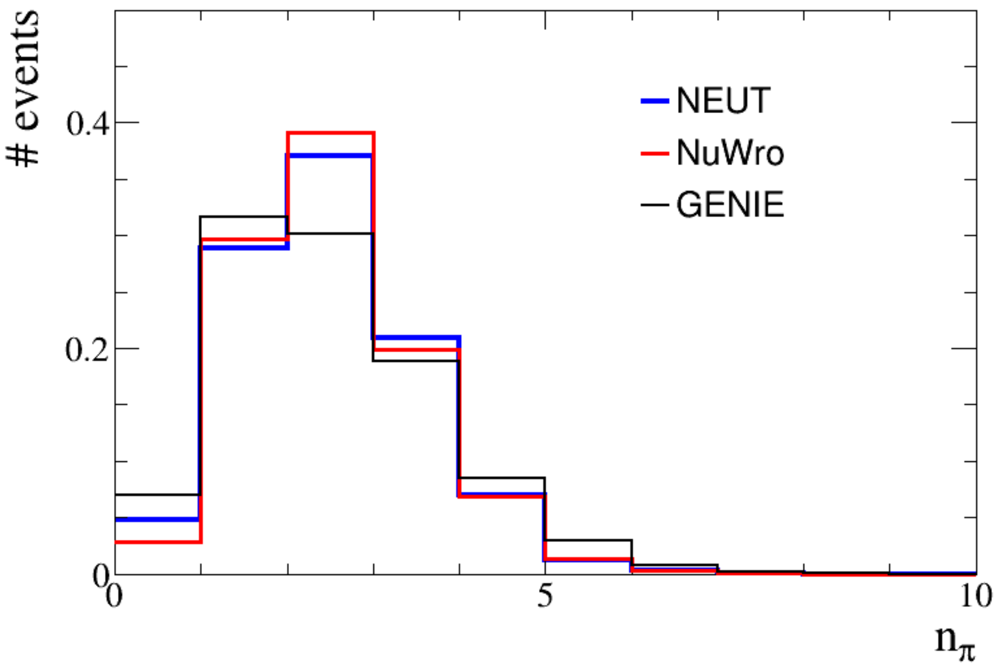
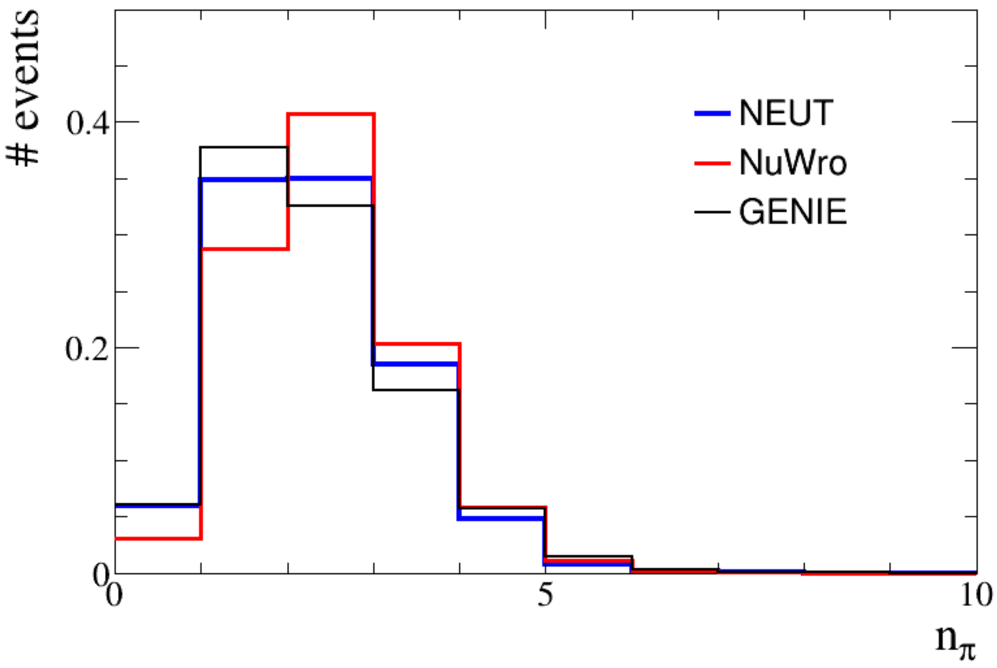


Pion multiplicities
H_2O, E_ν=4.0 GeV

Neutrino

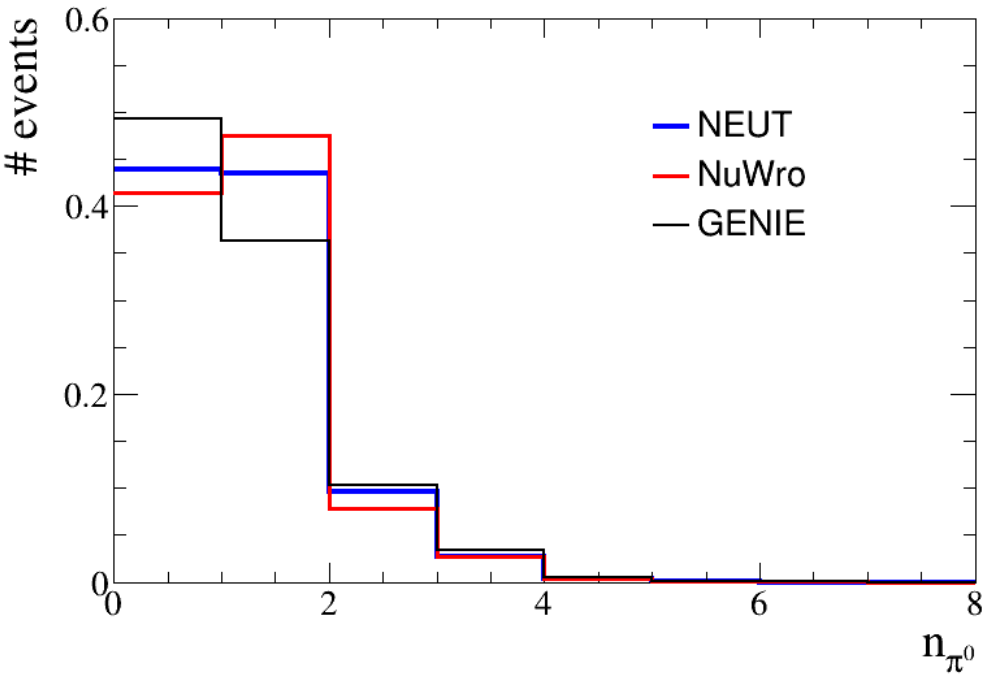


Anti-neutrino

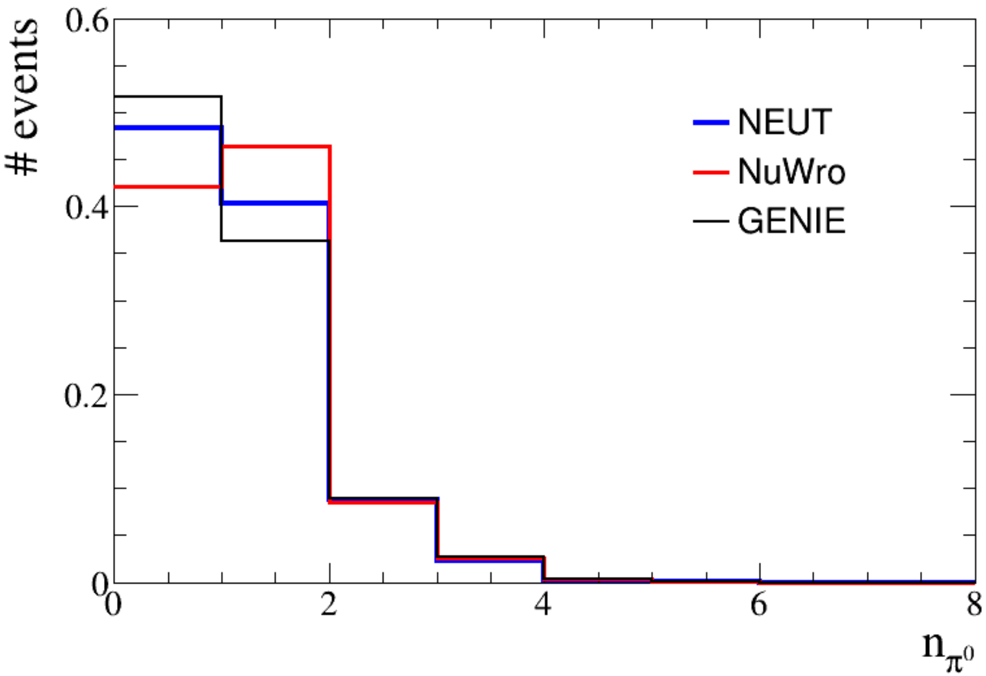


Neutral pion multiplicities
H_2O, E_ν=4.0 GeV

Neutrino



Anti-neutrino



BACKUP

Bodek-Yang corrections
Relations between structure functions

The problem is, which scaling variable (x or ξ) to use in those relations?

NEUT does:

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

GENIE does:

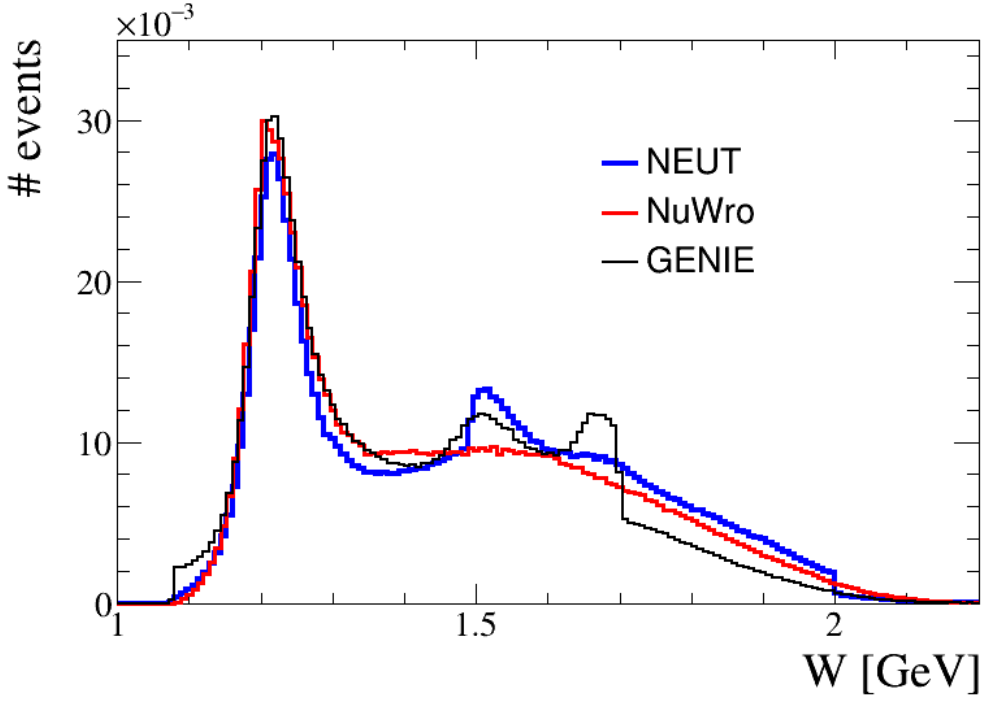
$$\begin{cases} F_1(x,Q^2)=\frac{1}{2\boldsymbol{\xi}}F_2(x,Q^2)\times\left(\frac{1+4M^2\boldsymbol{\xi}^2/Q^2}{1+R(\boldsymbol{x},Q^2)}\right) \\ F_3(x,Q^2)=\frac{\boldsymbol{x}F_3(x,Q^2)}{\boldsymbol{\xi}} \\ F_5(x,Q^2)=\frac{F_5(x,Q^2)}{\boldsymbol{\xi}} \end{cases}$$

NuWro does:
(GRV 94)

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

W distributions
CH, E_ν=2.0 GeV

Neutrino



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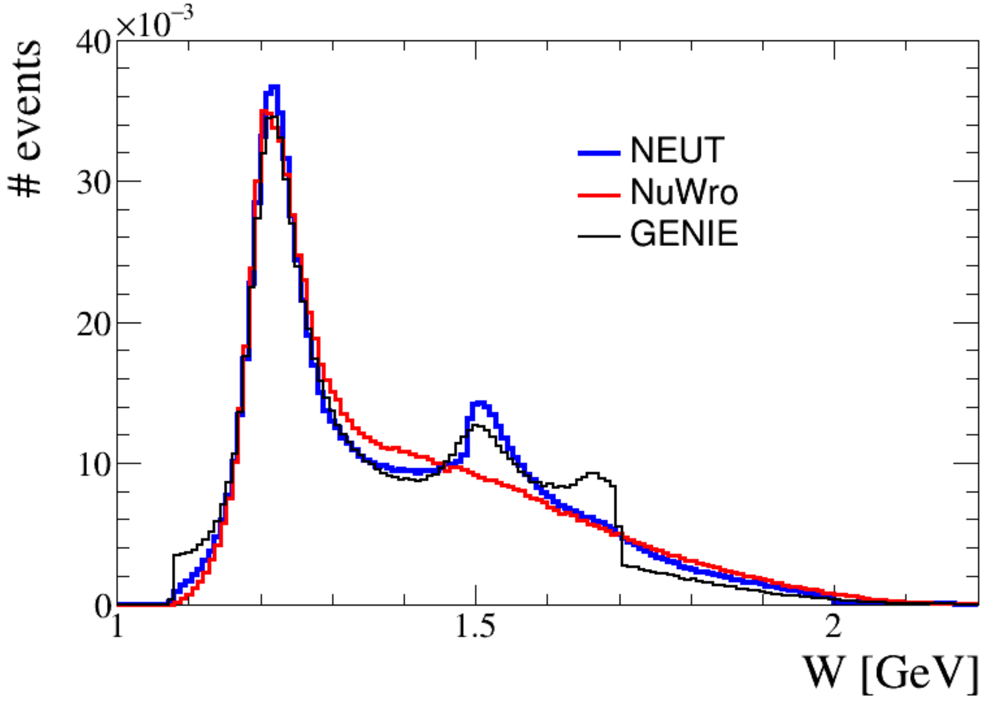
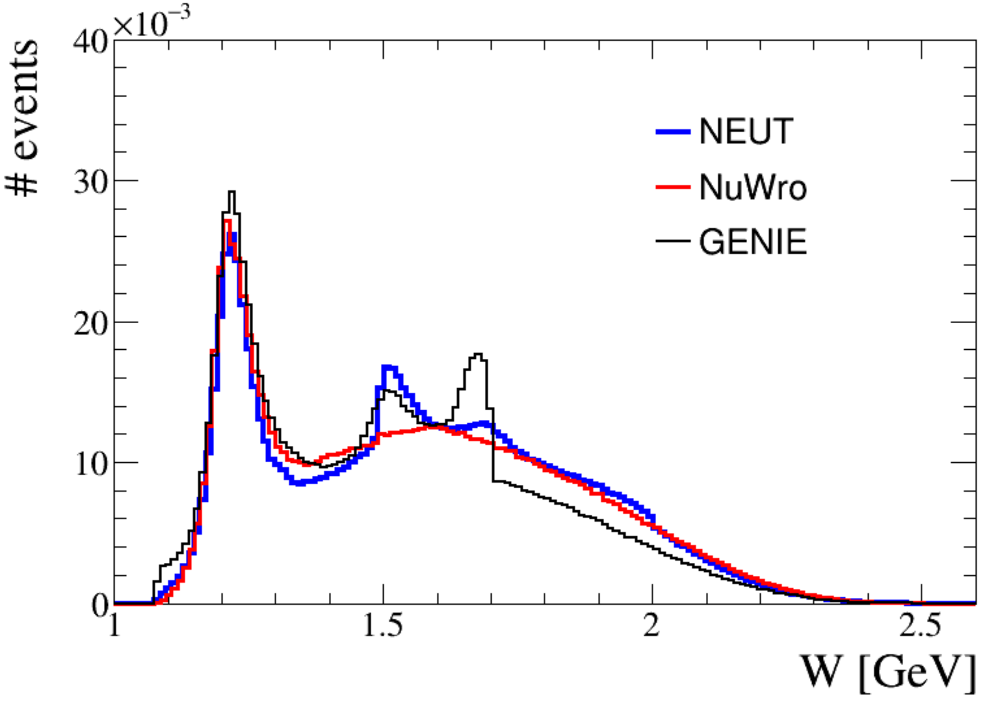


W distributions
Ar, E_ν=2.5 GeV

Neutrino



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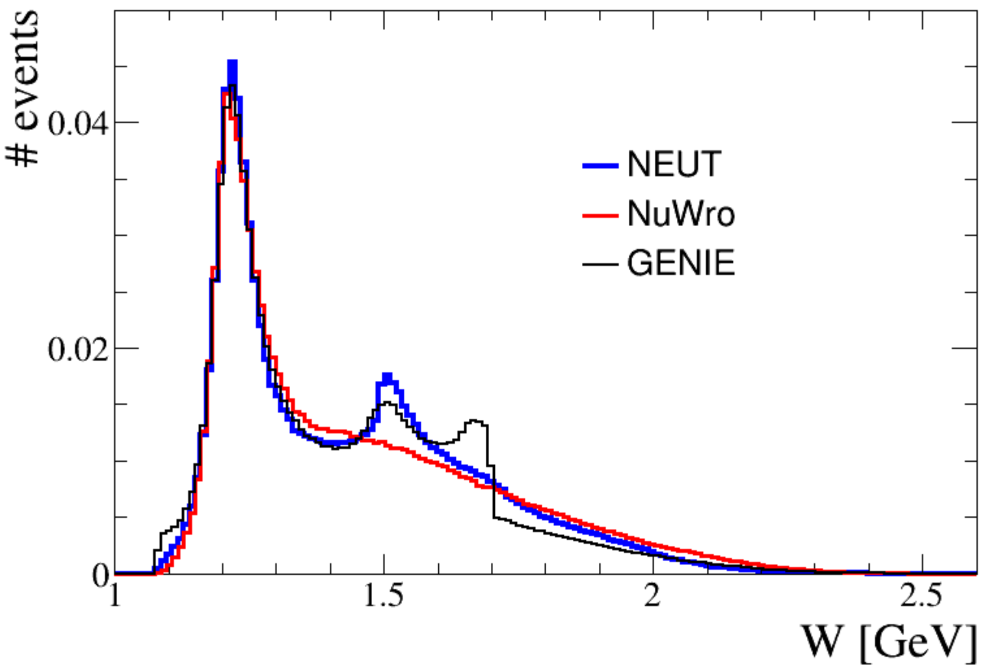
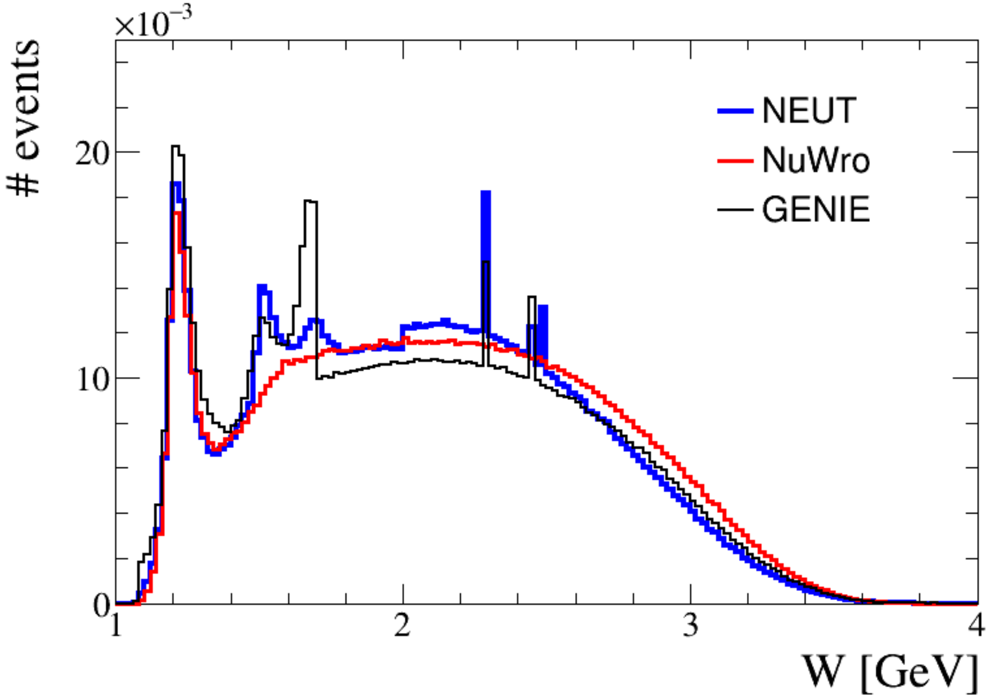


W distributions
Fe, E_ν=6.0 GeV

Neutrino



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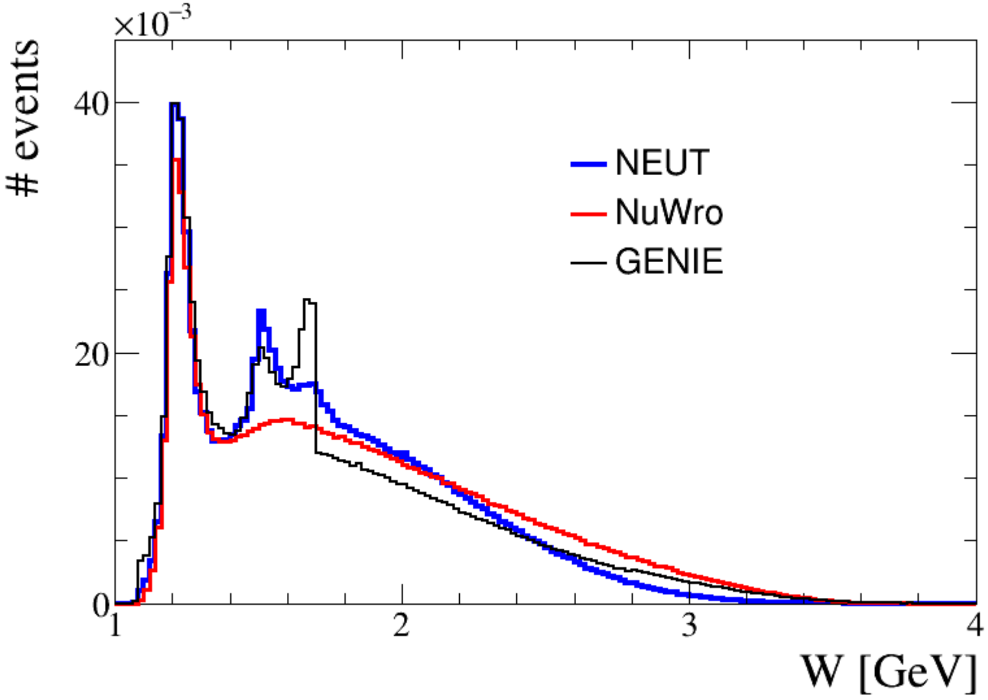
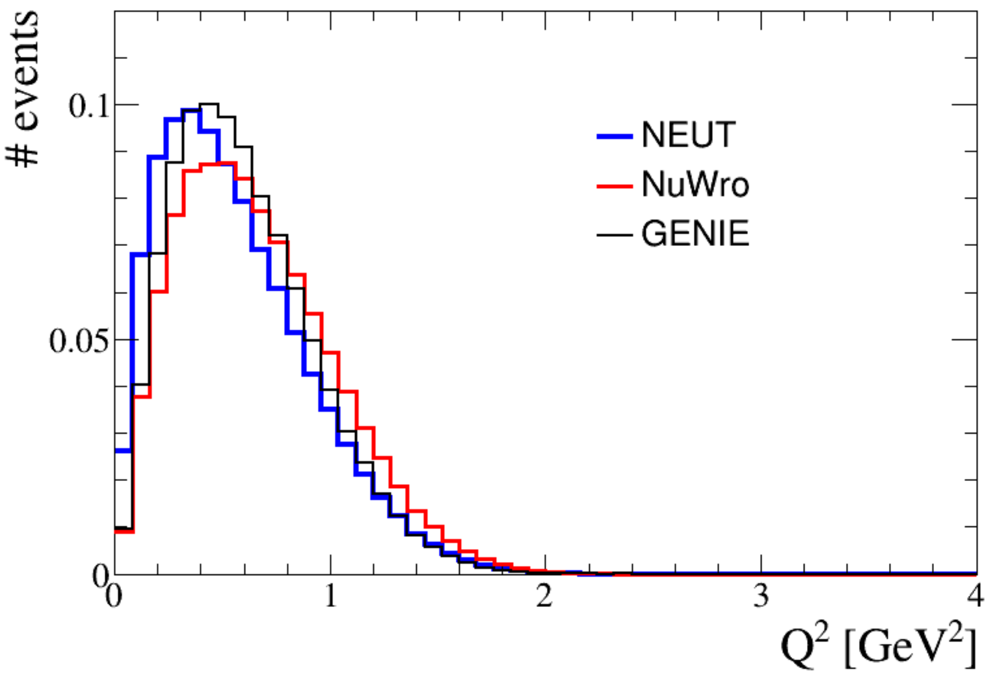
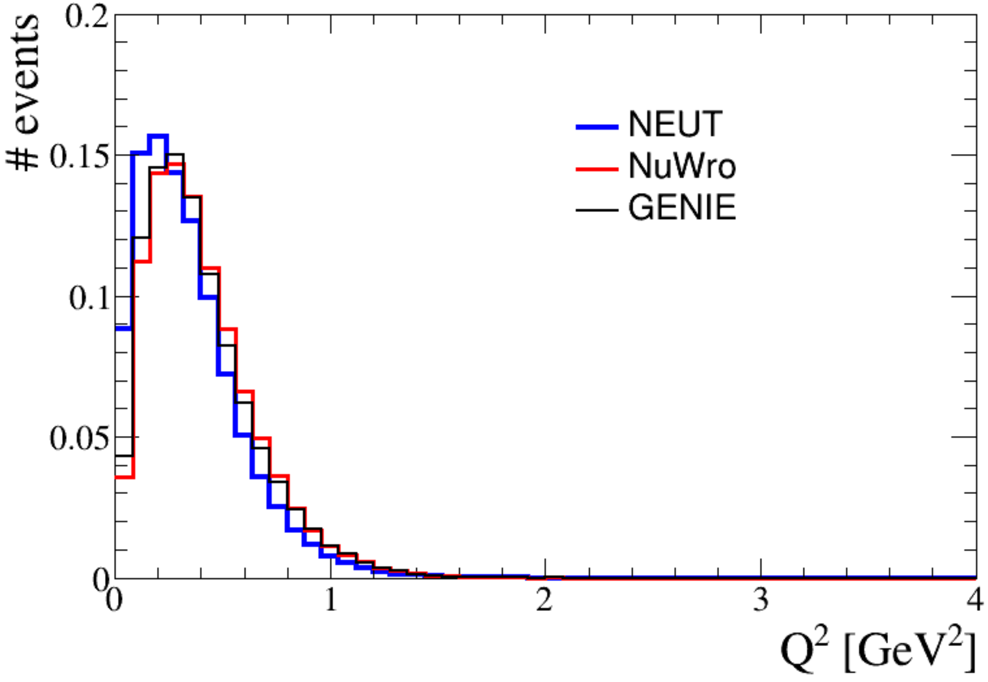


Q^2 distributions
CH, E_ν=2.0 GeV

Neutrino

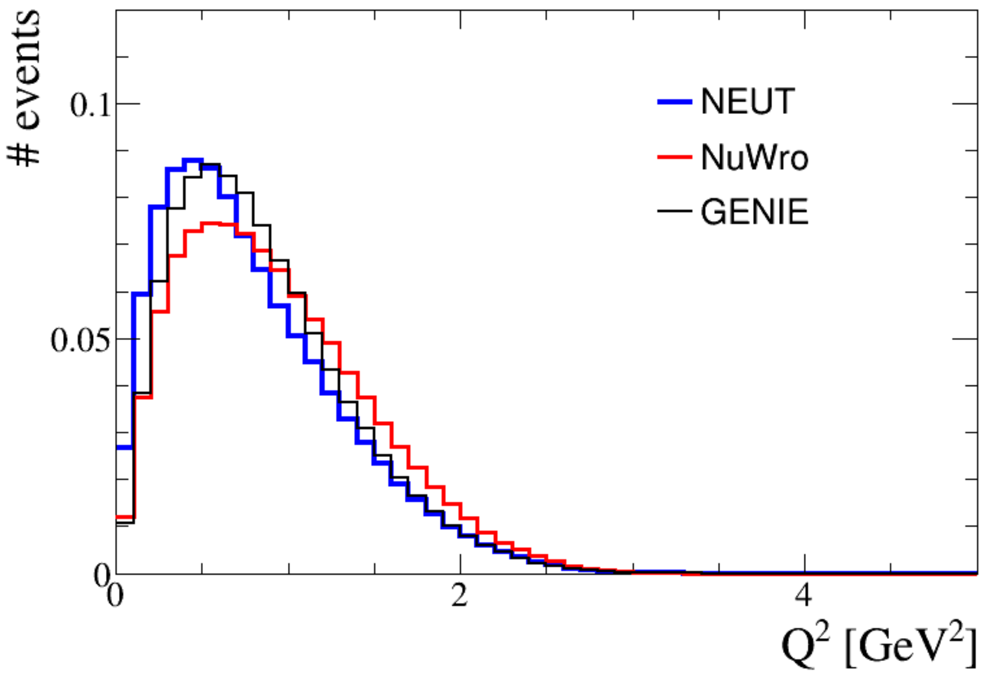


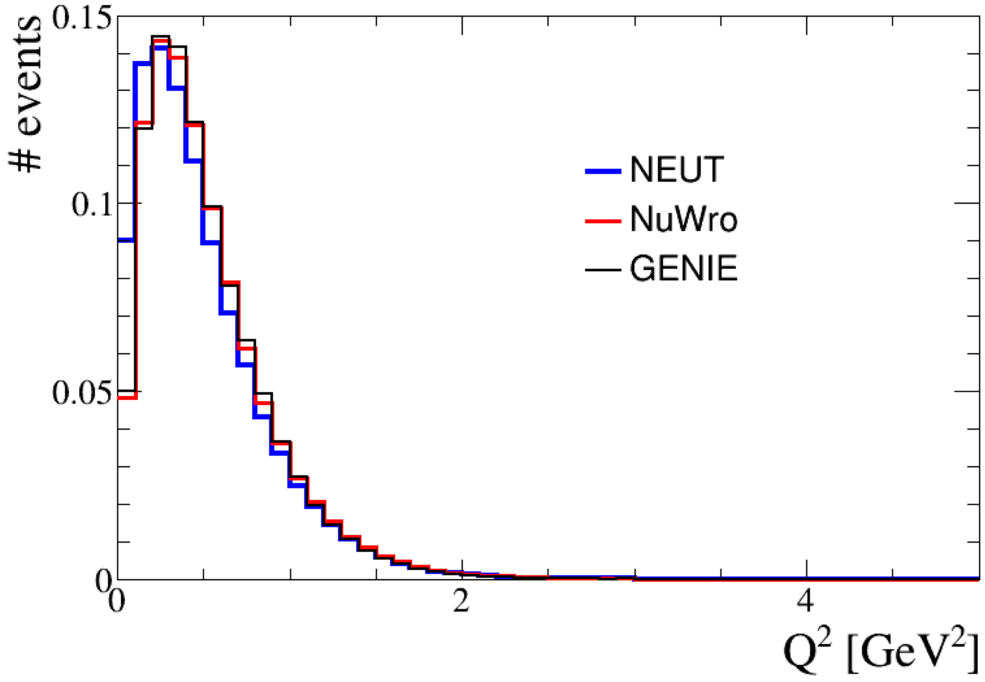
Anti-neutrino



Q^2 distributions
Ar, E_ν=2.5 GeV

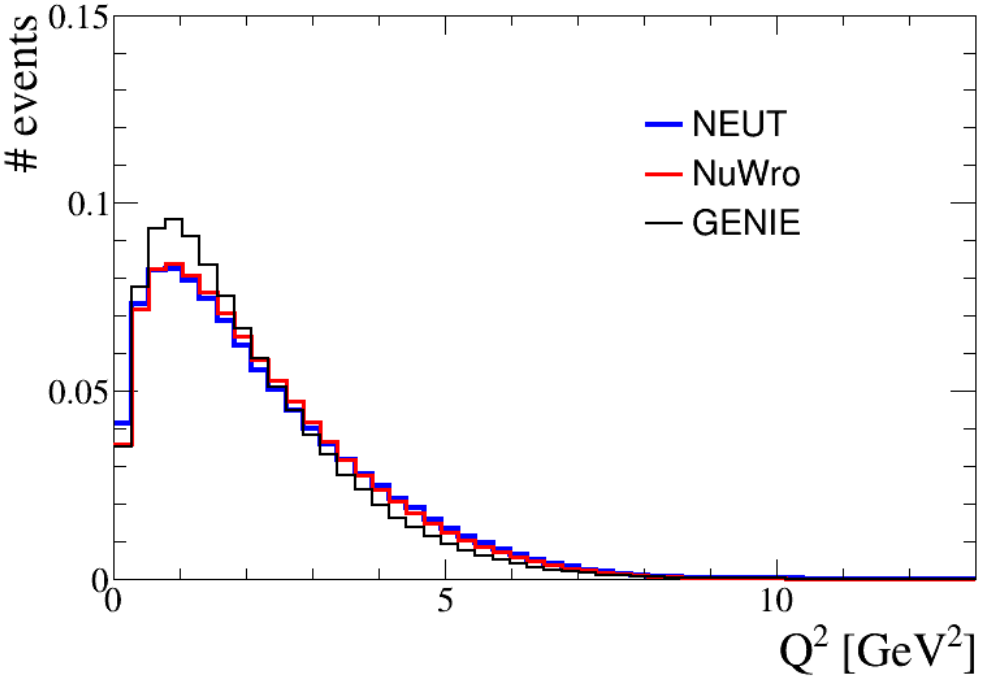
Neutrino	Anti-neutrino



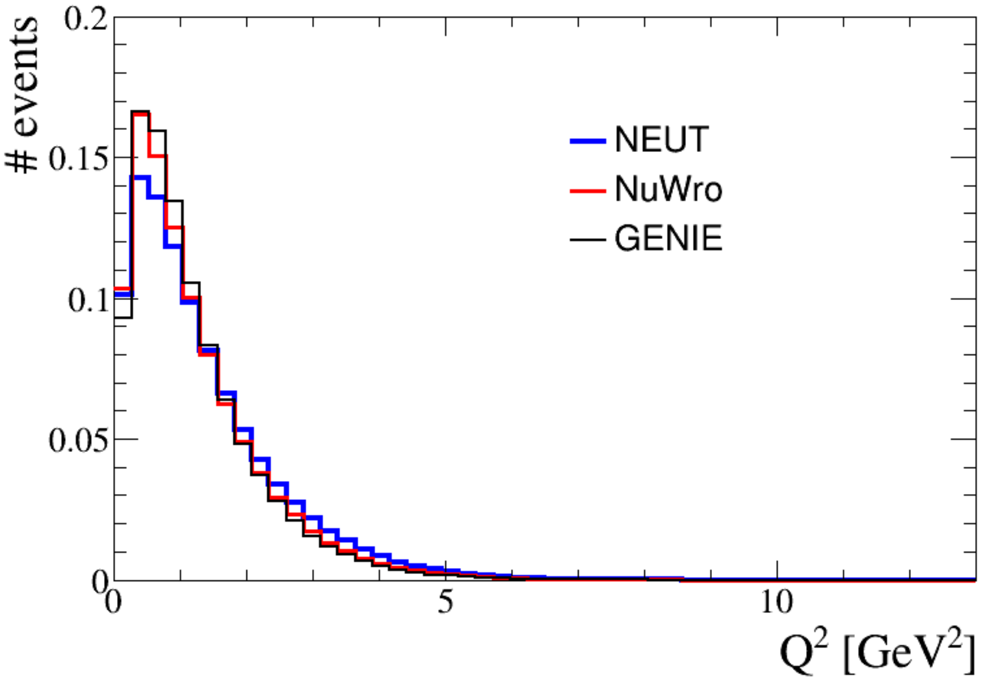


Q^2 distributions
Fe, E_ν=6.0 GeV

Neutrino

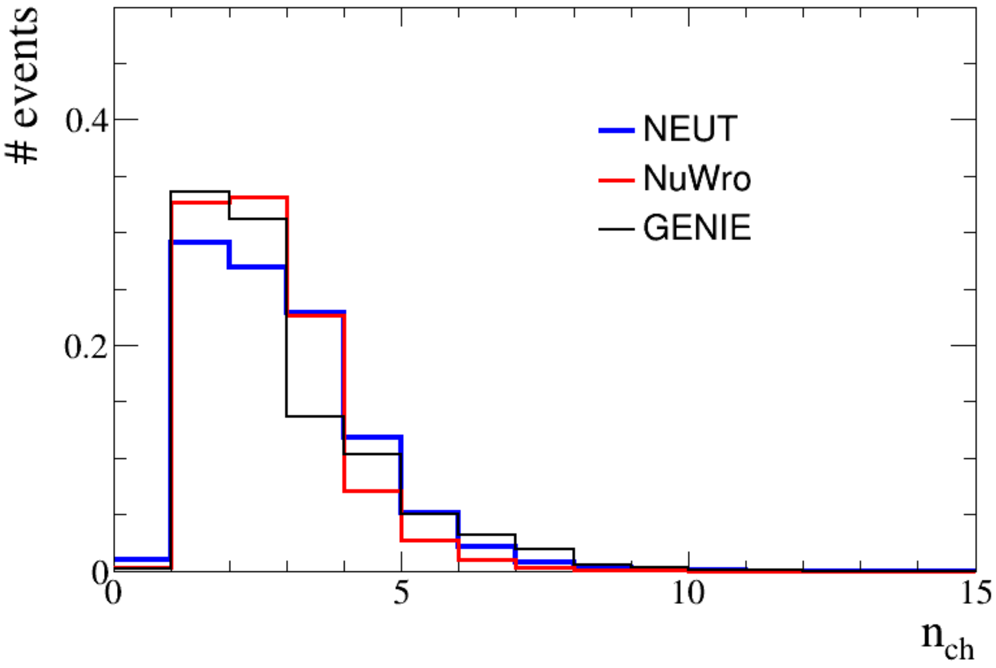


Anti-neutrino

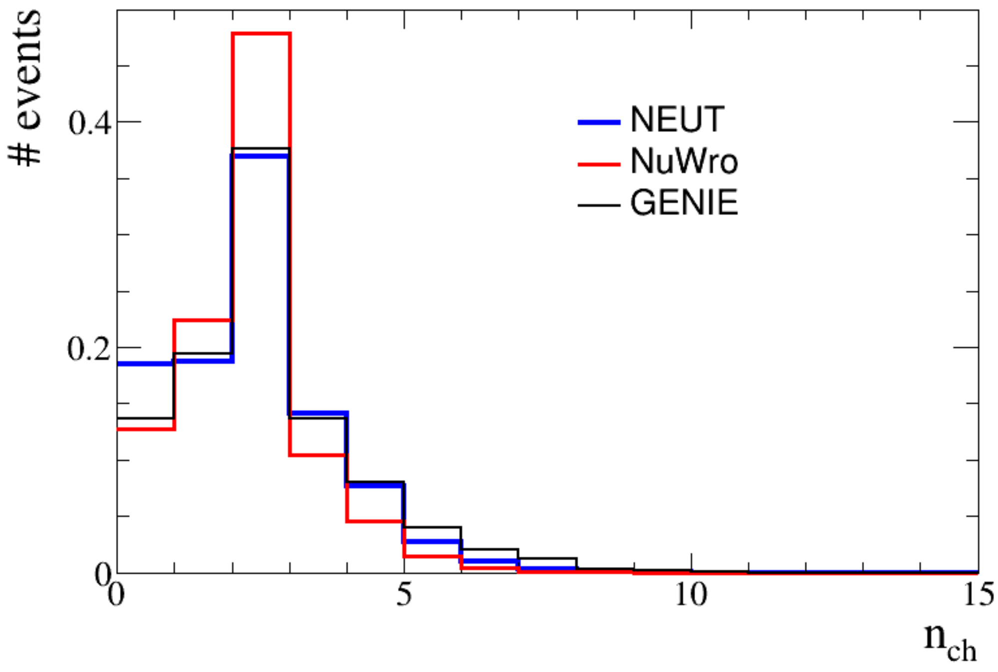


Charged hadron multiplicities
CH, E_ν=2.0 GeV

Neutrino

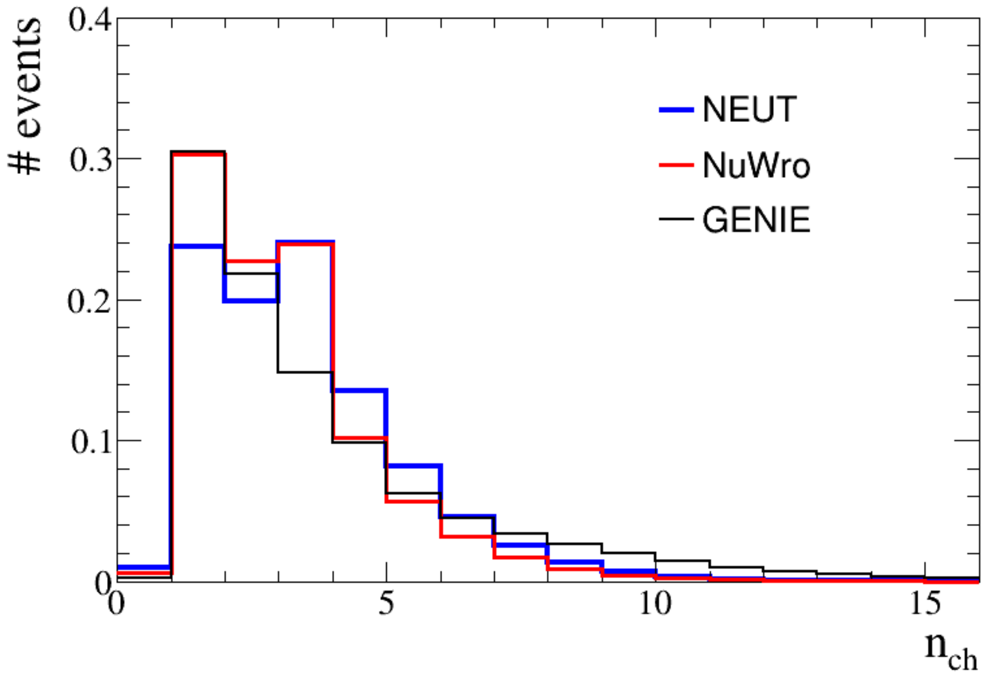


Anti-neutrino

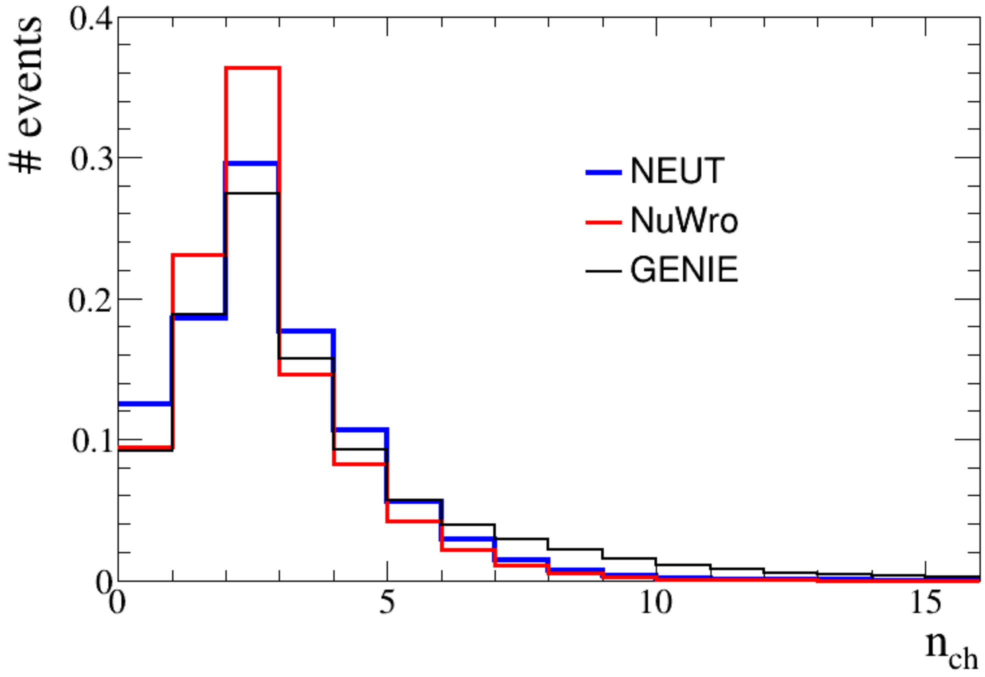


Charged hadron multiplicities
Ar, E_{ν}=2.5 GeV

Neutrino

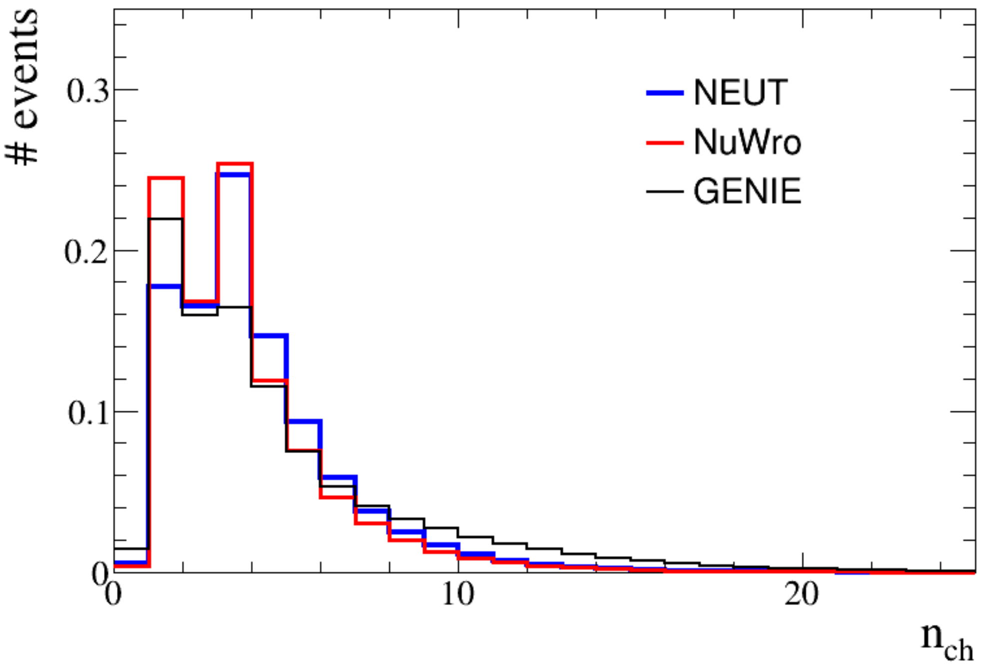


Anti-neutrino



Charged hadron multiplicities
Fe, E_ν=6.0 GeV

Neutrino



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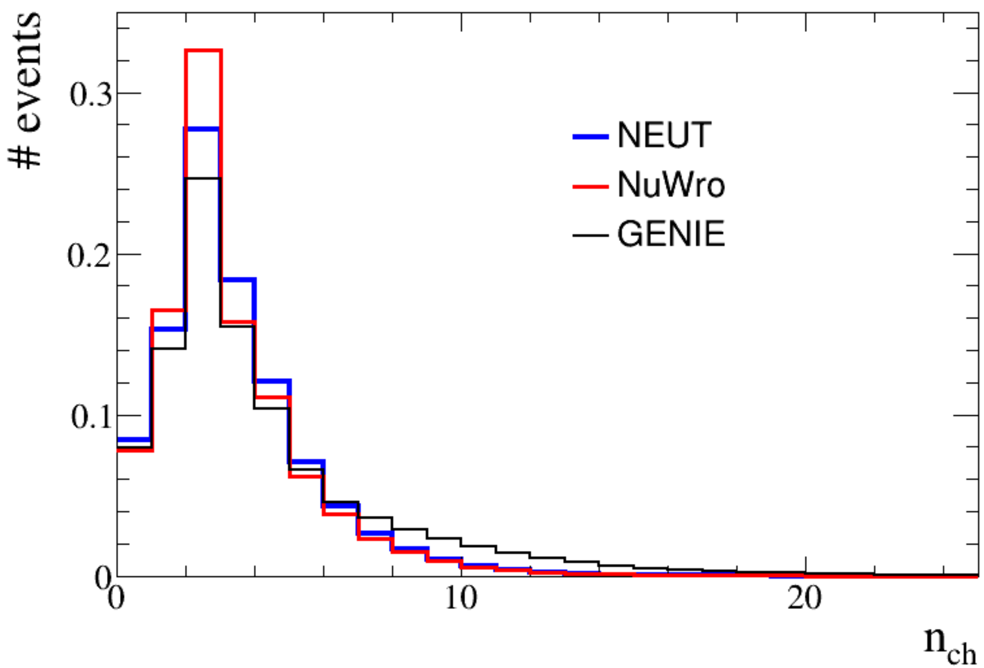
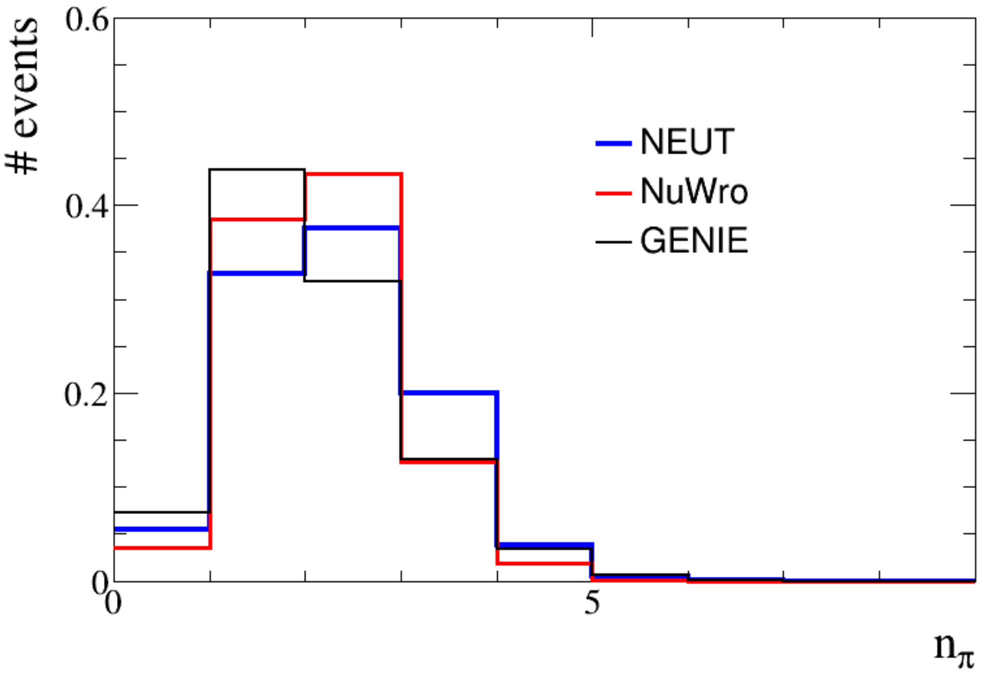


Pion multiplicities
CH, E_ν=2.0 GeV

Neutrino



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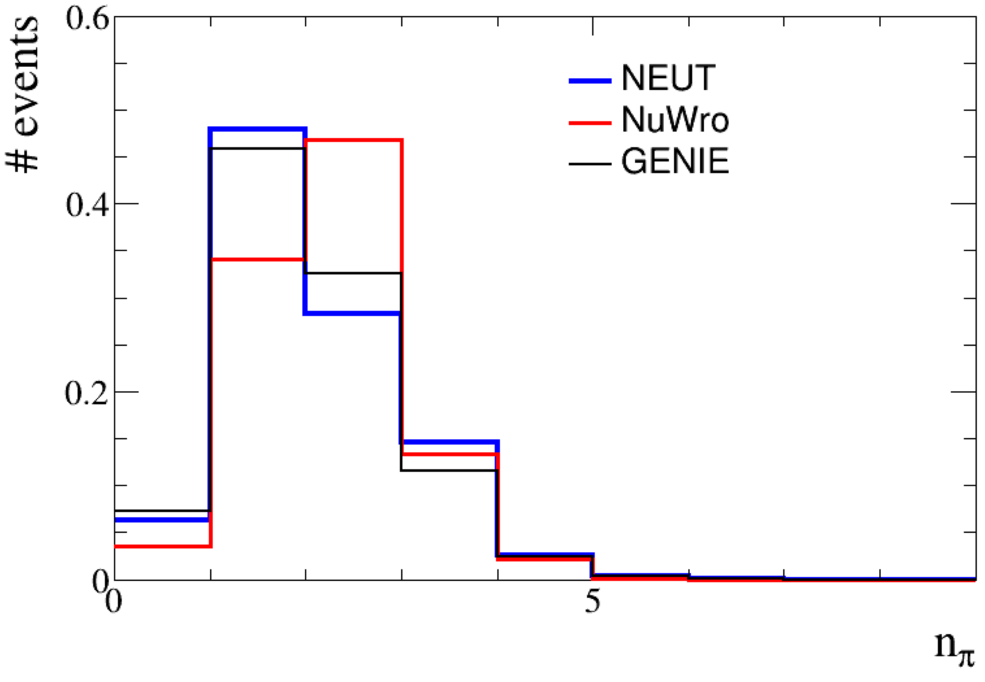
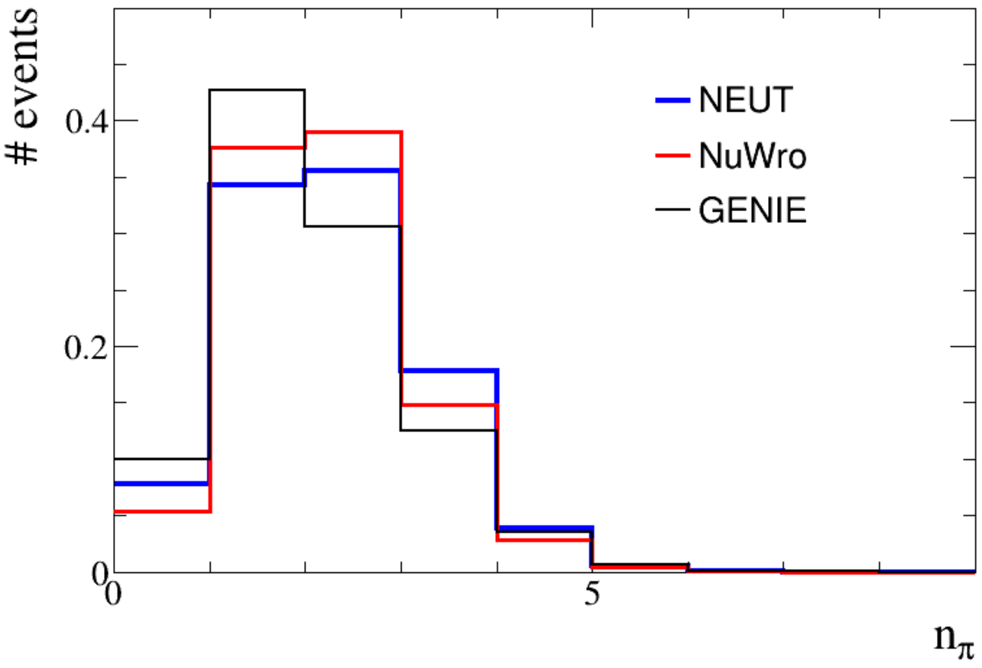
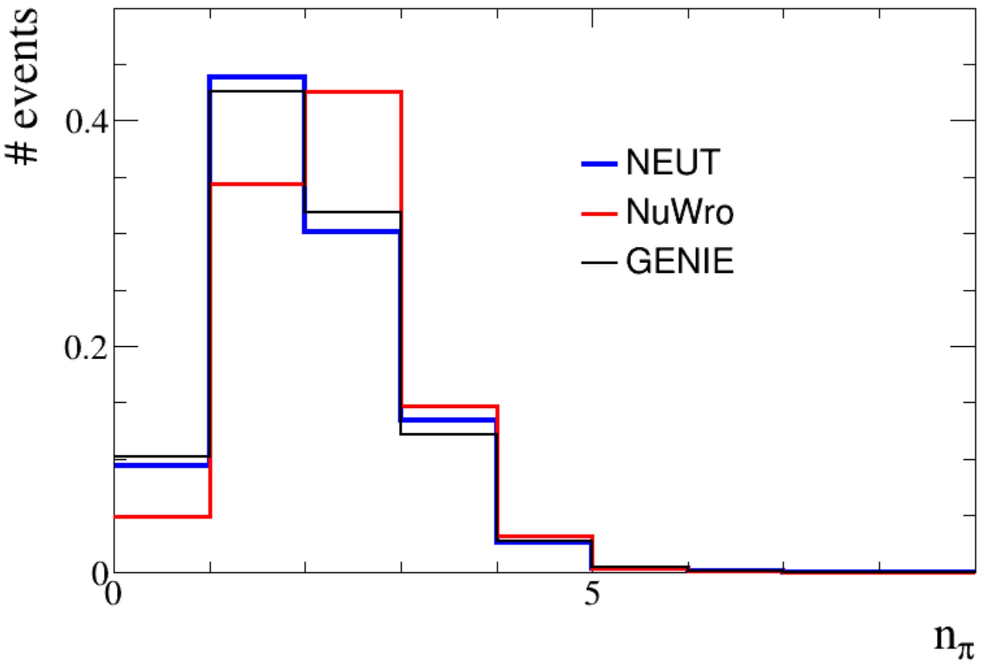


Pion multiplicities
Ar, E_ν=2.5 GeV

Neutrino

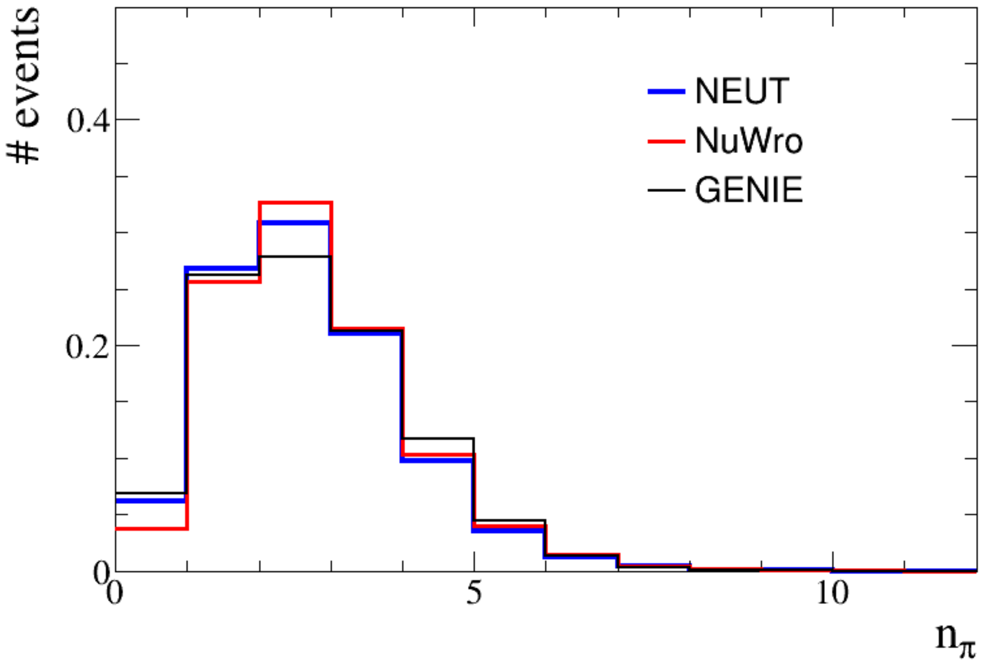


Anti-neutrino



Pion multiplicities
Fe, E_ν=6.0 GeV

Neutrino



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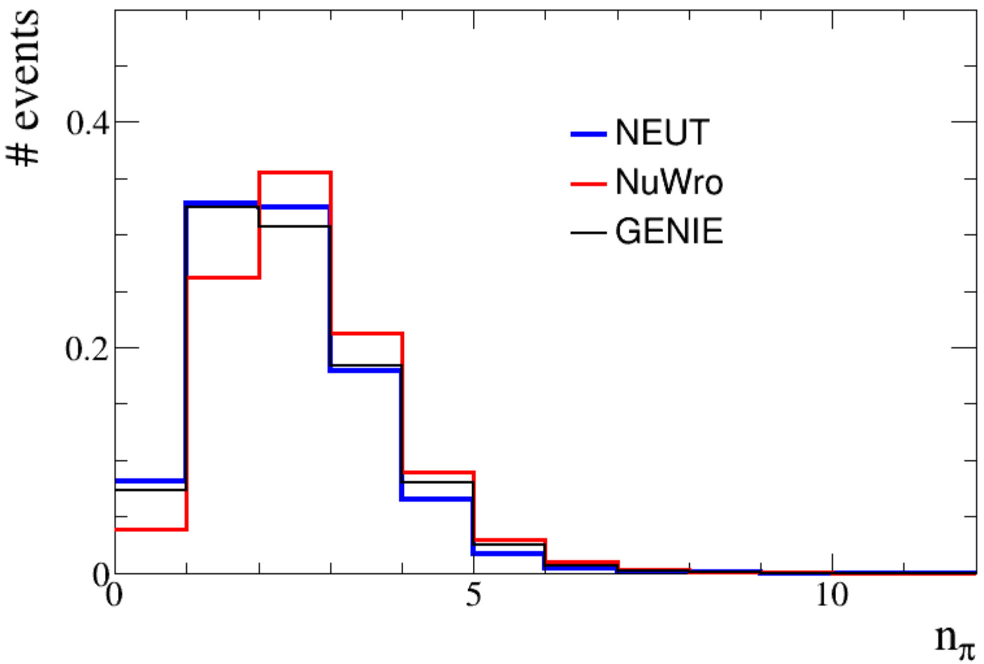
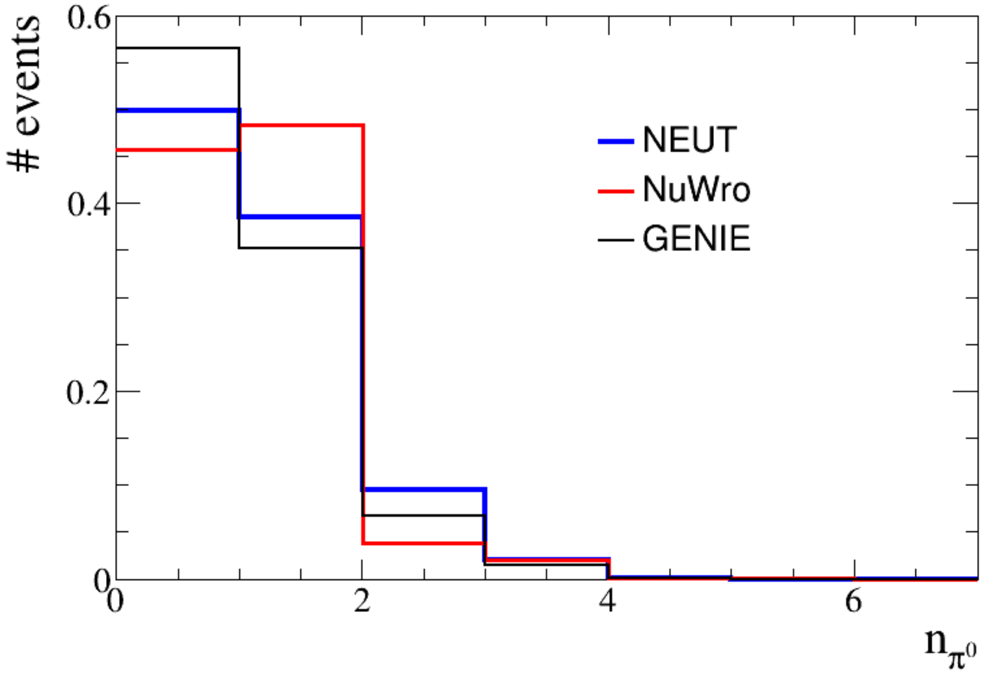
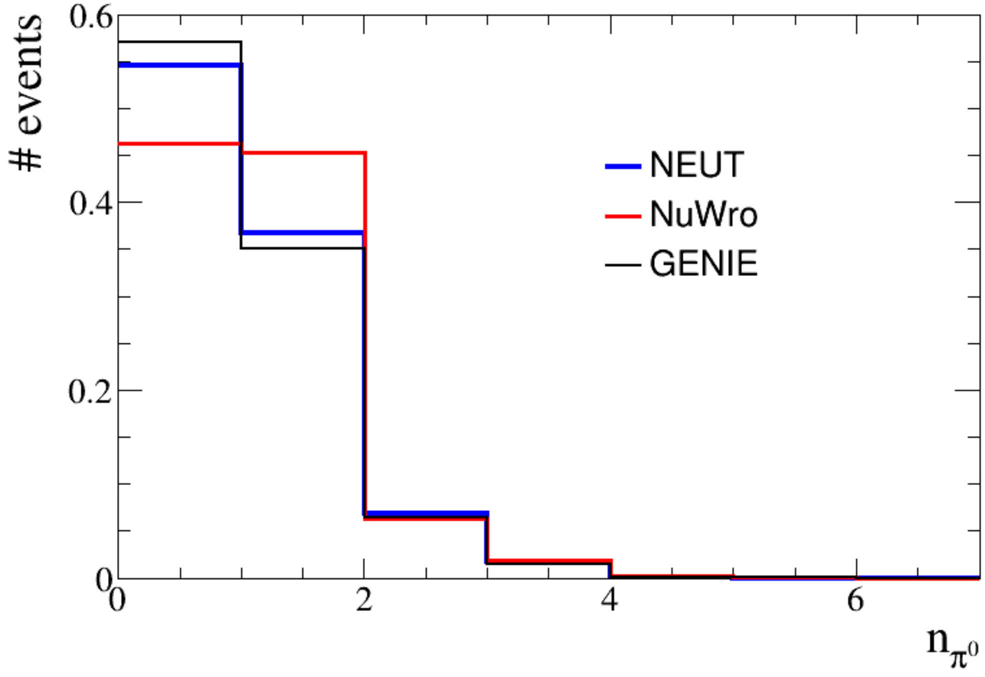


Neutral pion multiplicities
CH, E_ν=2.0 GeV

Neutrino

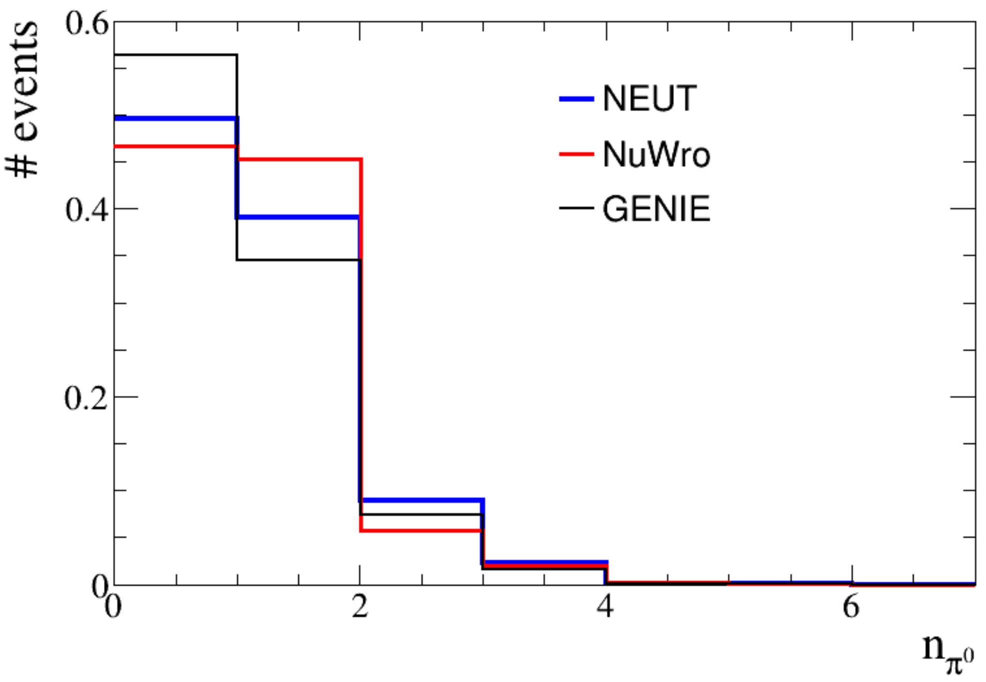


Anti-neutrino

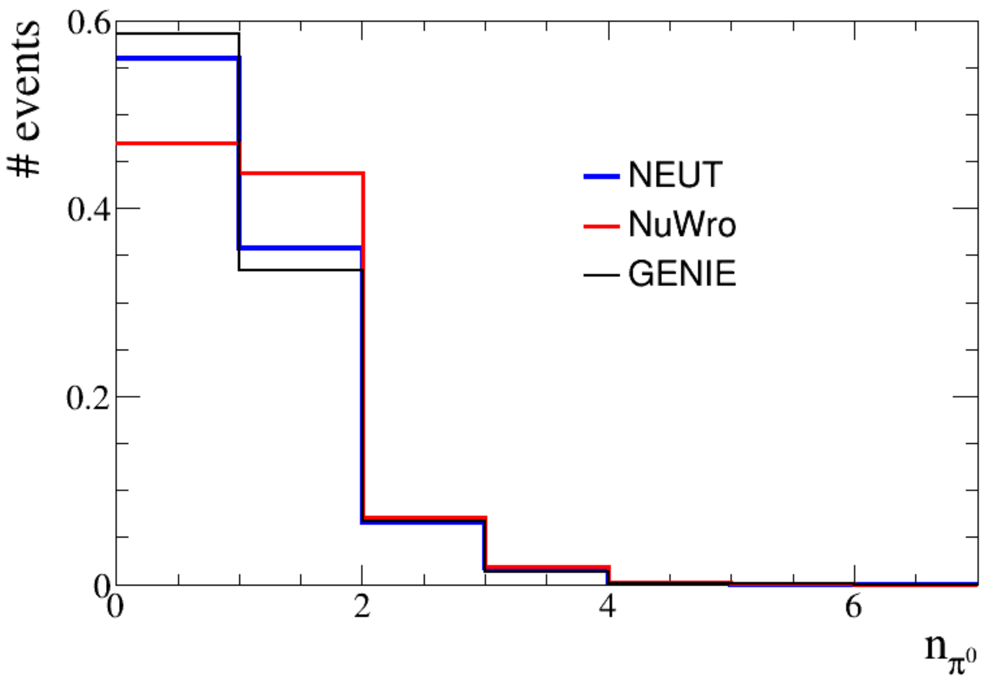


Neutral pion multiplicities
Ar, E_ν=2.5 GeV

Neutrino

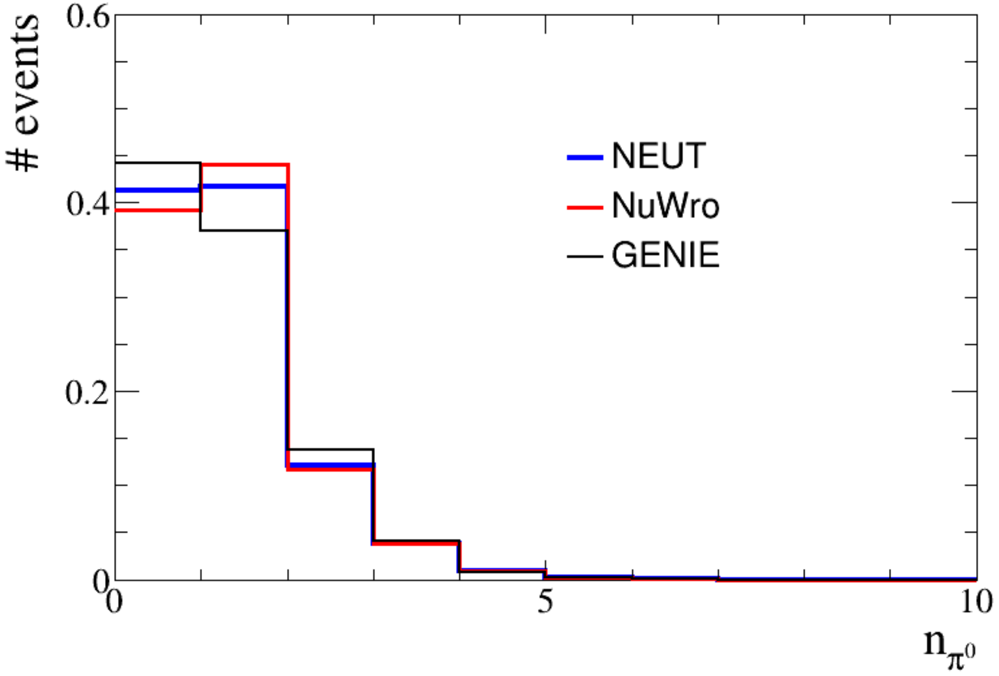


Anti-neutrino



Neutral pion multiplicities
Fe, E_ν=6.0 GeV

Neutrino



Anti-neutrino