NuSTEC workshop on Shallow- and Deep-Inelastic Scattering

DIS event generation in NEUT

C. Bronner
Kamioka Observatory, ICRR, Tokyo University

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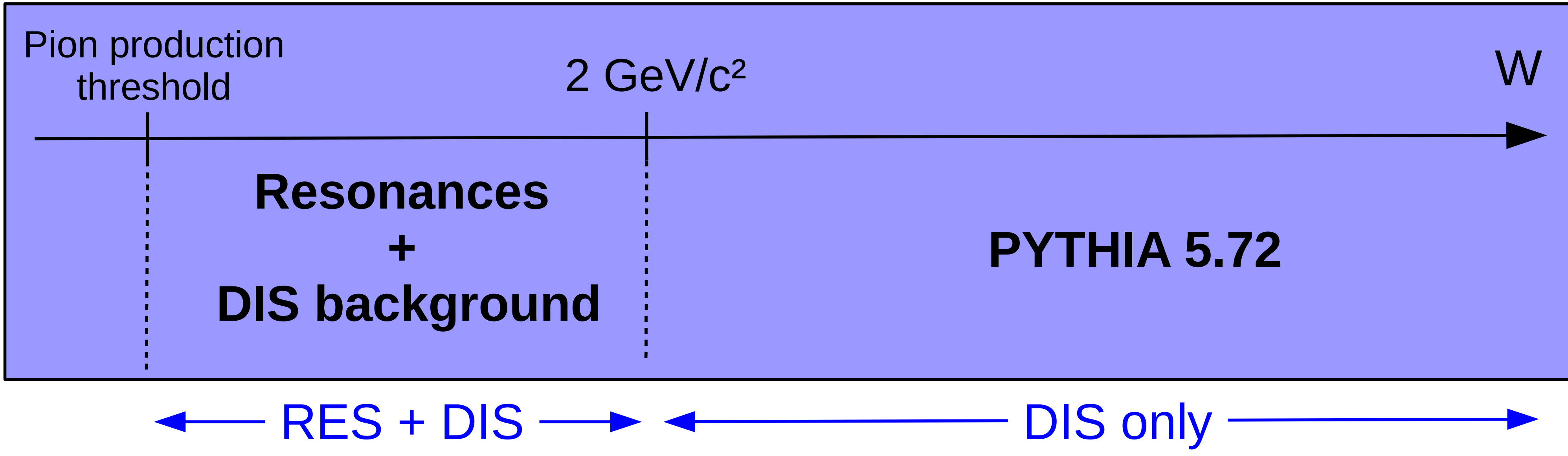
DIS modes in NEUT

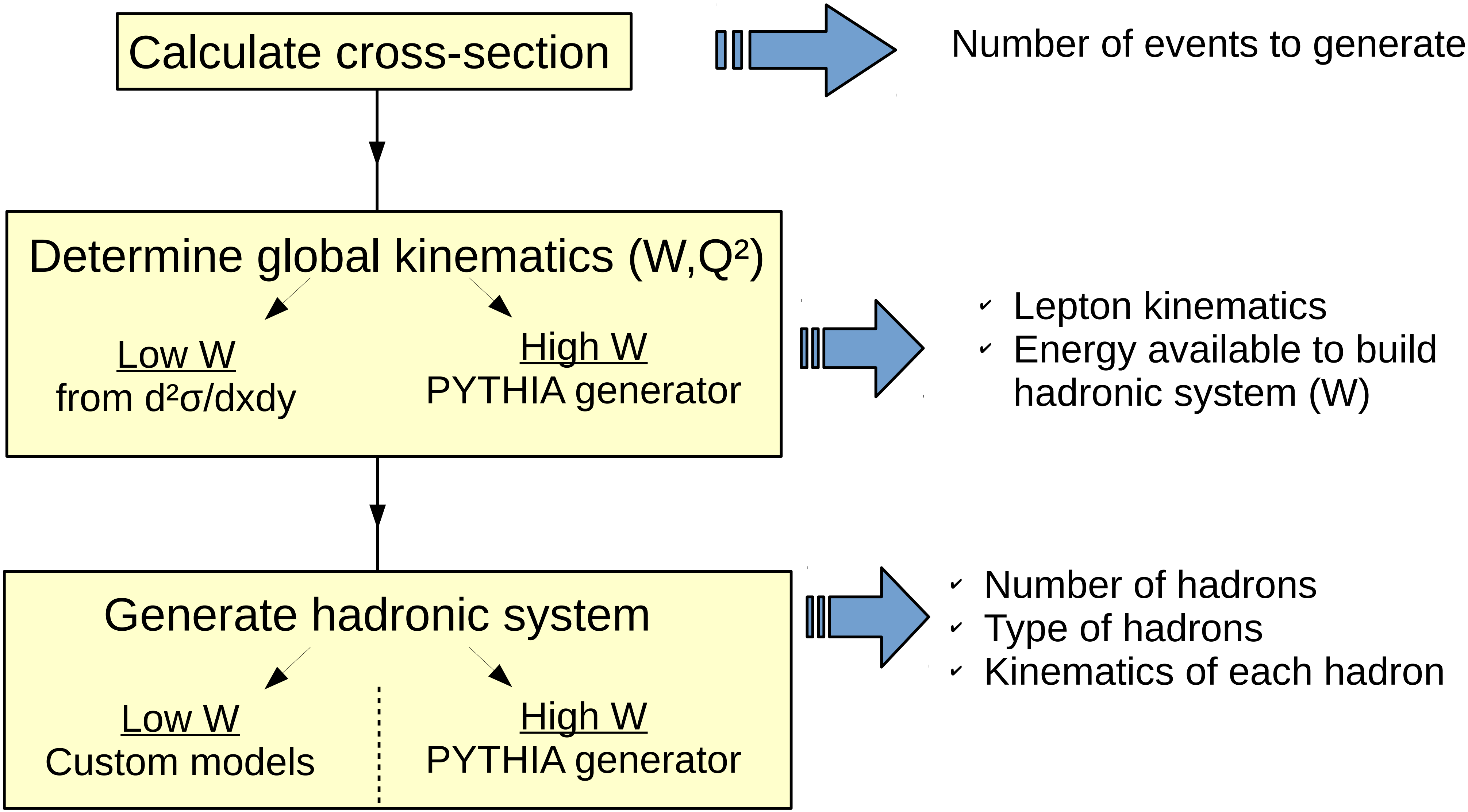
2 different DIS modes depending on the value of W



<u>W<2 GeV region:</u>

- Single particle production (lepton + baryon +X): resonances
- More than one particle (lepton + baryon +nX ,n≥2): custom DIS model “multi-pion” mode

DIS event generation



In practice for the high W mode, the event is generated with PYTHIA for a given energy and target nucleon until an event with W>2 GeV is obtained.

Cross-section calculation

- The DIS cross-section is computed by numerically integrating $d^2\sigma/dxdy$ over x an y

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2} \left\{ (y^2 x + \frac{m_\tau^2 y}{2E_\nu M_N}) F_1^{W^\pm} + \left[(1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{M_N x}{2E_\nu}) y \right] F_2^{W^\pm} \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M_N} \right] F_3^{W^\pm} + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M_N^2 x} F_4^{W^\pm} - \frac{m_\tau^2}{E_\nu M_N} F_5^{W^\pm} \right\} .$$

(From hep-ex/0208187, in the general case m_τ is replaced by the lepton mass)

- The part coming from values of x and y giving W>2 GeV gives the high W mode cross-section

- for values of x and y giving 1.3<W<2, the cross-section is multiplied by the fraction of events having more than 2 pions at this W to give the low W mode cross-section

Double differential cross-section calculation

- 5 structure functions needed for the double differential cross-section as a function of x and y.

- Calculate F2 and xF3 using Parton Distribution Functions
  PDFs: Bodek-Yang model from hep-ph/0508007
  (modified GRV98 LO)

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

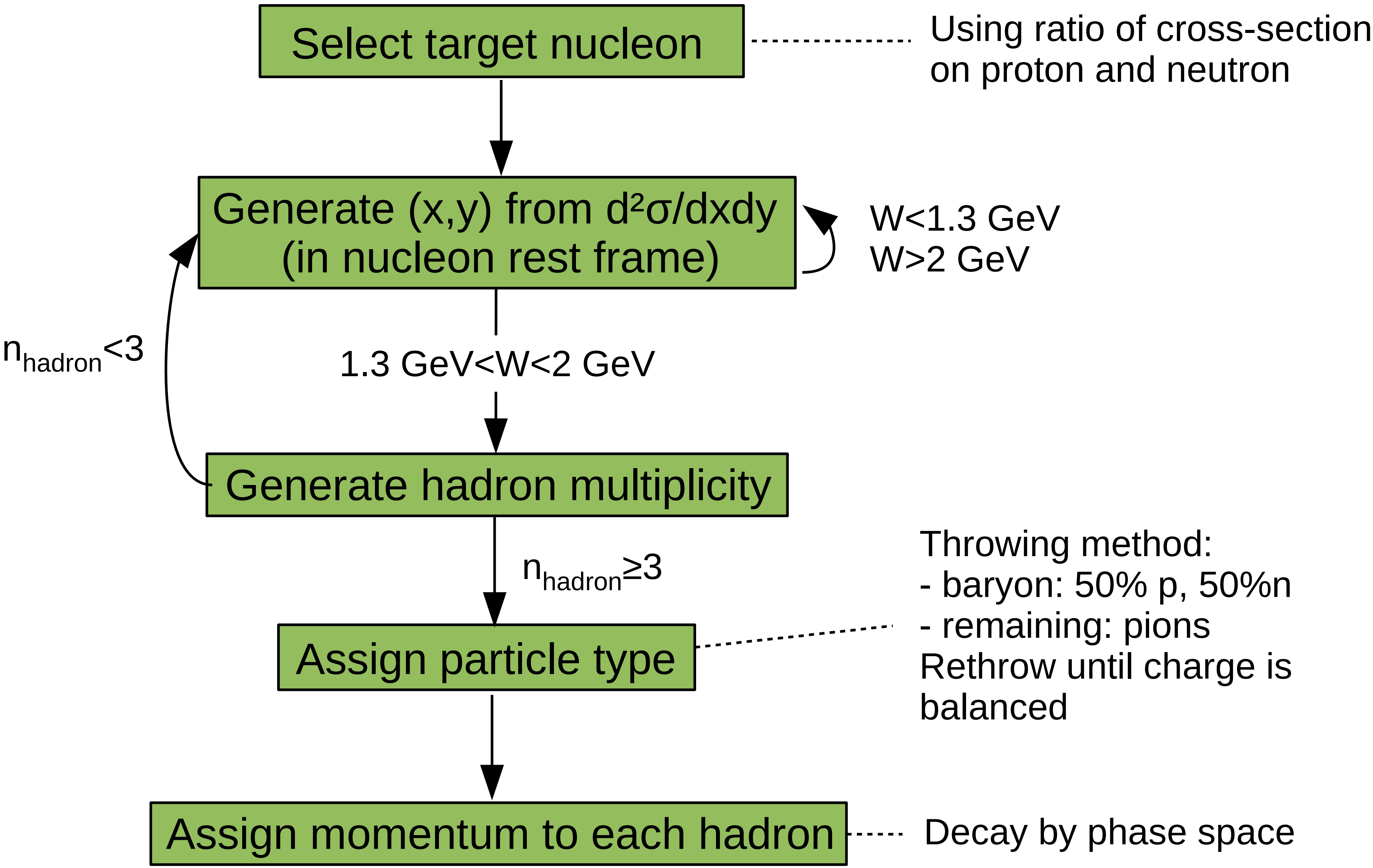
$$F_1(x,Q^2)=\frac{1}{2x}F_2(x,Q^2)\times\left(\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}\right)$$

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

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

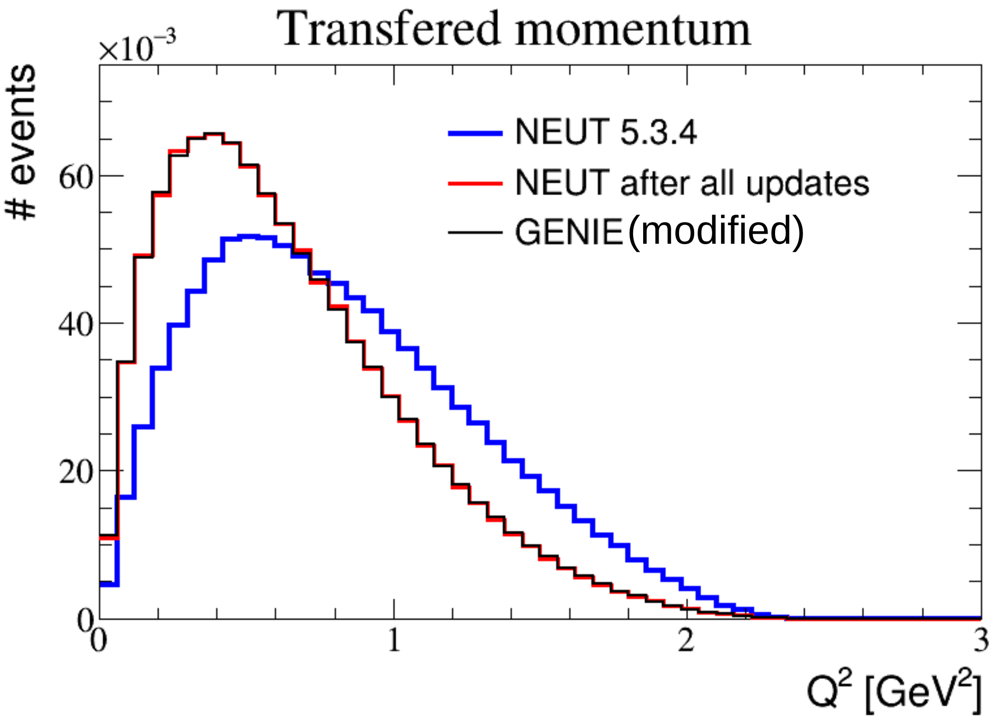
(Those relations are approximations, see for example S. Kretzer and M. H. Reno, hep-ph:0208187v1)

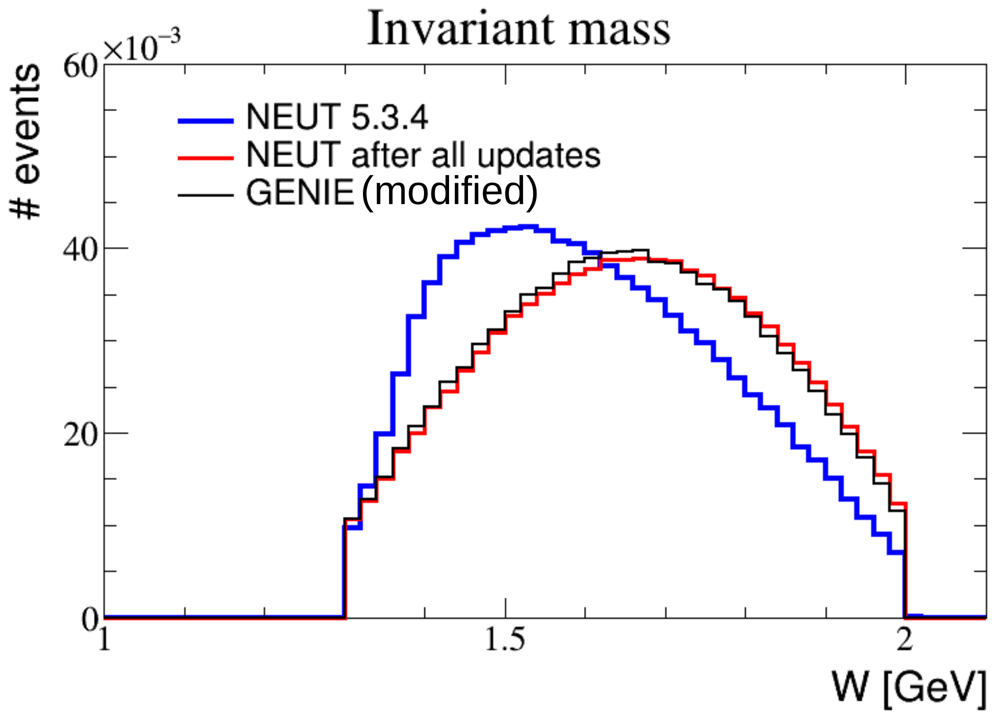
Low W model Flow



Low W model Updates

- NEUT and GENIE use similar method and inputs to generate (x,y)/(W,Q^2) in their low W models
- Found when doing generator comparison that obtained distributions were different for the 2
  → started systematic comparisons and updated NEUT as a result
  (one modification in GENIE as well – see next talk)





Note: Need special settings and cuts for generators to match. See next talk

2 GeV neutrinos on free protons
Normalized by area

Low W model Updates

List of updates NEUT 5.3.4 to 5.4.0:

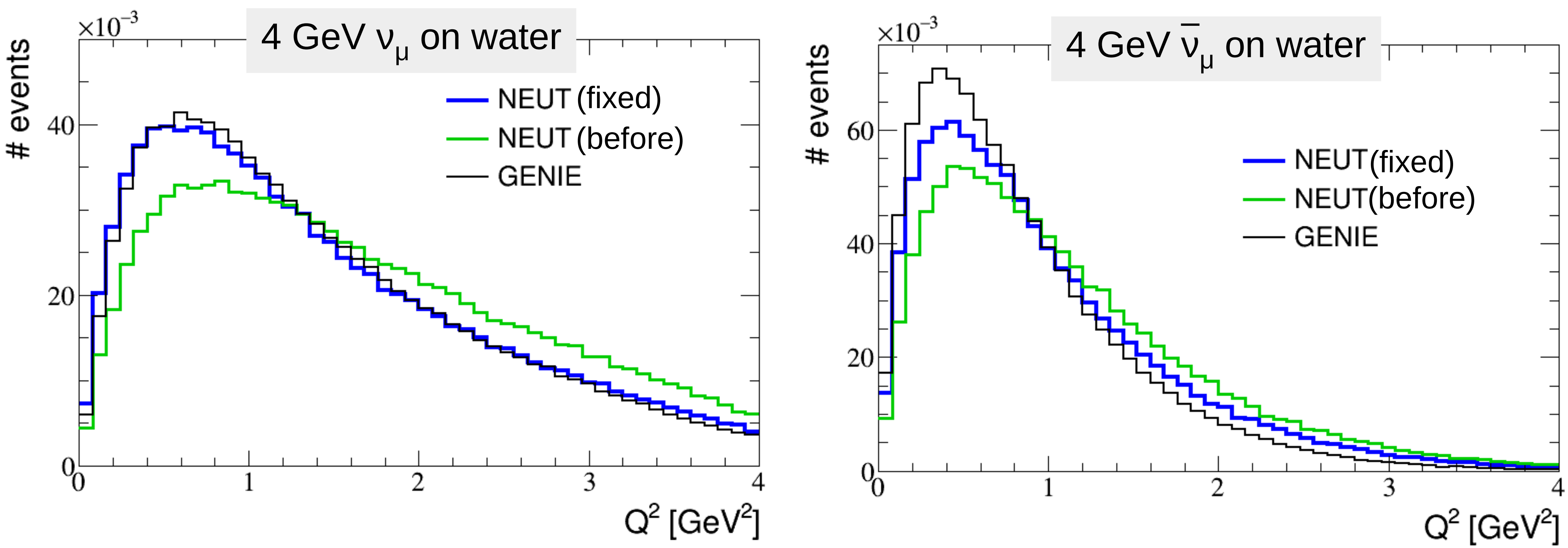
- **Fix relation between Q^2 and x (avoid double counting target mass corrections)**
- Use different cross sections to generate kinematics of interactions on protons and on neutrons
- Fix a typo in the implementation of the Bodek-Yang corrections
- target nucleon is selected based on the ratio of cross-sections on proton and neutron at the interaction energy
- Update version of the Bodek-Yang corrections used hep-ex/0301036 → hep-ph/0508007
- Change the scaling variable to the Nachtmann variable when Bodek-Yang corrections are not used
- Separate structure functions between CC and NC (still need to put the right formula for NC events)
- Use CKM matrix elements when calculating structure functions from PDF
- Added the charm related CKM matrix elements in the calculation of the structure functions if W is large enough to produce charmed particles (enough to produce a proton + a D0)
- Updated values of the CKM matrix elements to PDG 2015
- **Take into account effect of multiplicity on generation of x and y**
- **Added possibility to use different hadron multiplicity model:**
  - current NEUT one (with a small fix of the parameters)
  - my fit of deuterium bubble chamber data
  - AGKY model (used in GENIE)
- Removed passage through a Δ resonance

Low W model
Fix relation between x and Q²

- In the NEUT code, the definition of x used to obtain Q^2 was not the standard one:

$$x = \frac{Q^2}{2 M_{nuc} E y} \quad (1) \qquad \text{but instead:} \qquad x = \frac{Q^2}{2 M_{nuc} E y + M_{nuc}^2} \quad (2)$$

- It seems this is an old definition to take into account target mass effects, but they are already taken into account in corrections by Bodek and Yang
  In 5.3.4, x was generated assuming definition (1) but then (2) was used to deduce Q^2

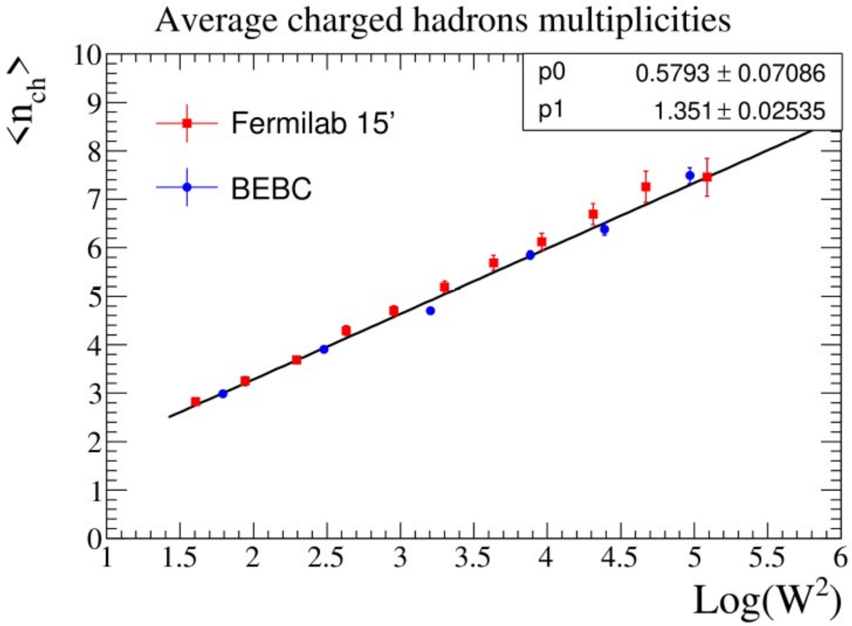


Low W model updates
Multiplicity model

- To determine the number of hadrons produced, use a multiplicity model
- Gives the probability to produce a given number of hadrons as a function of W, $\nu/\bar{\nu}$ and target nucleon

In NEUT 5.4.0, three hadron multiplicity models for the multi-pi mode

- NE-MULT=0: NEUT default (model used up to now, with a few minor changes)
- NE-MULT=1: results of my deuterium fits (hep-ph:1607.06558)
- NE-MULT=2: AGKY model (GENIE model, hep-ph:0904.4043)



To avoid double counting between RES and DIS, keep only events with $n_{had} \geq 3$

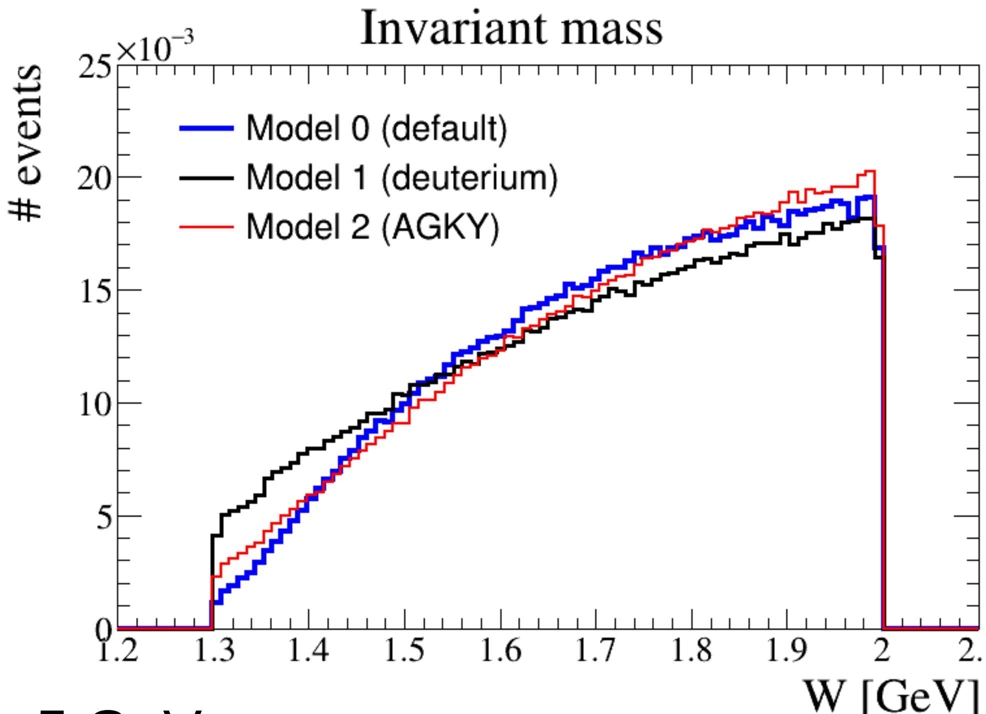
This multiplicity model has a large impact on low W model

Low W model updates
Multiplicity model – effect on W

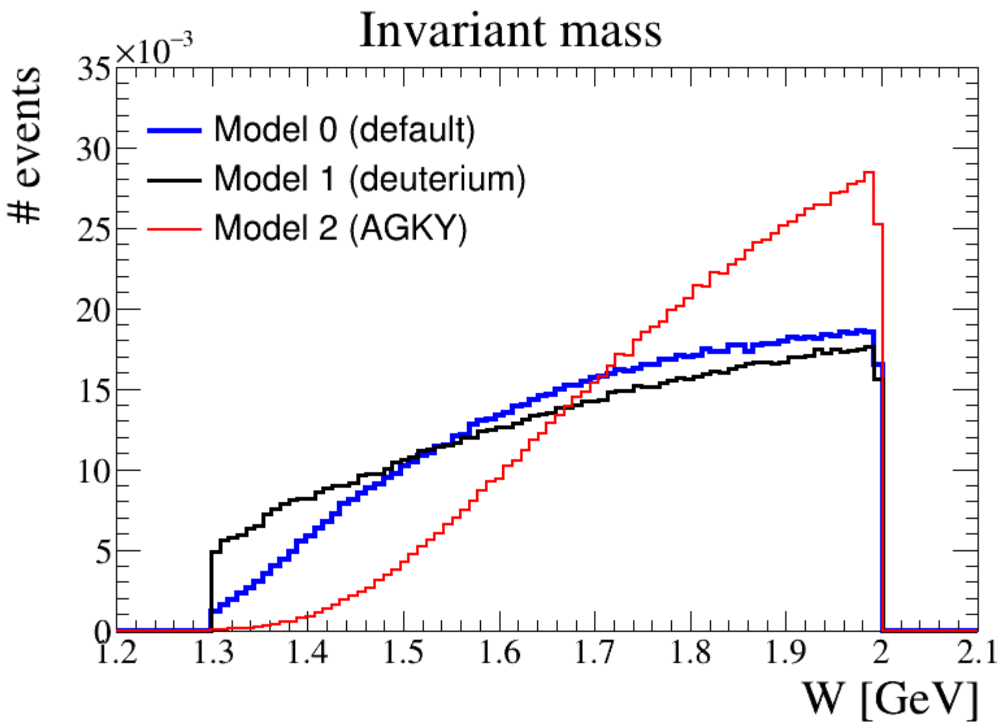
- $(x,y)/(W,Q^2)$ generated based on $d^2\sigma/dxdy$
- Number of hadrons generated for this W using multiplicity model
- Only keep event if $n_{had} \geq 3$

  → probability of a given throw to be accepted depend on multiplicity model

<u>Neutrino on proton</u>



<u>Neutrino on neutron</u>

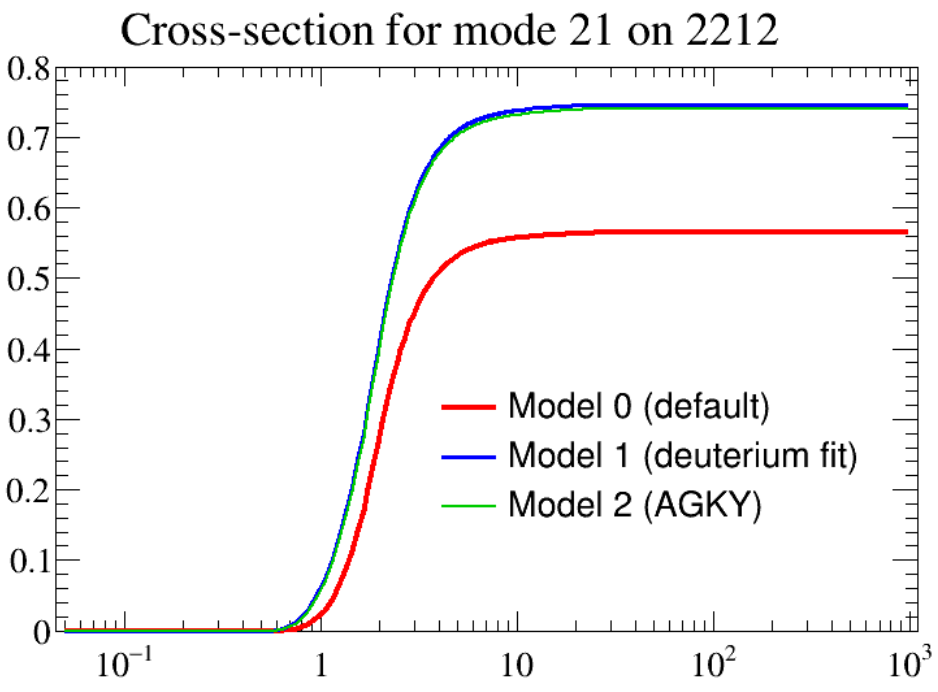


5 GeV ν_μ
(area normalized)

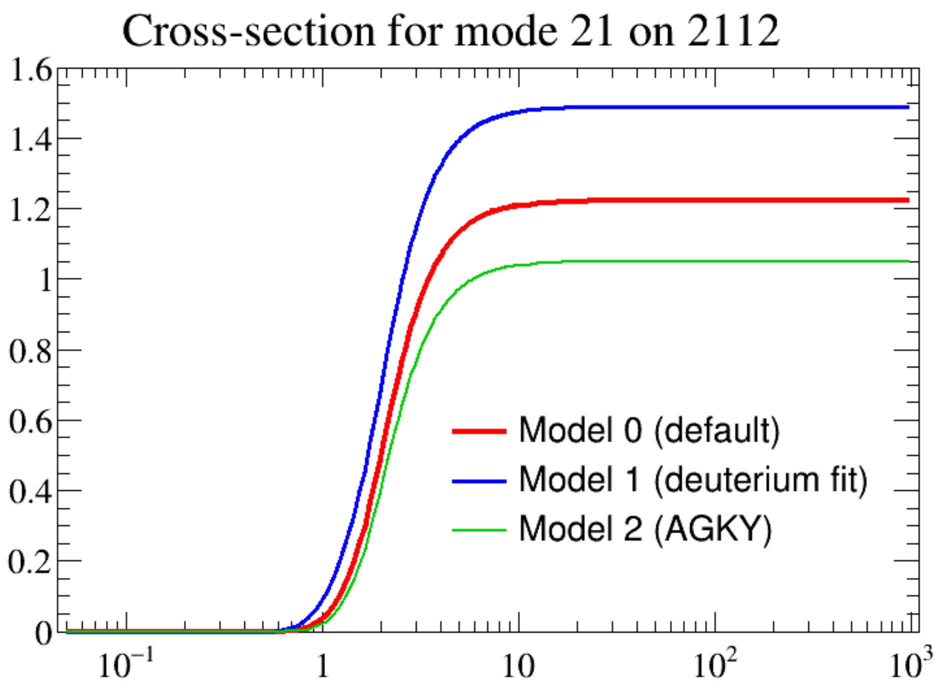
Low W model updates
Multiplicity model – effect on cross-section

Multi-pi mode cross-section is obtained by multiplying the total DIS cross section for W<2 GeV by the fraction of events that have at least two pions

Neutrino on proton



Neutrino on neutron

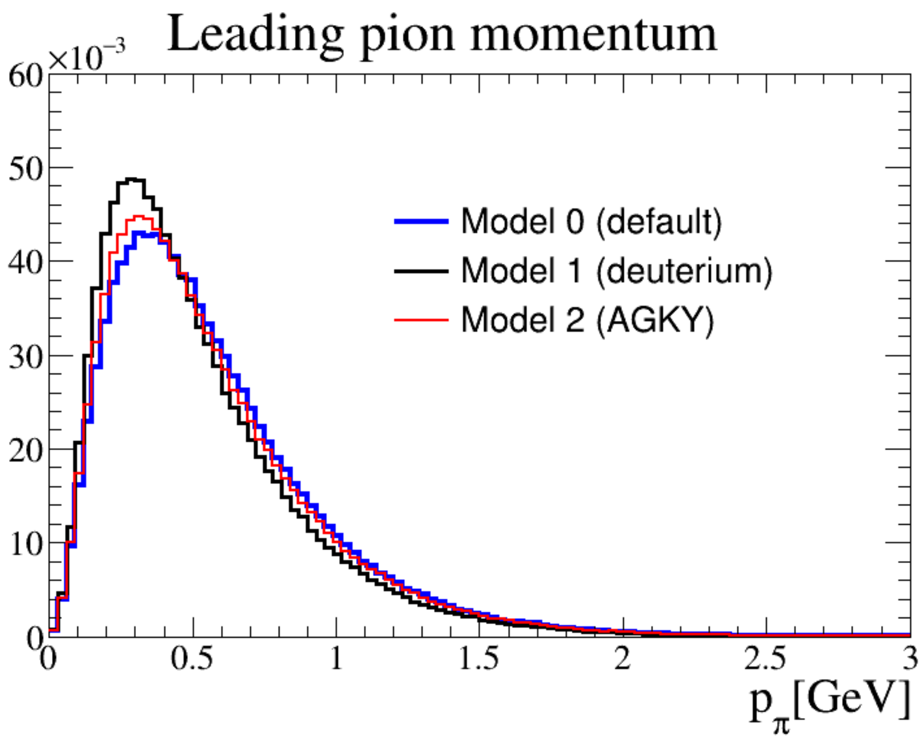


In current implementation (5.4.0), cross-sections computed with model 0 are always used, regardless of the multiplicity model used

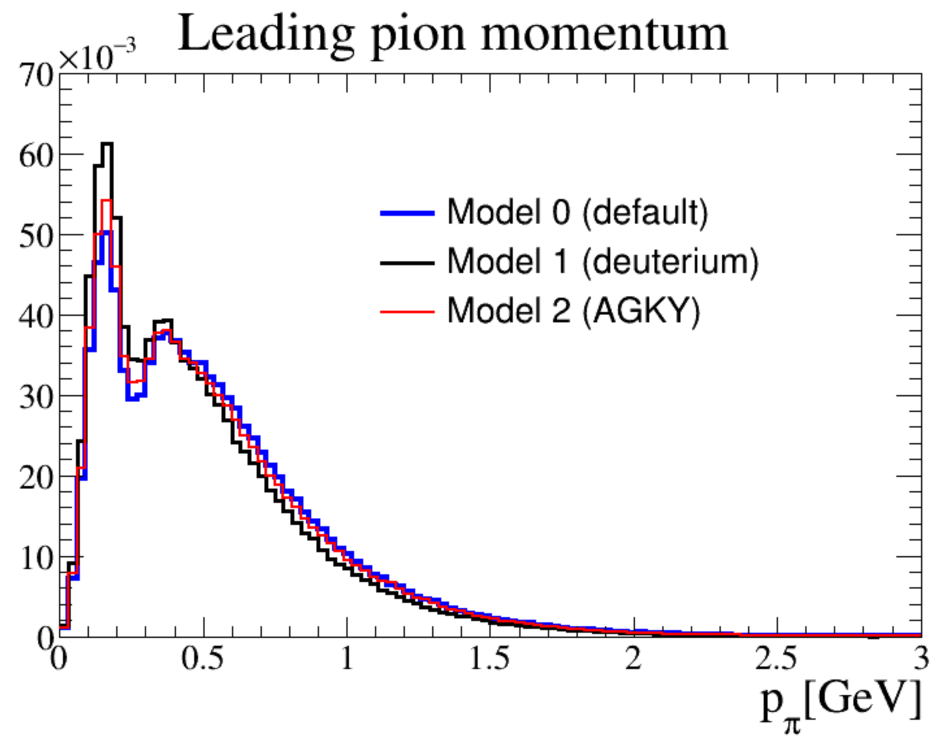
Low W model updates
Multiplicity model – effect on kinematics

More particles => less available energy per particle
→ Multiplicity model will also affect hadron kinematics

Before FSI



With FSI



5 GeV ν_μ on CH, interactions on protons only, area normalized

High W mode

- For W>2 GeV/c², all events are DIS and generated using PYTHIA 5.72
  Mostly default settings except:

```
*     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
```

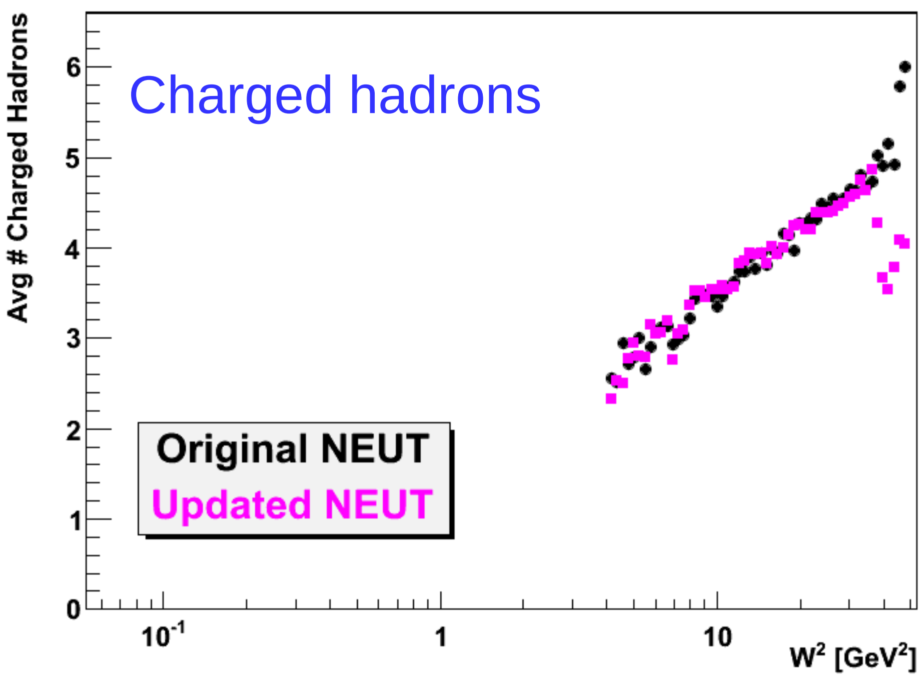
Don't do decays of π^0, η, K^0, ω and τ
Decay η'

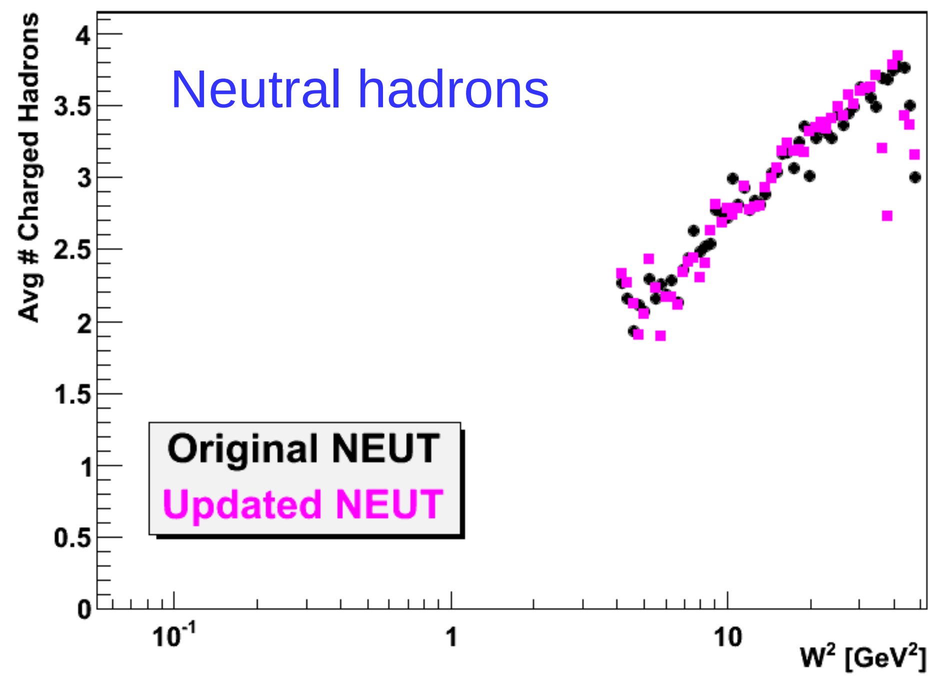
- Only provide neutrino and target nucleon four-momenta to PYTHIA
  Keep event if type (CC/NC) is the one desired, and W>2 GeV
  Redo PYTHIA generation with same inputs else

High W mode
Pythia 6 tests (J. Morrison - MSU)

- Other generators (NuWro, GENIE) use PYTHIA 6
- Does not allow E_{CM}<5.3 GeV: other generators pass hit quark, spectator diquark and W to Pythia and just use fragmentation routines

Tests in NEUT with PYTHIA 6 and 25 GeV neutrinos



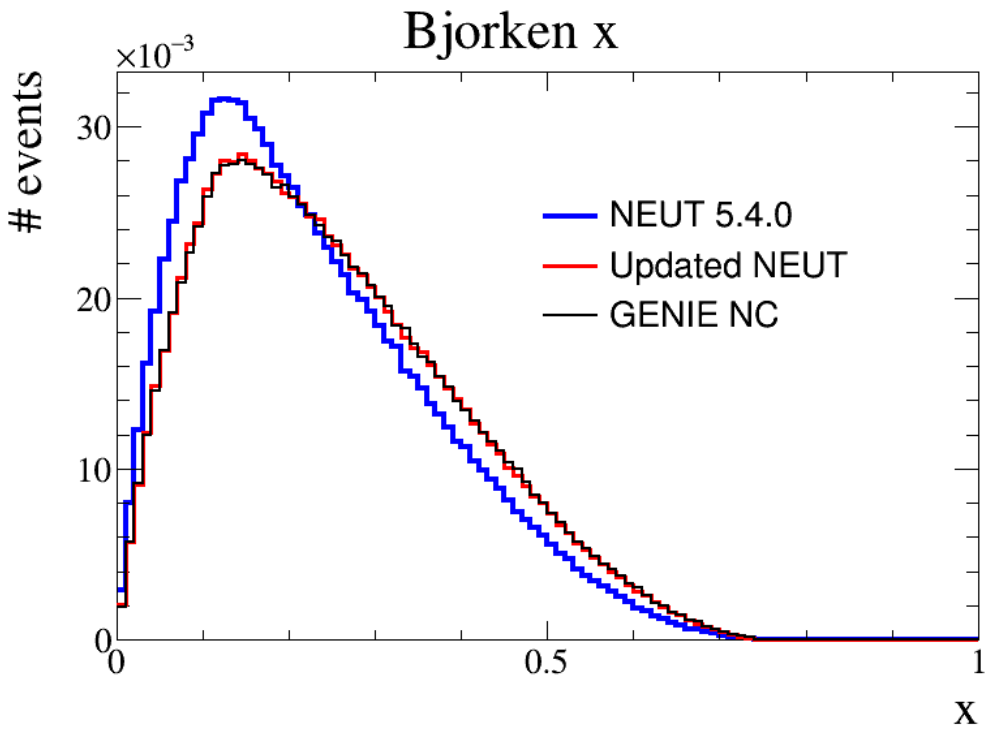


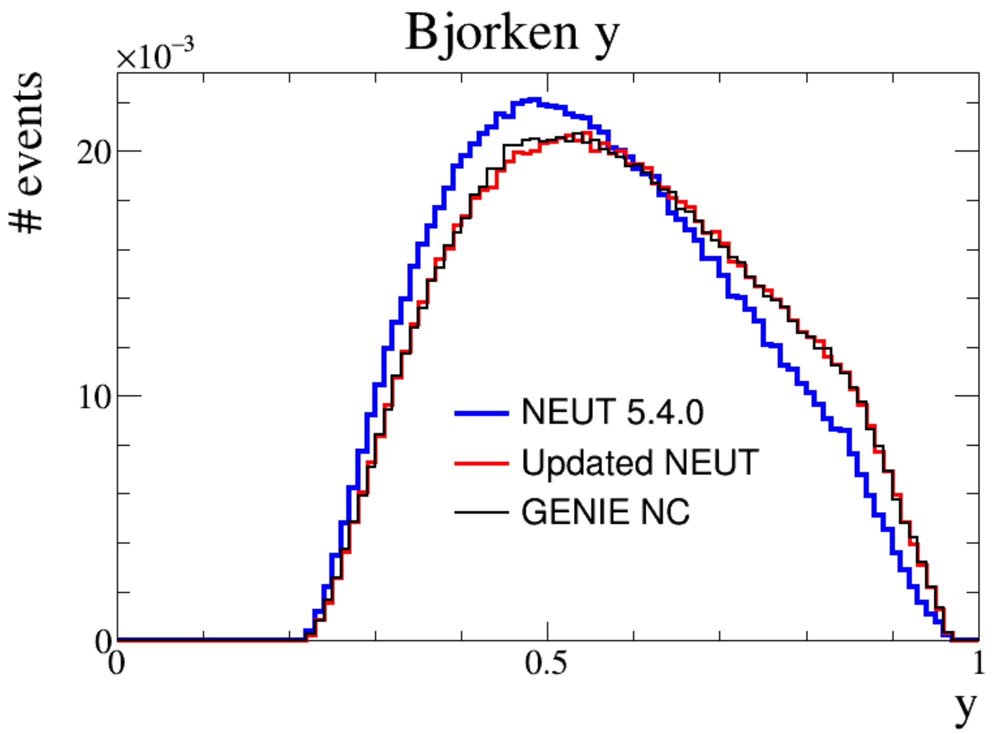
Hadronization looks similar, main difference with other generators is (W,Q^2) generated by PYTHIA 5 vs according to $d^2\sigma/dxdy$

Neutral current modes

- So far only presented CC DIS modes
  In 5.4.0, NC DIS modes uses CC structure functions (without CKM matrix element), and NC DIS cross-section obtained from CC one

- Started working on implementing correct NC structure functions.
  After this updates, low W NC mode compatible with GENIE
  (2 GeV $\bar{\nu}_\mu$ on free neutrons, usual settings to have agreement)





- Next step will be to compute NC cross-section by integrating $d^2\sigma/dxdy$

Summary

- 2 DIS modes in NEUT:
  - W<2 GeV: “multi-pion” mode, custom model for events with 3 or more hadrons produced
  - W≥2: based on PYTHIA 5.72
- Many updates from NEUT 5.3.4 to 5.4.0
  After the updates, the multi-pion mode predictions of (W,Q^2) agree with GENIE low W models (for free nucleons, when used in the same conditions)
- Given the way the transition from resonances to DIS is done, the hadron multiplicity model has a large impact on the predictions of the multi-pion mode
- Planning updates of the neutral current DIS modes in the future