Based on: [arxiv 2203.11821]

A substandard Candle: The low-ν Method

Rencontres du Vietnam: Neutrino

2022/07/22

Luke Pickering for the NUISANCE Collaboration

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Supported by URF\R1\211661

THE ROYAL SOCIETY

Motivation: Measuring the Neutrino Flux

$$N_{\text{near}}(E_{\text{obs}}) = \int dE_\nu\, \Phi_{\text{near}}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\text{near}}$$

$$N_{\text{far}}(E_{\text{obs}}) = \int dE_\nu\, \Phi_{\text{far}}(E_\nu) \cdot P_{osc}(E_\nu) \cdot \sigma(E_\nu) \cdot \mathbf{D}_{\text{far}}$$

Can access **Want to know**

Extract oscillation probability from observed rate.

- Observed rate is convolution of flux, cross-section, and oscillations
- Current uncertainty on flux (~5-10%) and cross-section (~10%)
- Use near detector to constrain rate+shape = flux ⓧ cross-section
- Use constrained model to predict observation for a oscillation hypothesis to test

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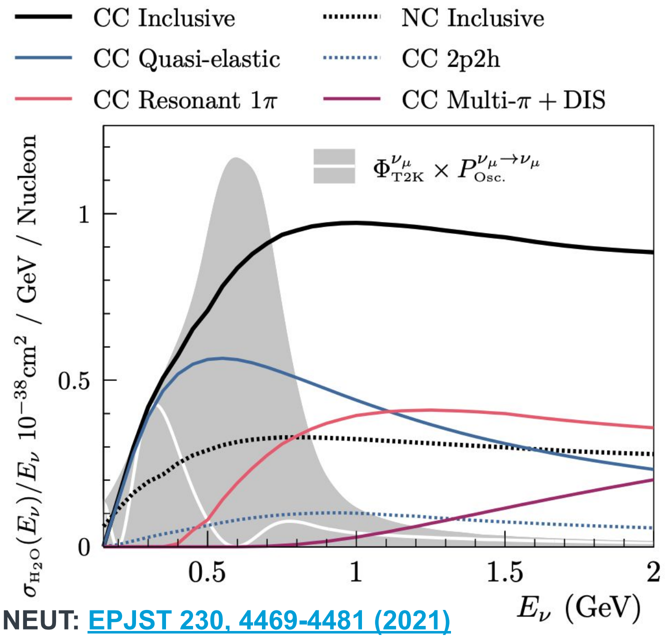
Ideally would use near detector to constrain flux and cross-section separately

in situ measurements are difficult:

- Wide band beam
- Cross-sections changing rapidly
- Detector effects cause significant smearing

Have to get creative...



NEUT: EPJST 230, 4469-4481 (2021)

Getting Creative

$$N_{\text{near}}\left(E_{\text{obs}}\right) = \int dE_{\nu}\, \Phi_{\text{near}}\left(E_{\nu}\right) \cdot \sigma\left(E_{\nu}\right) \cdot \mathbf{D}_{\text{near}}$$

General approach: Isolate events with a well-known cross-section and well understood detector effects

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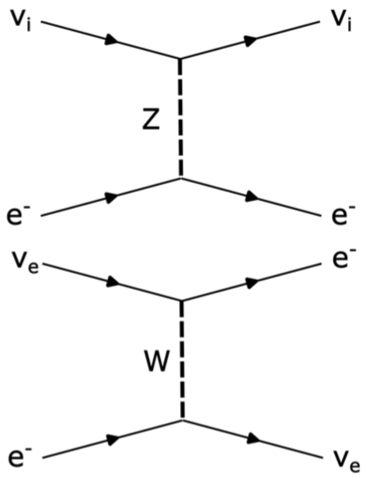
General approach: Isolate events with a well-known cross-section and well understood detector effects

Neutrino–electron elastic scattering:

- Simple interaction with no nuclear effects
- Rate is OOM lower than neutrino–nucleon scattering
- Future beams will produce sizeable sample
- Good for flux normalization



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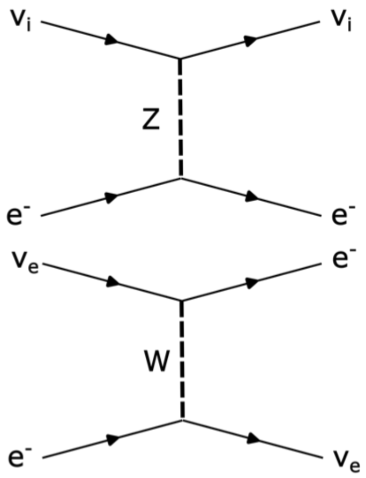

Can try to isolate neutrino–nucleon events with a well-known cross-section:

- Select very-elastic events
- → Cross-section saturates at some $E\nu$
- → Almost all energy to visible final-state charged lepton
- Minimal energy lost to nuclear response/hadron production

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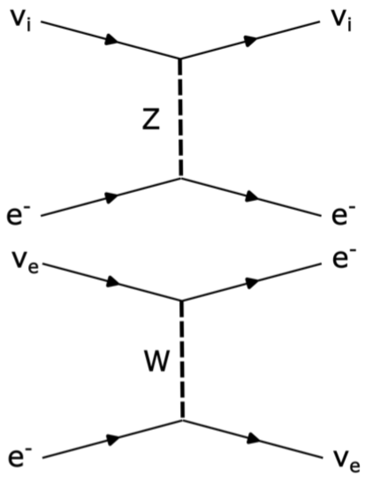

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The Original Idea

PHYSICAL REVIEW D VOLUME 38, NUMBER 9 1 NOVEMBER 1988

Neutrino reactions in the low-y region

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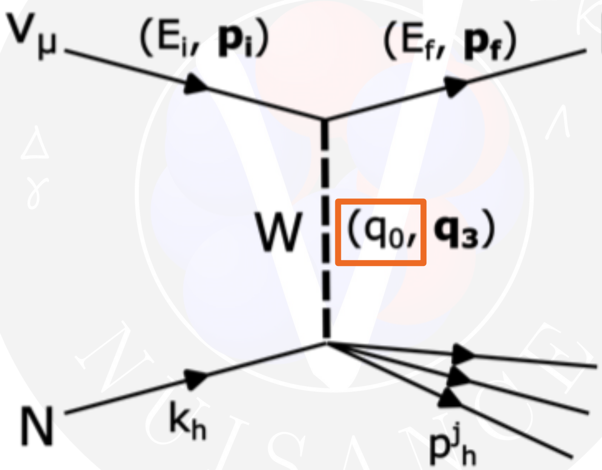
(Received 10 June 1987; revised manuscript received 30 June 1988)

The physics of nonscaling components in the region of low energy transfer (low-y region) is described. The following neutrino-induced processes were considered: resonance production, quasielastic scattering, and coherent meson production off nuclei or nuclear fragments. It is shown that the total exclusive cross section in a certain kinematical domain is energy independent at high energies (above 20 GeV). This fact can, in principle, be used for relative normalization of the neutrino flux.

Phys. Rev. D **38**, 2753 (1988)

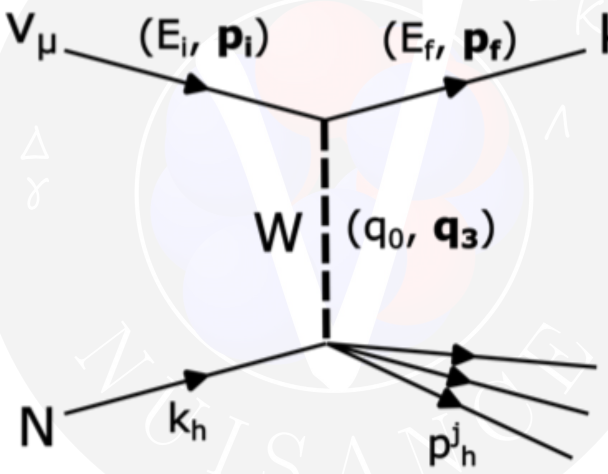
A Problem in Terminology



- Originally the "low-y" region
  - Low inelasticity → High elasticity
- "low-ν" coined in terms of DIS formalism
- ν is ambiguous in neutrino-scattering physics
- Has also been called "fixed ν_o" method
- Electron-scattering folks often use $\omega = E_i - E_f$

- I will try to use q_0 as in the 0^{th} component of the 4-momentum transfer q-vector.

The "low-ν" Method

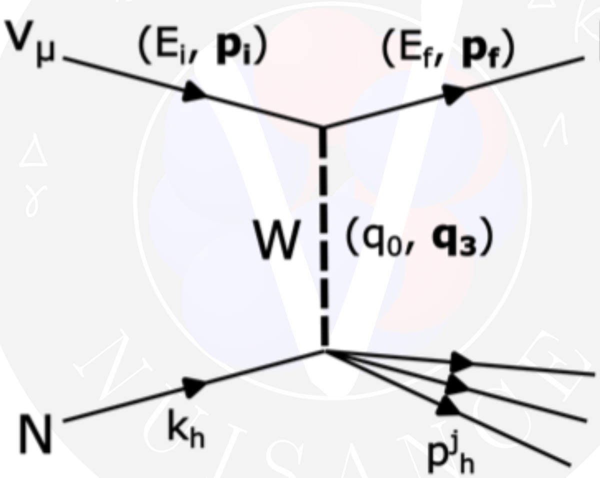


+(−) for (anti)neutrino

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_0} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu}\left[F_2 \overset{+}{(-)} xF_3\right] + \frac{q_0}{2E_\nu^2}\left[\frac{Mx(1-R_L)}{1+R_L}F_2\right] + \frac{q_0^2}{2E_\nu^2}\left[\frac{F_2}{1+R_L} \overset{+}{(-)} xF_3\right]\right) \mathrm{d}x, \qquad (1)$$

- Write down inclusive DIS cross-section in terms of nucleon structure functions
- Notice that if $\frac{q_0}{E_\nu} << 1$ any neutrino energy dependence disappears

The "low-ν" Method



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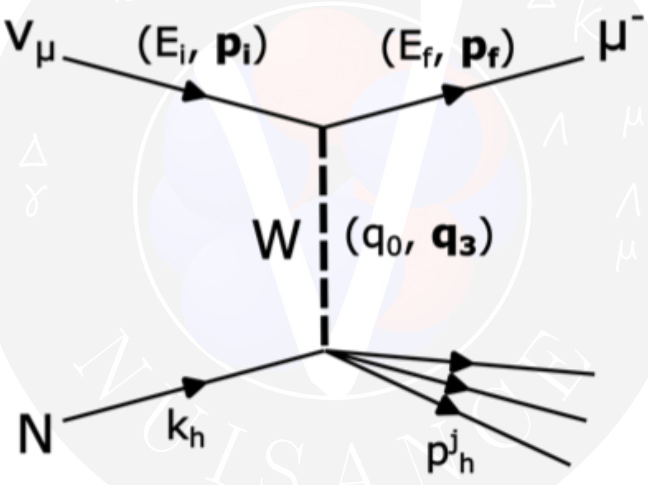

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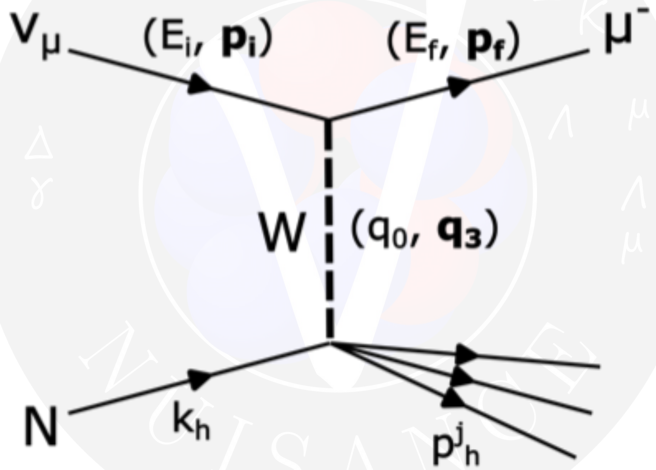
constant

$$N_{\text{near}}\left(E_{\text{obs}}\right) = \int dE_\nu \, \Phi_{\text{near}}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) \cdot \mathbf{D}_{\text{near}}$$

- Write down inclusive DIS cross-section in terms of nucleon structure functions
- Notice that if $\frac{q_0}{E_\nu} << 1$ any neutrino energy dependence disappears
- A flat cross-section can be used to access the shape of the flux from the event rate!

The Implicit Assumptions



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The "low-ν" method works well if:

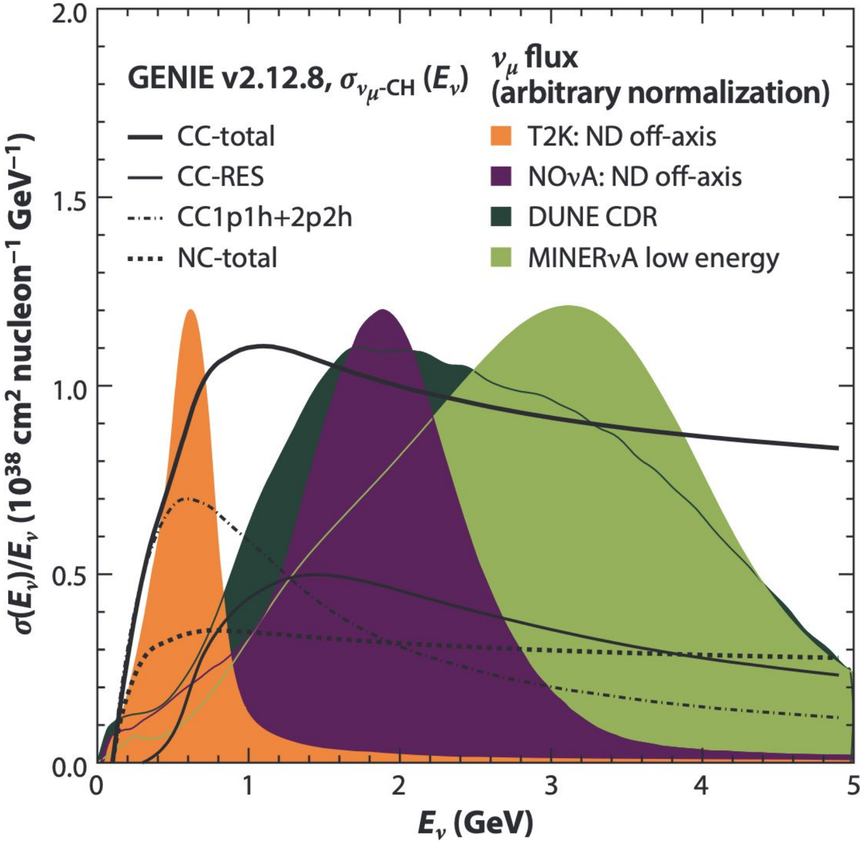
1. Eq. (1) describes the cross-section well in the region of interest
2. A sample with 'low enough' q_0 can be unambiguously experimentally selected
3. The neutrino energy for events in the sample can be accurately reconstructed.

Utility for Near-future Oscillation Measurements

Experimental Fluxes

Relevant neutrino energy range: < 5GeV

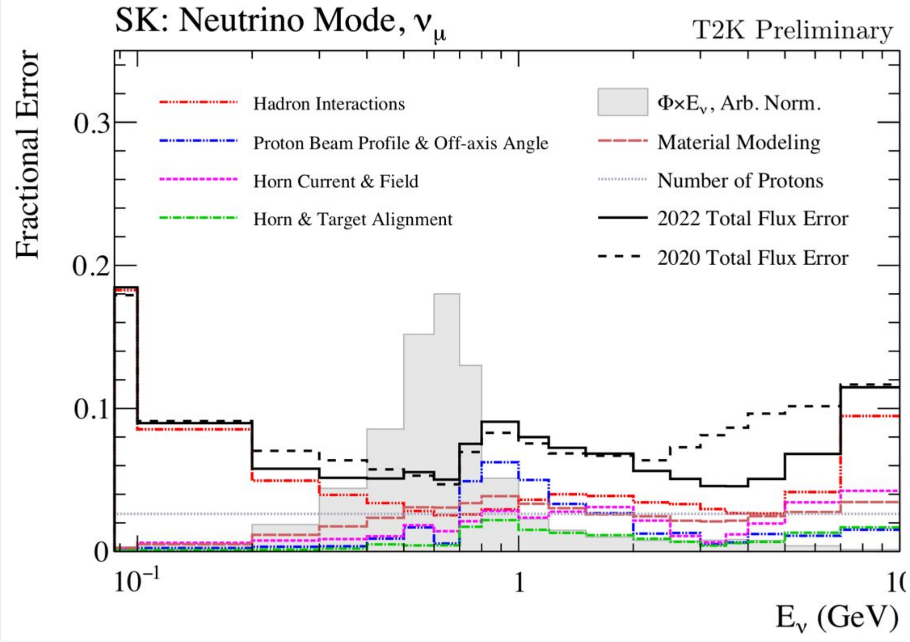
doi:10.1146/annurev-nucl-101917-020930



Experimental Fluxes

Relevant neutrino energy range: < 5GeV

Current flux uncertainty: ~ 5% in the peak



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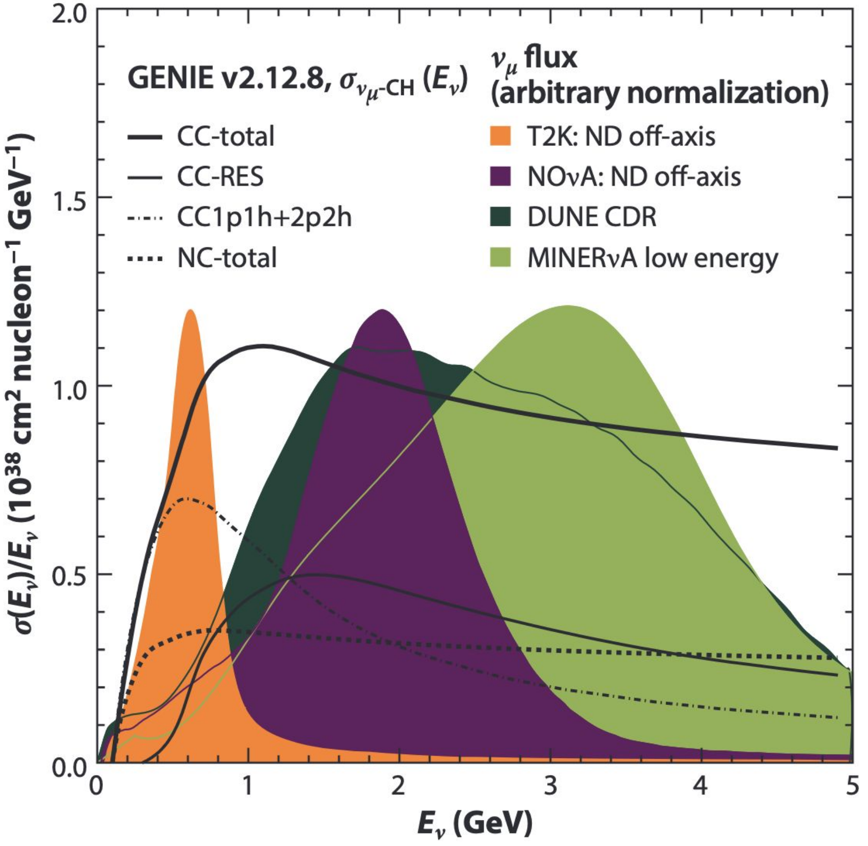

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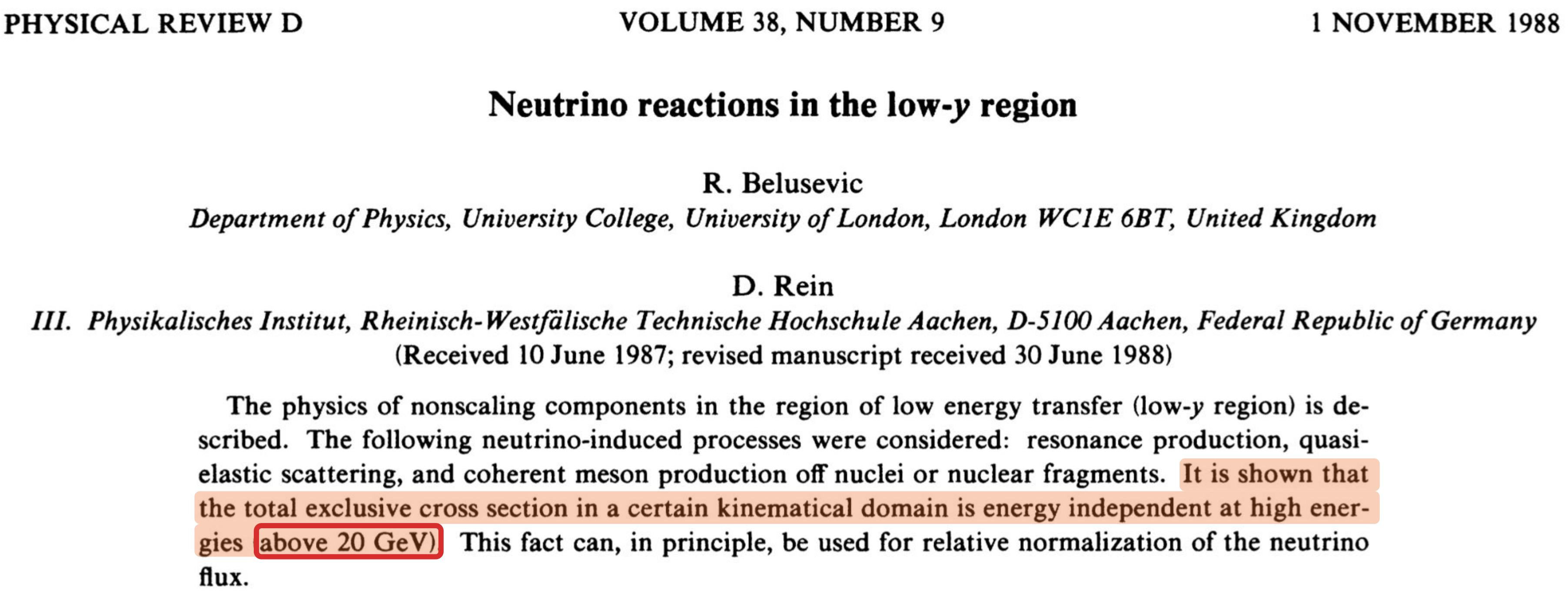
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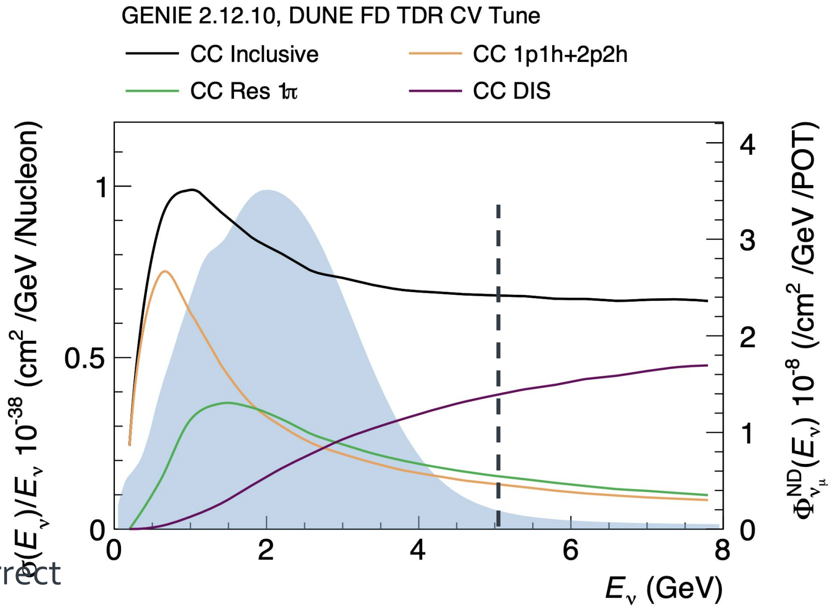
The Implicit Assumptions

- By 5 GeV the charged-current cross-section is *mostly* DIS.
- But we need $q_0/E\nu << 1$
  - **DIS** formalism, but a selection of very-not **DIS** events...
- At what (q_0,$E\nu$) does Eq. (1) break down?
  - Recent implementations ask the interaction model to correct for any non-constant behavior [EPJC **72**, 1973 (2012)]



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2. A sample with 'low enough' q_0 can be unambiguously experimentally selected
3. The neutrino energy for events in the sample can be accurately reconstructed.

Model Motivations

Need to investigate how well such a correction can be known with current simulation.

Use a spread of reasonable model predictions:

- Not a replacement for well motivated theoretical uncertainties…
- But they don't exist, so we have to make do with *semi*-sensible choices

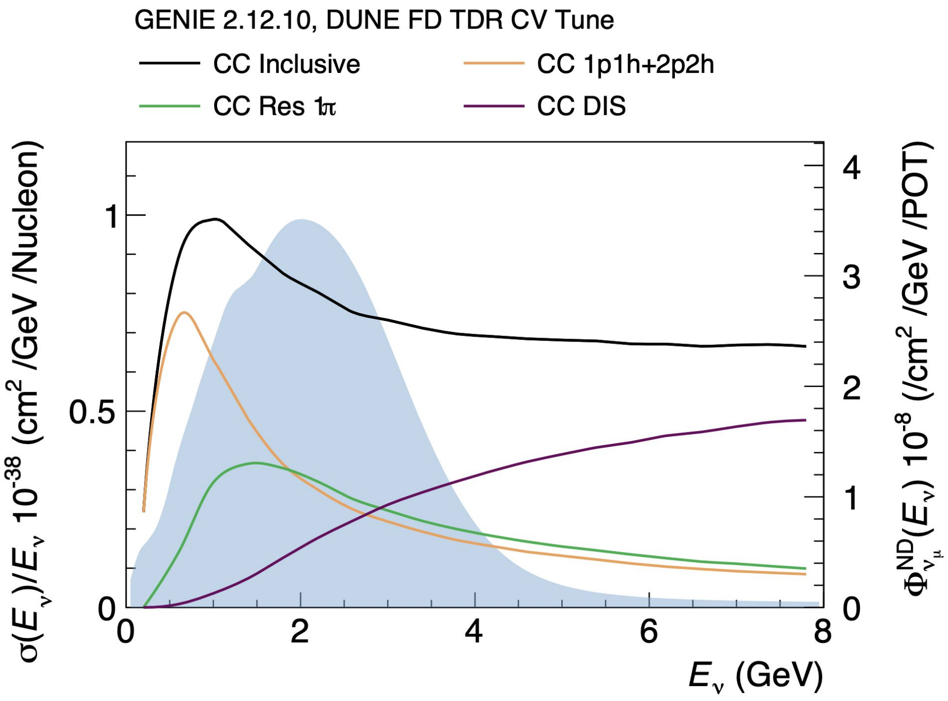
- **GENIE**:
  - Version 2 – Used by MINERvA in their Low-ν constraint [Phys. Rev. D **94**, 112007]
  - Version 3 – Currently used by NOvA, MicroBooNE for their analyses
- **NEUT**: Used by T2K
- **NuWro**: Performs well in comparisons to world cross-section data
- **GiBUU**: Sophisticated hadron-transport and quite different neutrino–nucleon model choices, also performs well in world data comparisons
- **SUSAv2 and CRPA**: State-of-the-art nuclear response modelling for pionless events

A View From The DUNEs

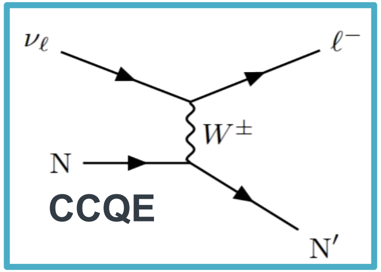
Study Configuration:

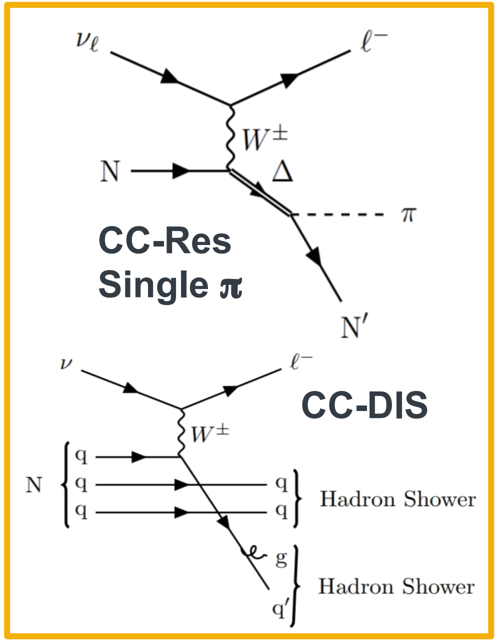
- Ar40 target
- Neutrinos and anti-neutrinos
- Spread of *reasonable* model choices

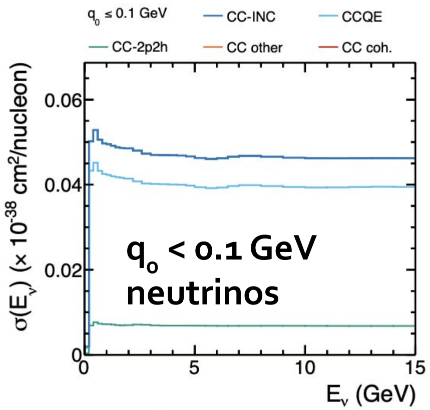
How well-understood is a perfect 'low-q_0' sample of events for a DUNE-like target?



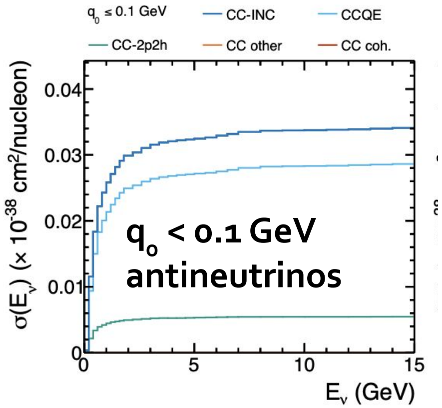
GENIE3: Total Cross Section







(a) ν_μ–^{40}Ar, $q_0 \leq 0.1$ GeV



(d) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.1$ GeV

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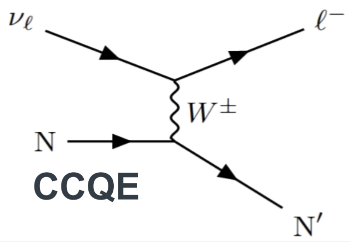

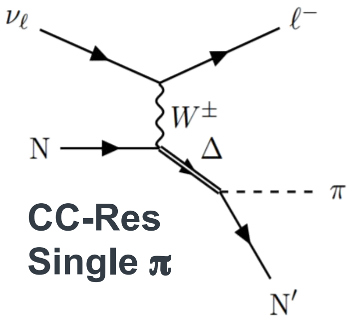

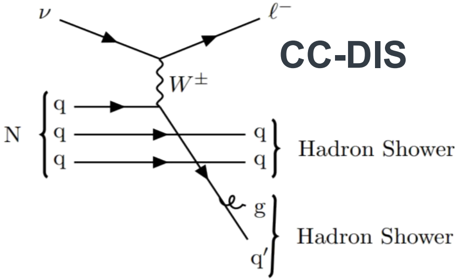

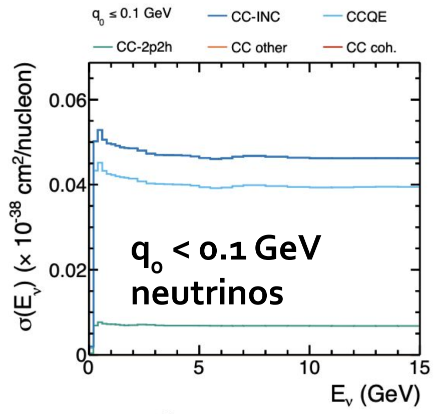

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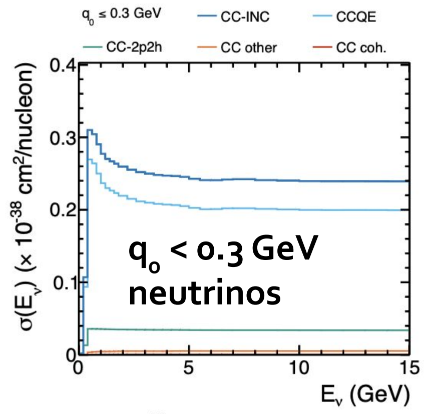
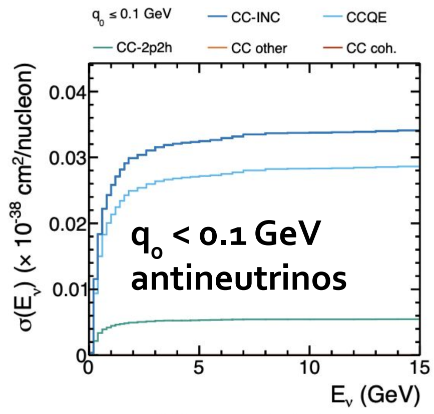
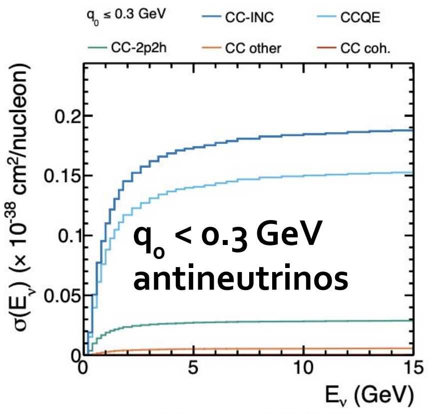


(b) ν_μ–^{40}Ar, $q_0 \leq 0.3$ GeV



(d) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.1$ GeV



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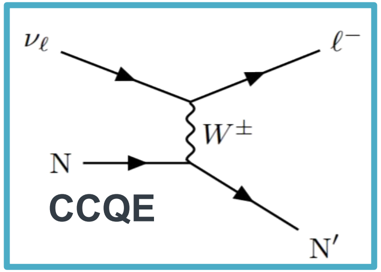

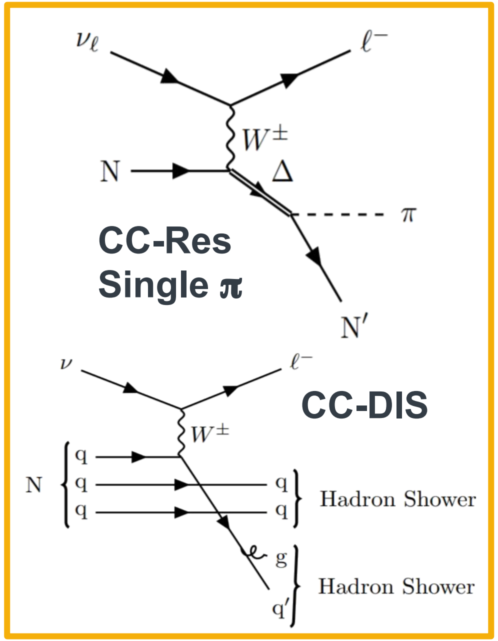

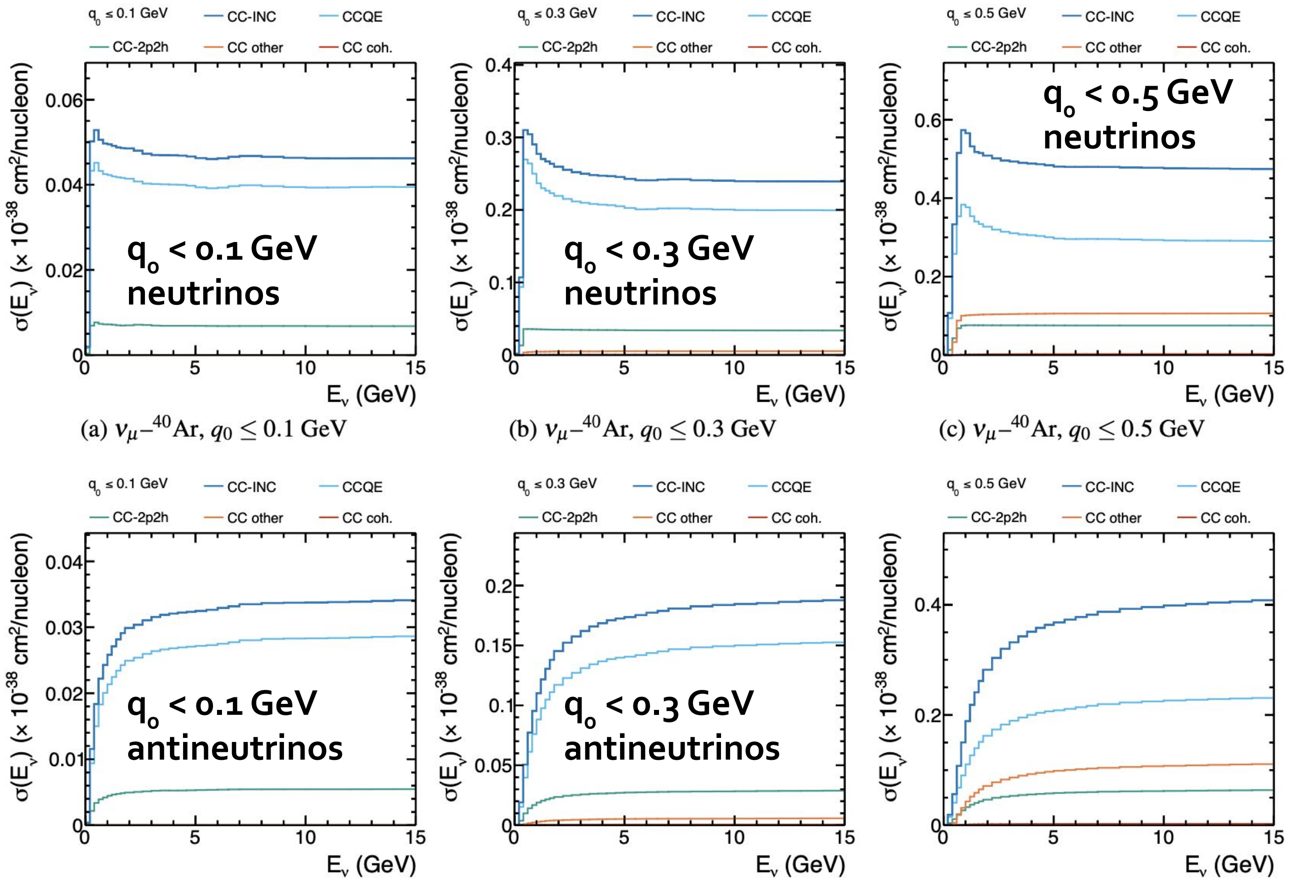

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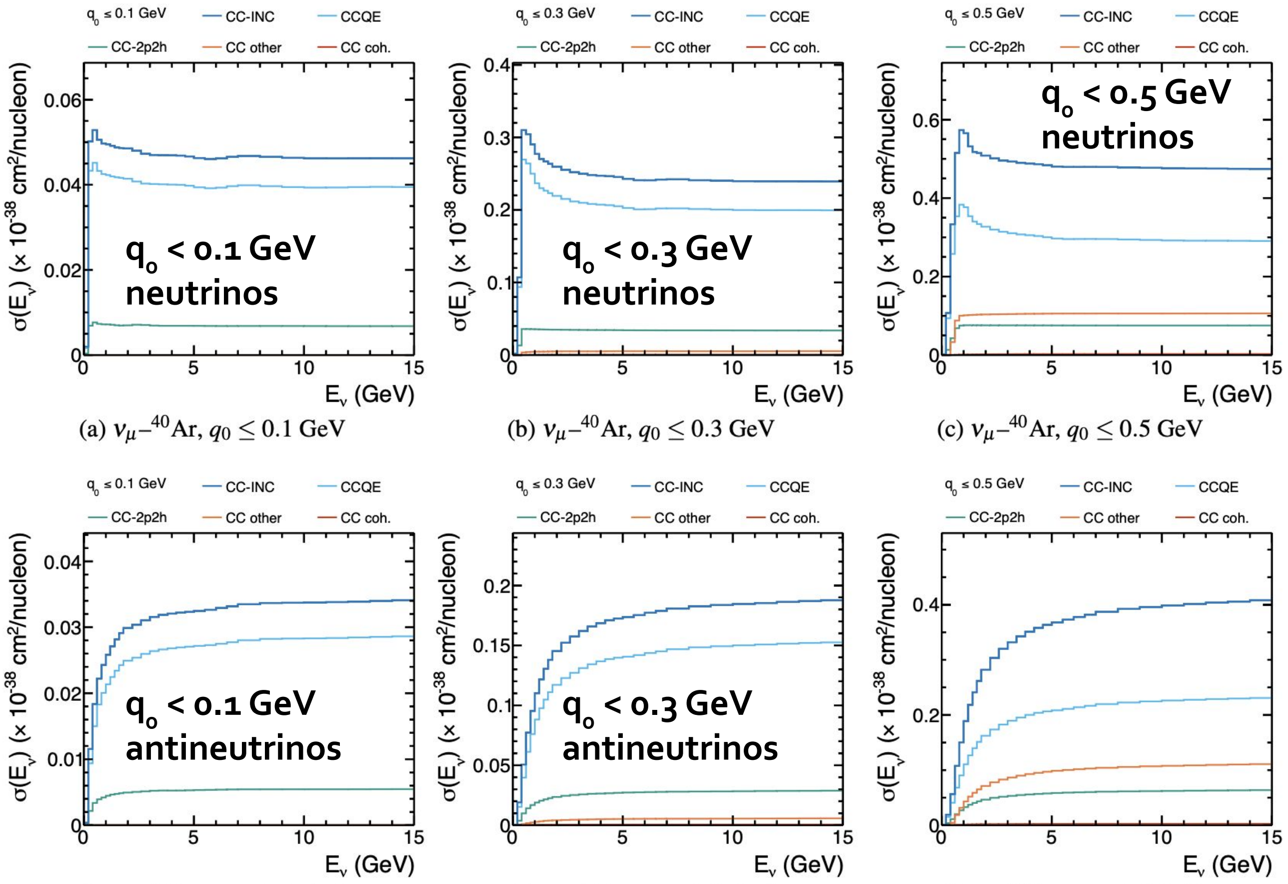
(c) ν_μ–^{40}Ar, $q_0 \leq 0.5$ GeV
(d) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.1$ GeV
(e) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.3$ GeV
(f) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.5$ GeV

GENIE3: Total Cross Section

Observations:

- Cross-section becomes ~flat for neutrinos at reasonable values of q_o
- It doesn't become flat for antineutrinos except for q_o<0.1 GeV



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(d) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.1$ GeV (e) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.3$ GeV (f) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.5$ GeV

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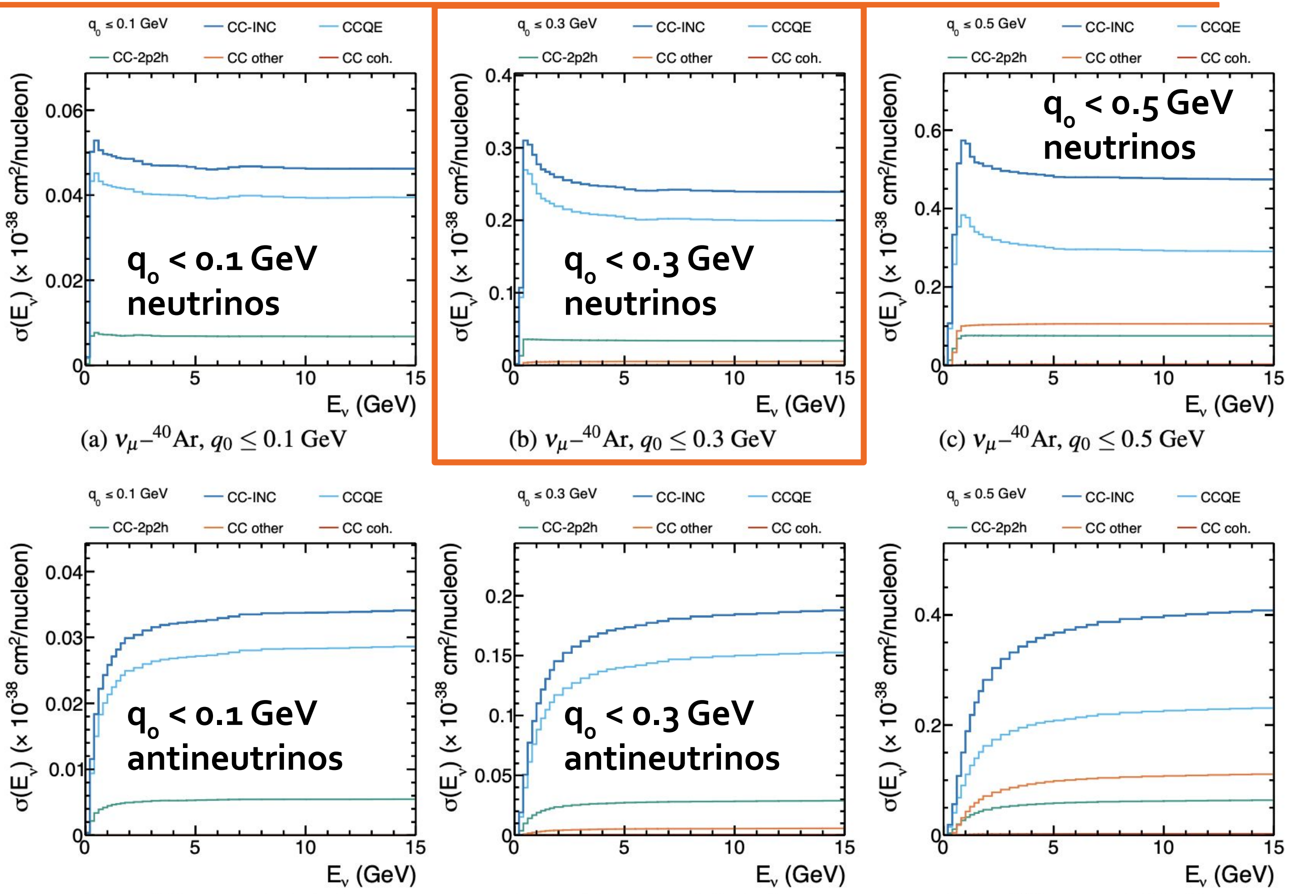

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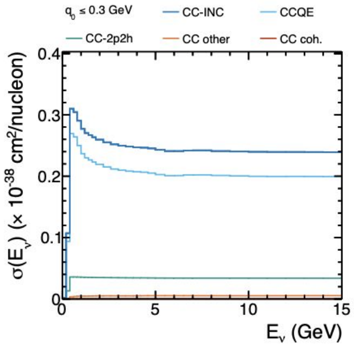
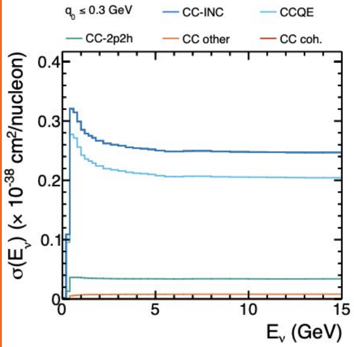
(f) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.5$ GeV

Alternate Predictions

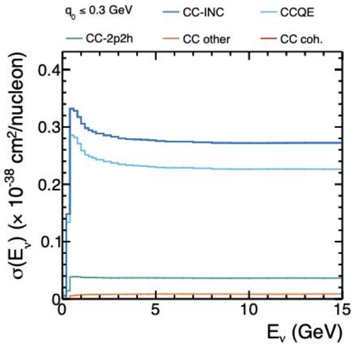
- General trends between predictions are similar by eye.
- GiBUU has very different 2p2h strength due to a model choice made for strength of correlated NN pairs.



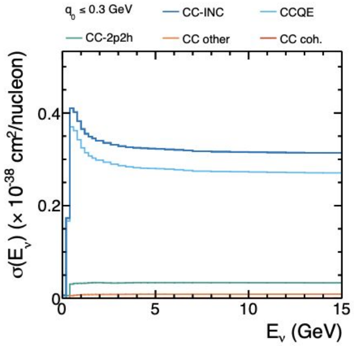
(a) GENIEv3 10a



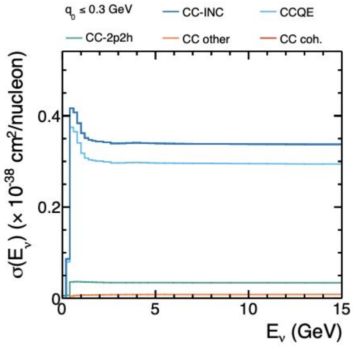
(b) GENIEv3 10b



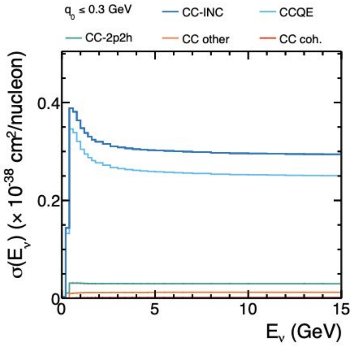
(c) CRPA



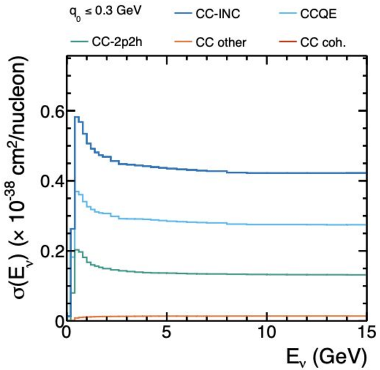
(d) SuSAv2



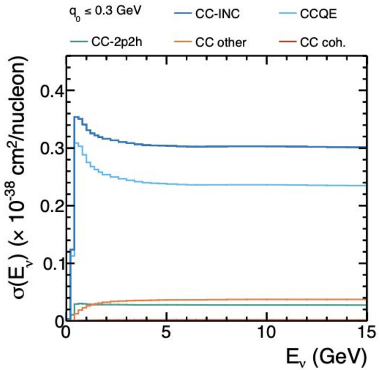
(e) GENIEv2



(f) NuWro



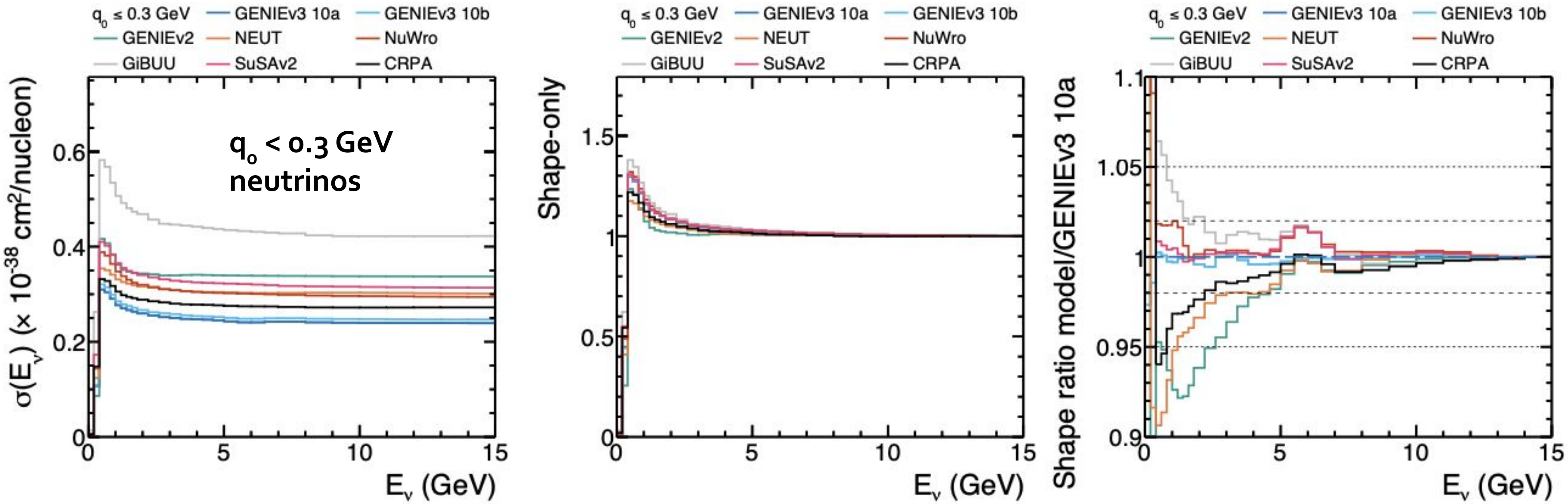
(g) GiBUU



(h) NEUT

Comparing the Predictions

- Want to evaluate uncertainty on the relative constantness of the low-q_0 cross-section
  - Take GENIEv3 10a as the reference model and examine variation of predicted low-q_0 shapes
- For illustration have chosen $q_0 < 0.3$ GeV



(a) Model comparison (b) Shape-only (c) Shape-only ratio

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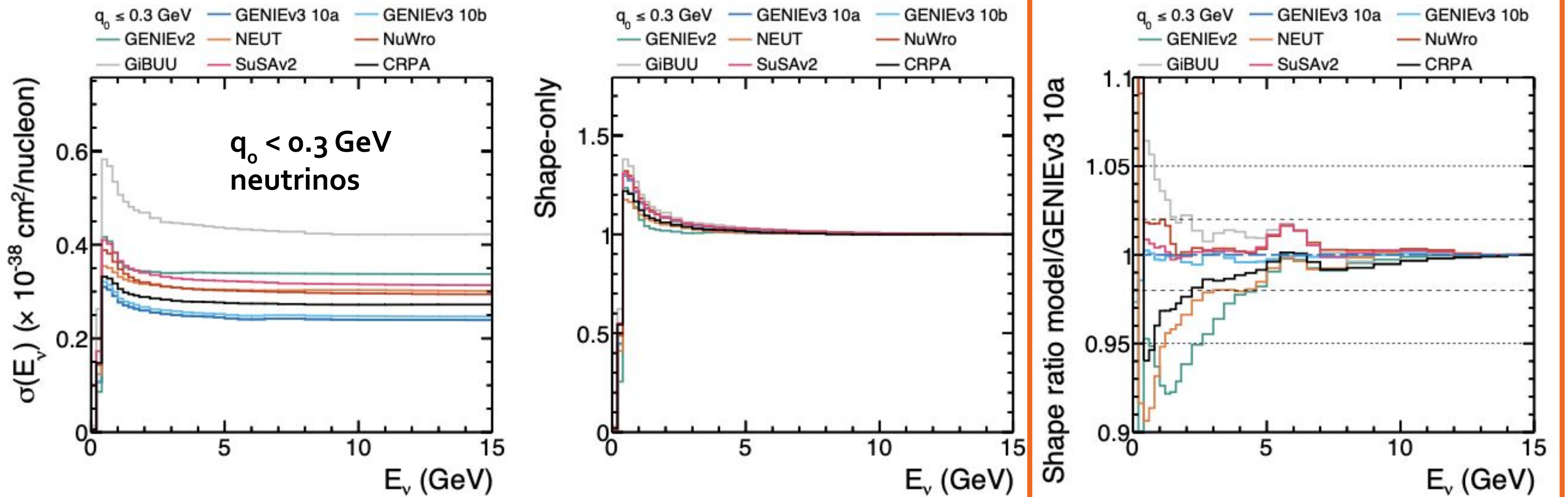

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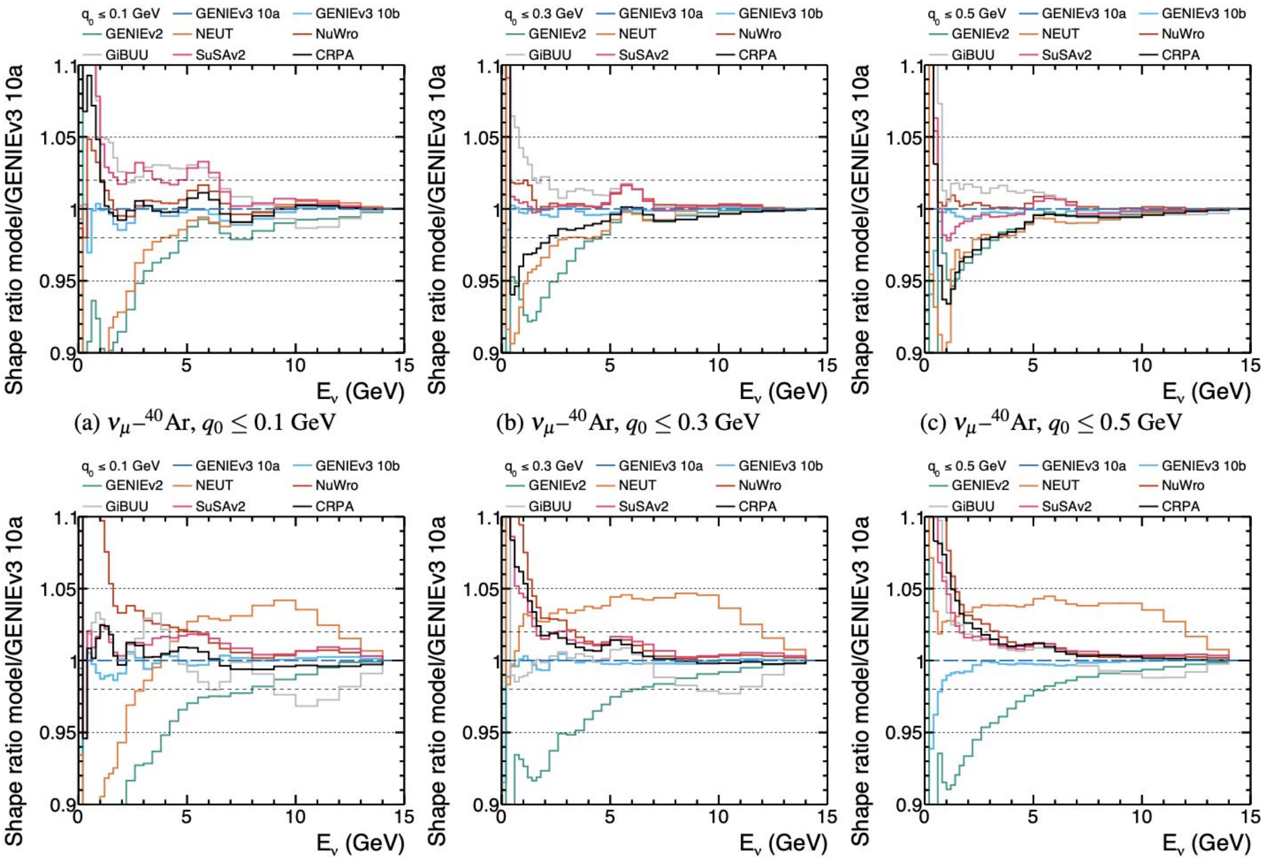
Model Spread

Important LBL oscillation region 0.5–5 GeV:

- Spread of 2–5% seen for neutrinos
- A bit larger for antineutrinos



(a) ν_μ–^{40}Ar, $q_0 \leq 0.1$ GeV (b) ν_μ–^{40}Ar, $q_0 \leq 0.3$ GeV (c) ν_μ–^{40}Ar, $q_0 \leq 0.5$ GeV

(d) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.1$ GeV (e) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.3$ GeV (f) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.5$ GeV

Model Spread

Important LBL oscillation region 0.5–5 GeV:

- Spread of 2–5% seen for neutrinos
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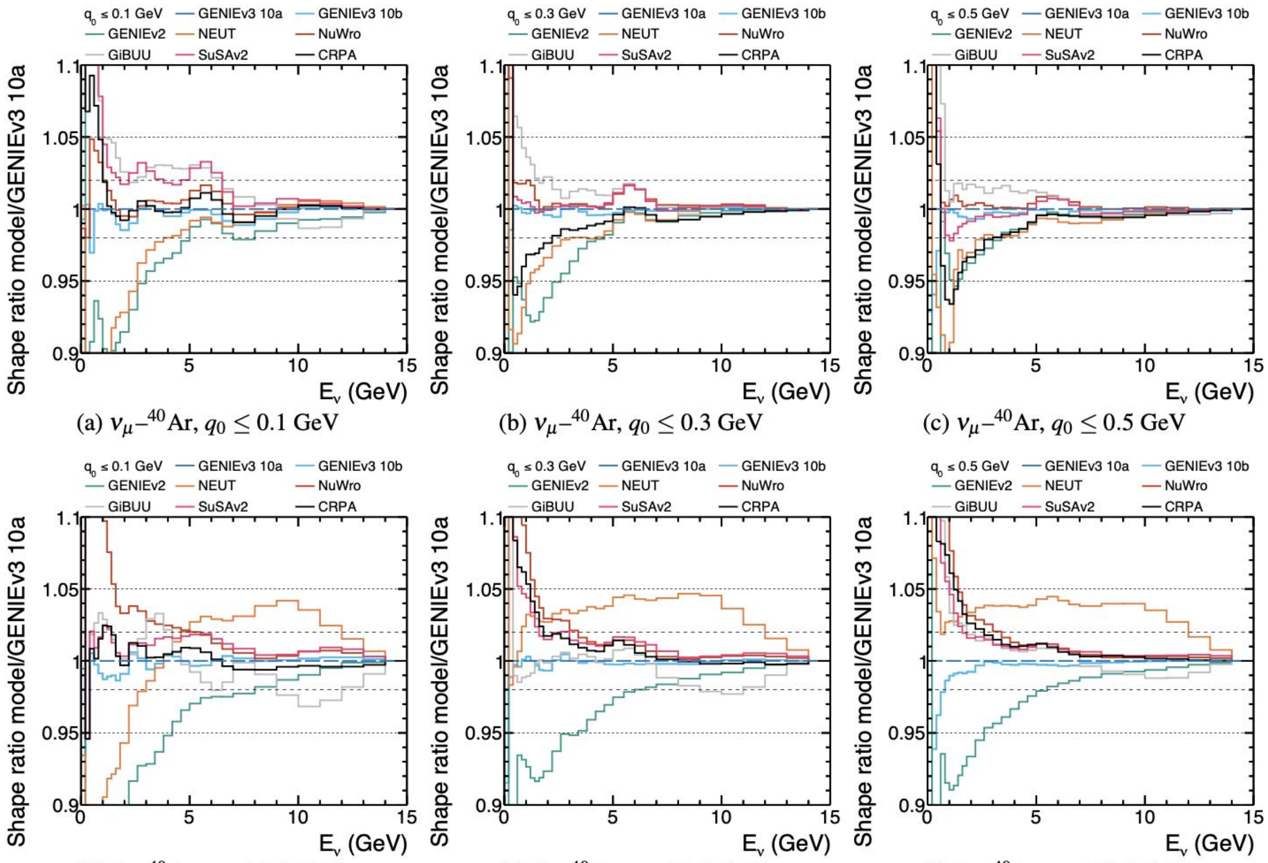
Counterintuitively the spread reduces for higher q_0 cuts:

- Opposite behavior than predicted by Eq. (1)
- Likely due to nuclear effects that do not fit well into Eq. (1)
- Pion-production and DIS models are more similar between generators



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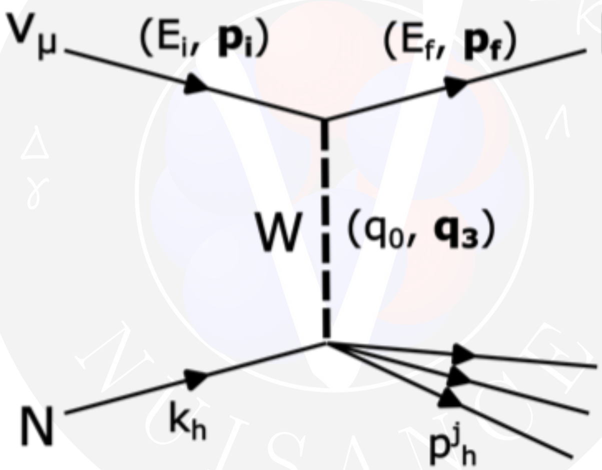
The Implicit Assumptions



The "low-ν" method works well if:

1. Eq. (1) describes the cross-section well in the region of interest
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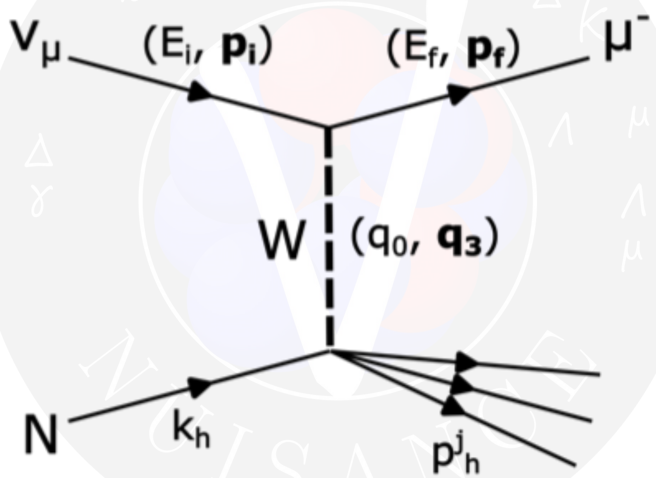

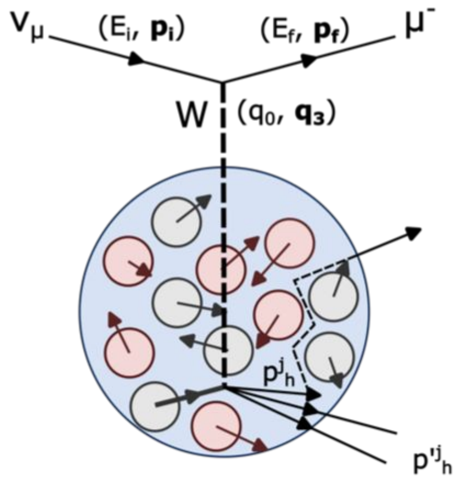

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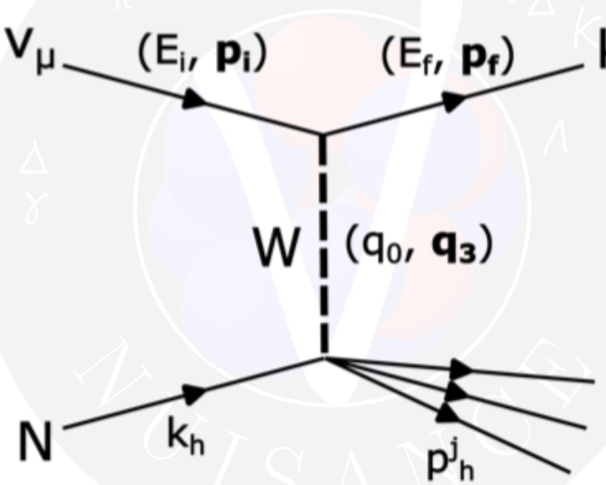

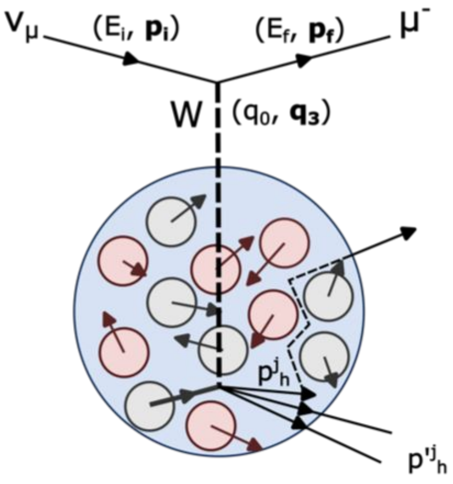

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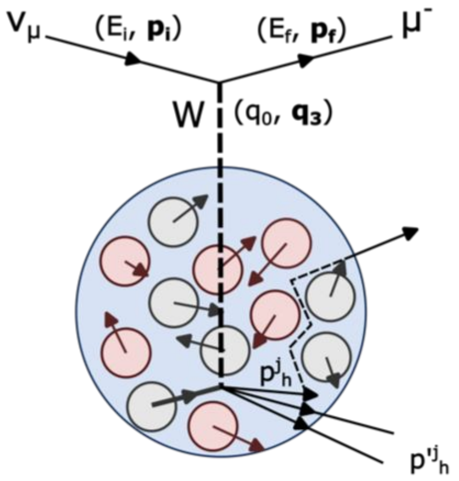
Selecting a Low-q_0 Sample

- Cannot access true q_0 because we cannot know incoming neutrino energy
  - Reconstruct from the hadronic side



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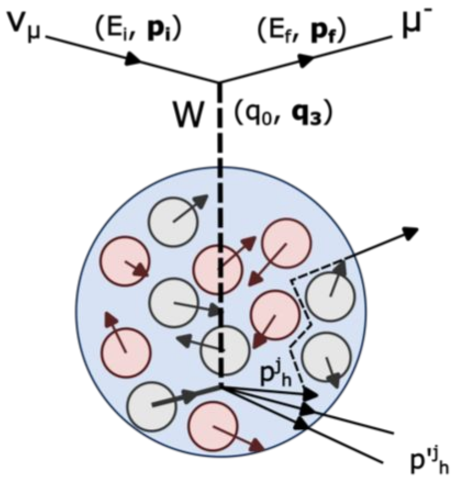
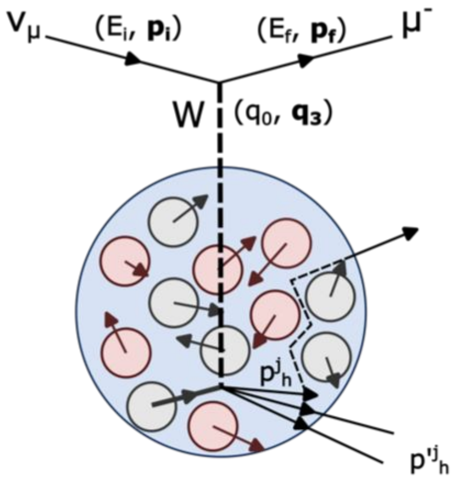
  - Missed-pion masses
  - Missed neutrons



Selecting a Low-q_o Sample

- Cannot access true q_o because we cannot know incoming neutrino energy
  - Reconstruct from the hadronic side
- Introduces significant dependence on nuclear response and detection capabilities:
  - Missed-pion masses
  - Missed neutrons
- Define three q_o proxy variables
  - Perfect detector, measures all hadrons
  - Optimistic detector, can't see neutrons but tags every pion
  - Pessimistic detector, misses all neutrons and charged-pion masses



$$E_{\text{had}}^{\text{true}} = \left(\sum_{i=n,p} E_{\text{kin}}^{i}\right) + \left(\sum_{i=\pi^{\pm},\pi^{0},\gamma} E_{\text{total}}^{i}\right)$$

$$E_{\text{had}}^{\text{reco}} = \left(\sum_{i=p} E_{\text{kin}}^{i}\right) + \left(\sum_{i=\pi^{\pm},\pi^{0},\gamma} E_{\text{total}}^{i}\right)$$

$$E_{\text{avail}} = \left(\sum_{i=\pi^{\pm},p} E_{\text{kin}}^{i}\right) + \left(\sum_{i=\pi^{0},\gamma} E_{\text{total}}^{i}\right)$$

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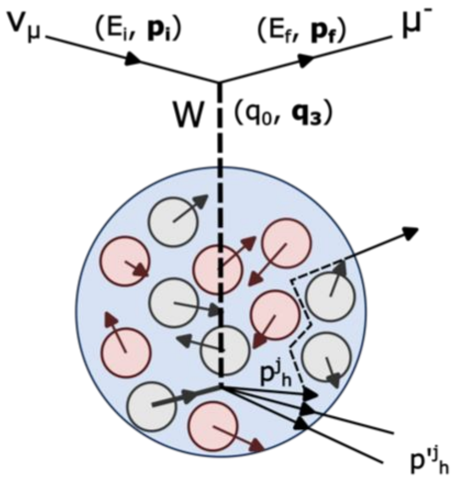

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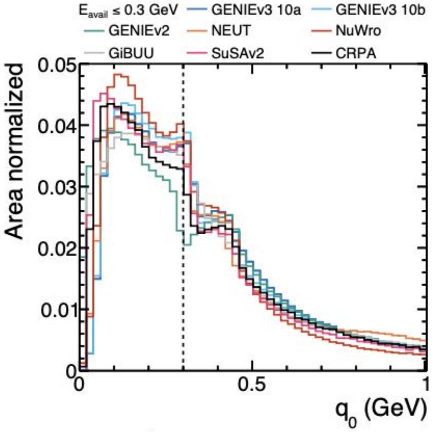
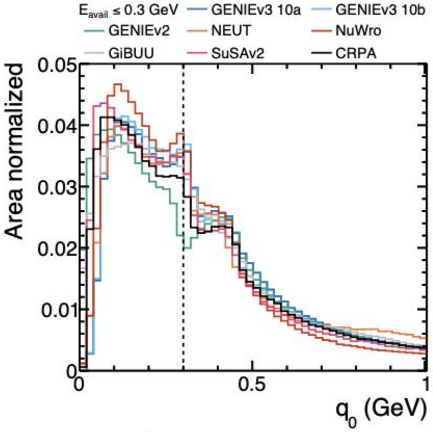
E_{avail} Smearing

Shows the ranges of true q0 values that pass E_{avail} < 0.3 cut for two neutrino energies.



(g) E_ν^{true} = 2 GeV, E_{avail}



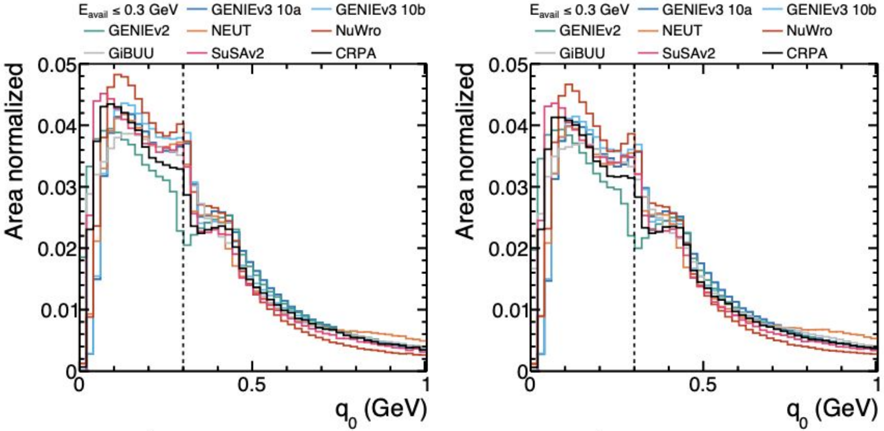
(h) E_ν^{true} = 5 GeV, E_{avail}

E_{avail} Smearing

Shows the ranges of true q0 values that pass E_{avail} < 0.3 cut for two neutrino energies.

Observations:

- "feed down" predicted from higher q_0
- Significant model spread near the cut value



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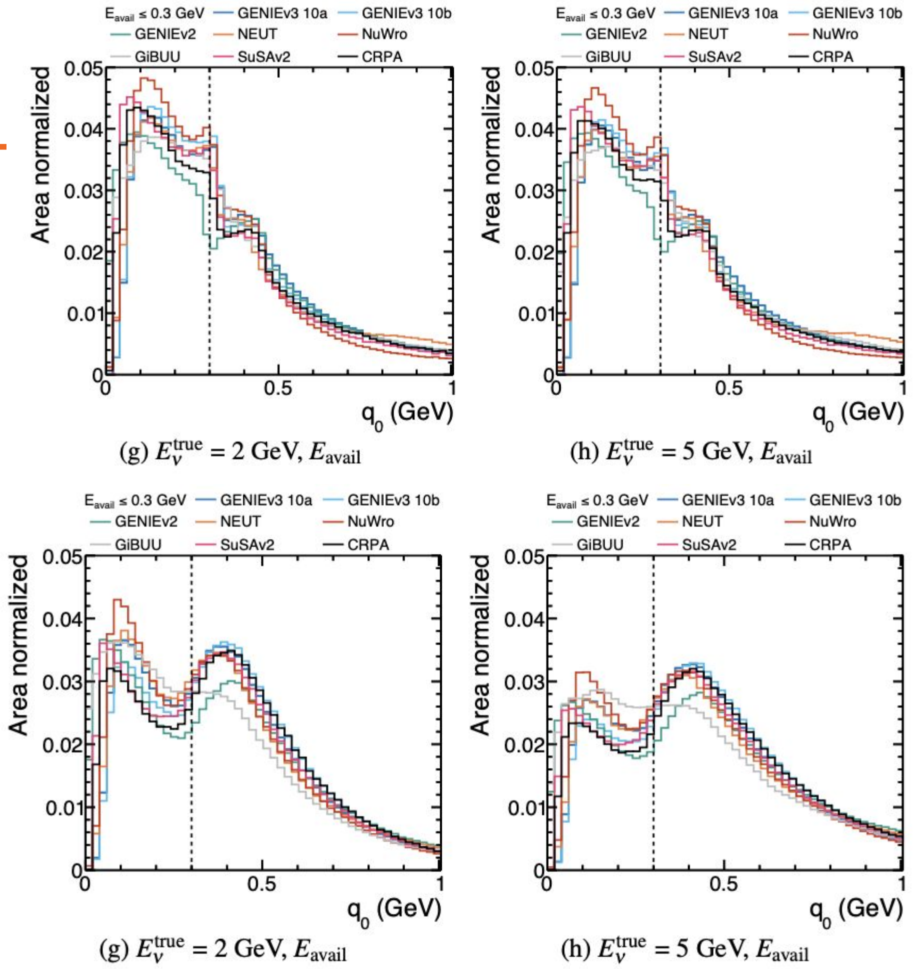
E_{avail} Smearing

Shows the ranges of true q0 values that pass E_{avail} < 0.3 cut for two neutrino energies.

Observations:

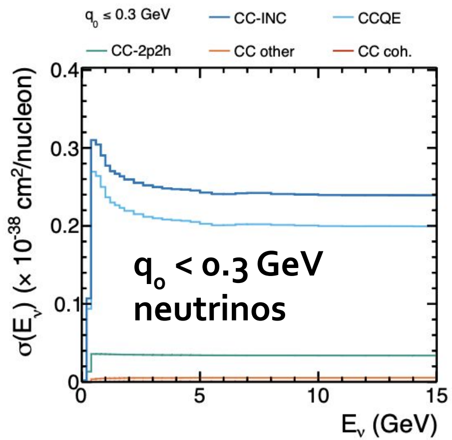
- "feed down" predicted from higher q_0
- Significant model spread near the cut value
- Feed-down is worse for antineutrino



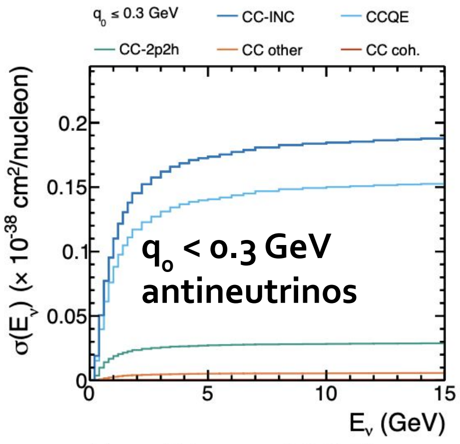
An E_{avail} Sample

Observations:

- True QE fraction is much lower
- Cross-section is not predicted to become flat for neutrinos or antineutrinos

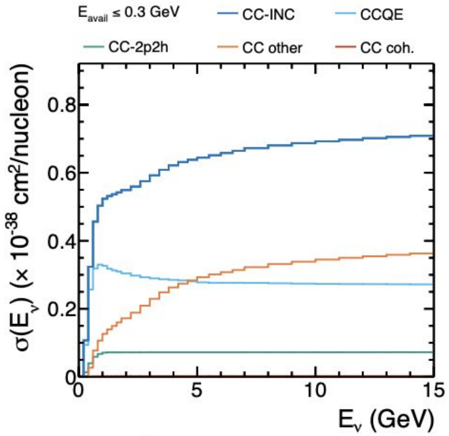


(b) ν_μ–^{40}Ar, $q_0 \leq 0.3$ GeV

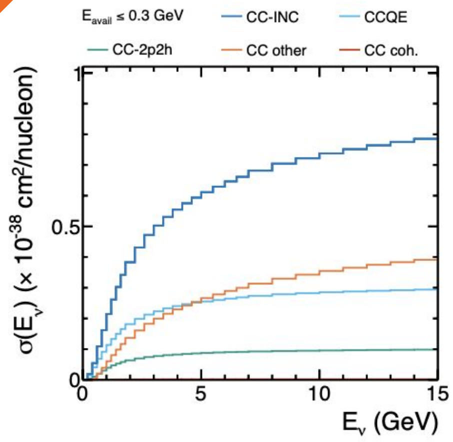


(e) $\bar{\nu}_\mu$–^{40}Ar, $q_0 \leq 0.3$ GeV

Select with E_{avail}



(c) ν_μ–^{40}Ar, $E_{avail} \leq 0.3$ GeV



(f) $\bar{\nu}_\mu$–^{40}Ar, $E_{avail} \leq 0.3$ GeV

An E_{avail} Sample

Observations:

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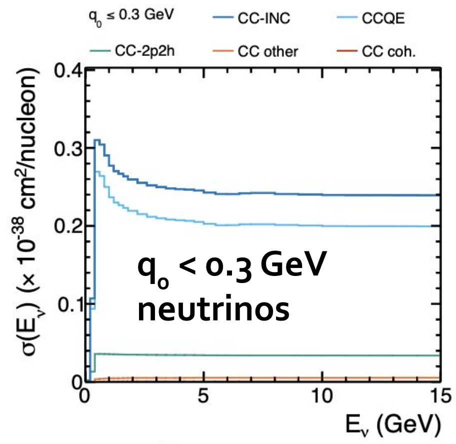
- $\rightarrow$ Rely on model-dependent corrections to use Low-ν



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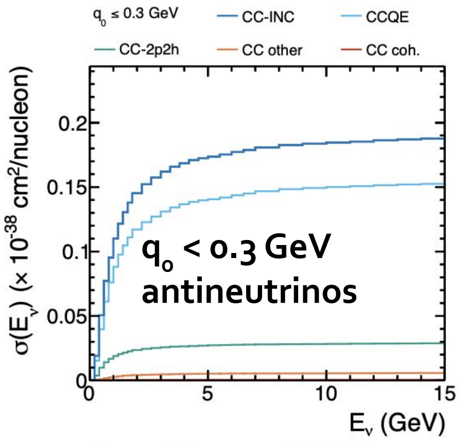

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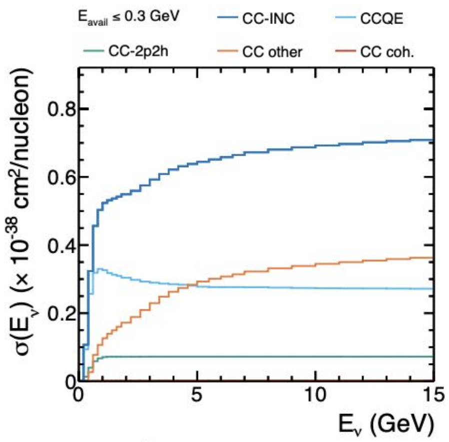
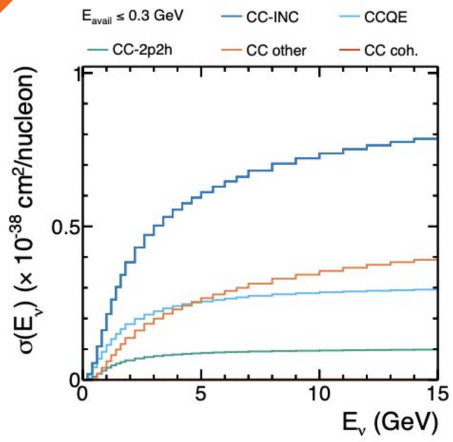


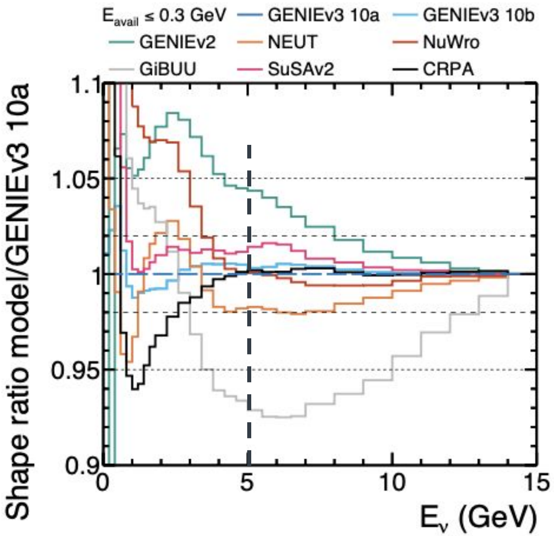
(c) ν_μ–^{40}Ar, $E_{\text{avail}} \leq 0.3$ GeV



(f) $\bar{\nu}_\mu$–^{40}Ar, $E_{\text{avail}} \leq 0.3$ GeV

A More Realistic Energy-transfer Analysis

- In the important region, we see model-spread of 5%
  - Performs similarly to current indirect flux constraints
  - Hadron-production measurements are expected to continue to improve before DUNE/HK are systematics limited
- This is not a motivation of systematic uncertainty:
  - It is almost certainly an underestimate of the uncertainty
  - But it is a more comprehensive study of available predictions than has been published by any Low-ν at few GeV Eν proponents



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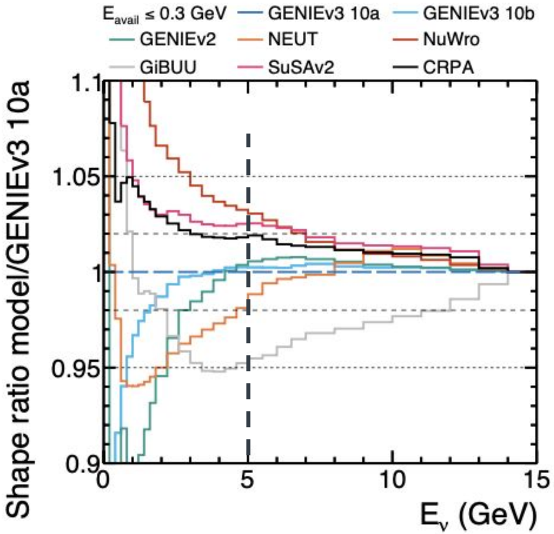
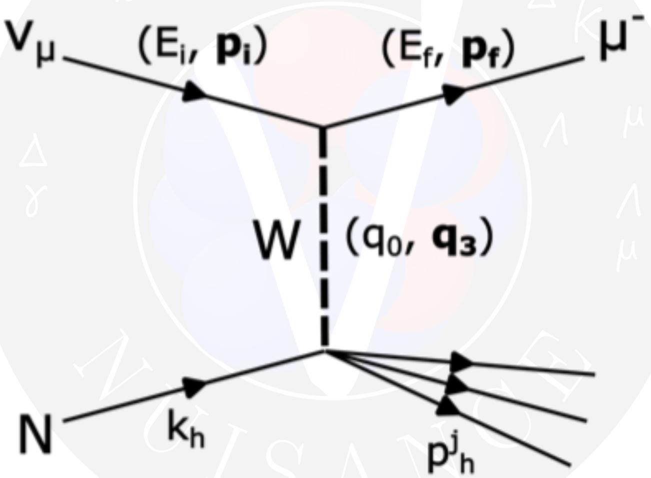
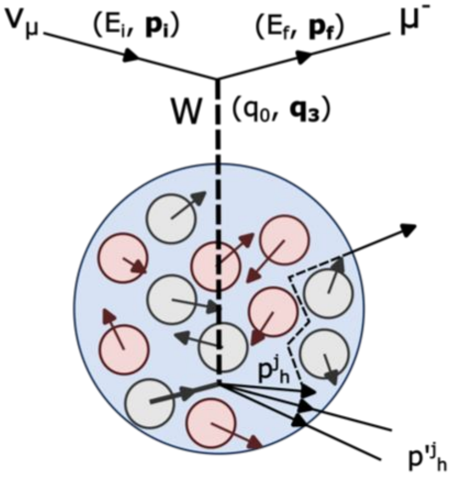


(f) $\bar{\nu}_\mu$–^{40}Ar, $E_{avail} \leq 0.3$ GeV

The Implicit Assumptions





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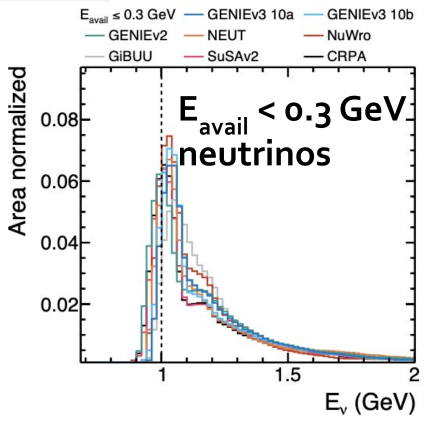
Neutrino Energy Smearing

Still cannot measure $E\nu$



(g) $E_\mu + E_{avail} = 1$ GeV

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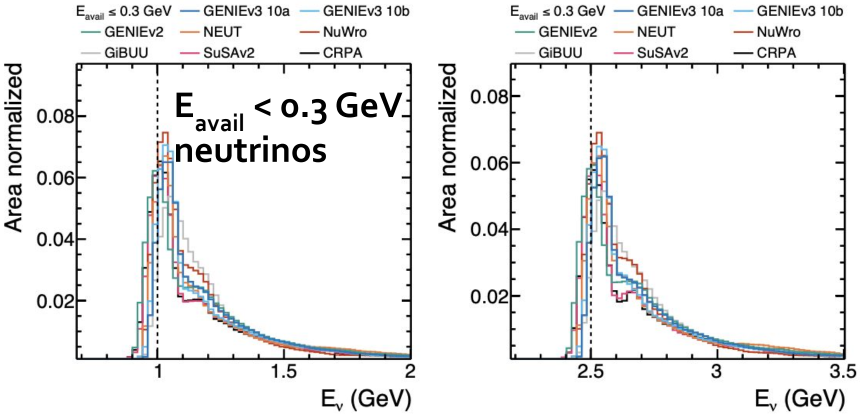

(g) $E_\mu + E_{avail} = 1$ GeV

(h) $E_\mu + E_{avail} = 2.5$ GeV

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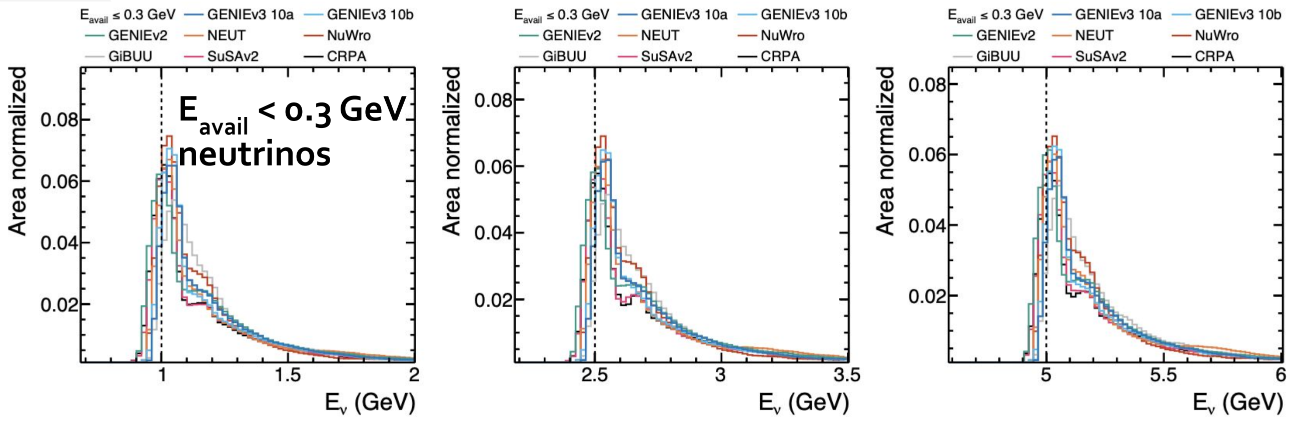
- Will observe significant smearing when trying to bin a Low-q_0 sample to measure the flux shape.



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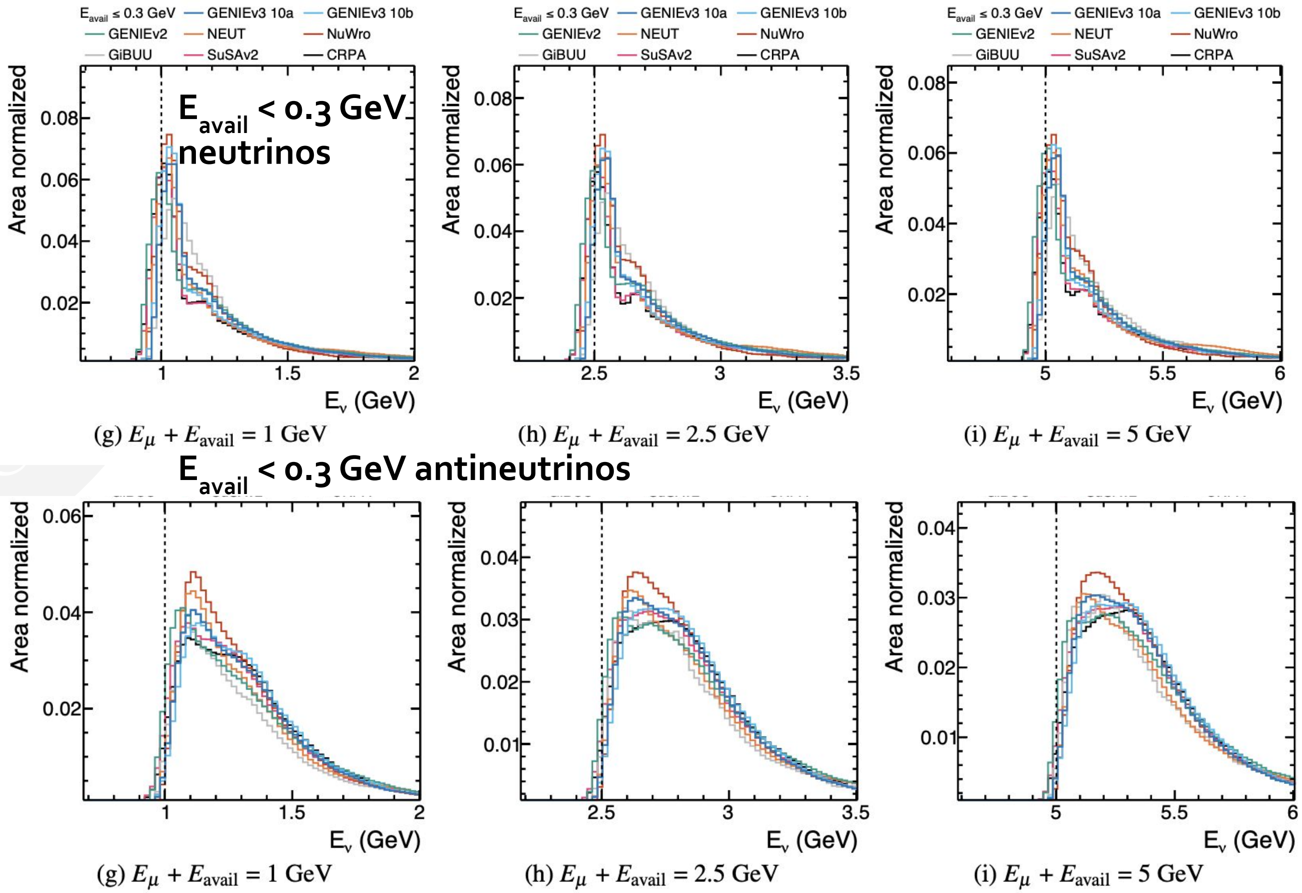

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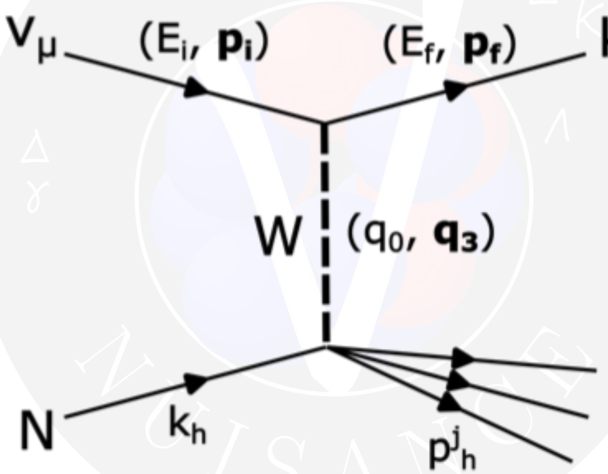

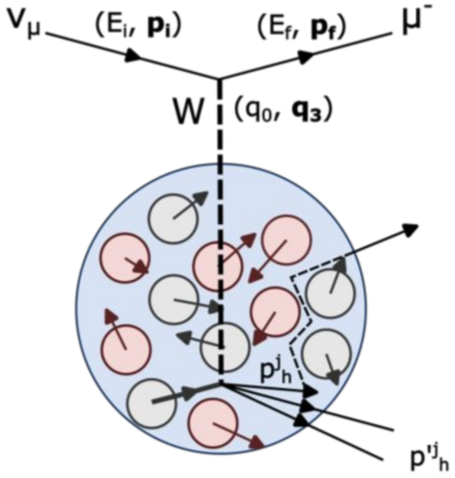

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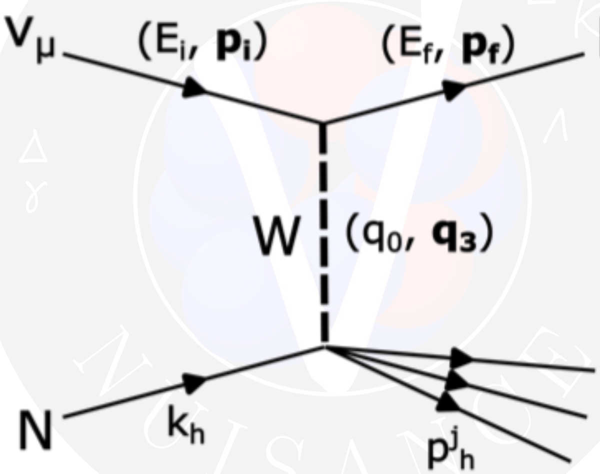

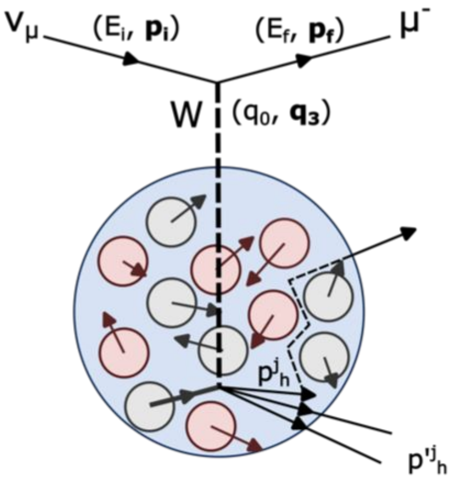

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Conclusions

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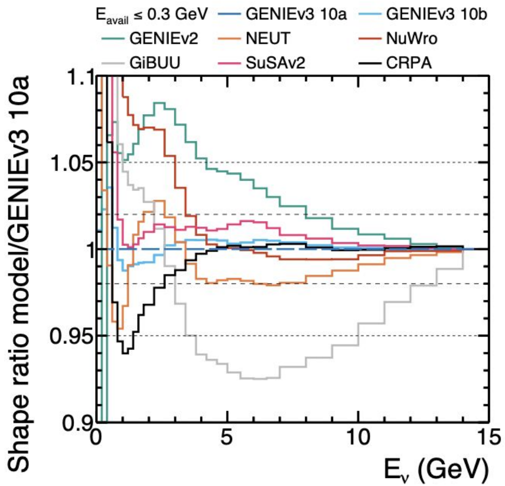

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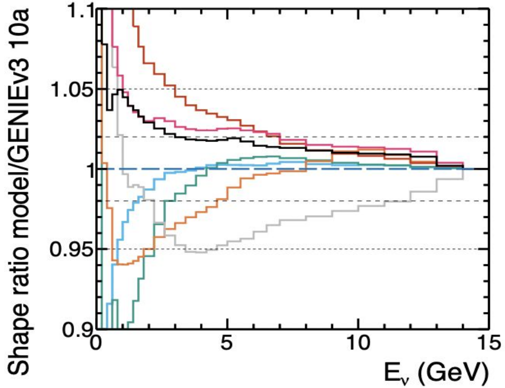

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Conclusions

- Far from relying on well-understood cross-section to detangle flux ⓧ cross-section the "Low-ν" method at low Eν is strongly neutrino interaction and nuclear response model dependent
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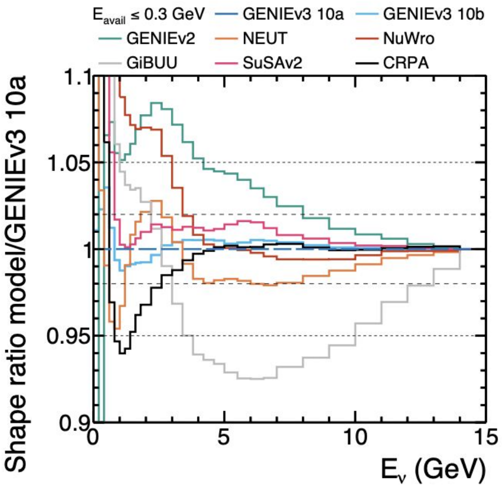
  - A real detector is likely to be even more messy.



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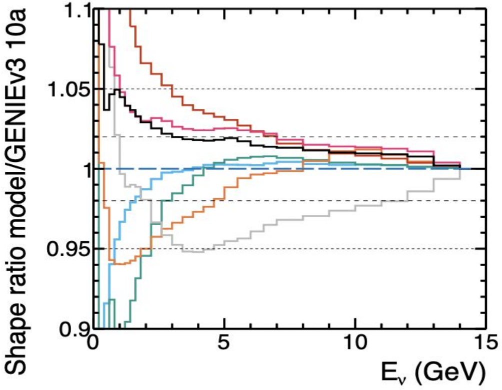

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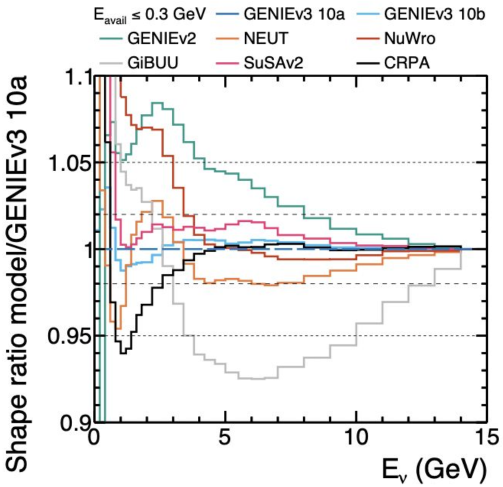
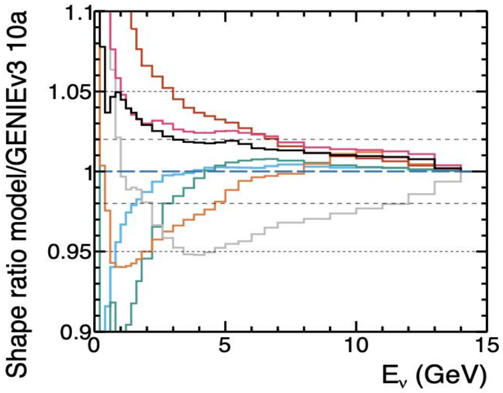
  - A real detector is likely to be even more messy.
- Hadron-production measurements and other *in situ* techniques should be preferred as the main source of flux constraints



(c) ν_μ–^{40}Ar, $E_{\rm avail} \leq 0.3$ GeV



(f) $\bar{\nu}_\mu$–^{40}Ar, $E_{\rm avail} \leq 0.3$ GeV

Thanks For Listening

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The Low-y Success Stories

- CCFR
- NuTeV
- ~NOMAD: Cut EHad < 20 GeV and Enu > 30 GeV