A substandard candle
The low-ν method at few-GeV neutrino energies

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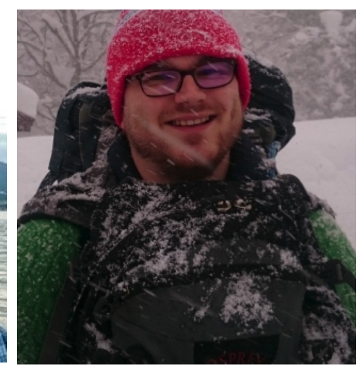
C. Wilkinson, S. Dolan, L. Pickering, C. Wret






Motivation

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

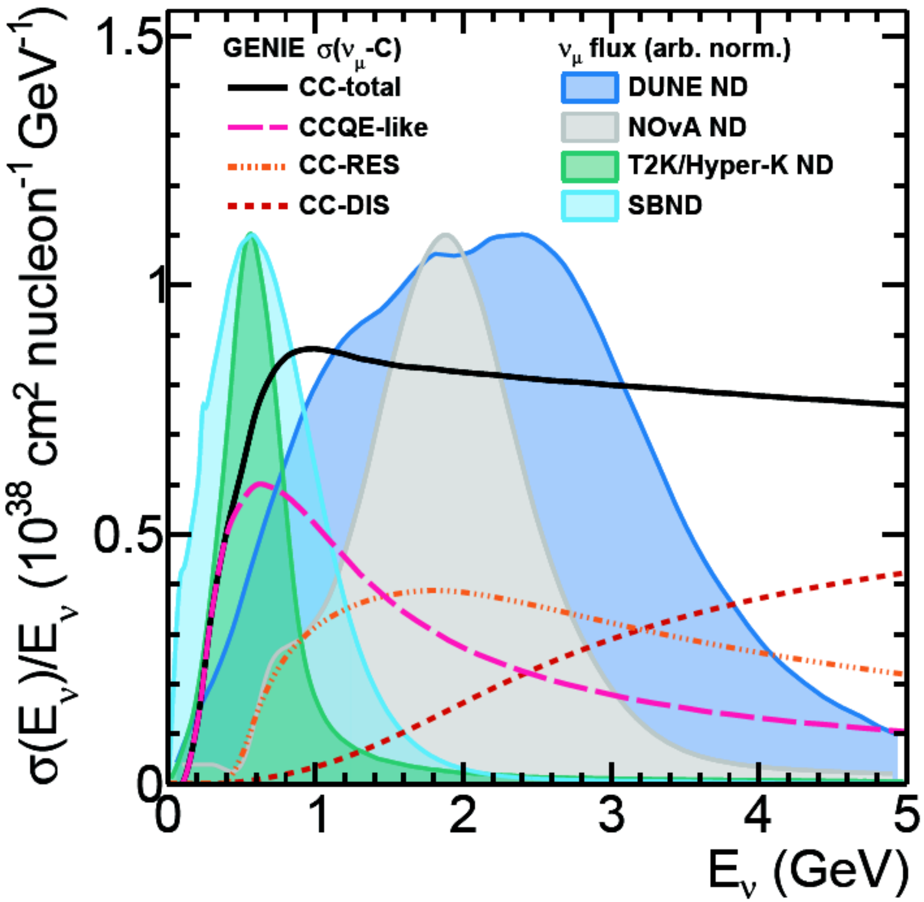
$$R(\vec{\mathbf{x}}) = \overbrace{\underbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}_{} \times P(E_\nu; \nu_A \rightarrow \nu_B)}^{\text{Near}}_{\text{Far}}$$

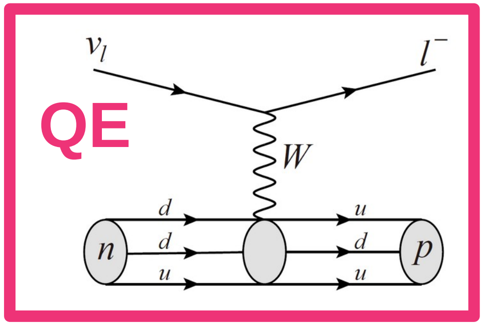
- In general, measure the rate, which convolves flux and XSEC
- Ability to extract information about one relies on assumptions about the other
- Ability to constrain both at the ND is important for ND → FD extrapolation in oscillation experiments

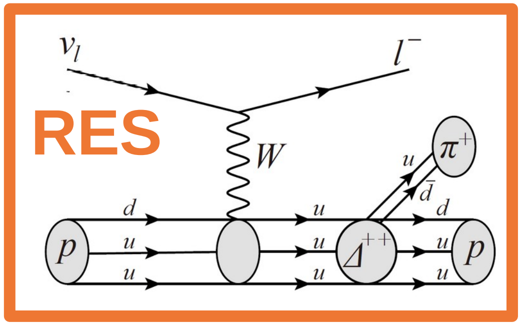
Motivation

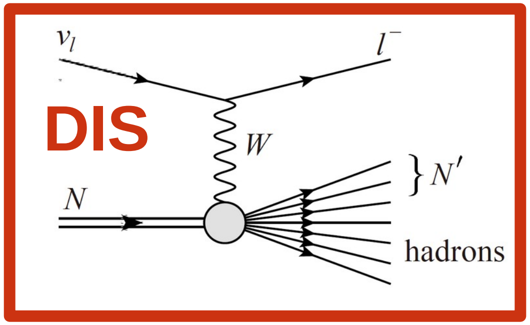
Challenging to measure flux or XSEC independently:

- Large a priori uncertainties
- Broad E_ν range in beam
- Multiple interaction processes
- Measureable states convolved by nuclear effects









Standard candles?

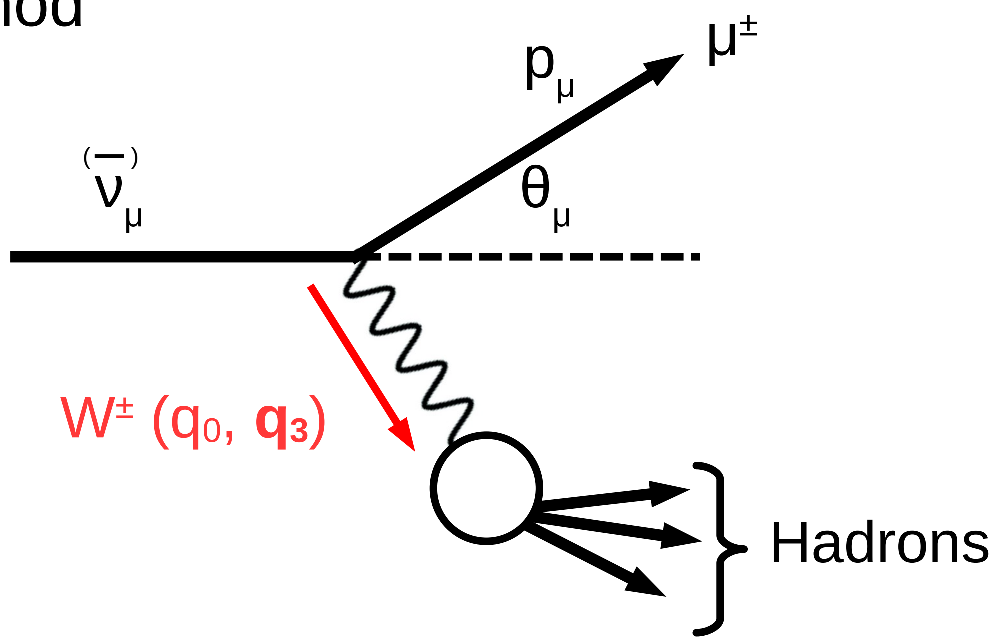
Potential for specific channels with known XSEC to break this degeneracy

Powerful beams at current and future experiments make small signals accessible

- $\nu+e \rightarrow \nu+e$ elastic scattering
- Inverse muon decay: $\nu_\mu + e \rightarrow \mu + \nu_e$
- Isolating hydrogen samples
- **The low-ν technique**
- **…?**

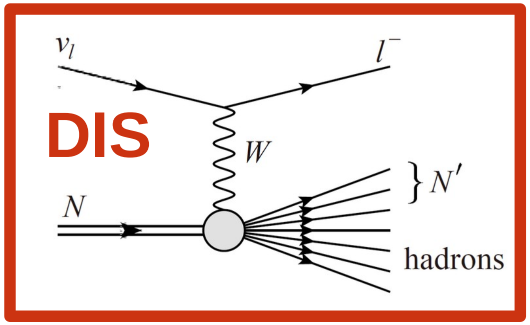
A note on terminology: what is ν?

- An overloaded character in neutrino physics!
- Different communities denote energy transfer to the hadronic system with ν/ω/q_0
- Here I will use "q_0" for the quantity and low-ν for the method



The low-ν method [1,2]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_0} = \frac{G_\mathrm{F}^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu} \left[F_2 \mp x F_3 \right] + \frac{q_0}{2E_\nu^2} \left[\frac{M x (1 - R_\mathrm{L})}{1 + R_\mathrm{L}} F_2 \right] + \frac{q_0^2}{2E_\nu^2} \left[\frac{F_2}{1 + R_\mathrm{L}} \mp x F_3 \right] \right) \mathrm{d}x$$



- Comes from the observation that if $q_0/E_\nu << 1$, the cross section is approximately constant with E_ν
- The rate as a function of E_ν gives acces to the flux *shape*
- Very closely linked to the “low-y” ($y = q_0/E_\nu$) method [2]

[1] S. R. Mishra in Workshop on Hadron Structure Functions and Parton Distributions, 84 , p84. World Scientific, 1990

[2] R. Belusevic and D. Rein Phys. Rev. D 38 (1988) 2753–2757

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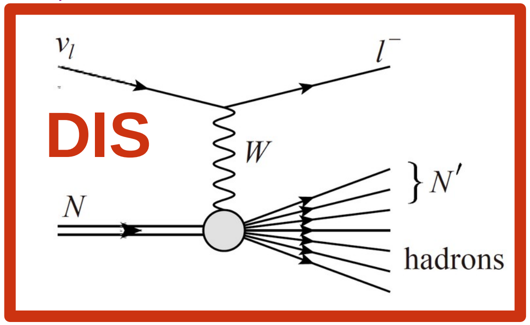

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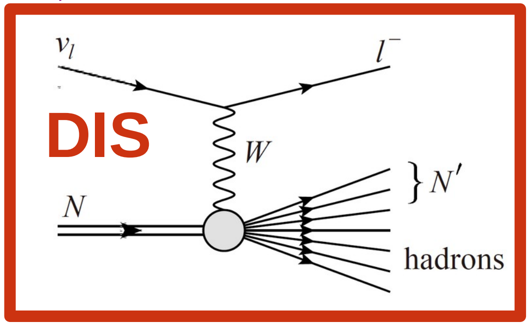
Implicit assumptions

$$\frac{d\sigma}{dq_0} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{q_0}{E_\nu} [F_2 \mp xF_3] + \frac{q_0}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{q_0^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} \mp xF_3 \right] \right) dx$$



The method works iff:

1) The above equation describes the cross section well

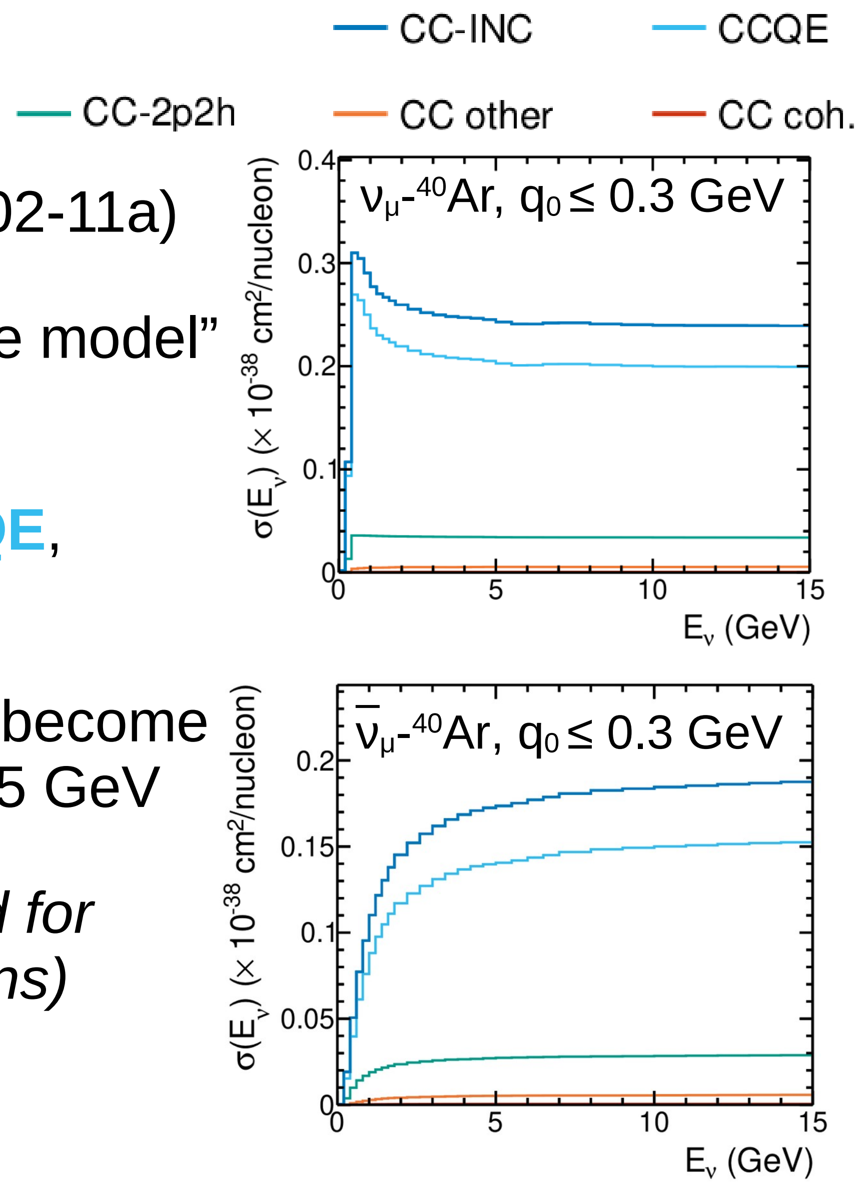
2) A sample with low q_0 can be experimentally selected

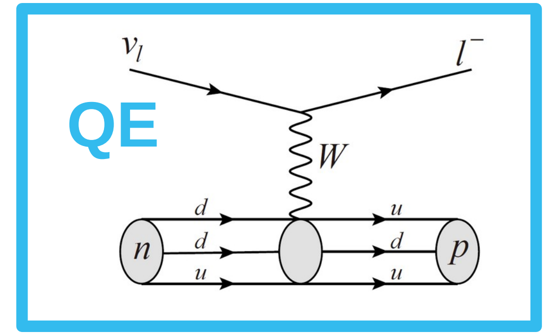
3) E_ν can be accurately reconstructed for that sample

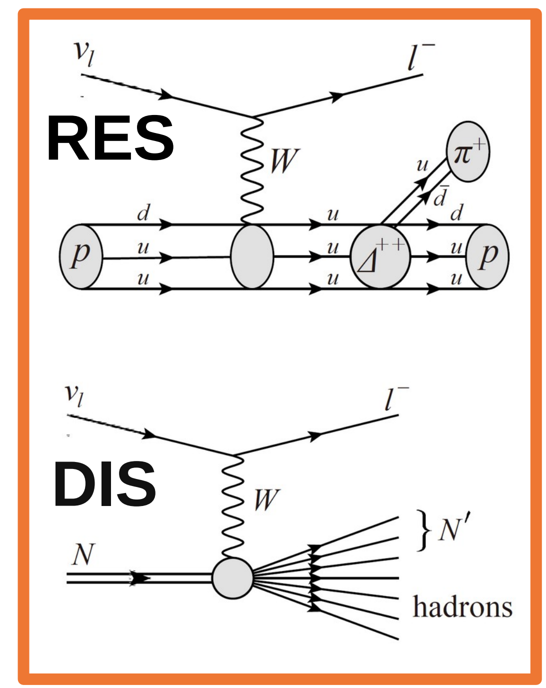
Is the cross section well described?

- GENIEv3 (10a-02-11a)
- A common "base model" for experiments
- Dominated by **QE**, **2p2h**, and **RES**
- XSEC does not become constant until ≥ 5 GeV

(Also studied for hydrocarbons)







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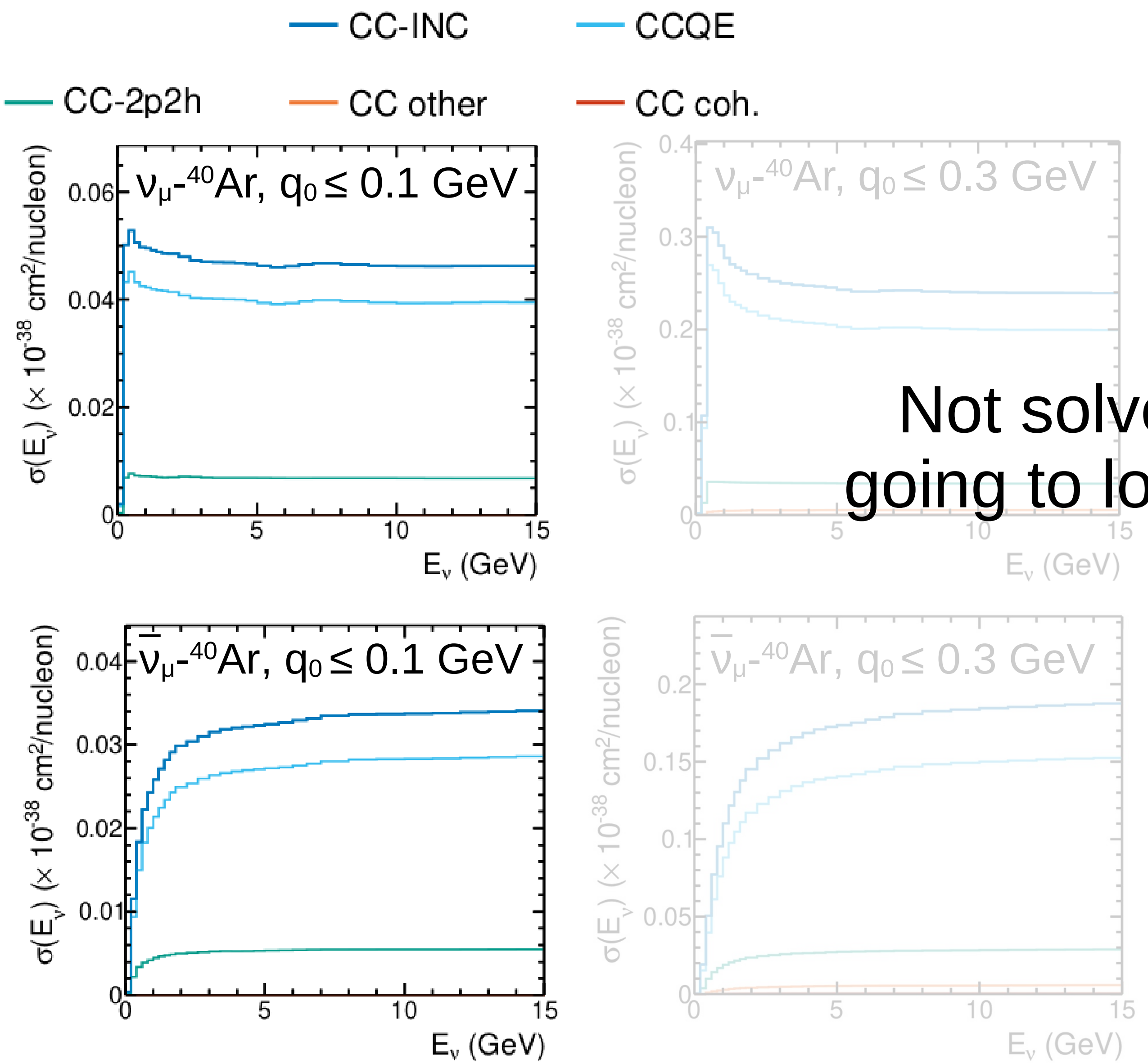
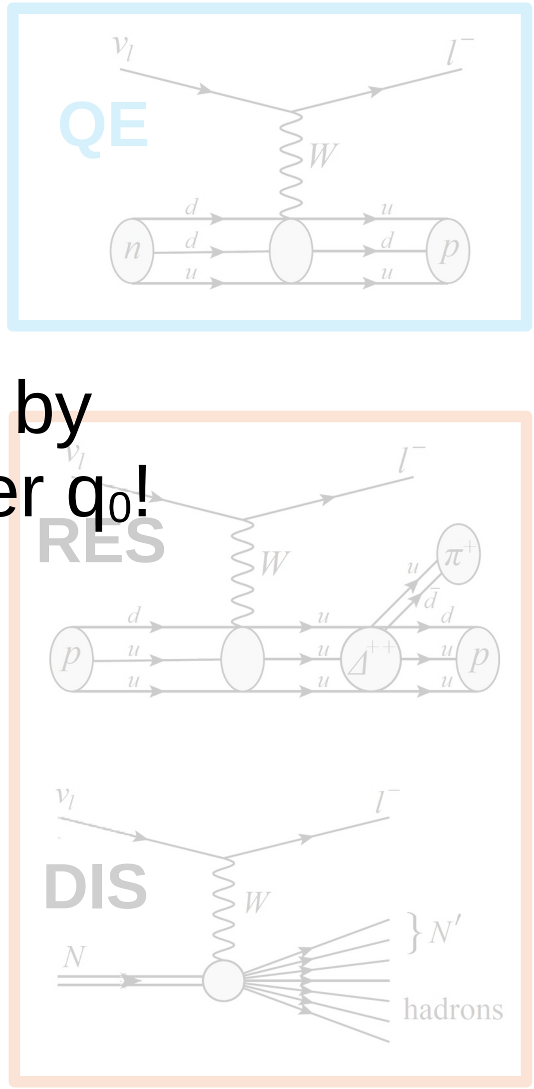
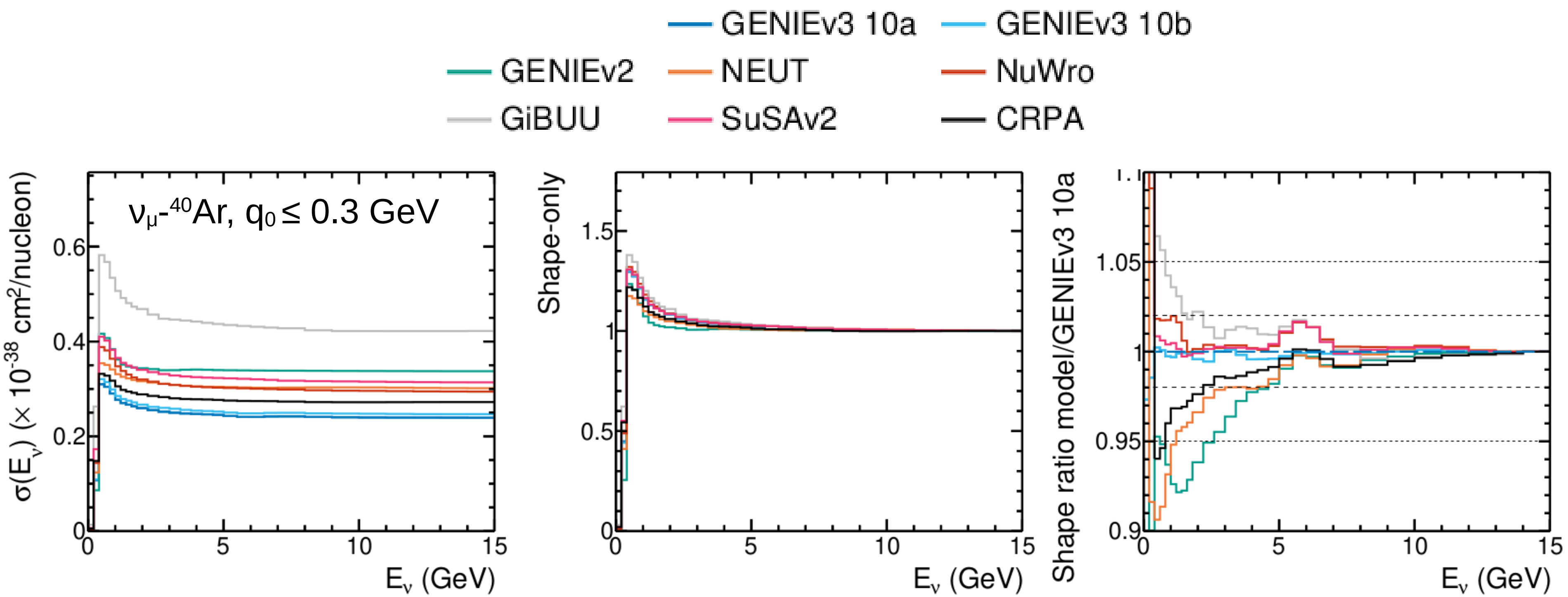




Not solved by going to lower q_0!

Is the cross section well described?



Compare a variety of new/commonly used generator models

Normalize to a fixed point at high energy – where q_0/E_ν corrections are smallest

Take a ratio w.r.t a reference model

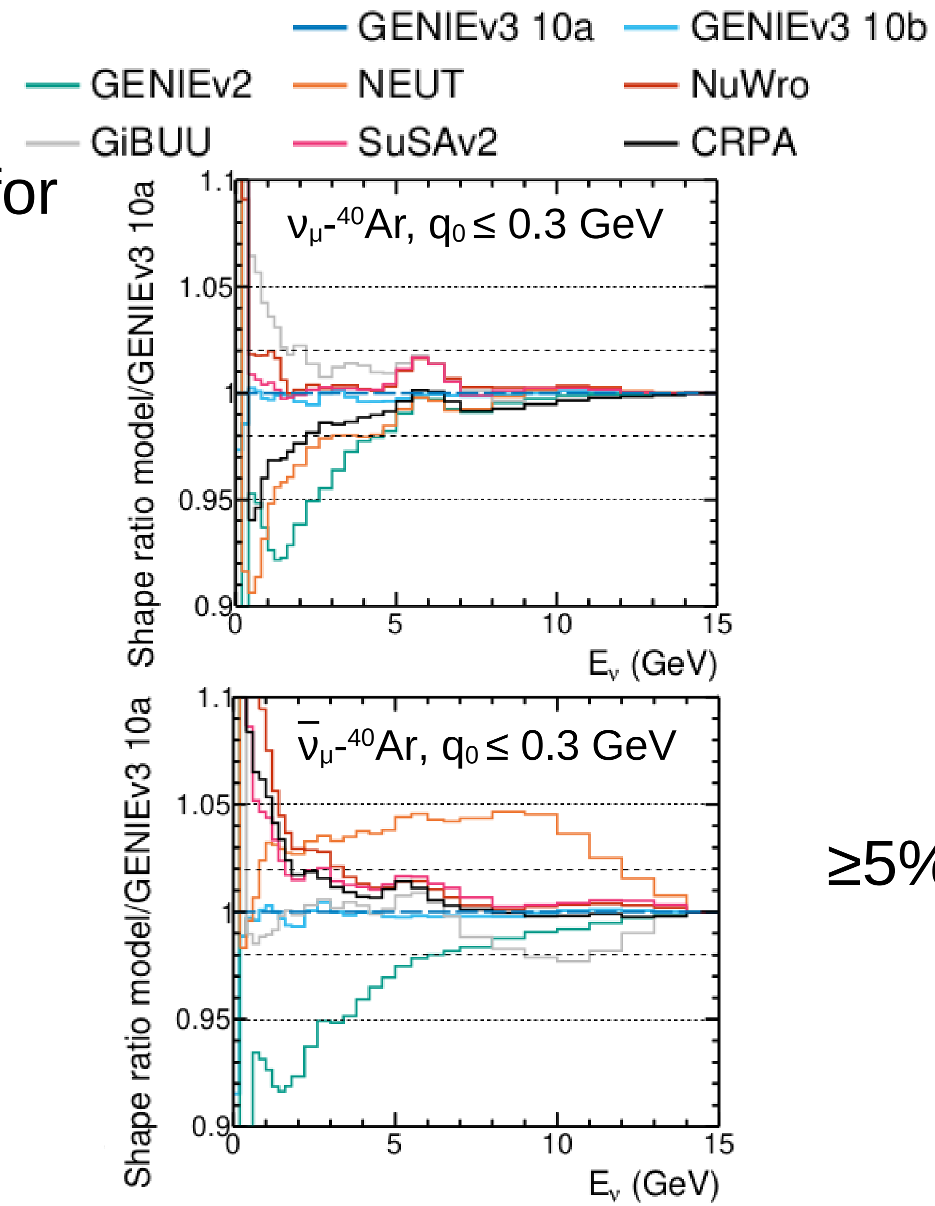
Aside: XSEC models used

Use a variety of reasonable model predictions to investigate potential for bias:

- **GENIEv2** – used in many published results
- **GENIEv3 10a** and **GENIEv3 10b** – currently used by many active experiments (10a vs 10b have different FSI models)
- **SUSAv2** and **CRPA**: state-of-the-art nuclear response modeling for pionless events (implemented in GENIE ~v3.2.0)
- **NEUT**: used by T2K
- **NuWro**: performs well w.r.t. world cross-section data
- **GiBUU**: sophisticated hadron-transport, different neutrino–nucleon model, also performs well in world data comparisons

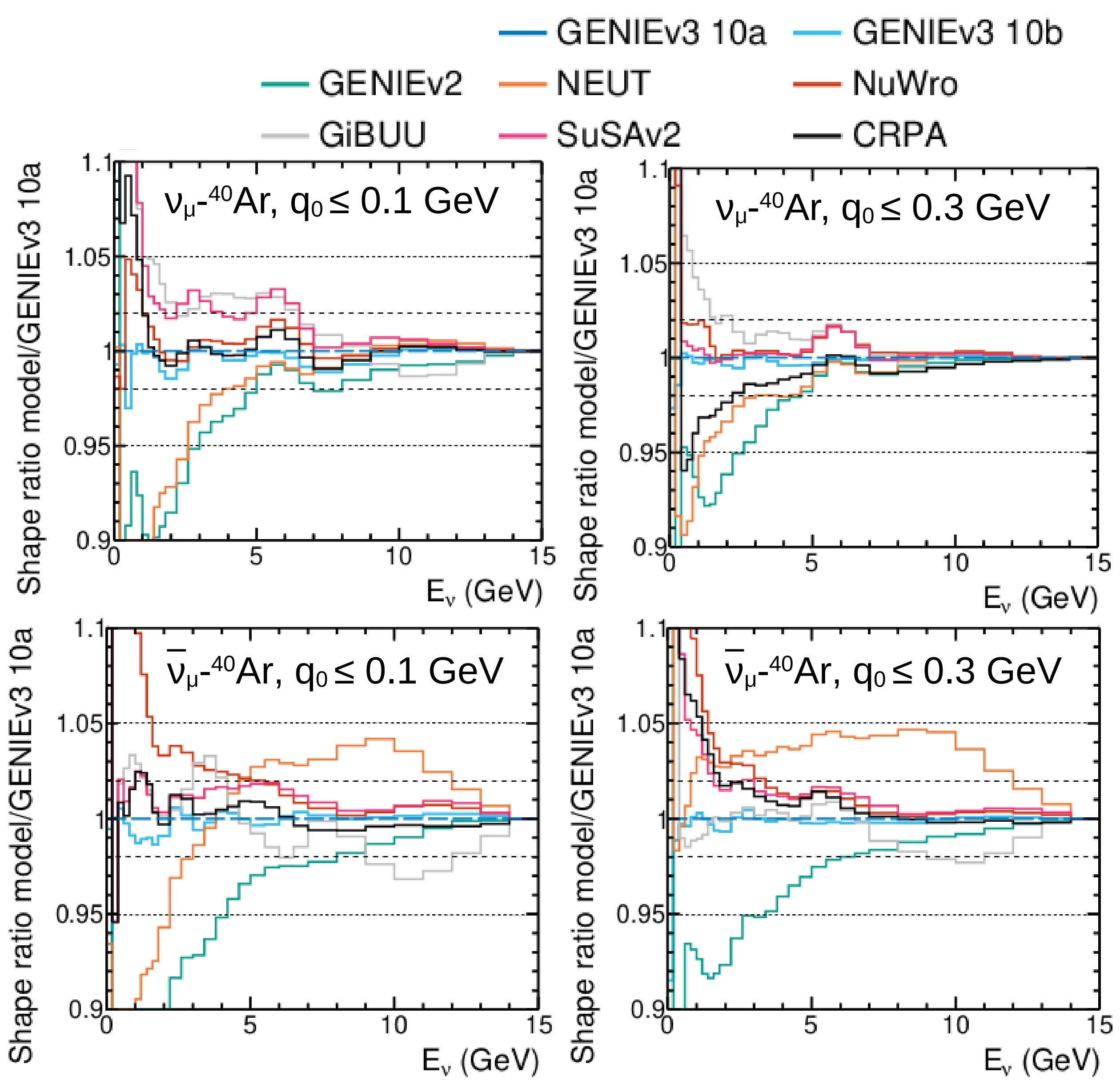
Is the cross section well described?

≥2% differences for $E_\nu \leq 5$ GeV



≥5% differences for $E_{\bar{\nu}} \leq 12$ GeV

Is the cross section well described?

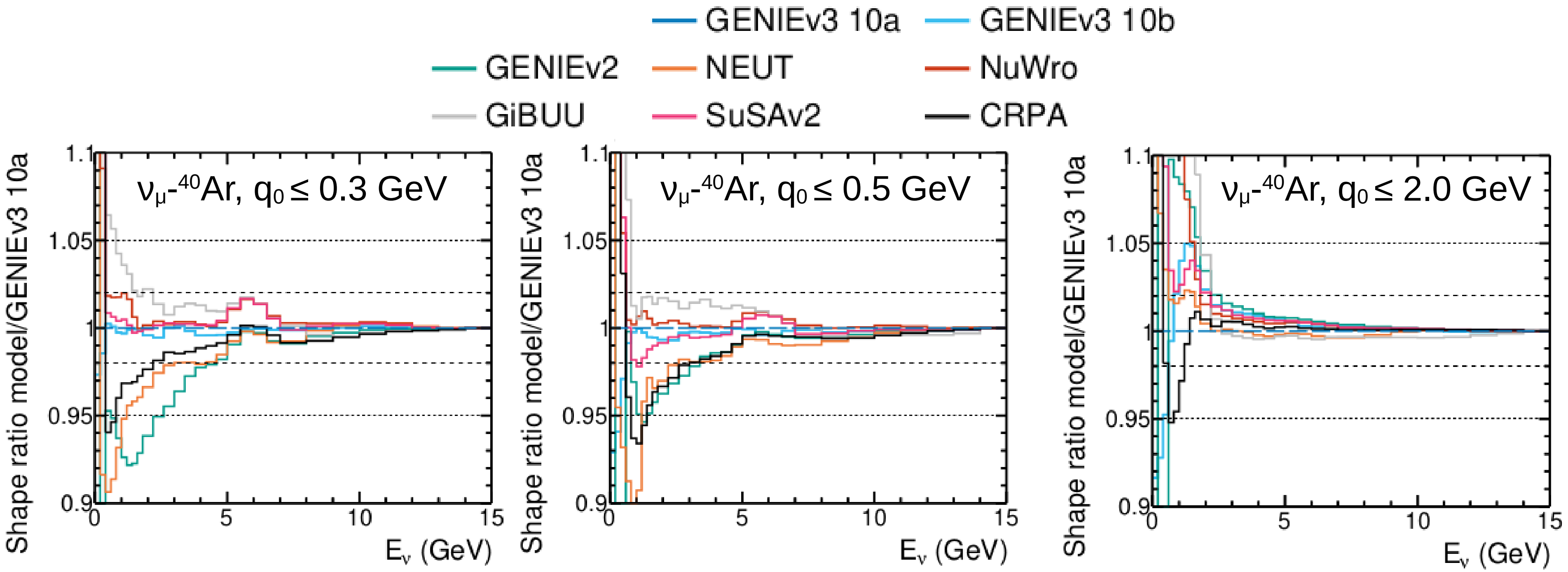


Situation not improved by going to a lower q_0 cut!

Is the cross section well described?

Counterintuitive(?) improvement at higher q_0

Larger model differences in the region low-ν isolates!



Implicit assumptions

The method works iff:

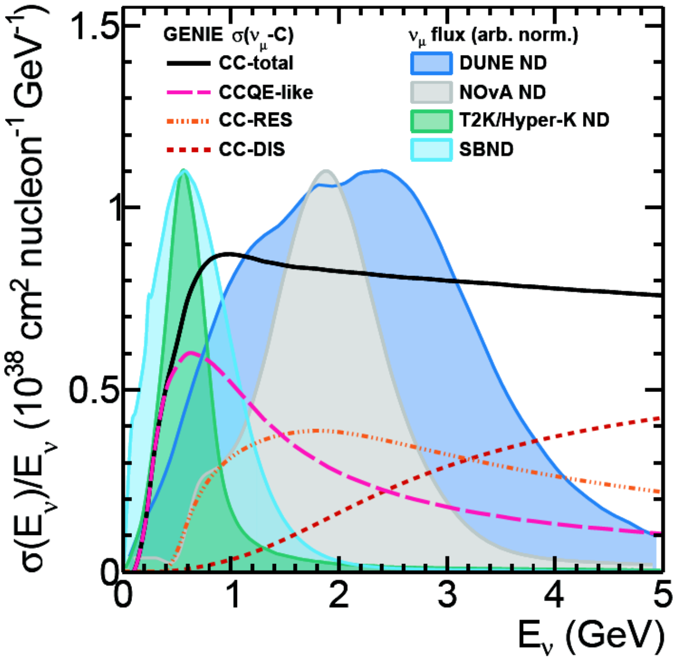
1) ~~The above equation describes the cross section well~~

2) A sample with low q_0 can be experimentally selected

3) E_ν can be accurately reconstructed for that sample

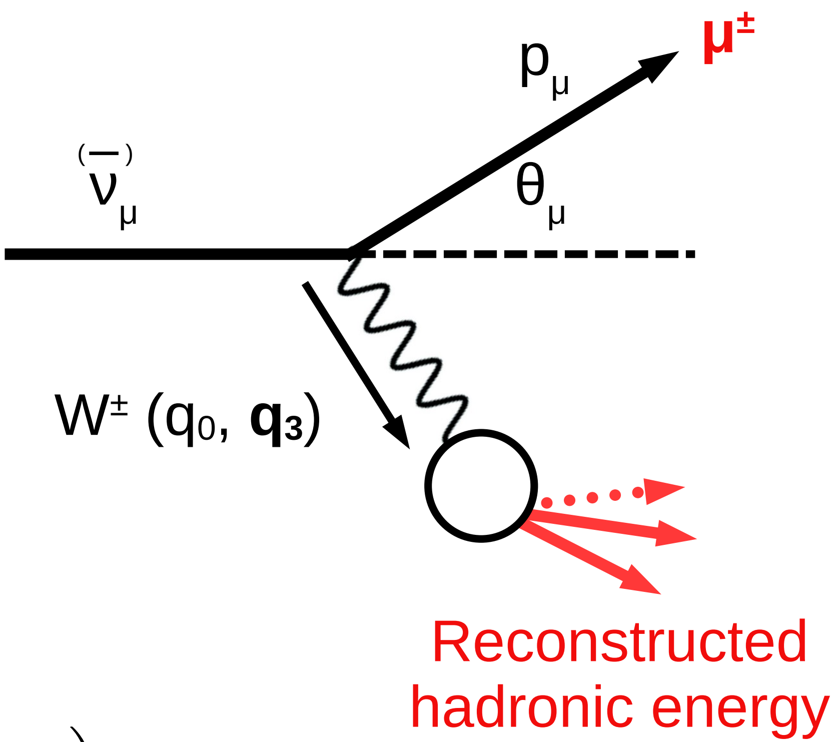
Non-trivial corrections – **the model matters** at low E_ν and q_0

True for region of interest of current/future LBL experiments



Can a low-q_0 sample be experimentally selected?

- Neutrino energy not known
- Not all hadrons are visible (detector dependent)
- Relevant, complex, nuclear dynamics
- I'll show two variables here:



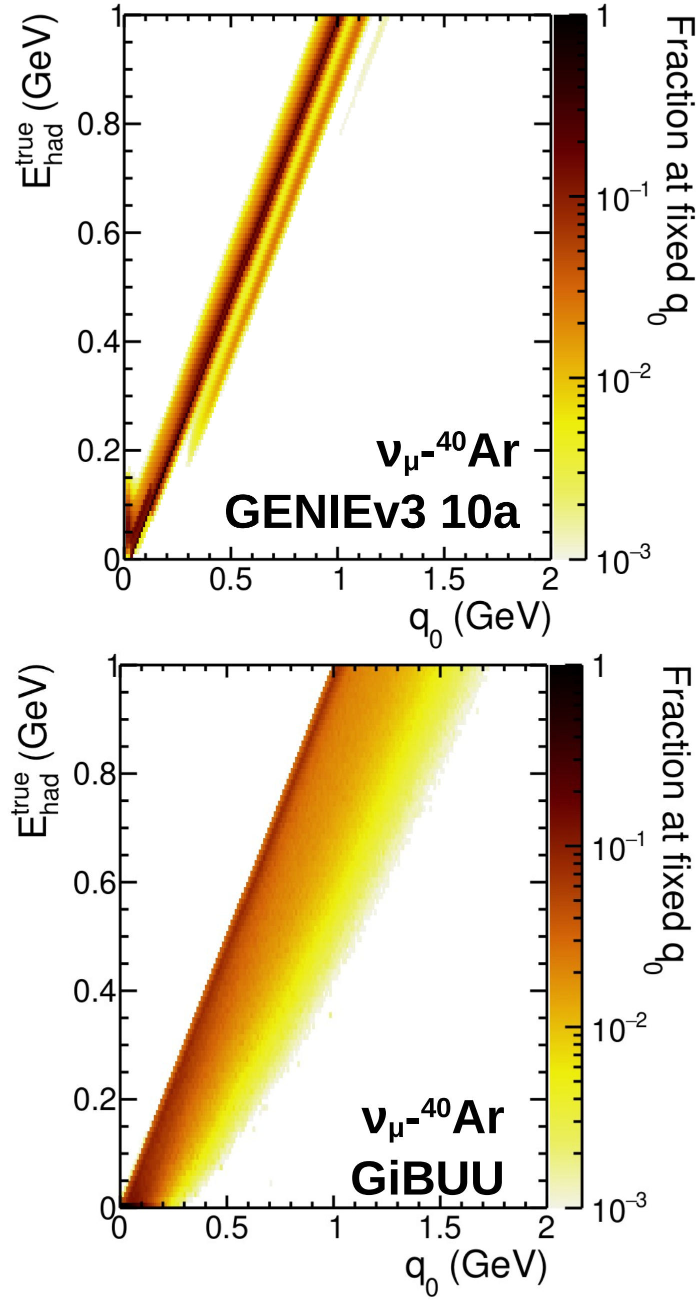
1) $$E_{\mathrm{had}}^{\mathrm{true}} = \Big(\sum_{i=n,p} E_{\mathrm{kin}}^{i}\Big) + \Big(\sum_{i=\pi^\pm,\pi^0,\gamma} E_{\mathrm{total}}^{i}\Big)$$ **Perfect!**

2) $$E_{\mathrm{had}}^{\mathrm{reco}} = \Big(\sum_{i=p} E_{\mathrm{kin}}^{i}\Big) + \Big(\sum_{i=\pi^\pm,\pi^0,\gamma} E_{\mathrm{total}}^{i}\Big)$$ **Miss neutrons**

Can a low-q_0 sample be experimentally selected?

- Even with perfect reco, complex $q_0 \leftrightarrow E_{had}$ relationship
- **Cannot infer q_0 without assuming a model!**

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

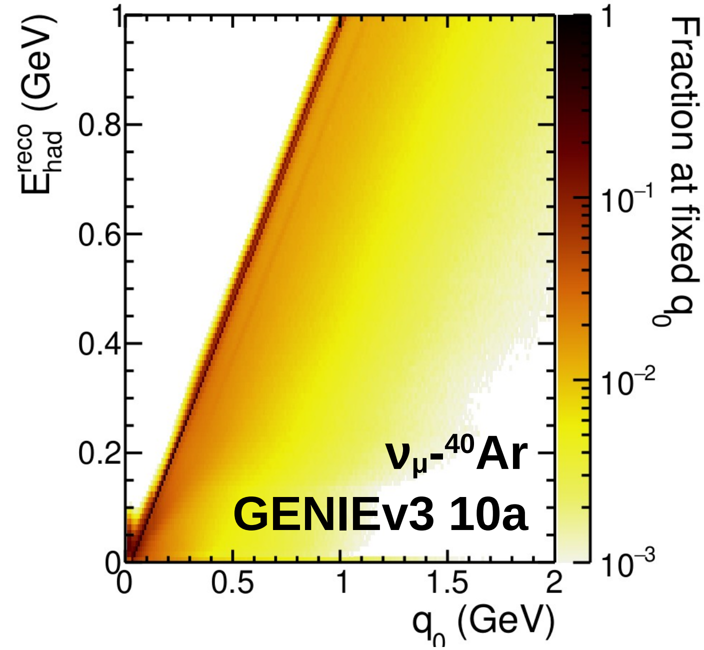


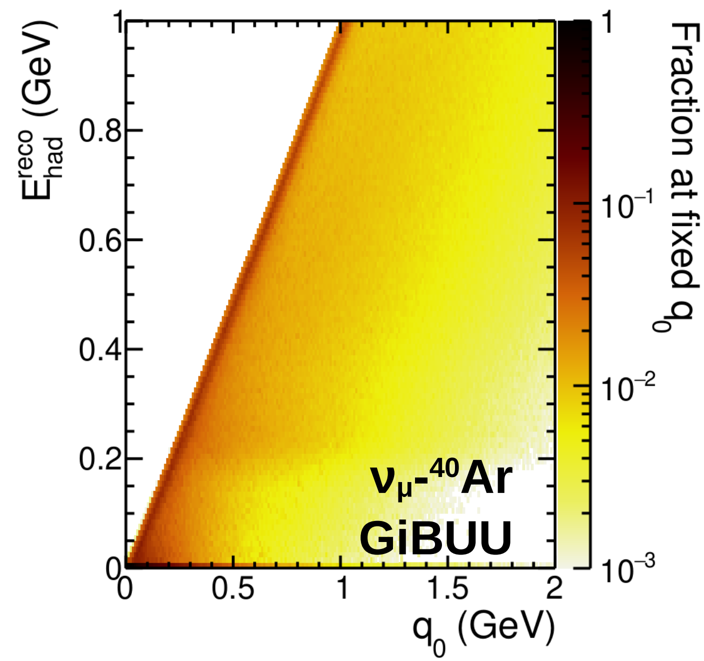
Can a low-q_0 sample be experimentally selected?

- Most detectors cannot recover energy lost to neutrons
- Significantly increases the smearing between $q_0 \leftrightarrow E_{\mathrm{had}}$

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

Situation worsens considerably if pion misreconstruction is considered: EPJC 82 (2022) 9, 808





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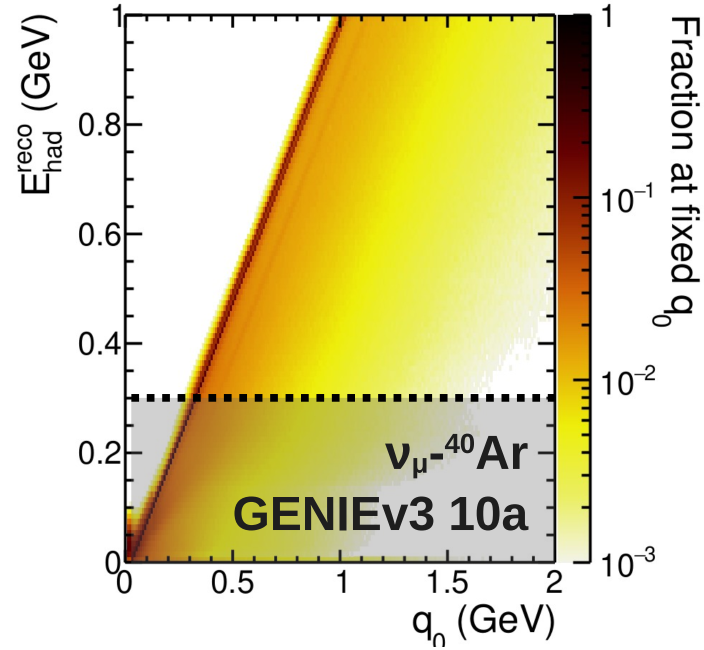
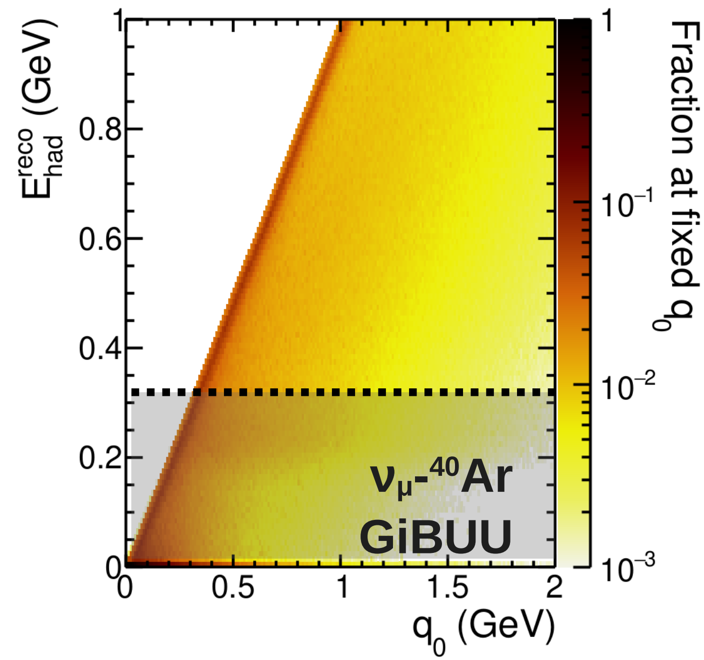
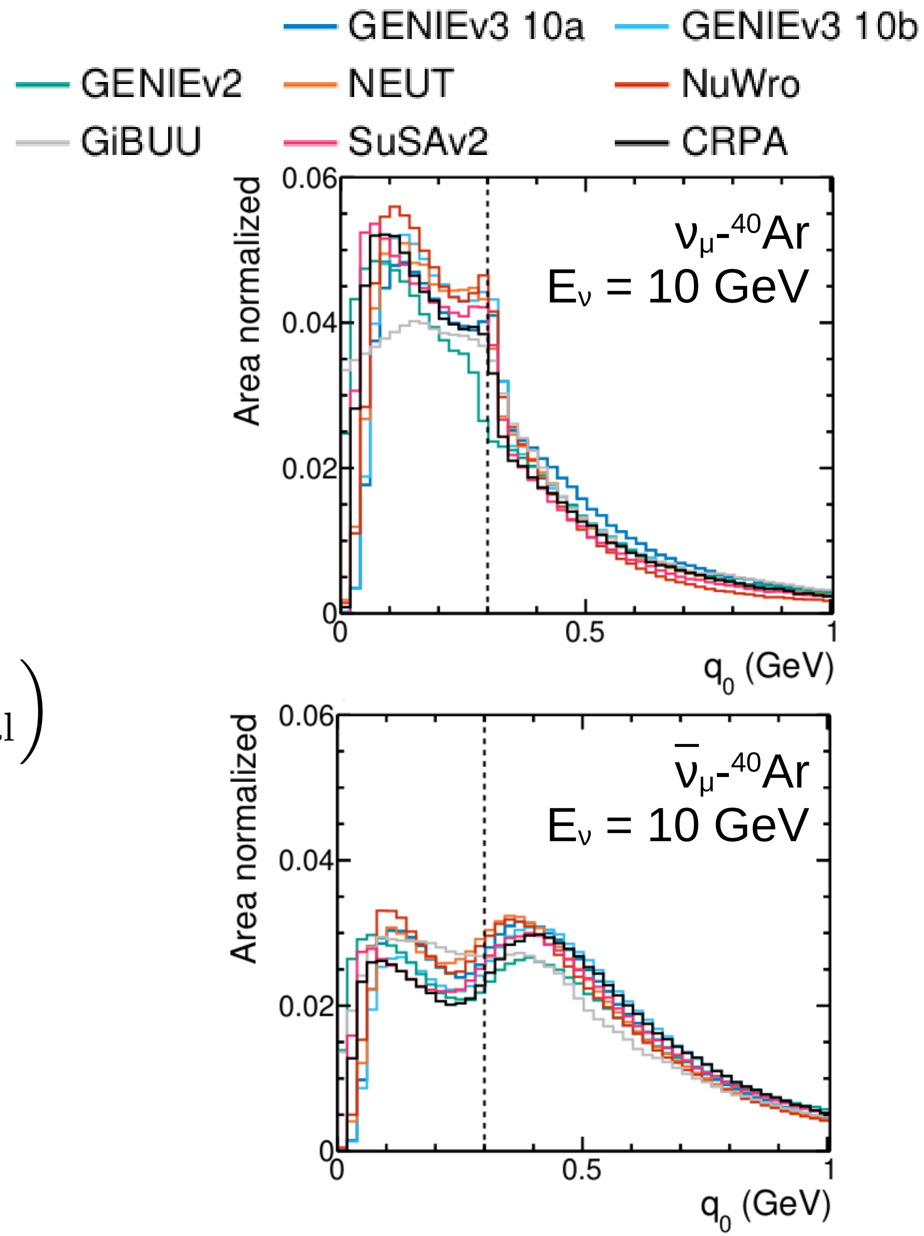




Can a low-q_0 sample be experimentally selected?

- Difficult to isolate a low-q_0 sample
- Different $q_0 \leftrightarrow E_{had}$ for different models
- More challenging for antineutrinos due to higher neutron content

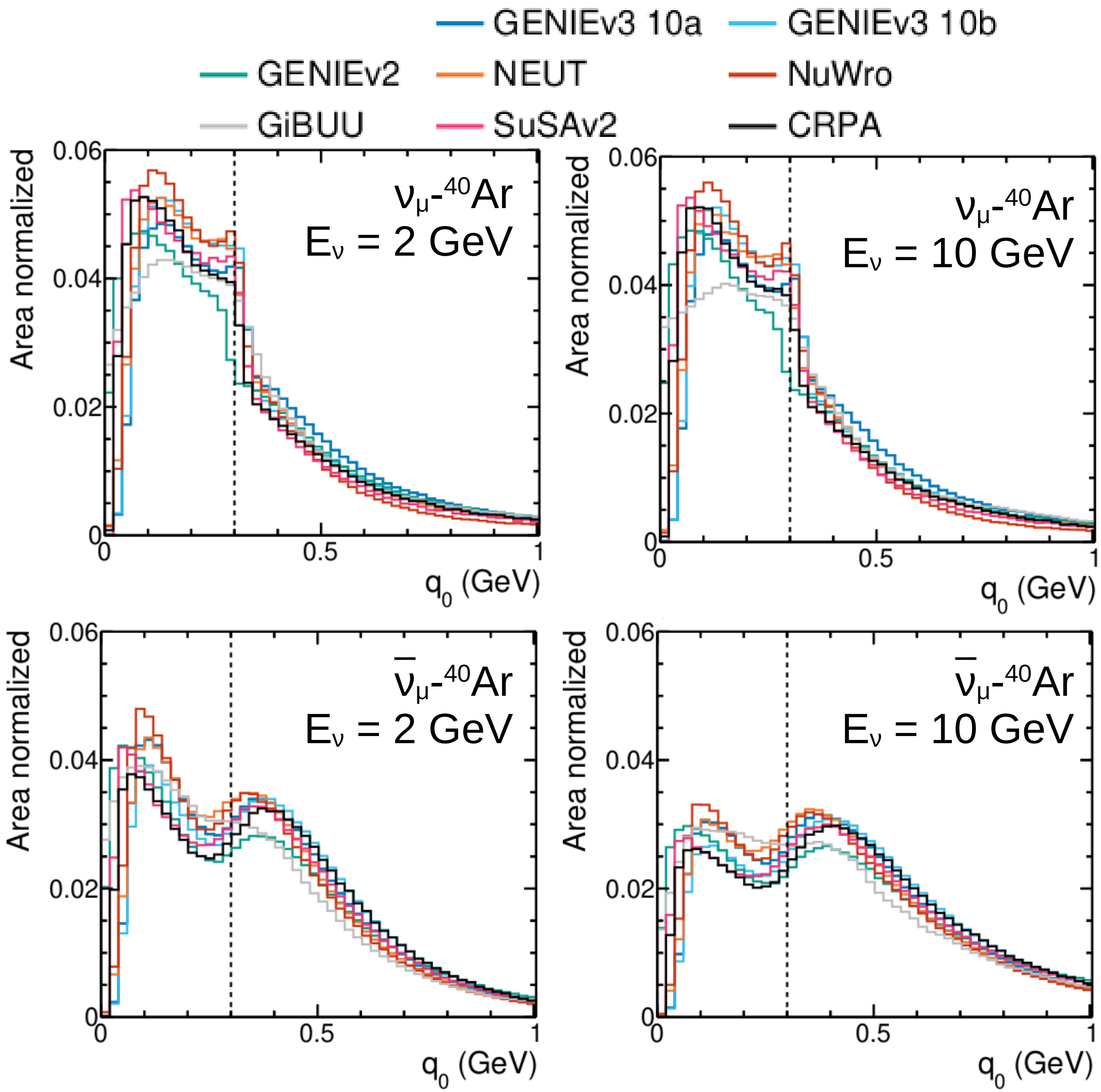
$$E_{\text{had}}^{\text{reco}} = \Big(\sum_{i=p} E_{\text{kin}}^{i}\Big) + \Big(\sum_{i=\pi^{\pm},\pi^{0},\gamma} E_{\text{total}}^{i}\Big)$$



Can a low-q_0 sample be experimentally selected?

Cut on $E_{HAD} \leq 0.3$ GeV

Smearing is not constant with E_ν, particularly for antineutrino!



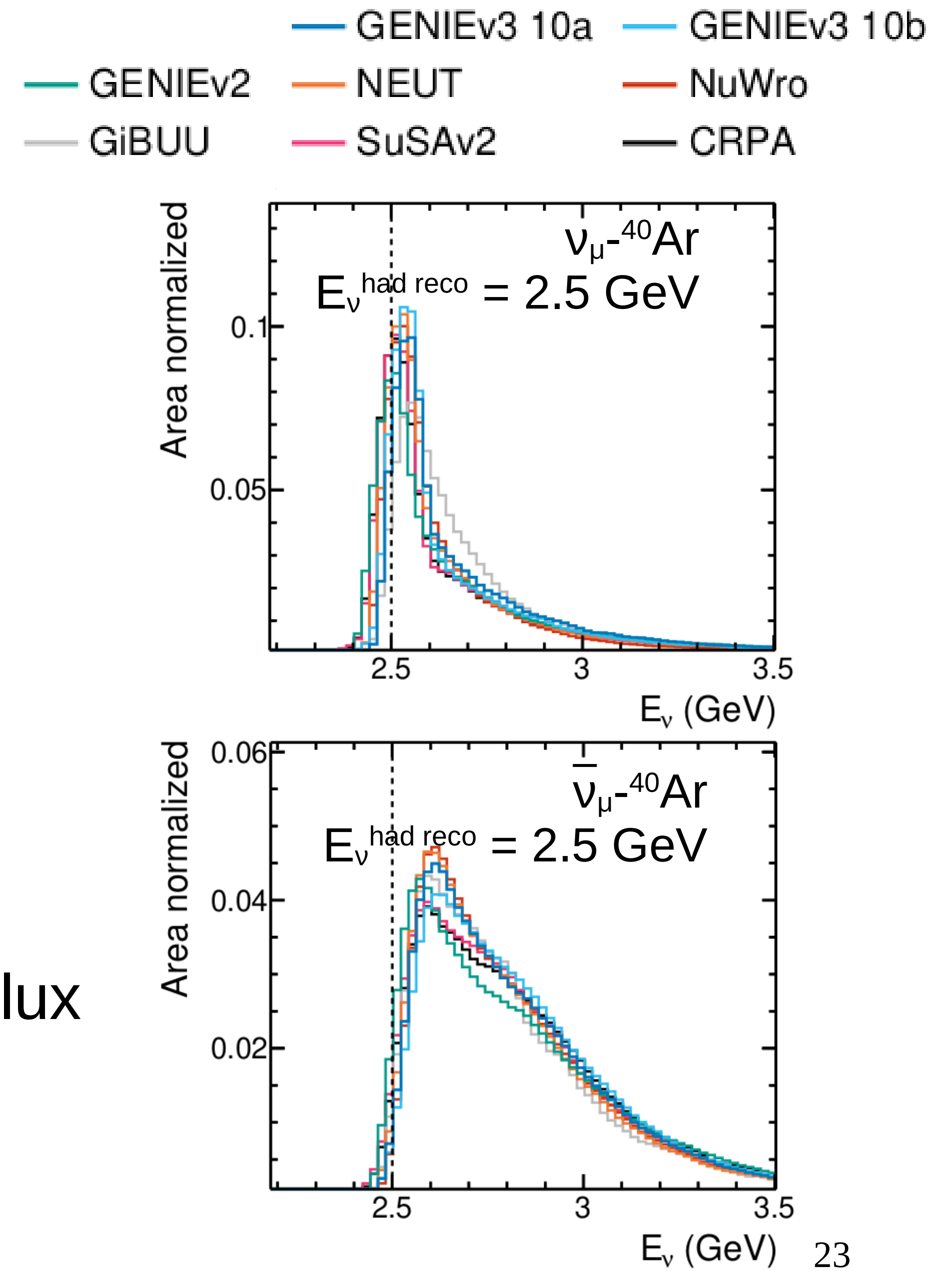
Can E_ν be reconstructed?

- Neutrino energy not known!
- Reconstructed from muon + the hadronic system
- The same caveats apply!

1) $$E_\nu^{\text{had true}} = E_\mu + E_{\text{had}}^{\text{true}}$$

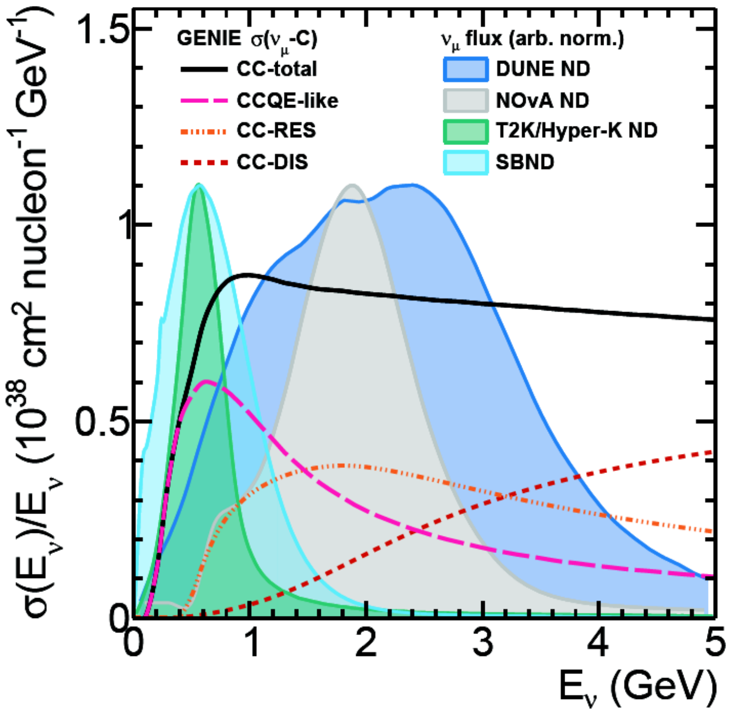
2) $$E_\nu^{\text{had reco}} = E_\mu + E_{\text{had}}^{\text{reco}}$$

Additional challenge to extract the flux with the low-ν method → model dependence



Conclusions

- The low-ν method relies on three assumptions that are interaction and/or nuclear model dependent
- Few percent or larger biases seen for $E_\nu \leq 5$ GeV or $E_{\bar{\nu}} \leq 12$ GeV, even for a perfect detector → reality will be worse
- **Not a standard candle for the few-GeV accelerator program**



Back to the future

PHYSICAL REVIEW D VOLUME 38, NUMBER 9 1 NOVEMBER 1988

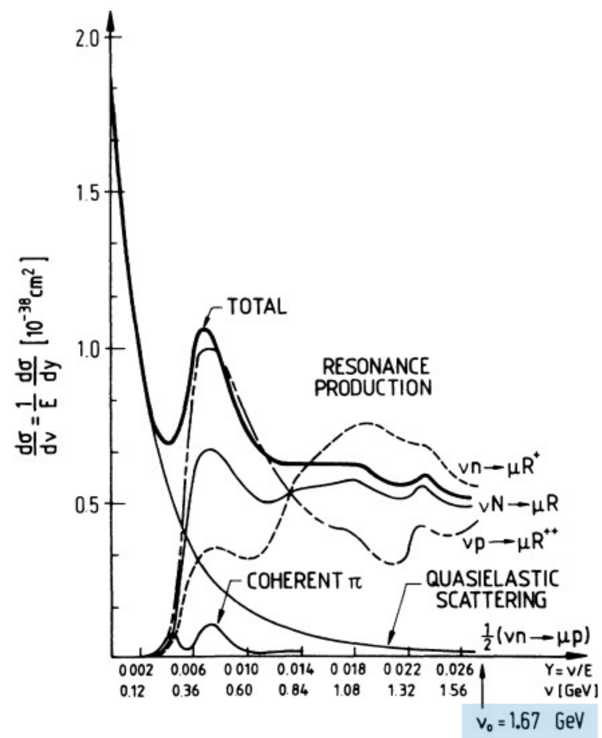
Neutrino reactions in the low-*y* region

R. Belusevic
Department of Physics, University College, University of London, London WC1E 6BT, United Kingdom

D. Rein
III. Physikalisches Institut, Rheinisch-Westfälische Technische Hochschule Aachen, D-5100 Aachen, Federal Republi

(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, quasi-elastic 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.



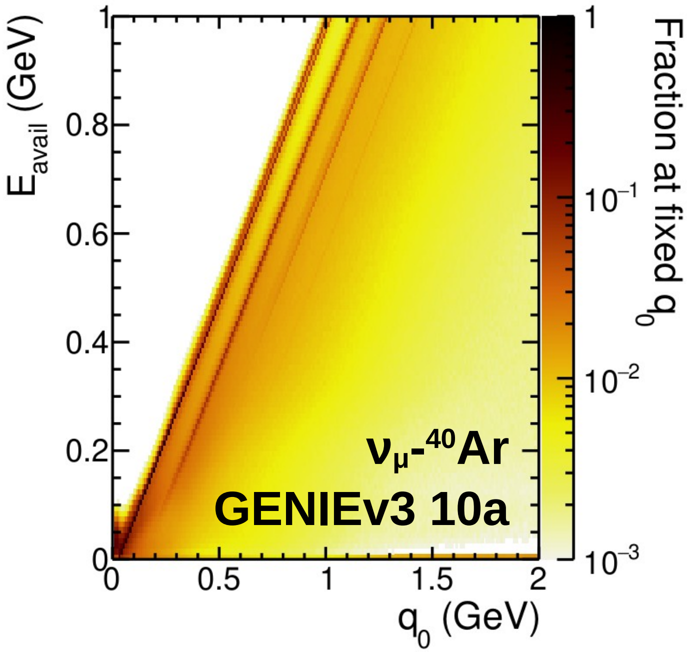
Concluded that low-q_0 effects mean that the low-y (q_0/E_ν) XSEC is energy dependent for E_ν < 20 GeV

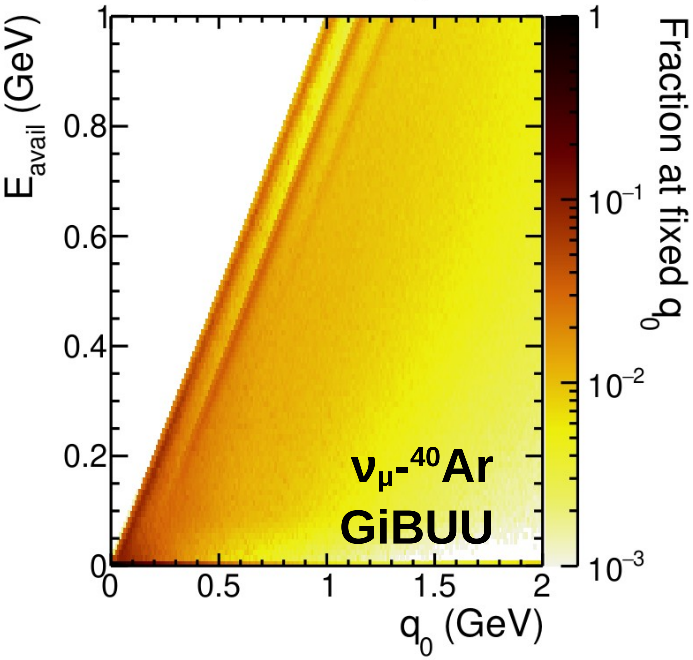
Backup

Can a low-q_0 sample be experimentally selected?

- Many detectors will mis-ID *some* pions as protons, missing the pion mass
- Here consider the case where all charged pions are mis-ID-ed

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





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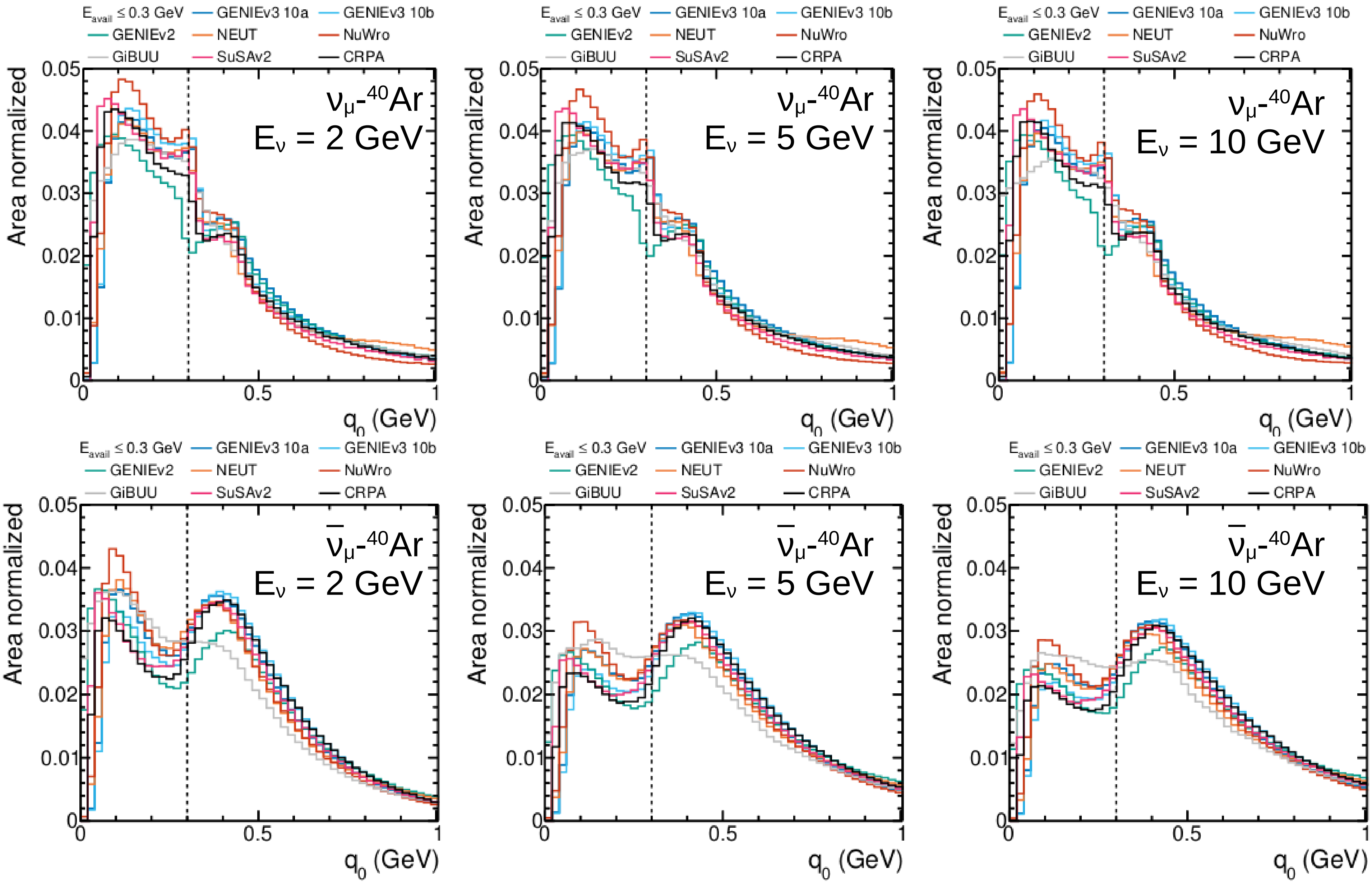

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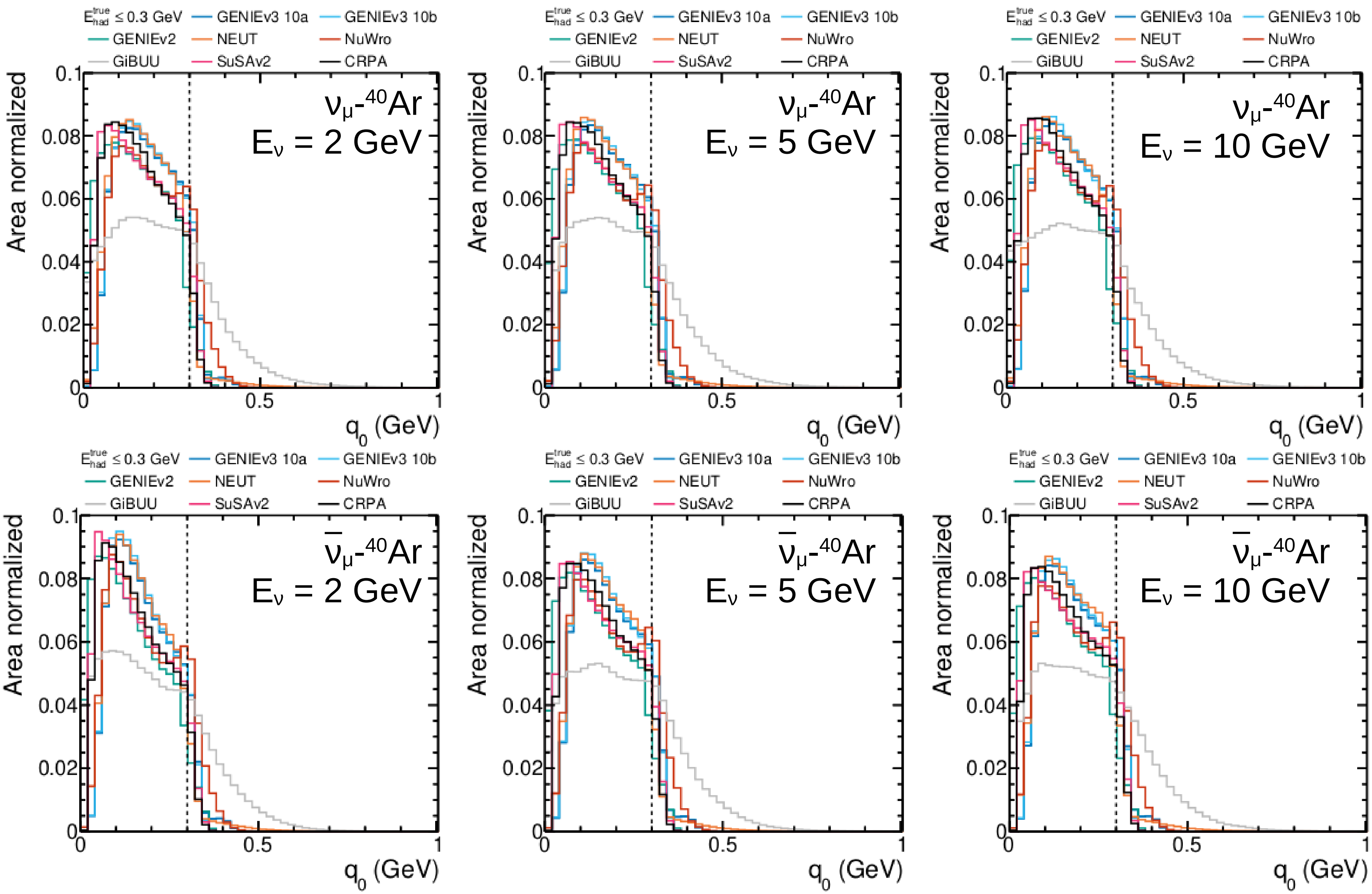
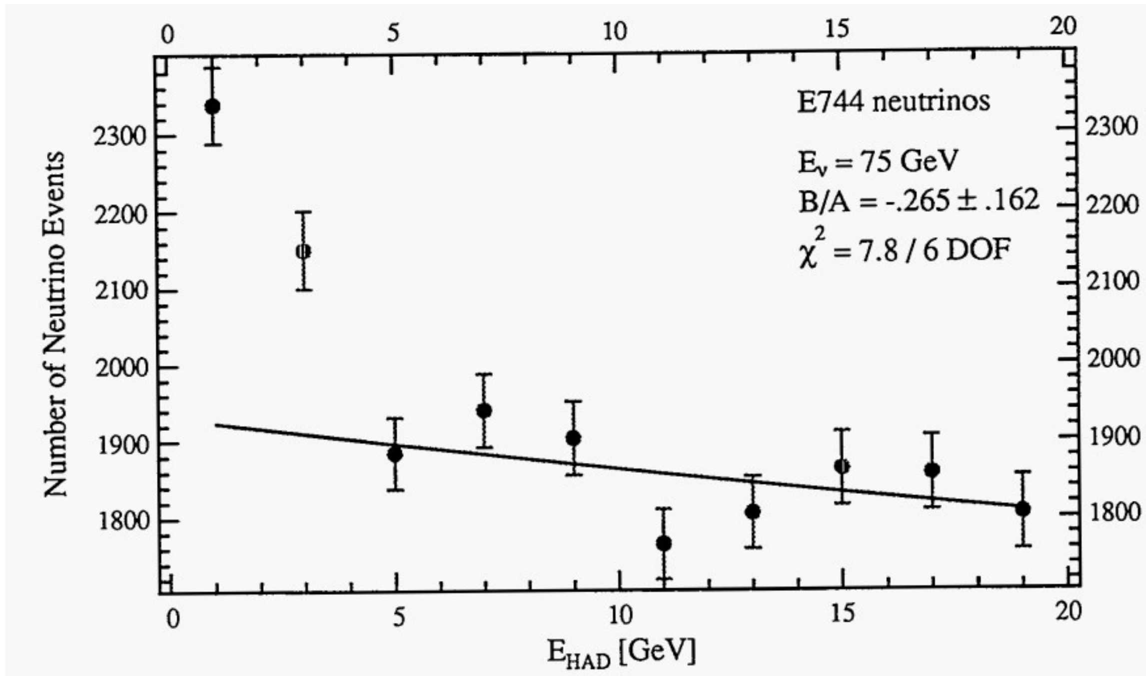


CCFR analysis

W. G. Seligman. PhD thesis,
Nevis Labs, Columbia U., 1997



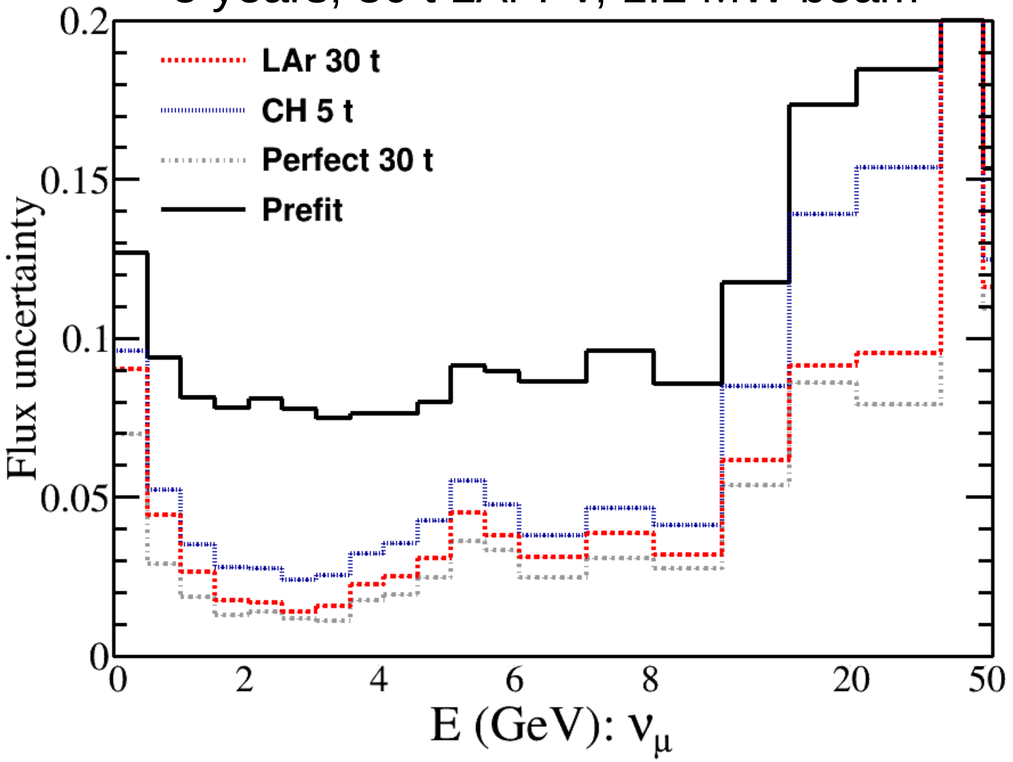
- CCFR use low-ν for $30 \le E_\nu \le 360$ GeV
- E_{HAD} is their q_0 proxy, and their low-ν sample is $E_{HAD} \le 20$ GeV
- To estimate the q_0/E_ν correction, they exclude $E_{HAD} \le 4$ GeV because resonant events don't have the correct scaling

Neutrino-electron elastic scattering

- The known, but small, cross section can be used to constrain the flux. ~5000 LAr ND events/year

- A powerful additional tool for achieving DUNE's sensitivities, and resolving flux ↔ cross section ambiguities

5 years, 30 t LAr FV, 1.2 MW beam



PRD 101, 032002 (2020)

$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}}$$

- Strong normalization contraint due to known XSEC

- Weak shape constraint due to detector smearing and beam divergence

Is the cross section well described?