Neutrino-Nucleus Scattering

at the GeV Scale

Jonathan Paley (Fermilab)

COMHEP 2021
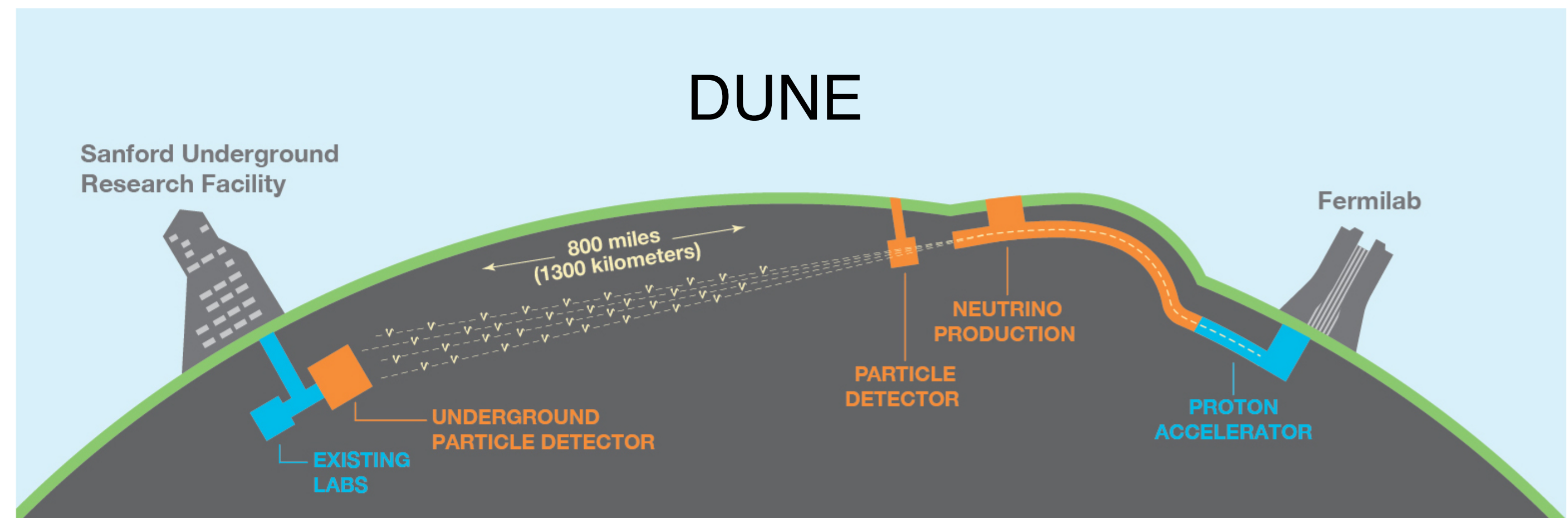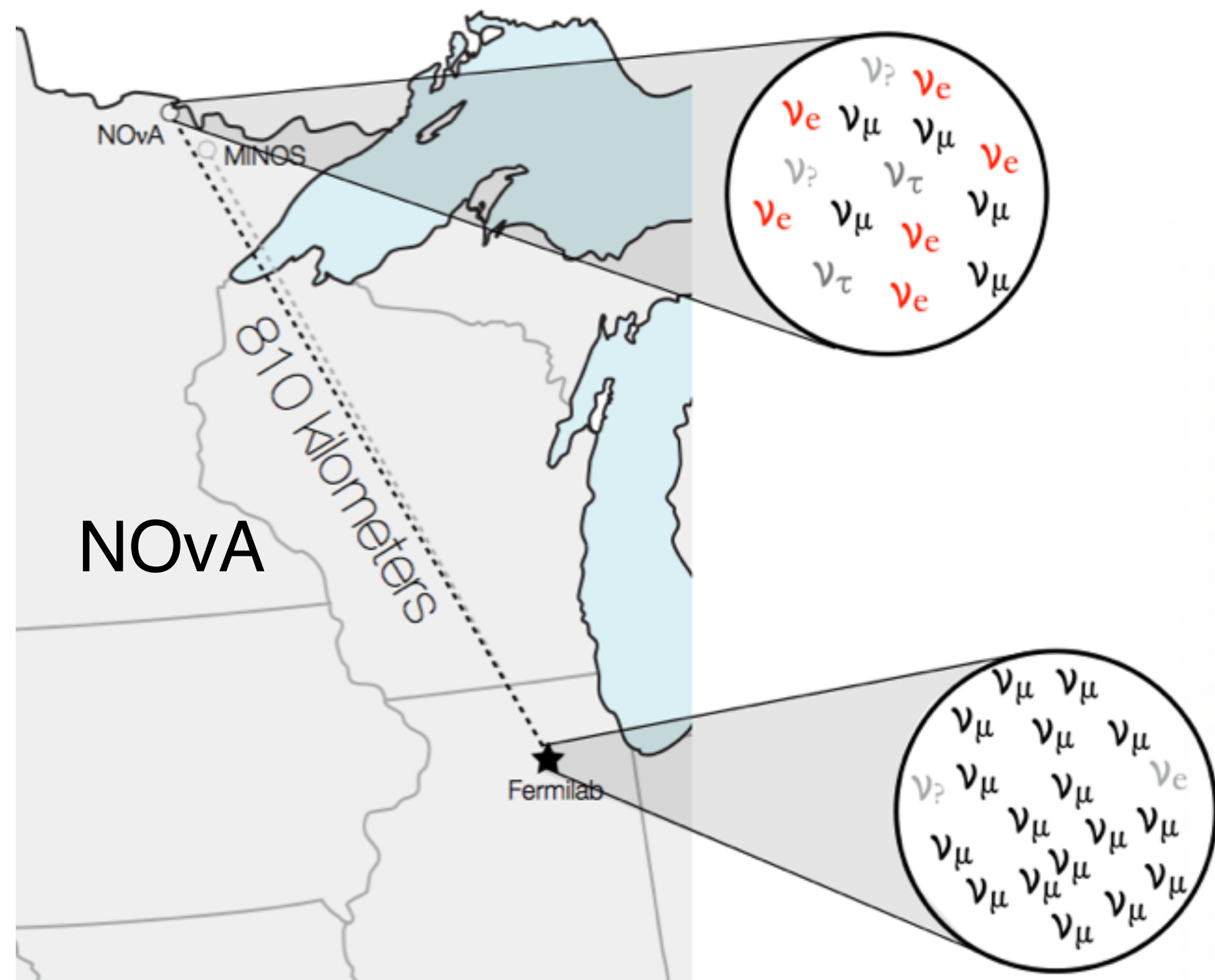
November 30, 2021

Outline

- **Neutrino Scattering: Why We Care**

- **Challenges:**

  - **Model Predictions**

  - **Making Measurements**

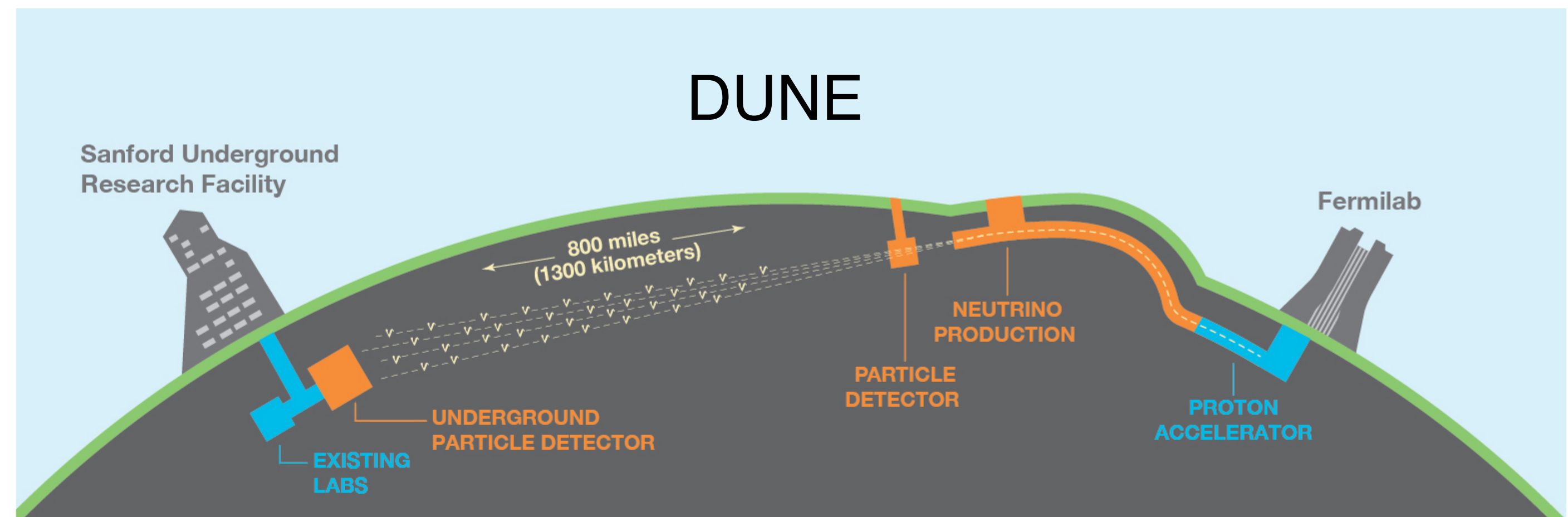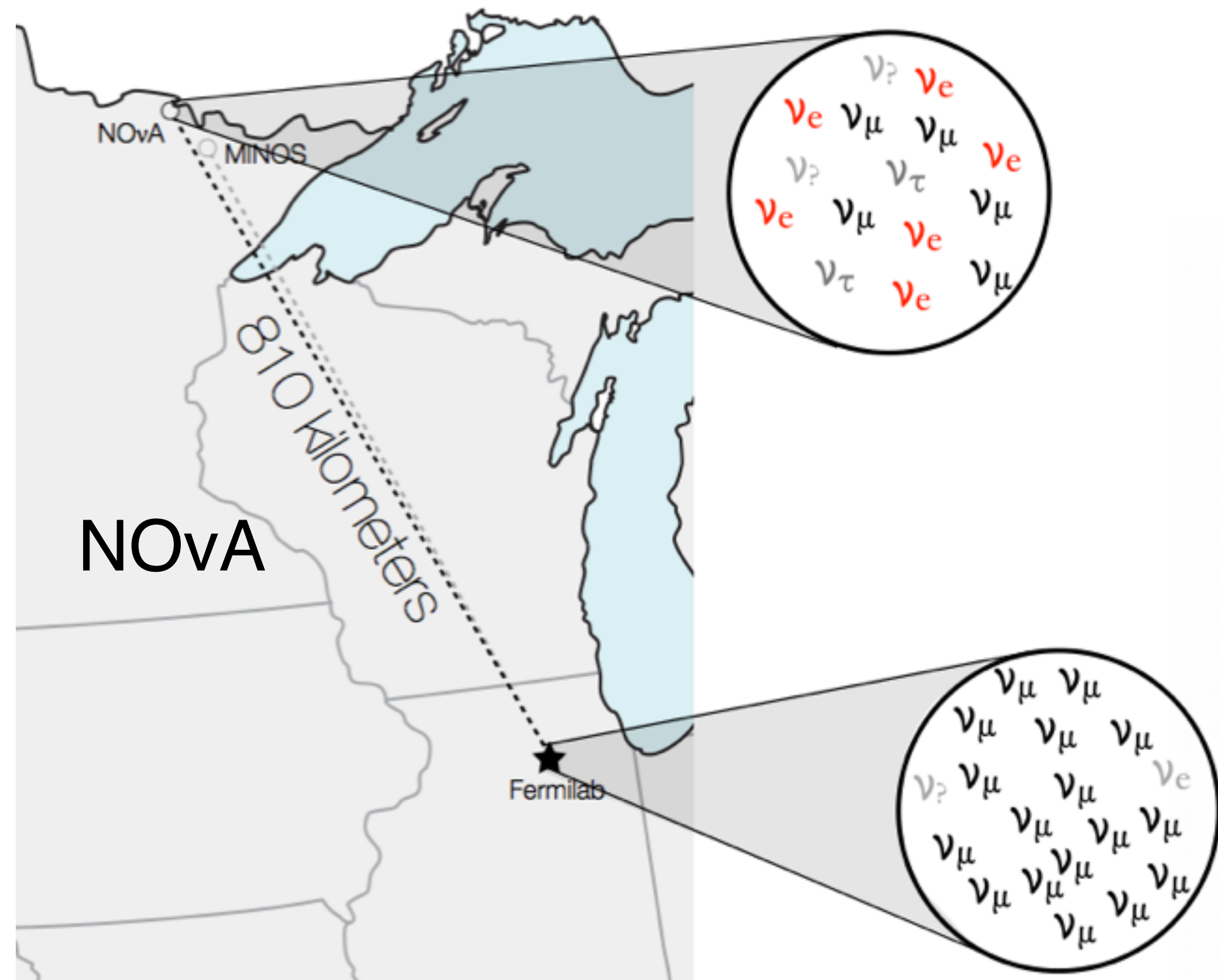- **Current Status**

- **Future Outlook**

Neutrino Scattering and Oscillations

$$N_\nu^{\mathrm{obs}}(E_\nu^{\mathrm{reco}}) \sim \vec{U}(E_\nu^{\mathrm{true}} \to E_\nu^{\mathrm{reco}})\Big(\Phi(E_\nu^{\mathrm{true}}) \times \sigma(E_\nu^{\mathrm{true}}) \times \epsilon(E_\nu^{\mathrm{true}}) \times P^{\mathrm{osc}}(E_\nu^{\mathrm{true}})\Big)$$

Neutrino Scattering and Oscillations

$$N_\nu^{\text{obs}}(E_\nu^{\text{reco}}) \sim \vec{U}(E_\nu^{\text{true}} \rightarrow E_\nu^{\text{reco}}) \Big(\Phi(E_\nu^{\text{true}}) \times \sigma(E_\nu^{\text{true}}) \times \epsilon(E_\nu^{\text{true}}) \times P^{\text{osc}}(E_\nu^{\text{true}}) \Big)$$
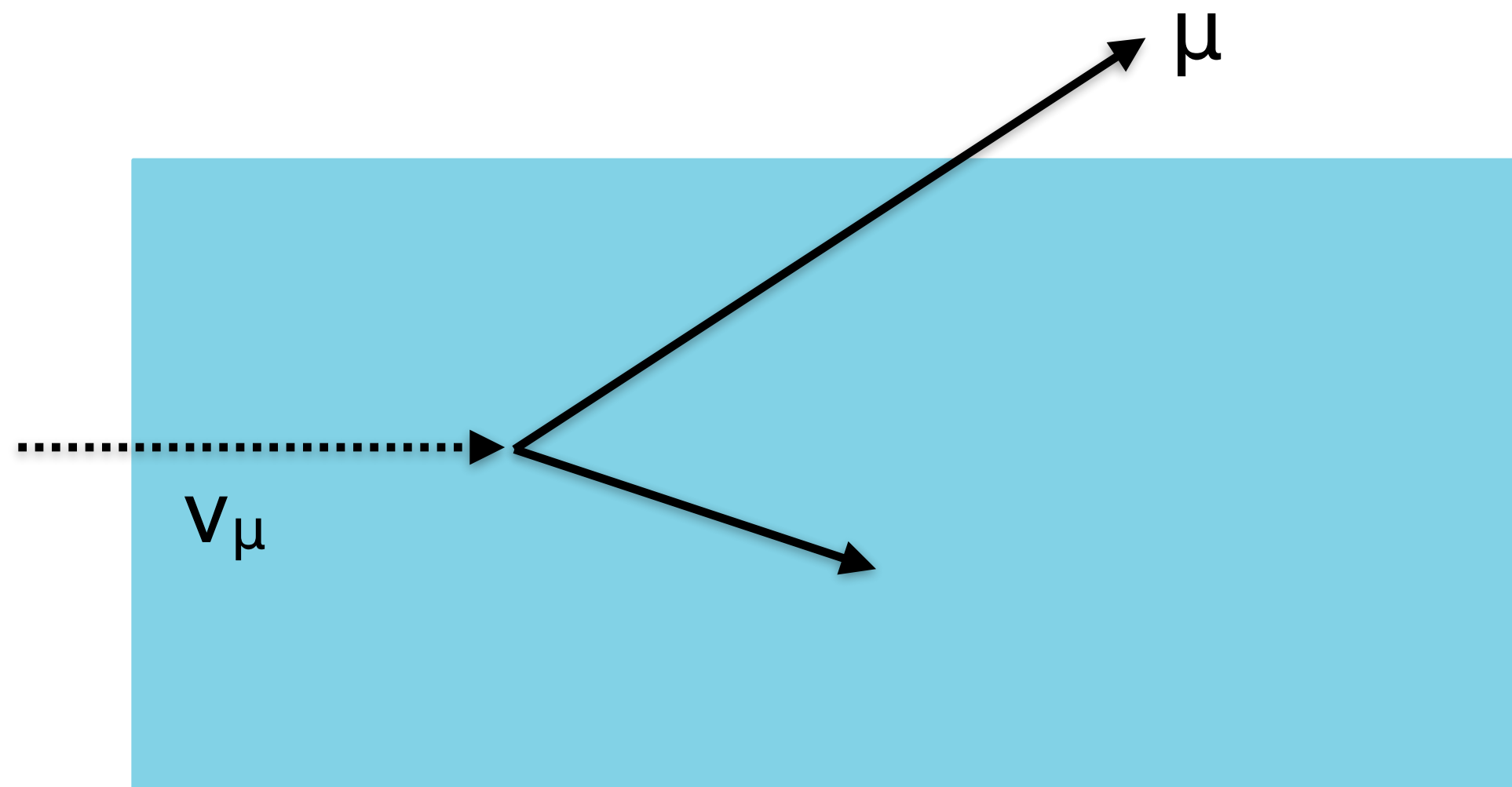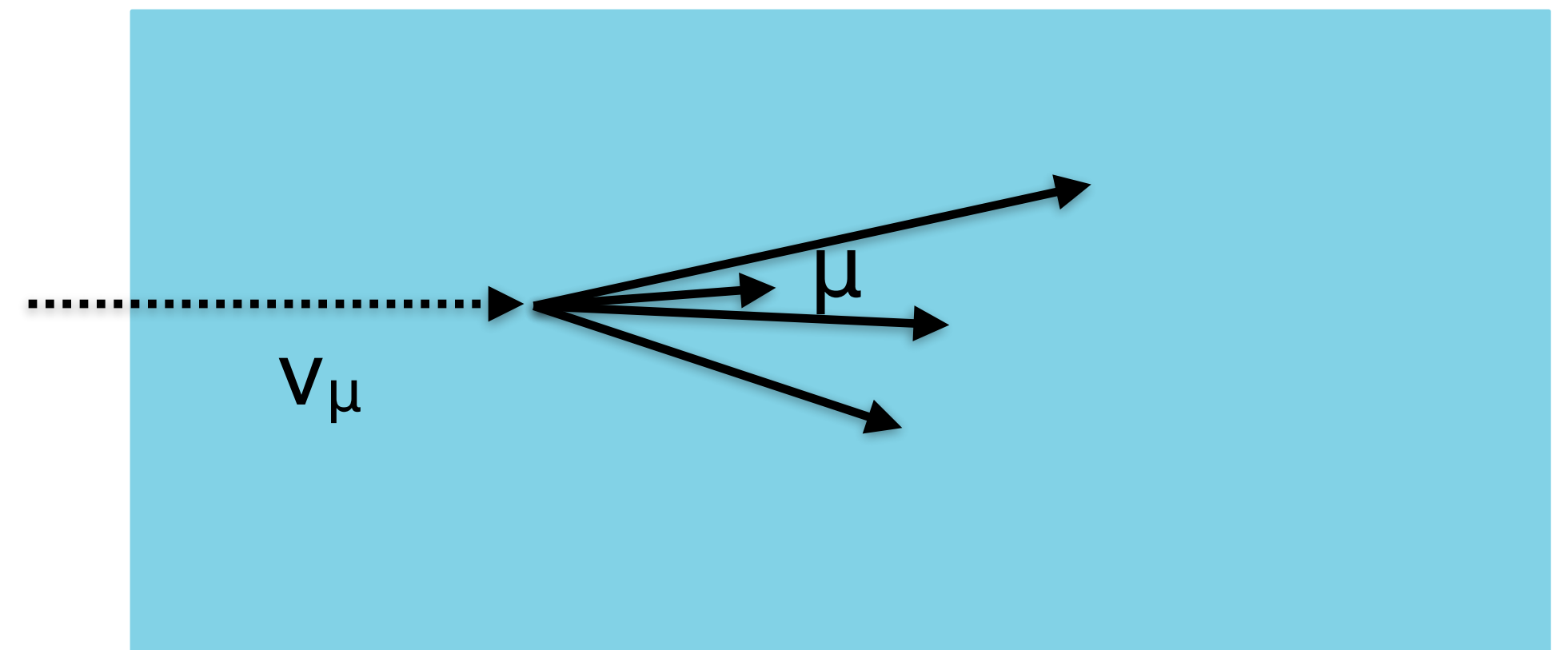
Neutrino Scattering and Oscillations

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$$\epsilon(E_{\nu_\mu}^{\mathrm{true}}) \propto \frac{d^N \sigma(E_{\nu_\mu}^{\mathrm{true}})}{d\vec{X}}$$
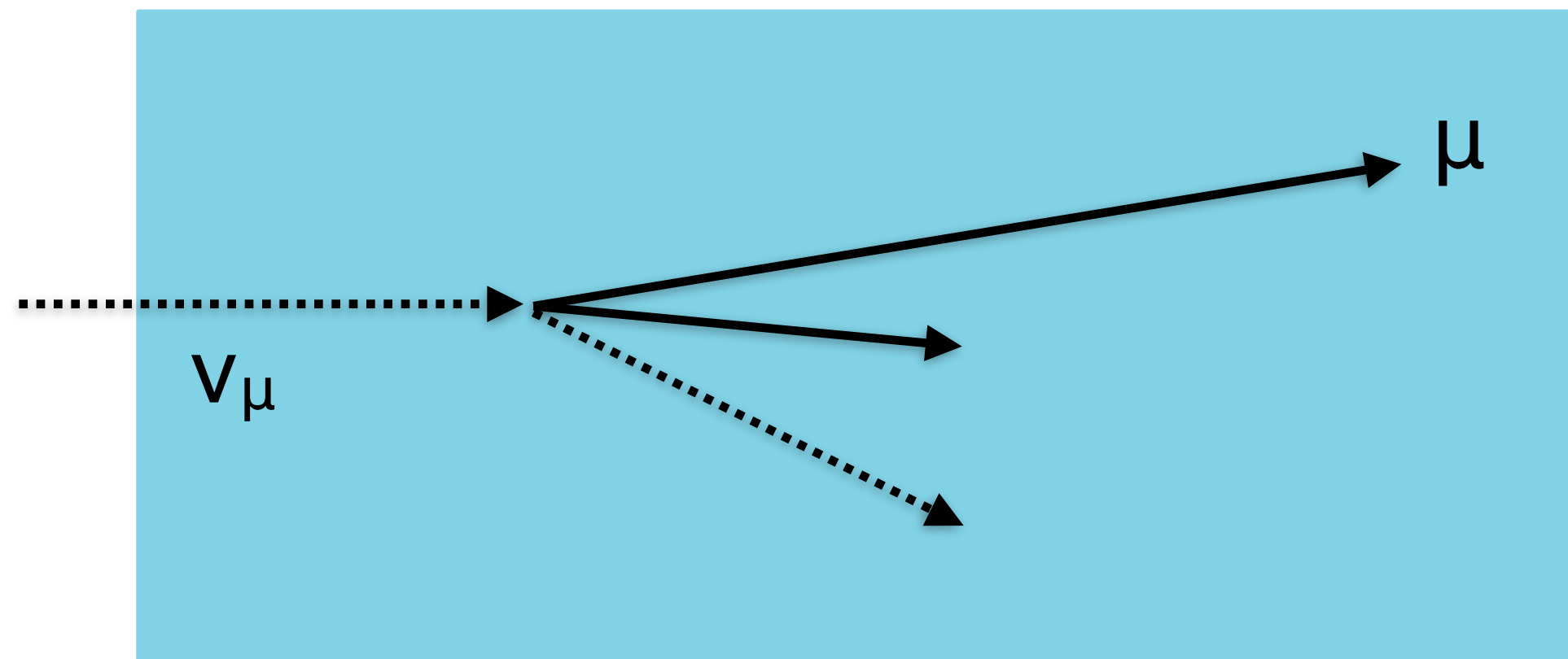

geometric acceptance corrections

missed signal event
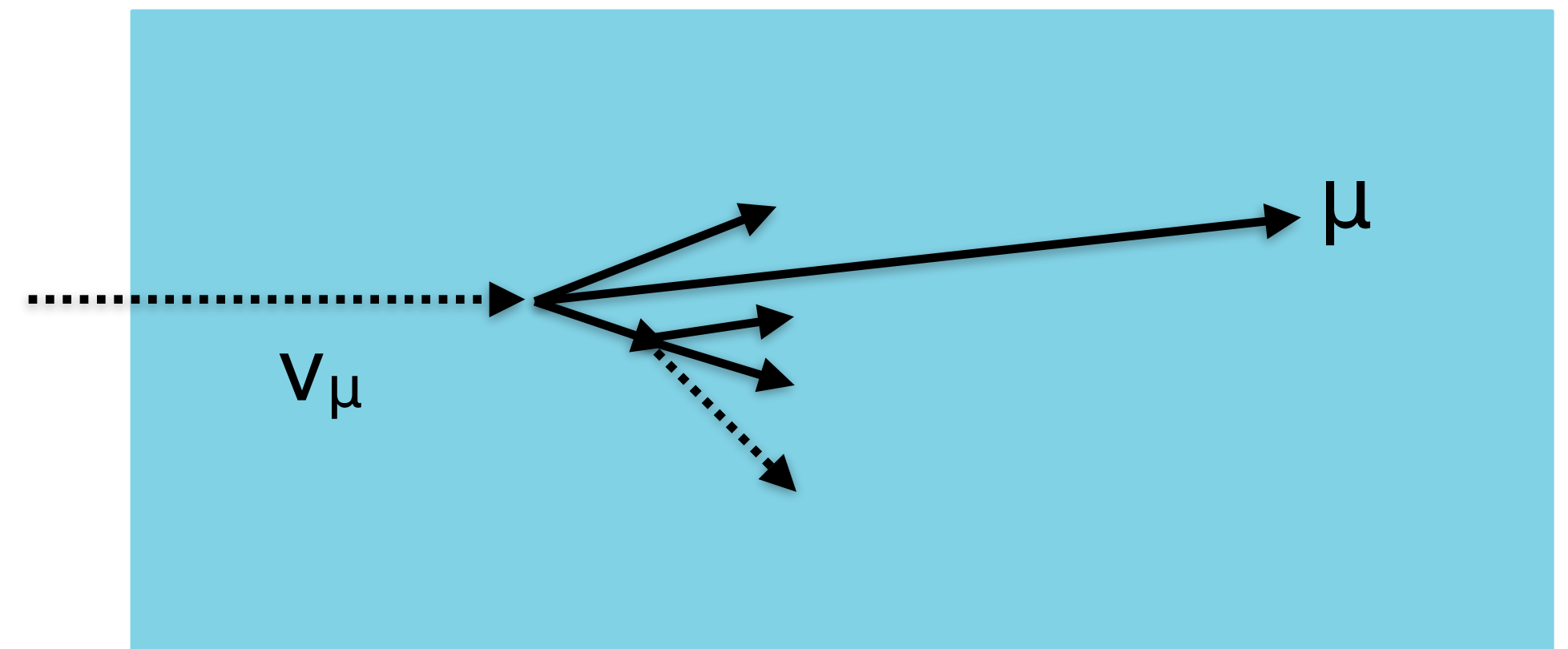
Neutrino Scattering and Oscillations

$$N_\nu^{\mathrm{obs}}(E_\nu^{\mathrm{reco}}) \sim \vec{U}(E_\nu^{\mathrm{true}} \to E_\nu^{\mathrm{reco}}) \Big(\Phi(E_\nu^{\mathrm{true}}) \times \sigma(E_\nu^{\mathrm{true}}) \times \epsilon(E_\nu^{\mathrm{true}}) \times P^{\mathrm{osc}}(E_\nu^{\mathrm{true}}) \Big)$$

Smearing matrix accounts for detector resolution, as well as other effects

$$\vec{U}(E_{\nu_\mu}^{\mathrm{true}}, E_{\nu_\mu}^{\mathrm{reco}}) \propto \frac{d^N \sigma(E_{\nu_\mu}^{\mathrm{true}})}{d\vec{X}}$$
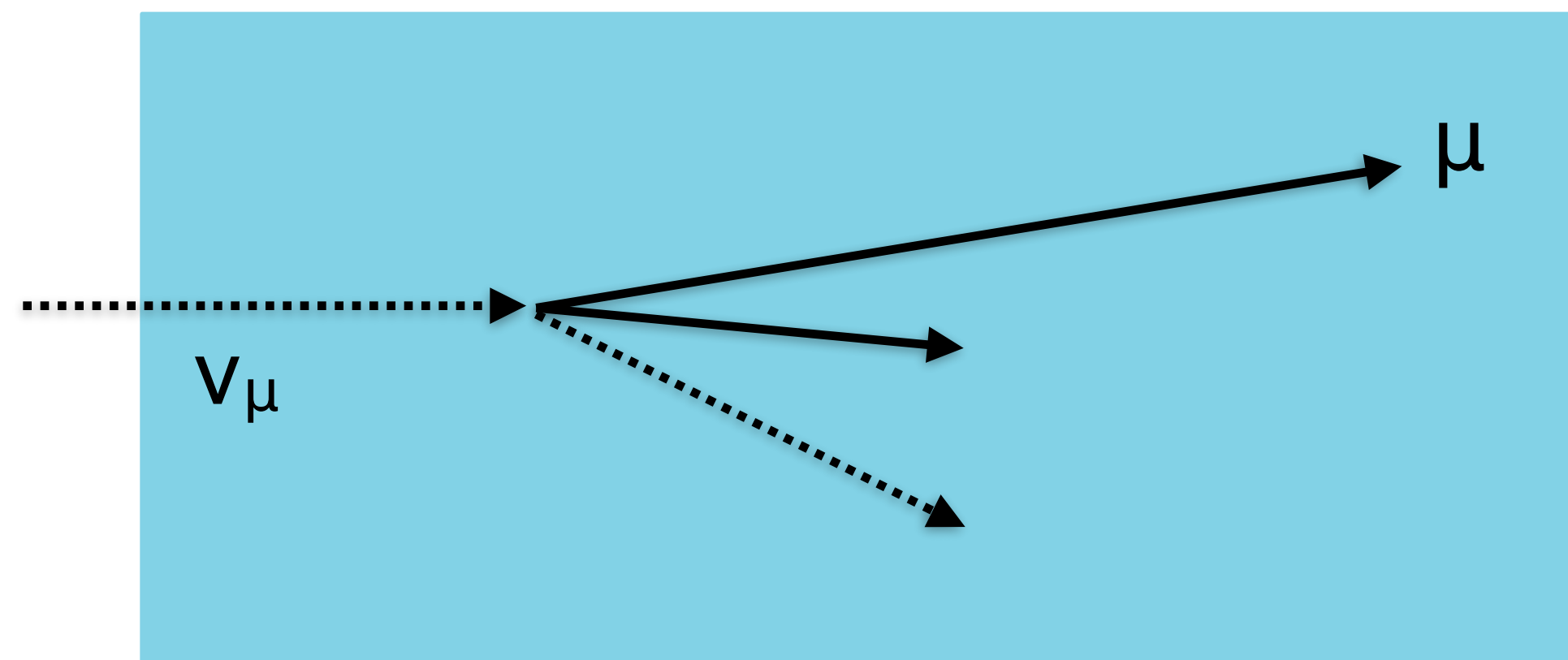

corrections for unobserved
final-state particles

corrections for final-state particles
that further interact in the detector

Neutrino Scattering and Oscillations

$$N_\nu^{\text{obs}}(E_\nu^{\text{reco}}) \sim \boxed{\vec{U}(E_\nu^{\text{true}} \to E_\nu^{\text{reco}})} \left(\Phi(E_\nu^{\text{true}}) \times \sigma(E_\nu^{\text{true}}) \times \epsilon(E_\nu^{\text{true}}) \times P^{\text{osc}}(E_\nu^{\text{true}}) \right)$$

Smearing matrix accounts for detector resolution, as well as other effects

$$\vec{U}(E_{\nu_\mu}^{\text{true}}, E_{\nu_\mu}^{\text{reco}}) \propto \frac{d^N \sigma(E_{\nu_\mu}^{\text{true}})}{d\vec{X}}$$

μ

ν_μ

corrections for unobserved
final-state particles

π (selected as μ)

μ (true)
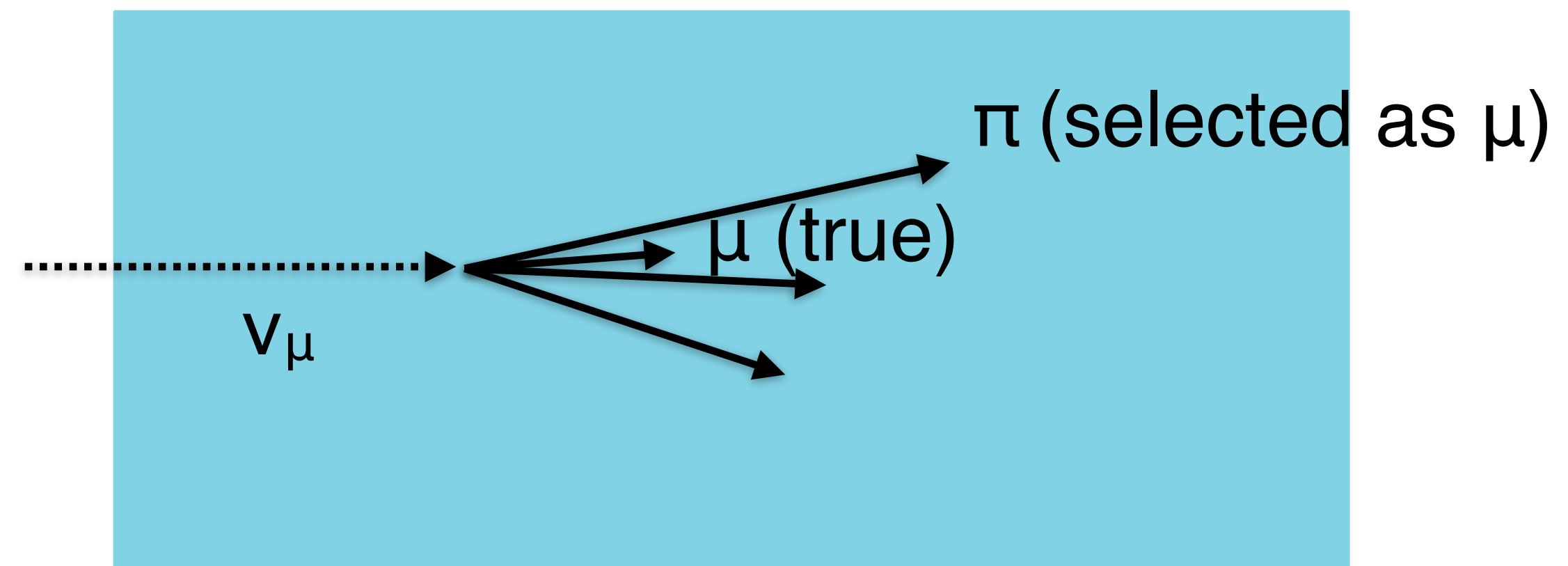
ν_μ

mis-identified muon

Neutrino Scattering and Oscillations

$$N_\nu^{\text{obs}}(E_\nu^{\text{reco}}) \sim \vec{U}(E_\nu^{\text{true}} \rightarrow E_\nu^{\text{reco}}) \left(\Phi(E_\nu^{\text{true}}) \times \sigma(E_\nu^{\text{true}}) \times \epsilon(E_\nu^{\text{true}}) \times P^{\text{osc}}(E_\nu^{\text{true}}) \right)$$

We rely on models to determine these corrections. As we move into the era of high-statistics neutrino oscillation measurements, systematic uncertainties associated with these models become very important.

Cross-section measurements made in today's experiments will guide the models used by future experiments.

Neutrino Energies in Current and Future Experiments
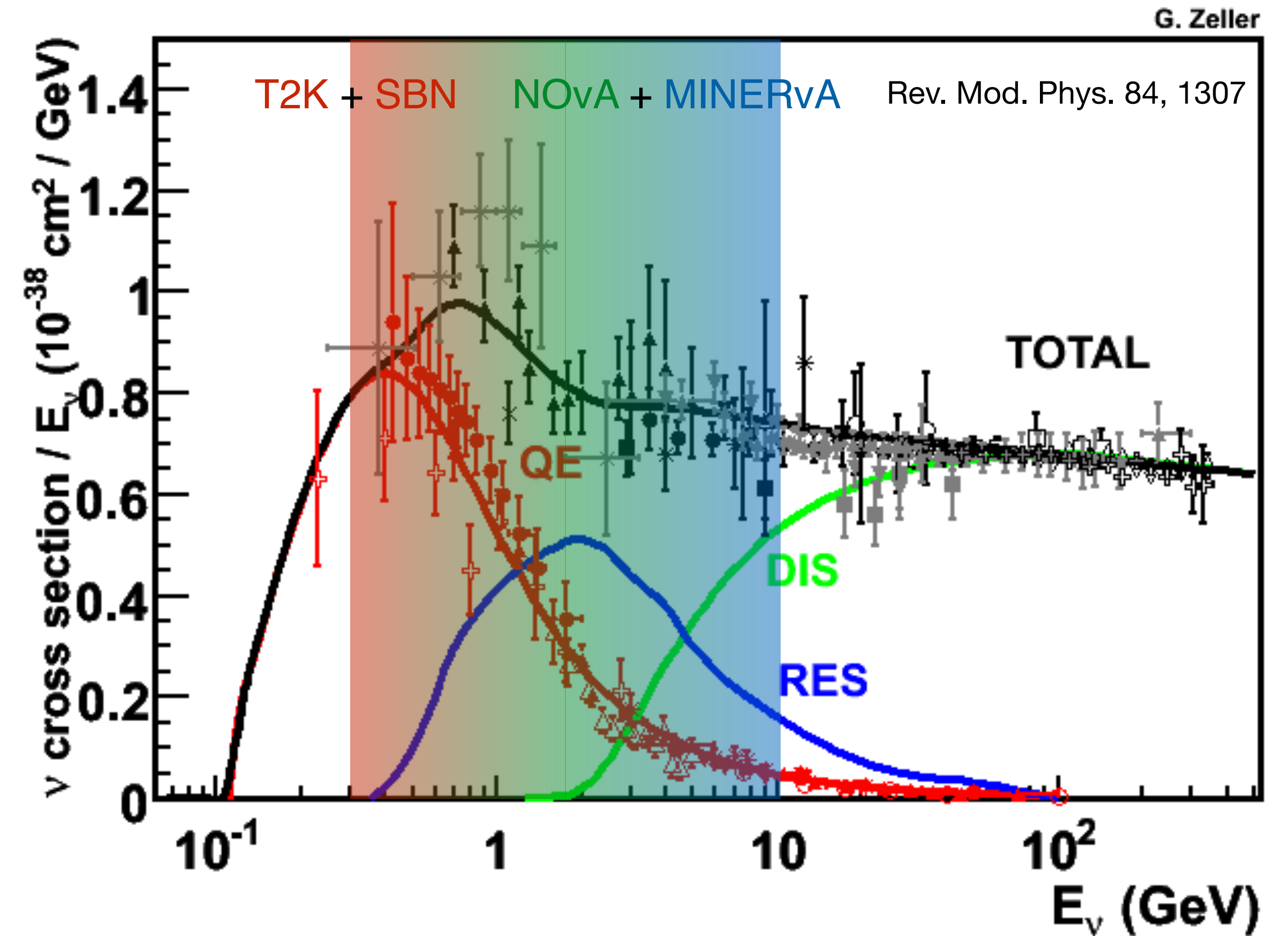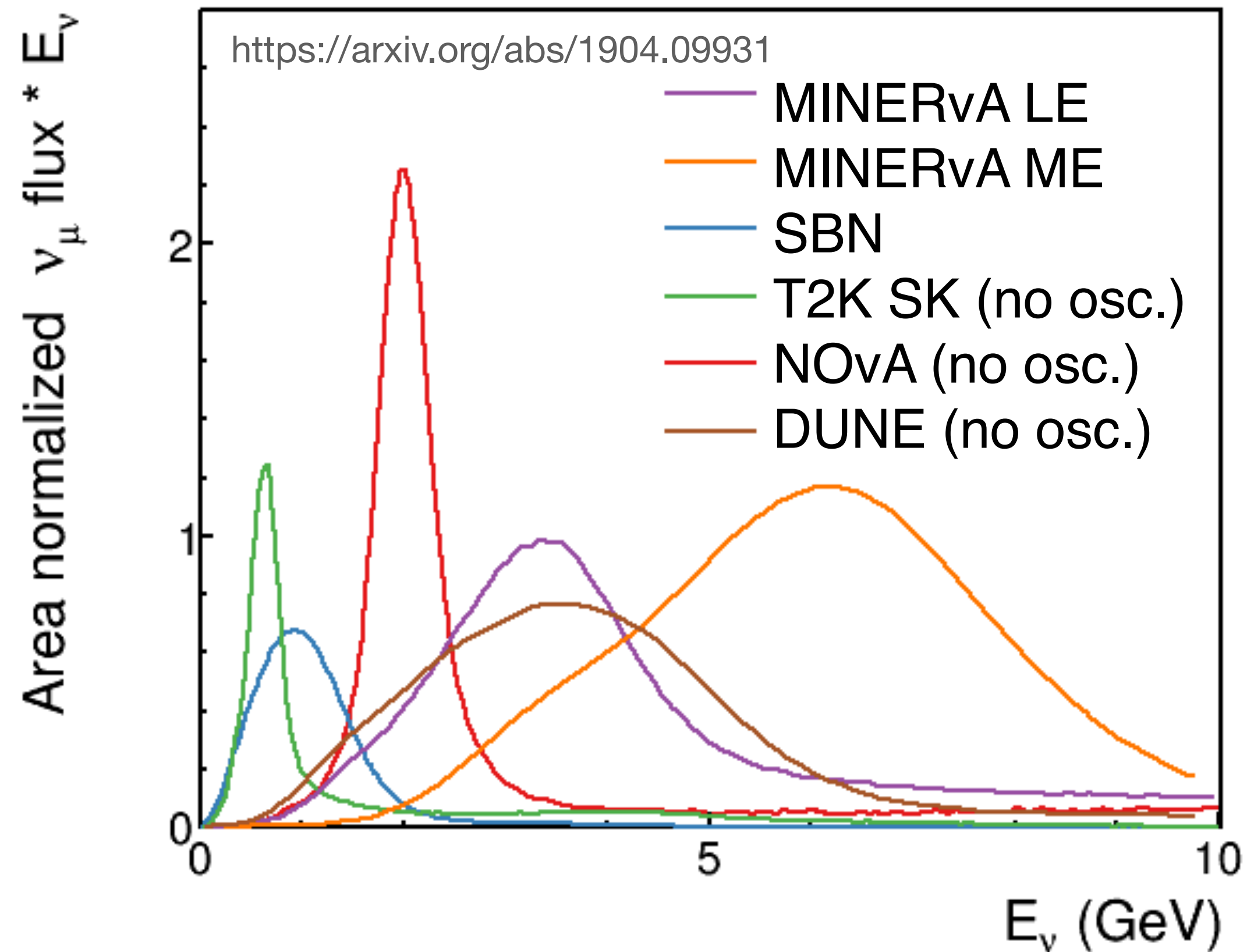
- Current neutrino experiments cover nearly two orders of magnitude of neutrino energies.
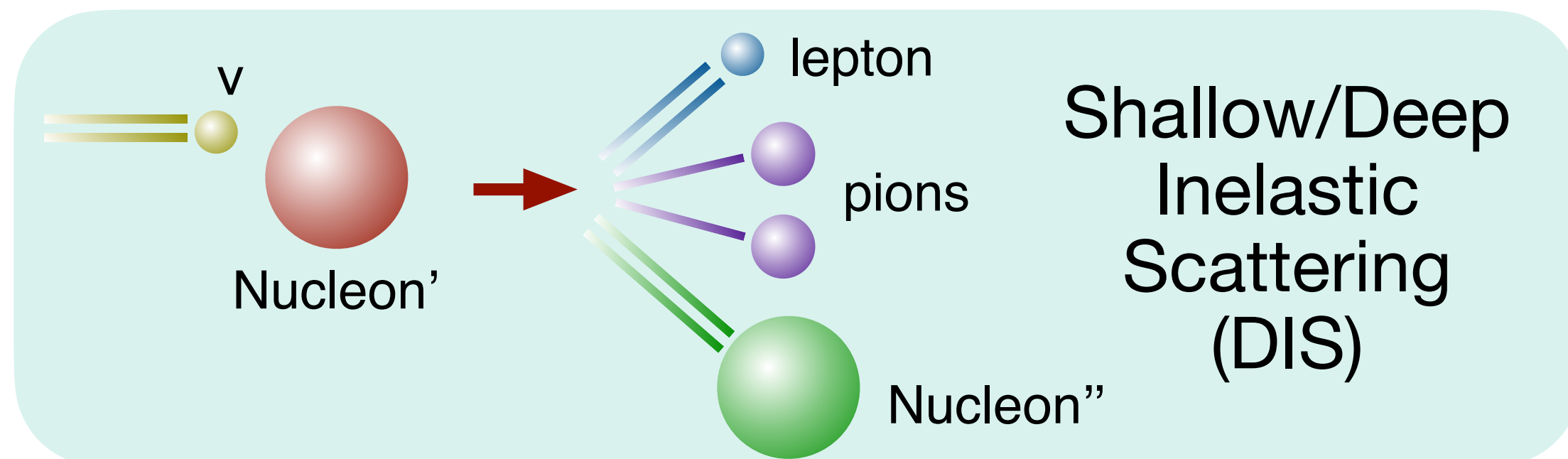- Life is made more interesting because over this range, there are several types of scattering modes.

Neutrino Interactions

Quasi-Elastic (QE)

Resonant (RES)

Shallow/Deep Inelastic Scattering (DIS)

Meson Exchange Currents (MEC)

Graphic by T. Golan
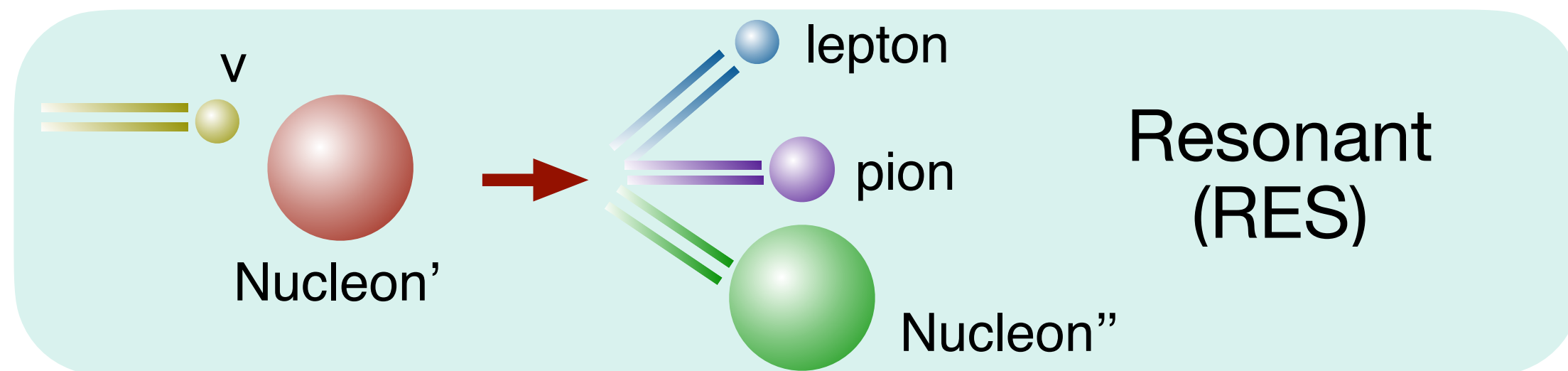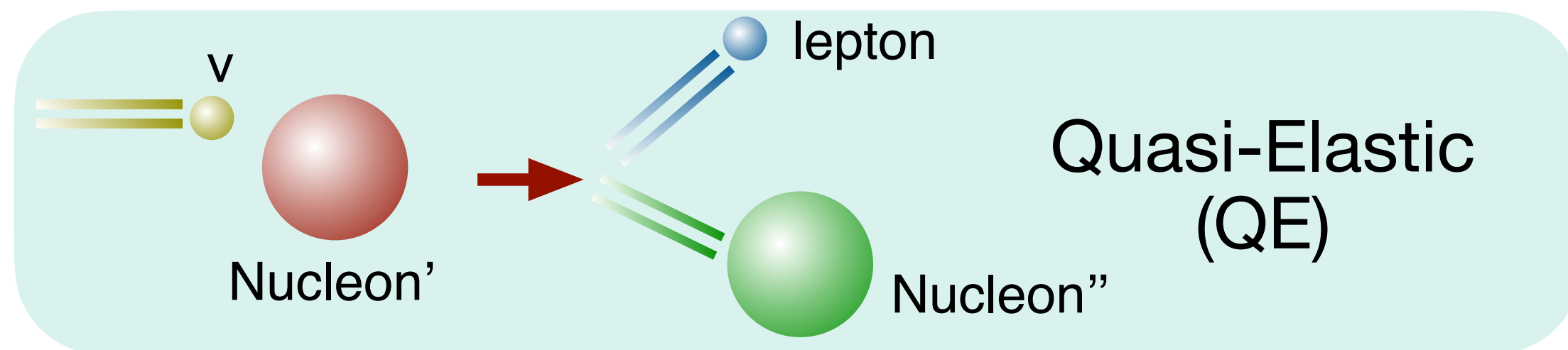
- Interactions at the ~GeV scale are often categorized by their scattering off of bound nucleons and their final state.
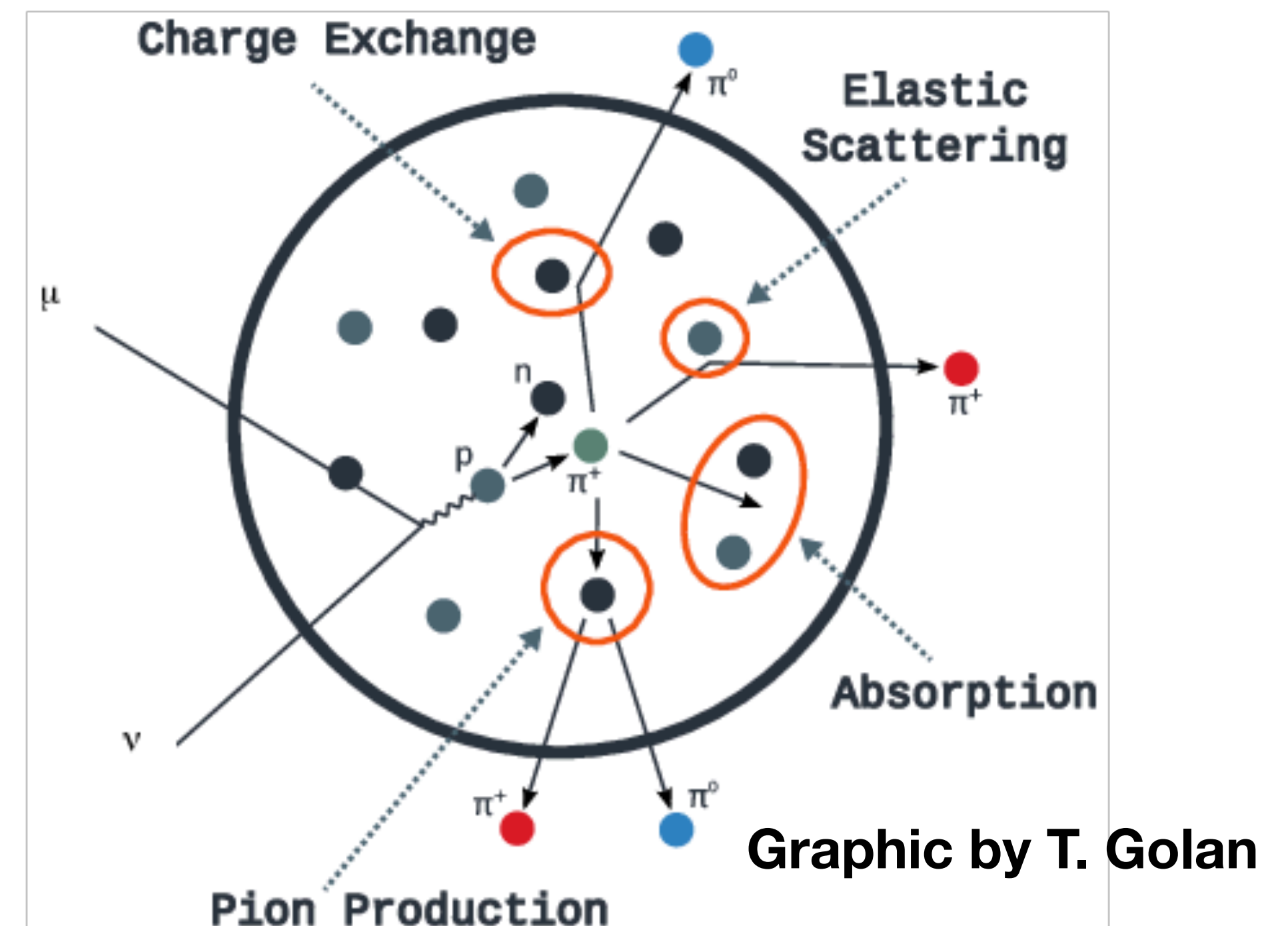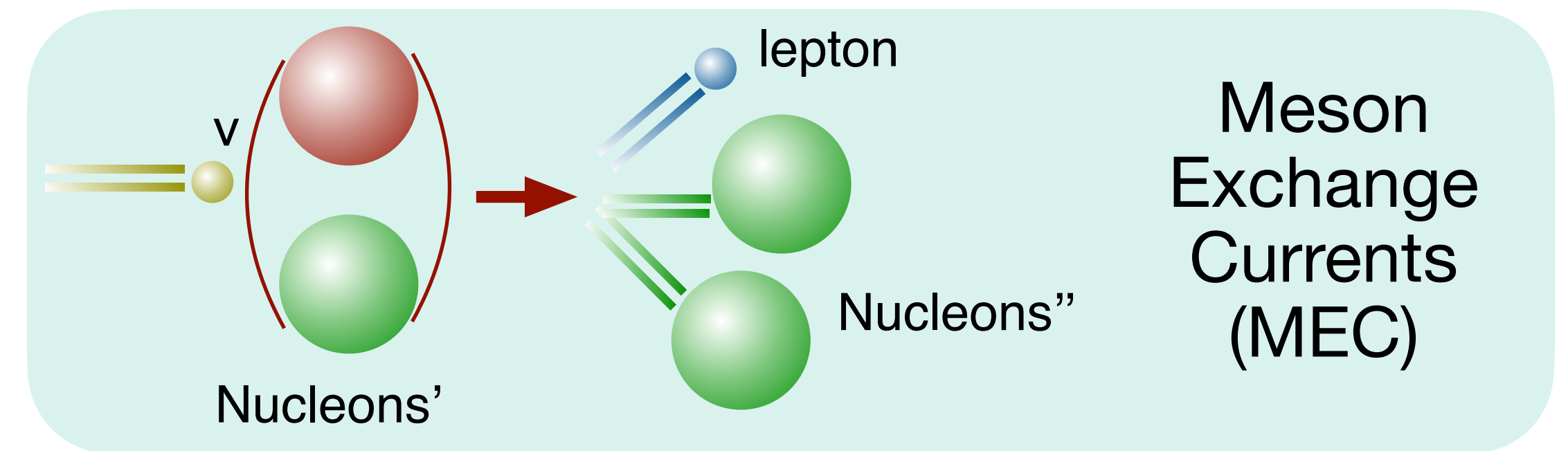
- But all of this happens in a nuclear environment, which impacts both the initial state and what we actually observe in the final state.

Generator Comparison - The Models

|	QE/MEC Initial State	QE	MEC	Res	DIS	FSI
GENIE v2.12.2	RFG	L-S	Empirical (NOvA tune)	R-S	PYTHIA 6	hA
GENIE v3.00.06	LFG	Valencia (Nieves, et al)	Valencia (Nieves, et al)	B-S	PYTHIA 6	hN
NEUT 5.4.0	LFG	Valencia (Nieves, et al)	Valencia (Nieves, et al)	B-S	PYTHIA 5	Oset (low mom. pions) + ext. data
NuWro 2019	LFG	L-S + RPA	Valencia (Nieves, et al)	NuWro	PYTHIA 6	Oset (pions) + NuWro (nucleons)
GiBUU 2019	LFG	GiBUU Model				BUU equations
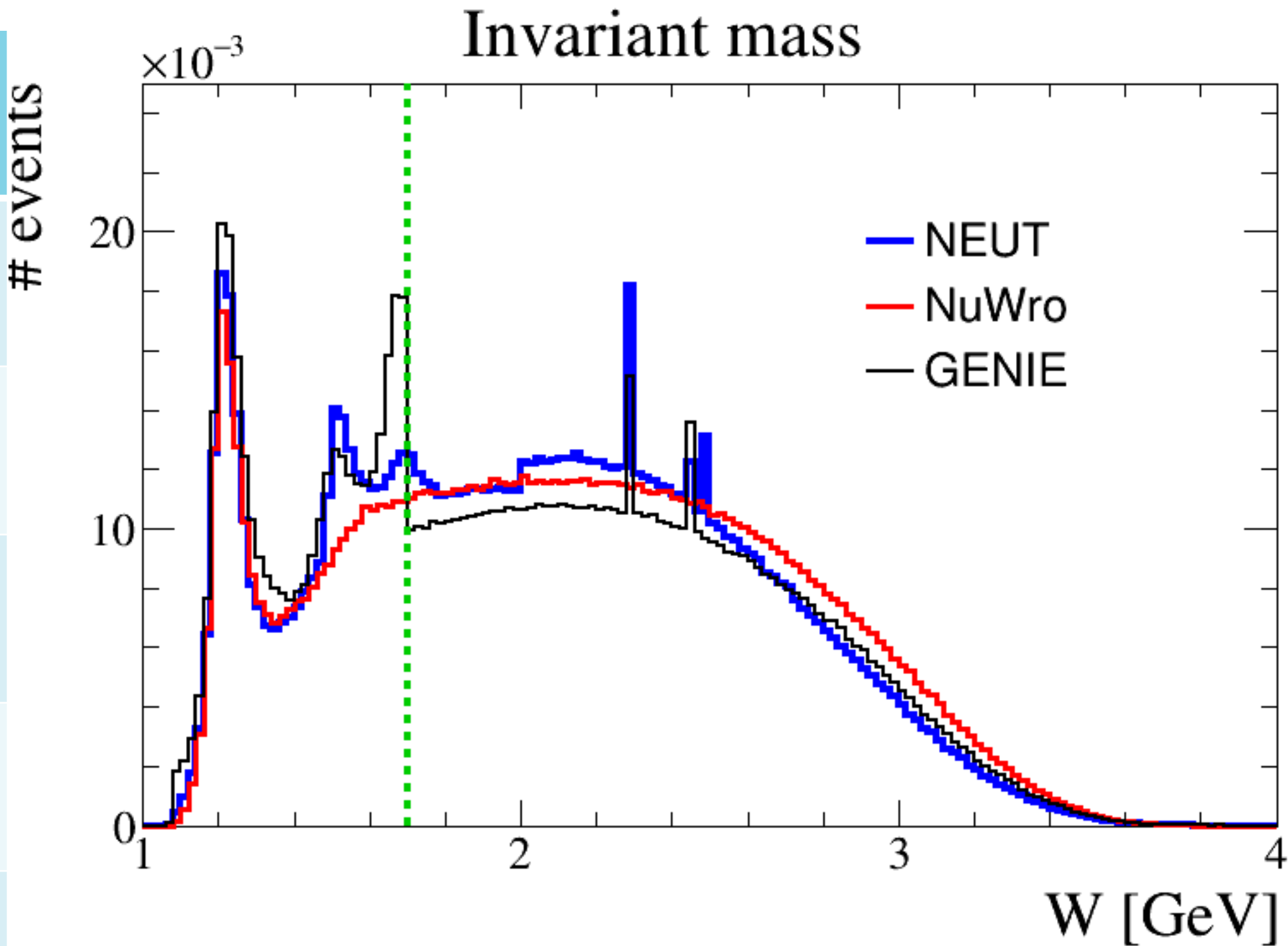
C. Bronner, NuSTEC 2018 Workshop Presentation

- Generators use very similar models. However, details of their implementation can be quite different.

- These models then need to be "stitched" together to give the "inclusive" prediction.

$$\sigma_{\mathrm{CC}}^{\mathrm{inclusive}}(E_\nu) = \sigma_{\mathrm{CC}}^{\mathrm{QE}} + \sigma_{\mathrm{CC}}^{\mathrm{MEC}} + \sigma_{\mathrm{CC}}^{\mathrm{Res}} + \sigma_{\mathrm{CC}}^{\mathrm{DIS}} + \sigma_{\mathrm{CC}}^{\mathrm{Coh}}$$

Generator Comparison - The Models

Predictions for the NOvA detectors

NEUT 5.4.0
NuWro 2019
GiBUU 2019
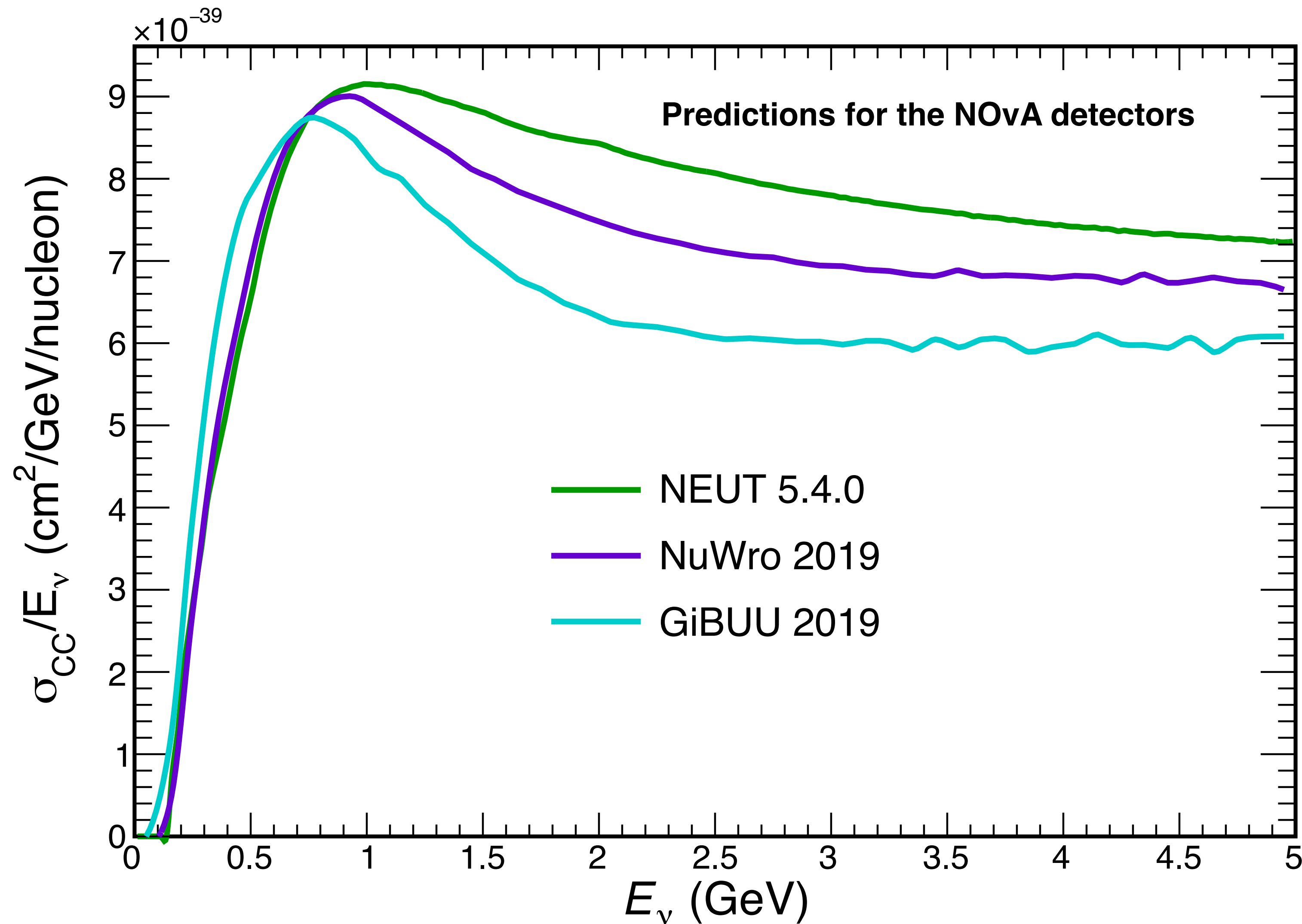
- Implementation and stitching differences between the generators is reflected in the spread of inclusive predictions from various generators.

- Cross section measurements are critical to improve our understanding of the individual processes and how all the pieces fit together.

How to Measure a Neutrino Cross Section

- Essentially, we are just measuring an event count as a function of some kinematic observable, but we need to relate it to a "true" cross section that theorists and other experiments can use.

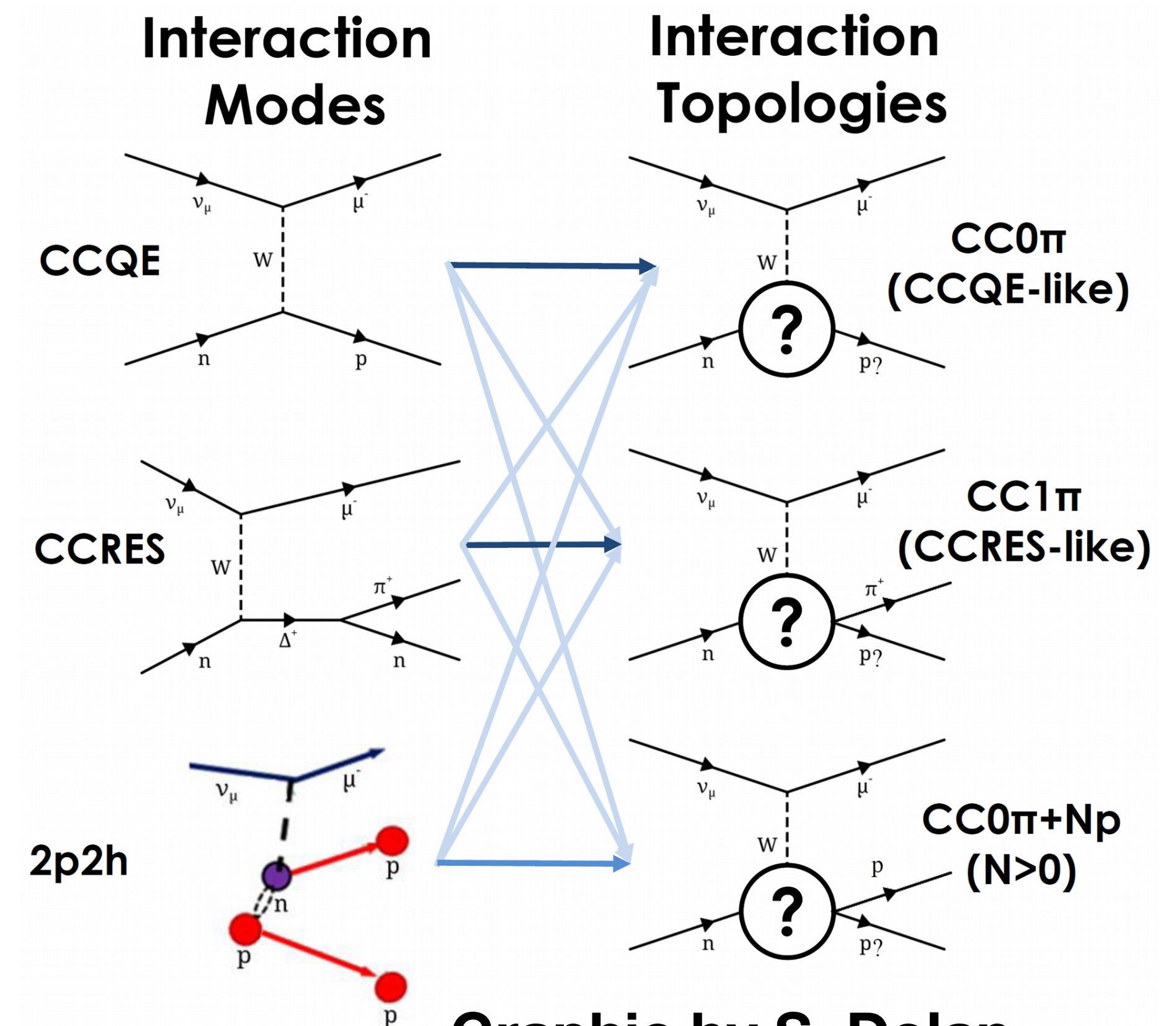- Note, since the neutrino is invisible, we only see [most of] the final state particles associated with its interaction with a nucleus.

  - What we really want to measure is the cross section as a function of E_ν and Q^2, or specific interaction "modes", but we can't, and must infer these quantities (introduces model dependence).

  - Model-independent measurements are of final-state kinematics for an integrated flux.

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} \times P_j)}{\epsilon_i N_{\text{T}} \langle \Phi \rangle \Delta x_i}$$

Interaction Modes

Interaction Topologies

CCQE → CC0π (CCQE-like)

CCRES → CC1π (CCRES-like)

2p2h → CC0π+Np (N>0)

Graphic by S. Dolan

How to Measure a Neutrino Cross Section

- To convert an event count to a cross section, we have several factors and corrections we need to apply.

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} \times P_j)}{\epsilon_i N_{\text{T}} \langle \Phi \rangle \Delta x_i}$$

P = purity correction, or background subtraction.

ϵ = efficiency correction.

Models of signal and backgrounds sometimes have large uncertainties. Data-driven constraints are always preferred, especially when background levels are significant and/or efficiencies are low.

Challenges: isolating a data "sideband" that has similar/overlapping kinematics as the background or signal in the signal selection. Eg, events that look like your signal were probably already selected!

How to Measure a Neutrino Cross Section

- To convert an event count to a cross section, we have several factors and corrections we need to apply.

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} \times P_j)}{\epsilon_i N_{\text{T}} \langle \Phi \rangle \Delta x_i}$$

U^{-1} = correction to go from "reconstructed space" to "true space".

This is the inverse of the smearing matrix mentioned earlier.

Challenges: inverting a smearing matrix when there are significant random fluctuations (due to statistics or systematics) can result in large fluctuations in the unfolded spectrum. This is particularly true when there are low statistics and the binning is chosen to be too aggressive (eg, finer than the detector resolution).

How to Measure a Neutrino Cross Section

- To convert an event count to a cross section, we have several factors and corrections we need to apply.

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} \times P_j)}{\epsilon_i N_{\text{T}} \langle \Phi \rangle \Delta x_i}$$

N_{T} = number of targets (usually nucleons).

$\langle \phi \rangle_T$ = integrated or average flux.

Δx = bin width.

These are just constants, and the number of targets and bin width are easy to calculate.

Challenge: The flux! State of the art is 5-15% uncertainties, arising from lack of hadron production data.

CC Inclusive Measurements and Models
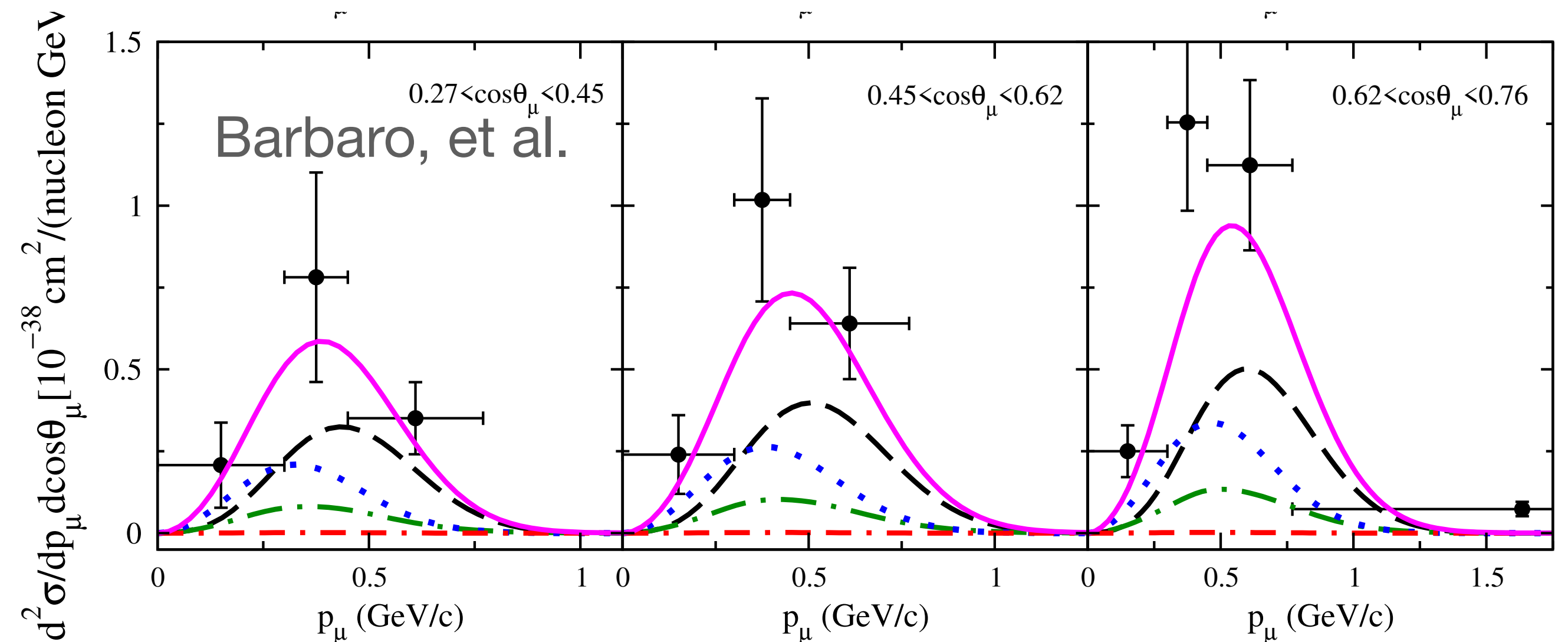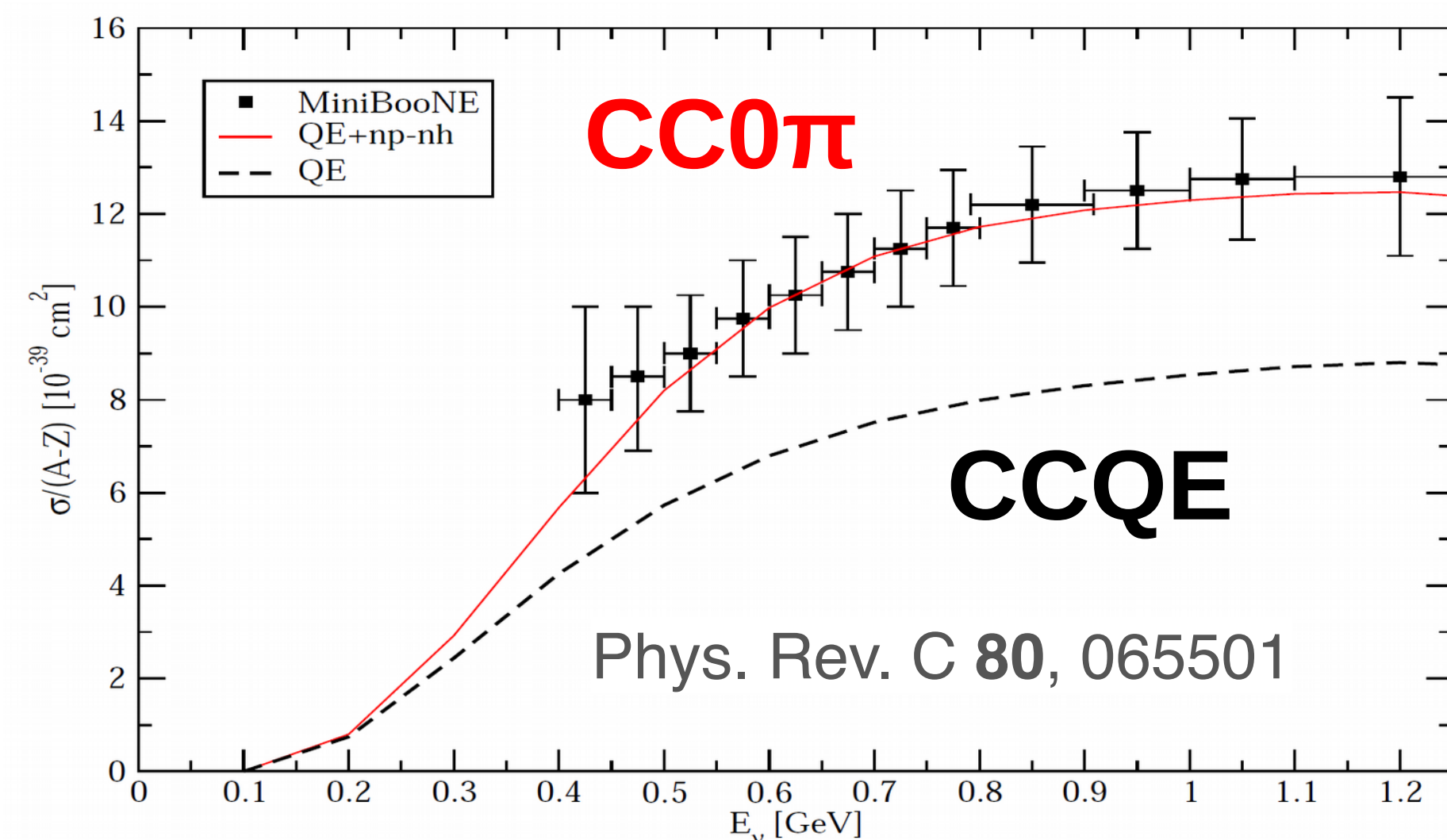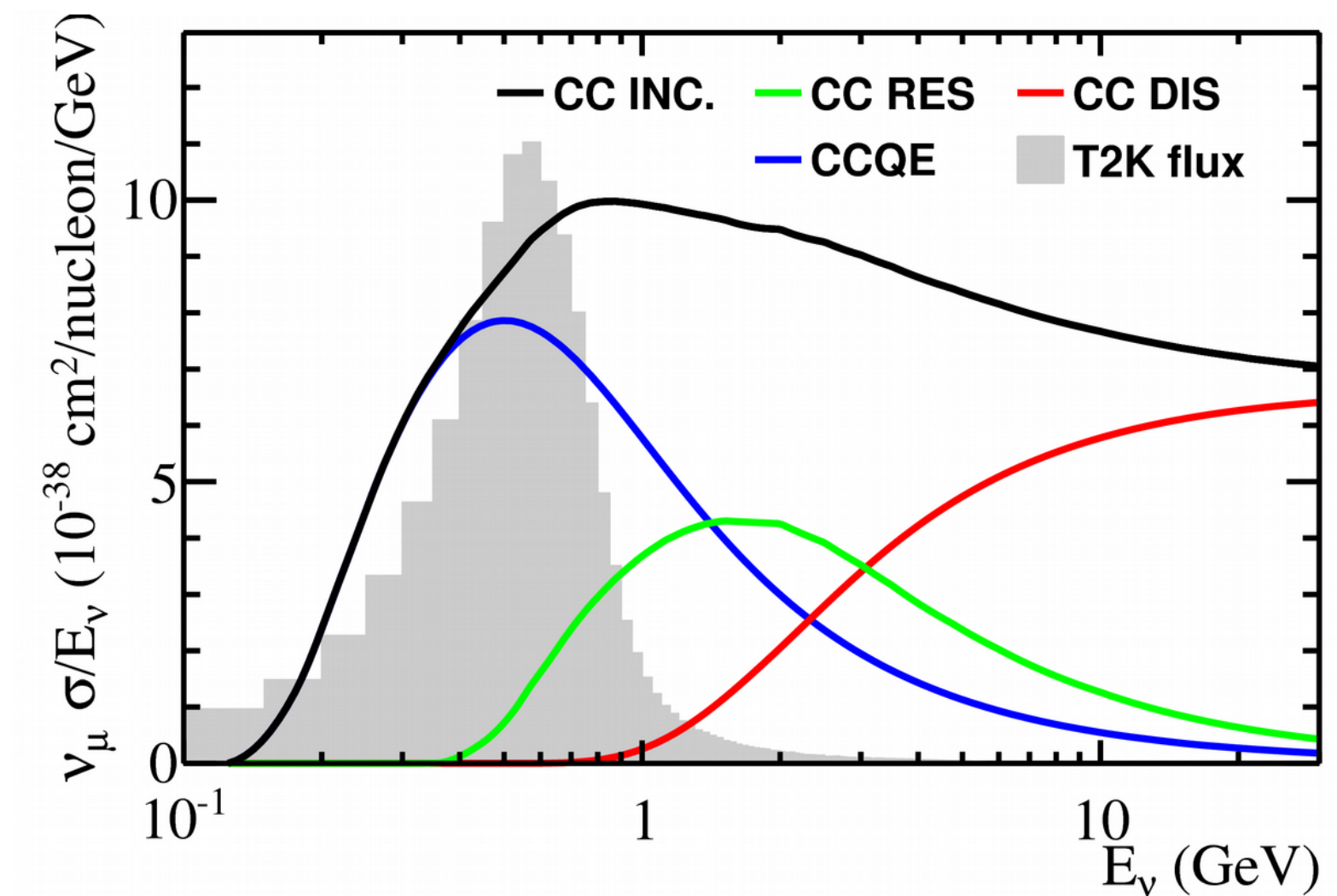
- Lots of very informative recent results, I can't show them all here!

- In short, none of the generators on the market do a great job of matching the data:
  - Many predictions seem to be off in their normalization (constant offset).
 - But shape-only comparisons also indicate significant discrepancies.

MINERvA, arXiv:2002.12496

NOvA, arXiv:2109.12220

MicroBooNE, arXiv:2110.14023
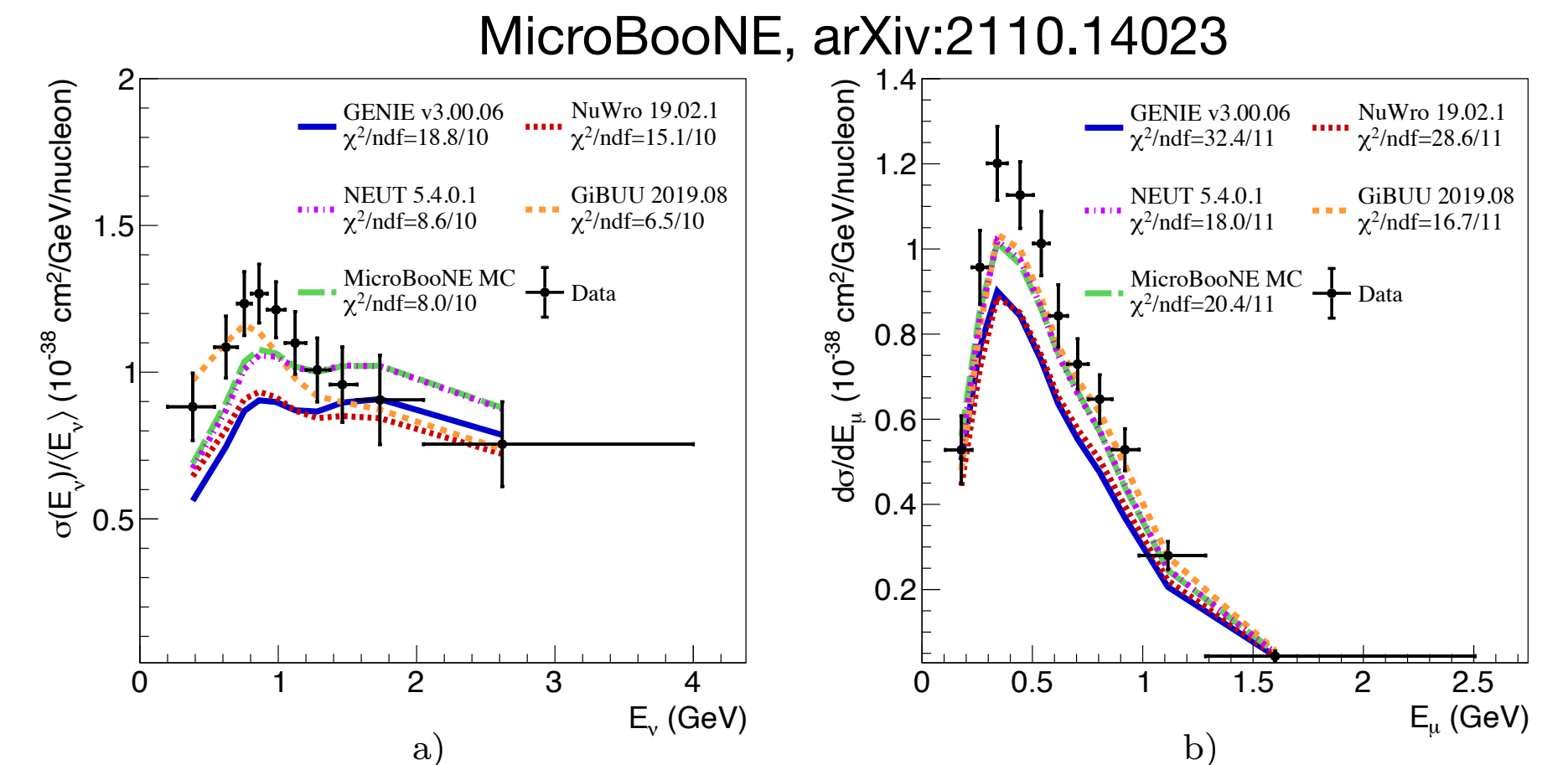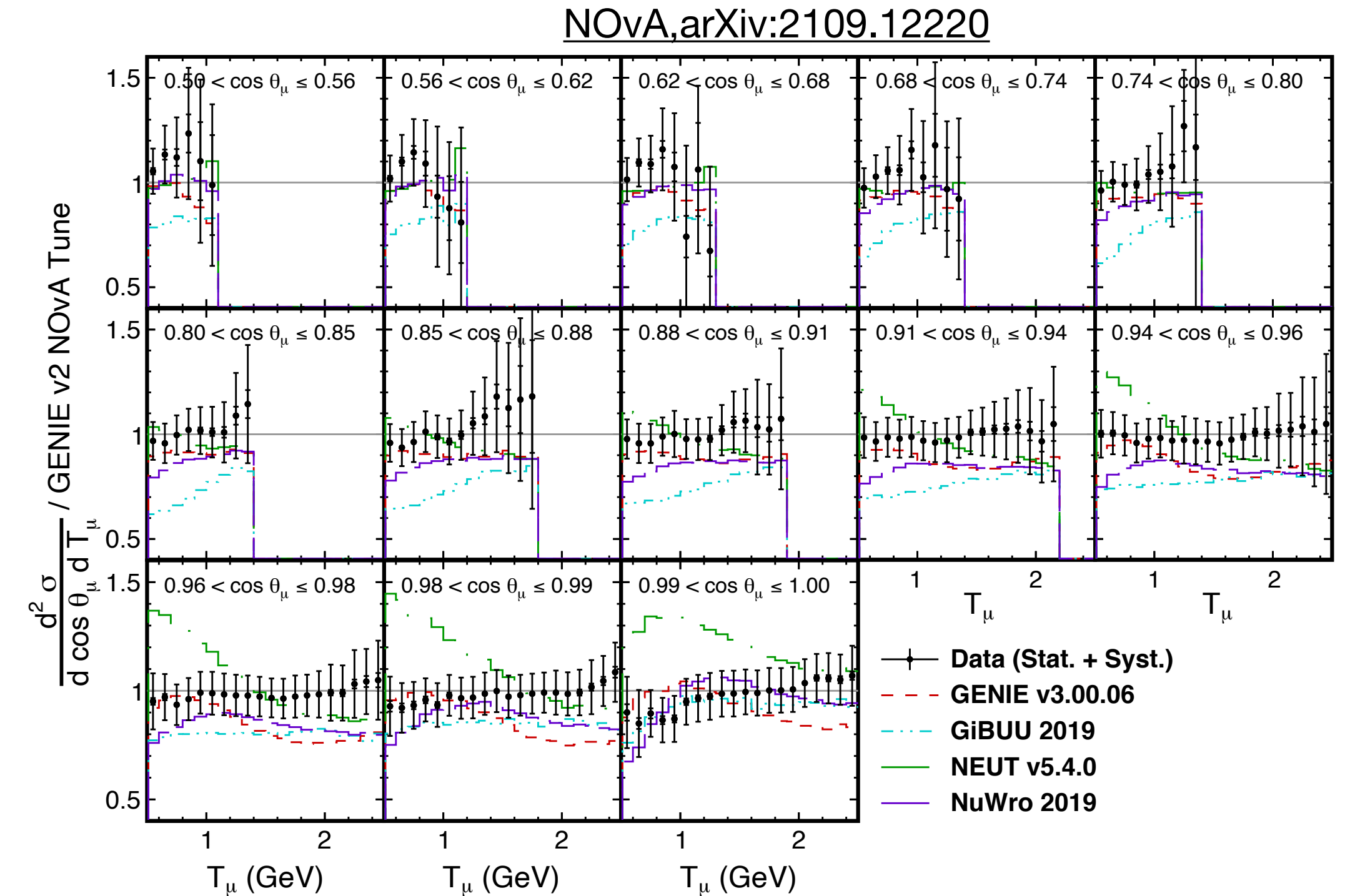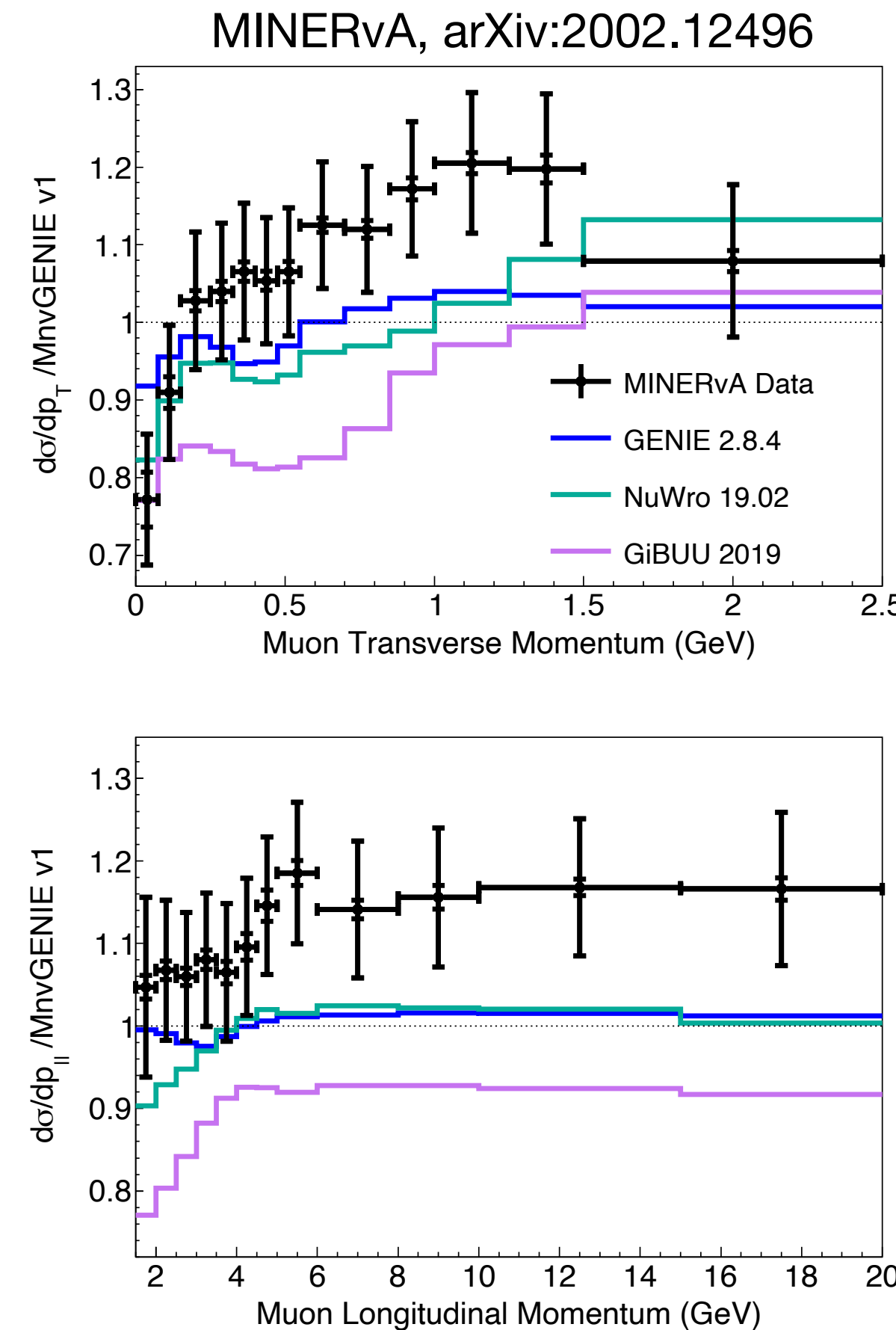
CC-0π Measurements and Models

- Includes QE, 2p2h, and some Res (π abs.)
- Has received a lot of attention by the scattering community:
  - It's the "simplest" interaction channel
  - Dominant channel for signal in MiniBooNE, T2K and uBooNE
- The model has improved significantly over the past decade:
  - Short-range nucleon correlations, initial nuclear state, 2p2h

CC INC.   CC RES   CC DIS
CCQE   T2K flux

$\nu_\mu \, \sigma/E_\nu \, (10^{-38} \, cm^2/nucleon/GeV)$

E_ν (GeV)

CC0π

CCQE

MiniBooNE
QE+np-nh
QE

$\sigma/(A-Z) \, [10^{-39} \, cm^2]$

E_ν [GeV]

Phys. Rev. C **80**, 065501

Barbaro, et al.

$0.27 < \cos\theta_\mu < 0.45$ $0.45 < \cos\theta_\mu < 0.62$ $0.62 < \cos\theta_\mu < 0.76$

$d^2\sigma/dp_\mu \, d\cos\theta_\mu \, [10^{-38} \, cm^2/(nucleon \, GeV]$

p_μ (GeV/c) p_μ (GeV/c) p_μ (GeV/c)

CC-0π Measurements and Models

- 2p2h models seem to be doing a reasonable job when comparing measurements at lower neutrino energies (MiniBooNE and T2K).

- Nevertheless, there remain significant shape differences in the energy dependence of the models.
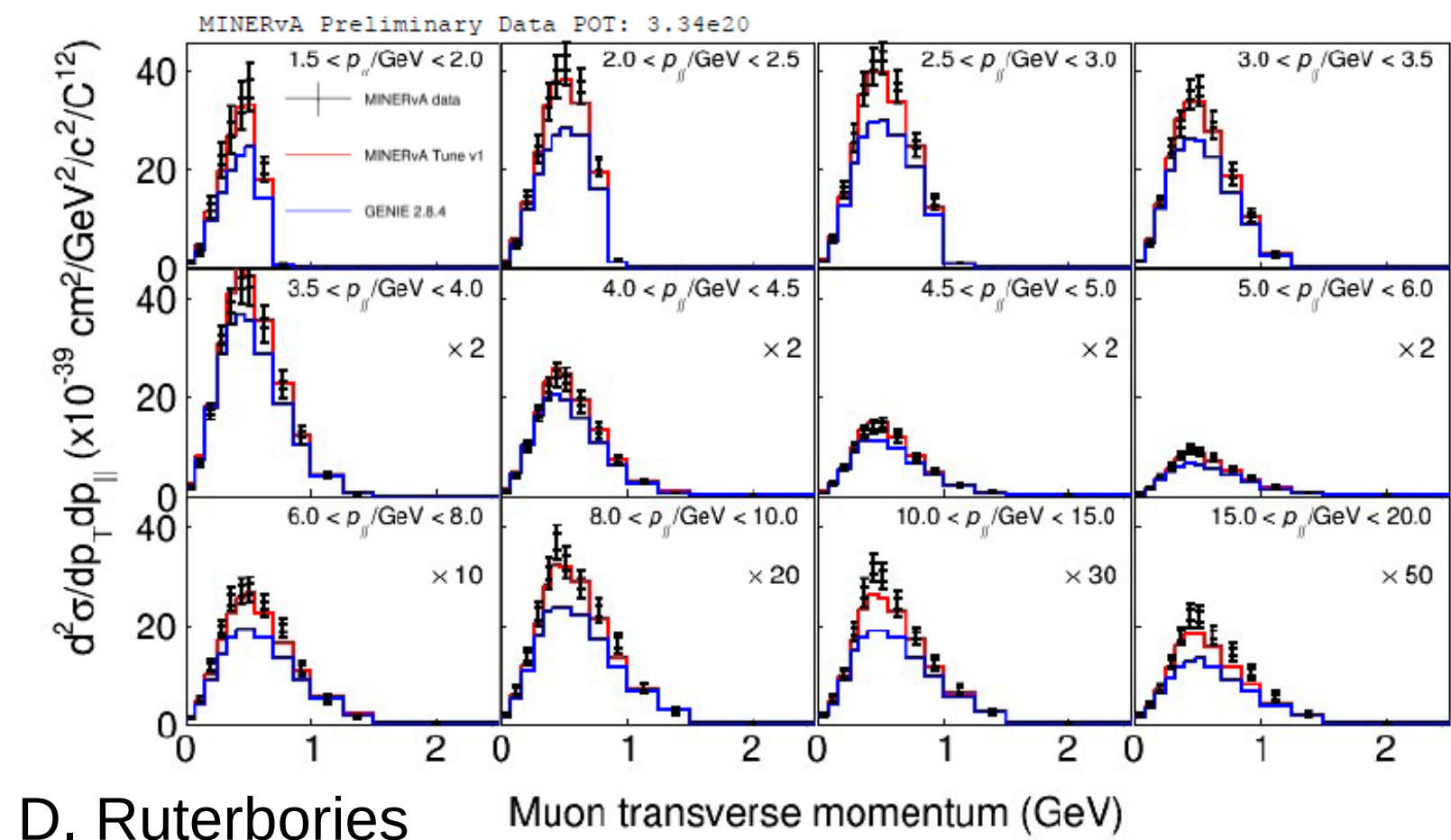
- Furthermore, the models significantly under-predict the rate in MINERvA and NOvA, which are at higher neutrino energies.
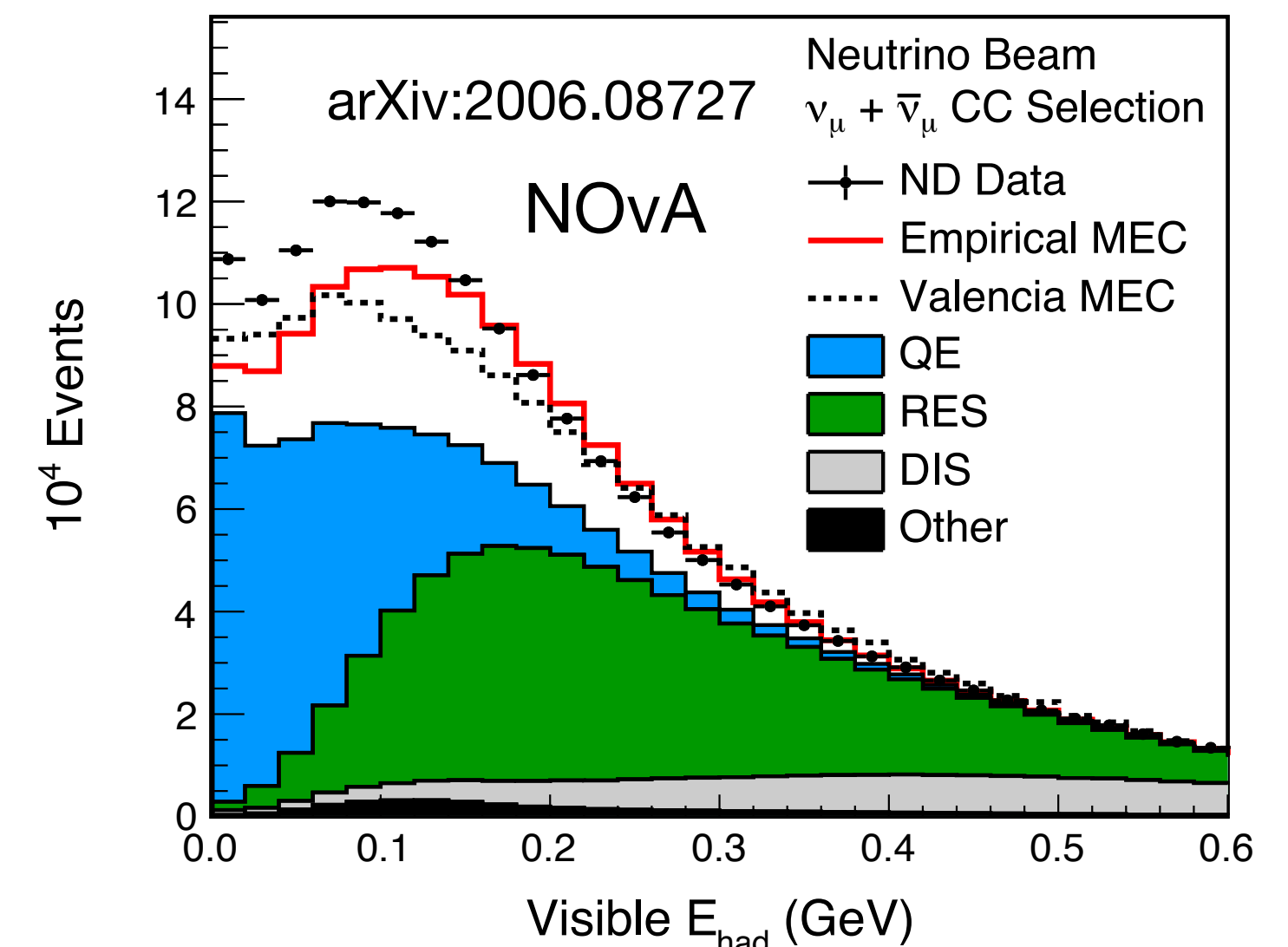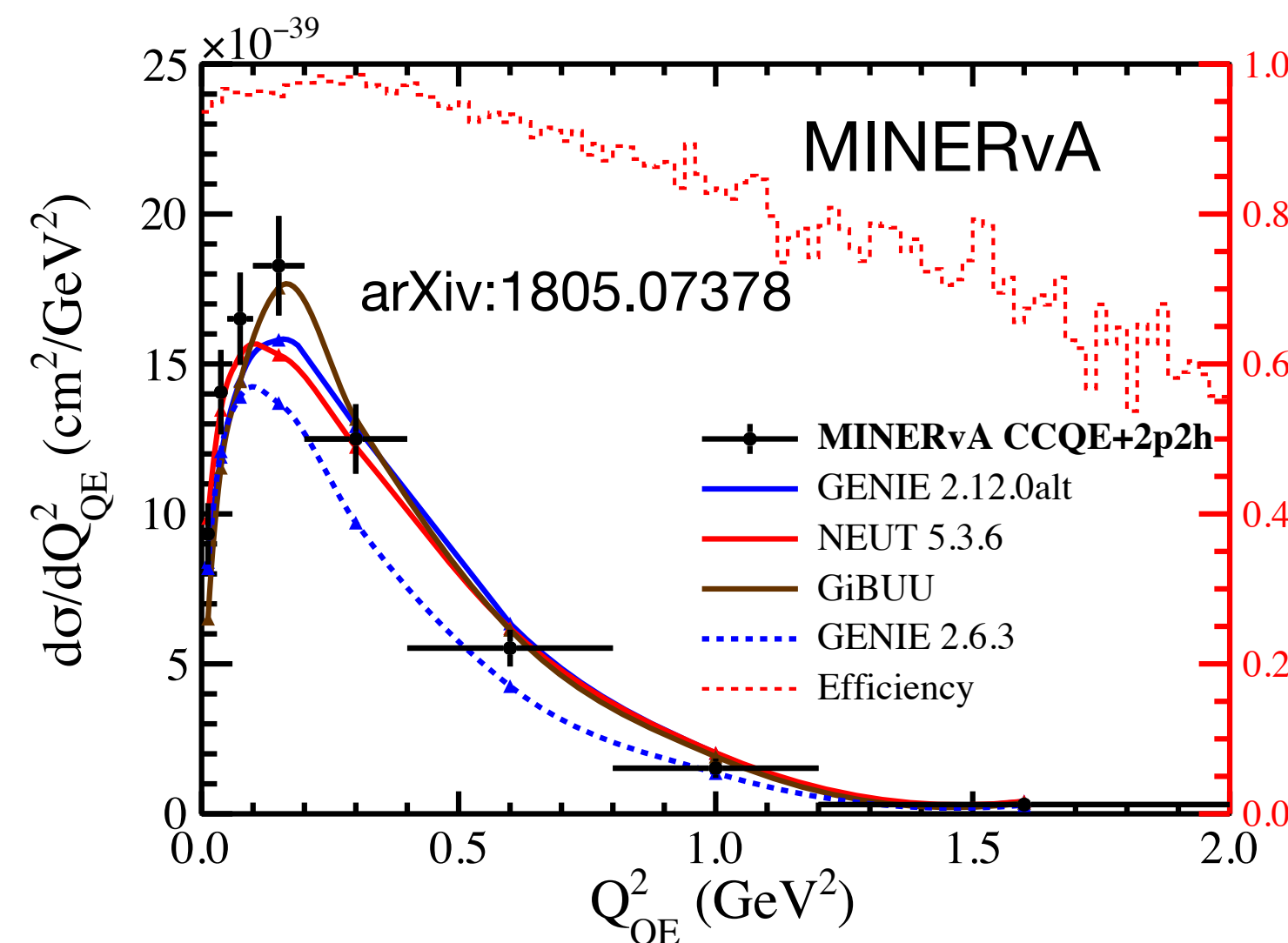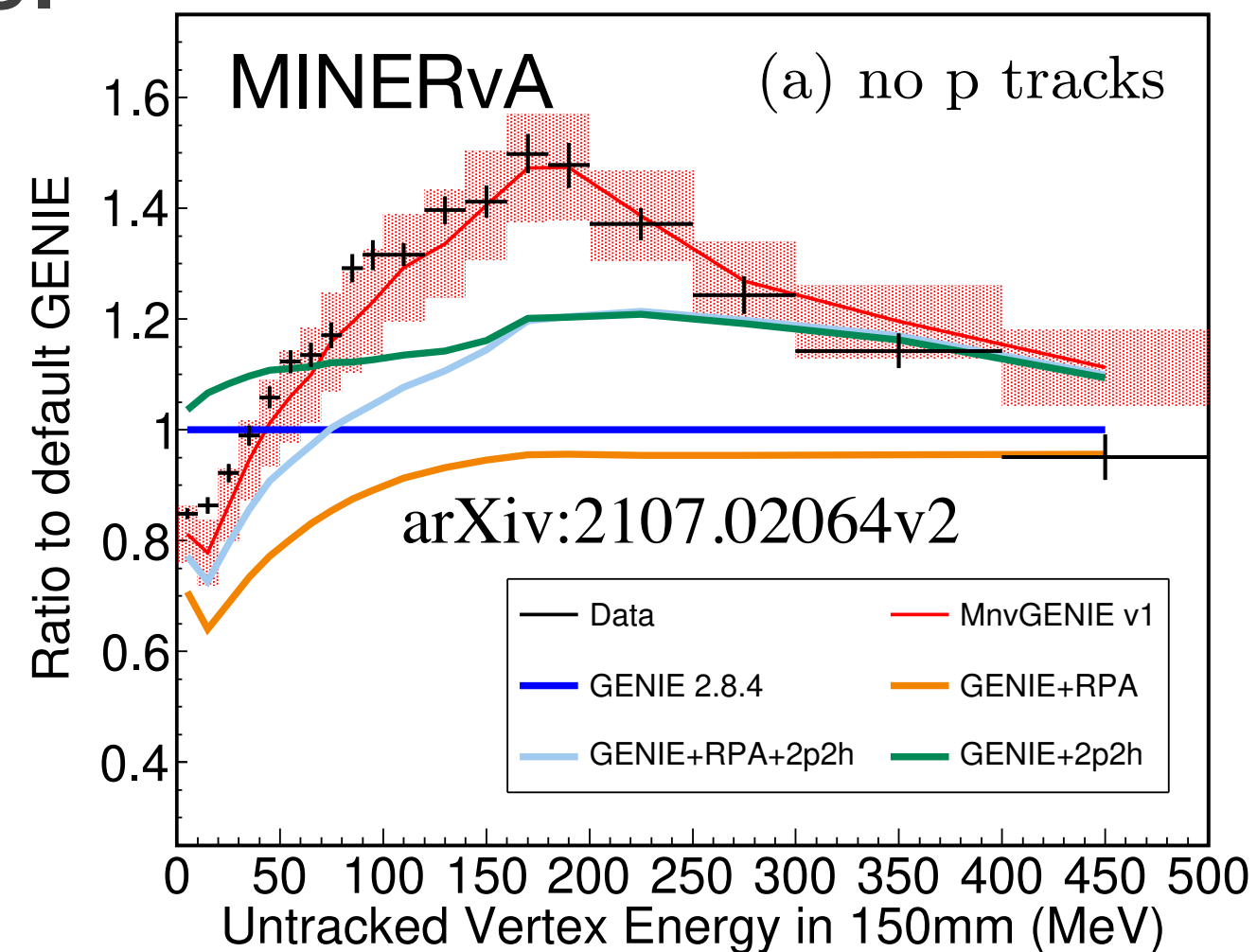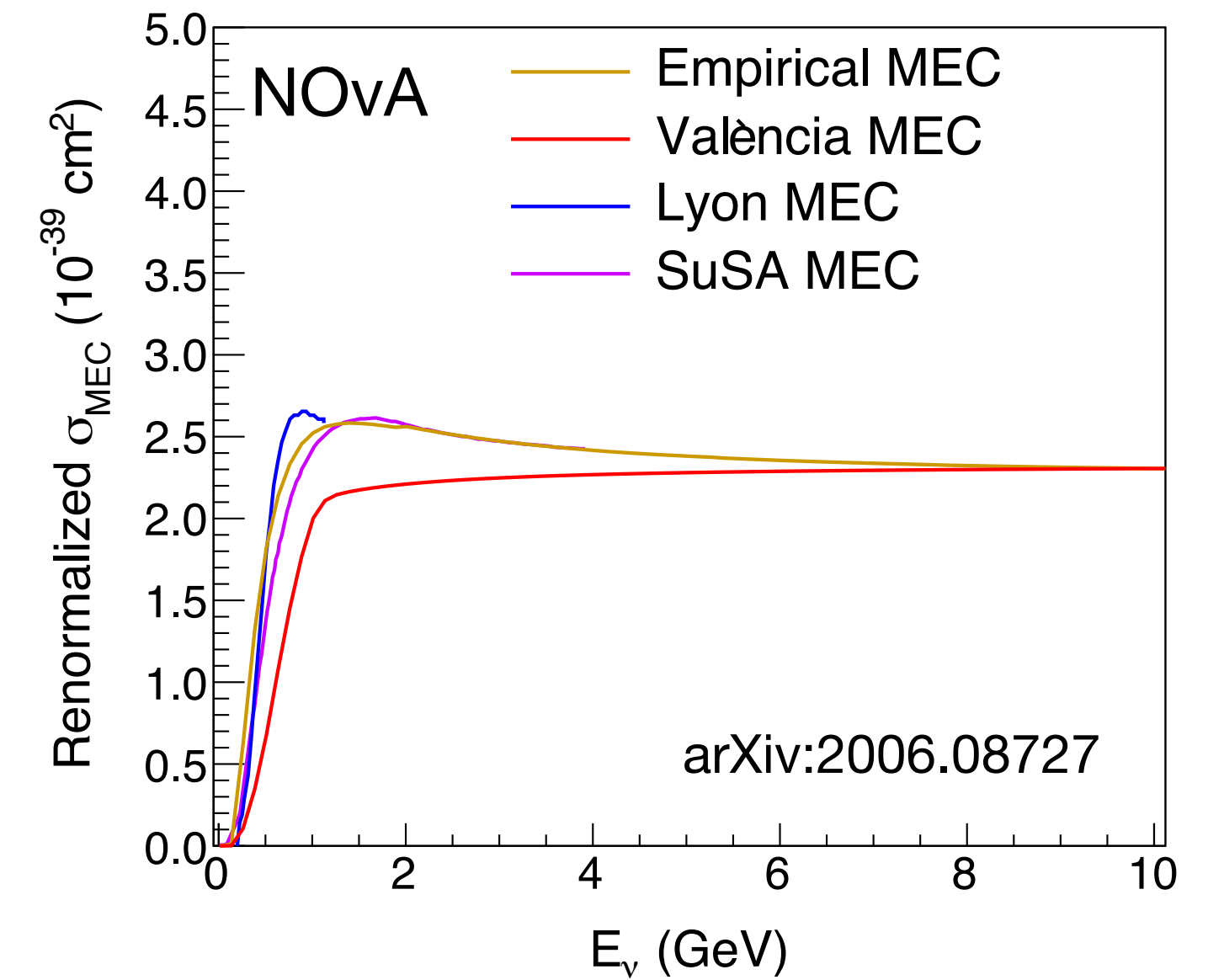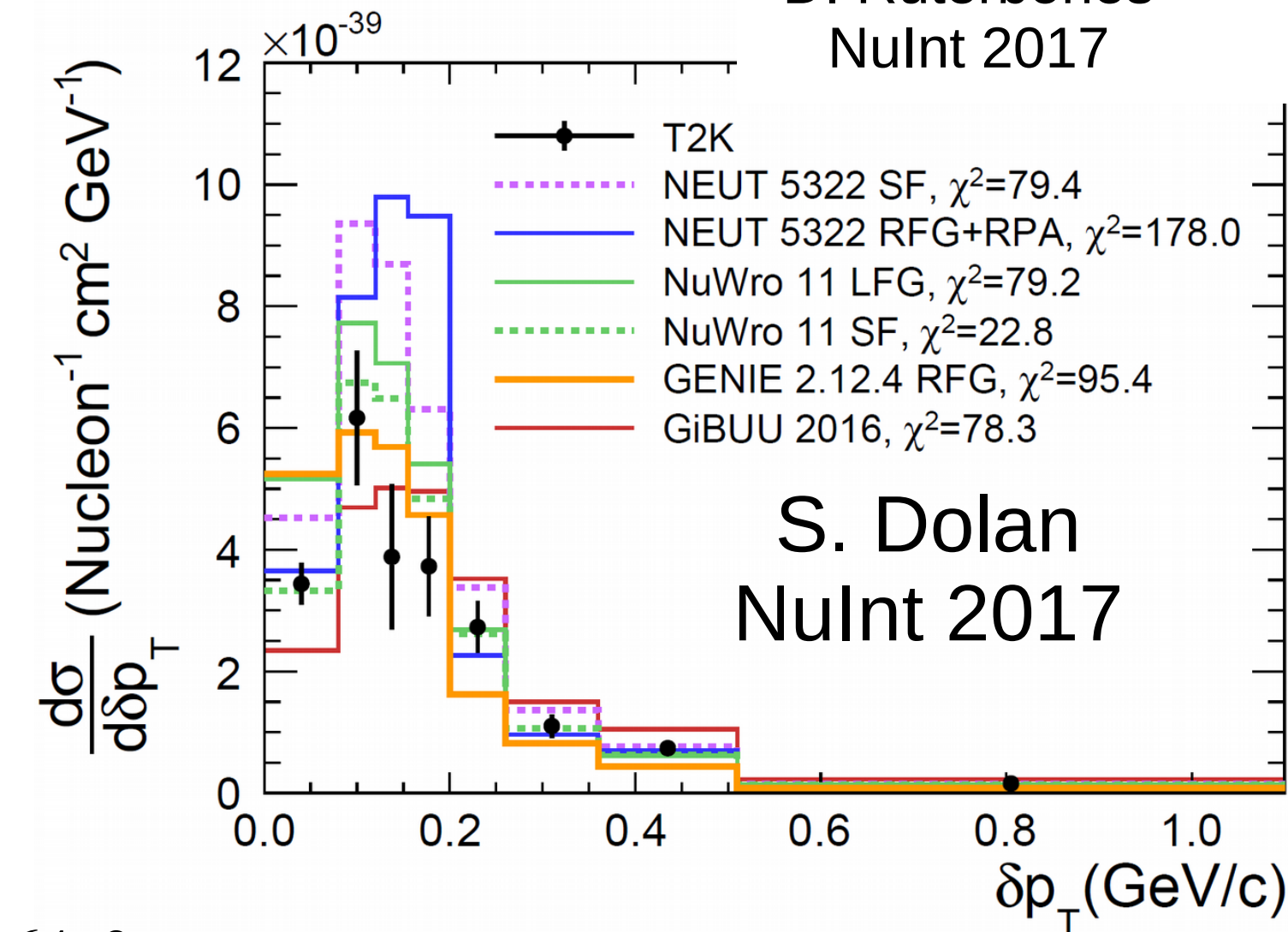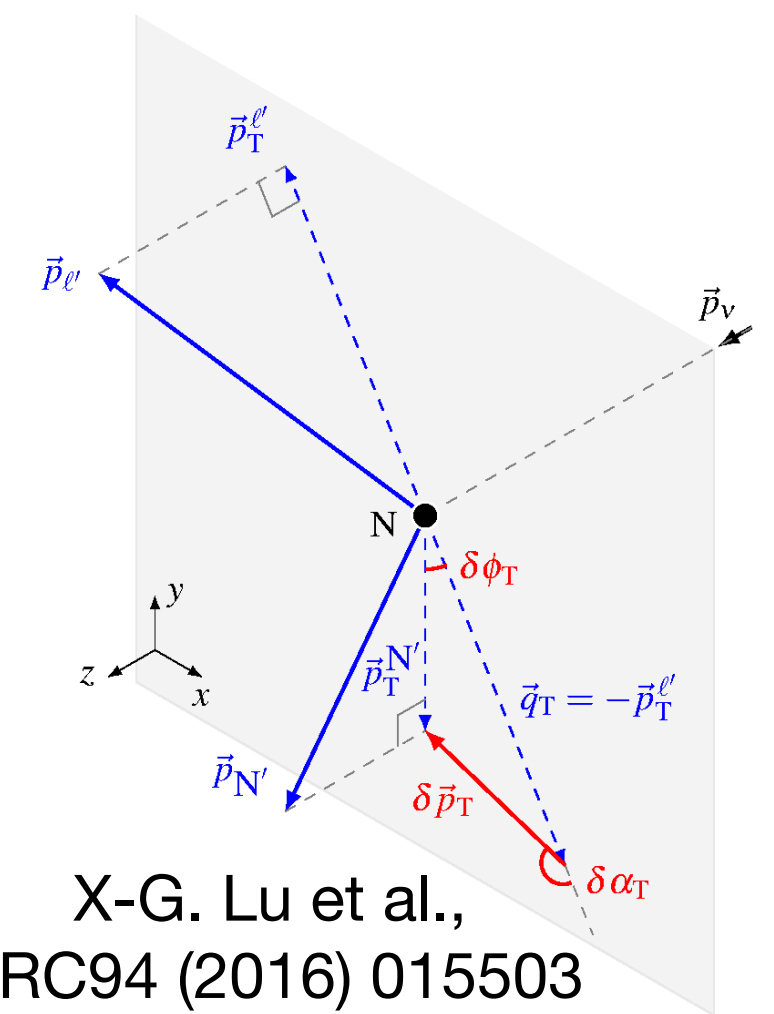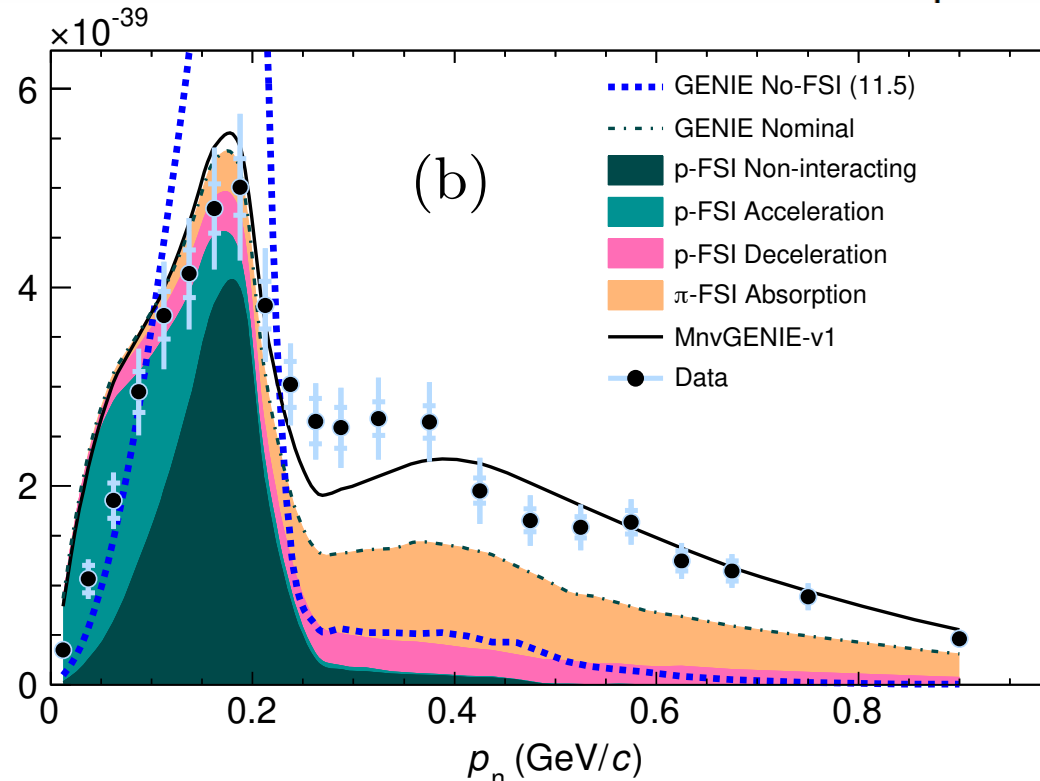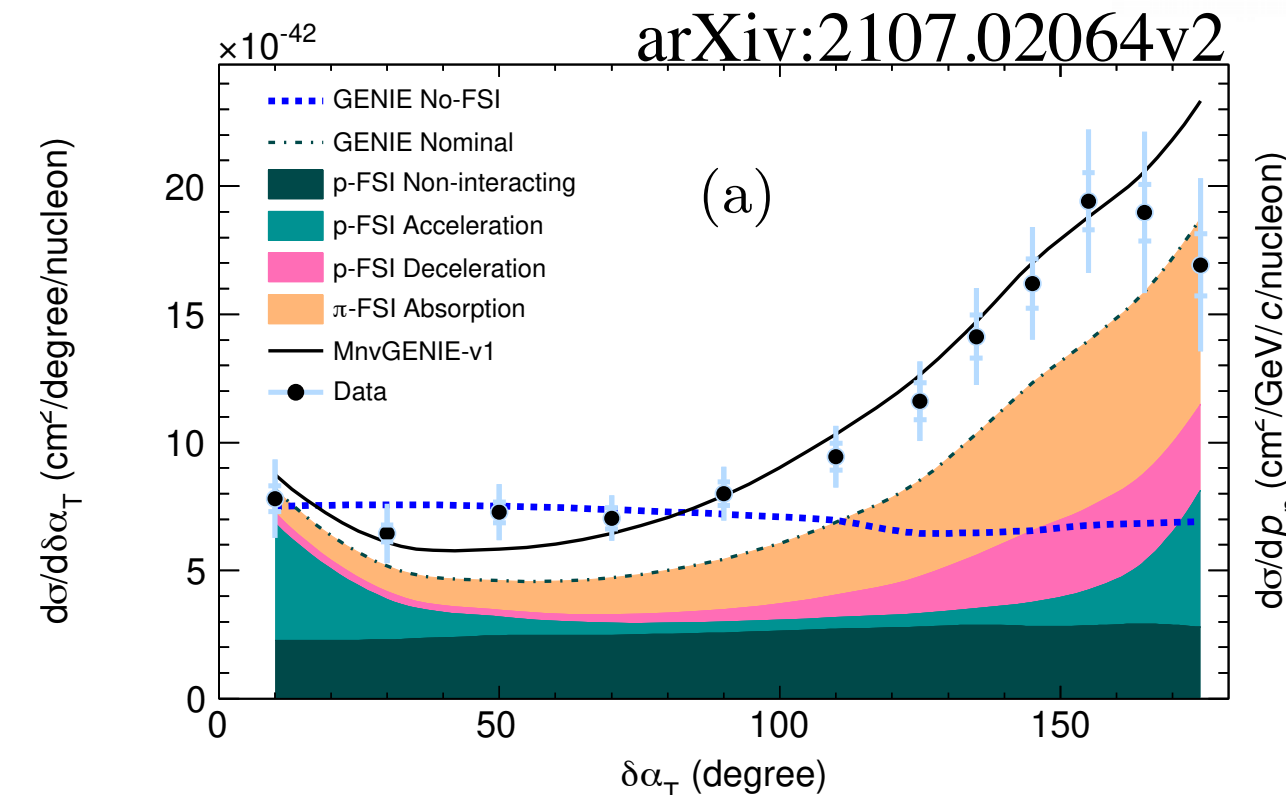
CC-0π New Probes

- Experiments are now focusing on additional probes (observables) that are sensitive to nuclear effects such as 2p2h, final-state interactions, and the initial state.

  - MINERvA and NOvA: some regions of the measured muon kinematics phase space are extra sensitive to 2p2h.

  - T2K and MINERvA: transverse imbalance between muon and proton, can potentially break the degeneracy between these nuclear effects.
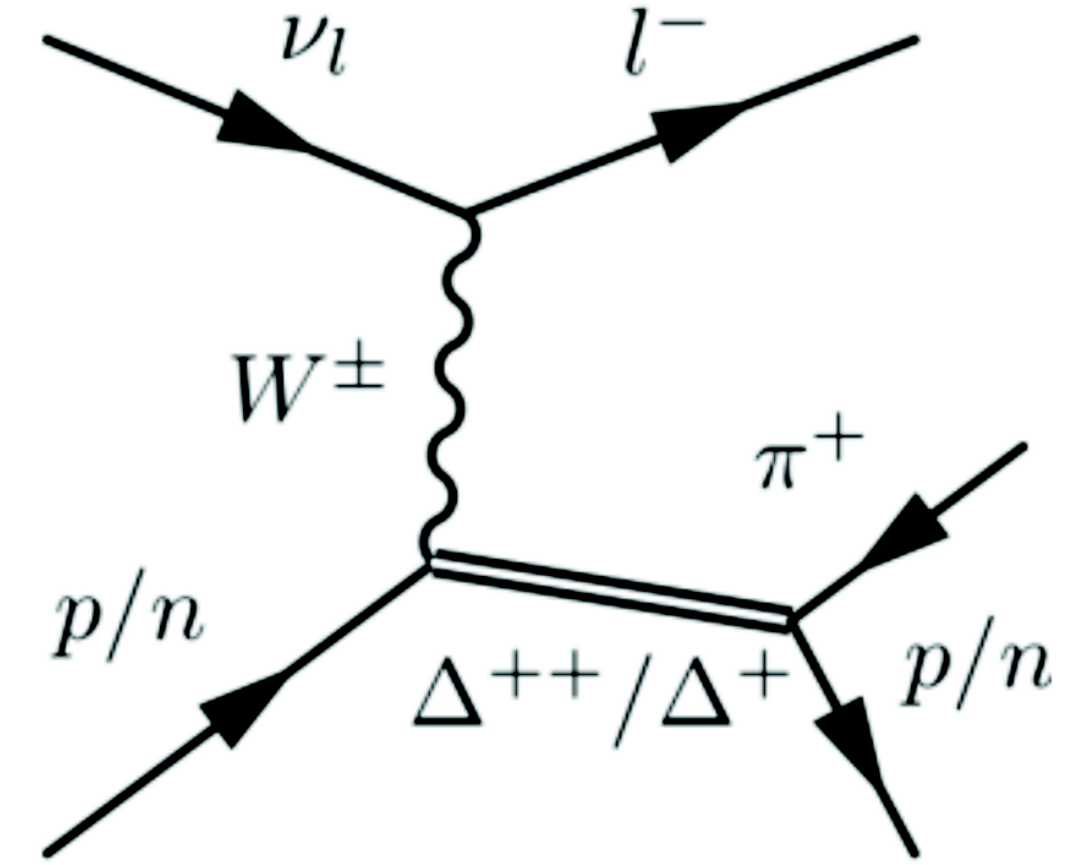
MINERvA Preliminary Data POT: 3.34e20

$\frac{d^2\sigma}{dp_T dp_{||}}$ ($\times 10^{-39}$ cm^2/c^2/GeV^2/C^{12})

Muon transverse momentum (GeV)

D. Ruterbories
NuInt 2017

$\frac{d\sigma}{d\delta p_T}$ (Nucleon^{-1} cm^2 GeV^{-1})

- T2K
- NEUT 5322 SF, χ^2=79.4
- NEUT 5322 RFG+RPA, χ^2=178.0
- NuWro 11 LFG, χ^2=79.2
- NuWro 11 SF, χ^2=22.8
- GENIE 2.12.4 RFG, χ^2=95.4
- GiBUU 2016, χ^2=78.3

S. Dolan
NuInt 2017

δp_T(GeV/c)

$\frac{d\sigma}{d\delta\phi_T}$ (Nucleon^{-1} cm^2 rads

- T2K
- NEUT 5322
- NEUT 5322
- NuWro 11 LF
- NuWro 11 S
- GENIE 2.12.
- GiBUU 2016

arXiv:2107.02064v2

$\frac{d\sigma}{d\delta\alpha_T}$ (cm^4/degree/nucleon)

- GENIE No-FSI
- GENIE Nominal
- p-FSI Non-interacting
- p-FSI Acceleration
- p-FSI Deceleration
- π-FSI Absorption
- MnvGENIE-v1
- Data

(a)

$\delta\alpha_T$ (degree)

$\frac{d\sigma}{dp_n}$ (cm^4/GeV/c/nucleon)

- GENIE No-FSI (11.5)
- GENIE Nominal
- p-FSI Non-interacting
- p-FSI Acceleration
- p-FSI Deceleration
- π-FSI Absorption
- MnvGENIE-v1
- Data

(b)

p_n (GeV/c)

X-G. Lu et al.,
PRC94 (2016) 015503
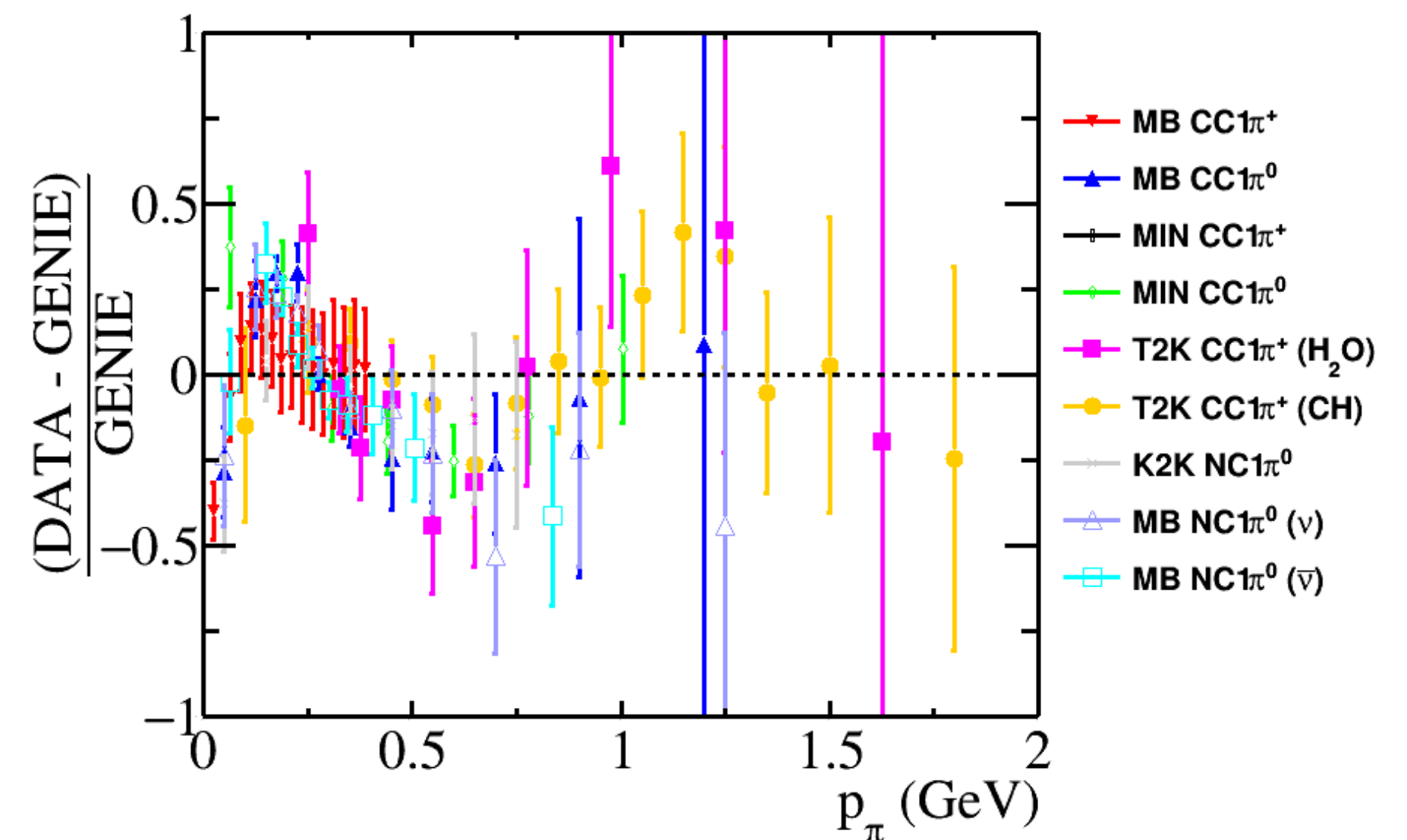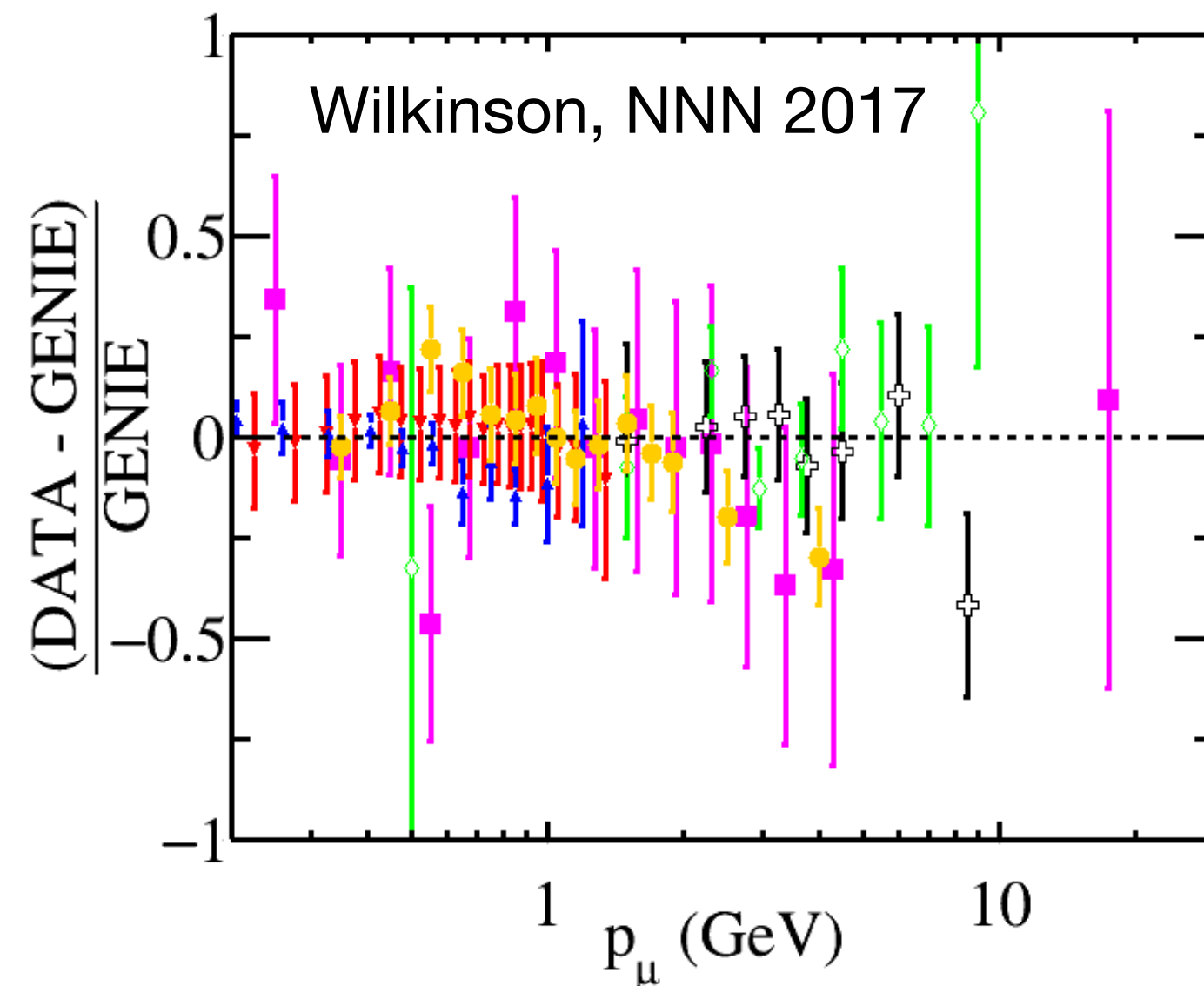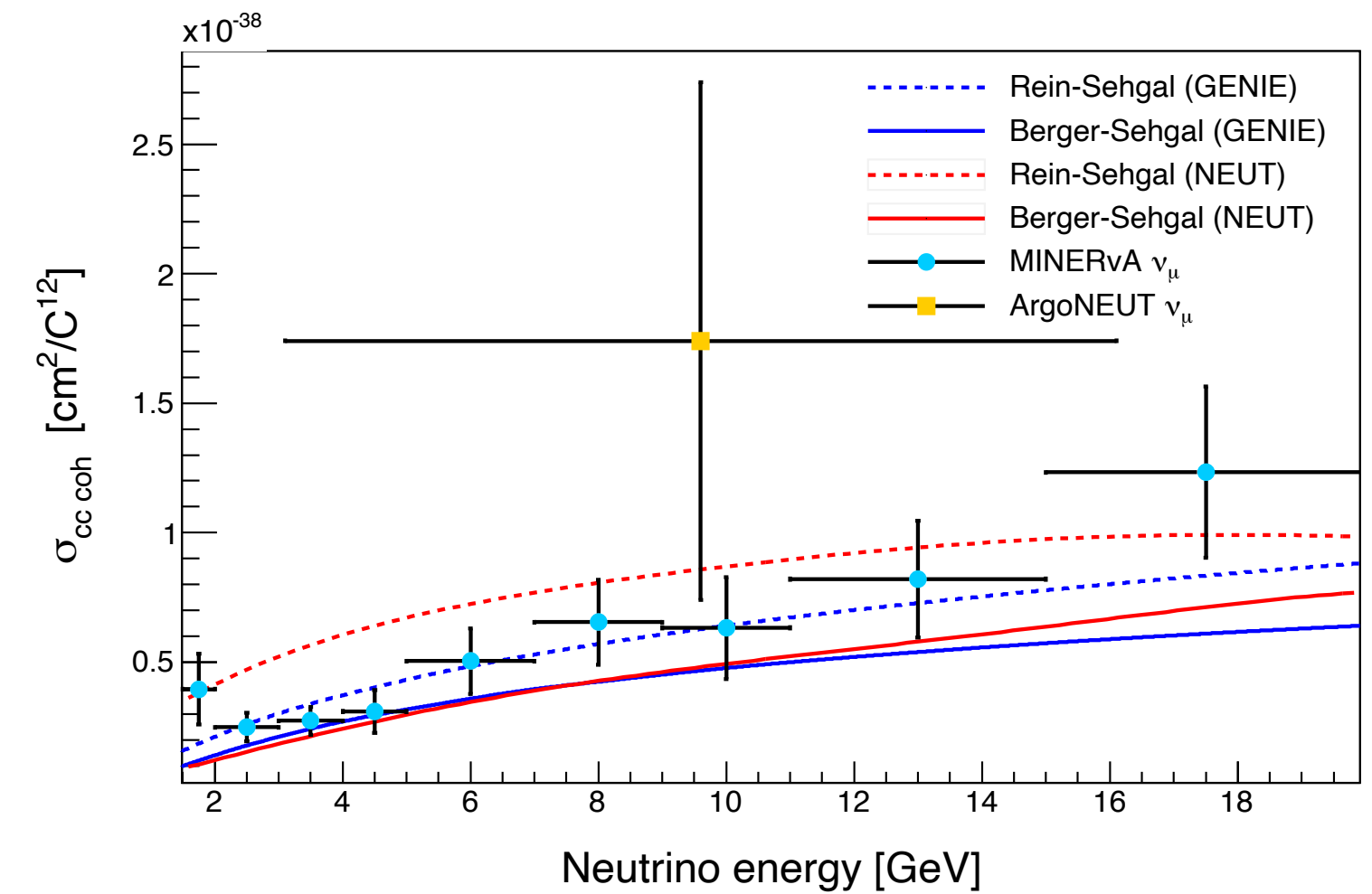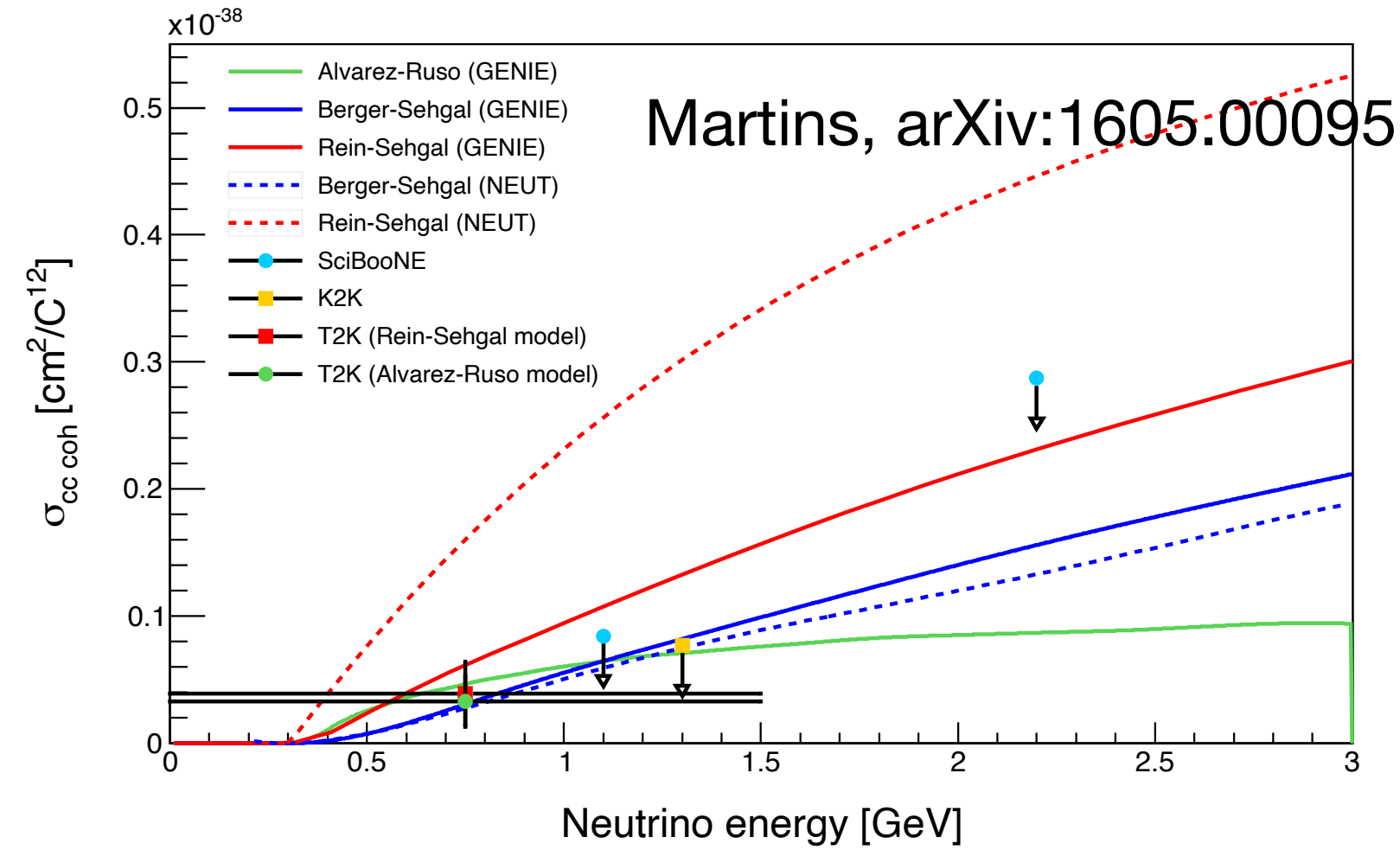
CC-1π Measurements and Models

- Significant process for signal events in NOvA and DUNE, a background in T2K/Hyper-K/SBN. Dominated by Δ resonance production and decay.

- Two model approaches:

  - use Adler's PCAC theorem to relate neutrino scattering amplitude to the pion decay scattering amplitude for ~18 nuclear resonances. Originally by Rein-Sehgal, later improved by Berger-Sehgal (using pion scattering data). Best for $E_\pi < 1$ GeV, $W < 2$ GeV.

  - Microscopic approach (eg, Alvarez-Ruso *et al.*): coherent sum of individual ν-A pion production processes, accounting for the Δ. Valid for $E_\nu < 3$ G

- R-S and B-S models are m generators and used by ex

$$\nu p \rightarrow \nu p \pi^0 \quad (a)$$
$$\nu p \rightarrow \nu n \pi^+ \quad (b)$$
$$\nu n \rightarrow \nu n \pi^0 \quad (c)$$
$$\nu n \rightarrow \nu p \pi^- \quad (d)$$

$$\bar{\nu} p \rightarrow \bar{\nu} p \pi^0 \rightarrow \bar{\nu} p \pi^0$$
$$\bar{\nu} p \rightarrow \bar{\nu} n \pi^+ \rightarrow \bar{\nu} n \pi^+$$
$$\bar{\nu} n \rightarrow \bar{\nu} n \pi^0 \rightarrow \bar{\nu} n \pi^0$$
$$\bar{\nu} n \rightarrow \bar{\nu} p \pi^- \rightarrow \bar{\nu} p \pi^-$$

|	ν	$\bar{\nu}$
CC	$\nu p \rightarrow \mu^- p \pi^+$	$\bar{\nu} n \rightarrow \mu^+ n \pi^-$
	$\nu n \rightarrow \mu^- p \pi^0$	$\bar{\nu} p \rightarrow \mu^+ n \pi^0$
	$\nu n \rightarrow \mu^- n \pi^+$	$\bar{\nu} p \rightarrow \mu^+ p \pi^-$
	$\nu p \rightarrow \nu p \pi^0$	$\bar{\nu} p \rightarrow \bar{\nu} p \pi^0$
	$\nu p \rightarrow \nu n \pi^+$	$\bar{\nu} p \rightarrow \bar{\nu} n \pi^+$
	$\nu n \rightarrow \nu n \pi^0$	$\bar{\nu} n \rightarrow \bar{\nu} n \pi^0$
	$\nu n \rightarrow \nu p \pi^-$	$\bar{\nu} n \rightarrow \bar{\nu} p \pi^-$

CC-1π Measurements and Models

- Broad range of predictions from the generators.

- Measurements from T2K and MINERvA indicate reasonable agreement in the muon kinematics, not-so-good agreement in the pion kinematics.


Martins, arXiv:1605.00095

Wilkinson, NNN 2017

CC-1π Measurements and Models

- Latest measurements are a mixed bag: in broad strokes, the predictions for the overall rate for interactions on carbon are not far off.

- But the shapes of the kinematic distributions need more work.
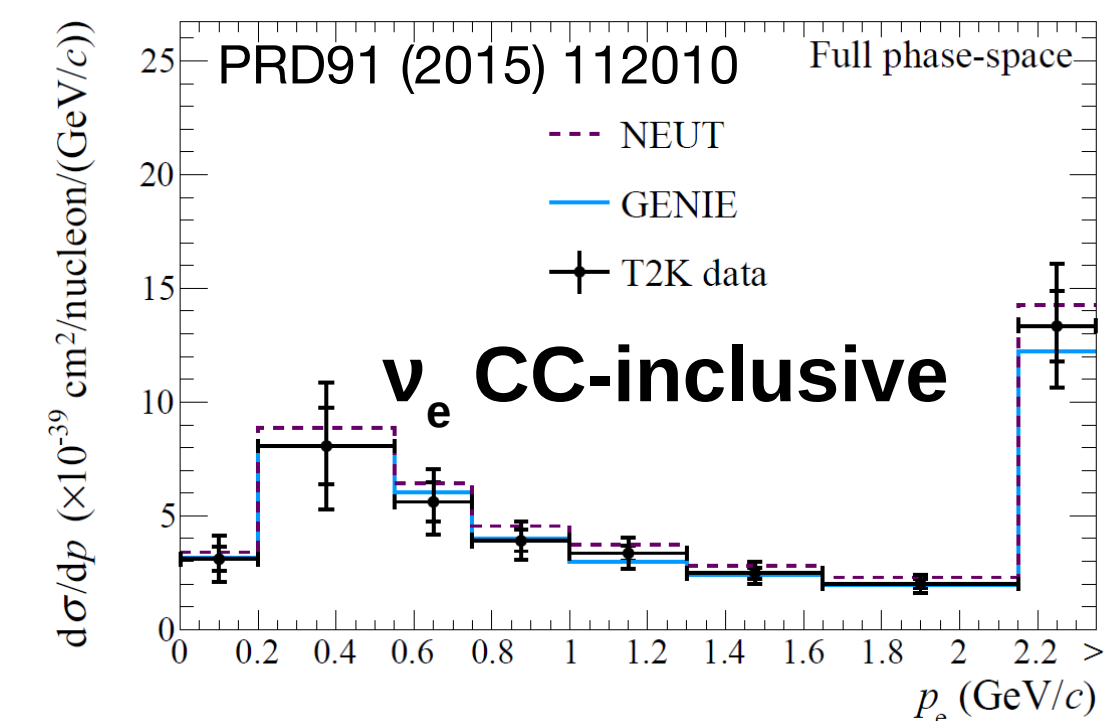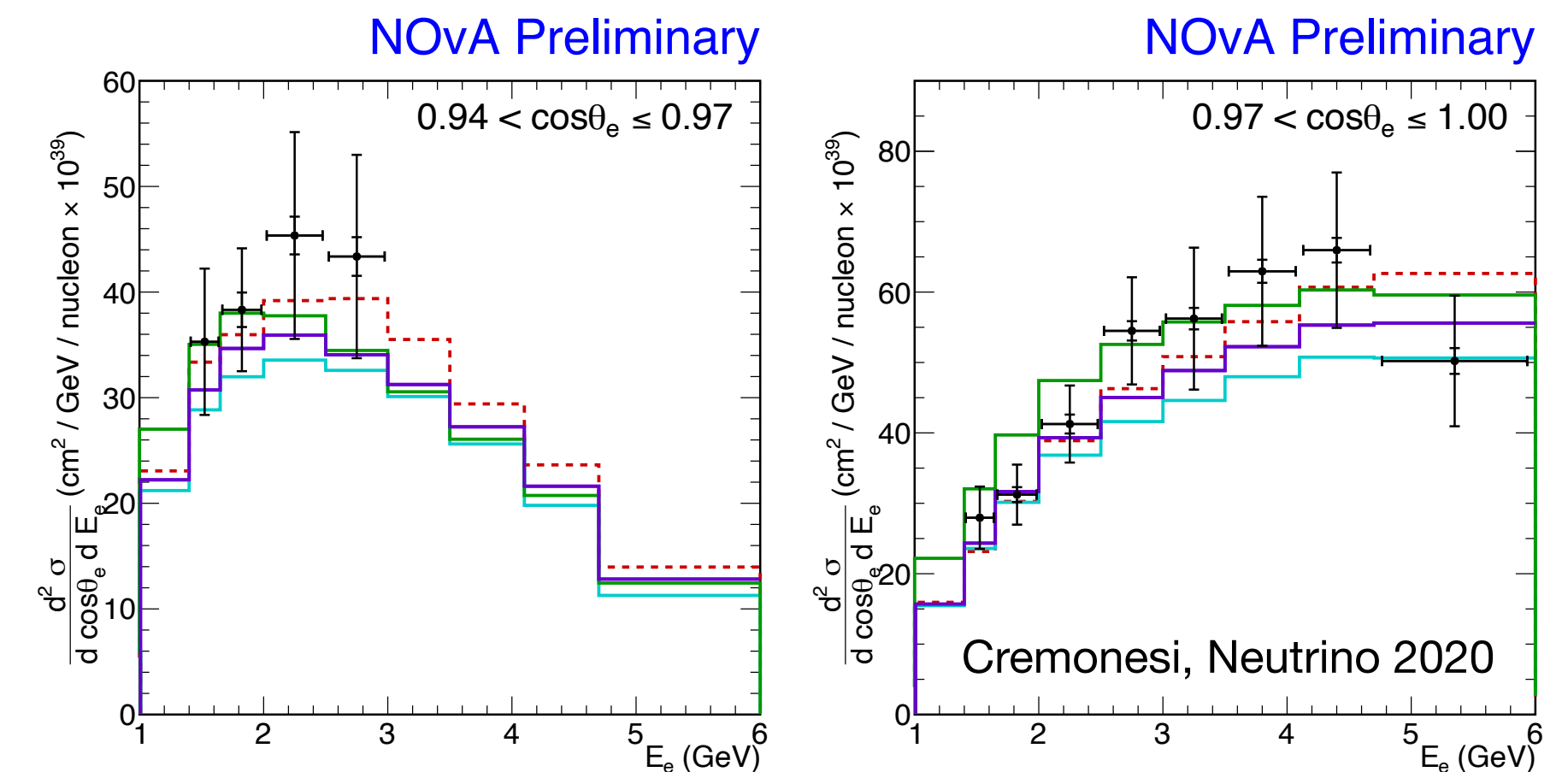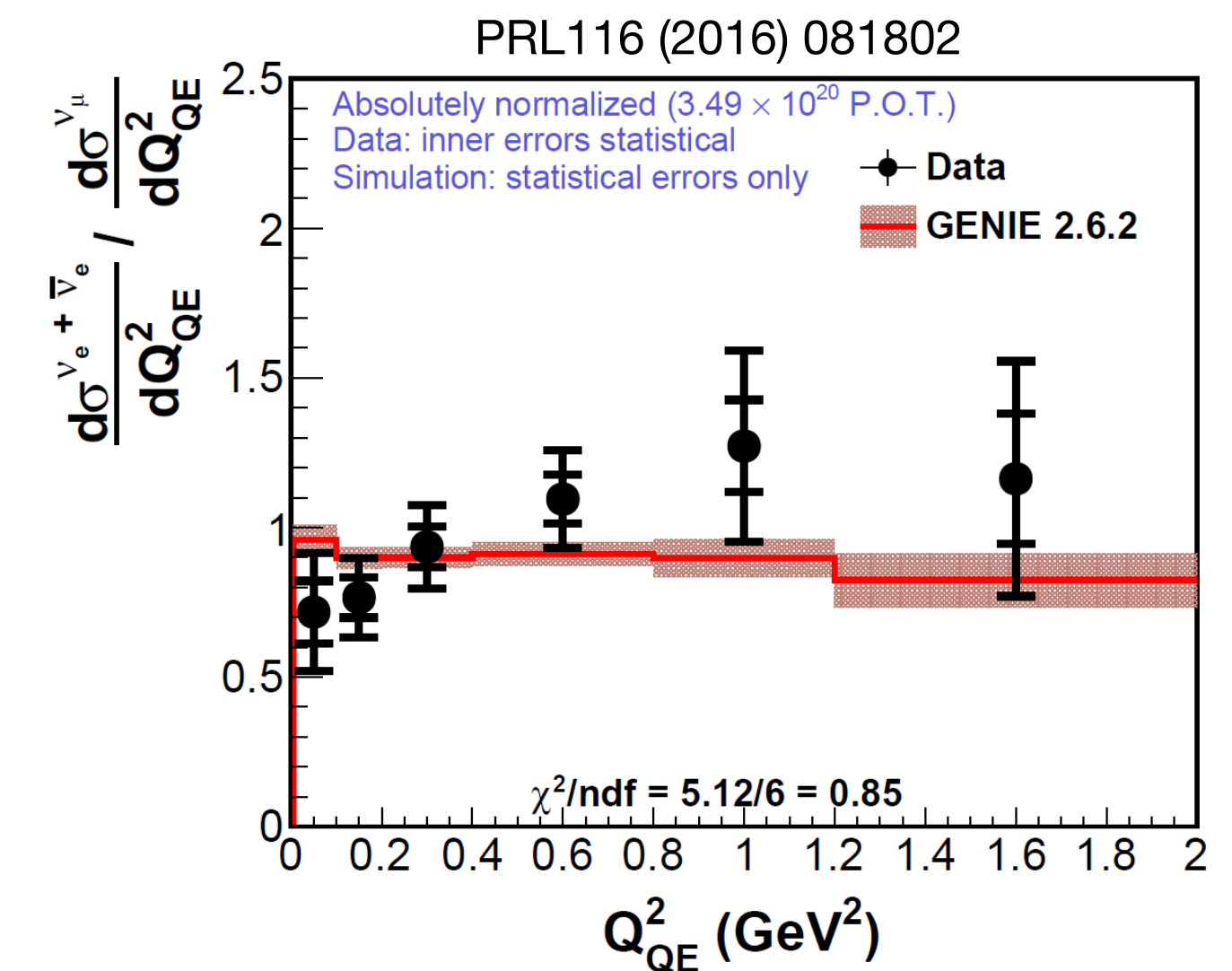
- We also need new/better data!

Phys. Rev. D **101**, 012007

Phys. Rev. D **102**, 012004
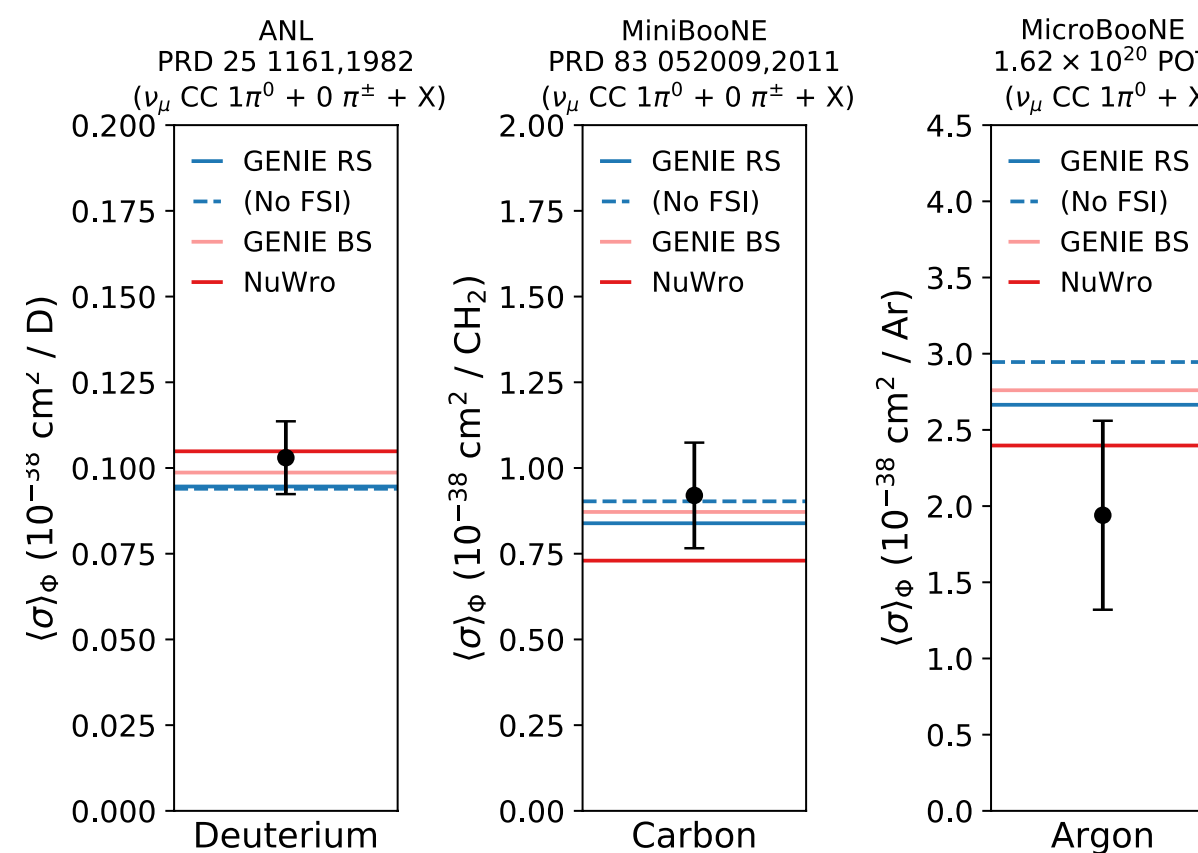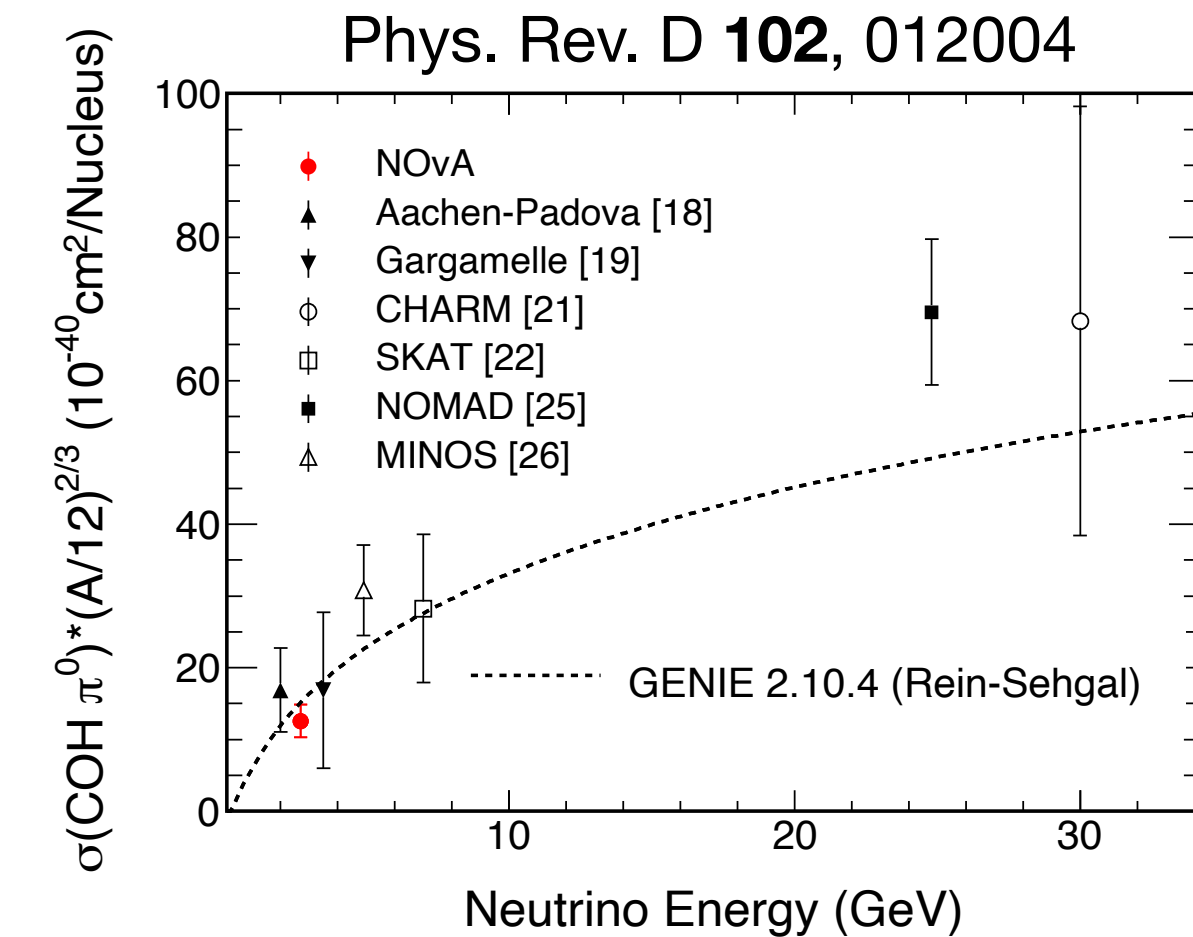
Phys. Rev. D **99**, 091102(R)

arXiv:2107.02064v2
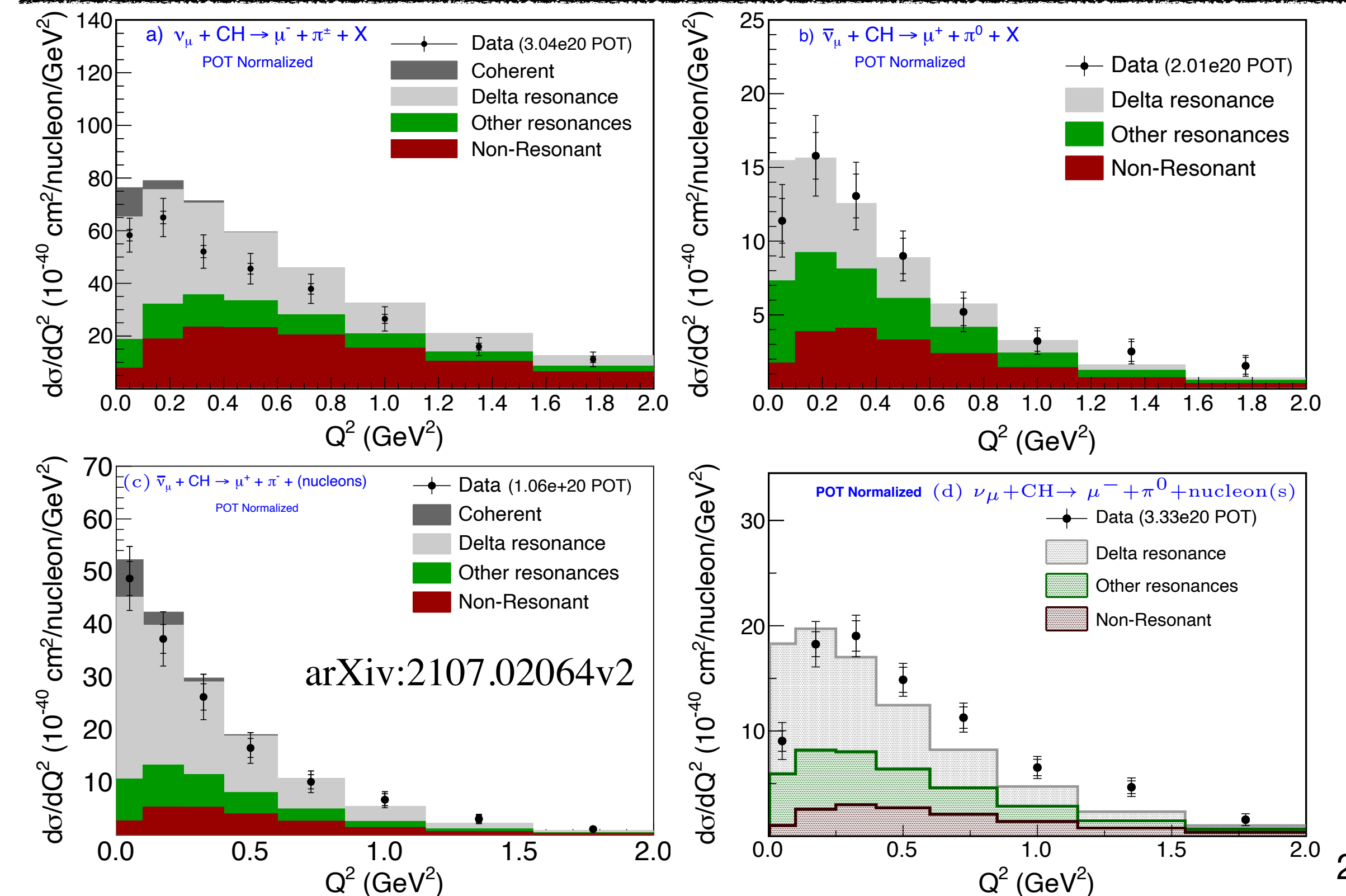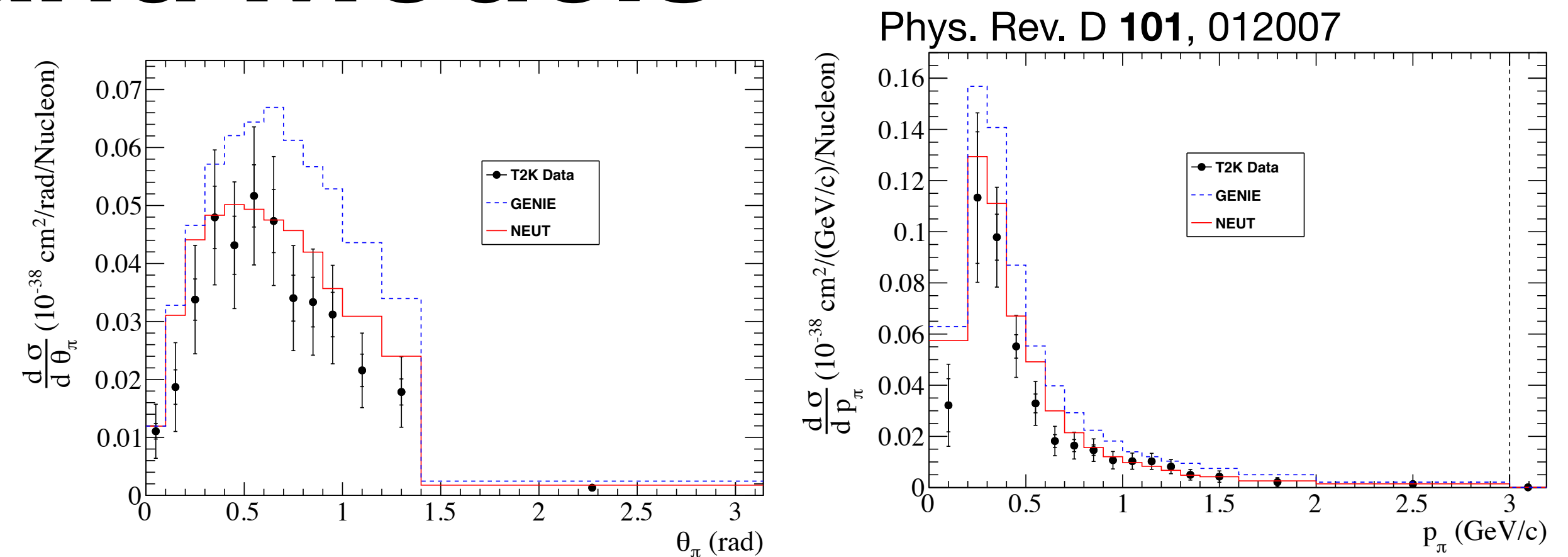
Other Hot Topics

- ν_e/ν_μ ratios: critically important for oscillation experiments that are measuring $\nu_\mu \rightarrow \nu_e$ appearance rates vs. E_ν. Even assuming lepton universality, the kinematics of the final-state lepton can differ, especially at lower neutrino energies.

- Modeling of scattering off of single nucleon, current models are based on low-statistics hydrogen/deuterium bubble chamber data with not-very-well-understood uncertainties. Need to strengthen our foundation of neutrino-nucleus scattering with new light-nuclei data!

- We have lots of data involving carbon as the nuclear target. Need more heavier-target data, especially argon!

- Modeling of higher resonances and the transition from Res to DIS, very important for DUNE.

- We've learned a lot from electron scattering (eg, 2p2h, Duality), what else can we learn? How can we use it to constrain neutrino scattering models?

PRL116 (2016) 081802

NOvA Preliminary

Cremonesi, Neutrino 2020

PRD91 (2015) 112010

ν_e CC-inclusive

The Future is Bright!

- ν-A scattering is a vibrant and dynamic field.

- We have made great strides in the past decade in improving our modeling of CC 0π processes, discrepancies in modeling nuclear effects are an opportunity for future improvement.

- There has been less progress on improving models of CC π-production, but new data s... xtremely valuable.

- W... tions that will be producing new results and st... ll improve our ability to tune our models of ν-A s...

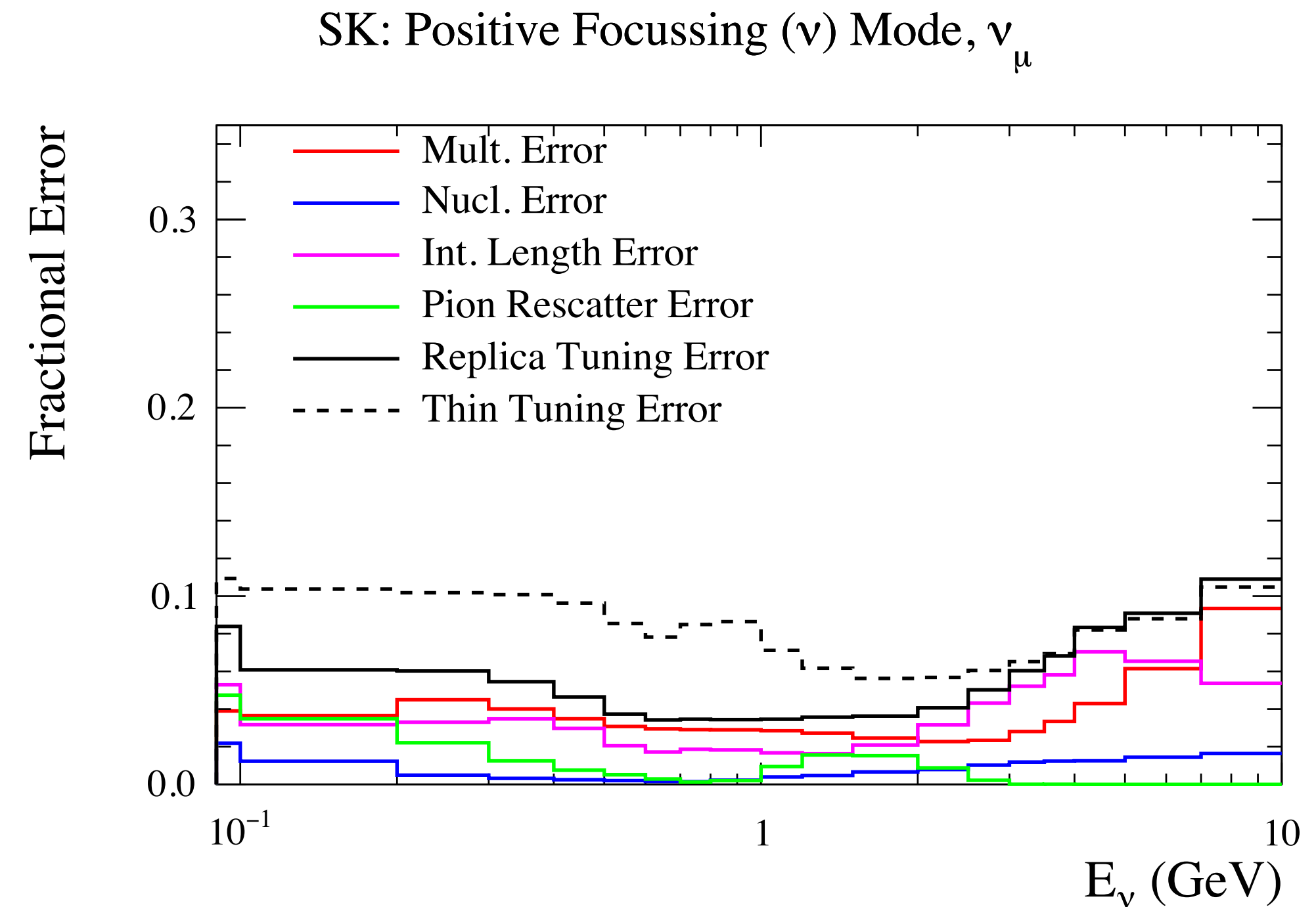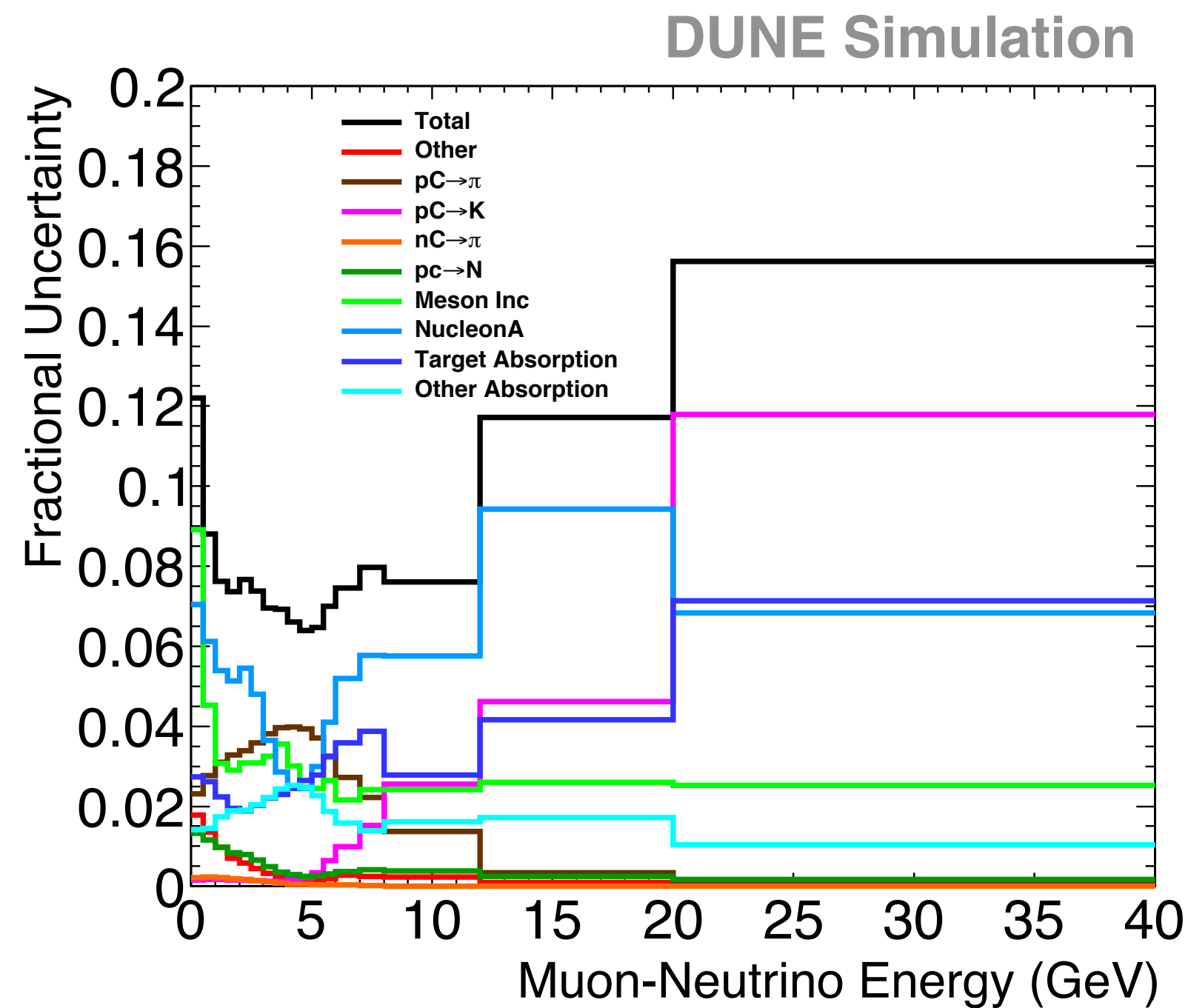- Stay tuned! Better yet, get involved!
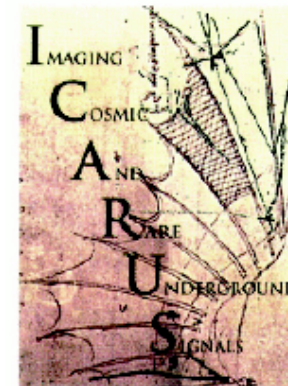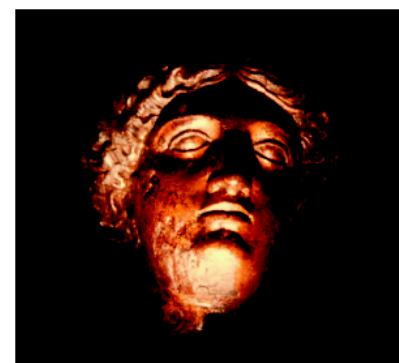
Backup

Aside: Neutrino Fluxes

- We measure flux * xsec in our detectors.

- Very difficult to measure the flux by itself

- We rely on simulation to predict the flux.

- Simulations need the production cross section for p, π, K hitting a broad range of nuclear targets across a broad range of energies. Eg, particles of all energies up to the beam energy interact in the production target (C or Be), focusing horns (aluminum), and lots of other material (water, Ti, Fe, He, rock, etc.)

- Uncertainties in the flux prediction come from uncertainties in scattering cross sections and uncertainties in the alignment and focusing elements.
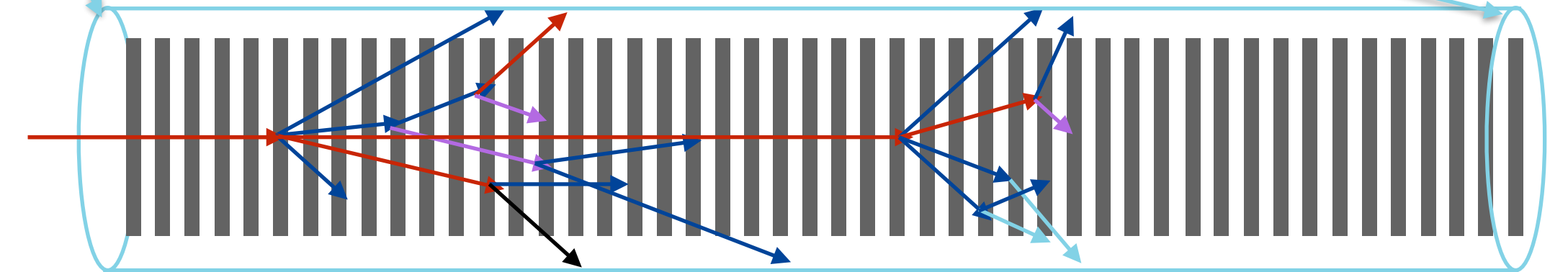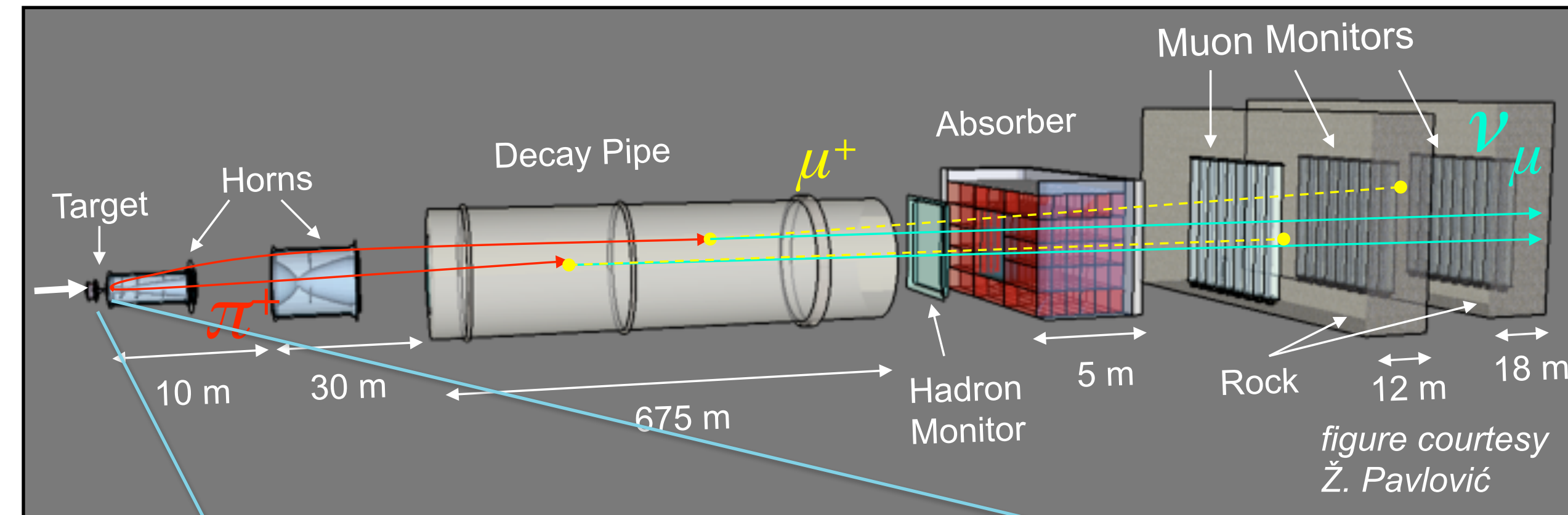
- Hadron production cross section uncertainties are the dominant source of uncertainty in flux predictions.

- There are a lot of relevant interactions that have not been measured [well].

Aside: Flux Uncertainties

SK: Positive Focussing (ν) Mode, ν_μ — Fractional Error vs E_ν (GeV): Mult. Error, Nucl. Error, Int. Length Error, Pion Rescatter Error, Thin Tuning Error

SK: Positive Focussing (ν) Mode, ν_μ — Fractional Error vs E_ν (GeV): Mult. Error, Nucl. Error, Int. Length Error, Pion Rescatter Error, Replica Tuning Error, Thin Tuning Error

- Left: SBN, NuMI and DUNE have ~10% uncertainties, based on hadron production measurements of interactions off of thin targets. Most of the uncertainty comes from interactions in the target and horns that have never been measured (or have large uncertainties/spread).

- Right: Recent NA61/SHINE measurements of hadron production off of T2K replica production target and other thin targets will reduce the flux uncertainties to ~5%.

What to Report: Cross Section or Event Rate?

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} \times P_j)}{\epsilon_i N_{\mathrm{T}} \langle \Phi \rangle \Delta x_i}$$

Most theorists

Some experimentalists

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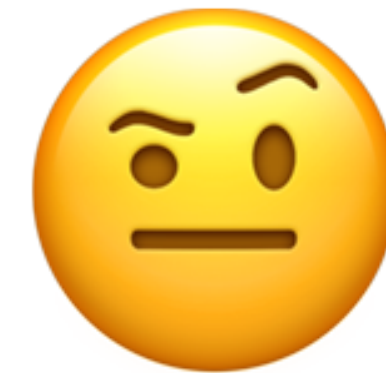
Most theorists

Some experimentalists

$$\frac{dN}{dx_j} \ + \ \mathbf{U}, \vec{P}, \ \vec{\epsilon}, N_{\text{T}}, \langle \Phi \rangle$$

This experimentalist

Most theorists

- Alternatively, we can simply measure our event rate and provide the community the rest of the information they need to compare predictions.

- Note, both involve unavoidable model-dependencies. Again, the challenge is to keep this to a minimum.