NP-HEP synergies for neutrino experiments

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Disclaimers

The following is my personal view.

I attempt to summarize major developments on the experimental program + discussions this last November at JLab and MSU.

Current:

Atmospheric: Super-Kamiokande

Accelerator: T2K, NOvA, Short-Baseline Neutrino Program (SBN)

US-funded program is broad.

Neutrino oscillation, exotica (e.g. sterile neutrino, dark matter searches), proton decay

Future:

Accelerator/Atmospheric: Deep Underground Neutrino Experiment

Signal (or background) processes are 0.1-20 GeV charged current (CC) or neutral current (NC) neutrino or antineutrino interactions for **atmospheric and accelerator based programs**

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Apologies, US centric talk

Examples follow with 3 flavor oscillation program, but, important to keep highlighting full program capabilities - *P. Machado's talk*

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Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}

Is $\sin^2(\theta_{23})=0.5$? (maximal mixing?)

- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}

What is the ordering of the masses ($\Delta m^2_{32/31} > 0$?)

- CP violating phase (CPV)

Is there CPV in neutrinos?

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Event rate used to infer oscillation physics

Oscillation analysis depends on interaction model

Cross section (true kinematics)

Efficiency (true kinematics)

Relationship between true and reconstructed kinematics)

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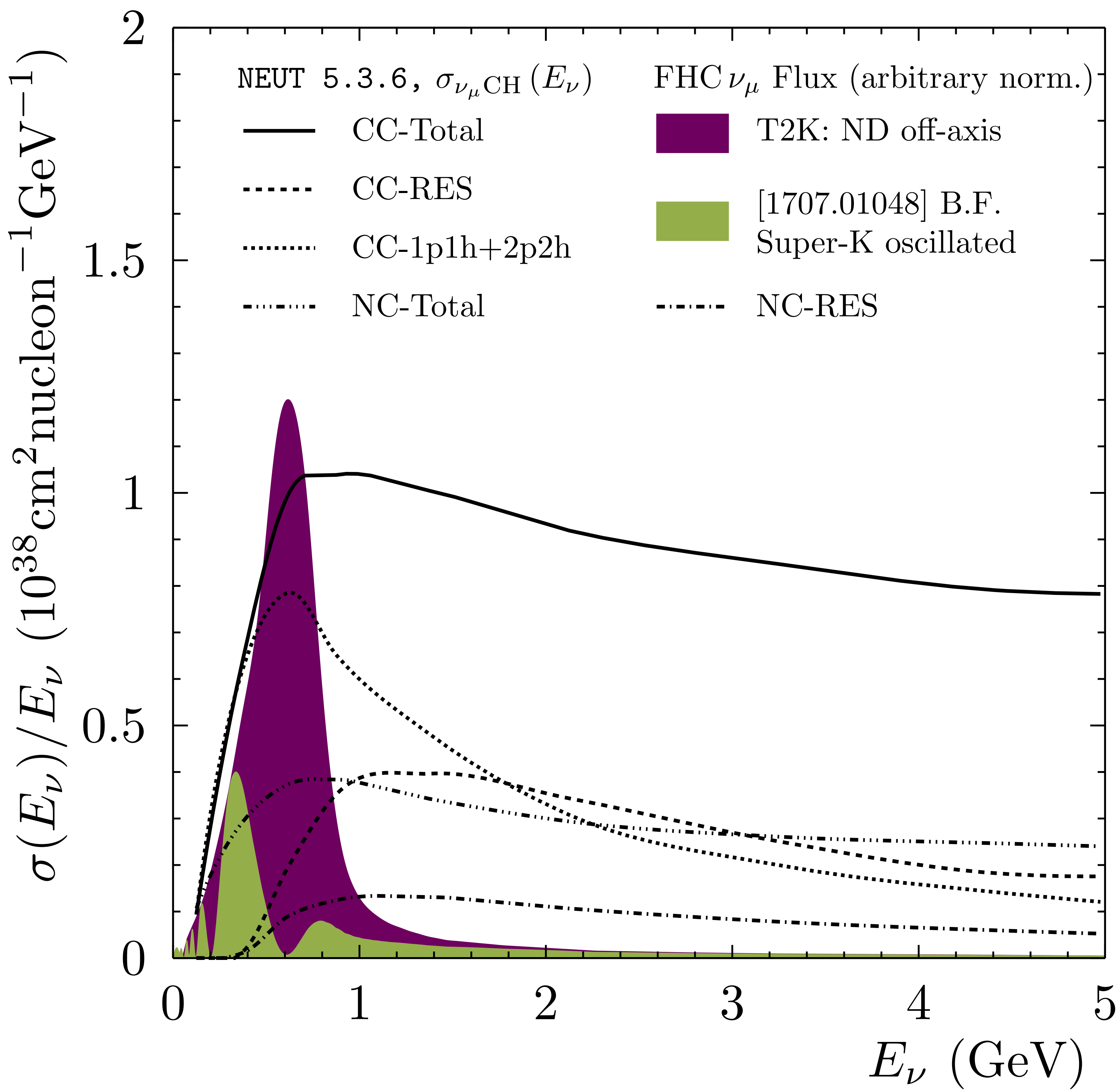
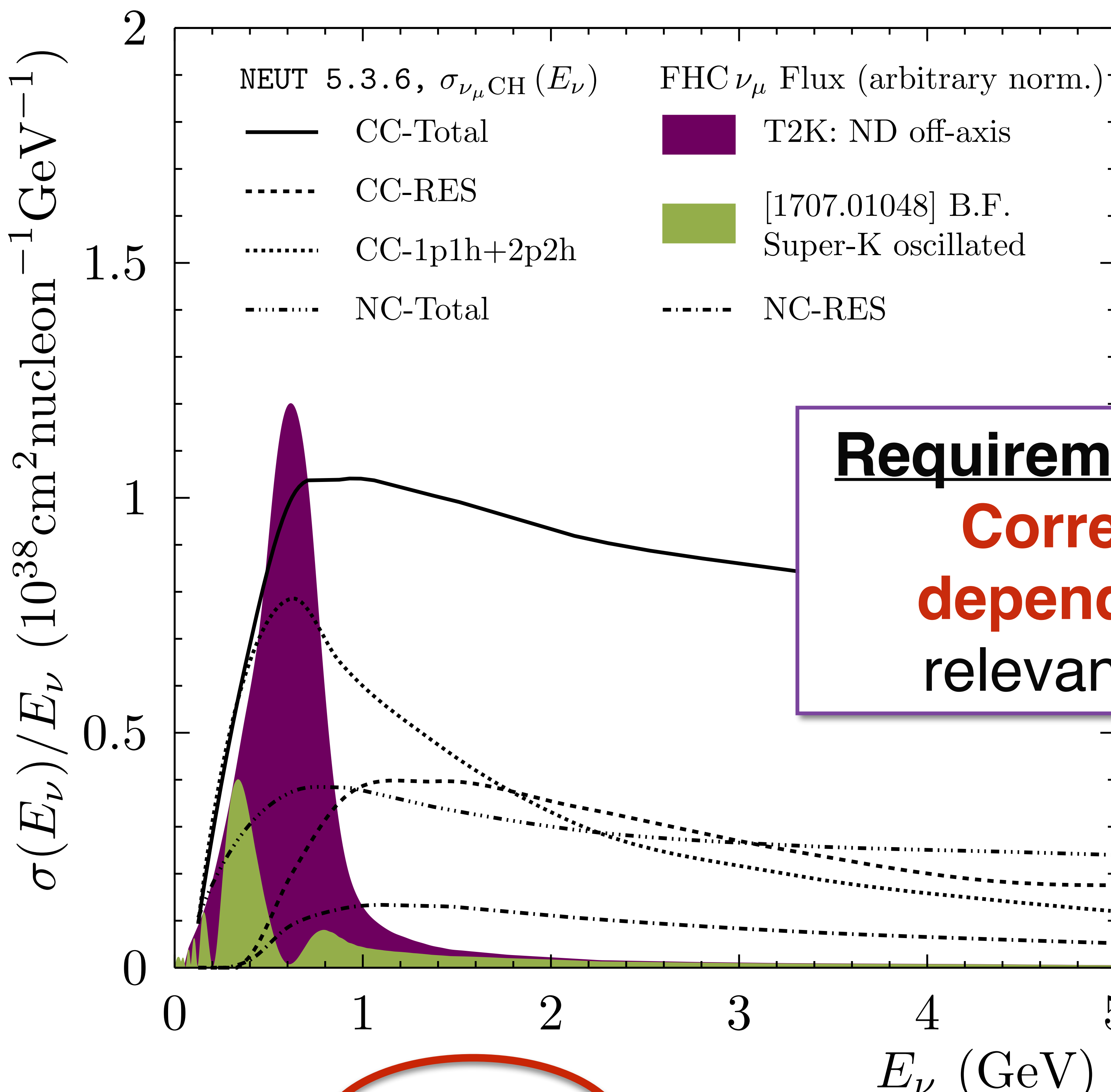
Can't isolate single processes: "wide beams"

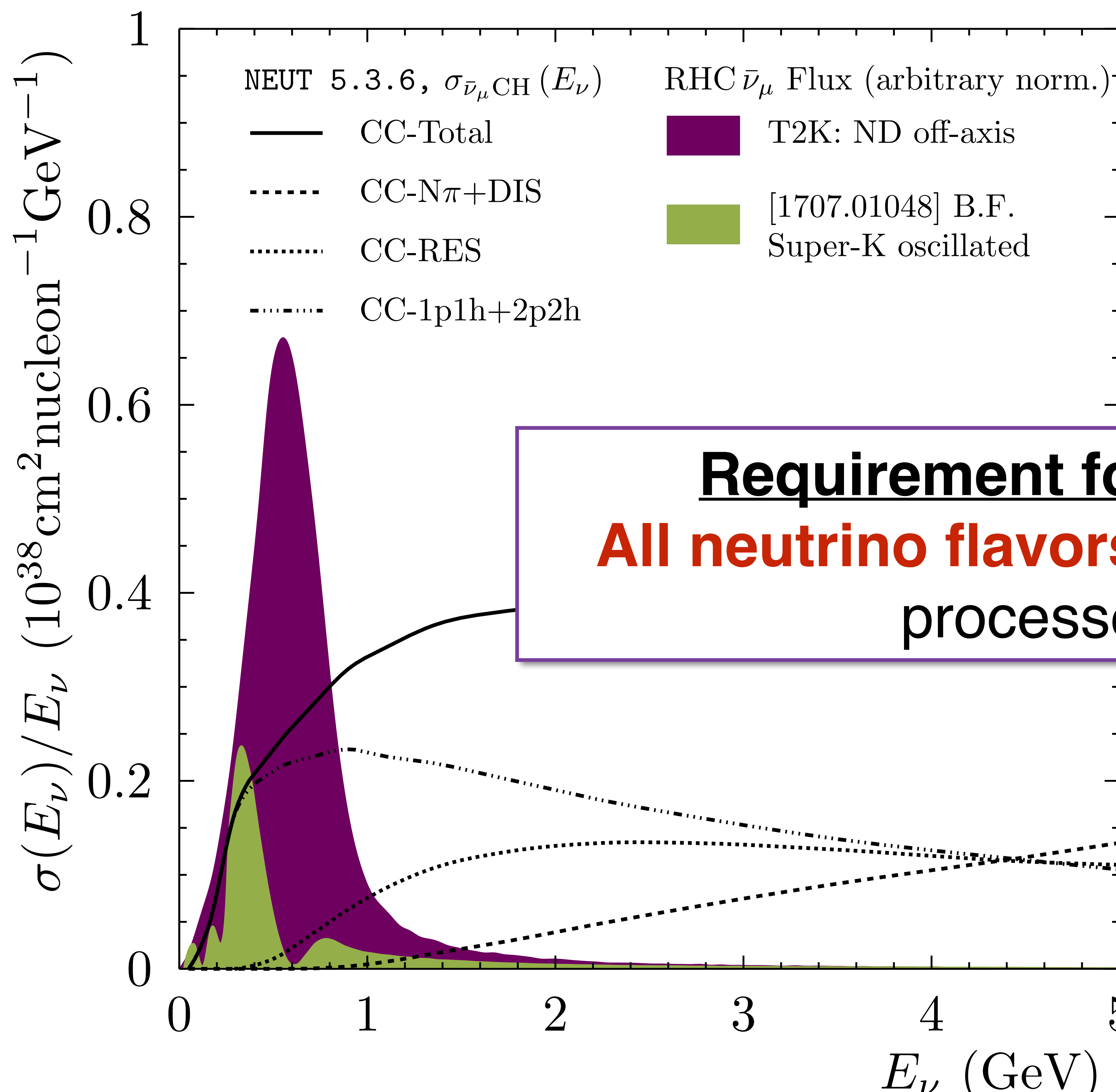


Incident energy is not known. Spread of beam is larger than nuclear effects.



Requirement for model:
Correct energy dependance for all relevant processes

$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$



<u>Requirement for model:</u>

All neutrino flavors! for relevant processes

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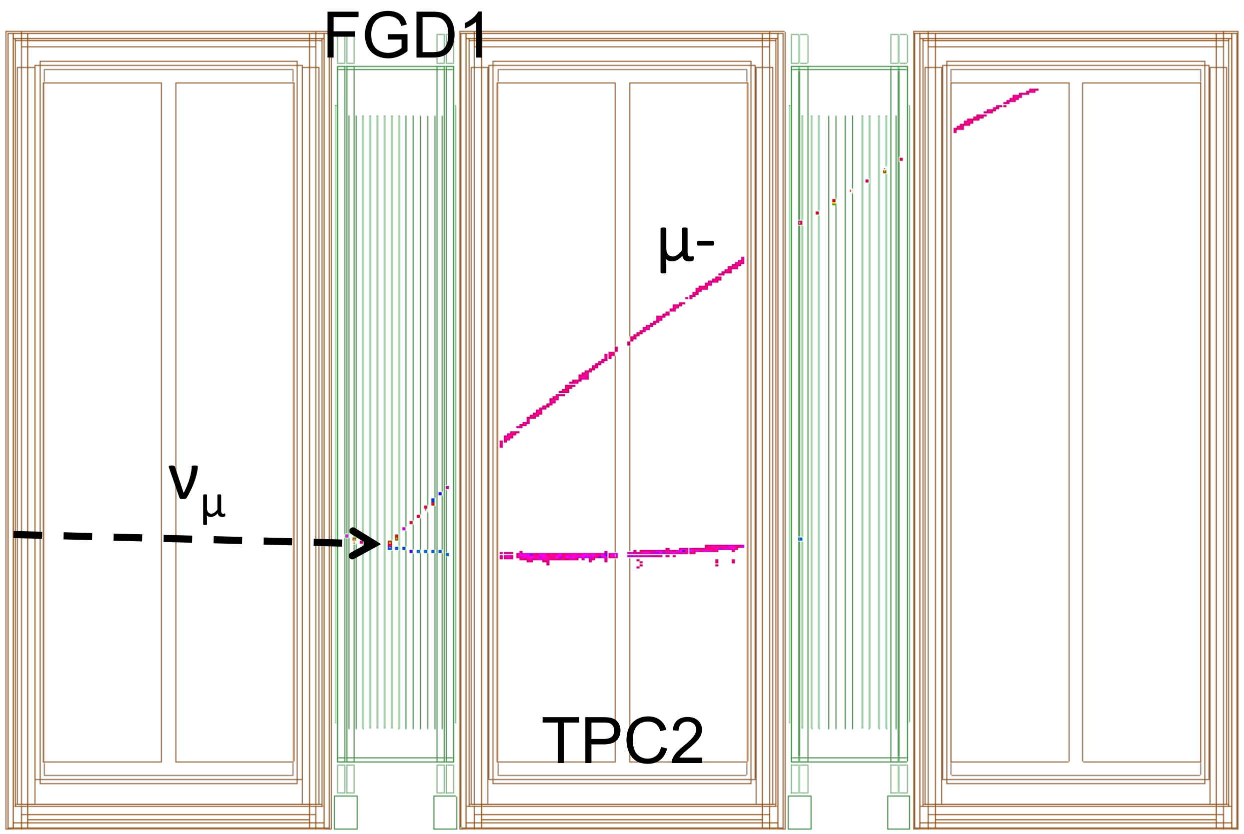
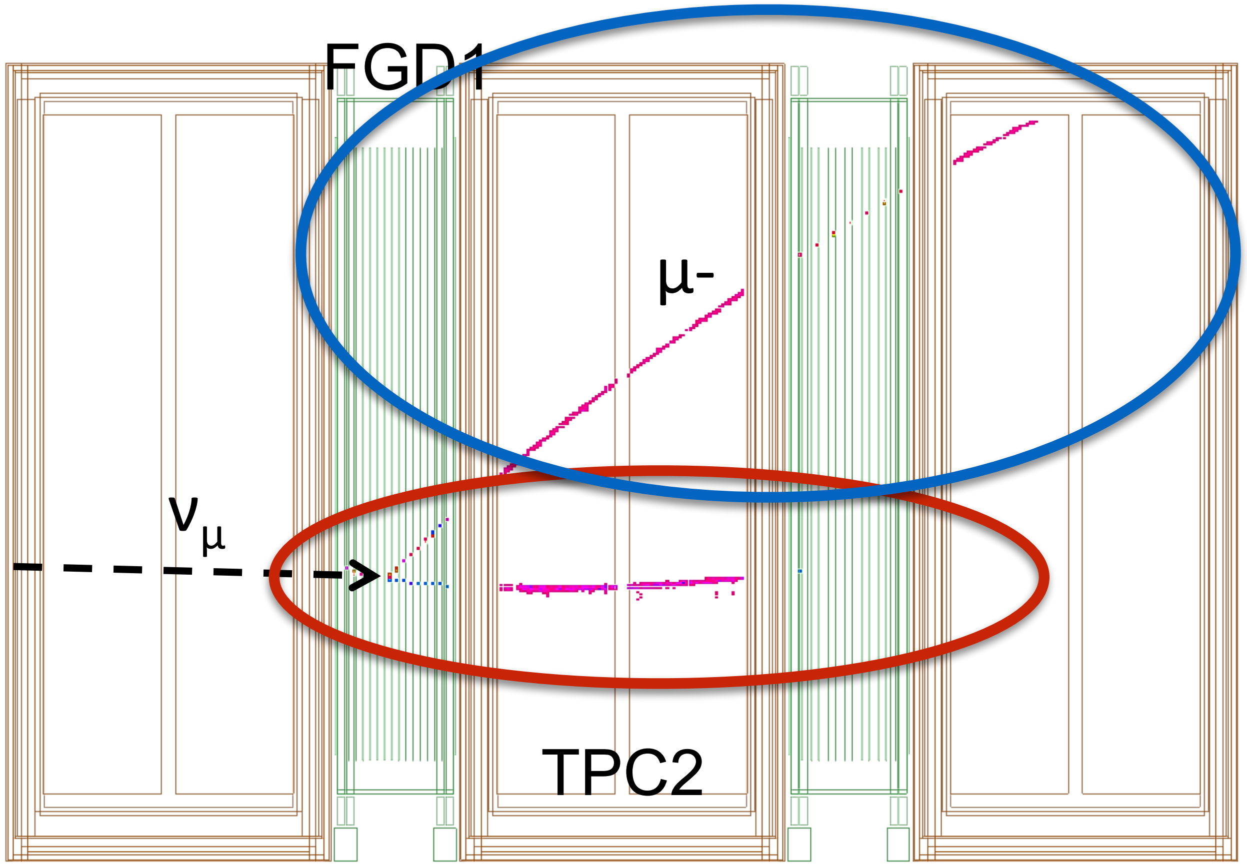
Need: hadronic state description



- T2K event display
- CC0π "topology": 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Needs: semi to exclusive final states



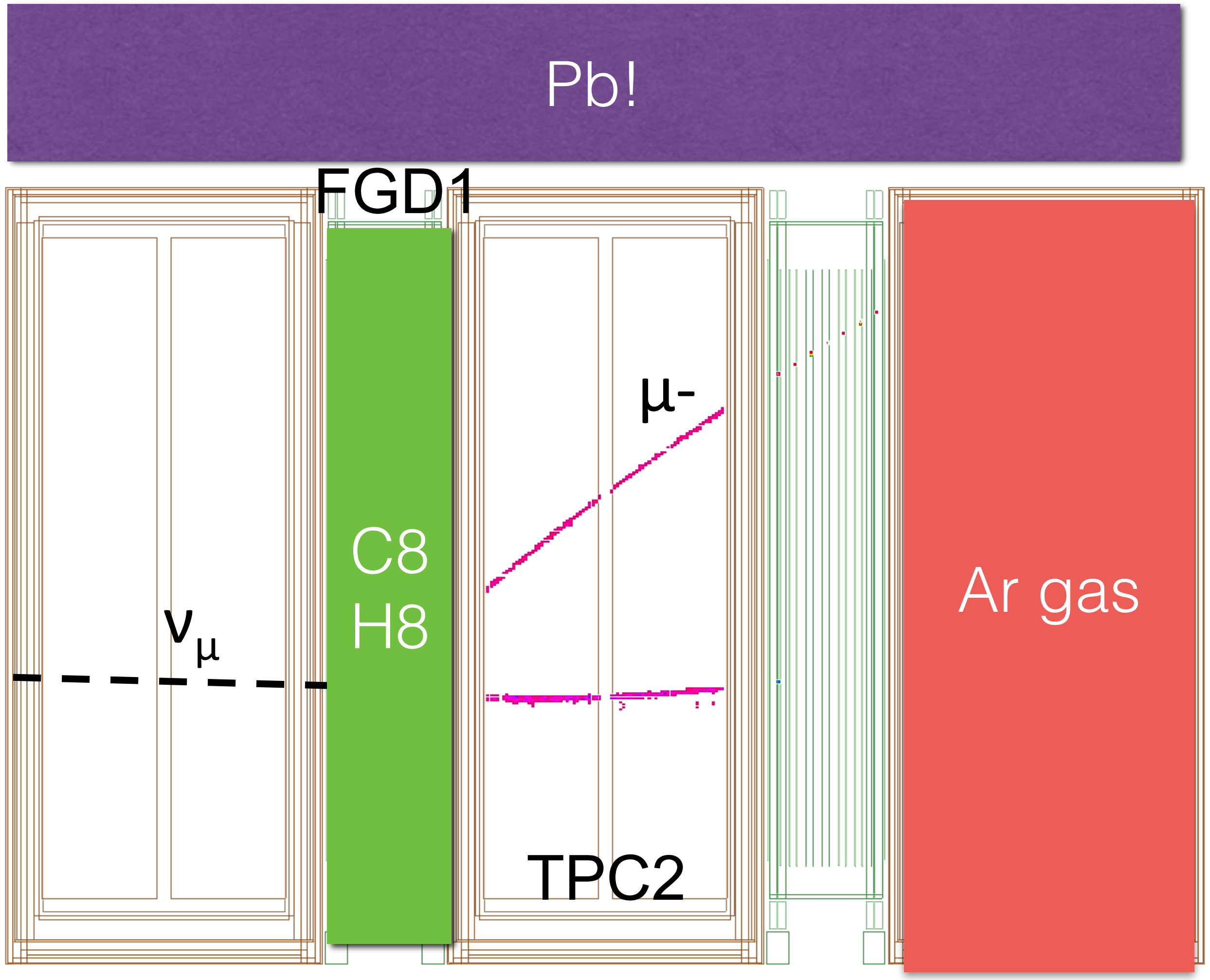
- T2K event display
- CC0π "topology": 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Requirement for model:

- All visible particles for efficiency (background) and energy estimates

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Needs: target material



Target materials:

- T2K: H_2O
- NOvA: CH+Cl
- SBN, DUNE: Ar

<u>Requirement for model:</u>

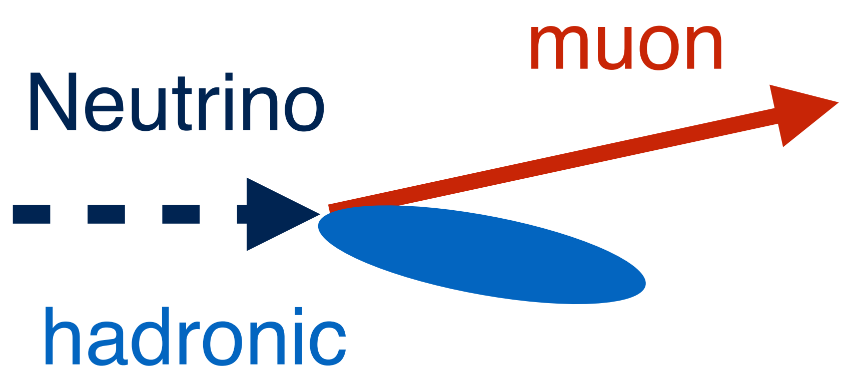
- Most nuclear targets, esp C, O, Ar

Needs: Energy estimation

- Oscillation depends on energy
  - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

$$E_\nu = E_\mu + \sum E_{hadronic}$$



T2K Super-Kamiokande	SBN DUNE	NOvA

Needs: Energy estimation

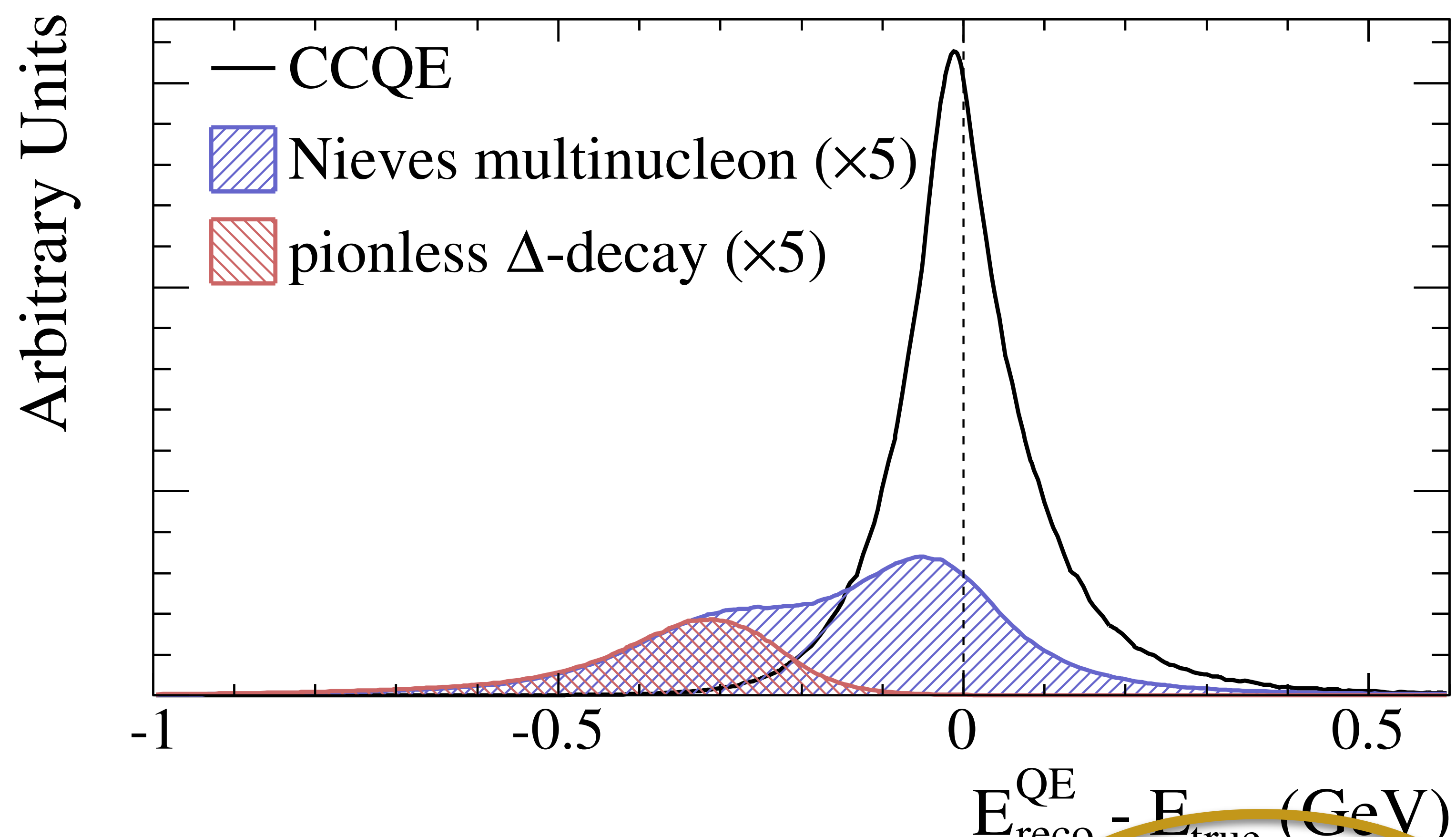
- Nuclear effects bias true and estimated neutrino energy

$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

T2K, PRL 112, 181801 (2014)

Requirement for model:

- Correct mix of processes per topology
- true - reconstructed kinematic relationship



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Experimental solutions

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

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- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
  - Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
  - Example in-situ information: beam line monitors

Experimental solutions

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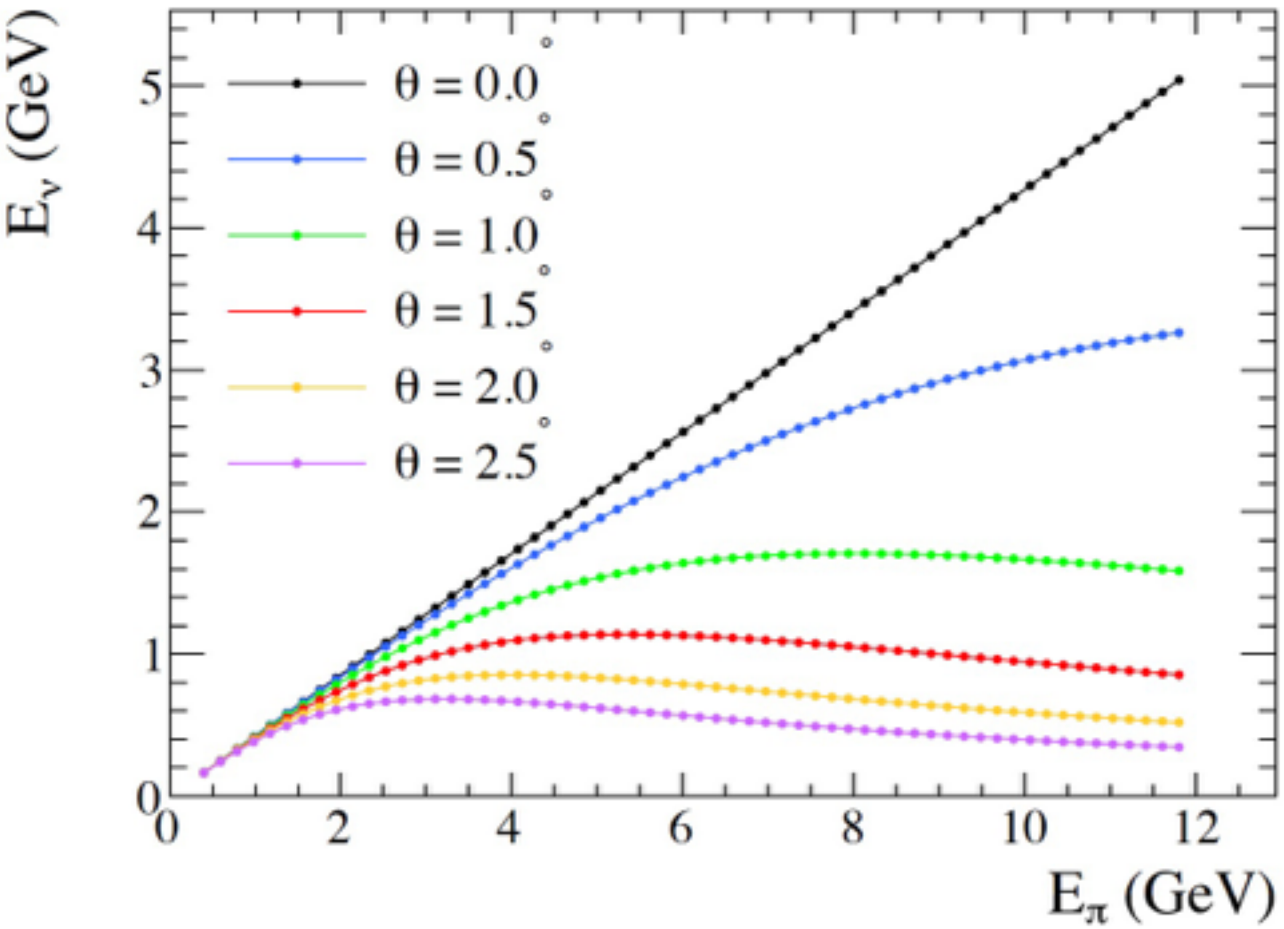
- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
  - Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
  - Example in-situ information: beam line monitors
- External experiments:
  - Example: electron scattering experiments

One new approach: νPRISM

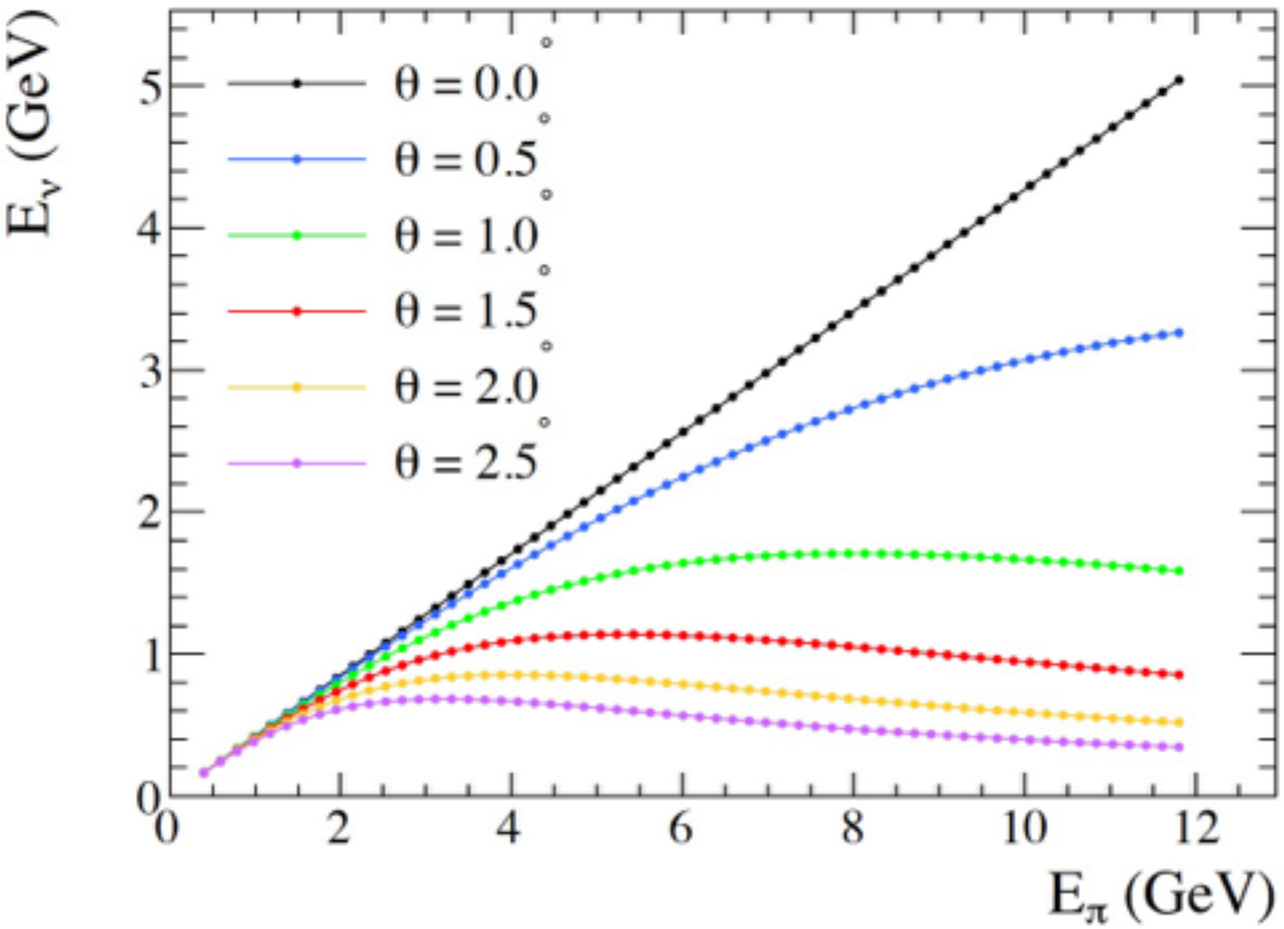
Precision Reaction Independant Spectrum Measurement

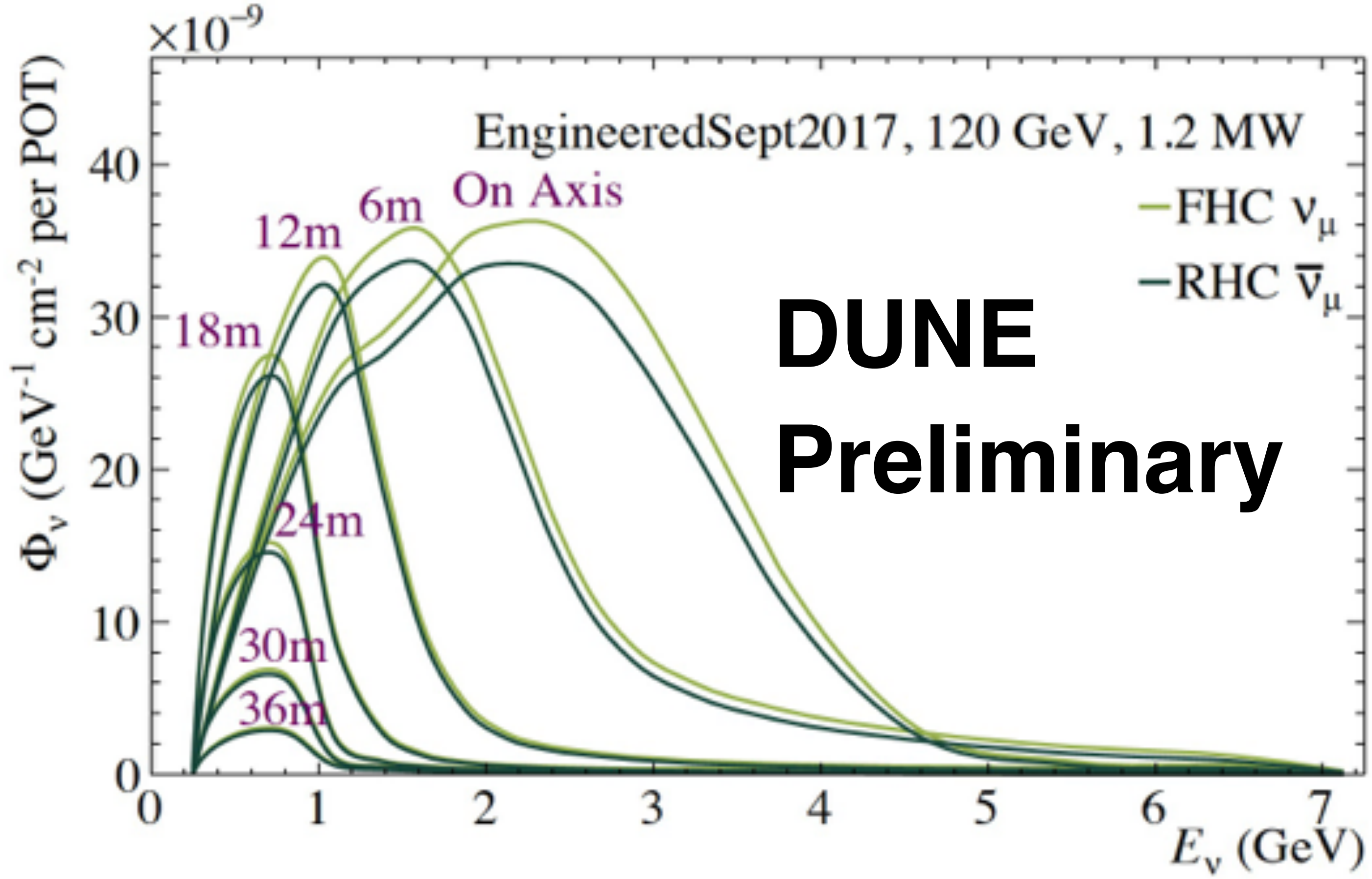


Neutrino energy spectrum changes in transverse direction to (proton) beam

One new approach: νPRISM

Precision Reaction Independant Spectrum Measurement





Peak shifts down, spectrum narrows

One new approach: νPRISM

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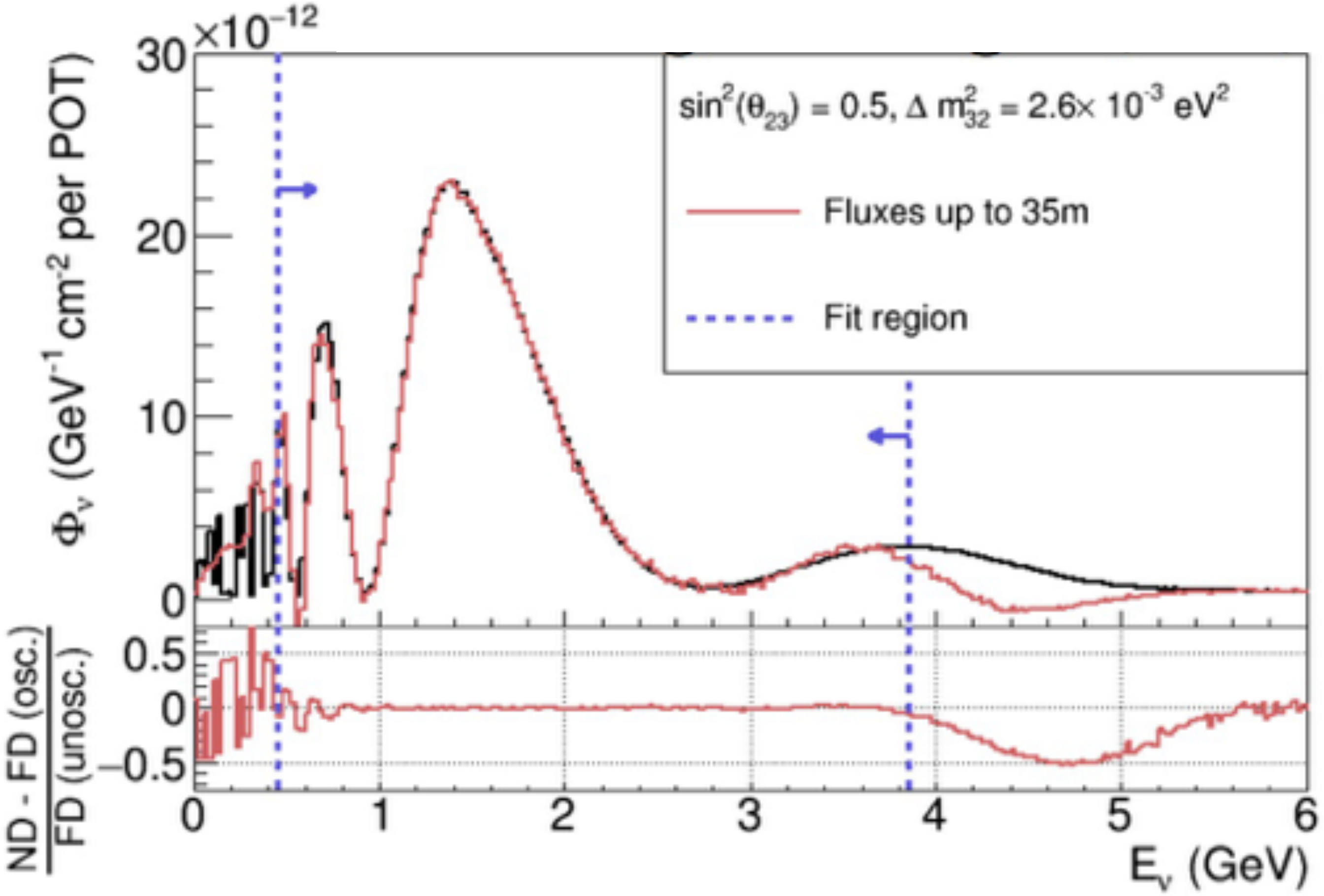

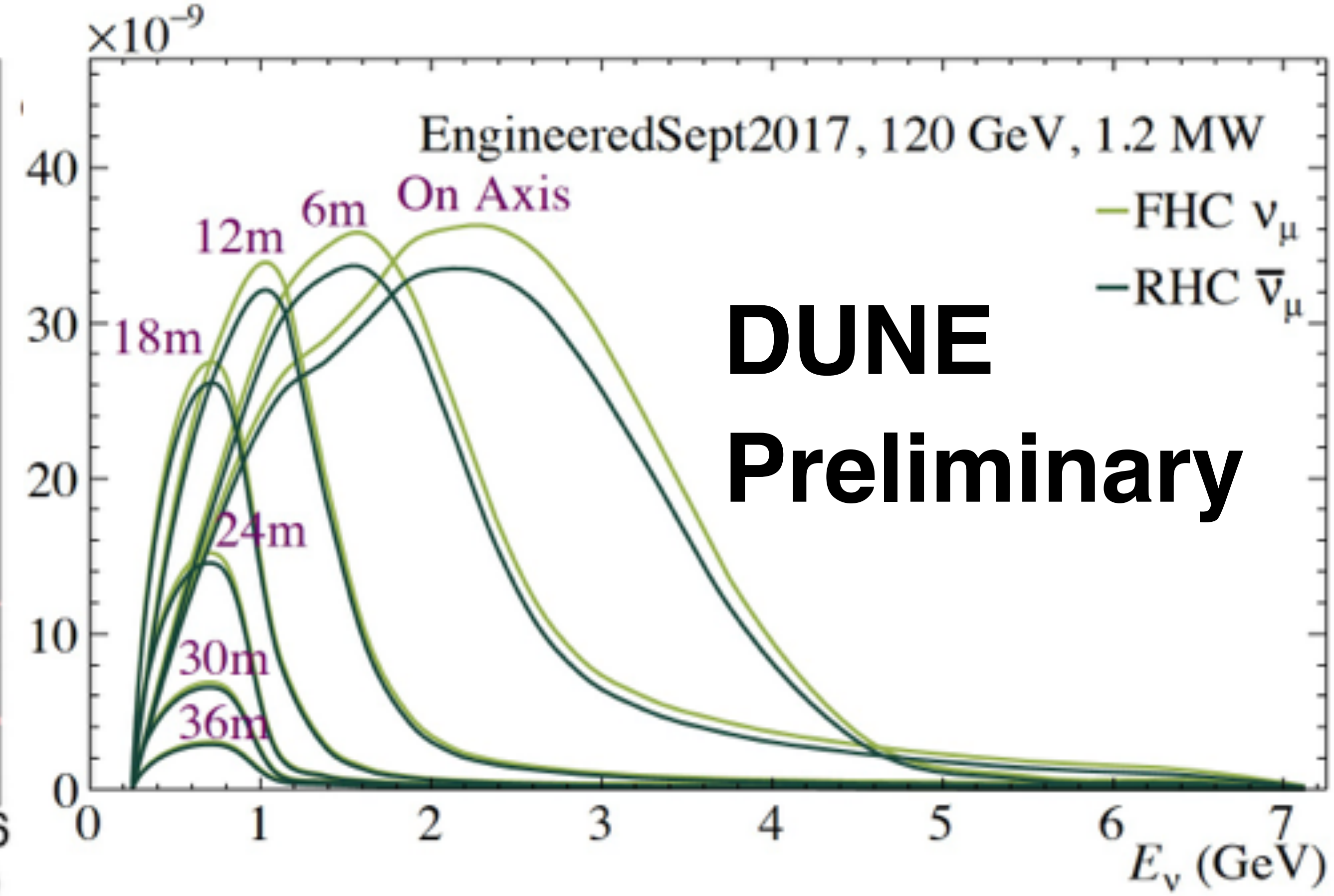

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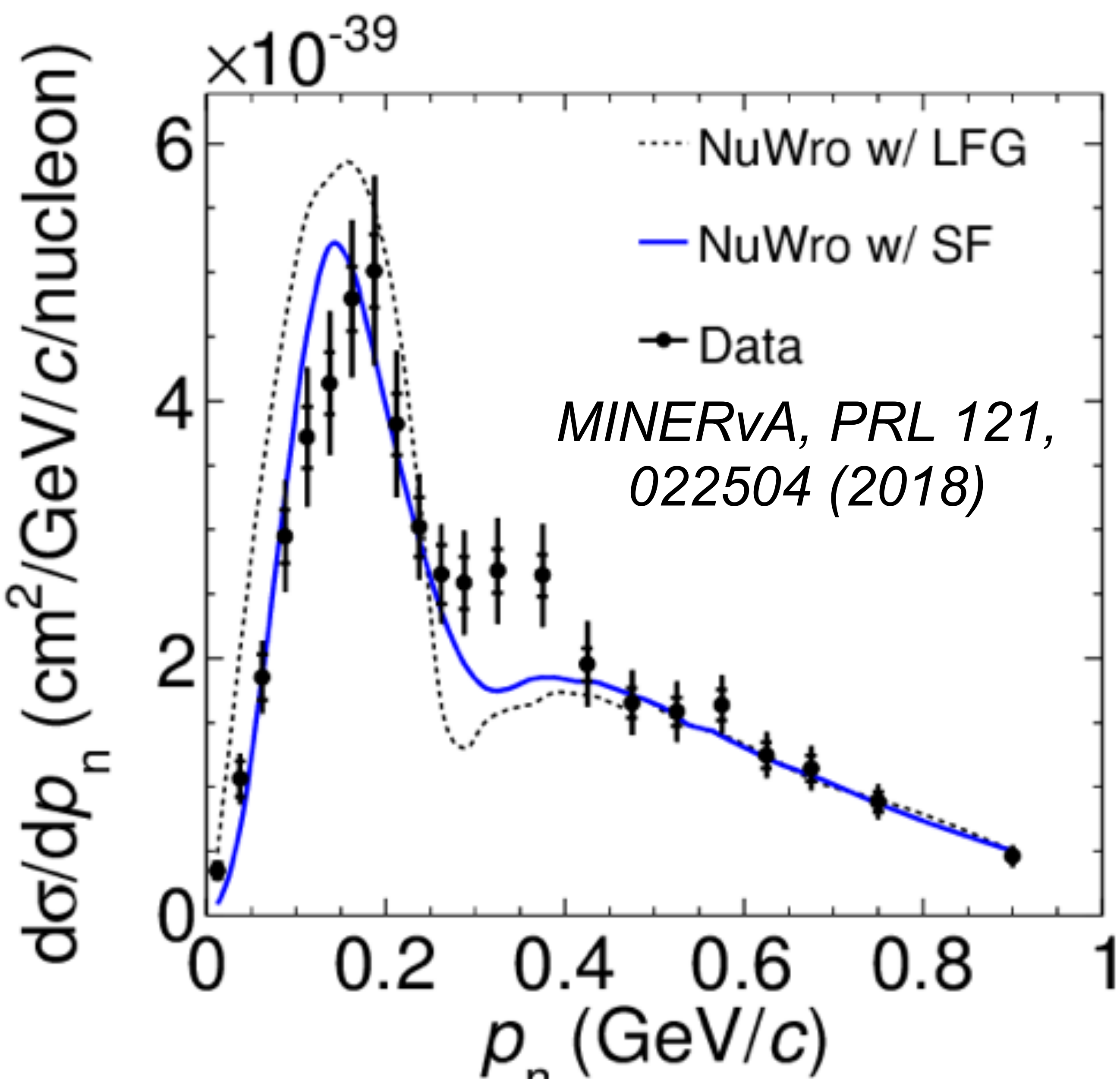
Many near detectors can approximate far detector oscillated flux! Changing beam line optics can help, too.

Persistent challenges: *we need theory*

- **Robust implementation**
  - Simulations are using inclusive calculations (quasielastic plus 2p2h plus pion production) with a fragmentation model, plus an FSI cascade or transport.
  - Example: Disagreements in semi-inclusive data



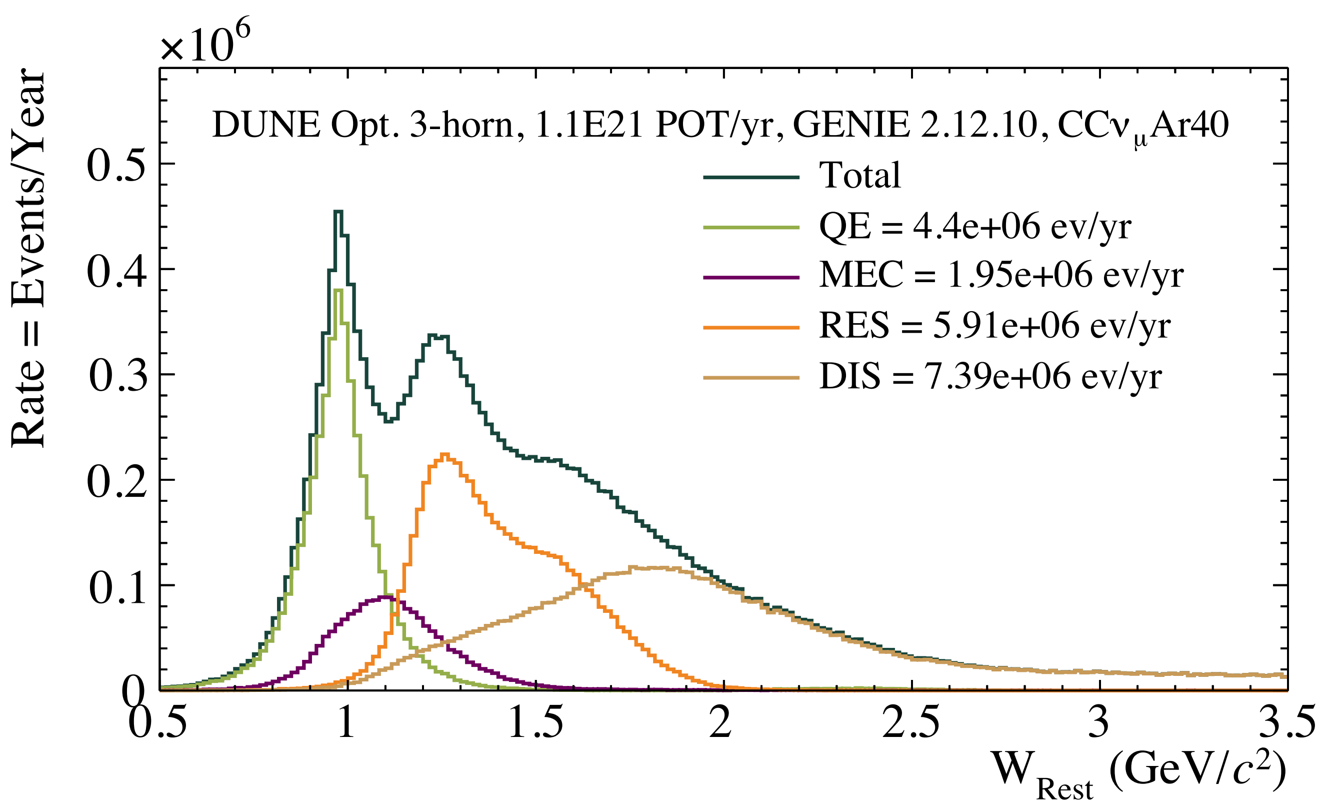
- OK, so this model doesn't agree… well none of them do!
- We need **real semi-inclusive** theory for the hadronic state (NOvA, SBN DUNE… and T2K's neutron tagging…)
- We need to question simplifications/approximations/extrapolations

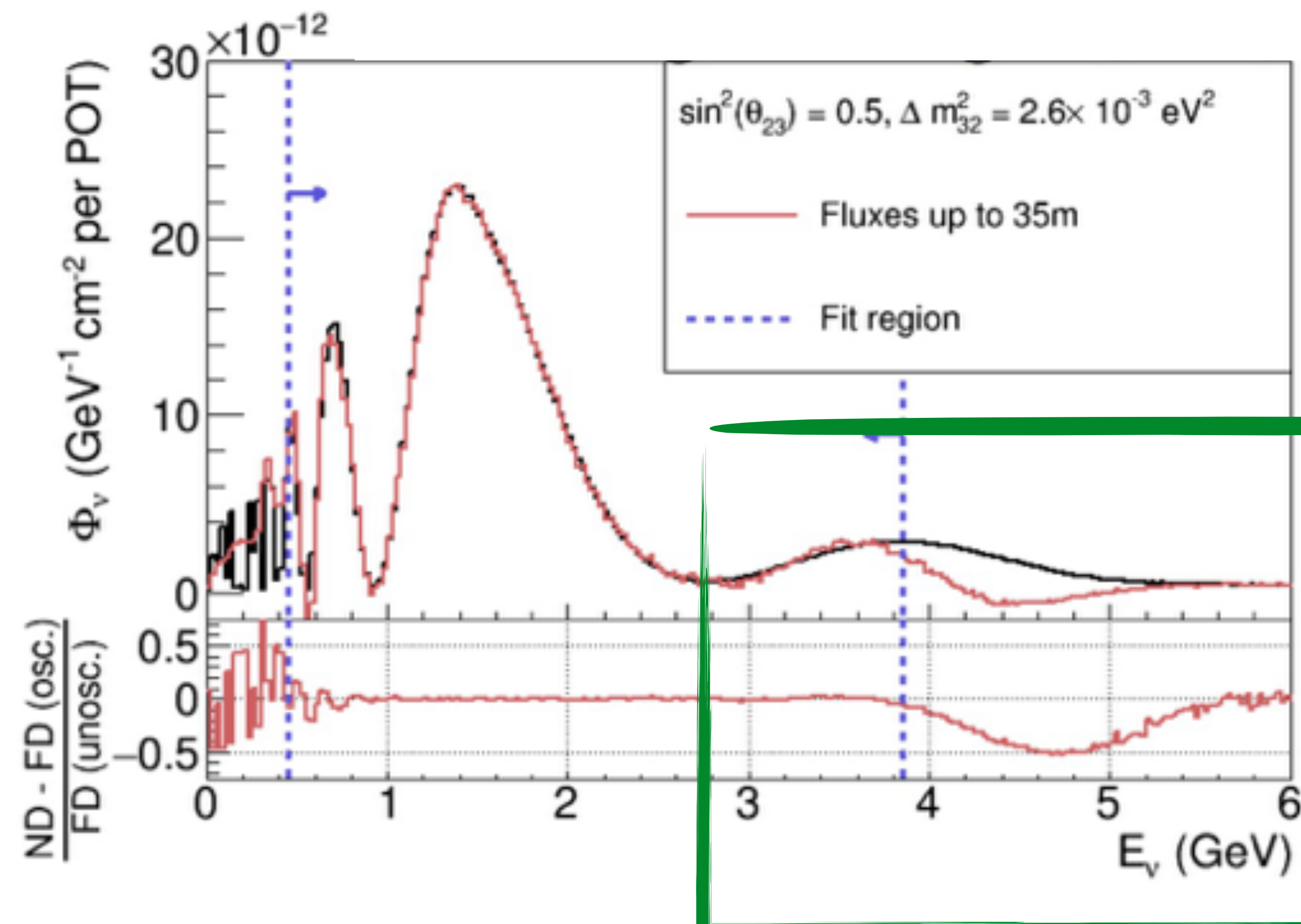
Persistent challenges: *we need theory*

- Robust implementation
- **Processes with small rates at near detectors**
  - Limited near detector information
  - NC single photon production, NC diffractive production
  - Electron (anti)neutrinos cross sections
  - Related: Radiative corrections to exclusive processes on nuclei

Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- **Transition region** // Shallow Inelastic // Deep Inelastic Scattering
  - Little/no single nucleon data to start from
  - How do we handle double counting? Extrapolations/approximations?





Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- **Continued work on QE/multinucleon/resonant processes**

- 5+ year effort to implement new QE, 2p2h models has produced a much easier interface for theory groups within generators and has been remarkably successful at predicting the lepton.
- Expand into resonance! semi-inclusive! Heavier targets!

Key feature: close collaboration between theory and experimental groups

Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- Continued work on QE/multinucleon/resonant processes
- **Uncertainty estimation and treatment**
  - Are there other processes missing?
  - Is our propagation of an uncertainty correct (within a model?) What alternate choices may be considered which are valid/reasonable?
  - Models may be limited in regions of validity (e.g. 2p2h status). We must push past incomplete models with some sensible uncertainty.
  - Crucial help in electron scattering data interpretation for neutrino experiments.

Key feature: confront and discuss issues together

Observations from the meeting

- Need for a clear (generator/experiment) interface for flexible, shared model development - *G. Perdue's talk*

- Possible path to semi-inclusive scattering theory - *S. Pastore's talk*

- Implied that physics strategy would be welcome

- Proposals encouraged. Topical working group?

Part II: Where do we go from here?

- First, what are the (common) issues?

See also: talks after this one!

- Then, what additional structures are helpful to address them?
- What can NuSTEC uniquely do or enable?

What the community is worried about

From Nu-Print workshop: https://indico.fnal.gov/event/15849/timetable/#20180312

- What are the uncertainties needed for the 2p2h?
  - Large uncertainties on leptonic side (across q0-q3?). Differences between nu and nubar in overall strength.
  - What should be the hadronic final state association? And how much energy into (which) outgoing particles?
- Insufficiency of current resonance model to describe pion kinematics, low Q2 discrepancies.
  - Is 2p2h-like processes in resonance production?
  - Need NC for significant backgrounds (or exotic signals)
- Transition region! Incomplete experimental and theoretical footing
- Need heavier targets (Ar!) model efforts
- Nue/numu uncertainties
- *Kendall adds: NC diffractive processes not explicitly assessed*

Useful structural elements

- Encourage documentation and transparency
    - What have we tried? What worked, what did not?
- Reduce barriers to collaboration
    - Need for a clear (generator/experiment) interface for flexible, shared model development, and uncertainty propagation.
    - Dedicated theory+experimental partnerships. What additional funding support should be encouraged?
    - What inter-experimental collaboration is useful?
    - Advertising: Are we participating in European Strategy document or other exercises?

Establishing a prioritization

- Do we agree on what is needed? Do we have to?
    - Different experiments may have (and indeed have) different needs. Do we at least see where work can be usefully shared?
    - Do the theory groups have "enough" to write strong proposals to meet those needs?