Exploring Neutrino Interactions in the NOvA Near Detector

A Selection of Forthcoming ν_μ CC Inclusive Results with Implications for Multinucleon Physics

NuFact 2024

by J. L. Barrow

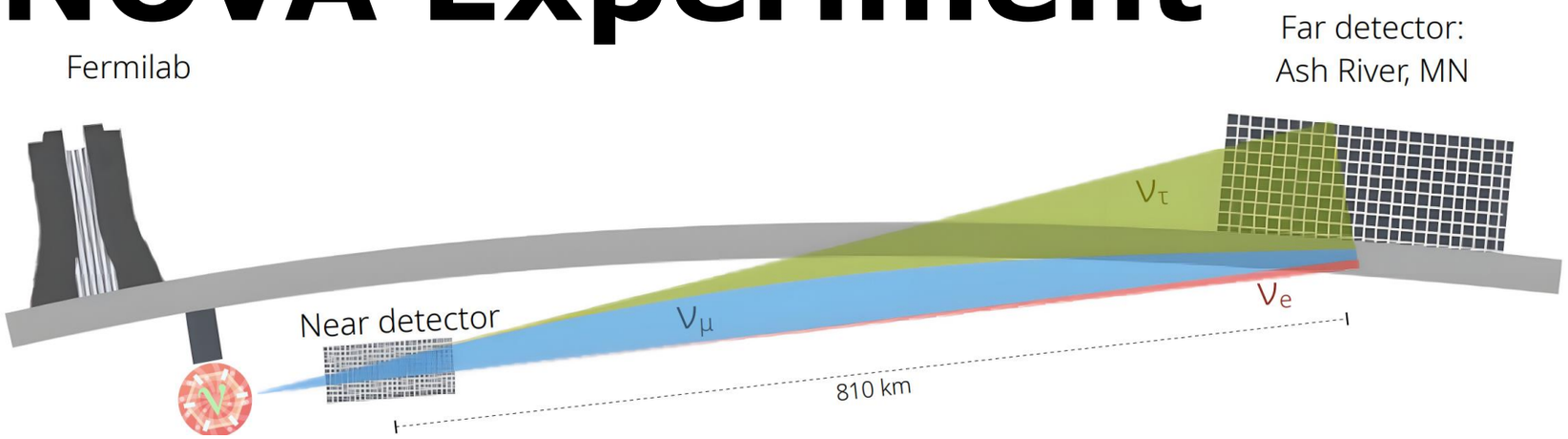
The University of Minnesota

with a Special Thanks to L. Aliaga Soplin & T. Olson

On Behalf of the NOvA Collaboration

September 18th, 2024

The NOvA Experiment

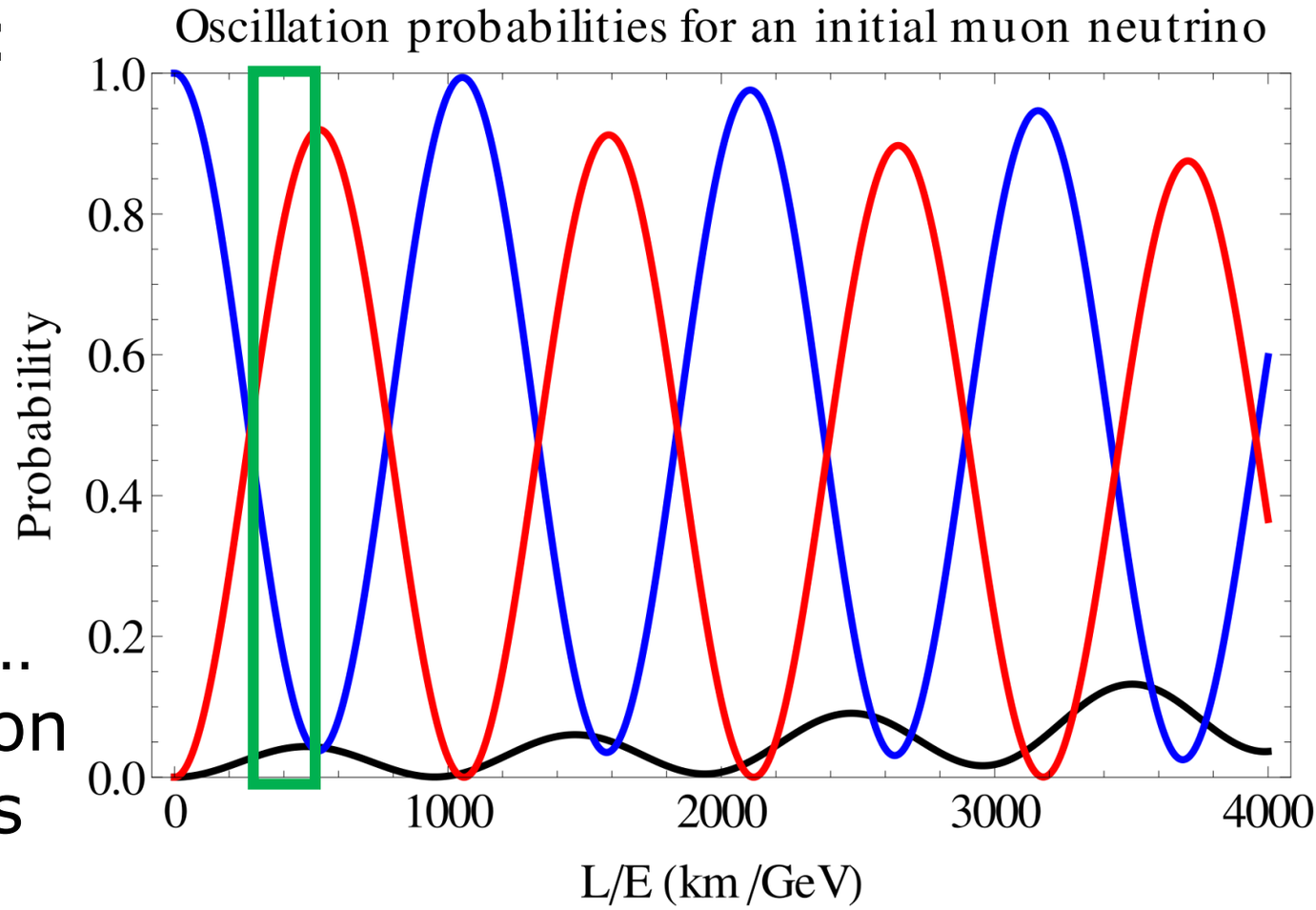


By Strait, Wiki Commons, CC0

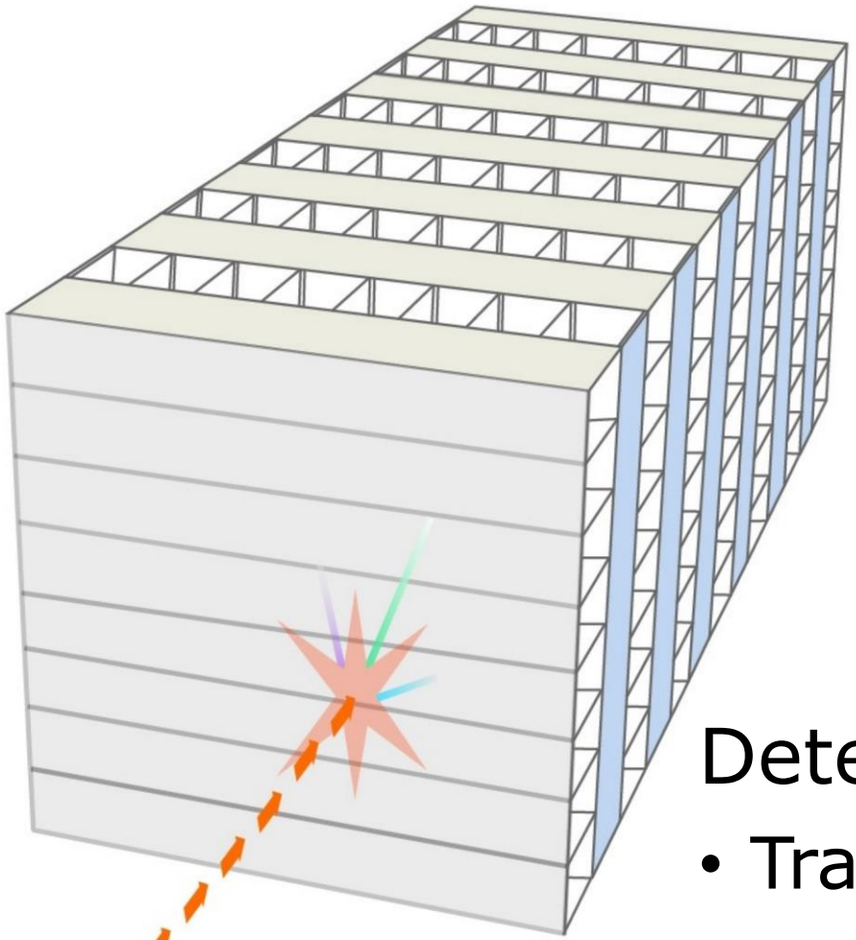
NuMI Off-Axis ν_e Appearance Experiment

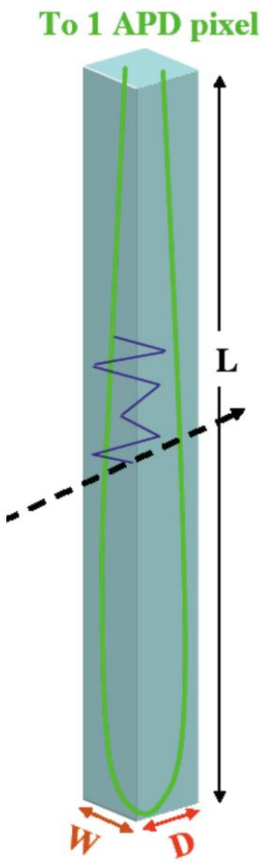
- 810km baseline
- ~2GeV neutrinos
  - **Near first ν_e appearance maximum**

Scientific mission includes…
- Mass ordering, CP-violation
- ND: Cross section physics



The NOvA Detectors



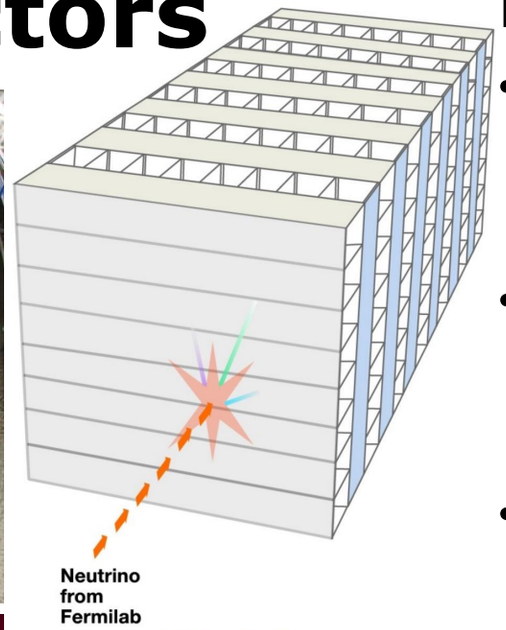


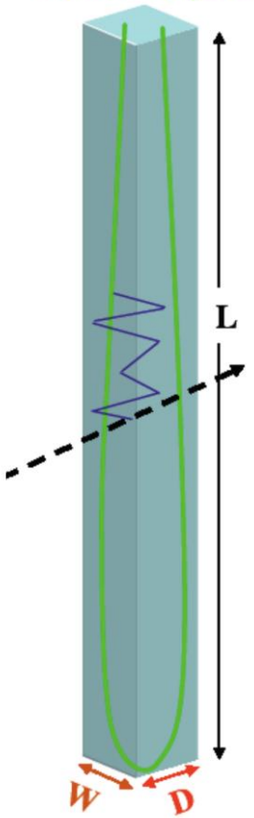
Neutrino from Fermilab

Detectors functionally identical

- Tracking calorimeters
  - Utilizes XY segmented/pixelated readout
  - Scintillating oil, extruded plastic
    - $\sim 66\%\ \mathrm{C}, 16\%\ \mathrm{Cl}, 11\%\ \mathrm{H}, 3\%\ \mathrm{O}, 2\%\ \mathrm{Ti} \rightarrow \sim 60\%$ active
    - $\sim 4\mathrm{cm} \times 6.5\mathrm{cm} \times \mathcal{O}(\mathrm{m})$ PVC cells $\rightarrow \sim 4\mathrm{cm}$ vtx. res.
  - Avalanche photodiodes
    - ND: $\sim 5\text{-}10\mathrm{ns}$ timing resolution

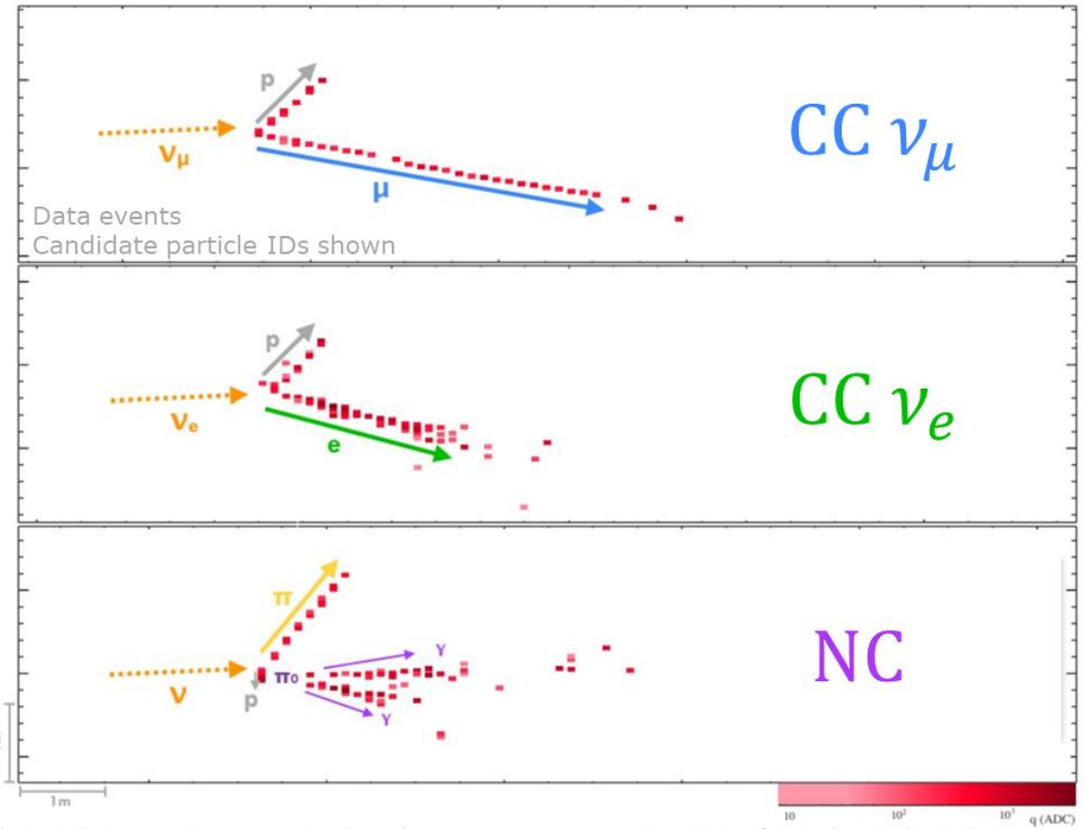
The NOvA Detectors





Detectors functionally identical

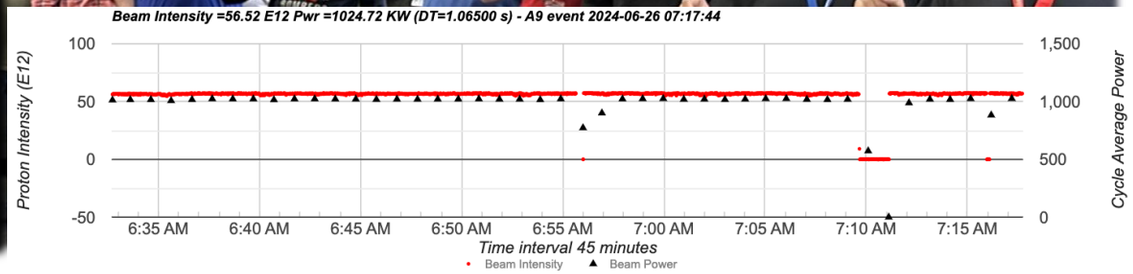
- $\sim 290\mathrm{T}, \sim 4 \times 4 \times 16\mathrm{m}$ ND w/μ catcher
  - $\sim 1\mathrm{km}$ from NuMI, $100\mathrm{m}$ underground
- $14\ \mathrm{kT}, \sim 16 \times 16 \times 60\mathrm{m}$ FD
  - $810\mathrm{km}$ from NuMI, on surface
- Good tracking for HE FG particles
  - Suffers at high transverse angles
  - LE hadron reconstruction difficult



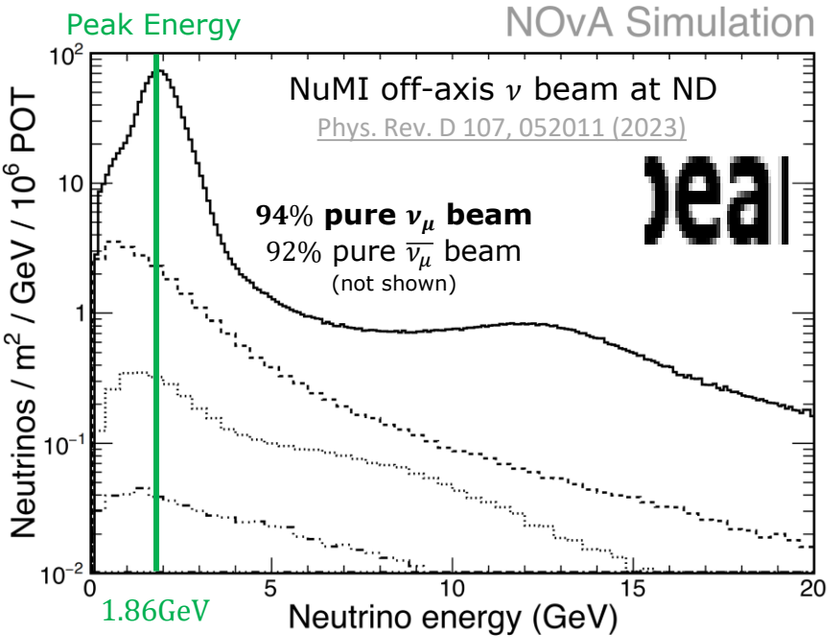
Some Recent Milestones

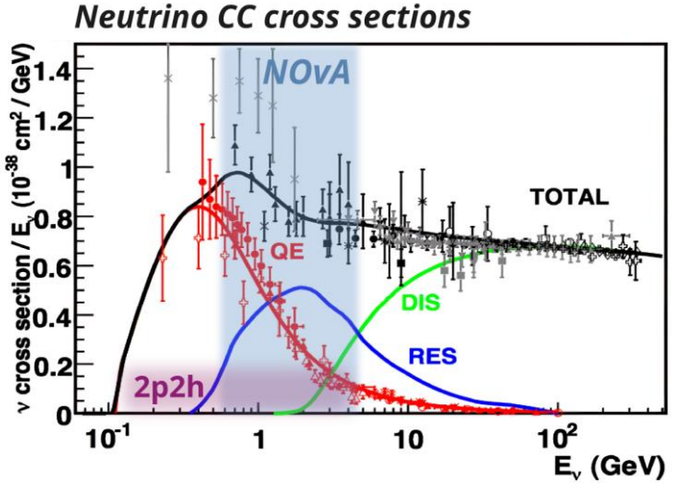
Near Detector Refurbishment ~400/600 APDs replaced!

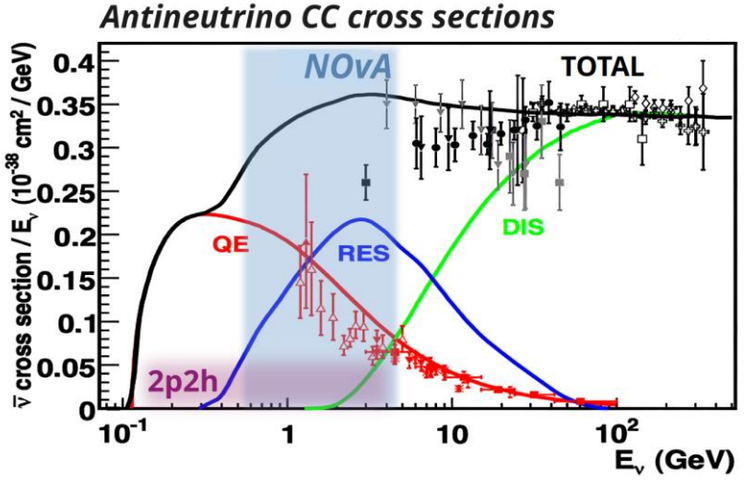
1.018MW from **NuMI** We've got the power!

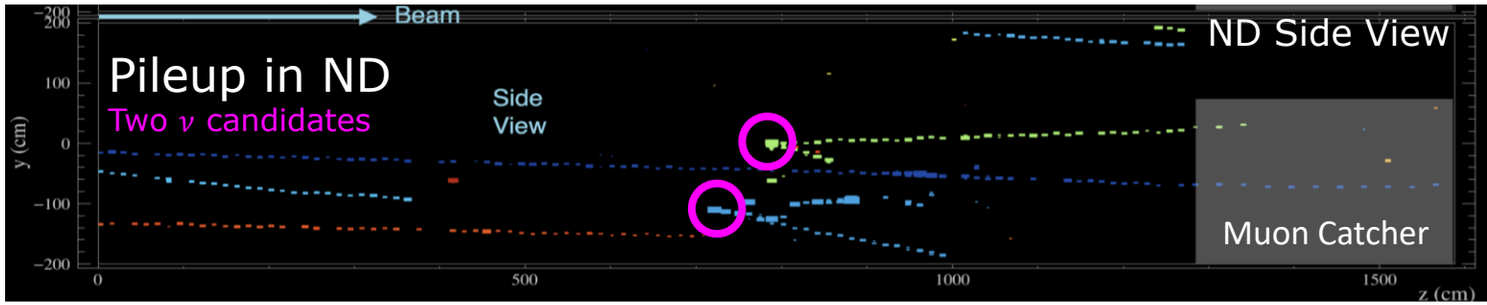


The NOvA ND at NuMI





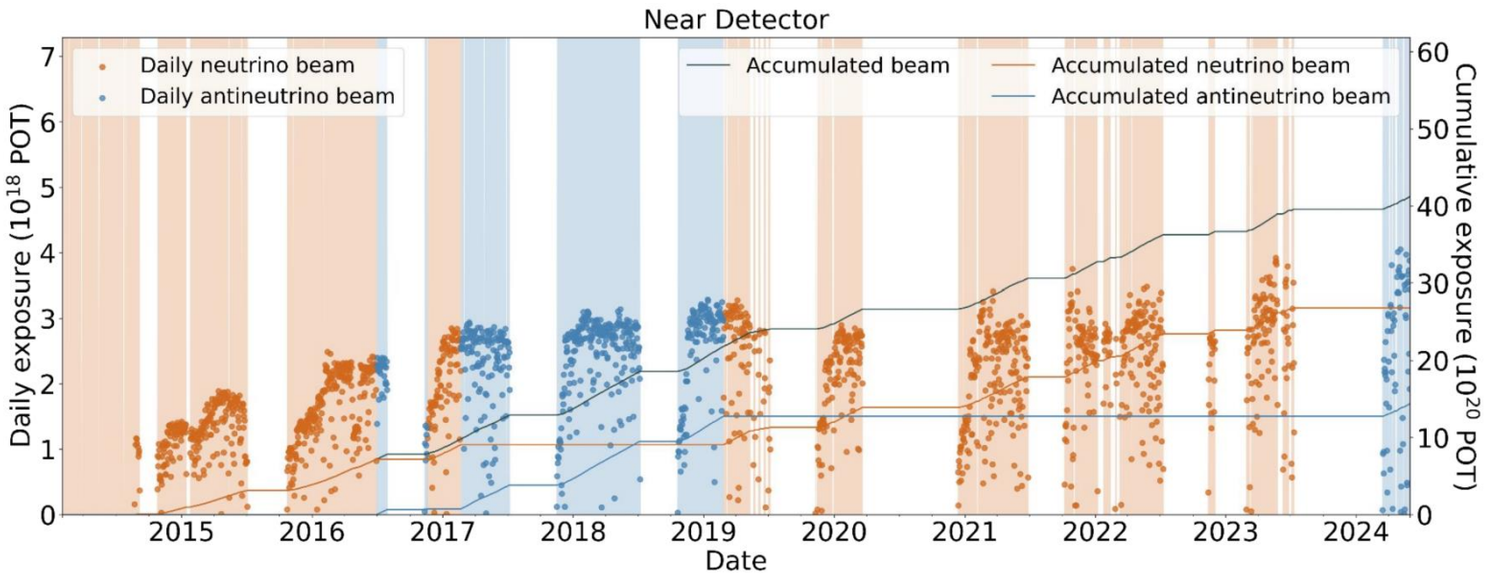




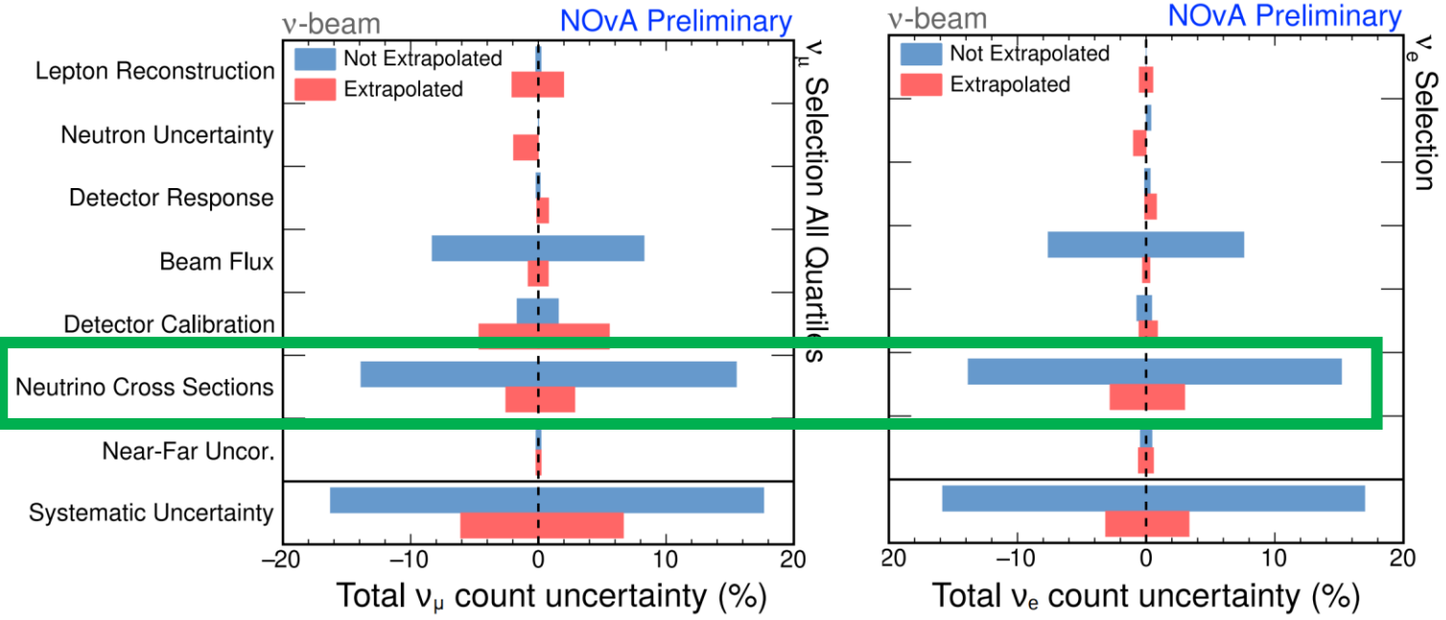
High intensity NuMI running
- Typical recent runs at 900kW
- $\nu + \bar{\nu}$: $\gtrsim 40 \times 10^{20}$ POT on tape
- ~6.5M ν_μ, $\gtrsim$ 1.5M $\overline{\nu_\mu}$ ND candidates in Nu24 oscillation results
  - Empowers XSec measurements!
    - Different PID methods lower XSec statistics

Narrow-band flux, 1.86GeV PE
- ND sits 14.6mrad off-axis
- HE beam better accesses processes important to DUNE

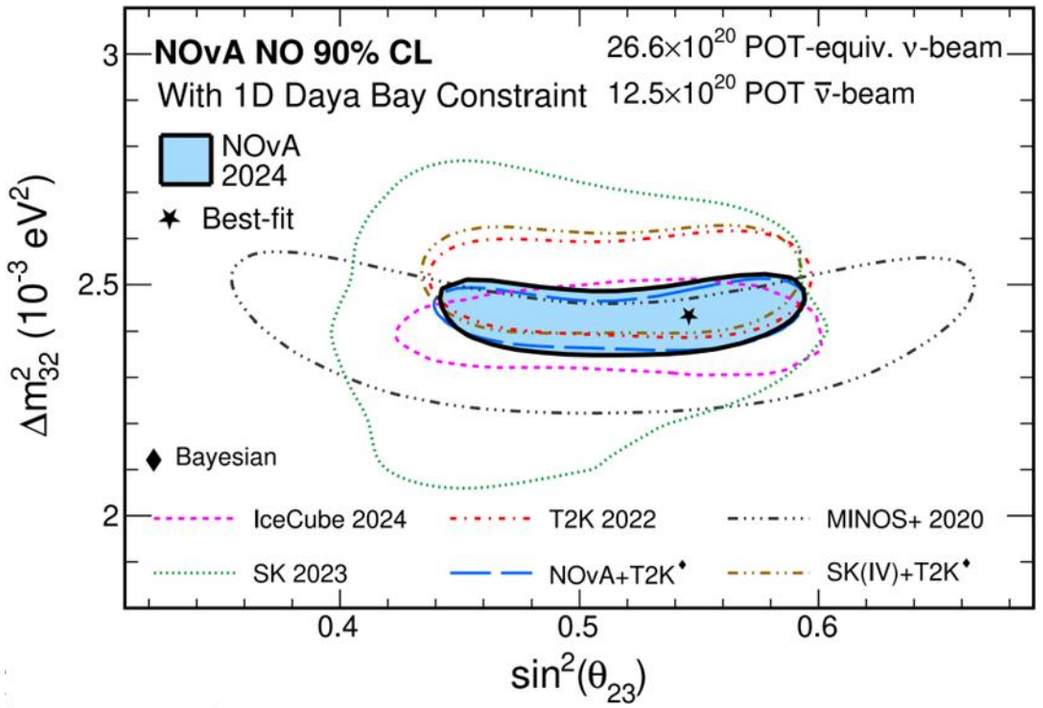
QE-to-RES transition regime
- ~30% of DUNE interactions: RES!



Why Cross Sections Matter



NOvA's recent $|\Delta m^2_{32}|$ measurement is now the most precisely known PMNS parameter! 1.5%!!



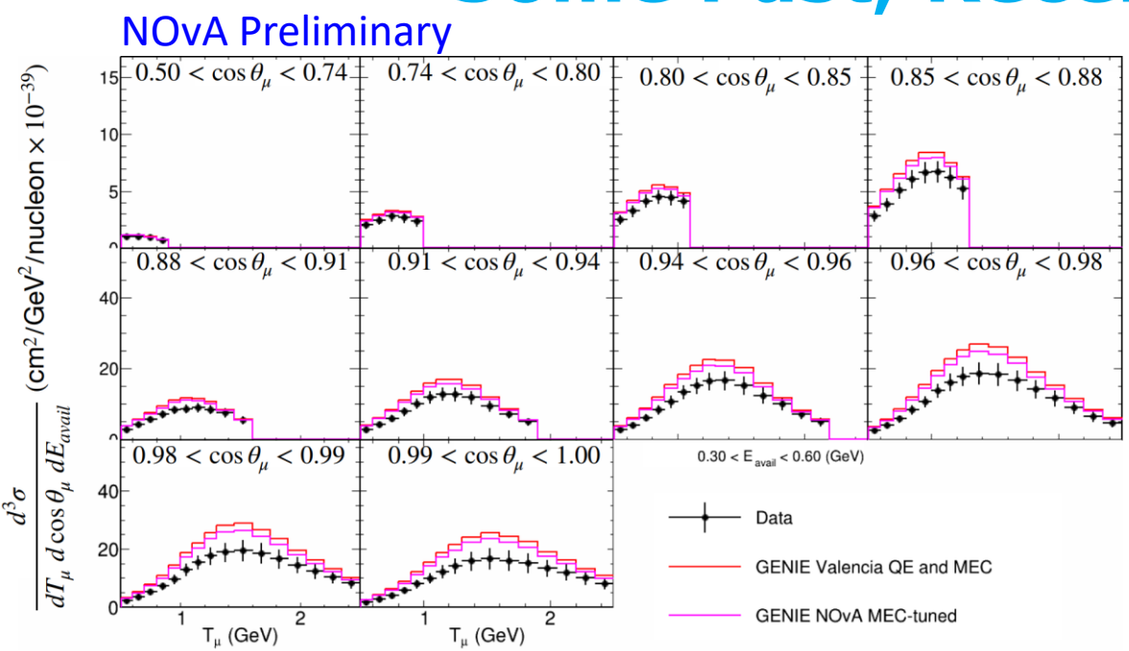
IceCube 2024
T2K@Neutrino 2022
MINOS+ 2020 PRL
SK 2023 PRD
NOvA+T2K 2024:
- KEK IPNS seminar
- FNAL JETP seminar

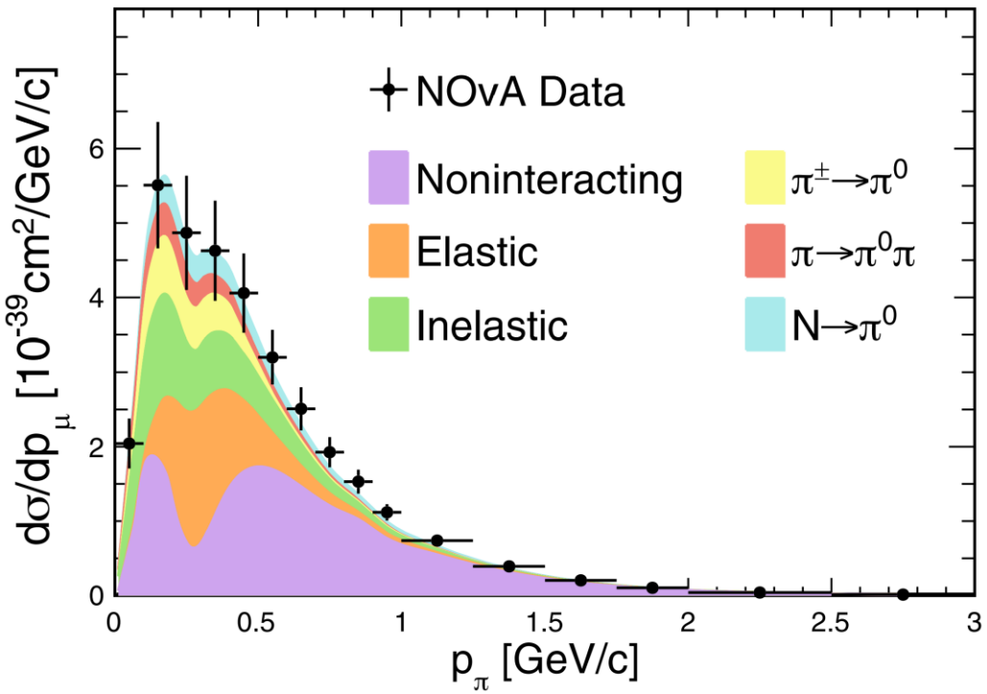
T2K+SK 2024

- ν oscillations are NOvA's focus
  - Facilitate precision measurements of PMNS parameters
- Precision is difficult…
  - Must understand and mitigate all sources of uncertainties
- νs are excellent probes of nuclear physics…
  - But such physics is always murky…
- **Nuclear modeling a leading systematic uncertainty**
  - Some ν scattering processes are not well understood
    - 2p2h interactions an important component of current NOvA analyses
- Goals include:
  - Improve NOvA's own precision
  - Empower future multiGeV exps. via inputs to future νA & eA tuning efforts
    - DUNE needs everything it can get!

NOvA Cross Section Analyses

Some Past, Recent & Future Results





[Measurement of Triple-Differential ν_μ Charged-Current Inclusive Cross Section in the NOvA Near Detector]

- W&C—**Publication in preparation**

[Measurement of ν_μ charged-current inclusive π^0 production in the NOvA near detector]

- Phys. Rev. D 107, 112008

[Measurement of the double-differential muon-neutrino charged-current inclusive cross section in the NOvA near detector]

- Phys. Rev. D 107, 052011

[Measurement of the ν_e-Nucleus Charged-Current Double-Differential Cross Section at $\langle E_\nu \rangle = 2.4\text{GeV}$ Using NOvA]

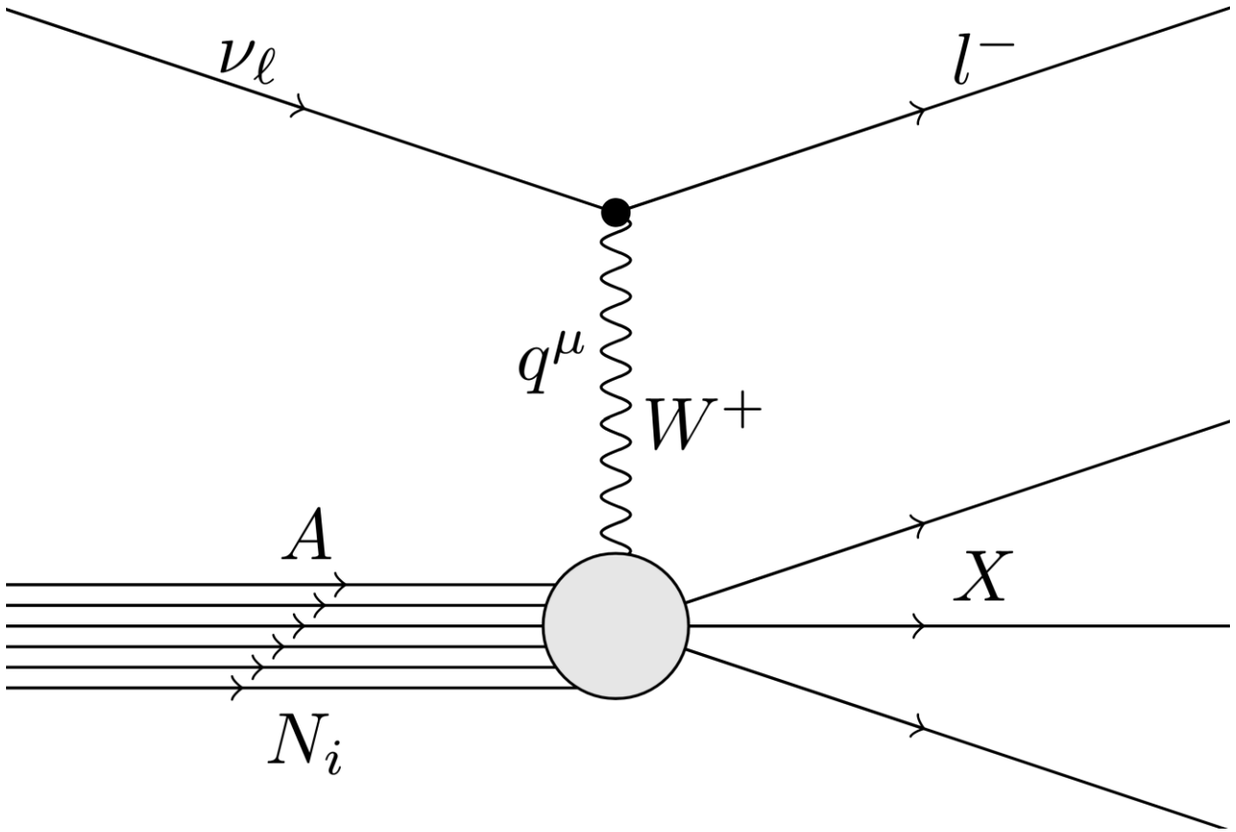
- Phys. Rev. Lett. 130, 051802

2p2h-Focused Cross Section Studies Using Inclusive ν_μ CC Interacitons

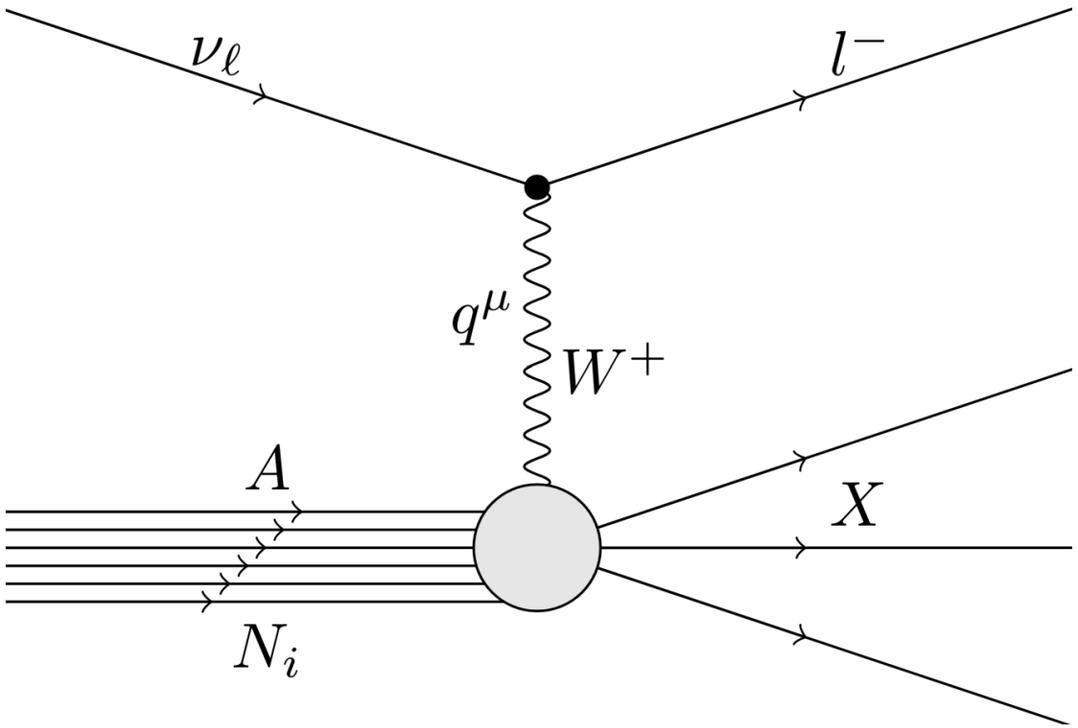
Publications in Preparation

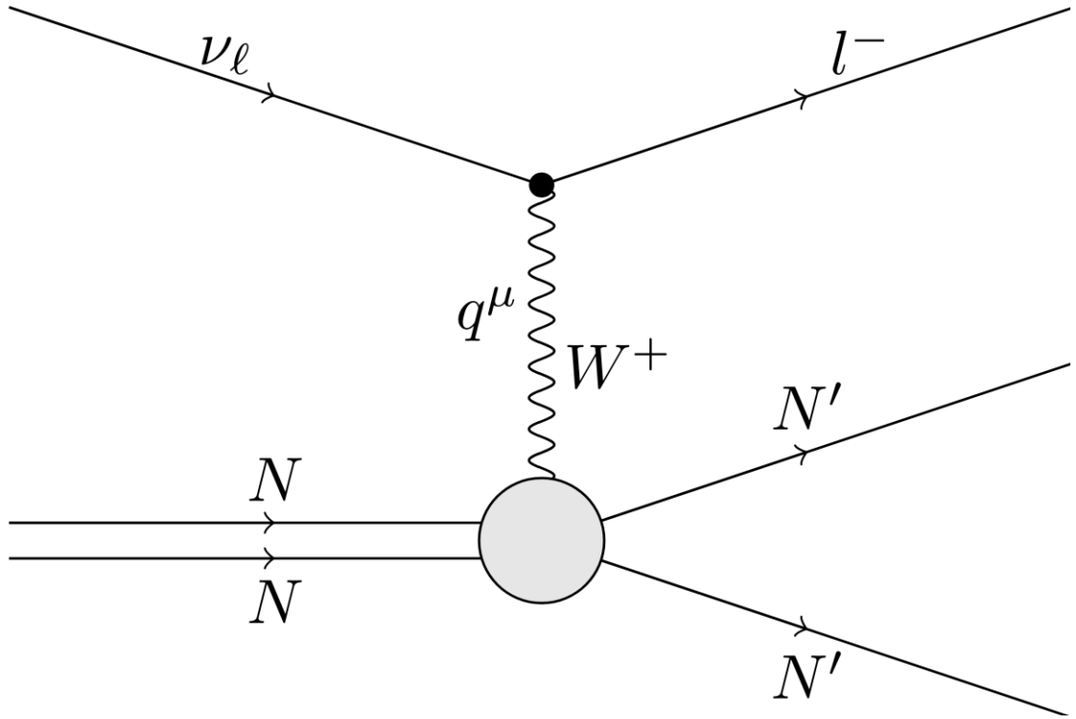
2p2h-Focused Cross Section Studies Using Inclusive ν_μ CC Interacitons

2p2h-Focused Cross Section Studies Using Inclusive ν_μ CC Interactions



2p2h-Focused Cross Section Studies Using Inclusive ν_μ CC Interactions





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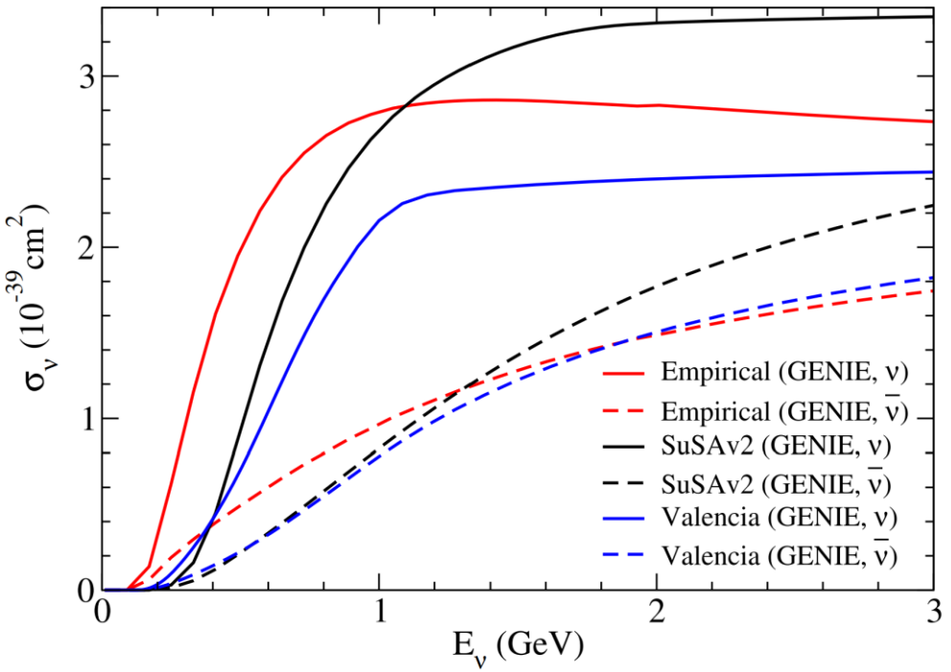
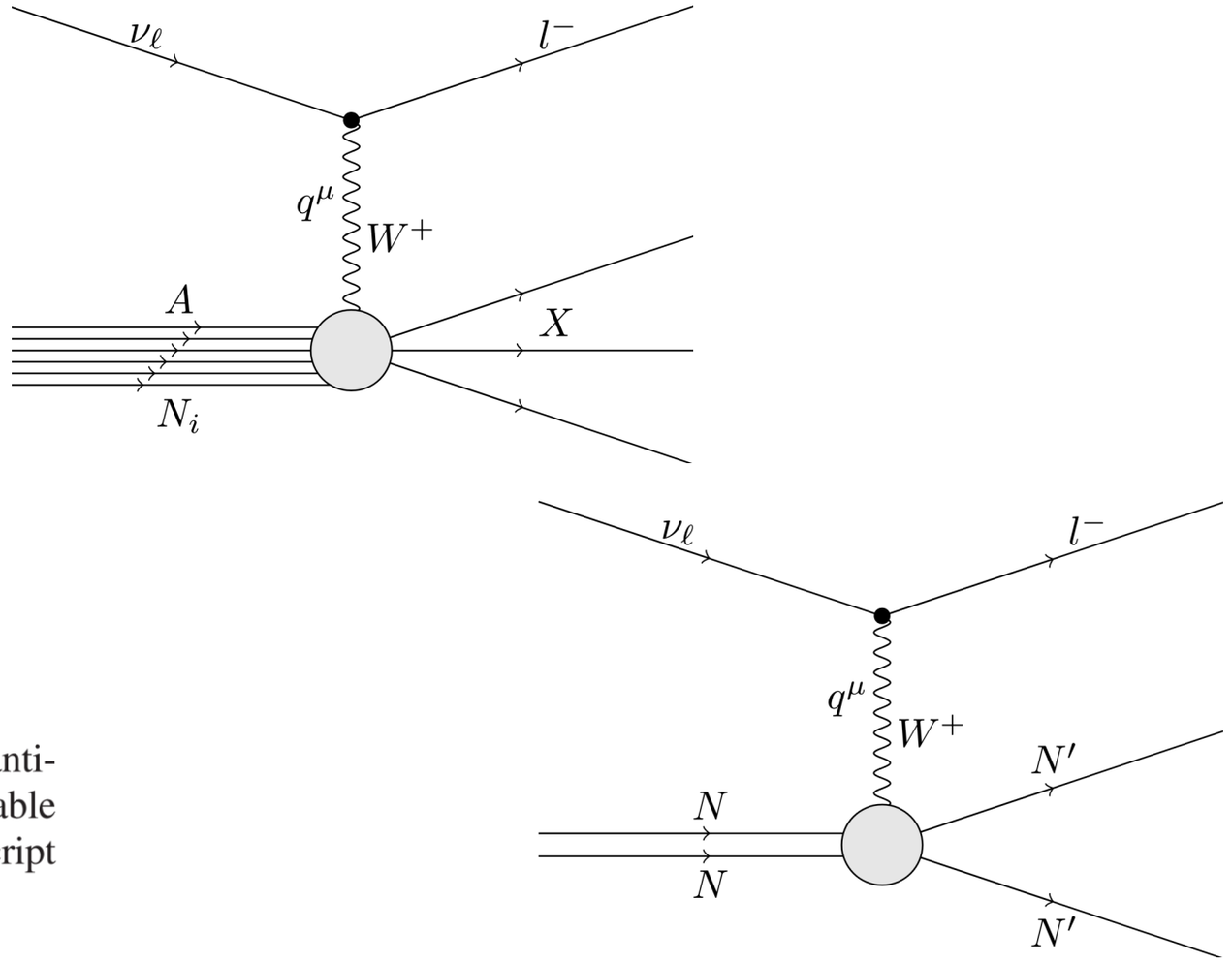


FIG. 1. Total 2p2h cross section for muon-neutrino and anti-neutrino interactions on carbon for the empirical model available in GENIE, the SuSAv2 2p2h model discussed in this manuscript and the Valencia model as implemented in GENIE [5,44].



Phys. Rev. D 101, 033003 (2020)

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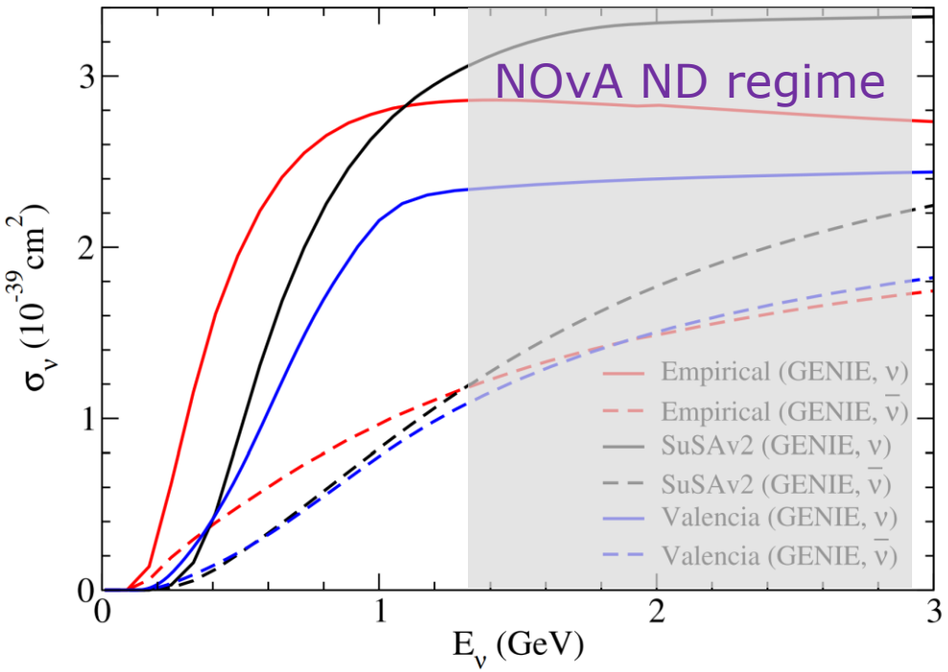

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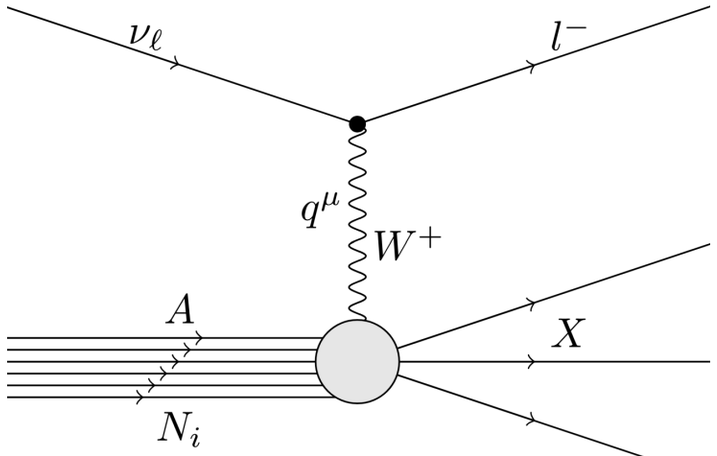
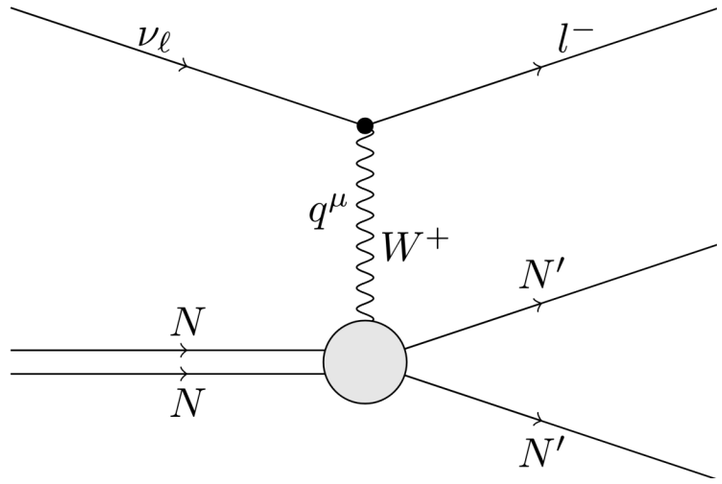


Two analyses



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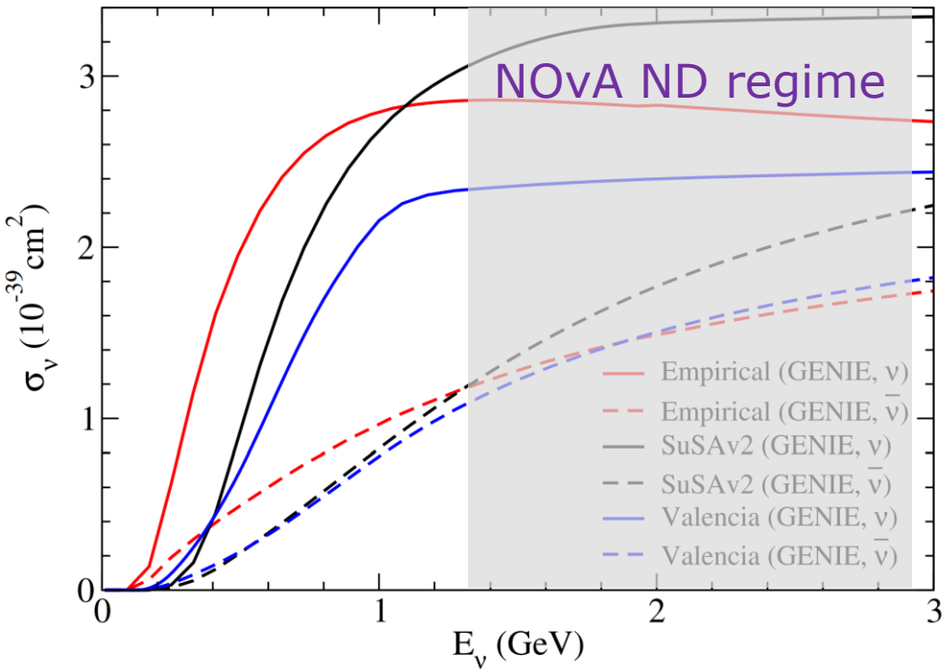

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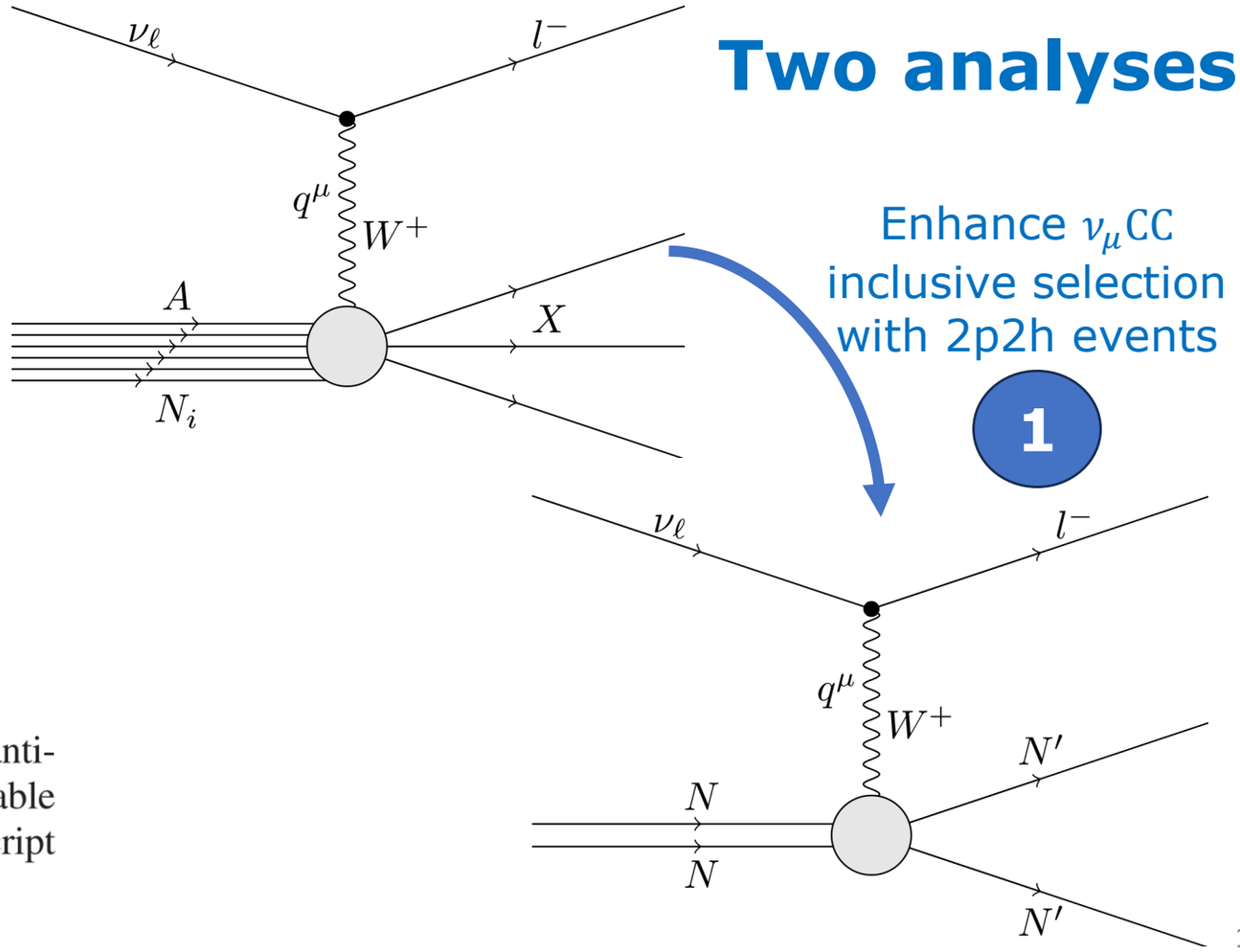
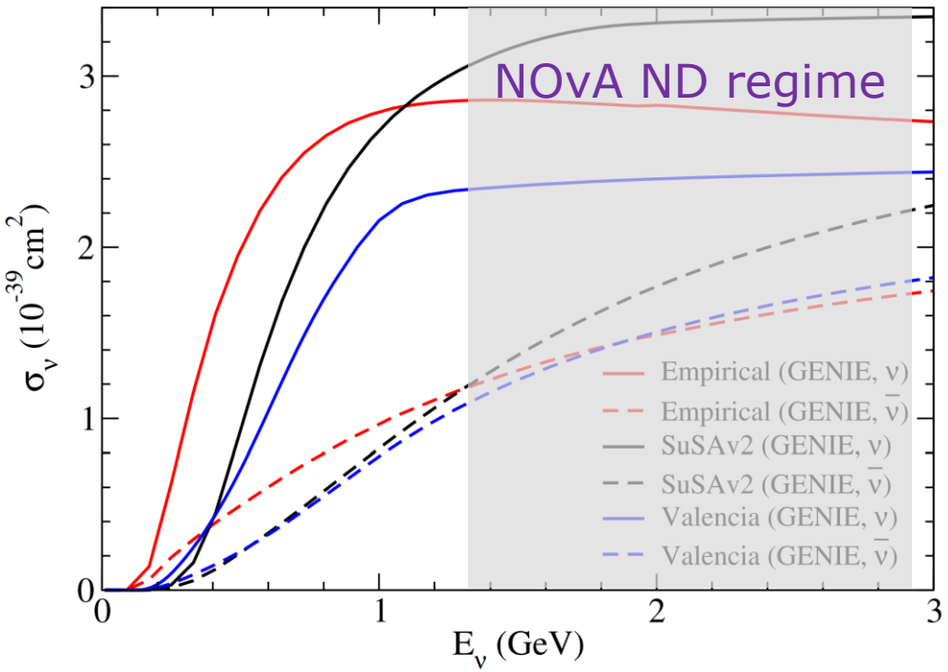


Two analyses

Enhance ν_μCC inclusive selection with 2p2h events

1

2p2h-Focused Cross Section Studies Using Inclusive ν_μ CC Interactions



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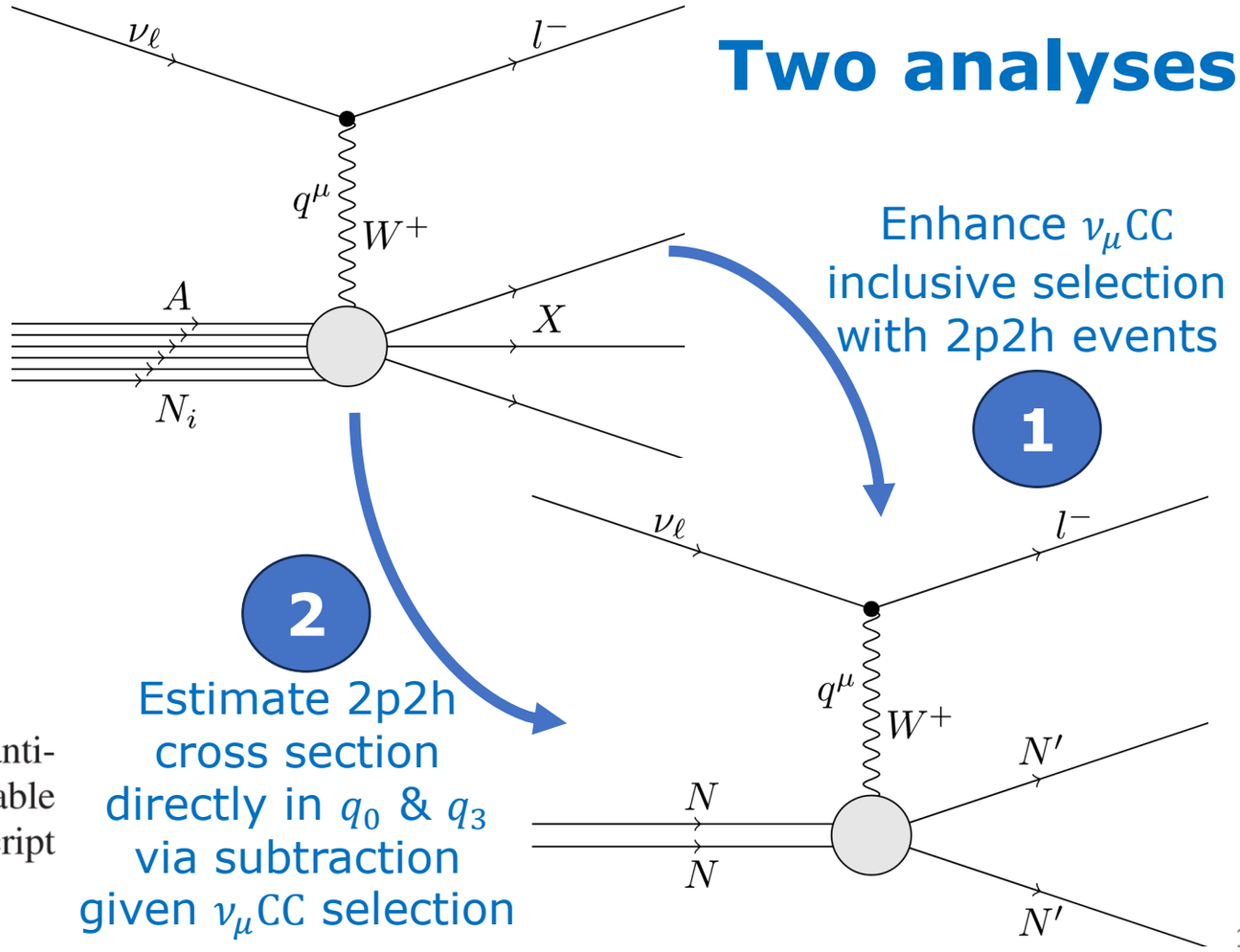


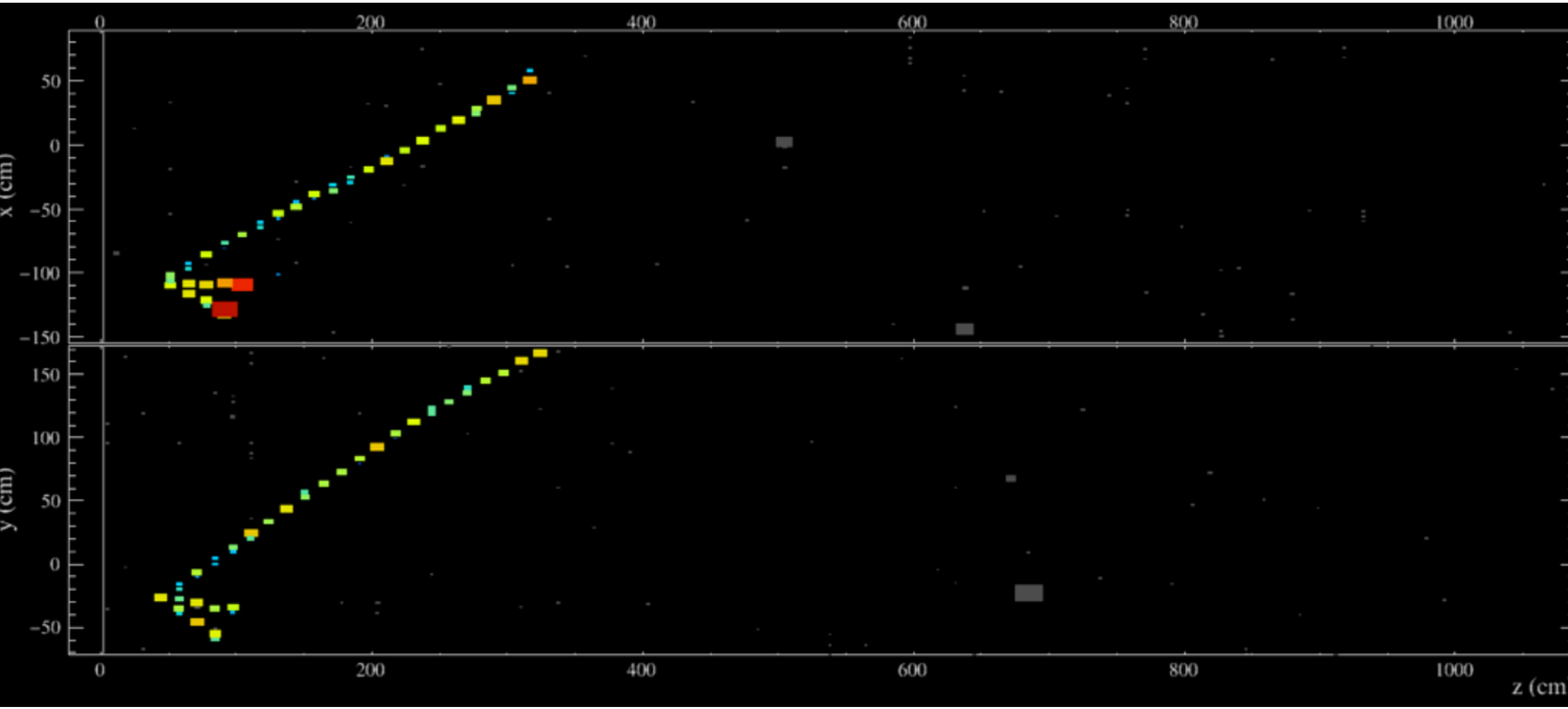
Two analyses

Enhance ν_μCC inclusive selection with 2p2h events

1

2

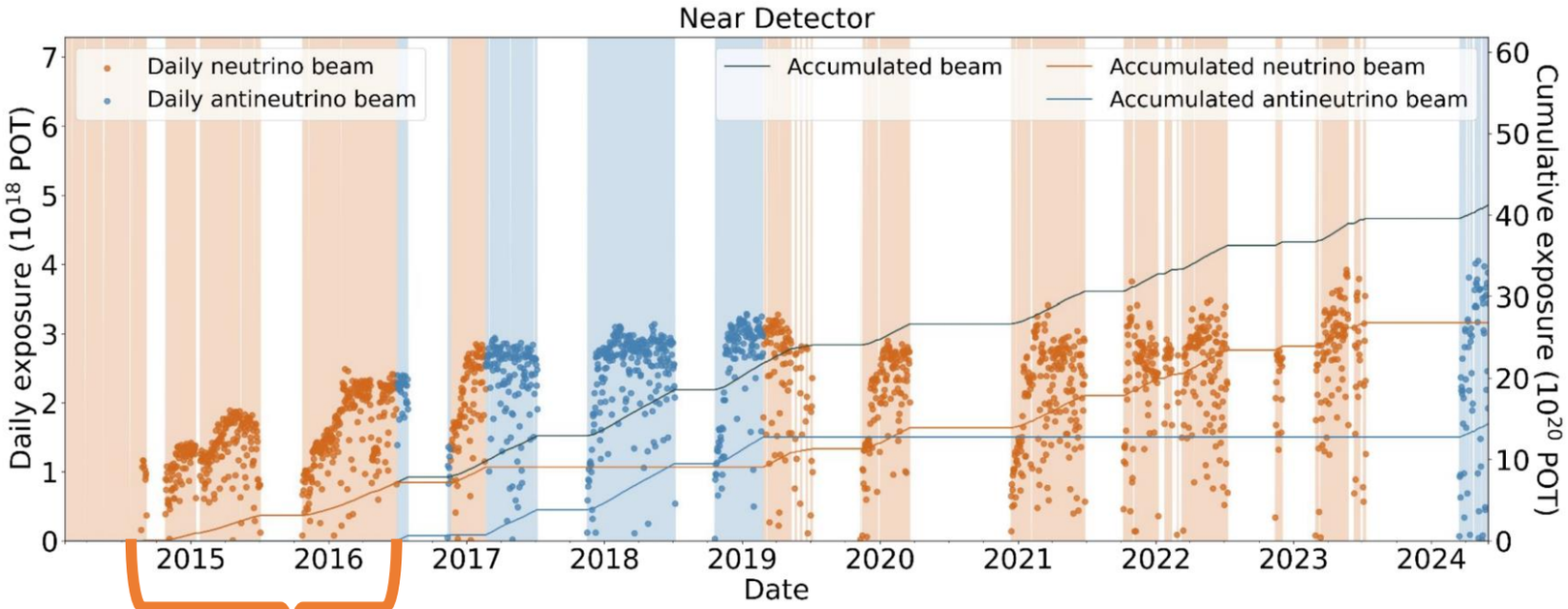
Estimate 2p2h cross section directly in q_0 & q_3 via subtraction given ν_μCC selection


0
200
400
600
800
1000
50
0
−50
−100
−150
x (cm)
150
100
50
0
−50
y (cm)
z (cm

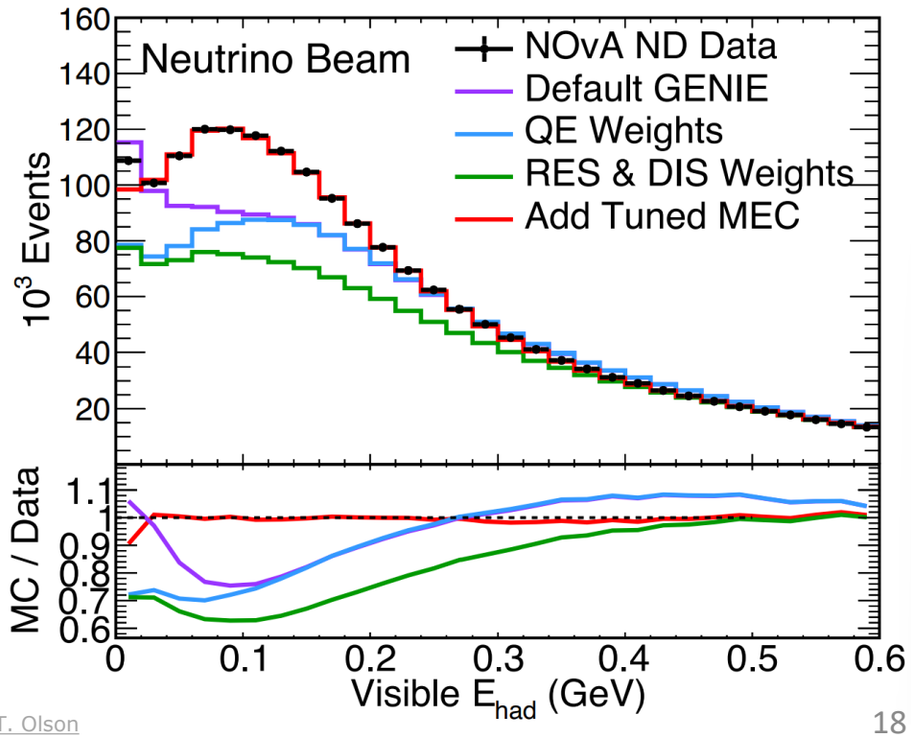
1 ν_μ CC Inclusive ND Data Set & Modeling 2

Eur. Phys. J. C 80, 1119 (2020)
(previous 2019 analysis)

NOvA analyses are always constructed with appropriate uncertainties to be insensitive to particulars of tuning



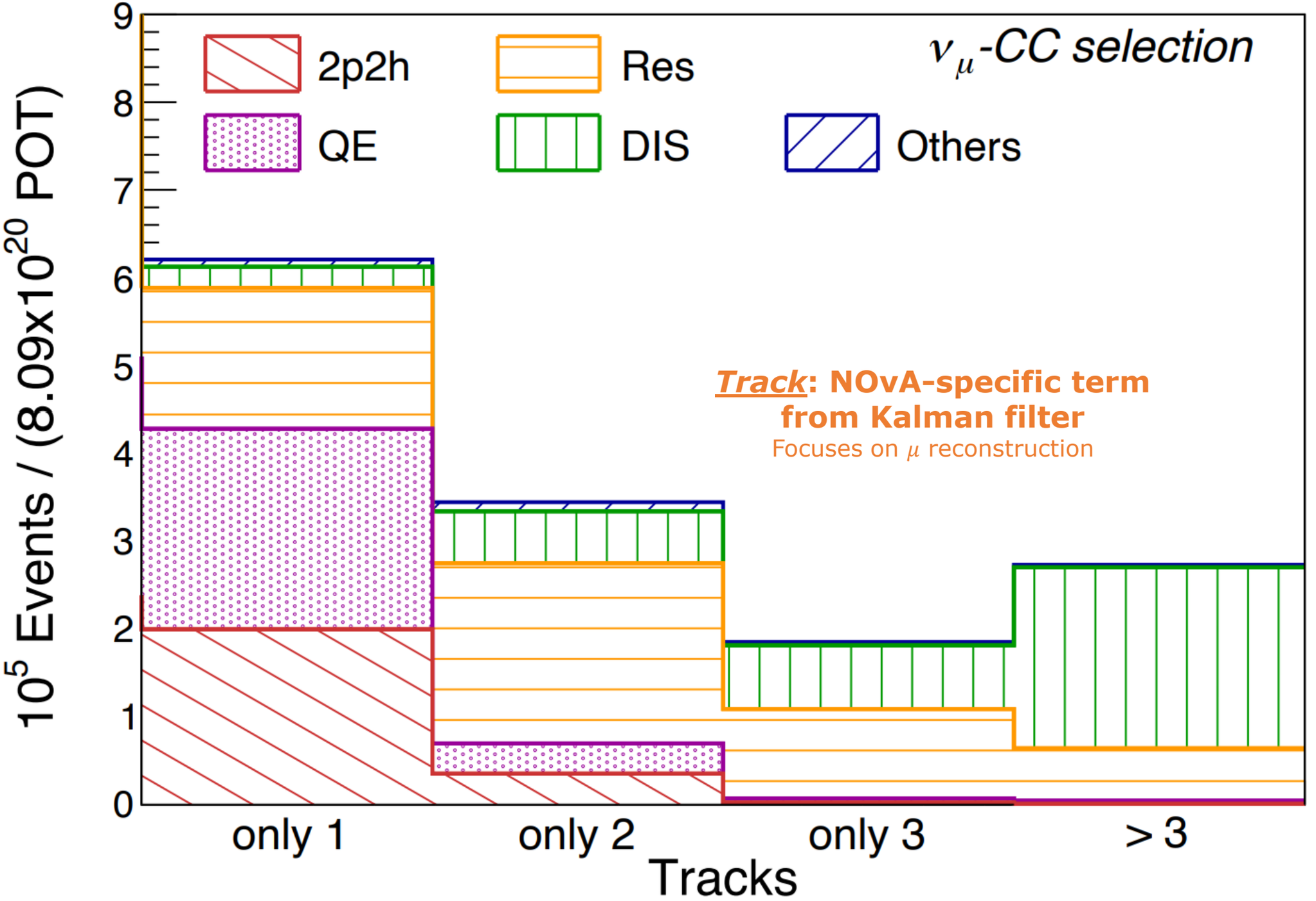
8.09×10^{20} POT ν beam sample used in each analysis



NOvA ND & World Data Tuned GENIEv2.12.2					
Fermi Motion	**QE**	**MEC**	**RES**	**DIS**	**FSI**
Rel. Fermi Gas (Bodek-Ritchie)	Llewelyn -Smith	Empirical	Rein-Sehgal	Bodek-Yang	hA Intranuke

1

NOvA Simulation

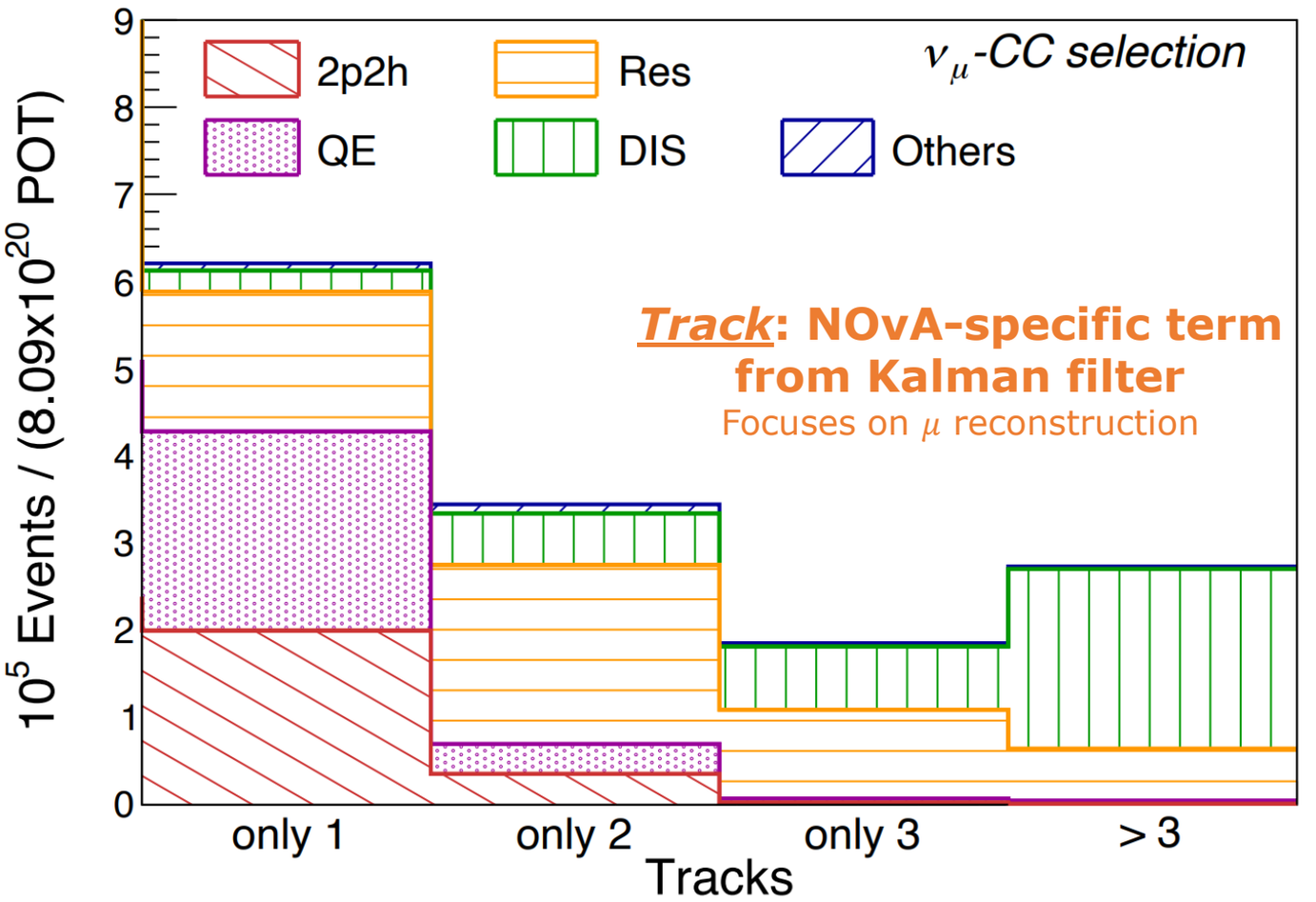


***Track*: NOvA-specific term from Kalman filter**

Focuses on μ reconstruction

1

2p2h Enhanced Selection

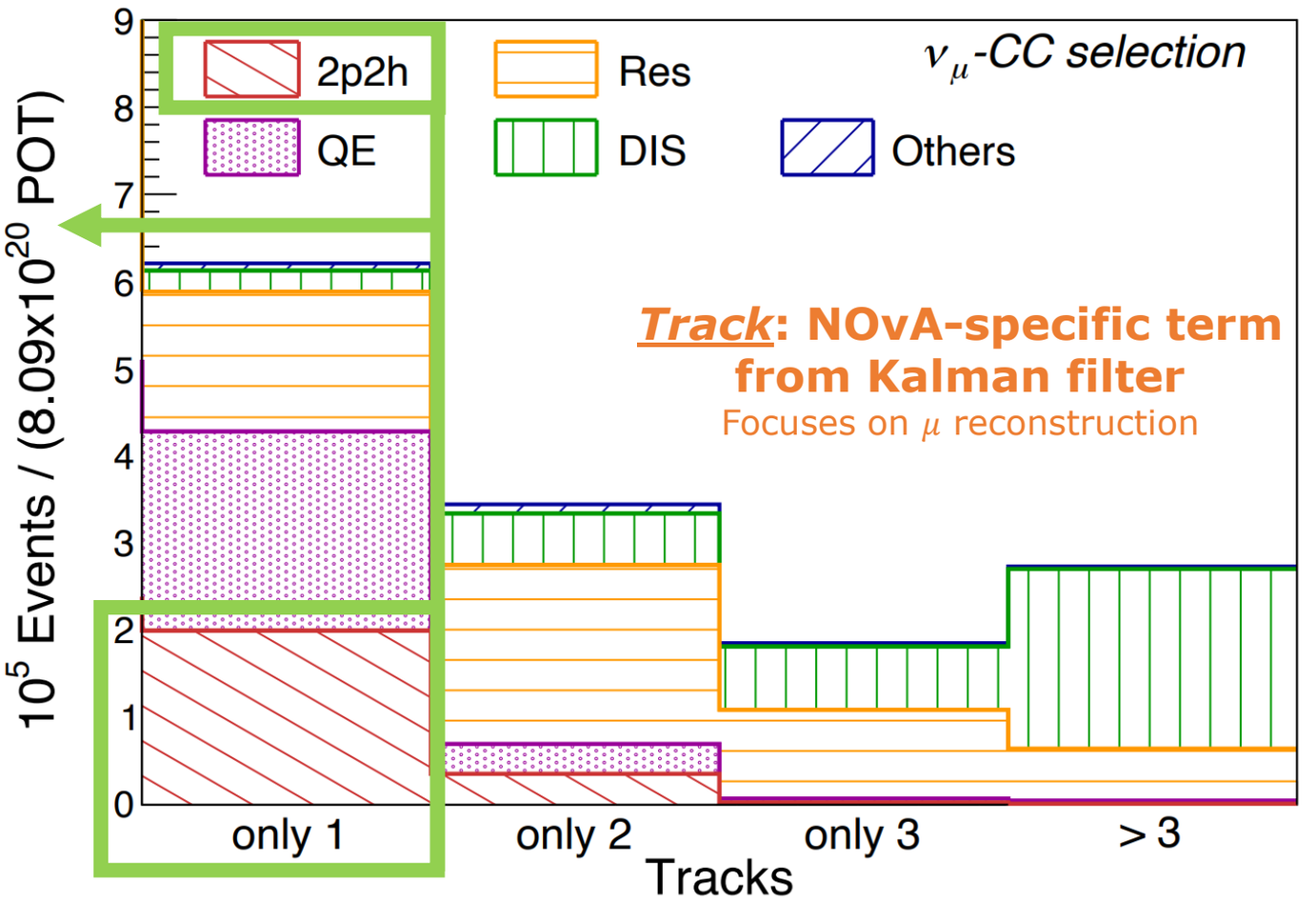


- Incl. ν_μ CC preselection w/full containment
  - Slices w/tracks, use fully active fiducial volume
- μ ID w/BDT (uses mainly dE/dx vars.)
  - 97% purity, ~98% efficiency wrt. preselection
- ν_μ CC w/single track, $T_p < 250\text{MeV}$, $T_\pi < 175\text{MeV}$

Expect statistics to grow by ~3X in future!

1

2p2h Enhanced Selection



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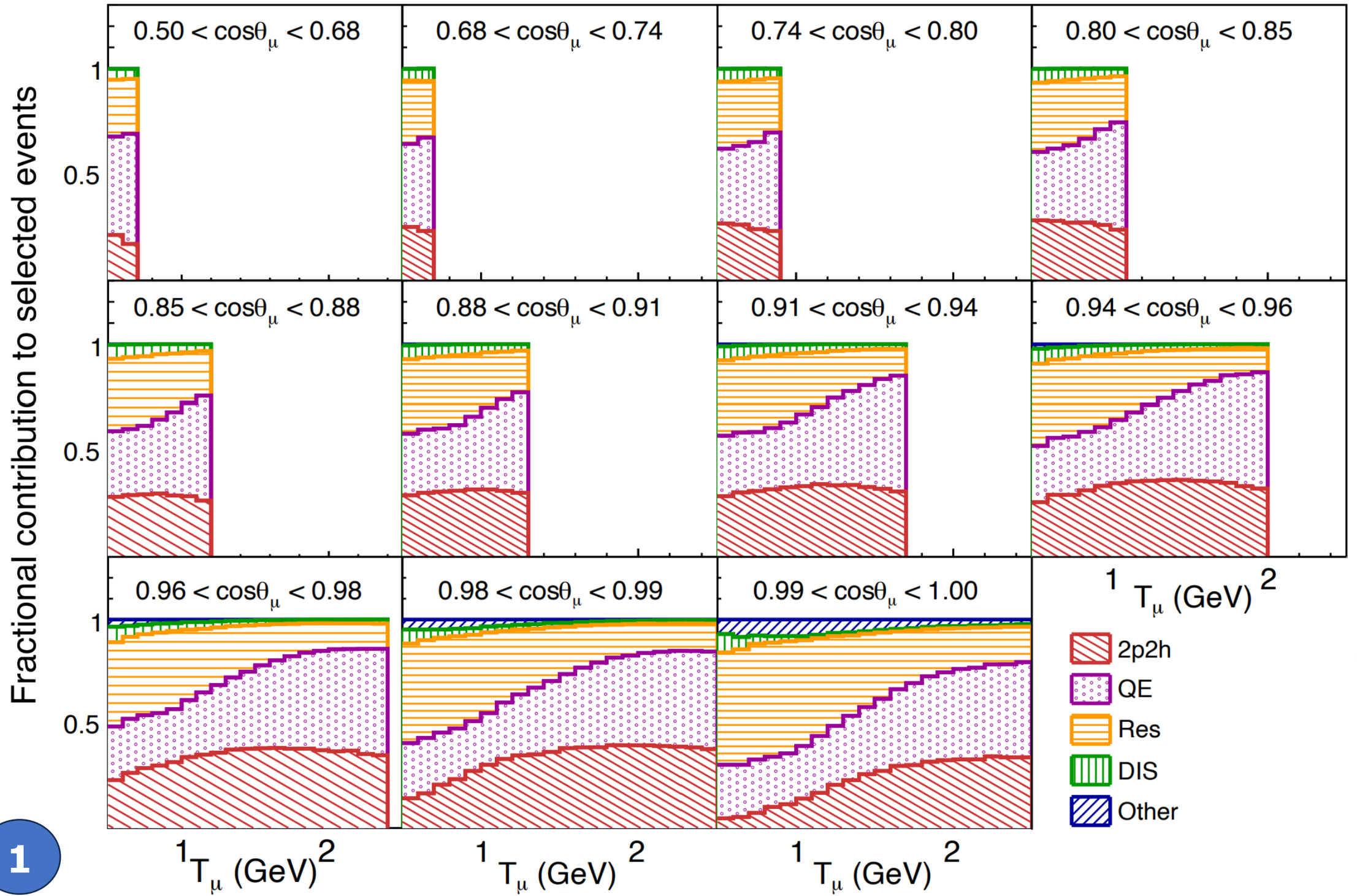
NOvA Simulation



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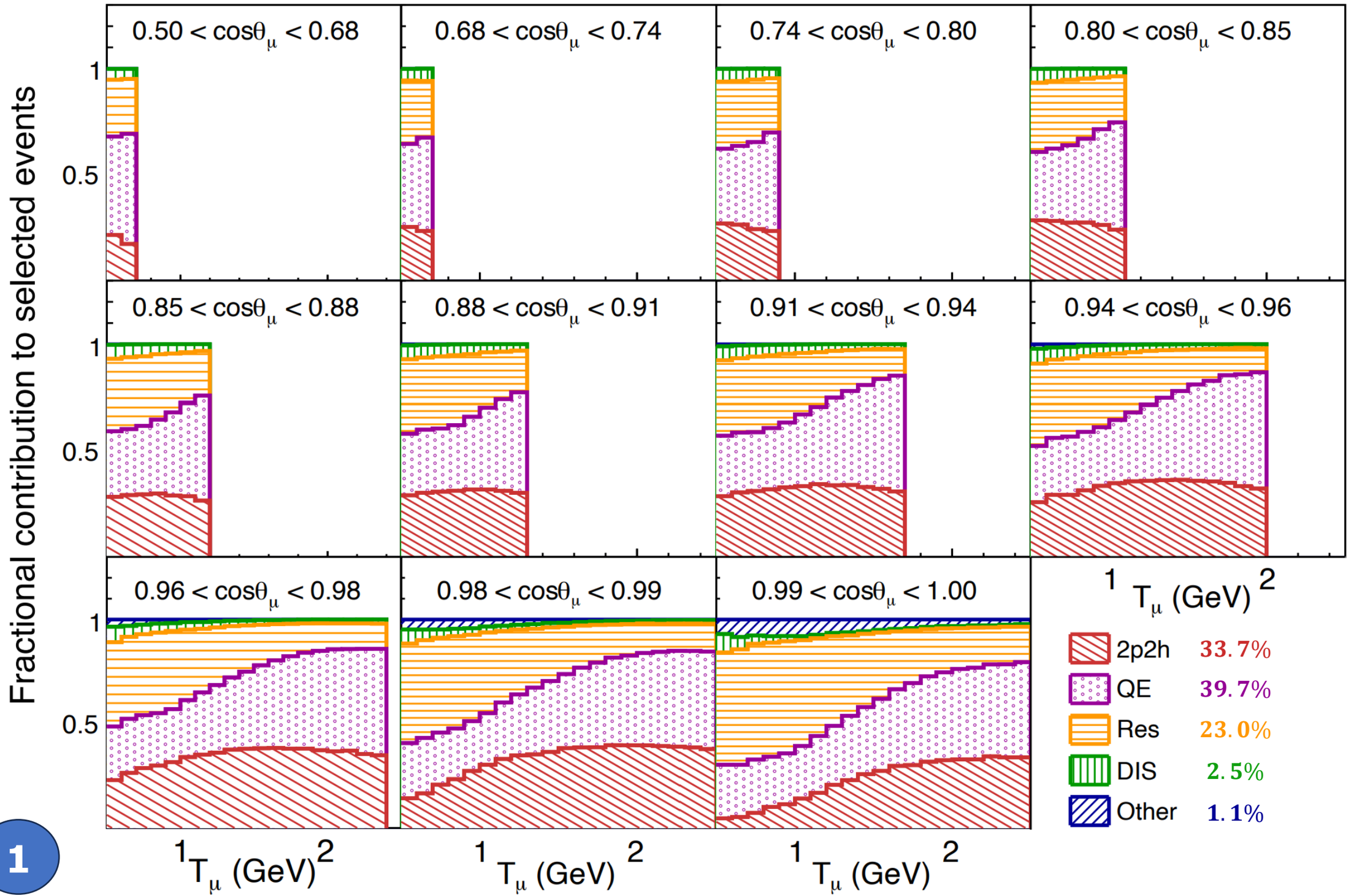
NOvA Simulation



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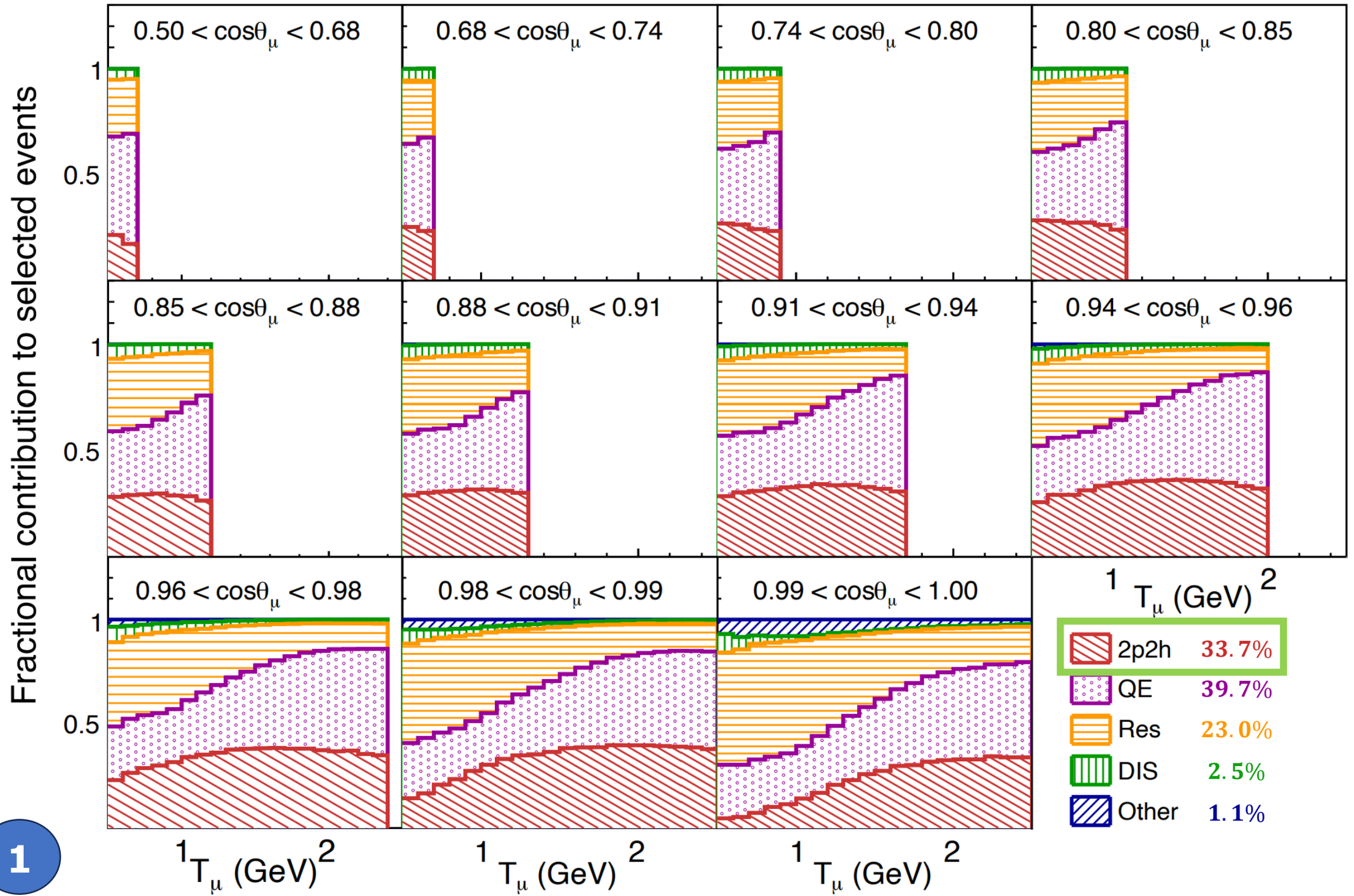
NOvA Simulation



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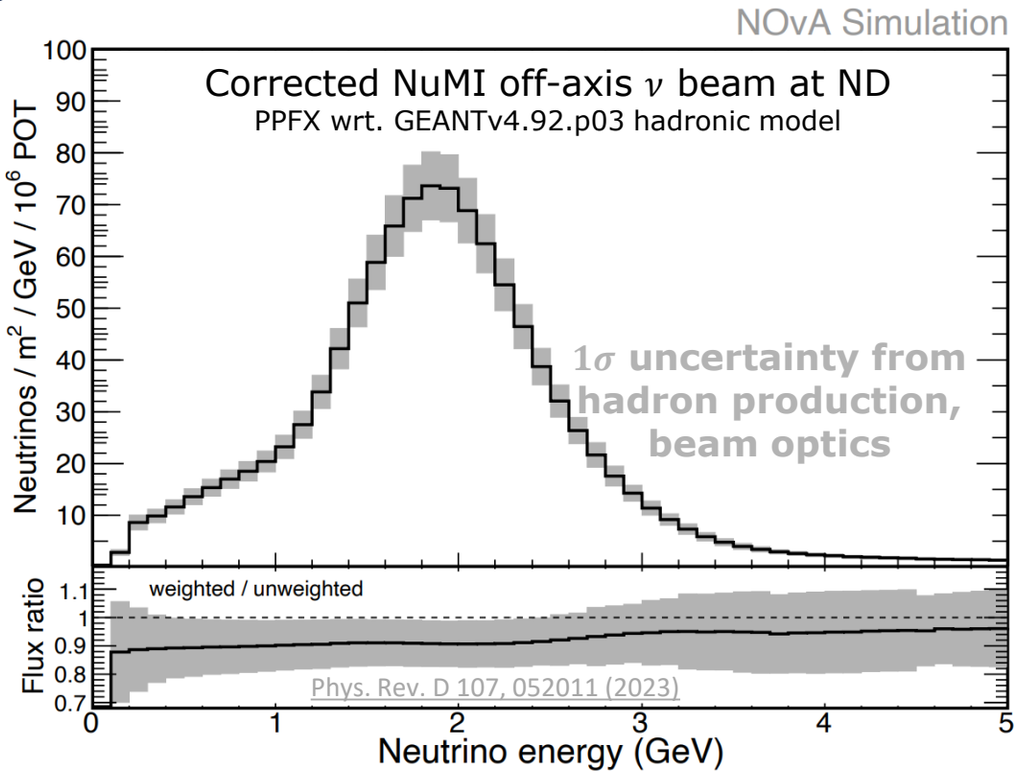
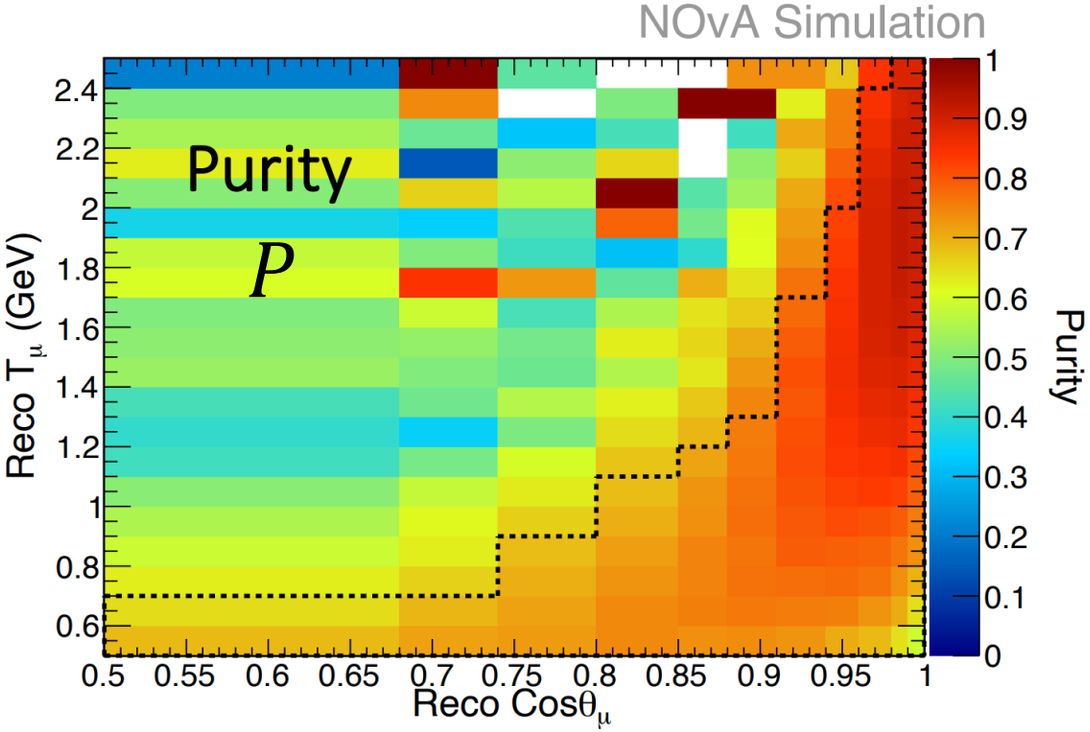
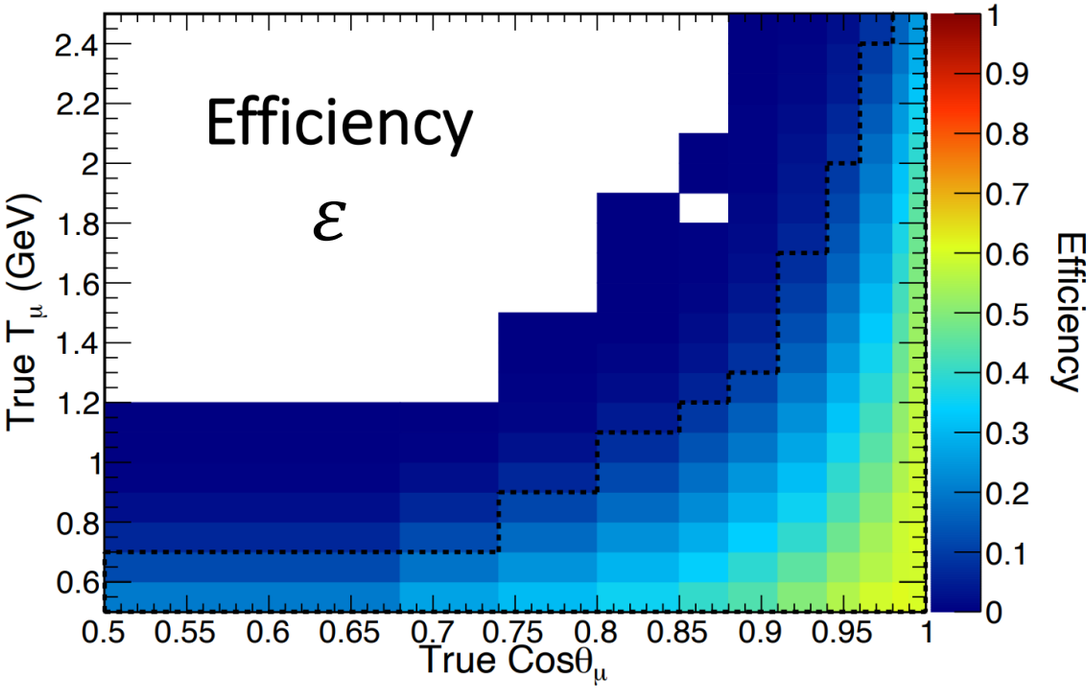
1 Unfolding & Cross Section





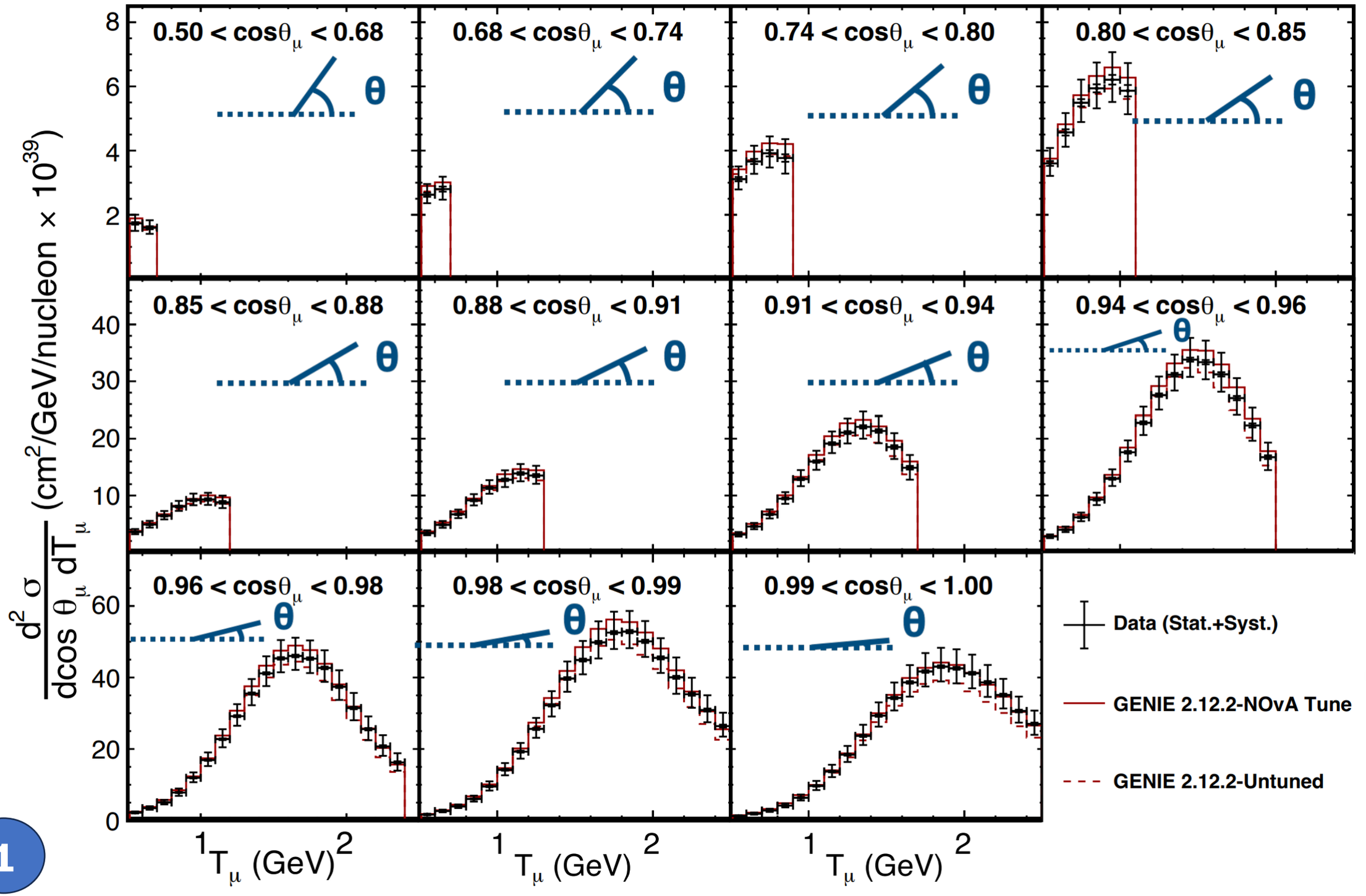


E_{avail} in MINERvA: Phys. Rev. Lett. 116, 071802
(~total E of all observable final state hadrons)

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu\, dT_\mu}\right)_i = \frac{1}{N_T \Phi_\nu} \sum_{E_{\text{avail}}} \frac{\sum_j U_{ij}^{-1}\left[N_{sel\,j} P_j\right]}{\varepsilon_i \Delta\cos\theta_{\mu_i}\, \Delta T_{\mu_i}}$$

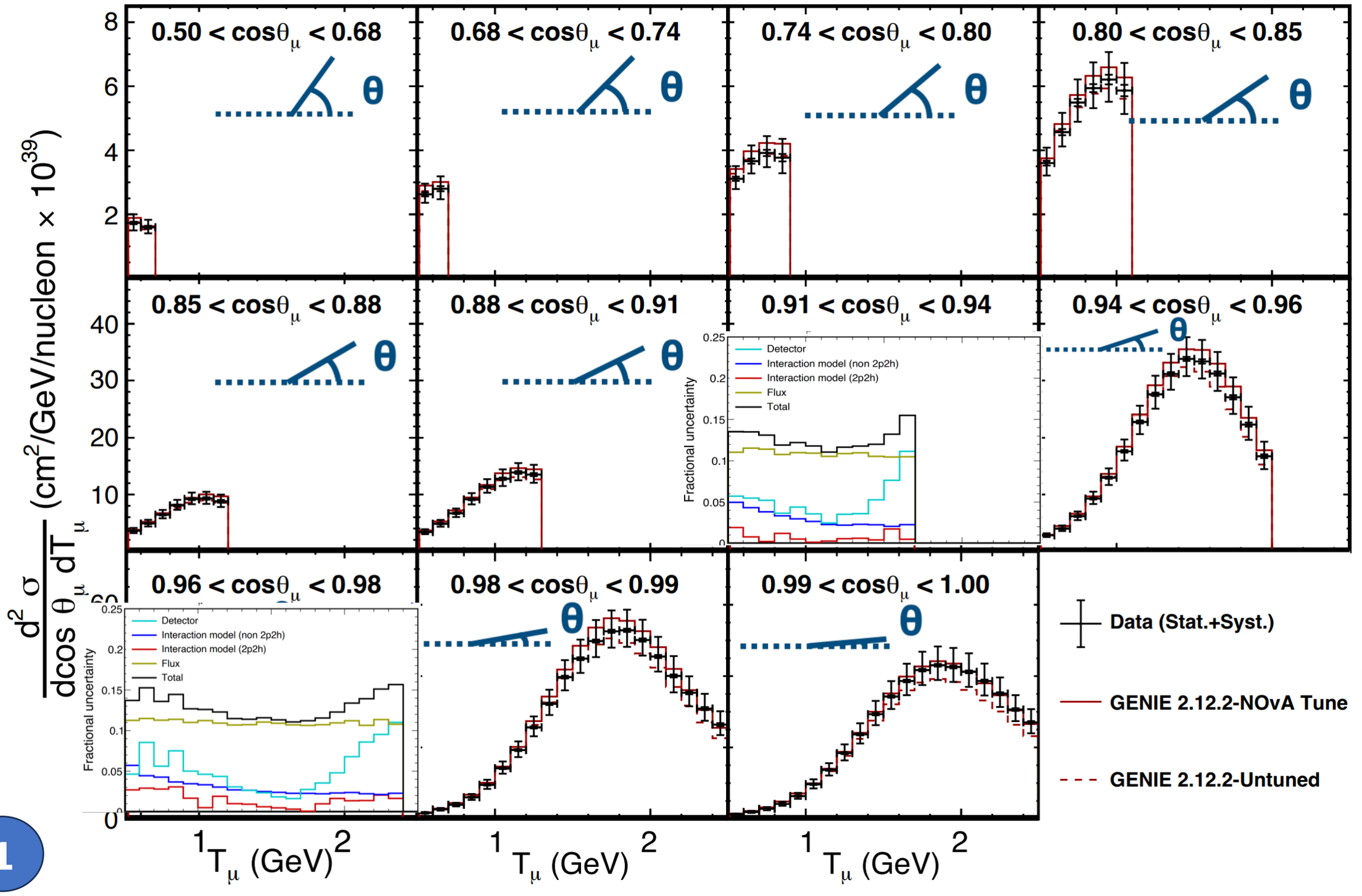
- Complete analysis in $\left(T_\mu, \cos\theta_\mu, E_{\text{avail}} \sim q_0\right)$
  - Project onto muon kinematics alone
- Unfolding uses D'Agostini via RooUnfold
- Dominant systematics come from flux
  - NA49: ~10% norm. unc. on Φ_ν, ~4% beam focusing

NOvA Preliminary



1

NOvA Preliminary



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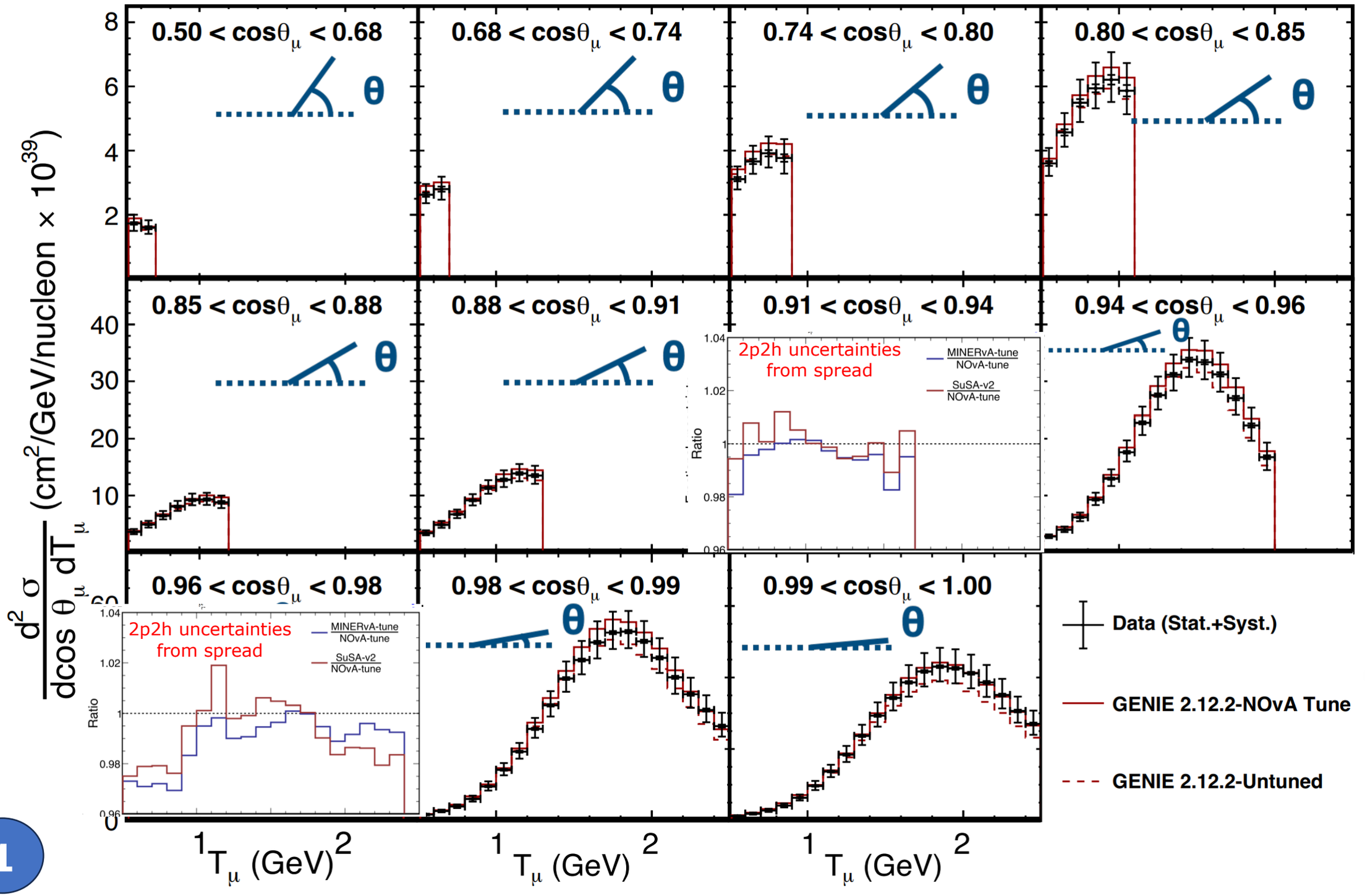
NOvA Preliminary



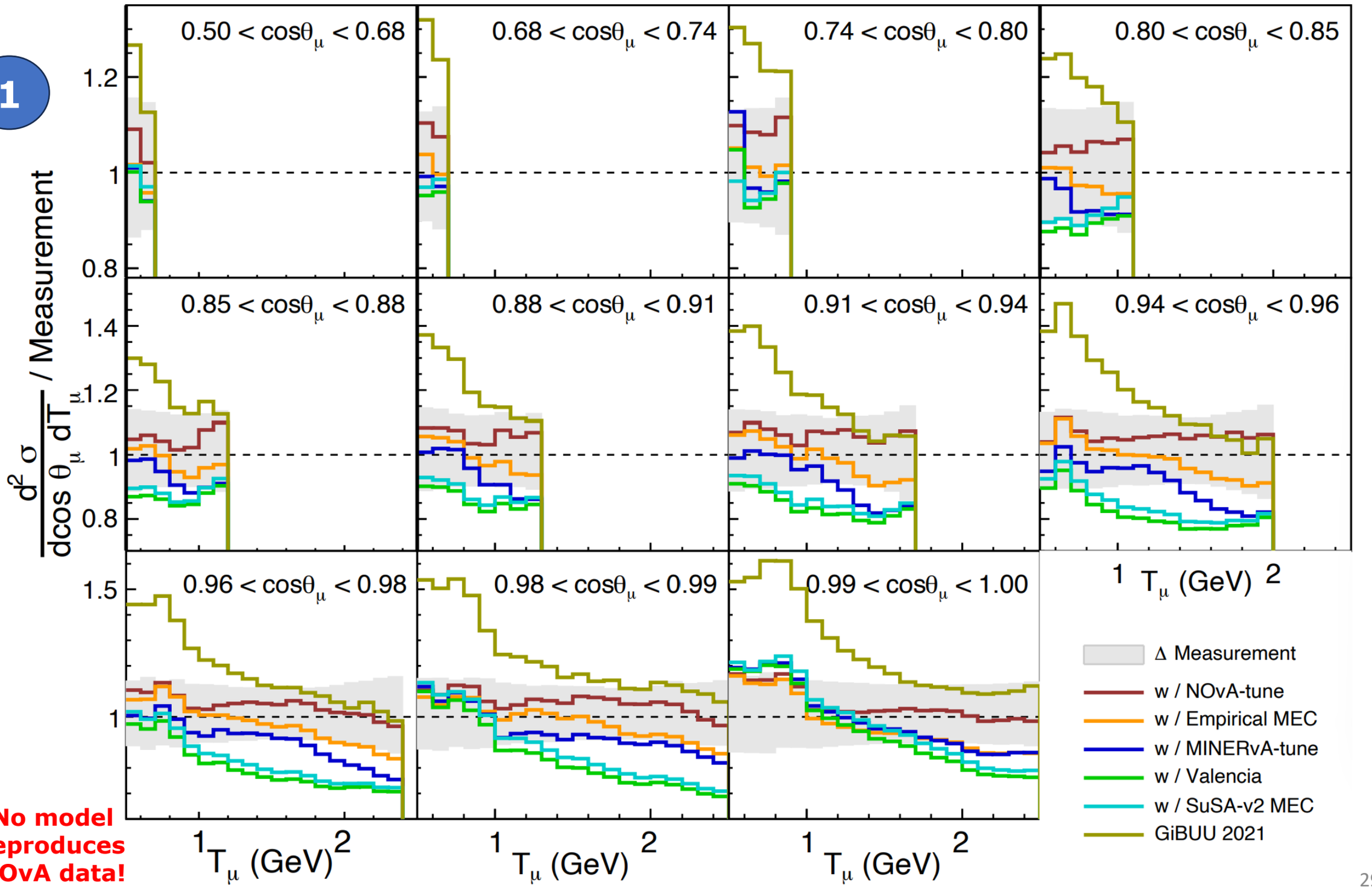
1

Slide adapted from *Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA*—FNAL W&C—L. Aliaga Soplin, T. Olson

Shape only uncertainties also available for comparison!

NOvA Preliminary

1



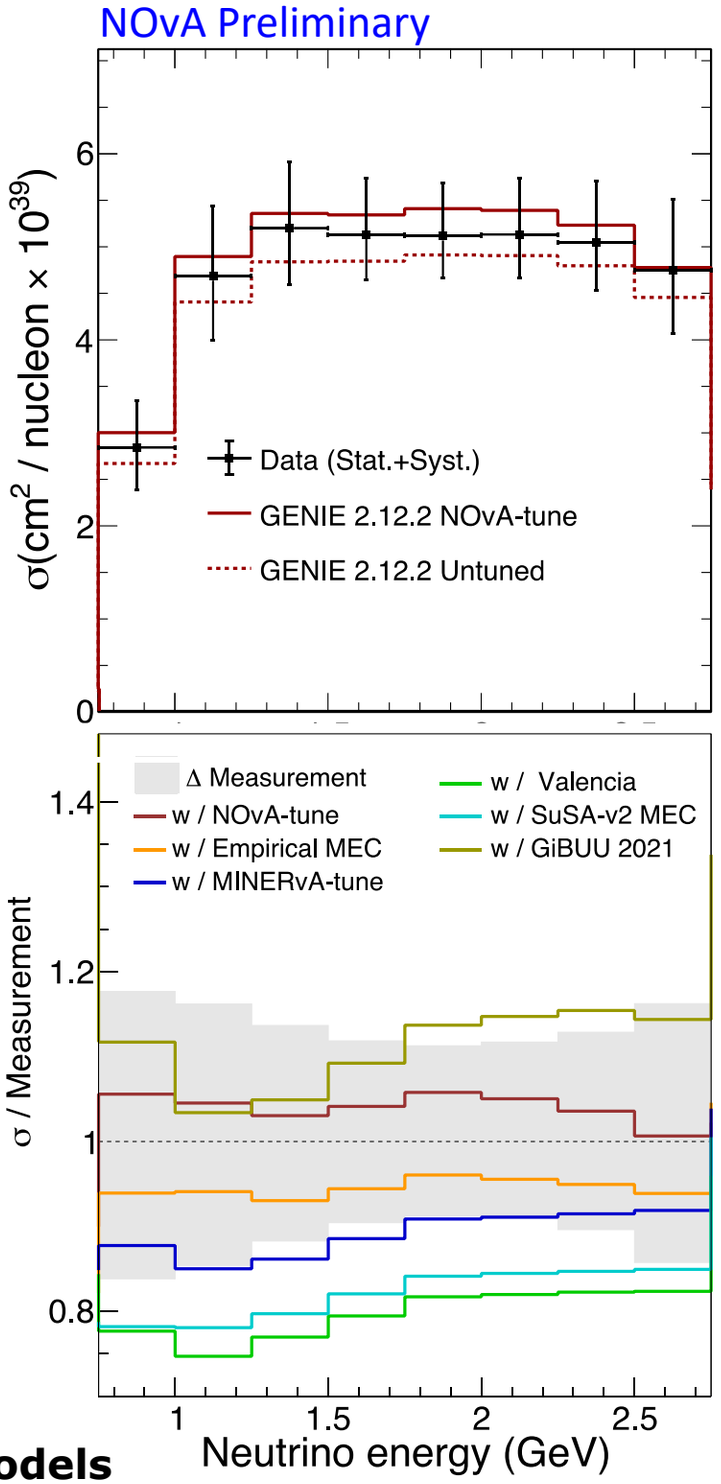
No model reproduces NOvA data!

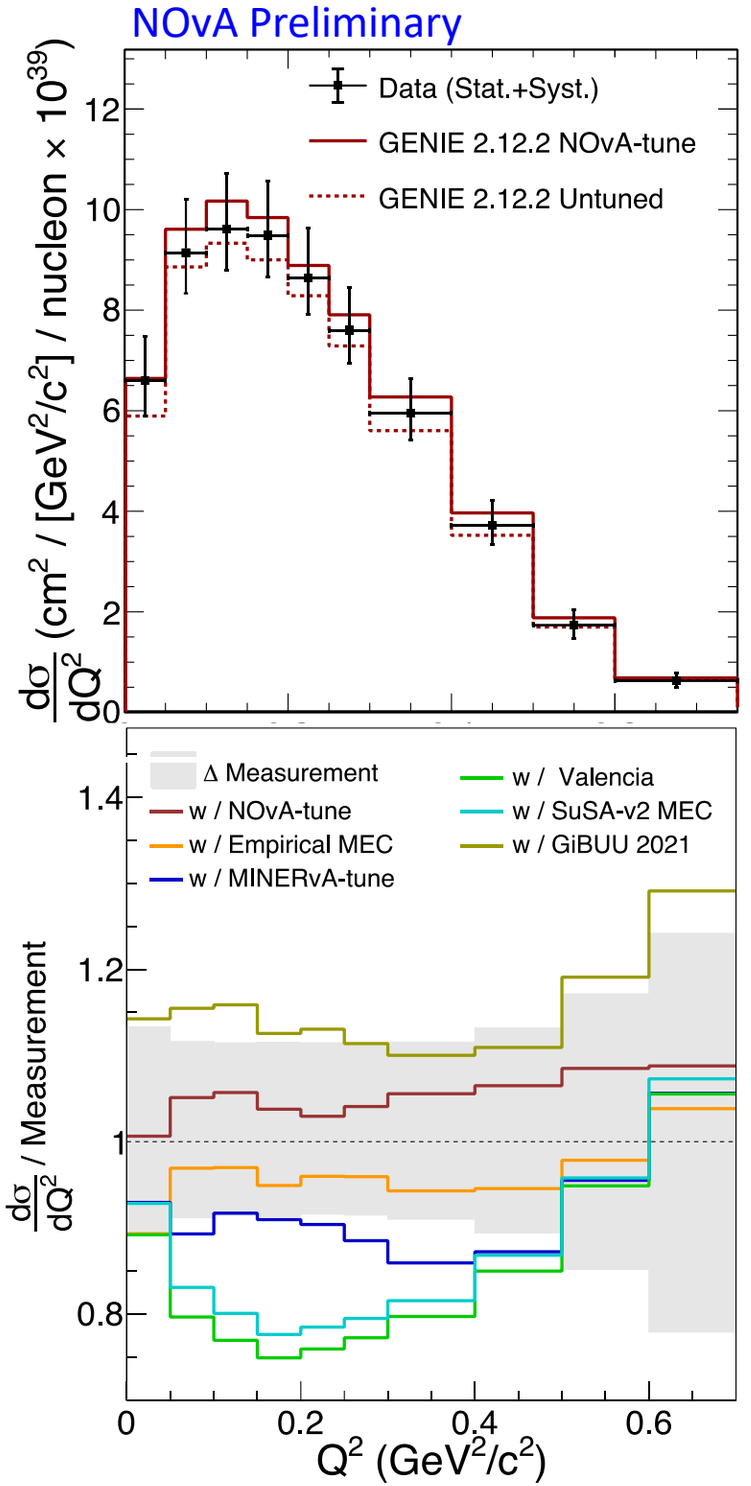
Derived Variables

Project this measurement in 1D
- Kinematics of energy, $Q^2 = -q^2$
- Computed via reconstructed E_μ and calorimetric energy

Excellent for comparisons to various modeling assumptions
- NOvA tune: performs well
- MINERvA tune: slight underestimates
- GiBUU: slight overestimates

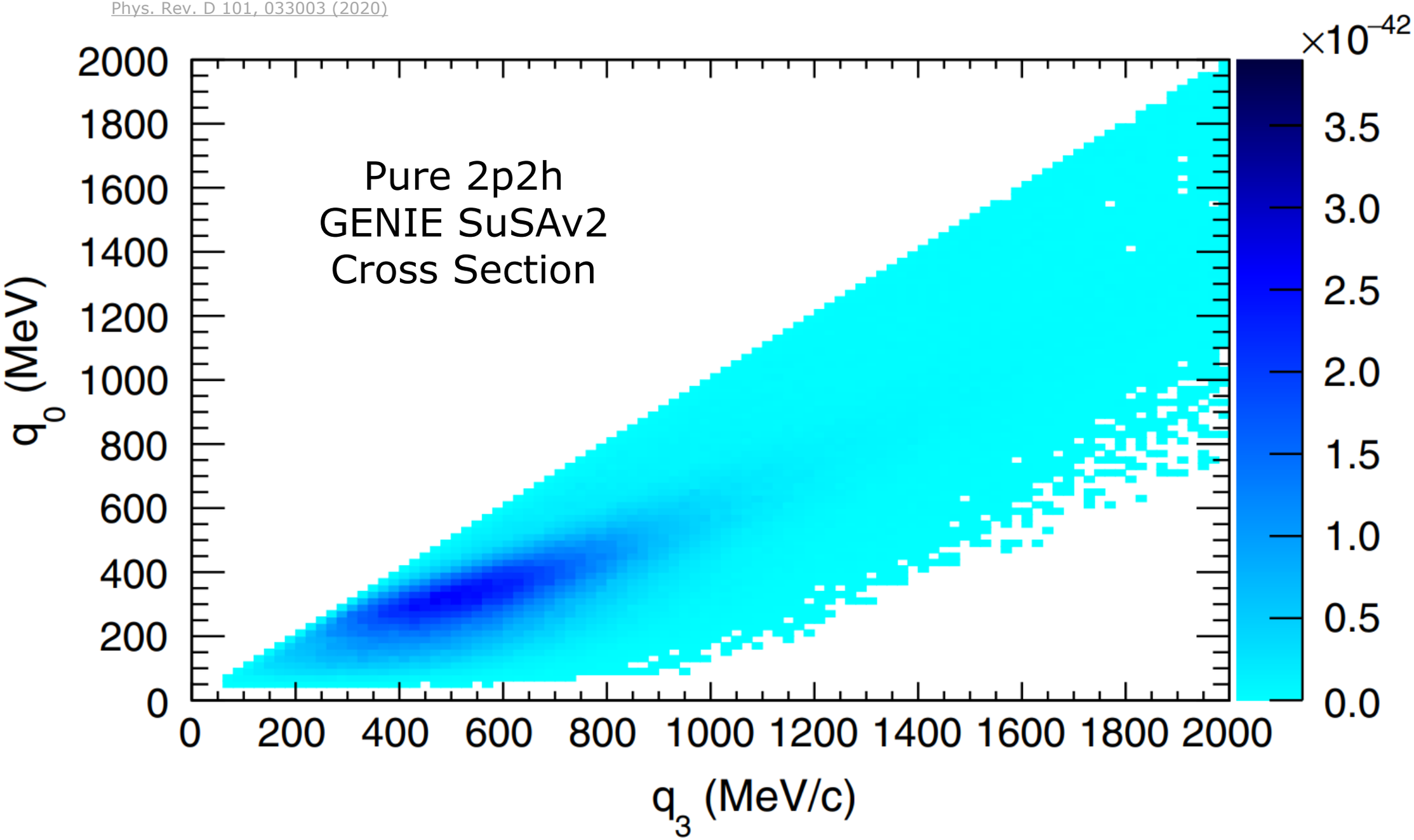
Tensions: SuSAv2/Valencia 2p2h models





2 Theoretical 2p2h $\{q_0, |\vec{q}| \sim q_3\}$-Space

Phys. Rev. D 101, 033003 (2020)



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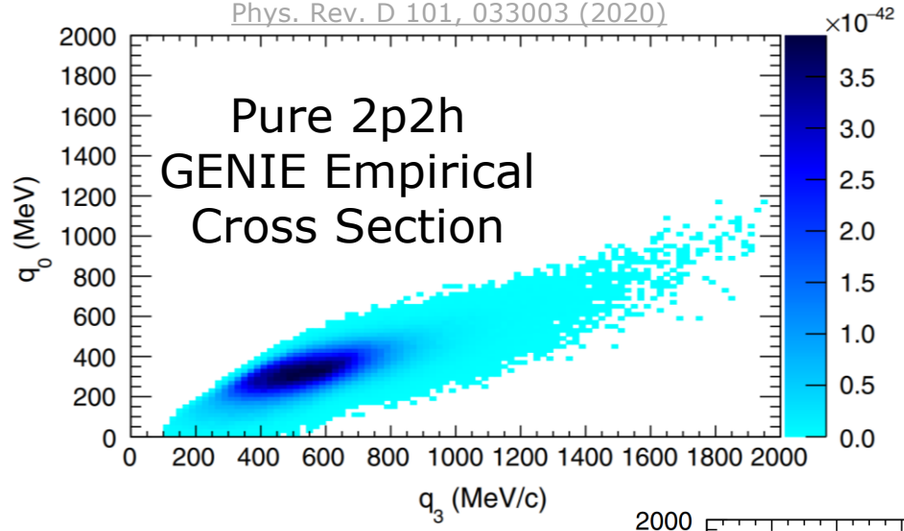

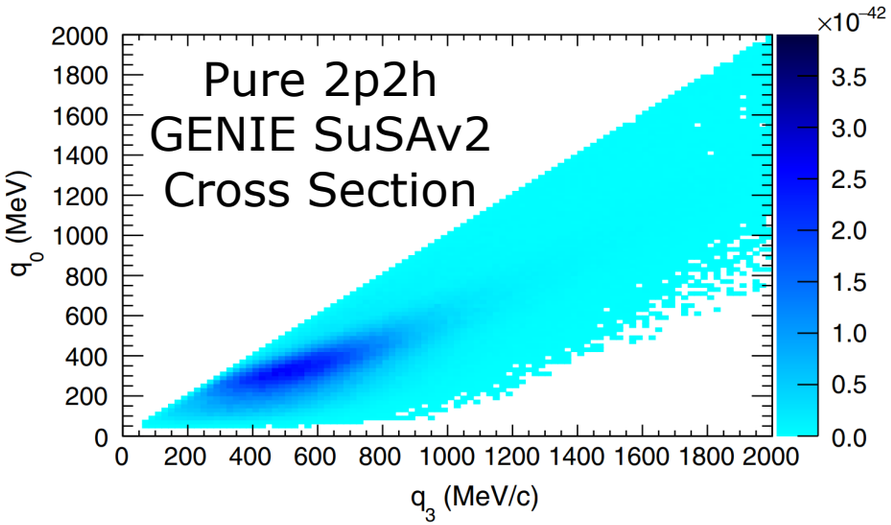

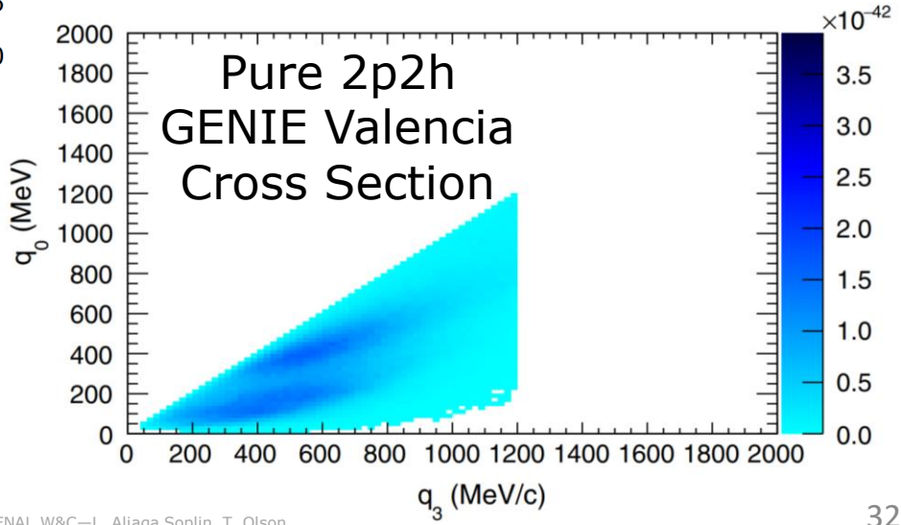

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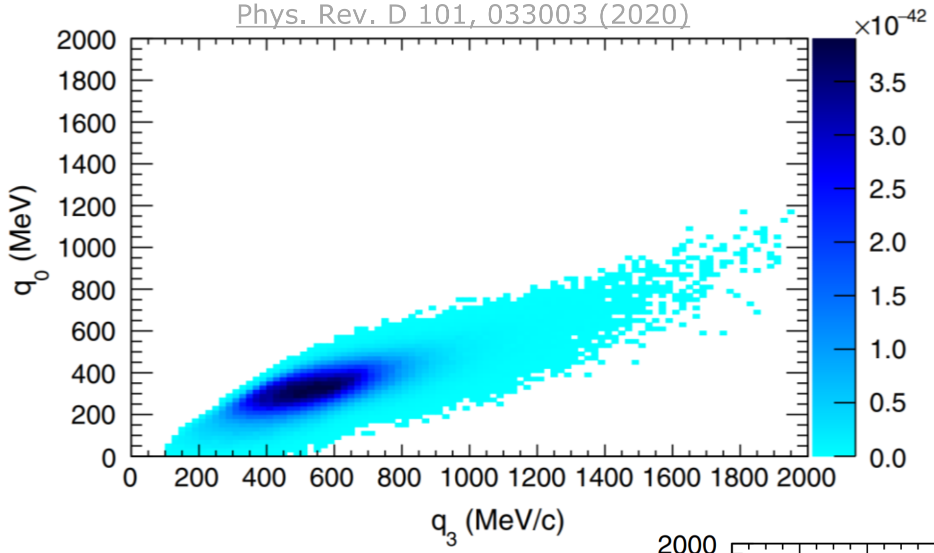

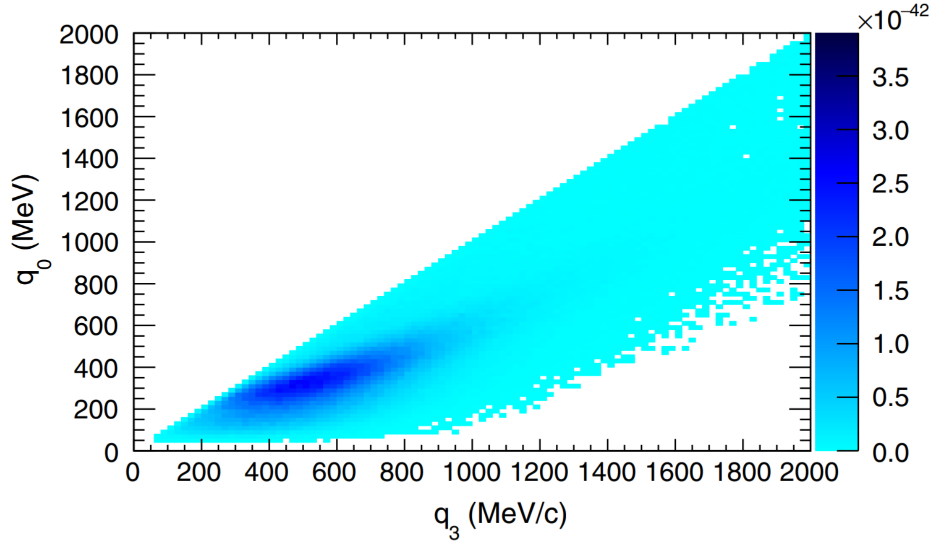

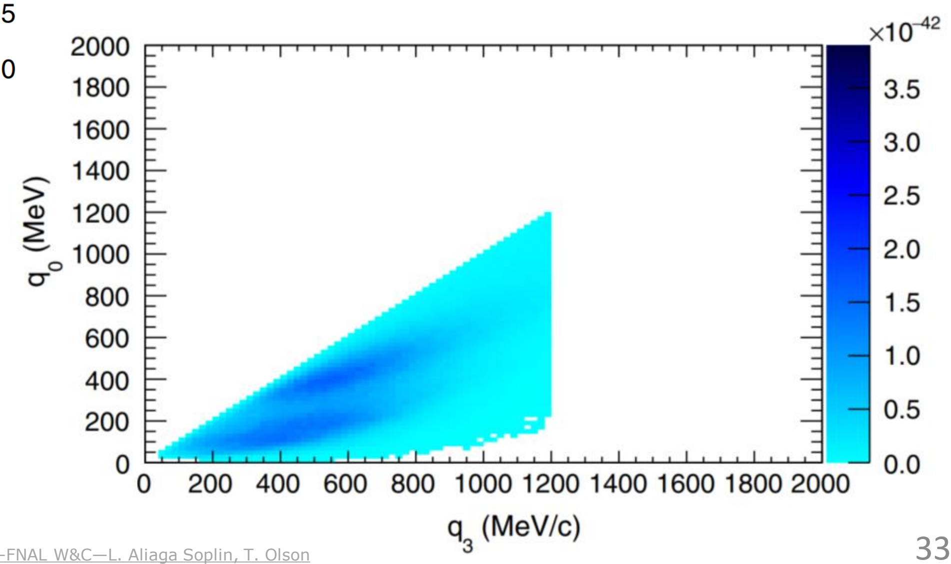

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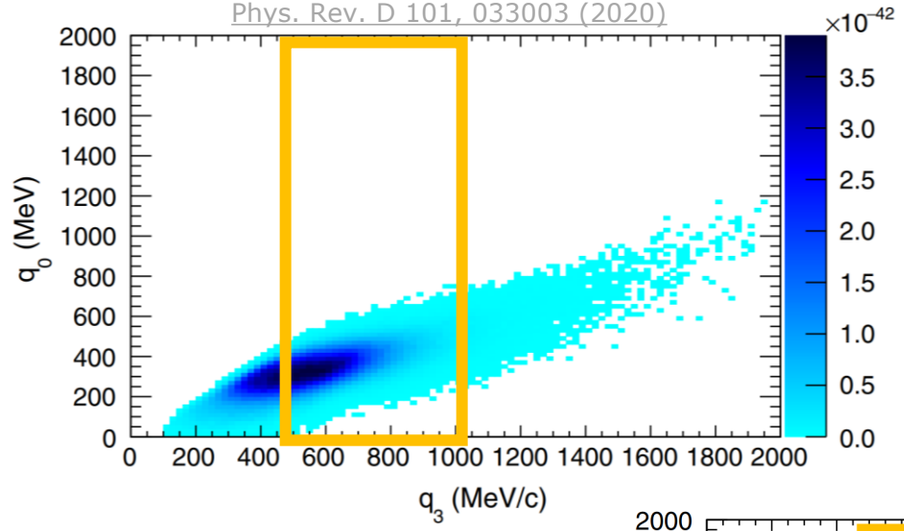

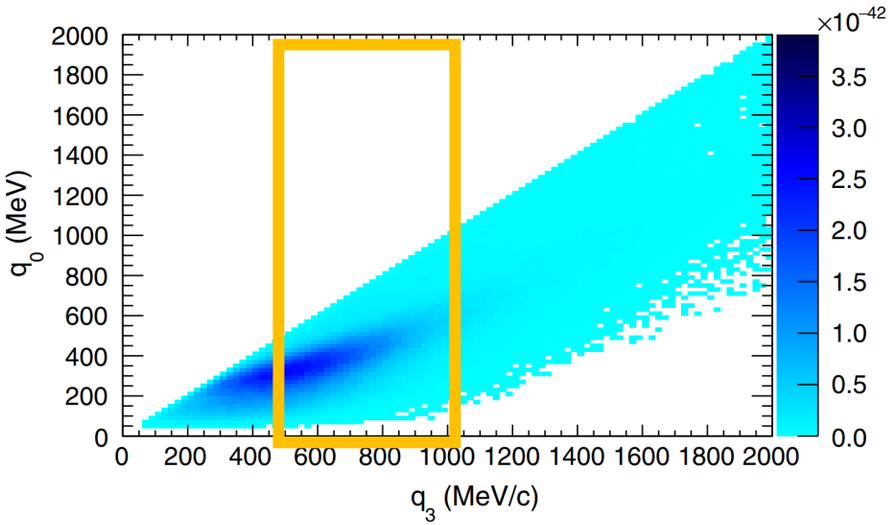

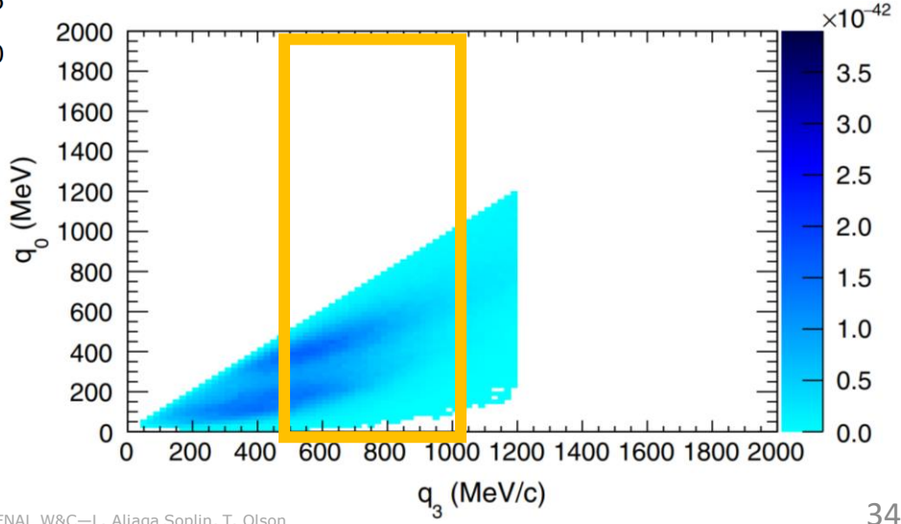

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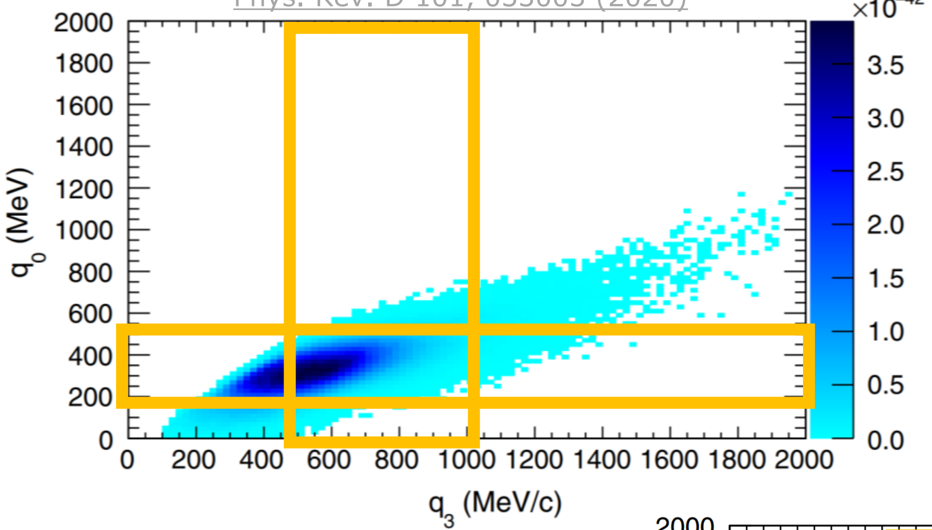
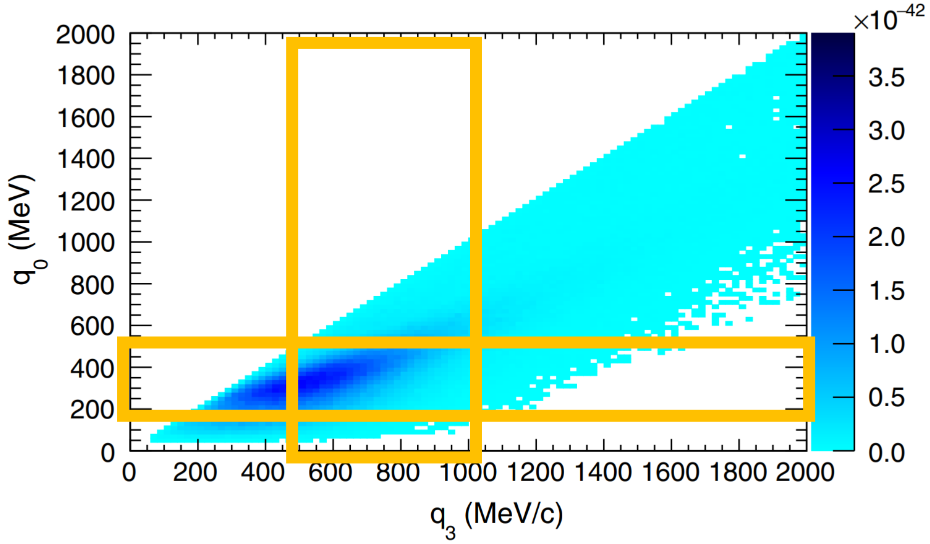
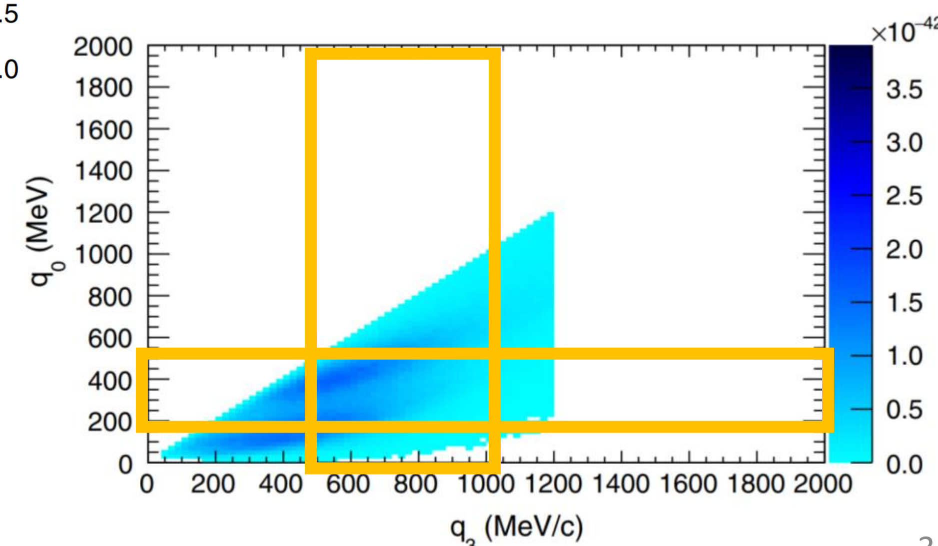
Theoretical 2p2h $\{q_0, |\vec{q}| \sim q_3\}$-Space

Phys. Rev. D 101, 033003 (2020)







Slide adapted from *Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA*—FNAL W&C—L. Aliaga Soplin, T. Olson

Theoretical 2p2h $\{q_0, |\vec{q}| \sim q_3\}$-Space

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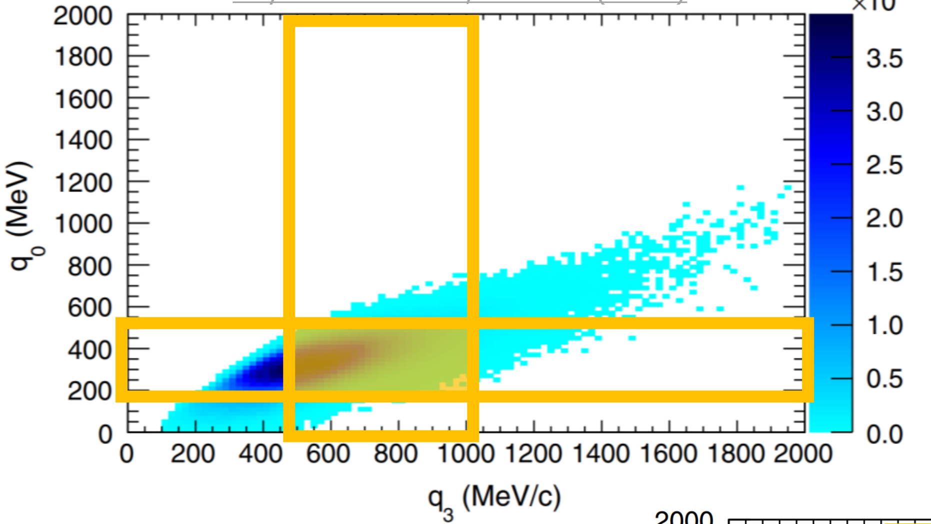
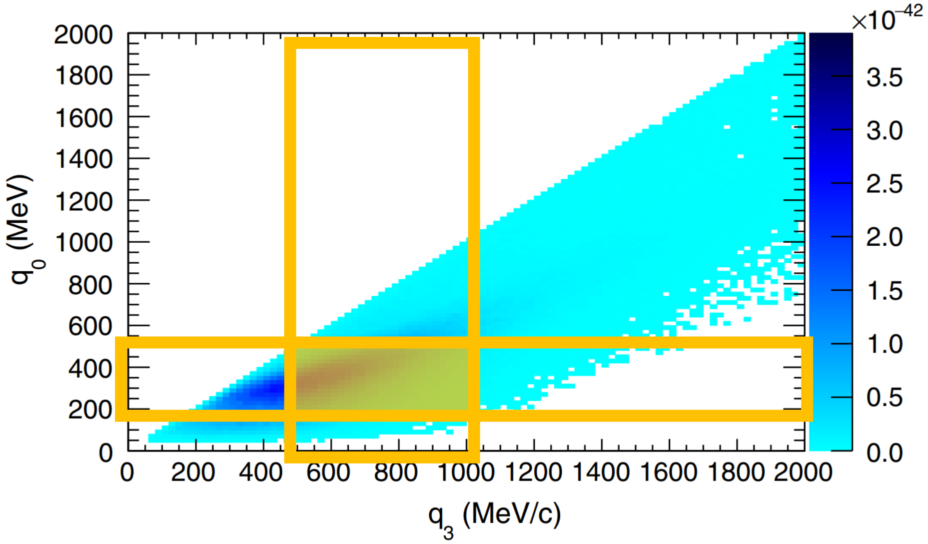
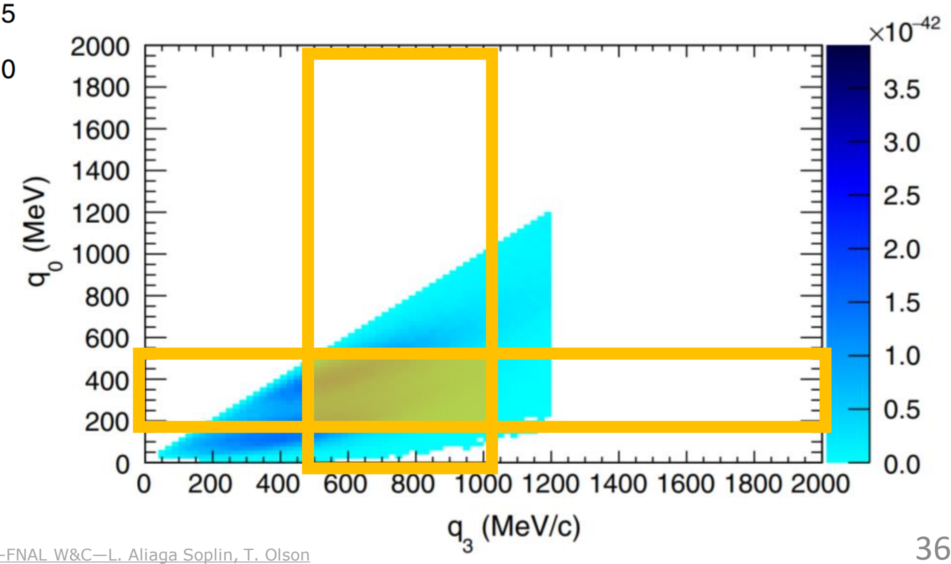
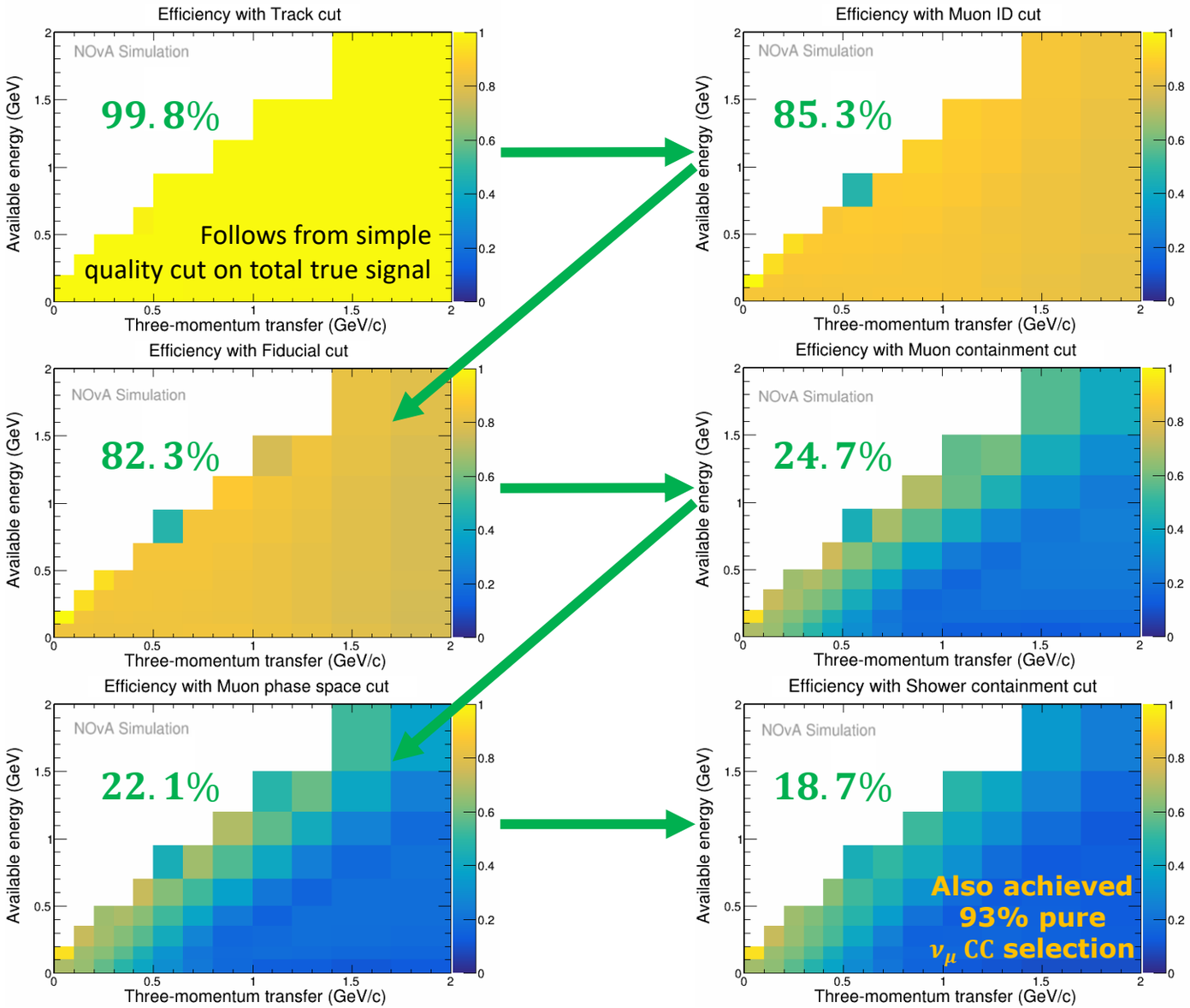


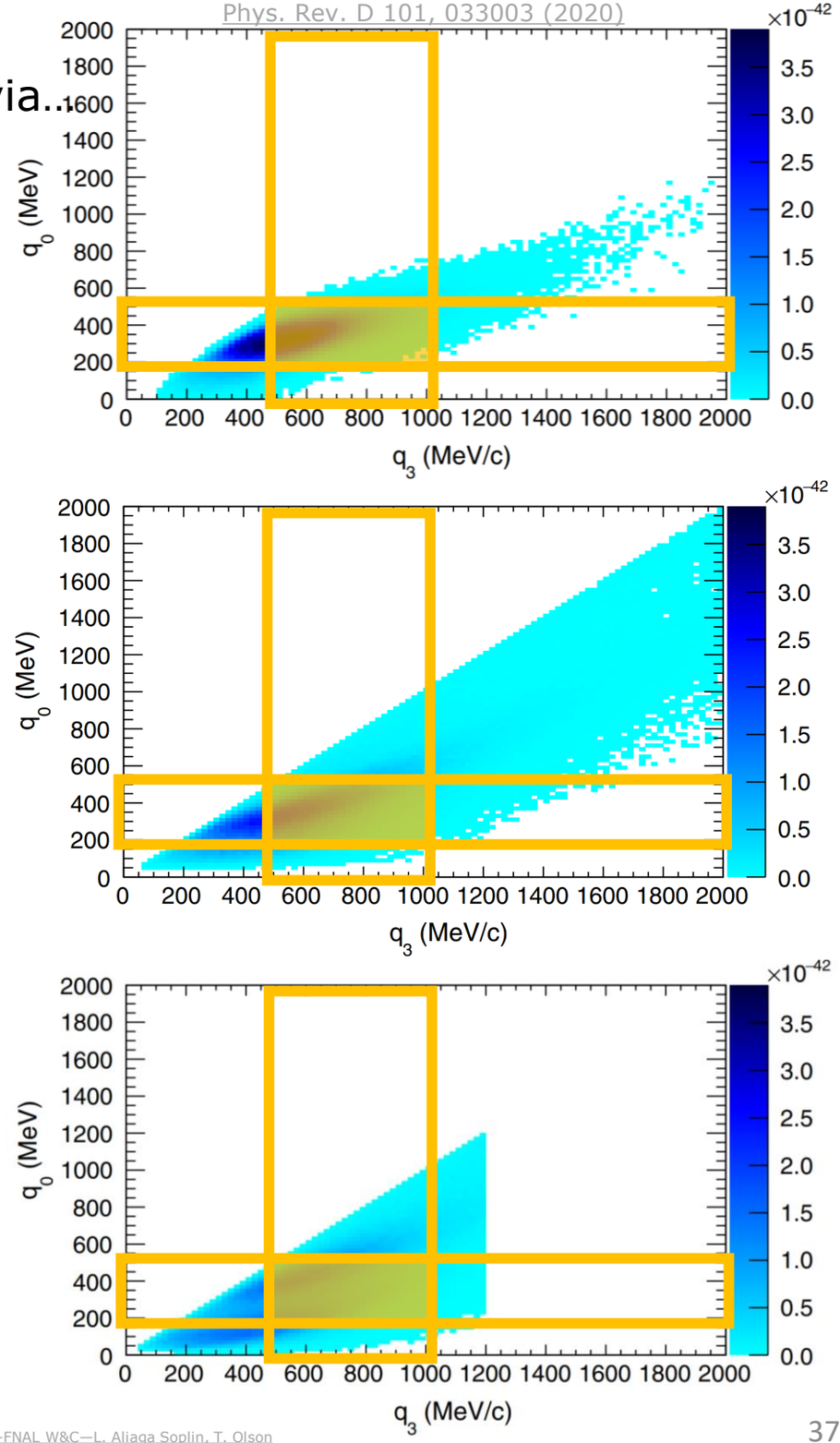




2

- No single track required, no hadron KE maxima
- Estimate relevant variables for this parameter space via..
  - $q_0 = \omega \sim E_{\text{had}} \sim E_{\text{avail}}$
  - $q_3 \sim |\vec{q}| = \sqrt{Q^2 - \left(E_\nu - E_\mu\right)^2}$ from reconstructed $\{Q^2, E_\nu, E_\mu\}$
- Measure cross section in these native variables





2 Cross Section Measurement

$U_{ij,\alpha\beta}$: Unfolding Matrix
Maps bins of reco. variables $\alpha\beta$ to bins of true variables ij

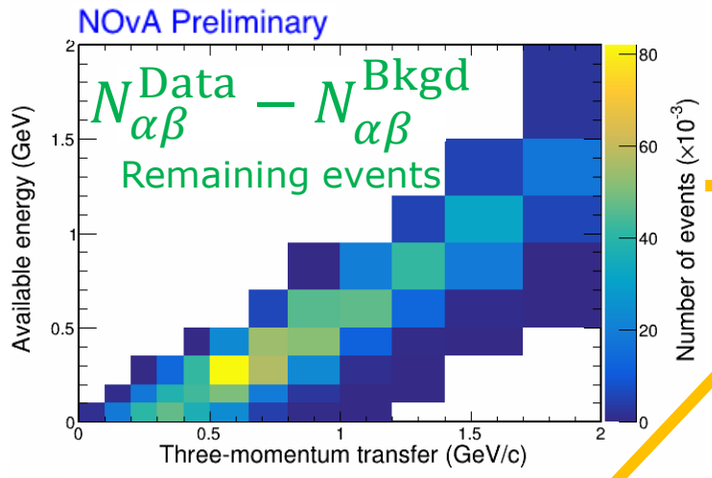
$N_{\alpha\beta}^{\text{Data}} - N_{\alpha\beta}^{\text{Bkgd}}$
Selected data minus estimated background in reco. bins $\alpha\beta$

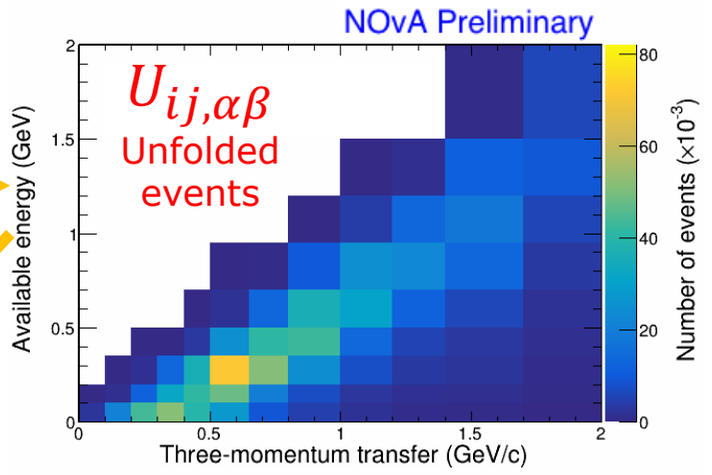
Inclusive ν_μ CC double differential cross section

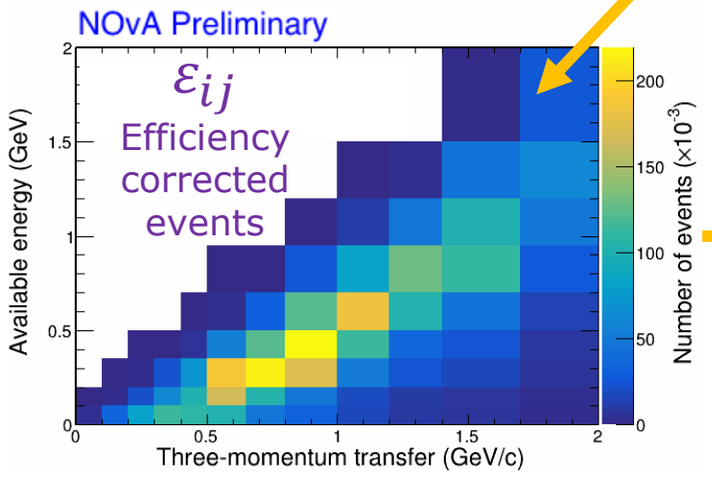
$$\left(\frac{d\sigma^2}{d|\vec{q}|dE_{\text{avail}}}\right)_{ij} = \frac{1}{\Phi_\nu N_T}\sum_{\alpha,\beta}\frac{U_{ij,\alpha\beta}\left(N_{\alpha\beta}^{\text{Data}} - N_{\alpha\beta}^{\text{Bkgd}}\right)}{\varepsilon_{ij}(\Delta|\vec{q}|)_i(\Delta E_{\text{avail}})_j}$$

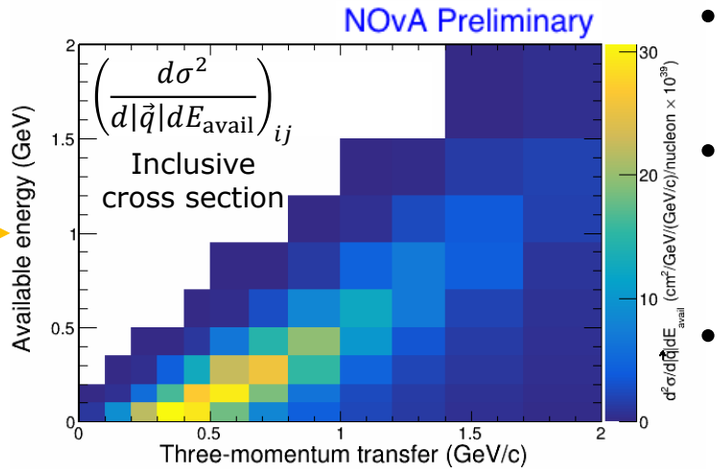
Signal selection efficiency

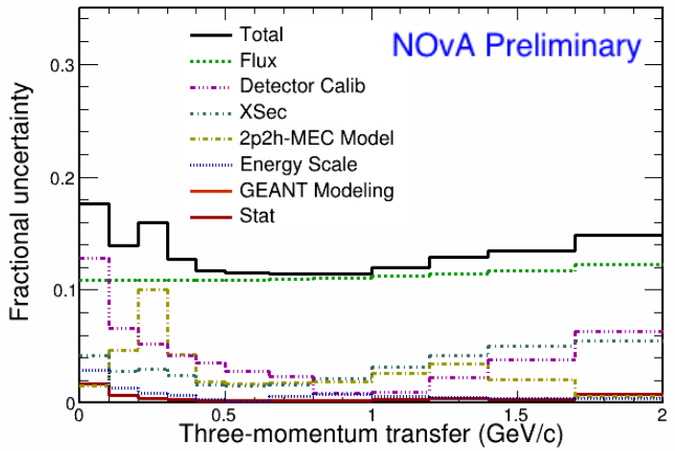
$(\Delta|\vec{q}|)_i$, $(\Delta E_{\text{avail}})_j$
Bin widths for the ith bin of $|\vec{q}|$ and the jth bin of E_{avail}







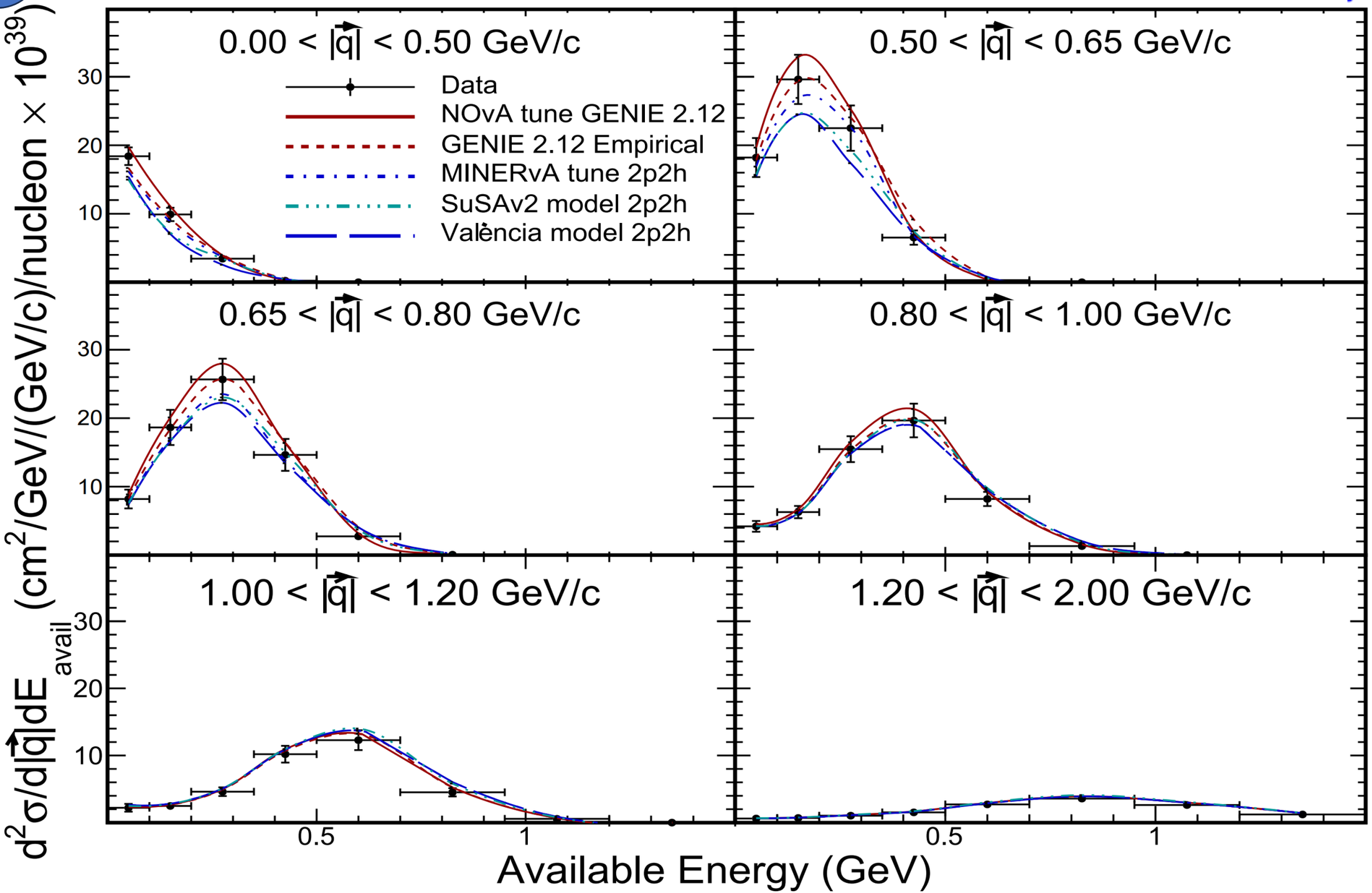




- Backgr. subtr. signal selection
  - No purity correction necessary
- Unfolded data events are then efficiency corrected
  - Including migration effects
- Weighted avg. fract. uncs:
  - 11% flux, 7.1% 2p2h, 5.6% cross section, 3.7% detector calibration…

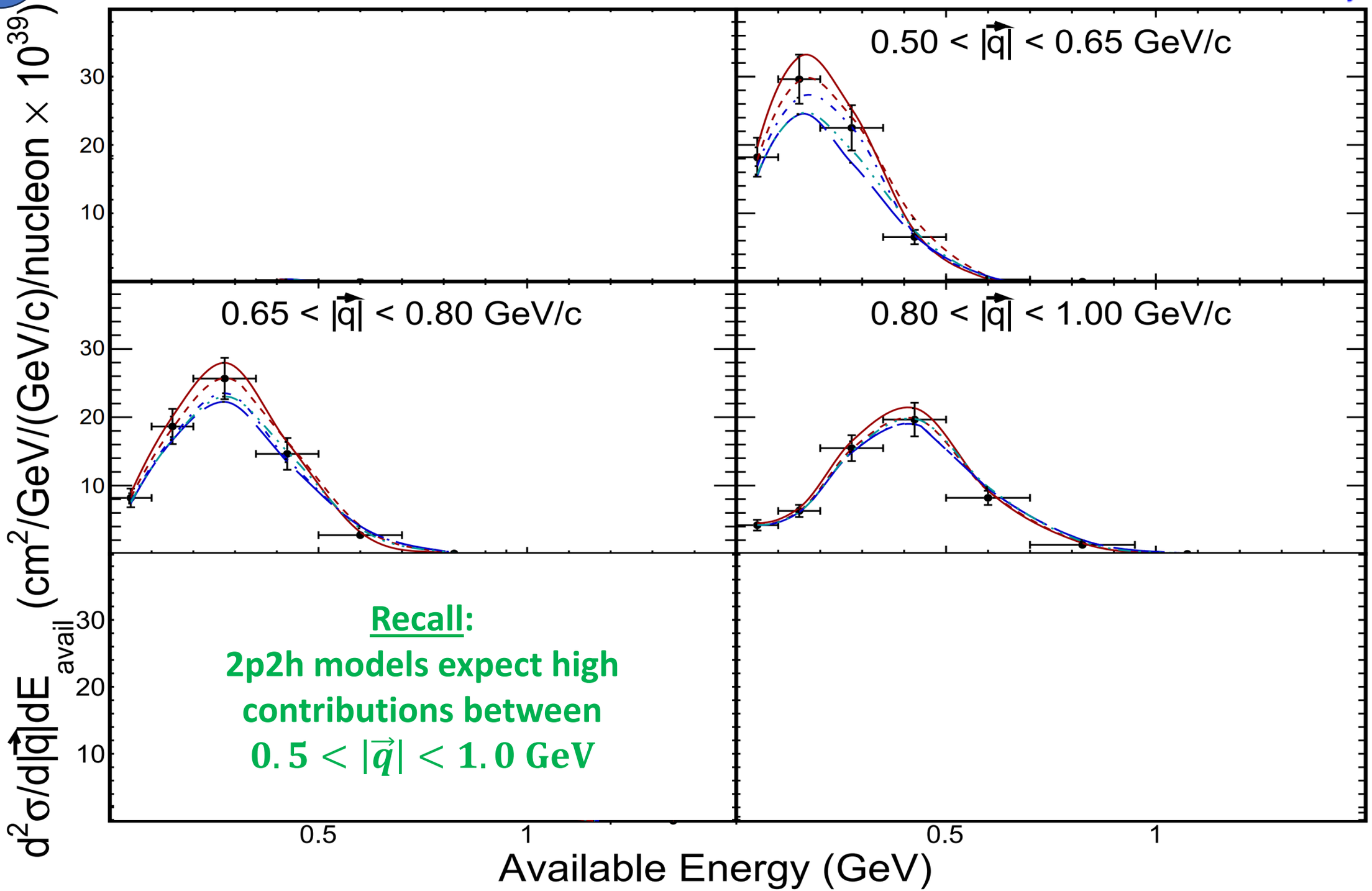
2

NOvA Preliminary



2

NOvA Preliminary



2

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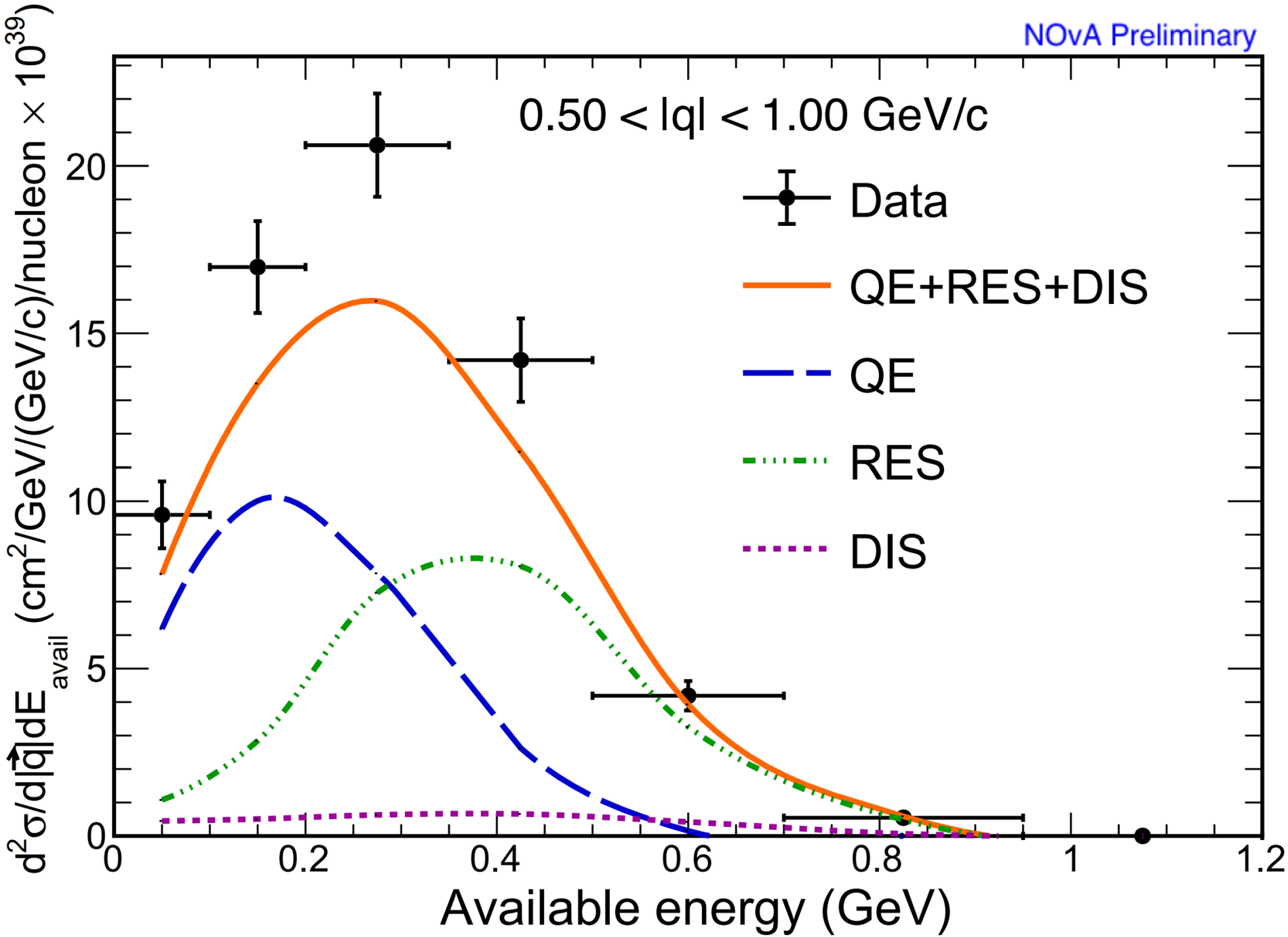

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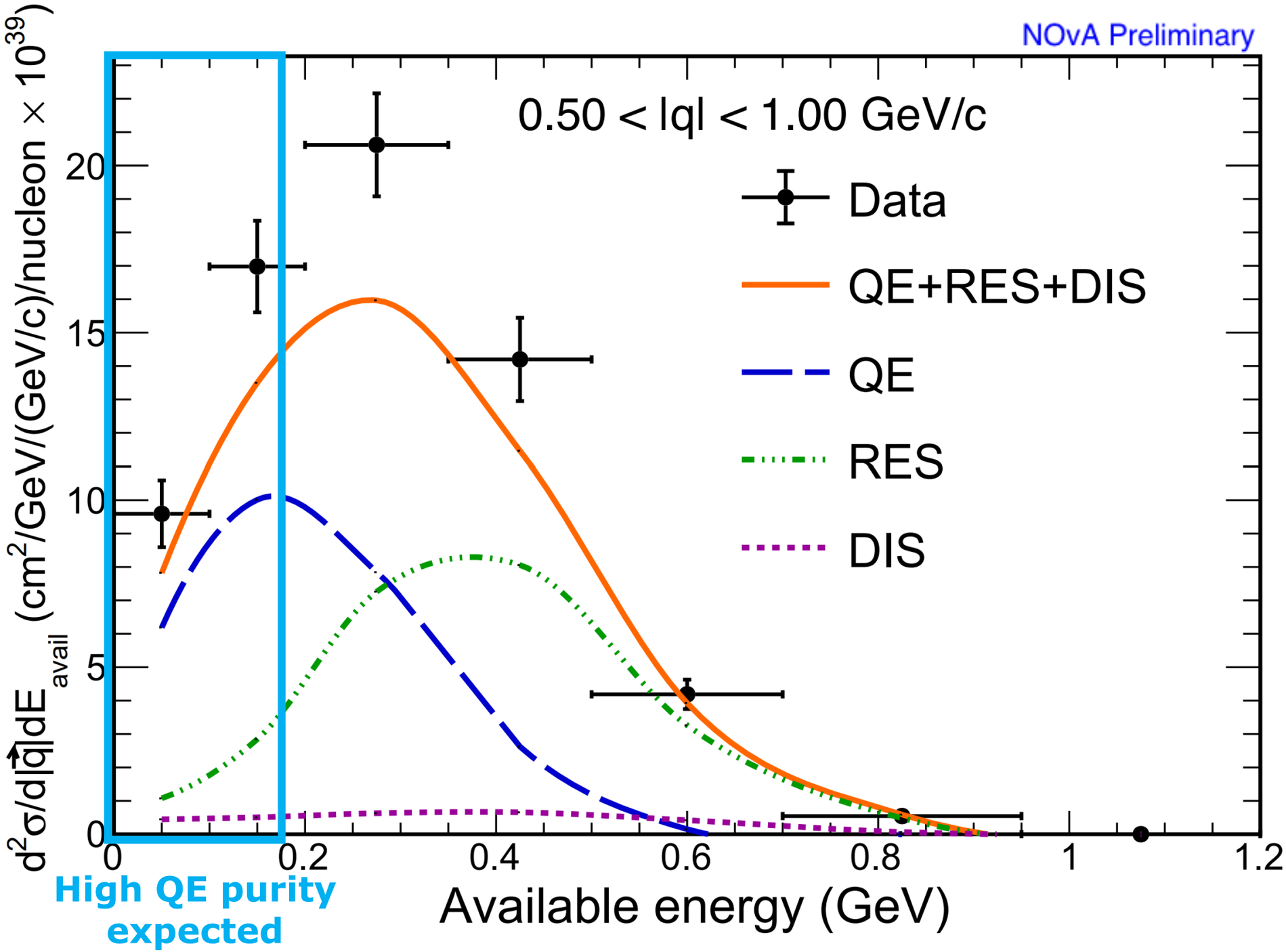
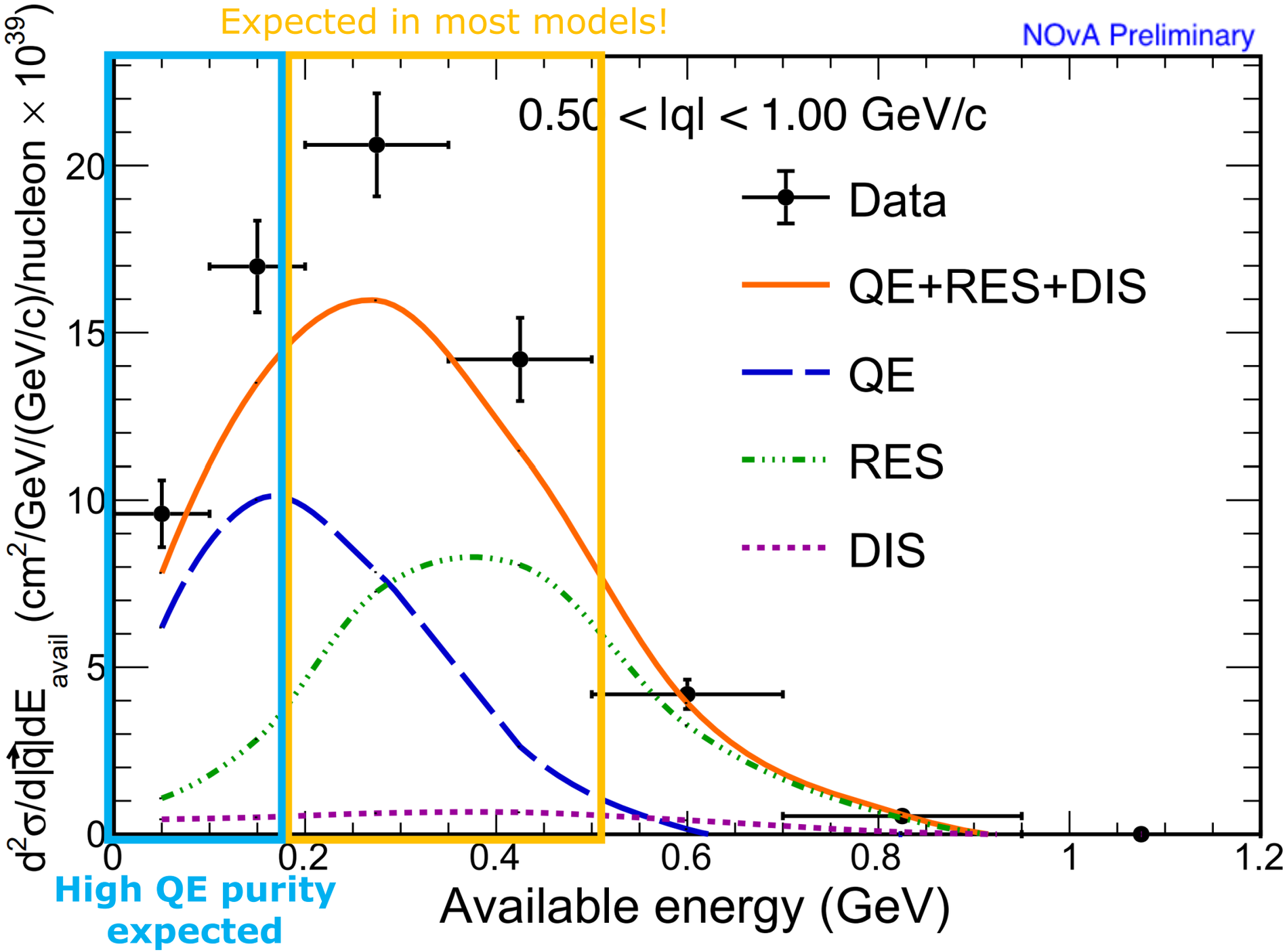


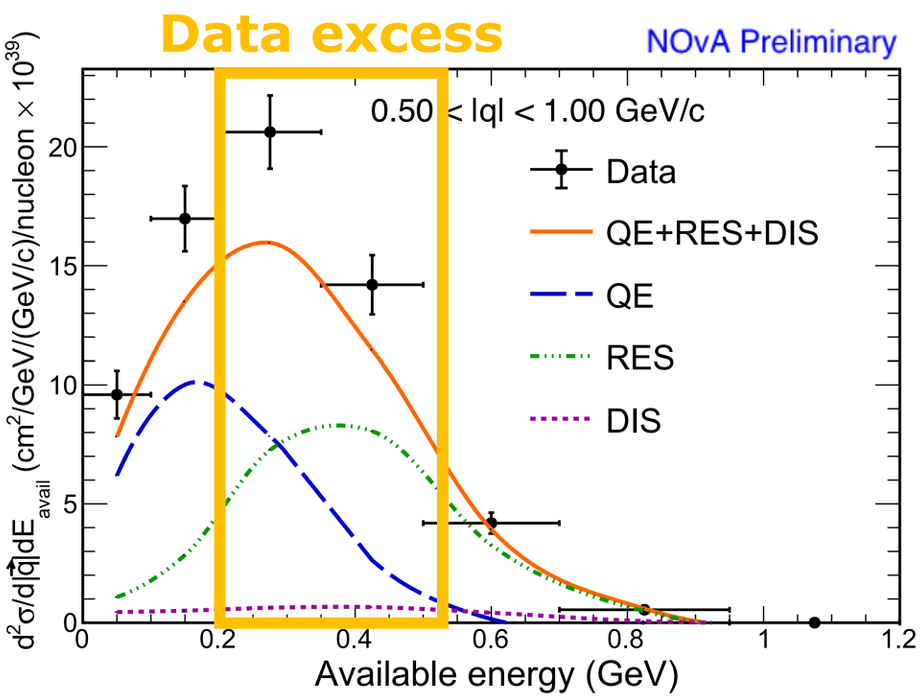
Data excess observed in CCQE-to-CCRES region

Expected in most models!



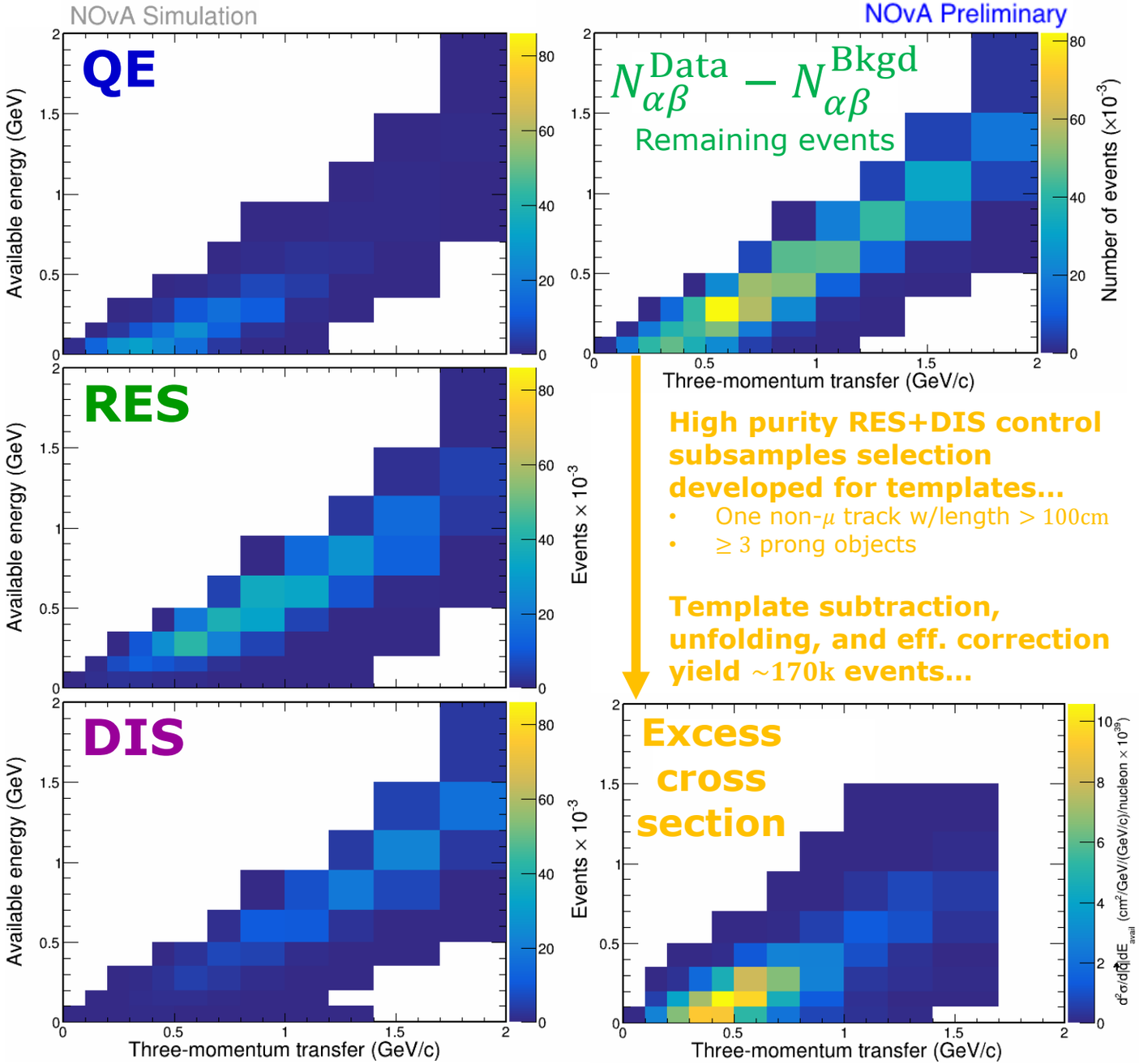
High QE purity expected

2 2p2h Cross Section *Estimation*



- Develop templates for subtraction
  - Utilize NOvA tune w/GENIEv2.12.2
  - QE+RES+DIS ≡ 1p1h totals
  - Excess taken as 2p2h *estimate*
    - 170,759 events remain

- MC predictions for RES+DIS in control subsample fit to data
  - Resulting normalization assigned to inclusive RES & DIS templates



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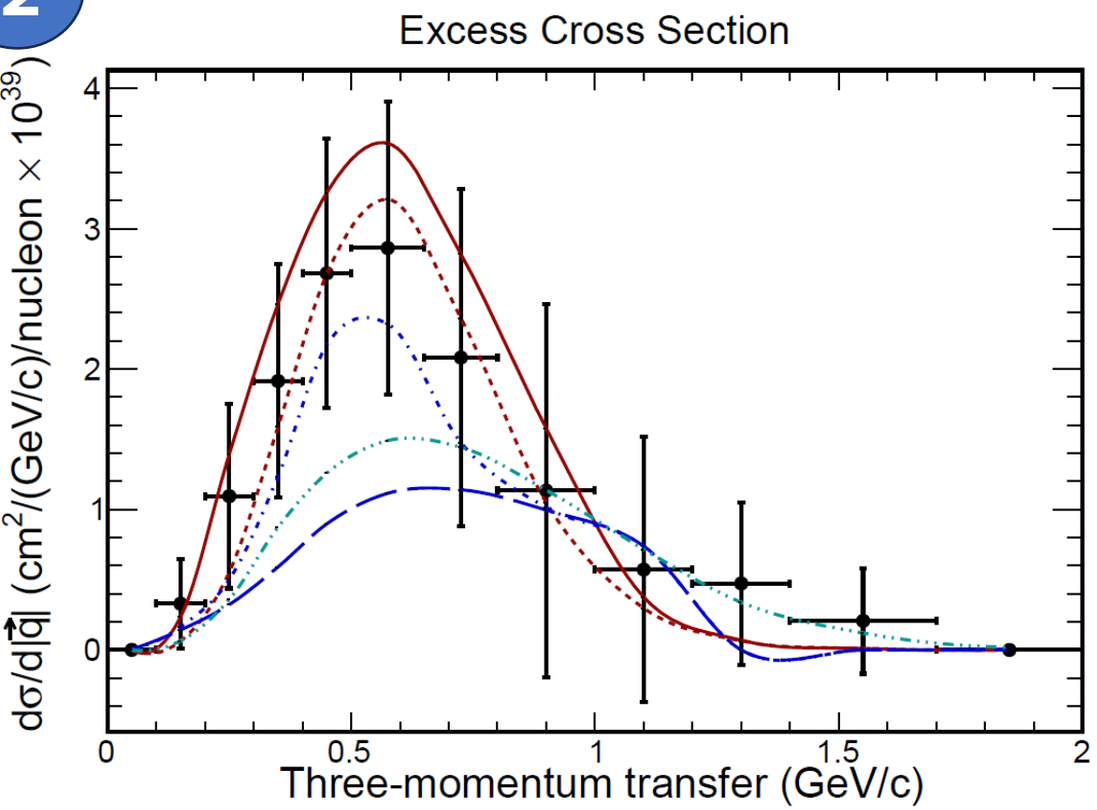
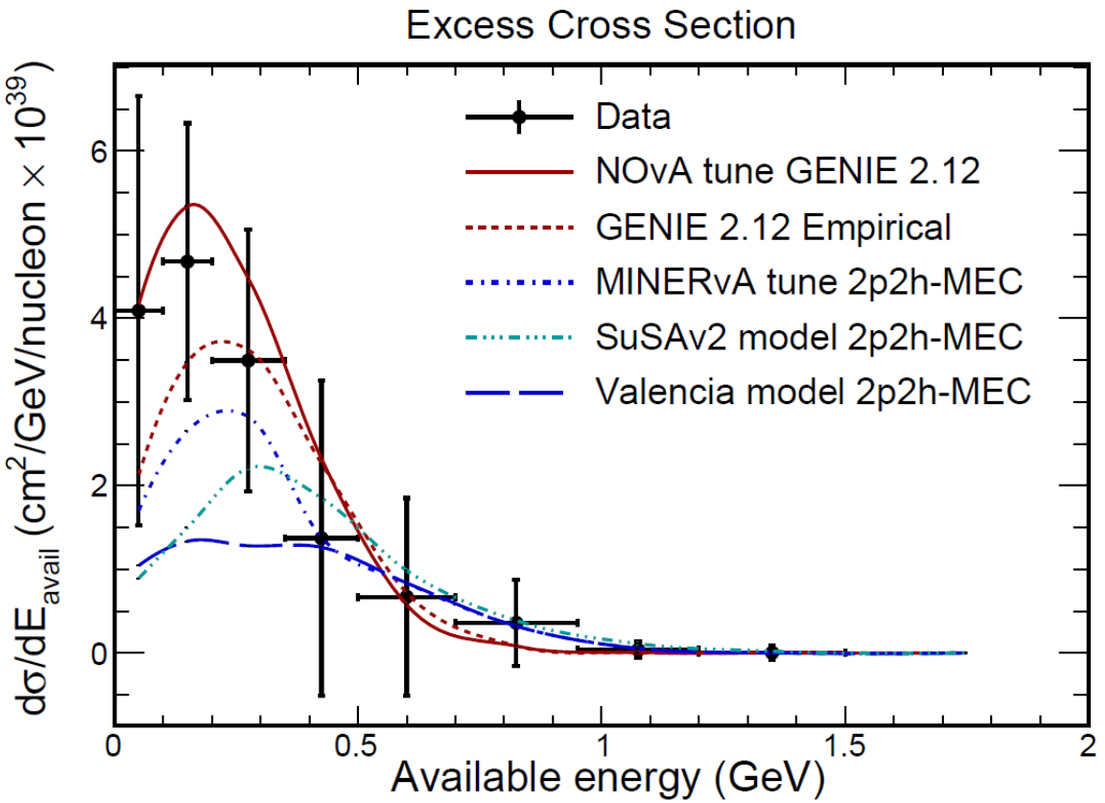
2p2h Cross Section *Estimation*



Single differential cross sections projected onto $|\vec{q}|$ and E_{avail}



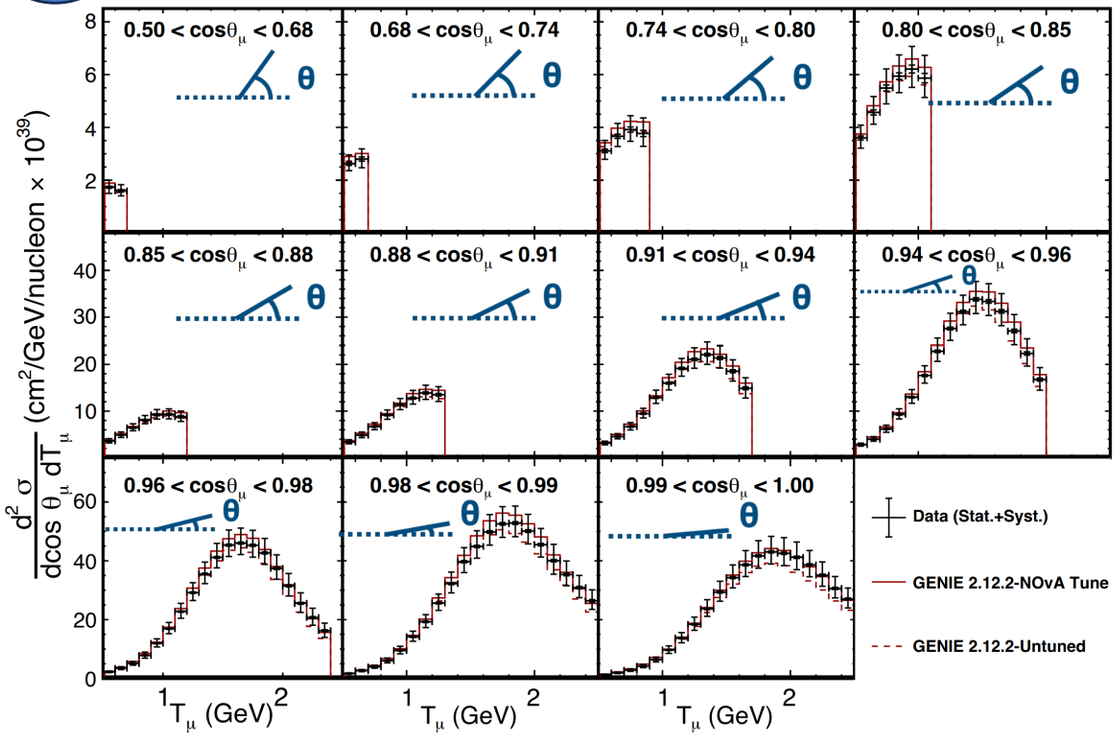
Tensions again observed wrt. to SuSAv2 & Valencia

Particularly true at low hadronic energy and medium momentum transfer

Speaks to needs for improved QE & 2p2h modeling

Summary & Conclusions

1



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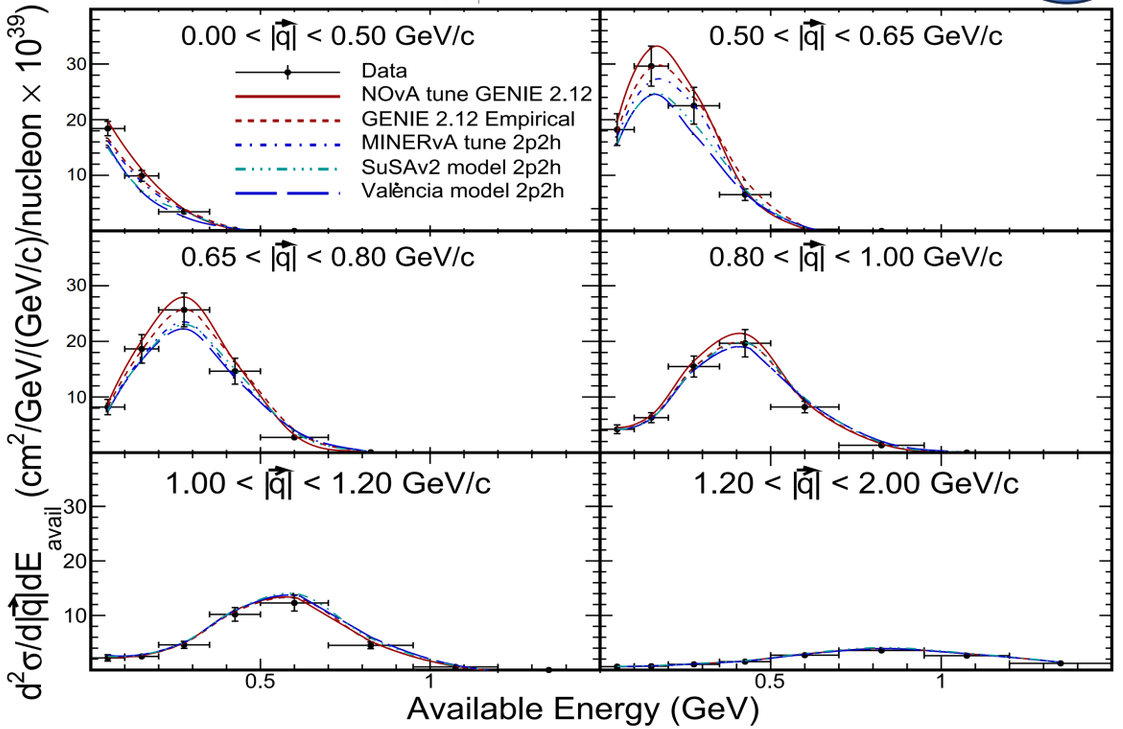


- NOvA offers excellent opportunities for high statistics cross section measurements to empower future experiments
- Inclusive ν_μ CC selections an excellent playground for semi-inclusive studies useful in understanding multinucleon scattering physics
  - More to come with improved reconstruction and statistics!
    - Novel ideas in current development!
- **These double differential measurements' publications being finalized!**

Thank-you for your attention!

Questions?

Backups

Adjusting neutrino interaction models and evaluating uncertainties using NOvA near detector data-EPJC (2020)

ZM/QE/2p2h-like
Neutrino Interaction Model

Released analyses: base model is **Genie 2.12.2**

ISA	QE	MEC	Res	DIS	FSI
RFG	L-S	Empirical	R-S	B-Y	hA

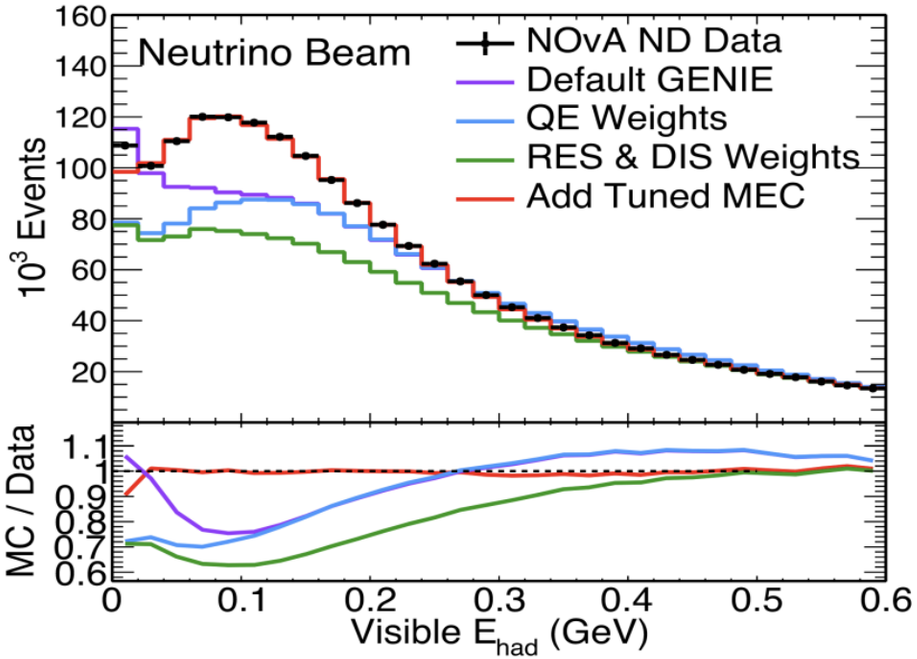
NOvA ND and **external data** are used to tune the model

- Correct QE to account for low Q^2 suppression
- Apply low Q^2 suppression to Resonant baryon production
- DIS at W>1.7 GeV/c^2 is weighted up 10% based on NOvA ND data
- **Empirical MEC based on NOvA ND data for 2p2h**

Upcoming Analyses: base model is **Genie 3.0.6**

IS	QE	MEC	Res	DIS	FSI
LFG	Valencia, Z exp	Valencia	B-S	B-Y + Pythia	hN

Plus improvements in the tuning application



All analyses are constructed to be insensitive to the tuning