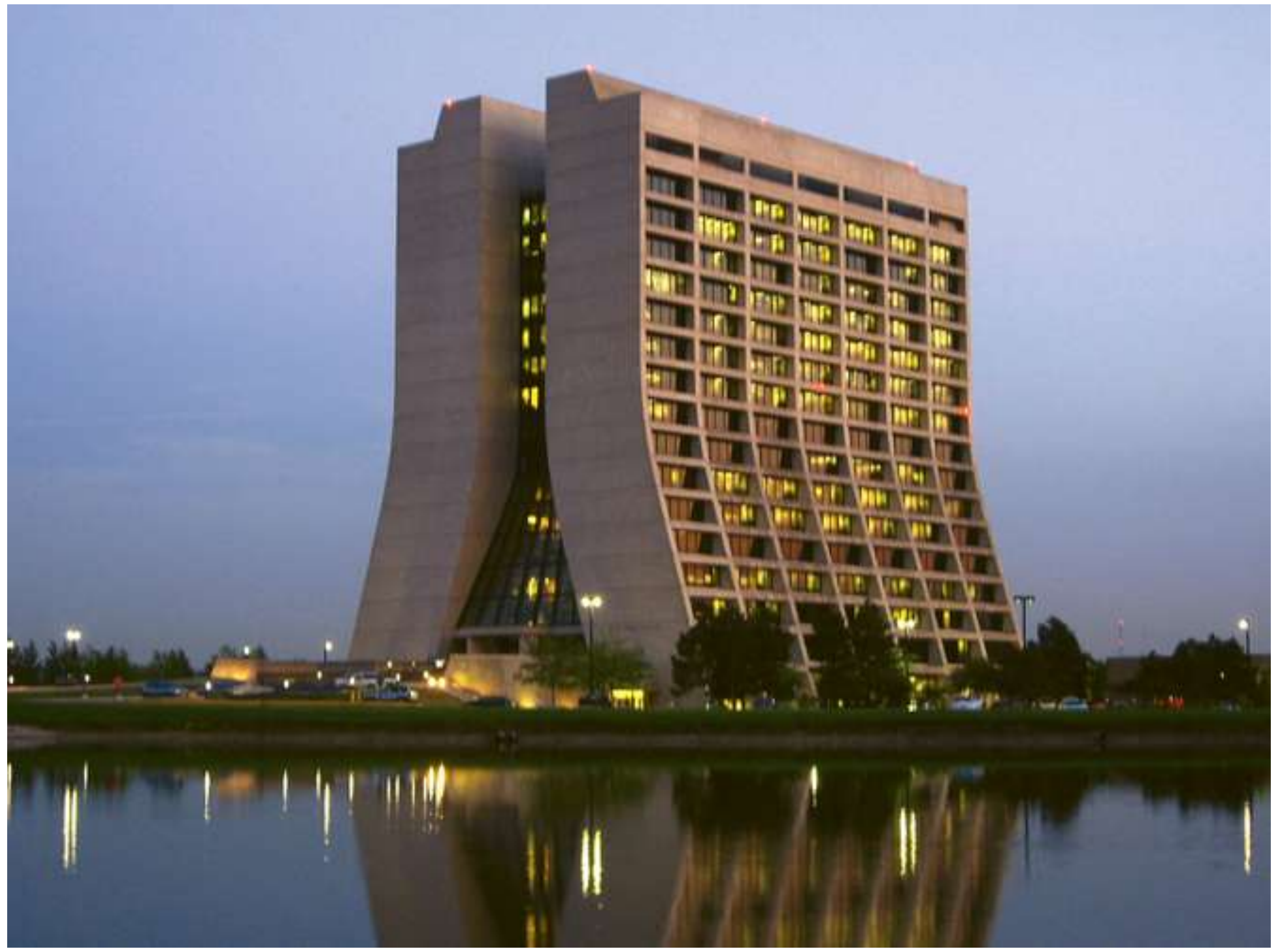
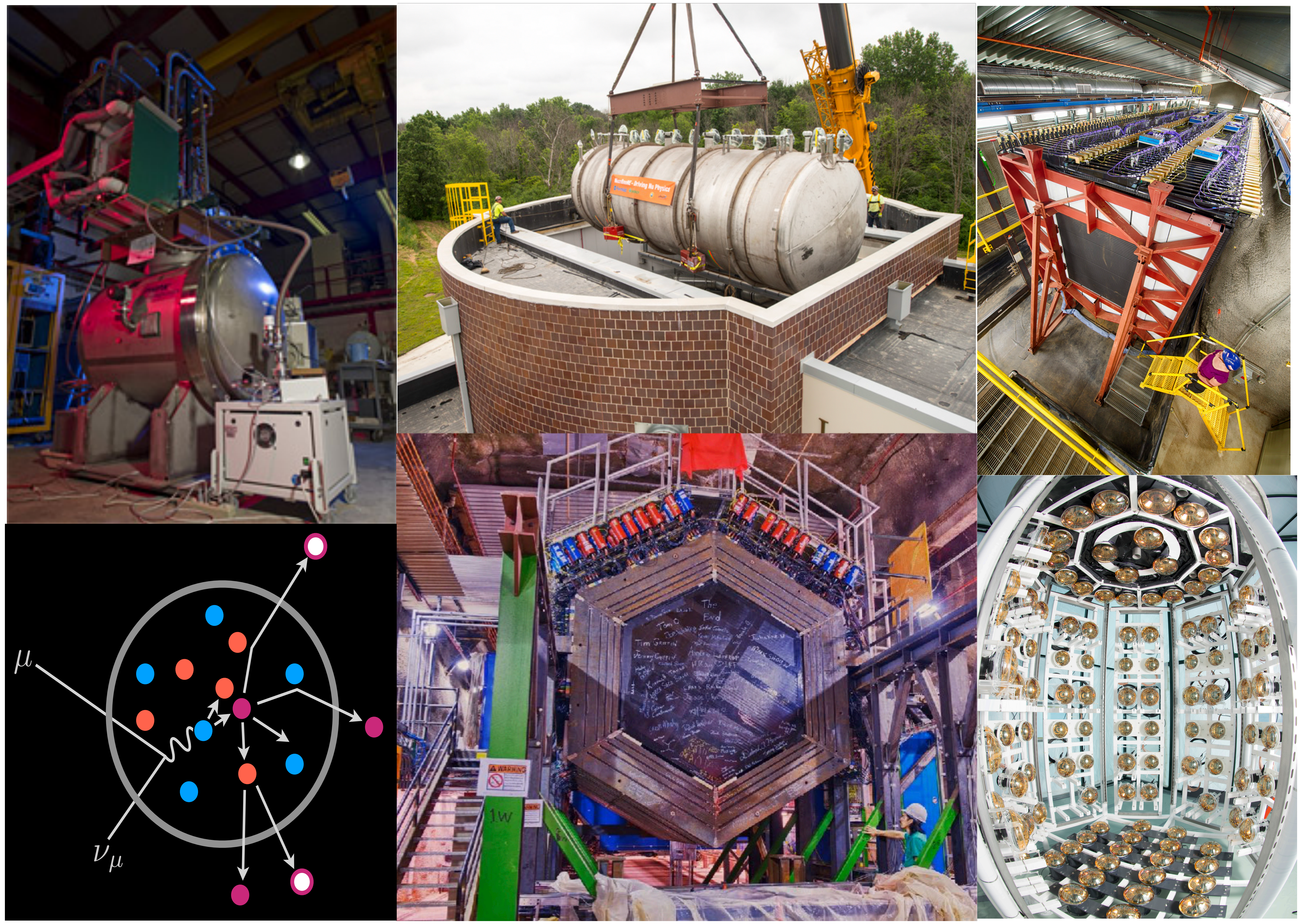
Neutrino cross-section measurements at Fermilab





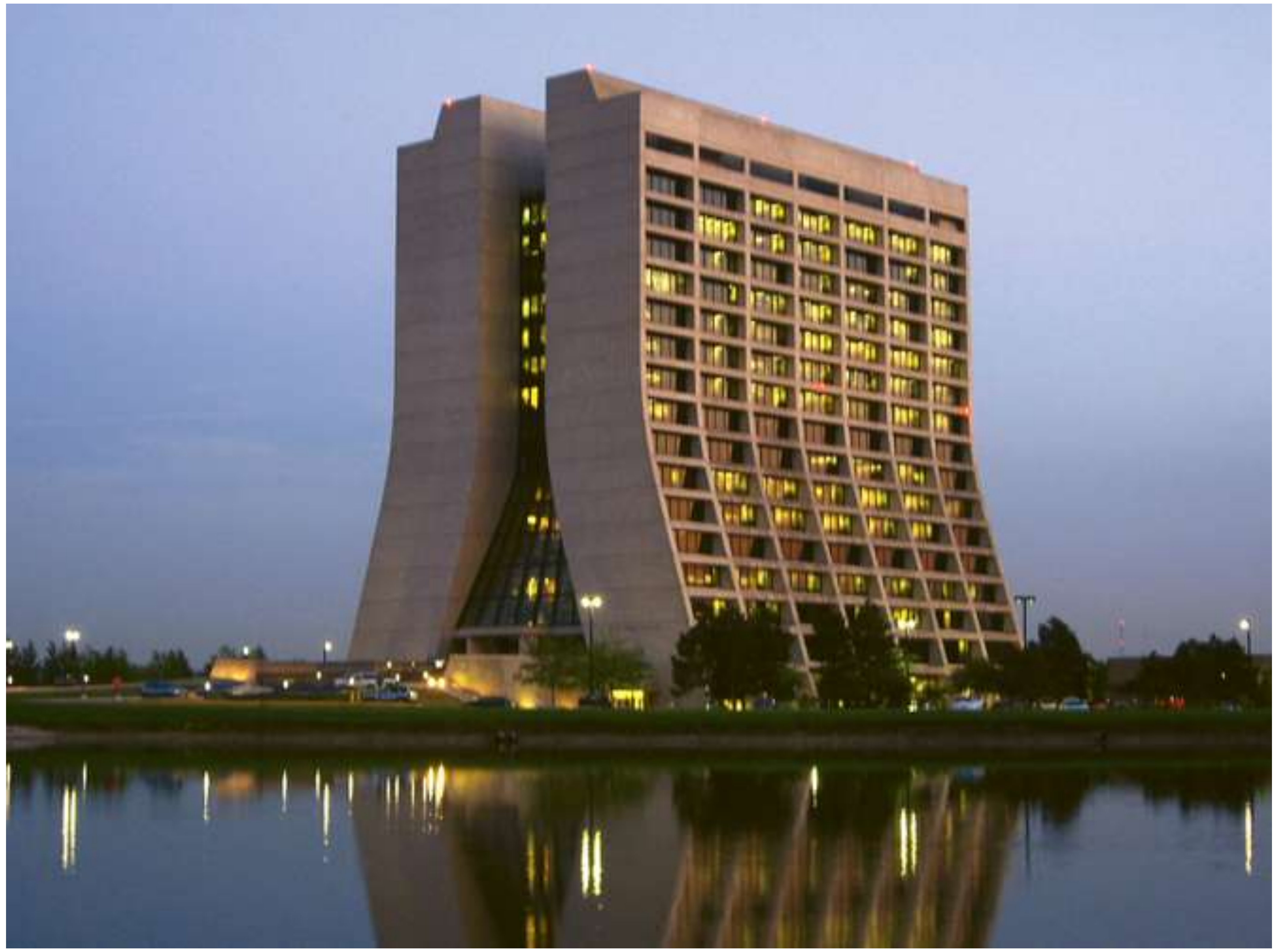
Steven Gardiner

53rd Annual Users Meeting
10–14 August 2020

Fermi National Accelerator Laboratory

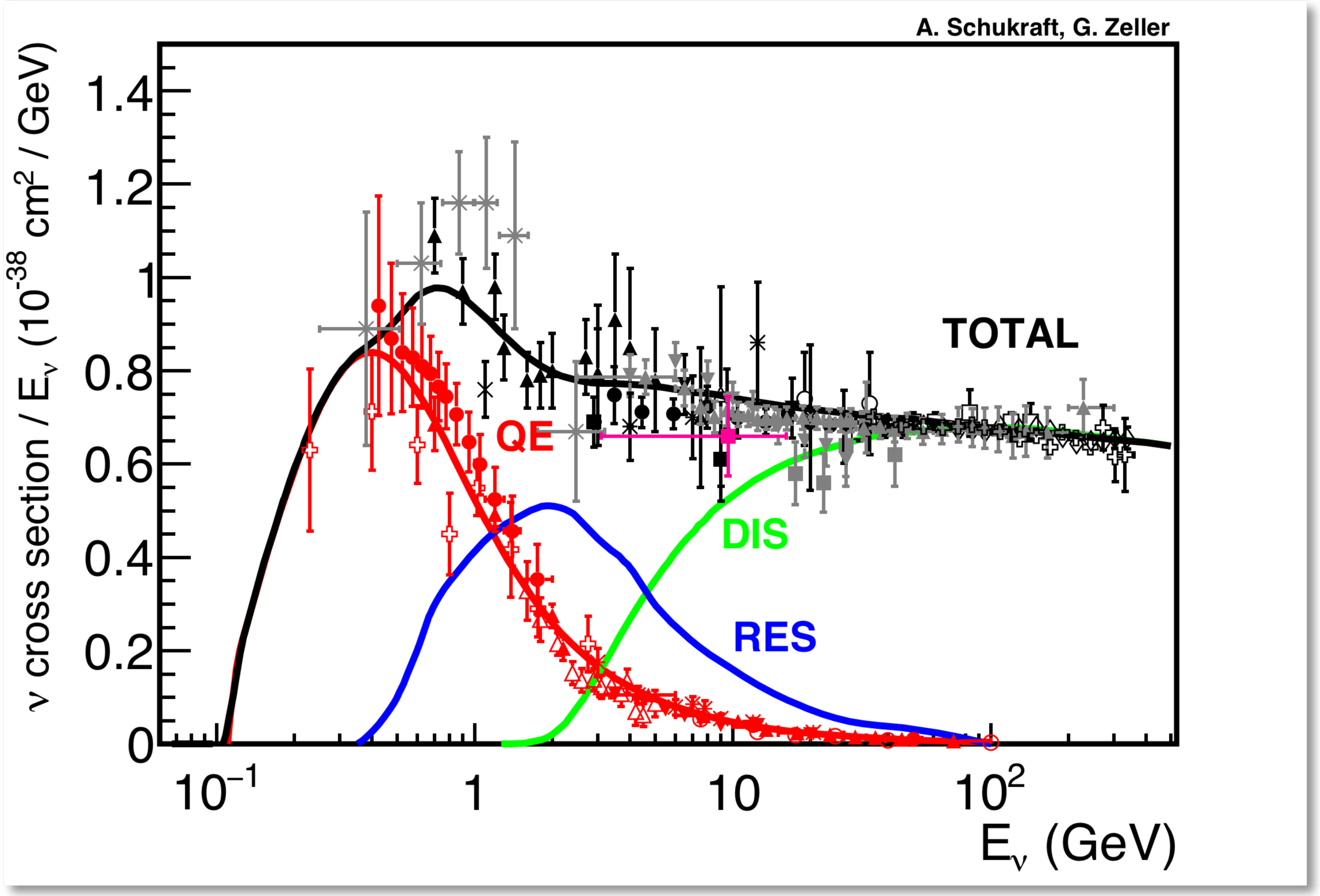
Outline

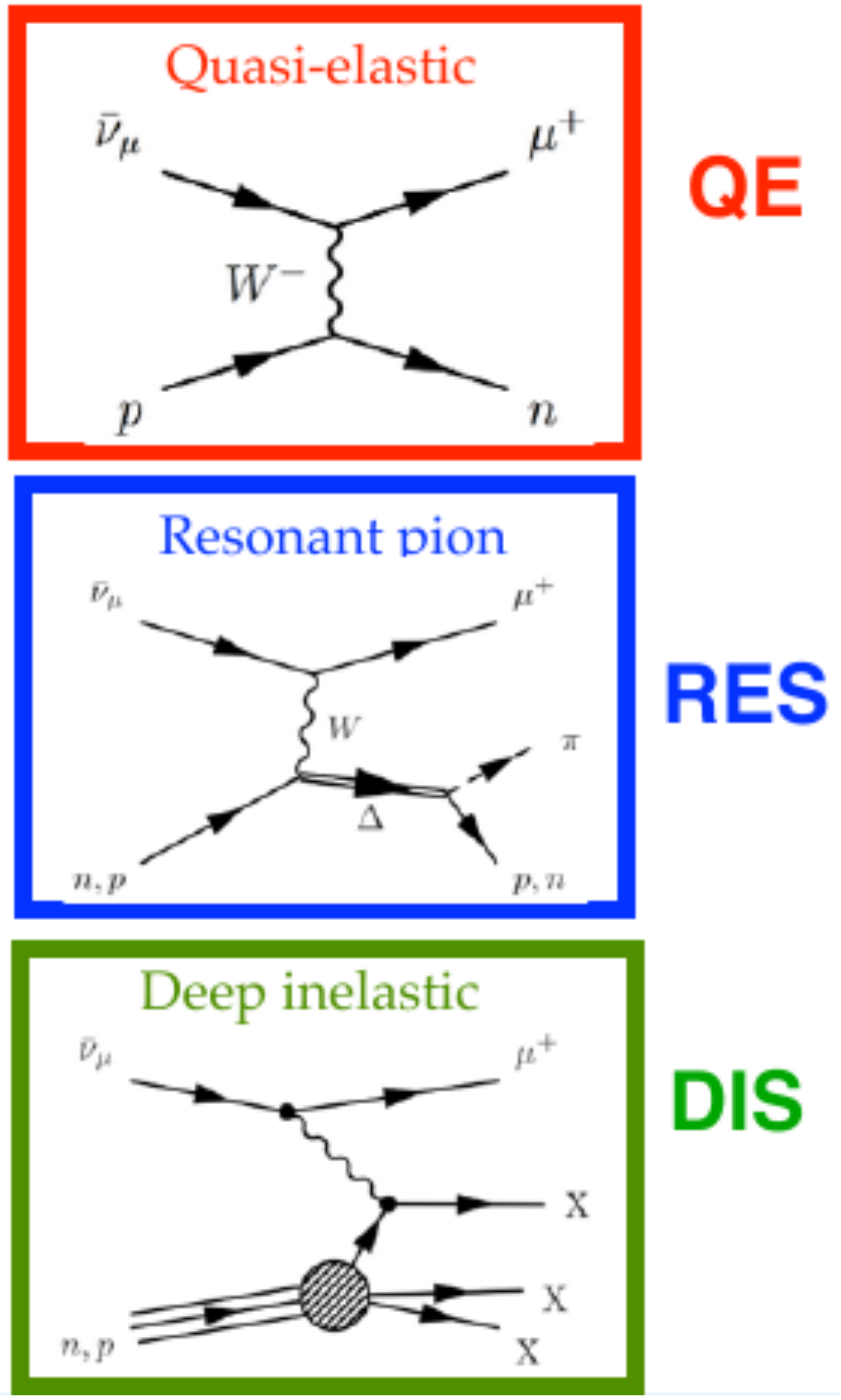
- Cross section needs for the neutrino oscillations program
- Recent highlights (incomplete!) from several experiments:
  - NOvA
  - MicroBooNE
  - MINERvA
  - ANNIE
  - ArgoNeuT
- Electrons for neutrinos ($e4\nu$)



Challenges in neutrino-nucleus cross section modeling

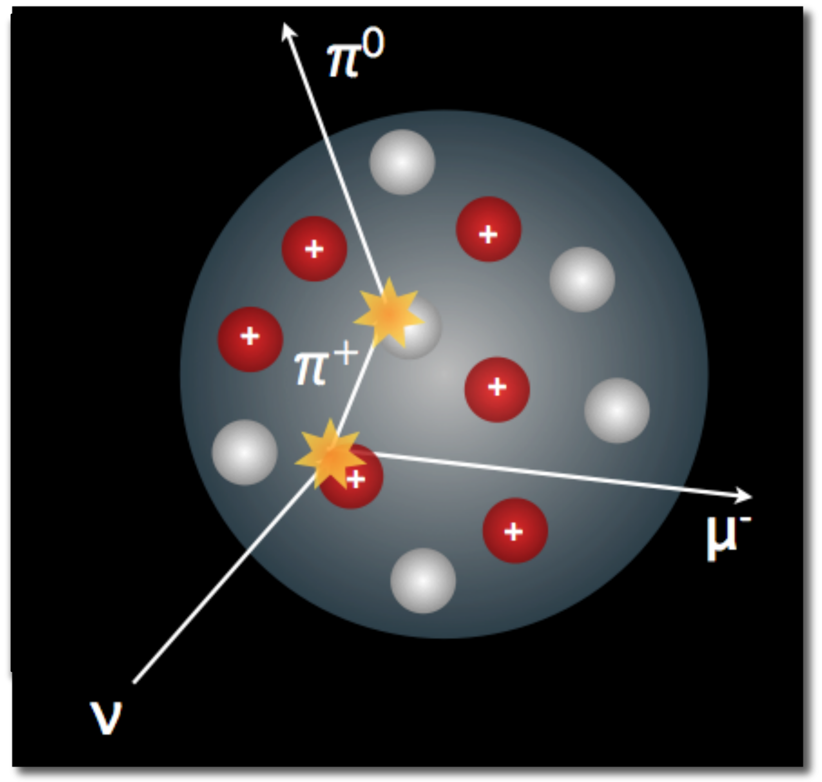
- Experiments need cross section models that predict
  - All final-state observables for
  - All important processes for
  - Many nuclear targets including inactive detector components and the surroundings ("dirt backgrounds")
  - Over a neutrino energy range spanning orders of magnitude
- Uncertainties must be well controlled for precision oscillation measurements
- Theory is **highly challenging**
- Cross section measurements **essential** to benchmark theory and help make it better



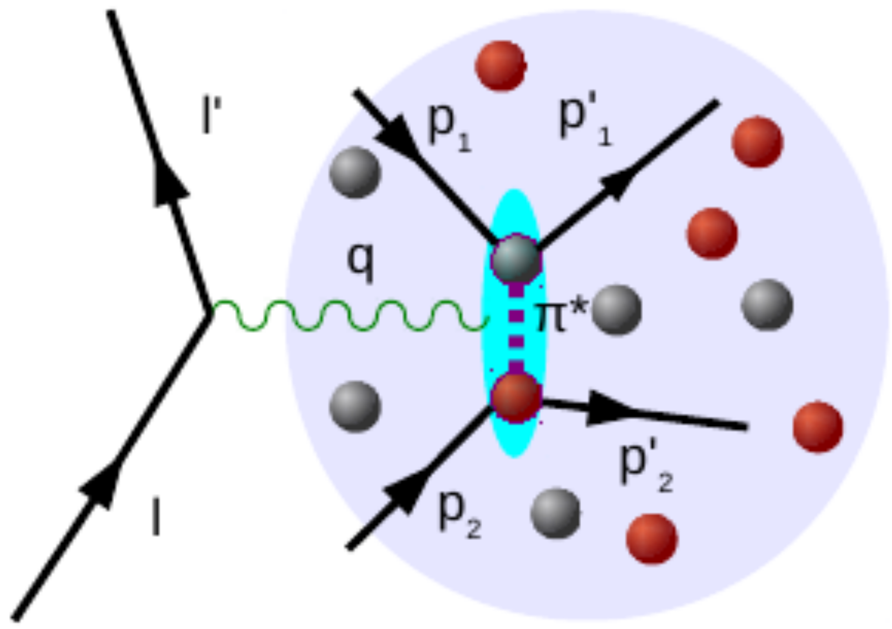


Nucleon-level processes

Final-state interactions (FSIs)



Two-particle two-hole (2p2h) interactions



Also referred to as MEC (for Meson Exchange Current)

Nuclear effects

Neutrino event generators

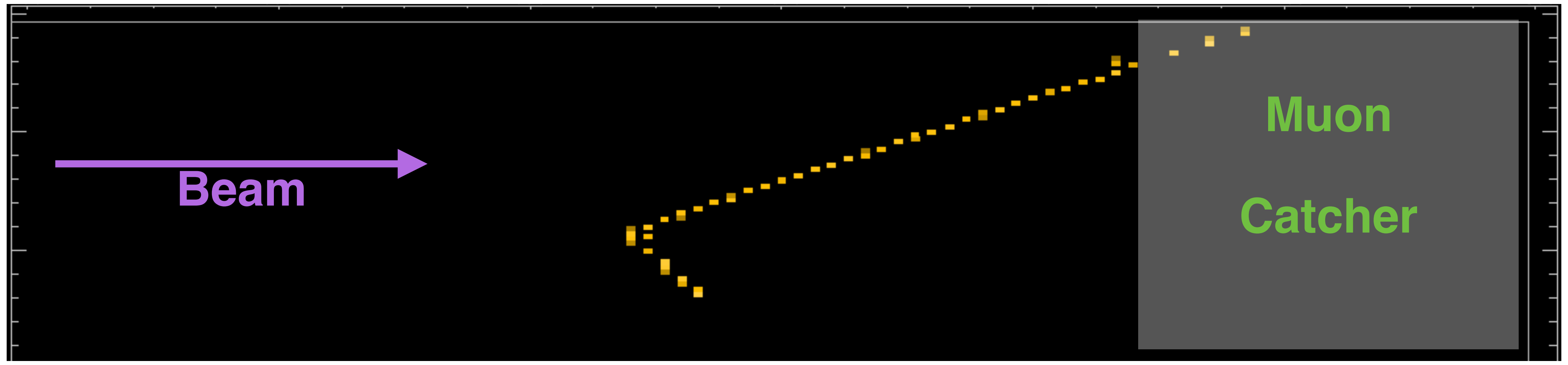
- Implement neutrino scattering theory for simulations by experiments
  - Full predictions for all relevant neutrino energies, reactions, and nuclei

- Several **modern generators** are widely used: GENIE, GiBUU, NEUT, NuWro

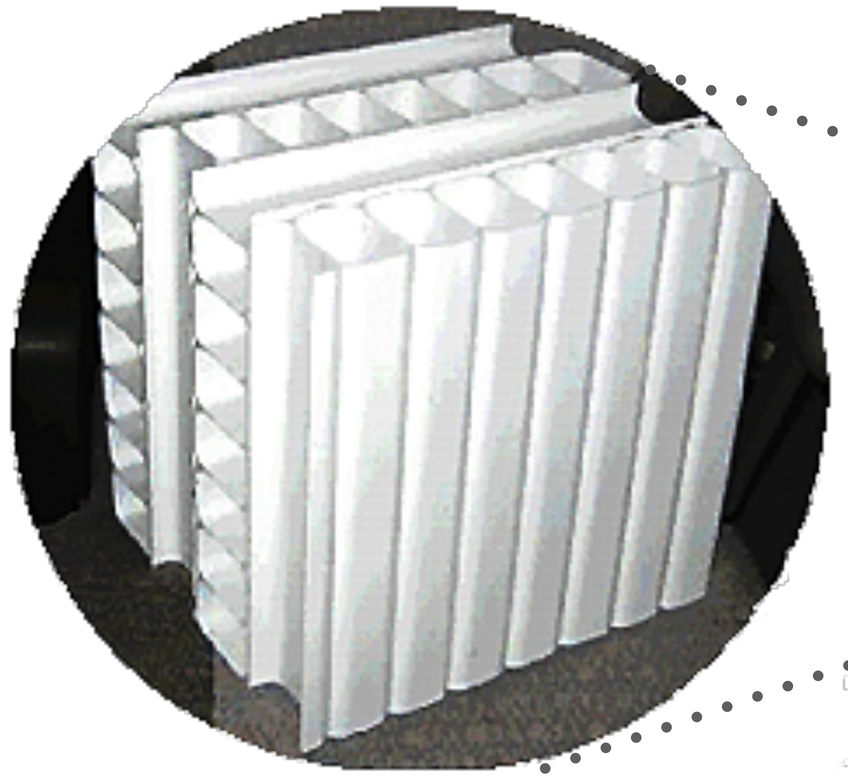
- **GENIE** especially popular at Fermilab
  - Employees and users actively contribute to its development
  - **Backup**: Preview of GENIE v3.2

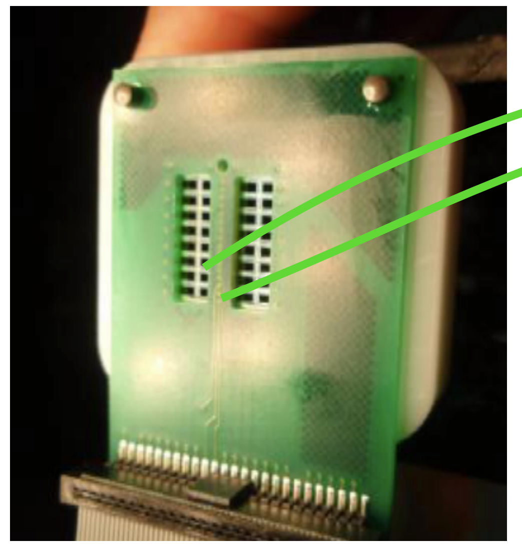
The NOvA experiment

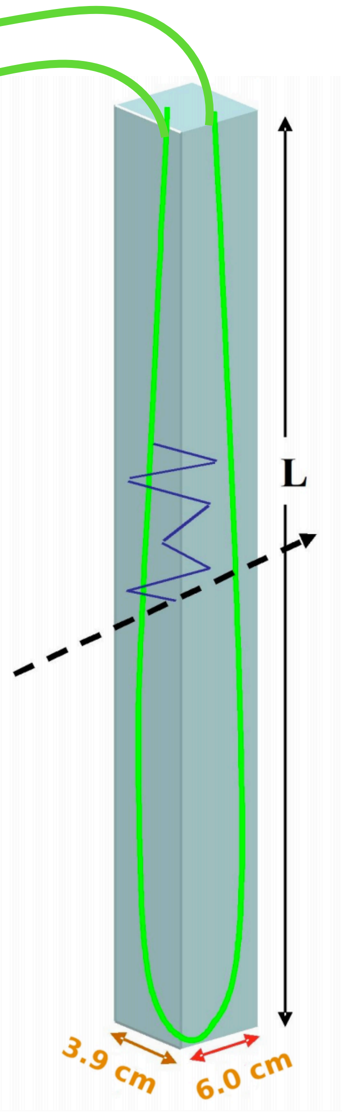
- Long-baseline neutrino oscillation experiment (see earlier talk by S. Calvez)
- **300-ton near detector**
  - Tracking calorimeter built using plastic cells filled with liquid scintillator
  - 1 km from NuMI target
  - Enables **high-statistics cross section measurements**
- **This talk:** CC inclusive analyses
- See also NC COH π^0 paper [Phys. Rev. D 102, 012004 (2020)]



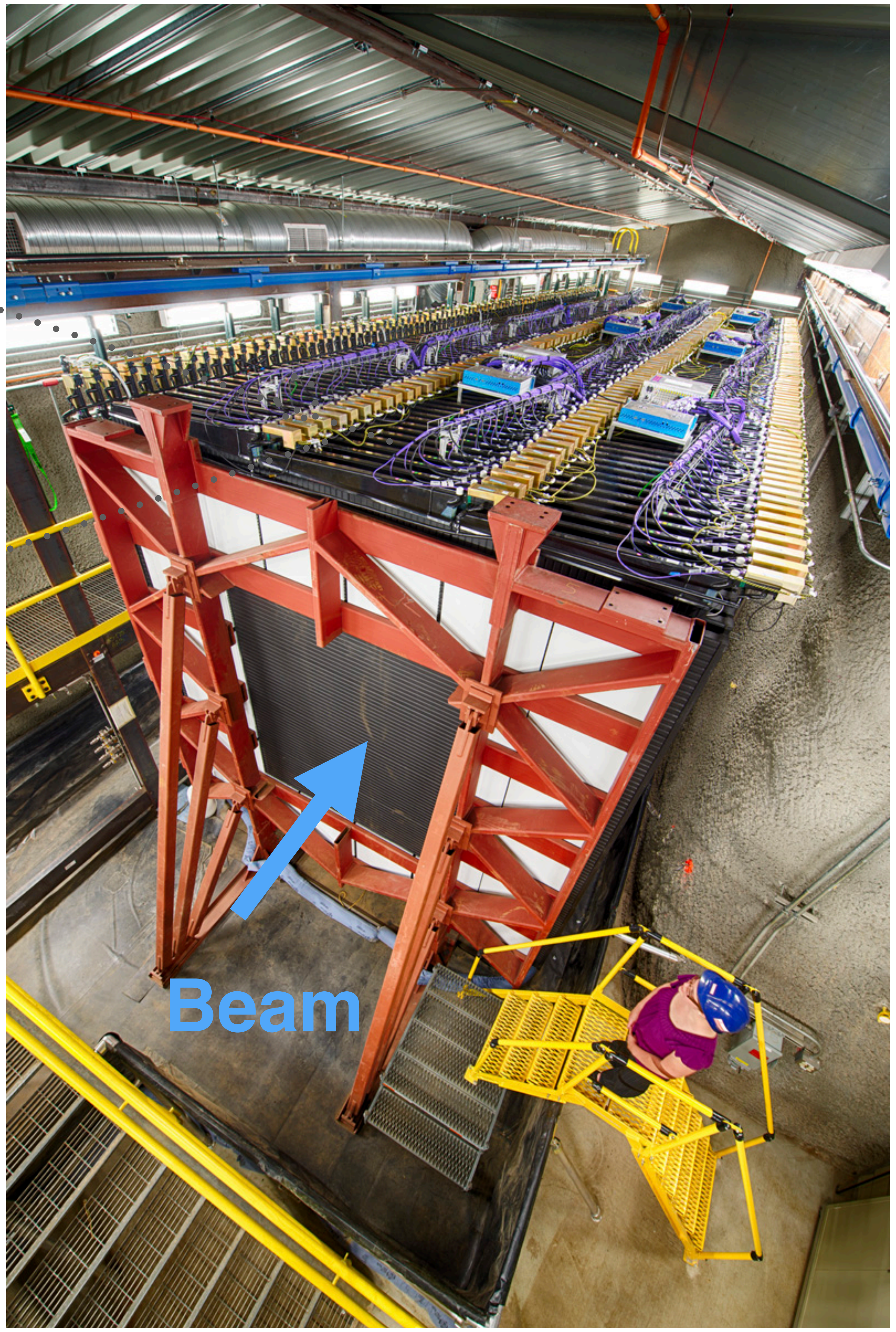
Alternating planes allow for 3D imaging





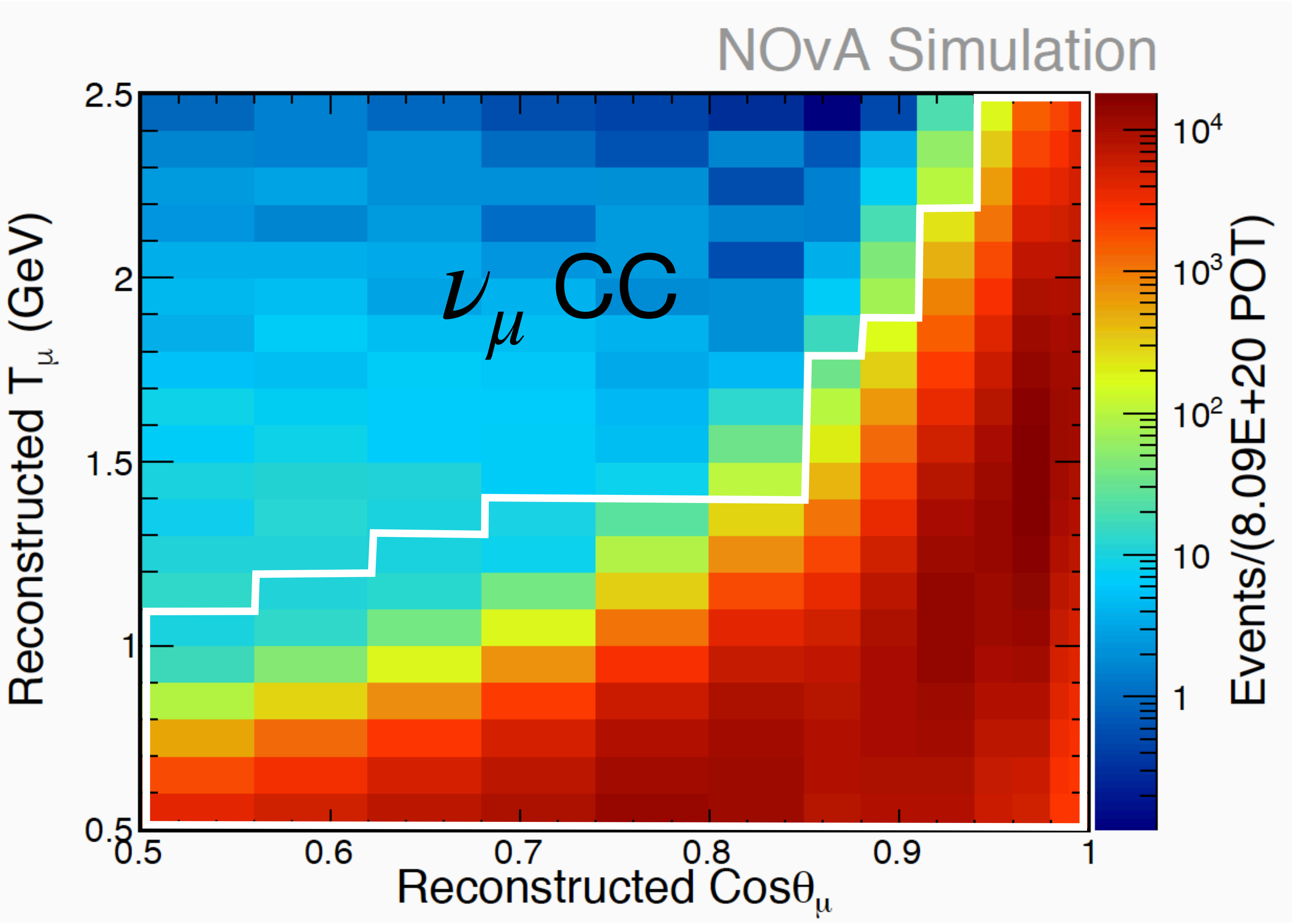


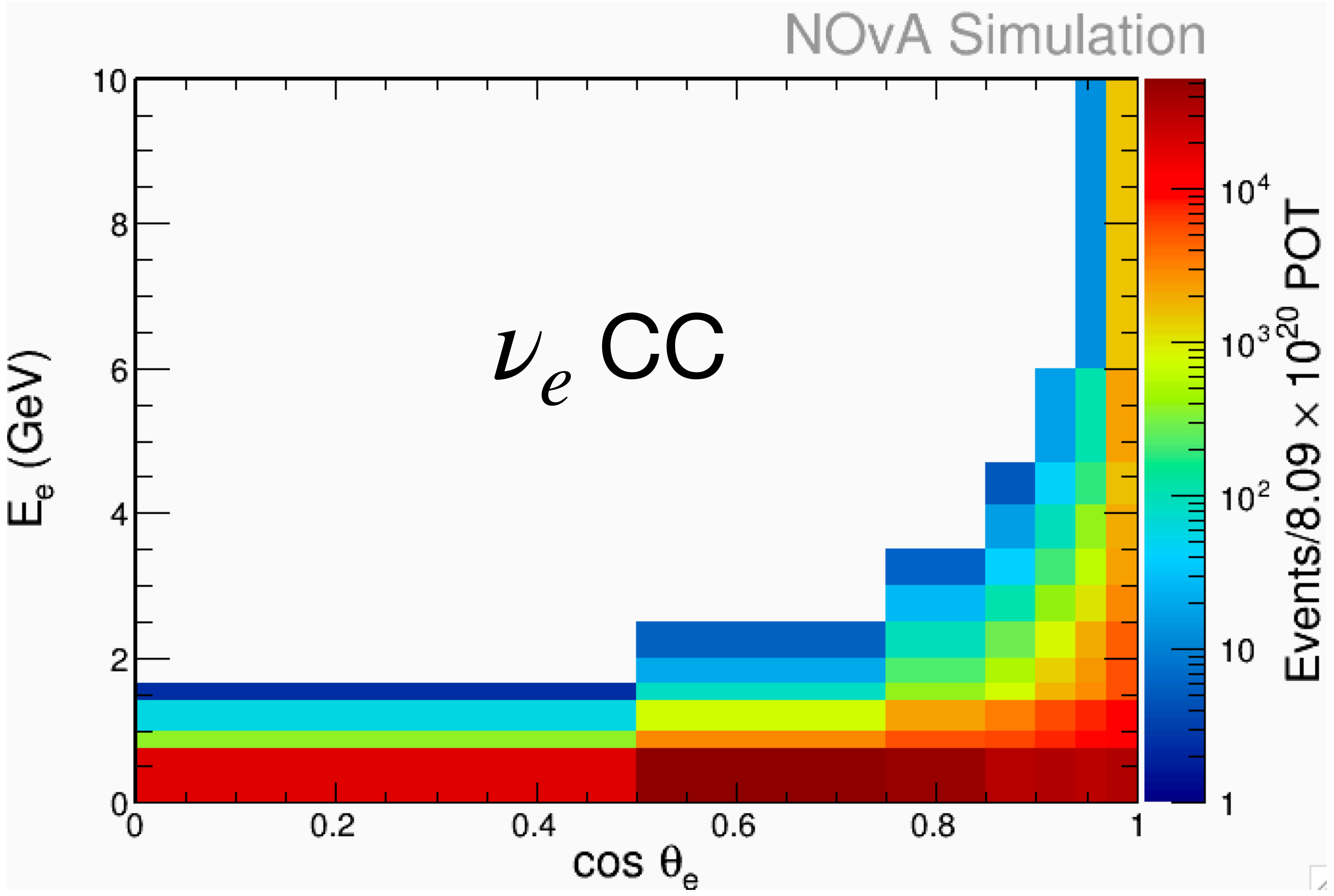
Wavelength shifting fibers read out by a single pixel on an avalanche photodiode



NOvA: CC inclusive measurements

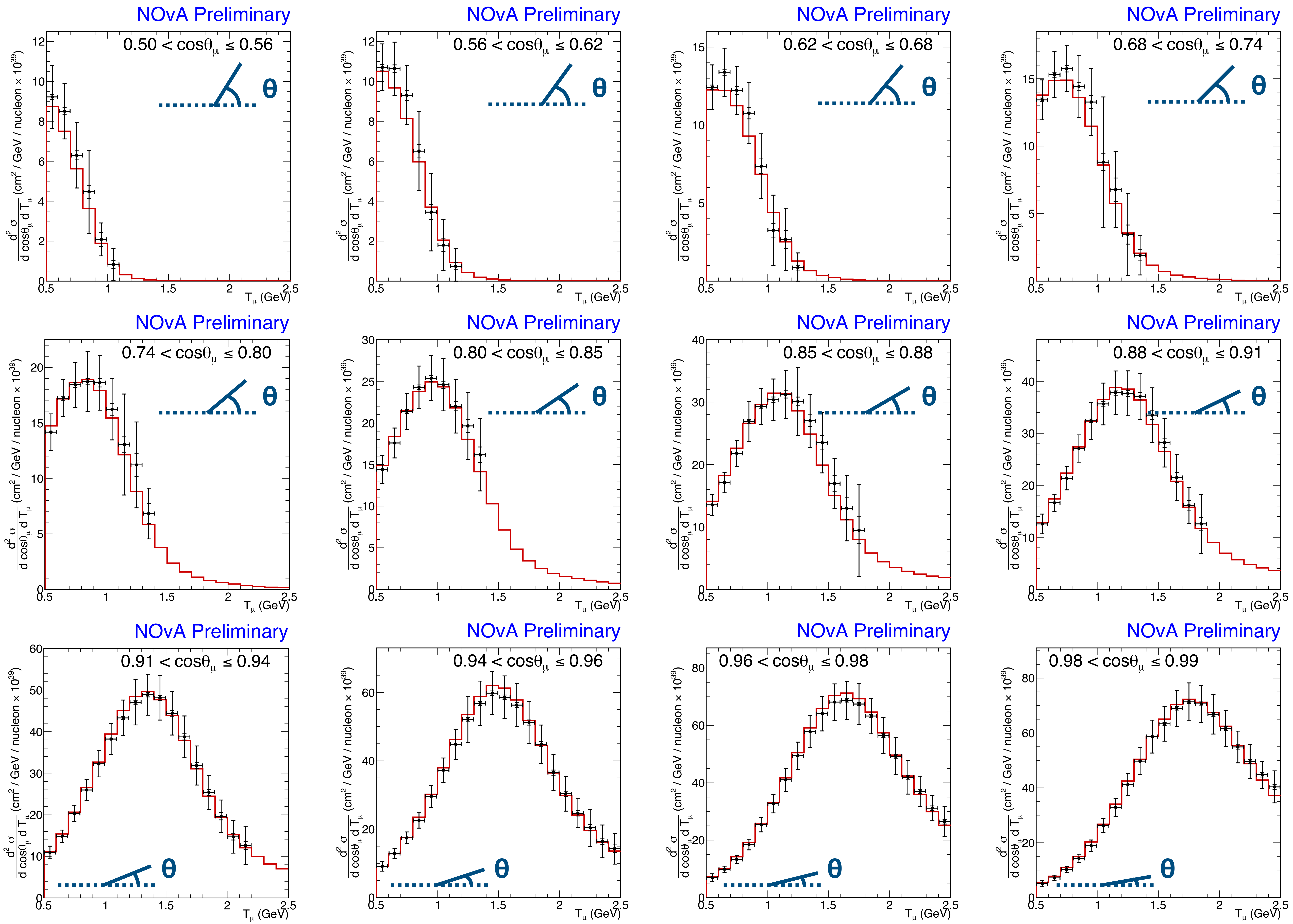
- Two double-differential CC **inclusive** results (lepton energy & angle)
  - $\nu_\ell + A \rightarrow \ell + X$
  - Particle ID via Boosted Decision Trees (BDTs)
- **ν_μ**: 172 bins, 1M+ selected events
  - HPC @ NERSC for systematics
  - **J. Paley, JETP seminar, 31 July 2020**
- **ν_e**: 17 bins, ~10K selected events
  - First ever 2D result for ν_e
  - **M. Judah, JETP seminar, 7 August 2020**

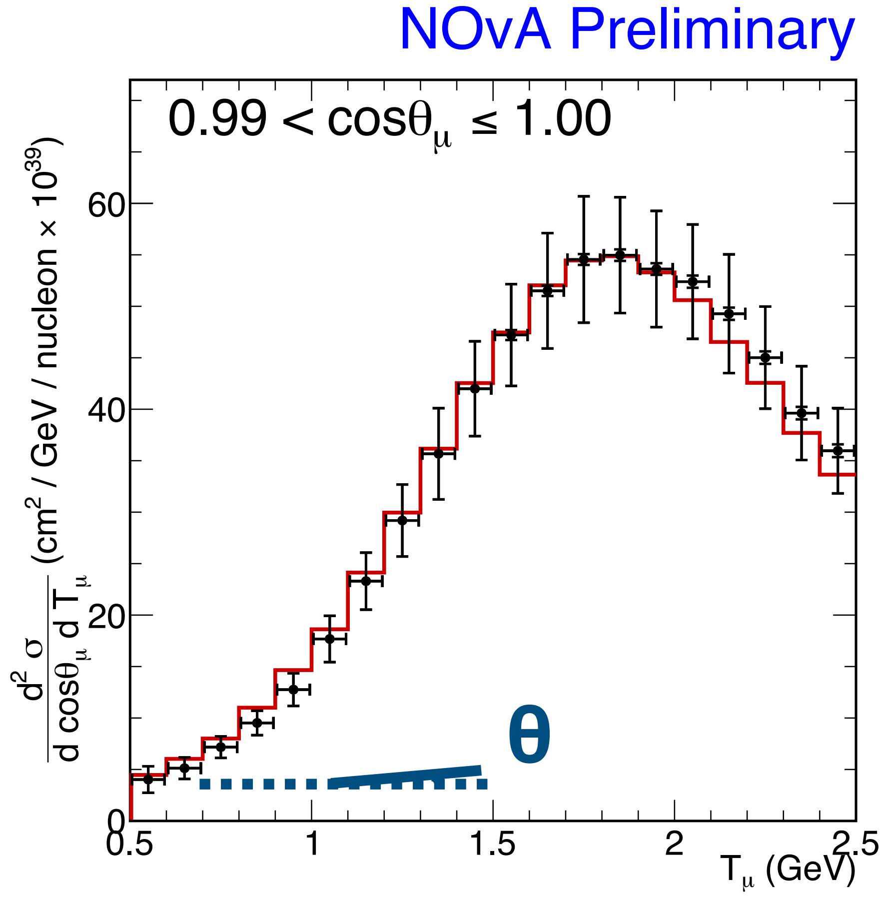




ν_μ CC inclusive results

Measurements shown in "cosine slices"





- Data (Stat. + Syst.)
- GENIE 2.12.2 - NOvA Tune

Good overall agreement with tuned prediction (p-value = 0.93)

ν_μ CC inclusive results

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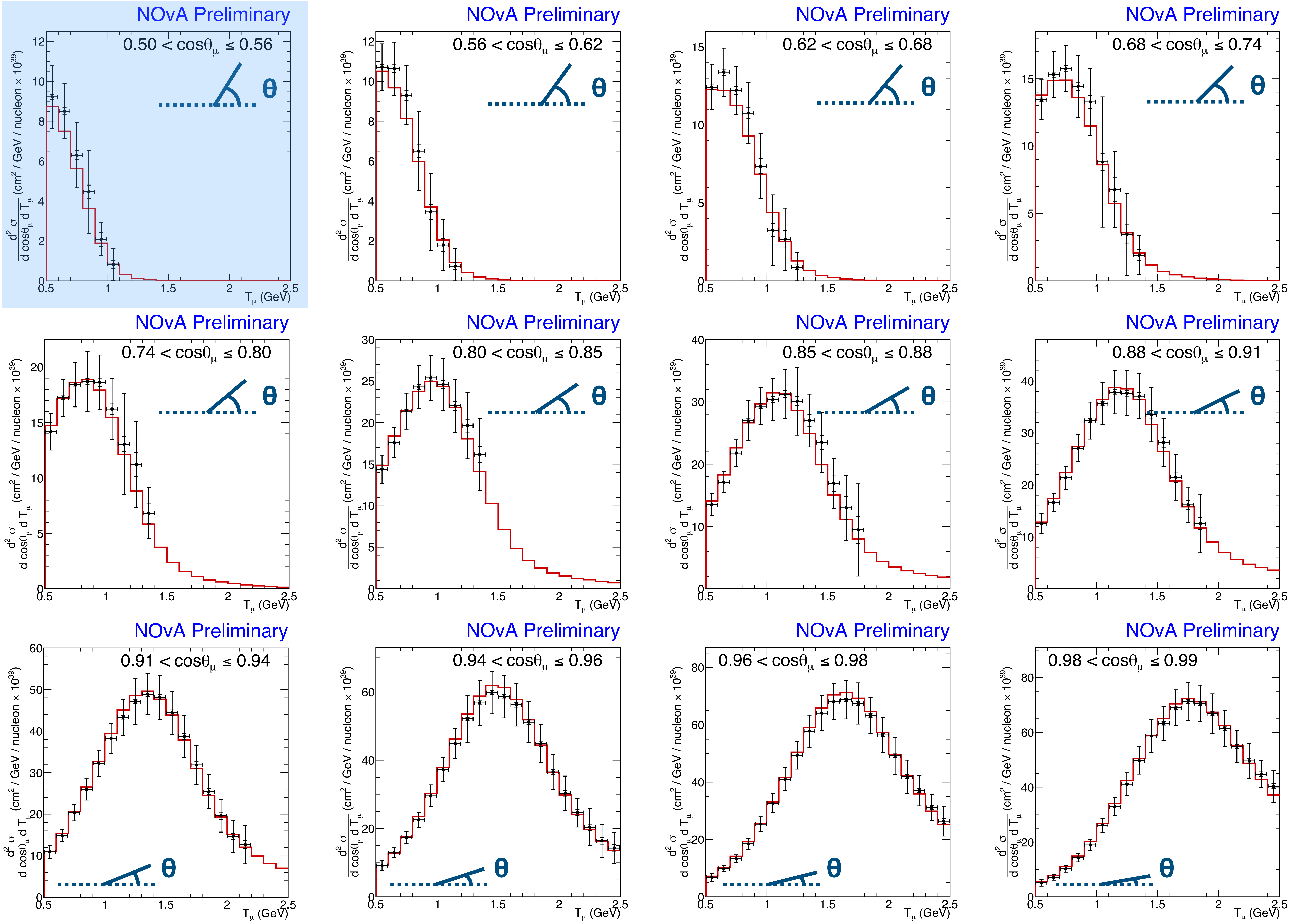

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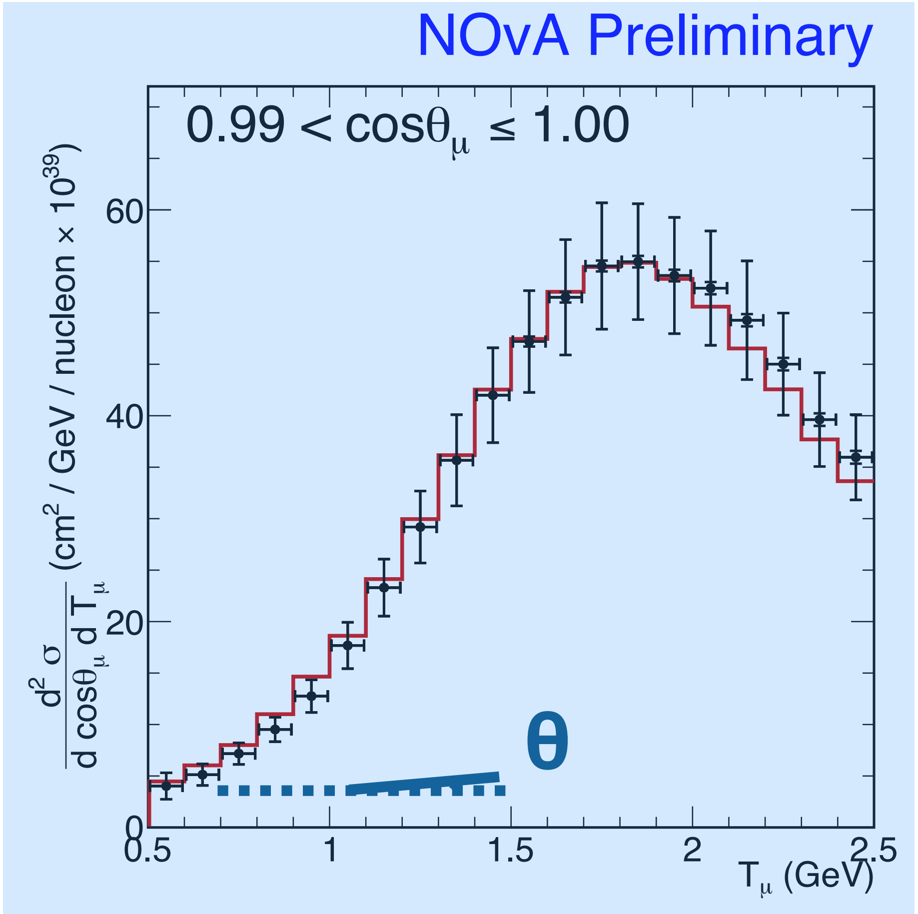
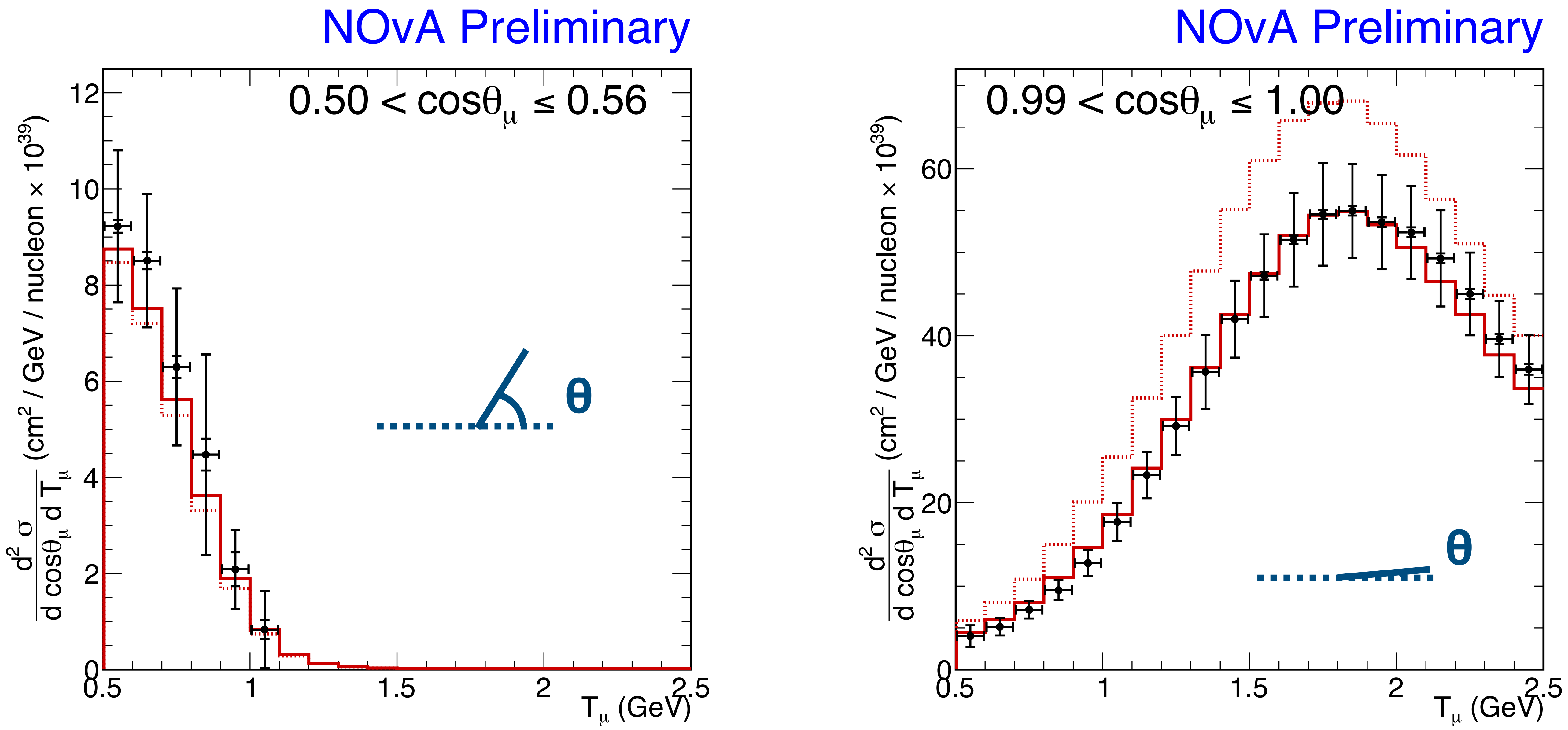
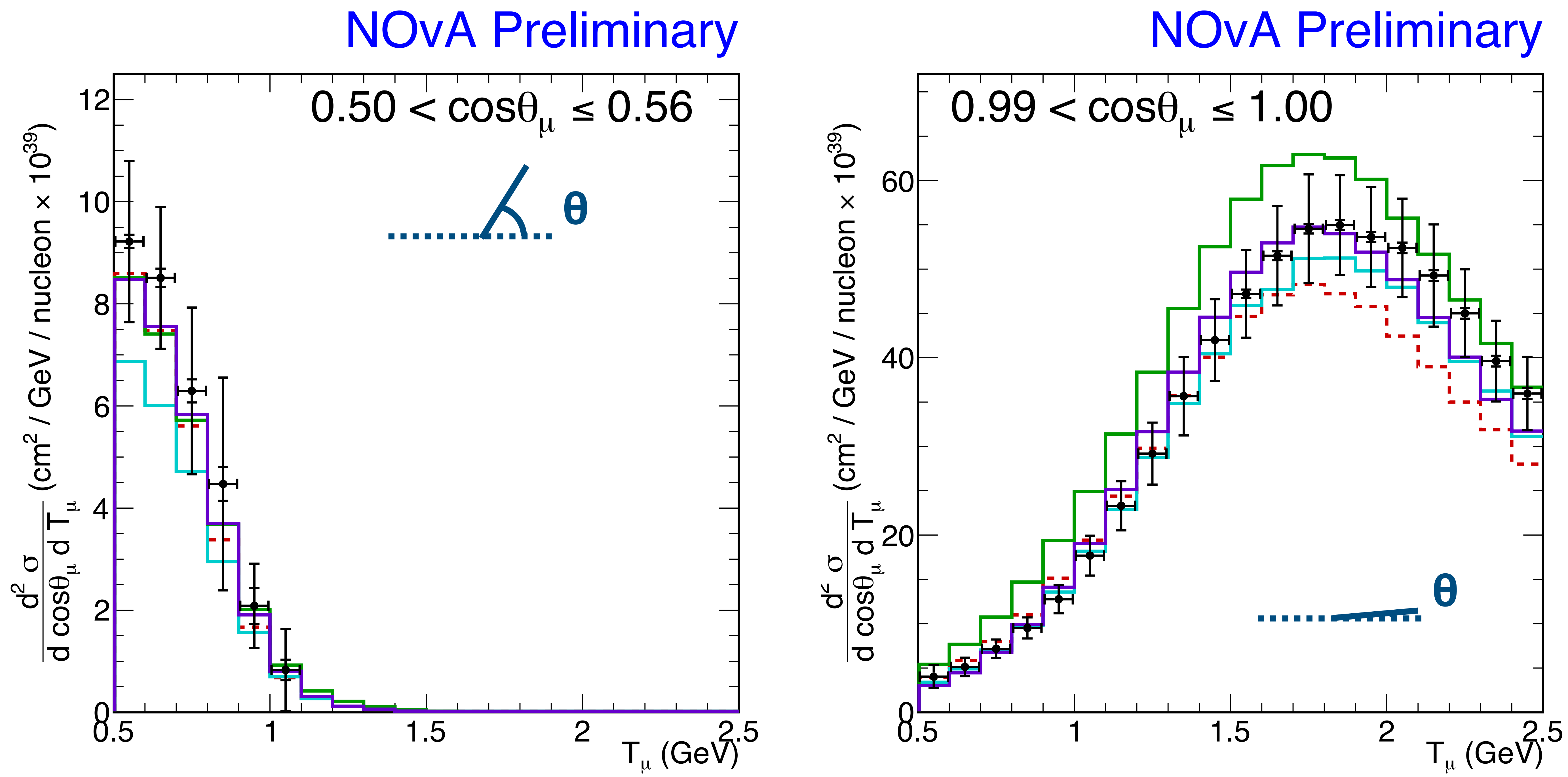


ν_μ CC inclusive results



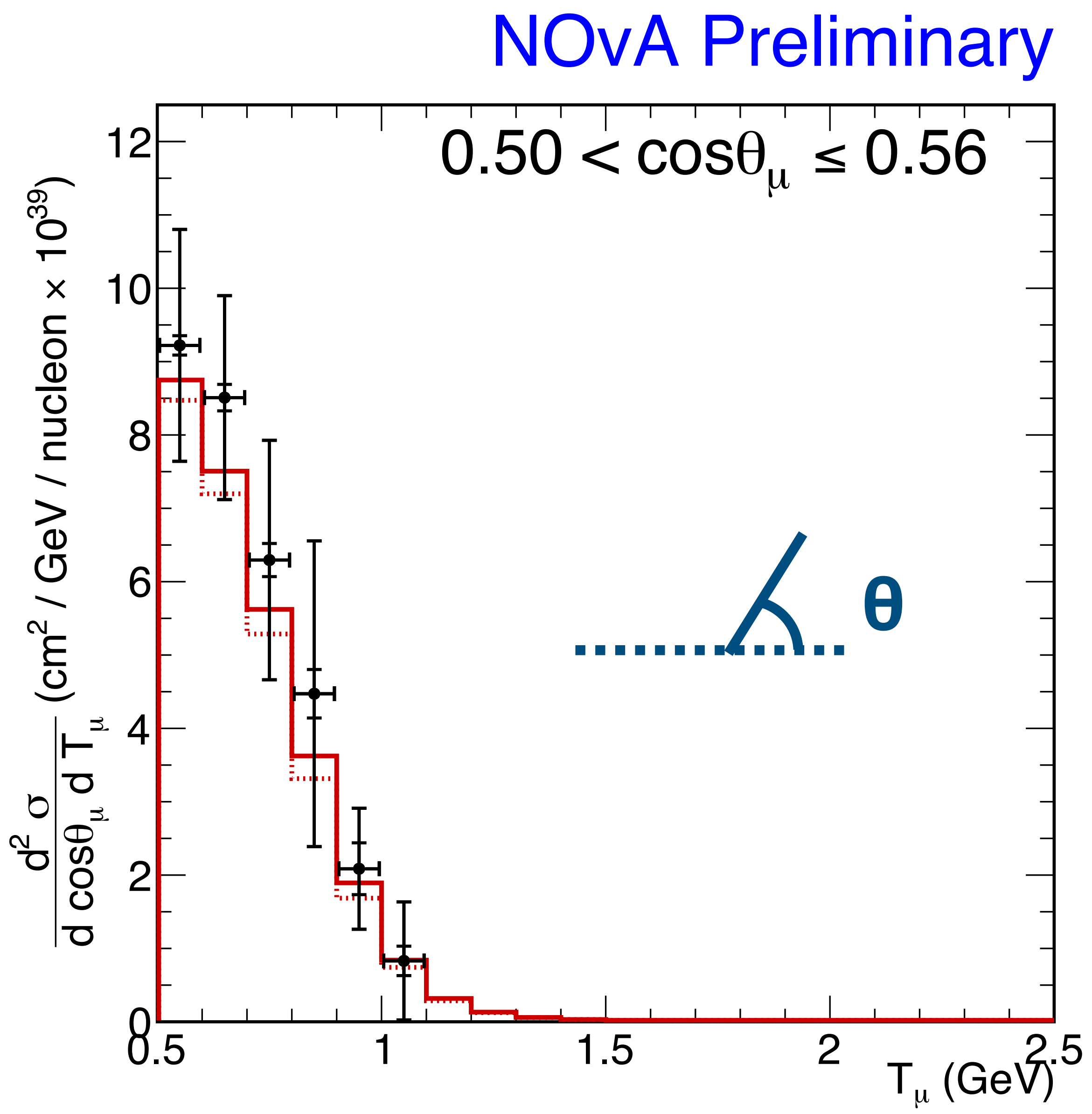
- For small angles (low Q^2), untuned model over-predicts data
  - QE- and 2p2h-dominated, sensitive to nuclear effects

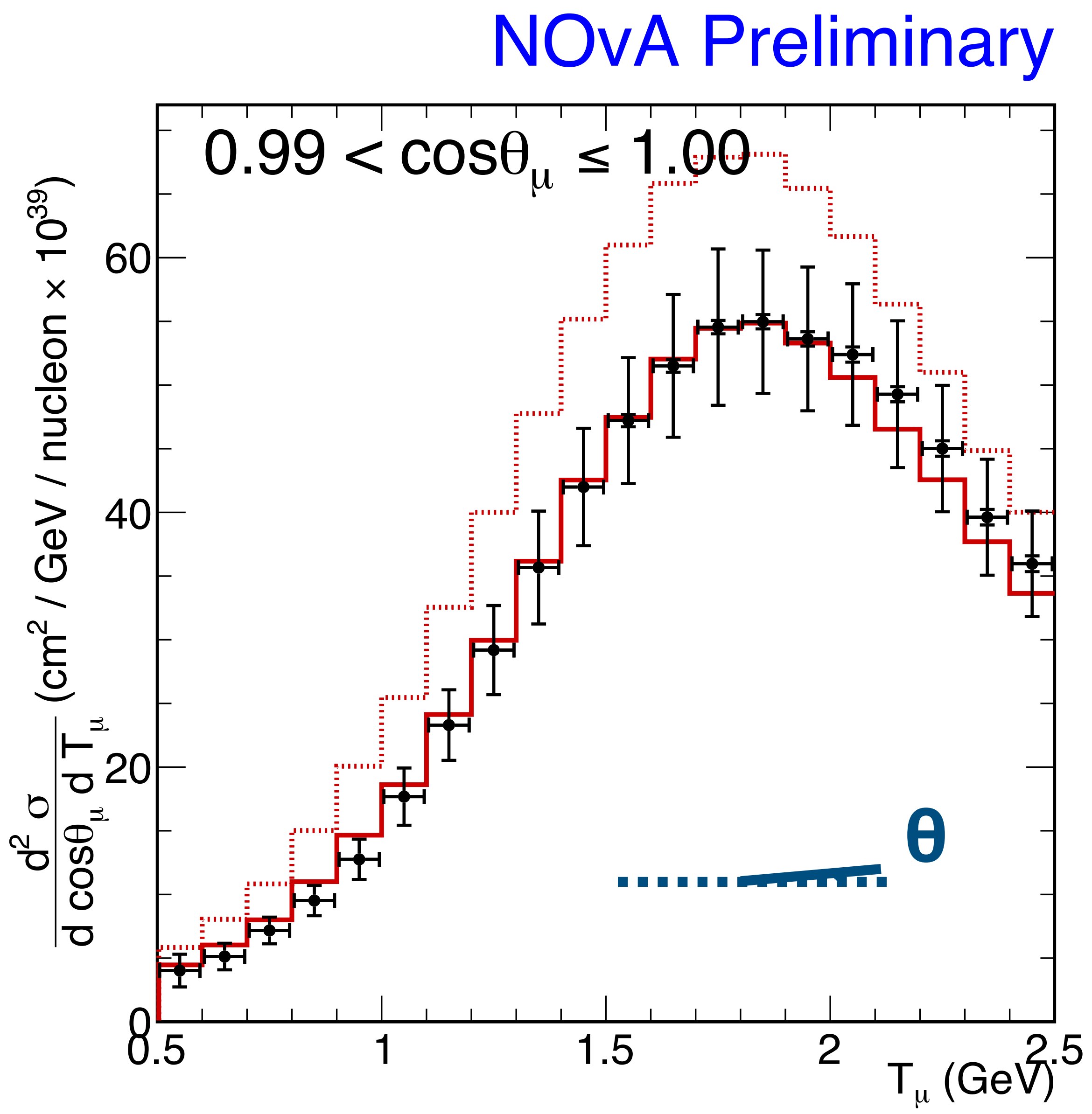
Generator	Total p-value
GENIE 2.12.2 - Tuned	0.93
GENIE 2.12.2 - Untuned	0.24



- "Out-of-the-box" generator predictions all describe the shape of the data well
- Normalization of GiBUU is low

ν_μ CC inclusive results





- Data (Stat. + Syst.)
- GENIE 2.12.2 - NOvA Tune
- GENIE 2.12.2 - Untuned

- For small angles (low Q^2), untuned model over-predicts data
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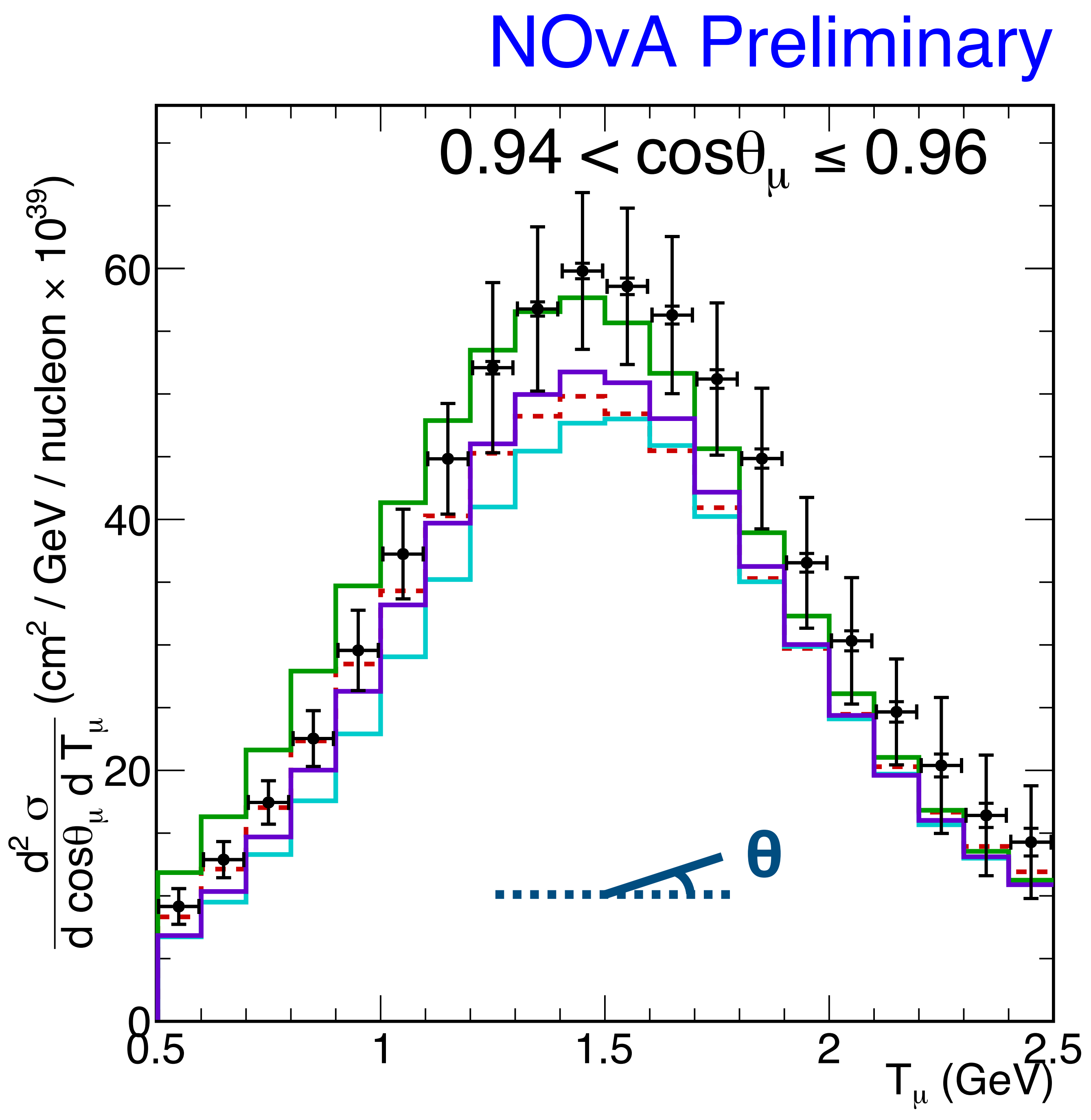
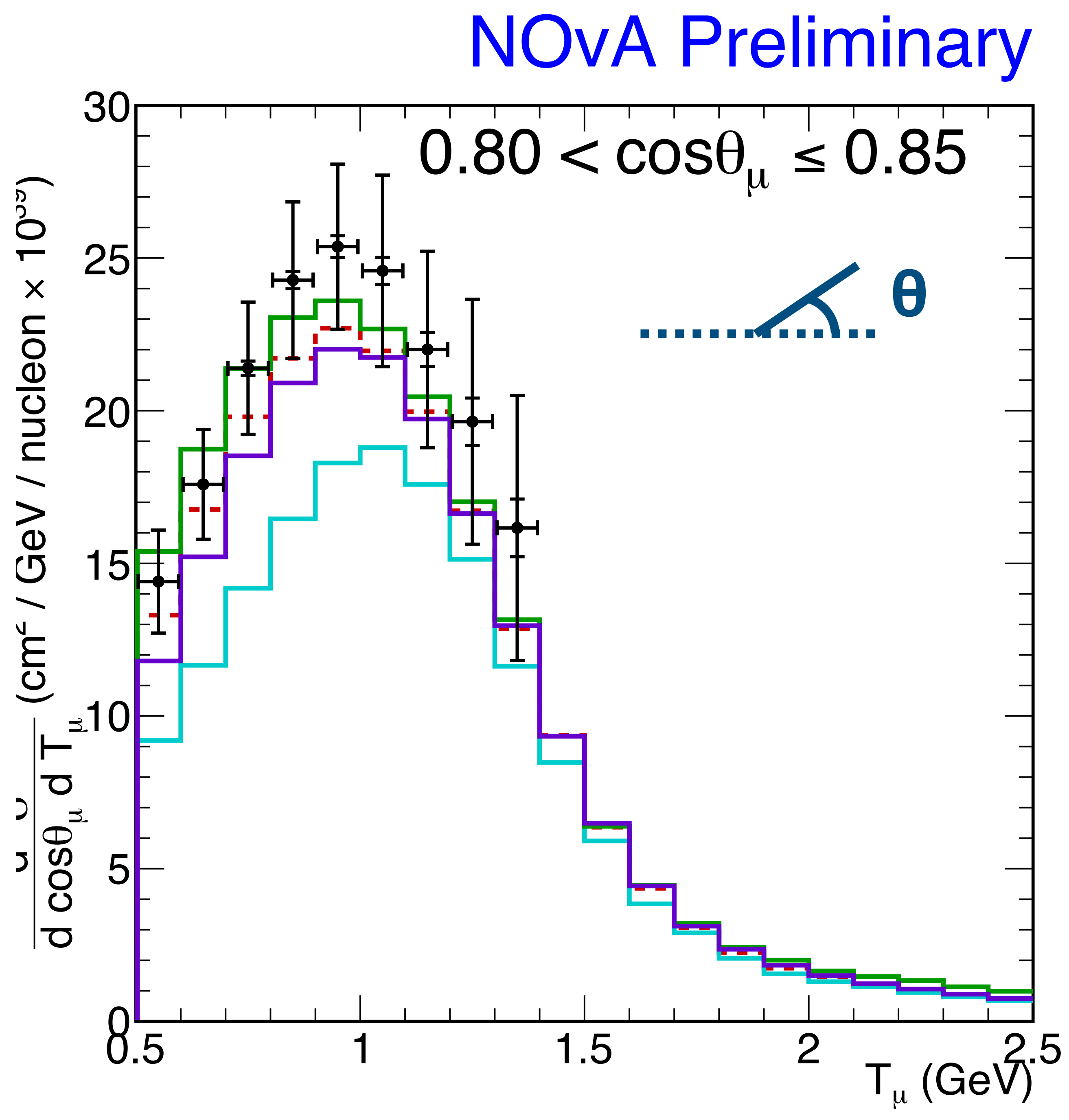
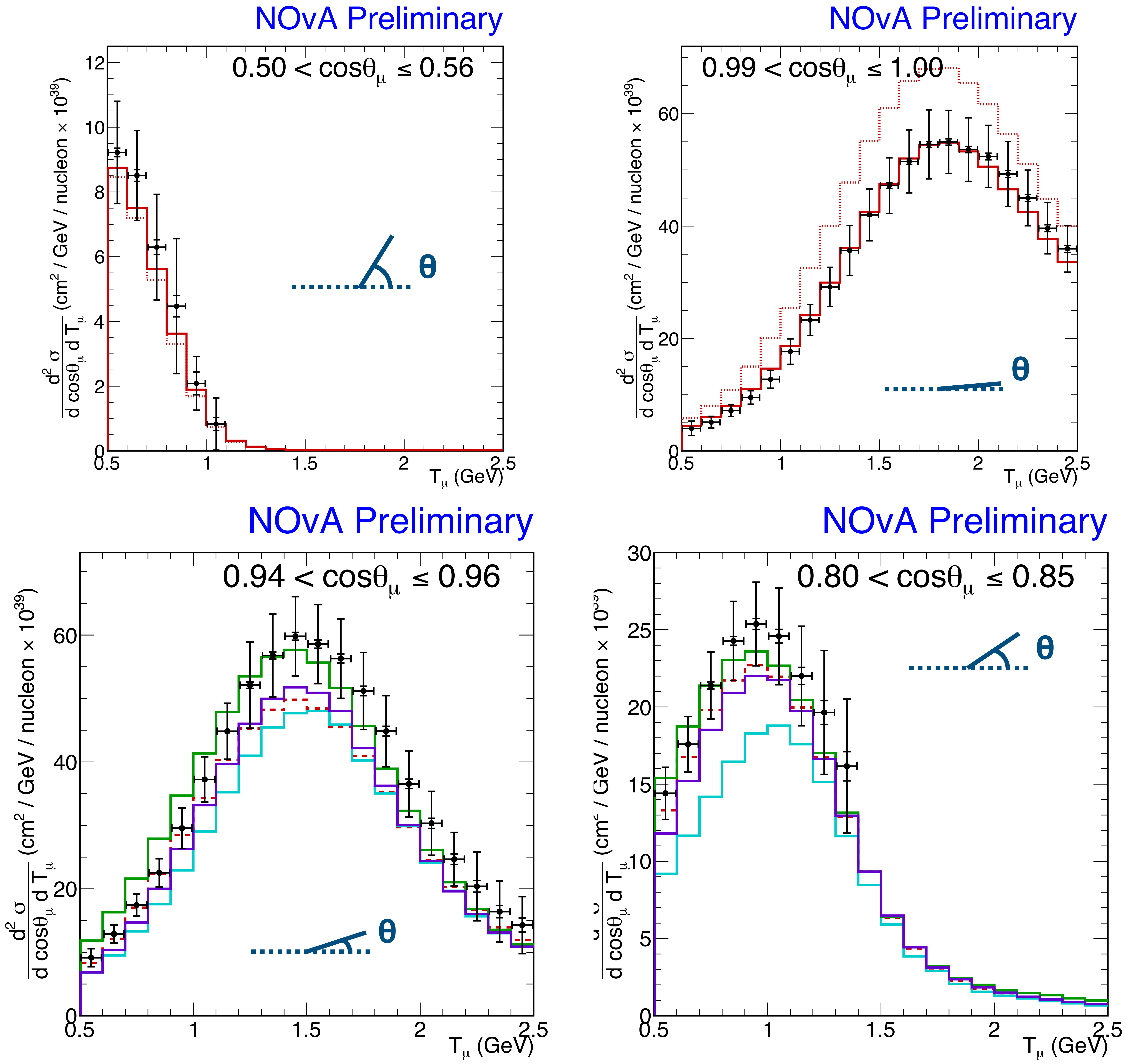




- Data (Stat. + Syst.)
- GENIE 3.00.06
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

- "Out-of-the-box" generator predictions all describe the shape of the data well
- **Normalization of GiBUU is low**

ν_μ CC inclusive results



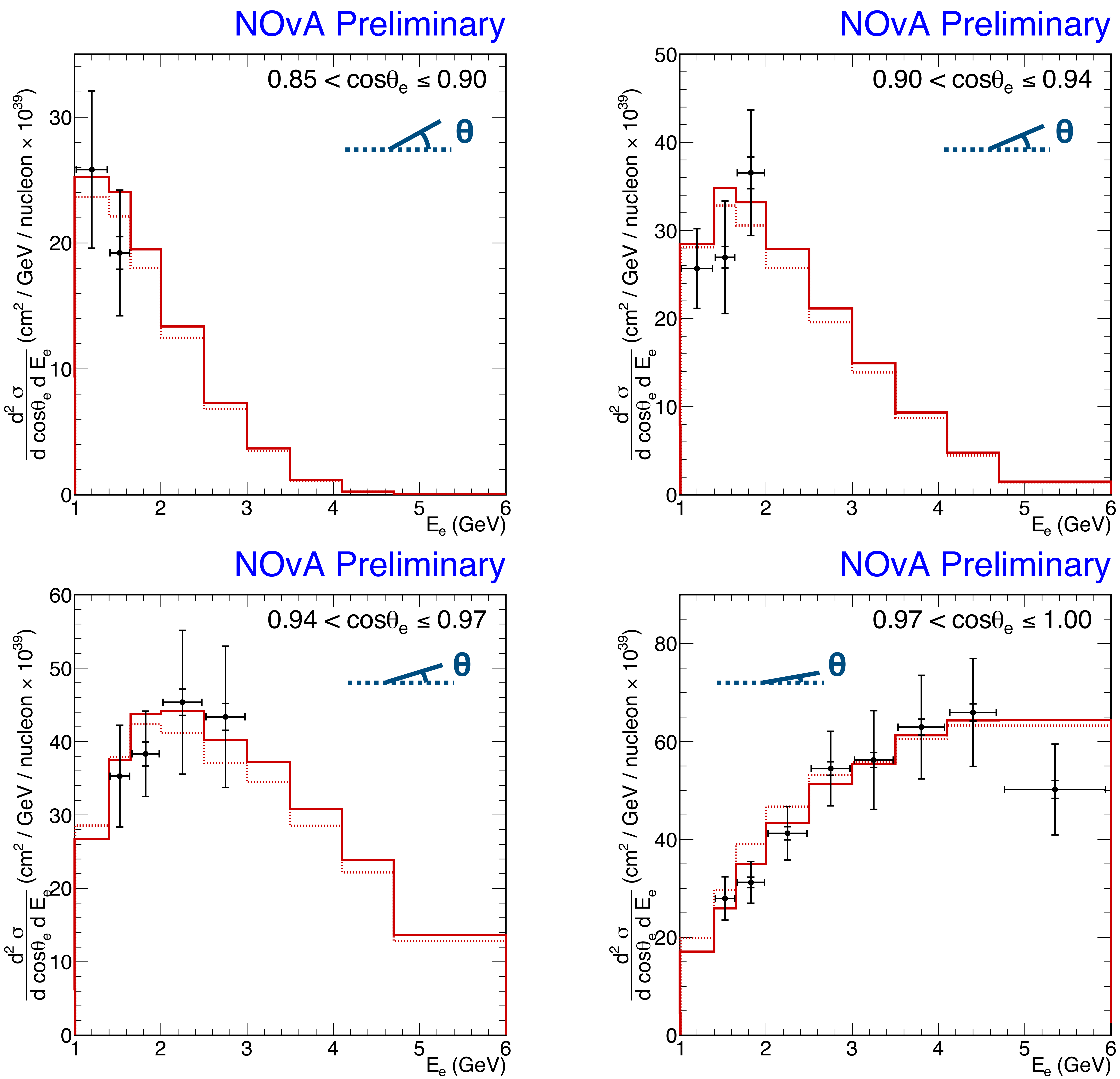
Data (Stat. + Syst.)
GENIE 2.12.2 - NOvA Tune
GENIE 2.12.2 - Untuned

- For small angles (low Q^2), untuned model over-predicts data
  - QE- and 2p2h-dominated, sensitive to nuclear effects

Generator	Total p-value
GENIE 2.12.2 - Tuned	0.93
GENIE 2.12.2 - Untuned	0.24

Generator	Total p-value
GENIE 3.00.06*	0.26
GiBUU 2019	0.03
NEUT 5.4.0	0.52
NuWro 2019	0.22

ν_e CC inclusive



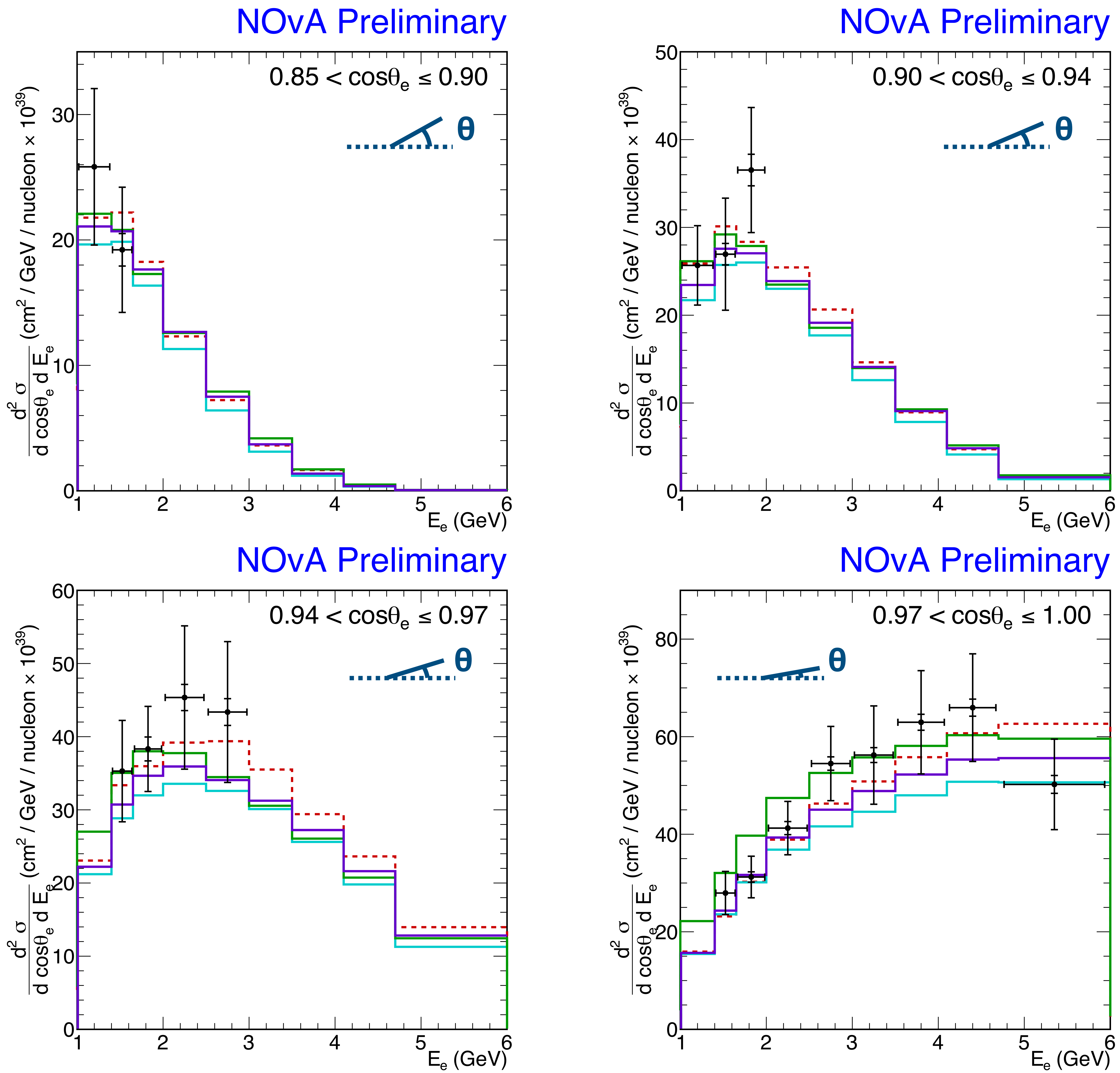
Measurements shown in "cosine slices"

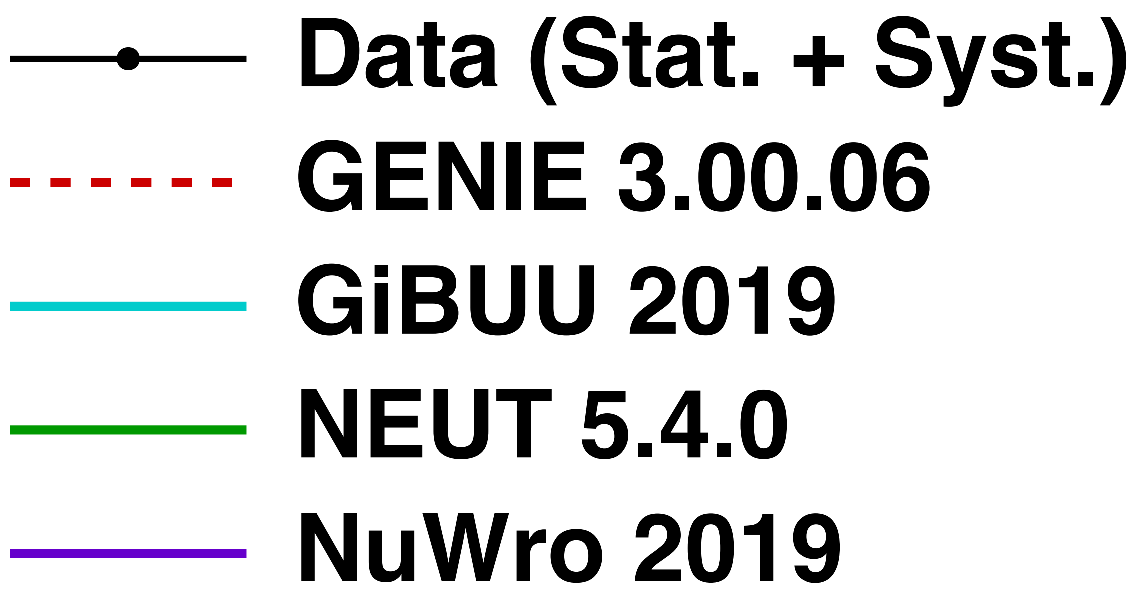
- **Data (Stat. + Syst.)**
- **GENIE 2.12.2 - NOvA Tune**
- **GENIE 2.12.2 - Untuned**

Good agreement with tuned/untuned GENIE v2 predictions for all angles studied

ν_e CC inclusive

Measurements shown in “cosine slices”

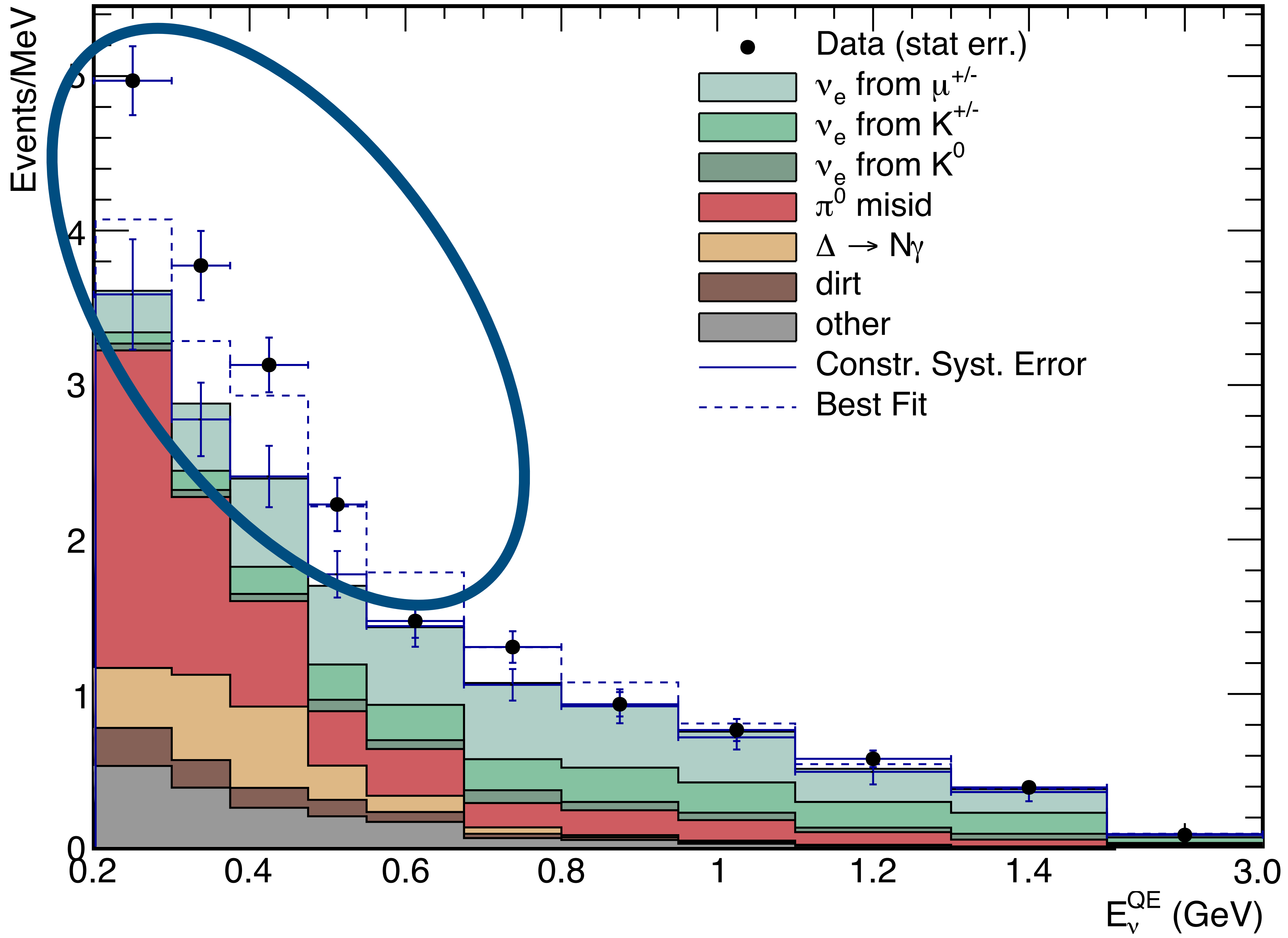




Good agreement with out-of-the-box predictions from multiple generators

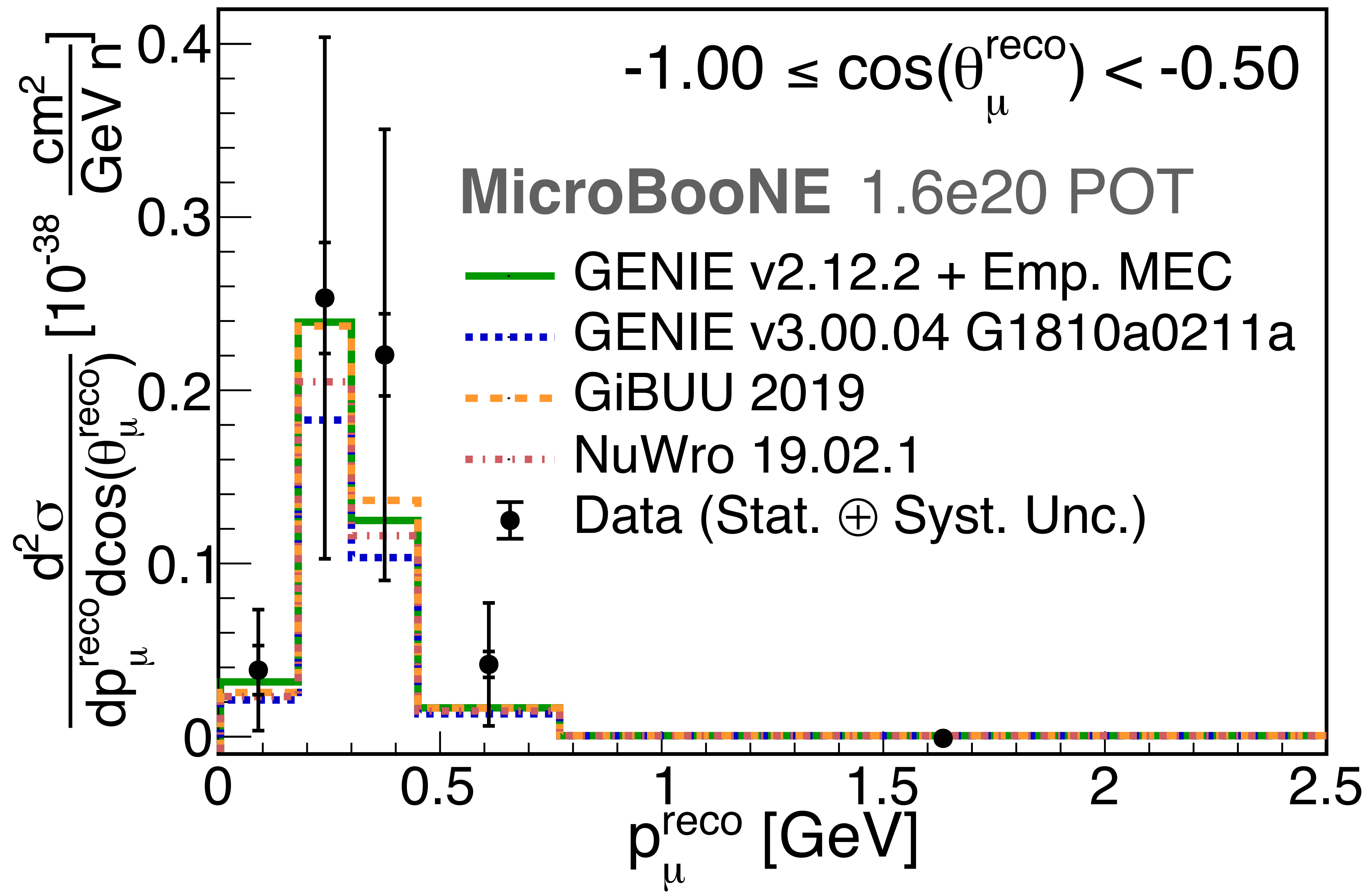
The MicroBooNE experiment

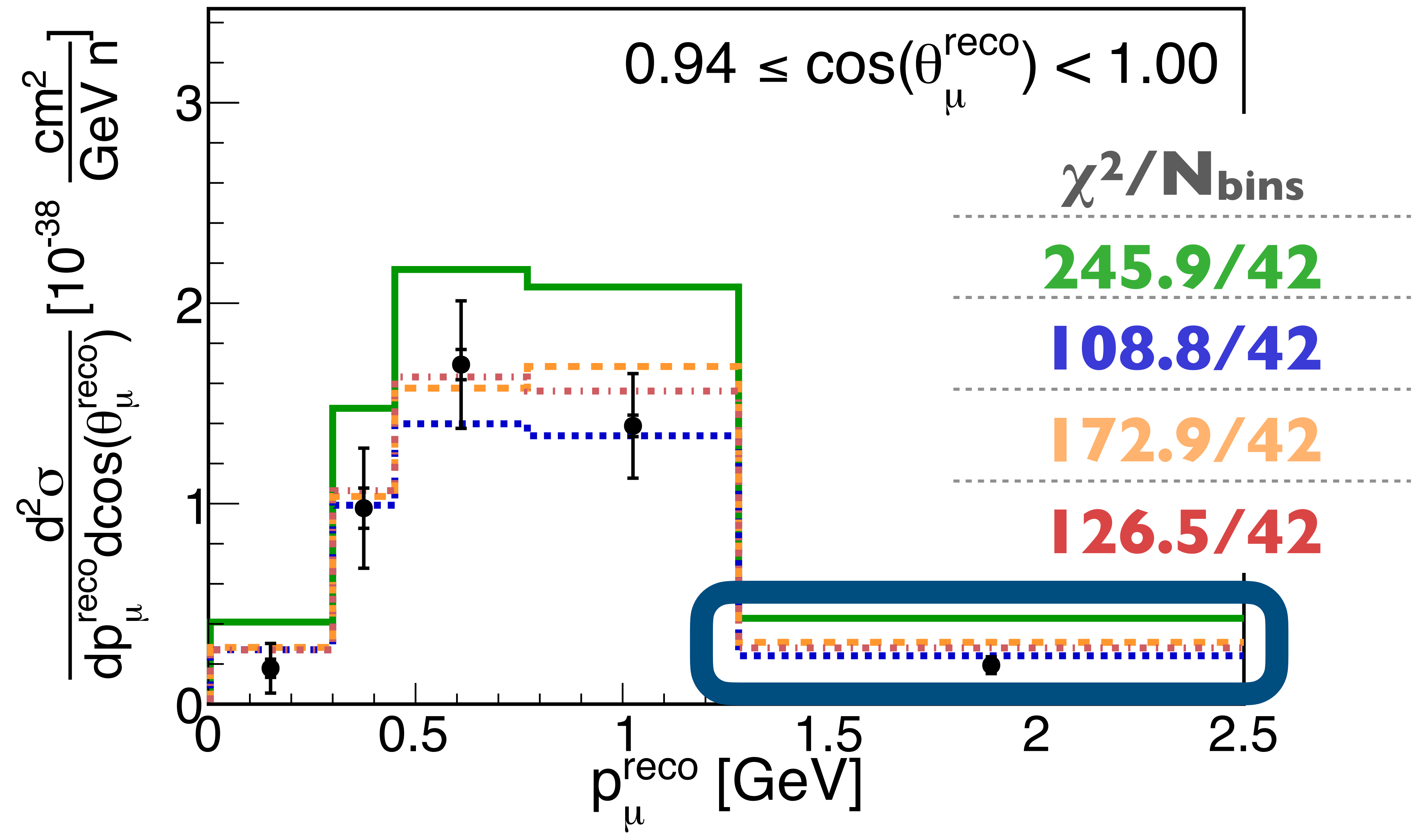
- Liquid argon time projection chamber (LArTPC) in the Booster Neutrino Beam
  - 60-ton fiducial mass
- **Largest sample** of ν-Ar interactions collected to date
- Primary physics goals
  - Investigate low-energy excess (LEE) of electron-like events seen by MiniBooNE
  - Pursue first high-statistics measurements of **neutrino-argon cross sections** (several recent publications)
- **This talk:** CC inclusive, CCQE-like, NC1p
- Other recent results
  - Track multiplicity: **Eur. Phys. J. C 79, 248 (2019)**
  - ν_μ CC π^0: **Phys. Rev. D 99, 091102(R) (2019)**



MicroBooNE: ν_μ CC inclusive analysis

- First double-differential measurement for ν_μ CC in argon: **[Phys. Rev. Lett. 123, 131801 (2019)]**
- Surface detector → often 20+ cosmic rays / event
  - 4.8 ms TPC readout window
  - Variety of techniques used to achieve 99.9% cosmic rejection
- All models **overpredict in high-momentum, forward-**going bins
  - GENIE v2 disfavored compared to other generators
- **Backup**: Improved measurement underway with drastically reduced systematic uncertainties

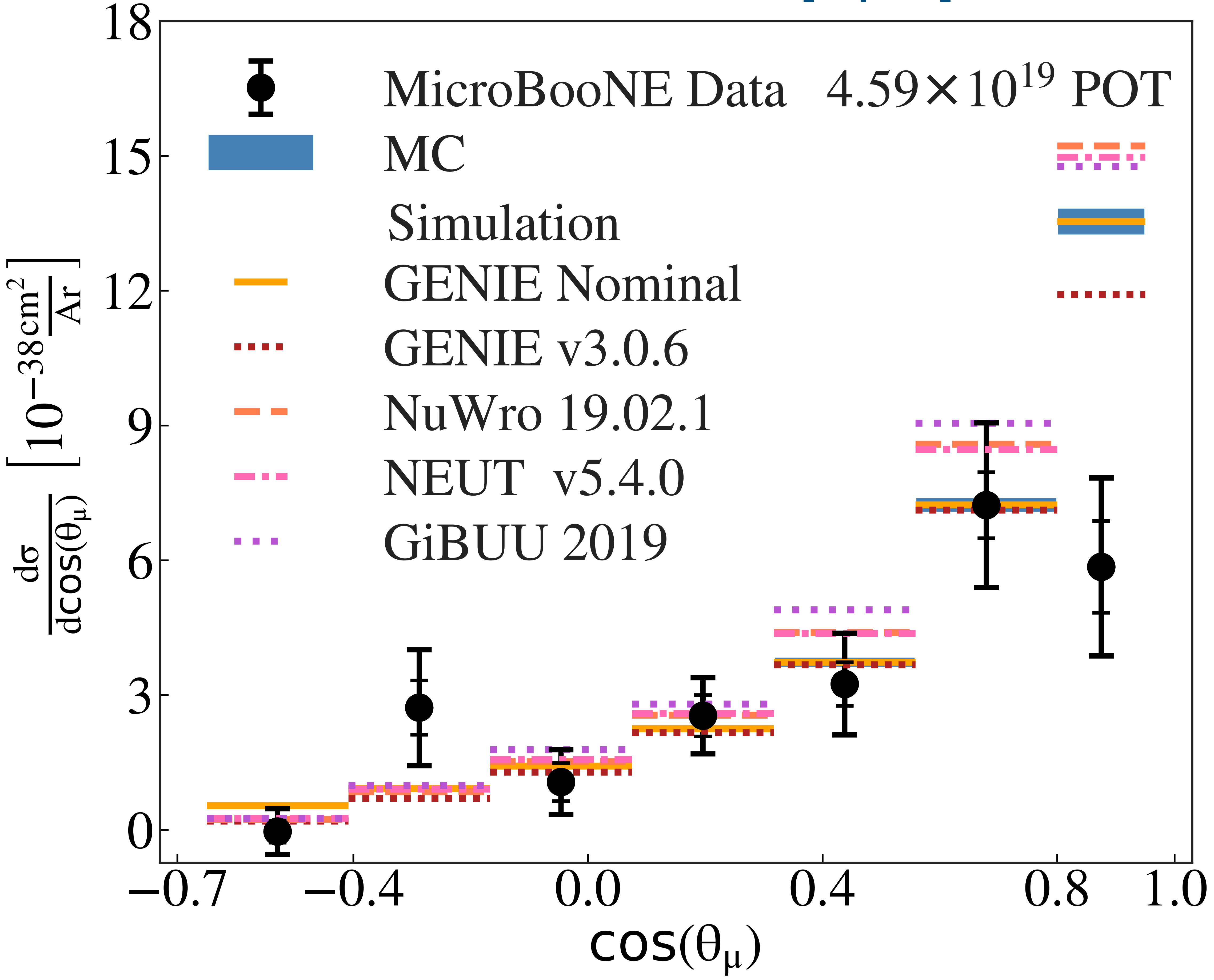




MicroBooNE CCQE-like cross section

- Recently submitted to PRL arXiv:2006.00108
- Signal definition: "CC1p0π"
  - 1 muon ($p_\mu > 100$ MeV/c)
  - 1 proton ($p_p > 300$ MeV/c)
  - Cuts to enhance CCQE contribution
- Purity: ~84% CC1p0π (~81% CCQE)
- Efficiency: ~20%
- Single-differential results obtained for several kinematic variables
  - **Backup**: plots for p_μ, p_p, cos θ_p
- Good agreement with generators, except at very **forward muon scattering angles** (low Q^2)

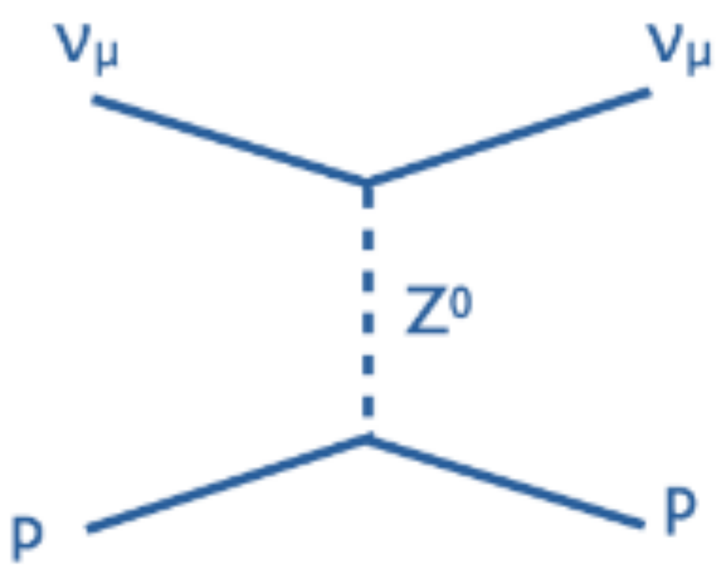
arXiv:2006.00108 [hep-ex]



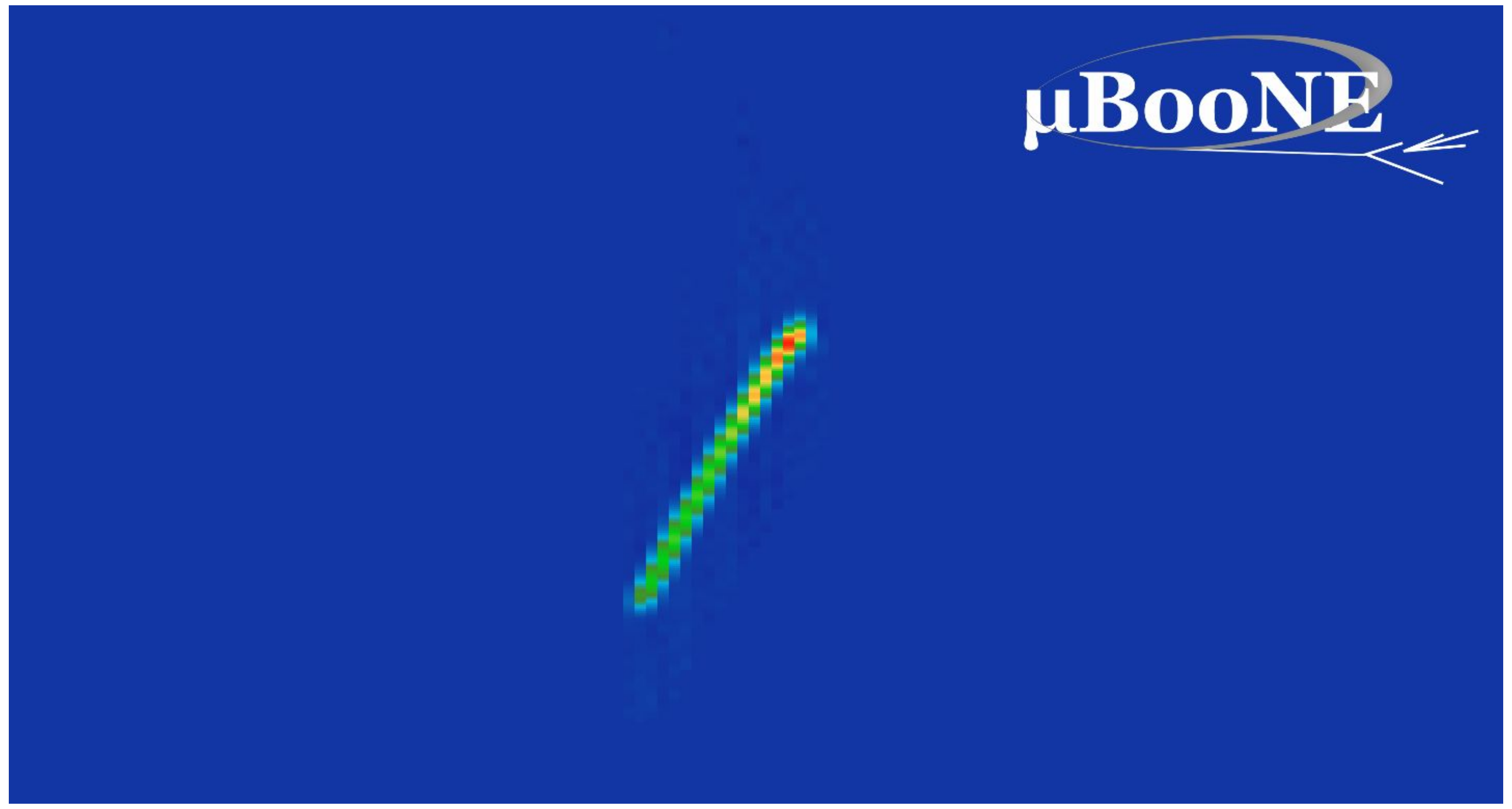
"GENIE Nominal" is the default configuration of GENIE v2.12.2, which was used in the analysis

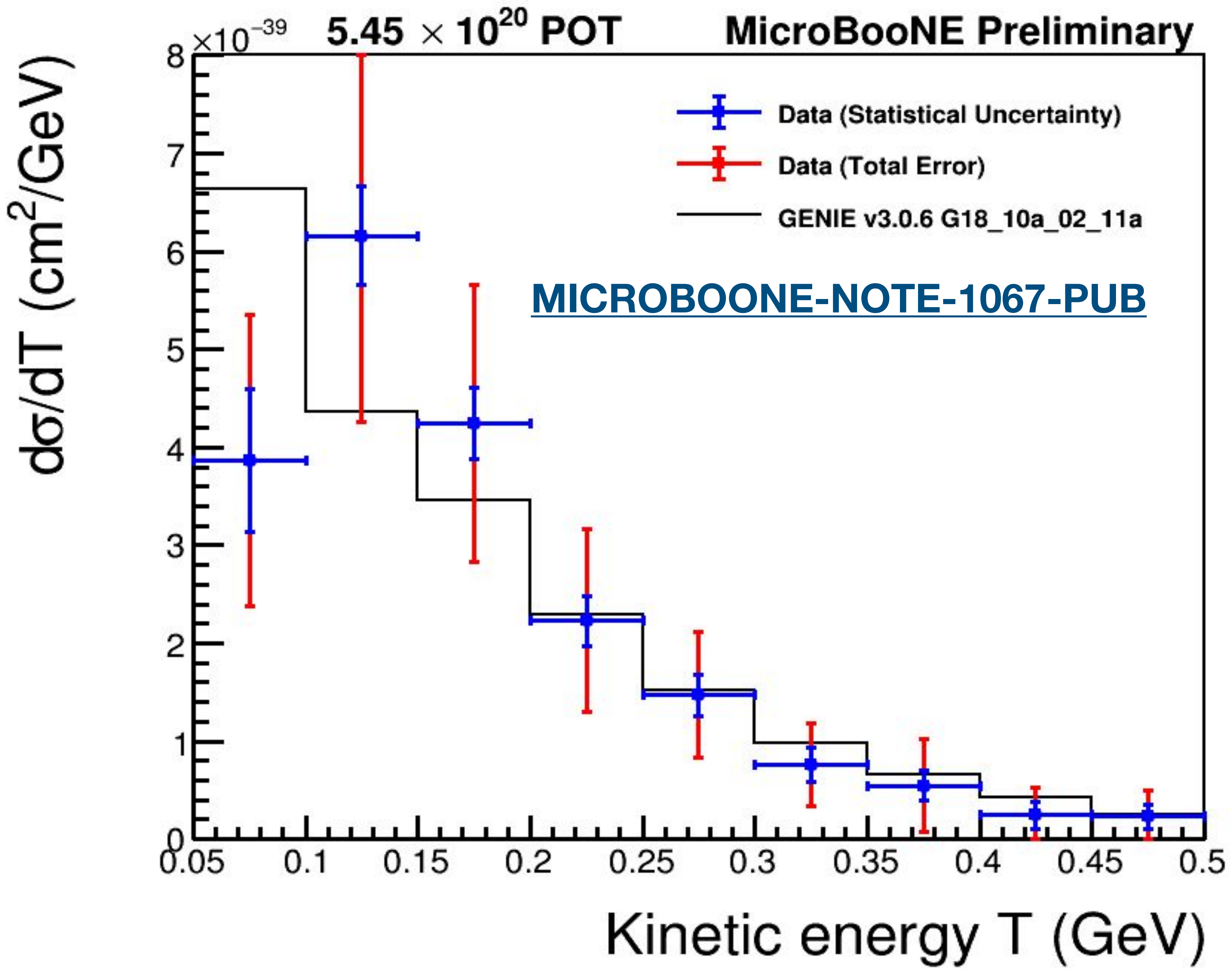
MicroBooNE NC1p cross section

- Signal definition:
  - 1 proton (p_p > 200 MeV/c)
  - No other detected particles
  - Main component is NC elastic scattering (NCEL)
- Single-differential cross section extracted in terms of reconstructed proton kinetic energy
  - Includes events down to $Q^2 \sim 2m_pT_p = 0.1\ \mathrm{GeV}^2$, **significantly lower** than previous measurements
- Future development toward an NCEL-like cross section



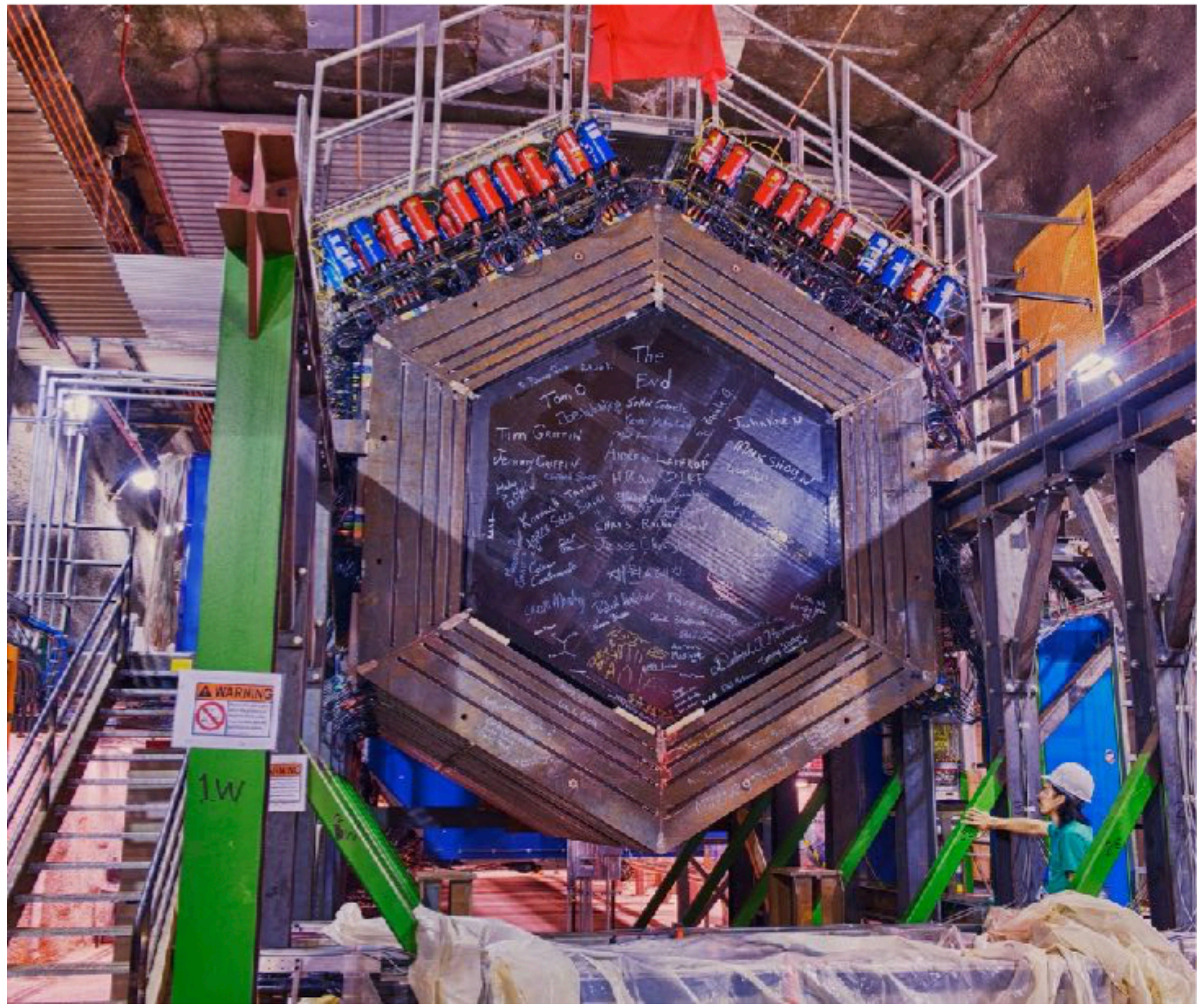
NC1p candidate event





The MINERvA experiment

- Dedicated specifically to studying neutrino cross sections
  - **6 new papers** since last Users Meeting
- Last data collected in February 2019. Analyses continue.
- Operated in the NuMI beam line in two modes
  - Low Energy (LE) → 2005–2012
  - Medium Energy (ME) → 2013–2019
- Segmented "active tracker" (CH scintillator) and passive nuclear targets (He, C, H_2O, Fe, and Pb)
  - Study A-dependence of cross sections
- **This talk**: ν-e^-, CCQE-like, and neutron measurements



Recent cross section results from MINERvA:

ν_μ CC inclusive: Phys. Rev. D 101, 11 (2020)

ν_μ CC π^0: arXiv:2002.05812 (submitted for publication)

$\boldsymbol{\nu_\mu}$ **CCQE-like**: Phys. Rev. Lett. 124, 121801 (2020)

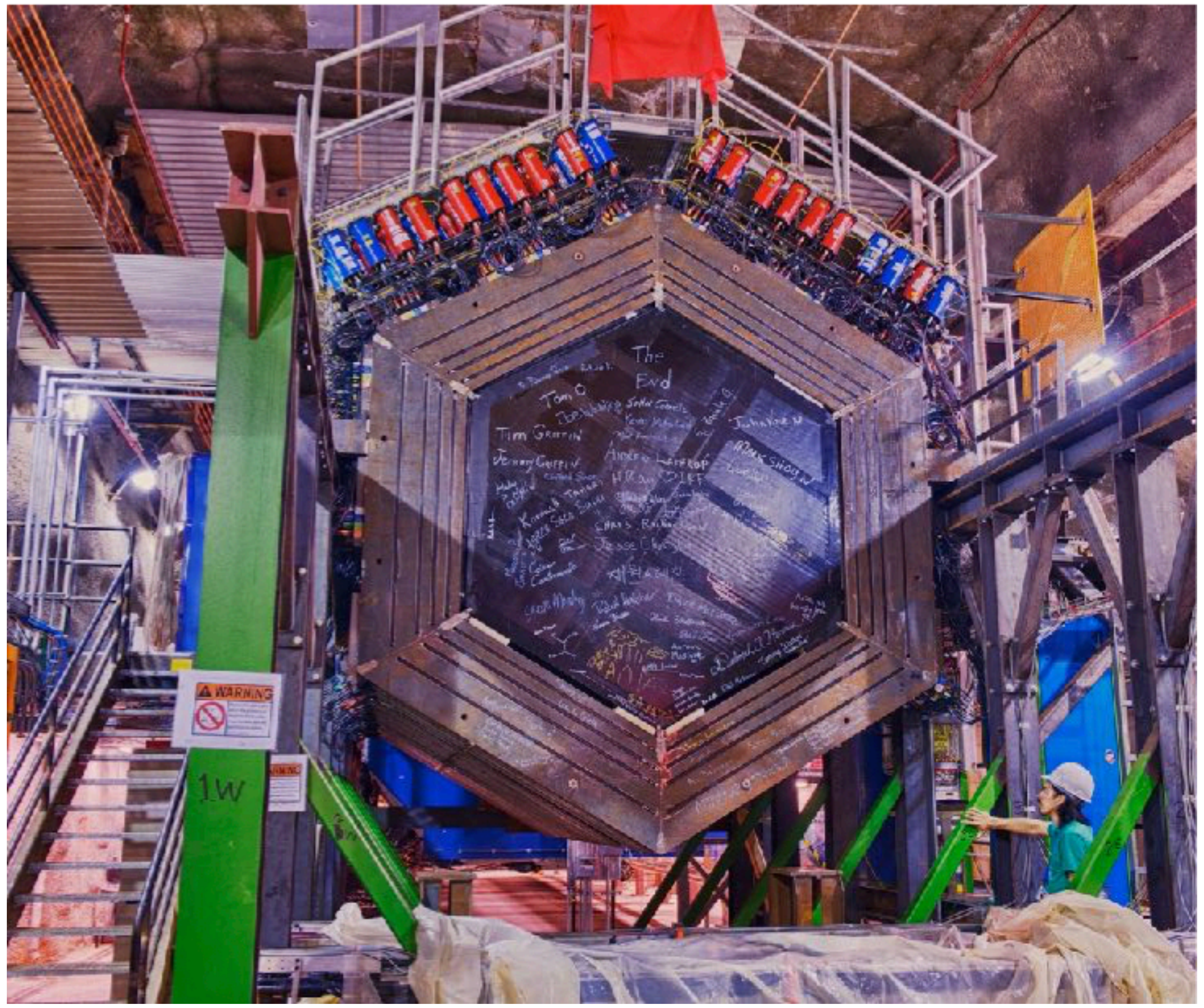
BE & transverse momentum imbalance: Phys. Rev. D 101, 092001 (2020)

Flux constraint via v-e scattering: Phys. Rev. D 100, 092001 (2019)

$\bar{\nu}_\mu$ CC π^-: Phys. Rev. D 100, 052008 (2019)

See https://minerva.fnal.gov/recent-minerva-results for many more!

The MINERvA experiment



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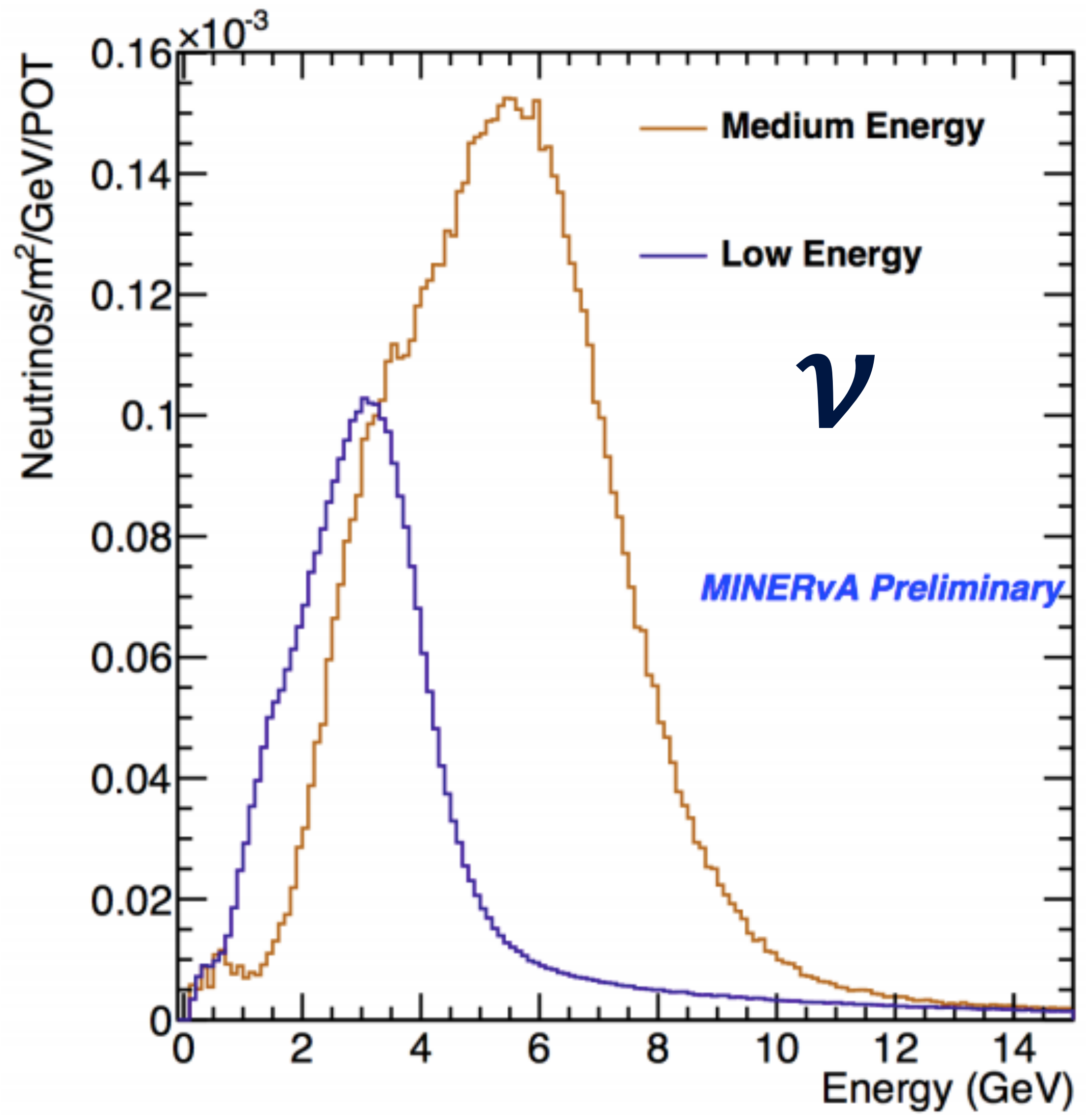
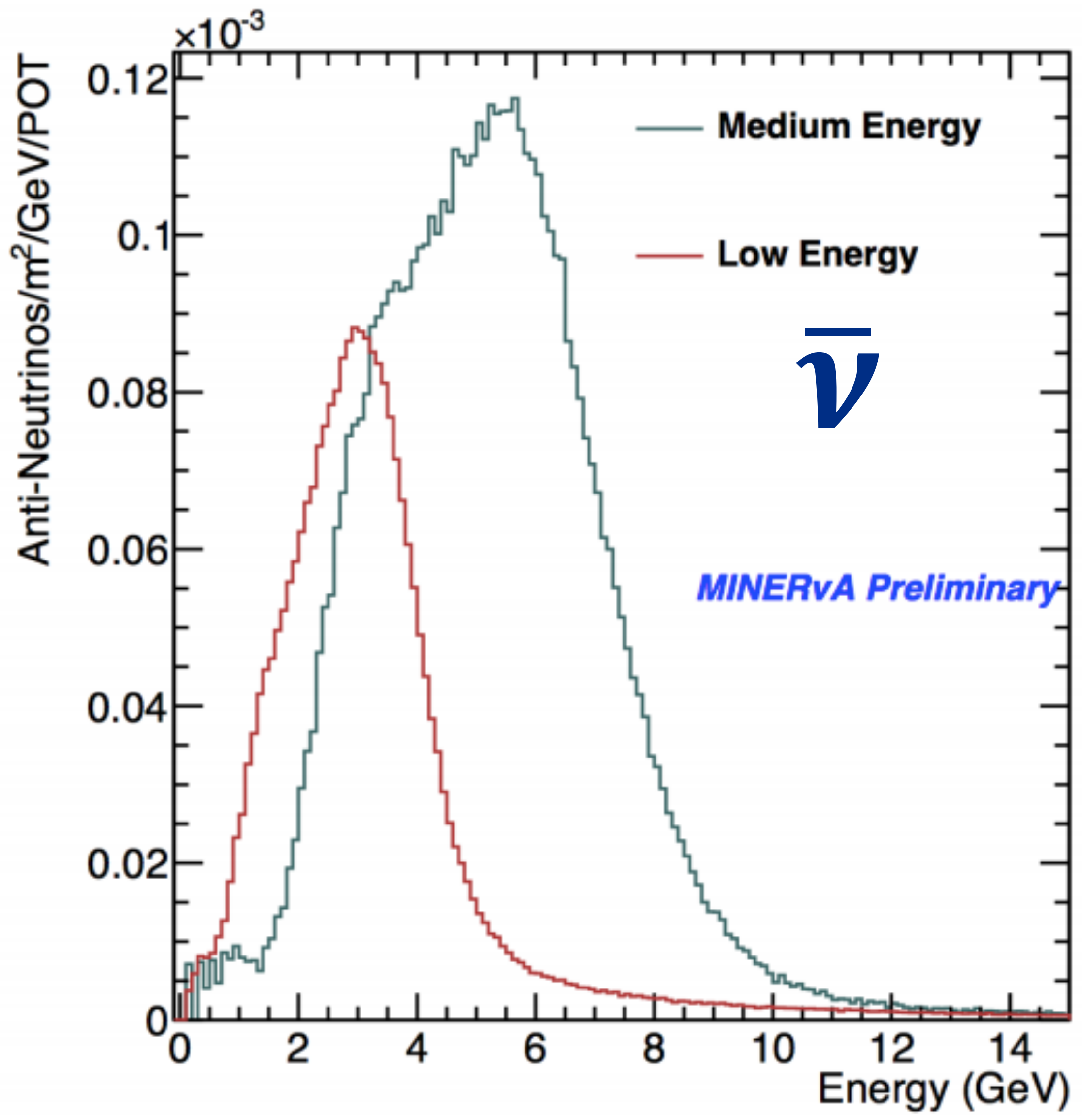
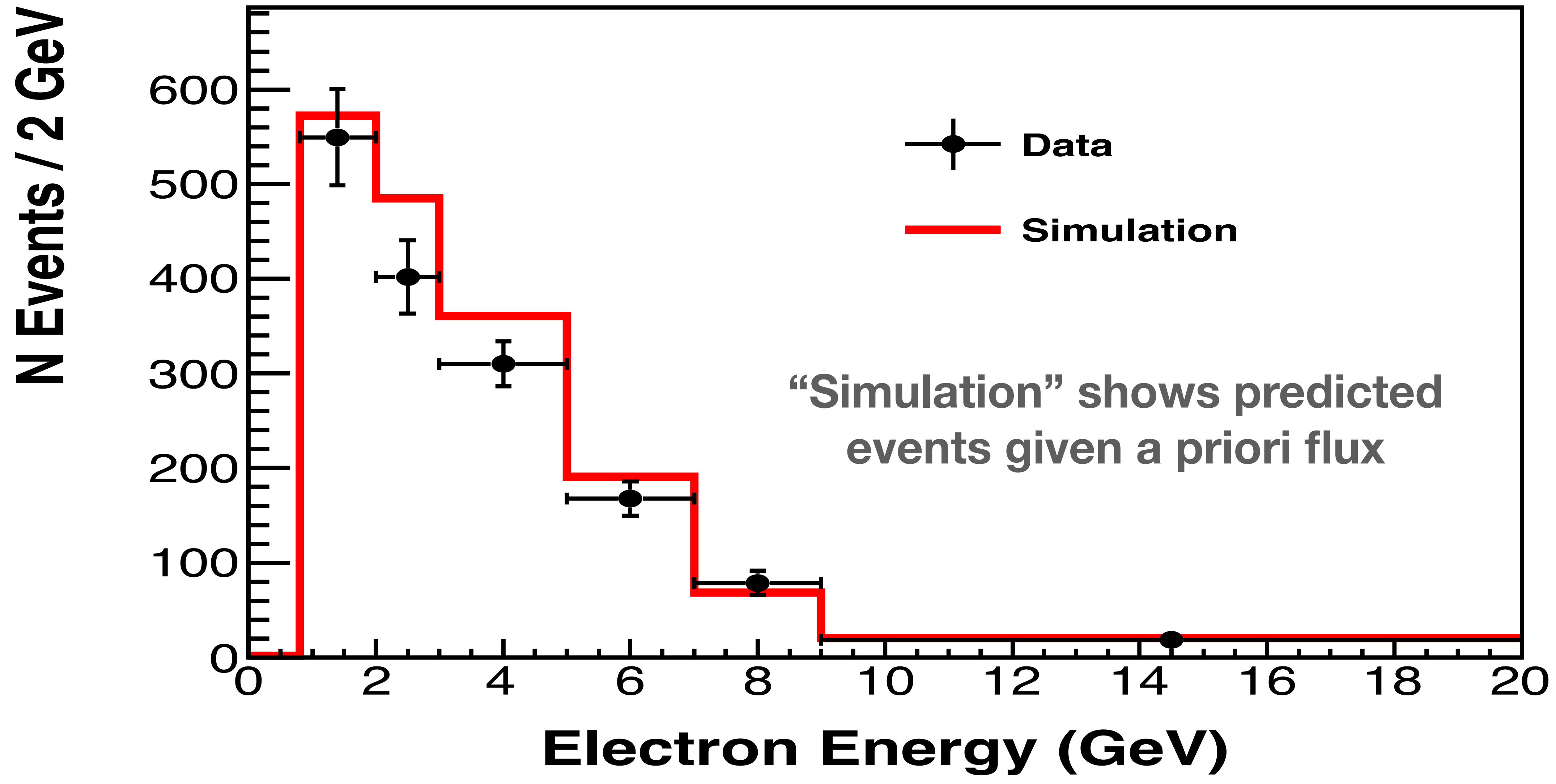


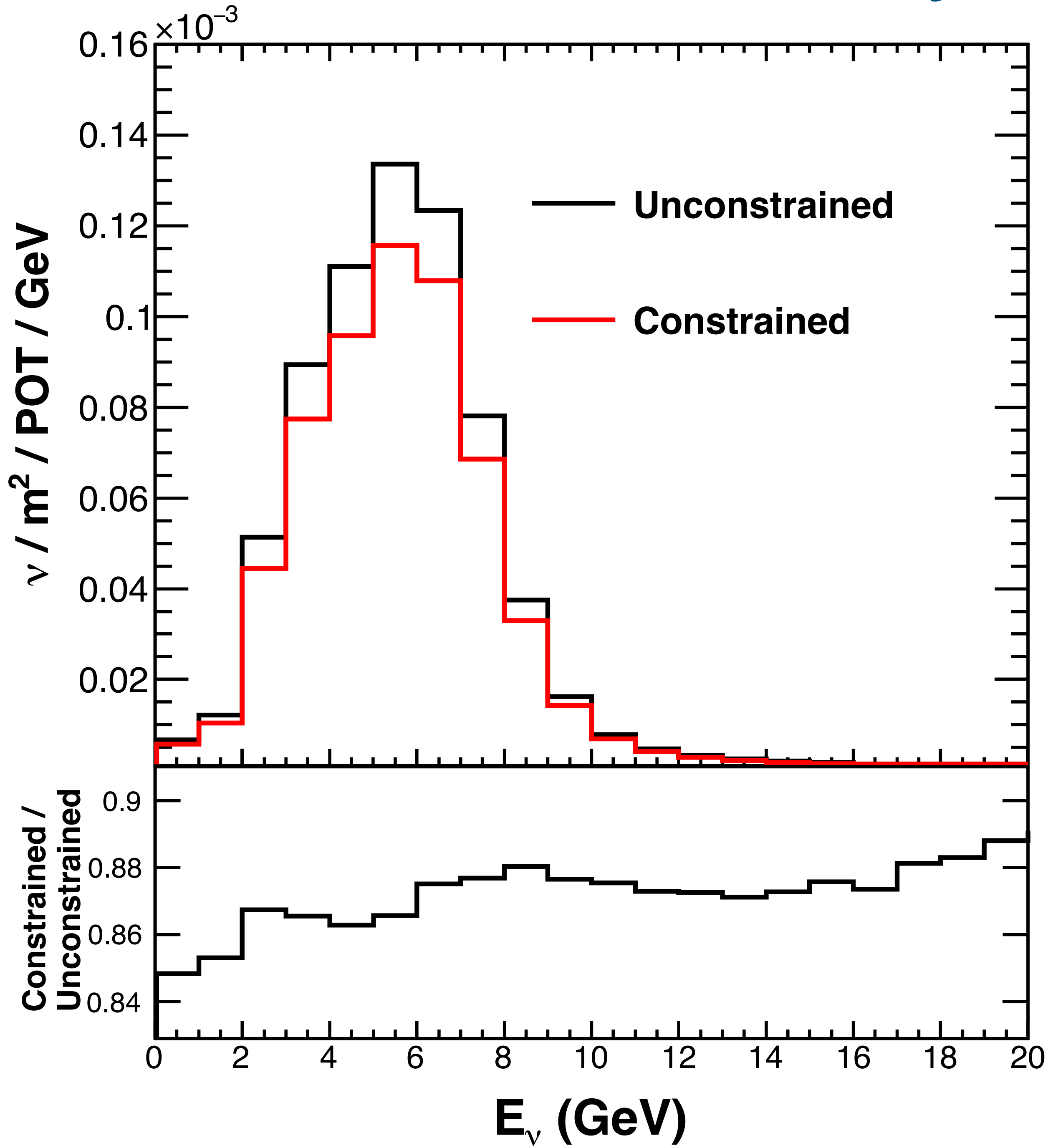


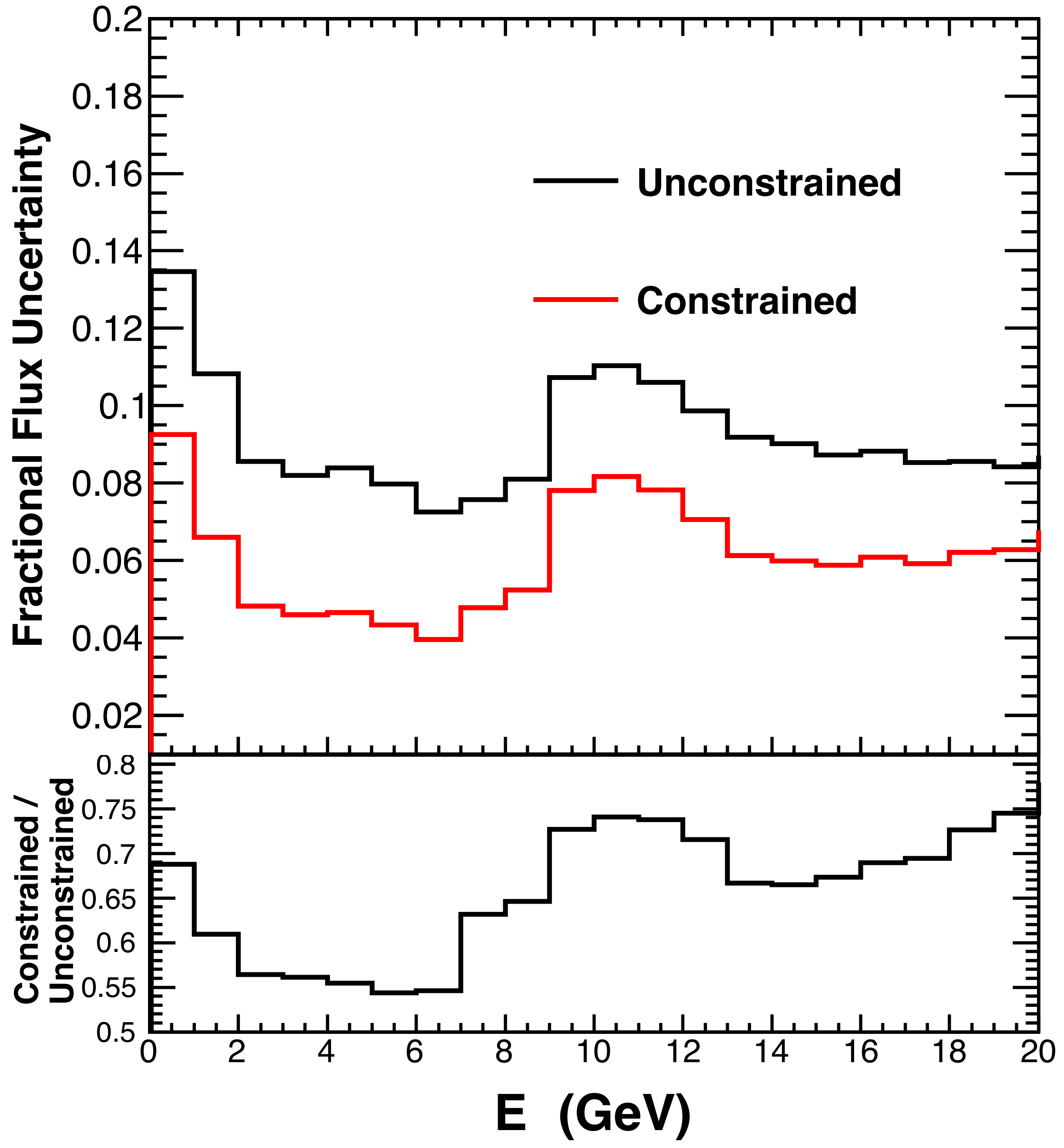
MINERvA ν-e^- analysis: *in situ* flux constraint

- Neutrino flux predictions typically good to ~10%, key input for oscillation analyses
- ν-e^- cross section small but well-known
  - “**Standard candle**”
  - Technique demonstrated by MINERvA for LE data in 2016 (**Phys. Rev. D 93, 112007**)
- **New ME analysis** has higher statistics (9×) and an improved treatment of systematic uncertainties
- Event rate in reconstructed E_e compared to a priori prediction
- **Bayes’ theorem** used to constrain the flux model given the observed data
- Improved precision will benefit all MINERvA ME analyses
  - Strategy can be applied to other experiments



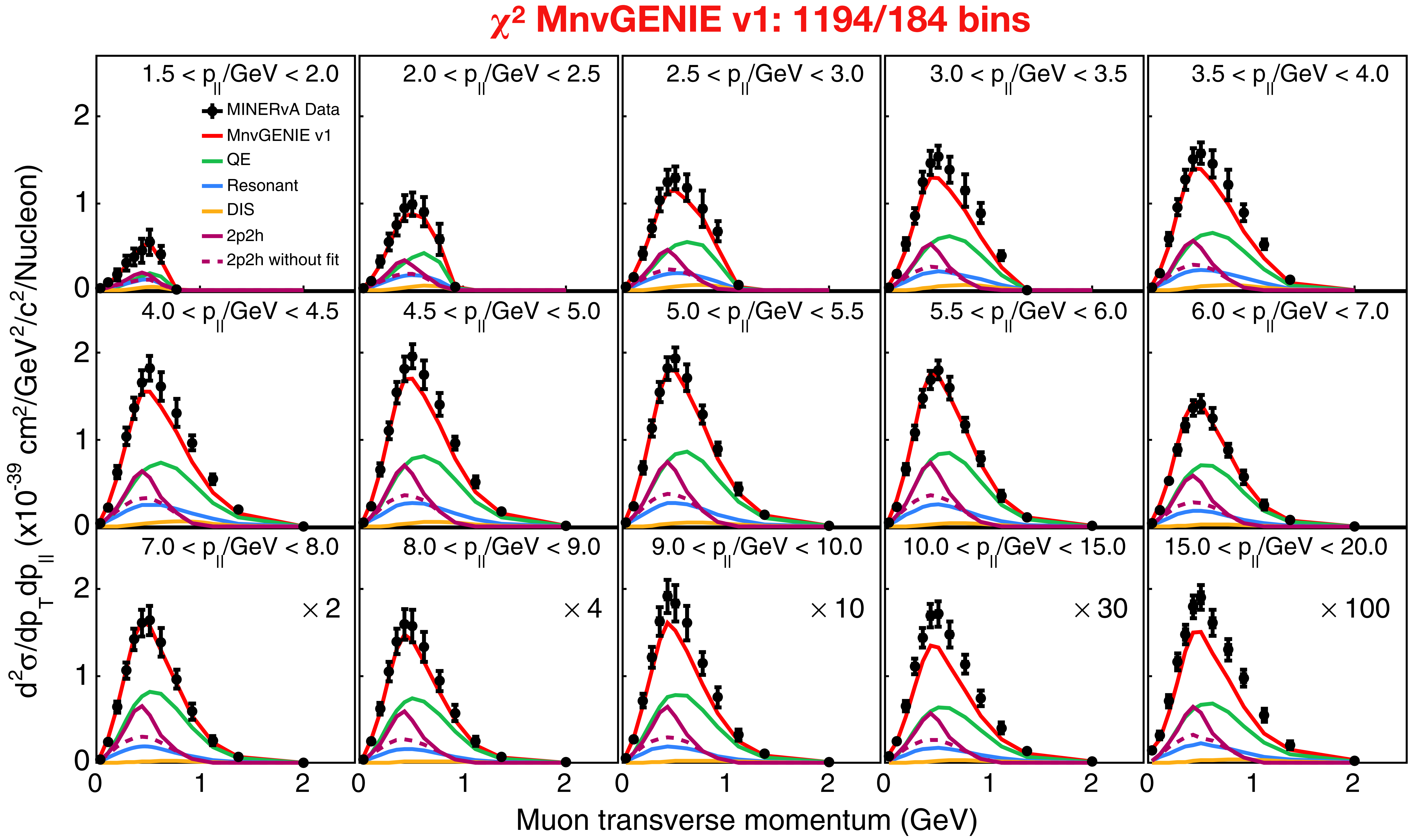
Phys. Rev. D 100, 092001 (2019)





MINERvA ν_μ CCQE-like cross section

- First ME cross section publication **Phys. Rev. Lett. 124, 121801 (2020)**
  - Uses ν-e^- result to reduce flux systematic uncertainties
- Signal definition: 1 muon, 0 mesons, 0 heavy baryons, and any number of nucleons
  - Note that this definition of "CCQE-like" is **different from MicroBooNE's** (CC1p0π)
- Data compared to generator predictions, including special GENIE v2.12.6 tunes by MINERvA
  - **MnvGENIE v1**: RPA corrections to CCQE + add 2p2h + adjust non-resonant π production



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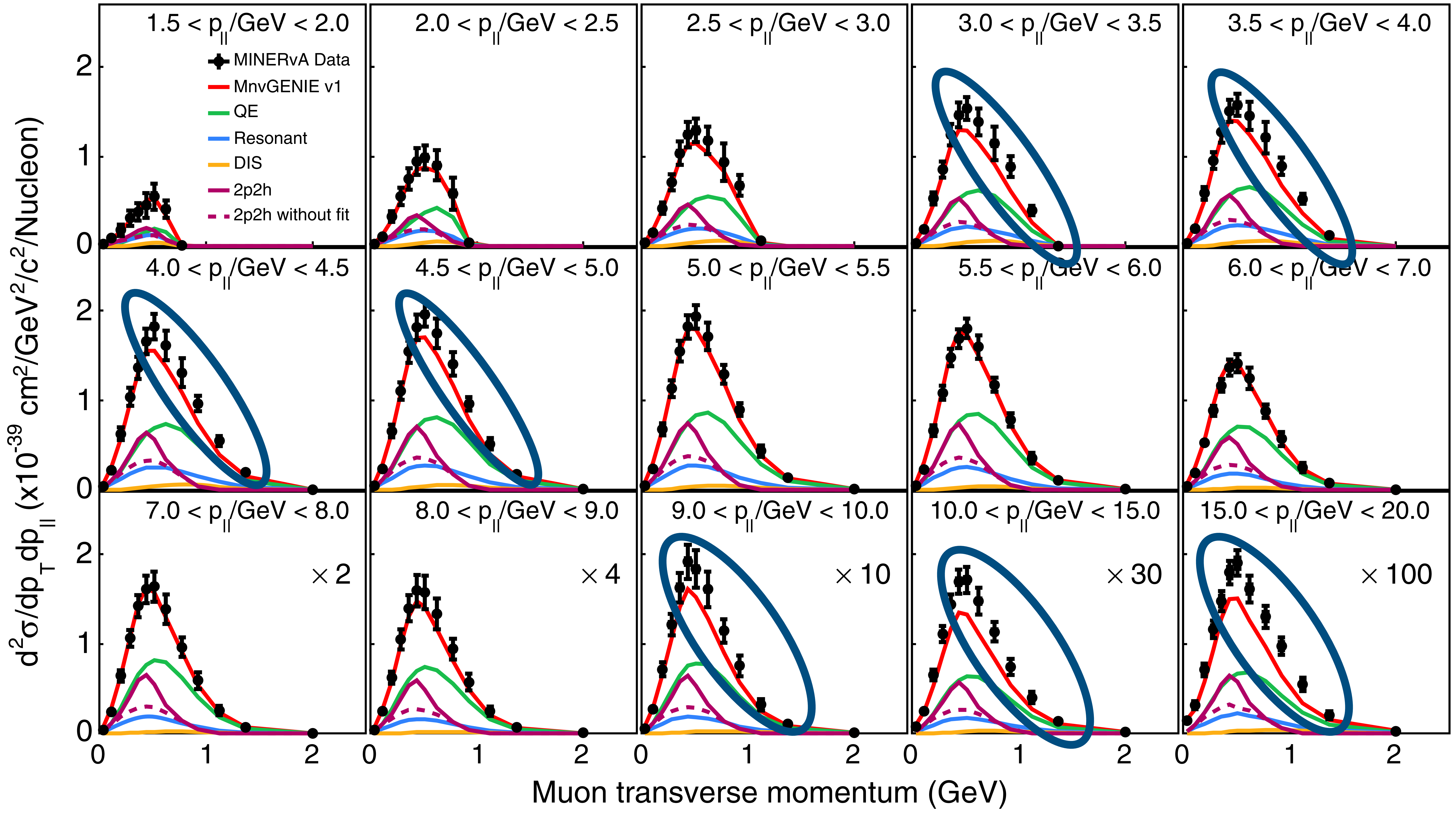
χ^2 MnvGENIE v1: 1194/184 bins

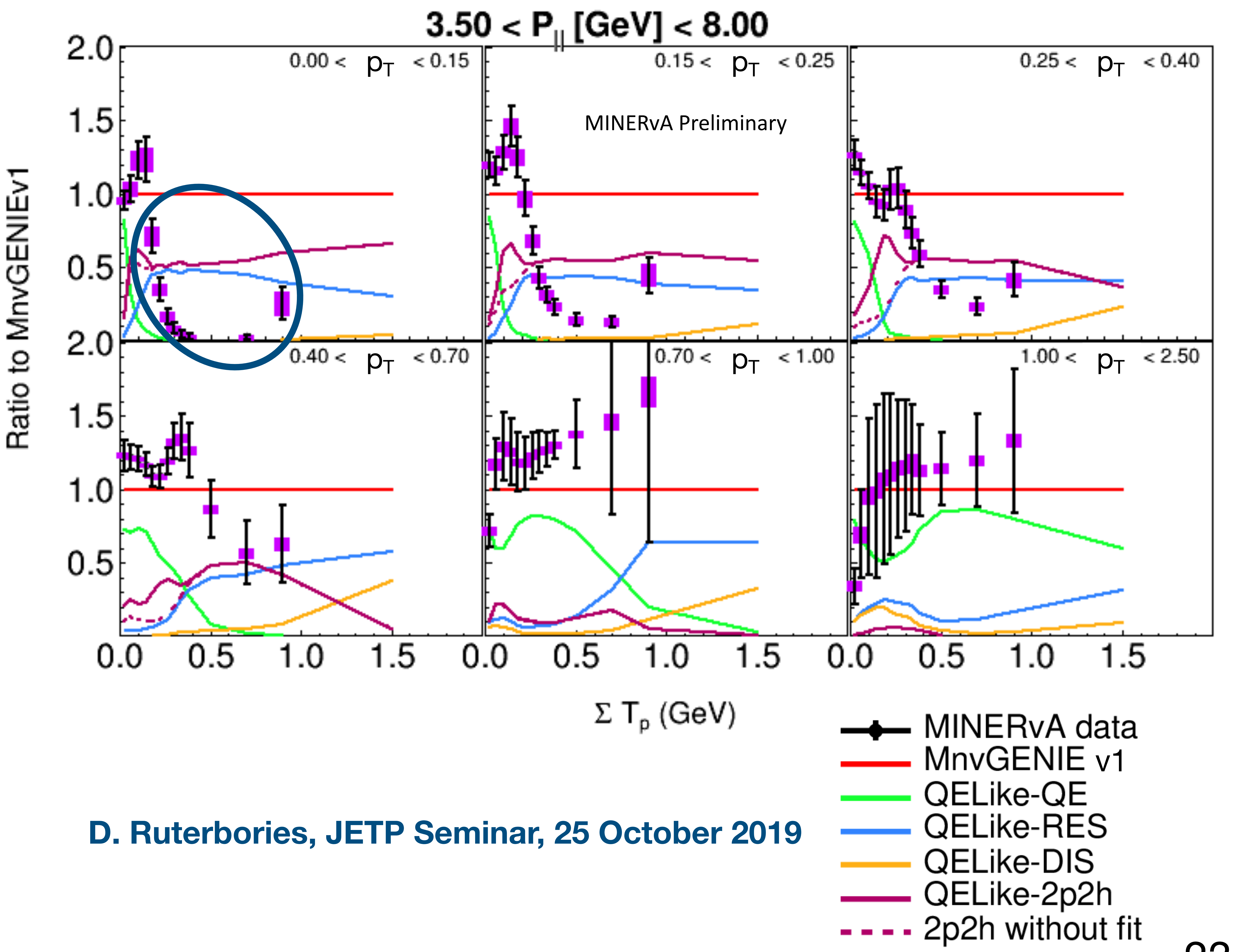


Underprediction of the cross section for high p_T and both $3 < p_{\|}/\text{GeV} < 5$ and $9 < p_{\|}/\text{GeV} < 20$. Tuning of QE contribution needed?

Backup: 1D $d\sigma/dQ^2_{\text{QE}}$ measurement

Triple-differential ν_μ CCQE-like cross section

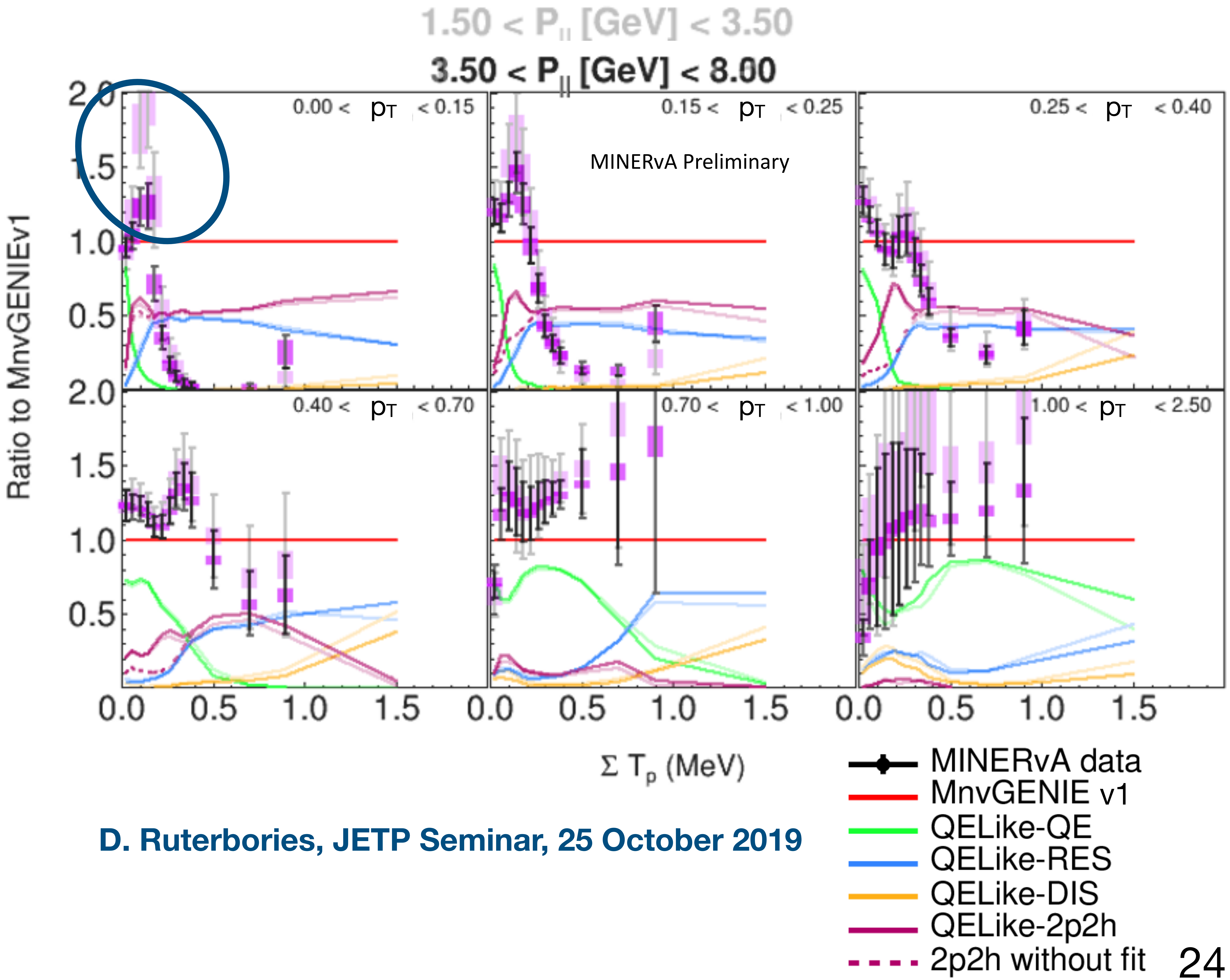
- **Extend analysis to 3D**
  - Correlate ΣT_p with muon kinematics
  - Very sensitive to nuclear effects!
- Reveals need for substantial model improvements
  - Combination of FSIs & 2p2h+RES strength



D. Ruterbories, JETP Seminar, 25 October 2019

Triple-differential ν_μ CCQE-like cross section

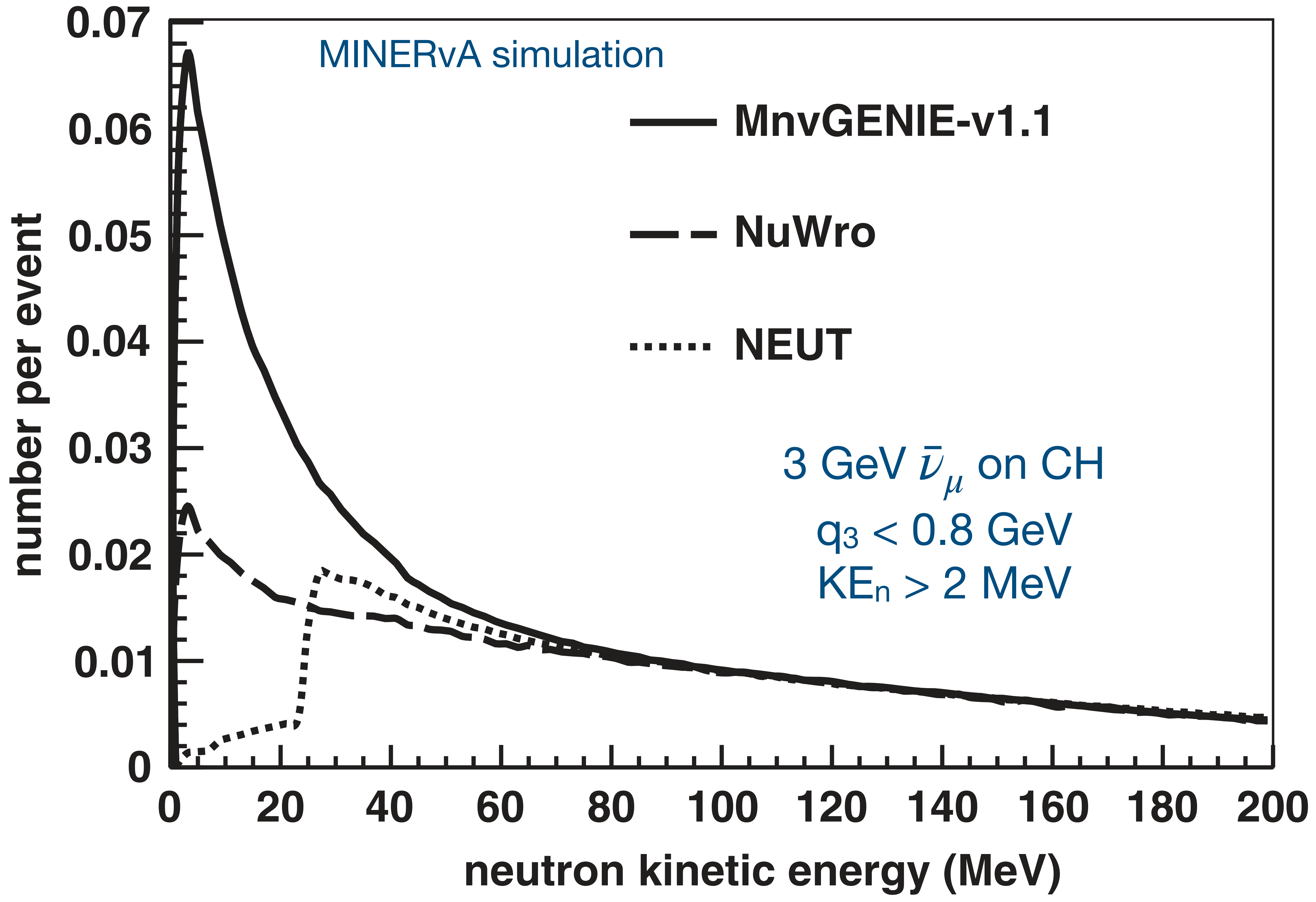
- **Extend analysis to 3D**
  - Correlate ΣT_p with muon kinematics
  - Very sensitive to nuclear effects!
- Reveals need for substantial model improvements
  - Combination of FSIs & 2p2h+RES strength
- Data/MC ratio is mostly consistent across $p_{||}$ bins → **good modeling of energy dependence**
  - An exception is low p_T



D. Ruterbories, JETP Seminar, 25 October 2019

Neutrino-induced neutrons in MINERvA

- Neutron multiplicities and kinematic distributions are difficult to predict
  - Substantial differences between generators
  - Modeling of secondary neutron production also needed (Geant4)
- LE analysis: $\bar{\nu}_\mu$ CC in CH active tracker
  - **Phys. Rev. D 100, 052002 (2019)**
  - Multiplicity, time-of-flight, position, speed (1/β), E_{dep}
  - Detection via p recoils, inelastic n-C scatters (p, γ, fragments) → ~10 MeV kinetic energy threshold
- ME analysis in progress
  - More efficient, 7.5× more data!
  - Data for **multiple targets**



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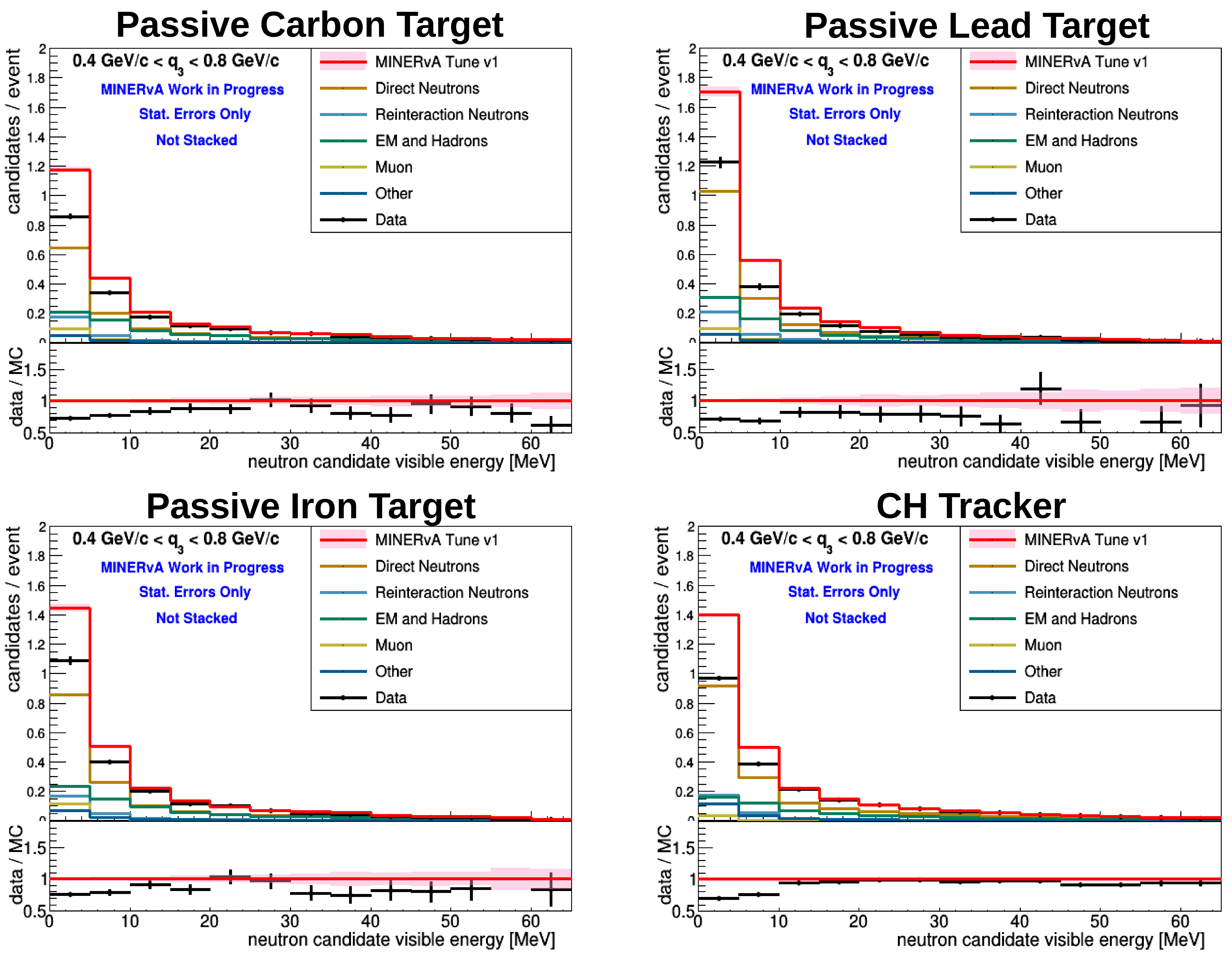
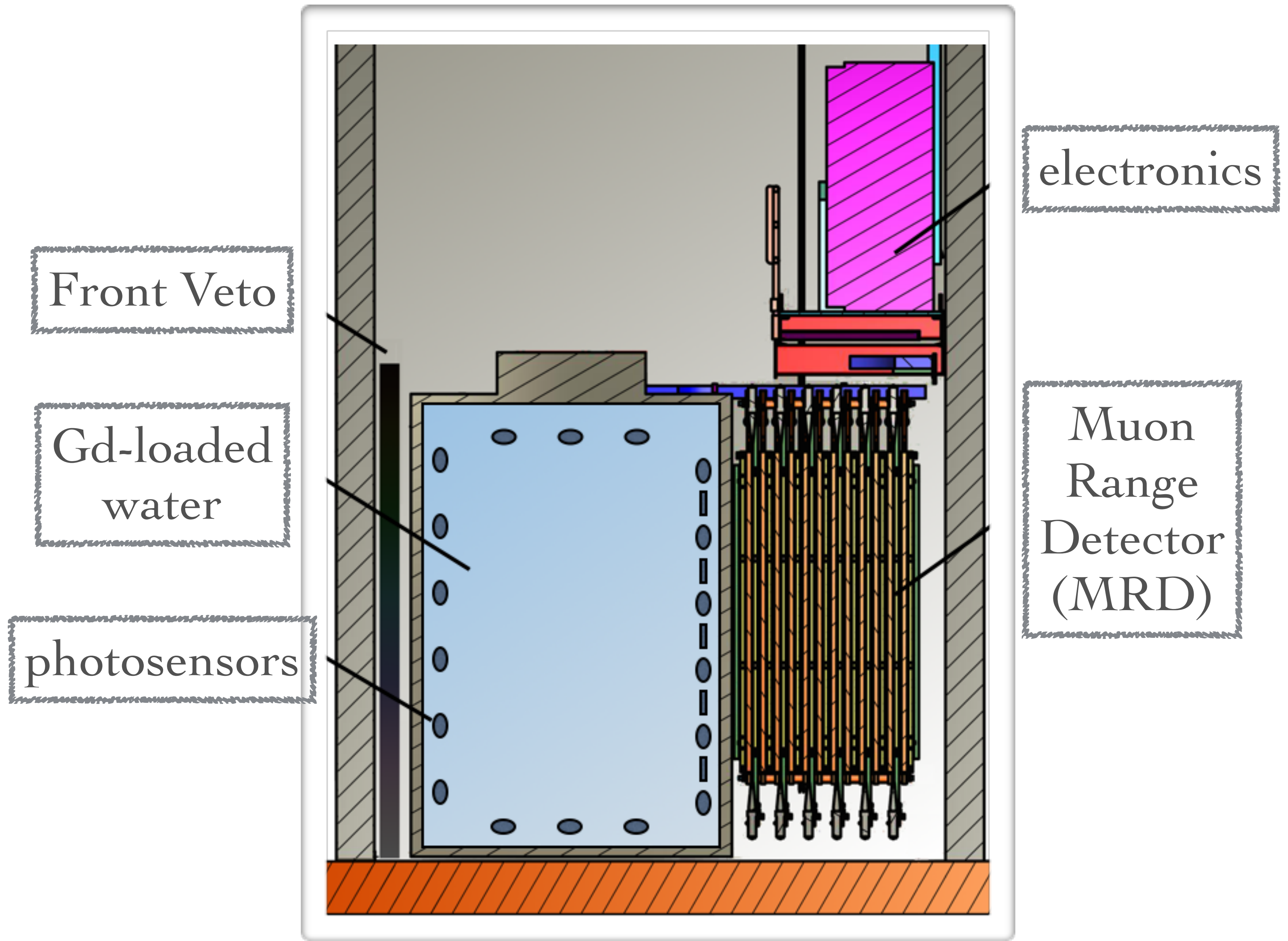
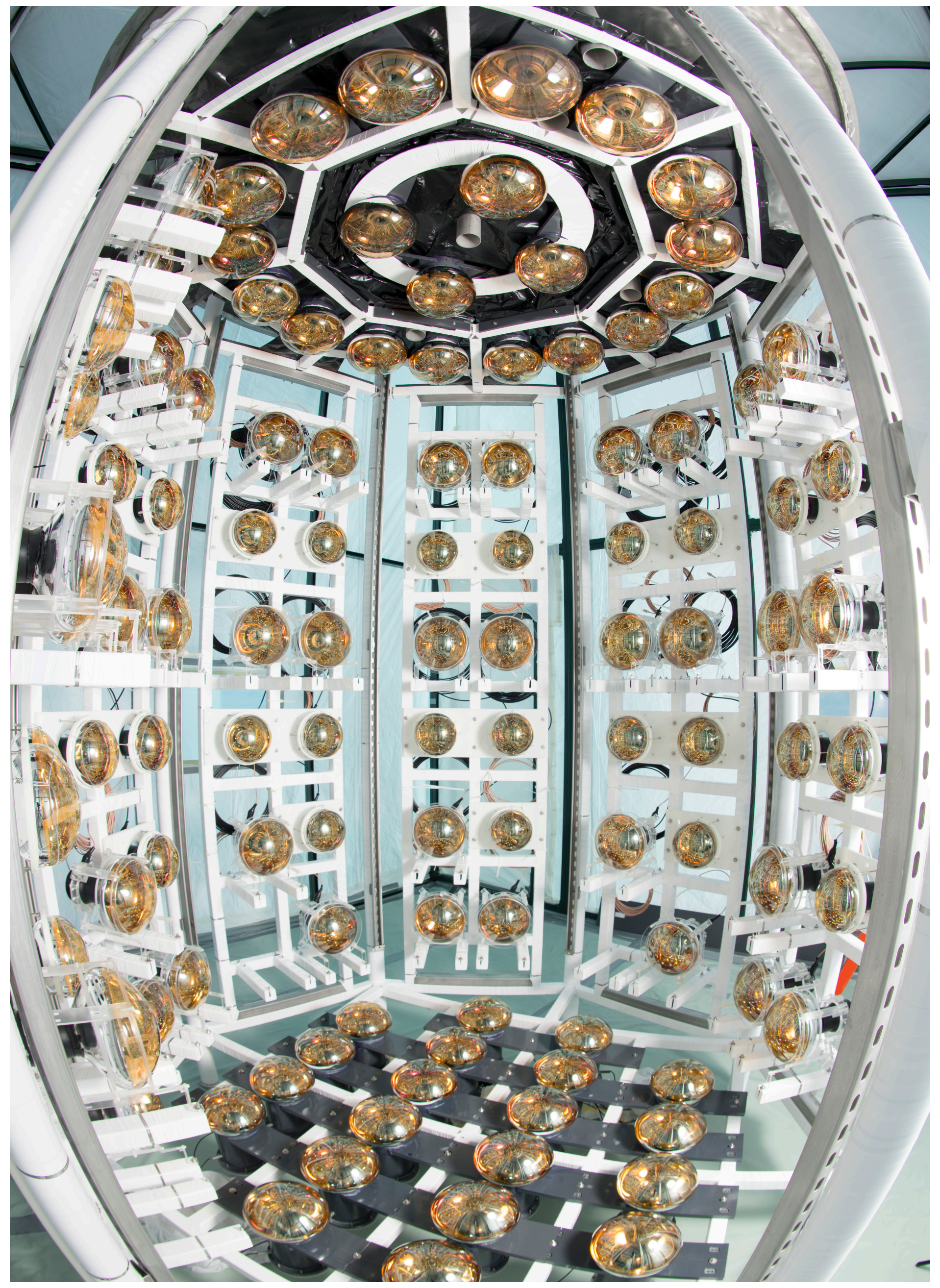


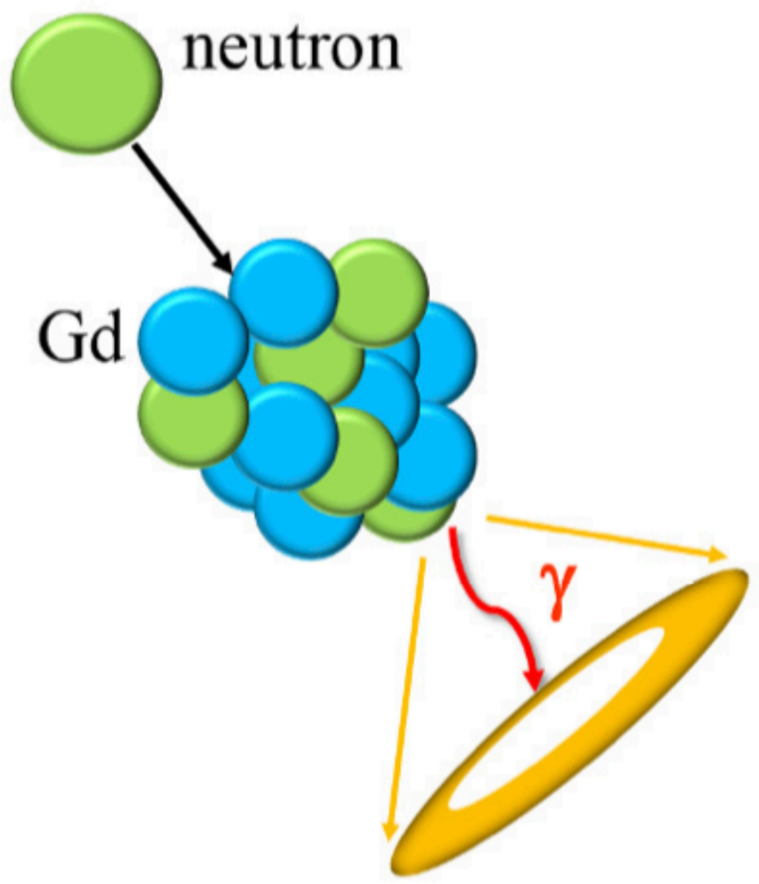
A. Olivier, New Perspectives 2020

The ANNIE experiment

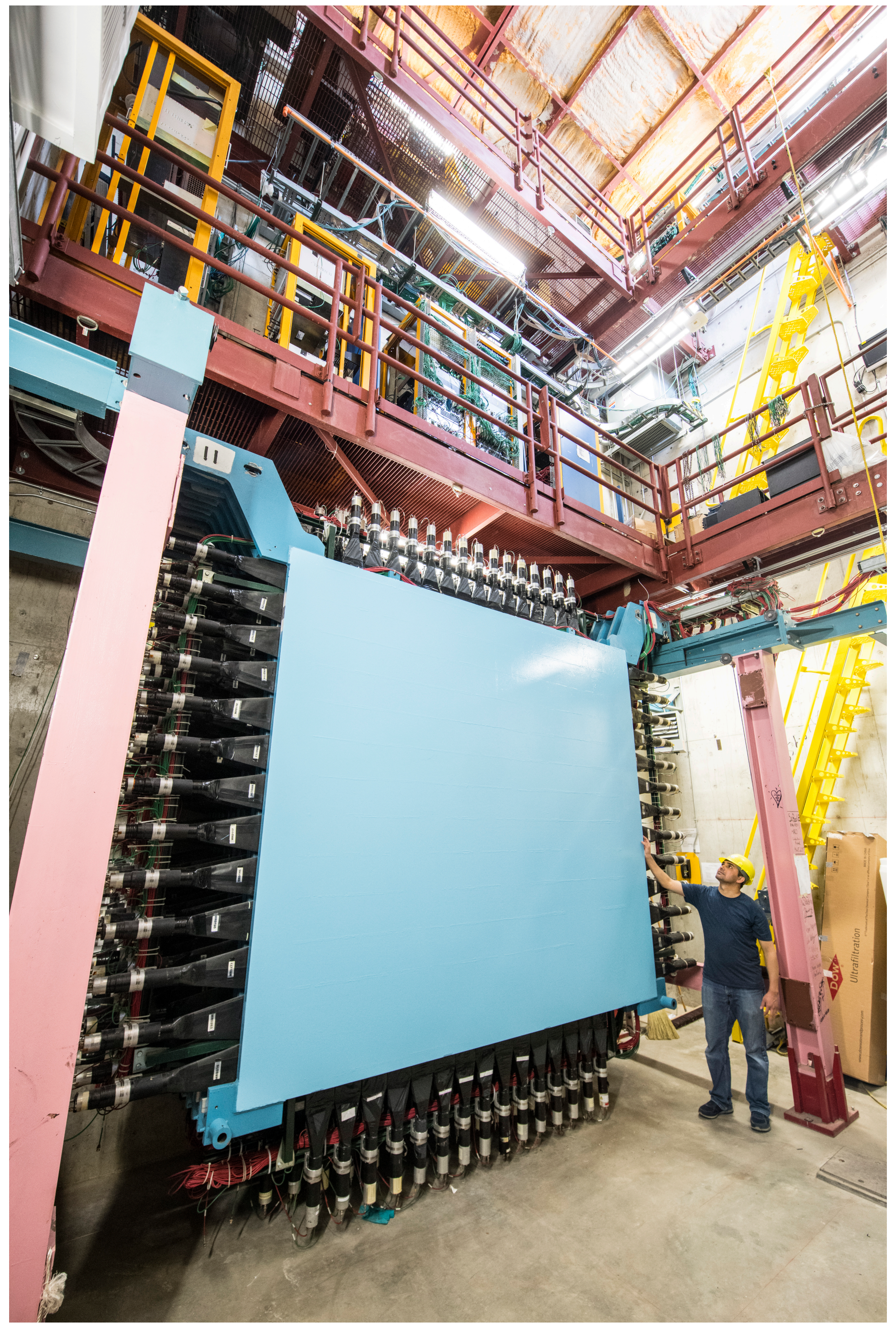
- Water Cherenkov detector installed in the Booster Neutrino Beam (~100 m from target)
  - 26 tons of Gd-loaded water
- **Physics mission**: measure neutrino-induced neutron yields as a function of outgoing lepton kinematics
- **Capture-based strategy** (no threshold)
  - Complementary to MINERvA measurements based on neutron scattering





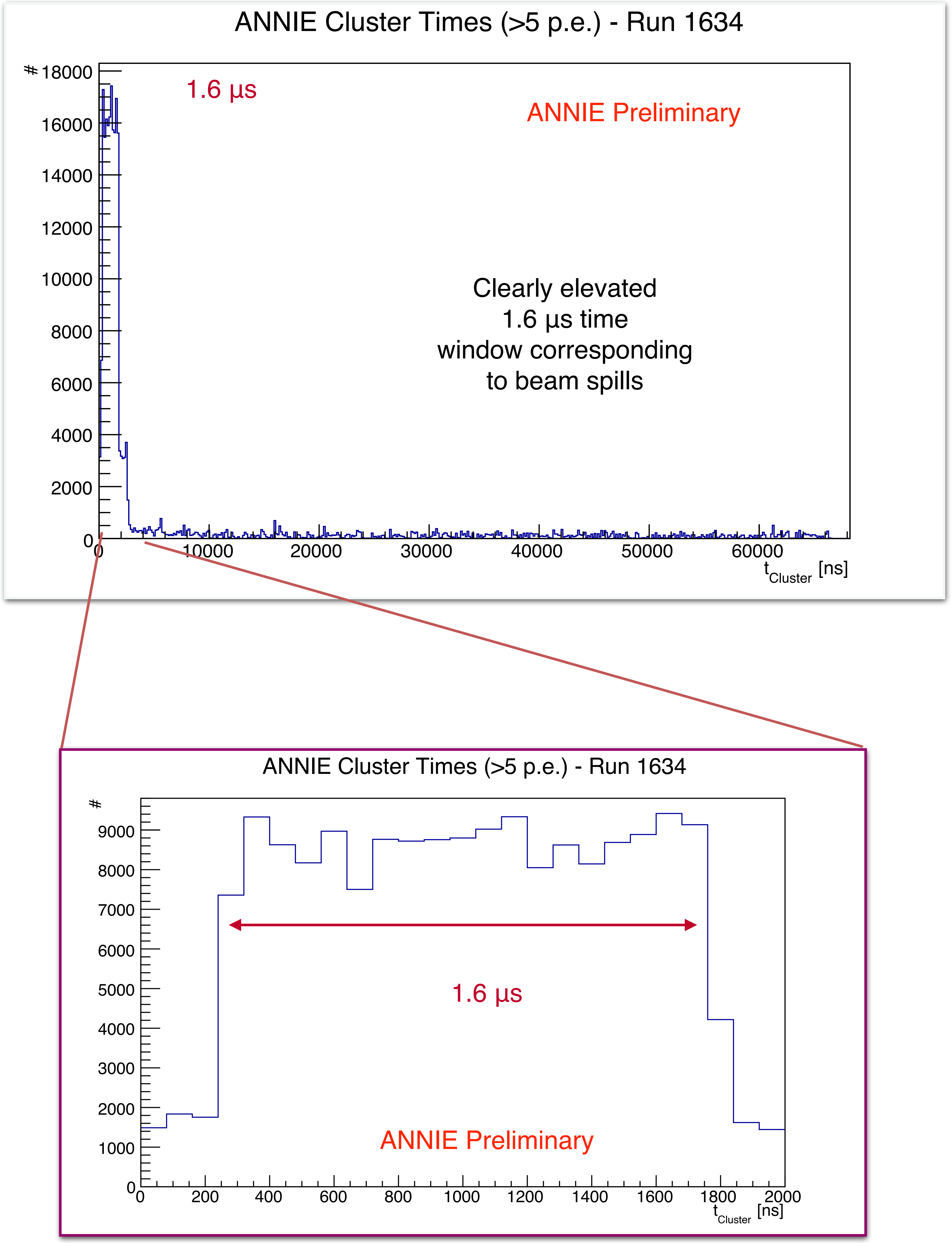


Gd-loading allows neutron tagging with high efficiency
Capture cross section: 5×10^{4} barn
Total energy in γ-rays: ~8 MeV



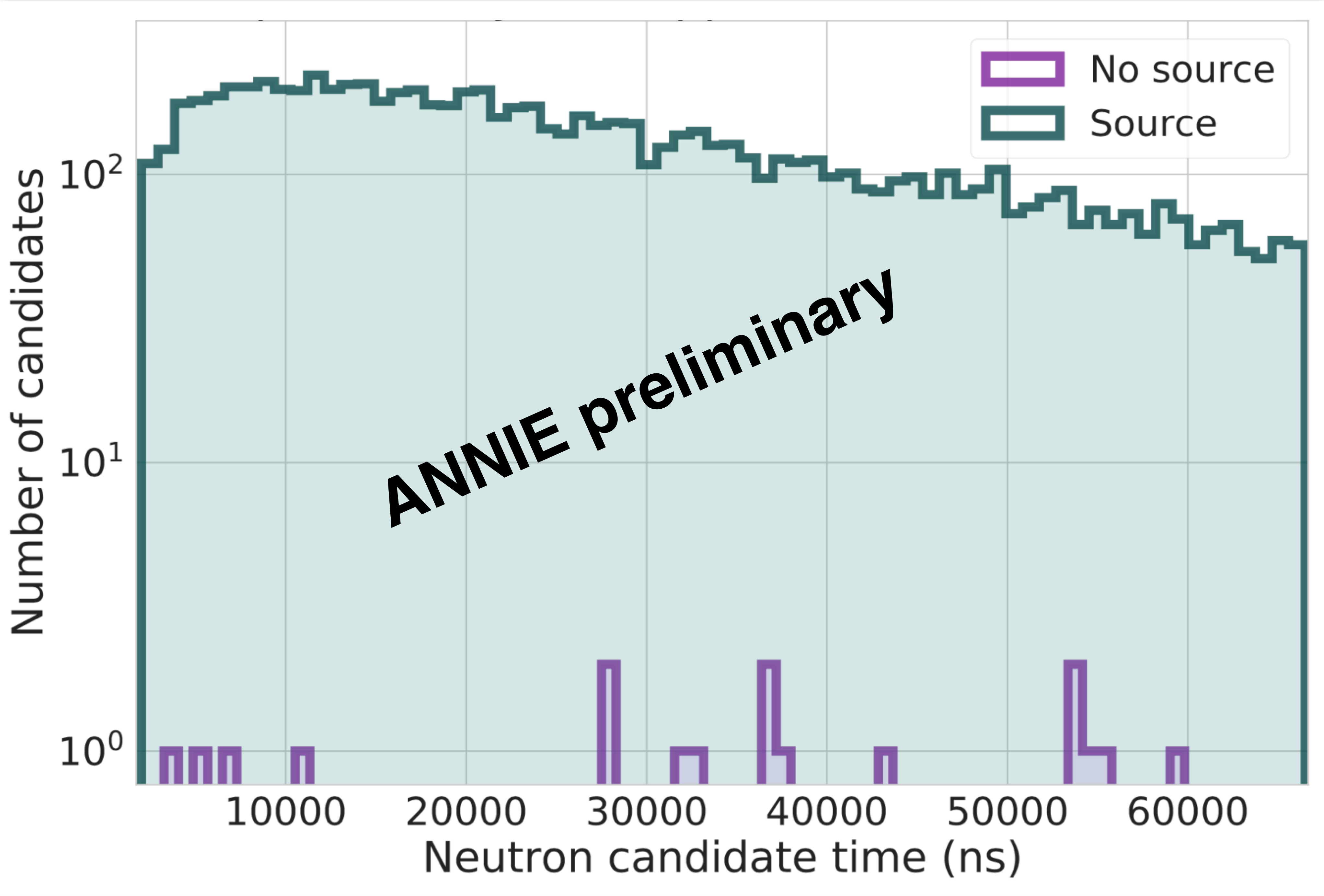
ANNIE status: neutrinos

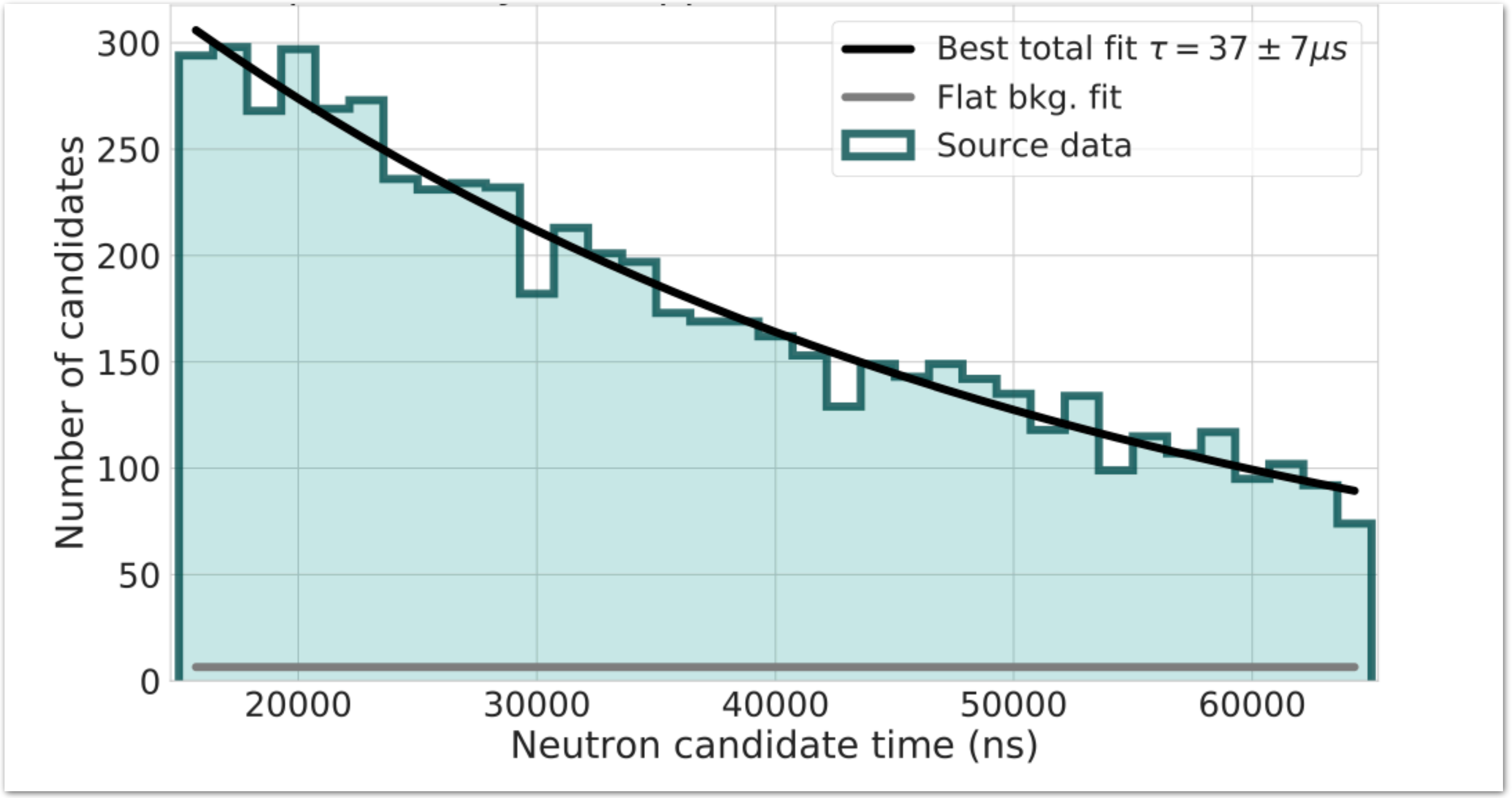
- Physics-quality data taking expected to start this Fall
- **First beam neutrinos seen**: elevated tank activity during 1.6 μsec beam spill
- 70 μsec readout window spans multiple capture times



ANNIE status: neutrons

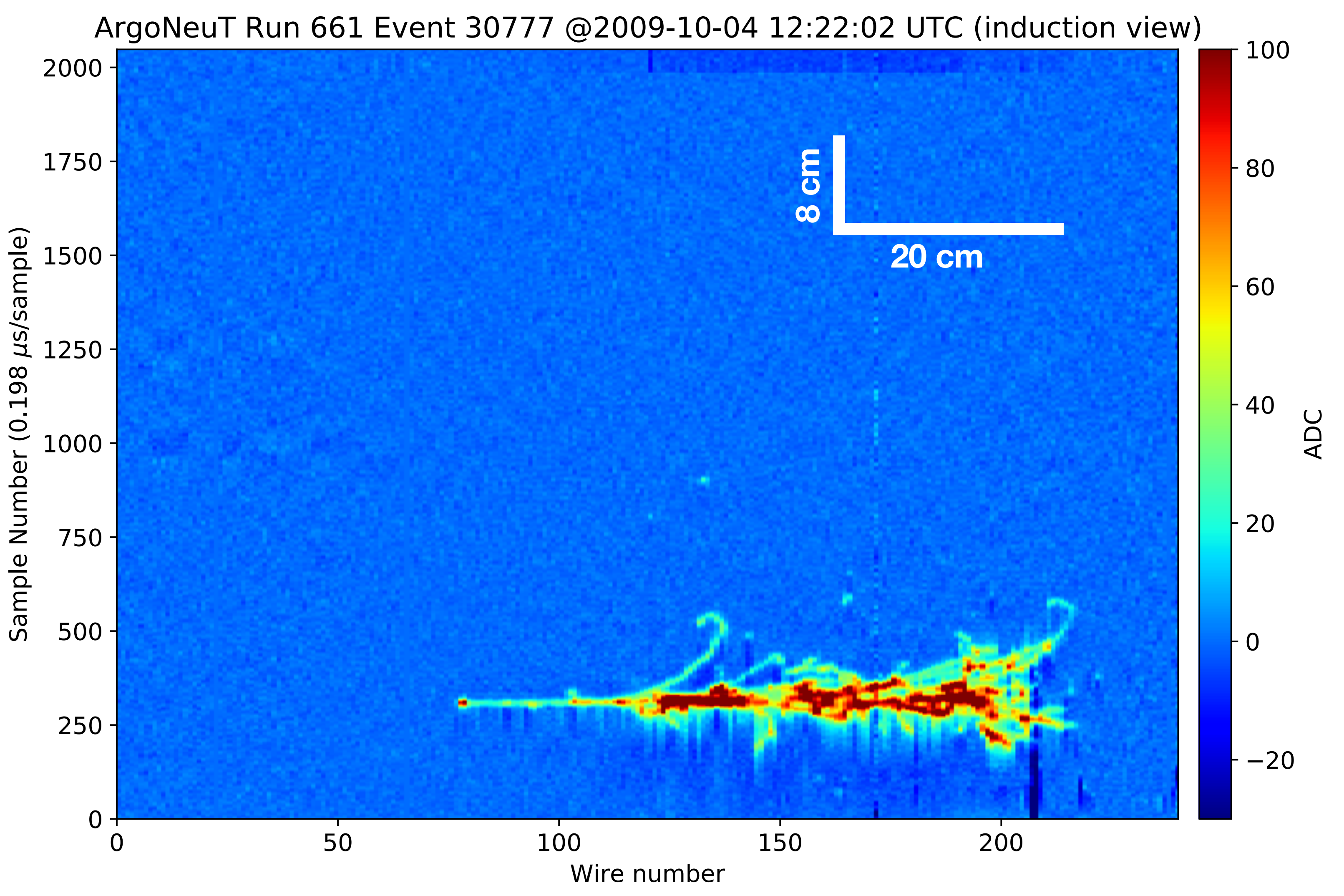
- AmBe source calibrations have now been performed
  - Determine efficiency for tagging neutron captures
  - Source data consistent with expected capture time distribution
- **ANNIE can see neutrons!**
- Beam-correlated neutron backgrounds previously found to be manageable in ANNIE Phase-I
  - **JINST 15 (2020) 03, P03011**





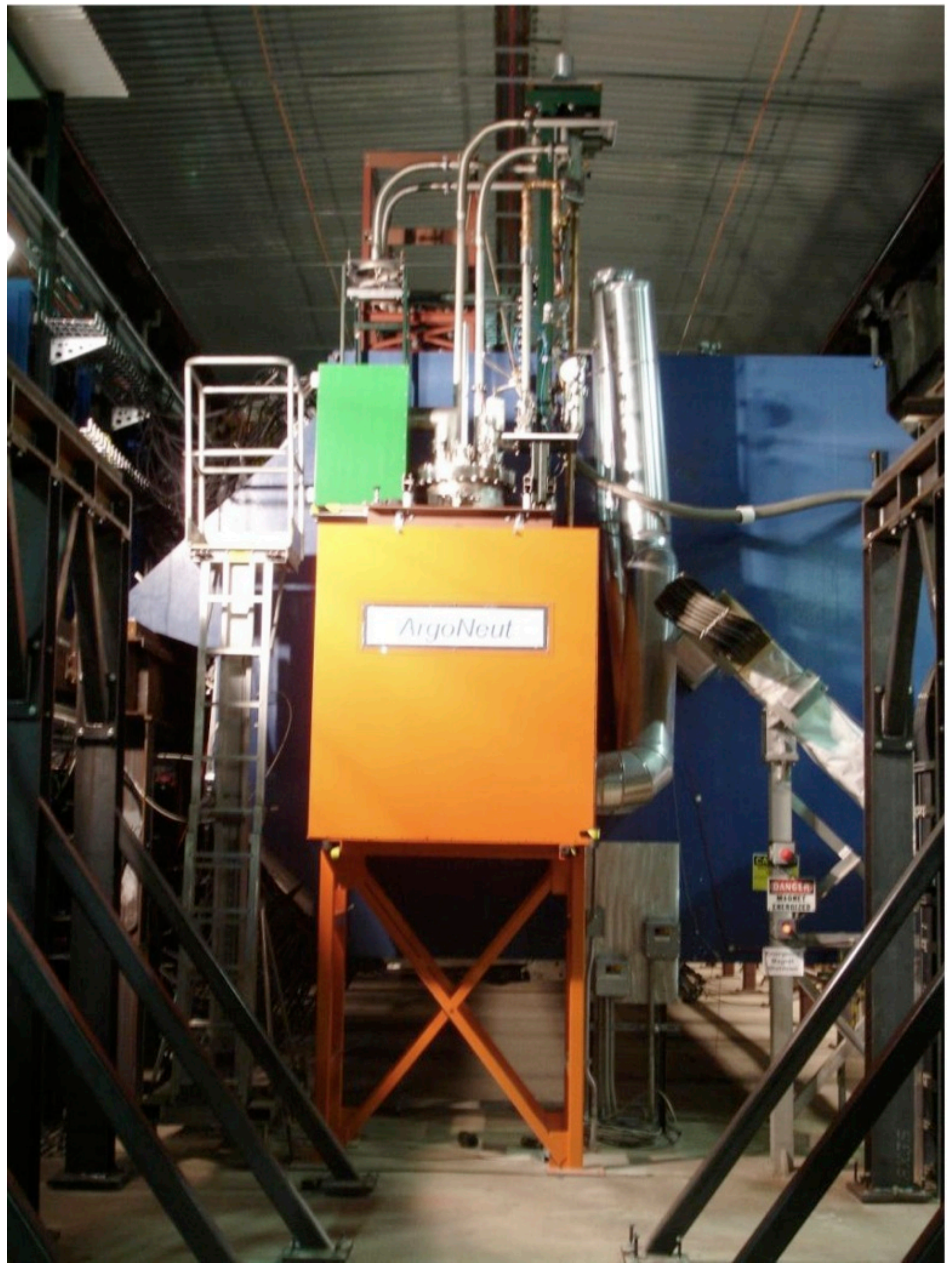
The ArgoNeuT experiment

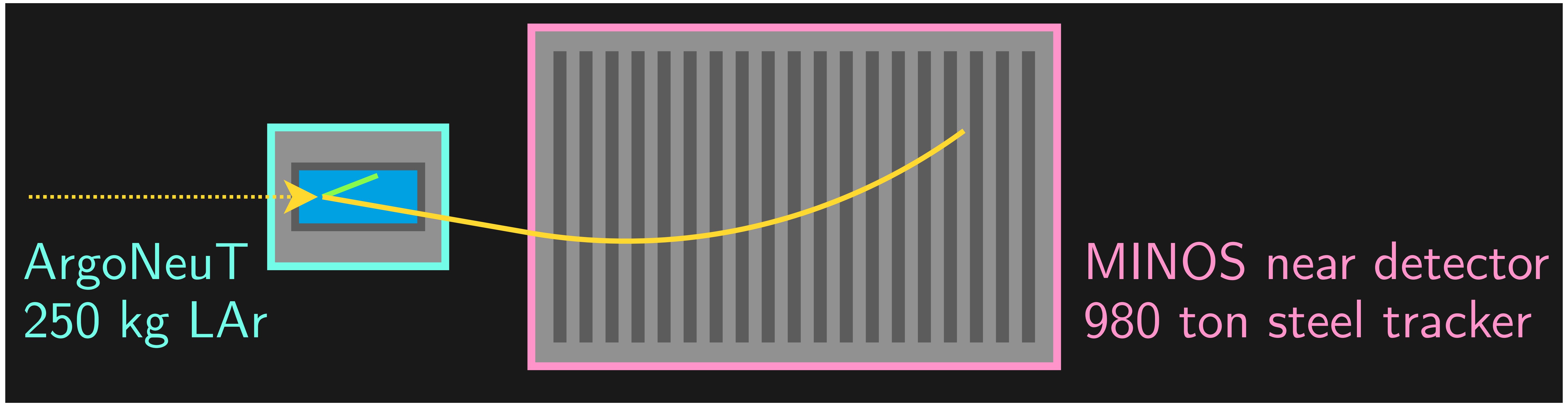
- Small LArTPC (40×47×90 cm³) that operated in the NuMI beam line from 2009–2010
- Many pioneering measurements
- Placed in front of MINOS near detector
  - Tracking muon spectrometer



ν_e CC candidate event display

Phys. Rev. D 102, 011101(R) (2020)

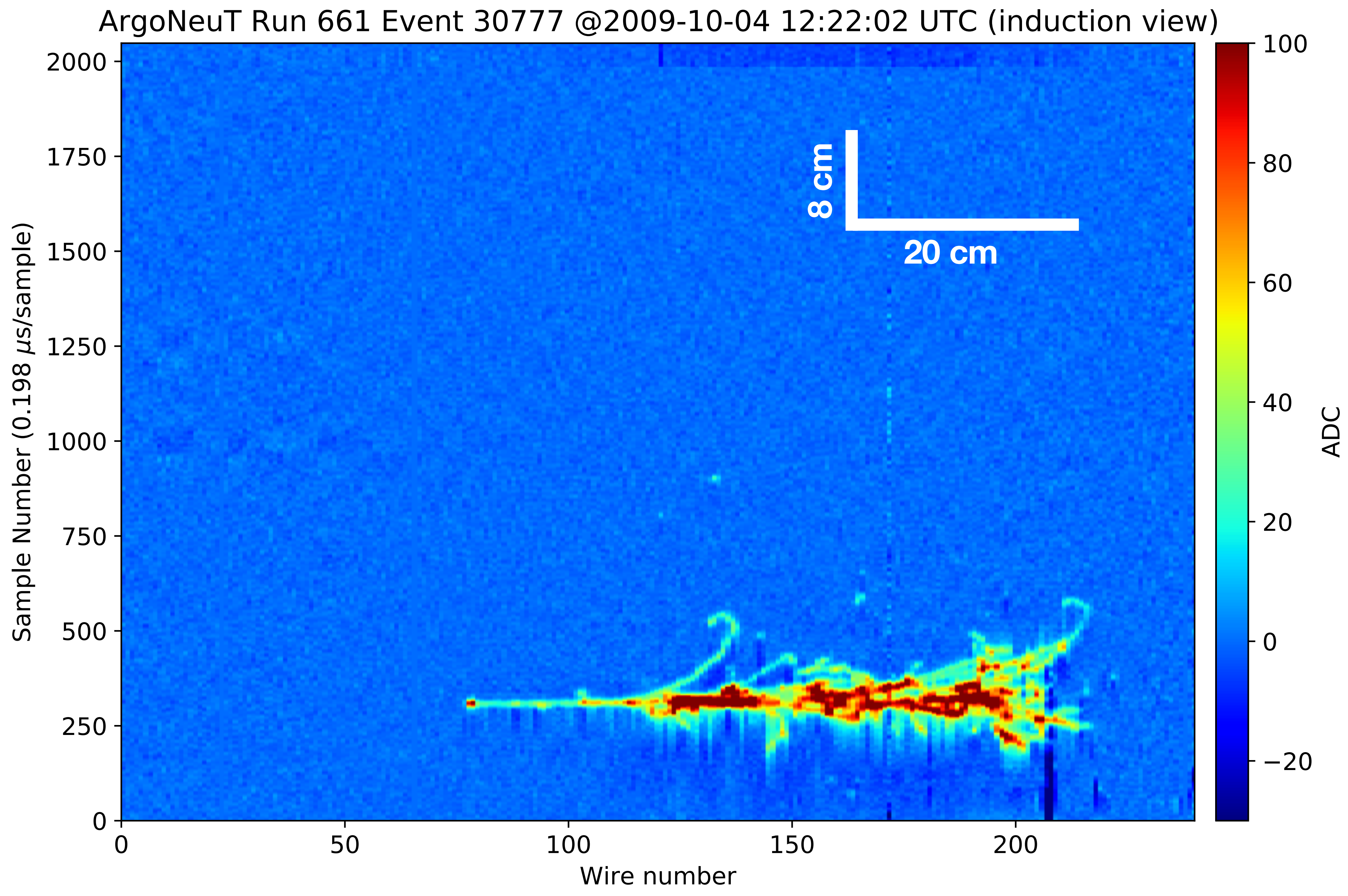


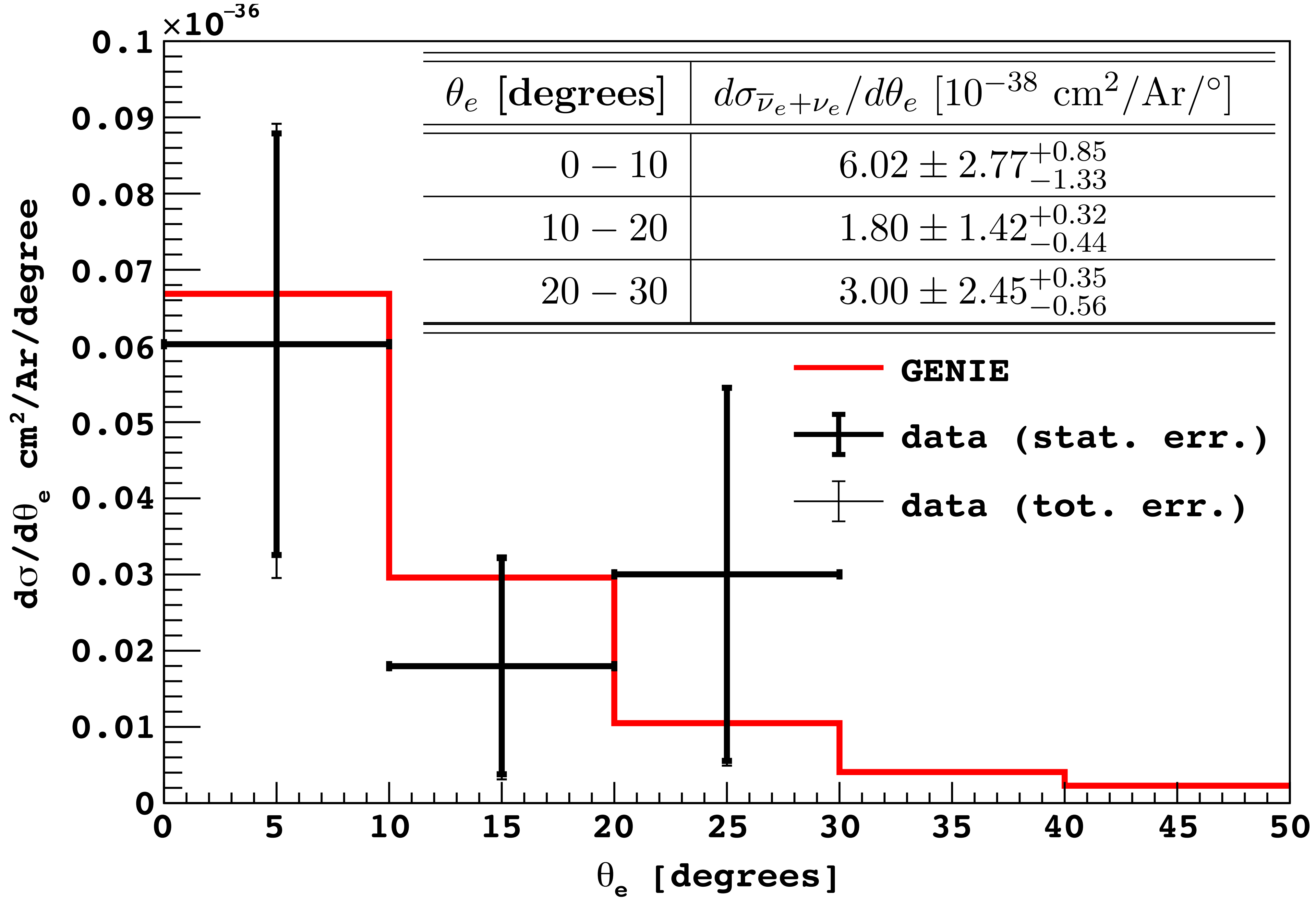


ArgoNeuT $\nu_e + \bar{\nu}_e$ CC inclusive analysis

- First measurement of this cross section on argon
  [Phys. Rev. D 102, 011101(R) (2020)]
- 13 events identified using fully automated selection & reconstruction
- Good agreement with GENIE
- **Backup**: Demonstration of MeV-scale reconstruction in a LArTPC
  [Phys. Rev. D 99, 012002 (2019)]

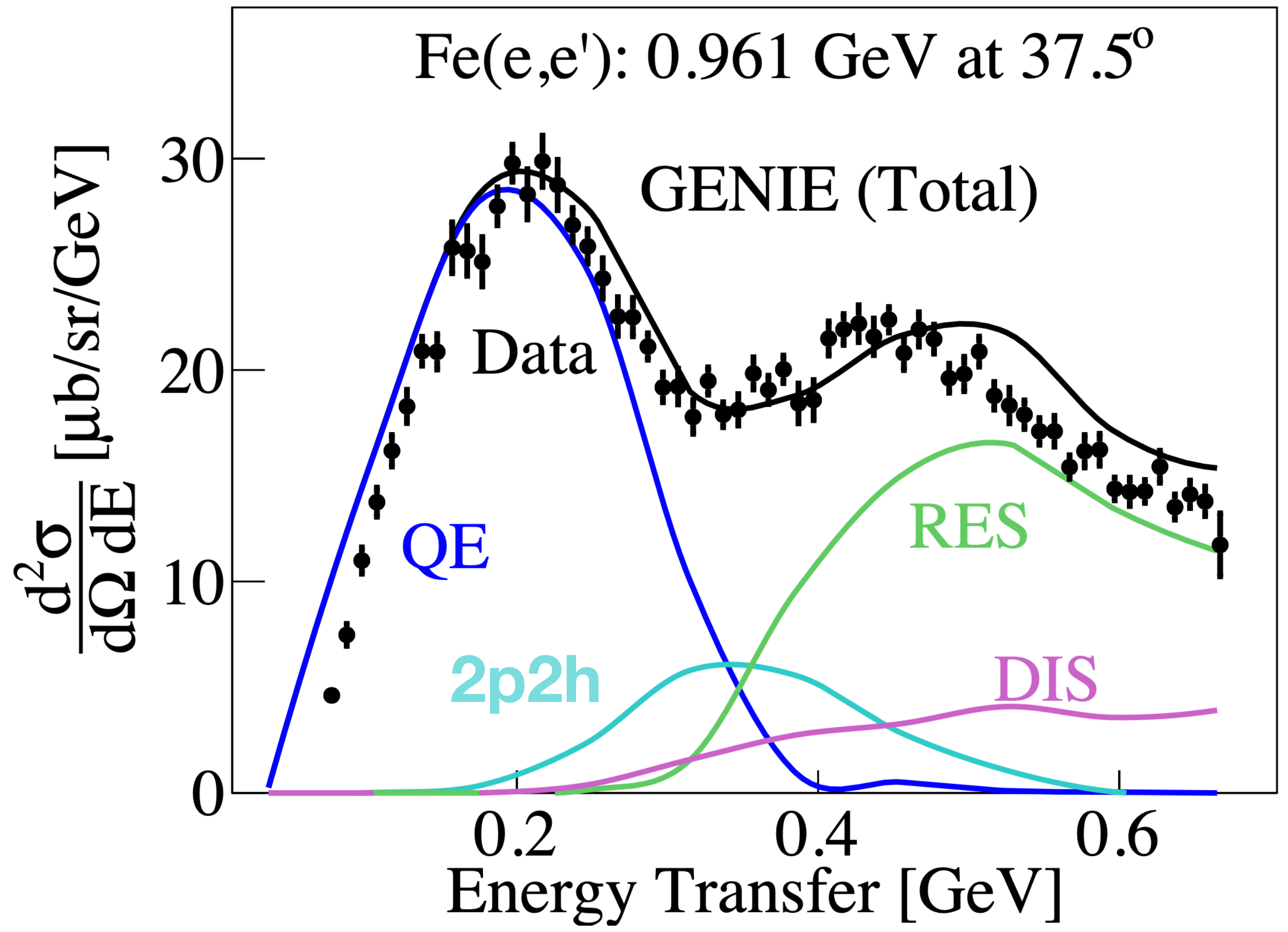
ν_e CC candidate event display



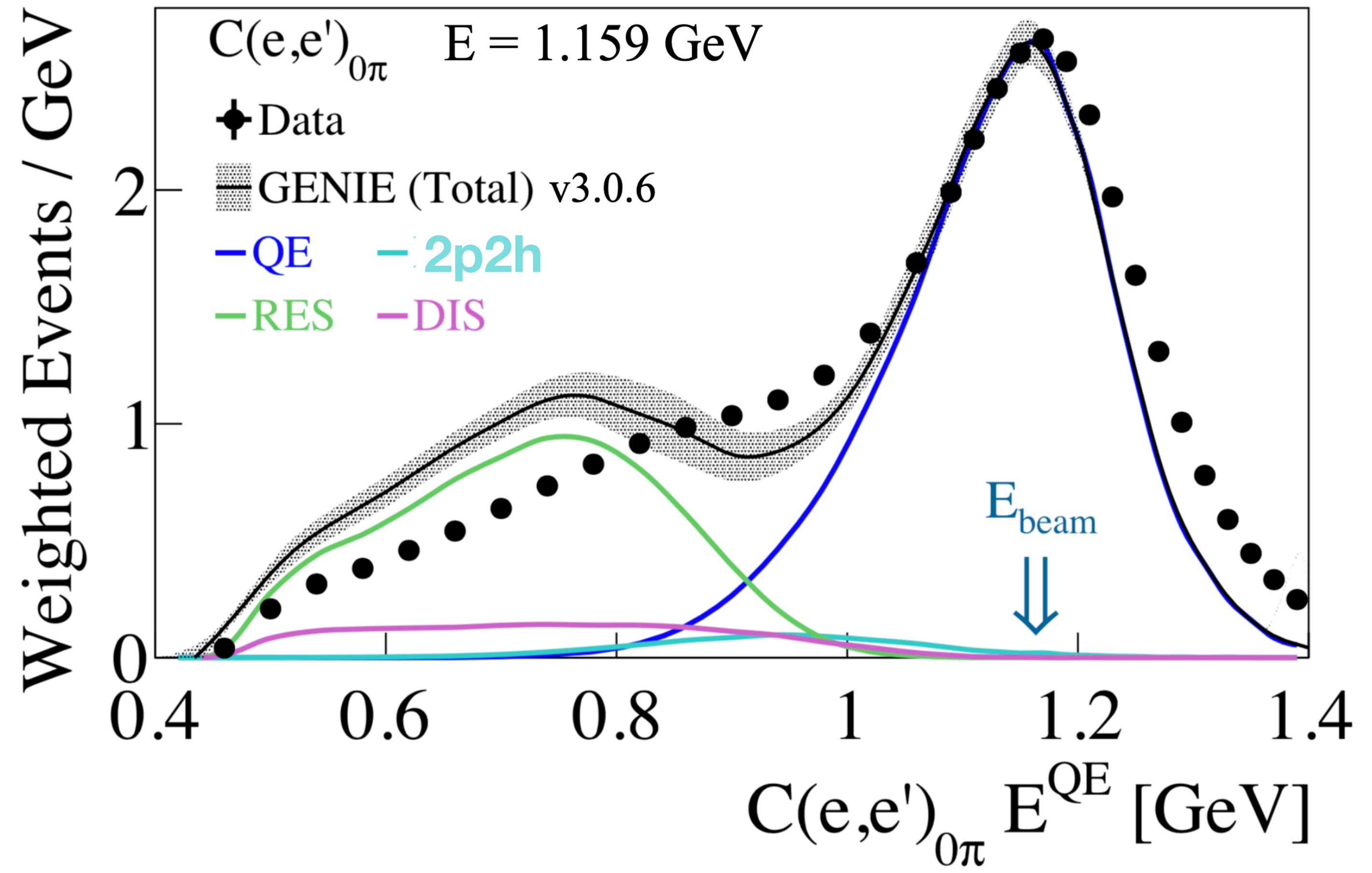


Electrons for Neutrinos ($e4\nu$)

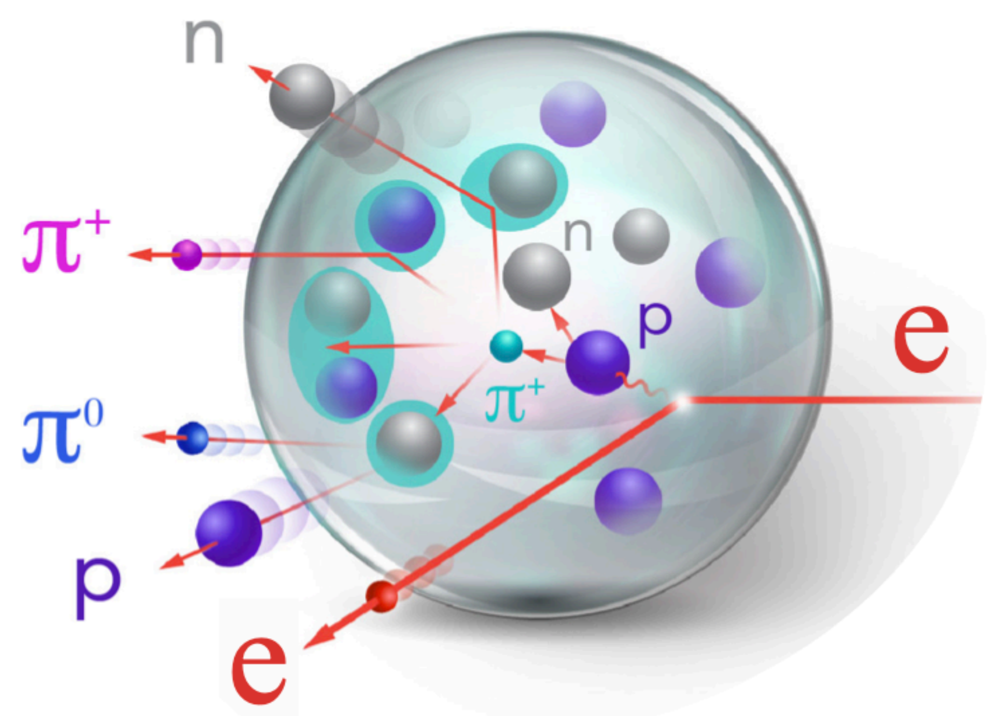
- Electron-nucleus scattering shares many similarities to the neutrino case
- Projectile energy precisely known
  - Test energy reconstruction techniques
- The $e4\nu$ collaboration works to improve neutrino generators by
  - Benchmarking predictions against electron scattering data
  - Improving quality & consistency of e^-/ν modeling
  - Pursuing new measurements
- Similar studies carried out for GENIE v2 by Ankowski & Friedland (arXiv:2006.11944)
- Related measurements also **proposed for LDMX** by Ankowski *et al*. (Phys. Rev. D 101, 053004)



A. Ashkenazi, Neutrino 2020

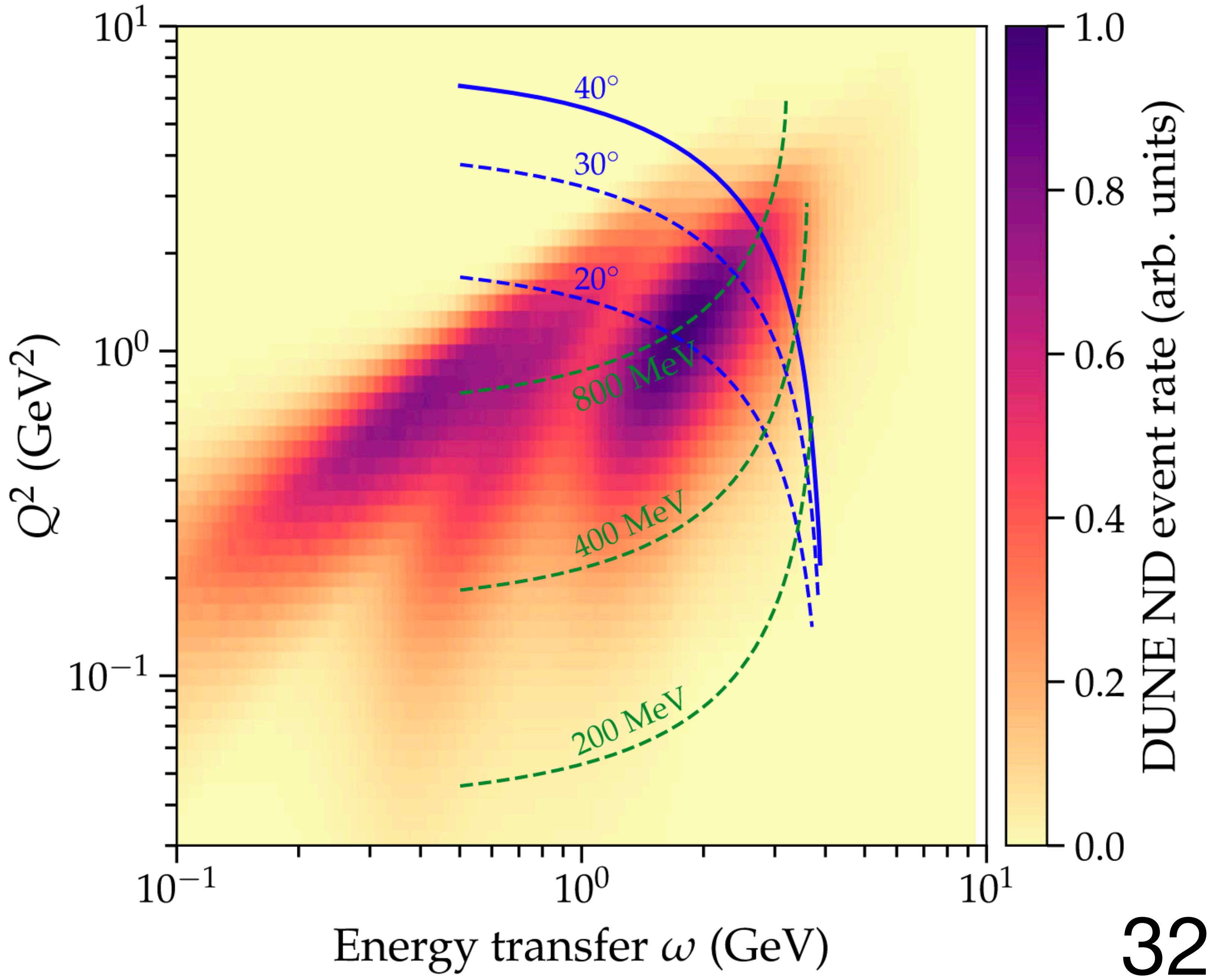


Genie v3.0.6 tune G18_10a_02_11a



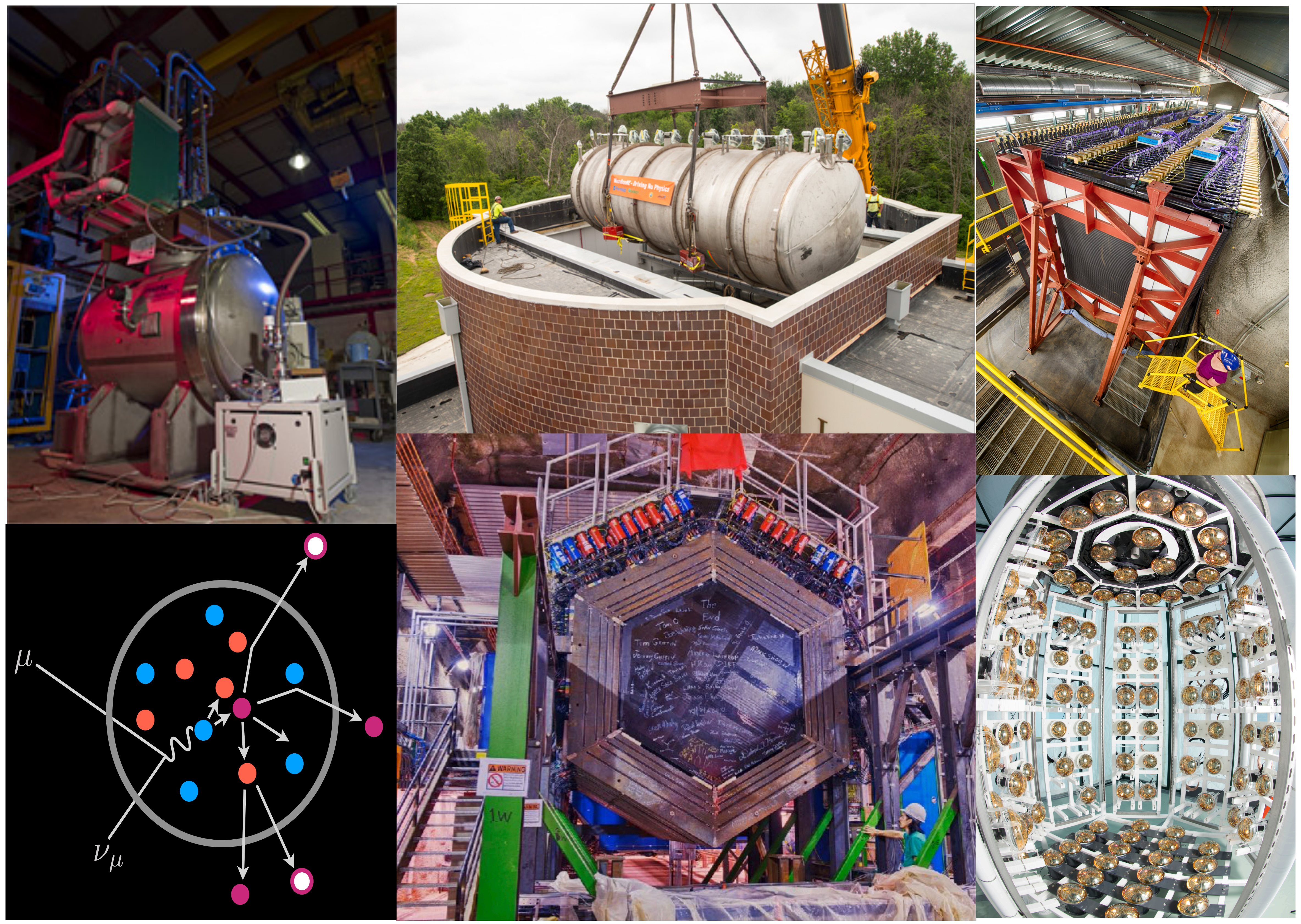
LDMX can probe kinematic regions ($\theta_e < 40^\circ$ on the plot) of high importance for DUNE

Phys. Rev. D 101, 053004



Conclusion

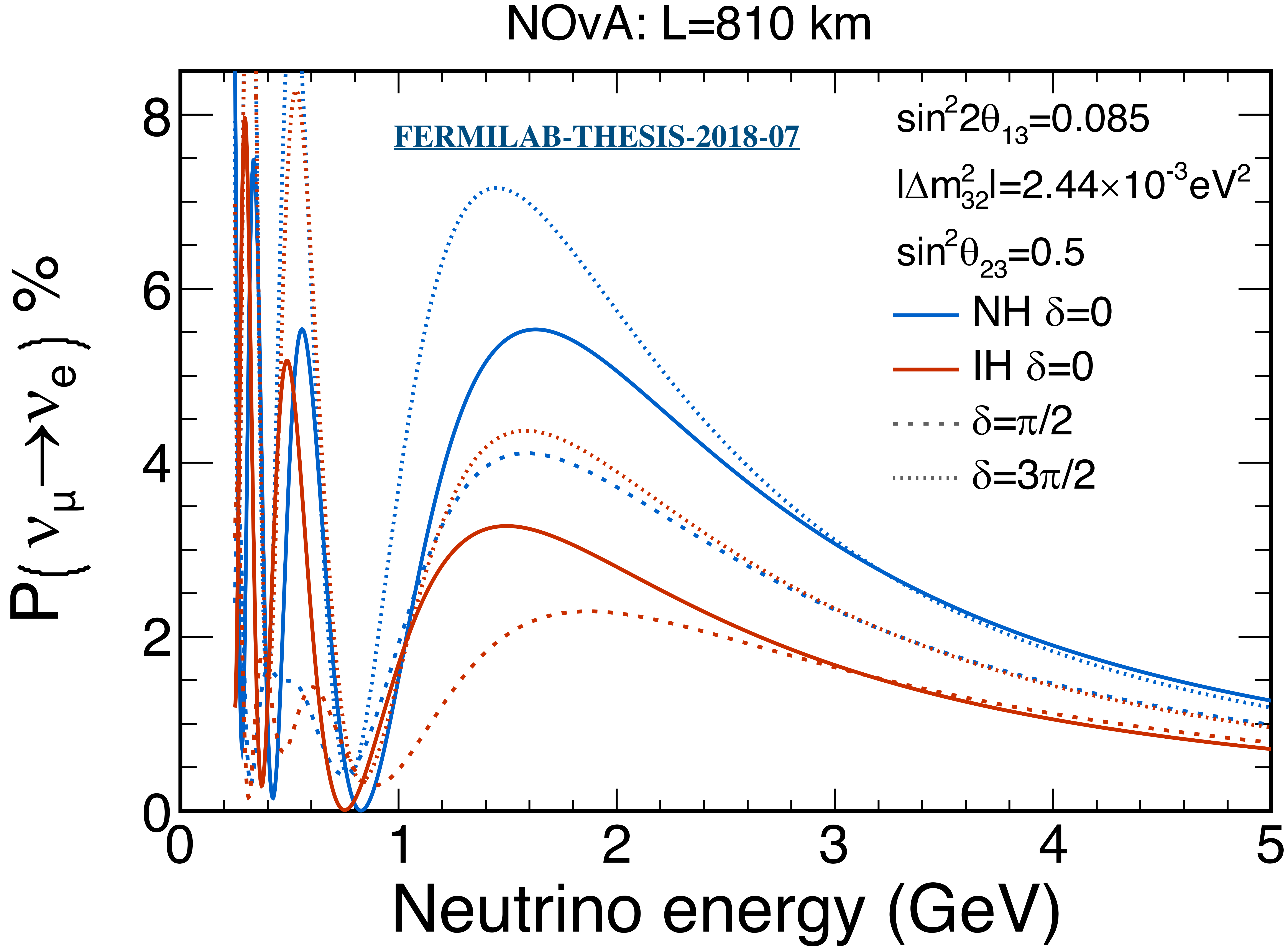
- The neutrino cross section program at Fermilab is delivering foundational results crucial for the success of current and future neutrino oscillation experiments
- Many people have worked tirelessly to do the cutting-edge science shown here. Congratulations on a job well done!
- Special thanks to all involved in delivering world-class, high-intensity neutrino beams to our detectors
- Stay tuned for much, much more as we move toward the era of SBN & DUNE



Backup

Neutrino oscillation measurements

- Precise measurements of **neutrino oscillation probabilities** will allow us to answer key questions
  - Leptonic CP violation
  - Neutrino mass hierarchy
  - Sterile neutrinos
- Detectors measure neutrino event rates rather than the probabilities themselves
- Oscillation parameters (θ, Δm^2, δ_{CP}) are inferred by comparing expected versus observed event rates



Cross sections for oscillation analyses

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

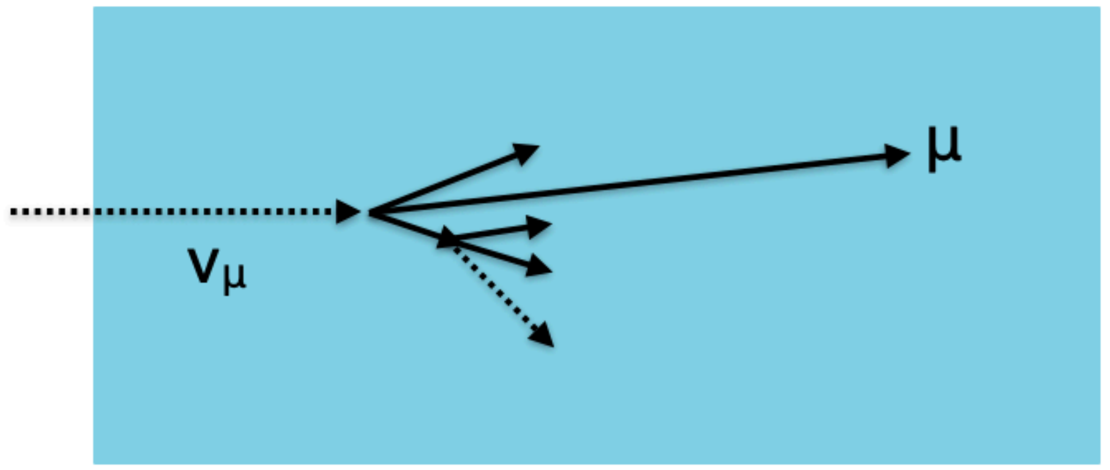
Required inputs for an oscillation analysis include:

- Prediction for the neutrino flux at the detector location
- Cross section models for both signal and background
- Selection efficiency
- Migration matrix: transform between $E_\nu^{\text{true}} \leftrightarrow E_\nu^{\text{reco}}$

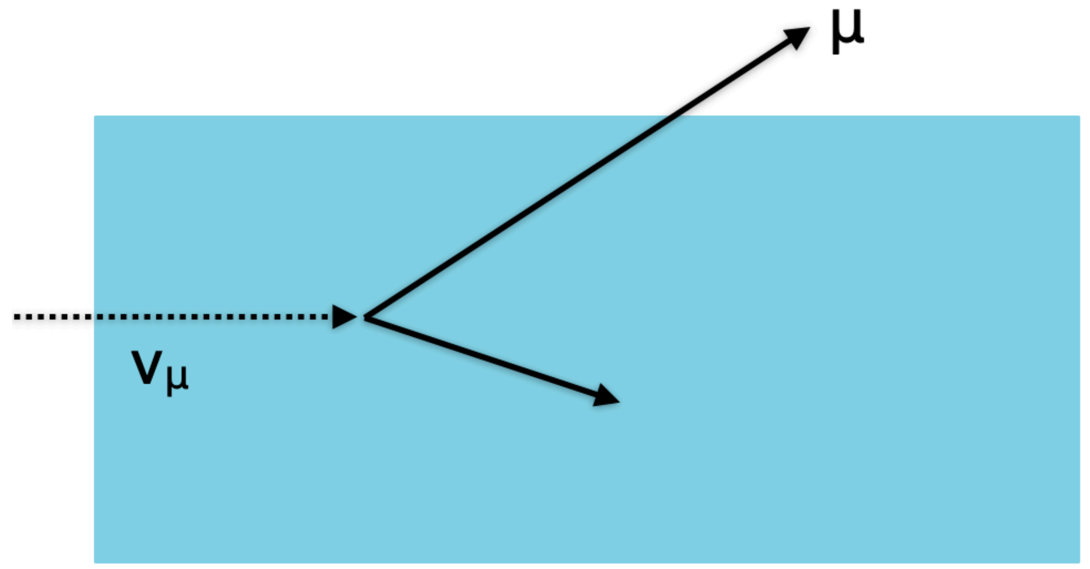
Corrections needed to connect true event rate to observation depend on many variables $\mathbf{X}$

- Must be studied in simulation using a full prediction of $d\sigma/d\mathbf{X}$

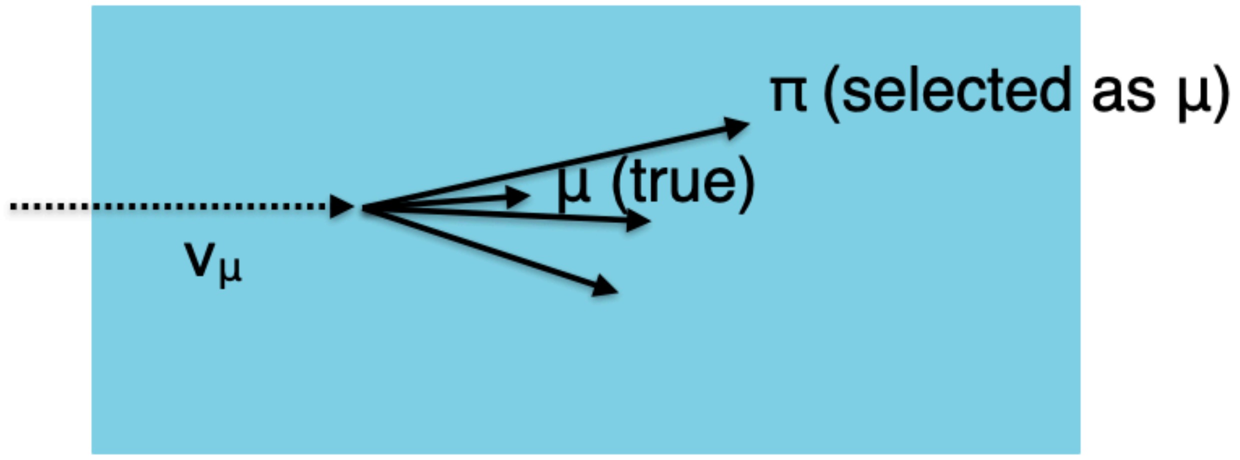
Precise extraction of P^{osc} depends on **well-controlled uncertainties** for the other factors



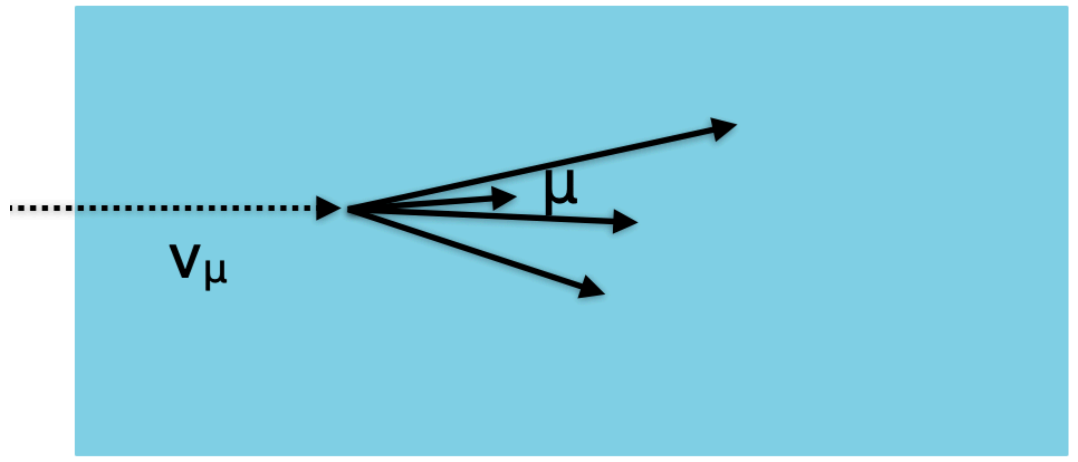
corrections for final-state particles that further interact in the detector



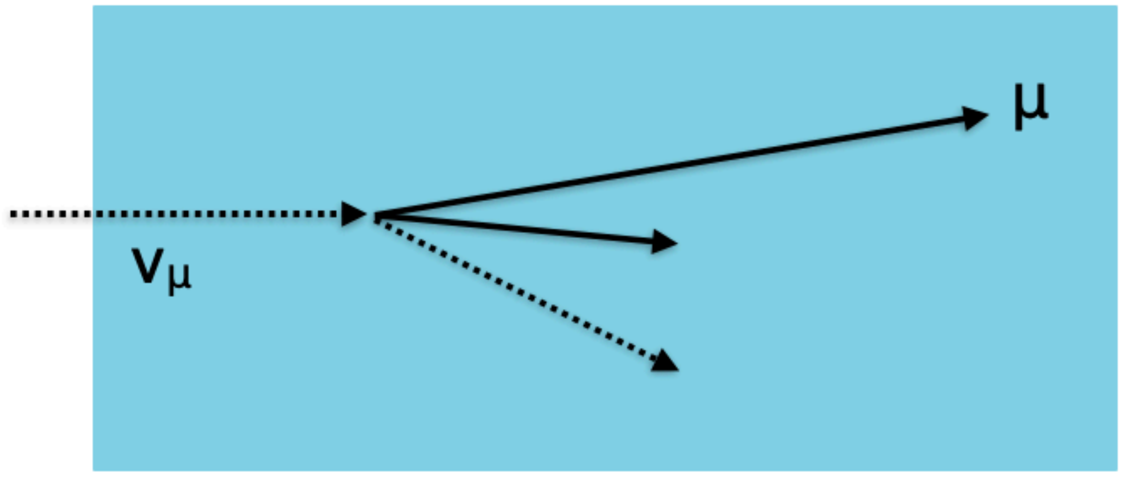
geometric acceptance corrections



mis-identified muon



missed signal event

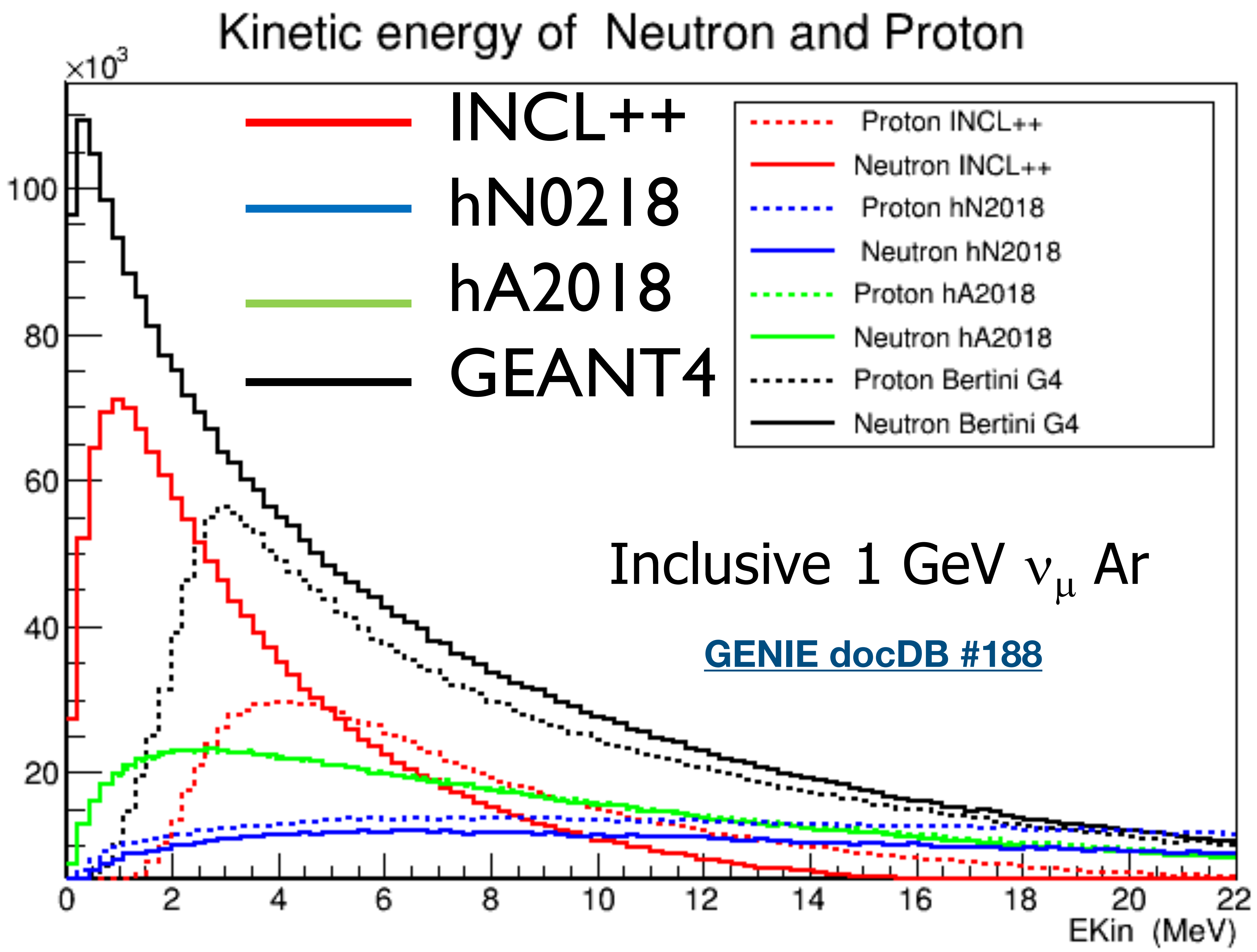


corrections for unobserved final-state particles

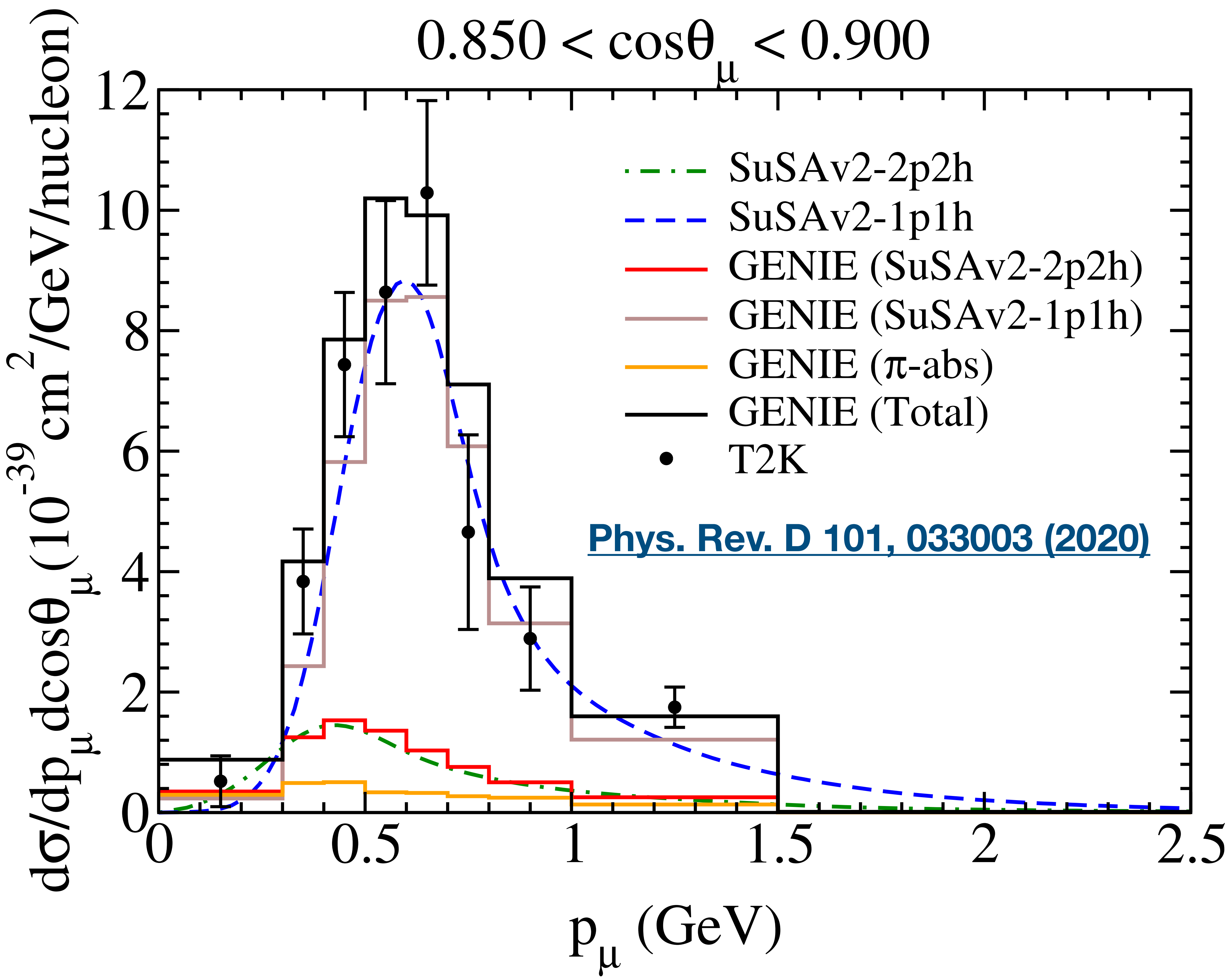
Preview of GENIE v3.2

Many other new features. See genie-mc.org for the current list.

New INCL++/ABLA07 & Geant4 FSI models

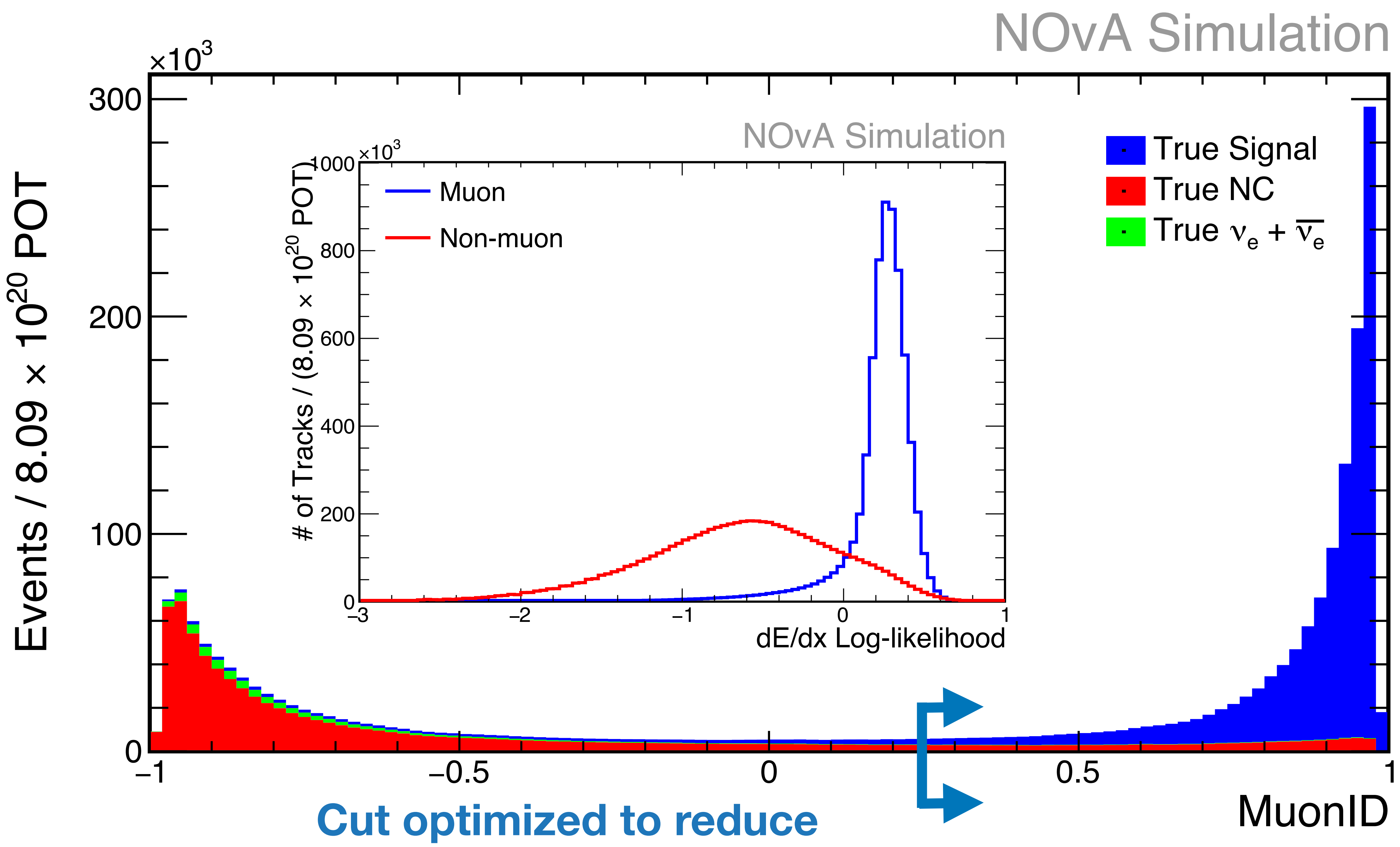


SuSAv2 QE + 2p2h cross sections



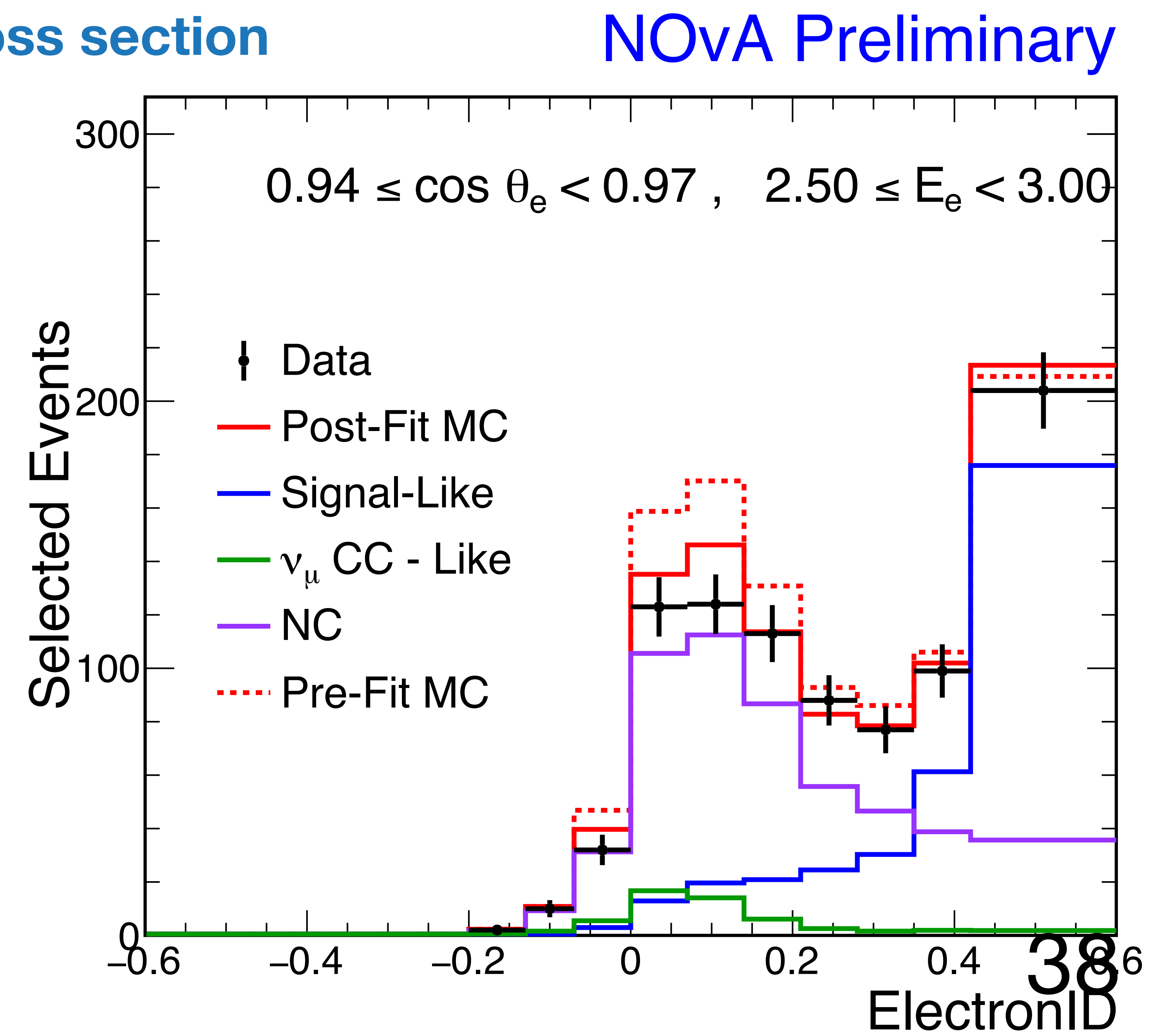
NOvA: inclusive cross sections

- Study outgoing lepton kinematics in the reaction $\nu_\ell + A \to \ell^- + X$
- NOvA has recently obtained two detailed inclusive measurements:
  - ν_μ: More than 1M selected events, 172 bins in $(T_\mu, \cos\theta_\mu)$ space
  - ν_e: About 10K selected events, **first ever double-differential measurement!**
- Analyses rely on well-understood **particle ID**
  - Implemented using Boosted Decision Trees (BDTs)
- Muon ID: 4-variable score leads to high purity
- Electron ID: templates separate signal/background



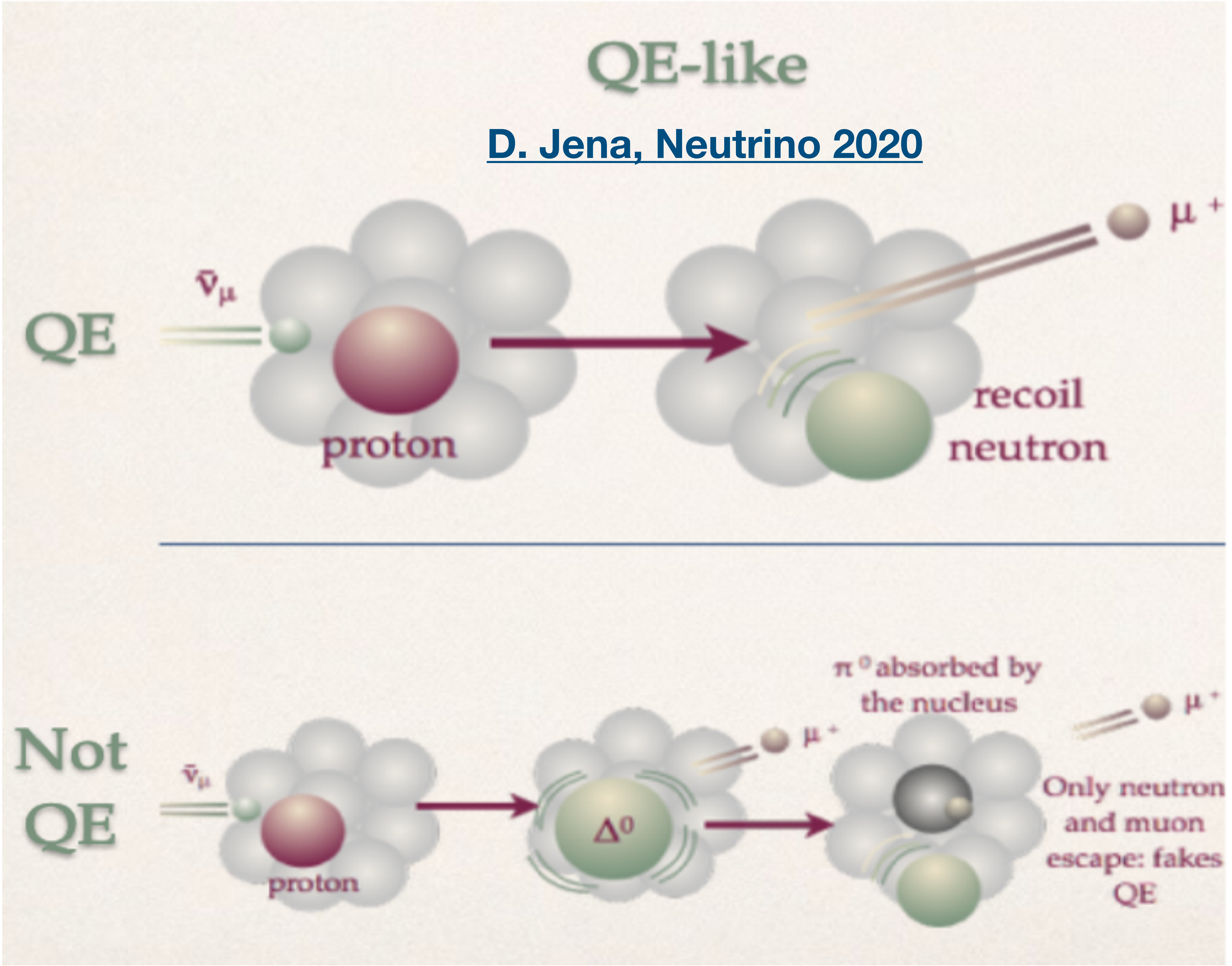
Cut optimized to reduce uncertainty on ν_μ CC cross section

For ν_e CC, ElectronID templates were fit to data on a bin-by-bin basis



Exclusive cross section measurements

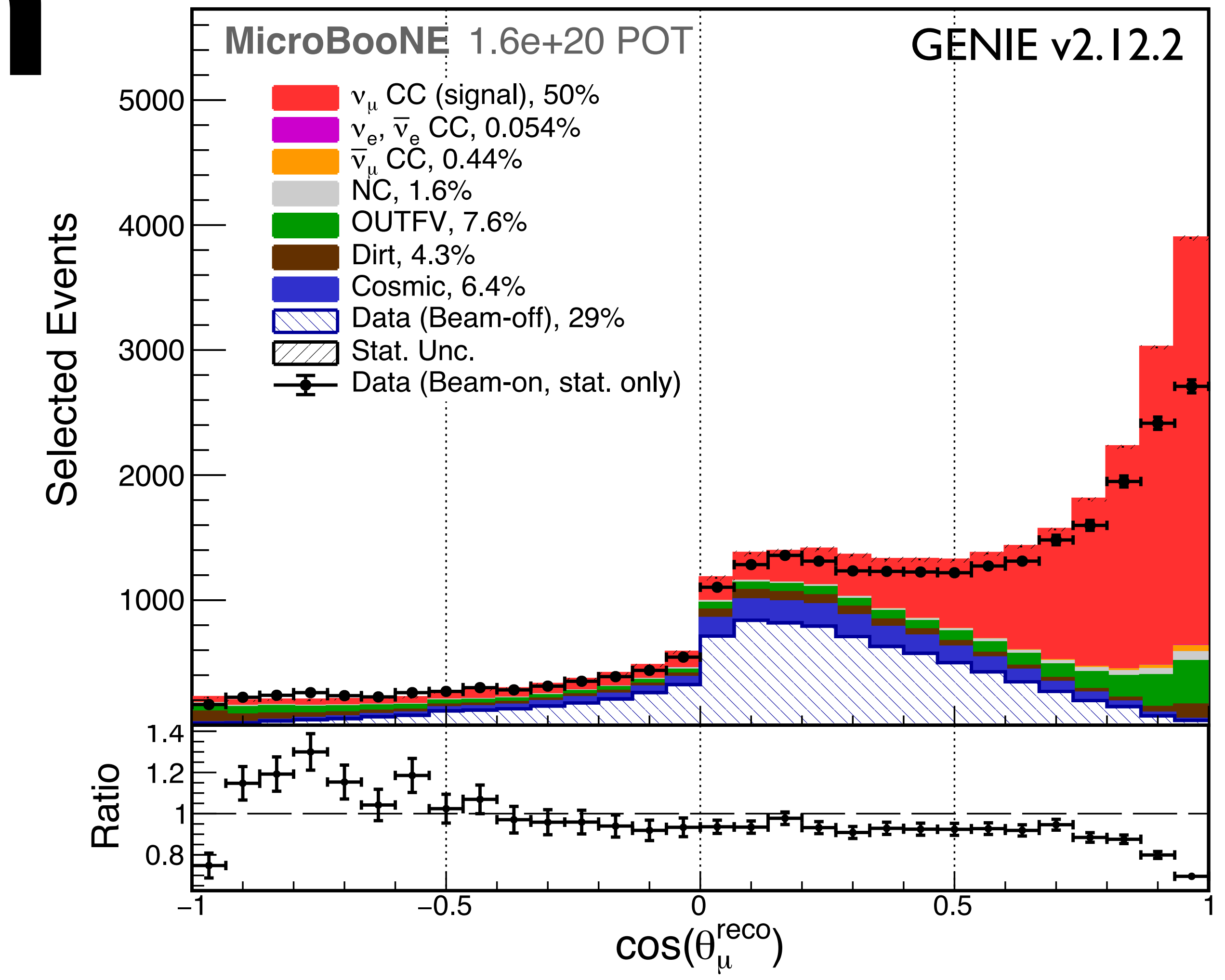
- Ideally, we'd like to measure the same cross sections a theorist calculates, e.g., CCQE
- Nature isn't quite so kind to us
  - Hadronic **final-state interactions** (FSIs)
  - Detector thresholds, resolution
- Instead, experiments routinely categorize events by observable topologies
  - "CC0π" → 1 charged lepton and zero pions detected
- Interaction mode separation is imperfect, but data nevertheless provide powerful model constraints



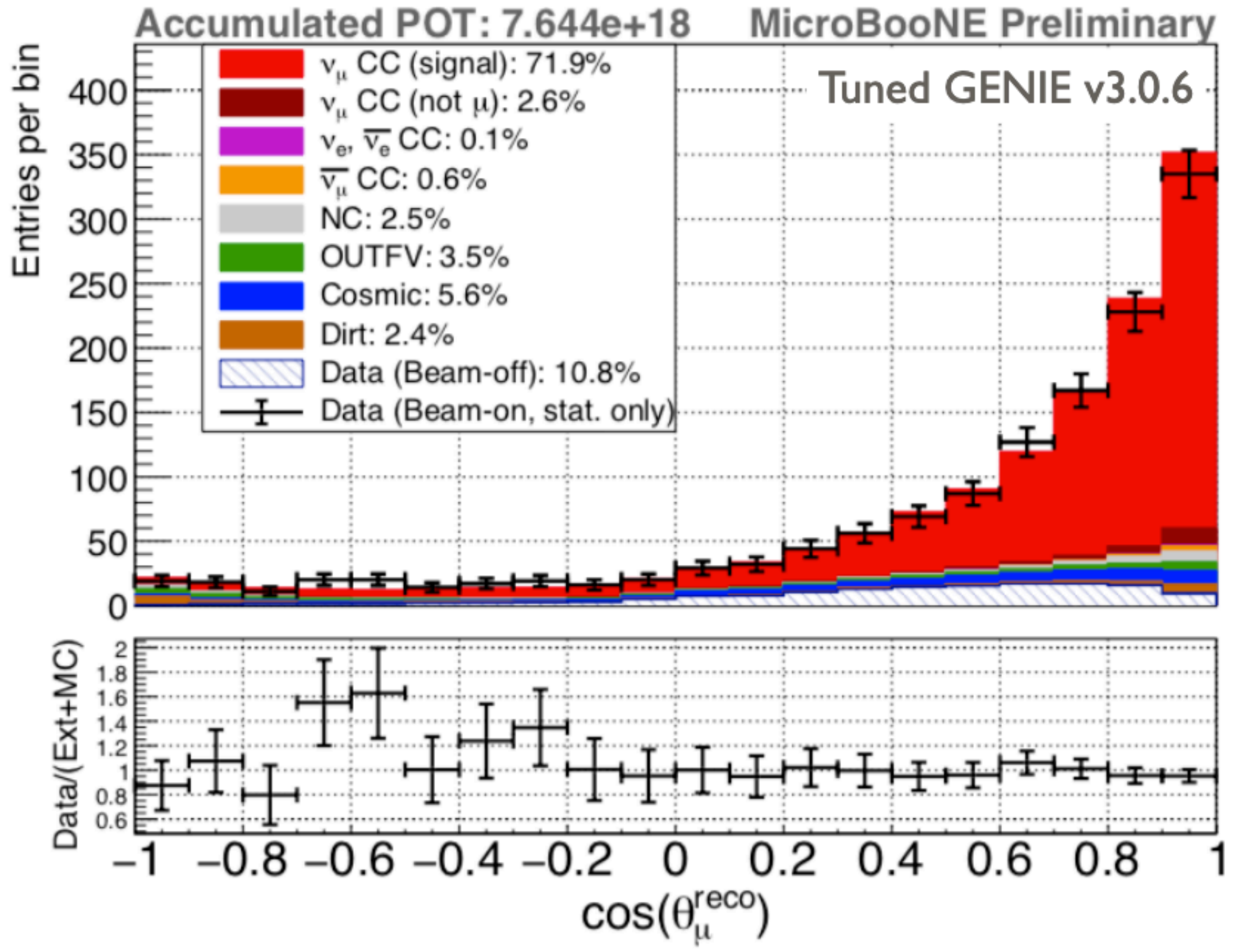
Toward higher precision

- Various improvements to MicroBooNE analysis tools over the past ~2 years
  - Detector response & reconstruction
  - GENIE v2.12.2 → v3.0.6 with tuning to T2K ν_μ CC0π data (CH target)
  - Overlay MC: eliminate cosmic-ray simulation in favor of off-beam data
- Big payoff: **drastically reduced systematic uncertainties**
- New CC inclusive analysis leverages these improvements and cosmic-ray tracker (CRT)
  - **Single-differential**: very good agreement with previous result, but reduced uncertainties
  - Future work toward double-differential cross section

Previous analysis



This analysis



ν_μ CC purity: 50% → 71.9%

Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	N/A
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

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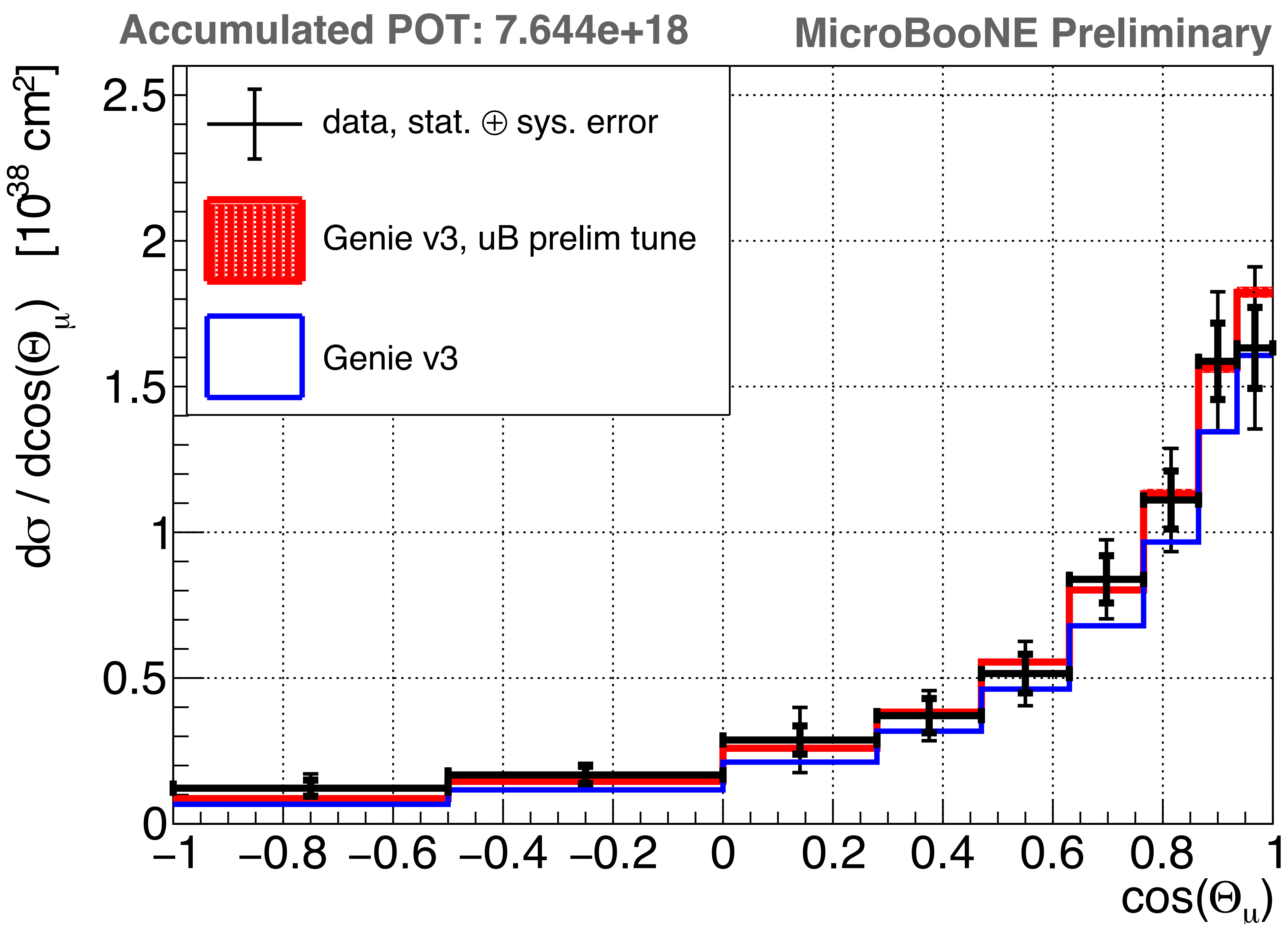
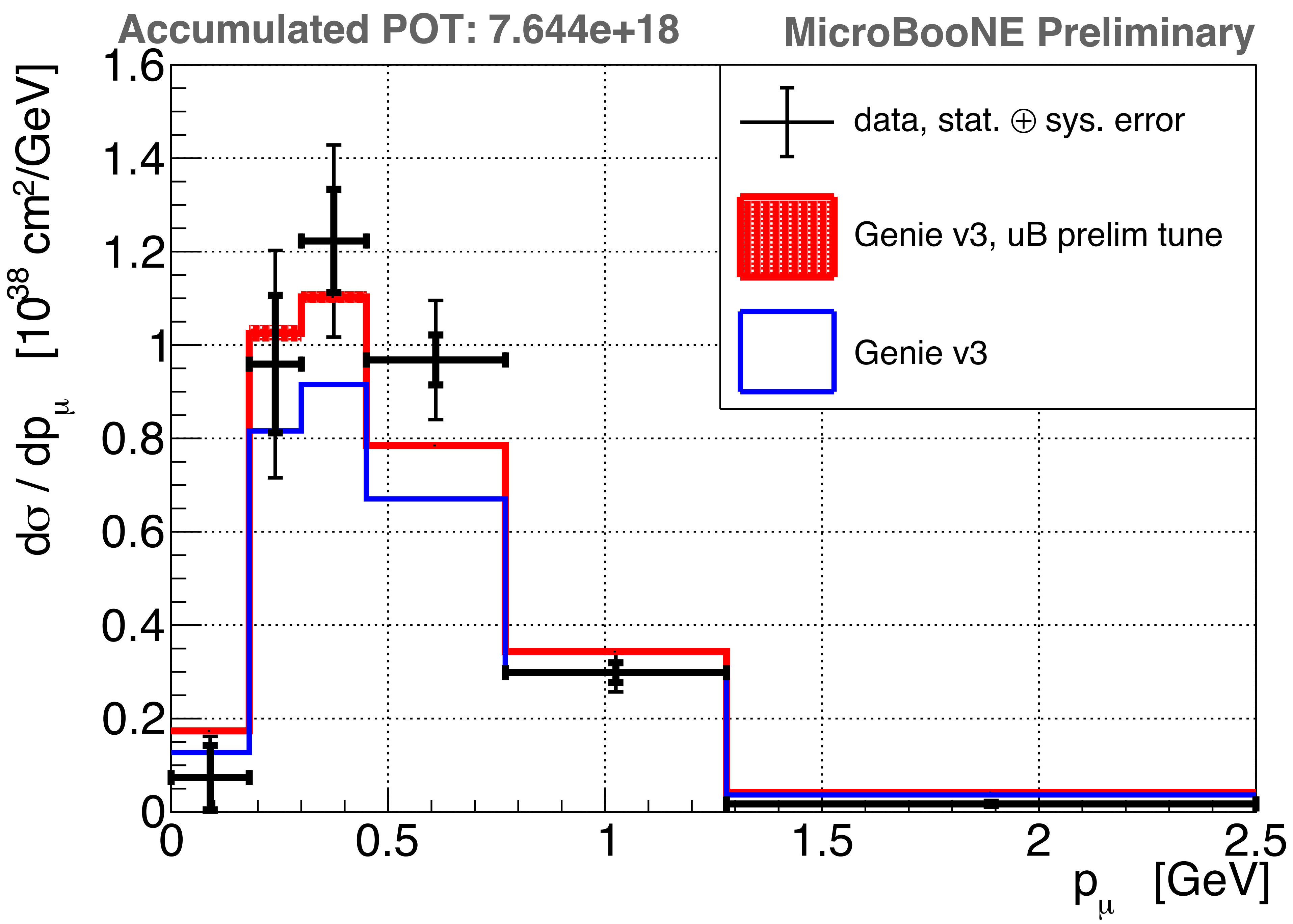
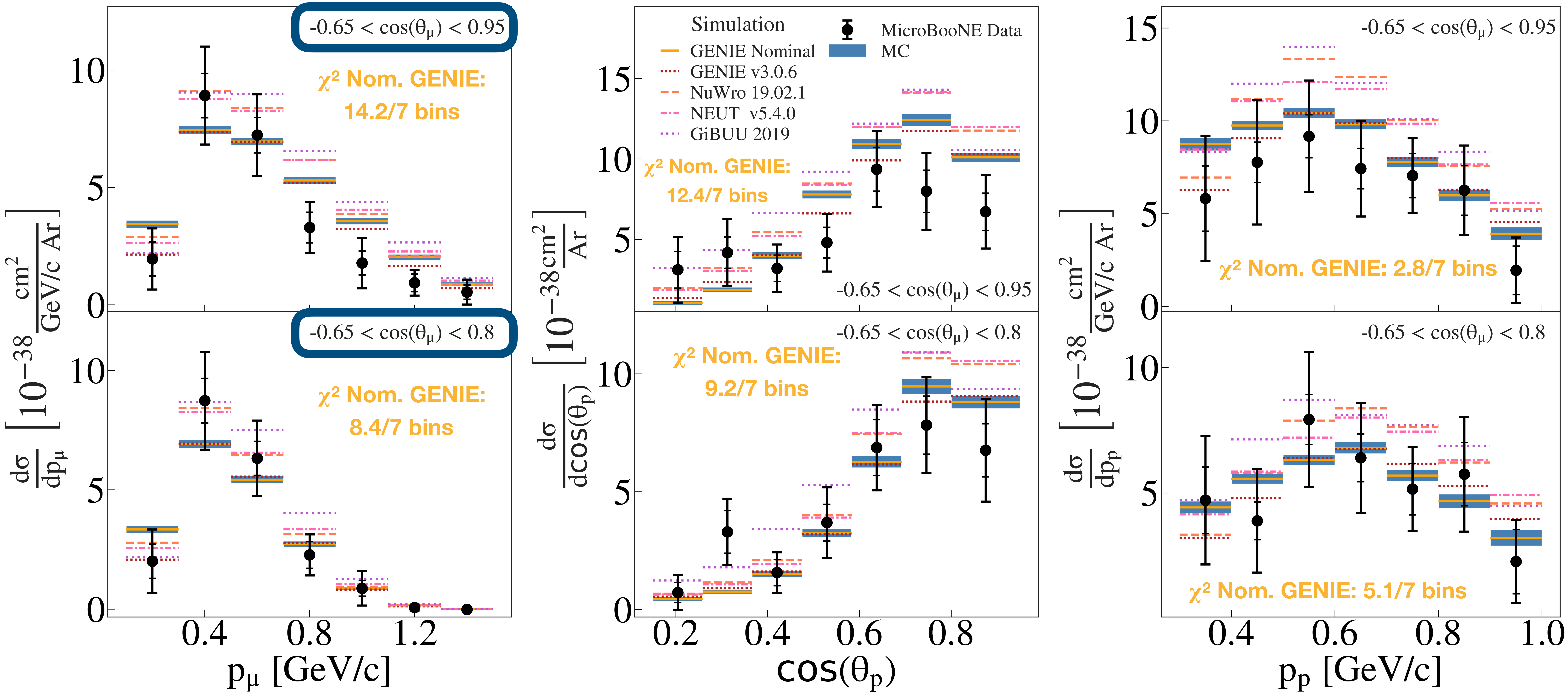


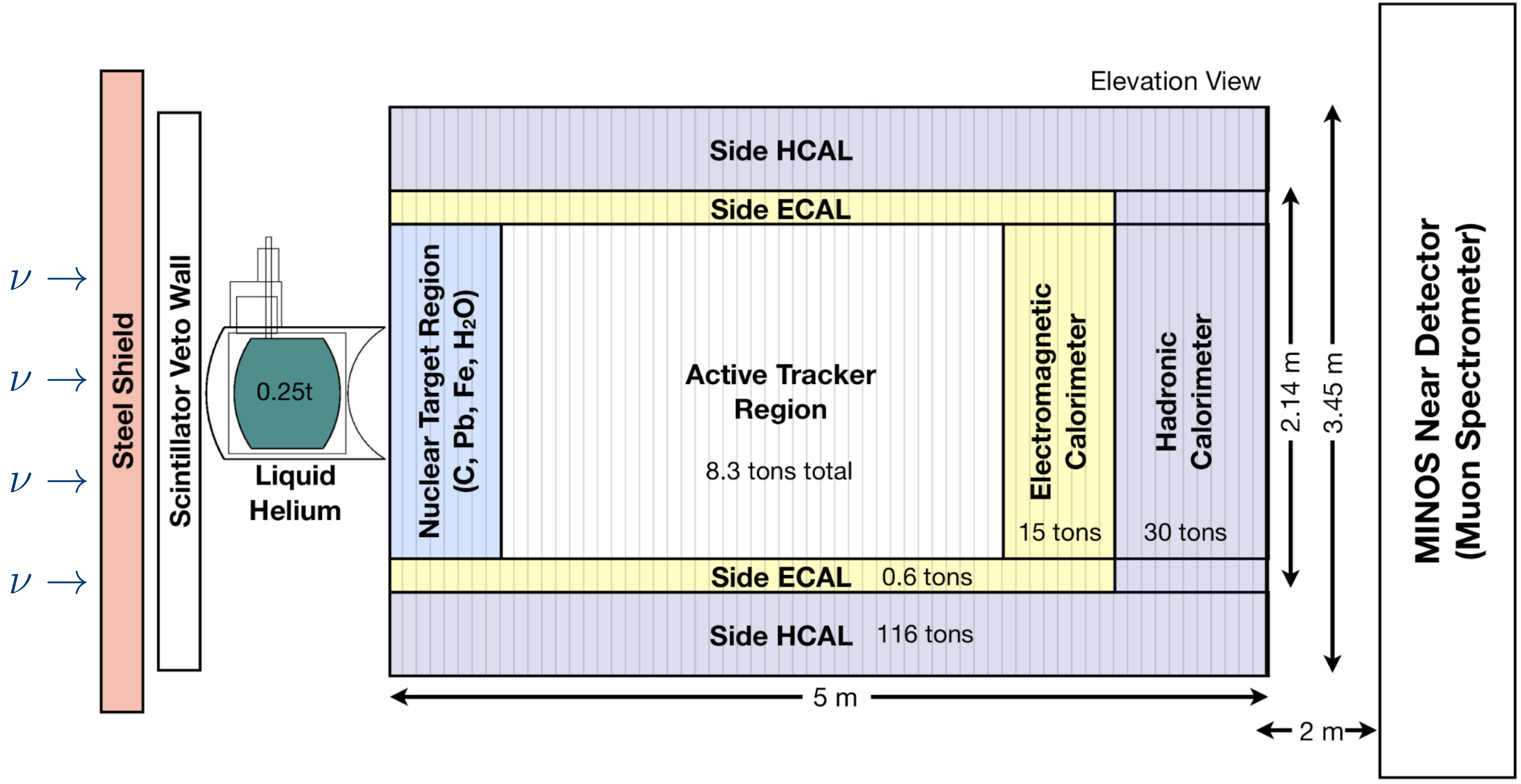


MicroBooNE CCQE-like cross section



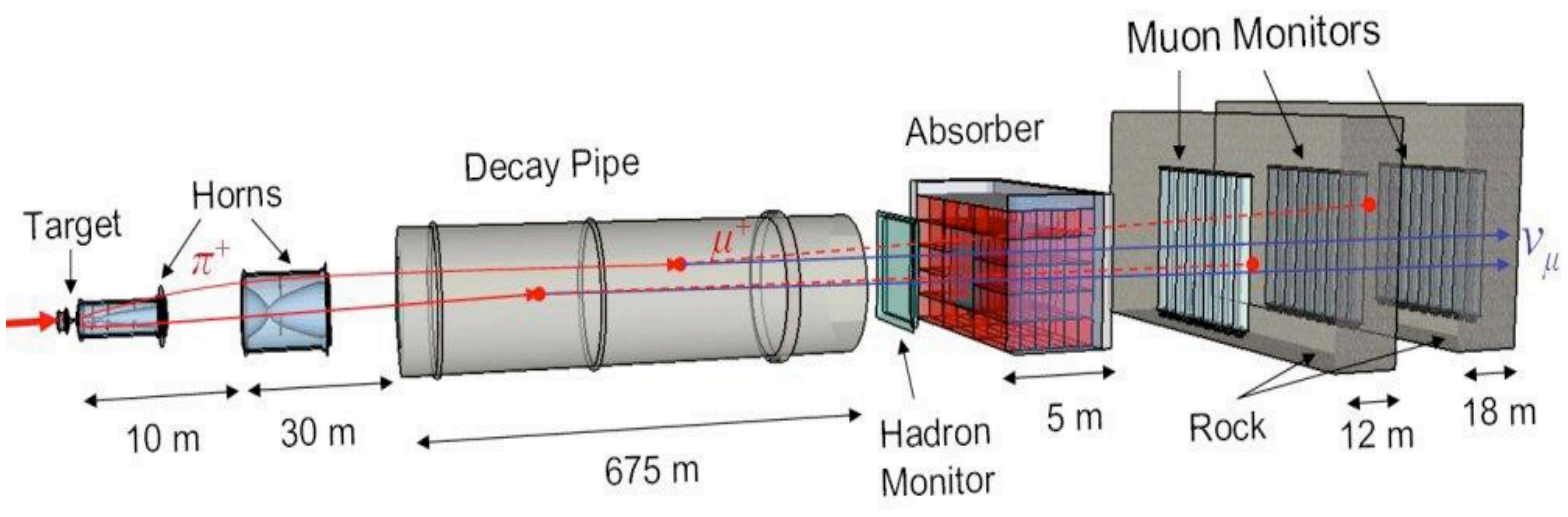
Agreement improves for multiple kinematic variables when forward muon angles are excluded.

The MINERvA experiment

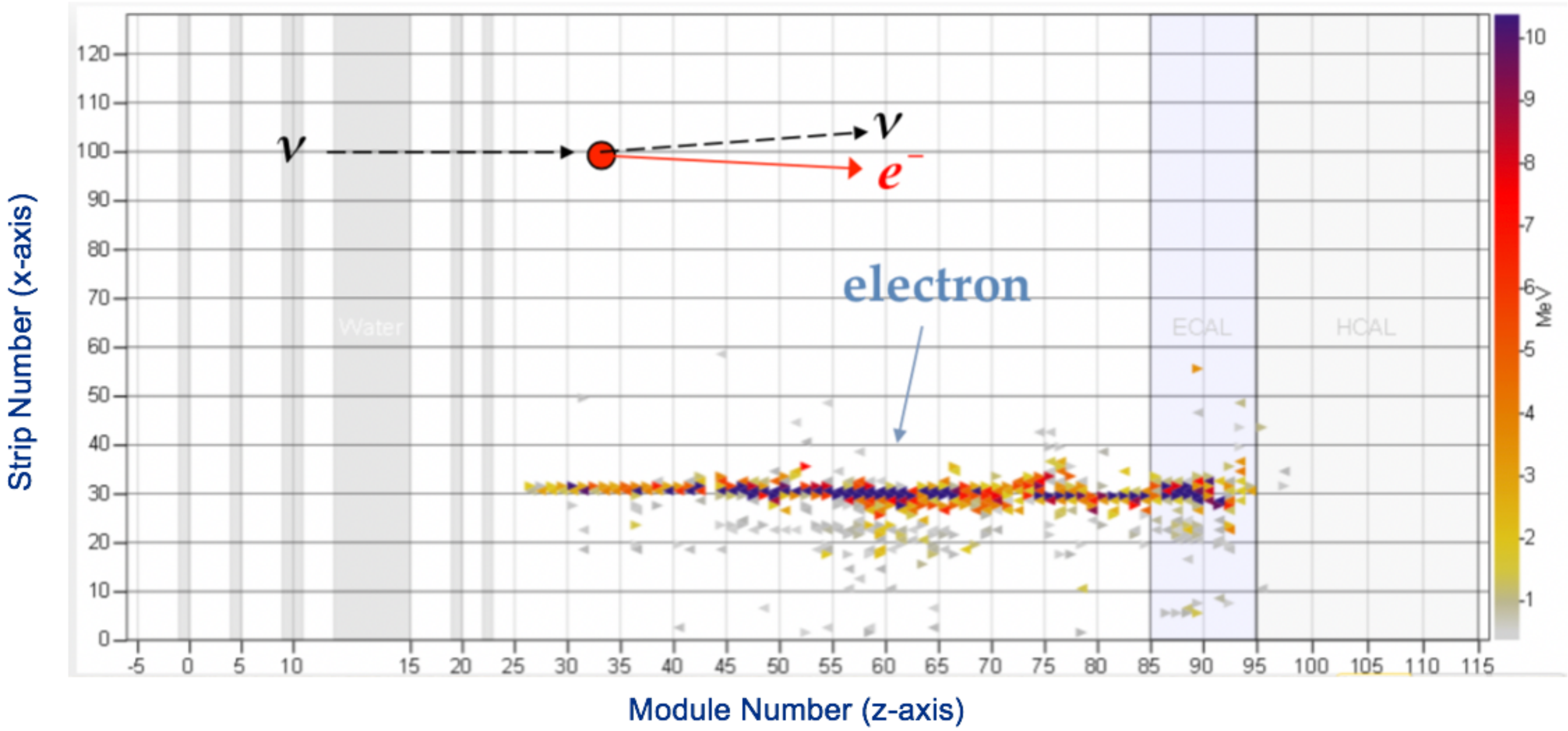


Constraining flux uncertainties with ν-e^- scattering

- Precise modeling of the neutrino flux is crucial for oscillation experiments
  - Uncertainties typically ~10%
  - Often a leading uncertainty for cross section measurements
- Flux predictions are made with detailed simulations of beam production
  - Hadron production cross sections important input
- ν-e^- cross section is precisely known
  - **Standard candle** for *in situ* flux measurement
  - Orders of magnitude smaller than ν-A
  - Backgrounds and low statistics
- Signal: very forward electron shower
- Backgrounds: ν_e CCQE, photons from π^0 decays, etc.

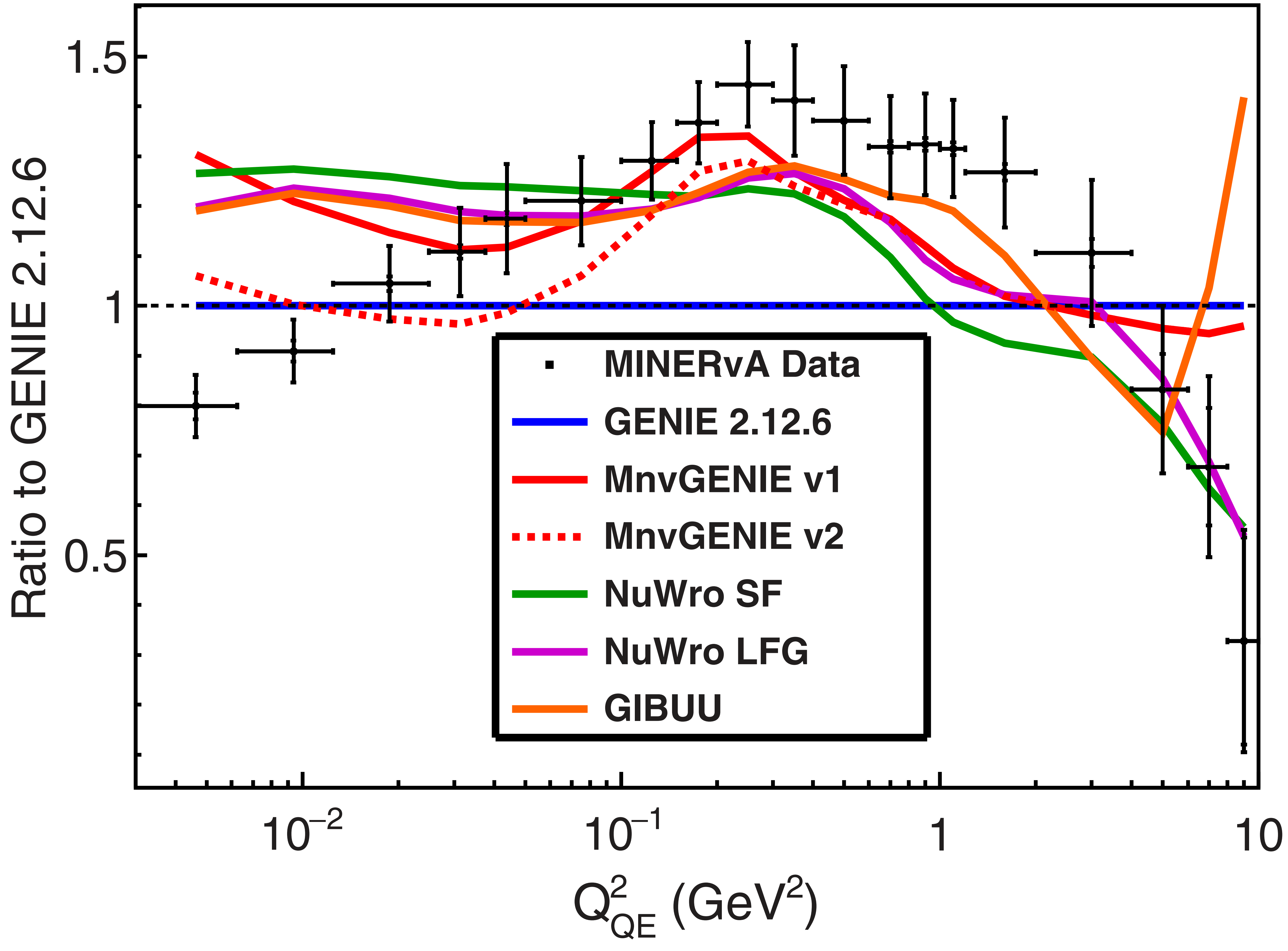


D. Jena, Neutrino 2020



MINERvA ν_μ CCQE-like cross section

- First ME cross section publication
  - Uses ν-e^- result to reduce flux systematic uncertainties
- Signal definition: 1 muon, 0 mesons, 0 heavy baryons, and any number of nucleons
  - Note that this definition of "CCQE-like" is **different from MicroBooNE's** (CC1p0π)
- Data compared to generator predictions, including special GENIE v2.12.6 tunes by MINERvA
  - **MnvGENIE v1**: RPA + 2p2h + adjusted non-resonant π production
  - **MnvGENIE v2**: MnvGENIE v1 + low-Q^2 suppression for RES

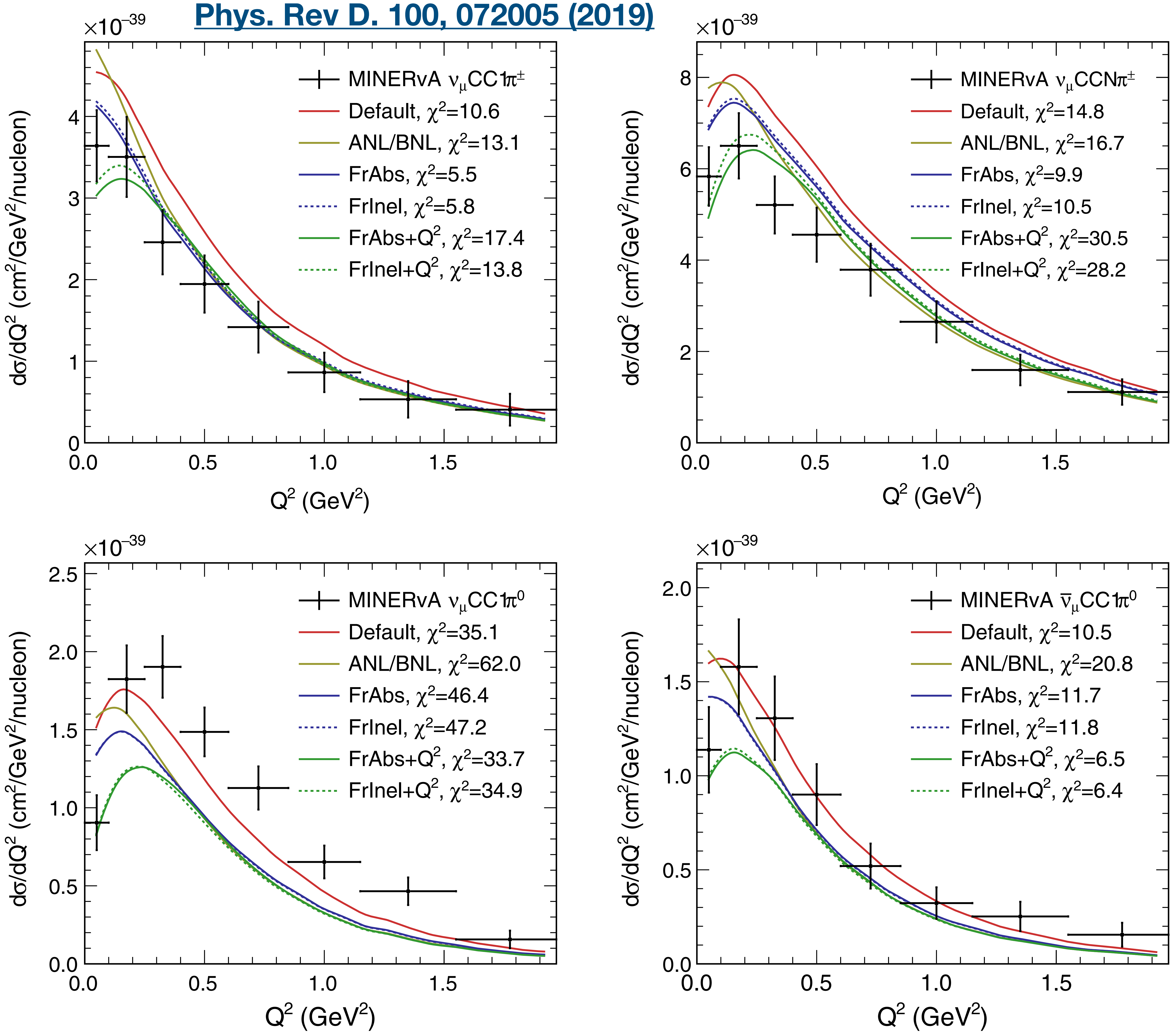


First measurement to probe $Q^2_{\mathrm{QE}} > 4\,\mathrm{GeV}^2$. All models studied cannot achieve good agreement over the full range.

Pion production

- Key for studying inelastic reaction modes (RES, DIS)
- Other Fermilab experiments have recently published total cross sections
  - NOvA: NC COH π^0
    Phys. Rev. D 102, 012004 (2020)
  - MicroBooNE: ν_μ CC π^0
    Phys. Rev. D 99, 091102(R) (2019)
- MINERvA has studied various differential cross sections in detail
- Recent paper examined tuning of GENIE π production modeling to four CC measurements from MINERvA
  Phys. Rev D. 100, 072005 (2019)
- Tension seen between MINERvA measurements (CH) and between MINERvA and older bubble chamber data (^{1}H, ^{2}H)
- Additional $\bar{\nu}_\mu$ CC $1\pi^-$ measurement not included in tuning study:
  Phys. Rev. D 100, 052008 (2019)

Phys. Rev D. 100, 072005 (2019)



Various model adjustments explored, including changes to standard GENIE parameters and an “ad hoc low-Q^2 suppression”

With the options available, good agreement with all measurements could not be achieved

Pion production

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  Phys. Rev. D 100, 052008 (2019)

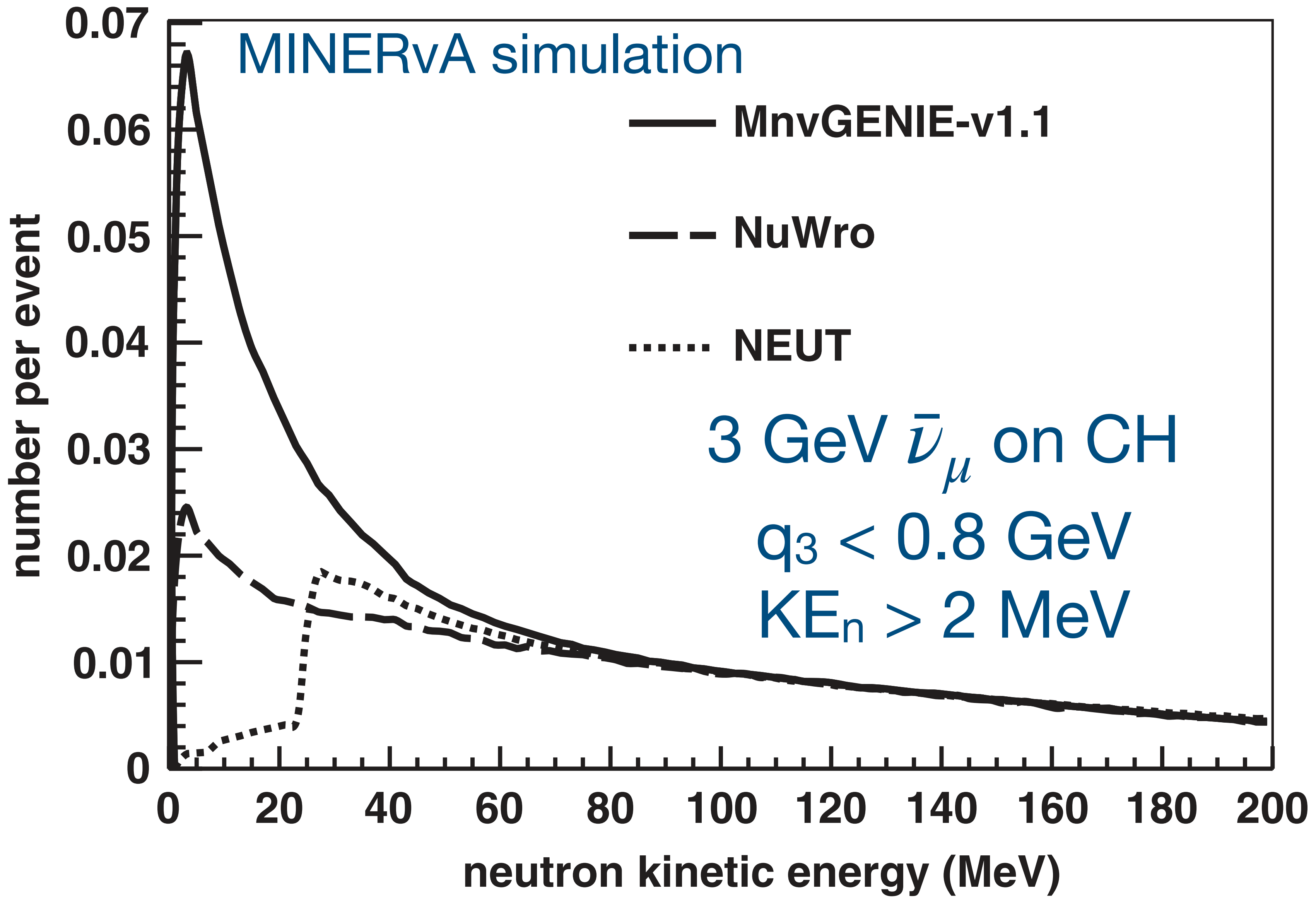
JINST 12 (2017) P01016

Fits shown here were performed using **NUISANCE**, a software framework for comparing and tuning neutrino generator predictions to experimental data

Used for some of the other comparisons in this talk as well (e.g., MicroBooNE CC inclusive)

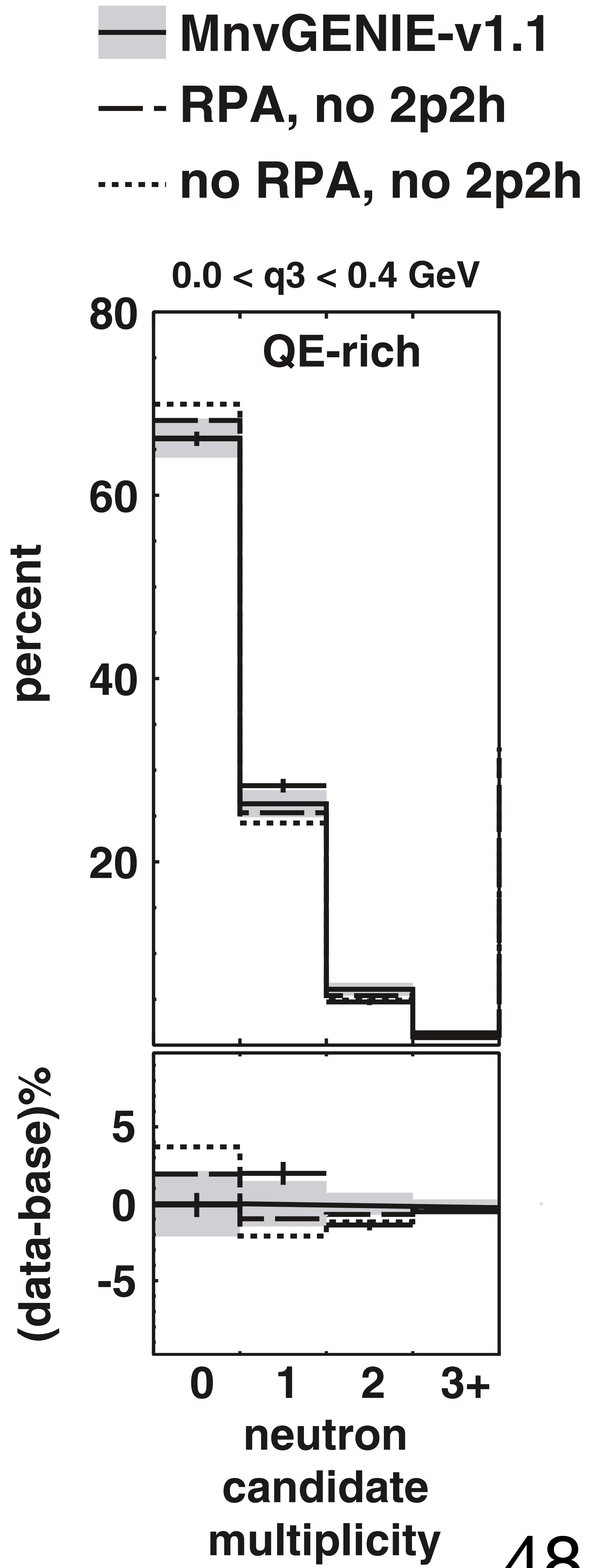
Neutrino-induced neutrons in MINERvA

- Neutron multiplicities and kinematic distributions are poorly understood at present
  - Theoretically challenging and difficult to measure
  - Substantial differences in generator predictions
  - “Generator” vs. “Geant4” neutrons
- LE analysis: $\bar{\nu}_\mu$ CC in CH active tracker
  - **Phys. Rev. D 100, 052002 (2019)**
  - Multiplicity, time-of-flight, position, speed (1/β), E_{dep}
  - Detection via p recoils, inelastic n-C scatters (p, γ, fragments) → ~10 MeV kinetic energy threshold
- HE analysis in progress
  - More efficient, 7.5× more data!
  - Data for **multiple targets**

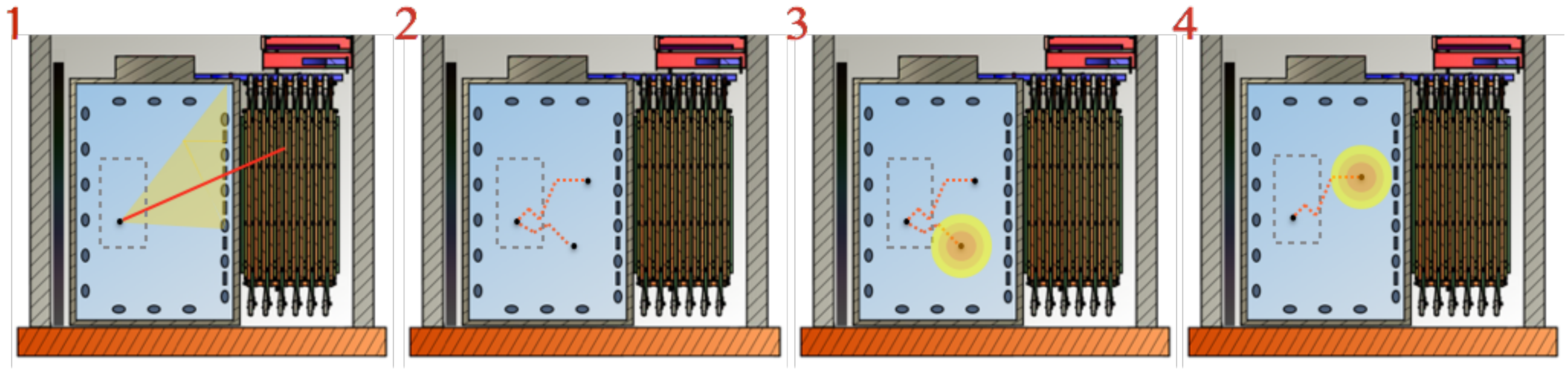


Preference for both RPA and 2p2h in measured “QE-rich” multiplicity distribution

“QE-rich” subsample: E_{avail} < 0.06 GeV



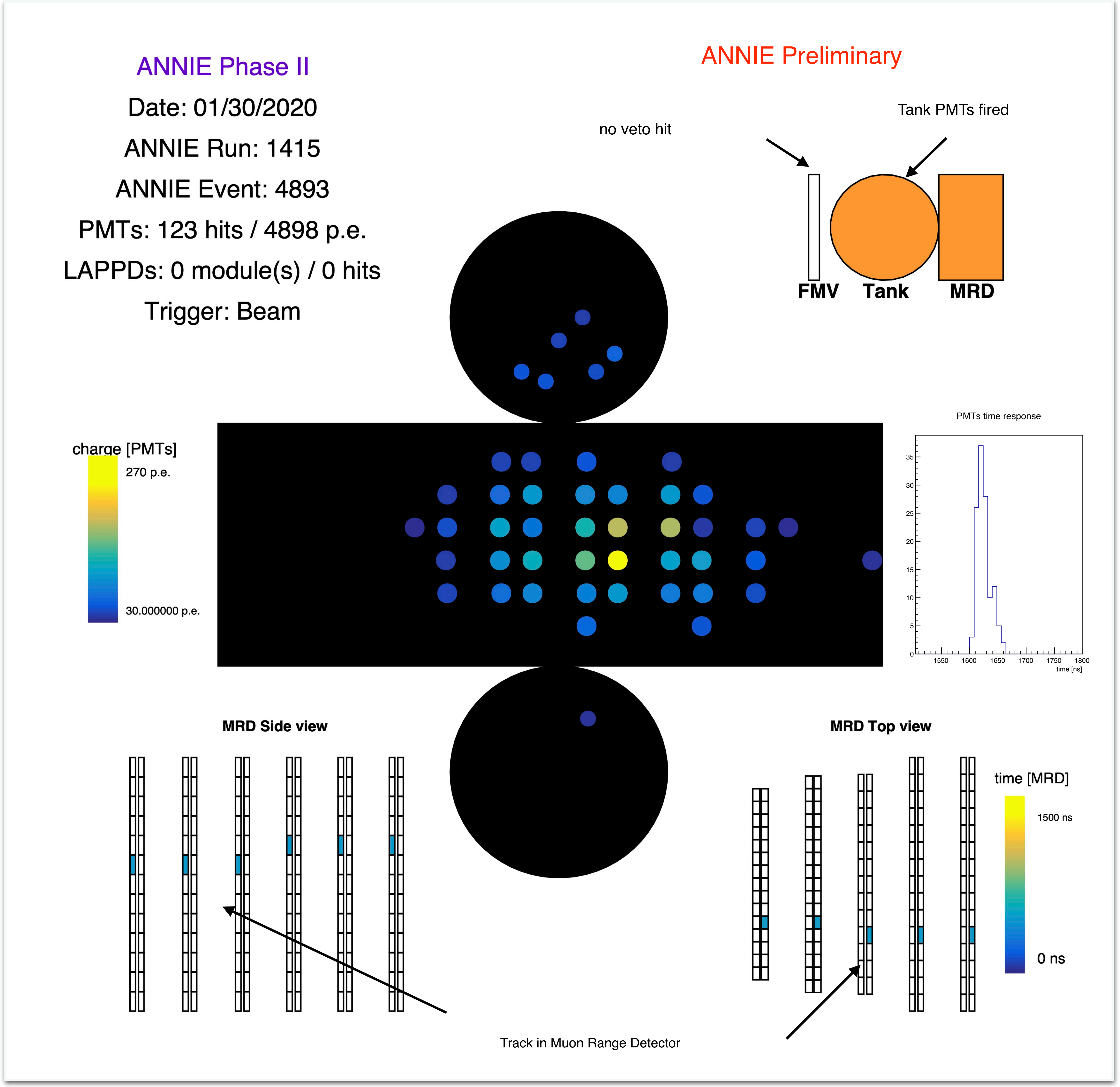
A neutrino event in ANNIE



1. CC interaction in fiducial volume produces a muon. Vertex reconstruction by LAPPDs, muon momentum reconstructed in MRD.

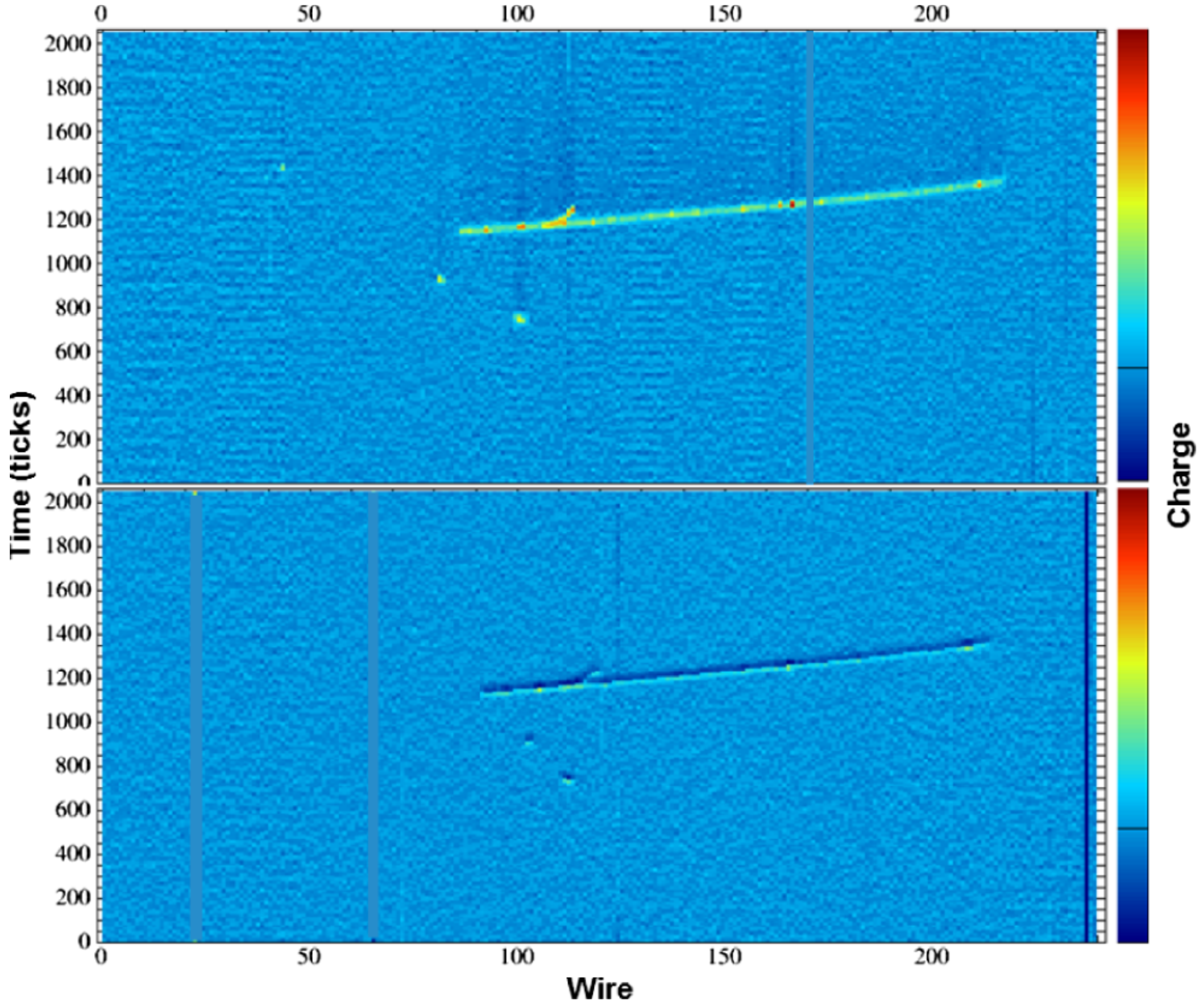
2. Neutrons travel, scatter and thermalize.

3.–4. Neutrons capture on Gd, γ-ray cascades detected by conventional PMTs


ANNIE Phase II
Date: 01/30/2020
ANNIE Run: 1415
ANNIE Event: 4893
PMTs: 123 hits / 4898 p.e.
LAPPDs: 0 module(s) / 0 hits
Trigger: Beam
ANNIE Preliminary
no veto hit
Tank PMTs fired
FMV
Tank
MRD
charge [PMTs]
270 p.e.
30.000000 p.e.
PMTs time response
time [ns]
MRD Side view
MRD Top view
time [MRD]
1500 ns
0 ns
Track in Muon Range Detector

ArgoNeuT MeV-scale reconstruction

- Phys. Rev. D 99, 012002 (2019)
- Multiple MeV-scale contributions needed to match data
  - De-excitation γ-rays
  - Neutron inelastic scatters
- **Applications**
  - Improved energy resolution for GeV neutrinos
  - DUNE supernova & solar neutrinos
  - Cross section measurements for ν-A scattering at tens-of-MeV
  - BSM searches
- See Phys. Rev. D 99, 036009 (2019) and arXiv:2006.14675 for details



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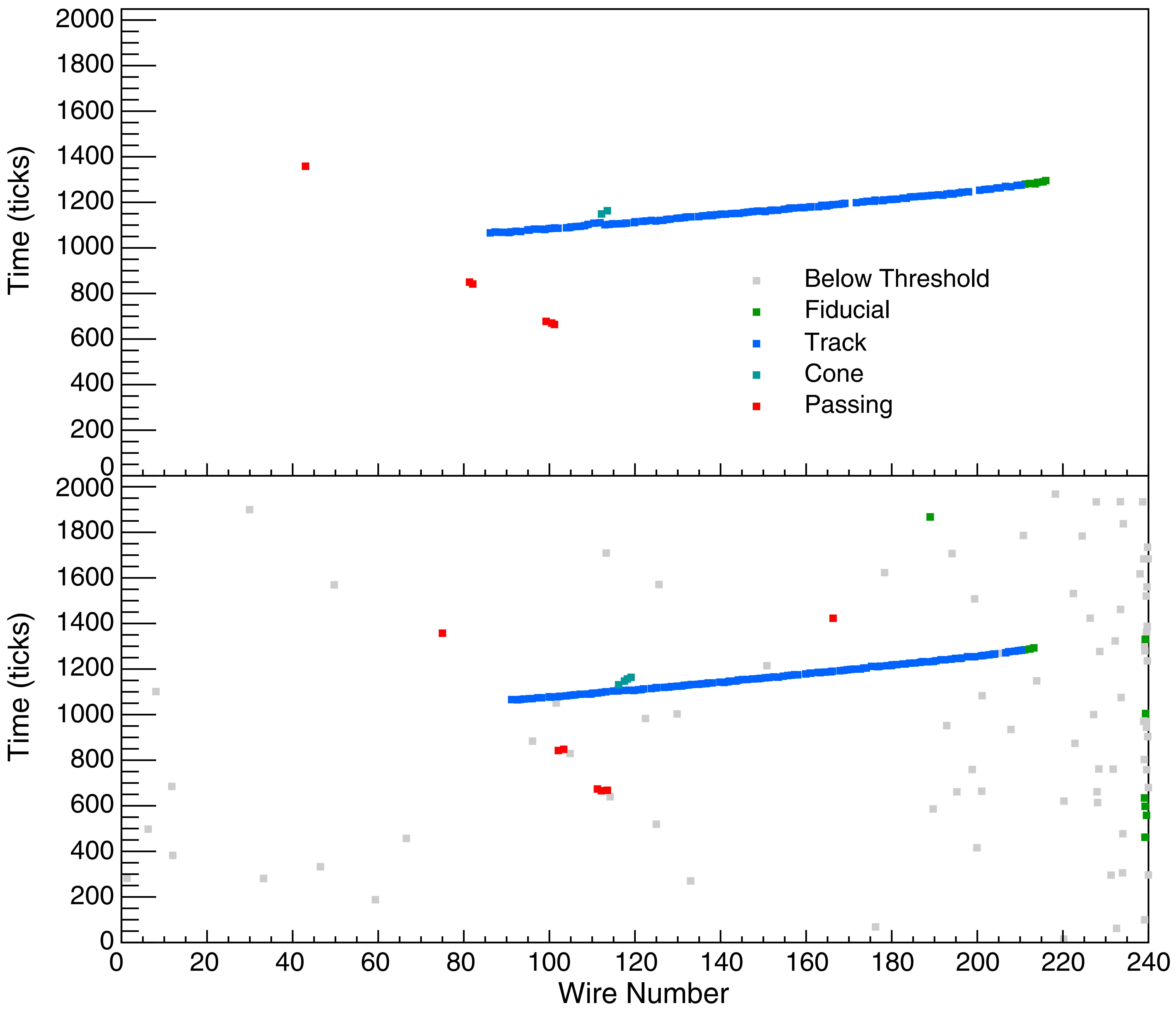

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