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March 4, 2021

NuSTEC CEWG

NOvA ν_μ Inclusive Cross-section Measurement Data to Generators Comparisons

Wichita State University

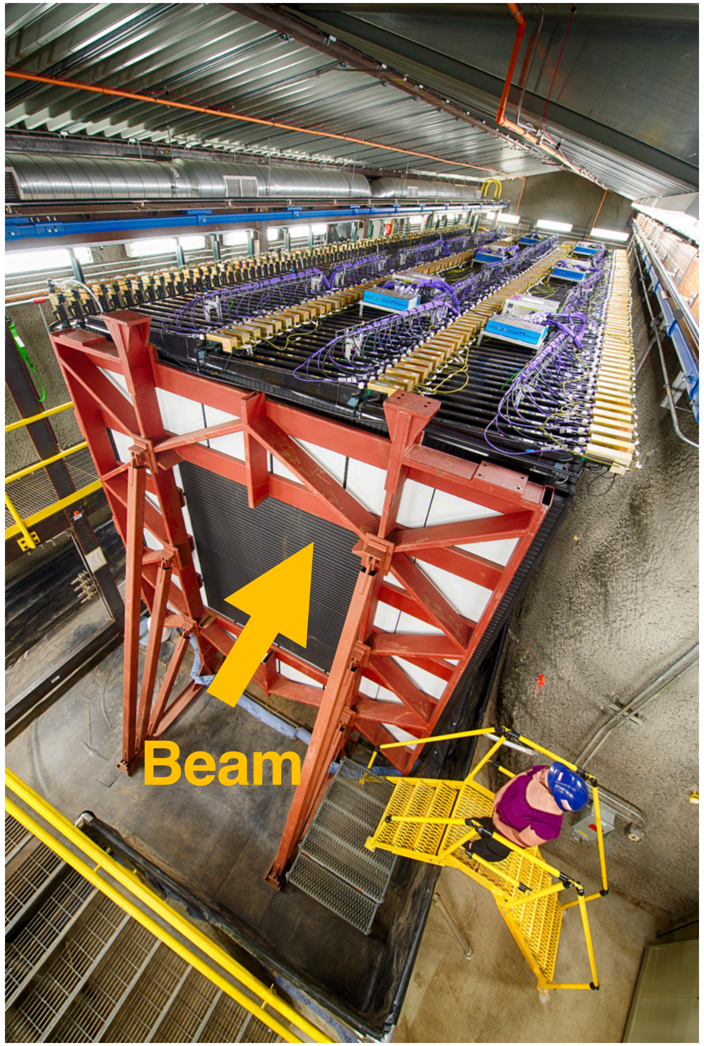
NOvA

Outline

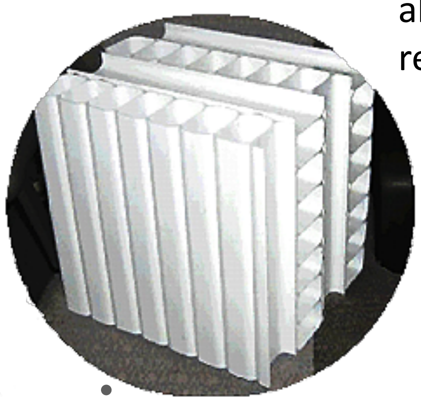
- Overview of NOvA Neutrino Interactions.
- Summary of ν_μ inclusive analysis and results.
- Discussion of p-value comparison to generators.
- Results
- Discussion

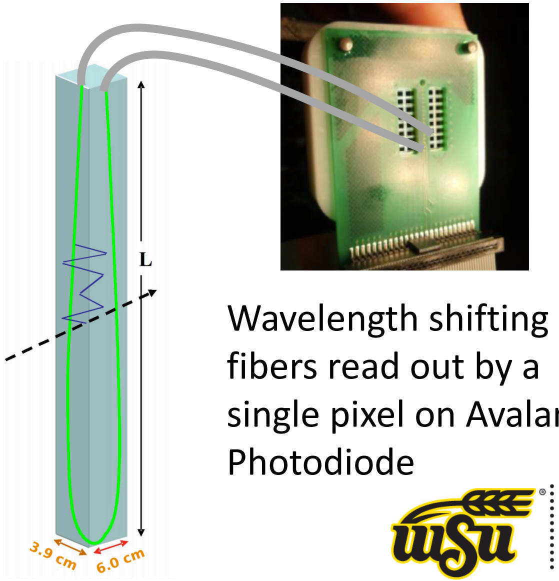
NOvA Near Detector

- 300t tracking calorimeter
- Extruded plastic cells, filled with liquid scintillator
- 0.17 X_0 per layer
- 77% hydrocarbon, 16% chlorine, 6% TiO_2 by mass
- Muon catcher (steel + NOvA cells) at downstream end to range out ~2 GeV muons.



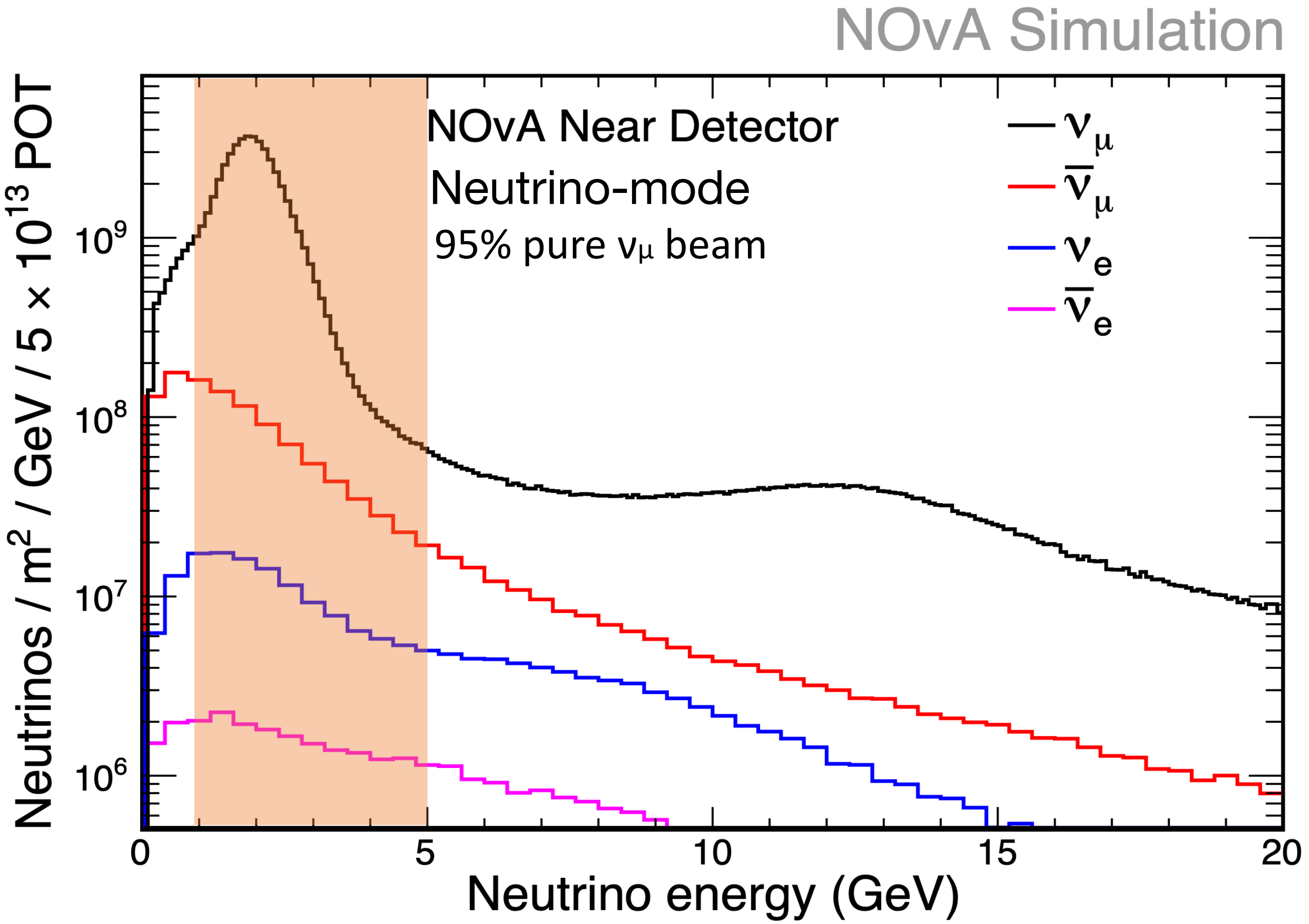
Alternating planes allow for 3D reconstruction





Wavelength shifting fibers read out by a single pixel on Avalanche Photodiode

The NuMI Beam in NOvA



- Off-axis position w.r.t. NuMI beam results in narrow-band beam centered around 2 GeV.
- 11 x 10^{20} POT of neutrino-mode data and 11.8 x 10^{20} POT of antineutrino-mode data collected in the near detector.
- Initial 8.09 x 10^{20} POT FHC data collected used in first inclusive results.

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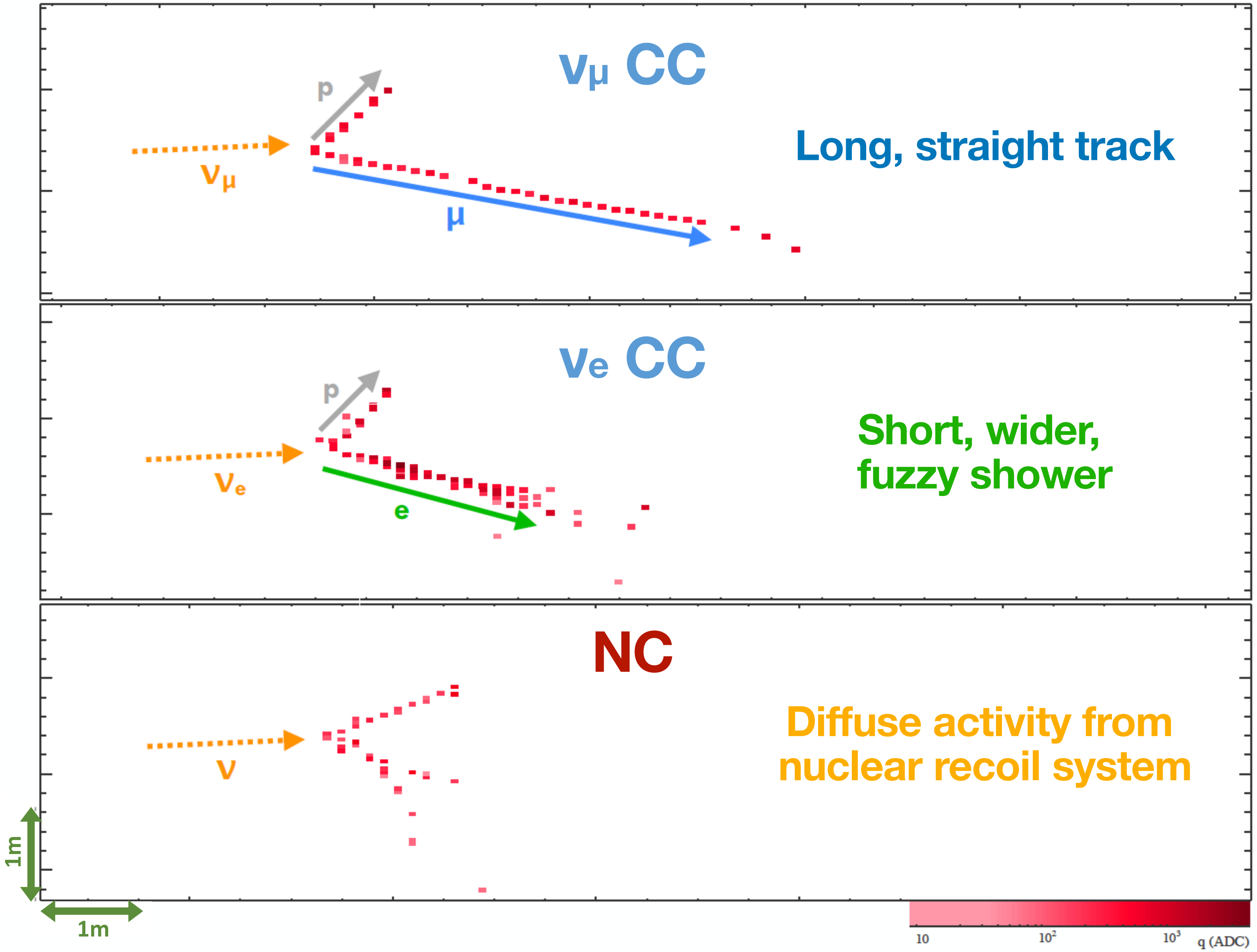
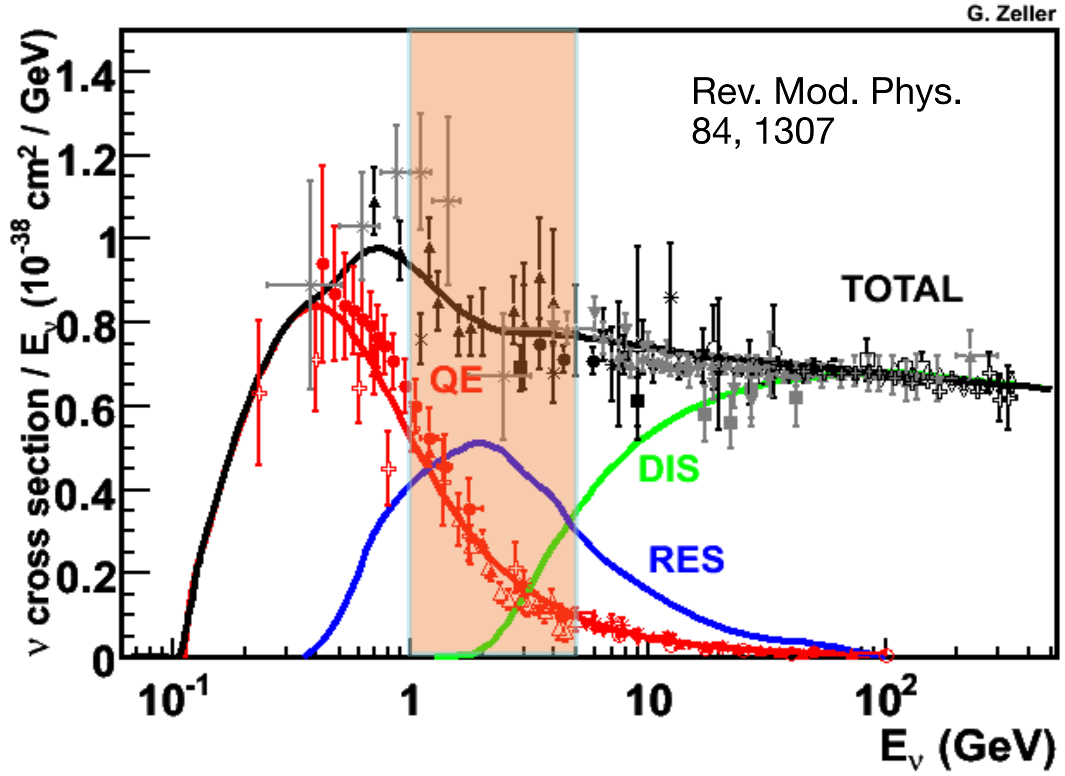
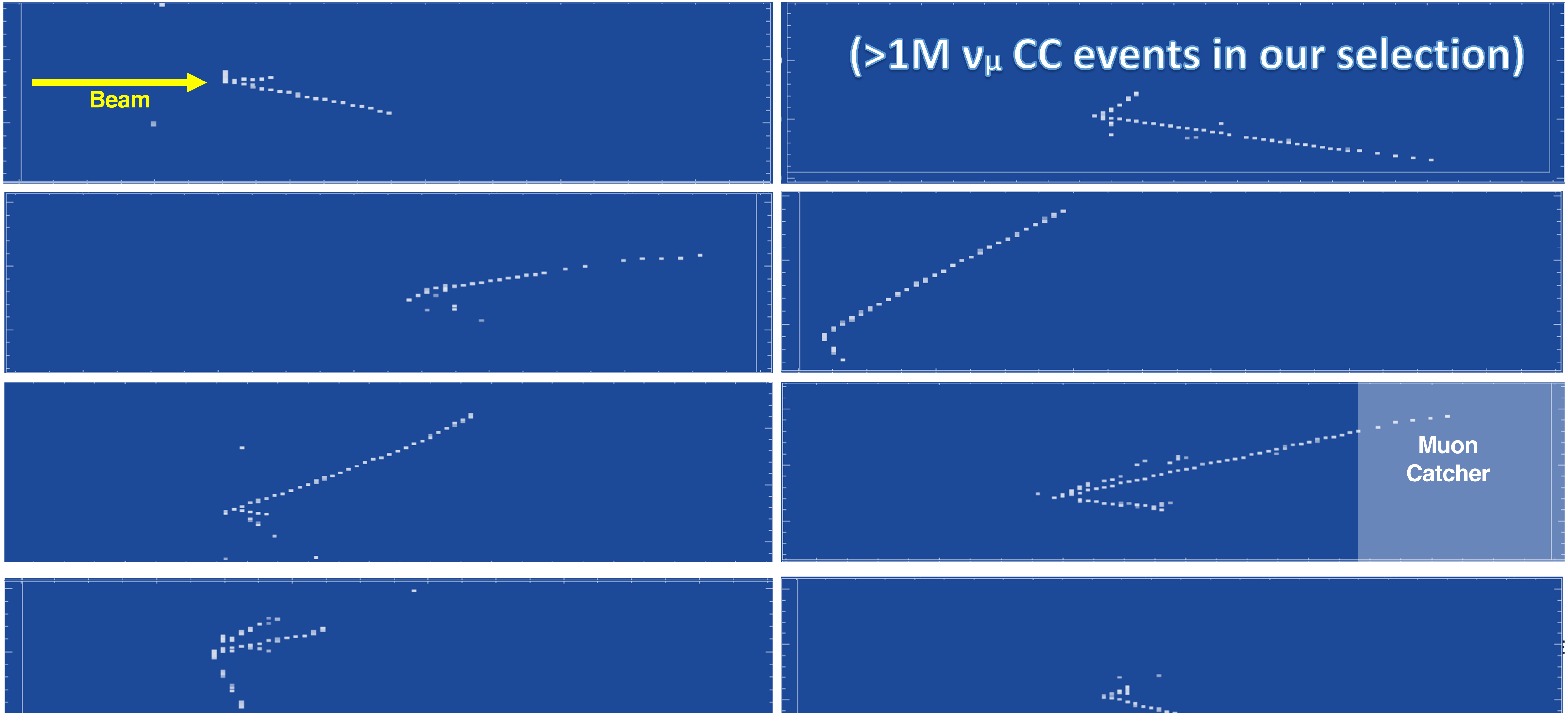
The NOvA Near Detector





+ Meson Exchange Currents

ν_μ Inclusive Analysis



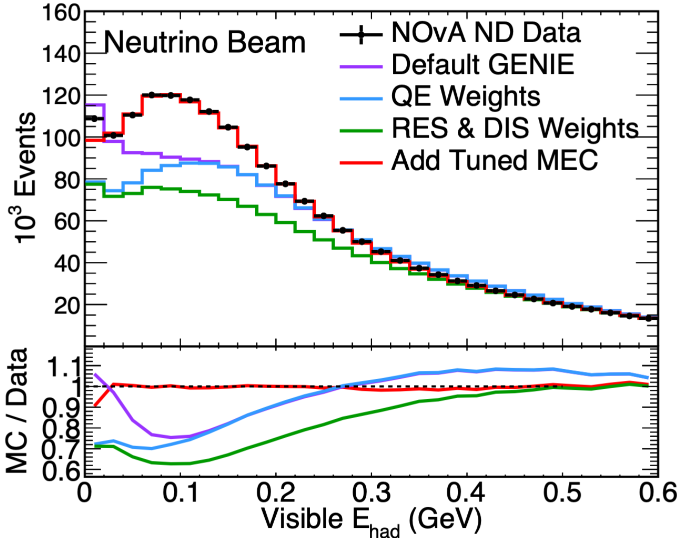
Double differential ν_μ Cross section

$$\left(\frac{d^2\sigma_{\text{incl}}}{d\cos\theta_\mu\, dT_\mu}\right)_i = \sum_{E_{\text{avail}}} \left(\frac{\sum_j U_{ij}^{-1}(N_{\text{sel}}(\cos\theta_\mu, T_\mu, E_{\text{avail}})_j\, P(\cos\theta_\mu, T_\mu, E_{\text{avail}})_j}{N_{\text{target}}\,\phi\,\epsilon(\cos\theta_\mu, T_\mu, E_{\text{avail}})_i\,\Delta\cos\theta_{\mu_i}\,\Delta T_{\mu_i}}\right)$$

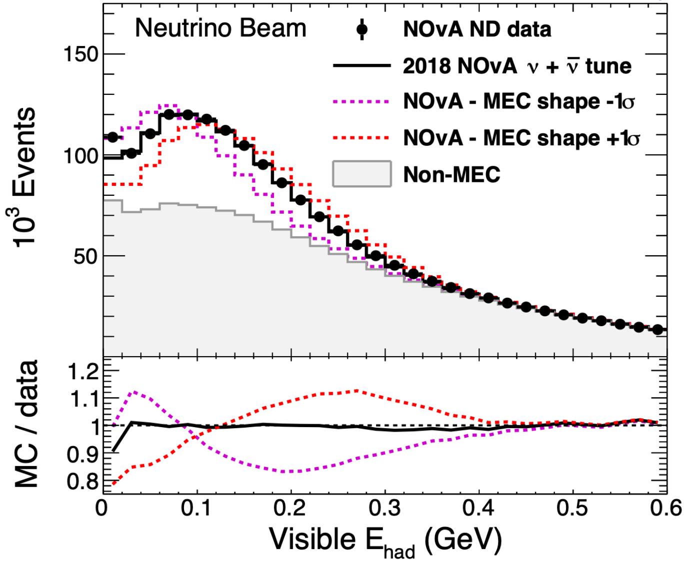
- Double Differential cross-section measurements require:
  - Selected candidate signal events, N_{sel}
  - **Smearing (U)**, **purity (P)** and **efficiency (ϵ)** corrections in 3D space (T_μ, $\cos\theta_\mu$, E_{avail}).
    - E_{avail} (available energy): total energy of all observable final state hadrons, integrated over for final result. (4 bins)
  - **an integrated flux**, ϕ
  - Binned in by muon energy and angle.
- **We rely on simulations for all the bold terms.**
  - **Beamline and Flux: G4NuMI -> ν-A modelling: GENIE -> Detector response: GEANT4-> Readout electronics & DAQ: Custom simulation routines**

We use the NOvA 2019 GENIE Tune

- Correct quasielastic (QE) component for low Q^2 suppression [R. Gran (MINERvA) https://arxiv.org/abs/1705.02932]
- Apply low Q^2 suppression to resonant (RES) baryon production.
- Nonresonant inelastic scattering (DIS) at high invariant mass ($W>1.7$ GeV/c^2) weighted up 10% based on NOvA data.
- "Empirical MEC" based on NOvA ND data to account for multinucleon knockout (2p2h). Tuning is done in bins of momentum transfer using the visible hadronic energy distribution.
- Details: *The European Physical Journal C* **volume 80**, Article number: 1119 (2020)



NOvA Preliminary



Systematic Uncertainties

- Most systematic uncertainties are assessed using modified MC simulation.
- **Universe approach**: modify systematic source by +/- 1 sigma of the effect. Usually used for single-source effects that impact event-level reconstruction and PID.
- **Multiverse approach**: construct "N" universes with systematic sources modified by a random from it's probability distribution. Usually used for multiple-source effects, where impact on event rates and shapes has been predetermined.

	Universe	***Multiverse***
Flux		✓
ν-A Modeling		✓
Calibration and Detector Response	✓	
Muon Energy Scale	✓	
Muon Angle - Alignment	✓	
Neutron Modeling	✓	
Total - Covariance Matrix		✓

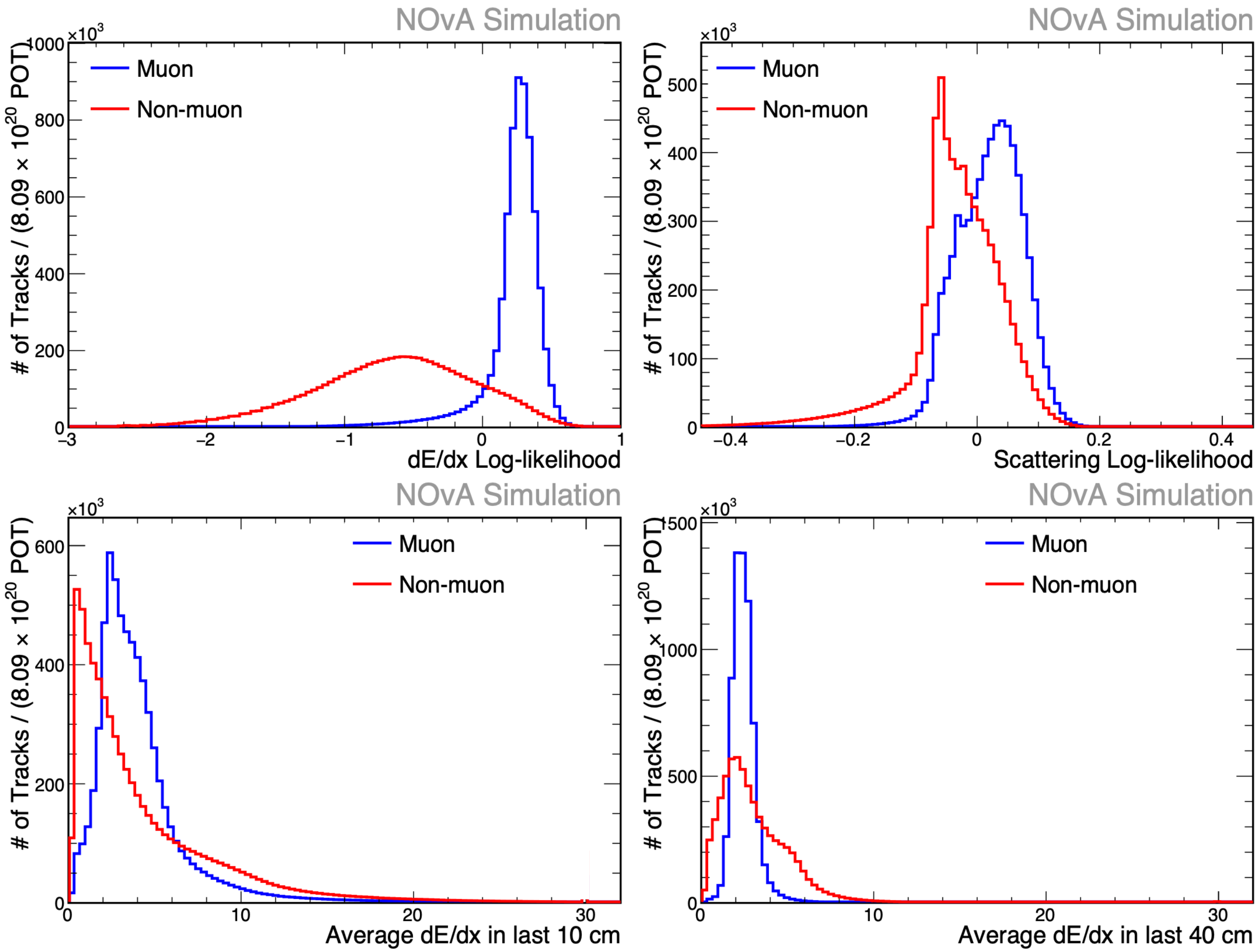
Hadron production model constrained with external measurements on thin target.

Resulting uncertainty ~10% in normalization.

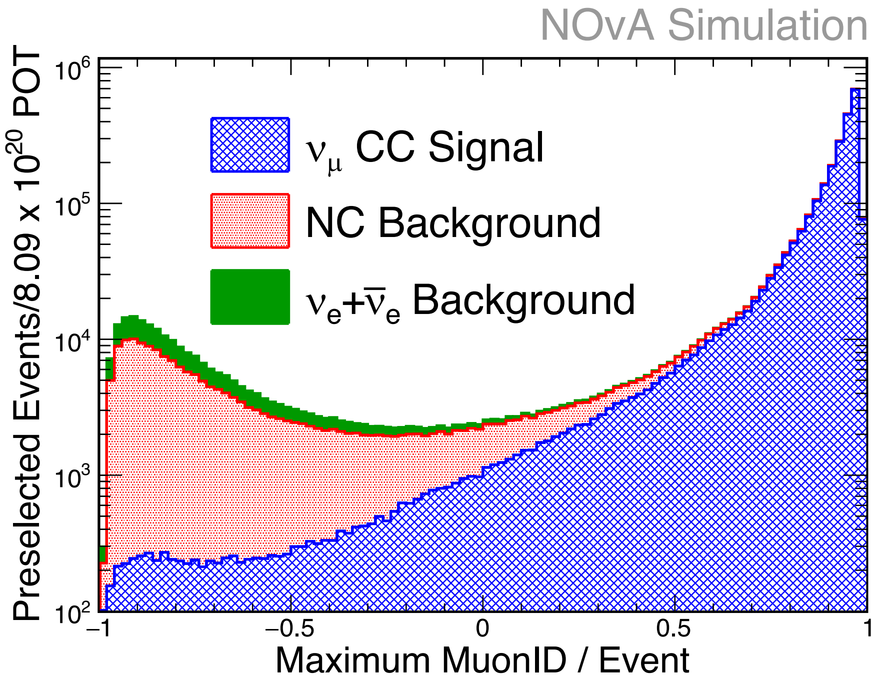
[Phys.Rev.D94, 092005] (PPFX)

Particle ID

- Preselection: events fully contained and with vertex in fiducial volume.



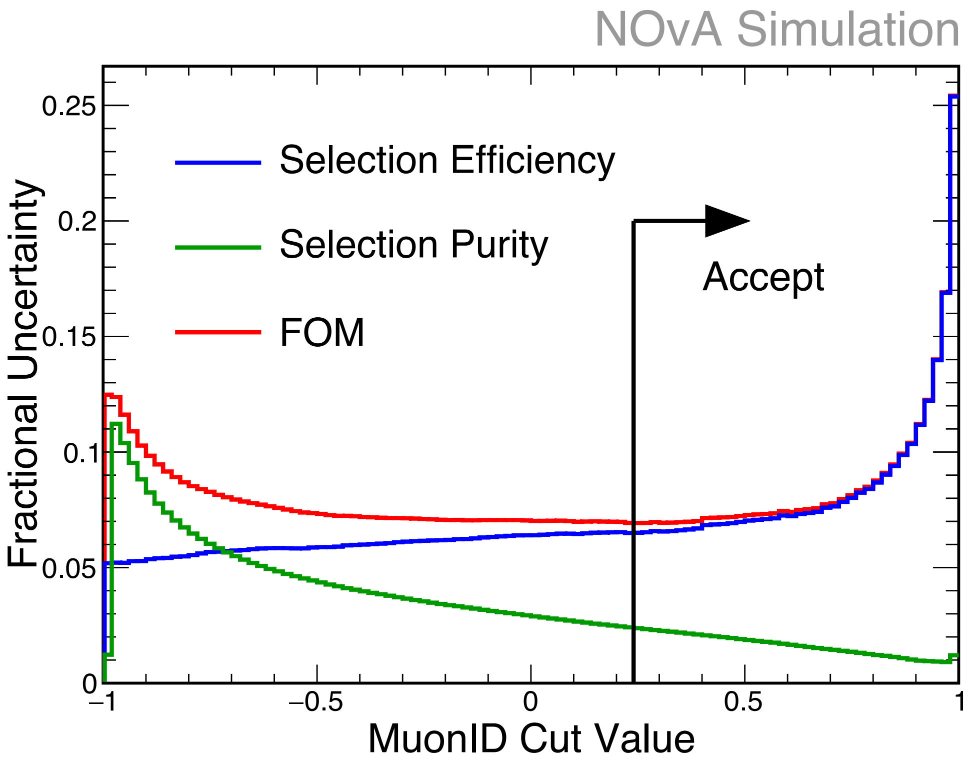
- Muon ID calculated with a Boosted Decision Tree.



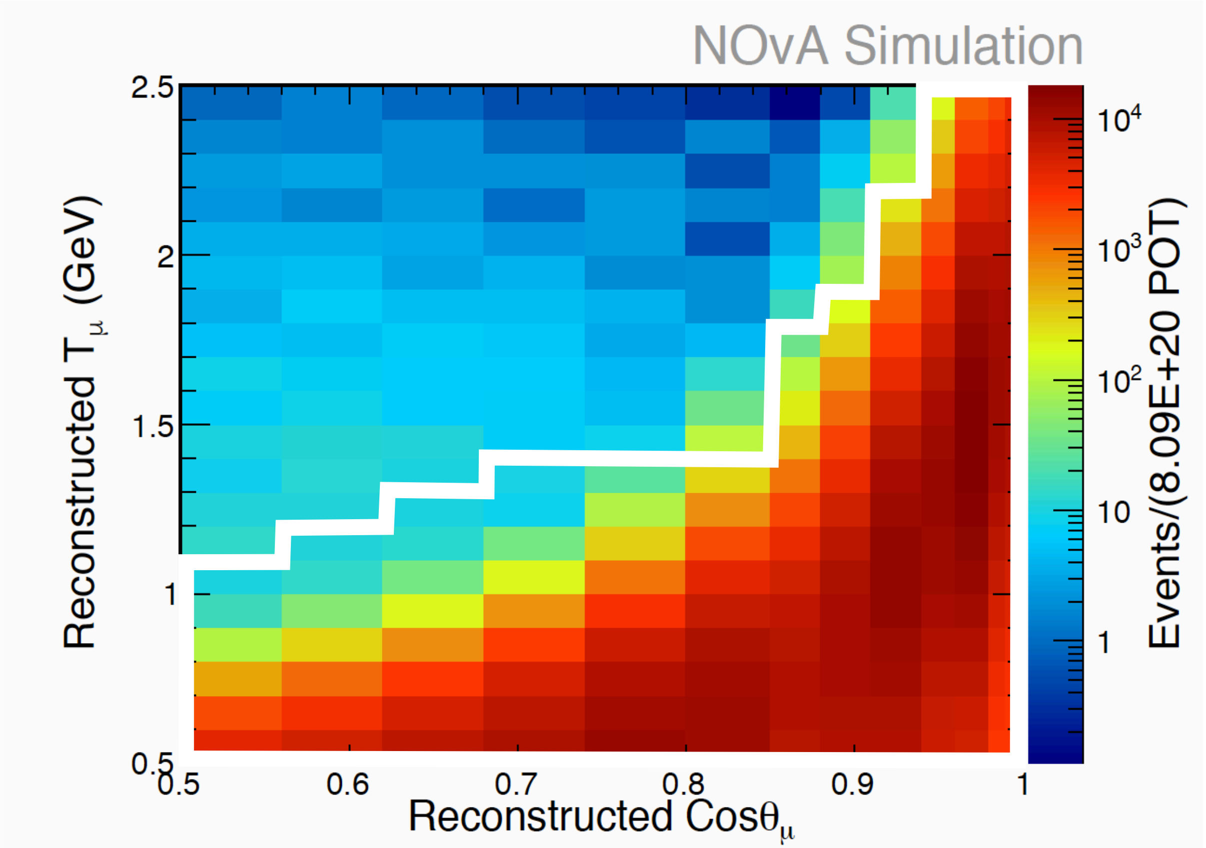
Cut optimization and binning

- Cut value corresponds to minimum fractional cross section uncertainty.

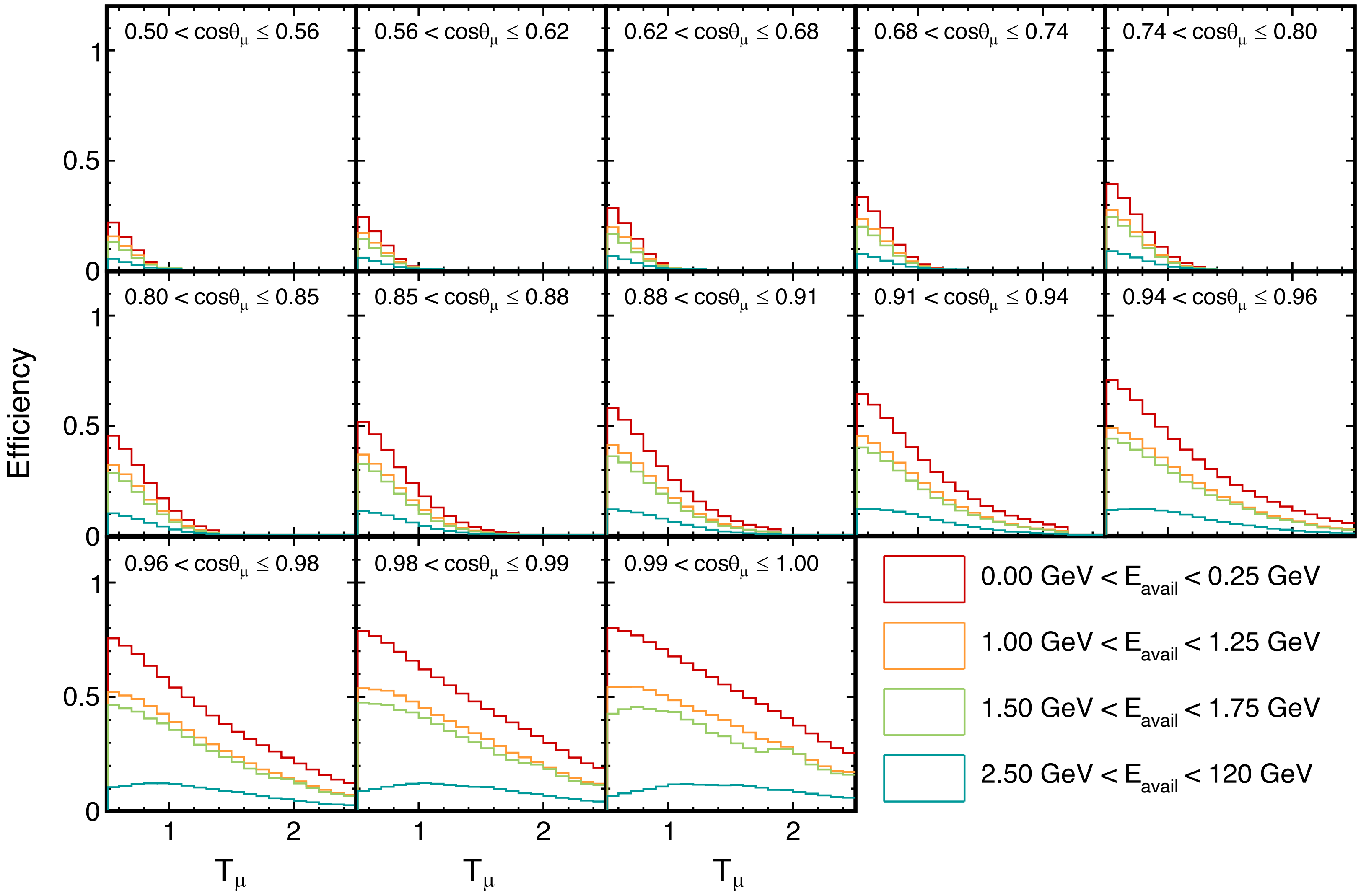
$$\text{FOM} = \left(\frac{\delta\epsilon}{\epsilon}\right)^2 + \left(\frac{\delta}{P}\right)^2$$



- 172 muon kinematic bins (white outline).
  - 20 equal bins from 0.5GeV to 2.5GeV for T.
  - 13 variable-sized bins for reconstructed angle.

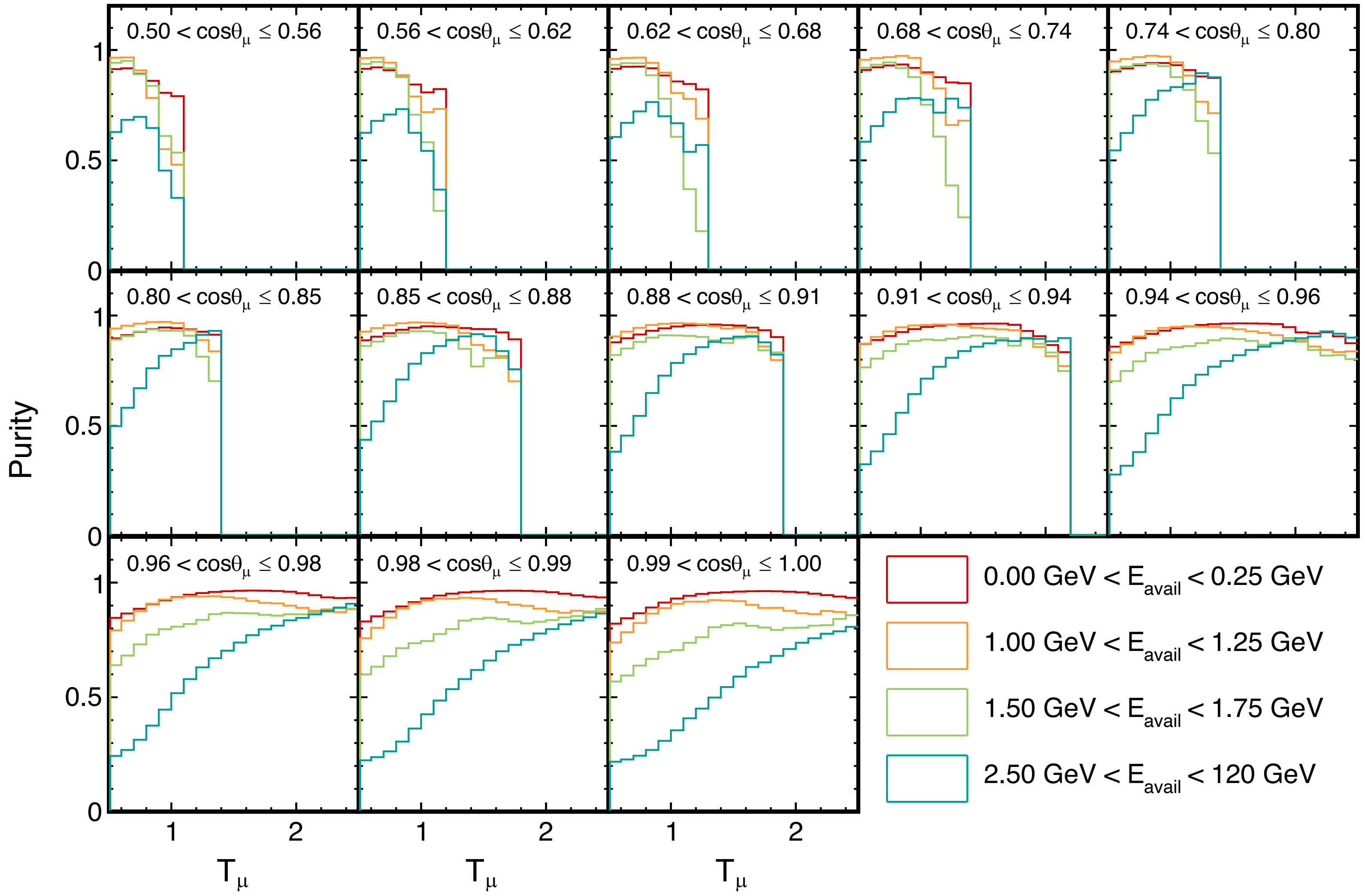


Efficiency



- Increases as a function of angle. (acceptance and reco effect)
- Decreases as a function of muon kinetic energy (containment effect)
- More hadronic activity makes the event reconstruction and muon identification more difficult.

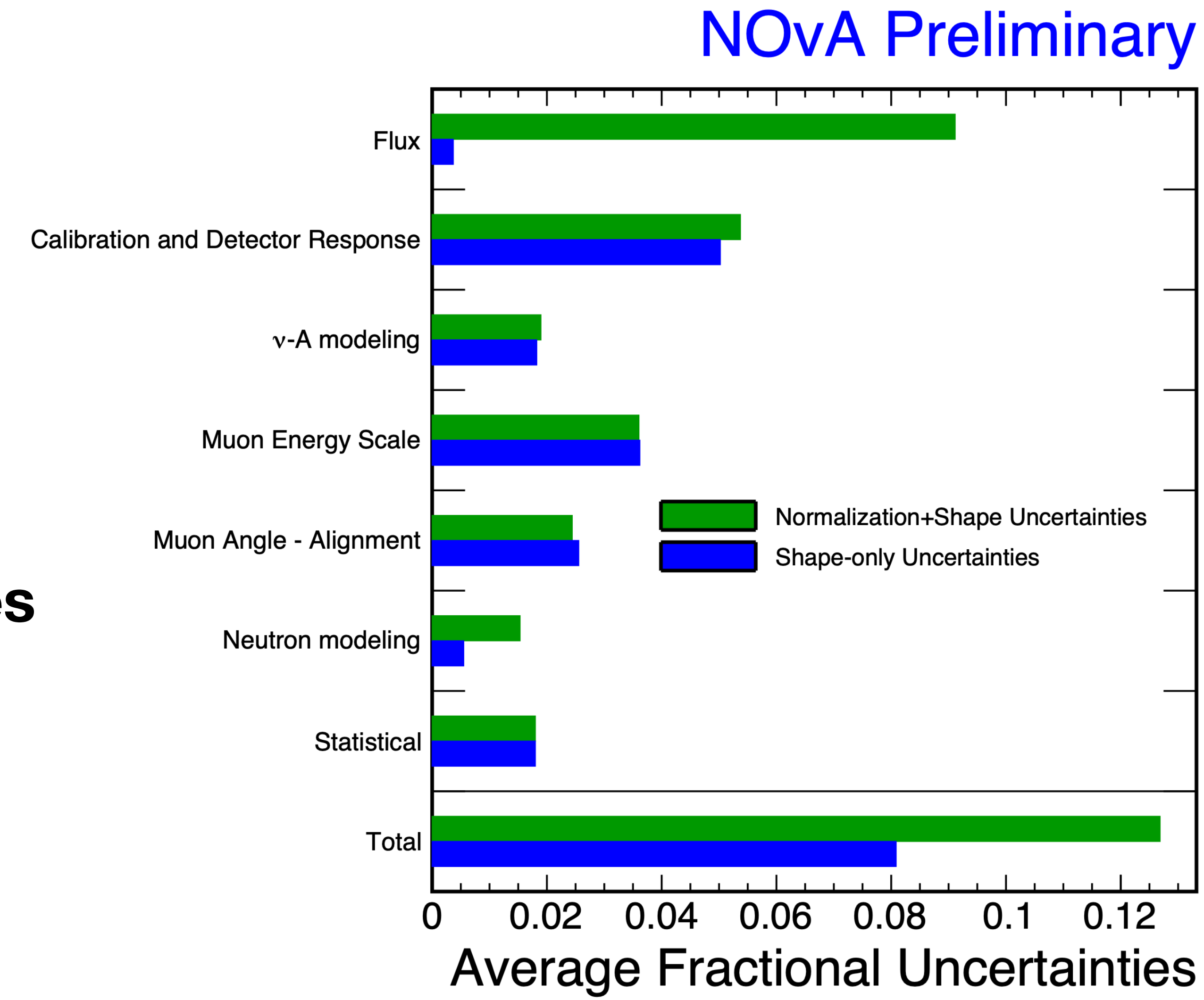
Purity



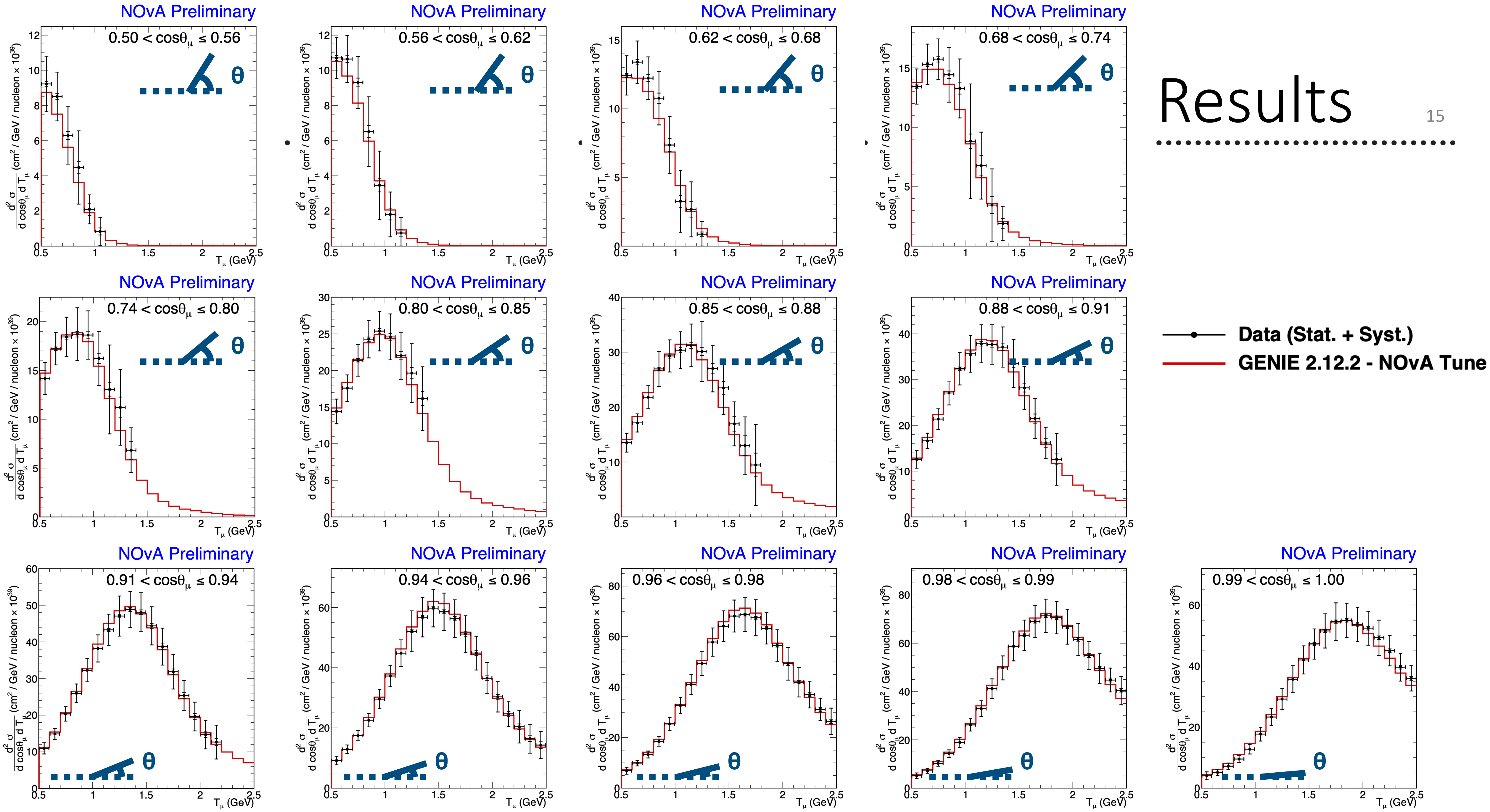
- At low T contamination from of NC interactions reduces purity

Sources of Systematic Uncertainty

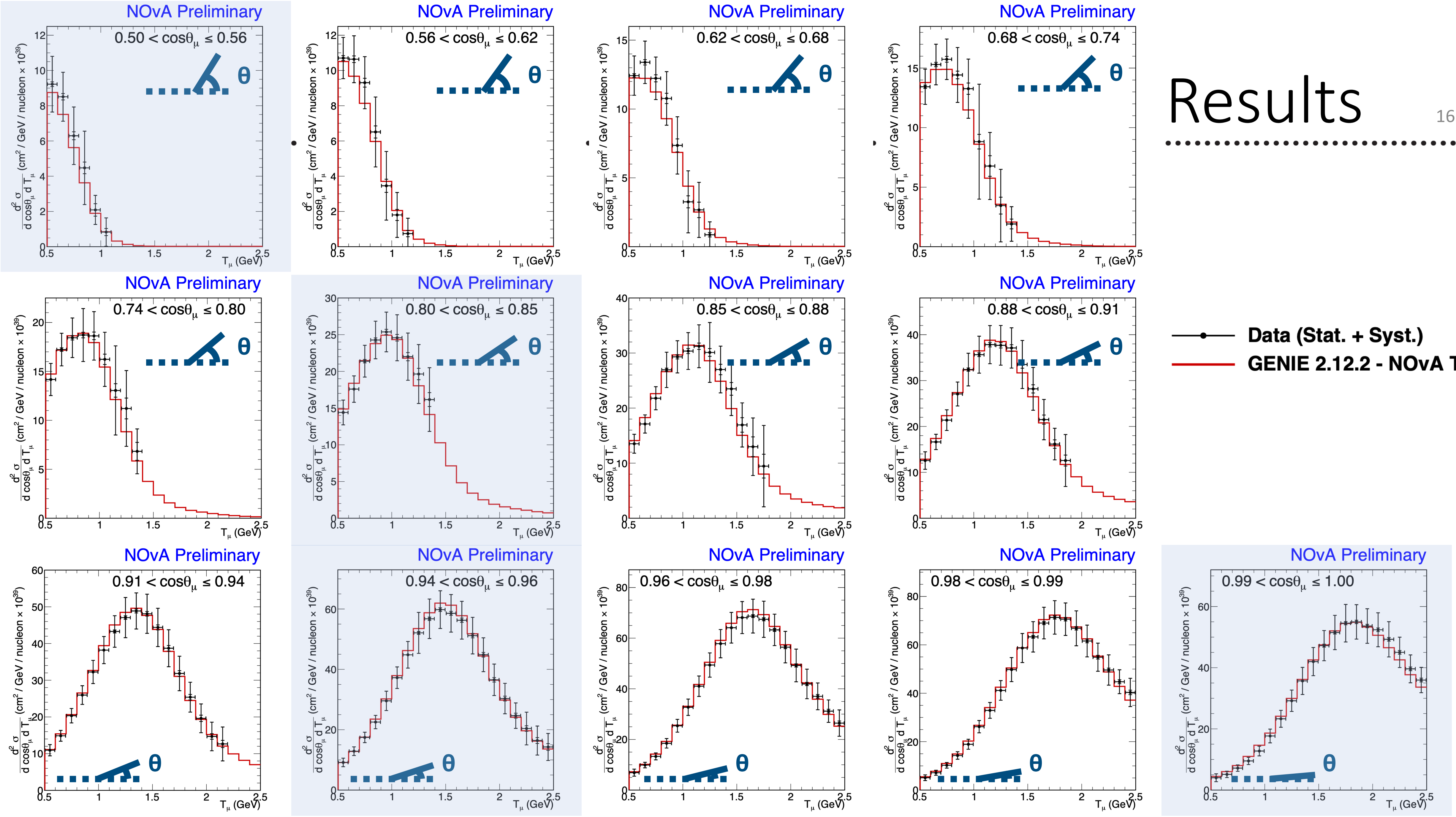
- Weighted average uncertainties to extracted cross section value.
- Flux is a [dominant] normalization uncertainty ~9%.
- Statistical uncertainties at level of a few %.
- **Interaction modeling uncertainties are sub-dominant.**
- Measurements has typical total [shape] uncertainties around 12% [8%] in each bin.



Results

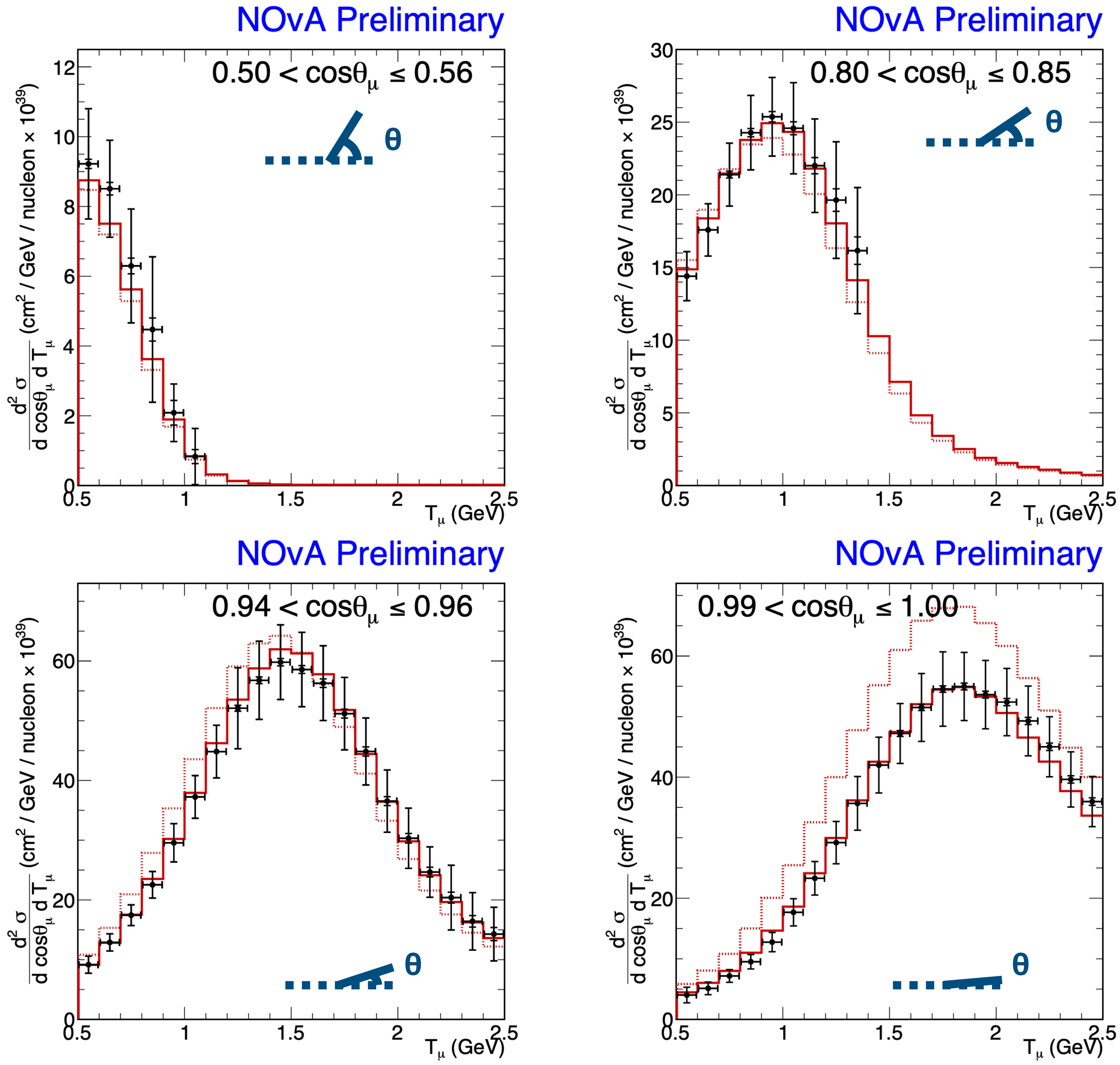

NOvA Preliminary
$0.50 < \cos\theta_\mu \leq 0.56$
$0.56 < \cos\theta_\mu \leq 0.62$
$0.62 < \cos\theta_\mu \leq 0.68$
$0.68 < \cos\theta_\mu \leq 0.74$
$0.74 < \cos\theta_\mu \leq 0.80$
$0.80 < \cos\theta_\mu \leq 0.85$
$0.85 < \cos\theta_\mu \leq 0.88$
$0.88 < \cos\theta_\mu \leq 0.91$
$0.91 < \cos\theta_\mu \leq 0.94$
$0.94 < \cos\theta_\mu \leq 0.96$
$0.96 < \cos\theta_\mu \leq 0.98$
$0.98 < \cos\theta_\mu \leq 0.99$
$0.99 < \cos\theta_\mu \leq 1.00$
θ
$\frac{d^2\sigma}{d\cos\theta_\mu\, d T_\mu}$ (cm^2 / GeV / nucleon × 10^{39})
T_μ (GeV)
Data (Stat. + Syst.)
GENIE 2.12.2 - NOvA Tune

Results



Data (Stat. + Syst.)

GENIE 2.12.2 - NOvA Tune



Genie Comparisons - Example cosine slices

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

- "Untuned" has no MEC.
- Good agreement between tuned/untuned GENIE versions in high angle slices.
- At forward angle (low Q^2), the untuned GENIE 2 overshoots data. (QE and MEC events dominate)

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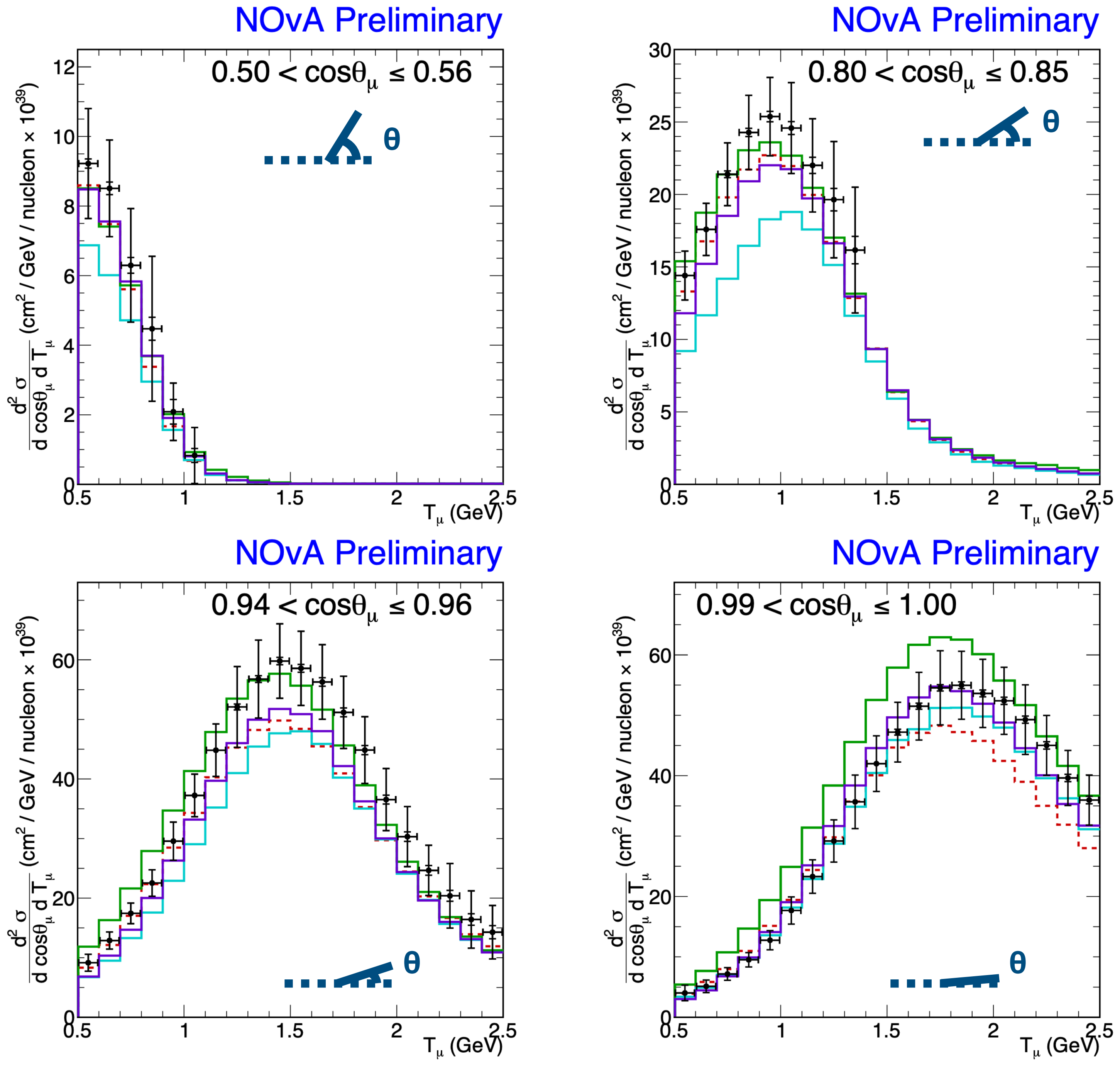
Generator Comparisons
Example cosine slices

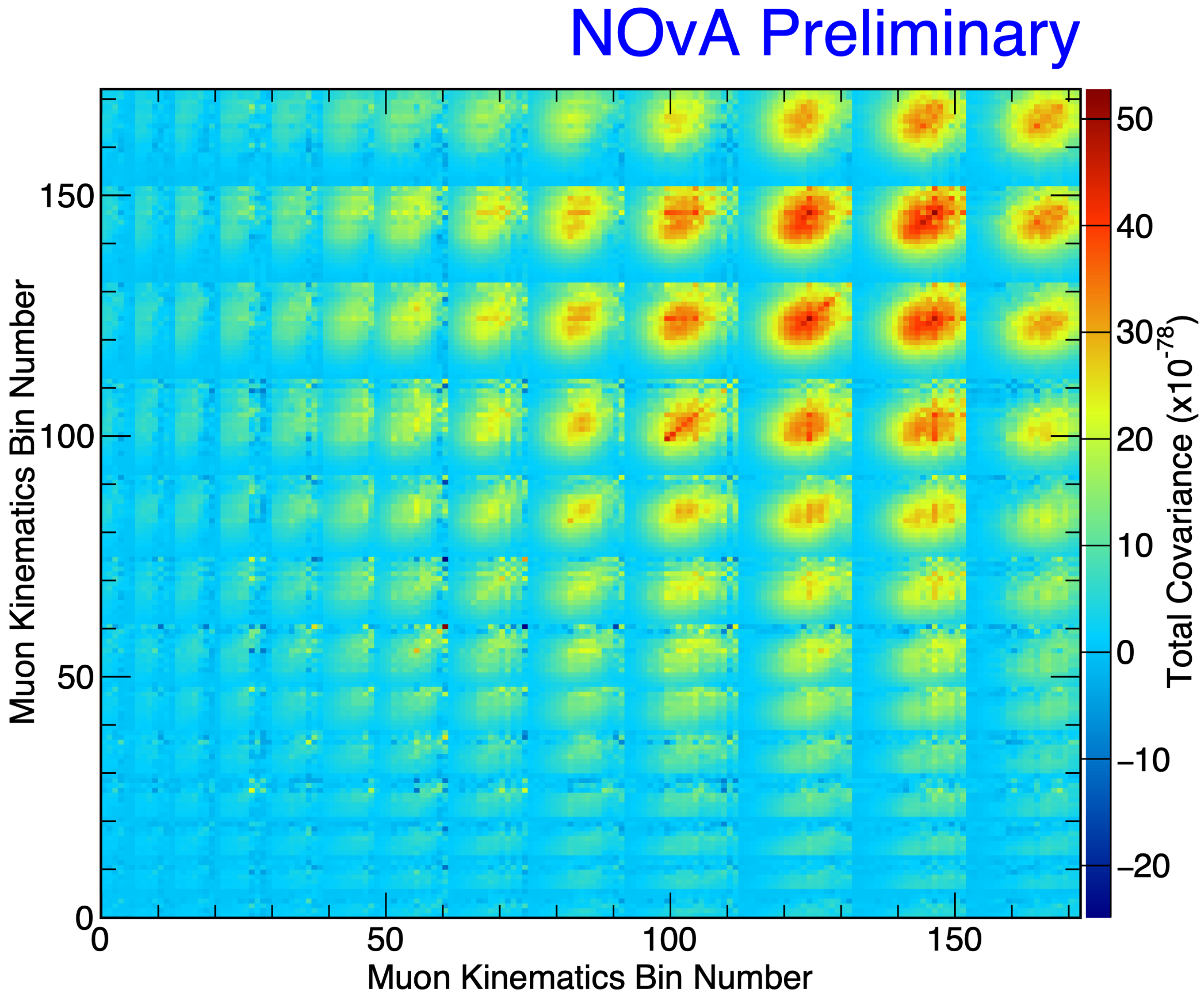


- Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

*N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a, used in latest osc. results

- Out of the box generator comparisons.
- All generators reproduce well the shape of our data.
- An overall normalization difference in GiBUU.
- How do we quantify the agreement?

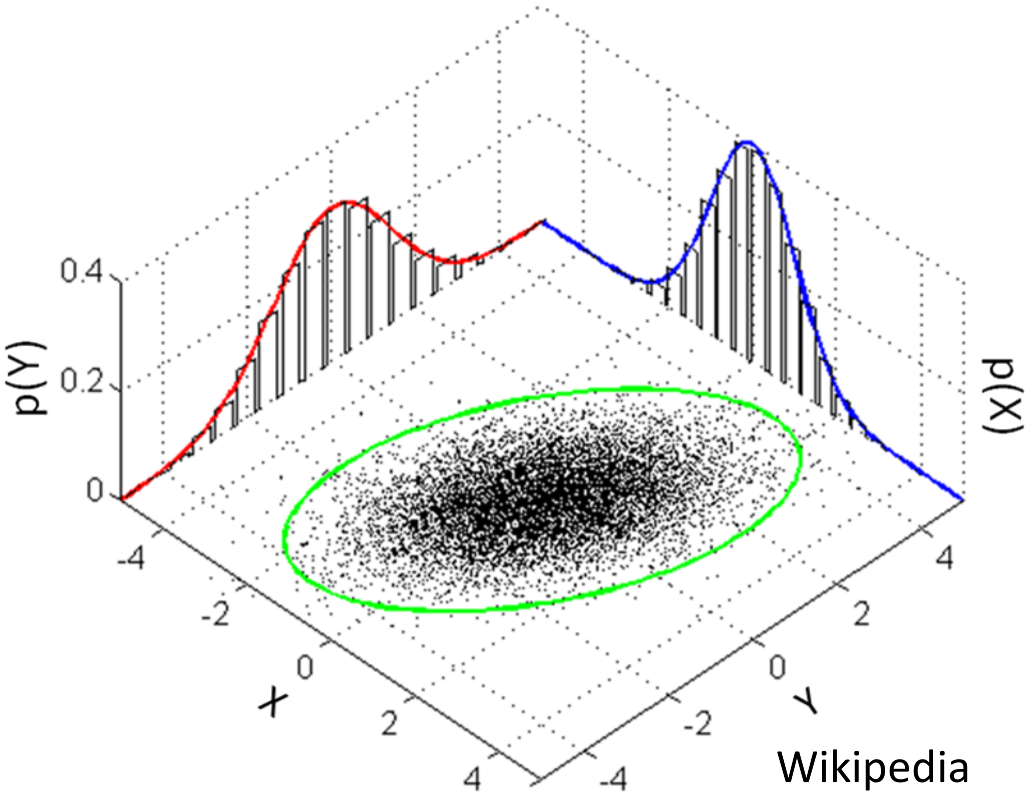
Covariance Matrix



- We generate 100k+ universes corresponding to different combinations of our systematic uncertainty samples to populate a covariance matrix. (Nominal and Shape Only)
- One of the key deliverables of the analysis, as it will allow users to properly handle bin-to-bin correlations.

Generate Multivariate Gaussian

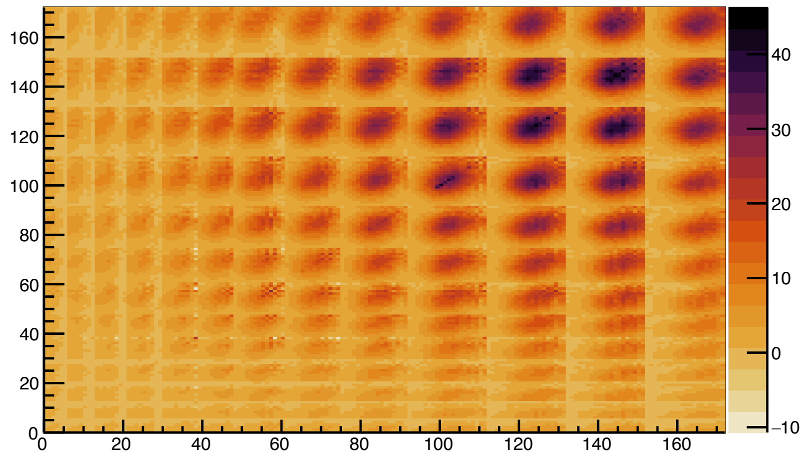
- Using RooFit (RooMultiVarGaussian) construct MVG from covariance and a given generator mean.
- Generate 50,000 sample points with our MVG (Simulate experiments)
  - Some example code: https://indico.fjfi.cvut.cz/event/90/contributions/2042/attachments/688/892/Sample.C



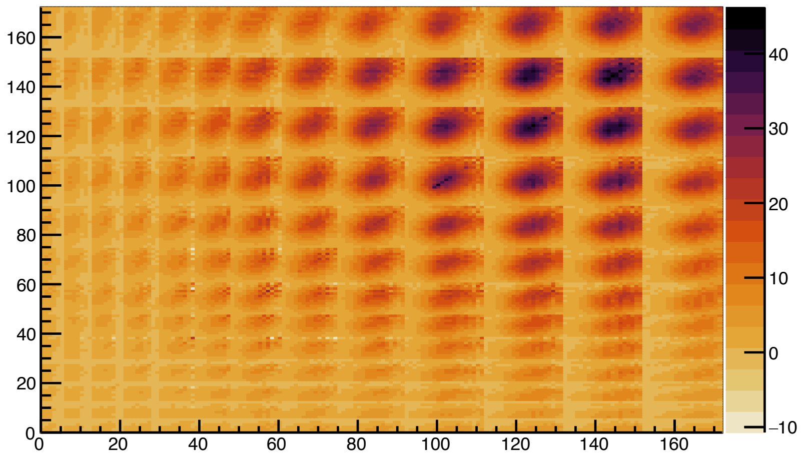
Wikipedia

Comparing MVG Throws to Full Covariance

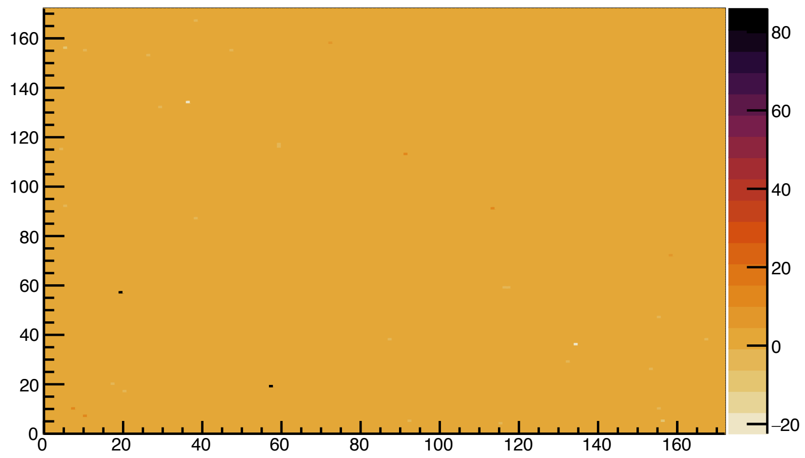
Covariance matrix MuKin NuWro 2019 total



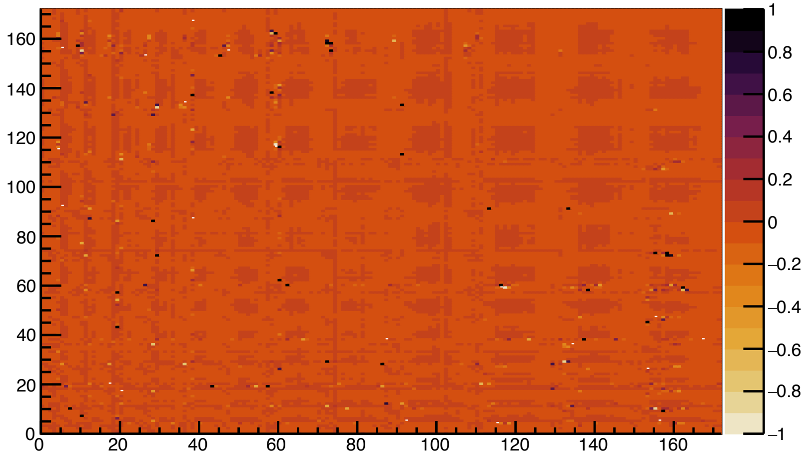
Covariance matrix from Throws



Fractional Difference



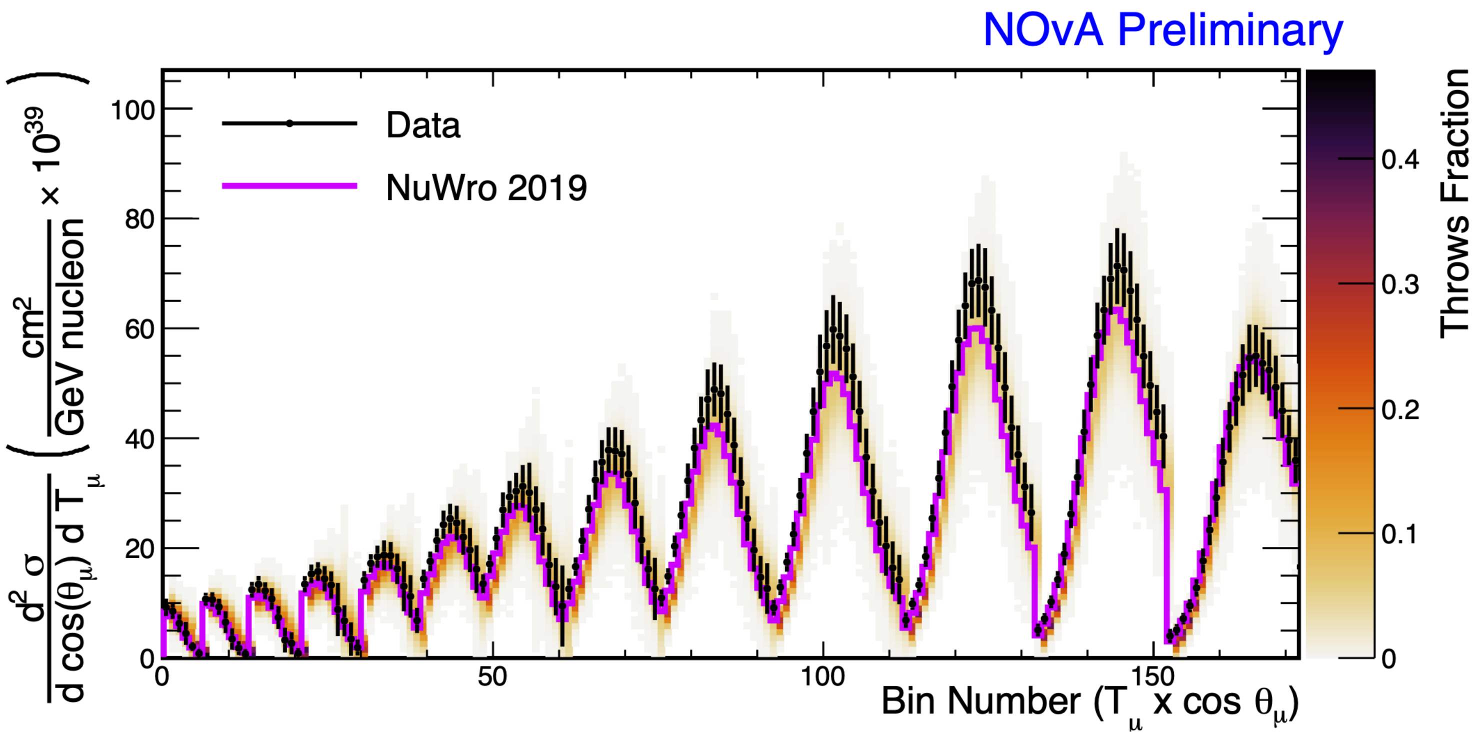
Fractional Difference ZOOM

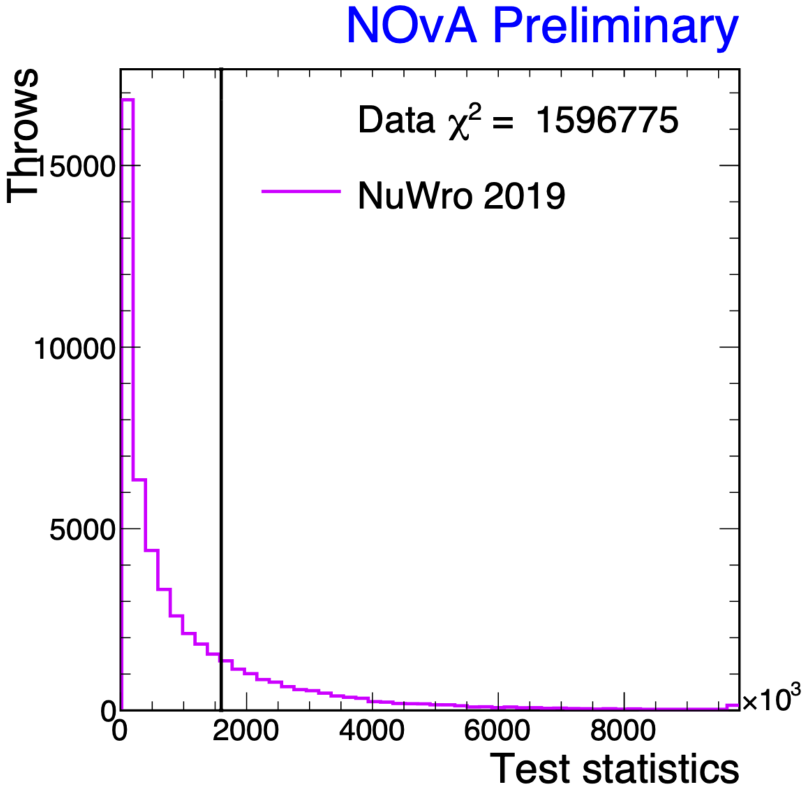


Cool it works!

Compute p-Value

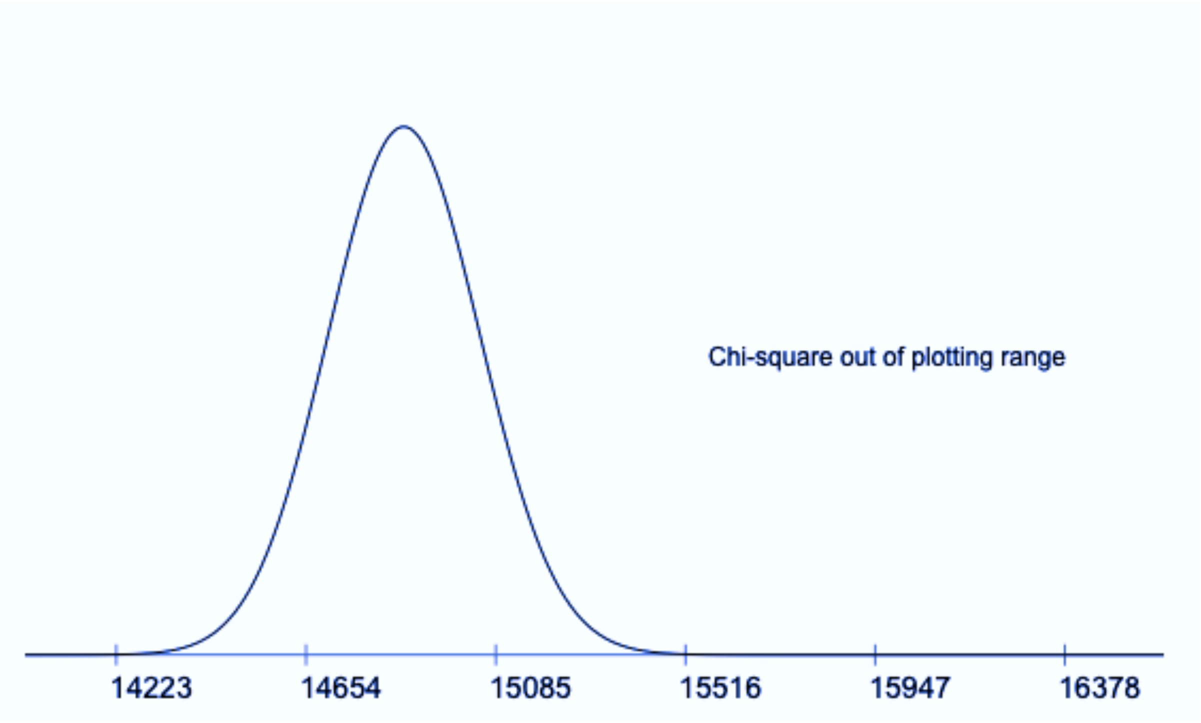
- For each simulated “experiment” or throw calculate test statistic to nominal generator.
- We’re using $$\chi^2 = \sum_{ij} (x_i - \mu_i)(\Sigma^{-1})_{ij}(x_j - \mu_j)$$
- Compare to test statistic of data to find p-values (fraction of throws above data).

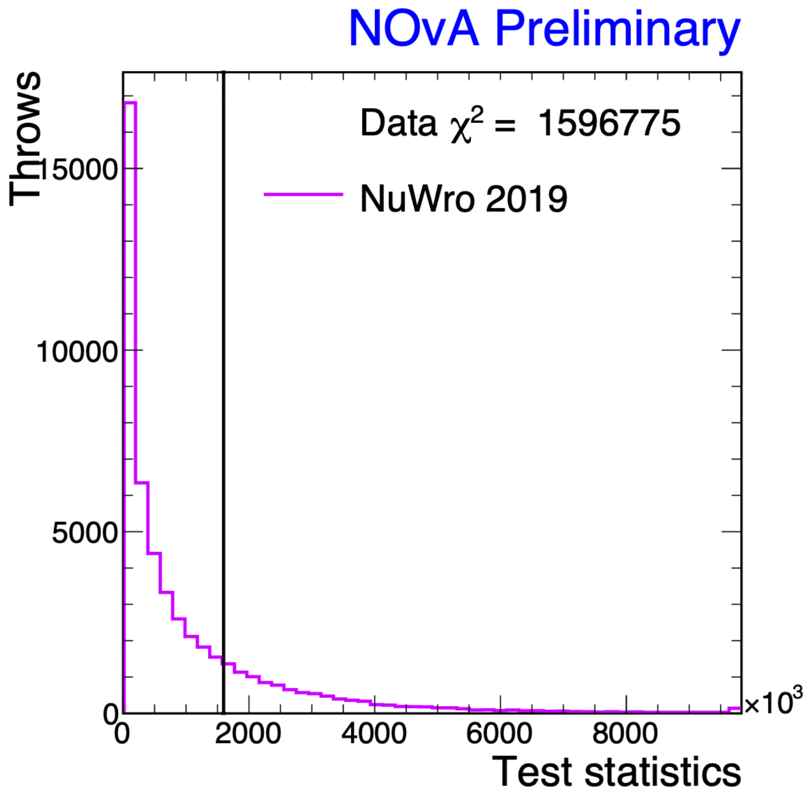




Why are we using this p-Value?

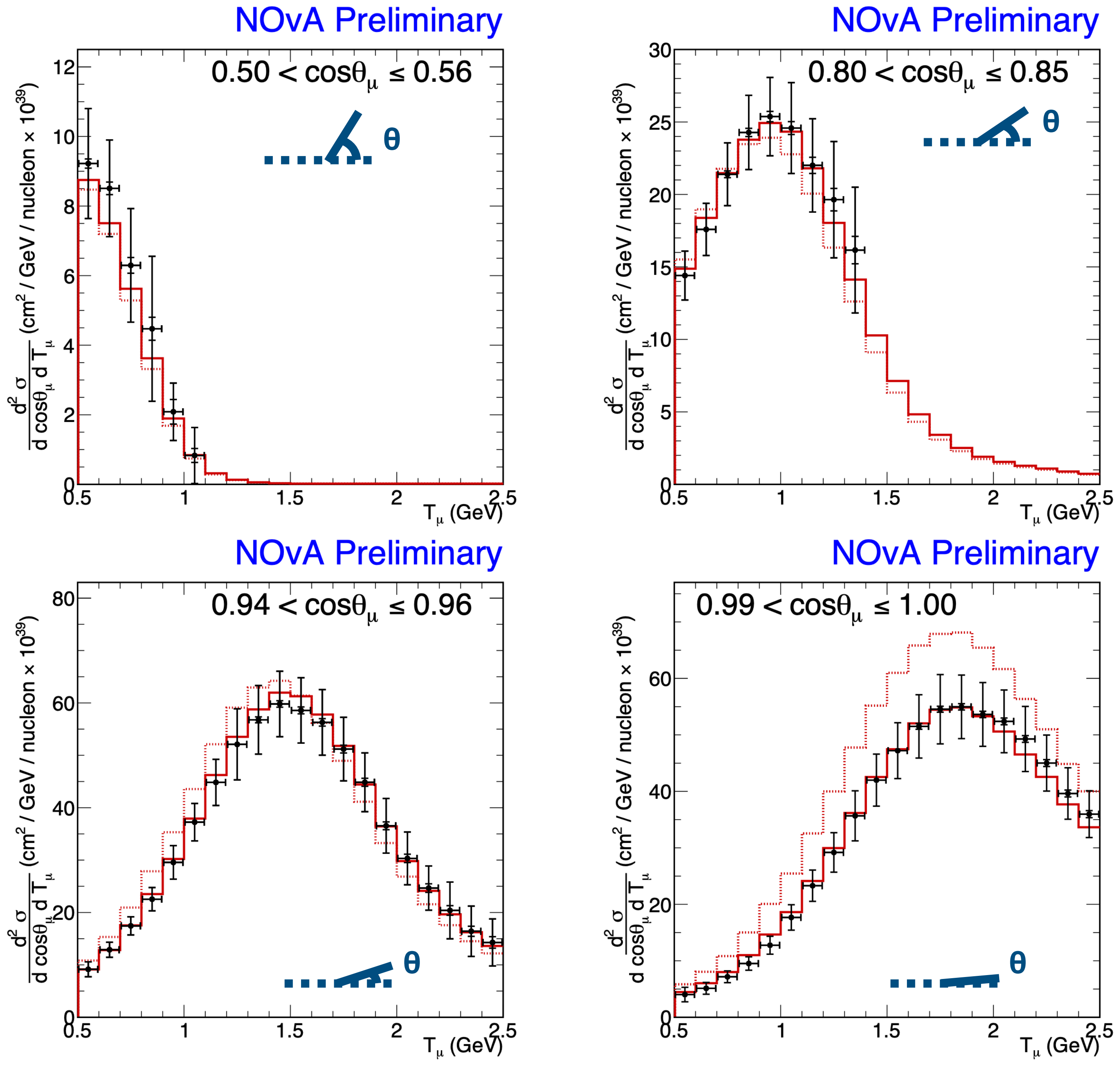
- We have 14878 (diagonal elements of covar. + half off diagonals)
- This gives the standard χ^2-squared distribution shown below which has a p-value of essential zero for the observed 1596775.
- Our pulls are not χ^2-squared distributed so p-value from thrown universes allows proper statistical interpretation.





Genie Comparisons - Example cosine slices

- Higher p-value for the tuned prediction by construction.
- Lower p-value for the untuned prediction from the forward bins.



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

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

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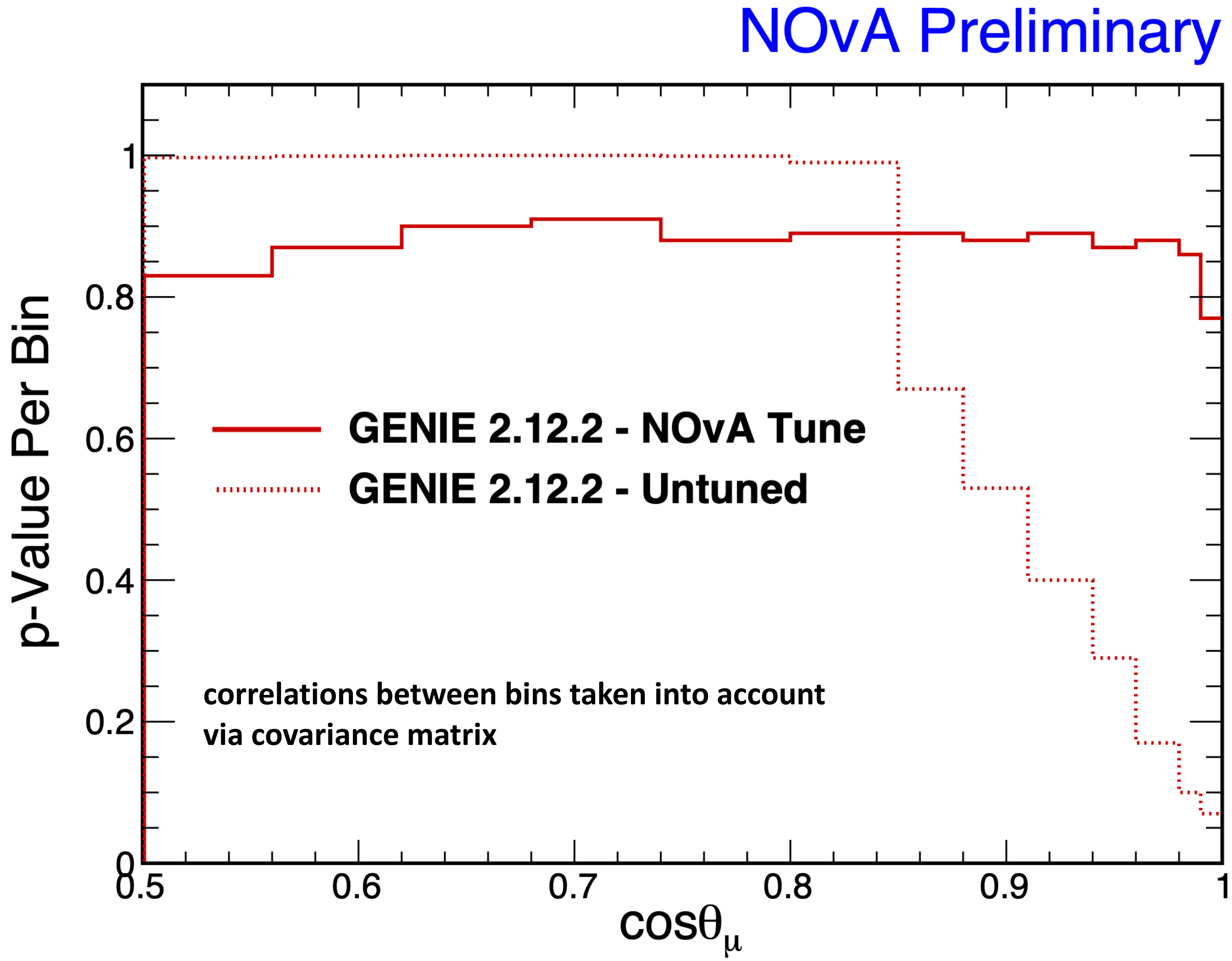
p-Values by angular bins



- Large disagreement between data and untuned prediction in the forward region.
- Tuning improves overall agreement, with a cost of slightly less agreement at higher angles.

GENIE 2.12.2 - NOvA Tune
GENIE 2.12.2 - Untuned

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

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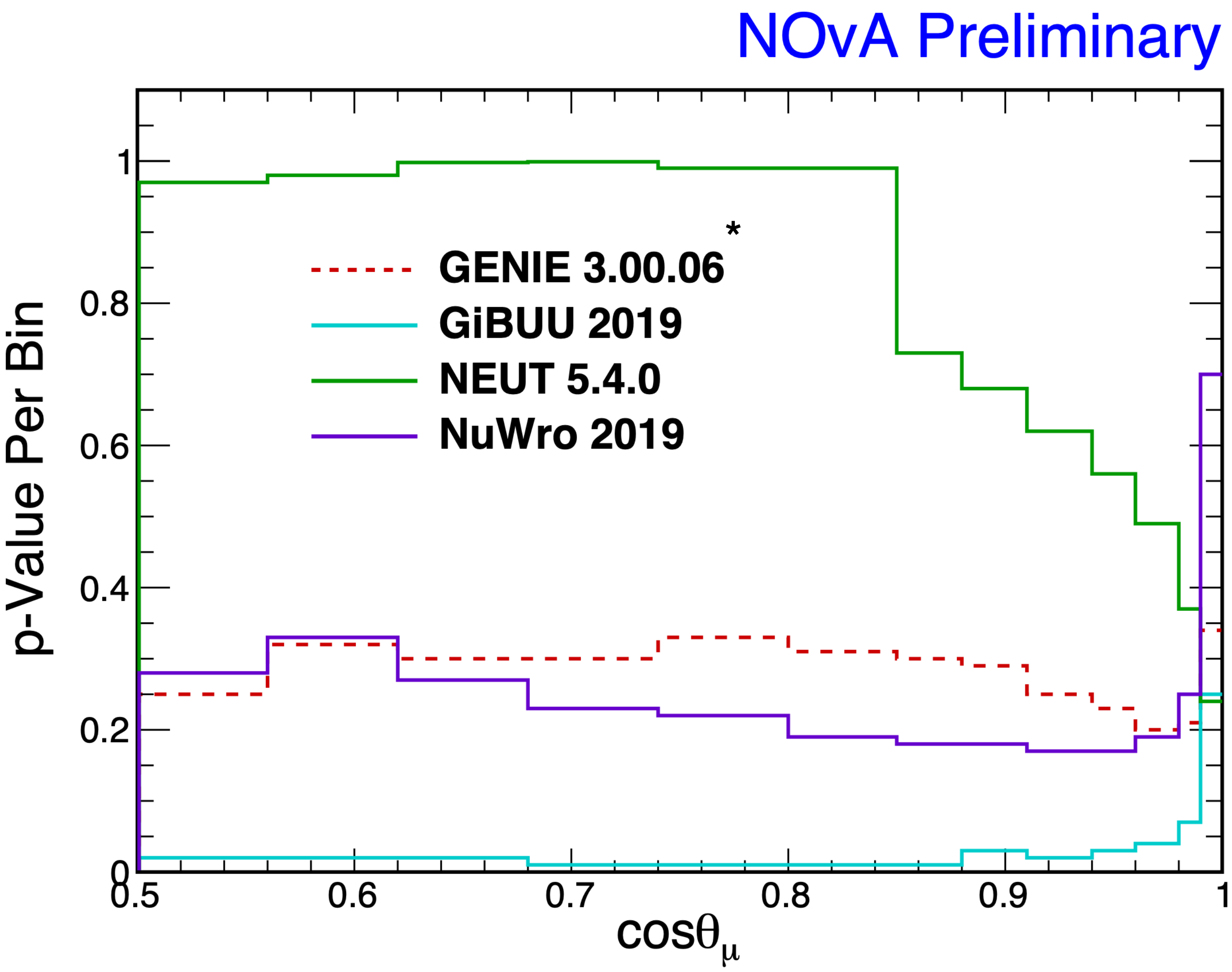
p-Values by angular bins

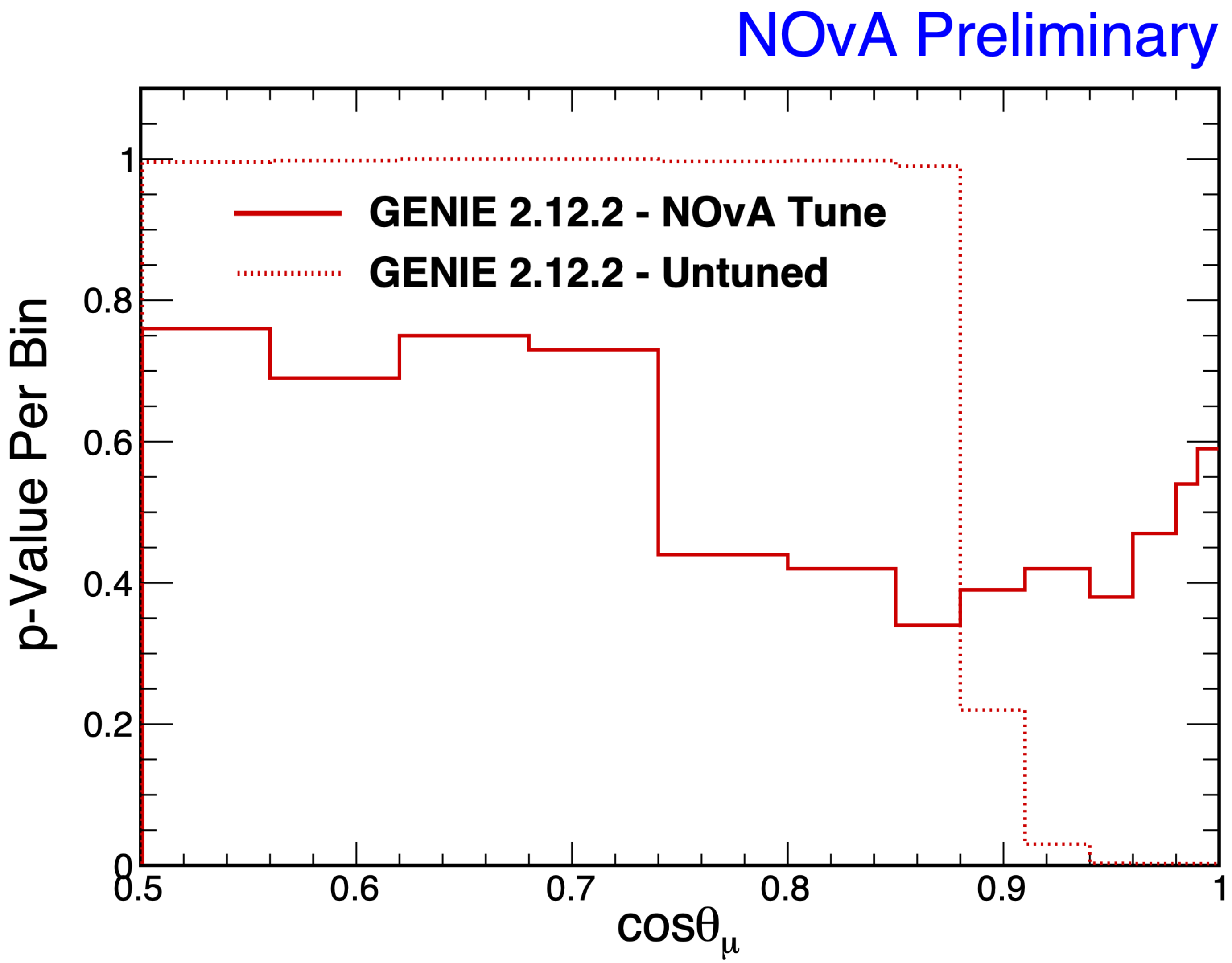


- p-values are reasonable for nearly all generators.
- Some generators see an improvement in their p-values at more forward angles.

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

*N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a, used in latest osc. results

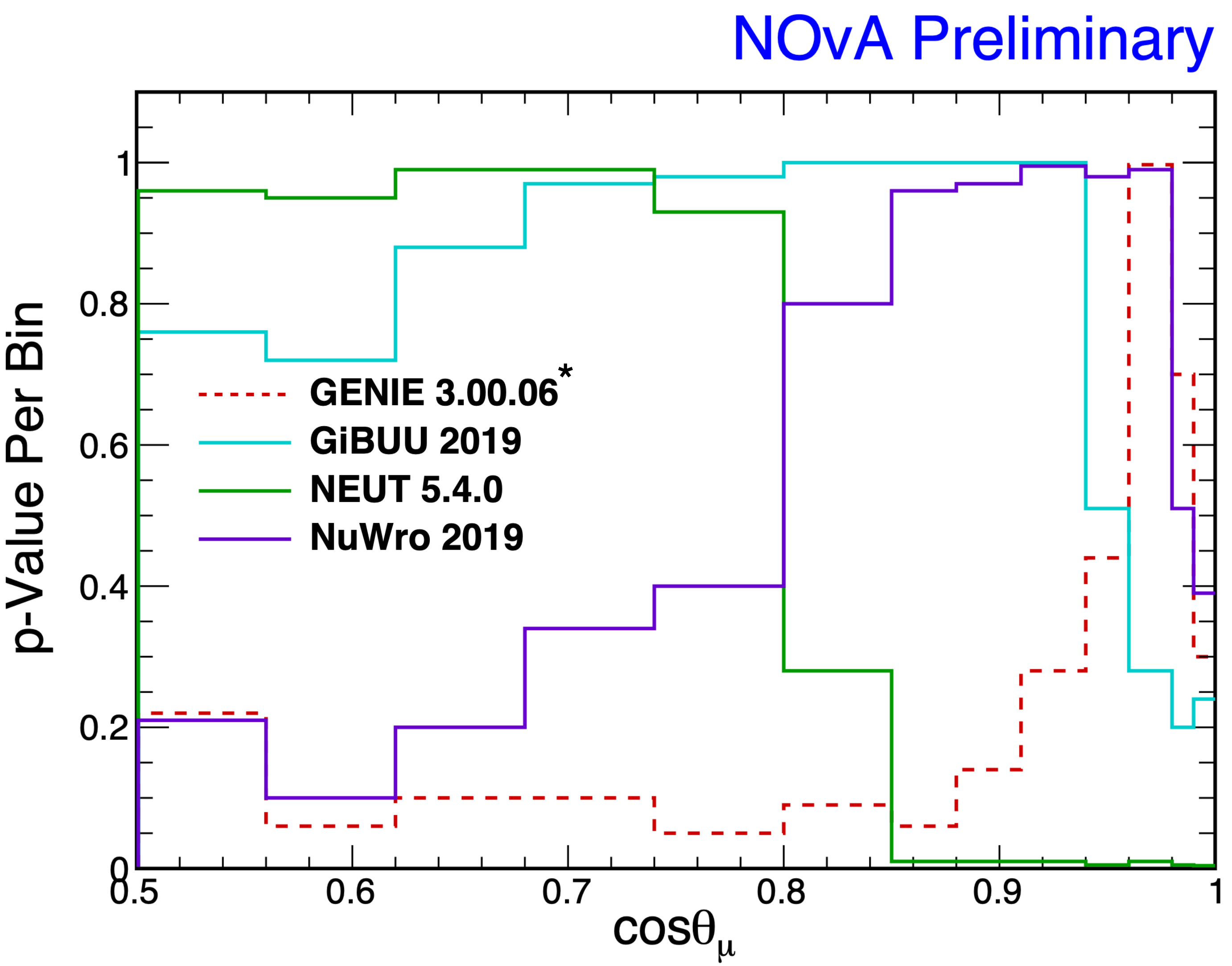
Shape-only p-values by angular bins



- Distributions area normalized, normalizations effects removed from covariance.
- Smaller shape-only uncertainties and renormalization result in overall lower p-values.
- Discrepancy between the higher angles and most forward-going angles in the tuned version.
- Improvement in agreement in the forward region.

Generator	Total p-value	Norm.
GENIE 2.12.2 - Tuned	0.54	1.01
GENIE 2.12.2 - Untuned	0.003	0.98

Shape-only p-values by angular bins



- GiBUU agrees much better with normalization increase.
- Interesting differences across space and generally low p-values at forward angles.

Generator	Total p-value	Norm. Factor
GENIE 3.00.06*	0.31	1.15
GiBUU 2019	0.38	1.28
NEUT 5.4.0	0.004	1.02
NuWro 2019	0.54	1.15

*N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a, used in latest osc. results

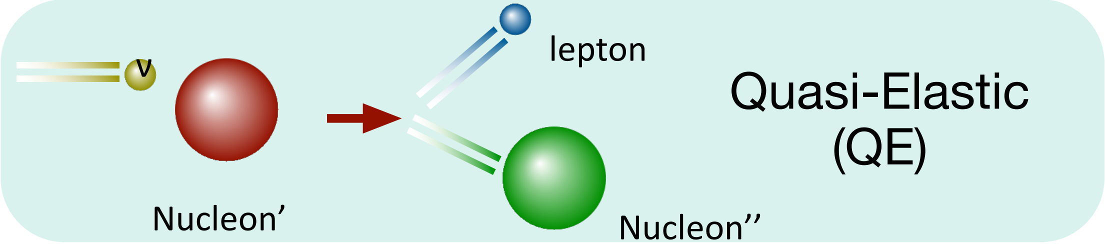
Summary

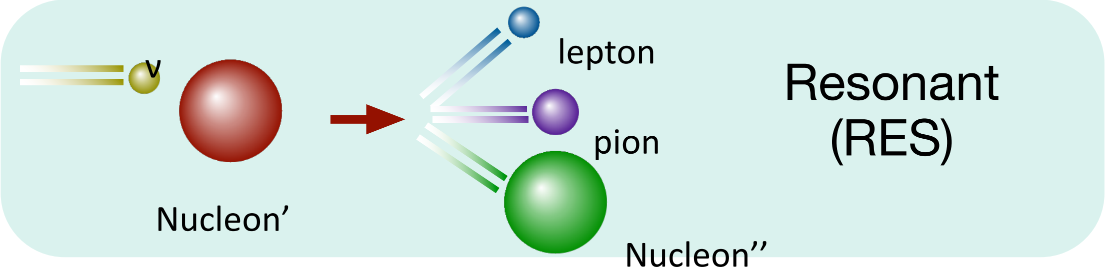
- NOvA has measured the double-differential muon-neutrino charged-current inclusive cross section in 172 bins with 12% average total uncertainty (8% average shape-only uncertainty).
- p-Value comparisons using covariance matrix are generated to quantify the level of agreement between our measurement and generator predictions.
  - Broad agreement between results and predictions.
  - Forward region (low Q^2) shows poor agreement across models.
- Paper and data release are in advanced collaboration review.
  - We can also release our MVG to allow others to compare models in this way.

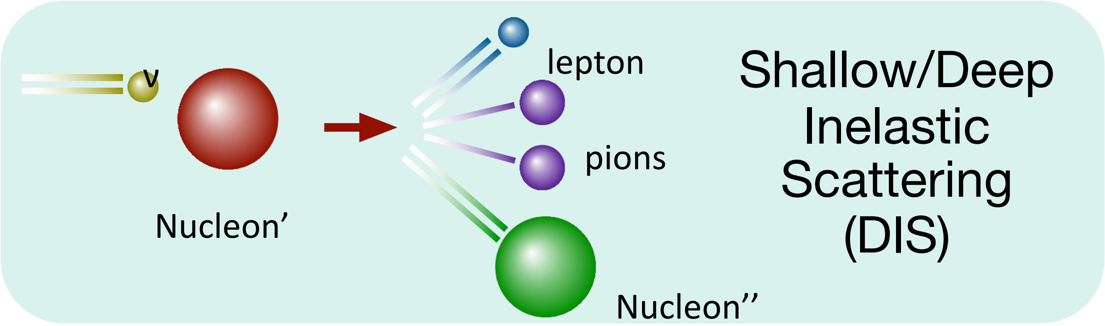
DISCUSSION

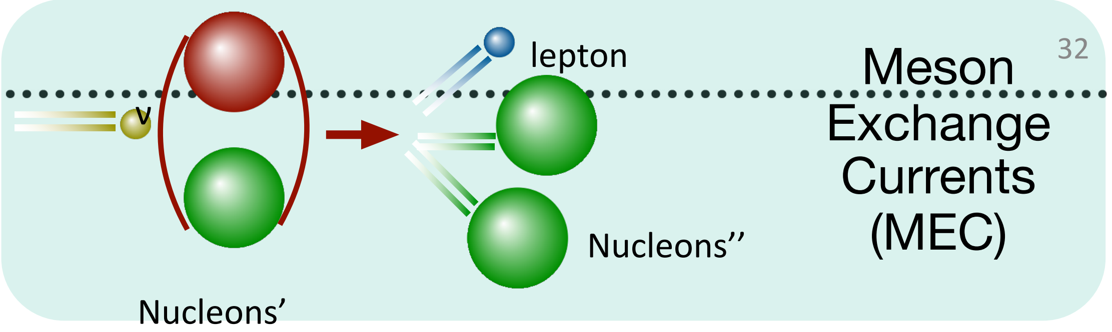
BACKUPS

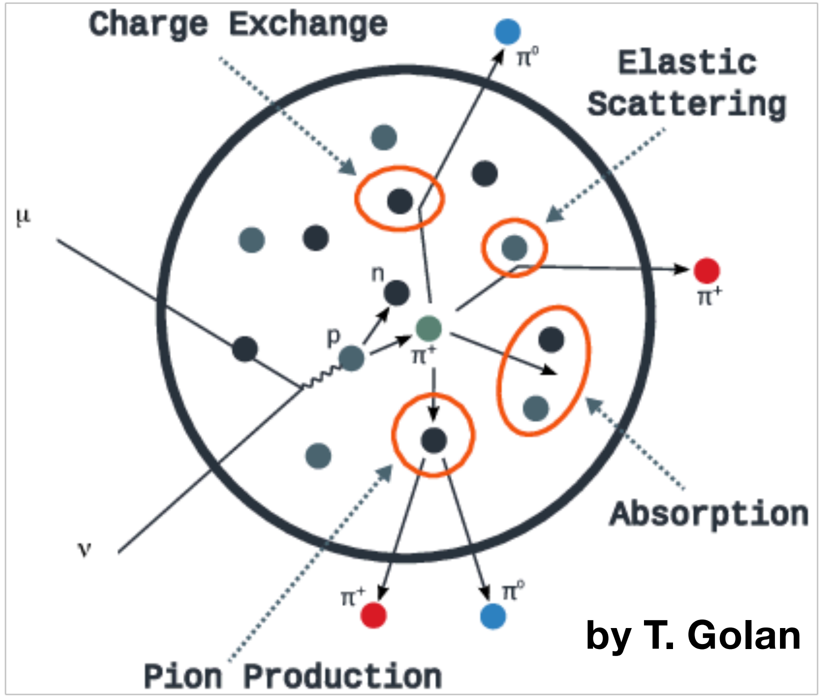
Neutrino Interactions





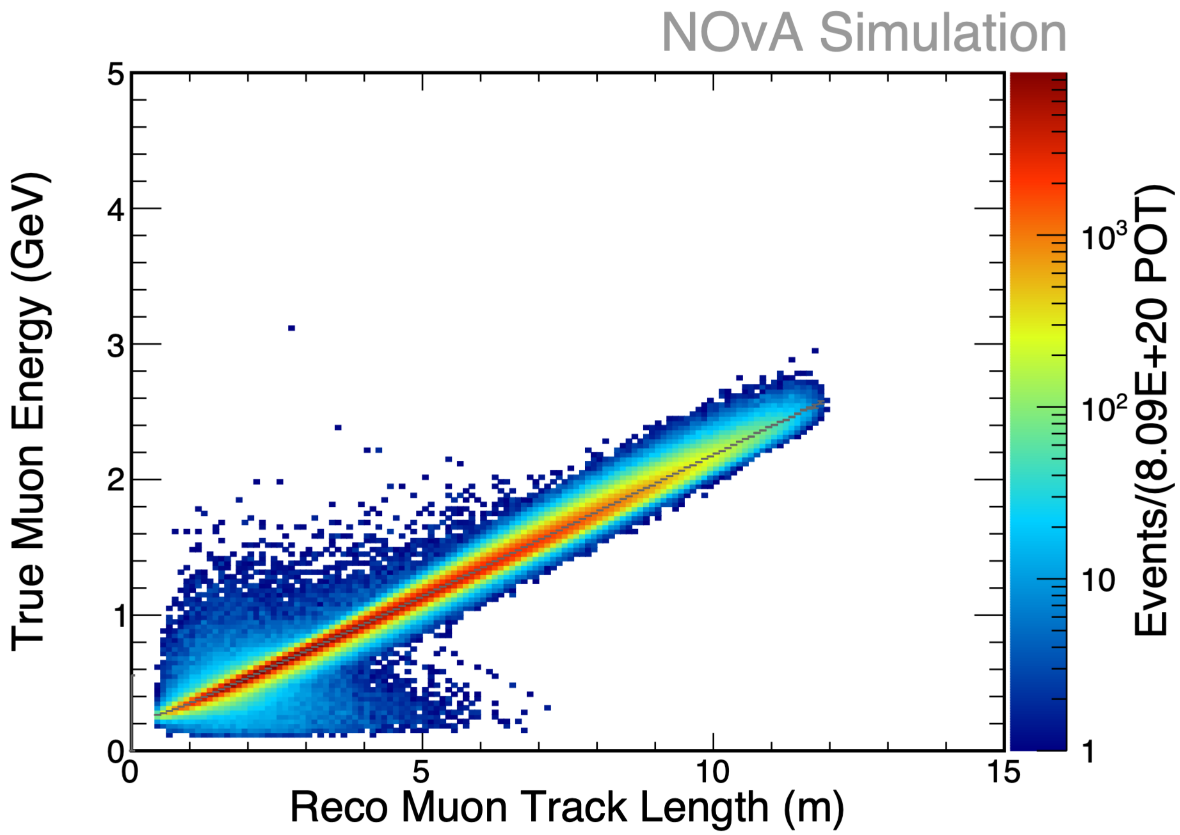




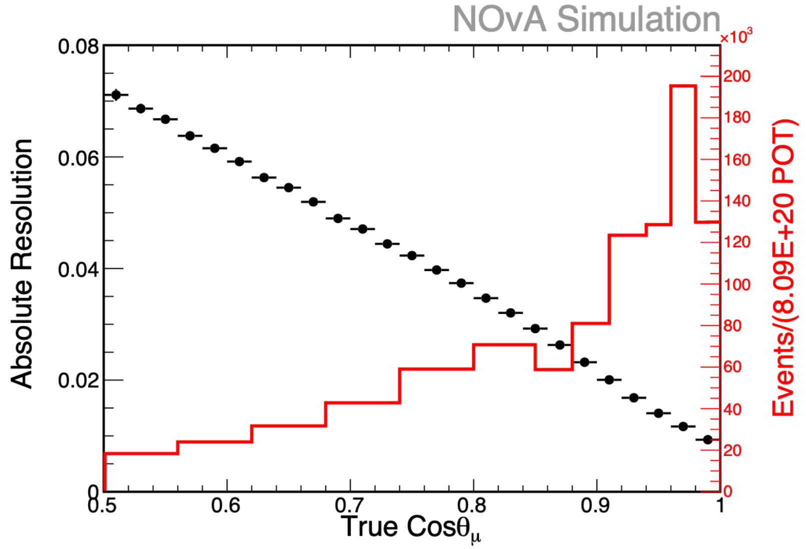


- Interactions at the ~GeV scale are often categorized by their scattering off of bound nucleons and their final state.

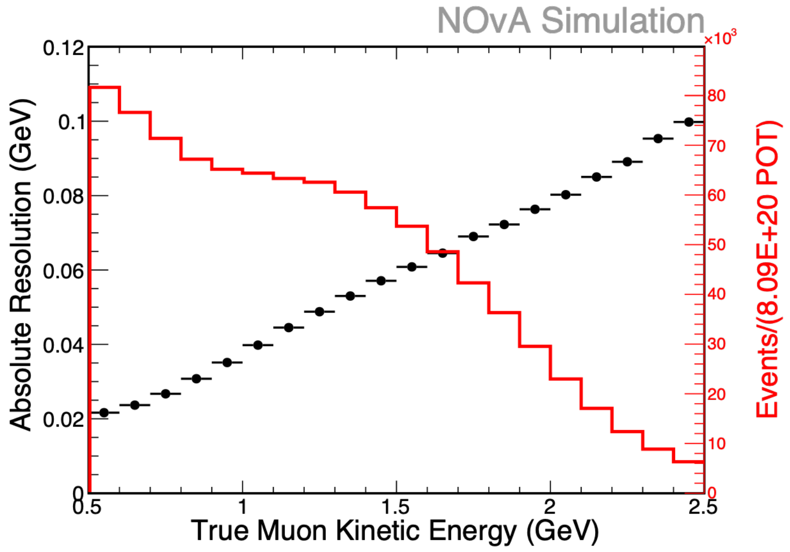
Muon Kinematics, Resolutions and Binning



Track segments in fully active and muon catcher are treated separately.



Bin widths are always larger than our resolution.

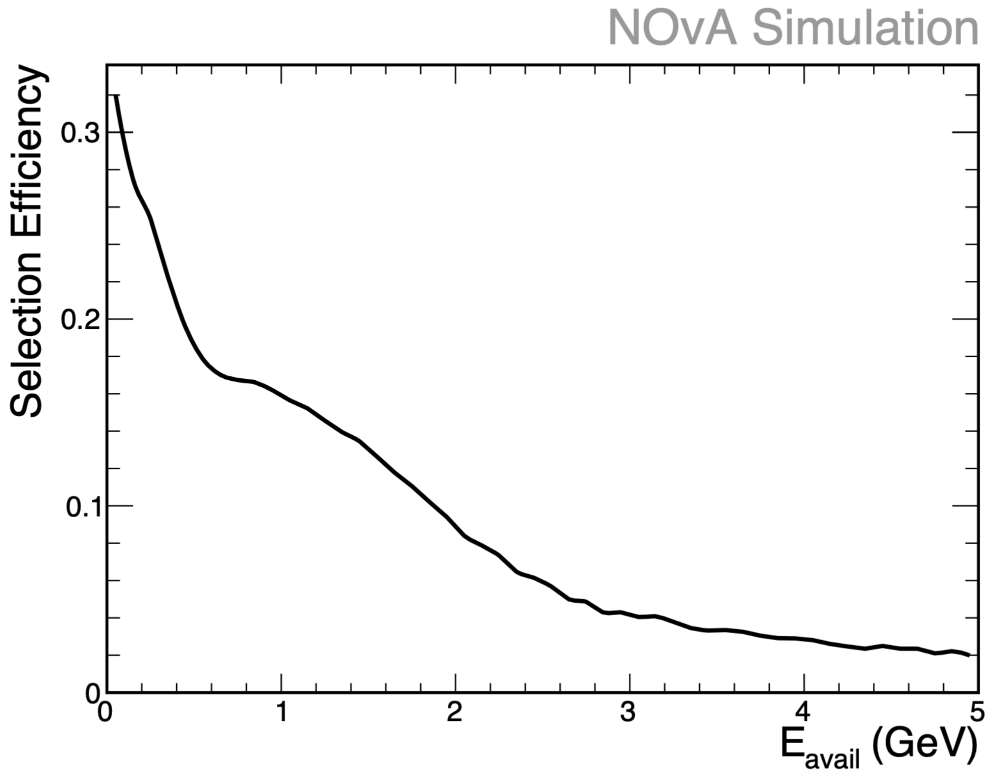


Above 2.5 GeV our acceptance suffers because of the containment requirement.

Three-Dimensional Corrections

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U^{-1}_{ijk}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{\text{avail}})_j P(\cos\theta_\mu, T_\mu, E_{\text{avail}})_j)}{N_{\text{t}}\Phi\epsilon(\cos\theta_\mu, T_\mu, E_{\text{avail}})_{ik}\Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}}\right)$$

- Selection efficiency, purity and unfolding corrections are applied in a 3-dimensional space: ($\cos\theta_\mu$, T_μ, E_{avail})
- E_{avail}: energy of all observable final-state hadrons. 11 bins used.
- Reduces potential model dependence of these corrections on the final-state hadronic system.
- Unfolded spectrum is then integrated over E_{avail}.



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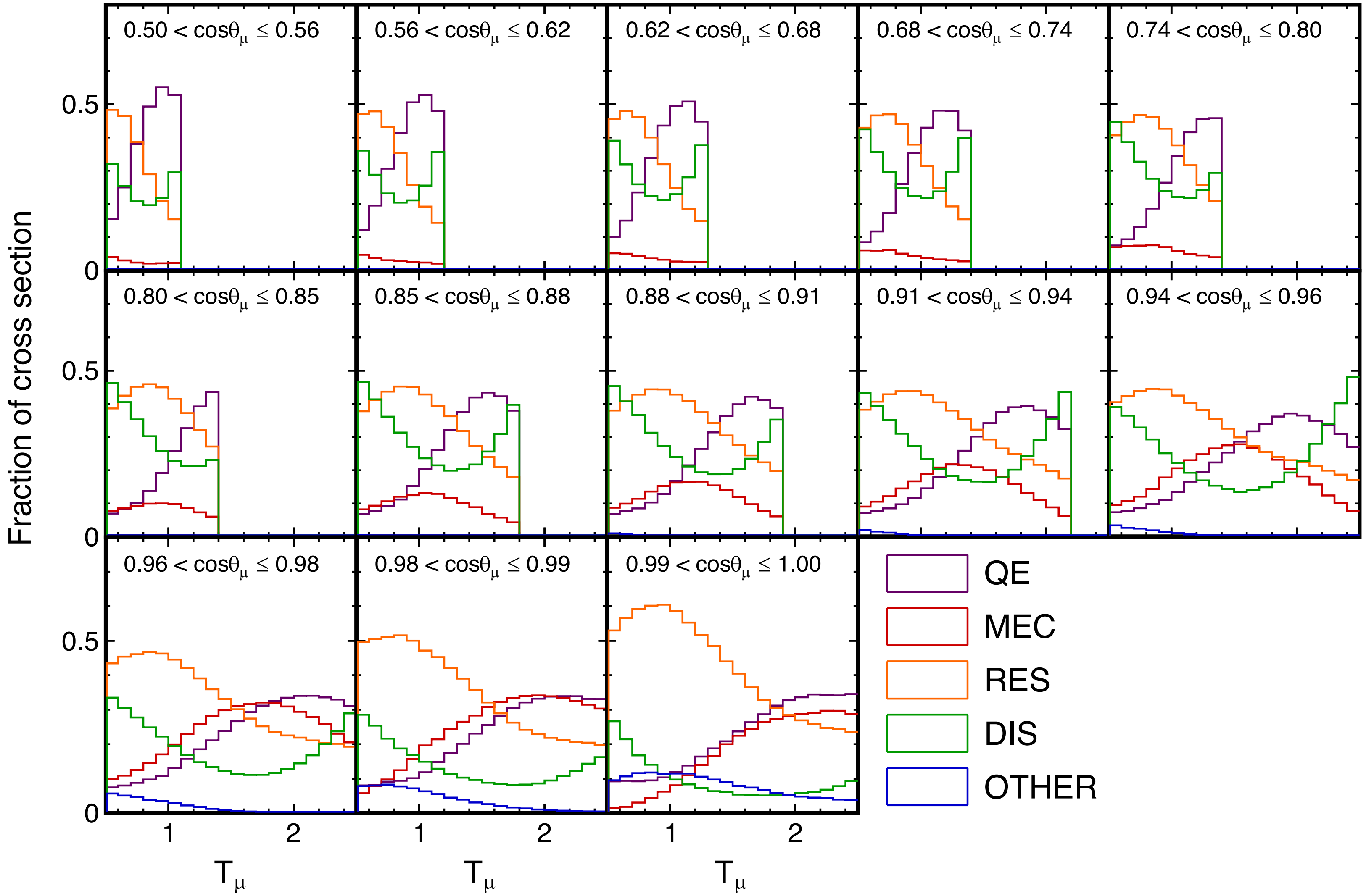
Interaction mode ratios



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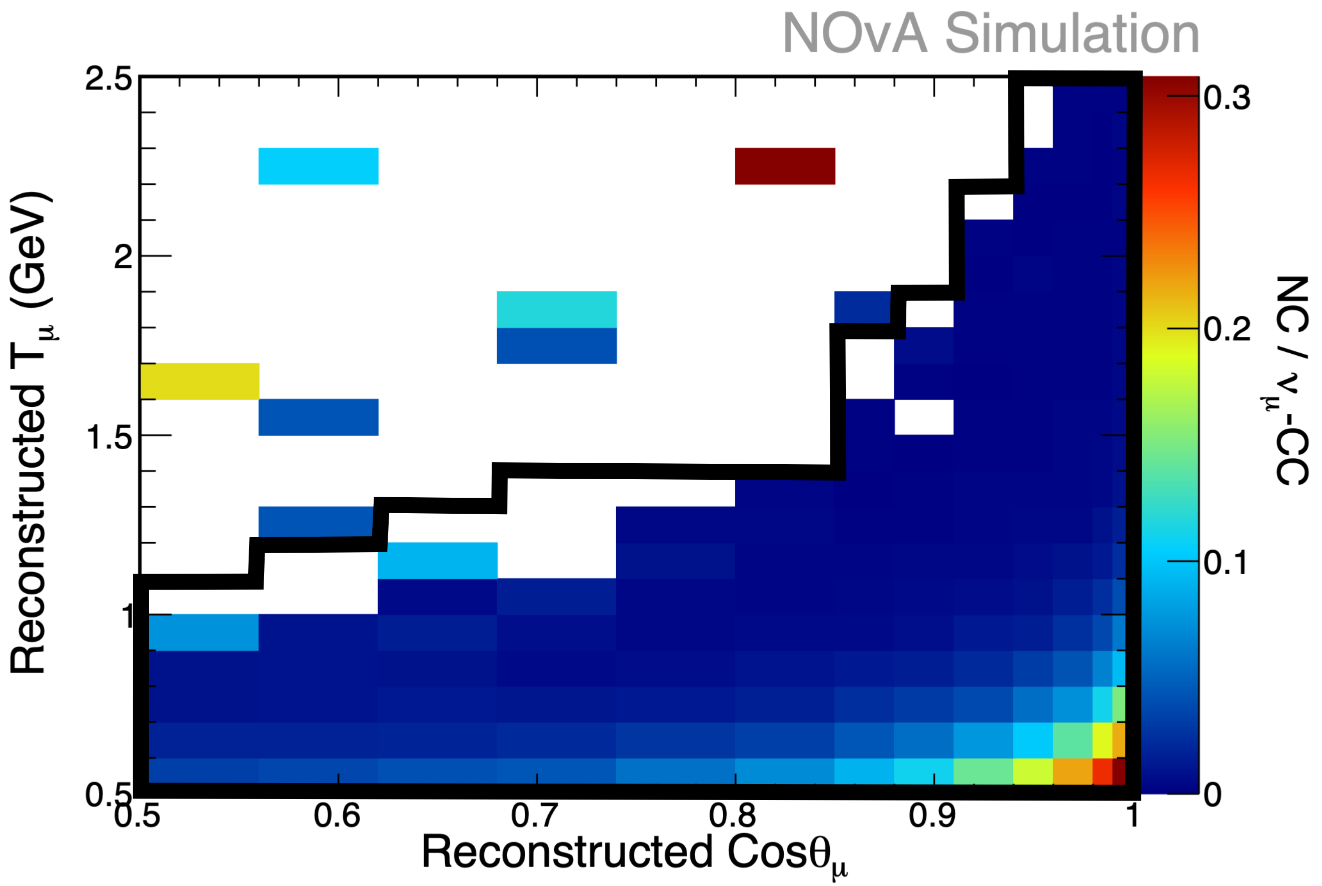
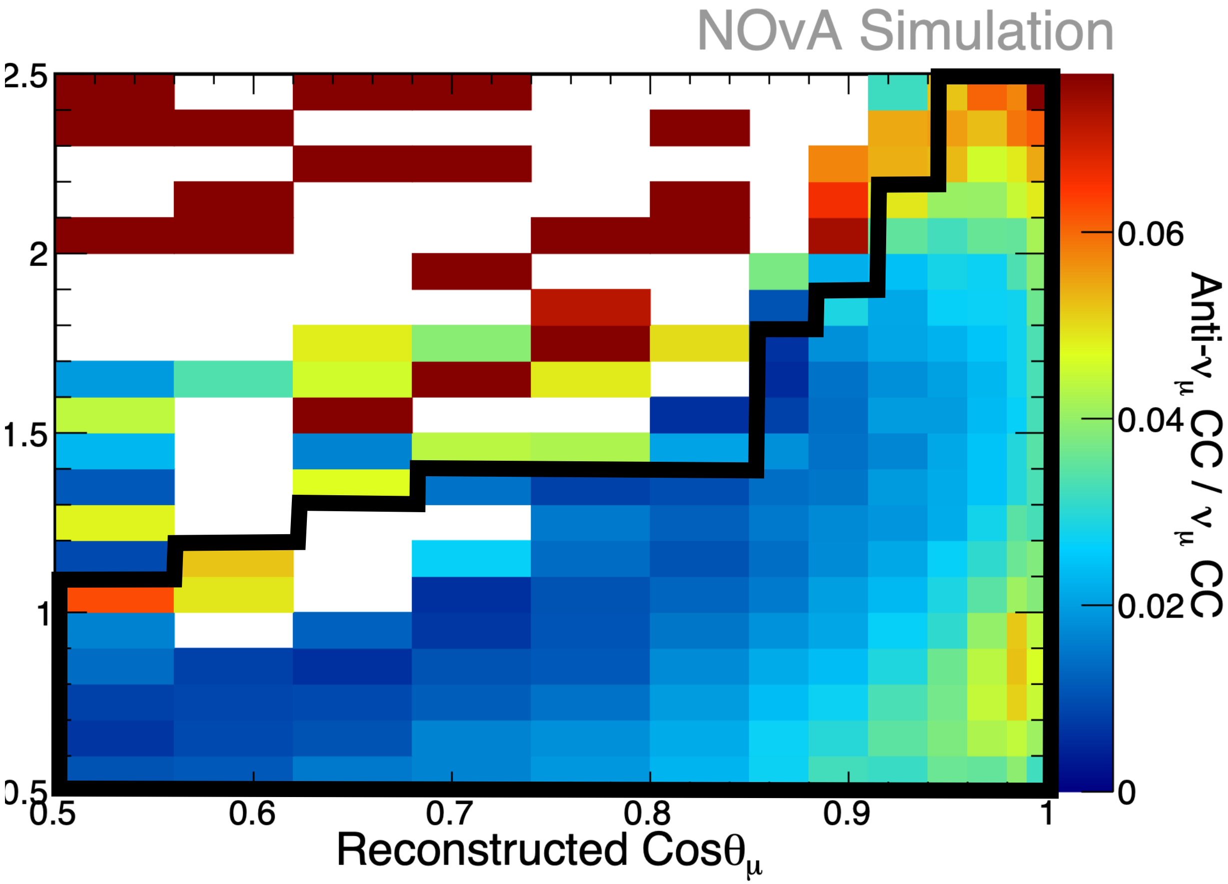
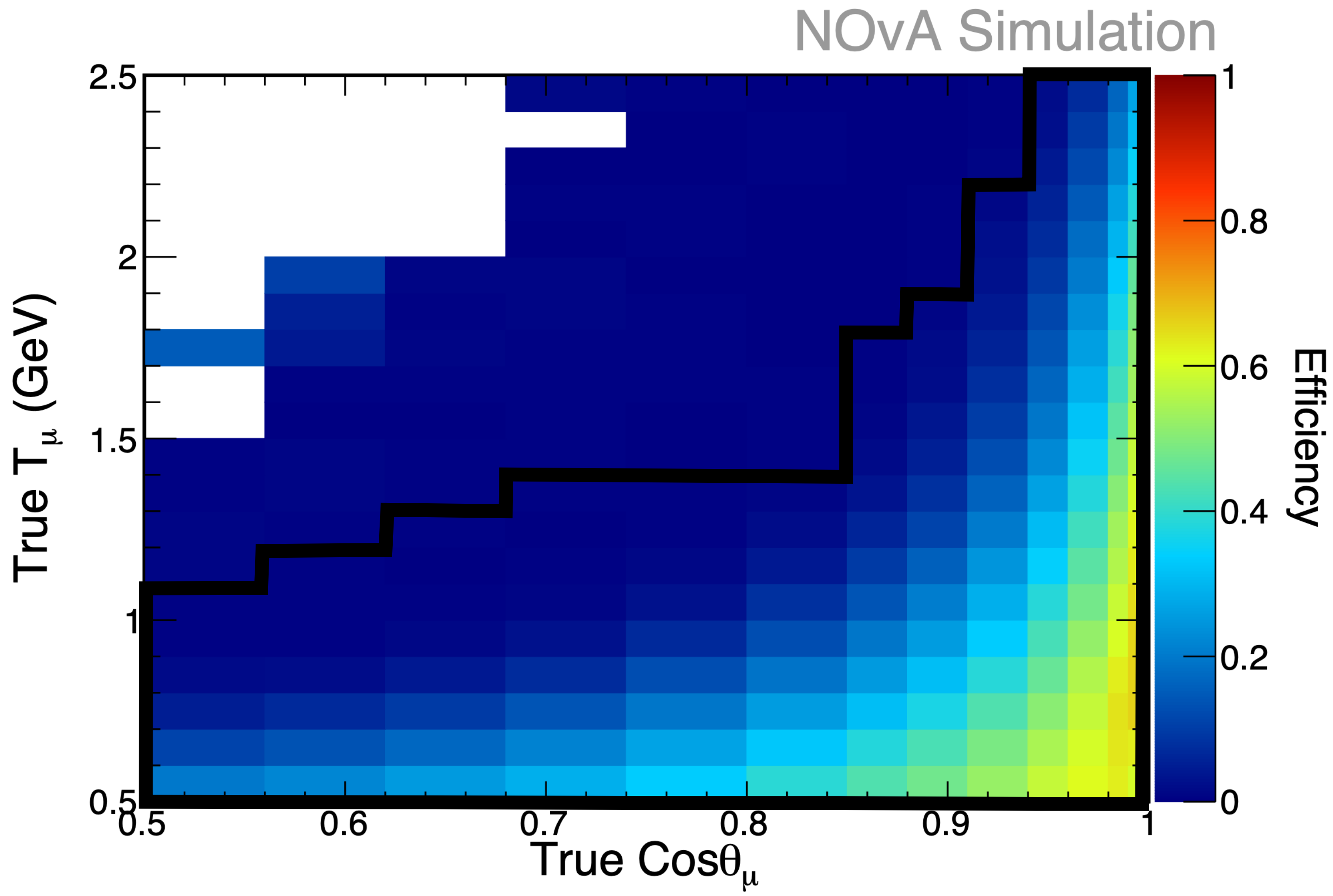
Background Breakdown





- NC backgrounds typically live in the Res- and DIS-dominated regions, where pions in the final state can get confused with muons.
- The background fractions are generally quite low.

Selection Efficiency



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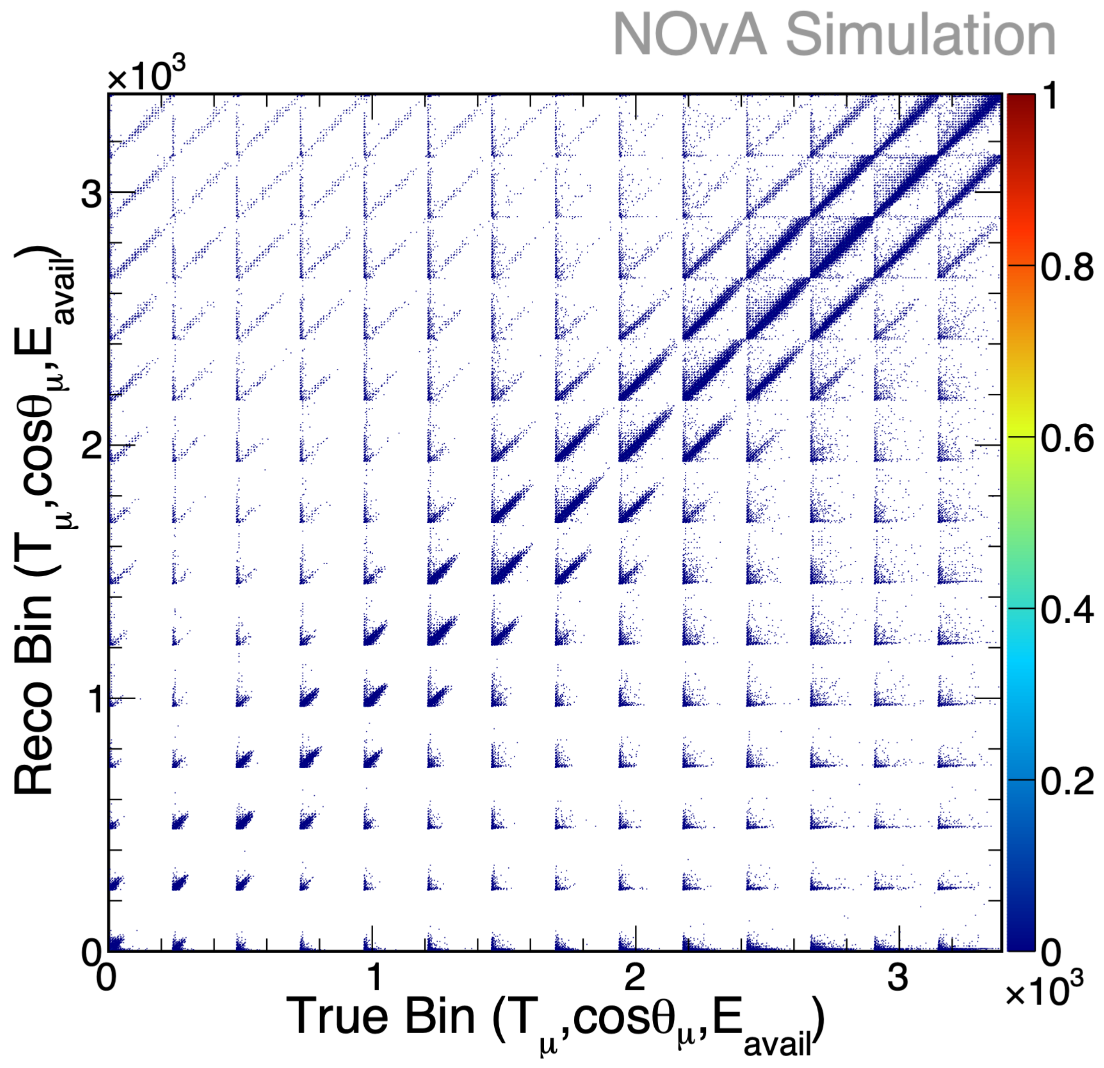
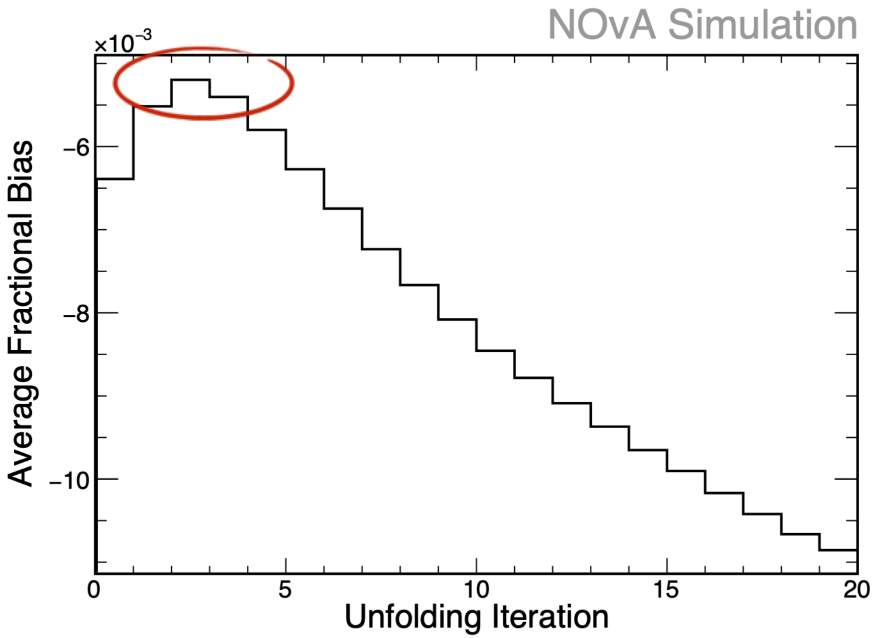
Unfolding - HPC to the Rescue!

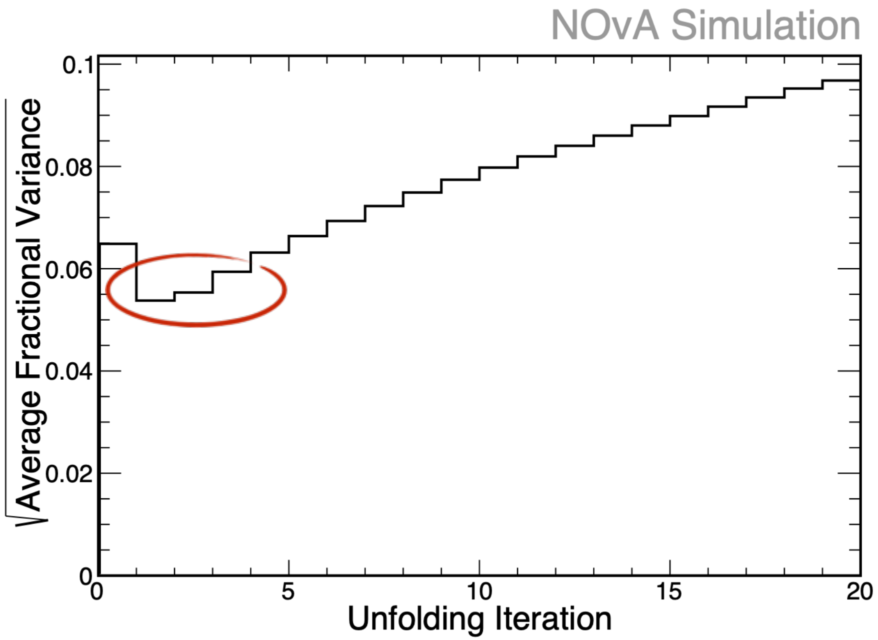
- Migration matrix has ~11.5 x 10^6 entries.
- We generate 100k+ universes to calculate our final covariance matrix.
- This takes many weeks on the Grid, where memory and nodes can be restricted.
- Thanks to the SciDAC-4: HEP Data Analysis Program, we were able to use NERSC HPCs to generate all universes in just days.
- We are looking forward to continuing to use these resources in the future.

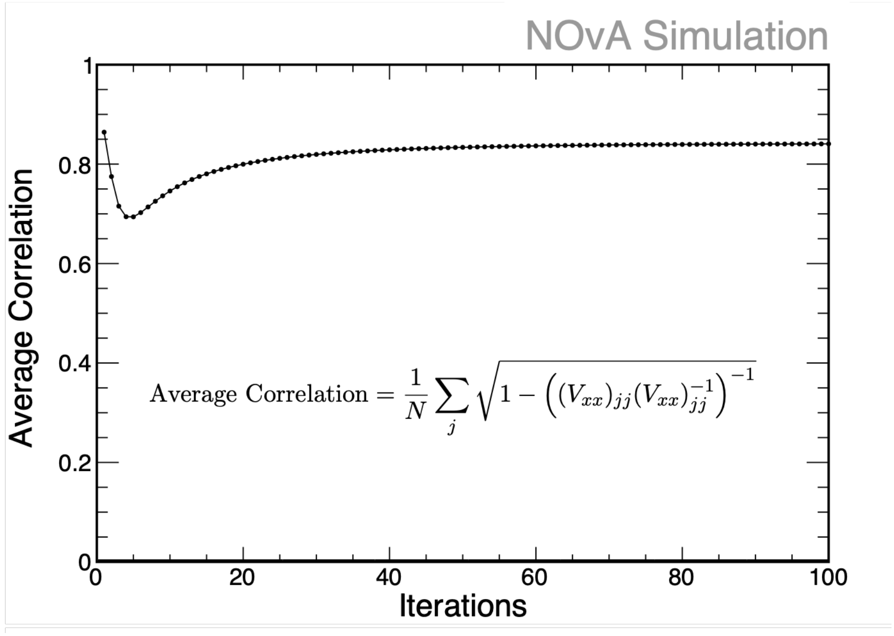


Unfolding - Implementation

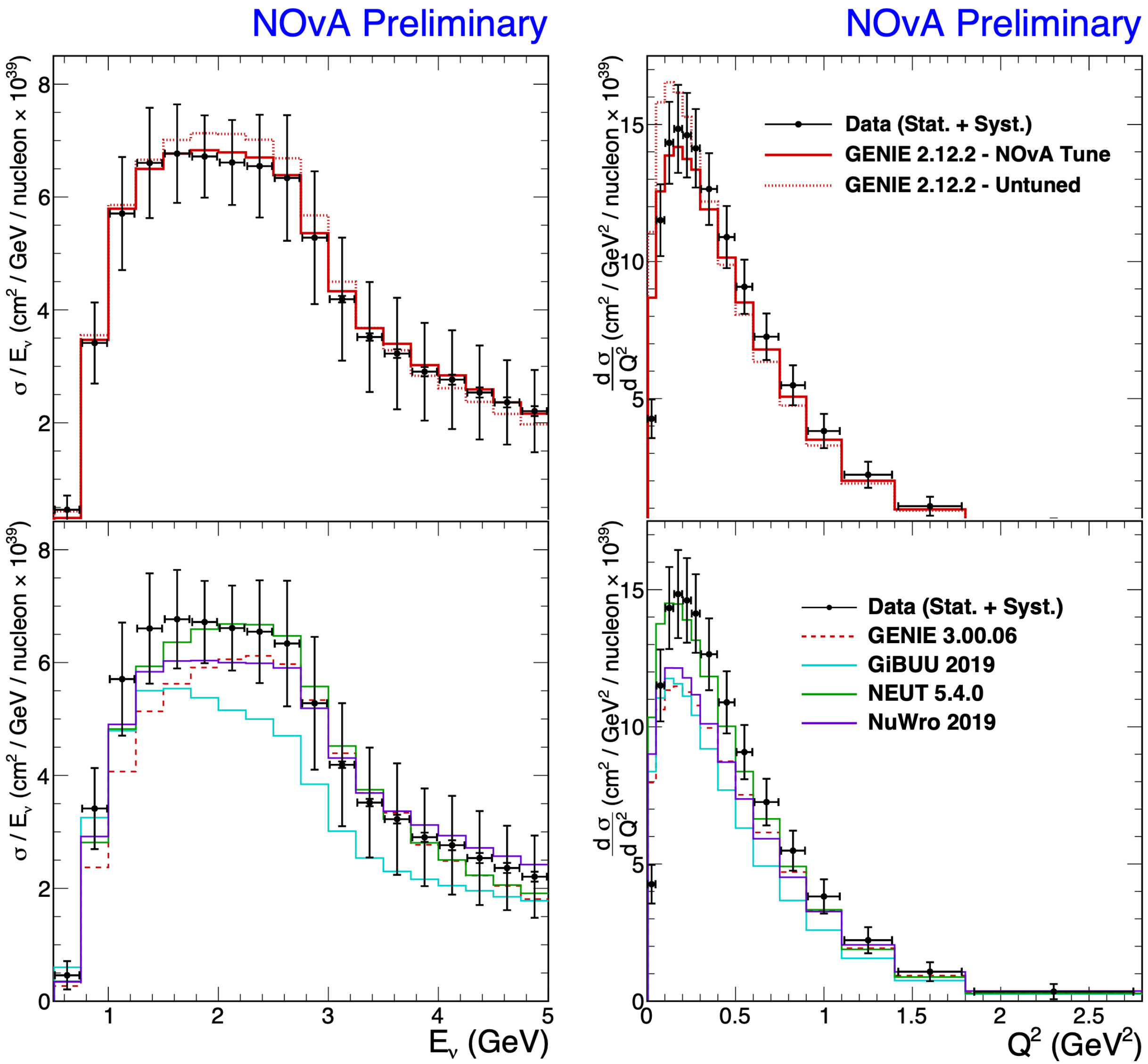
- We use Iterative Unfolding (D'Agostini).
- Studies of variance and bias as a function of iteration for systematically-shifted MC indicate 3 iterations is reasonable.
- Also explored the average correlation (arXiv:1611.01927) as a metric, but ran into problems with unstable covariance matrices for the 3D unfolding matrix. Studies of 1D spectra (eg, E_ν), indicate a "few" iterations is reasonable.







Cross-section vs. E_ν and Q^2



- E_ν and Q^2 are extracted only over the range of muon kinematics reported in the differential measurements.
- Overall good agreement between data and predictions for E_ν.
- We observe a low Q^2 suppression that is not well modeled by any generator.

Generator	E_ν p-value	Q^2 p-value
GENIE 2.12.2 - Tuned	0.93	0.90
GENIE 2.12.2 - Untuned	0.73	0.35
GENIE 3.00.06*	0.29	0.23
GiBUU 2019	0.08	0.08
NEUT 5.4.0	0.74	0.73
NuWro 2019	0.52	0.40

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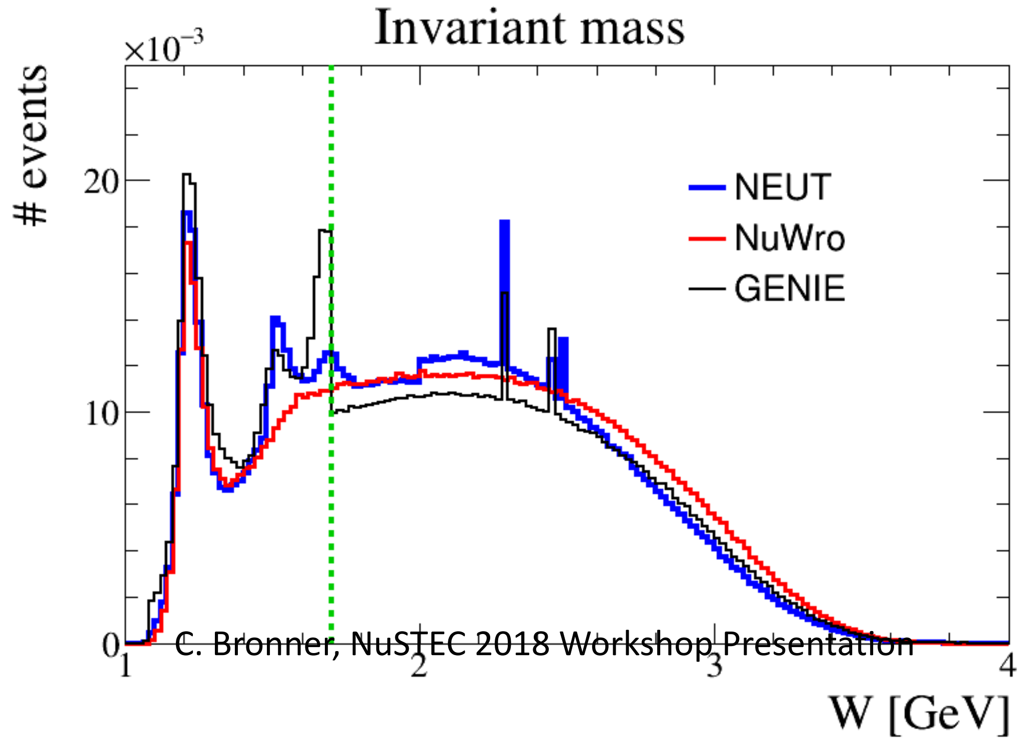
Generator Comparison - The Models

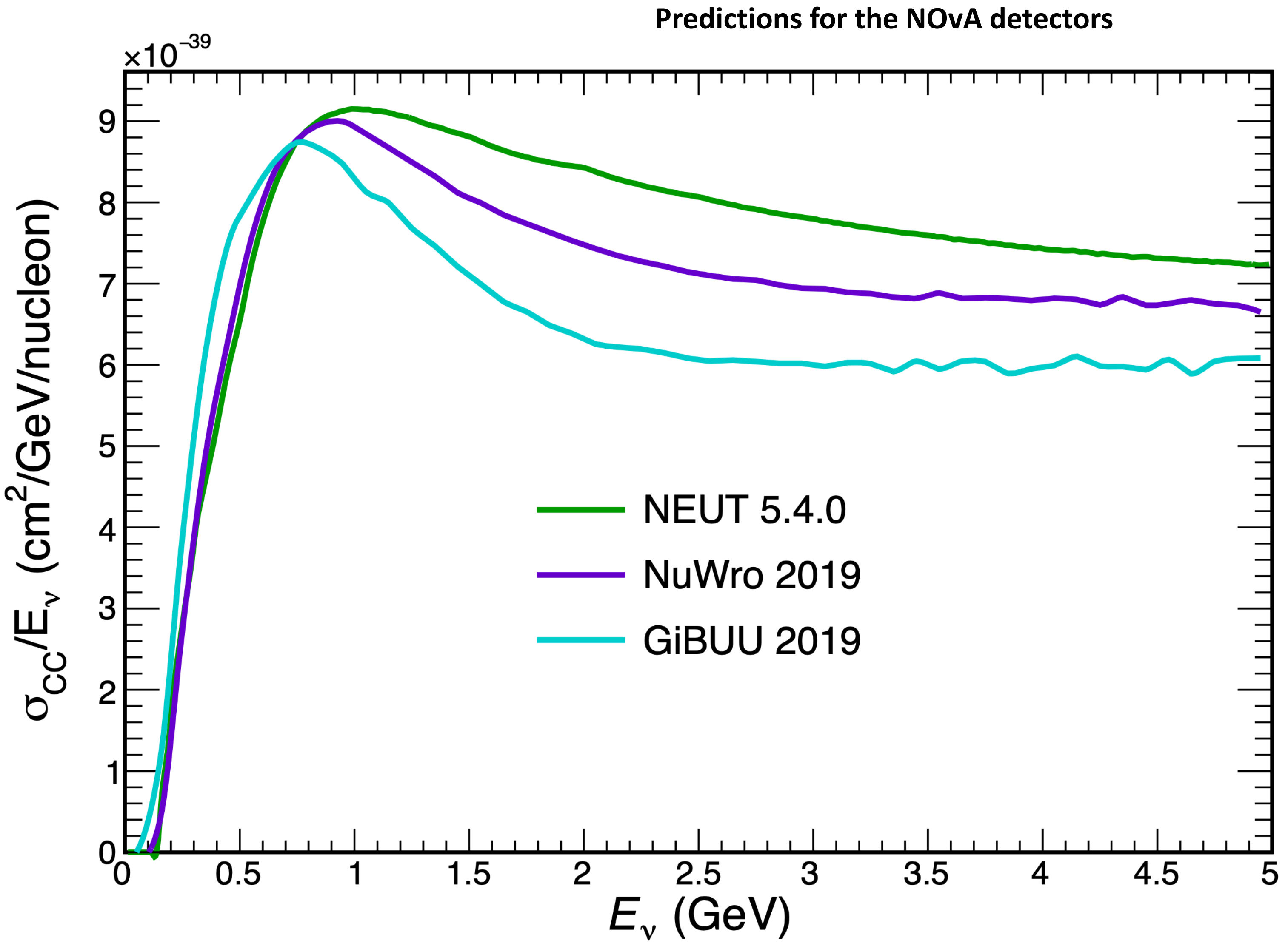
	QE/MEC Initial State	QE	MEC	Res	DIS	FSI
GENIE v2.12.2	**RFG**	**L-S**	Empirical (NOvA tune)	**R-S**	**PYTHIA 6**	**hA**
GENIE v3.00.06	**LFG**	Valencia (Nieves, et al)	Valencia (Nieves, et al)	**B-S**	**PYTHIA 6**	**hN**
NEUT 5.4.0	**LFG**	Valencia (Nieves, et al)	Valencia (Nieves, et al)	**B-S**	**PYTHIA 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**



- 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.

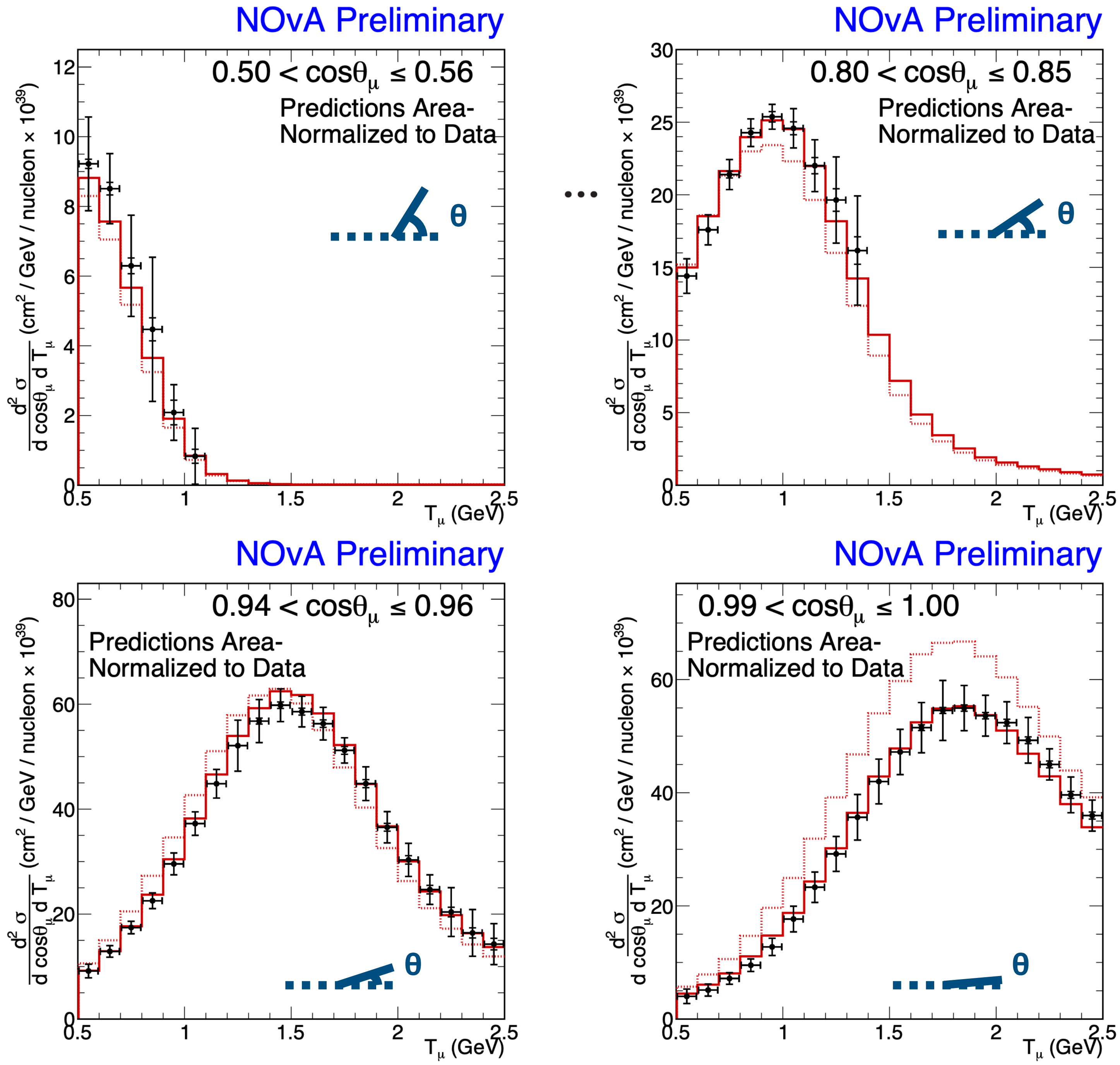
$$\sigma_{\mathrm{CC}}^{\mathrm{inclusive}}(E_\nu) = \sigma_{\mathrm{CC}}^{\mathrm{QE}} + \sigma_{\mathrm{CC}}^{\mathrm{MEC}} + \sigma_{\mathrm{CC}}^{\mathrm{Res}} + \sigma_{\mathrm{CC}}^{\mathrm{DIS}} + \sigma_{\mathrm{CC}}^{\mathrm{Coh}}$$

Generator Comparison - The Models



- Implementation and stitching differences between the generators is reflected in the spread of inclusive predictions from various generators.
- Inclusive cross section measurements like ours provide insight and constraints on how all the pieces fit together.

Shape Comparisons - Example 4 cosine slices

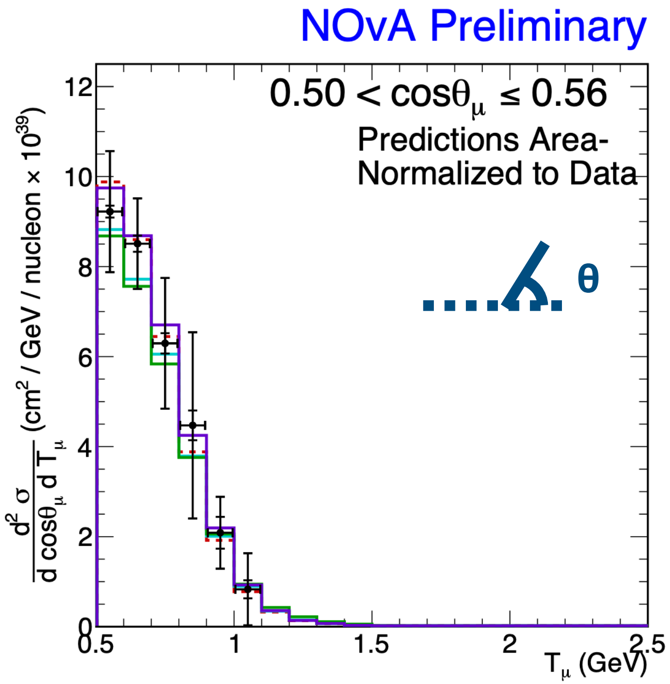


GENIE 2.12.2 - NOvA Tune

GENIE 2.12.2 - Untuned

Generator	Total p-value	Norm.
GENIE 2.12.2 - Tuned	0.54	1.01
GENIE 2.12.2 - Untuned	0.003	0.98

Shape Comparisons - Example 4 cosine slices



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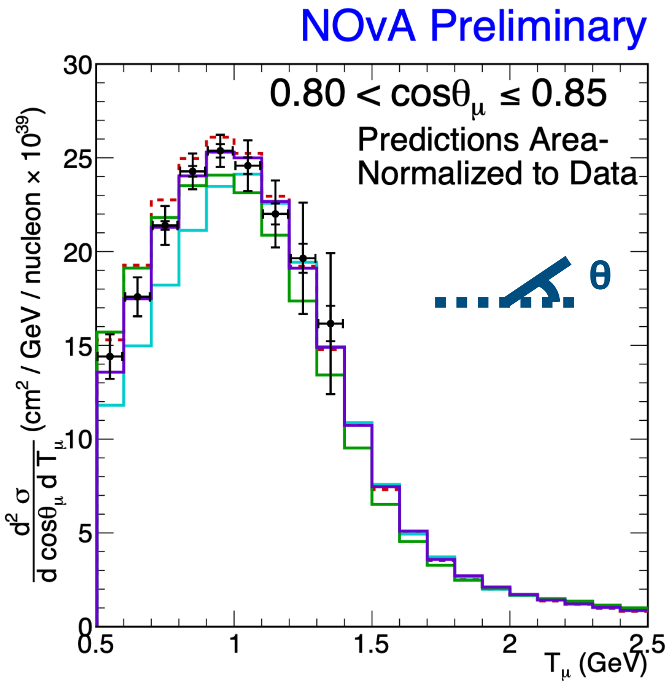

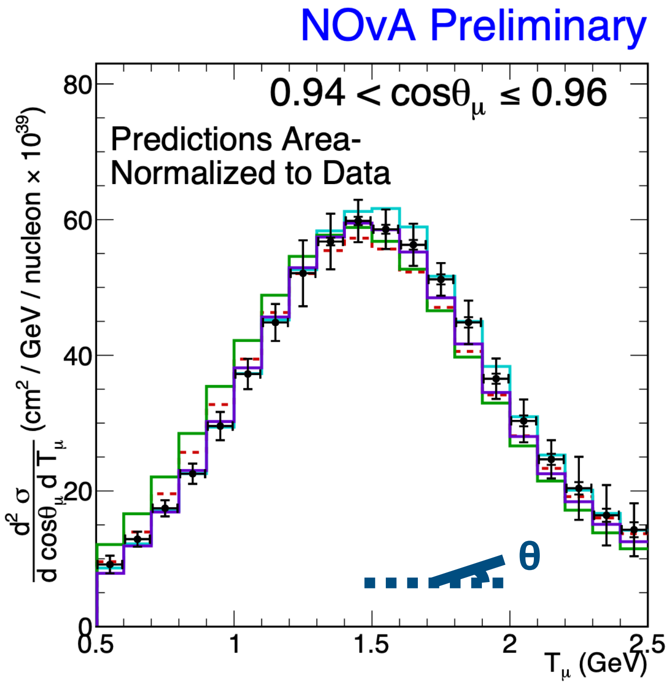

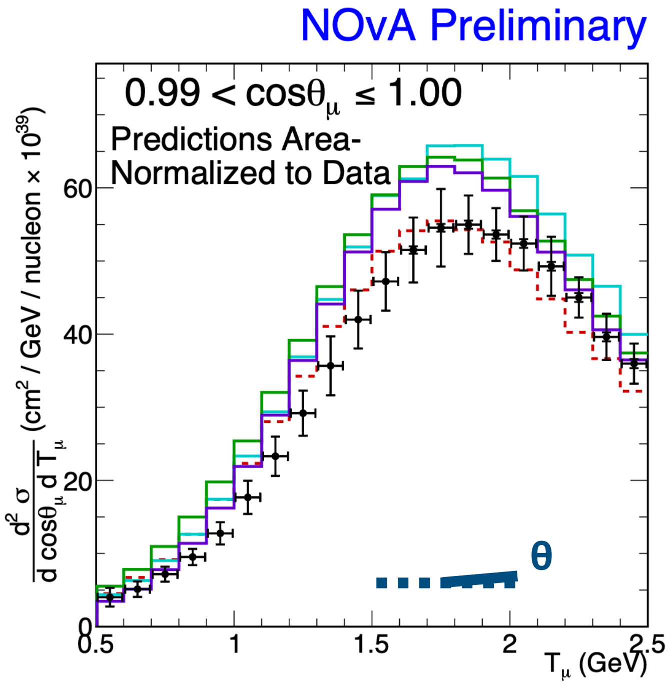

Data (Stat. + Syst.)
GENIE 3.00.06*
GiBUU 2019
NEUT 5.4.0
NuWro 2019

***N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a**

Generator	Total p-value	Norm. Factor
GENIE 3.00.06*	0.31	1.15
GiBUU 2019	0.38	1.28
NEUT 5.4.0	0.004	1.02
NuWro 2019	0.54	1.15

***N18_10j_02_11a: combination of G18_10j_00_000 and G18_10b_02_11a, used in latest osc. results**

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