Inclusive Cross Section Measurements at MINERvA

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For the MINERvA Collaboration

NuINT

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* Now at Syracuse University

WILLIAM & MARY

CHARTERED 1693

Outline

- **Measurements of CC ν_μ inclusive double differential cross sections as functions of muon $p_{||}$ and p_T**
  - **<E_ν>~ 3 GeV (“Low Energy”)**

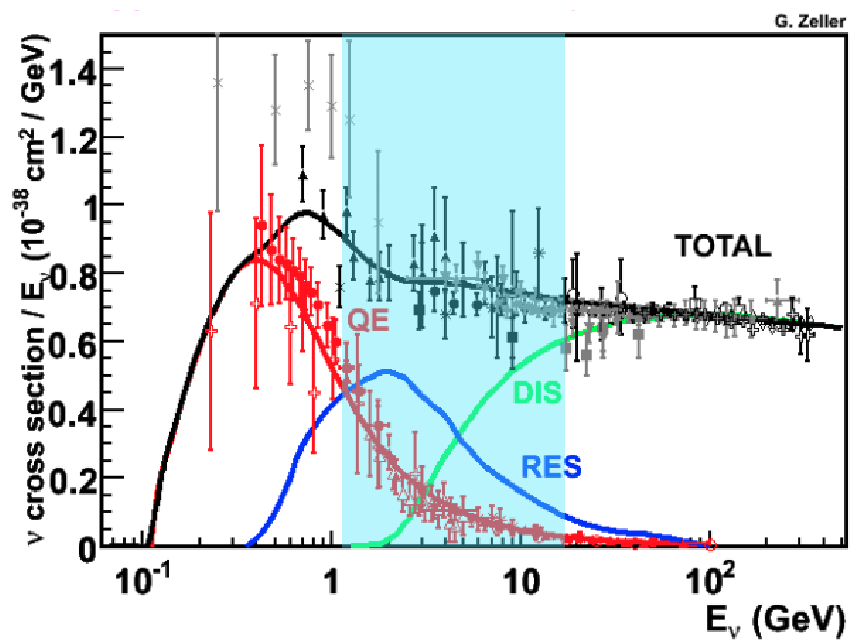
    Filkins et al. PRD 101, 112007 (2020)
  - **<E_ν>~ 6 GeV (“Medium Energy”)**
  - Ruterbories et al. PRD 104 092007 (2021)
- **Machine learning techniques used to find interaction vertex positions in MINERvA**

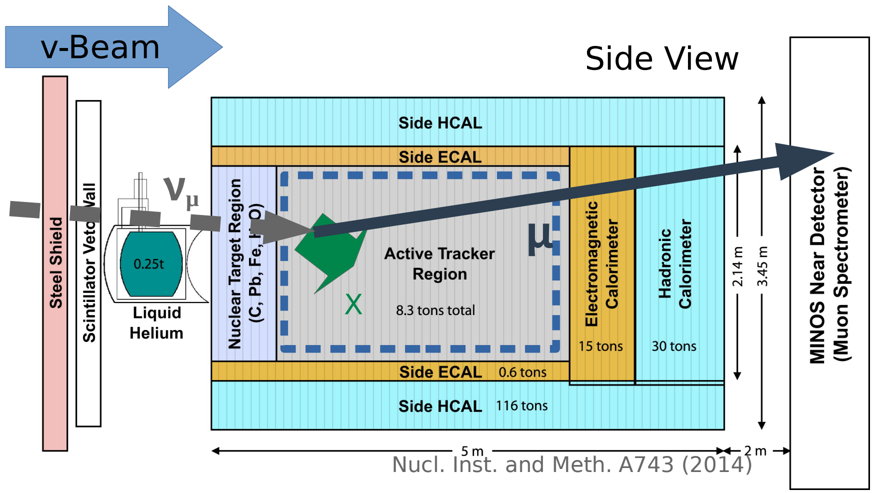
  JINST 13, P11020 (2018)
  - Model architecture comparison

    F. Akbar, A. Ghosh, S. Young et al 2022 JINST 17 T08013

Inclusive Cross Section Measurements

- **Many processes contribute to the cross section at a few GeV**
- **Inclusive measurements provide stringent test of generators**
- **High statistics, small backgrounds**
- **Double differential cross sections in muon $p_{||}$, p_T**
- **$p_{||}$ correlated with E_ν**
  p_T correlated with Q^2
  - Provides some nice process separation without the model dependence that comes with using hard to reconstruct variables



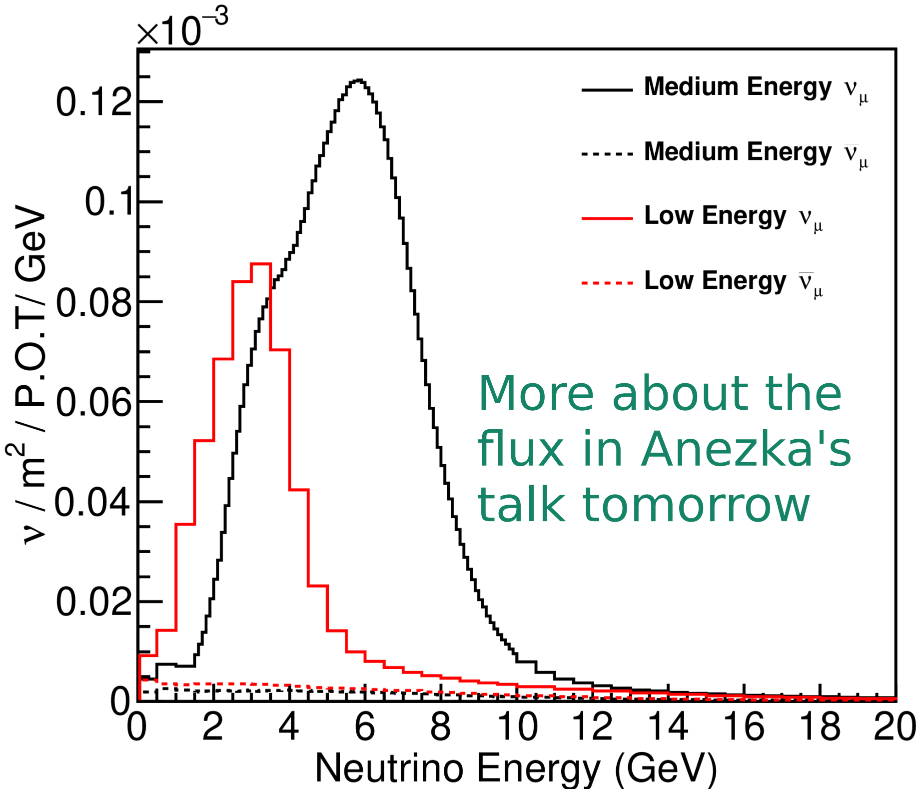


Nucl. Inst. and Meth. A743 (2014)

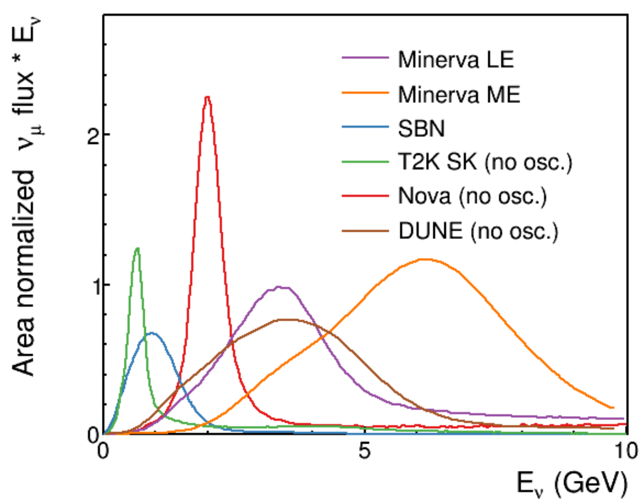
Scintillator – tracking
Lead – electromagnetic calorimetry
Steel – hadronic calorimetry

Analyses

- **Two parallel analyses done with different beam energies**
  - Low energy beam $\langle E_\nu \rangle \approx 3.5$ GeV
  - Medium energy beam $\langle E_\nu \rangle \approx 6$ GeV
- **Signal definition:**
  - ν_μ CC
  - Scintillator portion of the detector (hydrocarbon)
  - Muon angle < 20° wrt beam
  - p_μ >1.5 GeV

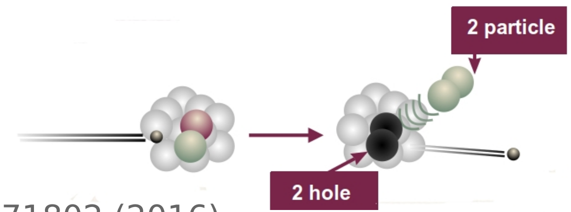


More about the flux in Anezka's talk tomorrow

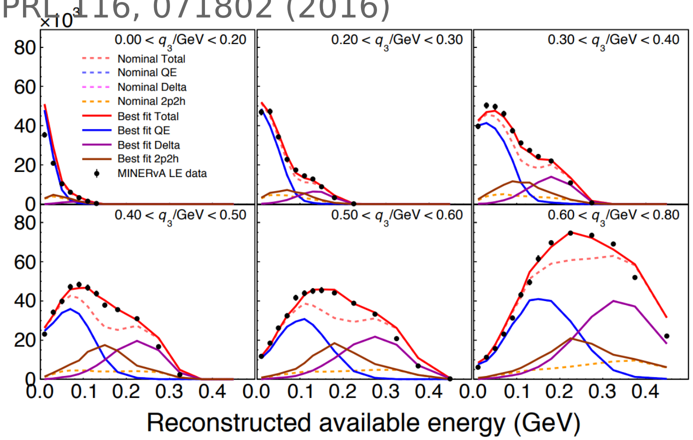


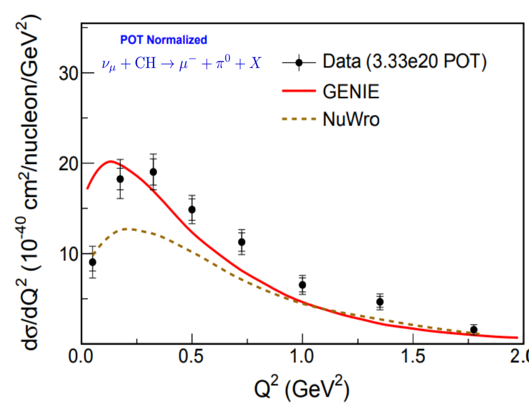
MINERvA Tunes

- **Most model comparisons shown in MINERvA talks will use MINERvA Tune v1 as a starting point**
- **MINERvA Tune v1**
  - Base of GENIE 2.8.4 (LE), 2.12.6(ME)
  - RPA
  - Valencia 2p2h + low recoil enhancement
  - Non-resonant pion tune
- **MINERvA Tune v2**
  - MINERvA Tune v1
  - ad hoc low Q2 resonant suppression based on MINERvA measurements of pion production



PRL 116, 071802 (2016)

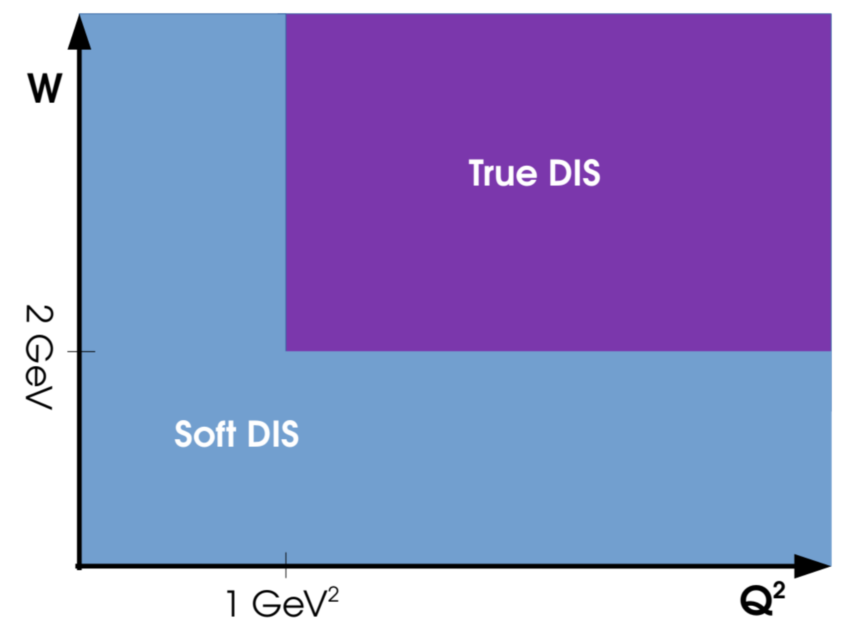




PRD 96, 072003 (2017).

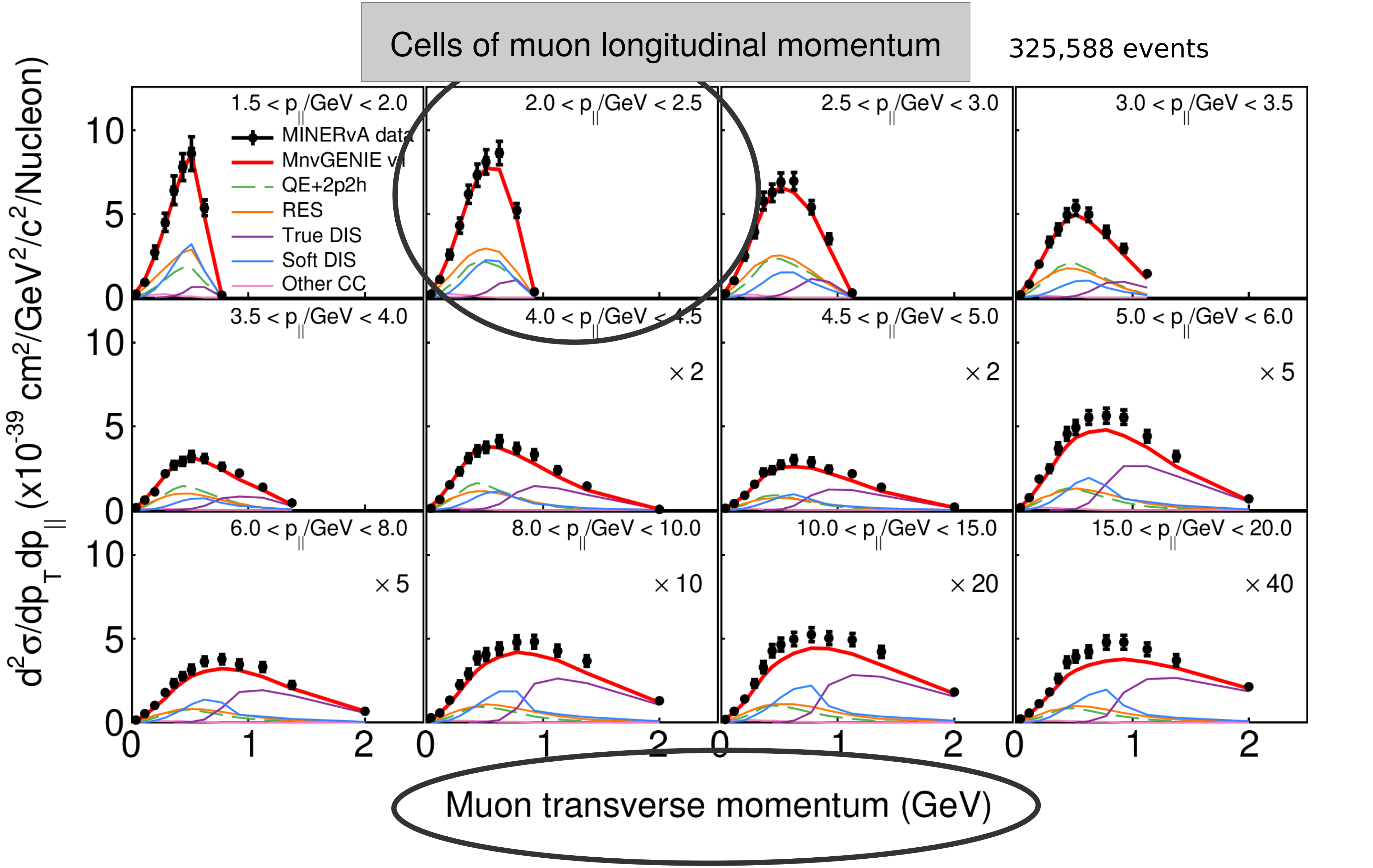
Deep Inelastic Scattering – Model Comparisons

- **Compare to 3 models of DIS**
- **Implemented by reweighing GENIE's "true DIS" events**
  - nCTEQ15 and nCTEQv DIS – global analyses of nuclear parton distribution functions
    - nCTEQ15 – charged lepton-nucleus scattering PRD 93, 085037 (2016).
    - nCTEQv – neutrino-nucleus scattering PRD 77, 054013 (2008).
  - AMU DIS – beyond leading order microscopic model Nucl. Phys A955, 58 (2016).
    - Developed at Aligarh Muslim University



- **All other components come from MnvGENIE v1**

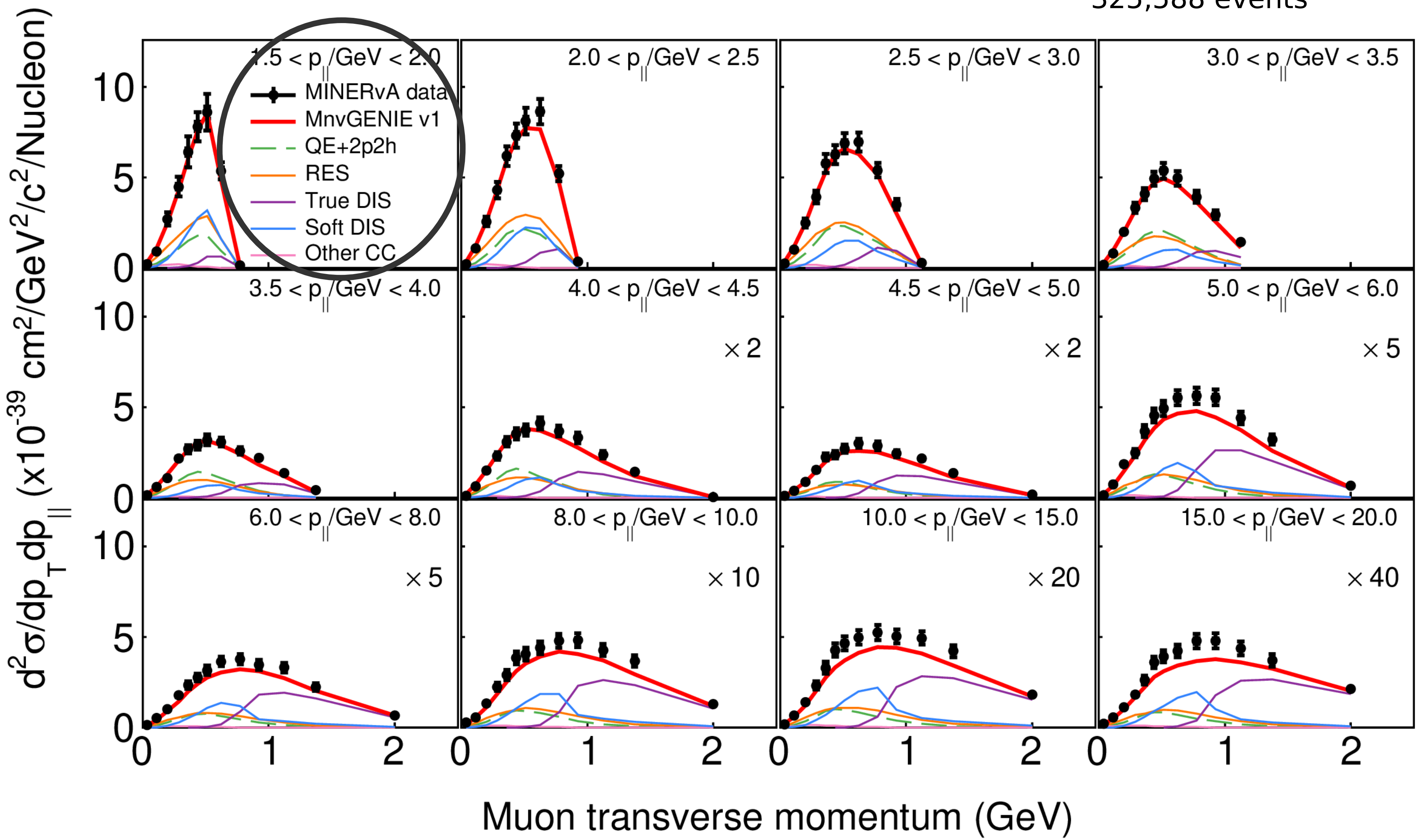
Low Energy Double Differential Cross Section



https://doi.org/10.1103/PhysRevD.101.112007

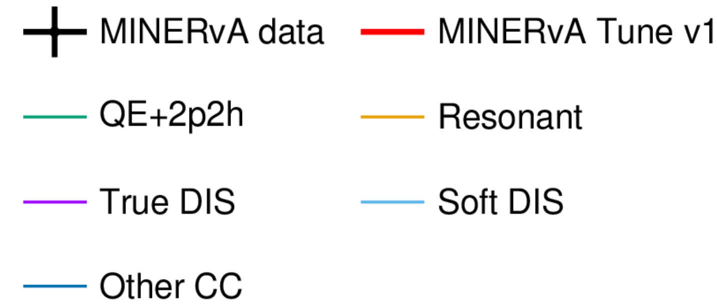
Low Energy Double Differential Cross Section

325,588 events

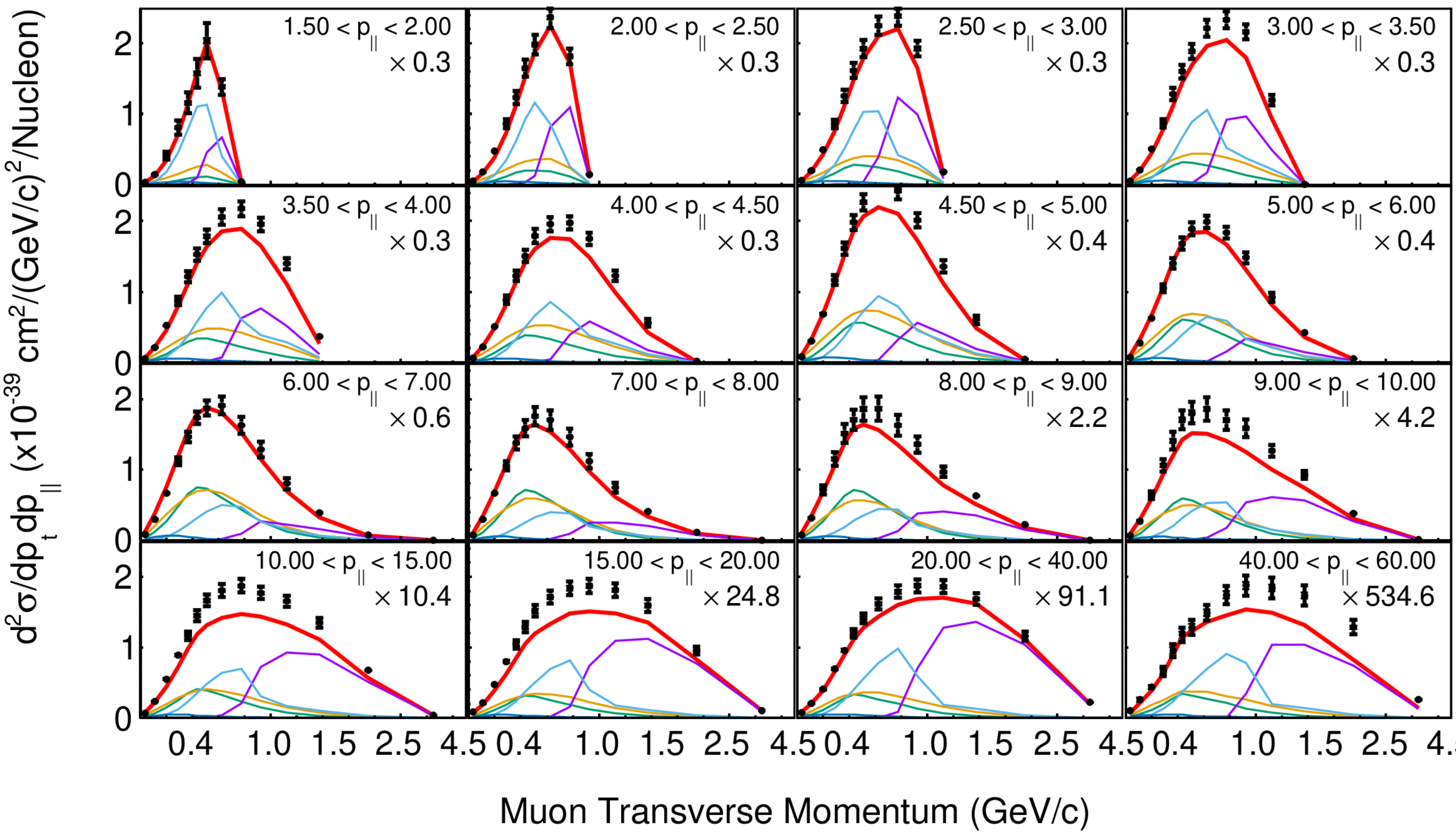


https://doi.org/10.1103/PhysRevD.101.112007

Medium Energy Cross Section

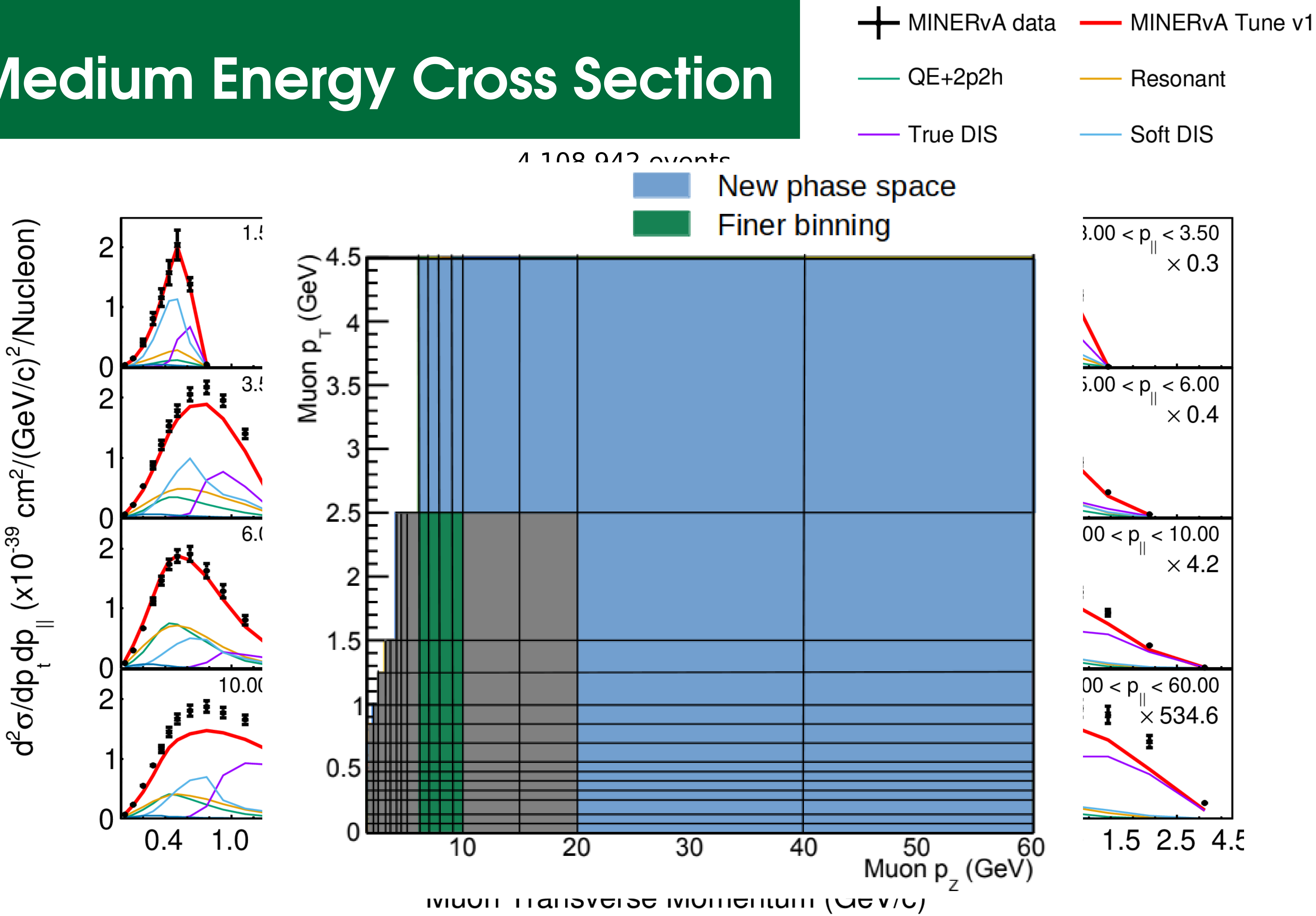


4,108,942 events



Expanded phase space: 4 more $p_{||}$ bins, 1 more p_T bin

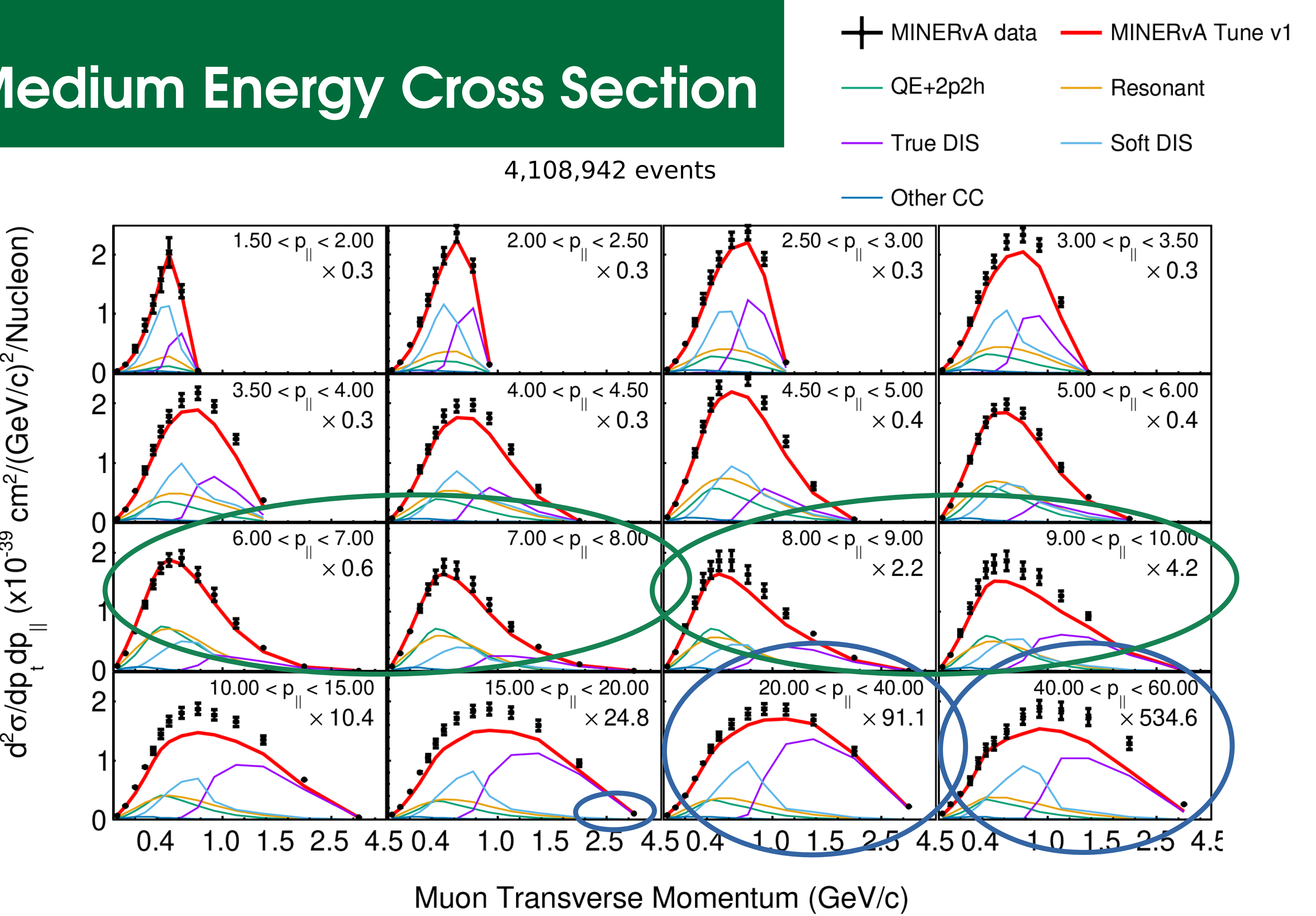
Medium Energy Cross Section



Expanded phase space: 4 more $p_{||}$ bins, 1 more p_T bin

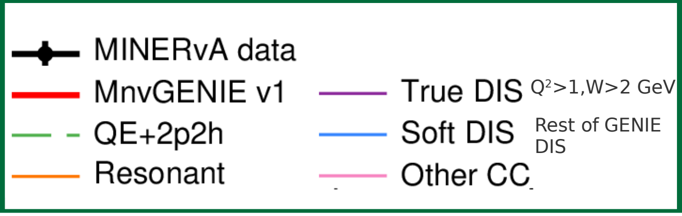
Medium Energy Cross Section

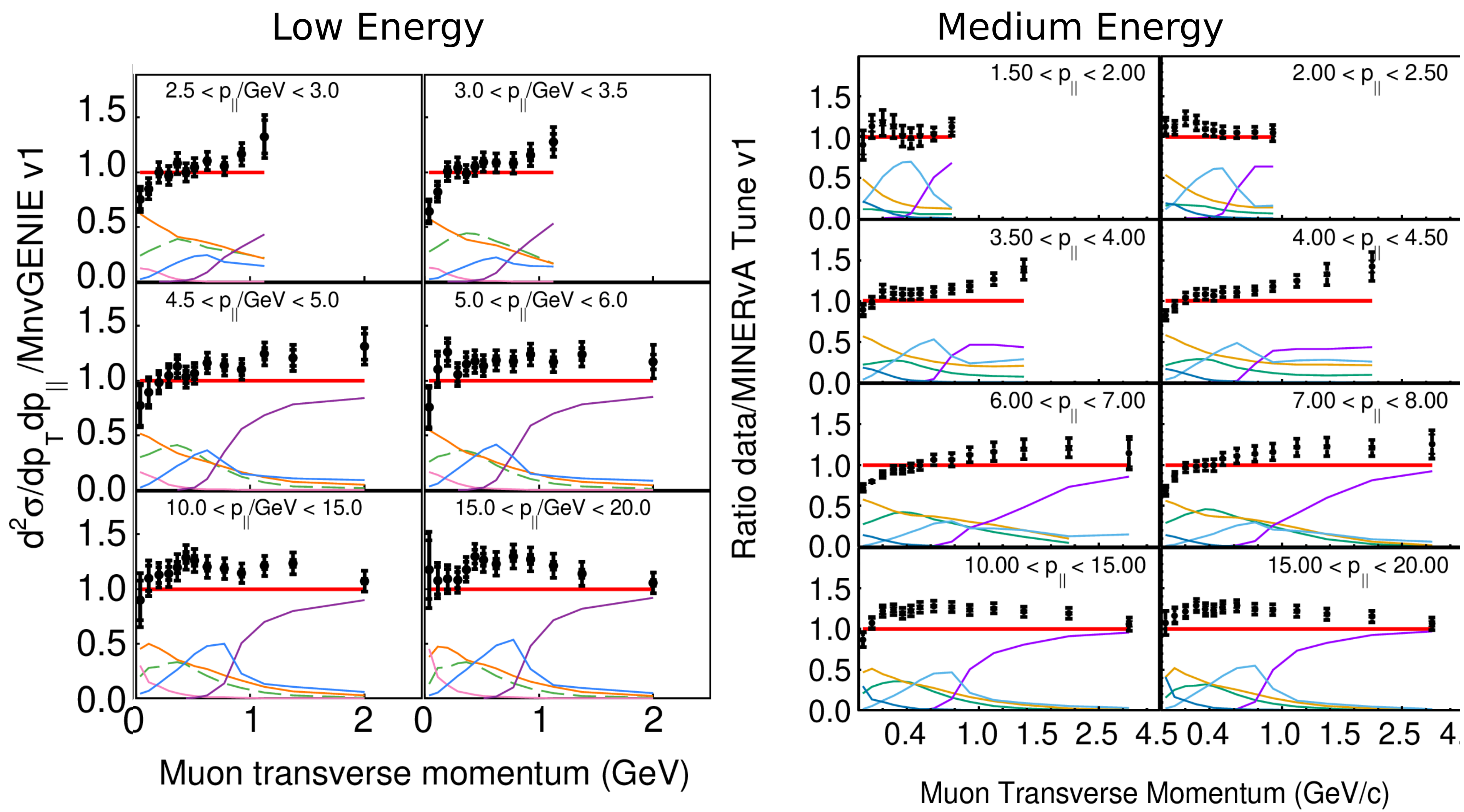
4,108,942 events



Expanded phase space: 4 more $p_{||}$ bins, 1 more p_T bin

Ratios to MnvTune

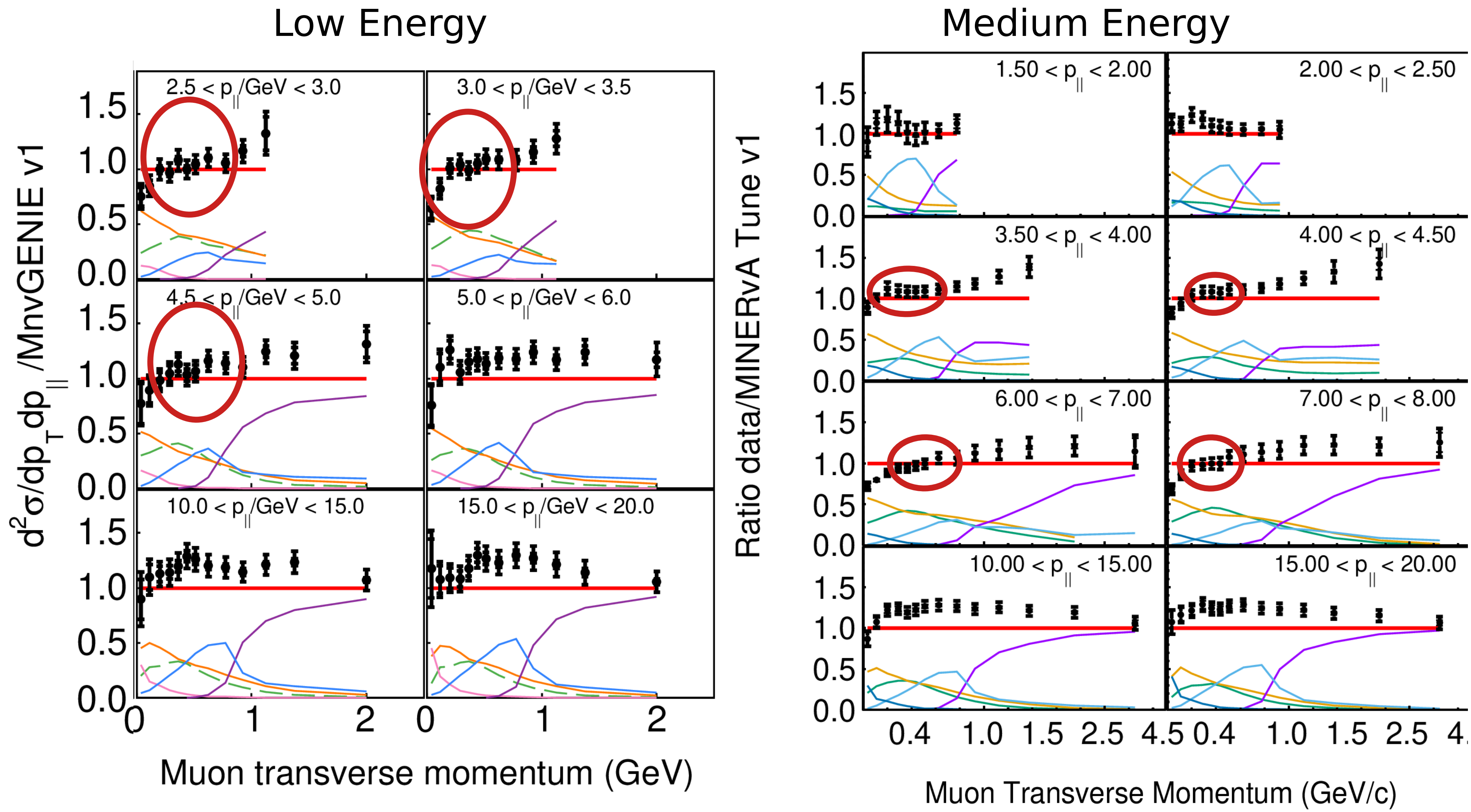




Ratio to MnvTune v1

Half of the $p_{||}$ bins from each data set

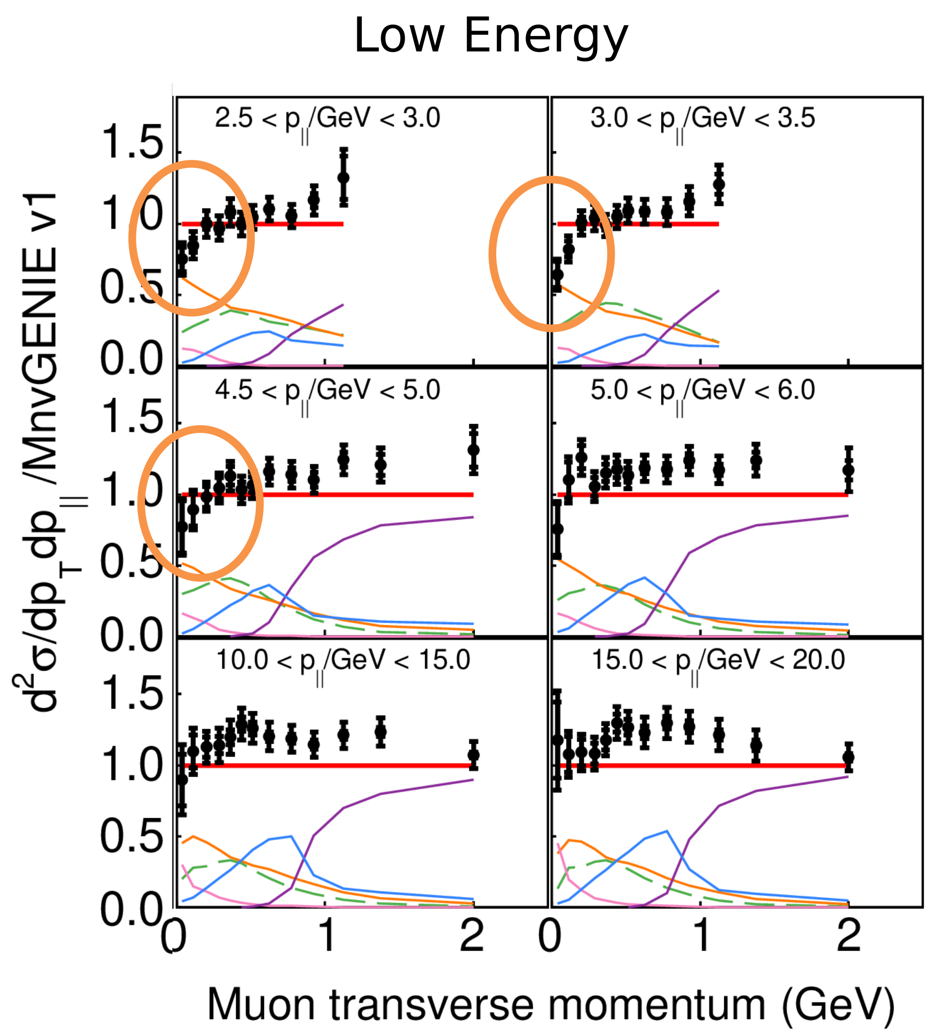
Ratios to MnvTune

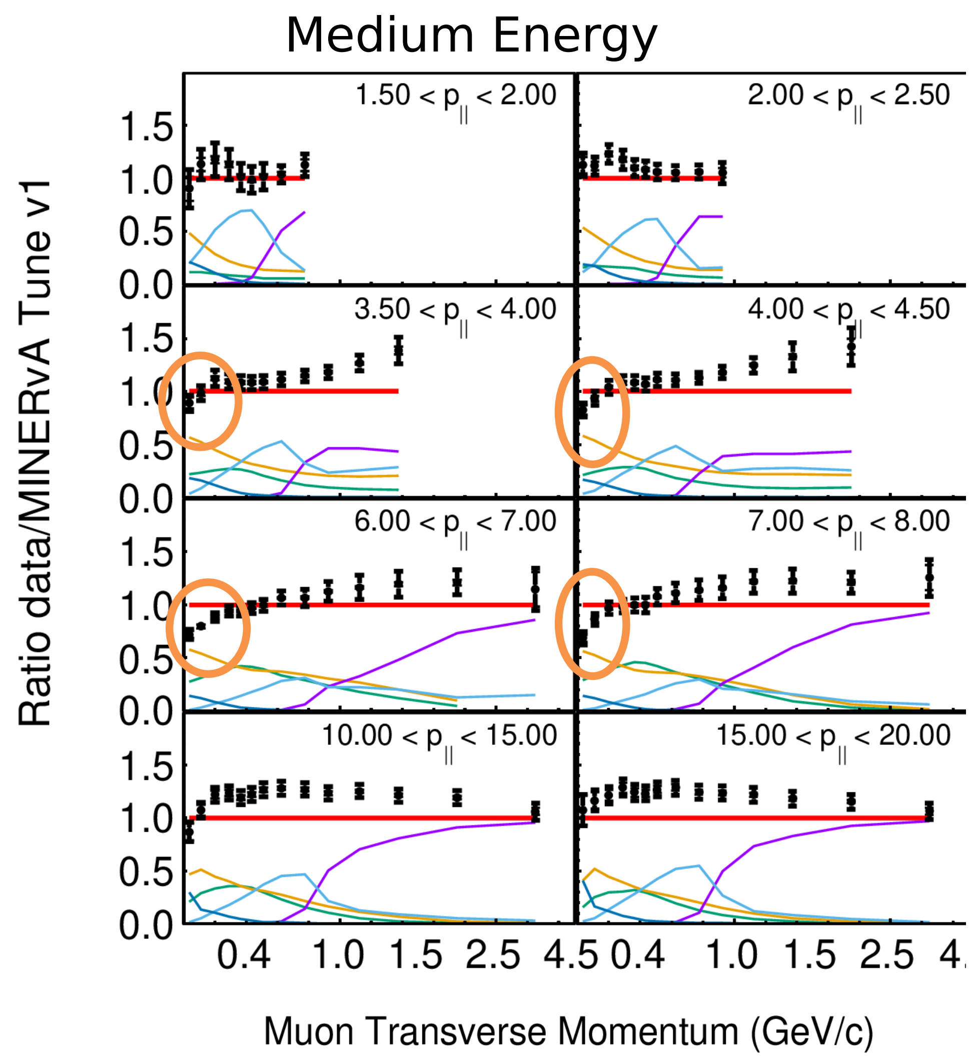


Around flux peak – area of agreement centered around p_T~0.5 GeV

Debbie, Andrew and Jeffrey will all talk about QE-like measurements on Tuesday

Ratios to MnvTune

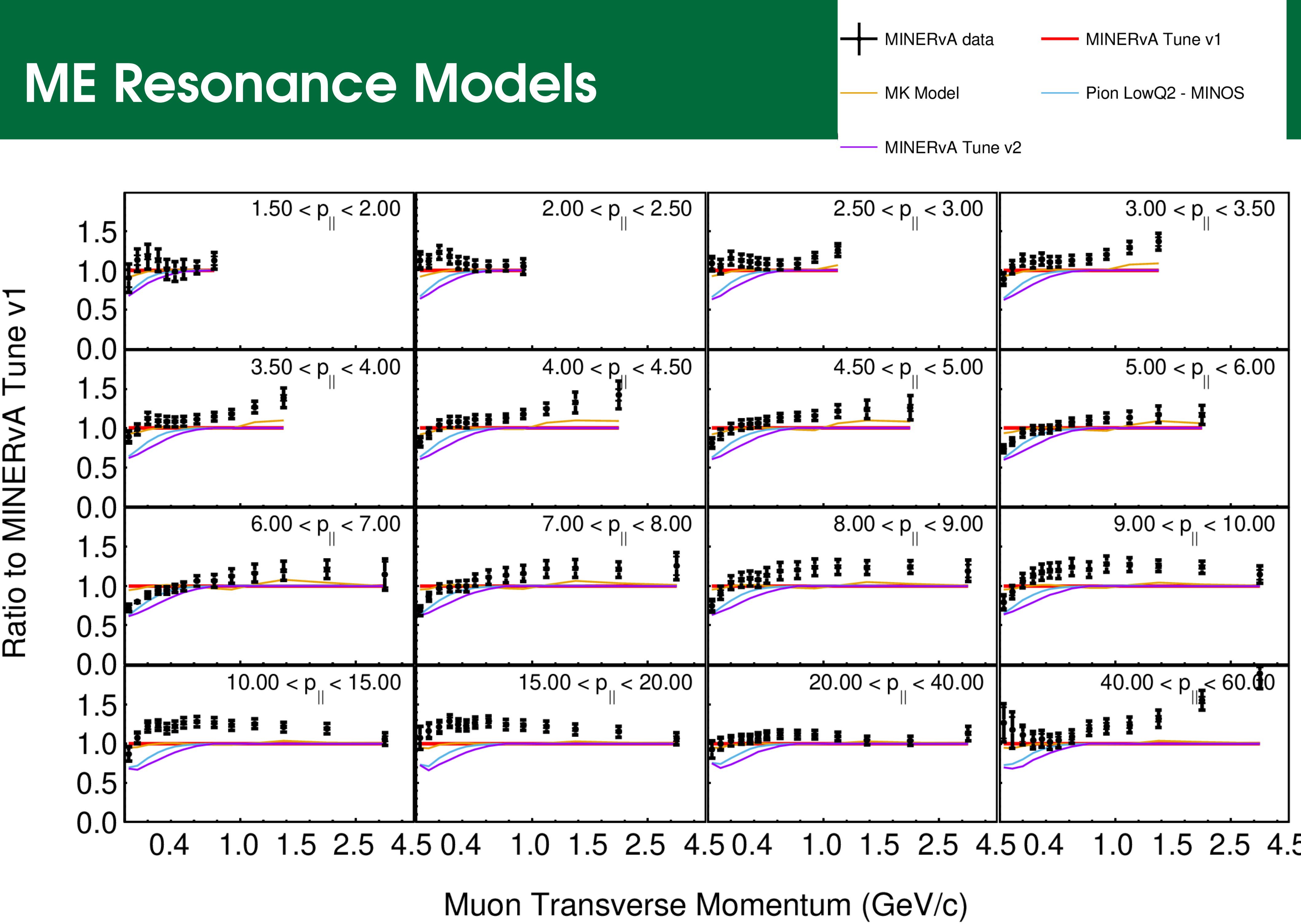




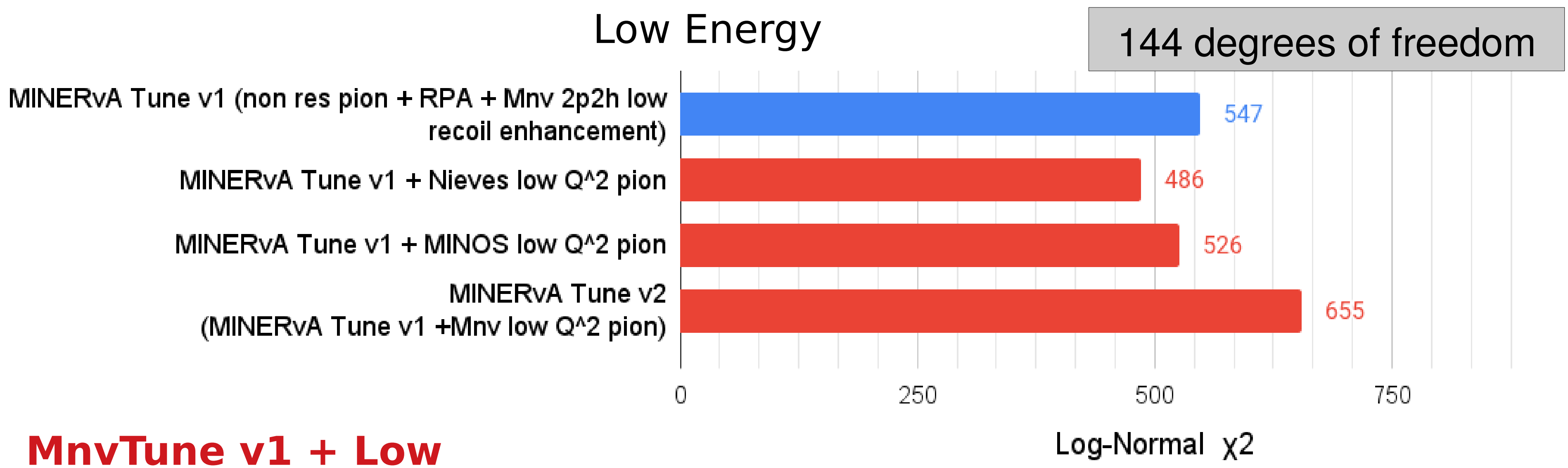
Around flux peak – overprediction at low p_T

Low Q^2 resonant suppression needed?

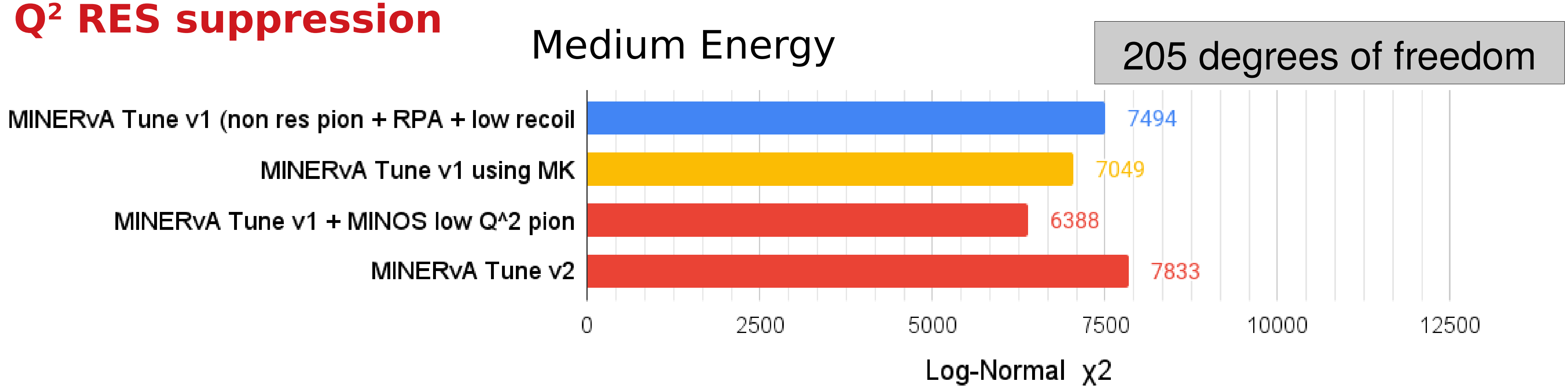
ME Resonance Models



Chi2s with changes to resonant model

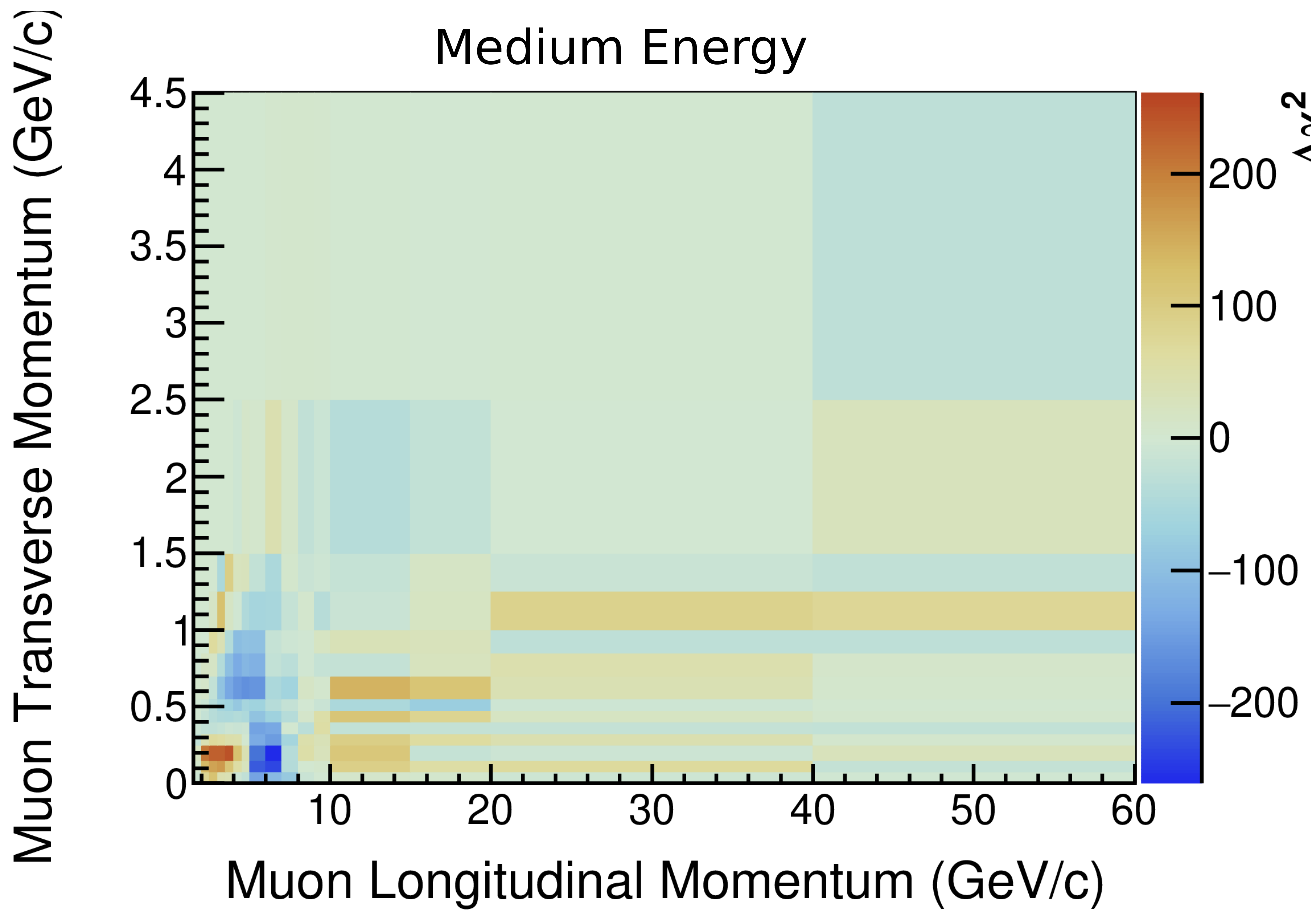


MnvTune v1 + Low Q^2 RES suppression



• Effect of MINOS Low Q^2 suppression on χ^2

- **Shows the difference in χ^2 per bin between MnvTune v1 with and without the addition of MINOS's ad hoc low Q^2 suppression**
- **Blue areas, the low Q^2 suppression reduces the bin's χ^2, orange area it increases**

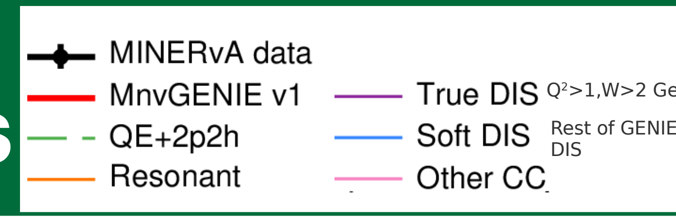


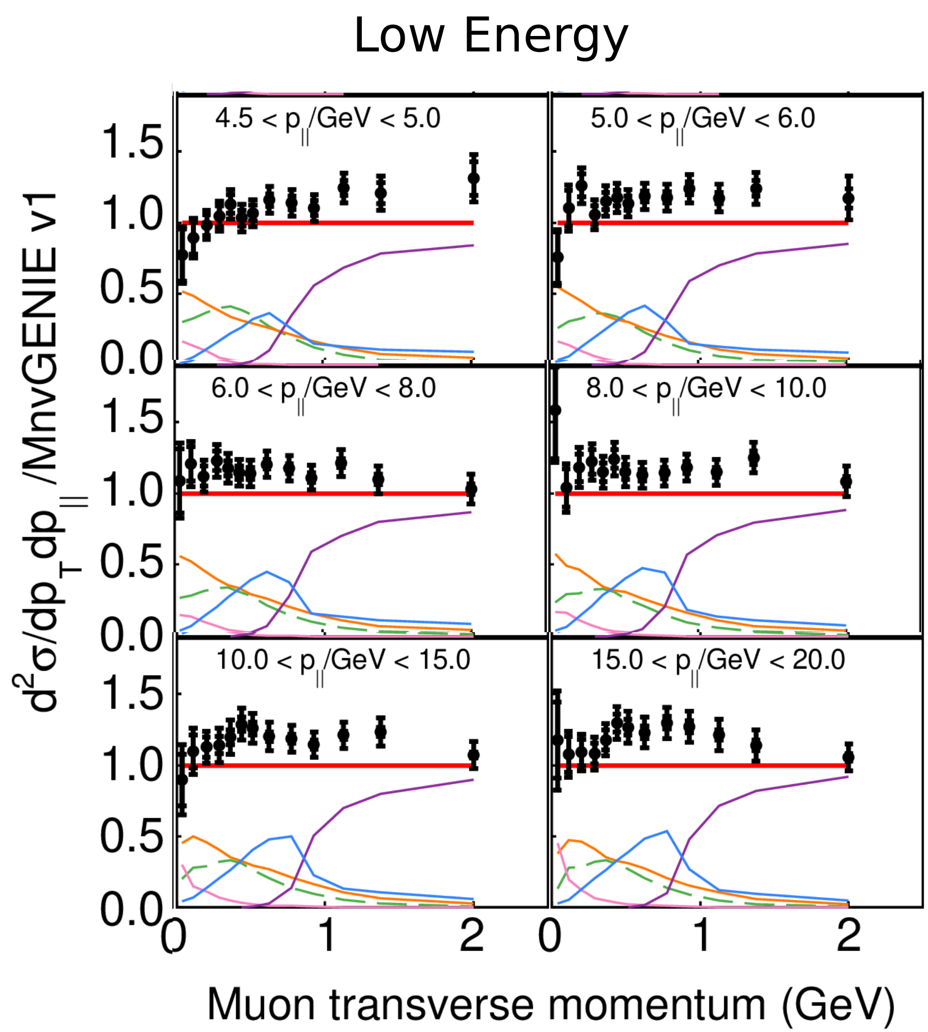
See Kevin's pion talk on Friday

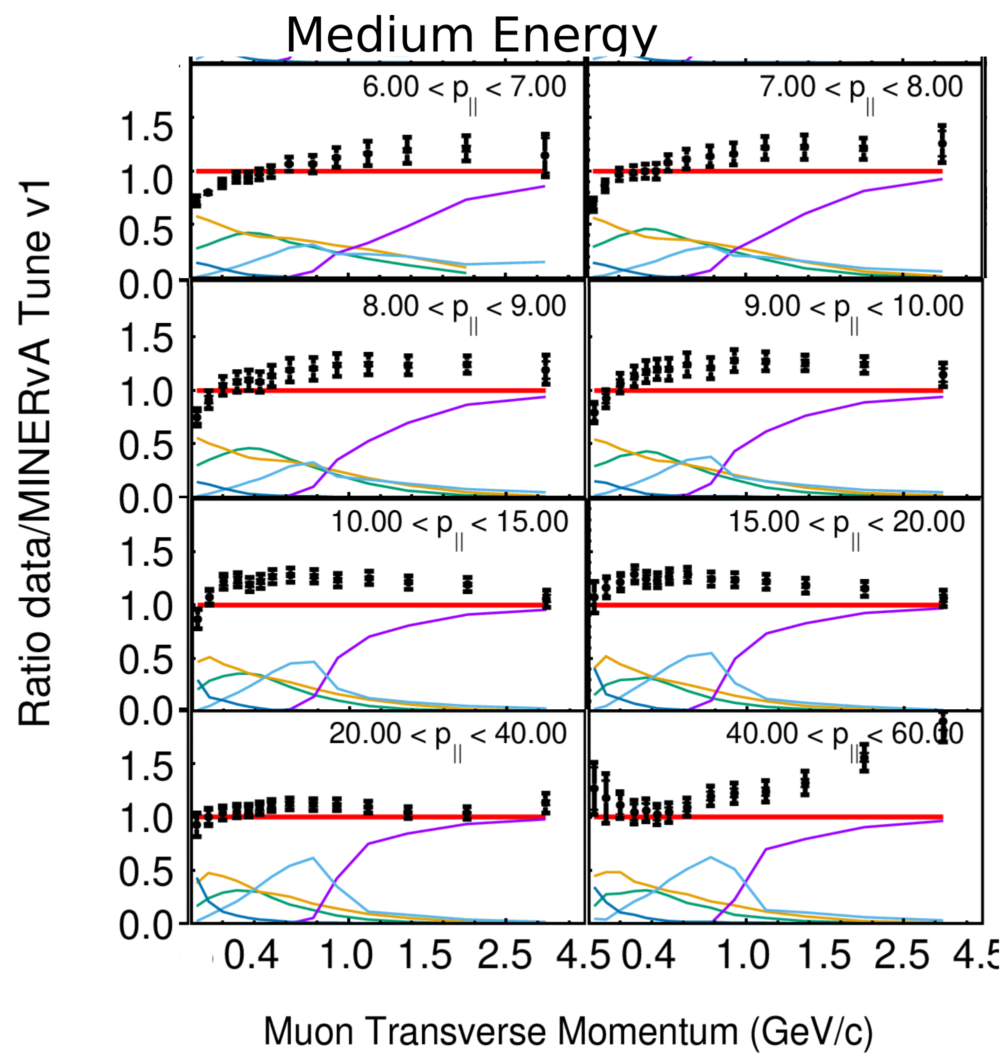
$$\chi^2_{i,j_{\text{model}}} = (x_{i,\text{measured}} - x_{i,\text{expected}_{\text{model}}}) \times V^{-1}_{ij} \times (x_{j,\text{measured}} - x_{j,\text{expected}_{\text{model}}}),$$

$$\Delta\chi^2_i = \sum_j (\chi^2_{i,j_{\text{model}}} - \chi^2_{i,j_{\text{MINERvA Tune v1}}}),$$

Ratios to MnvTune – Highest $p_{||}$ bins



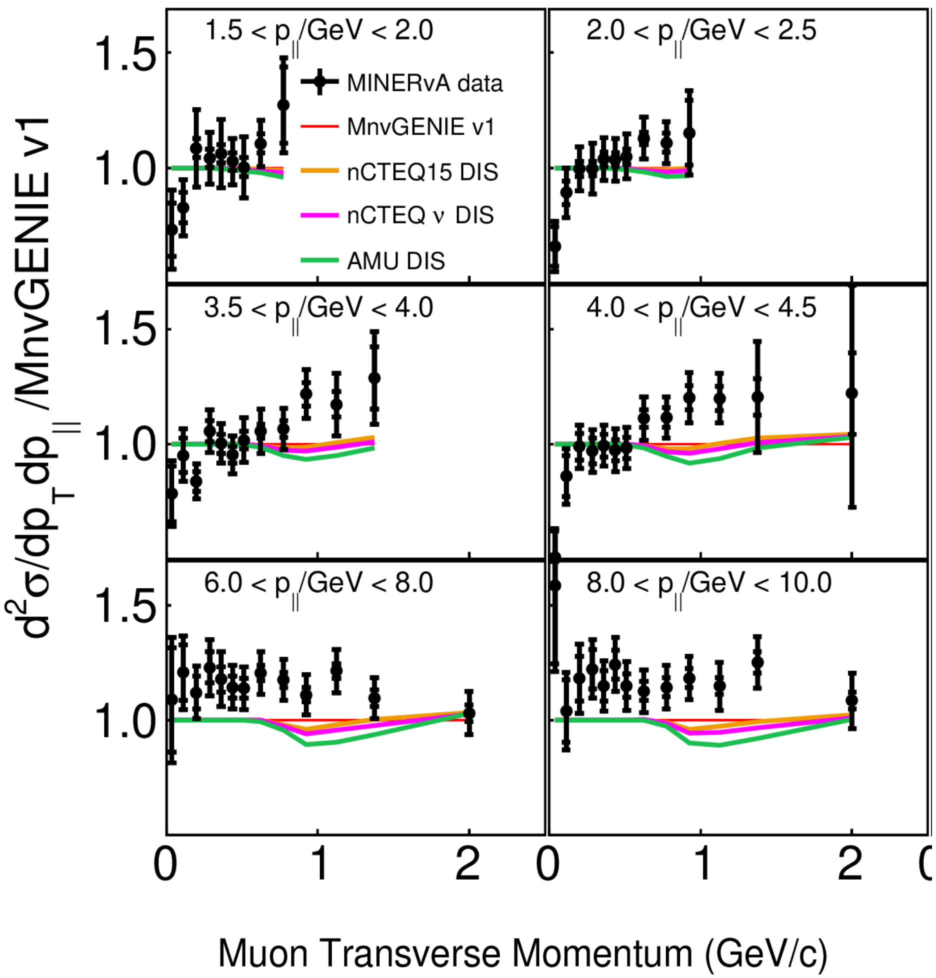




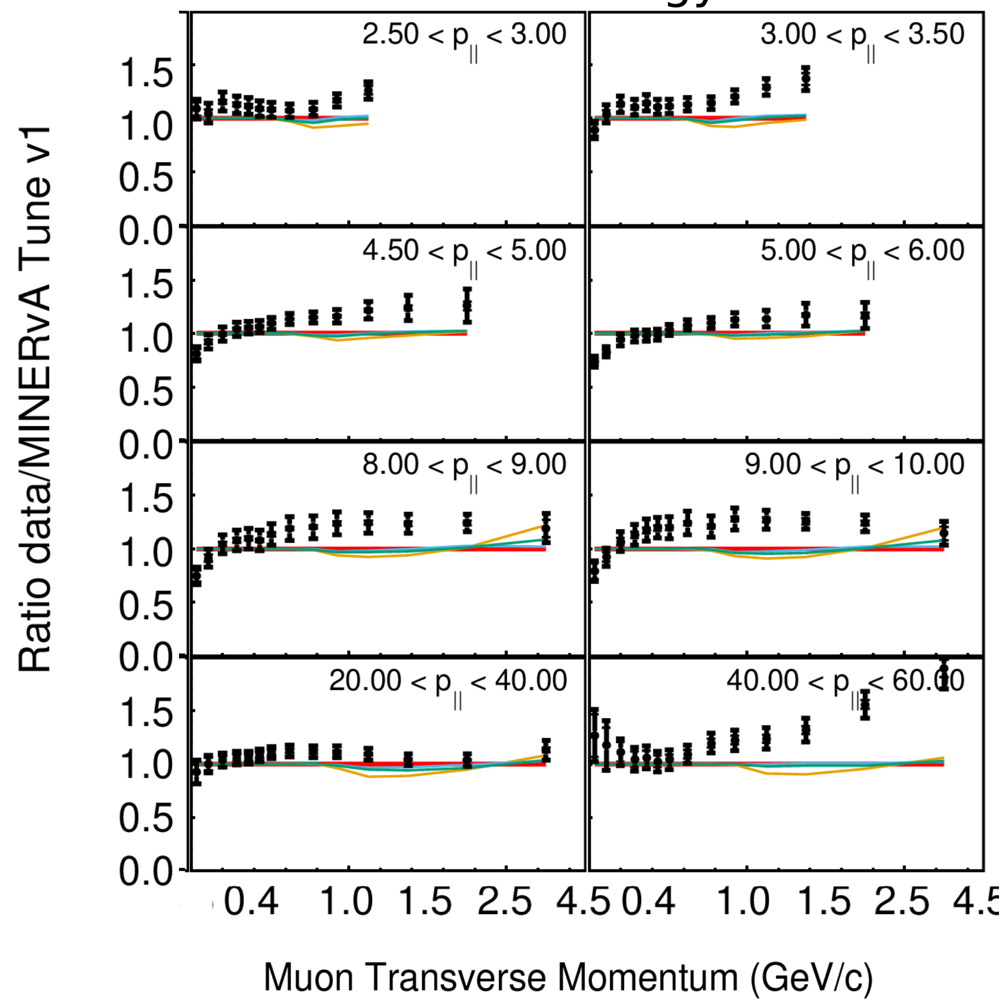
In the $p_{||}$ bins above the flux peaks, there starts to be greater discrepancies in the mid p_T .

DIS models

Low Energy

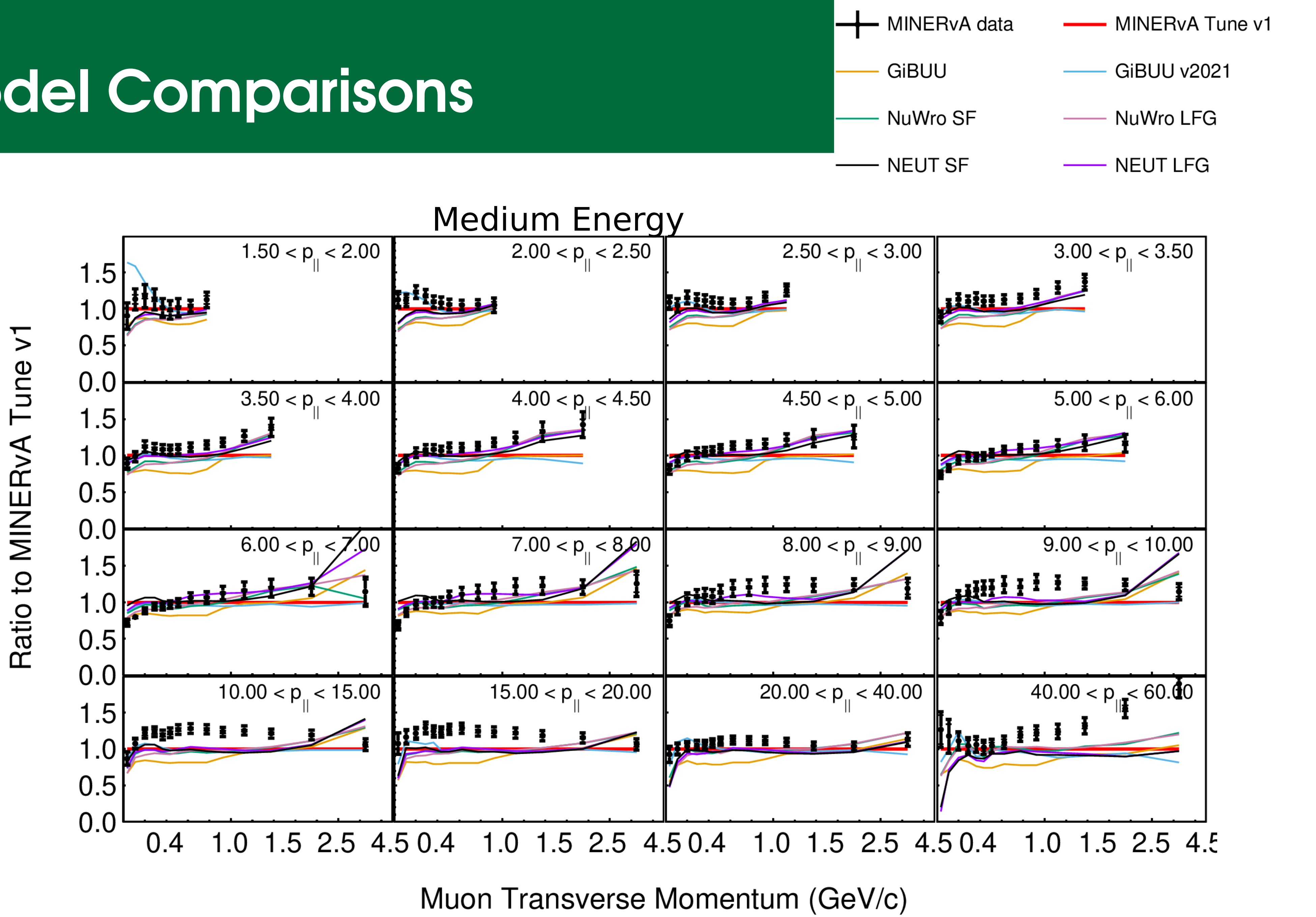


Medium Energy



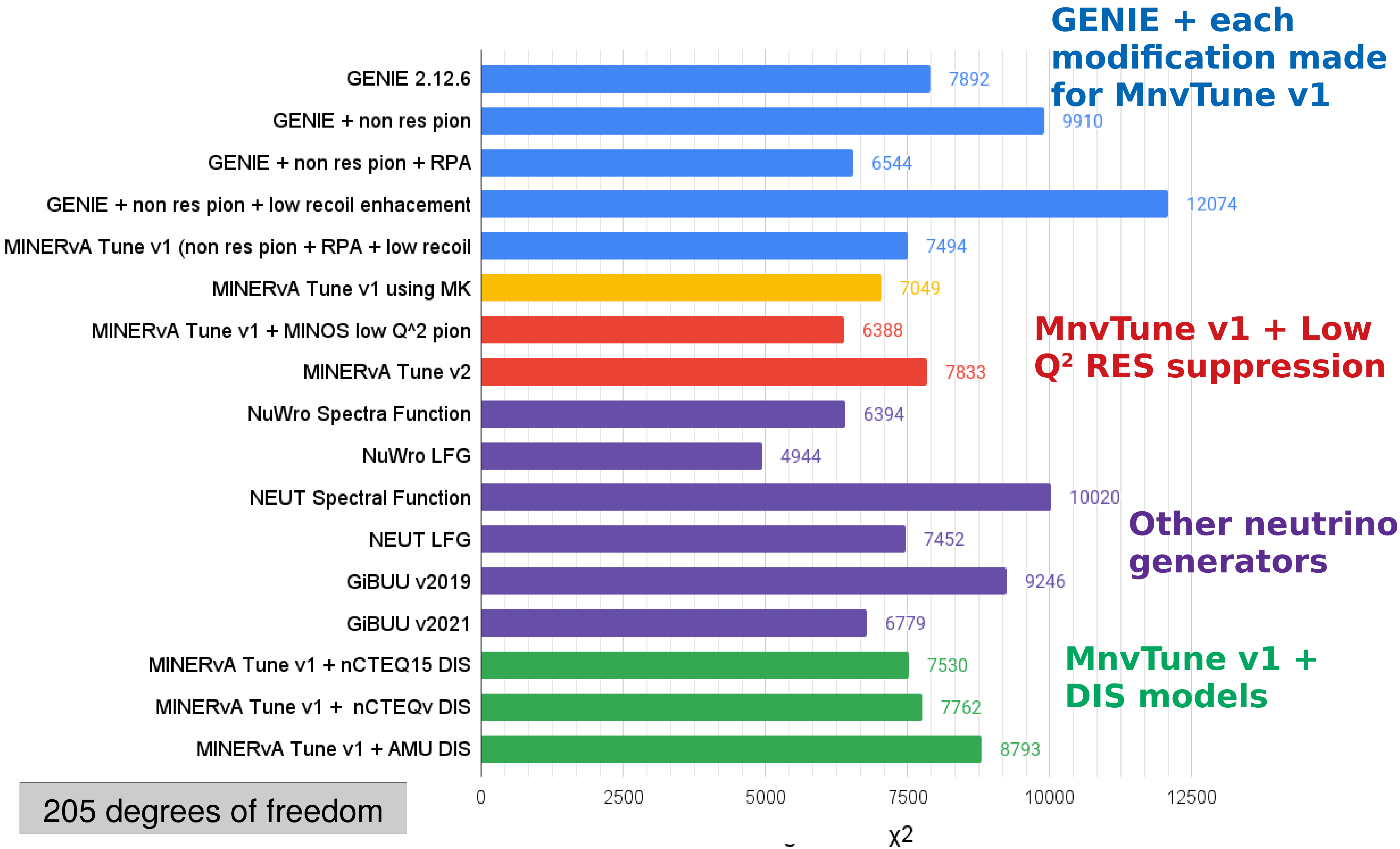
These DIS models all mostly decrease the MC predictions in an area were MnvTune v1 is underpredicted.

Model Comparisons



In comparisons to a suite of generators NuWro was among those to produce the lowest chi2 in both energies

Chi2s – Medium Energy

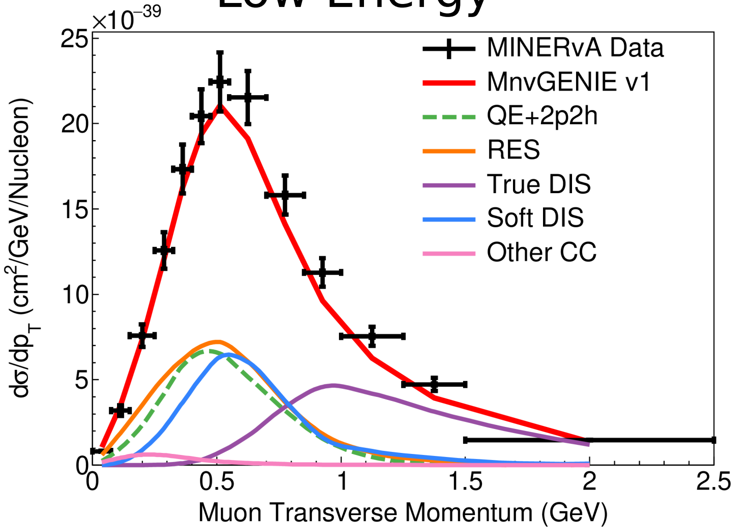


205 degrees of freedom

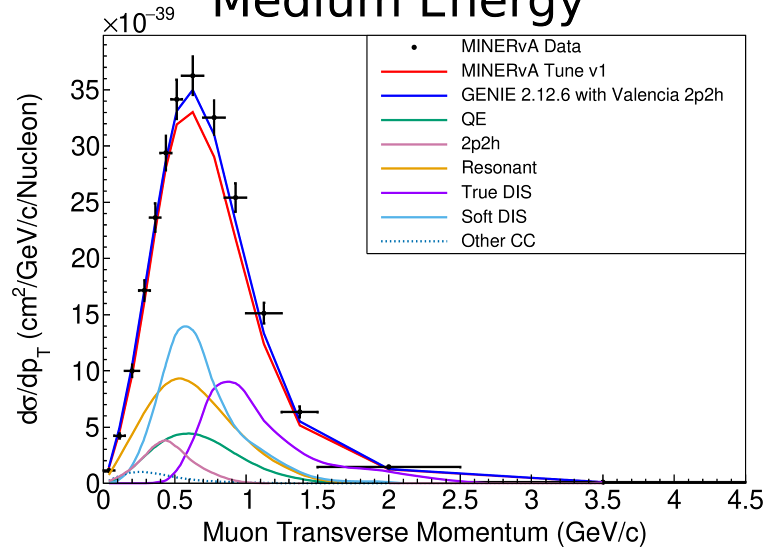
Single Differential Cross Sections -p_T

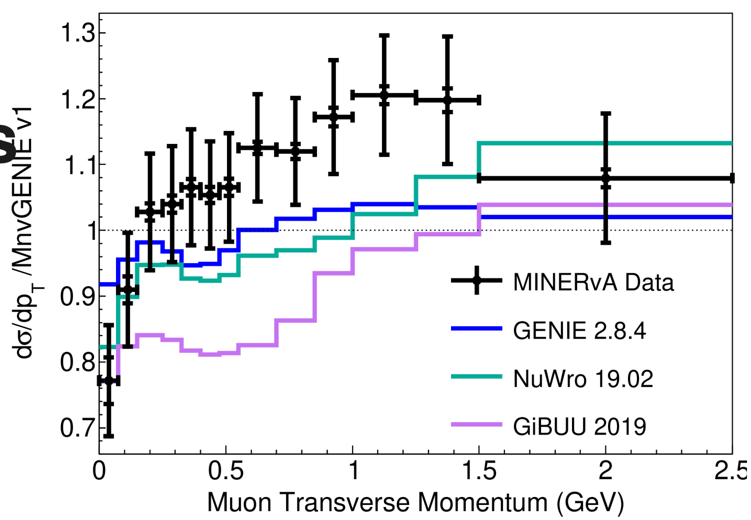
- **MnvTune cross section overpredicts at low p_T in both cross sections**
- **Underpredicts at higher p_T**
- **Very similar shapes**

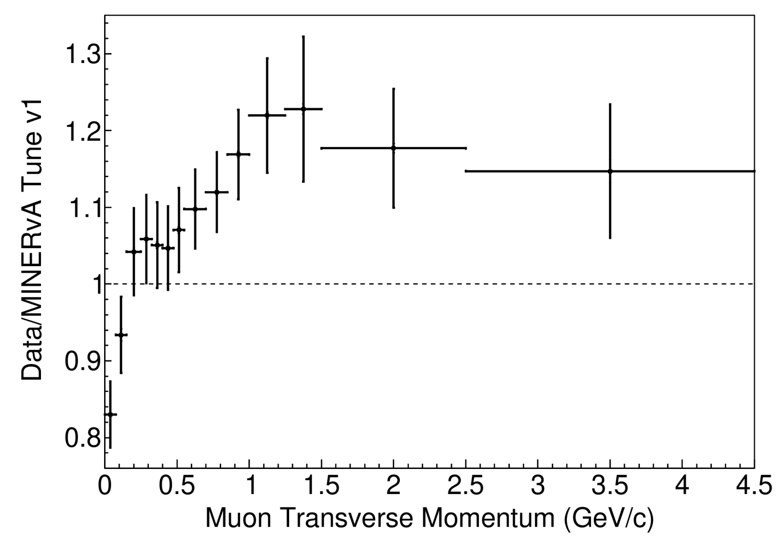
Low Energy



Medium Energy



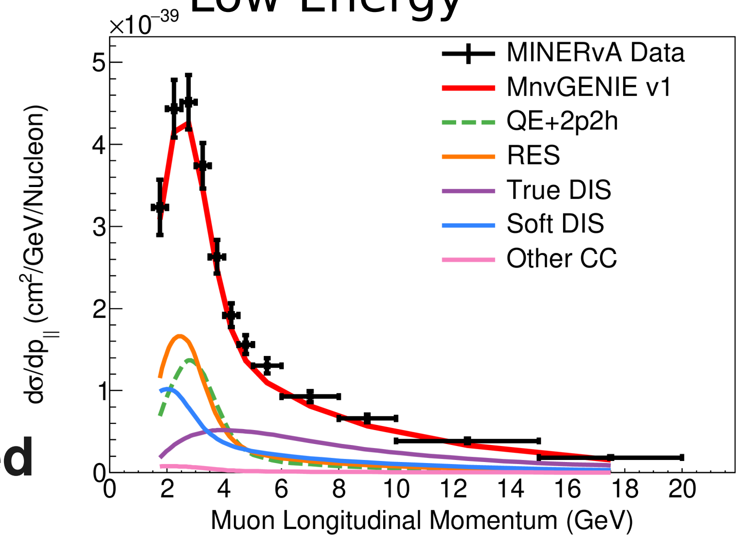




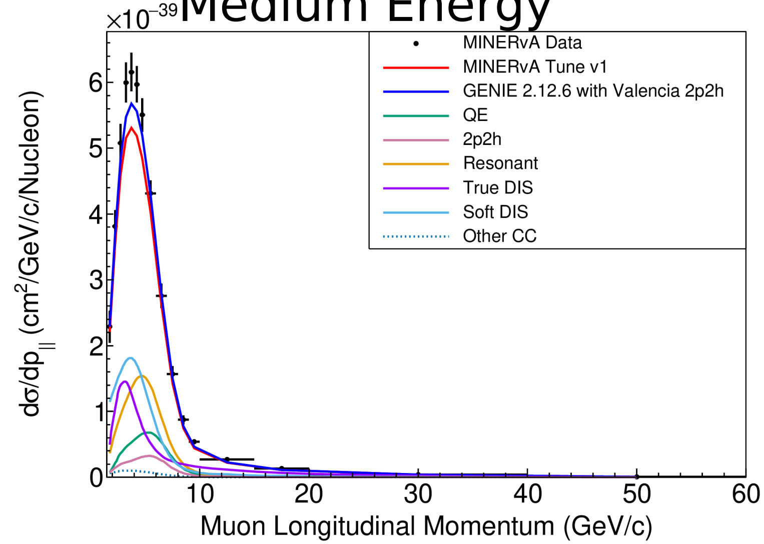
Single Differential Cross Sections -$p_{||}$

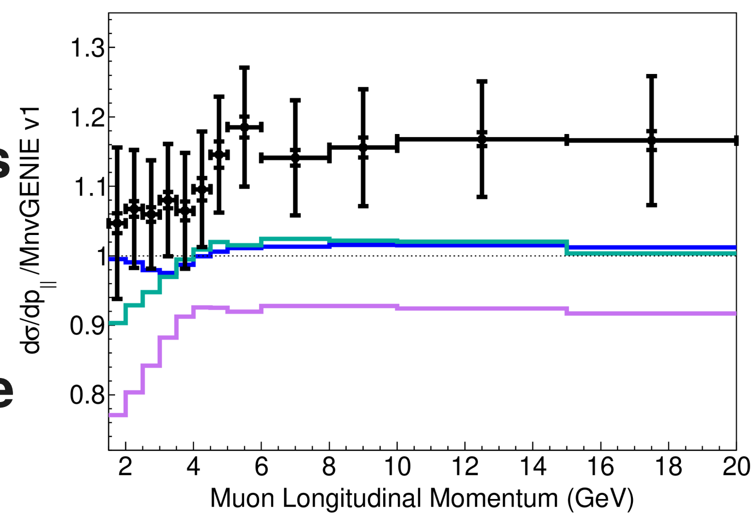
- **$P_{||}$ dependence isn't being accurately predicted**
- **General underpredictions**
- **Studies in ME showed that if MC was fit to data in p_T it agreed well in $p_{||}$, indicating mismodeling of cross section as a function of muon kinematics as well as acceptance and energy scale effects.**

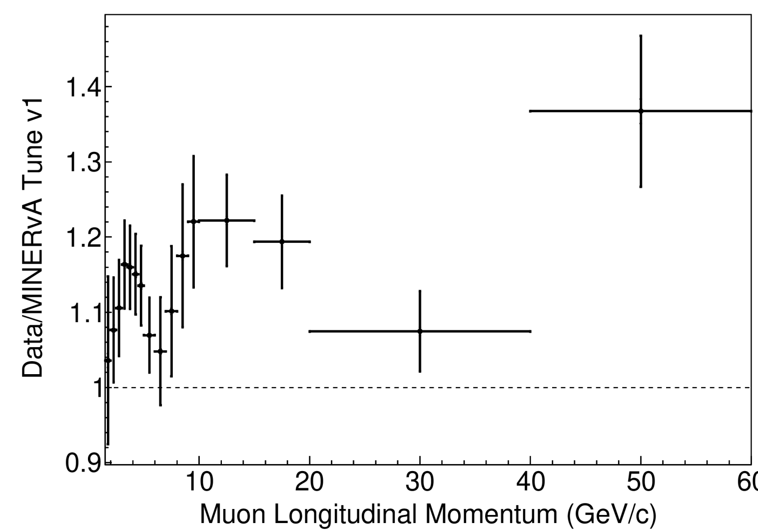
Low Energy



Medium Energy

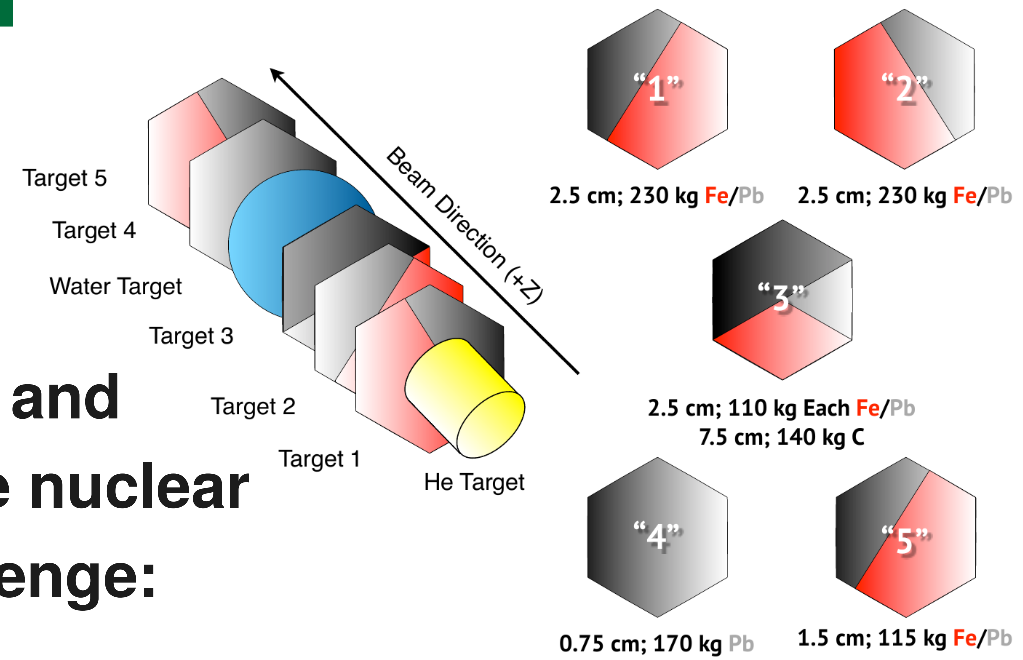






What about the nuclear targets?

- **MINERvA also has a nuclear target region for studying nuclear effects**
- **Measurements of inclusive, deep and shallow inelastic scattering in the nuclear target region face an added challenge: vertex position reconstruction**

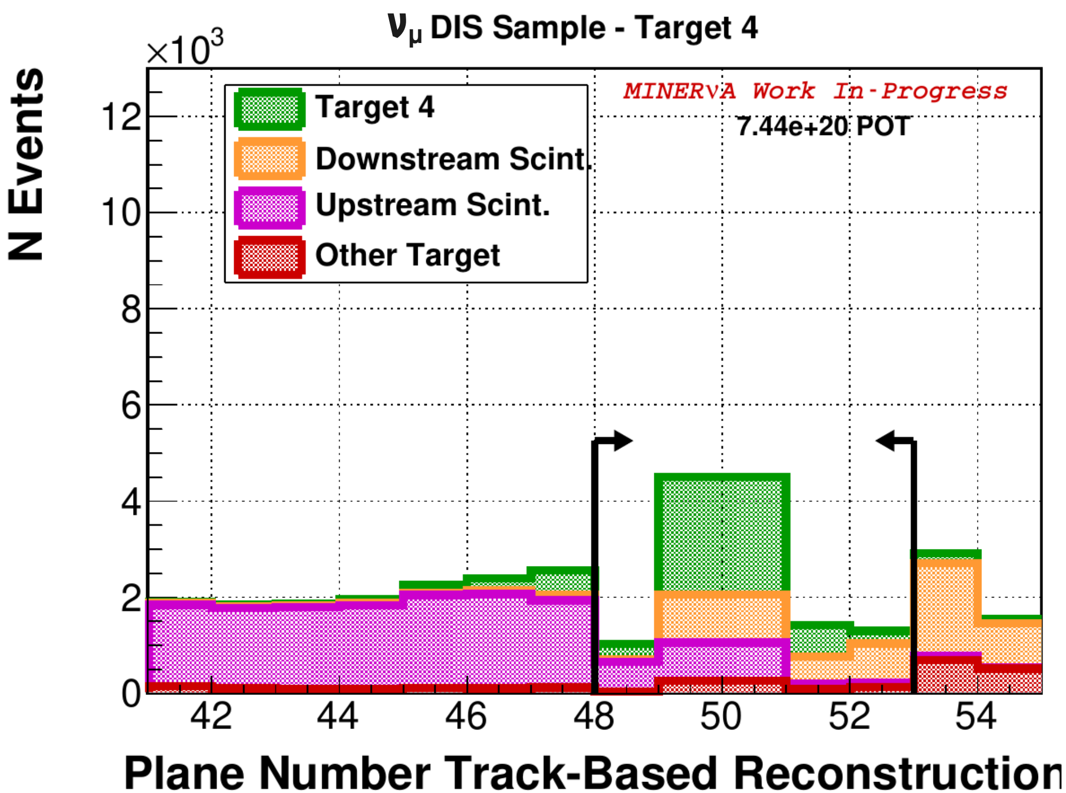


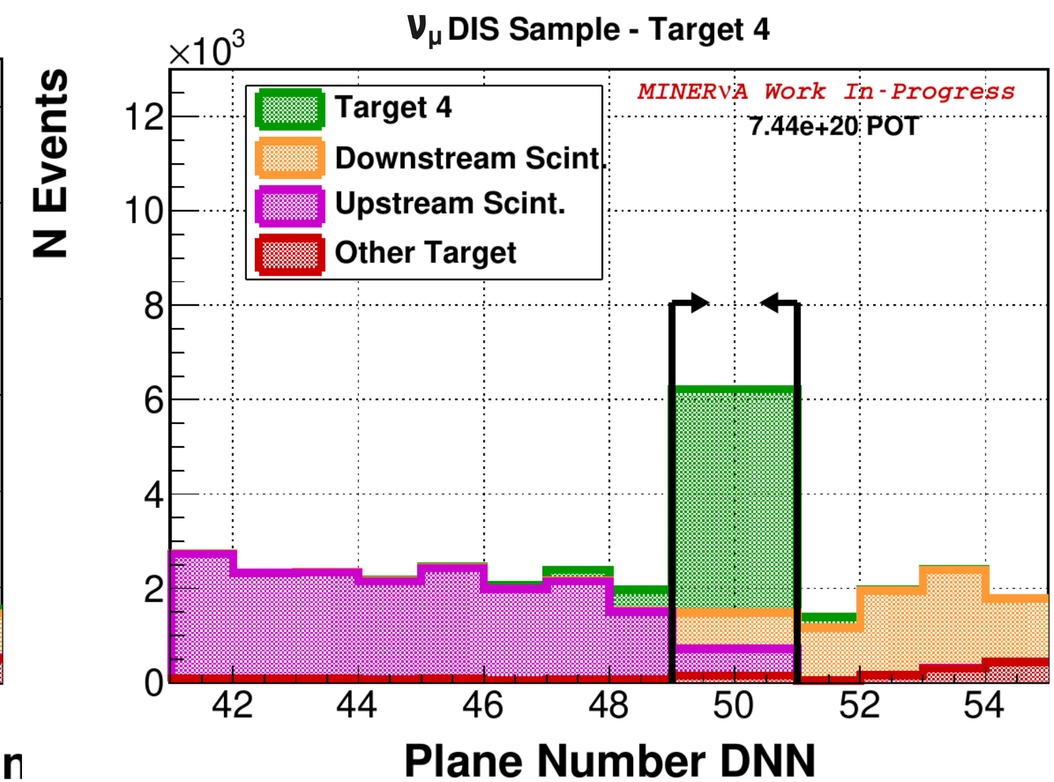
- **Interactions which produce large showers can obscure the starting point of the interaction and make it far more challenging to correctly identify the material which it took place in.**
- **Use of machine learning algorithms can greatly improve the efficacy of our vertex reconstruction, enabling greater precision in their measurements.**

Using Machine Learning for vertex reconstruction

- **Domain adversarial neural networks were used, which were trained to highlight common features between distinct domains, while de-emphasizing differences**

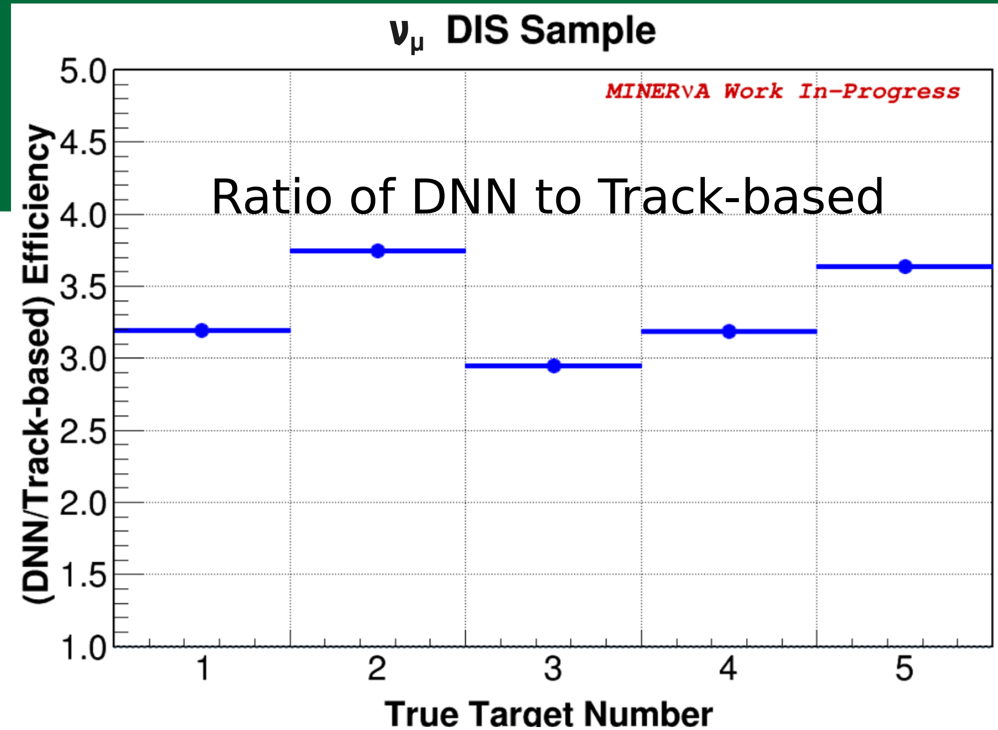
Track based vs ML vertex

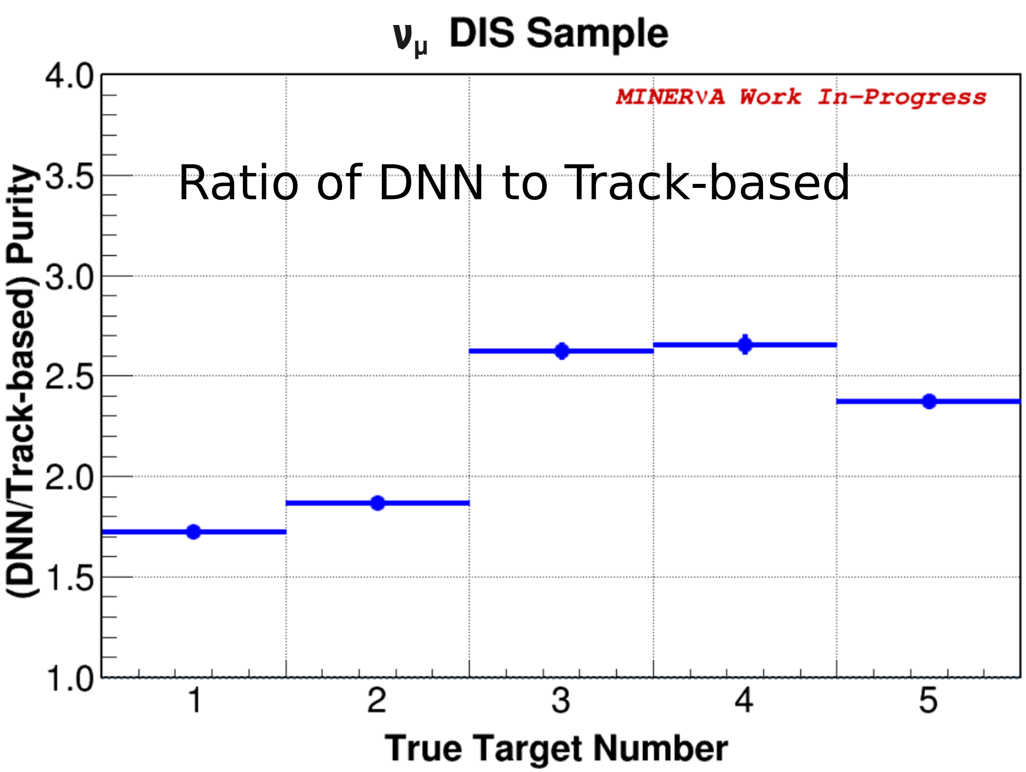




Efficiency of ML

- **DNN based vertex finding was ~3x more efficient than traditional track based methods**
- **A series of studies were done which varied underlying physics models in the simulation and compared the reconstruction:**
  - Flux model
  - FSI model
  - W kinematic dependence





Architecture Comparisons with ML vertexing

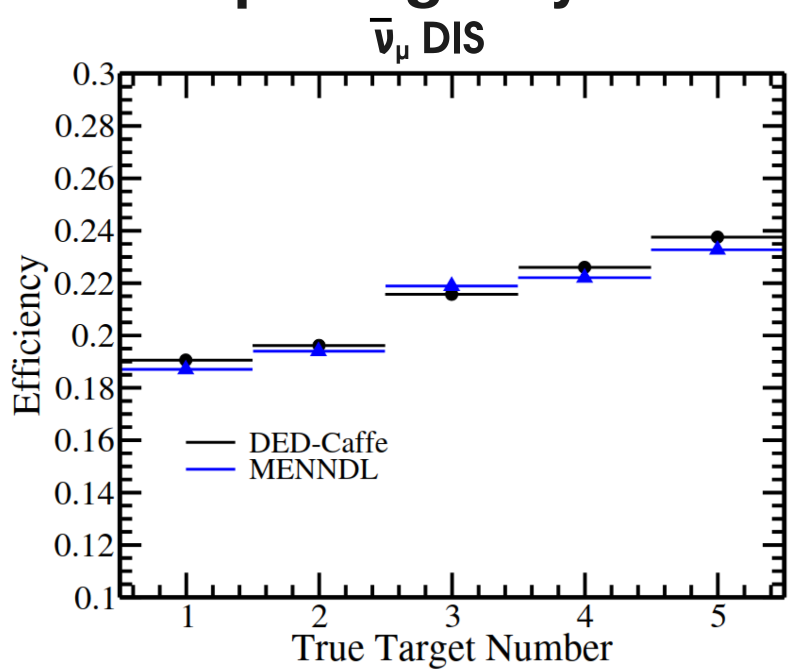
Akbar et al. JINST 17 T08013 (2022)

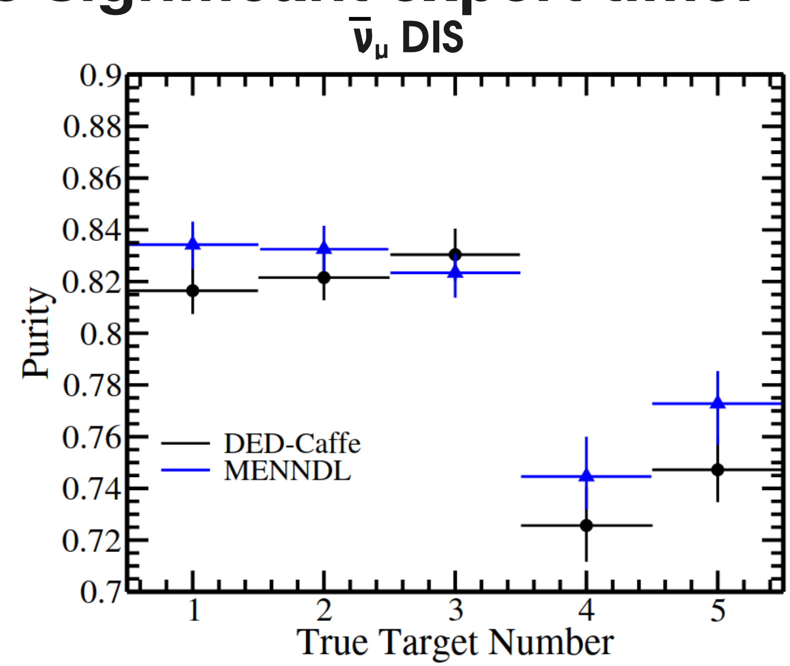
- **The architectures used were developed by hand domain-expert-designed (DED) but other automated architecture development methods are available which if used could save expert time**
  - MENNDL developed by a group at Oak Ridge is one such package

Young et al. MLHPC`15 4 p1-5 (2015)
Young et al. MLHPC`17 7 p1-7 (2017)

- **MENNDL was shown to perform similarly to DED models, suggesting its a compelling way to save significant expert time.**

Efficiency and purity for antineutrino DIS analysis





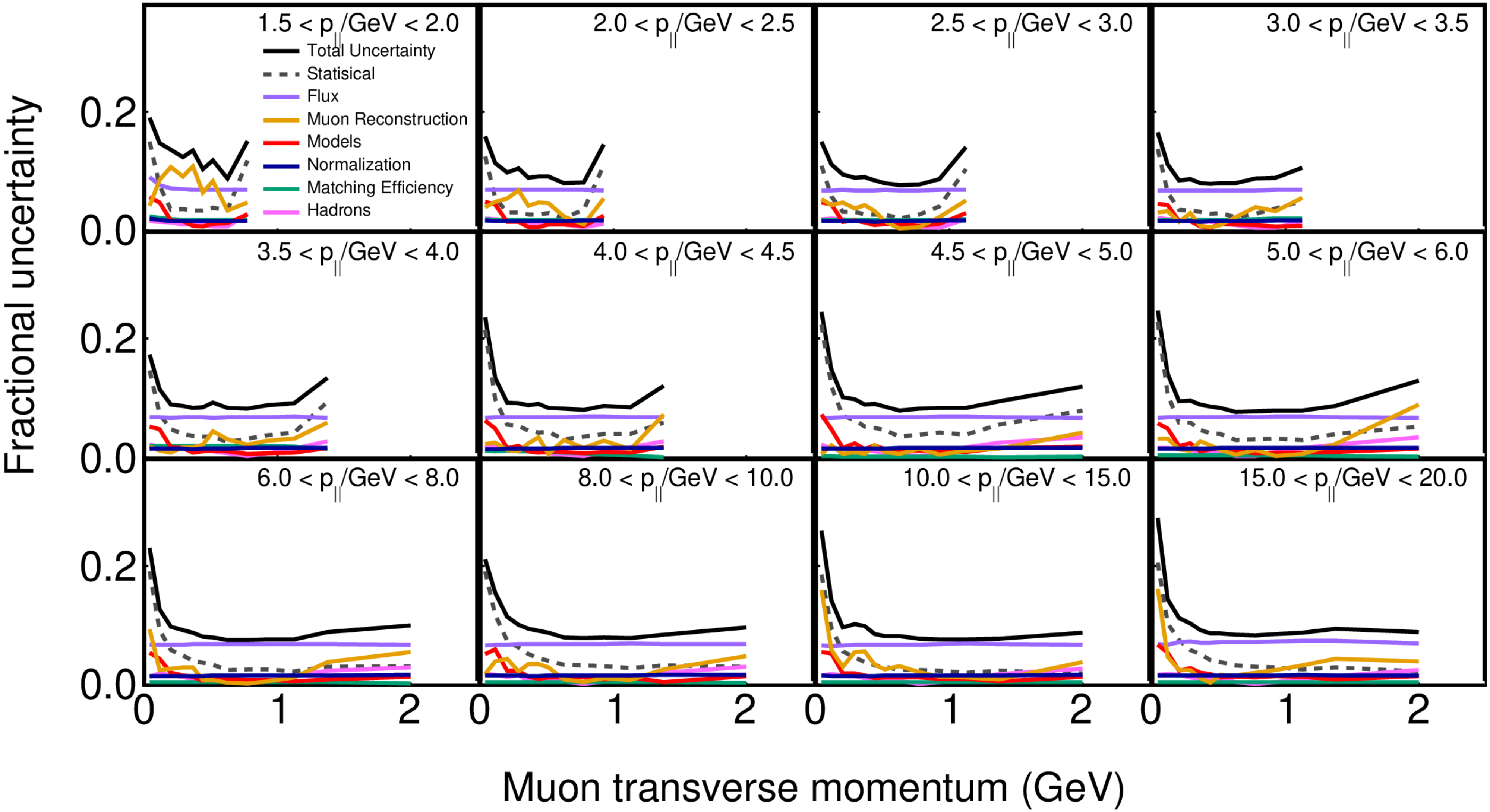
Summary

- **Measured inclusive cross sections aren't consistently reproduced by any model throughout phase space**
- **See similar trends with both data sets**
- **Indication that low Q^2 resonant suppression called for**
- **Exclusive results can help differentiate between possible sources of mismodeling seen in inclusive results**
  - Flux talk tomorrow, 3 QE-like talks Wednesday, Pion talk Friday
- **Use of ML to identify vertex position is a great tool to strengthen our analysis abilities, and will be featured in SIS, DIS and inclusive target analyses coming soon**

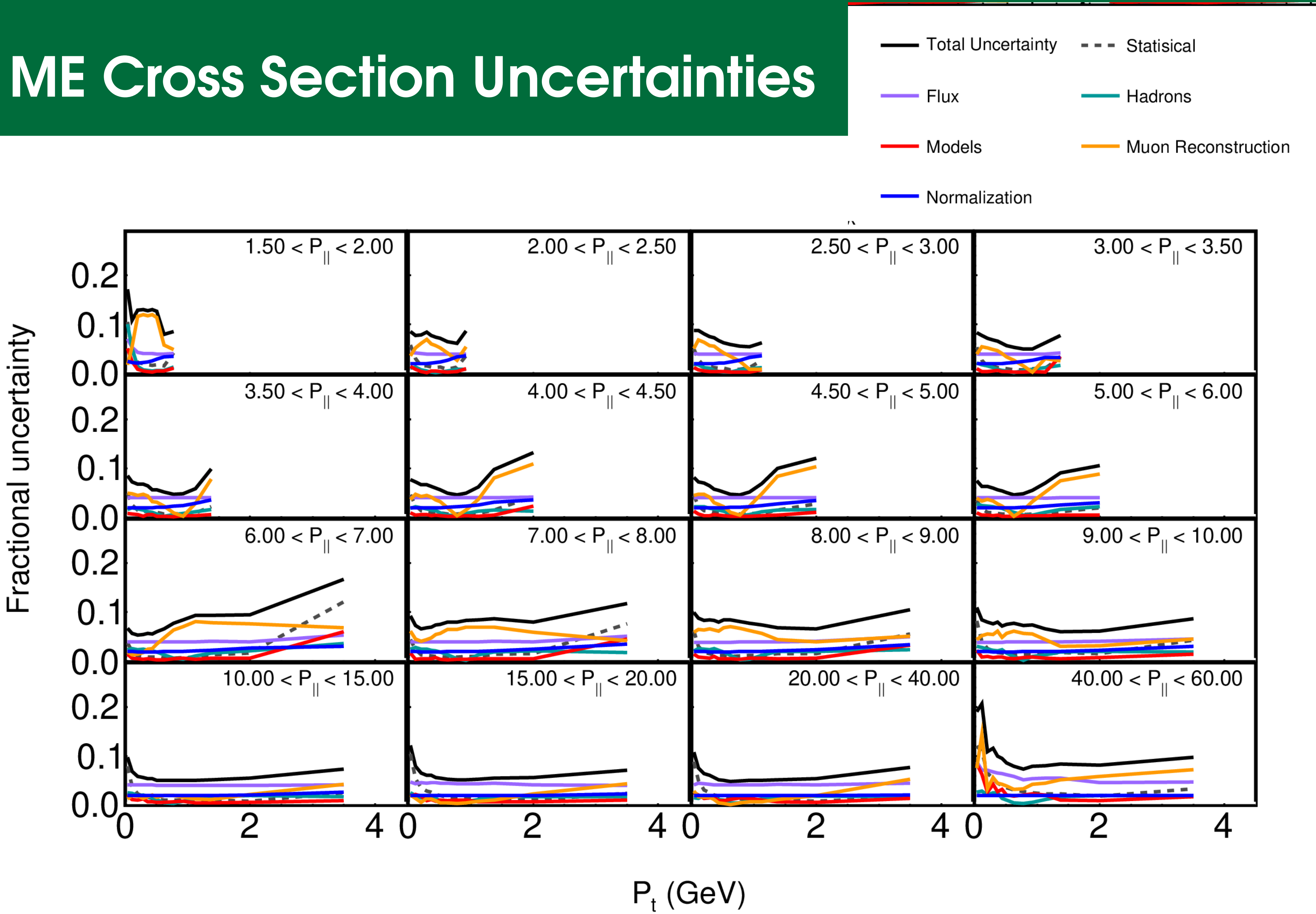
Thank you!

Backup

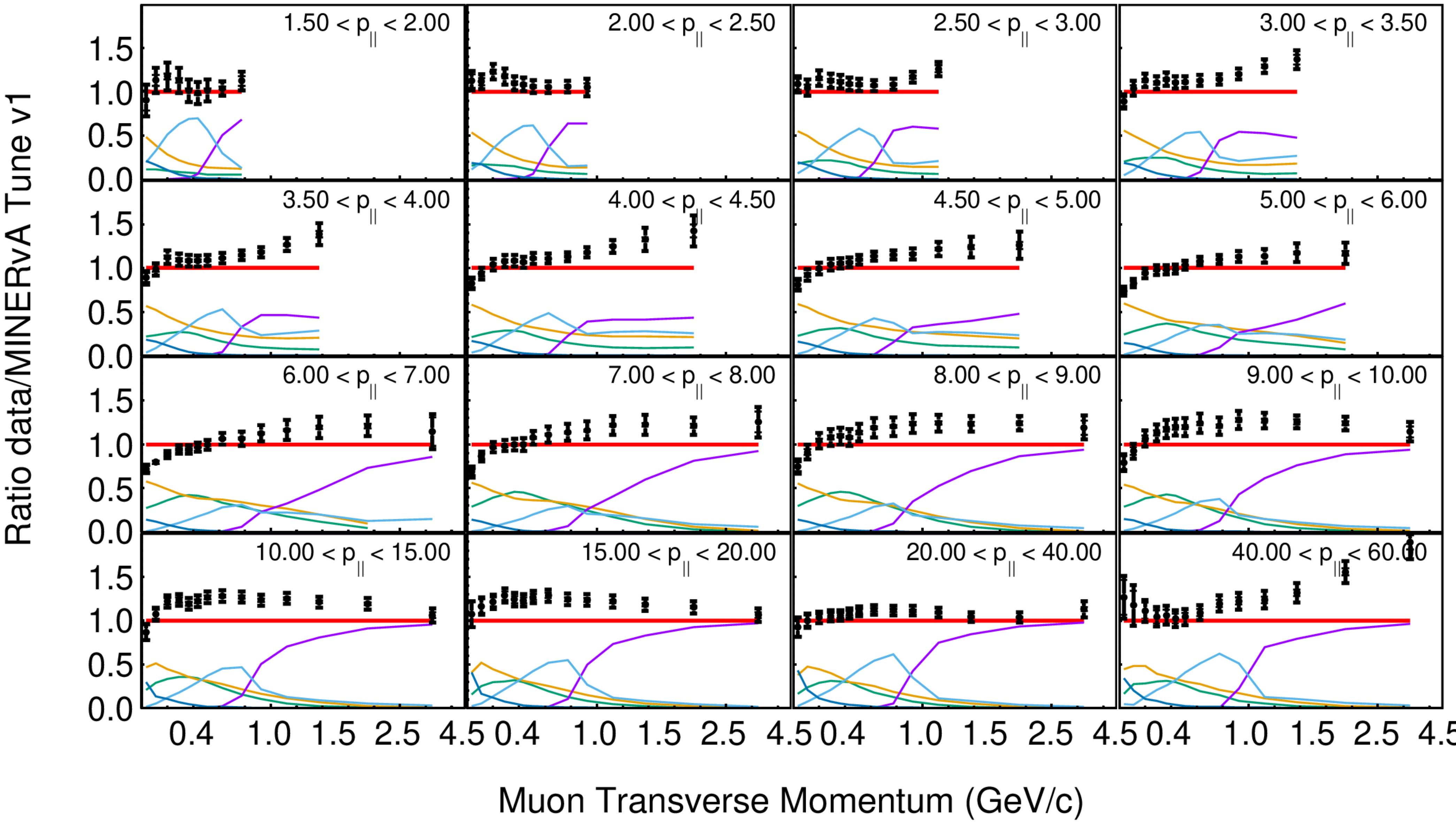
LE Cross Section Uncertainties



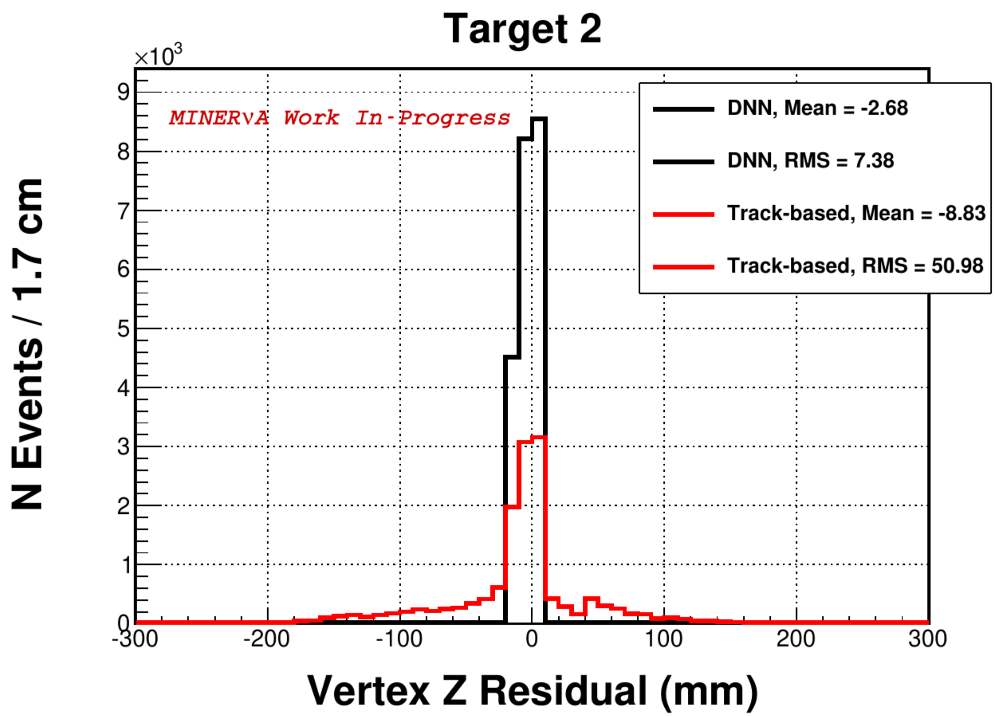
ME Cross Section Uncertainties

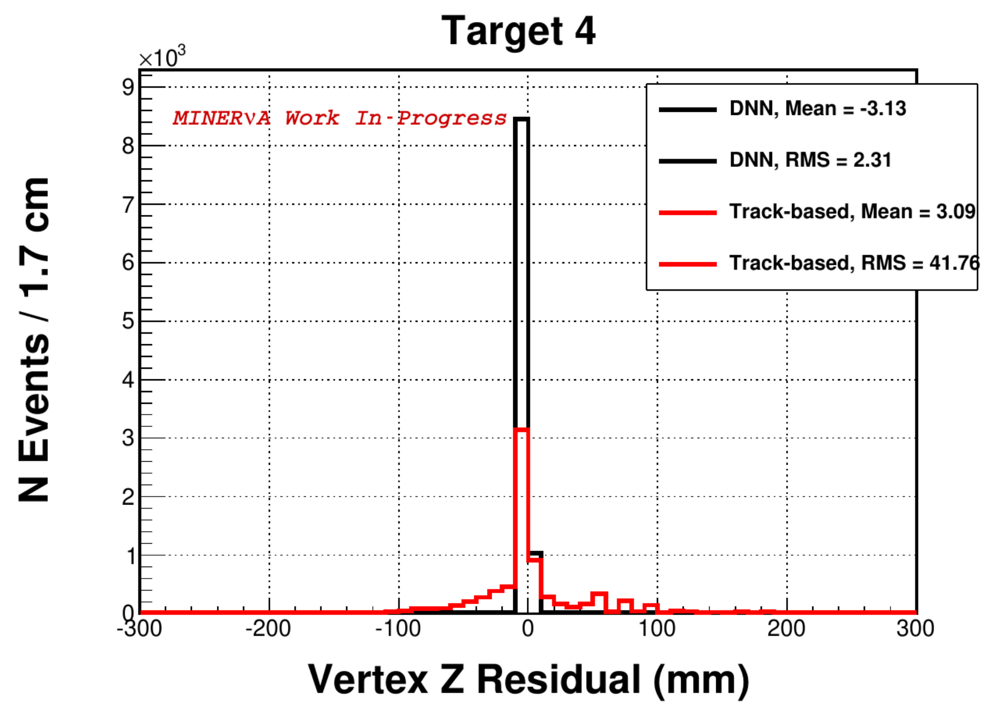


ME Cross Section Ratio



ML vertex residuals – Neutrino

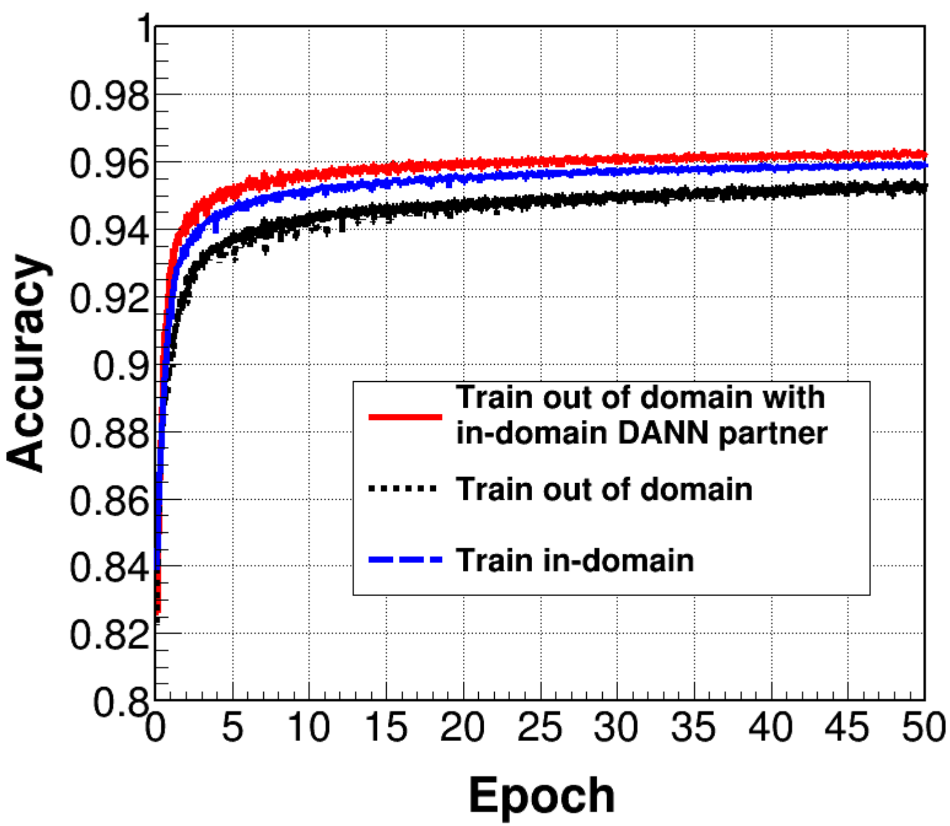


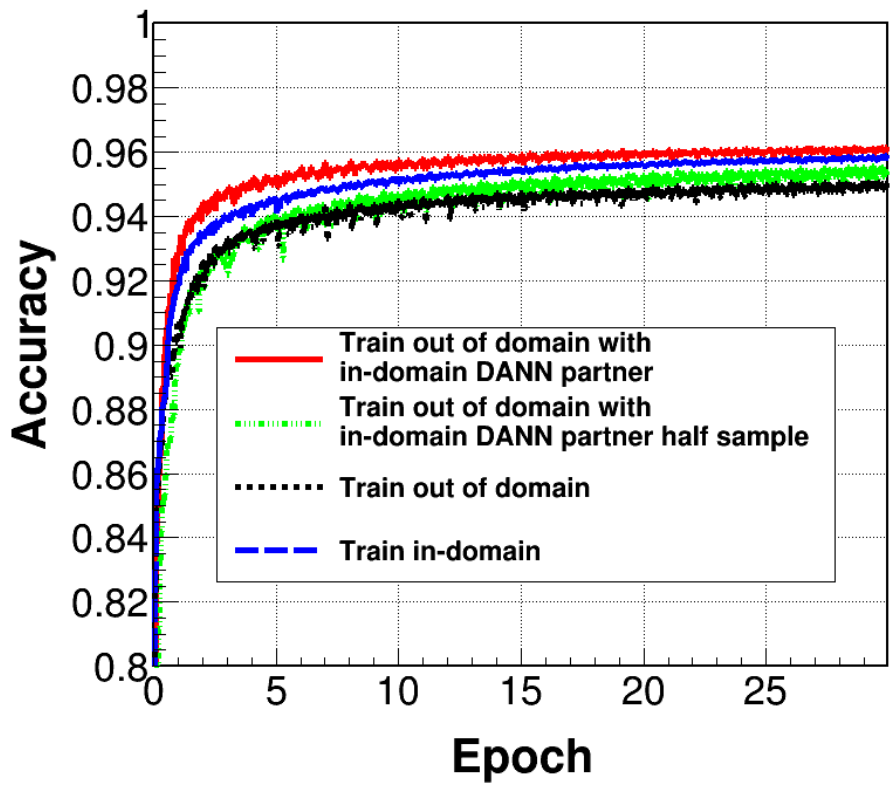


FSI model – verterxing accuracy

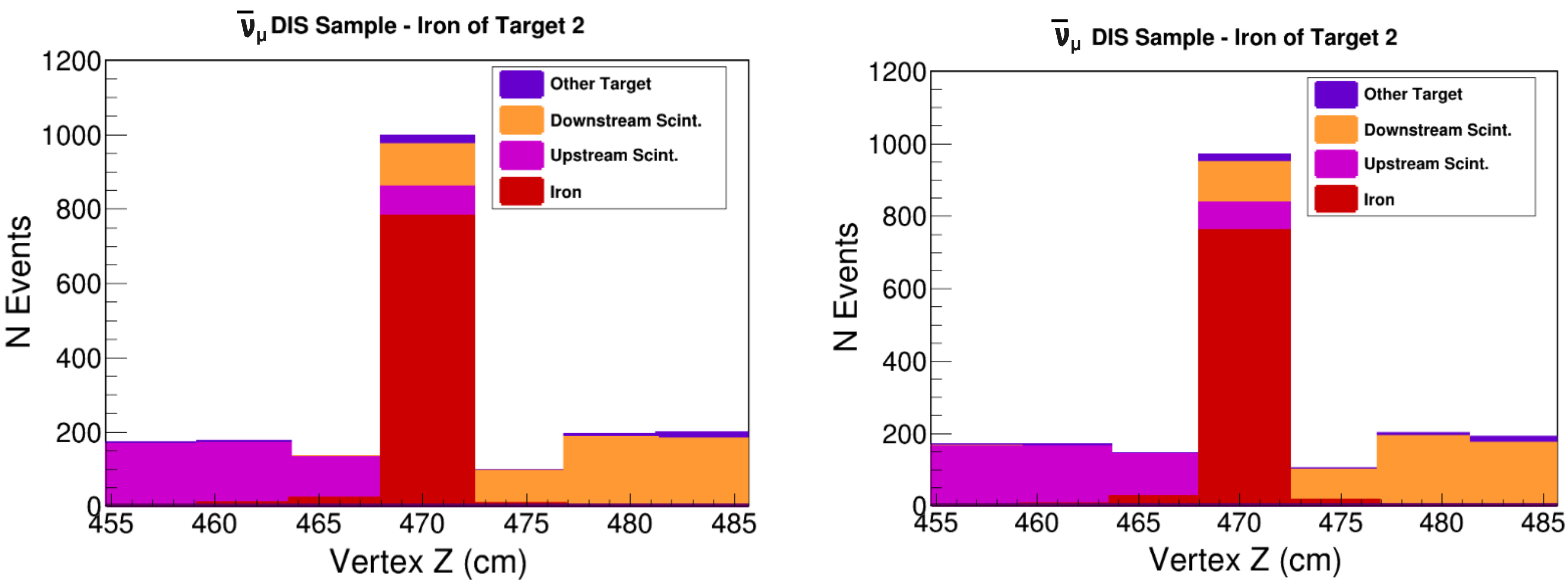
Curve	Train (labeled)	DANN partner (unlabeled)	Evaluation sample
Black (Train out-of-domain)	Source domain FSI-off	None	Target domain FSI-on
Blue (Train in-domain)	Target domain FSI-on	None	Target domain FSI-on
Red (Train out-of-domain with in-domain DANN partner)	Source domain FSI-off	Target domain FSI-on	Target domain FSI-on

Curve	Source domain sample	DANN partner sample
Blue	FSI activated - 1.2 million events	NA
Black	FSI deactivated - 1.2 million events	NA
Red	FSI deactivated - 1.2 million events	FSI activated - 1.2 million events
Green half-DANN	FSI deactivated - 0.6 million events	FSI activated - 0.6 million events





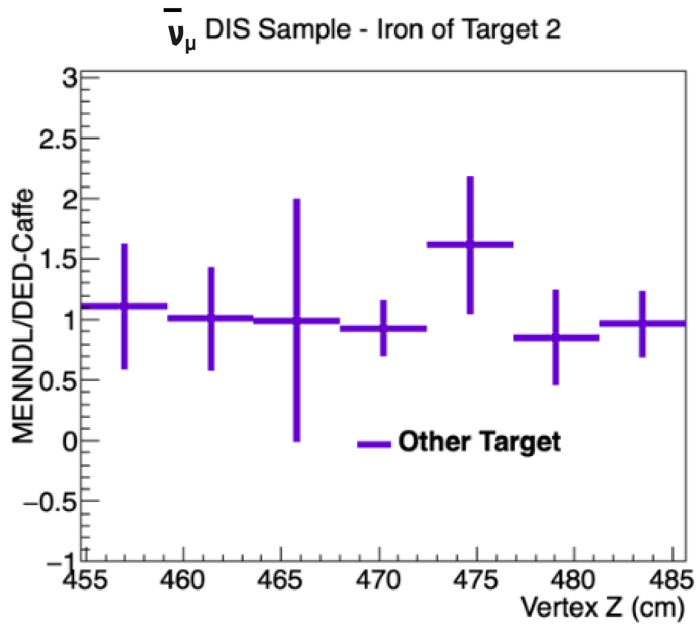
ML vertex model comparison

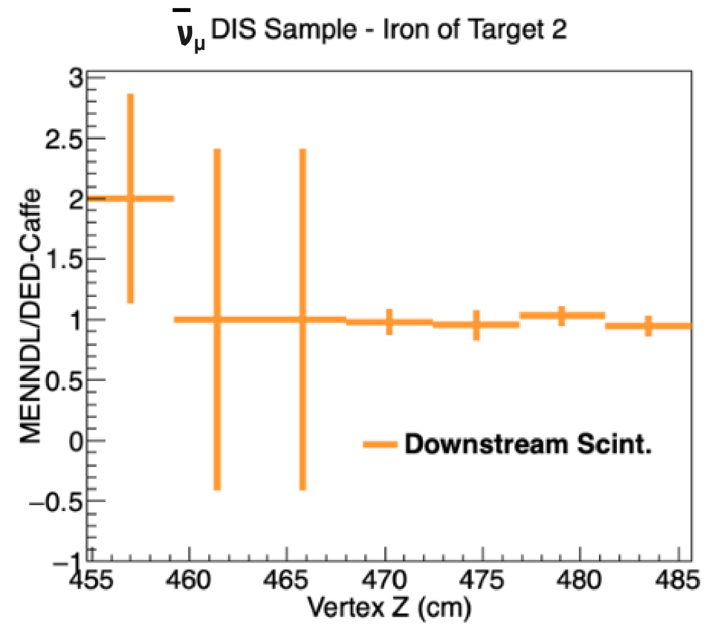


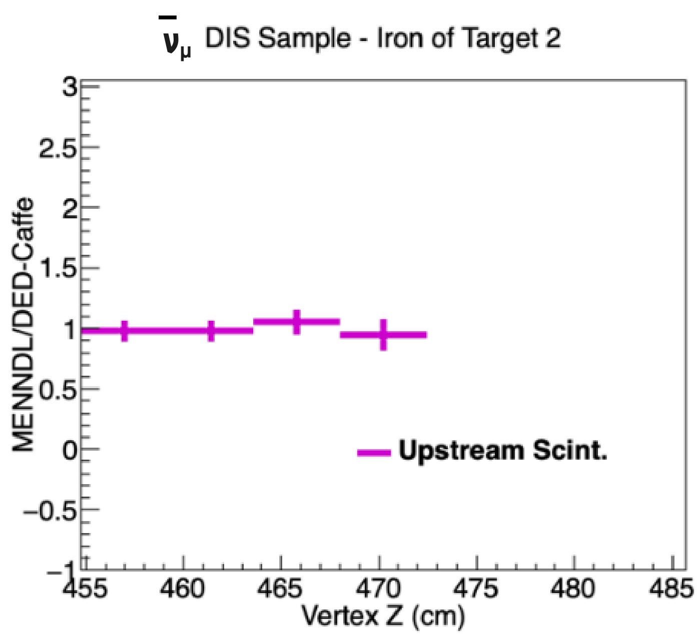
(a) Domain-expert-designed(DED)-Caffe

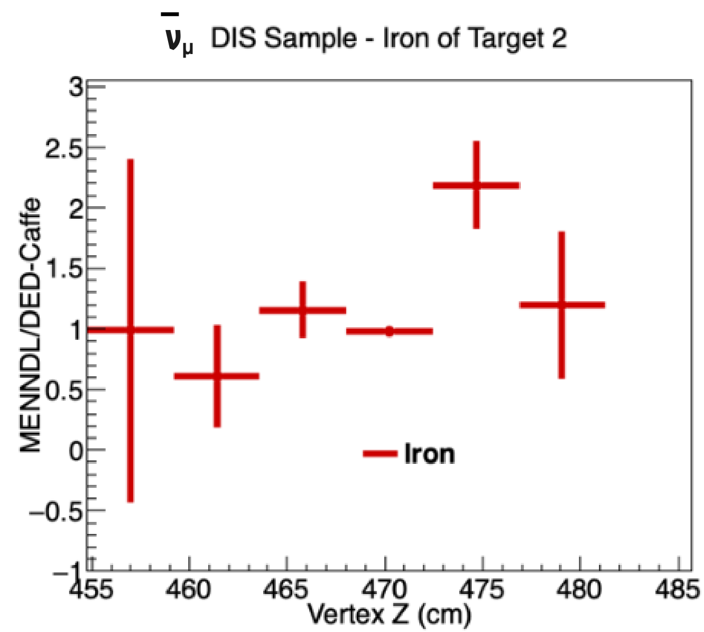
(b) MENNDL

Vertex reconstruction MENNDL vs DED-Caffe

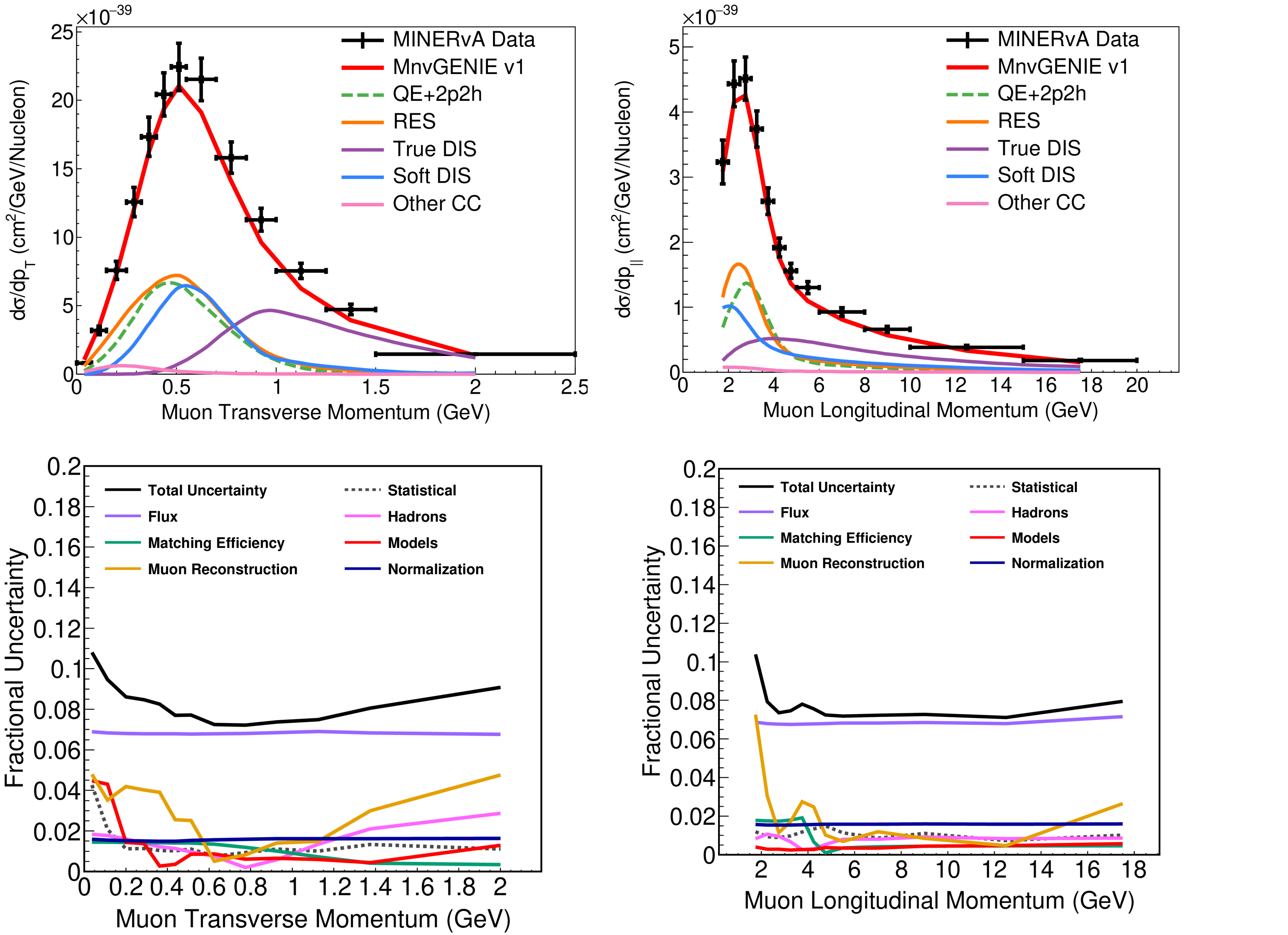




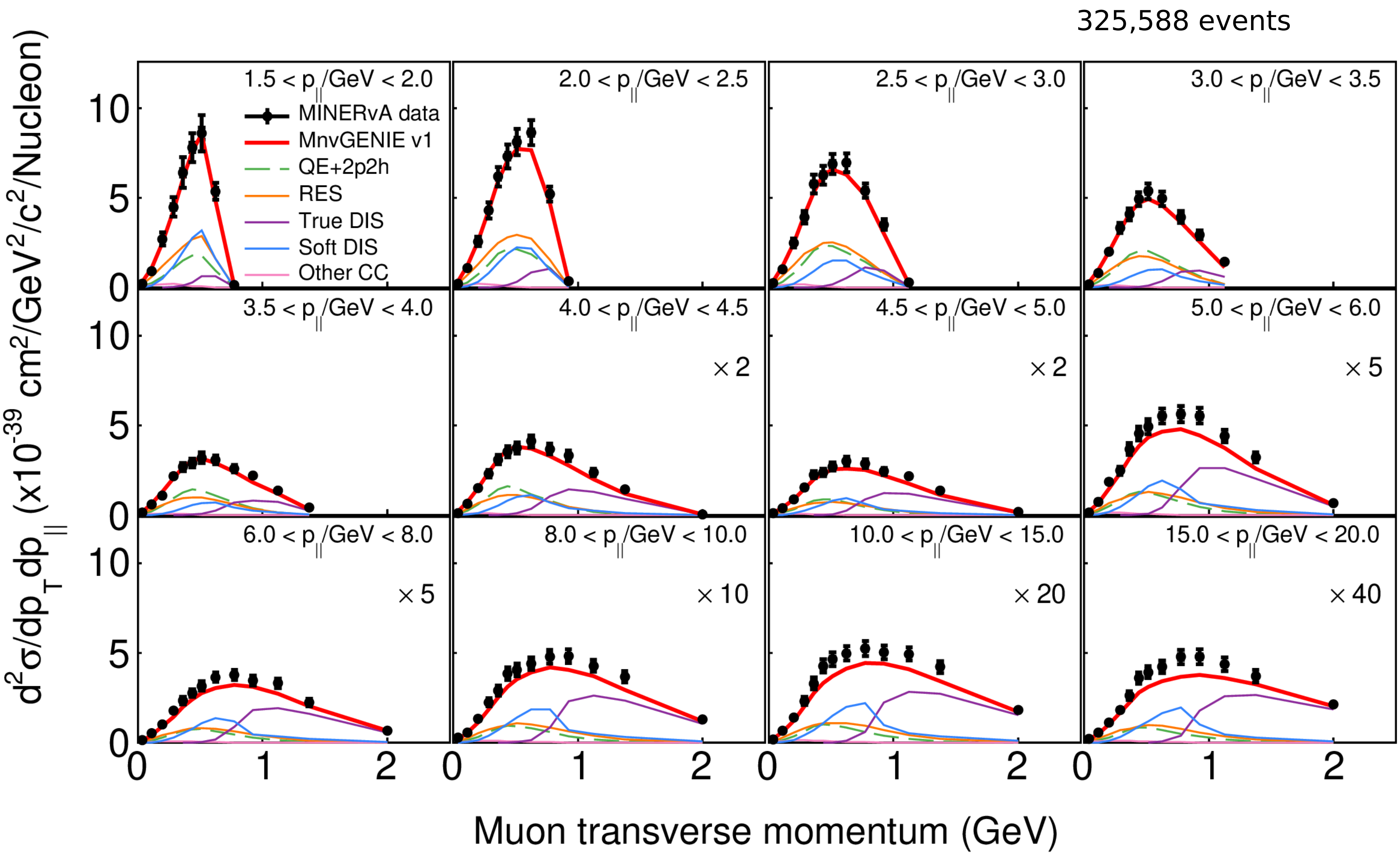




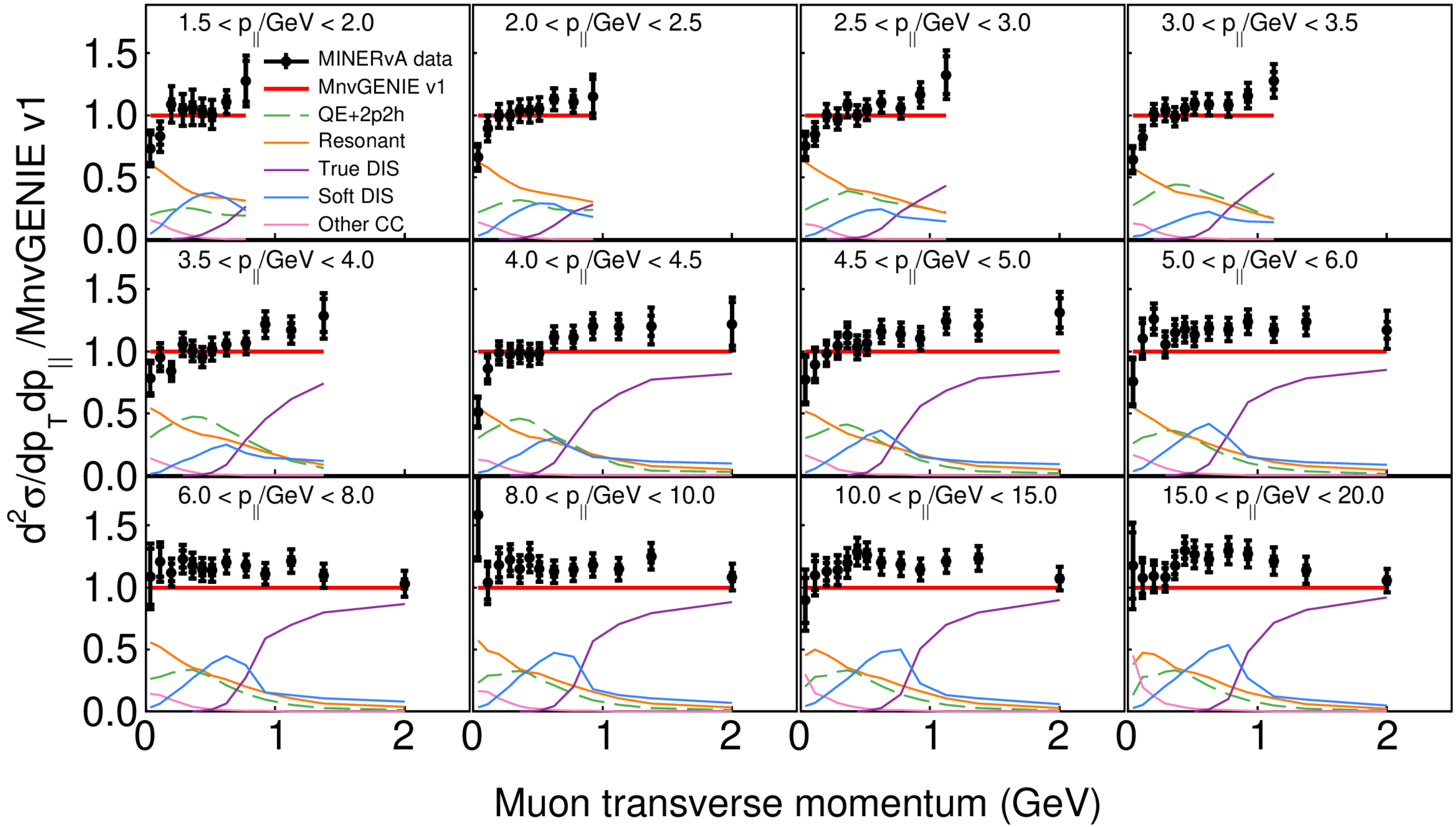
LE Single Differential Cross Sections



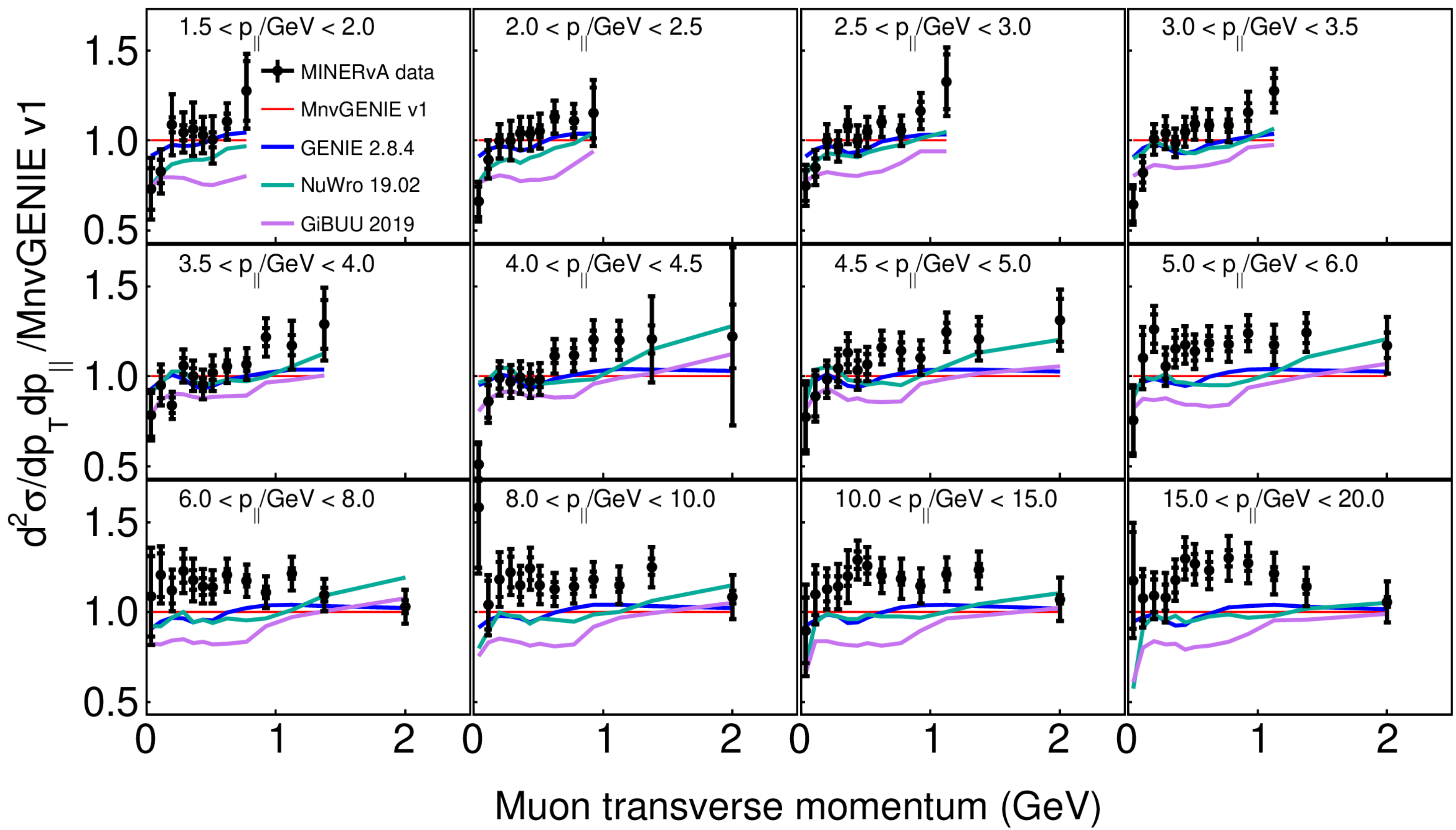
Low Energy Double Differential Cross Section



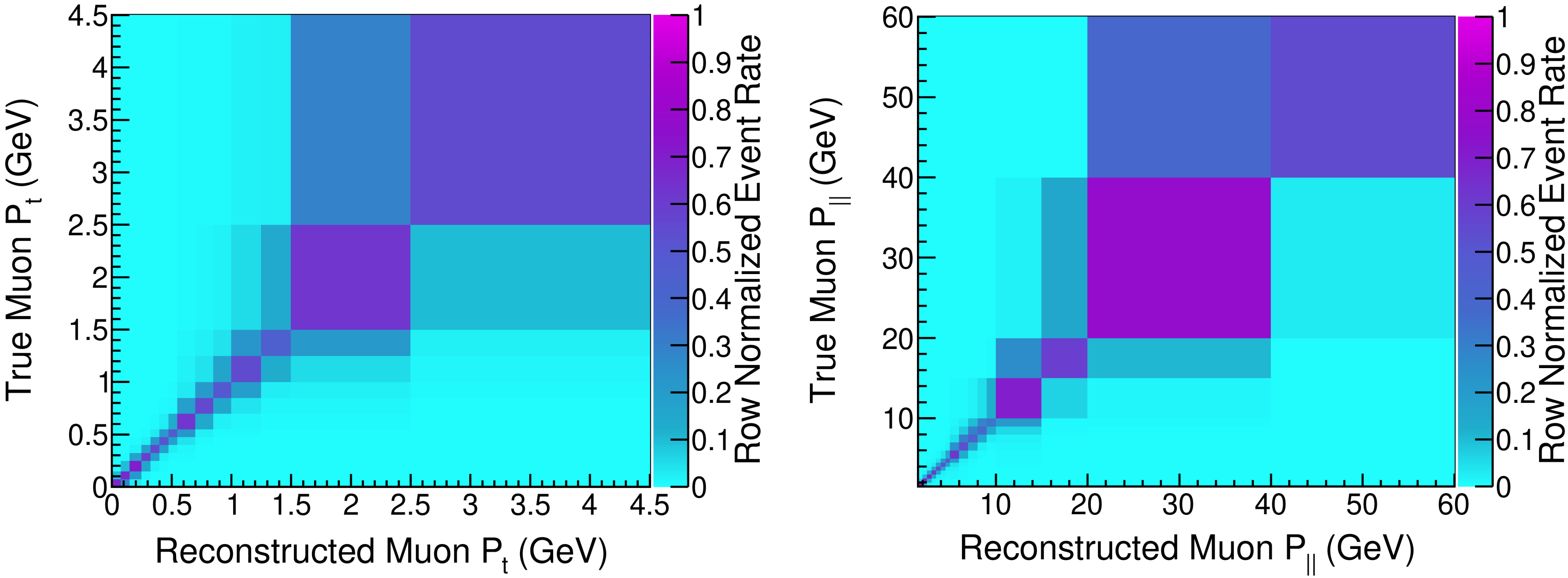
Low Energy cross section ratio



Model comparisons – Low Energy



ME Migration



- **Mostly diagonal**
- **There is more migration in the higher p_T and $p_{||}$ bins**

Analysis

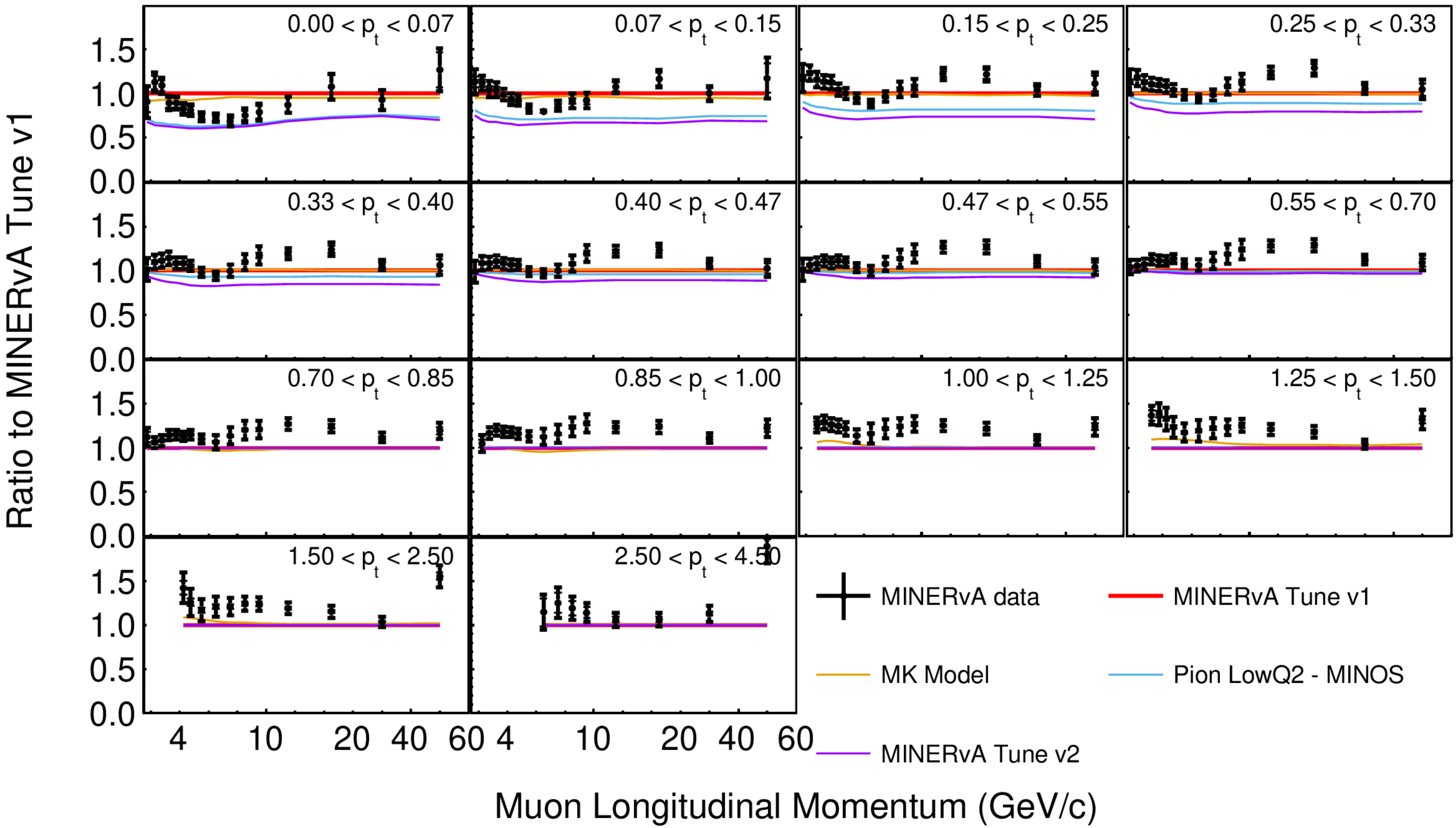
- **Signal Definition**
  - ν_μ CC
  - Muon angle less than 20 degrees with respect to beam

cos(20°)=0.94

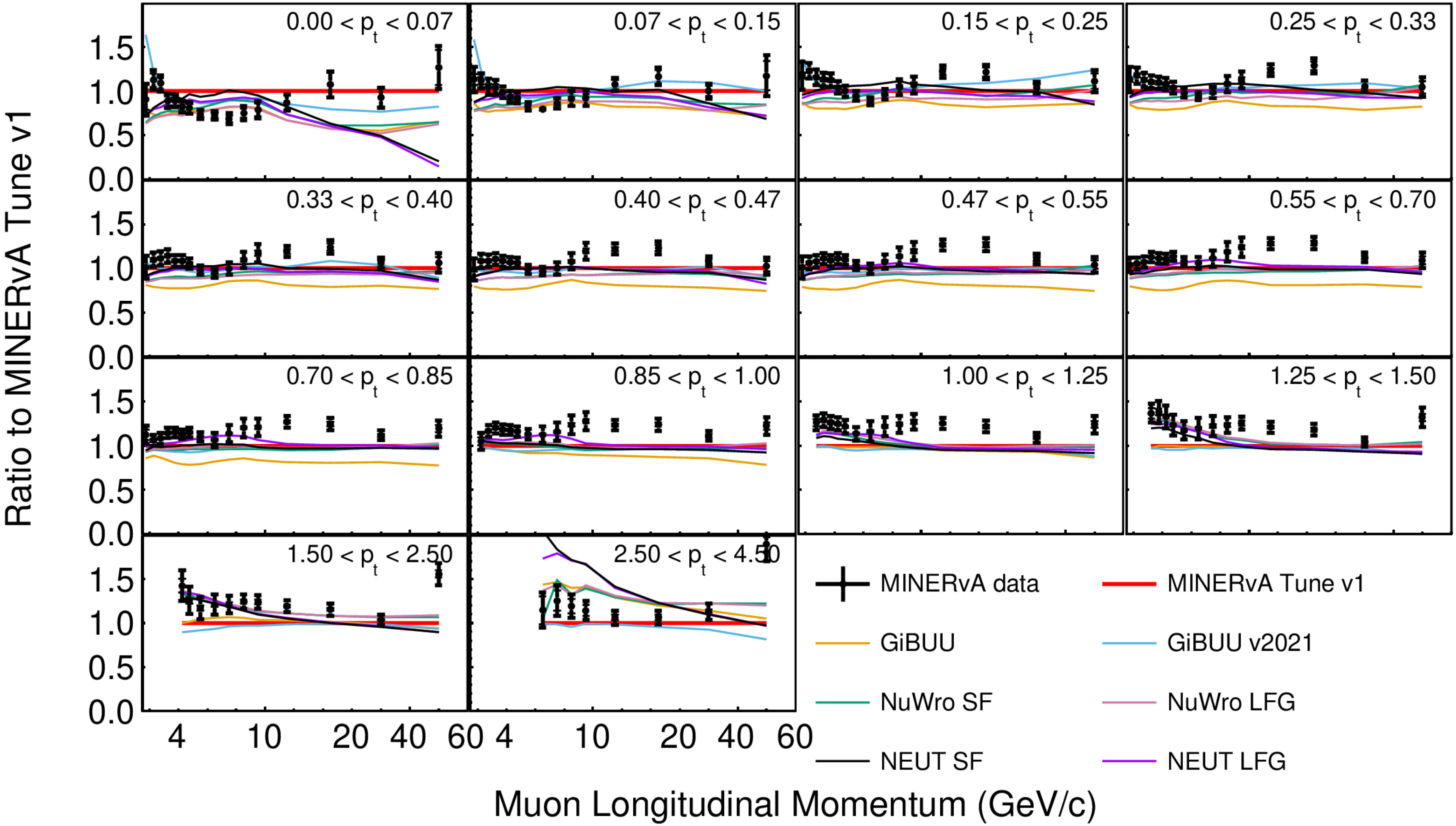
- **Event Selection:**
  - Interaction vertex in active tracking fiducial region
  - Muon track in MINERvA that matches with a track in MINOS
  - Muon angle less than 20 degrees with respect to beam
  - Passes 5 sigma charge-sign (curvature) significance

Low Q^2 Resonant Suppressions Medium Energy

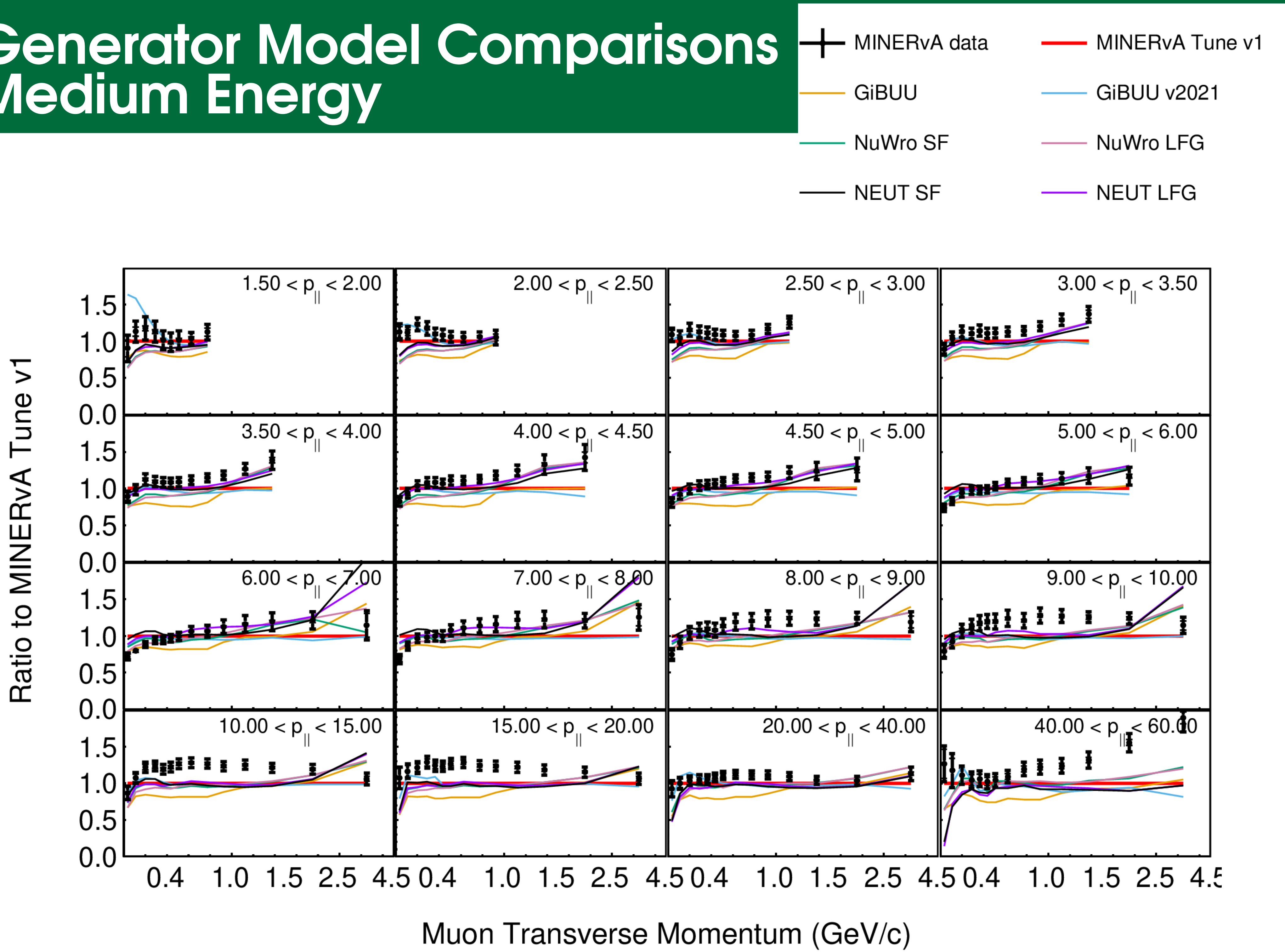
MINERvA data
MINERvA Tune v1
MK Model
Pion LowQ2 - MINOS
MINERvA Tune v2



Generator Model Comparisons – Medium Energy

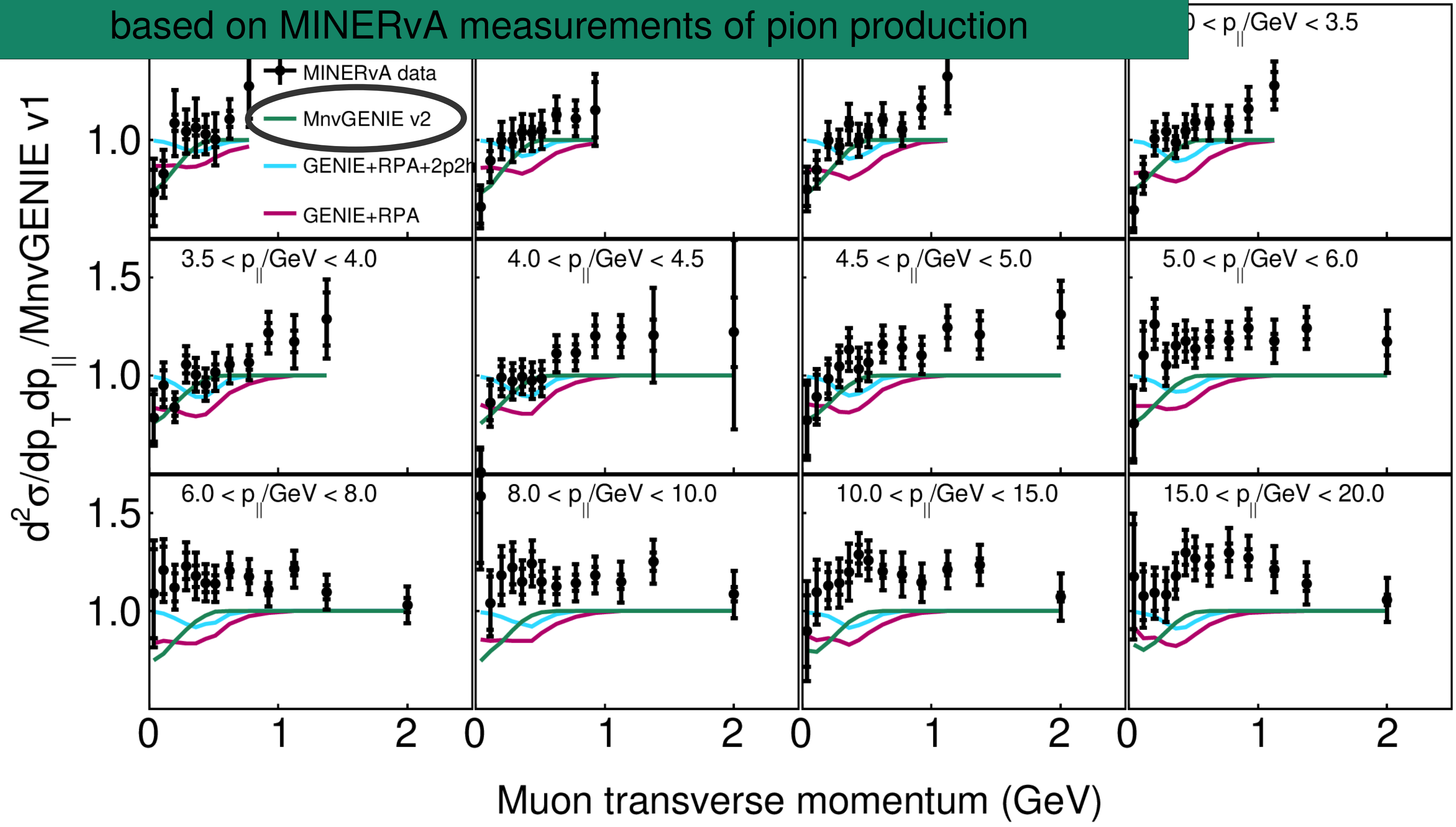


Generator Model Comparisons Medium Energy



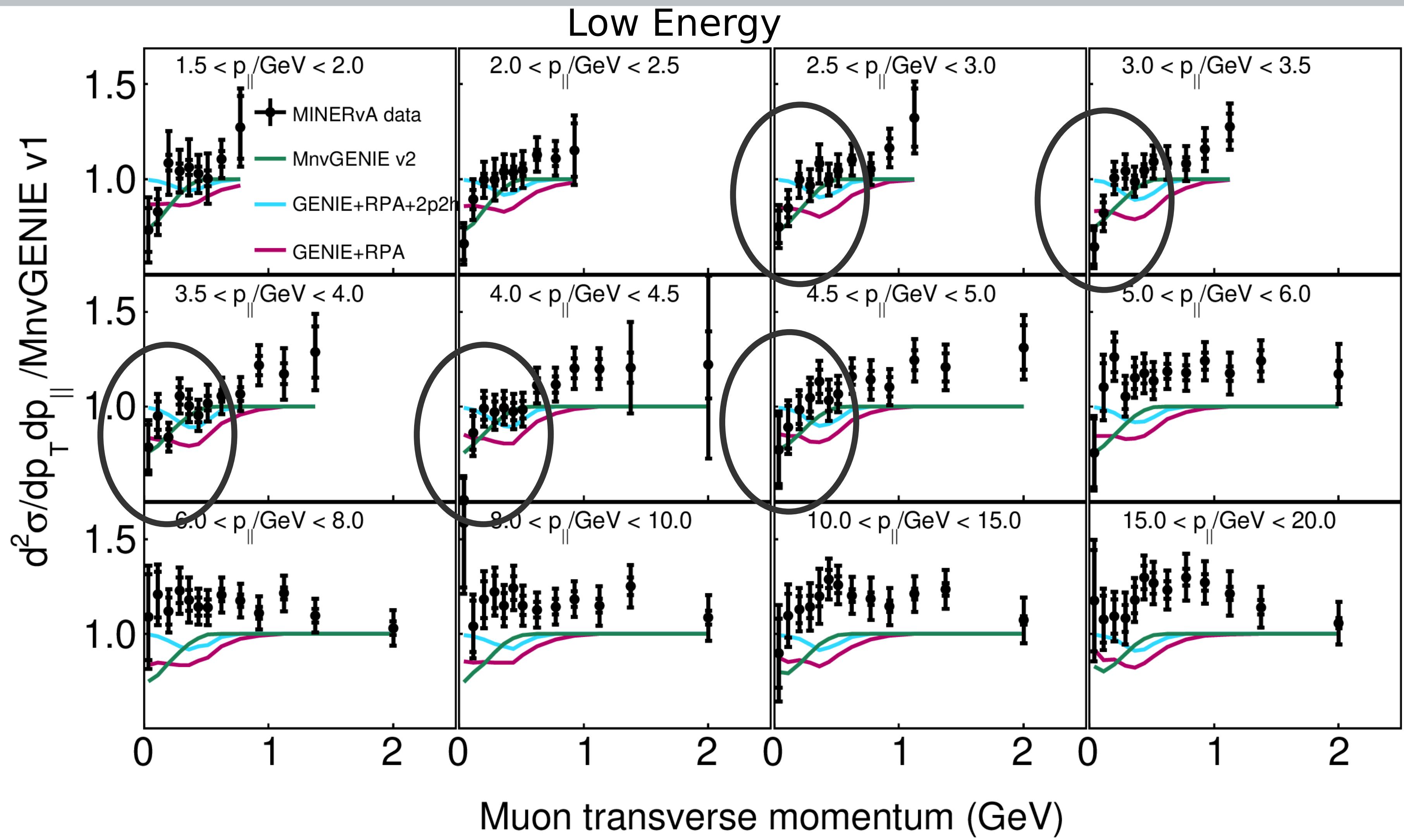
Low Q^2 Resonant Suppression – Low Energy

MnvTune v2= MnvTune v1 +ad hoc low Q^2 resonant suppression based on MINERvA measurements of pion production



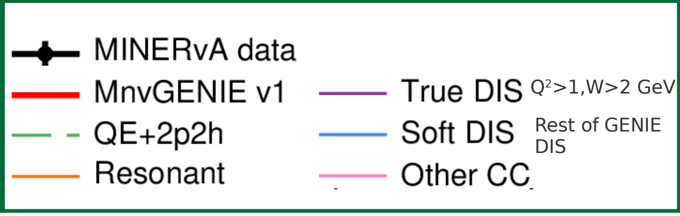
Addition of a low Q^2 resonant suppression better matches data in some regions (especially around flux peak)

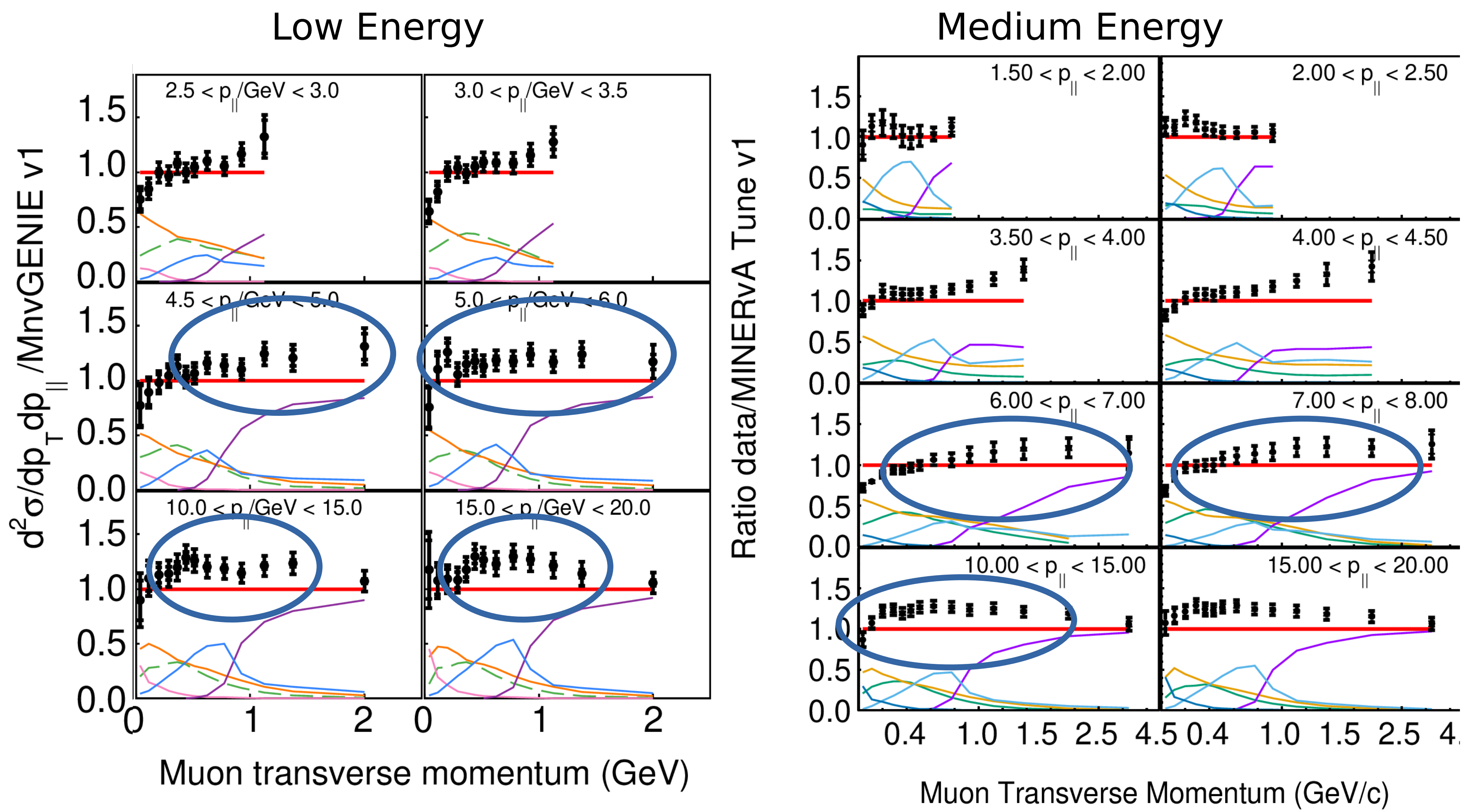
Low Q² Resonant Suppression – Low Energy



Addition of a low Q² resonant suppression better matches data in some regions (especially around flux peak)

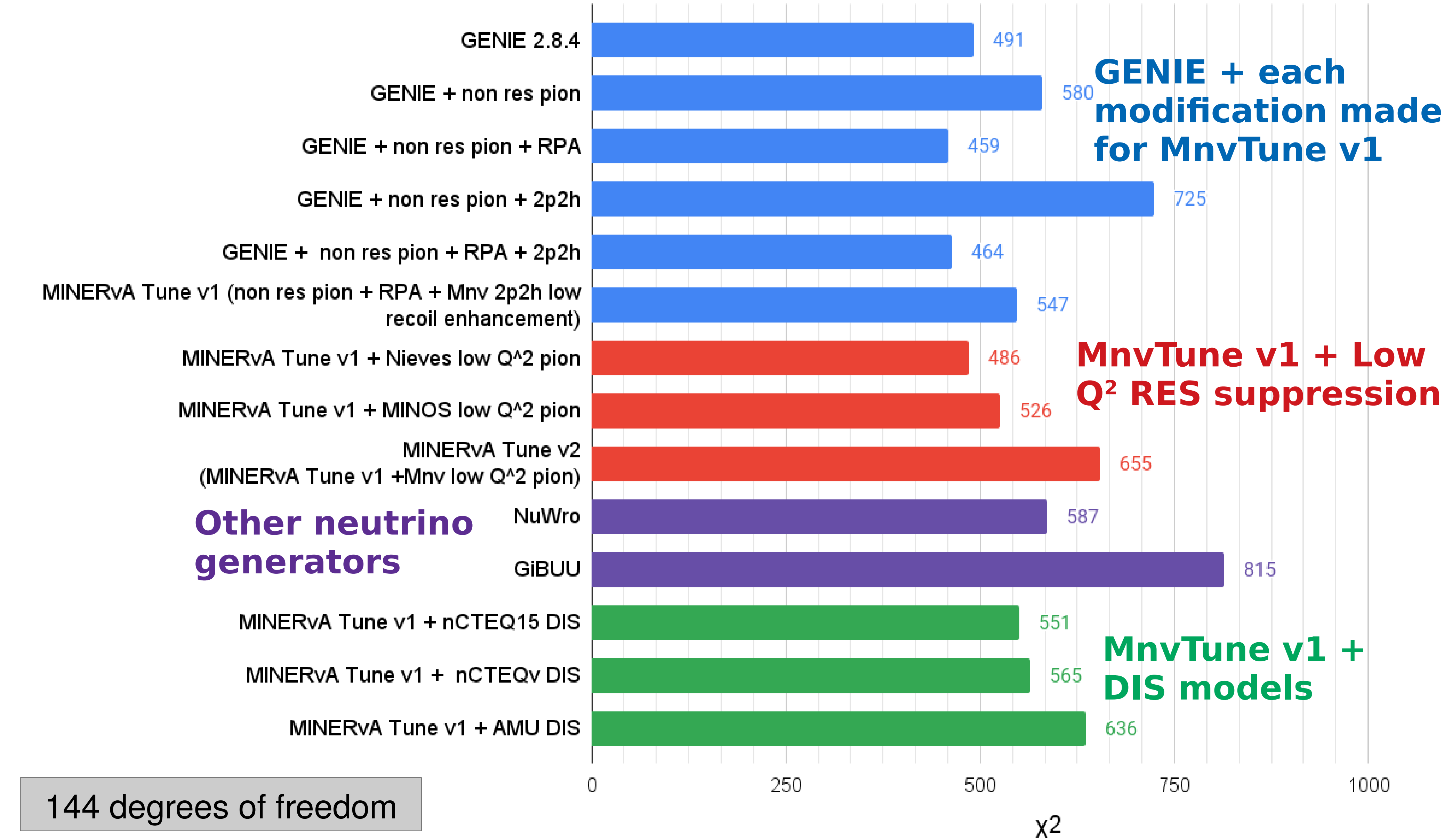
Ratios to MnvTune





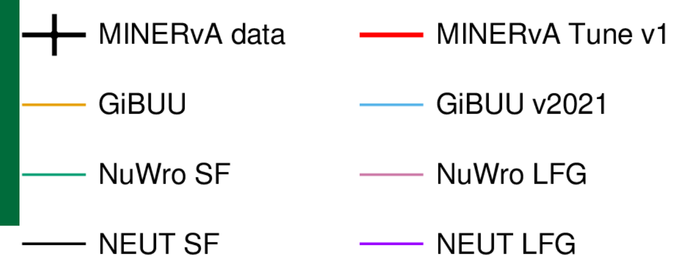
At high $p_{||}$ underpredictions

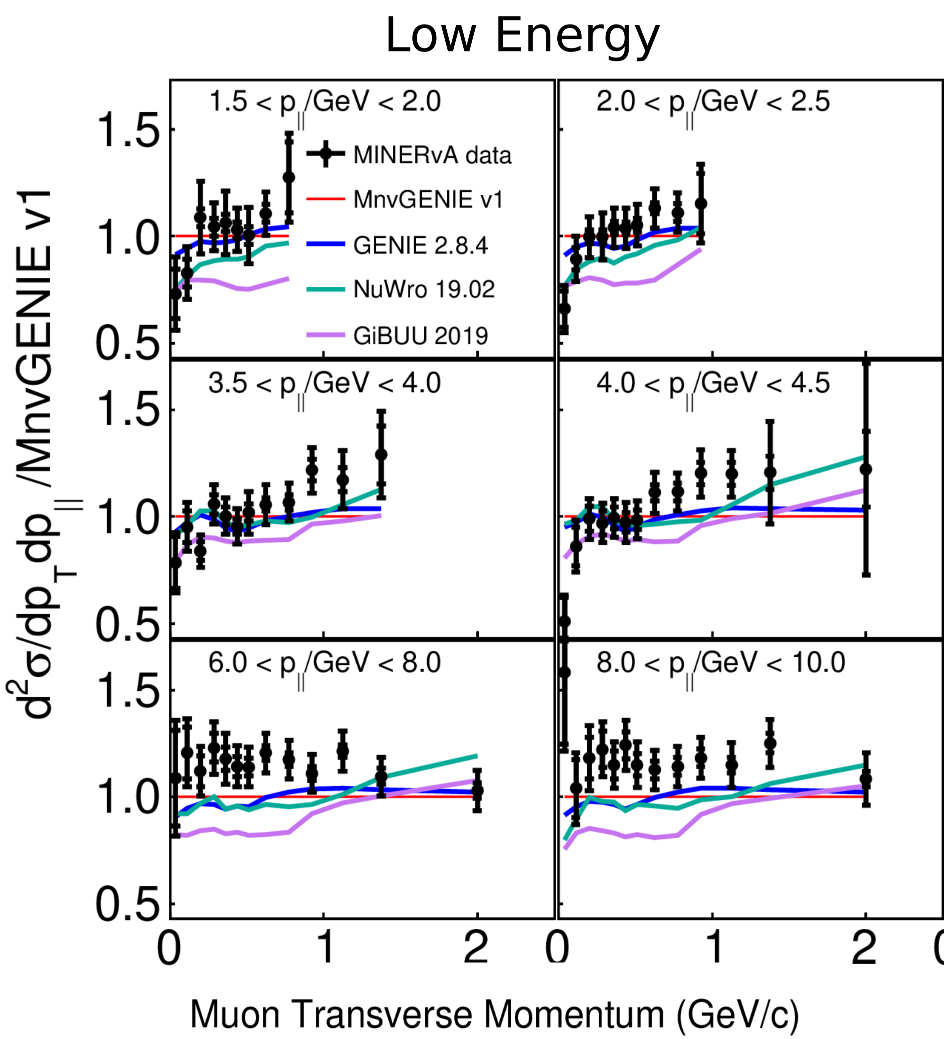
Chi2s – Low Energy

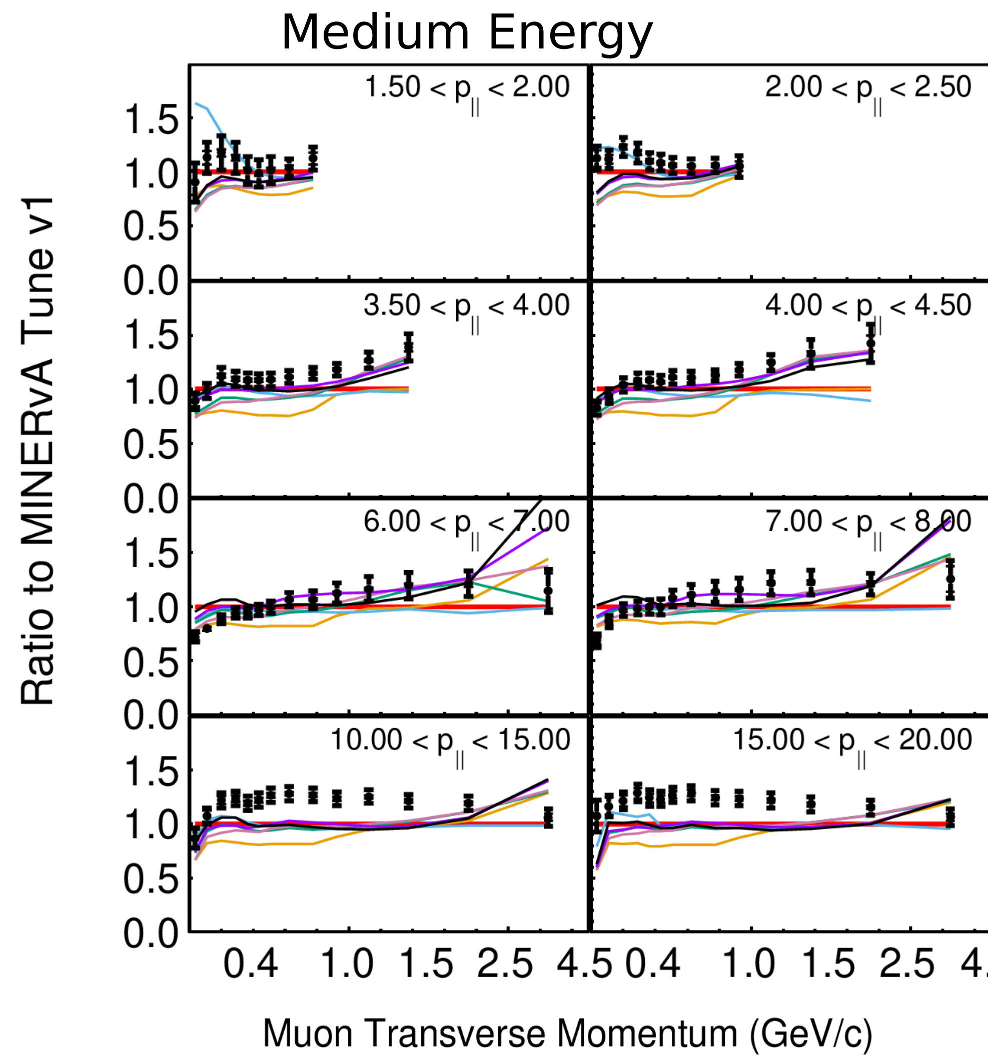


144 degrees of freedom

Model Comparisons







In comparisons to a suite of generators NuWro was among those to produce the lowest chi2 in both energies