Comparing pion production models and MiniBooNE data

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NuInt 2012

October 22

Erratum

- A bug in my plotting macros caused GENIE differential cross sections to be too high by an overall scale factor (shapes were correct). The factor is different for each sample. The bug affected the version of the talk given at NuInt12, but is fixed in this version of the document. Other generators/models are unaffected.

Outline

- Single-pion production
- Models
- MiniBooNE datasets
- Comparisons

Single-pion production

- Experimentally, three different channels: CC1π^+, CC1π^0, NC1π^0
  - Choice of definition (see later)
- Theoretically: same resonance model

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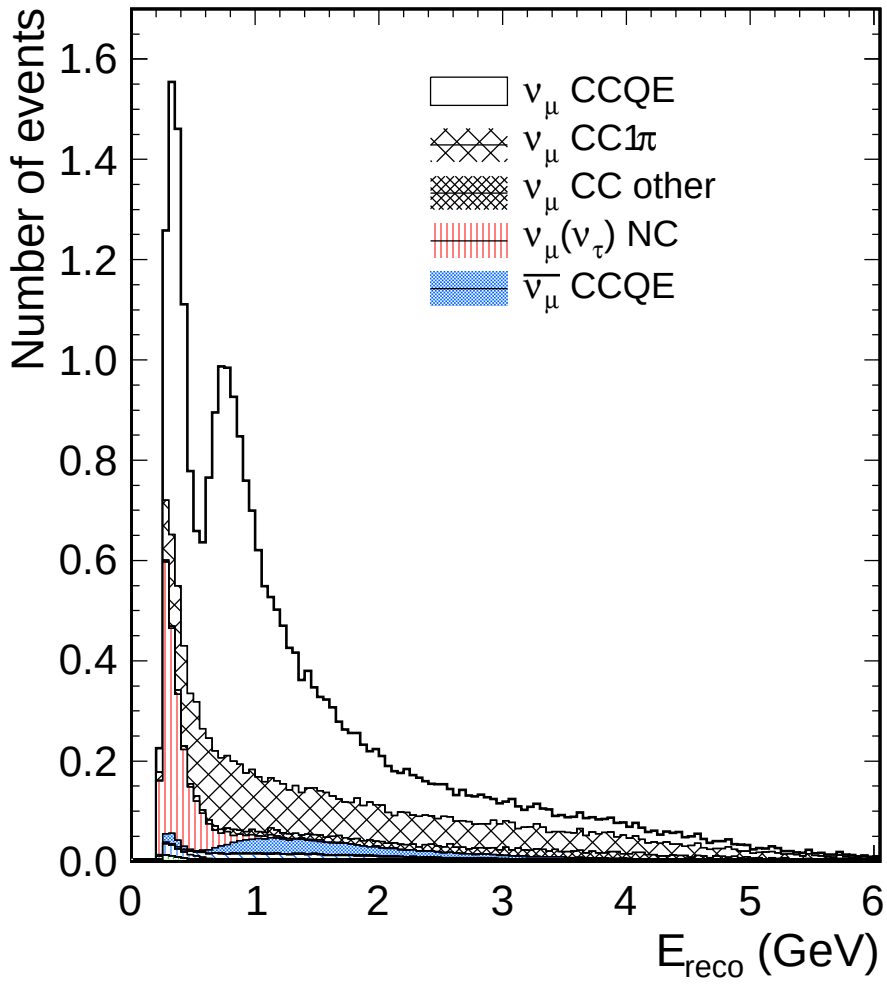
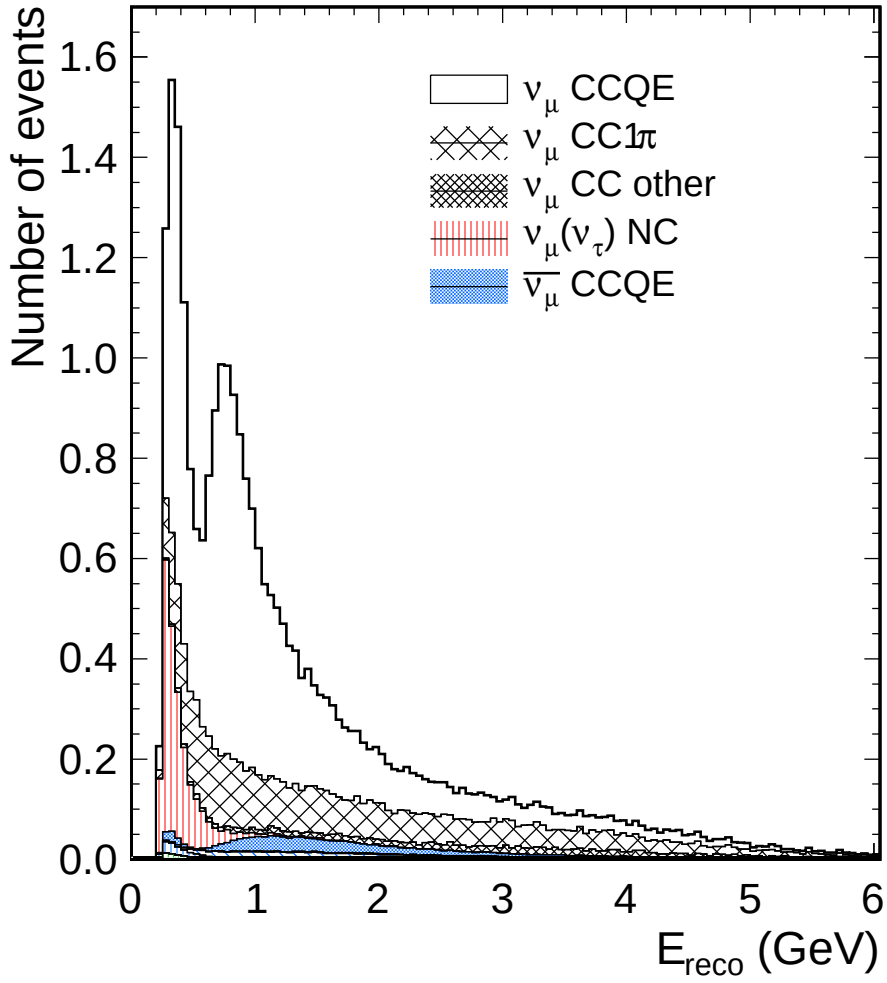
- Theoretically: same resonance model
- As backgrounds to oscillations:
  - NC1π^0 background to ν_e
  - CC1π^+ background to CCQE



T2K SK selected ν_μ CCQE after oscillations. Energy reconstructed from CCQE hypothesis

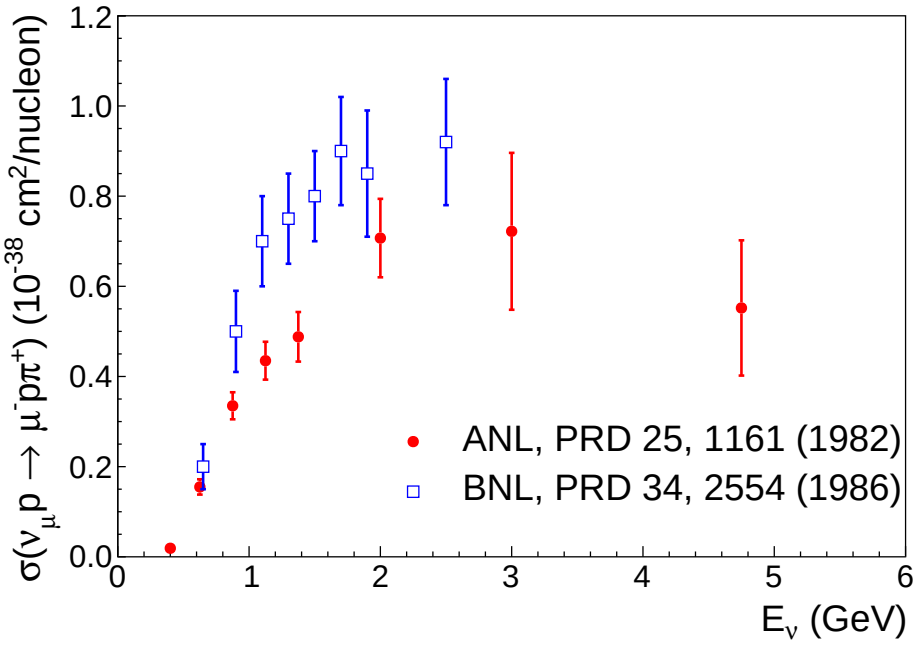
Single-pion production

- Experimentally, three different channels: CC1π^+, CC1π^0, NC1π^0
  - Choice of definition (see later)
- Theoretically: same resonance model
- As backgrounds to oscillations:
  - NC1π^0 background to ν_e
  - CC1π^+ background to CCQE
- In their own right:
  - Size of nonresonant contributions
  - Final state effects
  - Multi-nucleon effects?



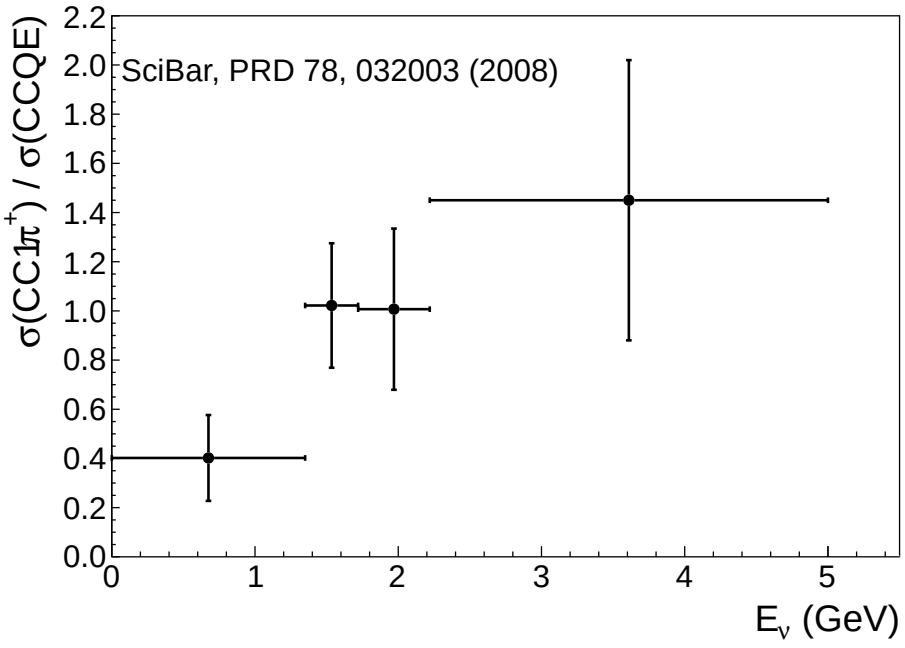
T2K SK selected ν_μ CCQE after oscillations. Energy reconstructed from CCQE hypothesis

Previous single-pion datasets



- Limited absolute cross section measurements in few GeV region
  - ANL and BNL on deuterium – significant disagreement

Previous single-pion datasets



- Limited absolute cross section measurements in few GeV region
  - ANL and BNL on deuterium – significant disagreement
- More recently, measurements from K2K, SciBooNE

PRD 77, 032003 (2008); PRD 81, 033004 (2010); PLB 619, 255 (2005); PRD 83, 054023 (2011)

  - Given as ratios to CCQE or shape-only

Models

- Not a comprehensive set, but hopefully a "representative" sample
- Theoretical models and full MC generators
- Many, many variables, tunings and other choices
- Thanks to M. Athar, S. Chauhan, S. Dytman, H. Gallagher, T. Golan, Y. Hayato, E. Hernandez, O. Lalakulich, U. Mosel, J. Nieves, J. Sobczyk, M. Vicente

Theoretical models

Nieves *et al* Includes 2p2h contributions. Integrates over muon variables.

PRC 83, 045501 (2011)

Athar *et al* Delta dominance model. Nuclear effects from local density approximation.

Eur. J. Phys. A 43, 201 (2010). J. Phys. G 37, 015005 (2010)

GiBUU Detailed final state model via the BUU equation. Includes multiple resonances

Phys. Rept 512 1-124 (2012)

Generators

GENIE 2.6.2 Rein-Sehgal model for $W < 1.7$ GeV. RFG for nuclear effects.

NIM A 614, 87 (2010)

NEUT 5.1.4.2 Rein-Sehgal for $W < 2$ GeV. RFG for nuclear effects.

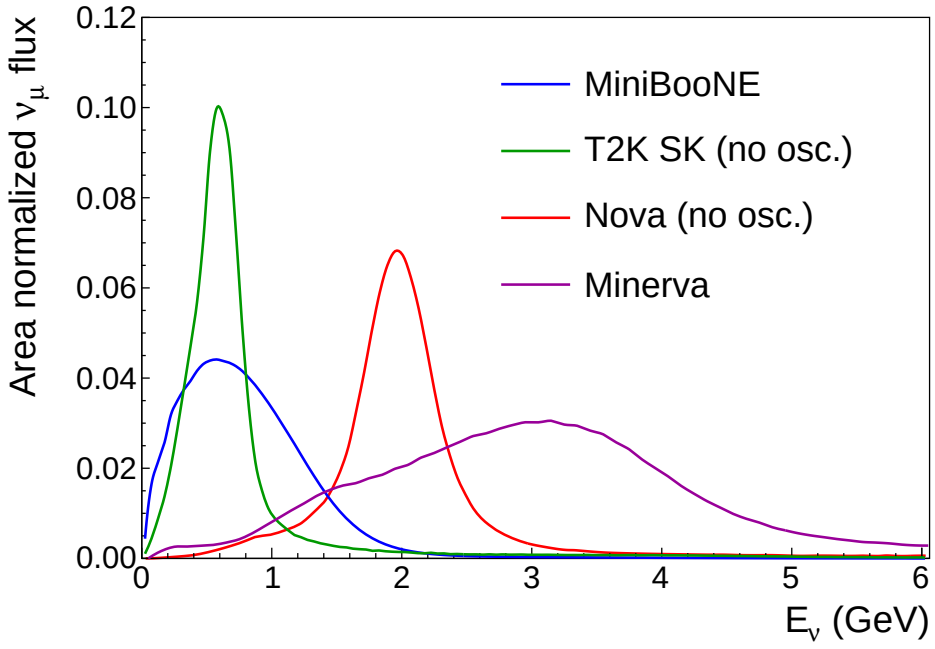
Acta Phys. Polon. B 40, 2477 (2009)

NuWro Only Δ resonance included explicitly. SF for nuclear effects

Proc. NuFact08 141

- All use (different) cascade models for final state effects

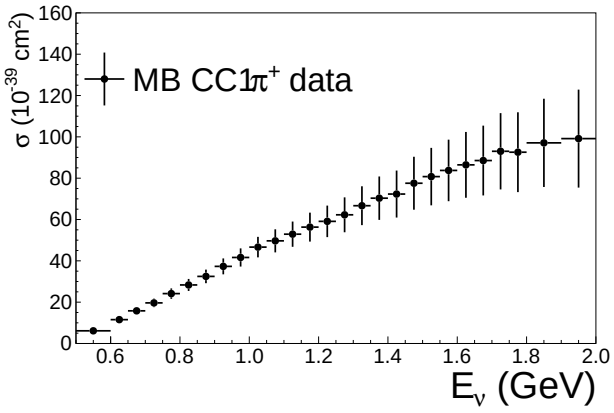
MiniBooNE

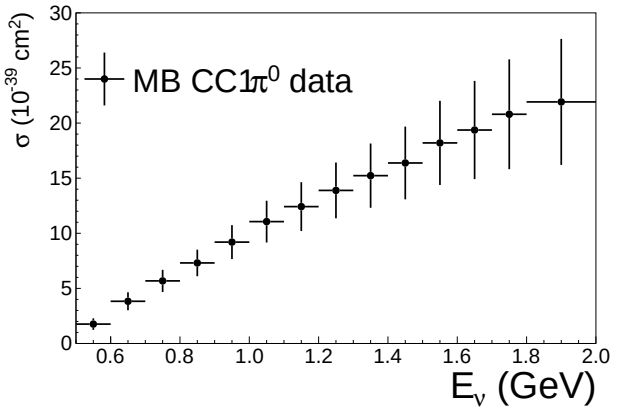


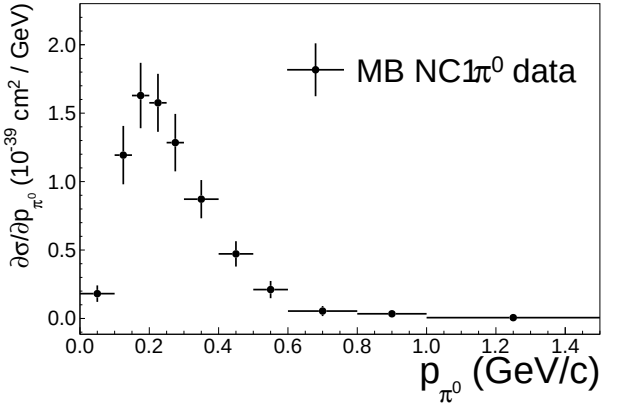
- BNB ν_μ flux peaks at $E_\nu \approx 0.6$ GeV
- Target material CH_2
- Čerenkov detector

  $\Rightarrow$ Nucleons not observed

MiniBooNE datasets





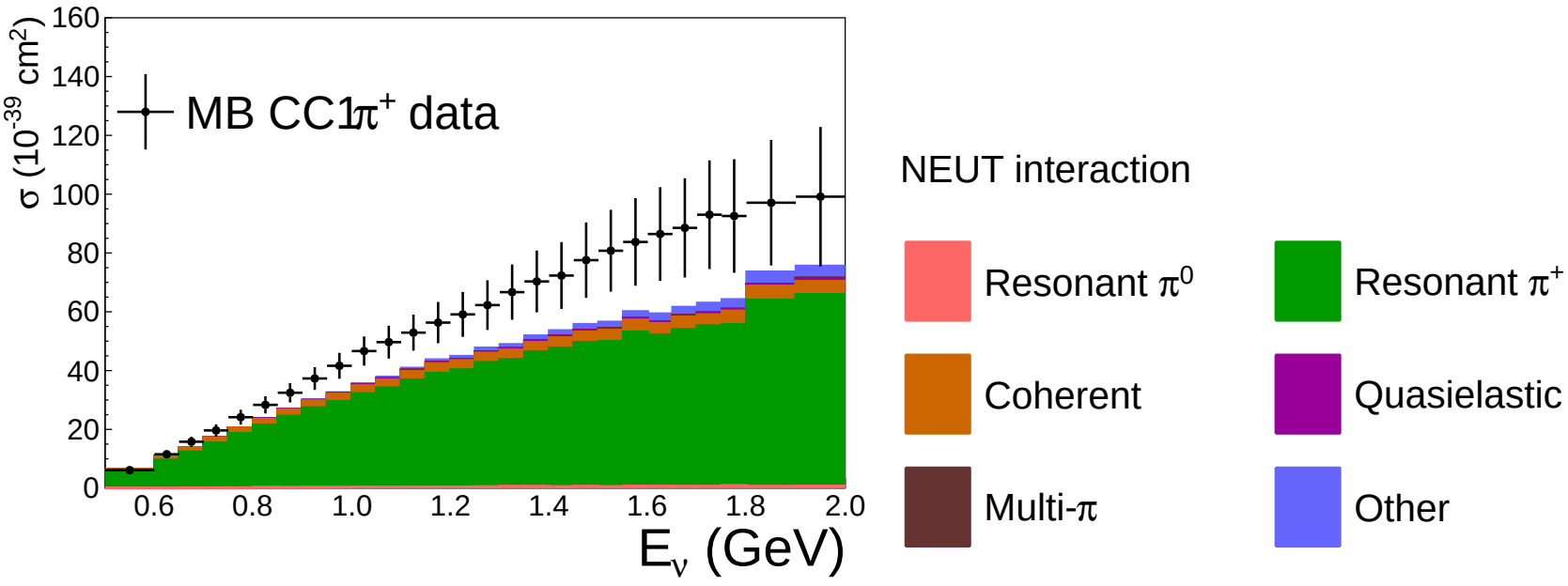


- Datasets defined by particles exiting the nucleus
  - Nucleon-level $\sigma \otimes$ Nuclear eff $\otimes$ FSI
- High statistics, model-independent, absolute cross sections
- Data released, with flux, and some correlation matrices

MiniBooNE dataset limitations

- In principle: joint fit to tune resonance production in model/generator
- But...
  - CC1π^+ covariance matrices are not given
  - Correlations between datasets are not given (eg from flux, det. systs)
  - Even covariance matrix alone can be insufficient information

MiniBooNE CC1π^+

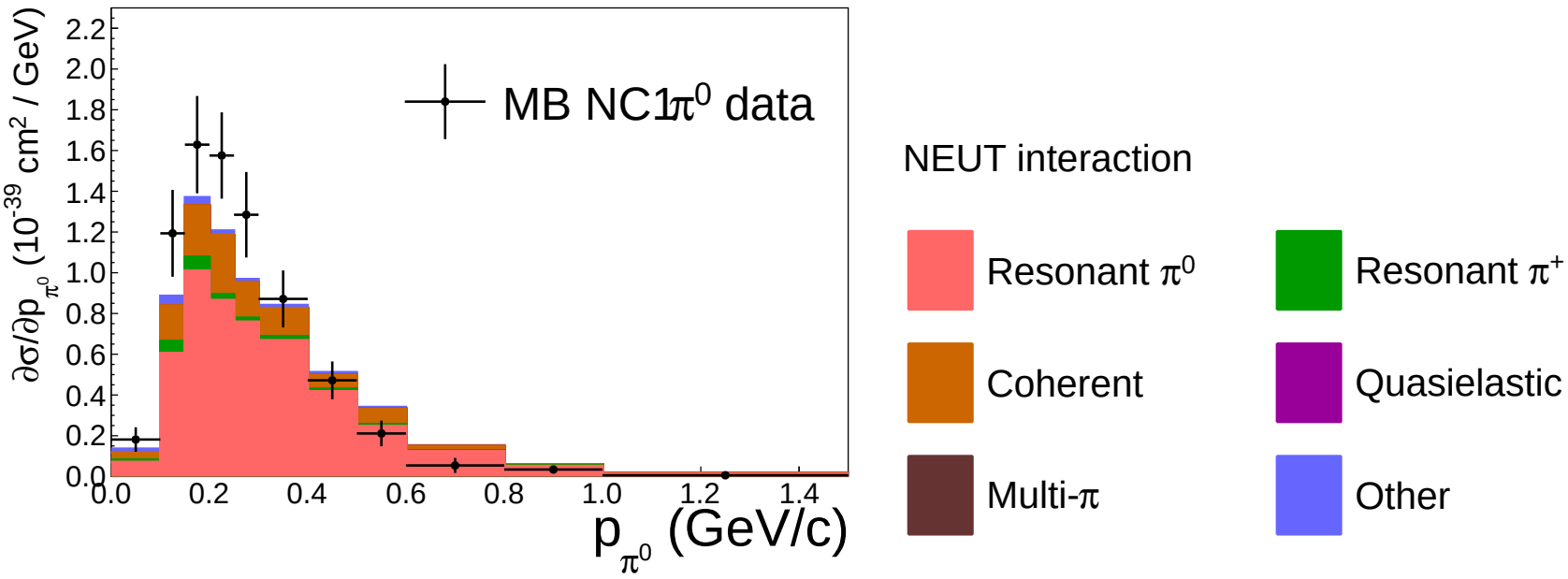


FS particles $1\ \mu^-$, $1\ \pi^+$
No other mesons, but any nucleons

Nucleon-level Resonant π^+, coherent π^+

Distributions $\sigma(E_\nu)$, Q^2, T_μ, T_π, +2D distributions

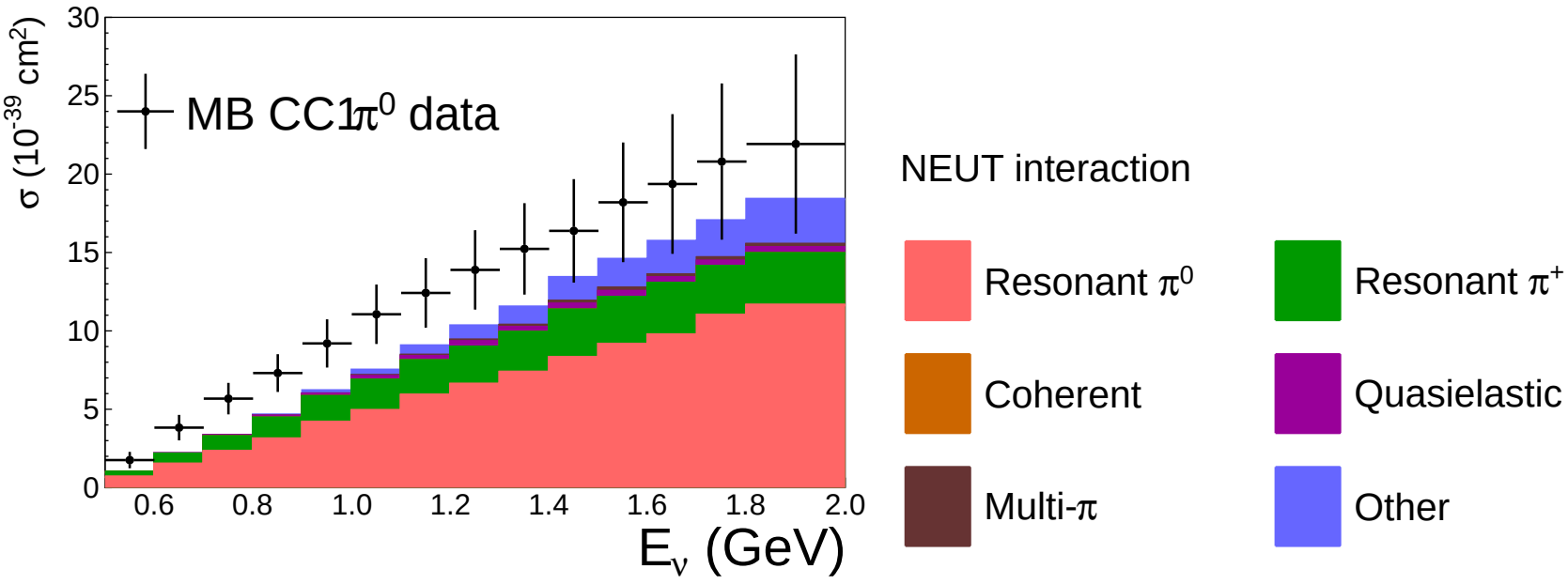
MiniBooNE NC1π^0



FS particles	0 μ, 1 π^0
	No other mesons, but any nucleons
Nucleon-level	Resonant π^0, coherent π^0
Distributions	p_π, $\cos\theta_\pi$

- (Also $\bar{\nu}$, not considered here)

MiniBooNE CC1π^0



FS particles $1\ \mu^-$, $1\ \pi^0$

No other mesons, but any nucleons

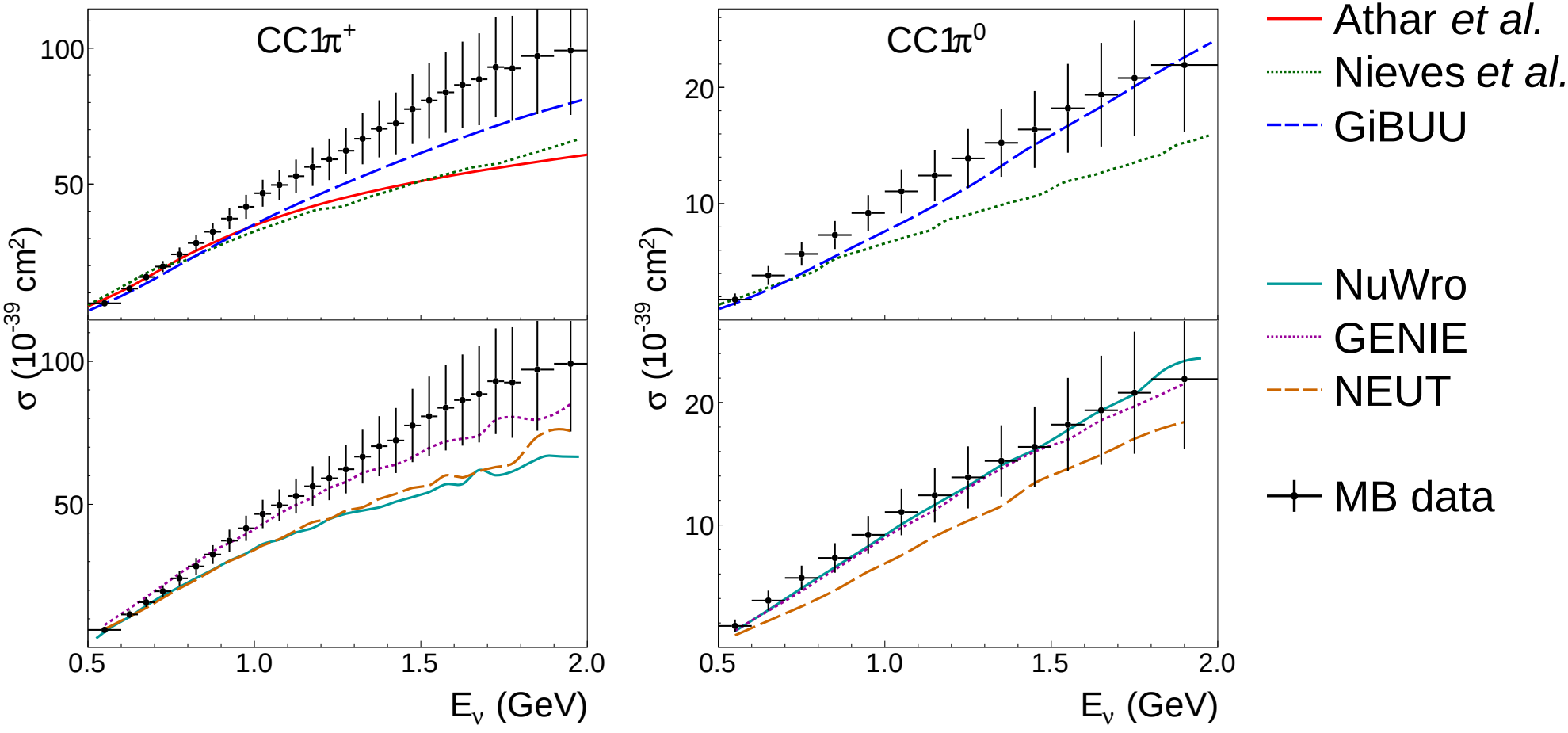
Nucleon-level Resonant π^0, res. $\pi^+ \longrightarrow \pi^0$

Distributions $\sigma(E_\nu)$, Q^2, T_μ, $\cos\theta_\mu$, p_π, $\cos\theta_\pi$

- Flux-averaged over $0.5 < E_\nu/\text{GeV} < 2.0$

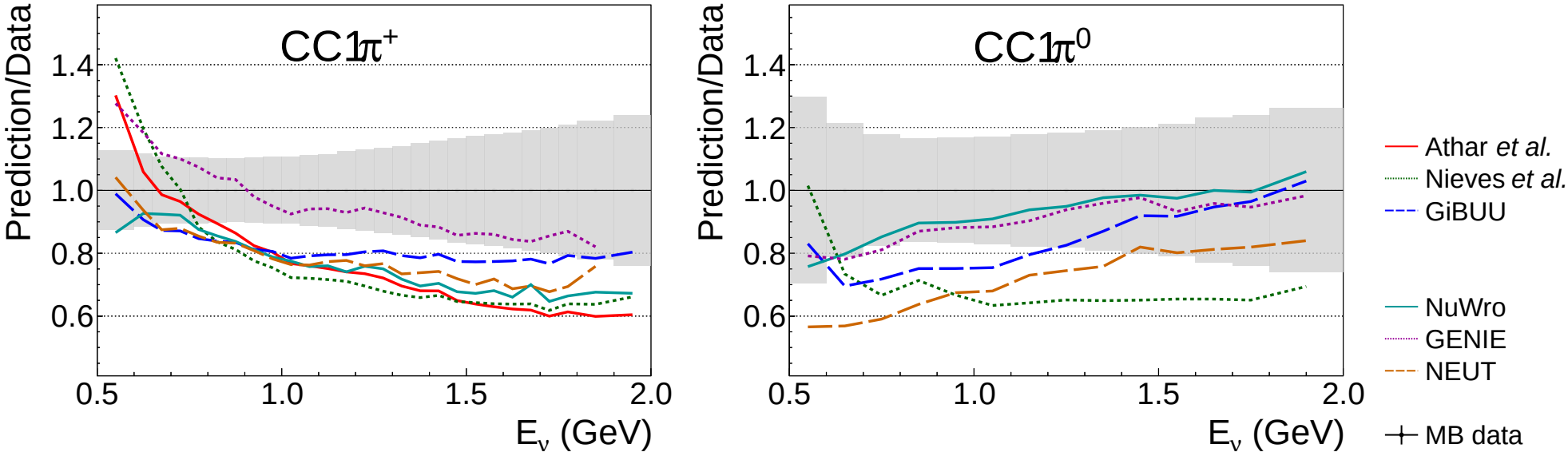
Comparisons

Total cross sections



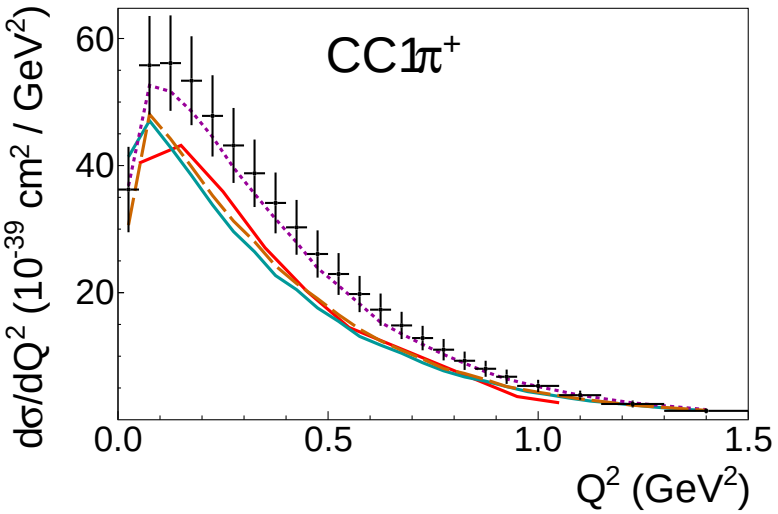
- Disagreements in normalization and shape
- Agreement in CC1π^+ $\not\Leftrightarrow$ Agreement in CC1π^0

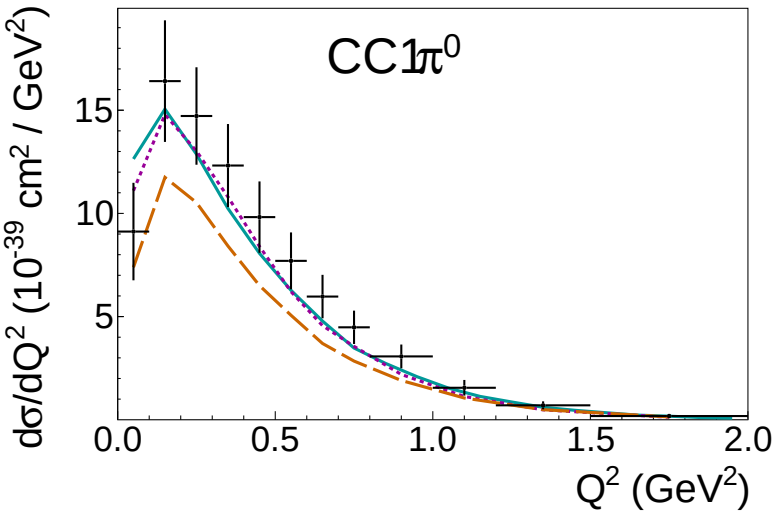
A feature in ratios

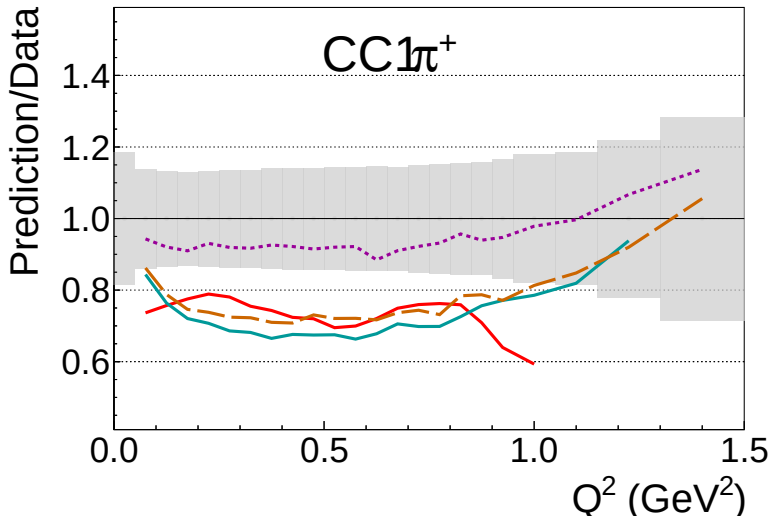


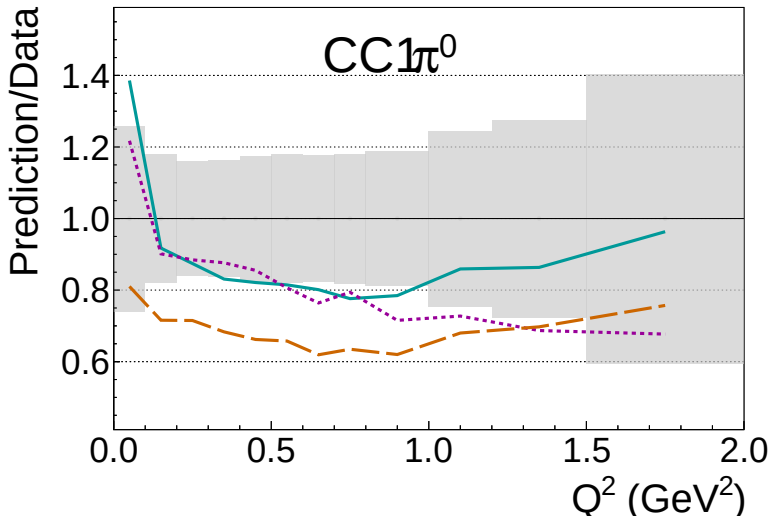
- CC1π^+: Shape difference between model and data is common to all models
- CC1π^0: Similar shape commonality, but in opposite direction
- Can't *just* be the flux
  - "Glass half full:" taking datasets together provides more information
  - "Glass half empty:" simultaneous agreement difficult/impossible

$d\sigma/dQ^2$









Athar *et al.*
Nieves *et al.*
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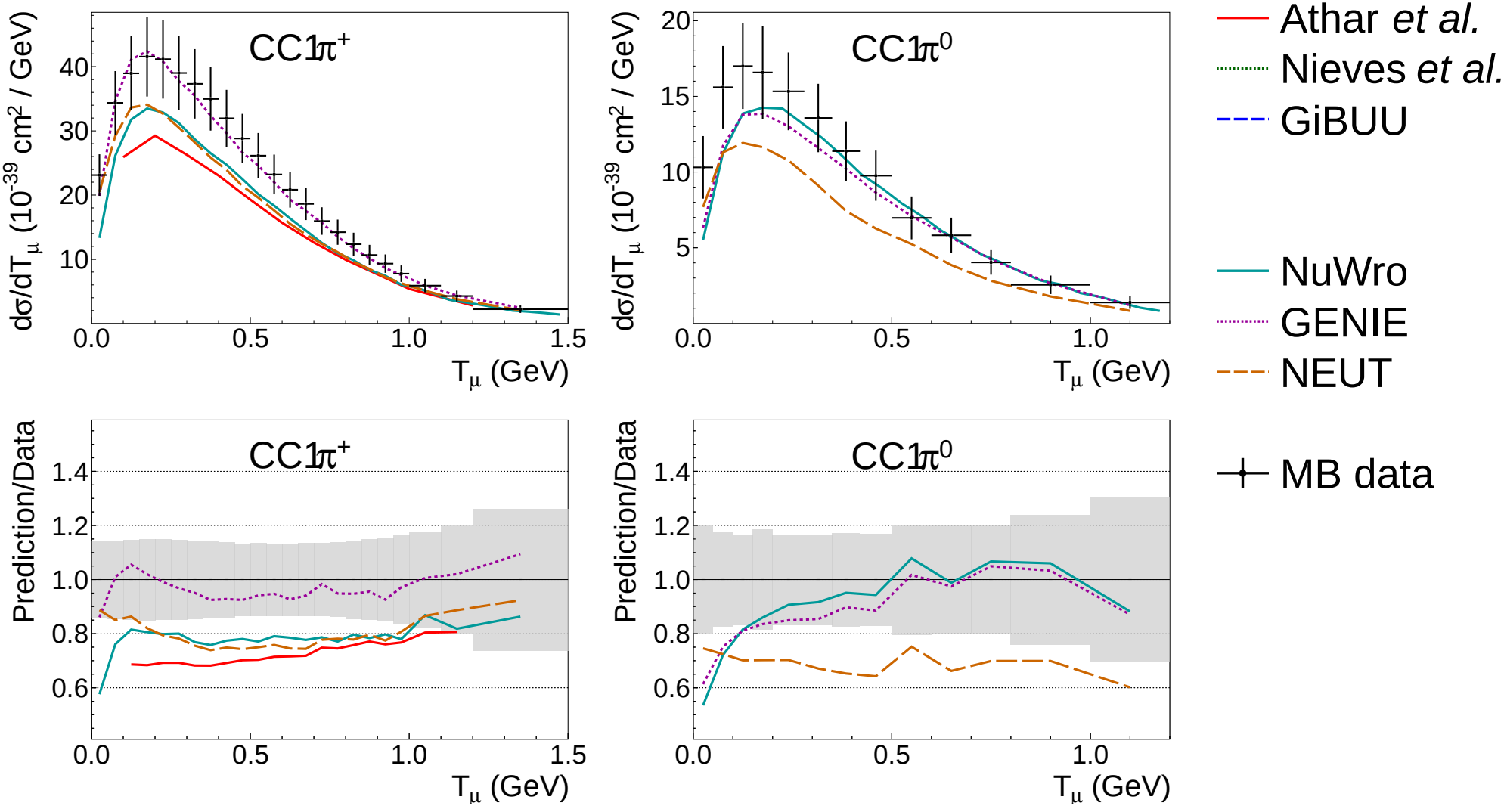
MB data

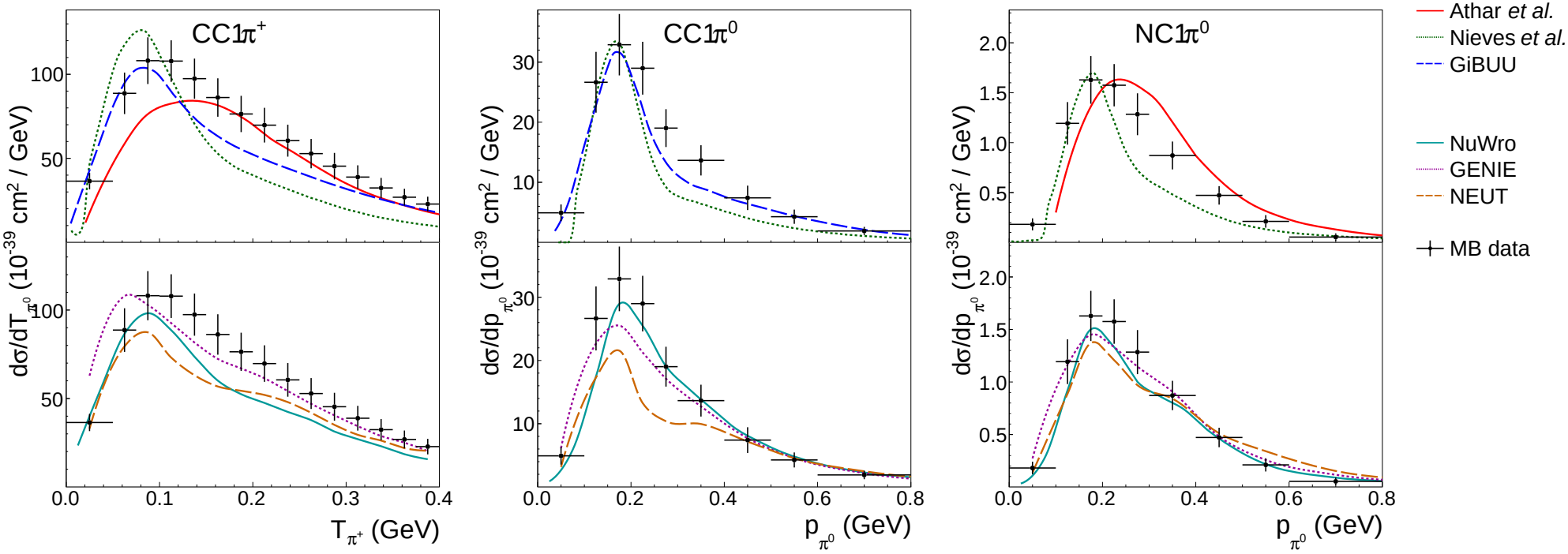
- Some shape difference commonalities

Muon kinetic energy



- Additional discrepancy cf $Q^2 \Rightarrow \cos\theta_\mu$ disagreement

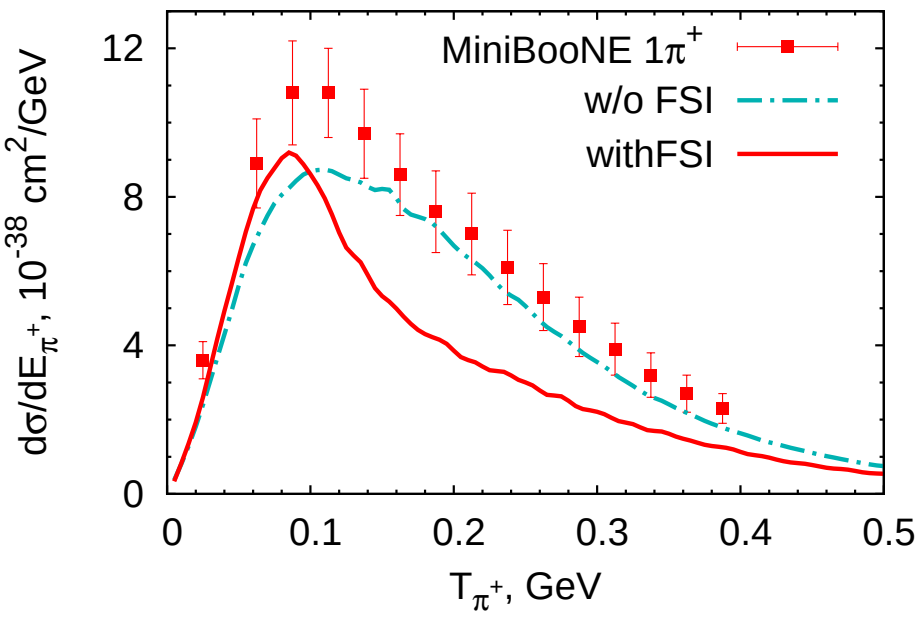
Pion momentum/energy



- Poor agreement across the board in CC1π^+
- Generators do better than theoretical models in CC1π^0, NC1π^0

Final state effects

GiBUU



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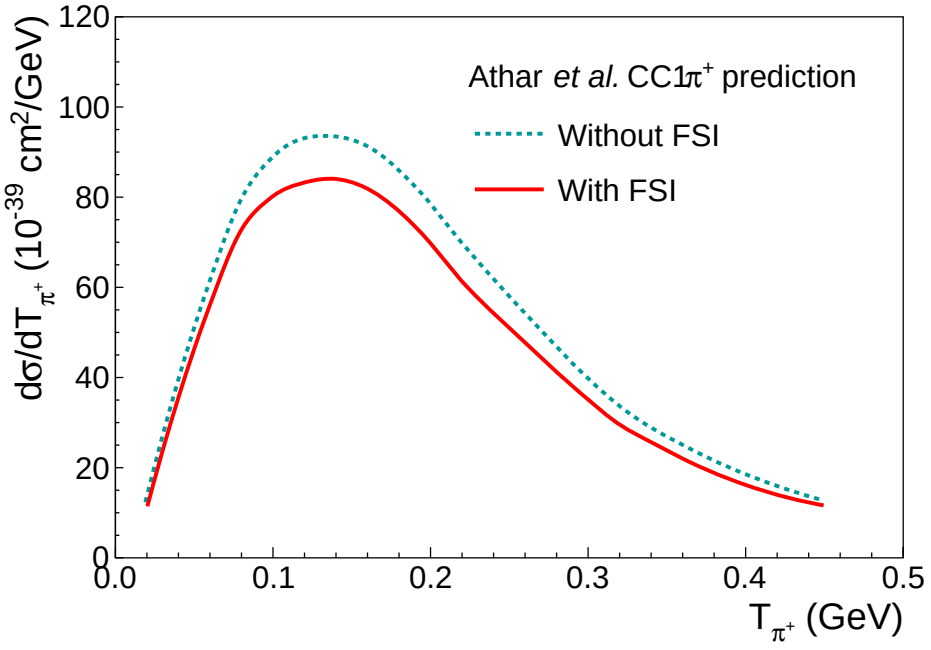
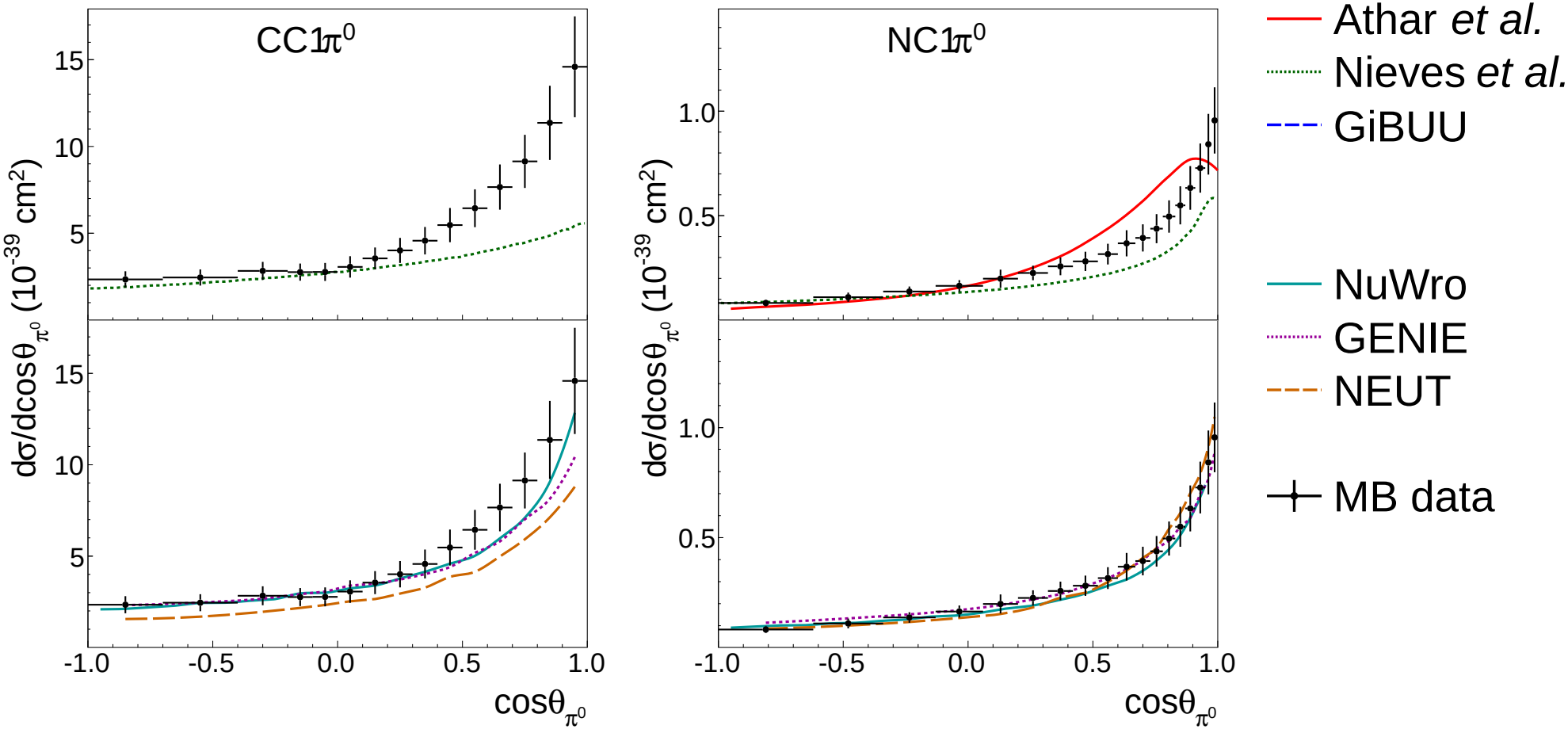


Plot from arXiv:1107.5947 (NuInt11 proceedings)

- Significant, but uncertain, effect
- Shape and normalization

Pion angle



- CC1π^0 pion angle more forward-peaked in data than most models
- NC1π^0 better described by generators (tuning?)

Conclusions

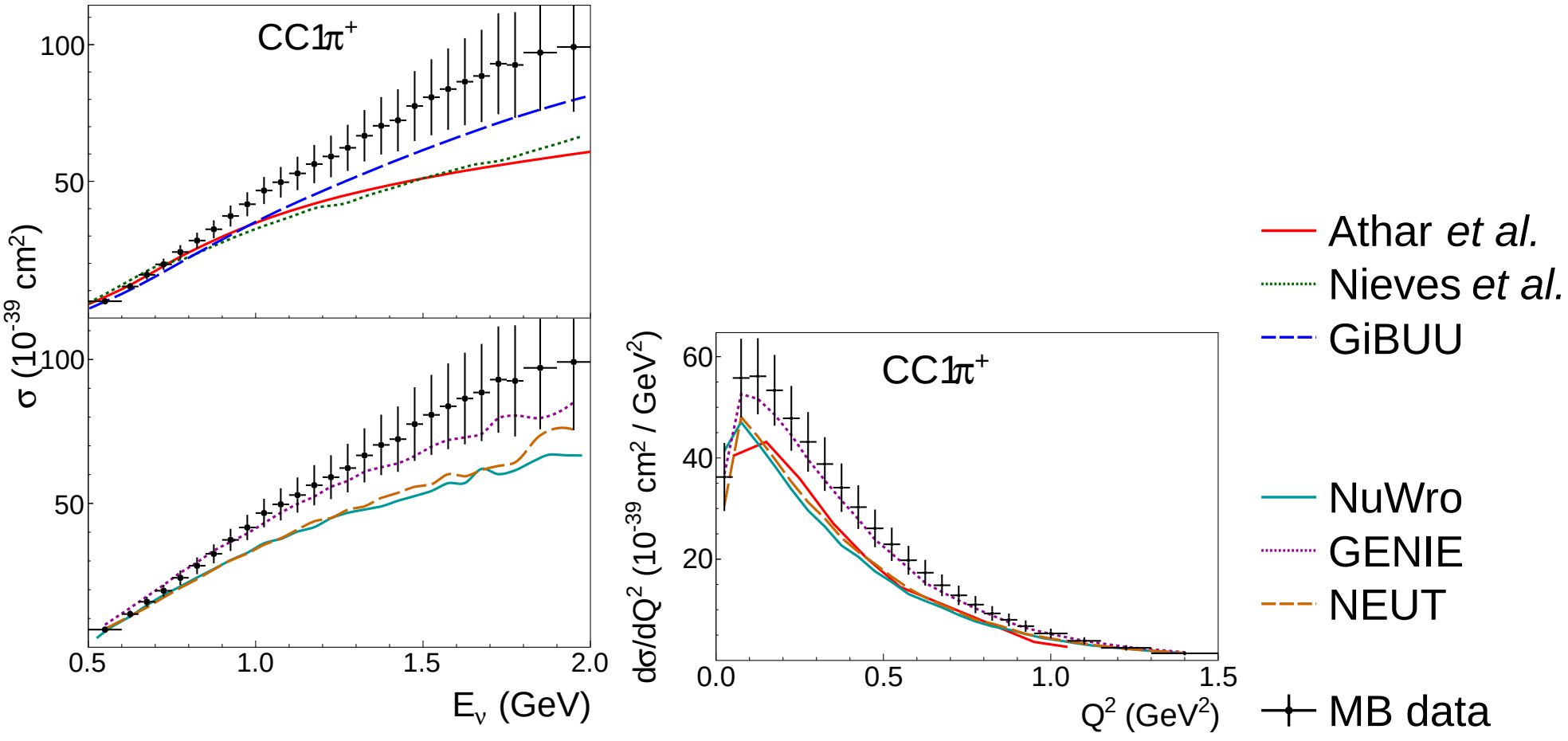
- General:
  - Detailed data allows stringent model tests
  - Maximize value by considering datasets together
- Specific:
  - Generator agreement better than theory models(?) How much of this is "tuning"?
  - Some large pion kinematic variable discrepancies

The future

- Get advanced theoretical models into experimental generators. (How?)
- Experiments
  - (Even) More detailed systematics information needed
  - Can ratios between datasets help deconvolve nucleon-level and FSI effects?

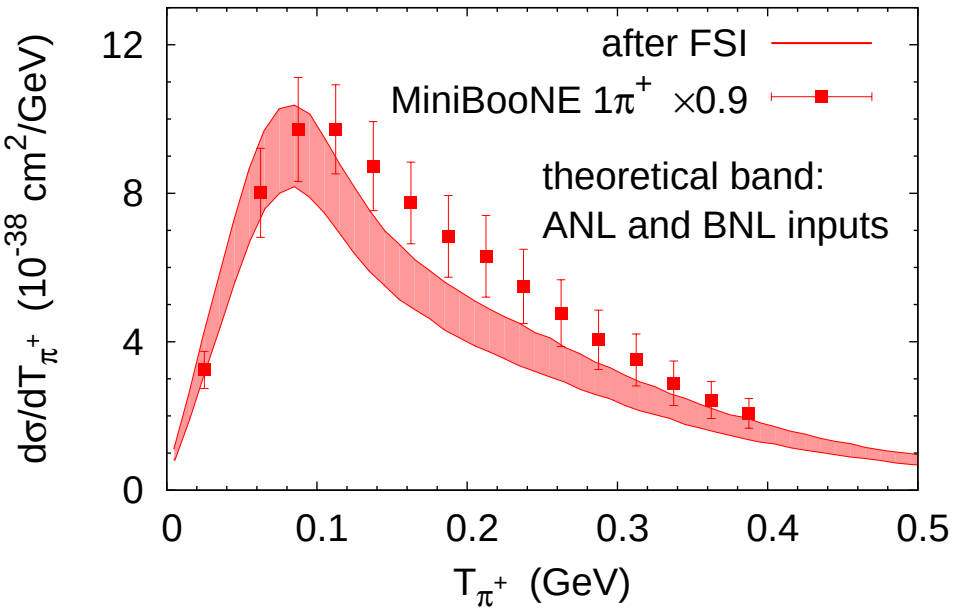
Backup slides

MiniBooNE CC1π^+ comparisons 1



- All models below data above $E_\nu \sim 0.8$ GeV. Shapes also differ. GENIE has larger nonresonant component than others.

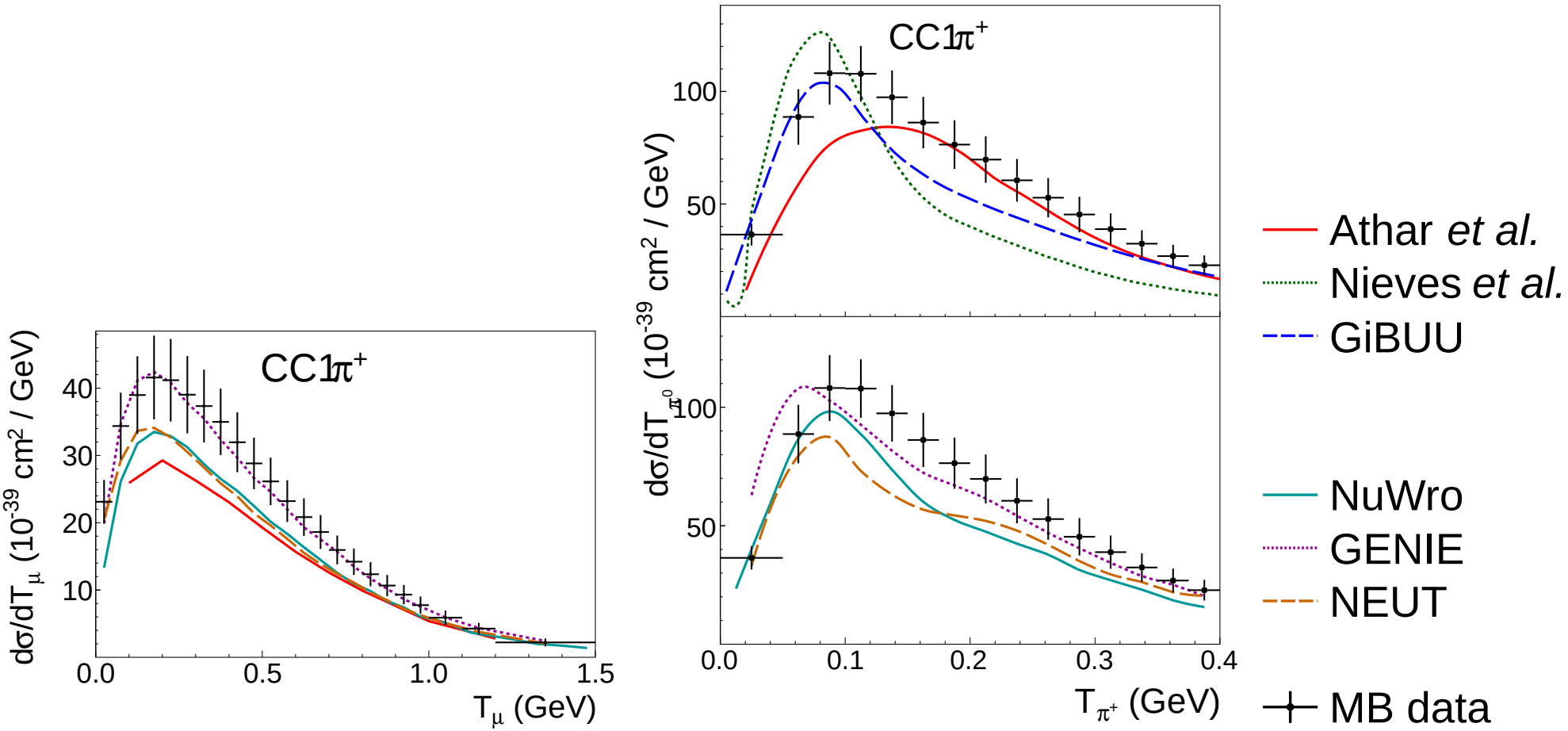
Relation to deuterium data



Plot courtesy O. Lalakulich

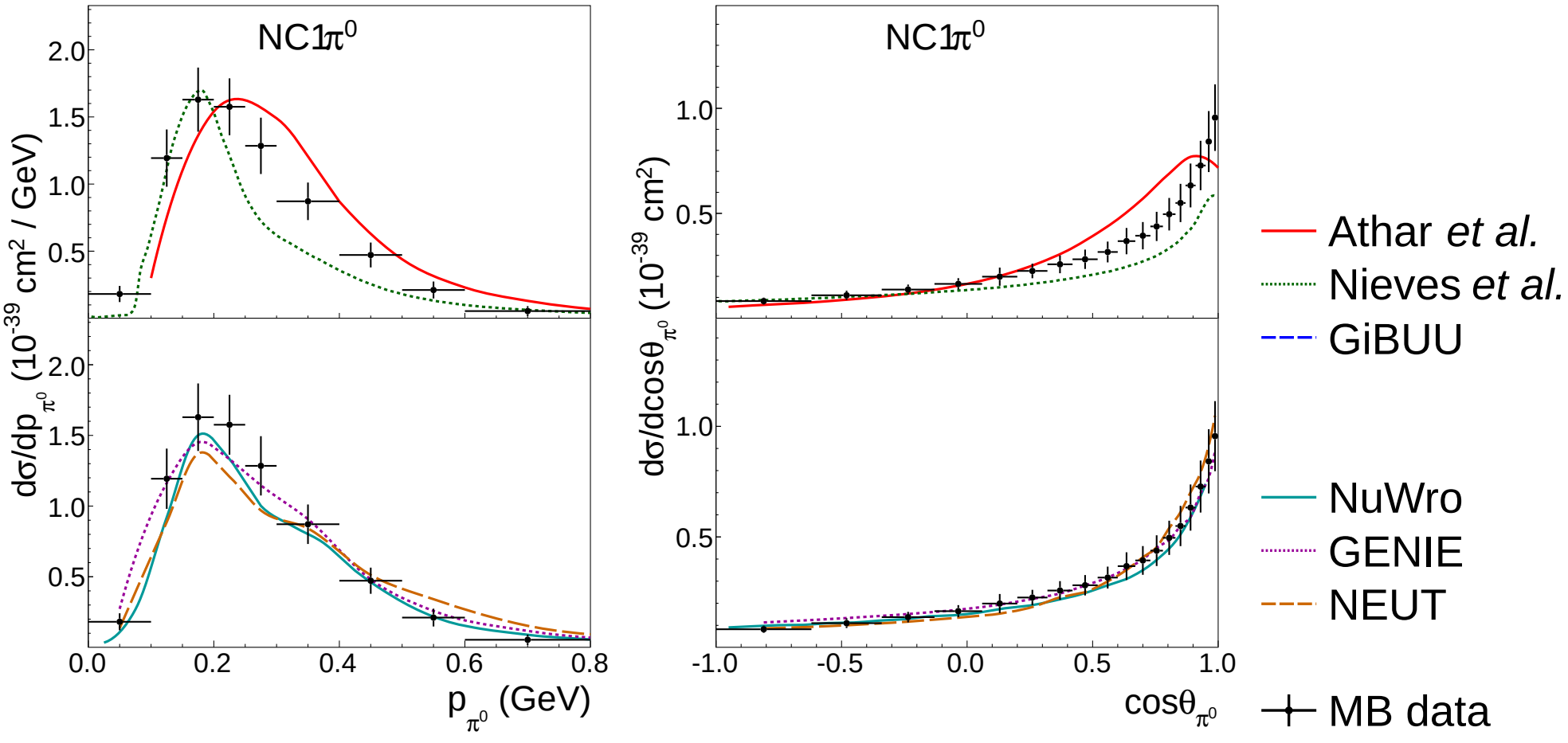
- Disagreement between MiniBooNE and deuterium data...
- Disagreement between deuterium data and deuterium data

MiniBooNE CC1π^+ comparisons 2

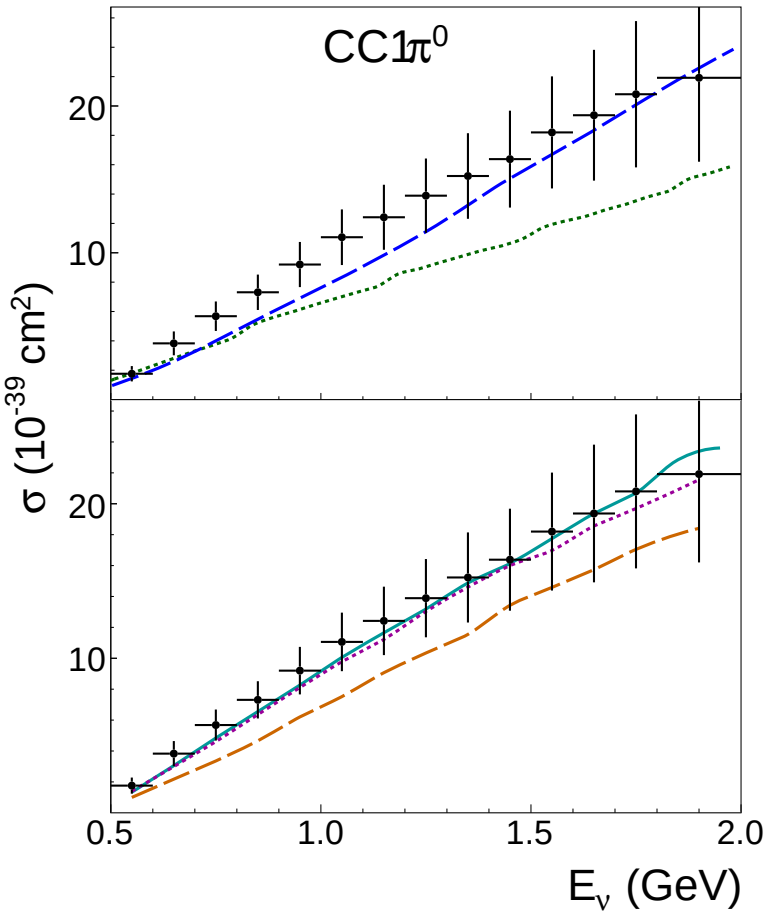


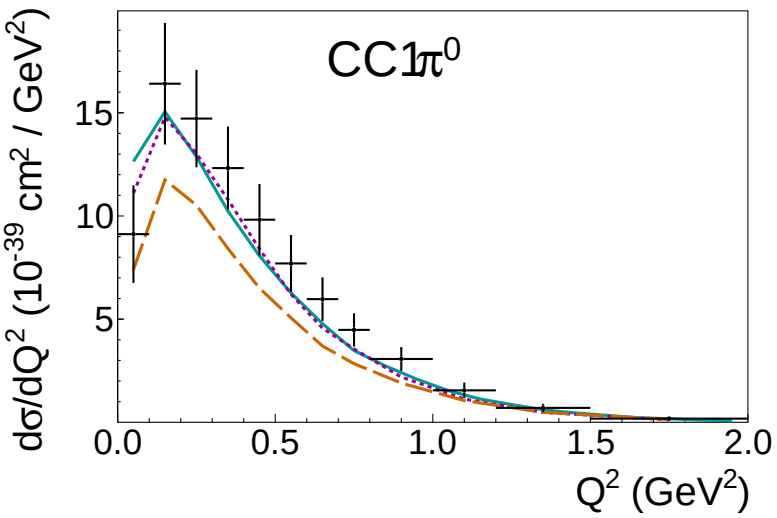
- T_π distribution sensitive to final state effects. No model with good agreement

MiniBooNE NC1π^0 comparisons



MiniBooNE CC1π^0 comparisons 1





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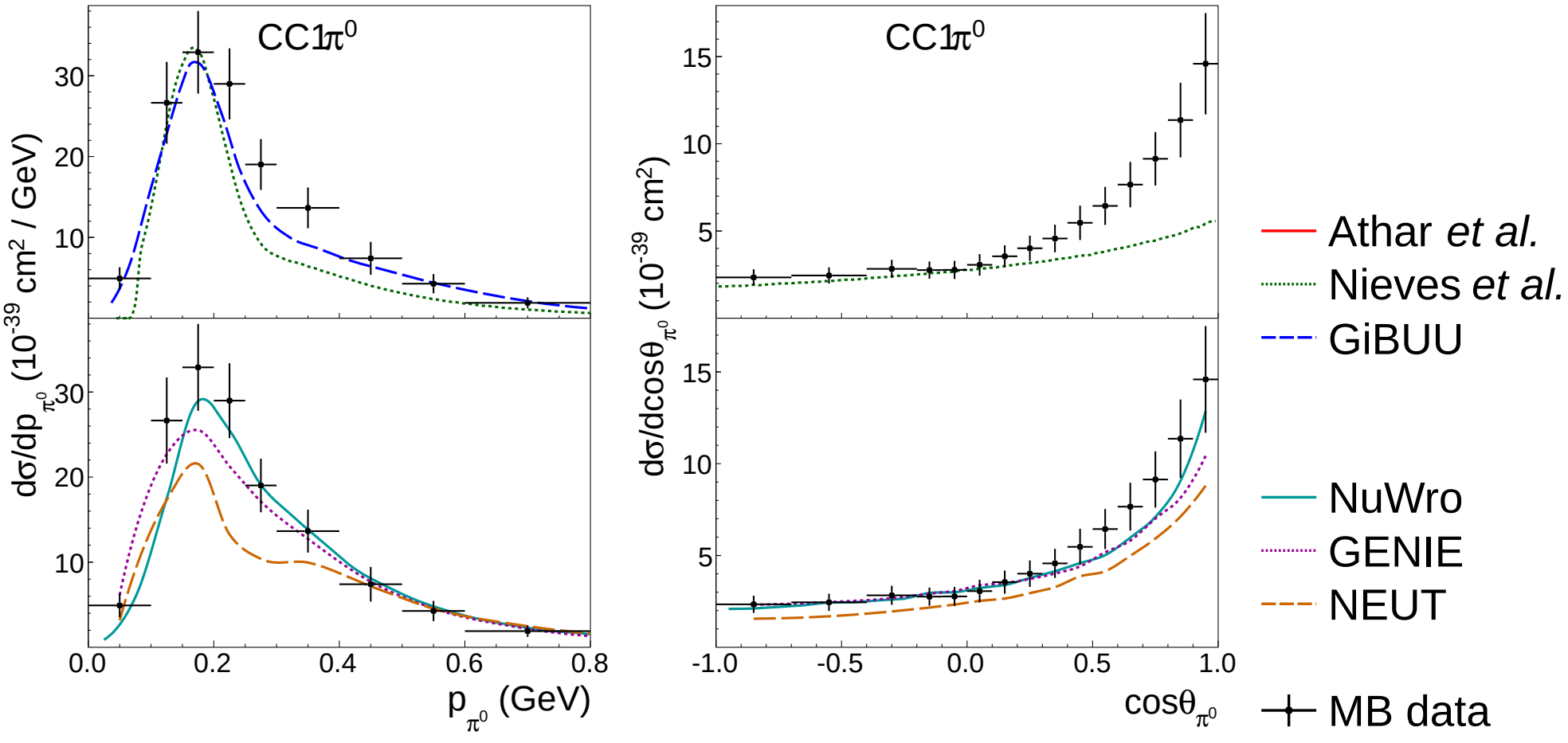
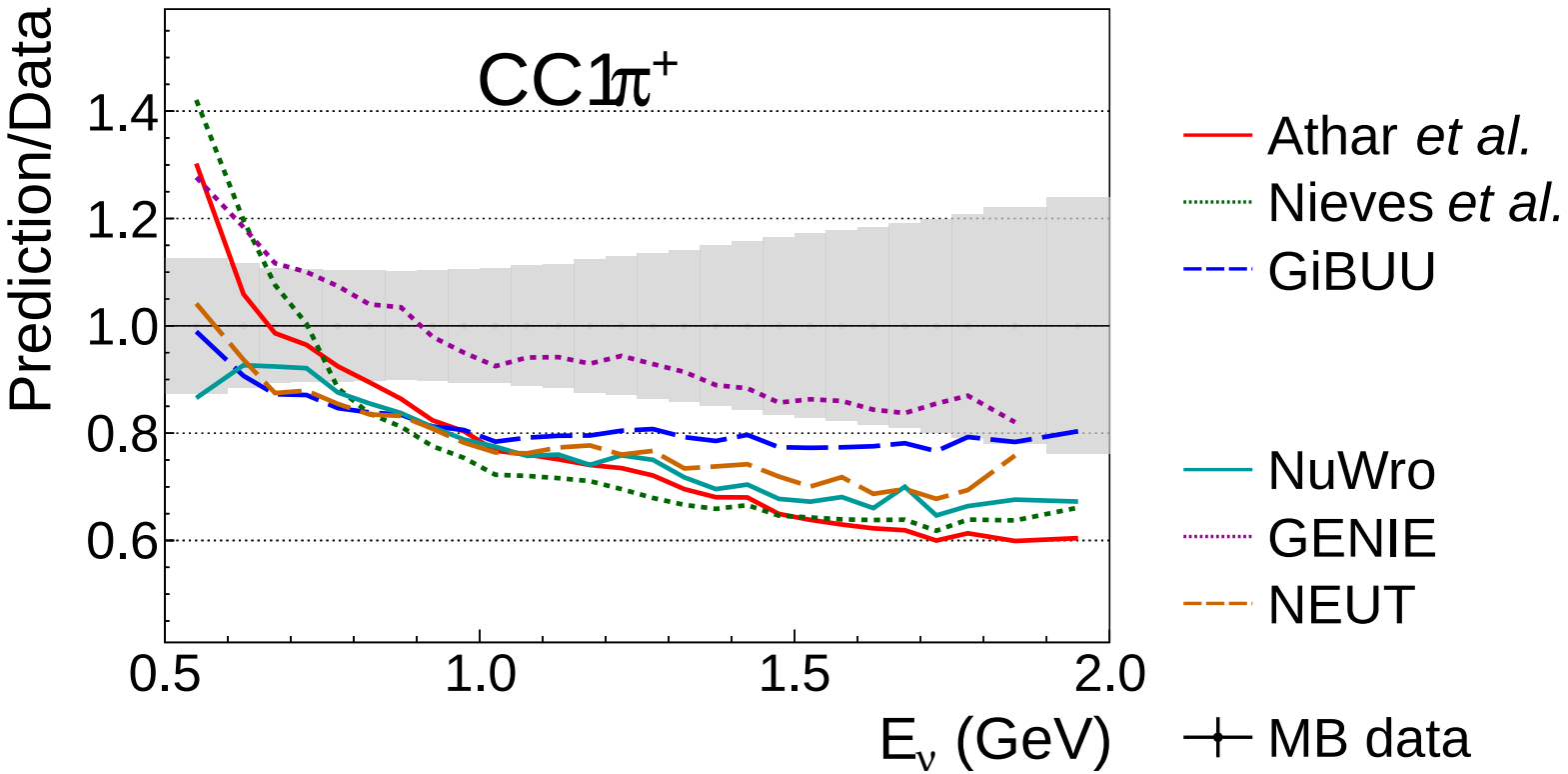
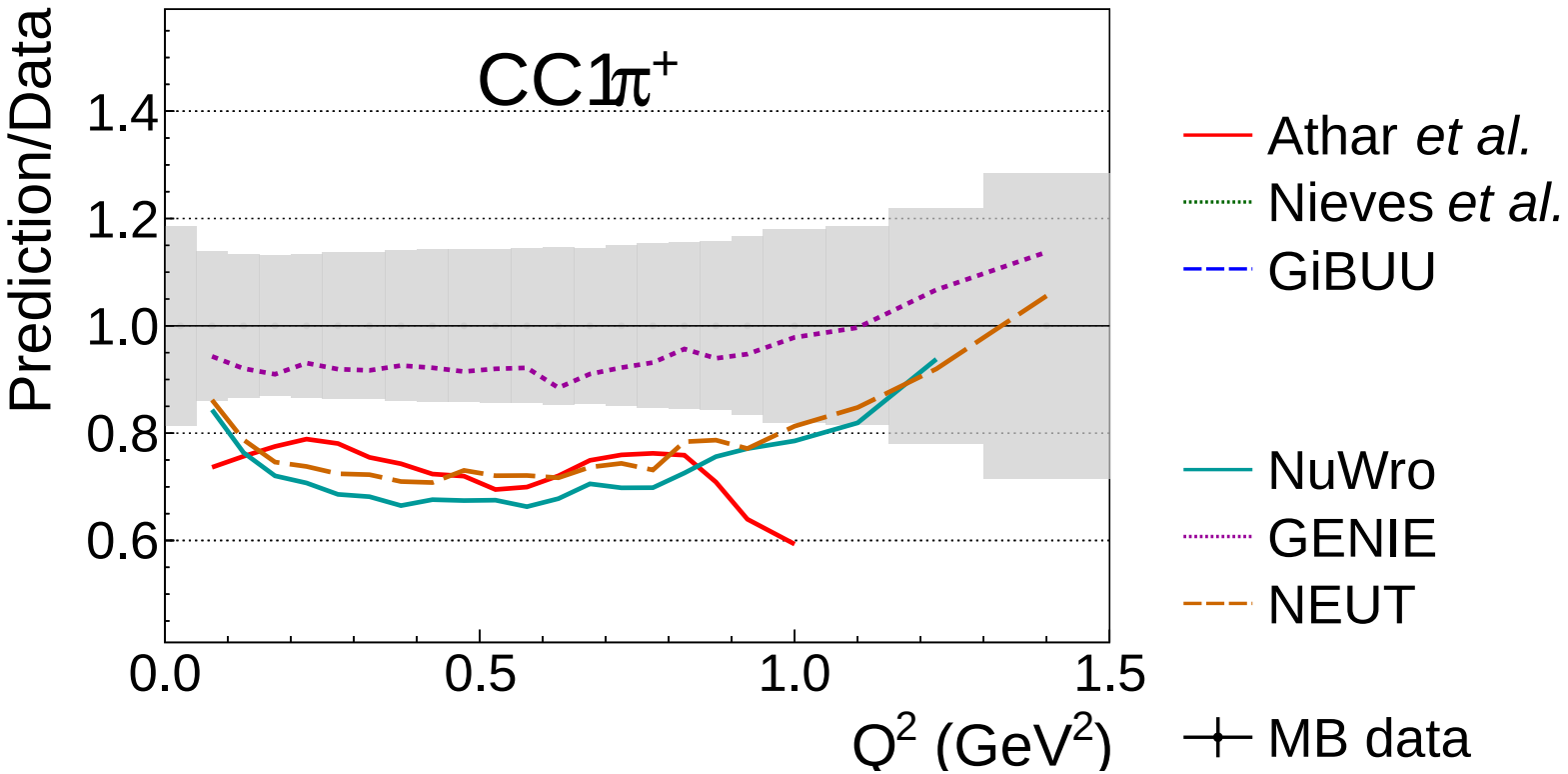


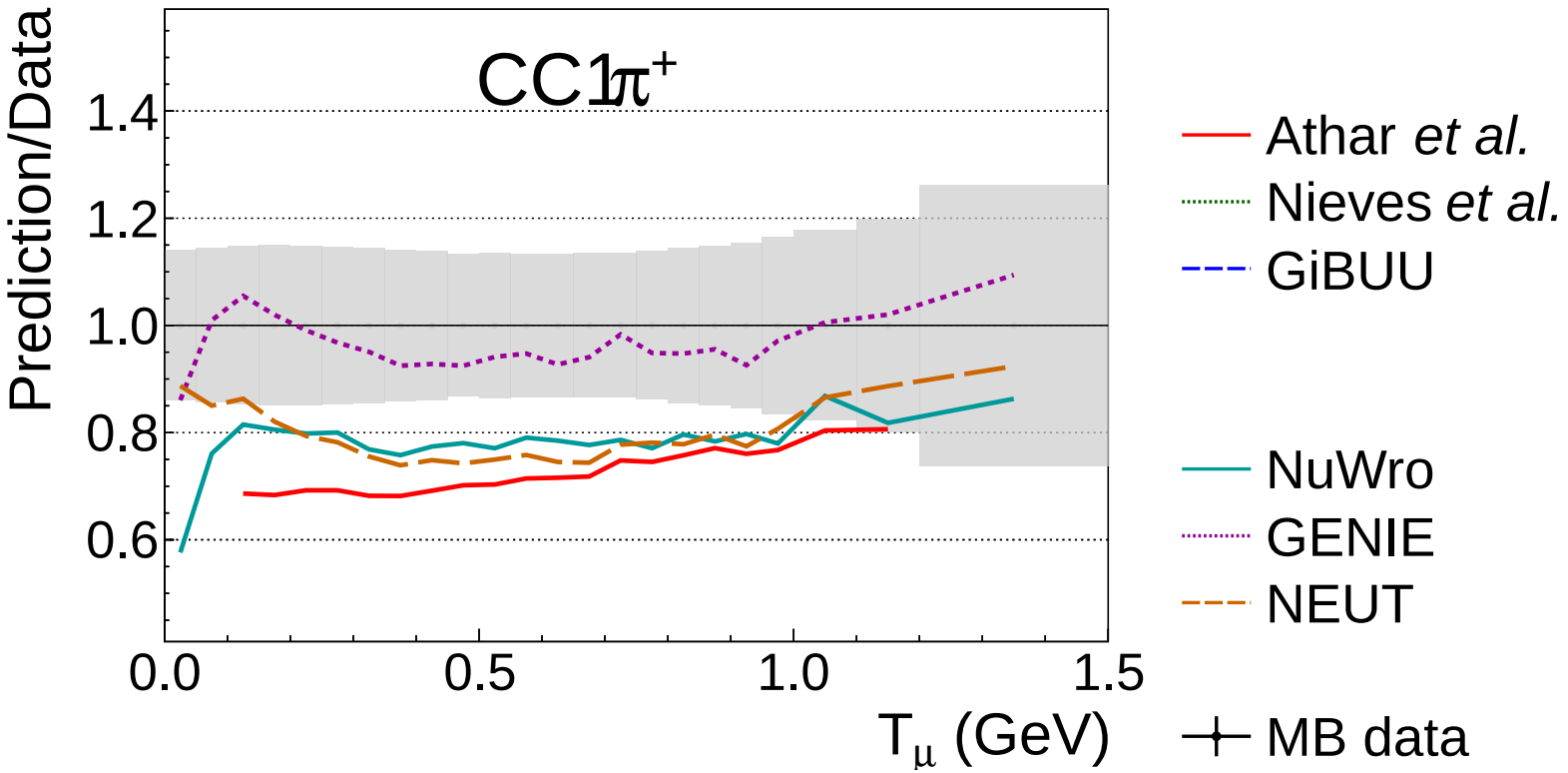
ccpip-enu-ratios



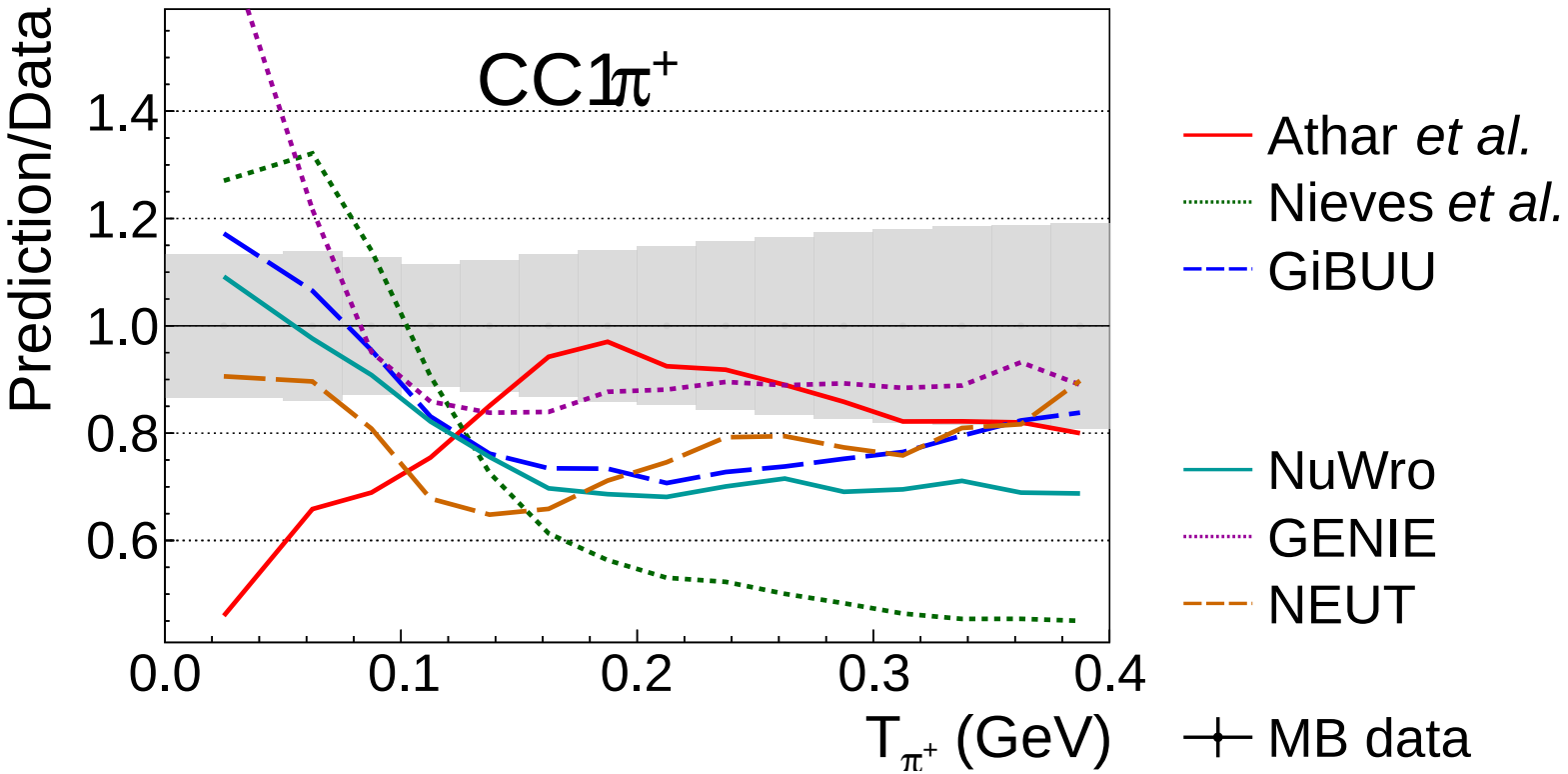
ccpip-q2-ratios



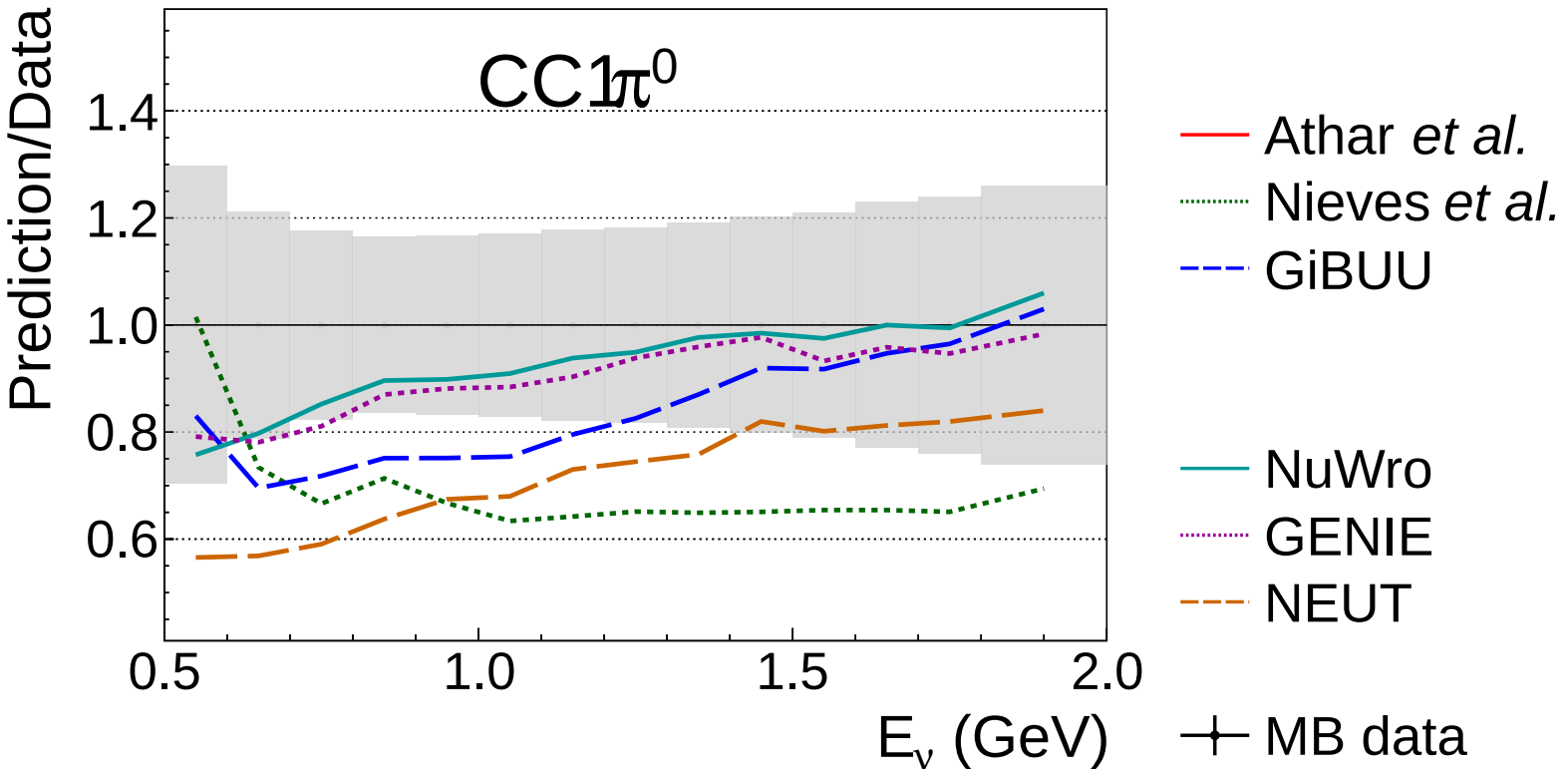
ccpip-tmu-ratios



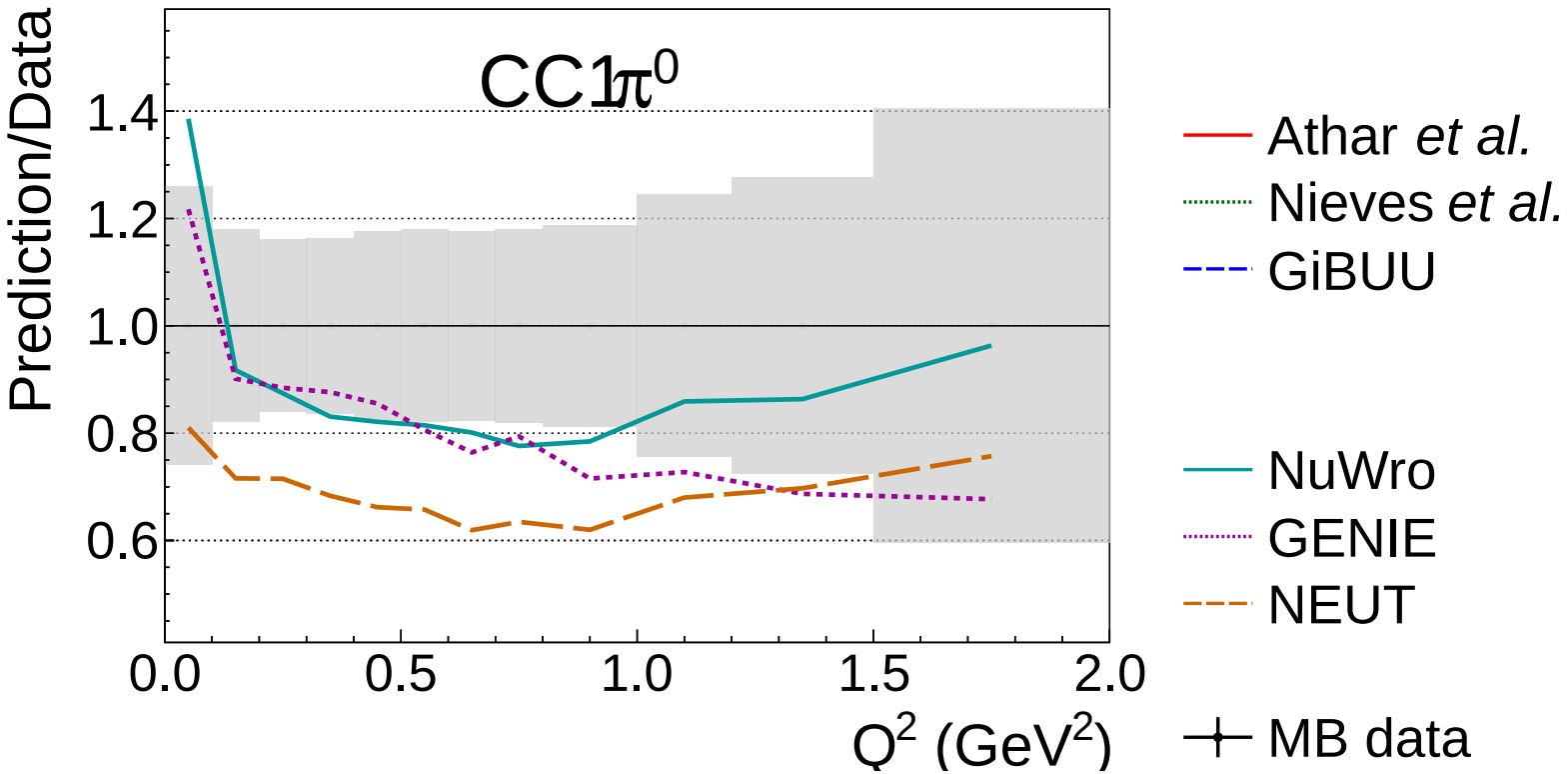
ccpip-tpi-ratios



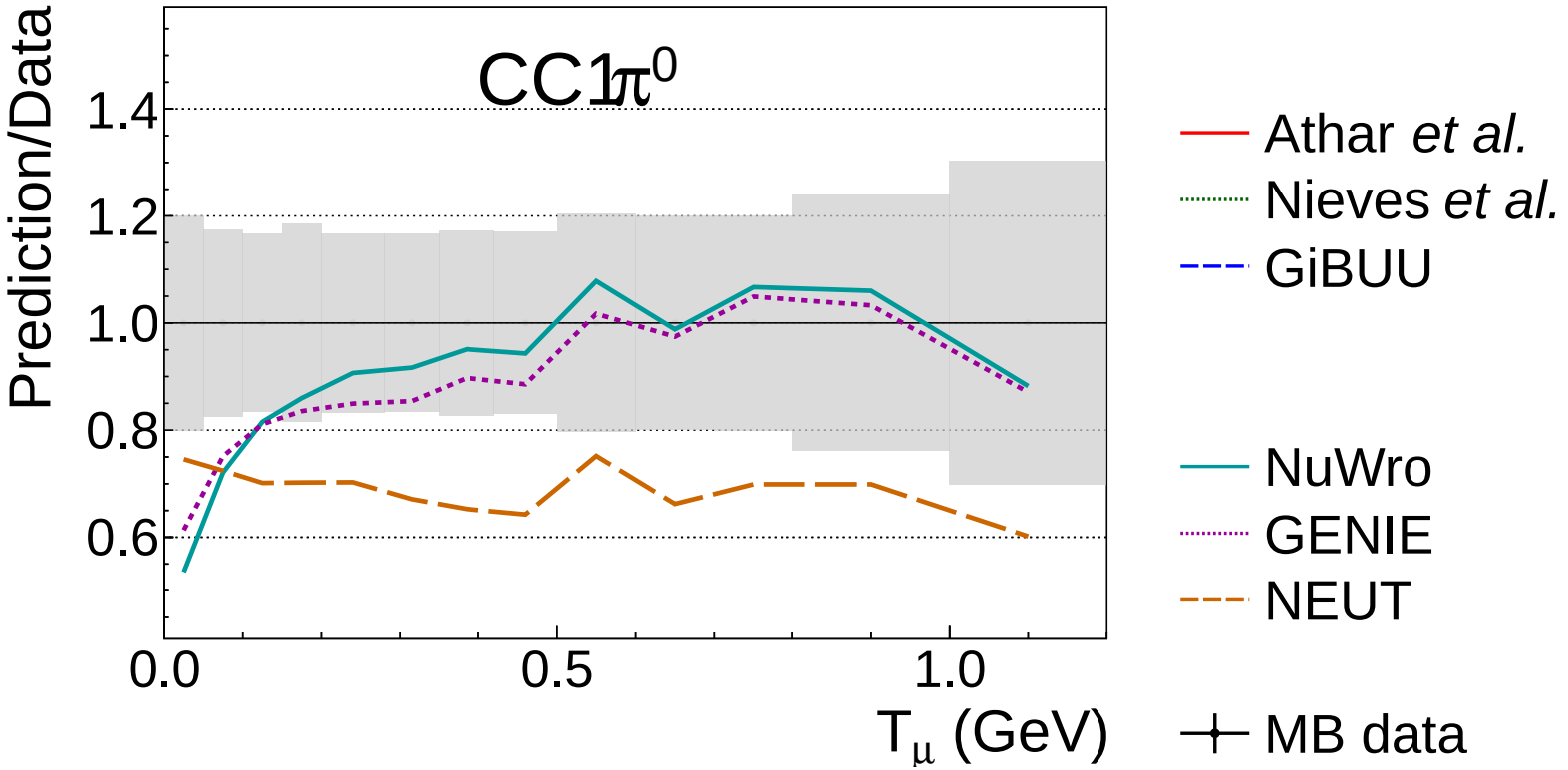
ccpi0-enu-ratios



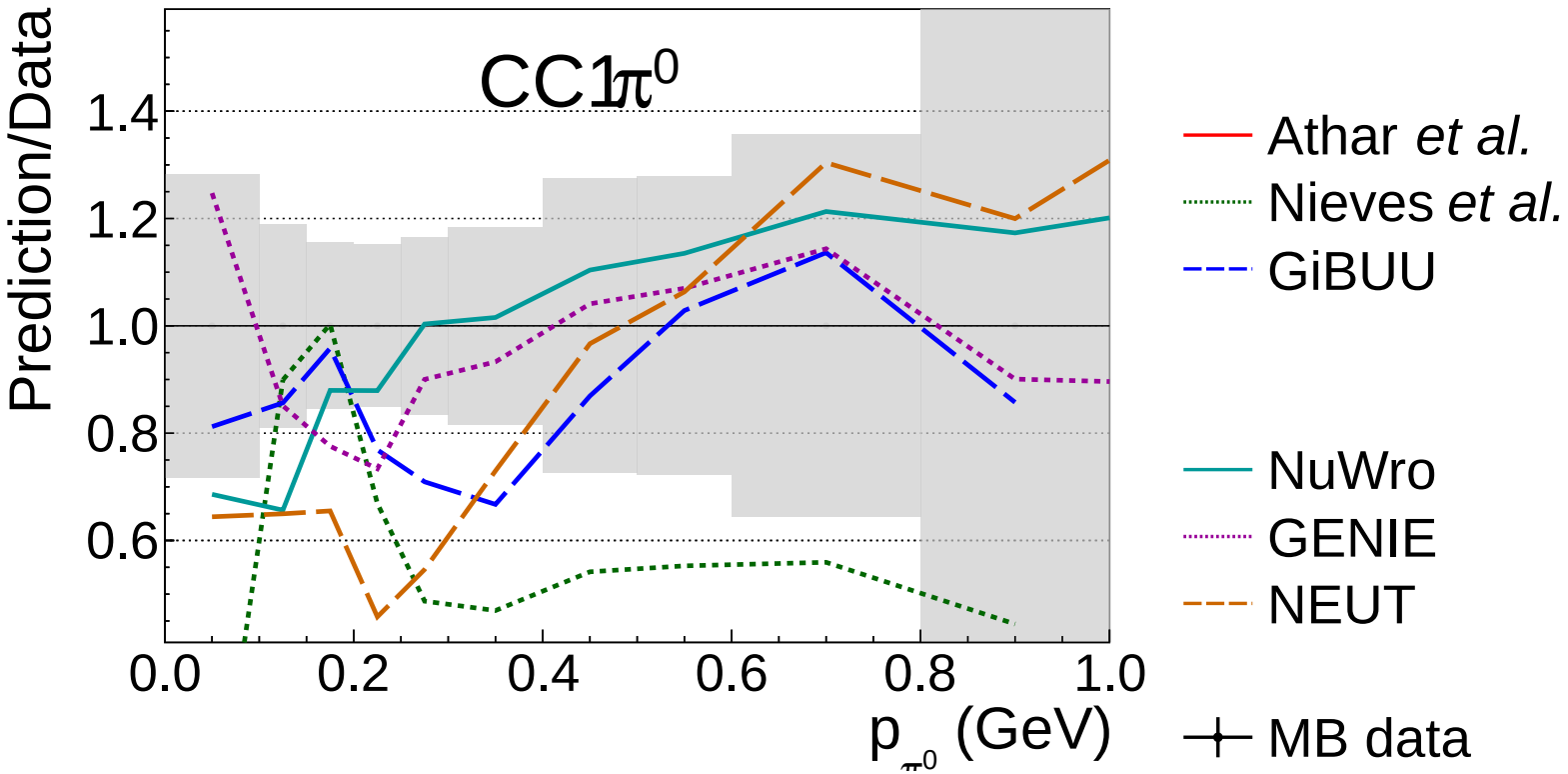
ccpi0-q2-ratios



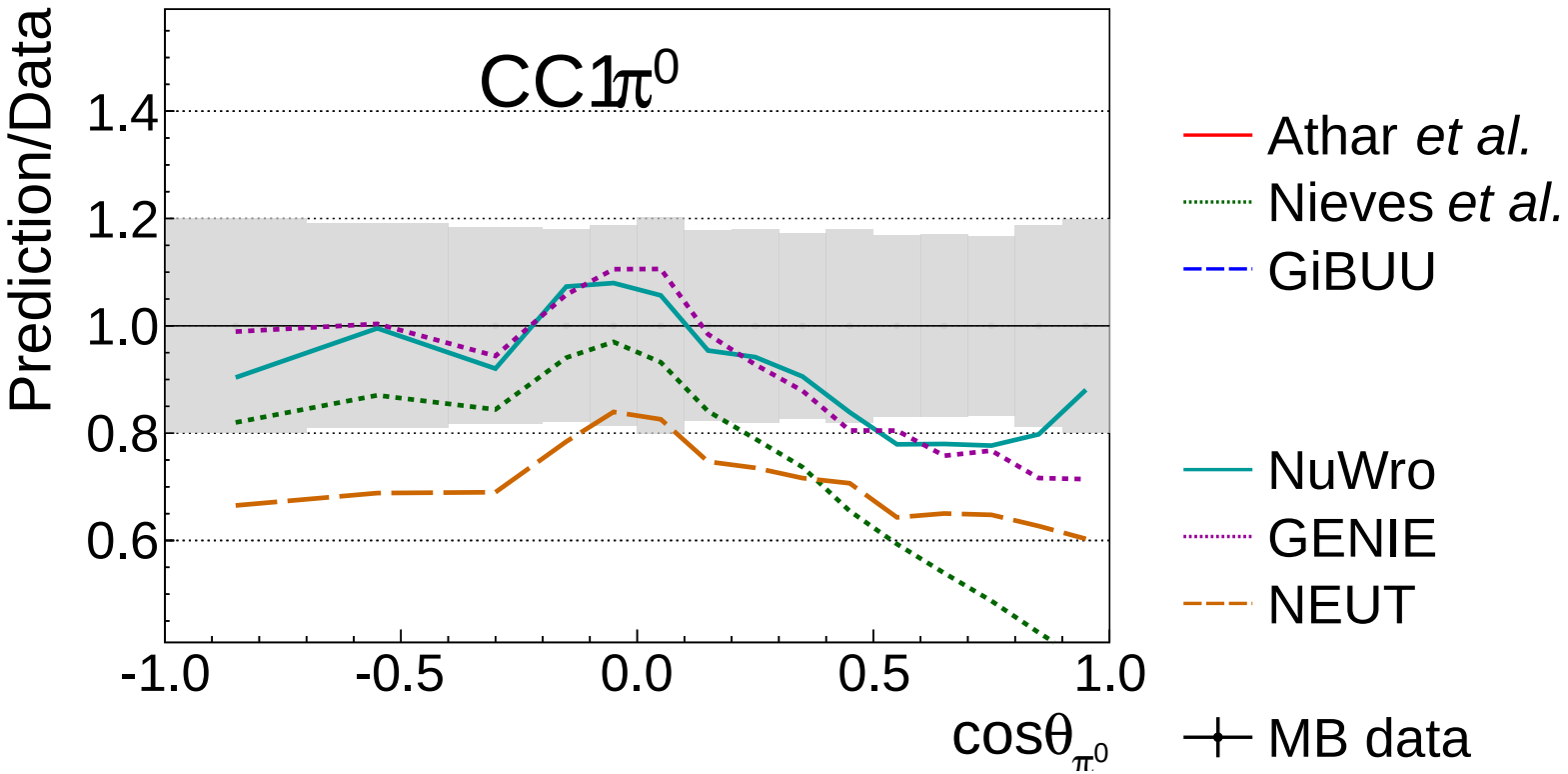
ccpi0-tmu-ratios



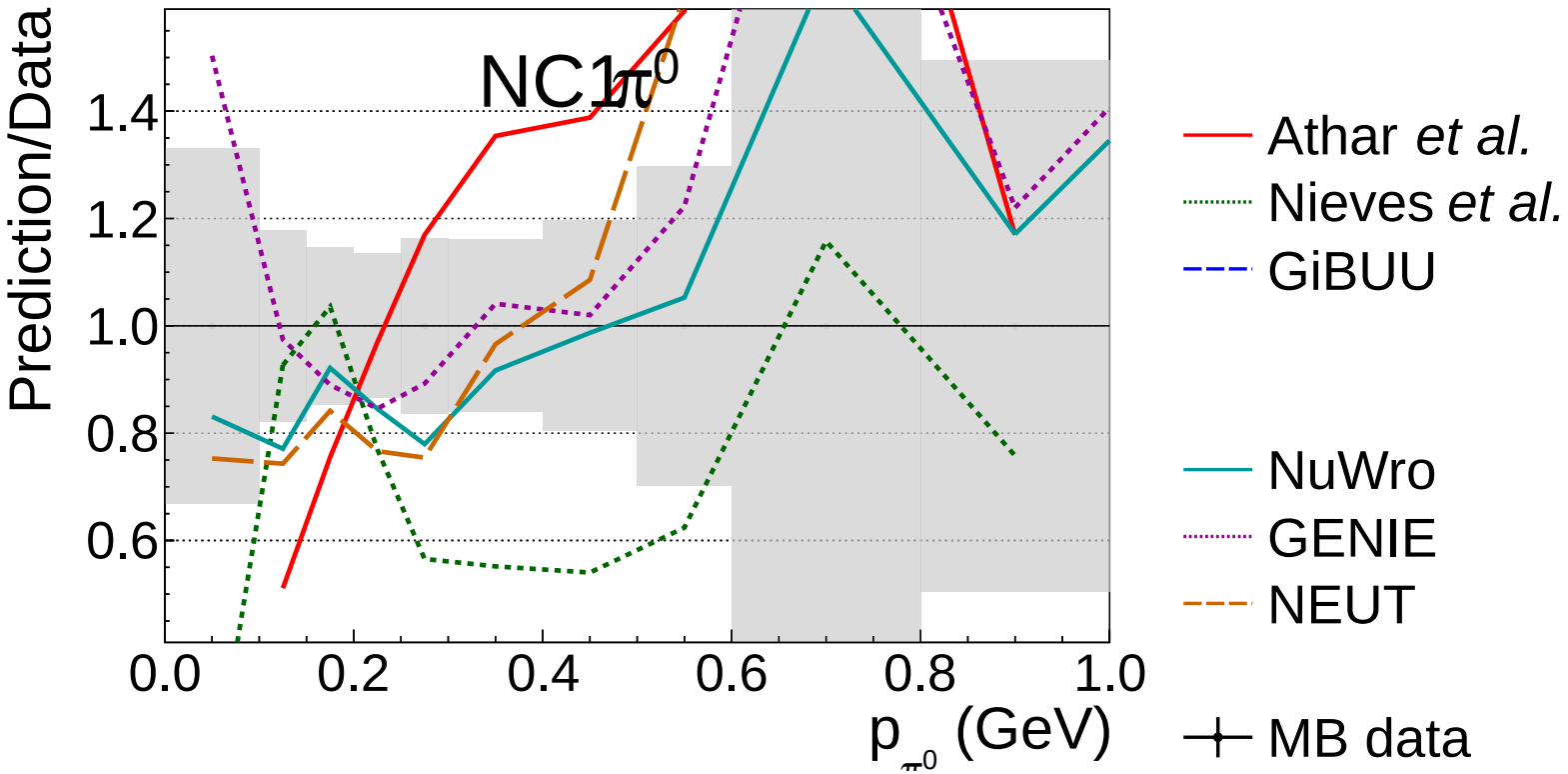
ccpi0-ppi-ratios



ccpi0-cospi-ratios



ncpi0-ppi-ratios



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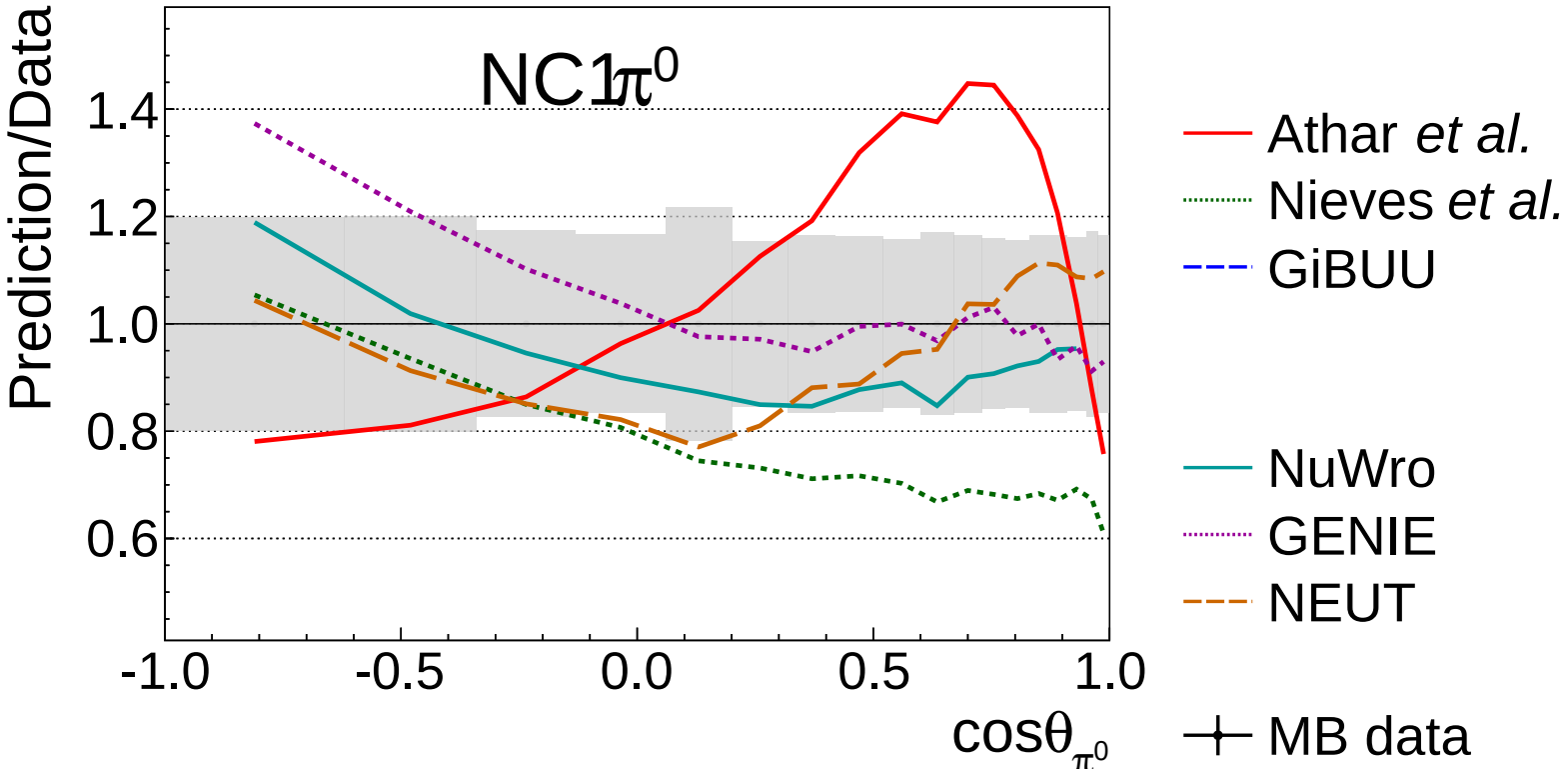
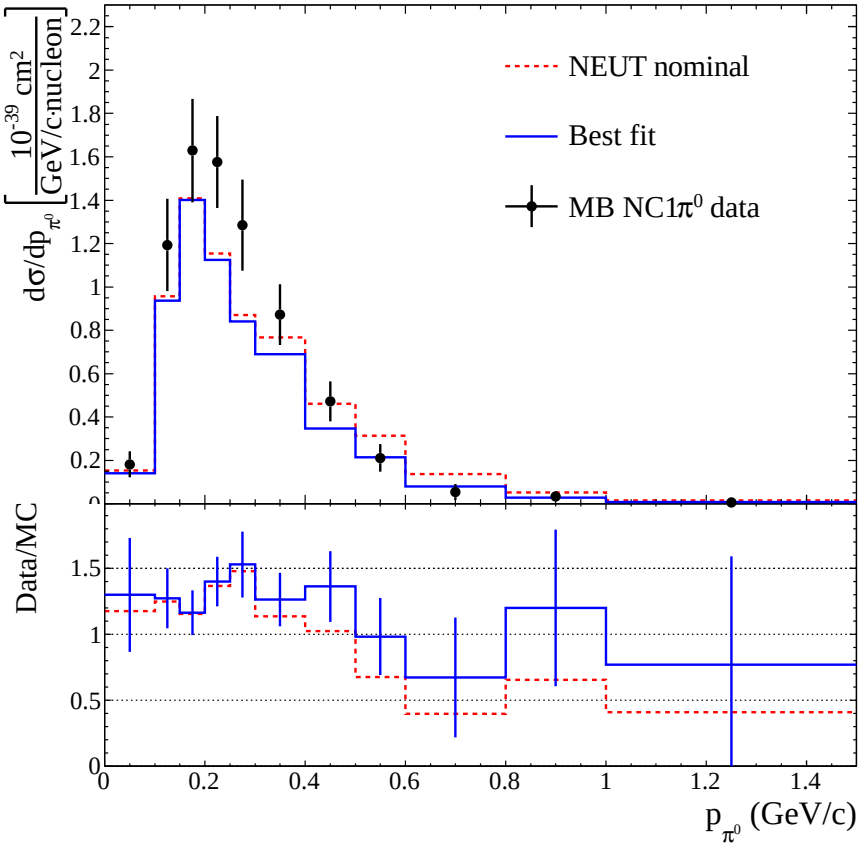


Correlations and "Peelle's Pertinent Puzzle"

$$\chi^2 = (\mathbf{D} - \mathbf{M})^{\mathsf{T}} \mathbf{V}^{-1} (\mathbf{D} - \mathbf{M})$$



- Bin-bin correlations make fit undershoot
  - "Peelle's Pertinent Puzzle"[1]

[1] "International evaluation of neutron cross-section standards", IAEA (2007)

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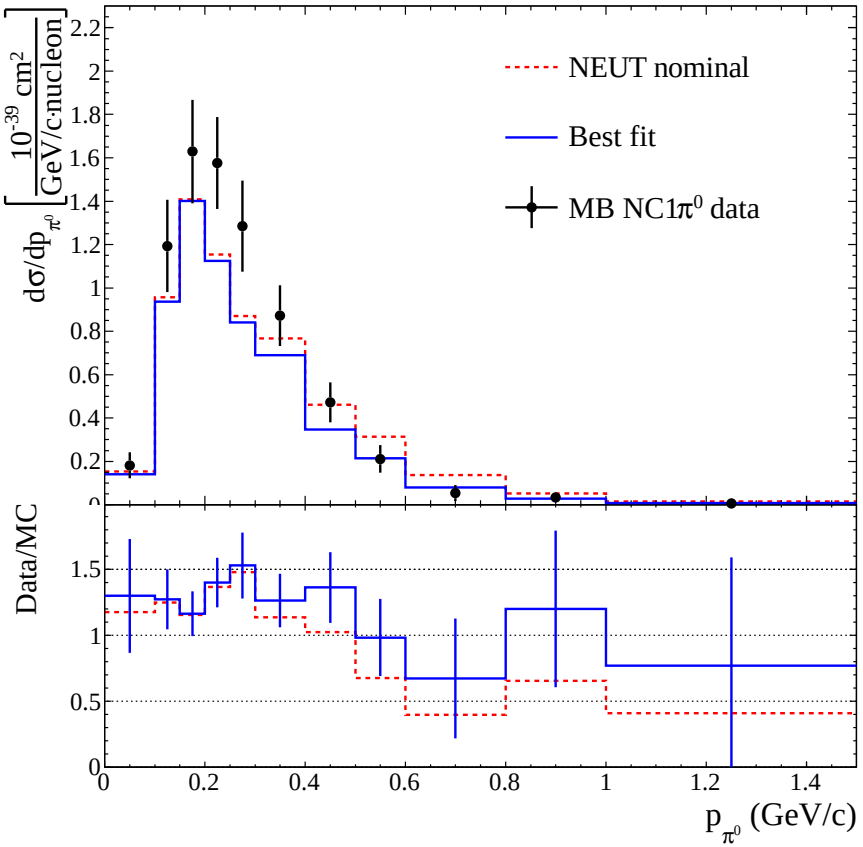

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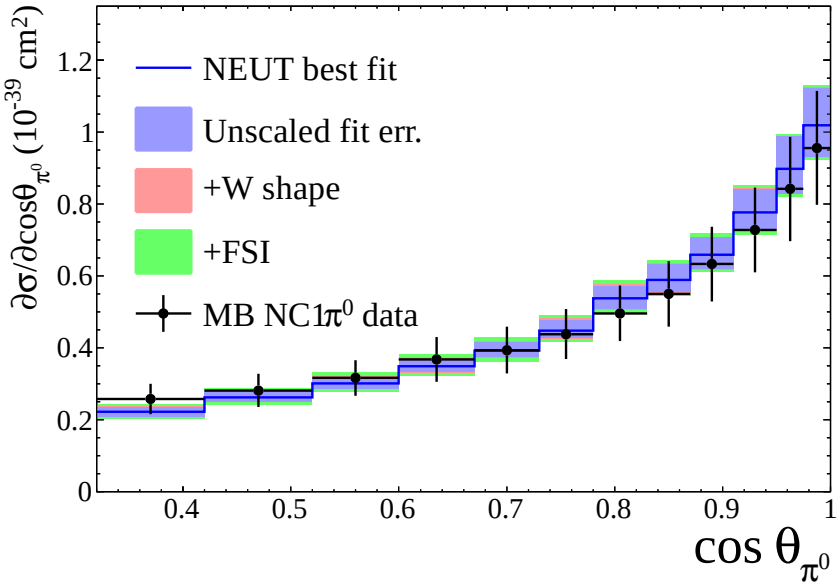

- Exclude correlations ⇒ too-small errors

Correlations and "Peelle's Pertinent Puzzle"

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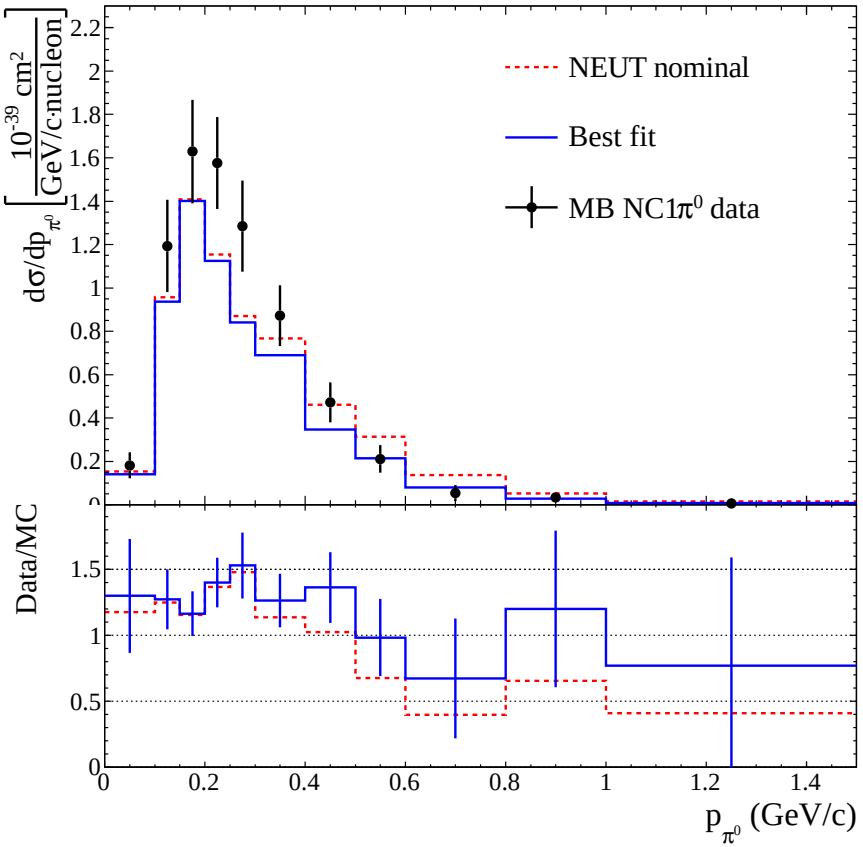
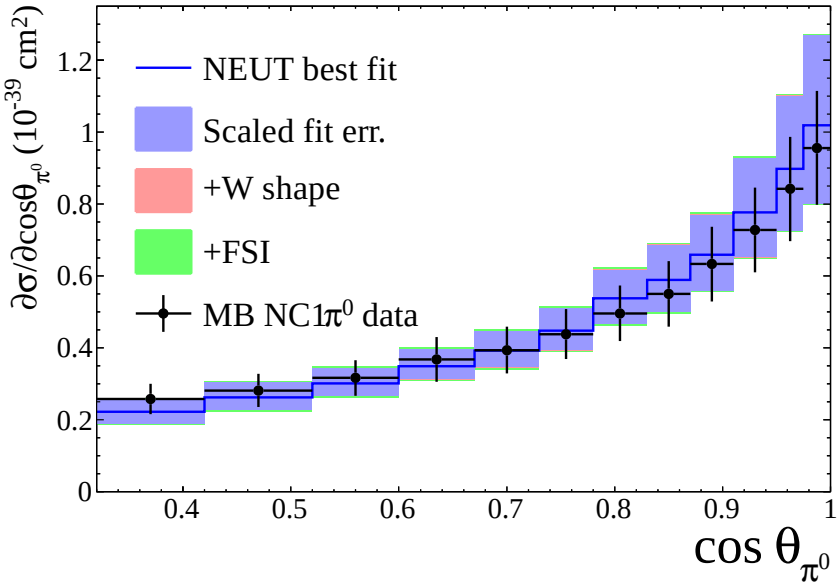
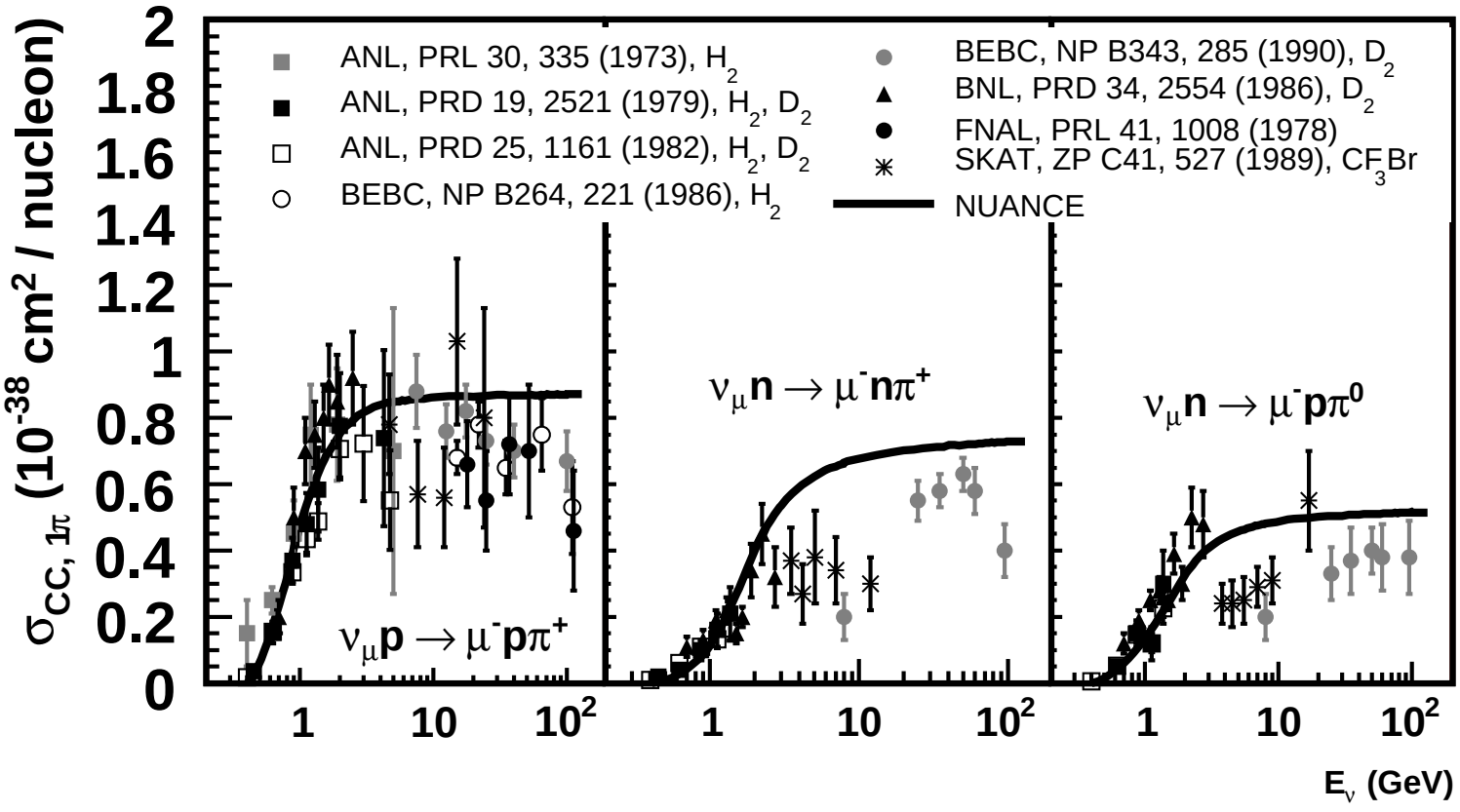


- Bin-bin correlations make fit undershoot
  - "Peelle's Pertinent Puzzle"[1]



- Exclude correlations ⇒ too-small errors
- For now: drop correlations, scale errors after fit
  - Match MB flux-averaged cross section error
- Next time: parametrize systs to add as penalty terms to fit



Plot from G. P. Zeller, PDG 2012