# Comparing pion production models and MiniBooNE data

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# Outline

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

# Single-pion production

- Experimentally, three different channels: CC1$\pi^+$, CC1$\pi^0$, NC1$\pi^0$
  - Choice of definition (see later)
- Theoretically: same resonance model

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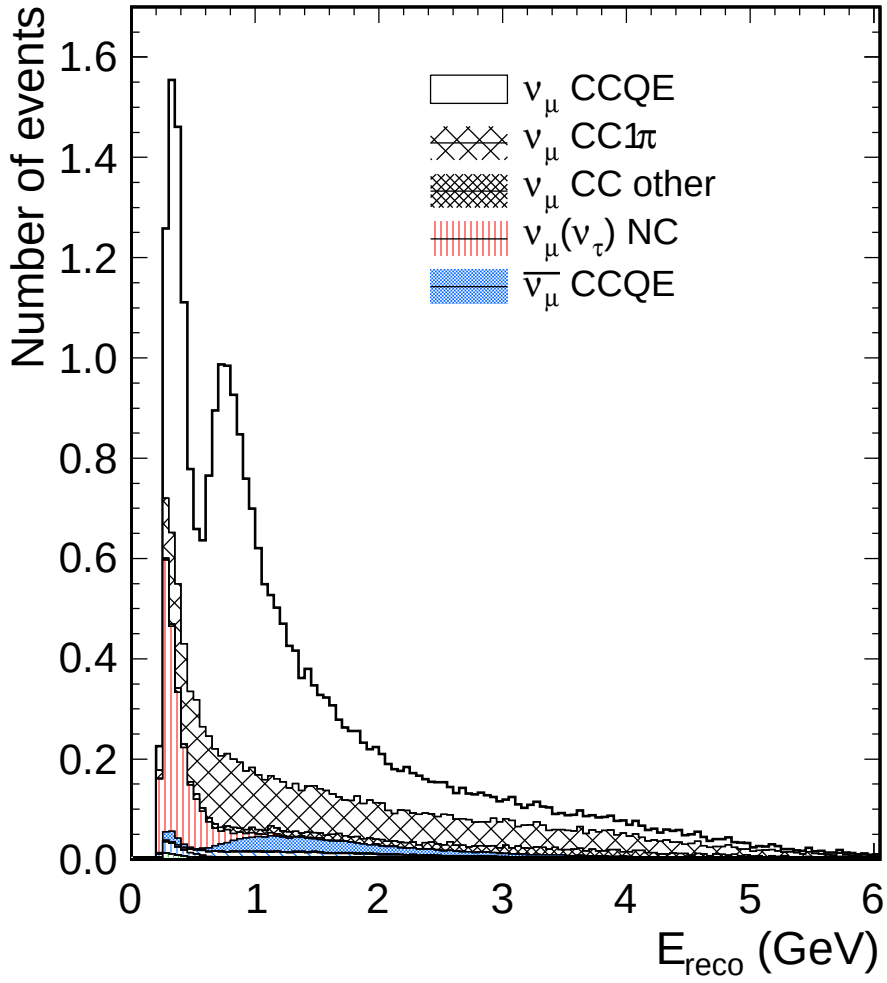
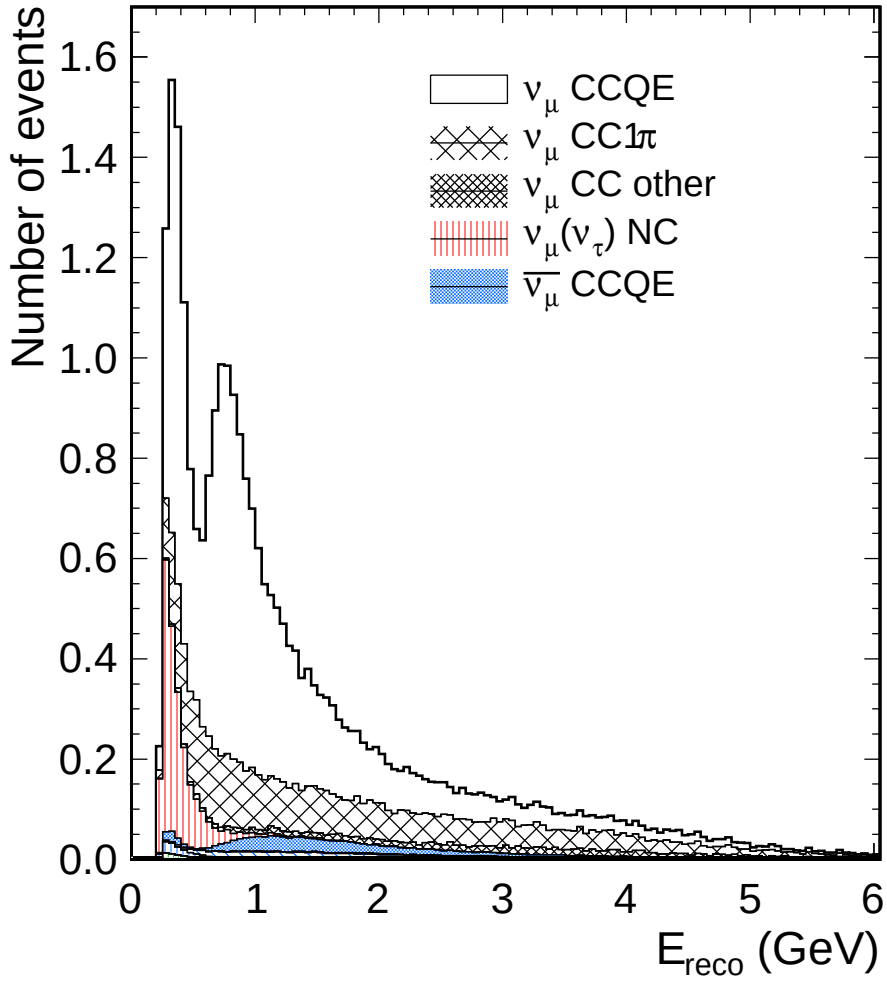
- As backgrounds to oscillations:
  - NC1$\pi^0$ background to $\nu_e$
  - CC1$\pi^+$ background to CCQE




T2K SK selected $\nu_\mu$ CCQE after oscillations. Energy reconstructed from CCQE hypothesis

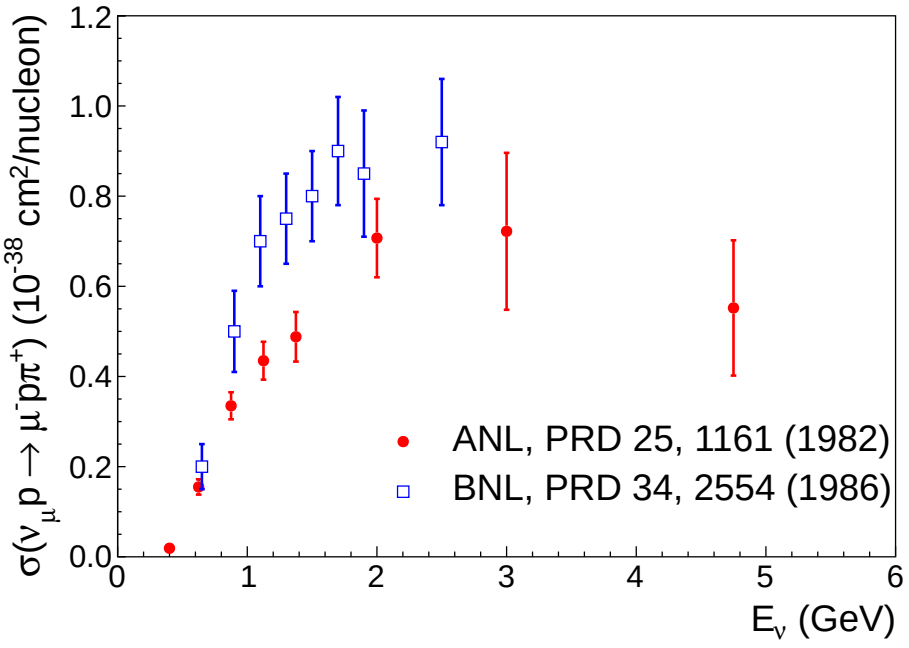
# Single-pion production

- Experimentally, three different channels: CC1$\pi^+$, CC1$\pi^0$, NC1$\pi^0$
  - Choice of definition (see later)
- Theoretically: same resonance model
- As backgrounds to oscillations:
  - NC1$\pi^0$ background to $\nu_e$
  - CC1$\pi^+$ background to CCQE
- In their own right:
  - Size of nonresonant contributions
  - Final state effects
  - Multi-nucleon effects?



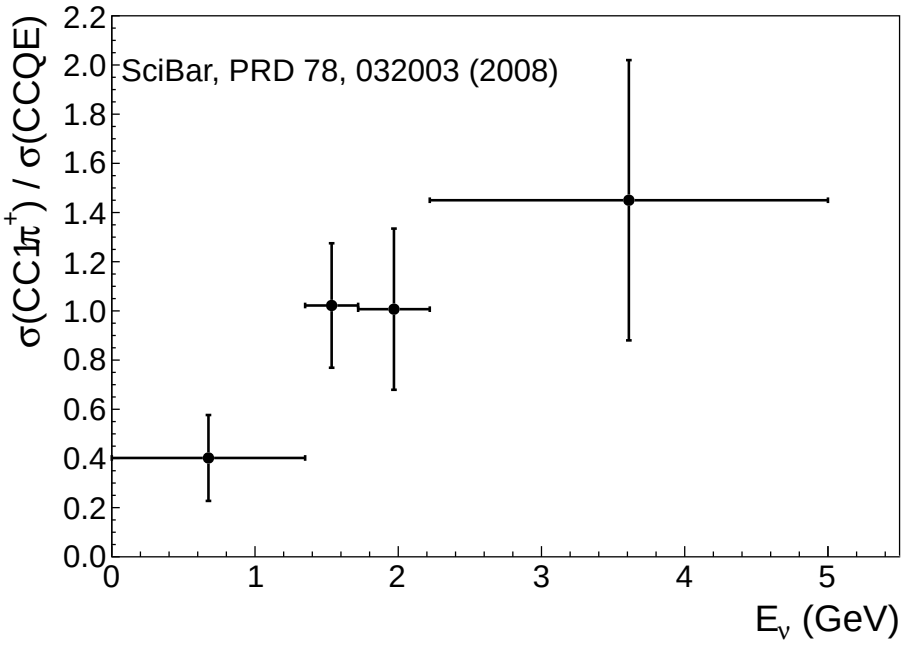

T2K SK selected $\nu_\mu$ CCQE after oscillations. Energy reconstructed from CCQE hypothesis

# 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.

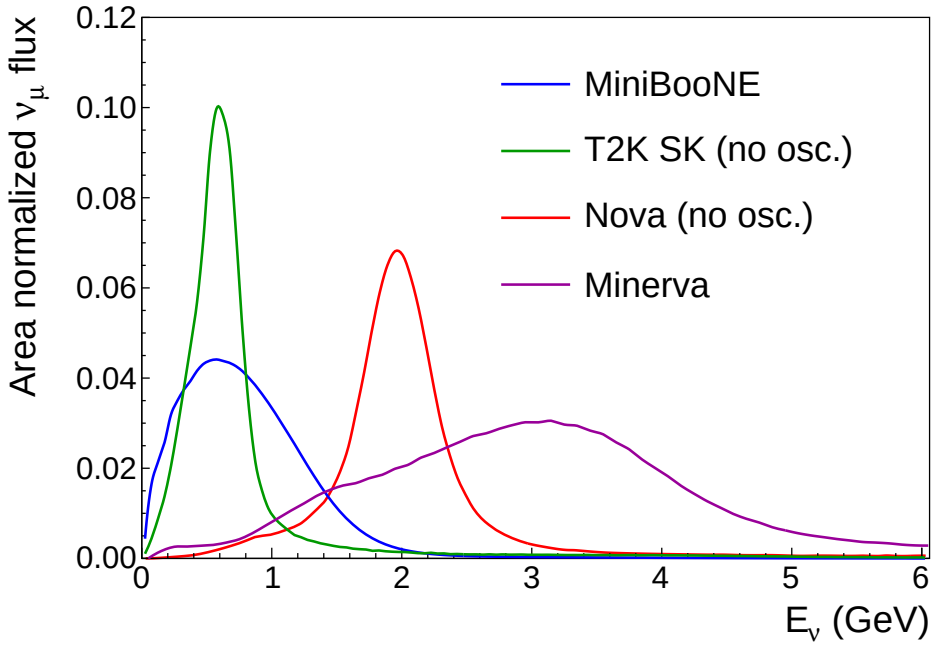
Acta Phys. Polon. B 40, 2477 (2009)

**NuWro** Only $\Delta$ resonance included explicitly. SF for nuclear effects

Proc. NuFact08 141

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

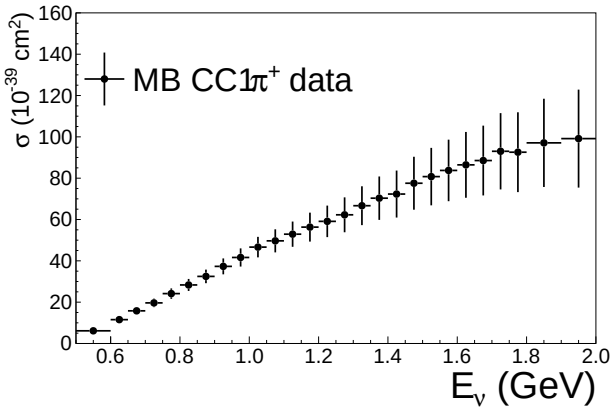
# MiniBooNE

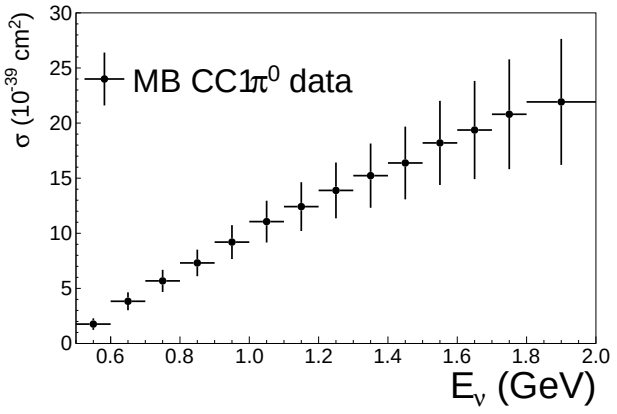


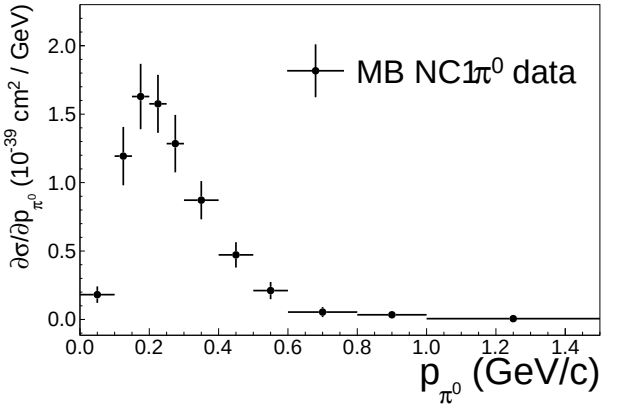

- BNB $\nu_\mu$ flux peaks at $E_\nu \approx 0.6$ GeV
- Target material $CH_2$
- Čerenkov detector

  $\Rightarrow$ Nucleons not observed

# MiniBooNE datasets



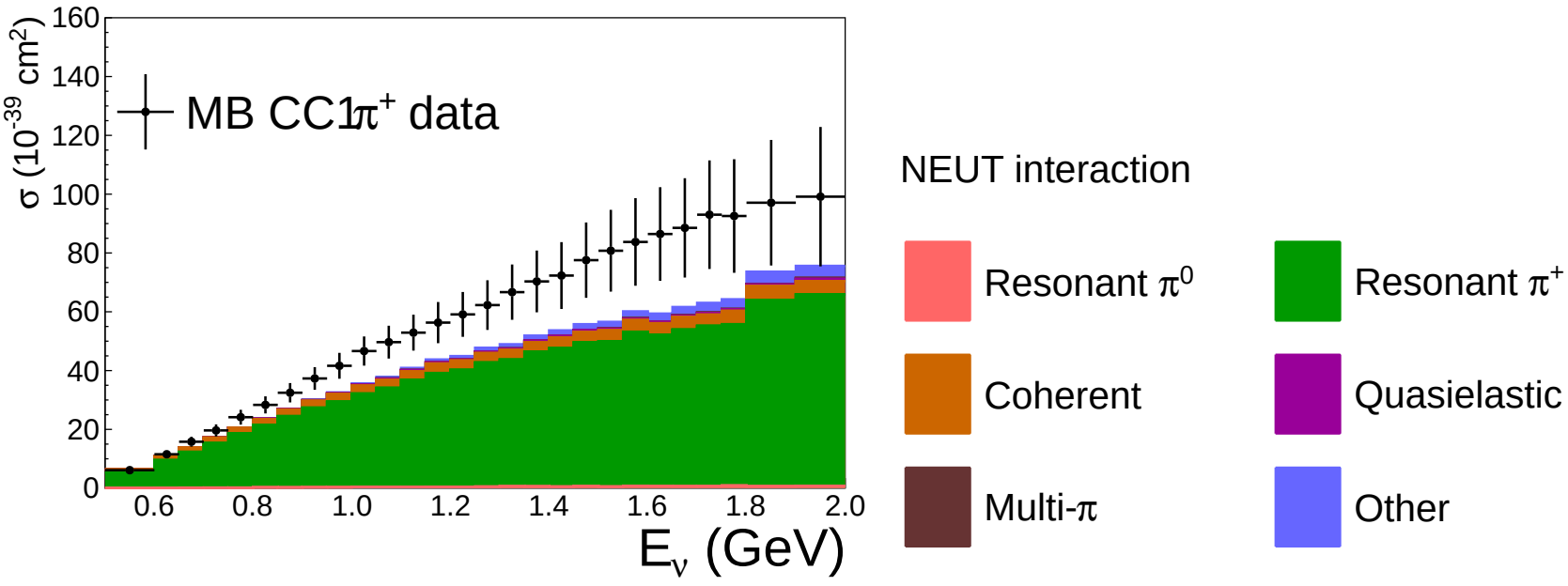




- Datasets defined by particles exiting the nucleus
  - Nucleon-level $\sigma \otimes$ Nuclear eff $\otimes$ FSI
- High statistics, model-independent, absolute cross sections
- Data released, with flux, and some correlation matrices

# MiniBooNE dataset limitations

- In principle: joint fit to tune resonance production in model/generator
- But...
  - CC1$\pi^+$ 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 CC1$\pi^+$



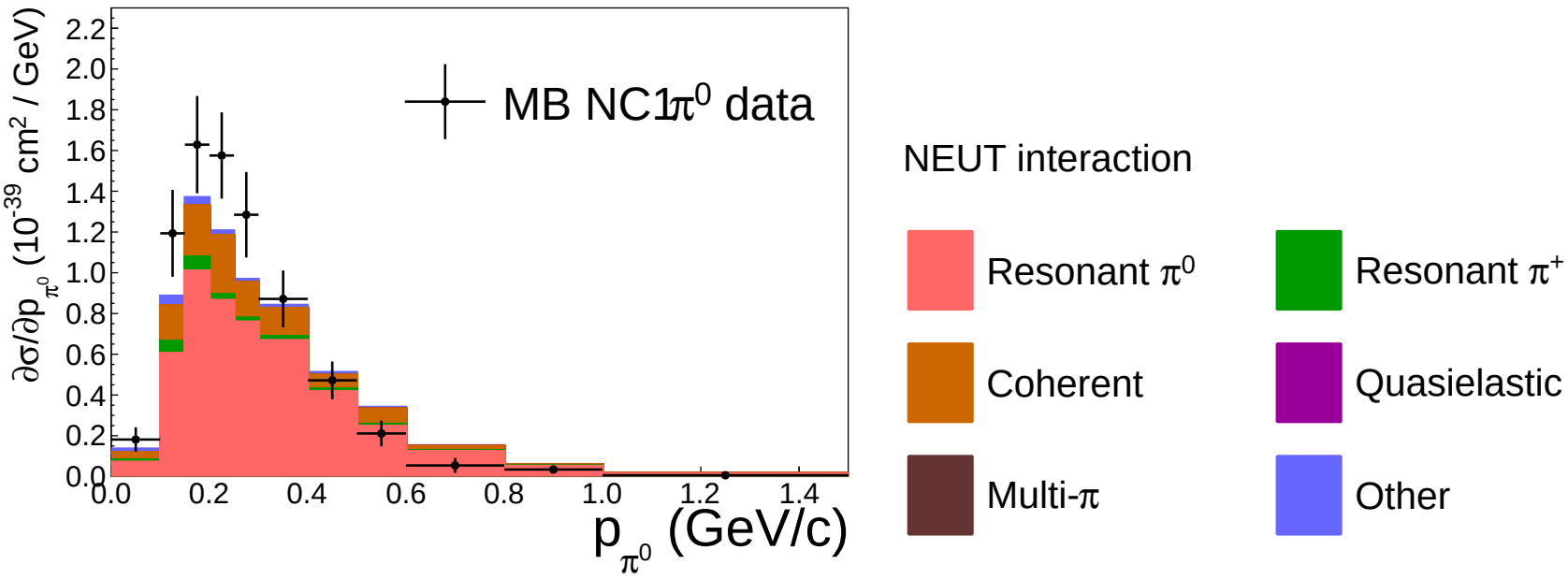

FS particles $1\ \mu^-$, $1\ \pi^+$

No other mesons, but any nucleons

Nucleon-level Resonant $\pi^+$, coherent $\pi^+$

Distributions $\sigma(E_\nu)$, $Q^2$, $T_\mu$, $T_\pi$, +2D distributions

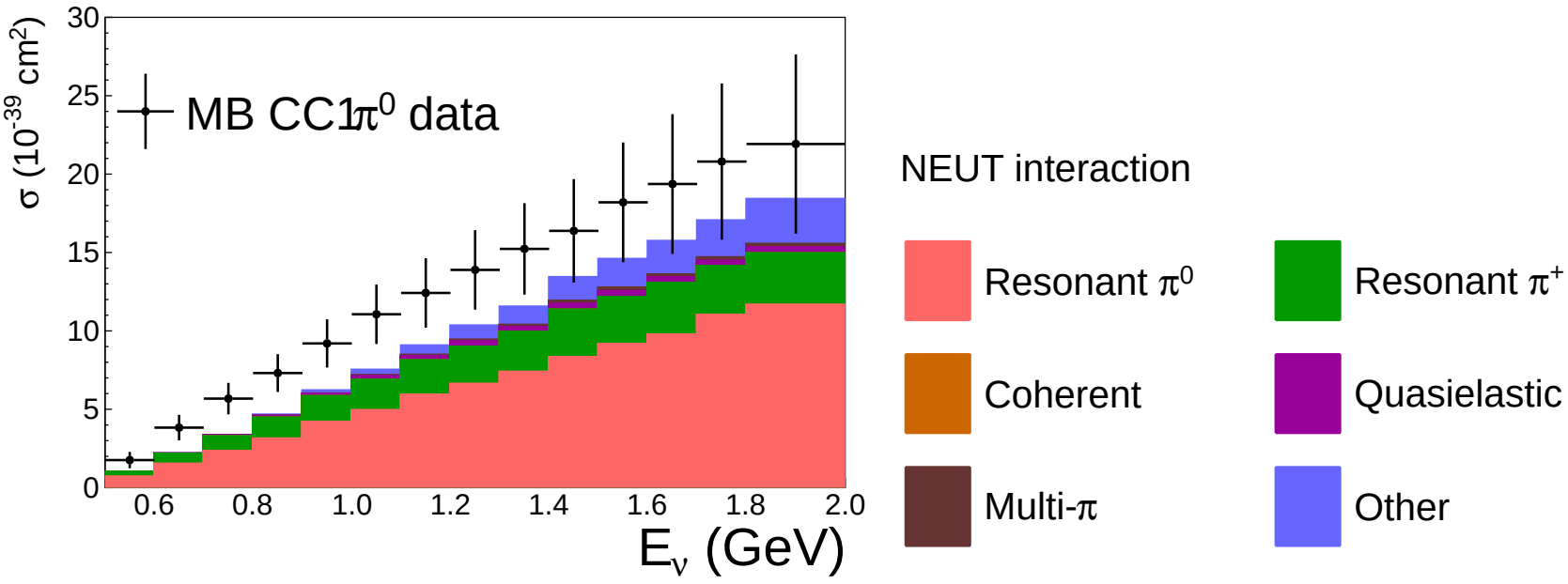
# MiniBooNE NC1$\pi^0$




| | |
|---|---|
| FS particles | 0 $\mu$, 1 $\pi^0$ |
| | No other mesons, but any nucleons |
| Nucleon-level | Resonant $\pi^0$, coherent $\pi^0$ |
| Distributions | $p_\pi$, $\cos\theta_\pi$ |

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

# MiniBooNE CC1$\pi^0$




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

No other mesons, but any nucleons

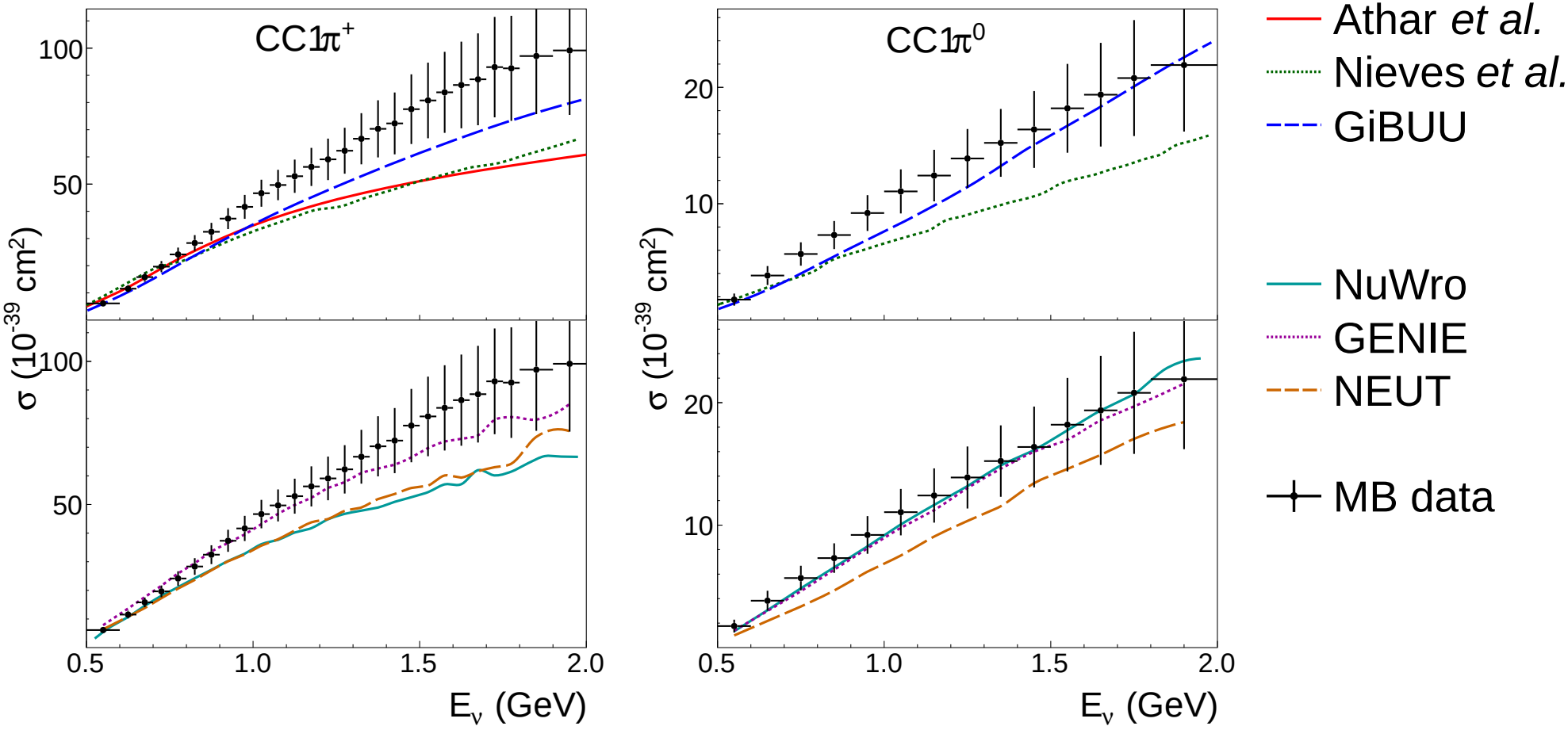
Nucleon-level Resonant $\pi^0$, res. $\pi^+ \longrightarrow \pi^0$

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

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

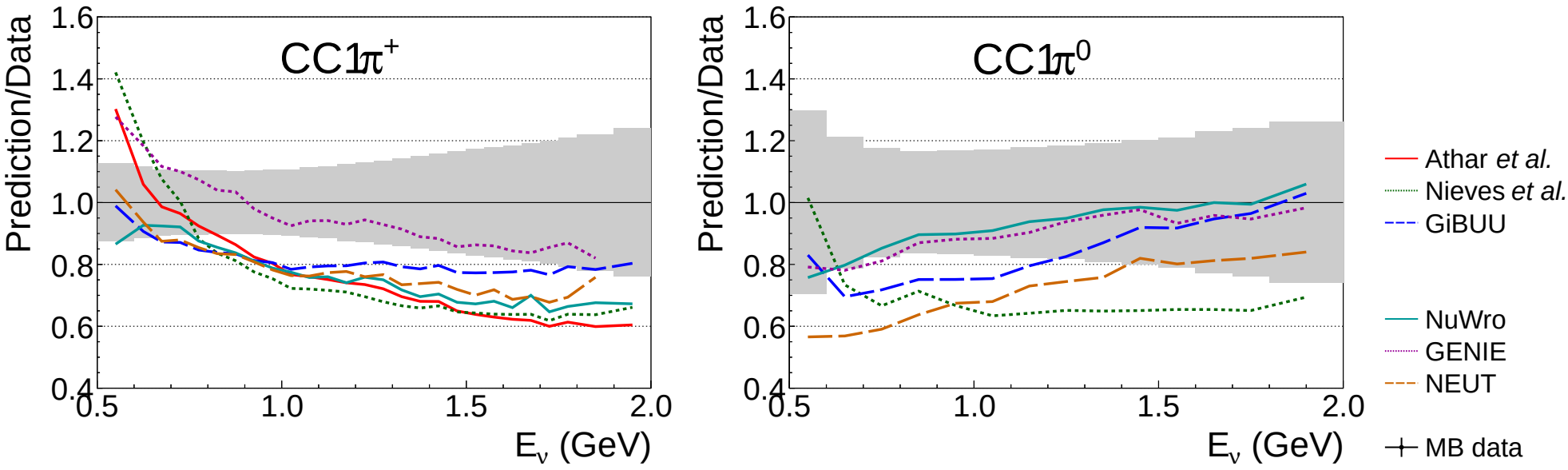
# Comparisons

# Total cross sections



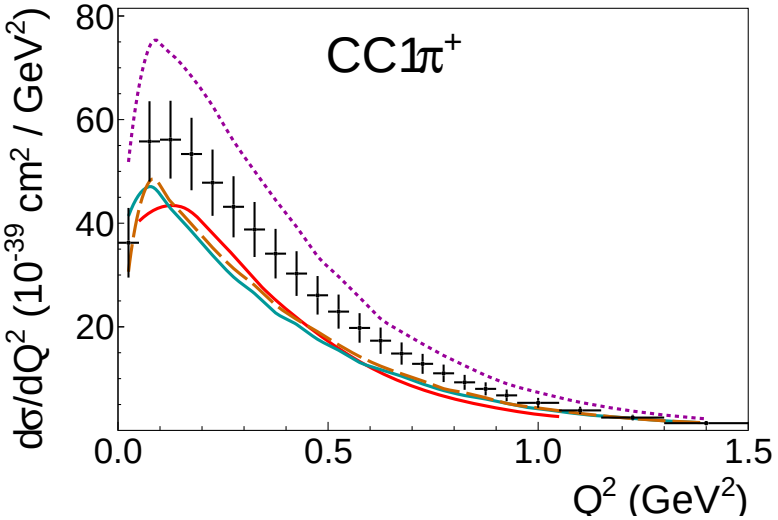

- Disagreements in normalization and shape
- Agreement in CC1$\pi^+$ $\not\Leftrightarrow$ Agreement in CC1$\pi^0$

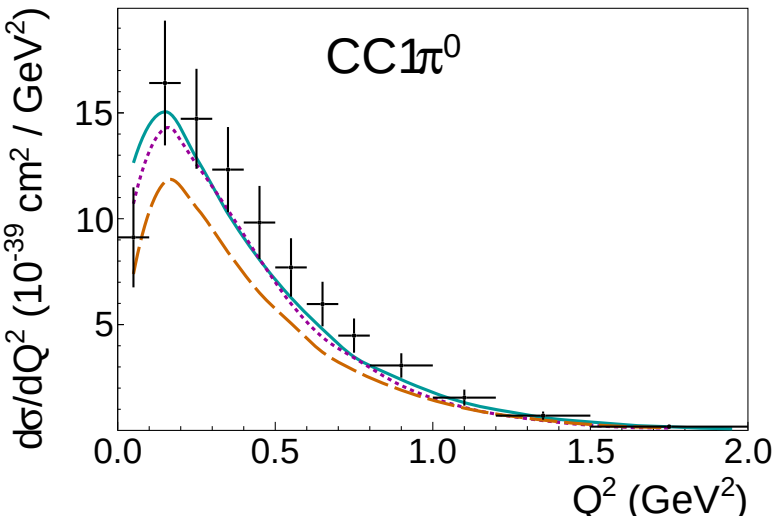
# A feature in ratios

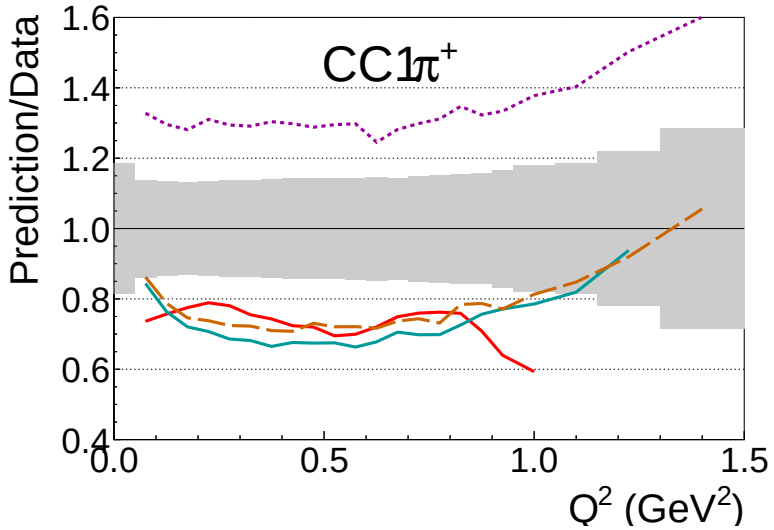


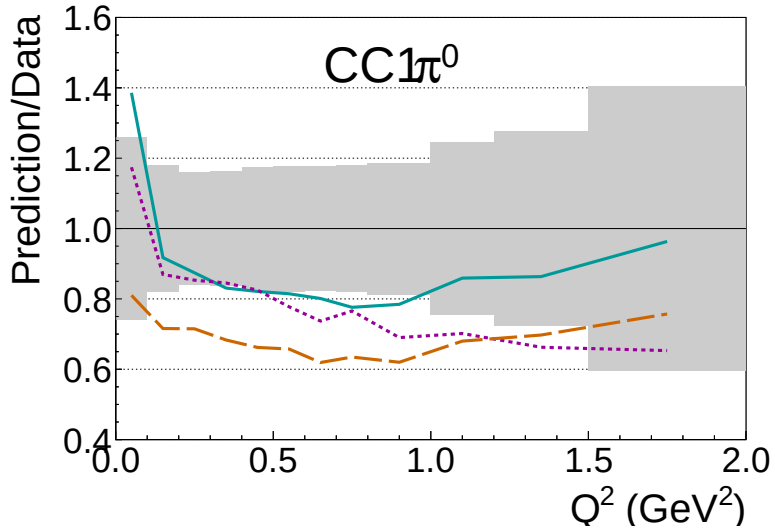

- CC1$\pi^+$: Shape difference between model and data is common to all models
- CC1$\pi^0$: Similar shape commonality, but in opposite direction
- Can't *just* be the flux
  - "Glass half full:" taking datasets together provides more information
  - "Glass half empty:" simultaneous agreement difficult/impossible

# $d\sigma/dQ^2$




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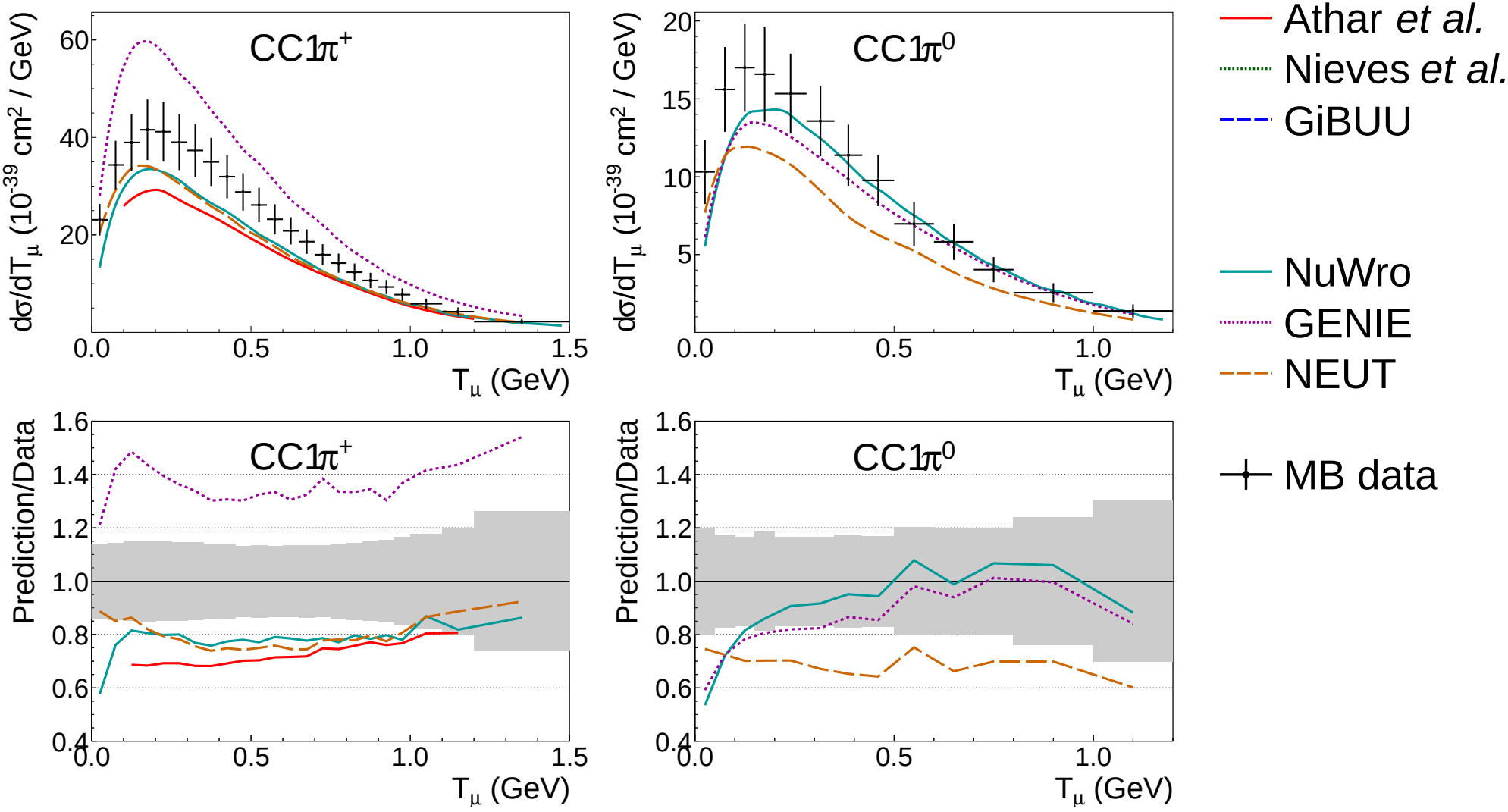
MB data

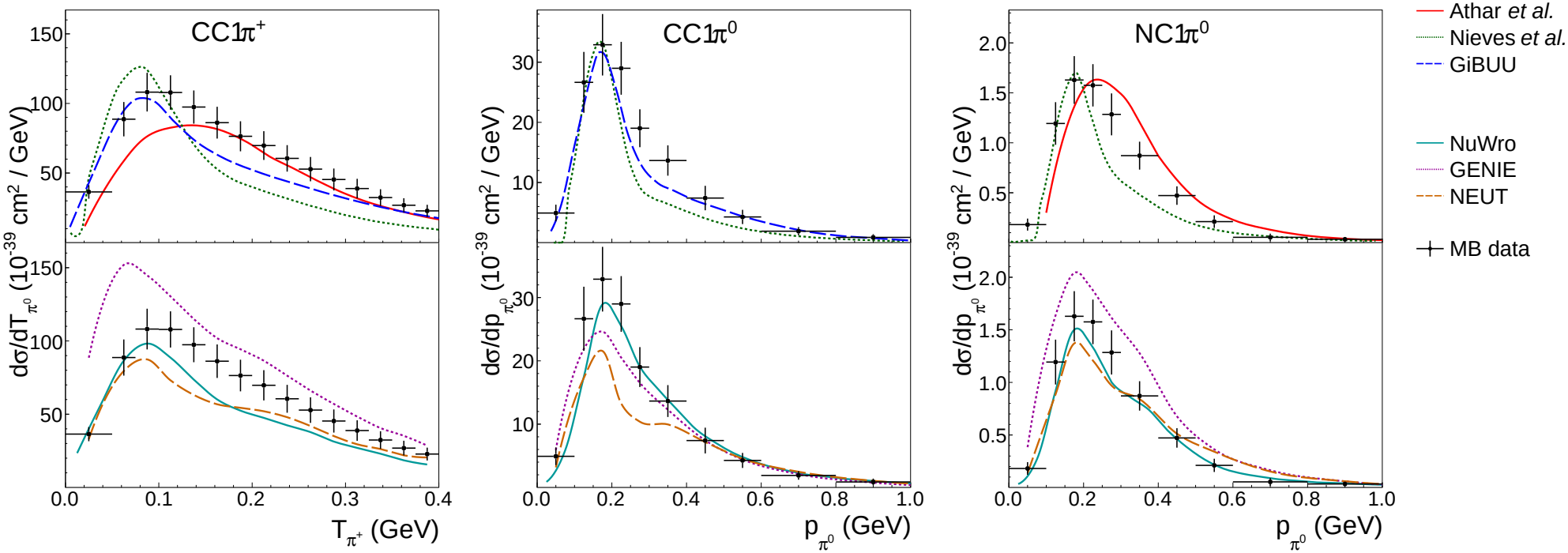
- Some shape difference commonalities

# Muon kinetic energy




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

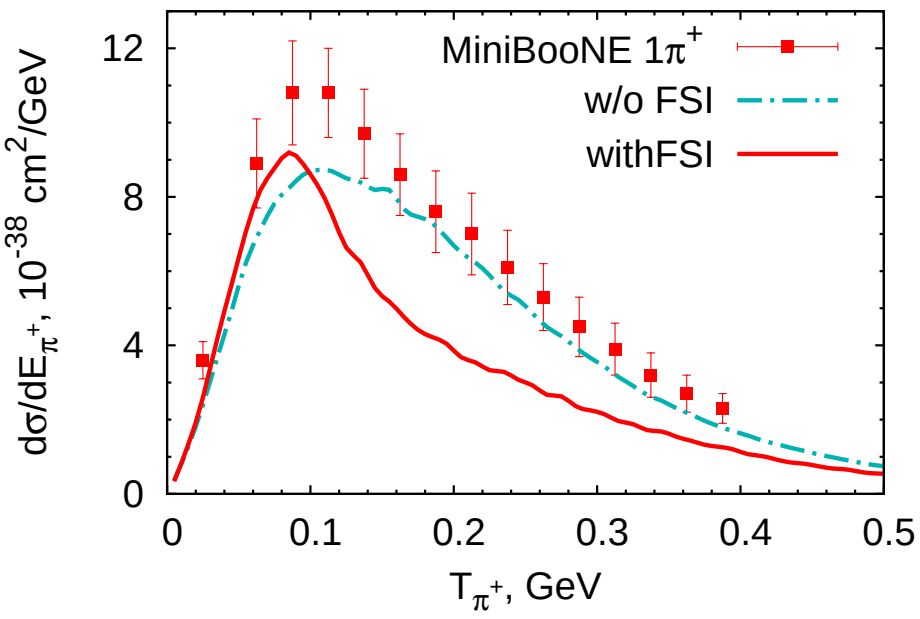
# Pion momentum/energy




- Poor agreement across the board in CC1$\pi^+$
- Generators do better than theoretical models in CC1$\pi^0$, NC1$\pi^0$

# Final state effects

GiBUU

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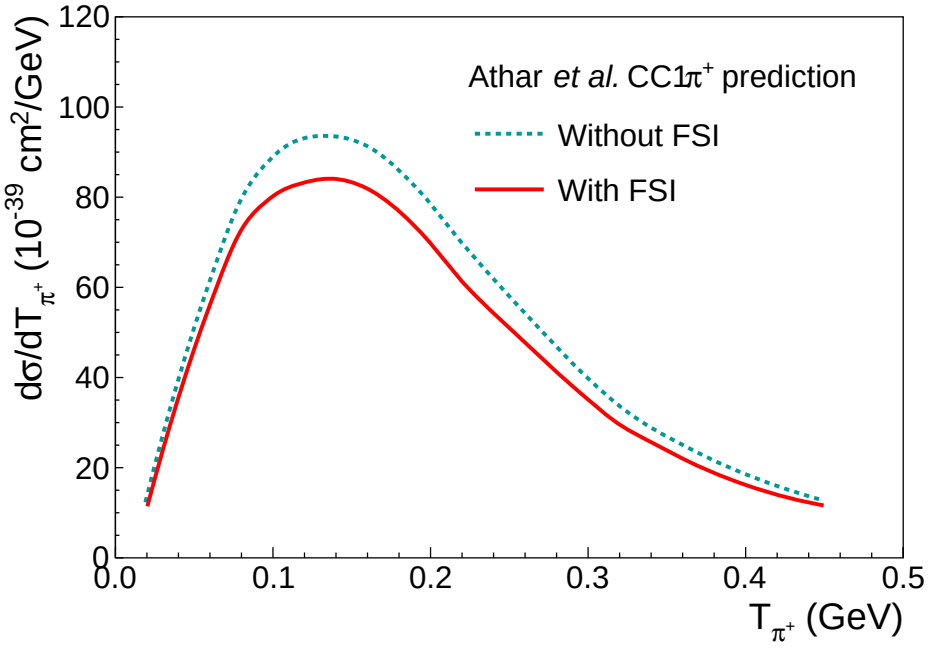
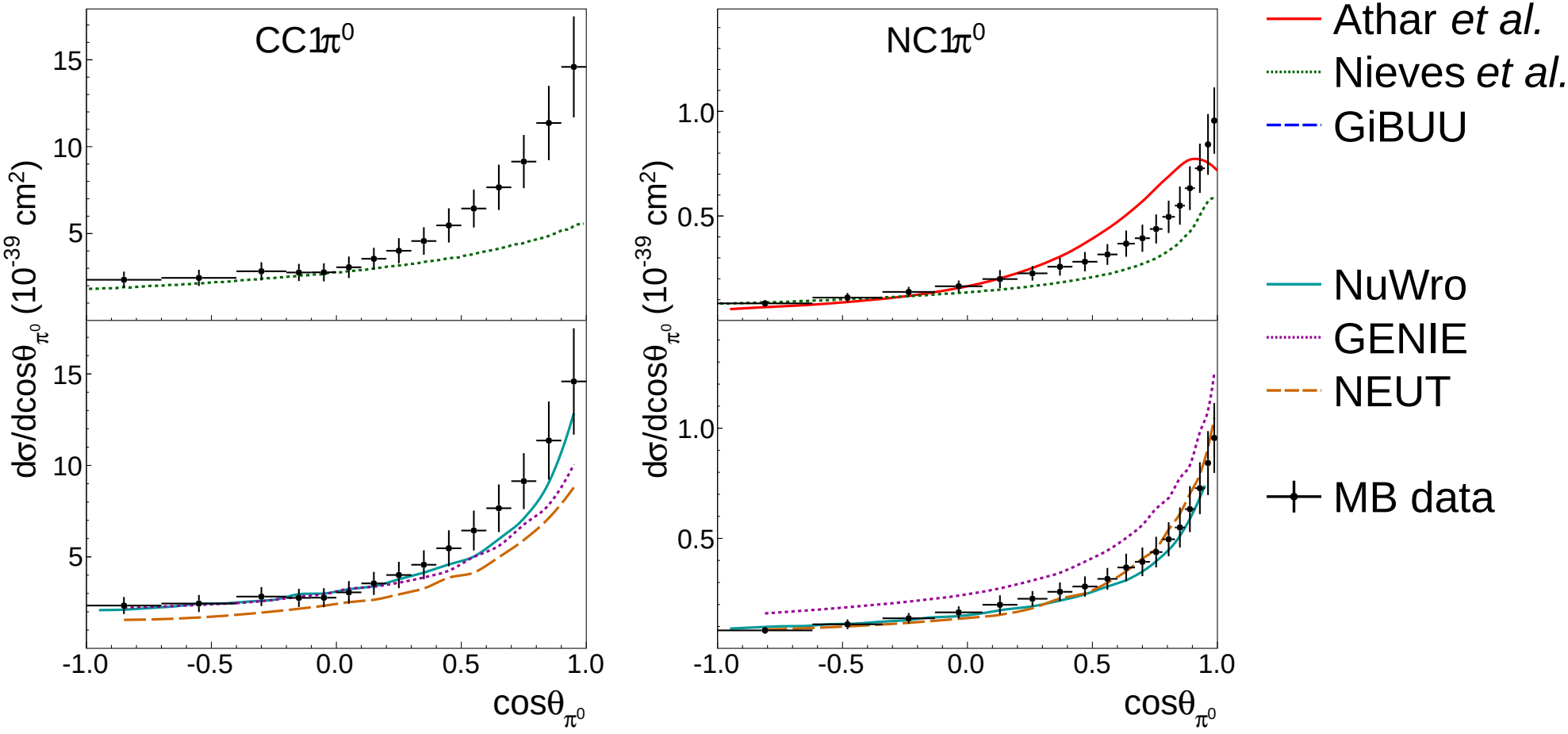



Plot from arXiv:1107.5947 (NuInt11 proceedings)

- Significant, but uncertain, effect
- Shape and normalization

# Pion angle




- CC1$\pi^0$ pion angle more forward-peaked in data than most models
- NC1$\pi^0$ better described by generators (tuning?)

# Conclusions

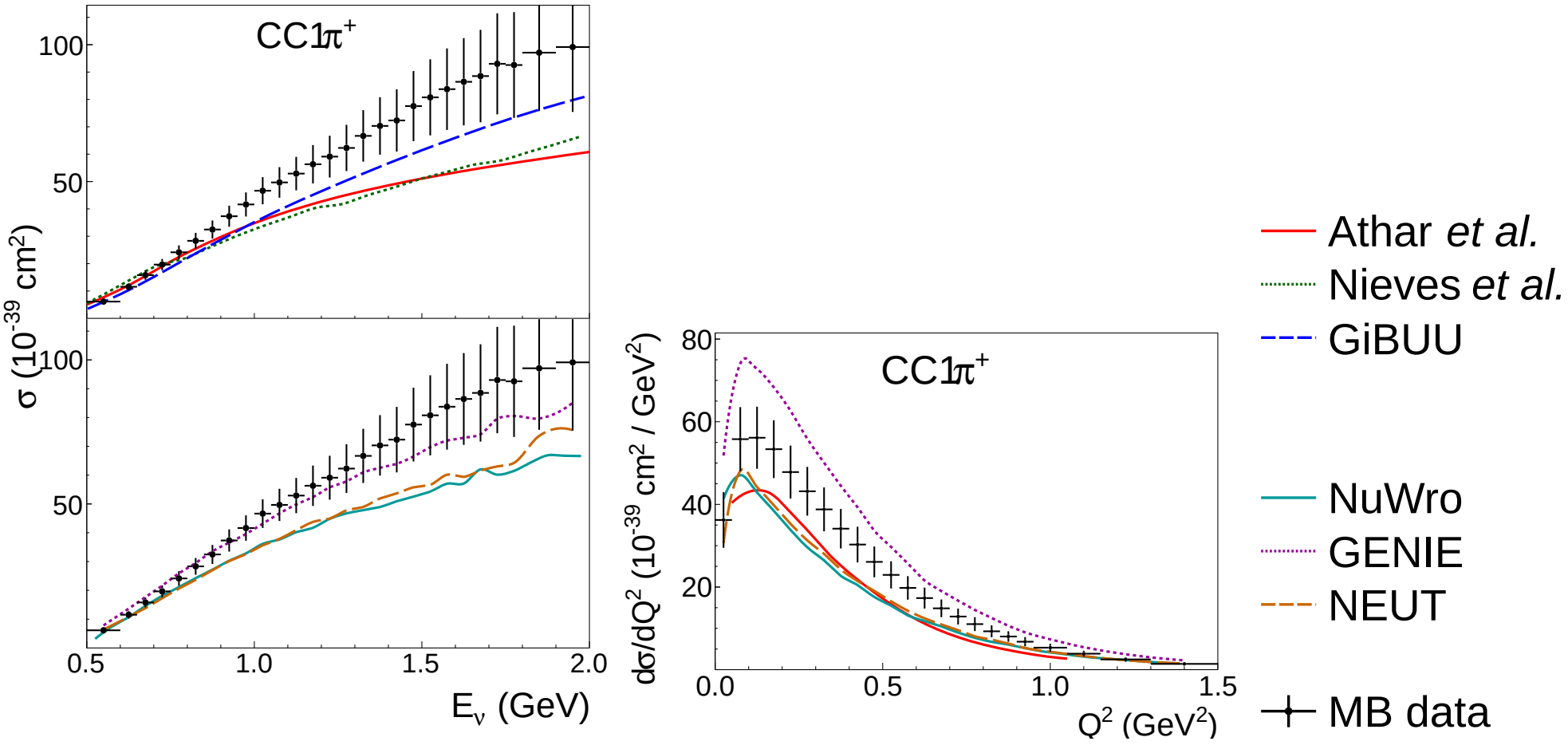
- General:
  - Detailed data allows stringent model tests
  - Maximize value by considering datasets together
- Specific:
  - Generator agreement better than theory models(?) How much of this is "tuning"?
  - Some large pion kinematic variable discrepancies

# 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?

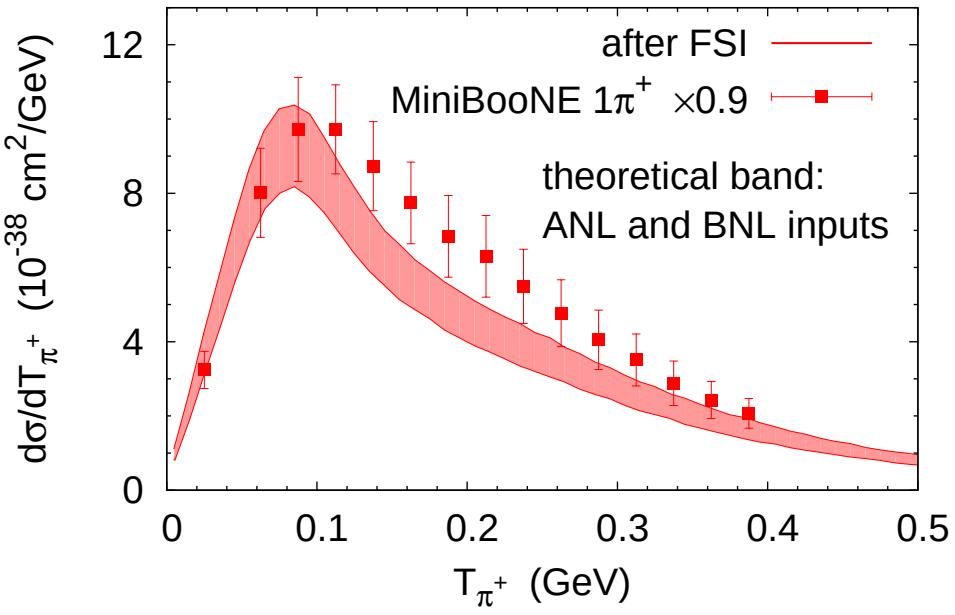
# Backup slides

# MiniBooNE CC1$\pi^+$ comparisons 1




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

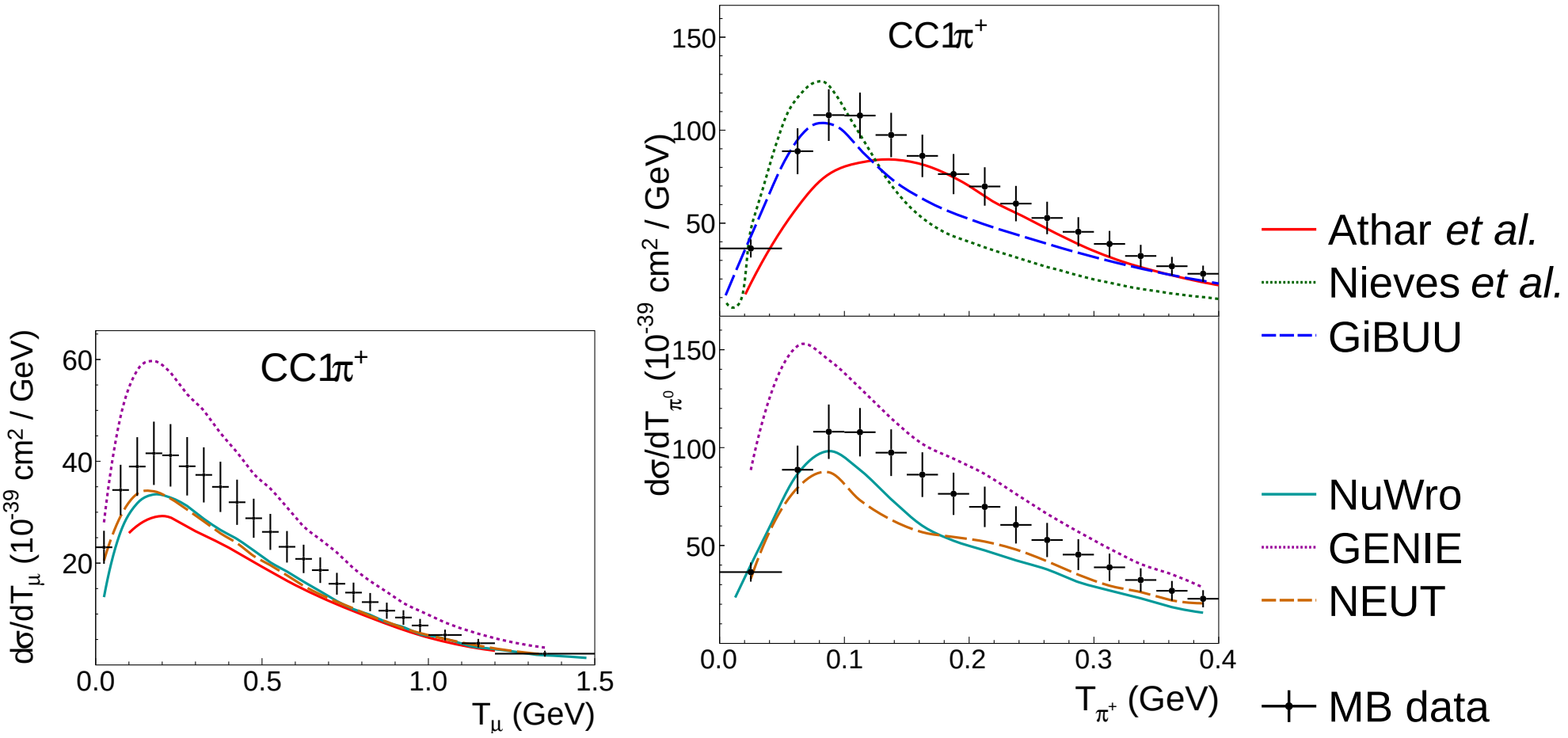
# Relation to deuterium data




Plot courtesy O. Lalakulich

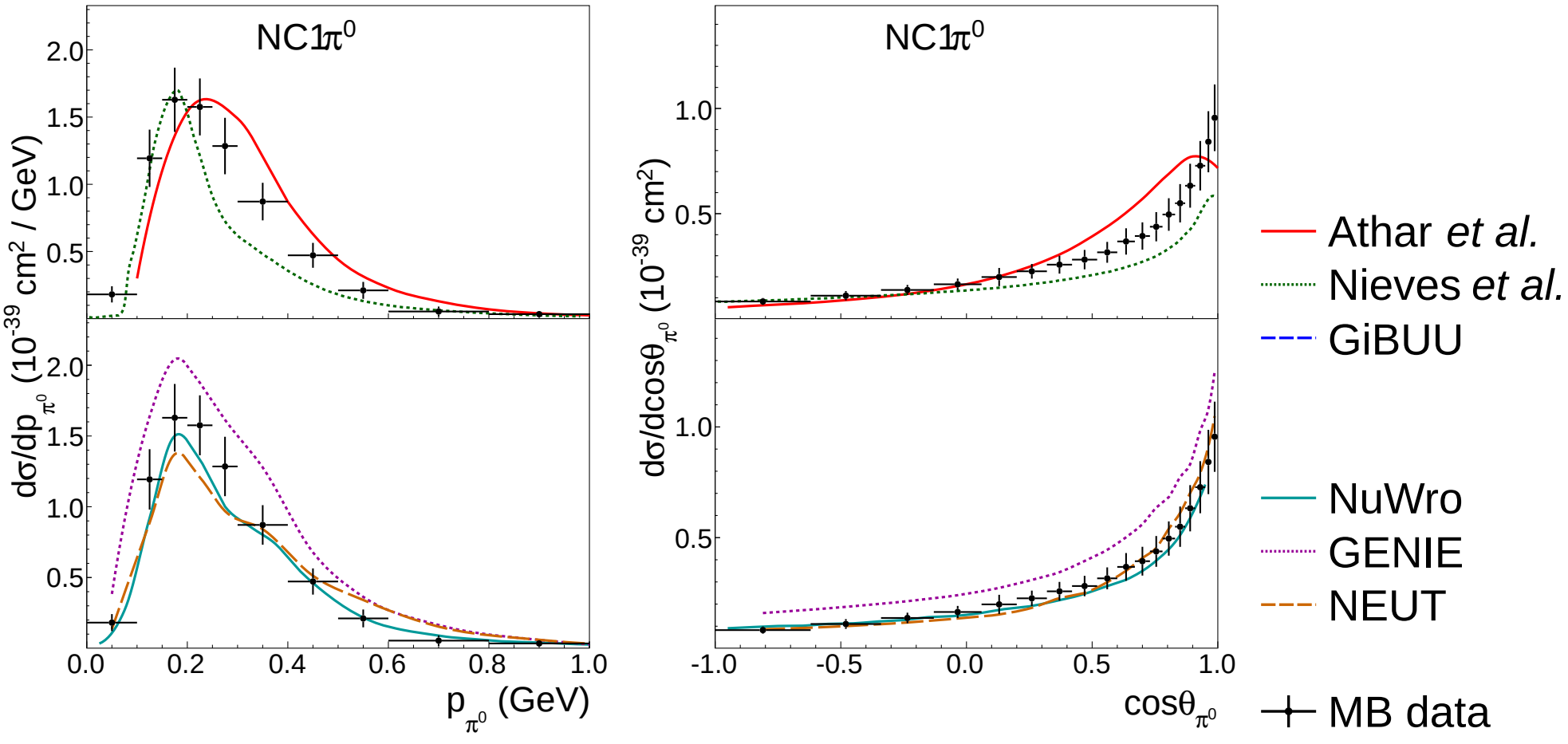
- Disagreement between MiniBooNE and deuterium data...
- Disagreement between deuterium data and deuterium data

# MiniBooNE CC1$\pi^+$ comparisons 2

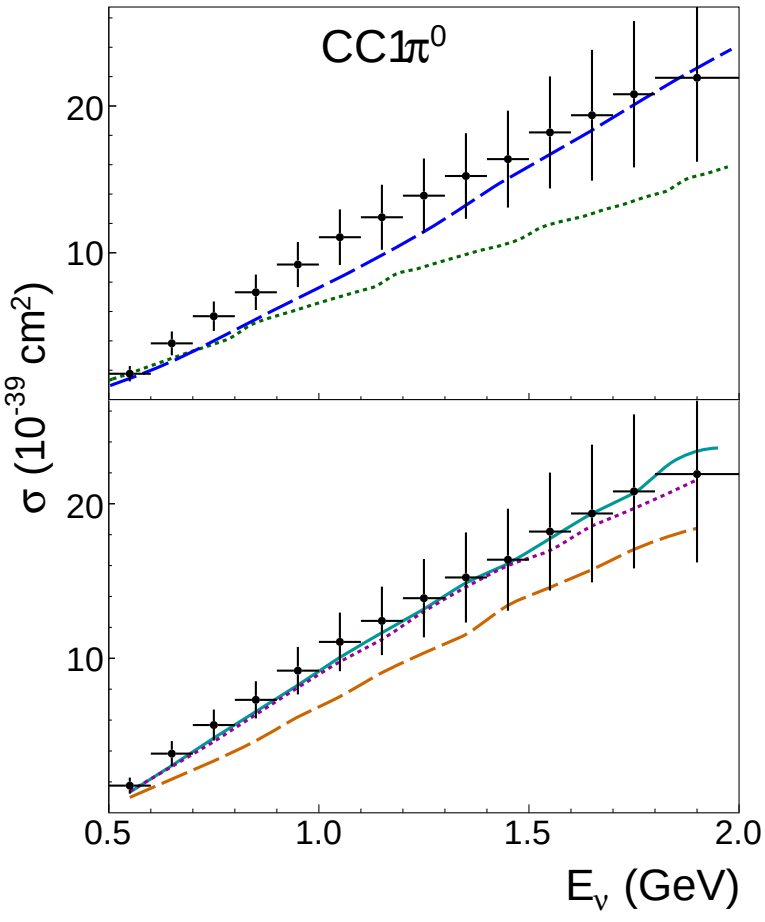


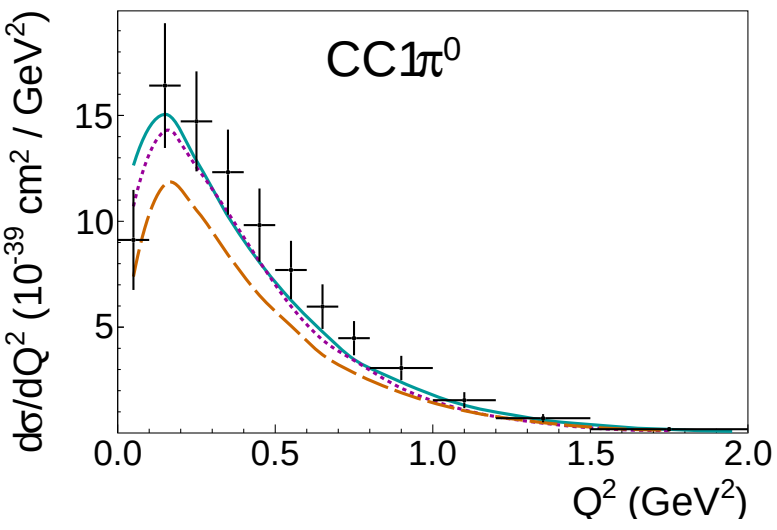

- $T_\pi$ distribution sensitive to final state effects. No model with good agreement

# MiniBooNE NC1$\pi^0$ comparisons



# MiniBooNE CC1$\pi^0$ comparisons 1

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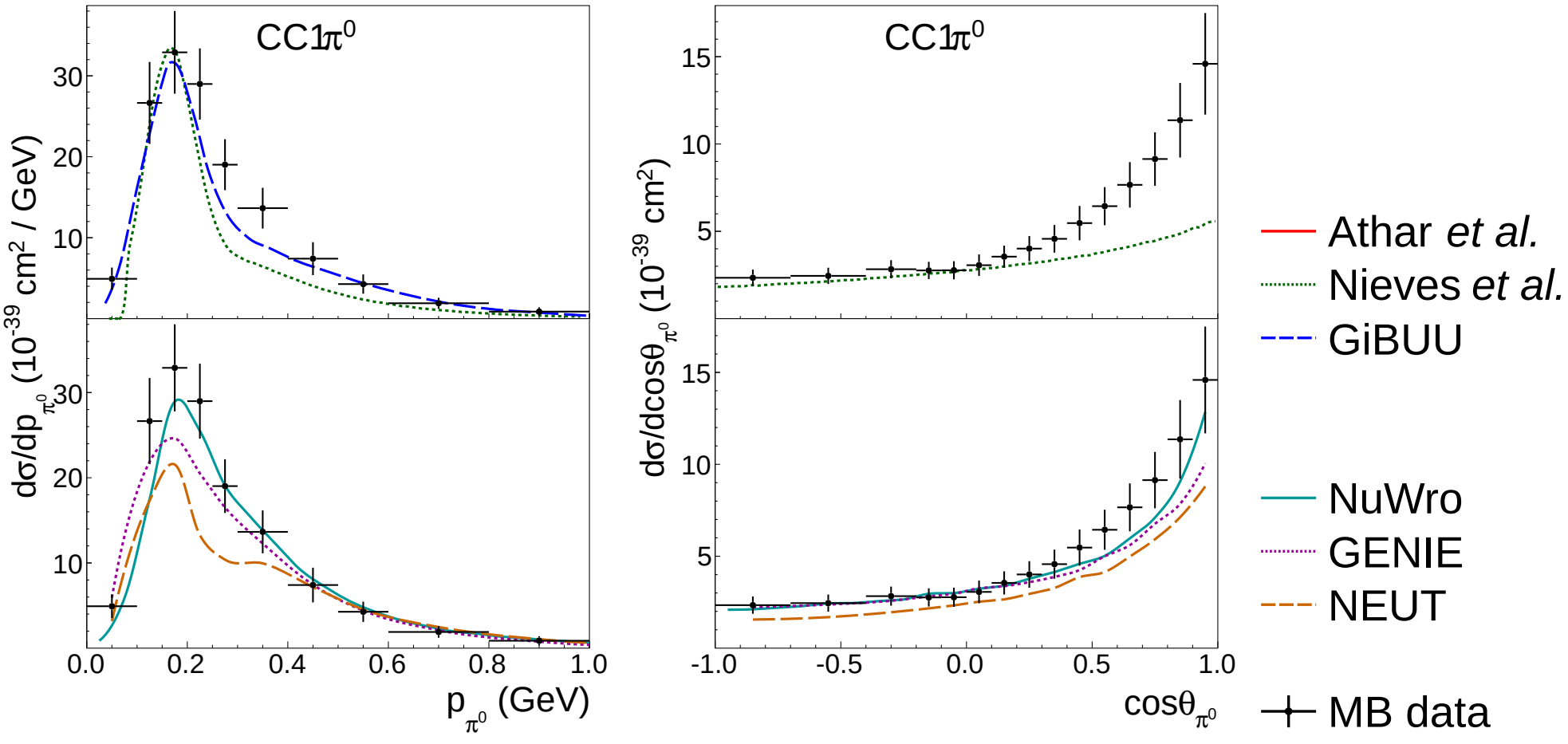
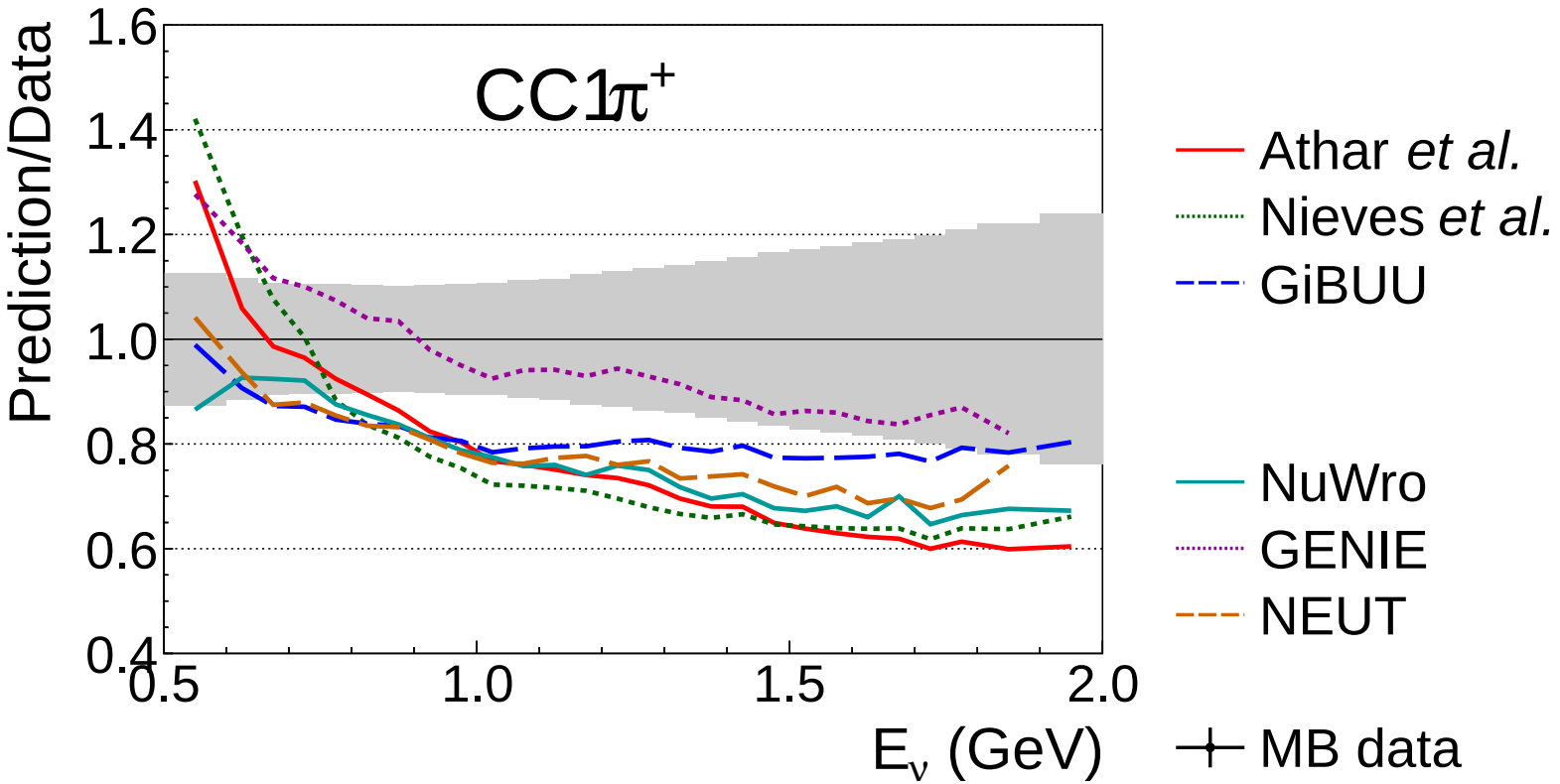
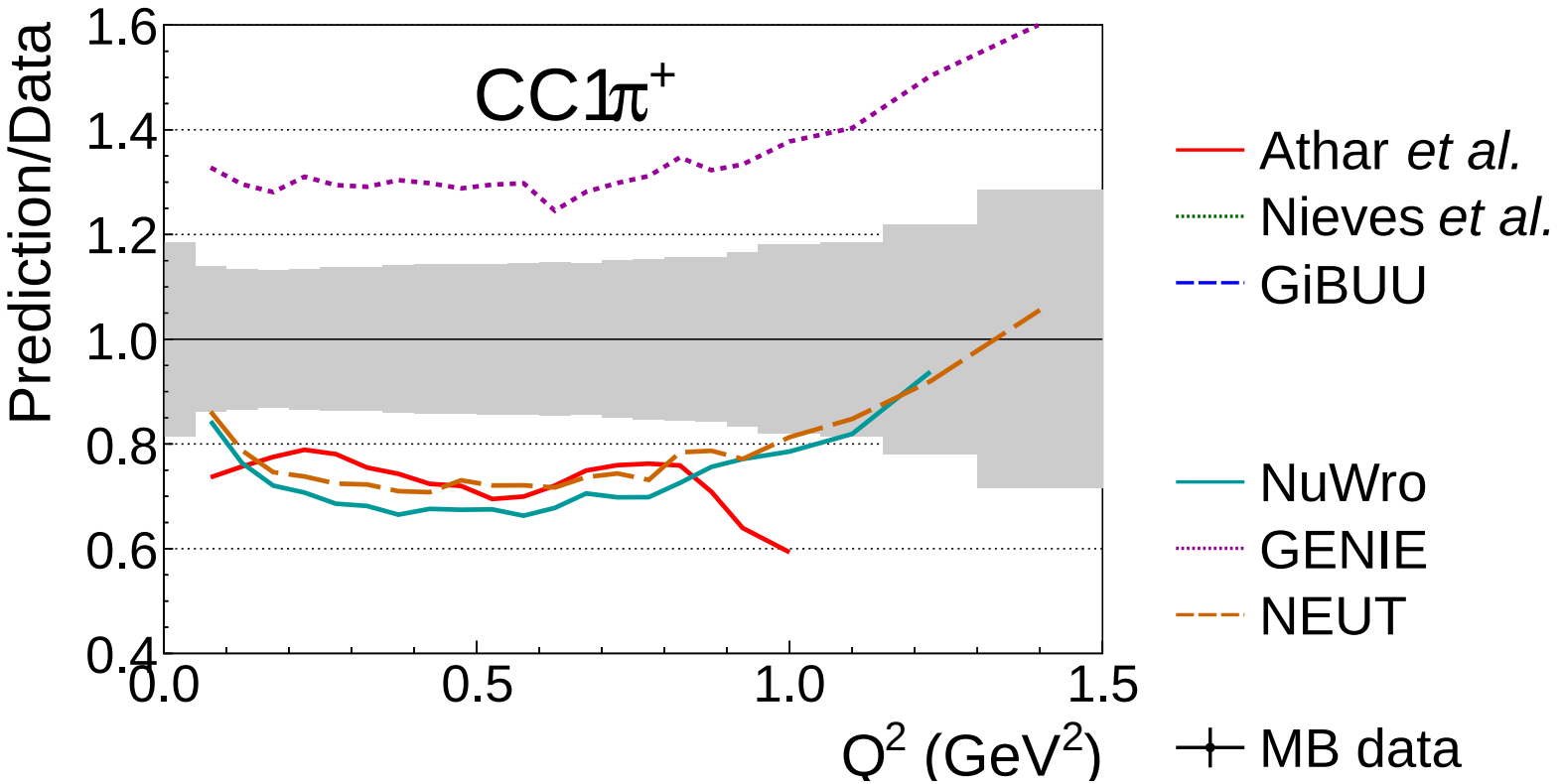


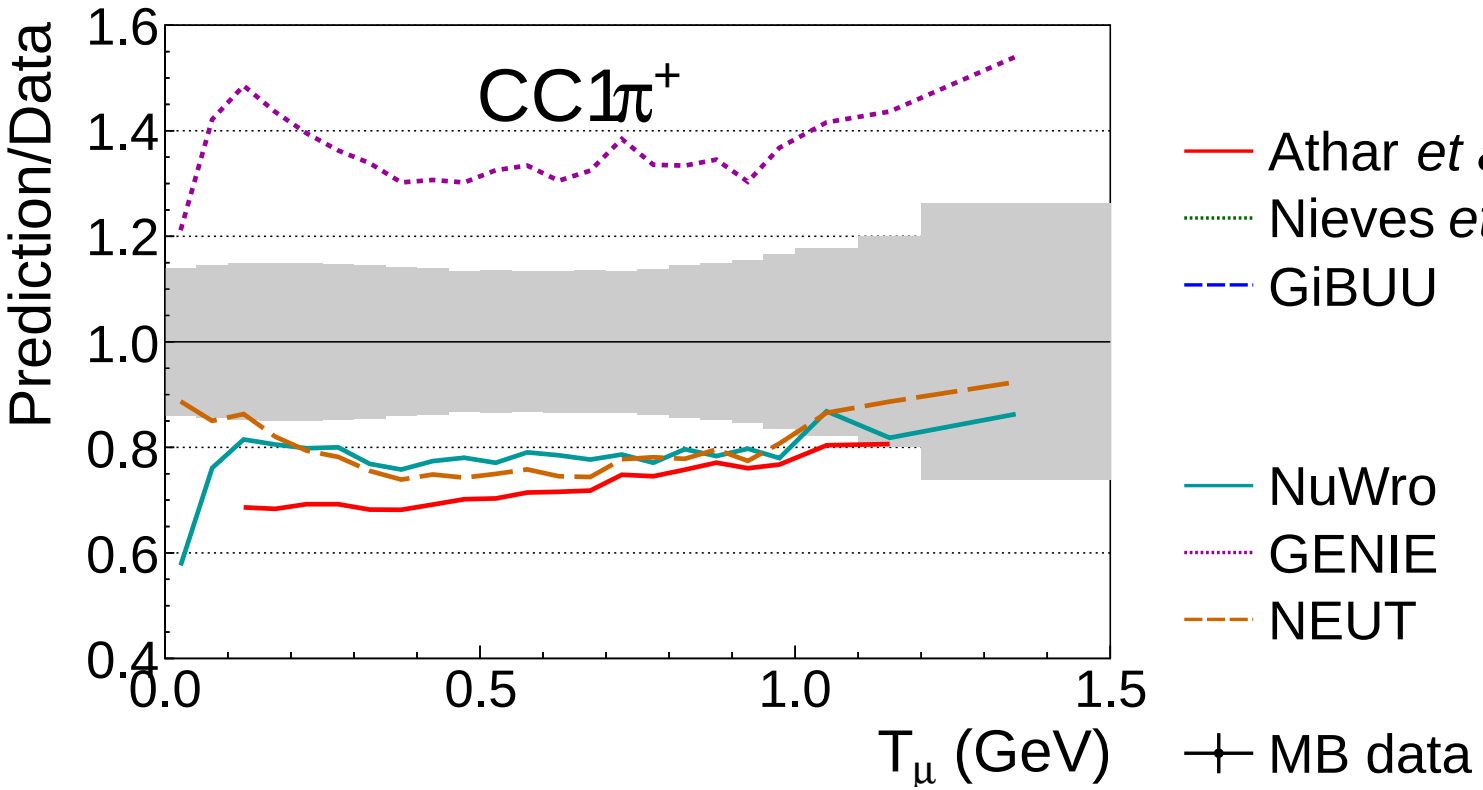
# ccpip-enu-ratios



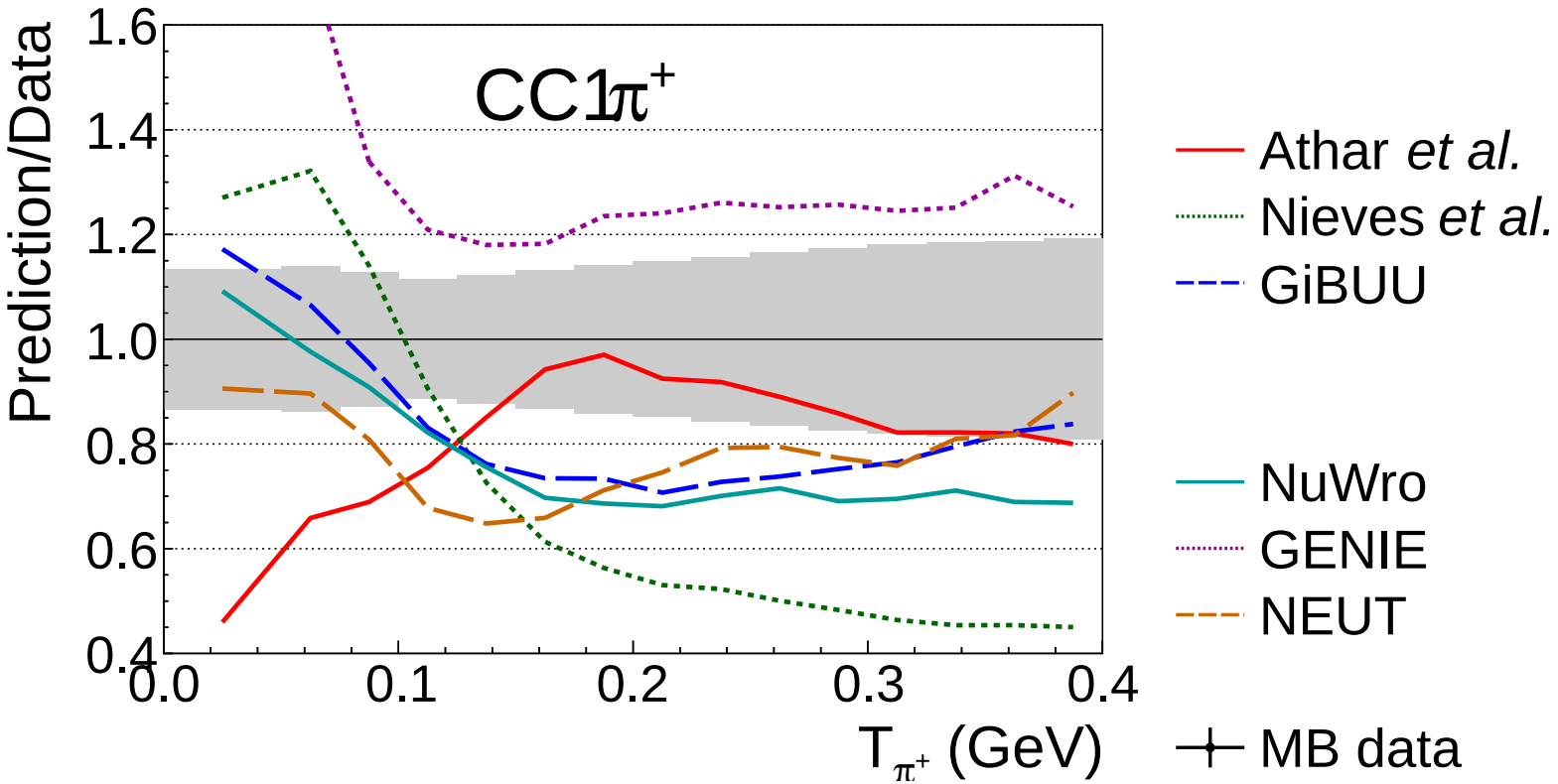
# ccpip-q2-ratios



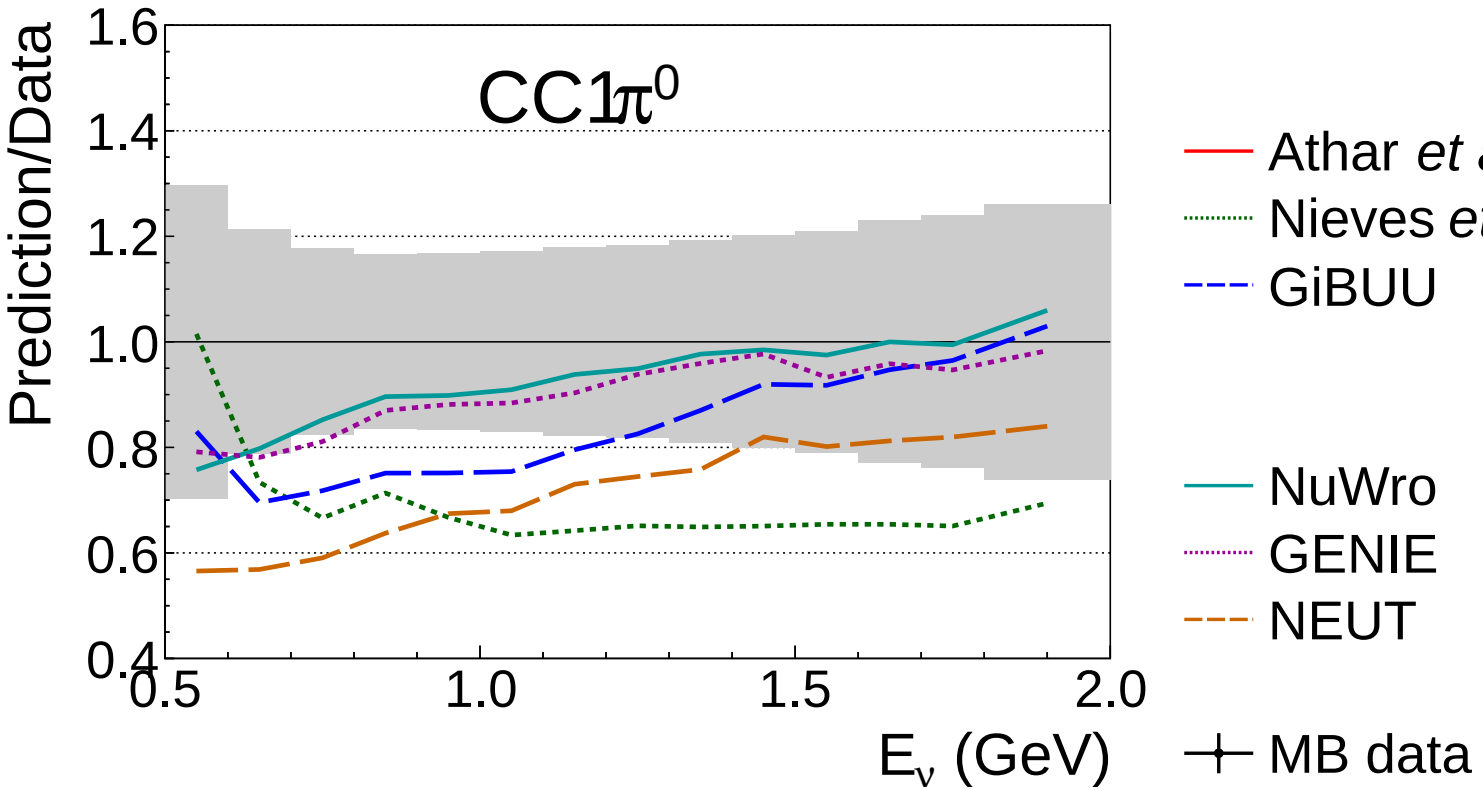
# ccpip-tmu-ratios



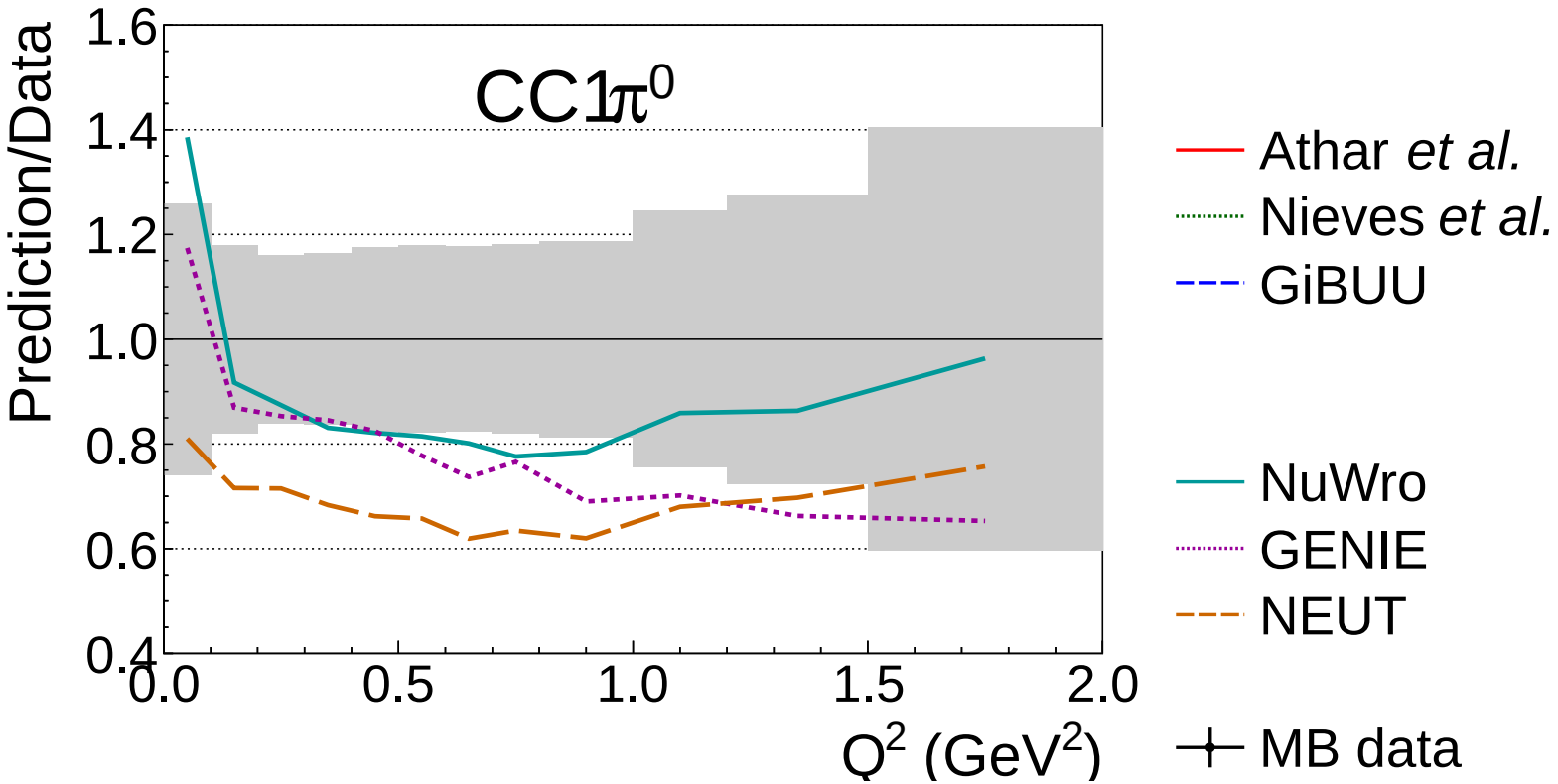
# ccpip-tpi-ratios



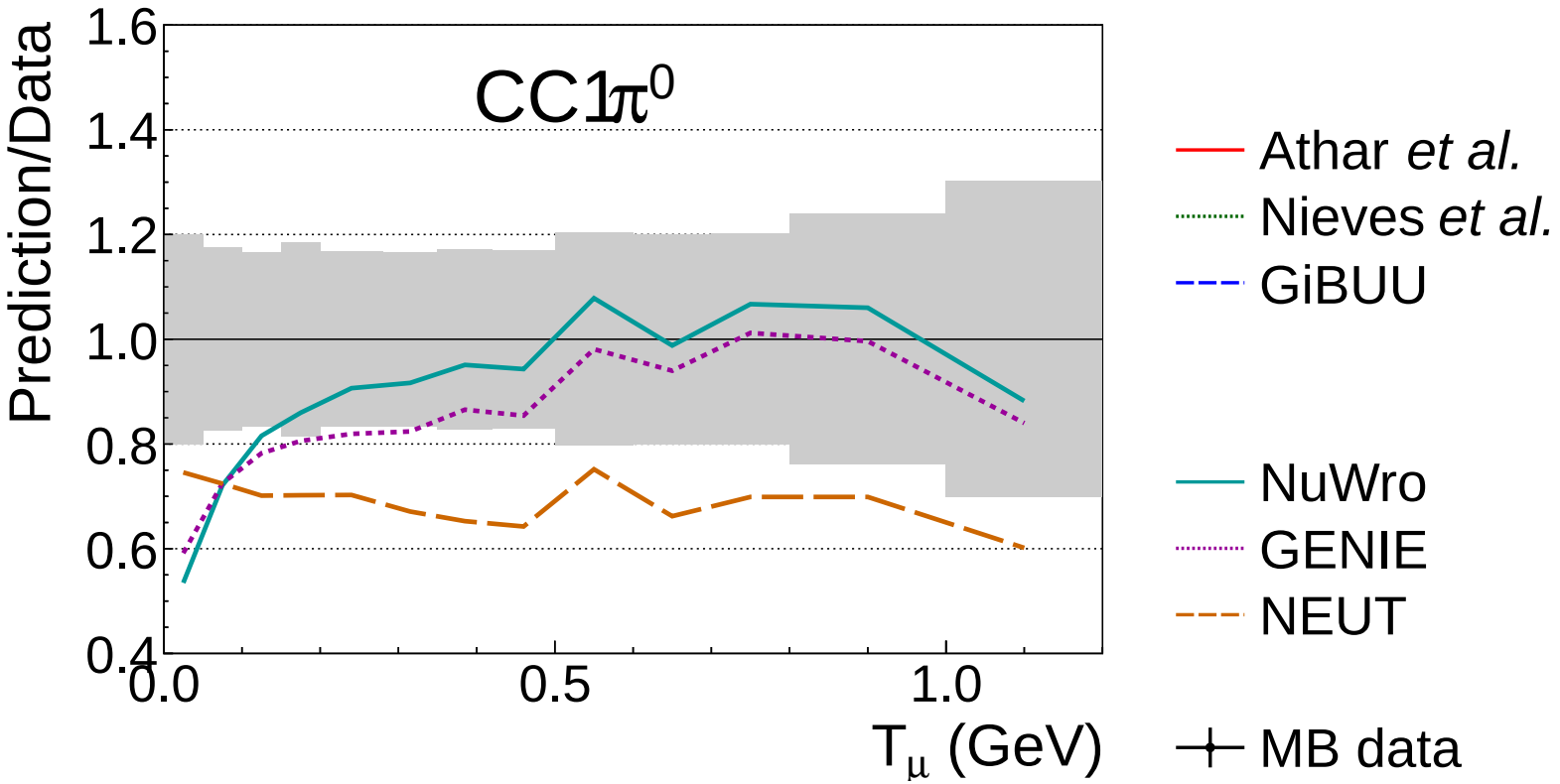
# ccpi0-enu-ratios



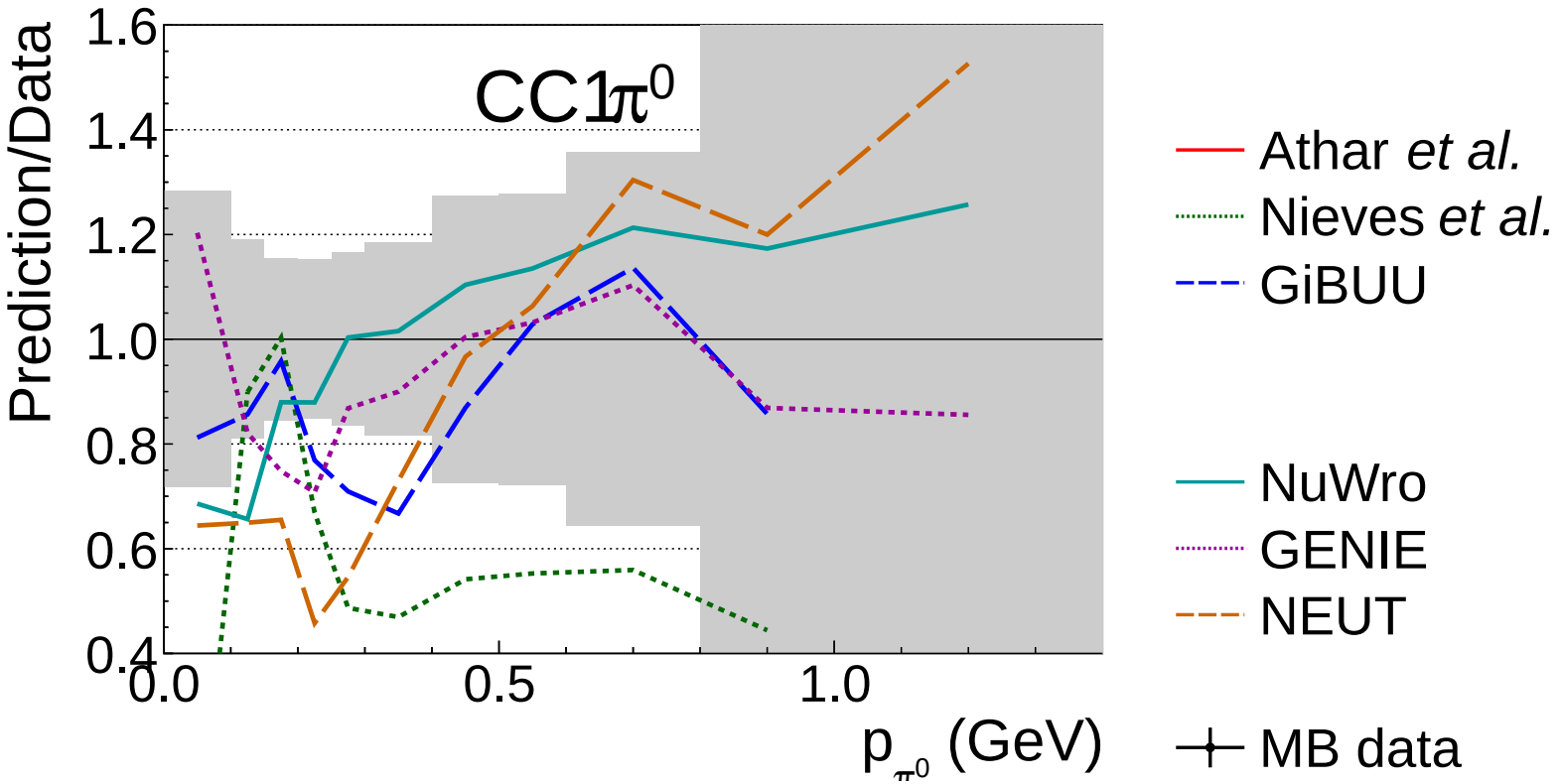
# ccpi0-q2-ratios



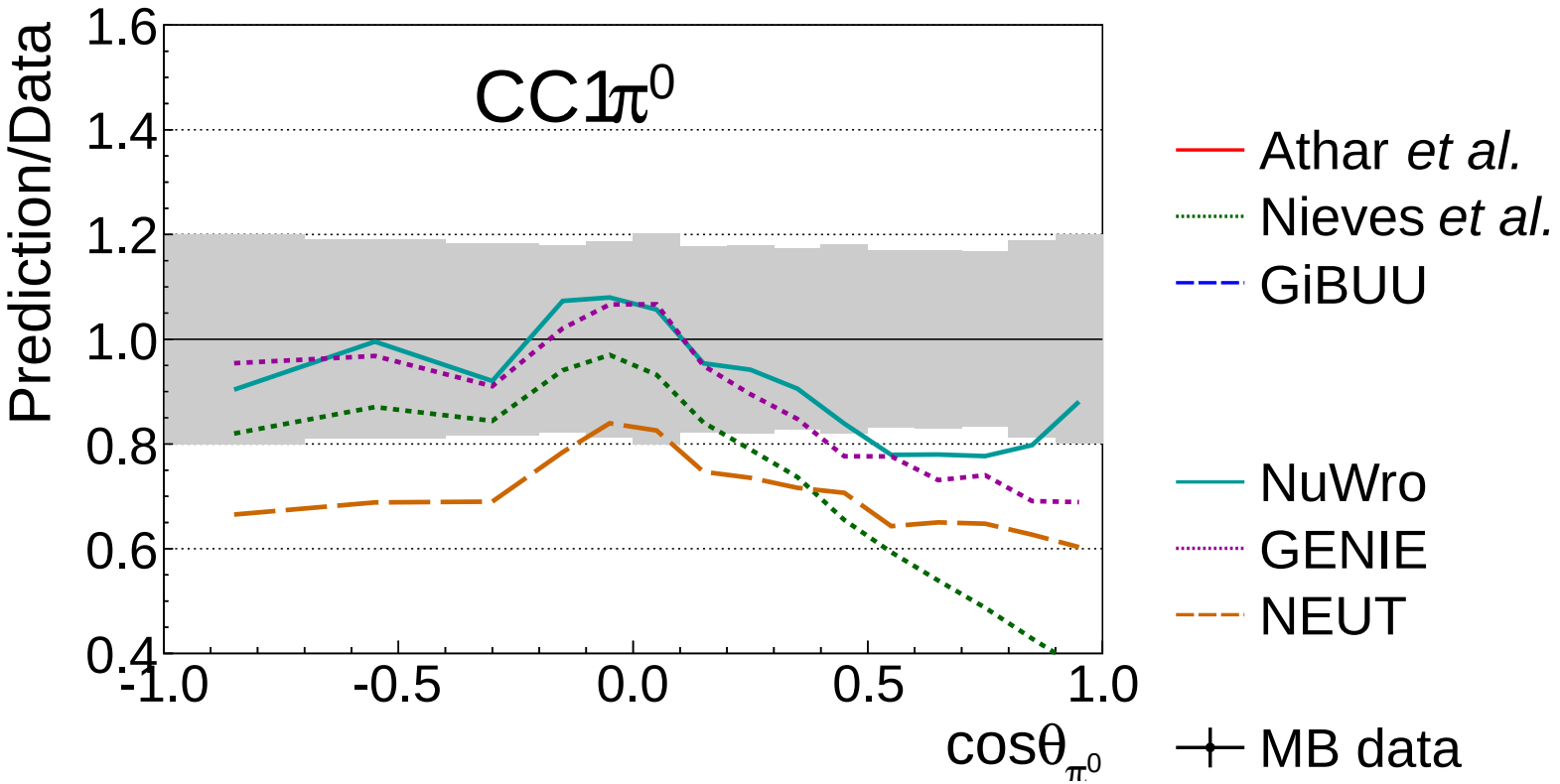
# ccpi0-tmu-ratios



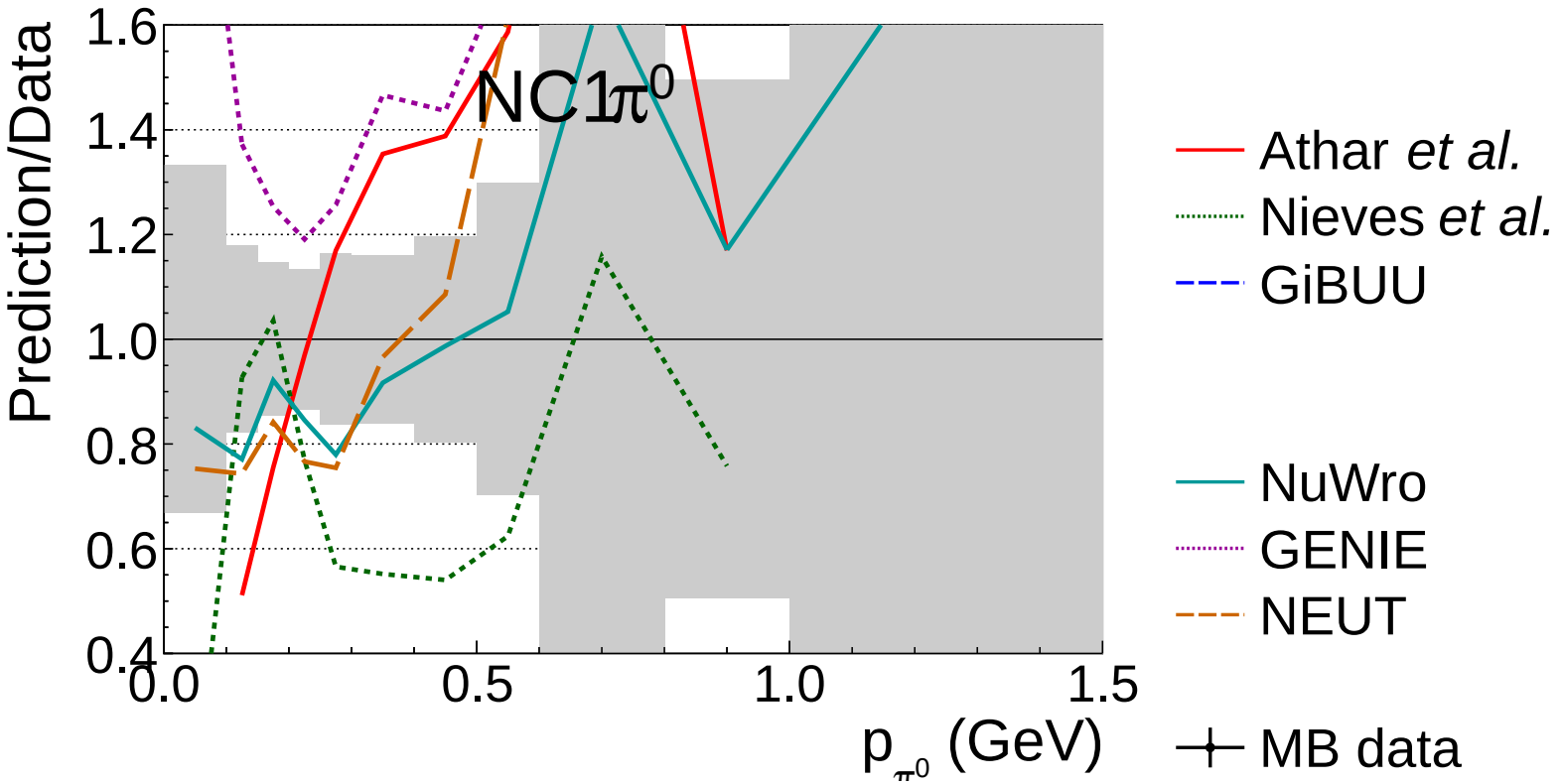
# ccpi0-ppi-ratios



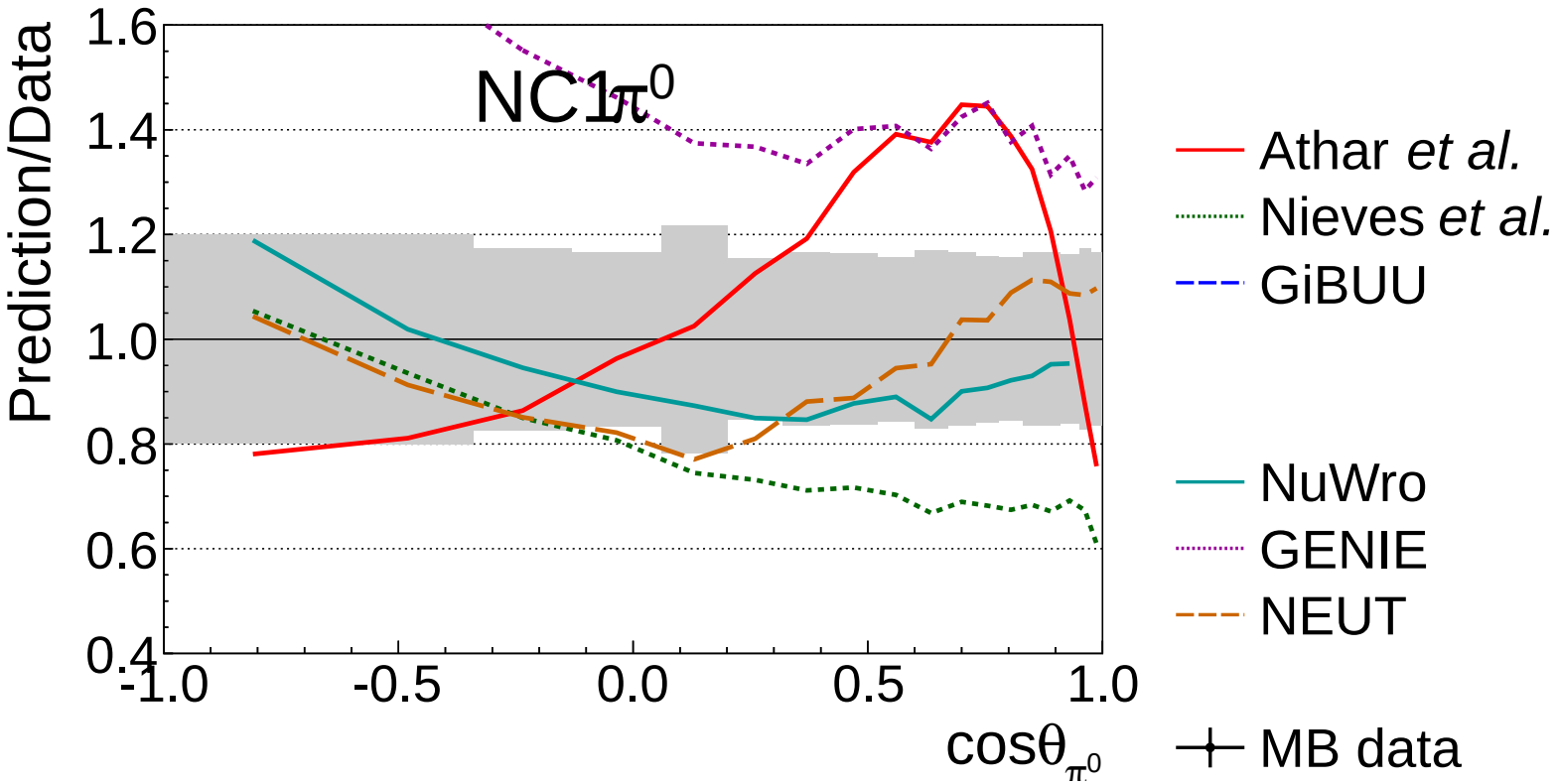
# ccpi0-cospi-ratios



# ncpi0-ppi-ratios

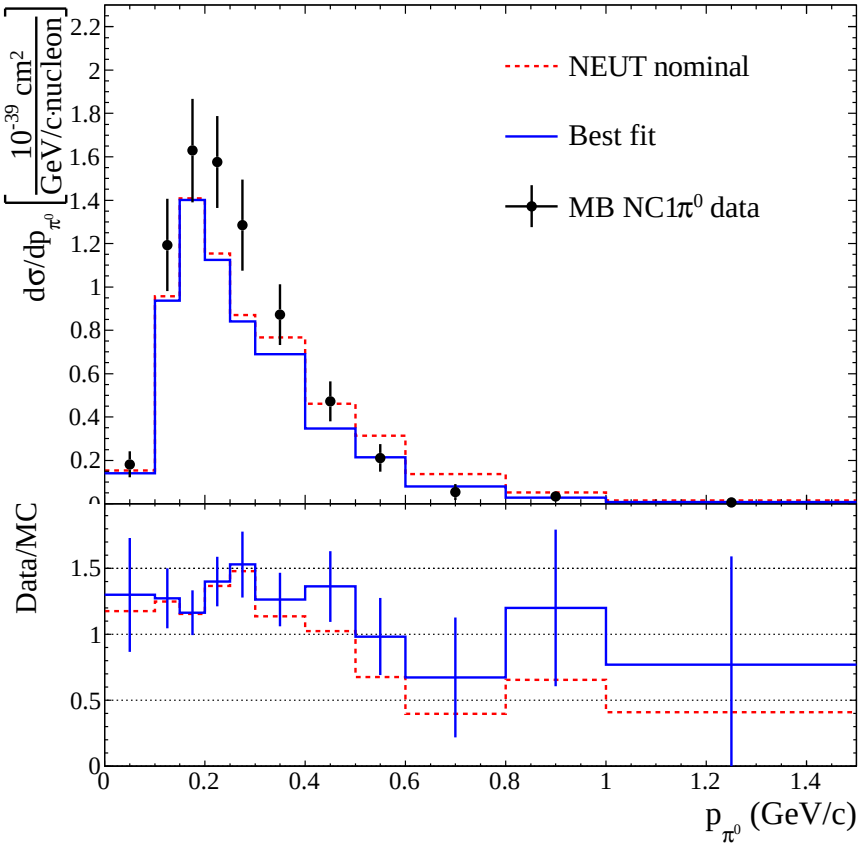


# ncpi0-cospi-ratios



# 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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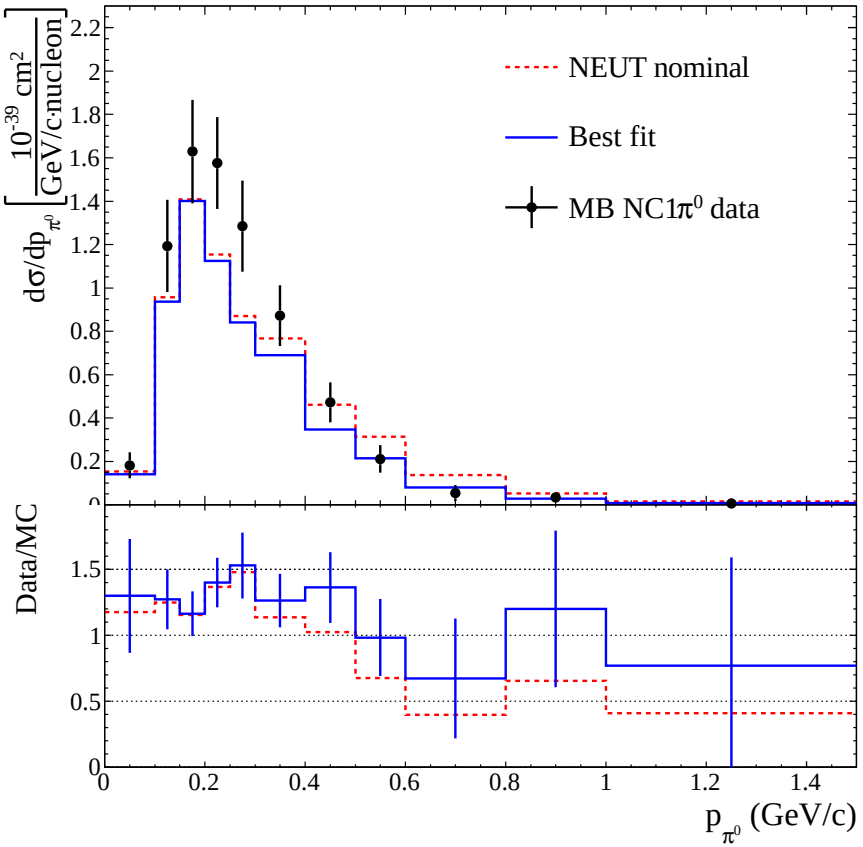


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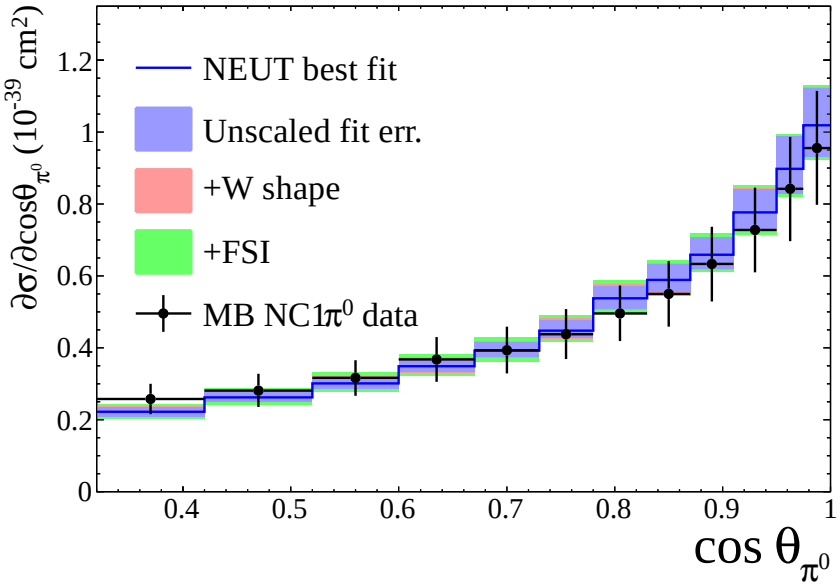
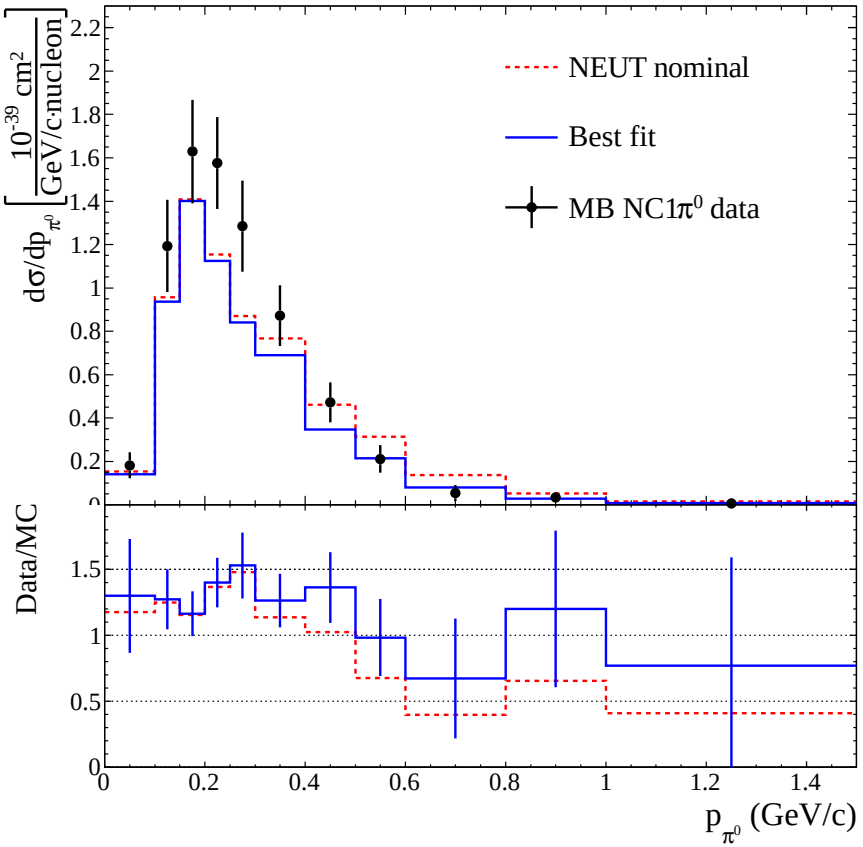


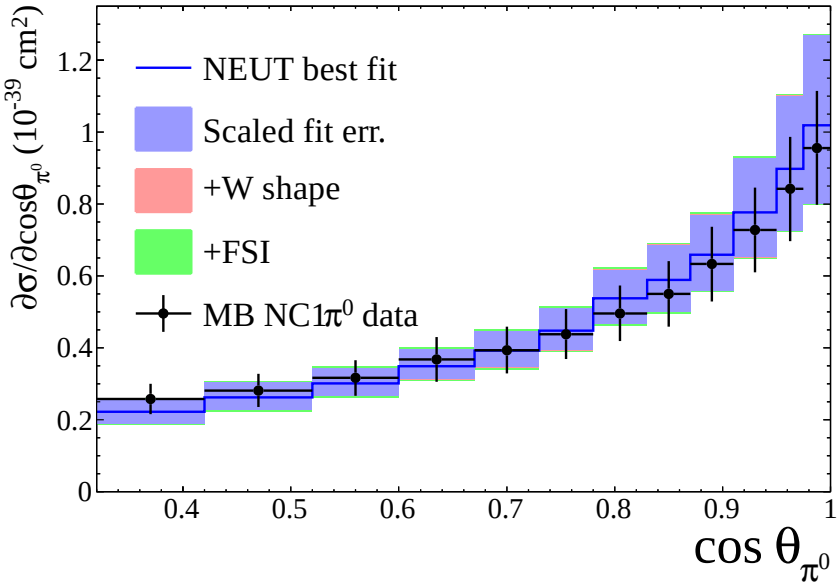

- Exclude correlations ⇒ too-small errors

# Correlations and "Peelle's Pertinent Puzzle"

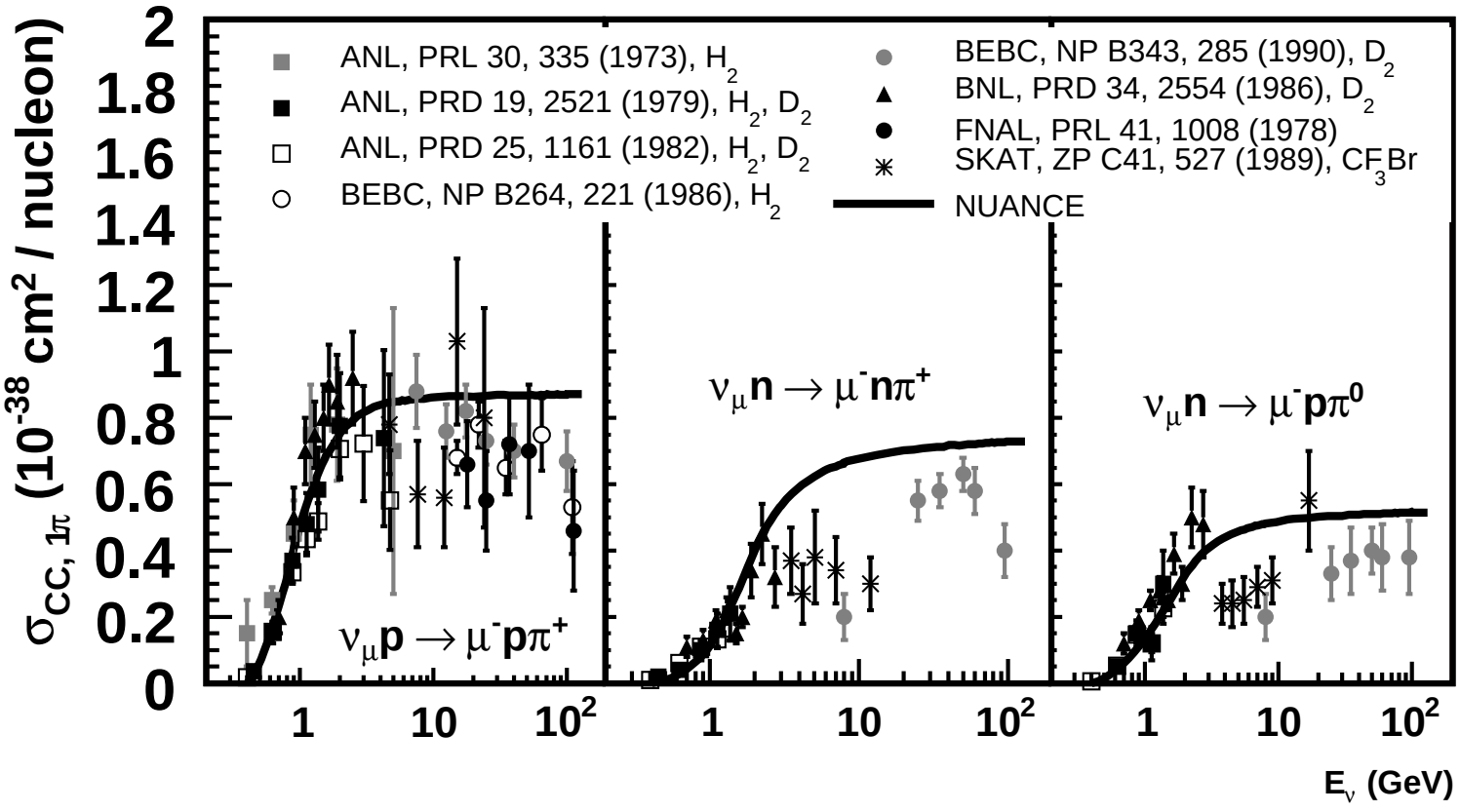
$$\chi^2 = (\mathbf{D} - \mathbf{M})^T \mathbf{V}^{-1} (\mathbf{D} - \mathbf{M})$$




- 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