FERMILAB-POSTER-23-206-STUDENT

Coherent Pion Production to Constrain DUNE Flux

Jonathan Rositas, University of Chicago – SULI Intern

Introduction

Neutrino-induced Coherent Pion Production (CPP) is an interaction between a neutrino and target nucleus where the nucleus stays in its ground state, the neutrino is converted into an appropriate lepton (in the charged current case), and a pion of appropriate charge is produced, as shown in fig 1. CPP has few products, is relatively easily identified, and has negligible effects from final state interactions, so it is promising as a candidate to constrain neutrino flux at the Deep Underground Neutrino Experiment (DUNE).

Motivation

CPP's cross section is proportional to the poorly constrained value of the axial form factor, $F_A(Q^2)$, where Q^2 is the momentum transfer from the neutrino. Accordingly, various descriptions have been presented to constrain this value, and the sensitivity of measurements to these descriptions should be evaluated.

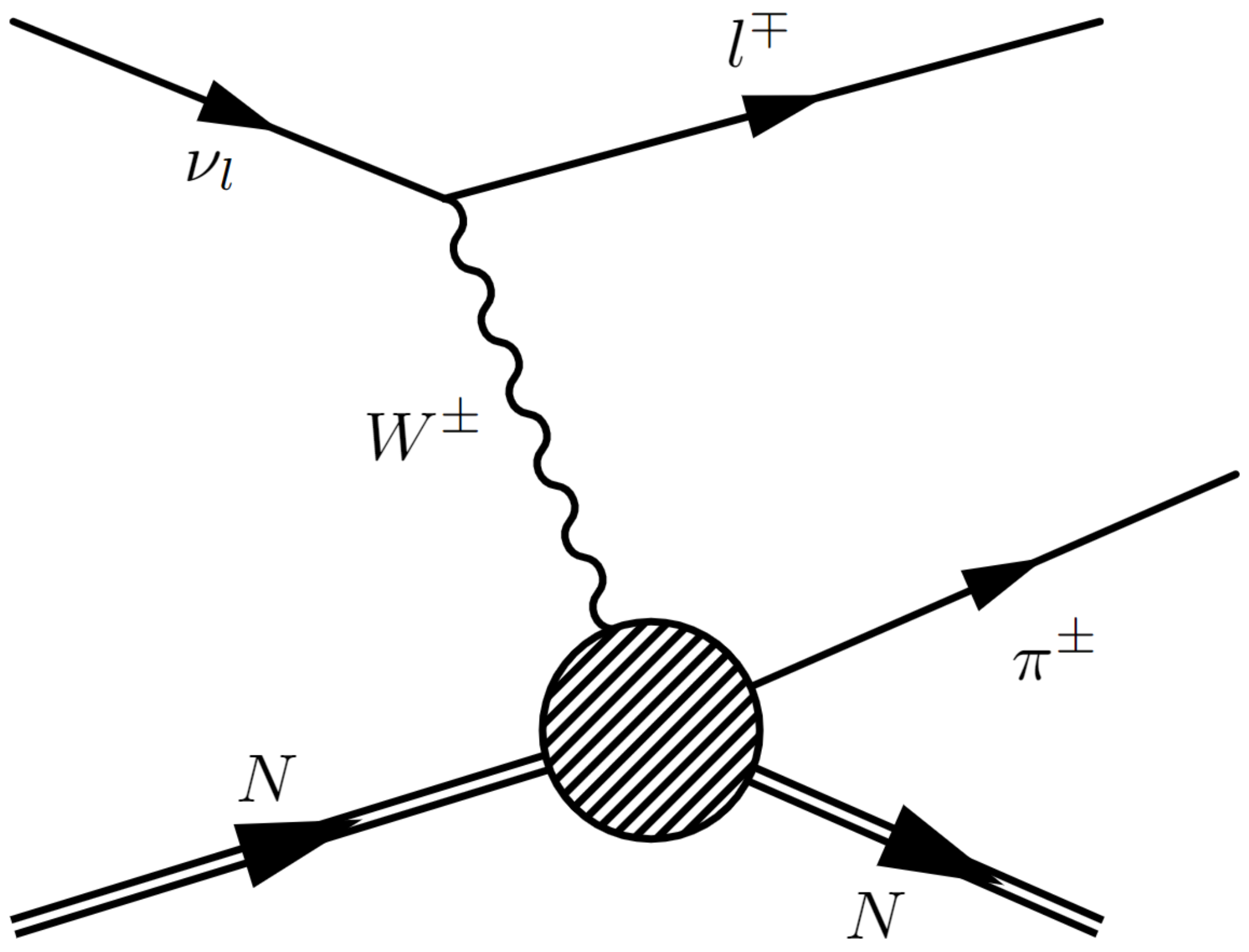

Fig. 1. Feynman diagram depicting charged current CPP where a neutrino of arbitrary flavor, ν_l, interacts with a nucleus, N, producing a lepton, l, and pion, $\pi^{\pm}$, while leaving the nucleus unchanged.

Different Axial Form Factor Descriptions

There are 2 families of descriptions for $F_A(Q^2)$:

- Dipole Approximation: A simple dipole model shown in Eq. 1, this description relies on an experimentally determined value: the axial mass, M_A, which is estimated to lie between 1.00 – 1.30 GeV.
- z Expansion: A model-independent description of $F_A(Q^2)$, as shown in Eq. 2, this description utilizes a power series expansion with coefficients determined in 2 ways:
  - Deuterium Data: Coefficients determined experimentally from 1980s bubble chamber experiments, as shown in Table 1.
  - Lattice QCD: Coefficients determined theoretically from Lattice Quantum Chromodynamics calculations, as shown in Table 1.

z Expansion Parameters	t_{cut}	t_0	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Deuterium Data, Meyer, et al. [1]	**$9(m_\pi)^2$**	**-0.28**	**0.759**	**-2.300**	**0.600**	**3.800**	**2.300**	**-**	**-**
LQCD, Bali, et al. [2]	**$9(m_\pi)^2$**	**$-t_{cut}$**	**1.013**	**-1.713**	**-0.591**	**-0.771**	**7.790**	**-8.418**	**2.689**
LQCD, Djukanovic, et al.[3]	**$9(m_\pi)^2$**	**0**	**1.225**	**-1.274**	**-0.379**	**-**	**-**	**-**	**-**

Table 1. Description of coefficients and constants used in the various z expansion representations of $F_A(Q^2)$. m_π denotes the mass of the pion.

$$F_A^{Dip}(Q^2) = \frac{g_A}{(1+\frac{Q^2}{M_A^2})^2}$$

Eq. 1. Dipole Approximation for $F_A(Q^2)$. g_A is the axial coupling constant, whose value is known to high confidence, and M_A is the experimentally determined axial mass.

$$F_A^z(Q^2) \approx \sum_{k=0}^{k_{max}} a_k z(Q^2)^k,$$

$$z(Q^2) = \frac{\sqrt{t_{cut}+Q^2} - \sqrt{t_{cut}-t_0}}{\sqrt{t_{cut}+Q^2} + \sqrt{t_{cut}-t_0}}$$

Eq. 2. z Expansion for $F_A(Q^2)$ and explicit expression for $z(Q^2)$, where t_{cut} is a constant defined by the pion mass and t_0 is a constant chosen somewhat freely by each collaboration.

Results & Discussion

For direct comparisons of $F_A(Q^2)$, the formulas for each theory were evaluated over the range of momentum transfer relevant to CPP: $0.00 < Q^2 < 0.20$ GeV^2. To compare the event rates, a root file from GENIE containing data for 1 million events in the DUNE Near Detector was generated using the dipole approximation with M_A = 1.00 GeV and had its events reweighted by each $F_A(Q^2)$ being considered.

Although there are noticeable differences in the shape of $F_A(Q^2)$ for each description (Fig. 2) and the relative differences between descriptions (Fig. 3), event rates were minimally affected as they were reweighted (Fig 4). This suggests that the CPP cross section is not greatly sensitive to different descriptions of $F_A(Q^2)$ over the relevant range of Q^2.

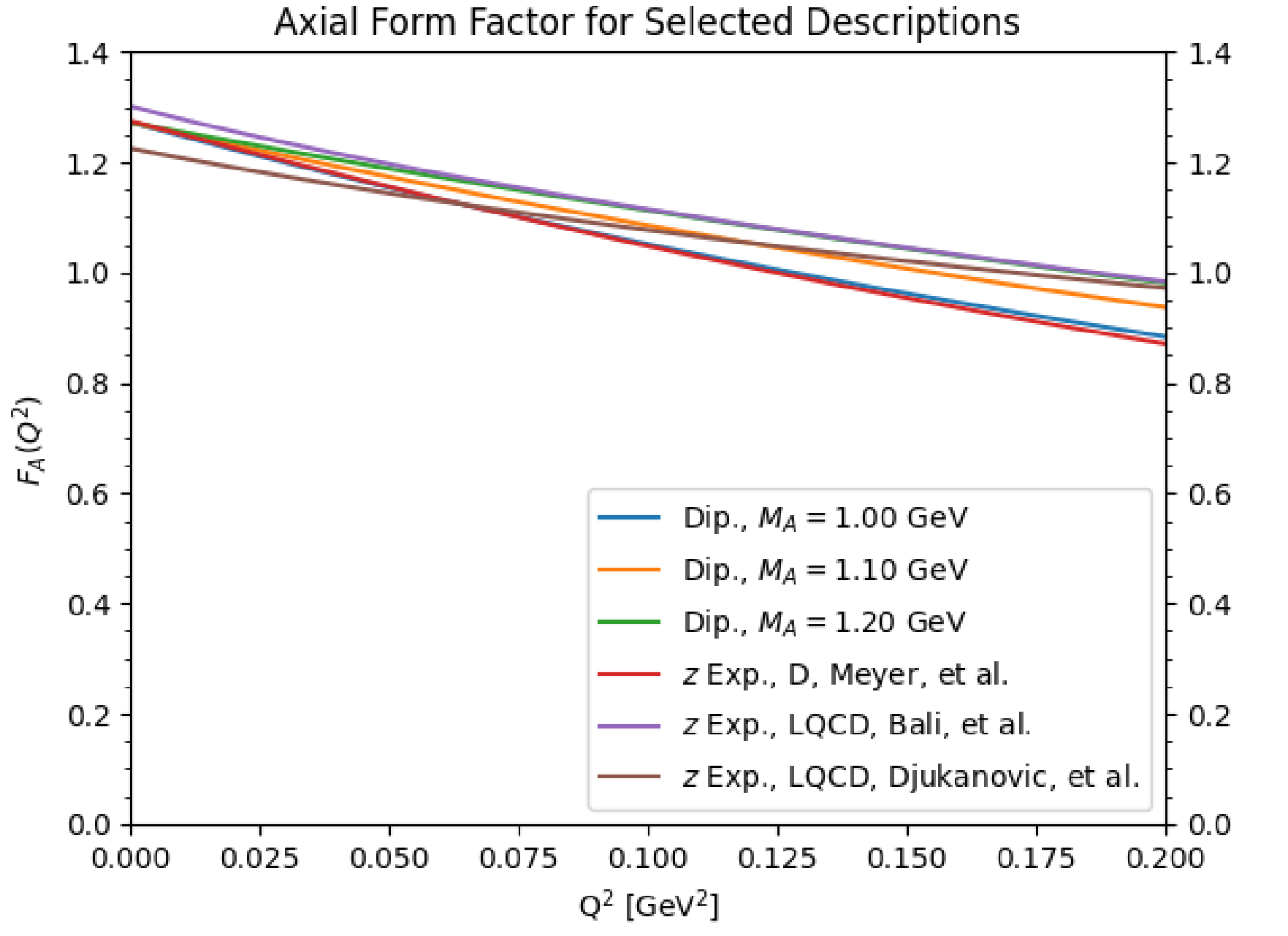

Fig. 2. Comparison of $F_A(Q^2)$ curves over the relevant range of Q^2 for various descriptions.

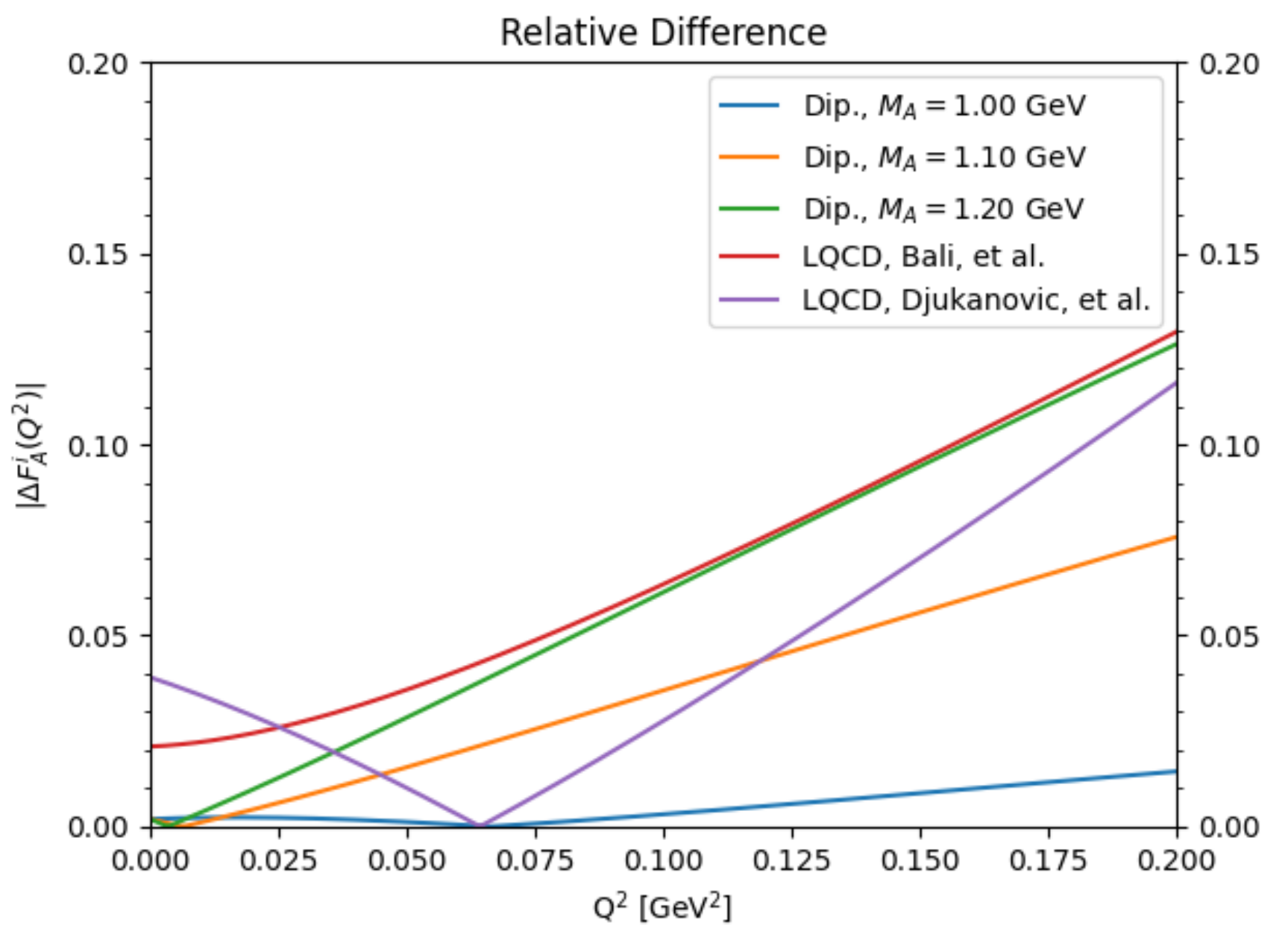

Fig. 3. Relative difference as given in Eq. 3 giving the respective percent differences for selected $F_A(Q^2)$ descriptions.

$$|\Delta F_A^i(Q^2)| = \frac{|F_A^i(Q^2) - F_A^{z,D}(Q^2)|}{|F_A^{z,D}(Q^2)|}$$

Eq. 3. Relative difference, $|\Delta F_A^i(Q^2)|$, formula where $F_A^i(Q^2)$ is a selected form factor description and $F_A^{z,D}(Q^2)$ is the deuterium data z expansion description.

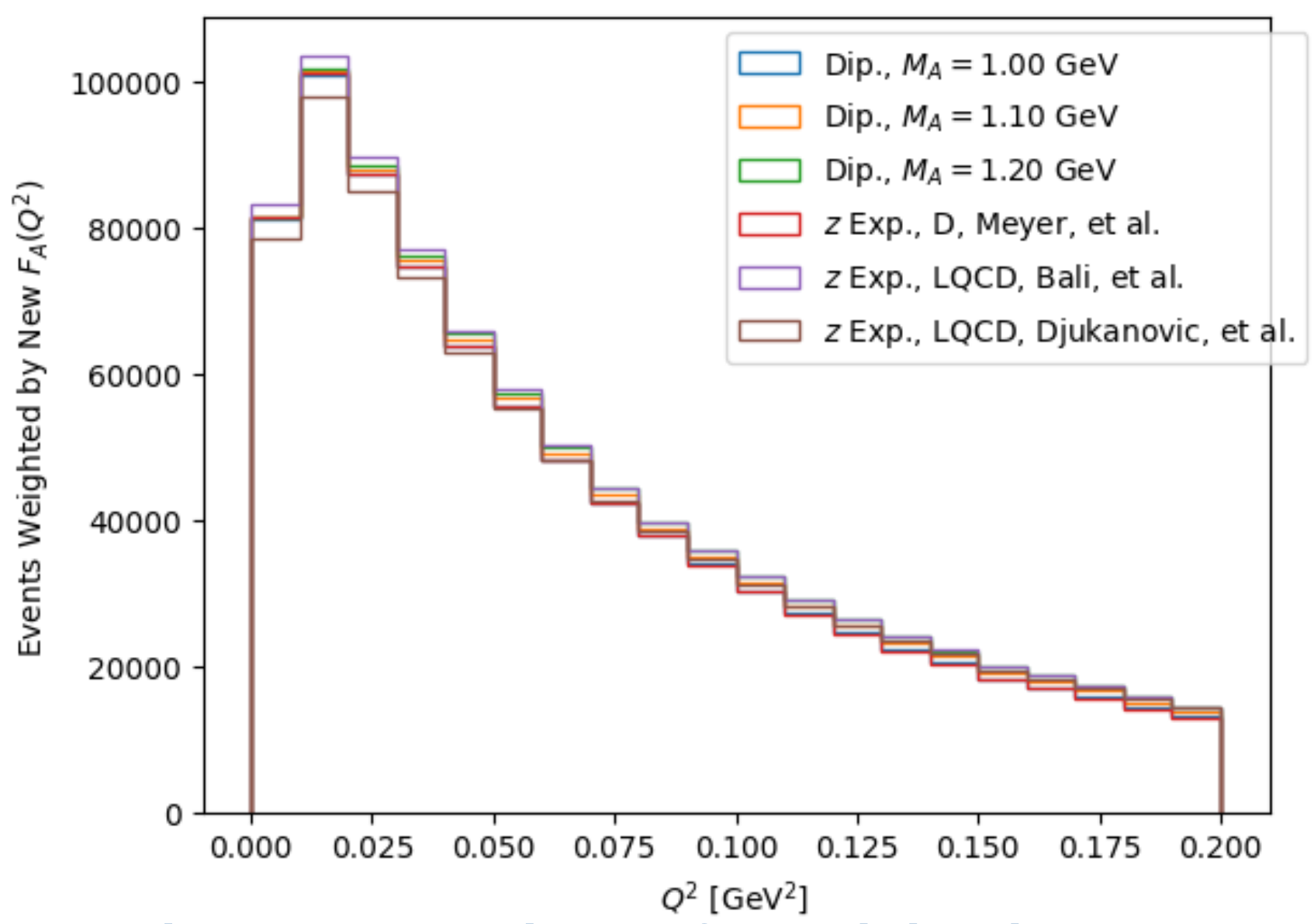

Fig. 4. Comparison of reweighted CPP events in bins of momentum transfer from the neutrino, Q^2.

Summary

The main uncertainty in Coherent Pion Production, CPP, comes from the axial form factor, $F_A(Q^2)$. The 3 main descriptions of $F_A(Q^2)$ are the dipole approximation and the z expansion using either deuterium bubble chamber data or Lattice QCD theoretical calculations. In this work I have extensively compared these various $F_A(Q^2)$ descriptions over the relevant Q^2 range and have demonstrated that the event rates are minimally affected; therefore, CPP can be used in constraining neutrino flux in DUNE within these uncertainties.

References

[1] A. S. Meyer, et al. Phys. Rev. D 93, 113015 (2016).
[2] G. S. Bali, et al. (RQCD), JHEP 05, 126.
[3] D. Djukanovic, et al. Phys. Rev. D 106, 074503 (2022).

Acknowledgements

I would like to thank Moon Jung for providing foundational code for this project, Gray Putnam for guidance and explanation, and, with utmost gratitude, Vishvas Pandey for advising, revision, and invaluable pedagogy. This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).