Superscaling in the inelastic region: The SuSAv2-inelastic model.

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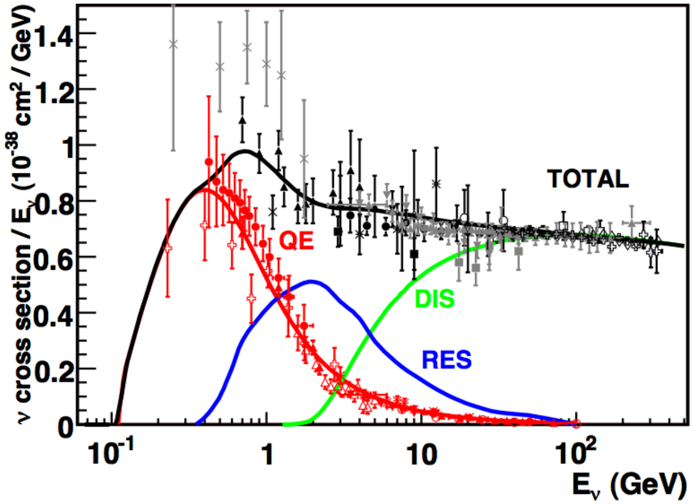
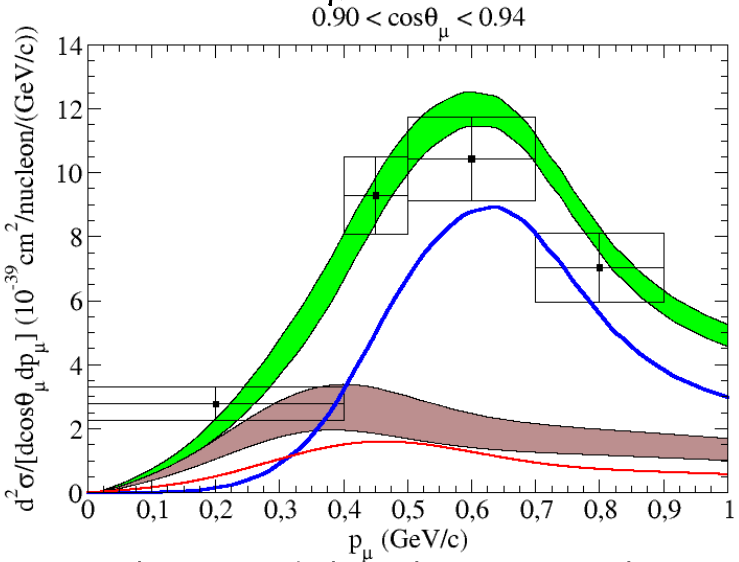
Introduction



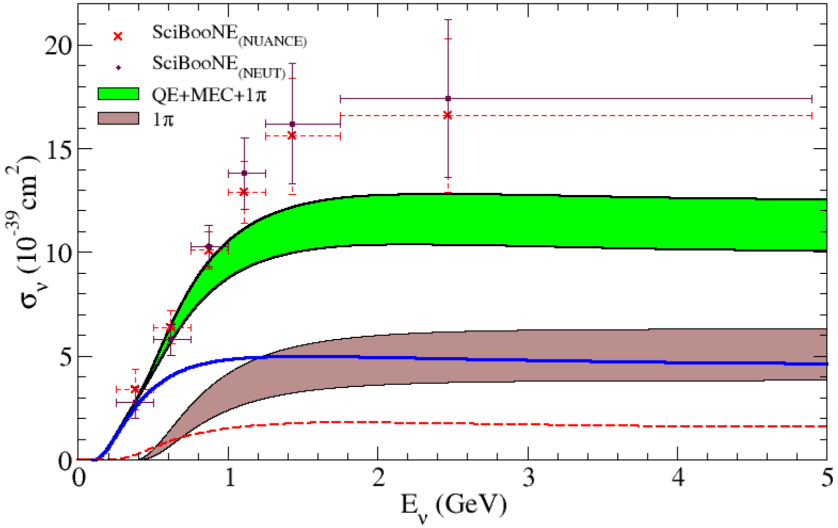
- Quasielastic region (QE).
- Resonance (RES).
- Deep Inelastic Scattering (DIS).

[J. M. Campbell et al., arXiV:2203.11110 (2024)]

T2K CC ν_μ, $< E_{\nu_\mu} > \sim 0.8\ GeV$, inclusive data



Total Inclusive Cross Section



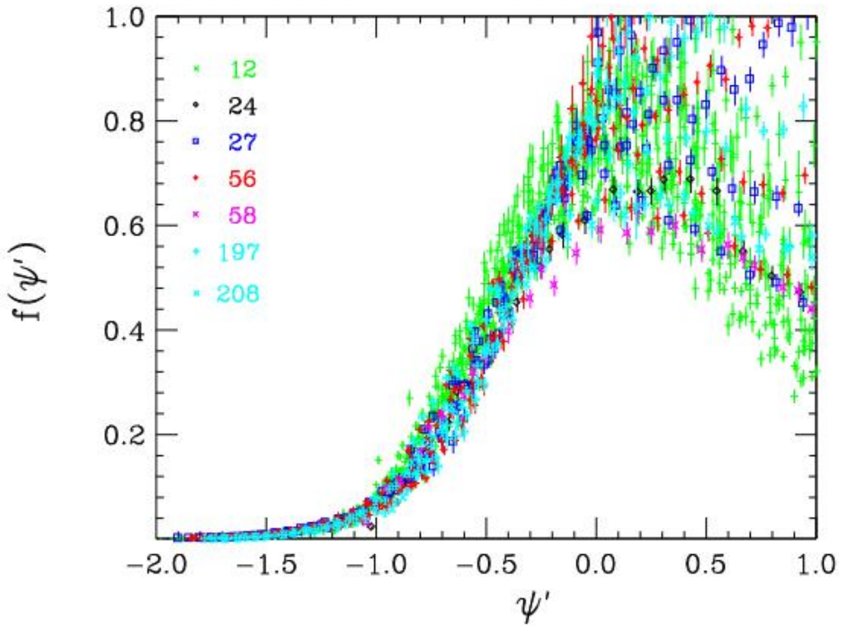
Superscaling model with QE + 2p2h + 1π [M.V Ivanov et al., J. Phys. G 43, 045101 (2016)].

Introduction

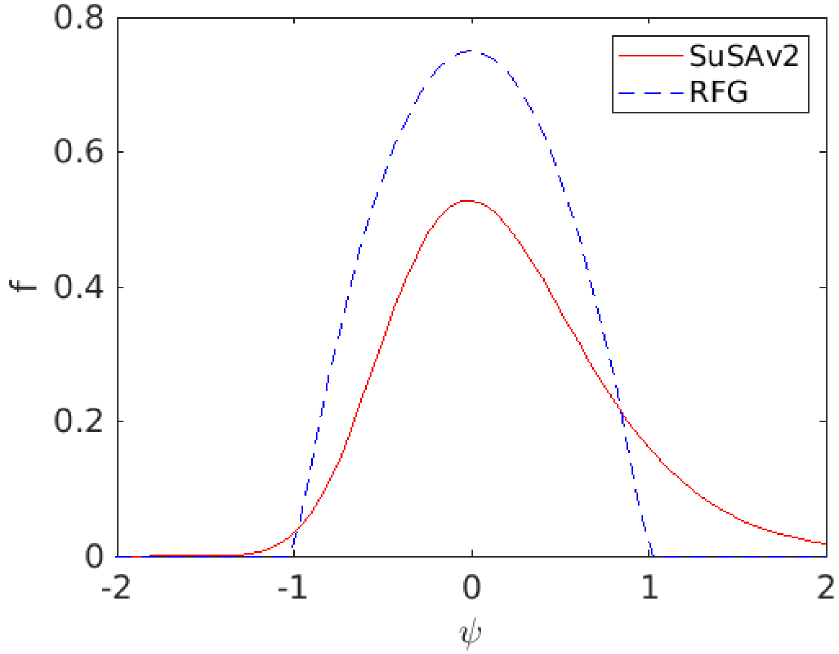
The scaling function does not depend explicitly on the transferred momentum or the nuclear species [J. E. Amaro et al., J. Phys. G 47, 124001 (2020), G. D. Megias, PhD Thesis (2017)].

$$f(\psi) = k_F \frac{\left(\frac{d^2\sigma}{d\Omega dw}\right)}{\left(\frac{d^2\sigma}{d\Omega dw}\right)_{s.n}}$$

SuSAv2 model takes into account the complexities of nuclear structure.



[T. W. Donnelly et al., Phys. Rev. C 60, 065502 (1999)].



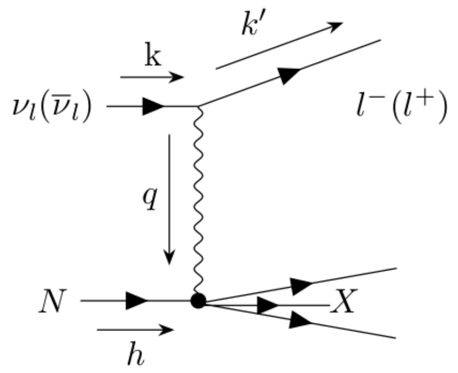
Comparison between SuSAv2-QE and Relativistic Fermi Gas (RFG) scaling function.

SuSAv2-QE scaling function is going to be implemented in the inelastic regime.

Model: SuSAv2-inelastic

SuSAv2-inelastic model describes the full inelastic spectrum (Δ, other res. And DIS)[G. D. Megias, PhD Thesis (2017), M. B. Barbaro et al., Phys. Rev. C 69, 035502 (2004), J. Gonzalez-Rosa et al., Phys. Rev. D 105, 093009 (2022)]. Good agreement with (e,e') data.

$$R^K_{inel}(\kappa,\tau) = \frac{N}{\eta_F^2 \kappa} \xi_F \int_{\mu_X^{min}}^{\mu_X^{max}} d\mu_X f^{model}(\psi'_X) U^k$$

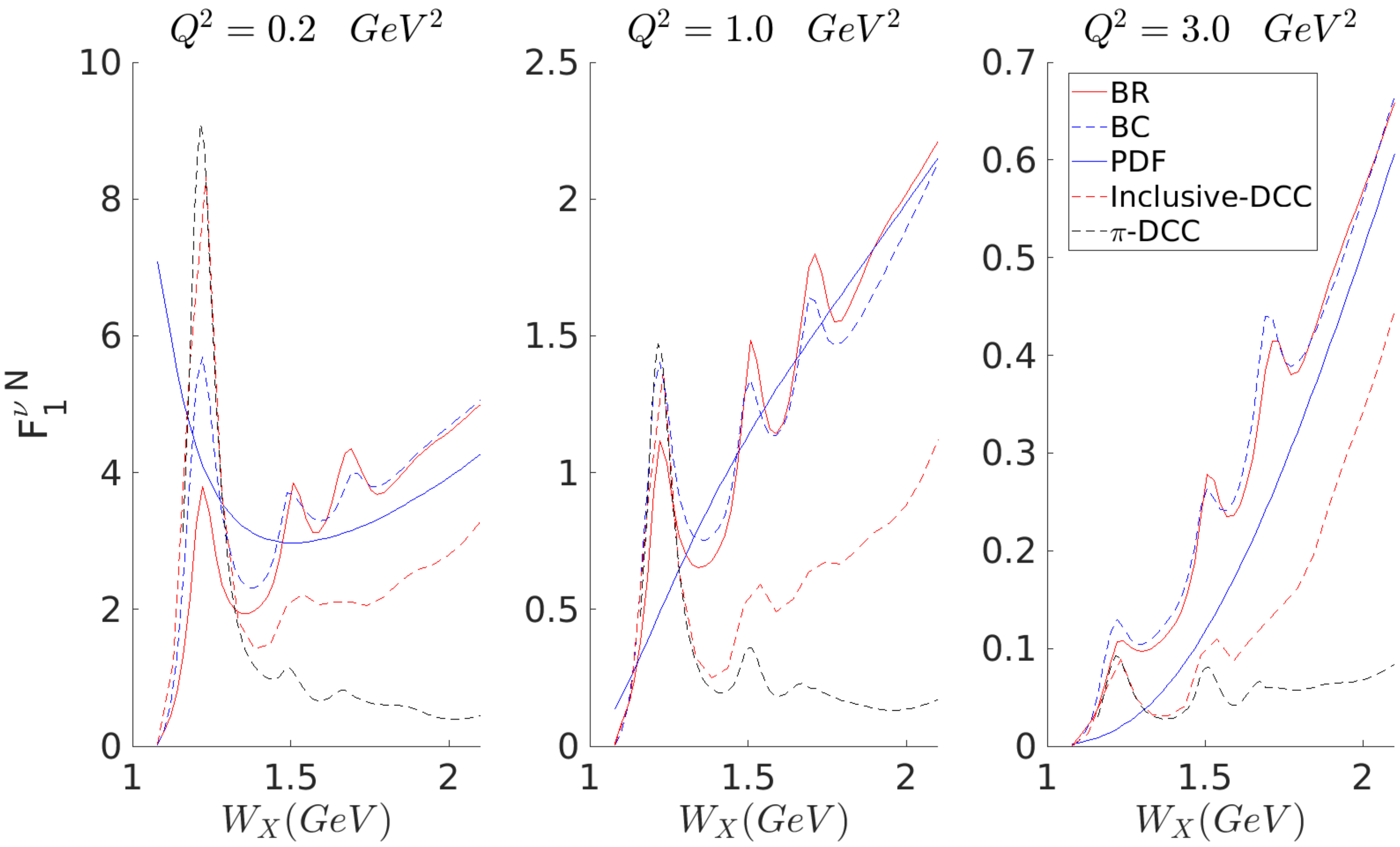


Inelastic Feynmann Diagram

The hadronic response is given by an integration of the single-nucleon tensor over the invariant mass. This tensor depends on the inelastic structure functions.

- Bodek-Ritchie parametrization (BR) [A. Bodek and J. L. Ritchie, Phys. Rev. D 23, 1070 (1981)].
- Bosted-Christy parametrization (BC) [P. E. Bosted and M. E. Christy, Phys. Rev. C 81, 055213 (2010)]
- Parton Distribution Functions (PDF) [M. Sajjad Athar and J. G. Morfín, J. Phys. G 48, 034001 (2021)]
- Dynamical Coupled Model parametrization (DCC) [S. X. Sakamura, H. Kamano and T. Sato, Phys. Rev. D 92, 074024 (2015)]

Model: SuSAv2-inelastic



Model: SuSAv2-inelastic

The contribution analysed depends of the limits of the integral and the parametrization used

- TrueDIS (Deep inelastic scattering)

$W_x^{min} = 2.1\ GeV;\ \ W_x^{max} = m_N +\ \omega\ -\ E_s$

Bodek-Ritchie/ Bosted-Christy/ Parton Distribution Function

- RES (Resonances)

$W_x^{min} = m_N +\ m_\pi;\ \ W_x^{max} = 2.1\ GeV$

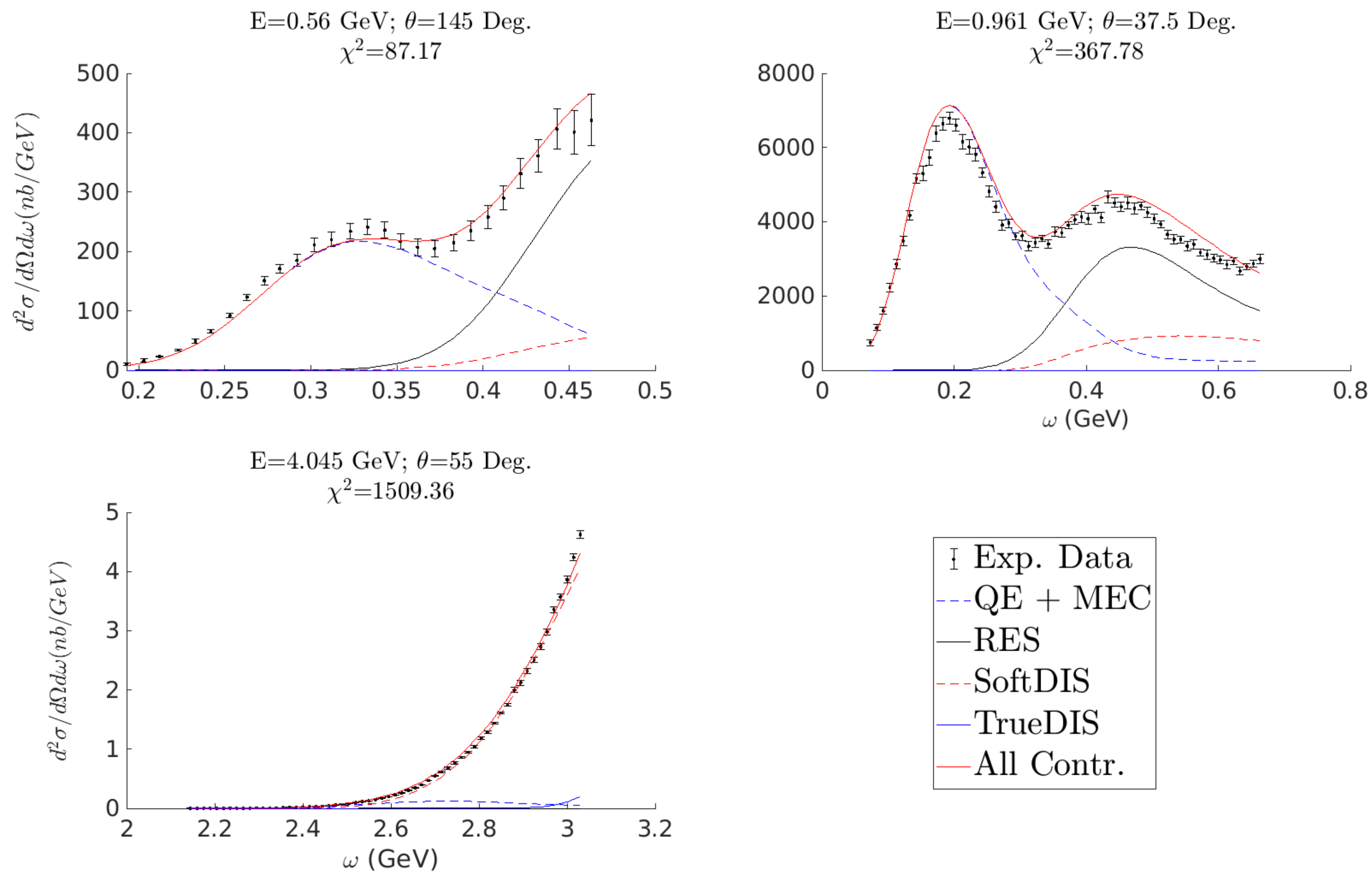
Dynamical Coupled Channels

- SoftDIS (Deep inelastic scattering in the resonance region)

$W_x^{min} = m_N +\ m_\pi;\ \ W_x^{max} = 2.1\ GeV$

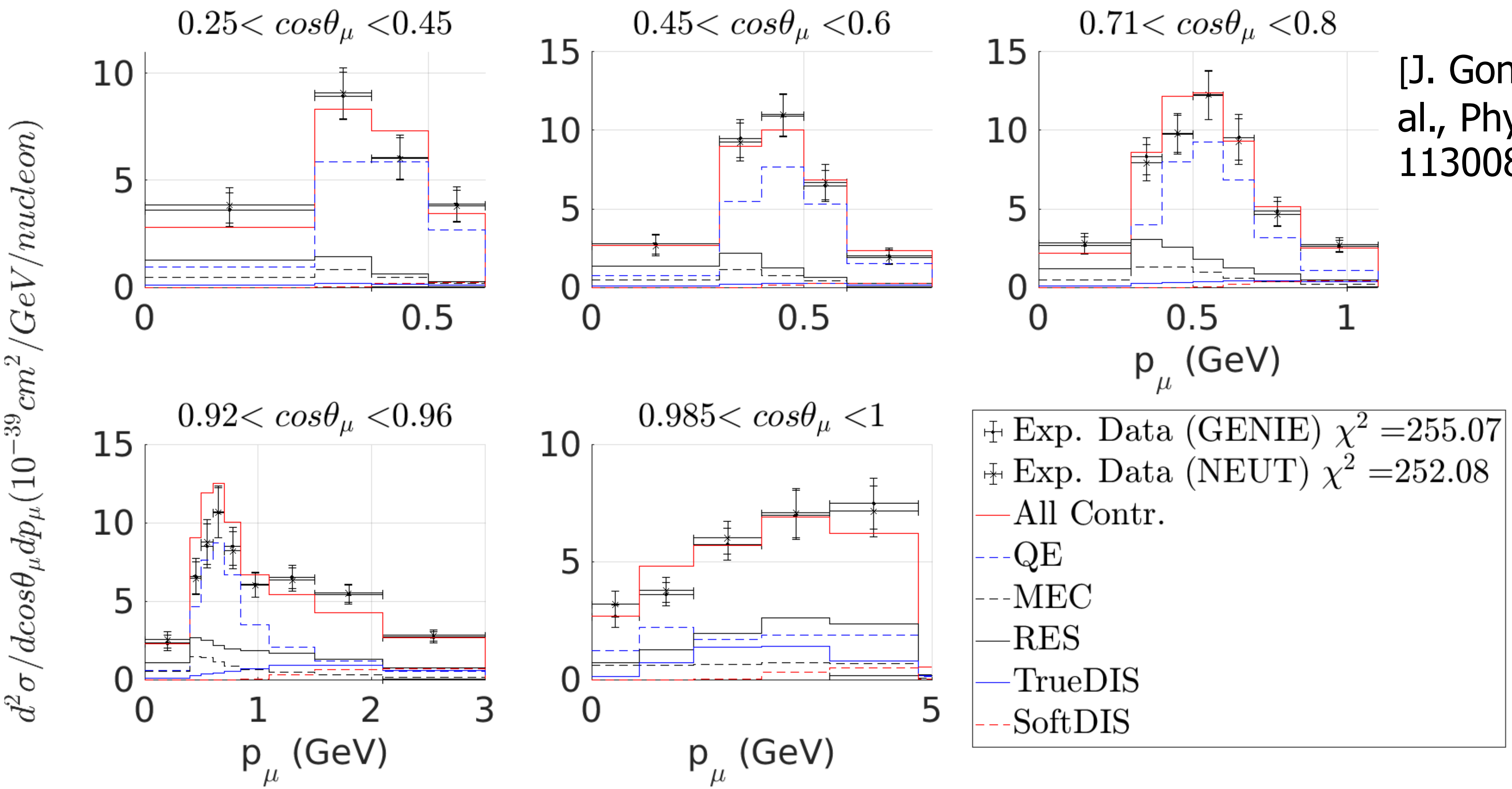
Dynamical Coupled Channels and Bodek-Ritchie/Bosted-Christy

Results: Electron scattering



[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

Results: T2K

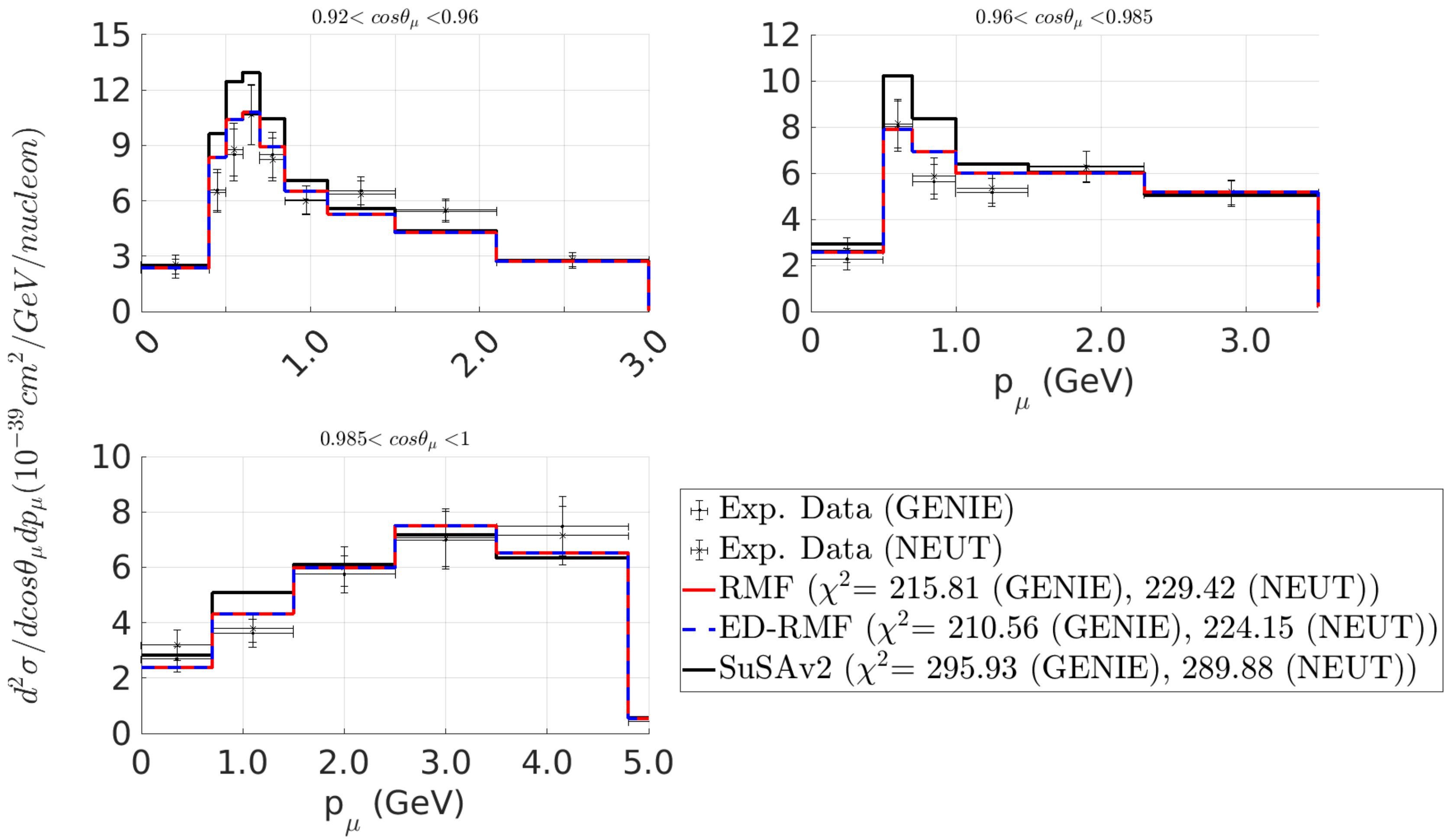


[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

$\chi^2 = 218.3$ (GENIE)
$\chi^2 = 192.0$ (NEUT)

T2K CC $\nu_\mu, < E_{\nu_\mu} > \sim 0.6\ GeV$

Results: T2K (RMF)



[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

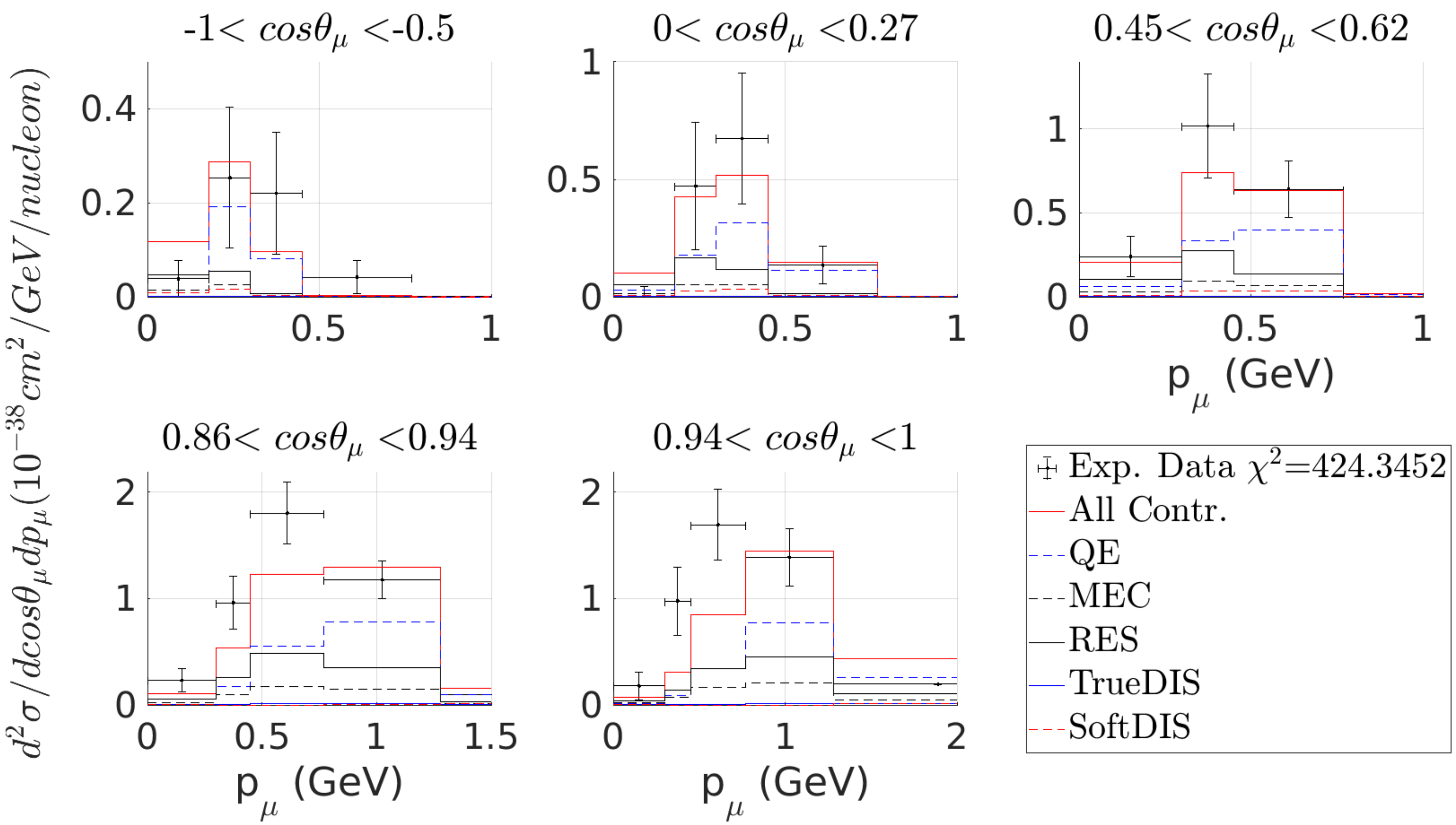
QE contribution using different models: RMF, ED-RMF and SuSAv2.

$\chi^2 = 218.3$ (GENIE)

$\chi^2 = 192.0$ (NEUT)

T2K CC ν_μ, $< E_{\nu_\mu} > \sim 0.6\ GeV$

Results: MicroBooNE

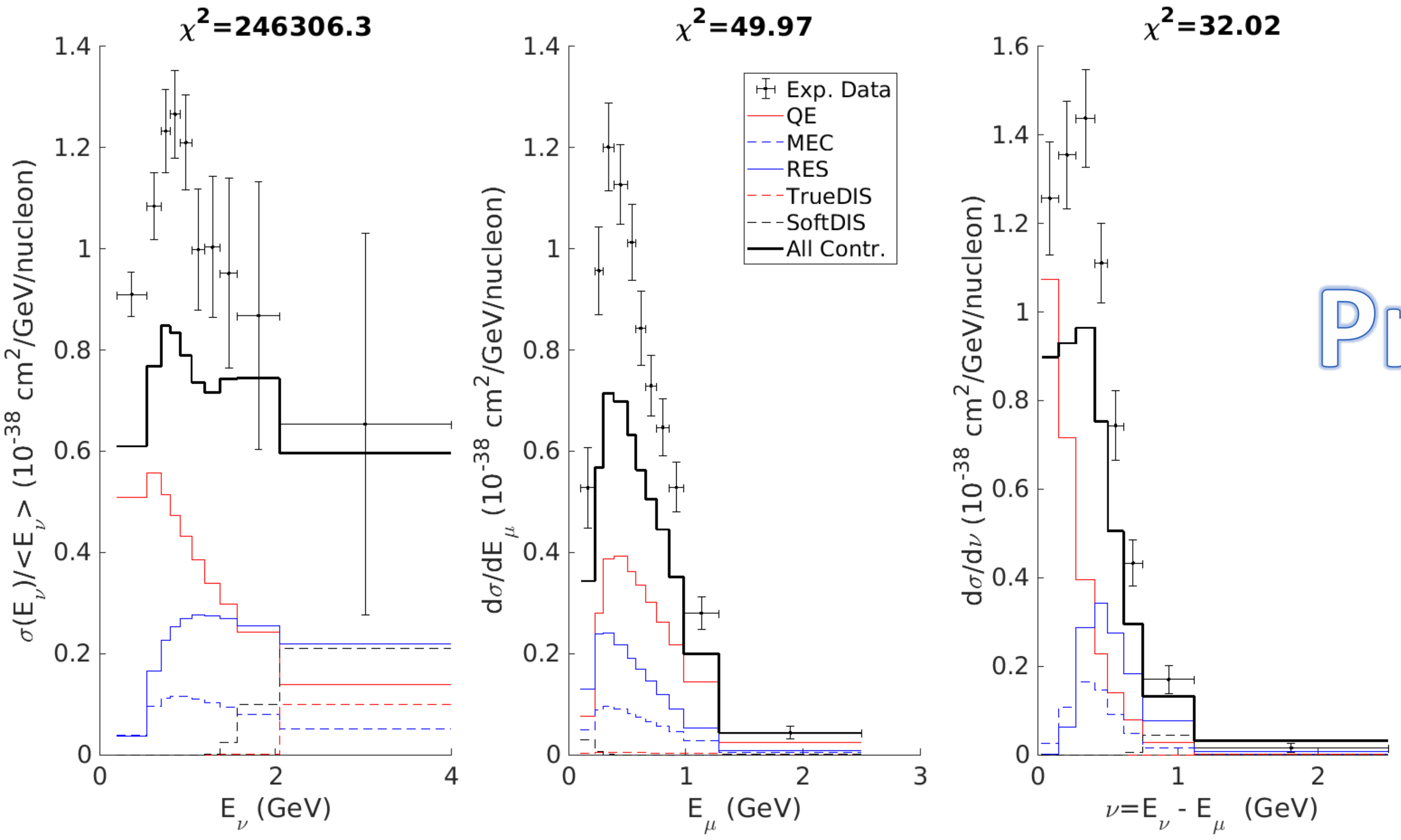


[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

$\chi^2 = 103.9$
(GENIEv3)

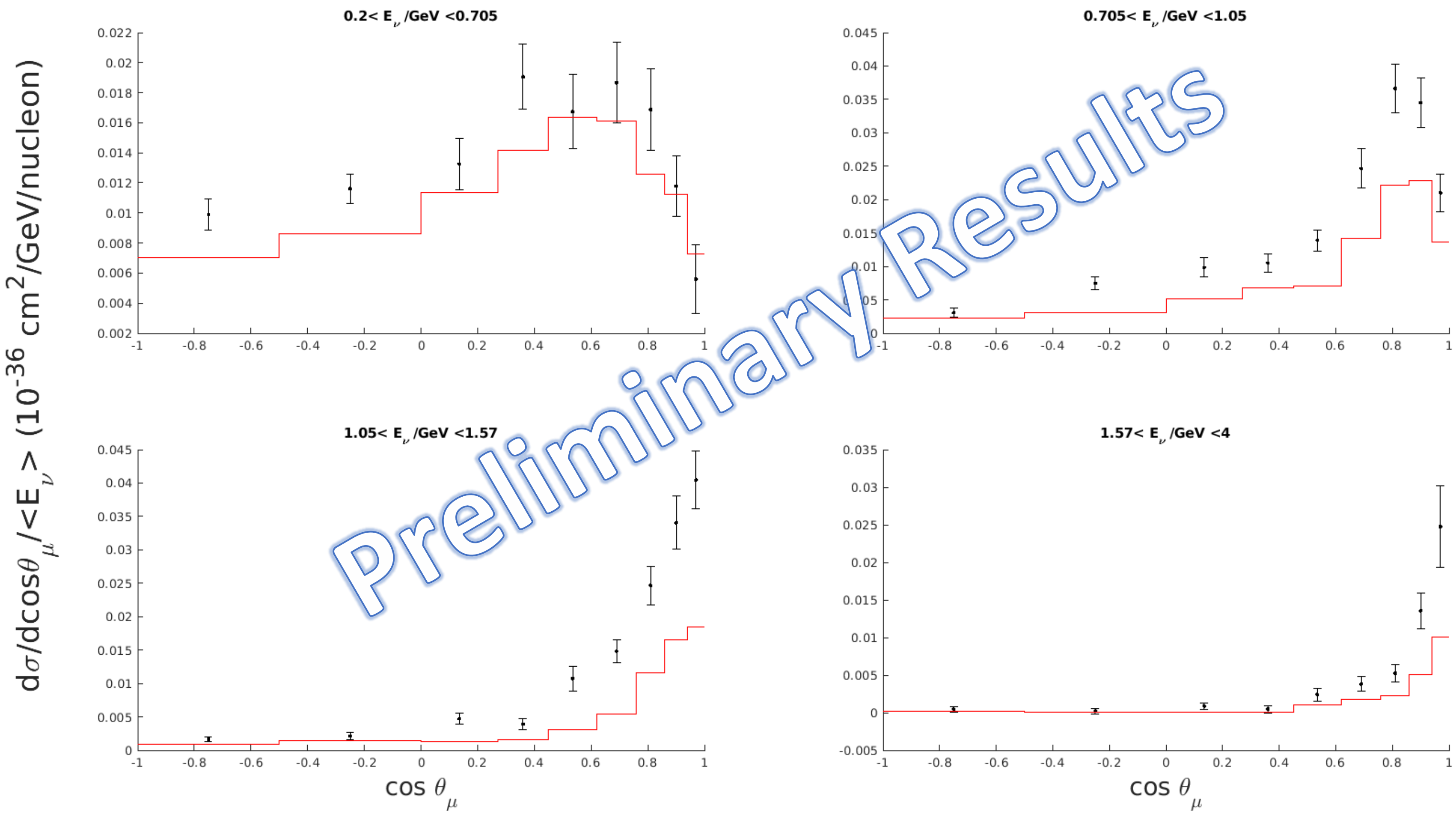
MicroBooNE CC ν_μ, $< E_{\nu_\mu} > \sim 0.8\ GeV$

Results: MicroBooNE

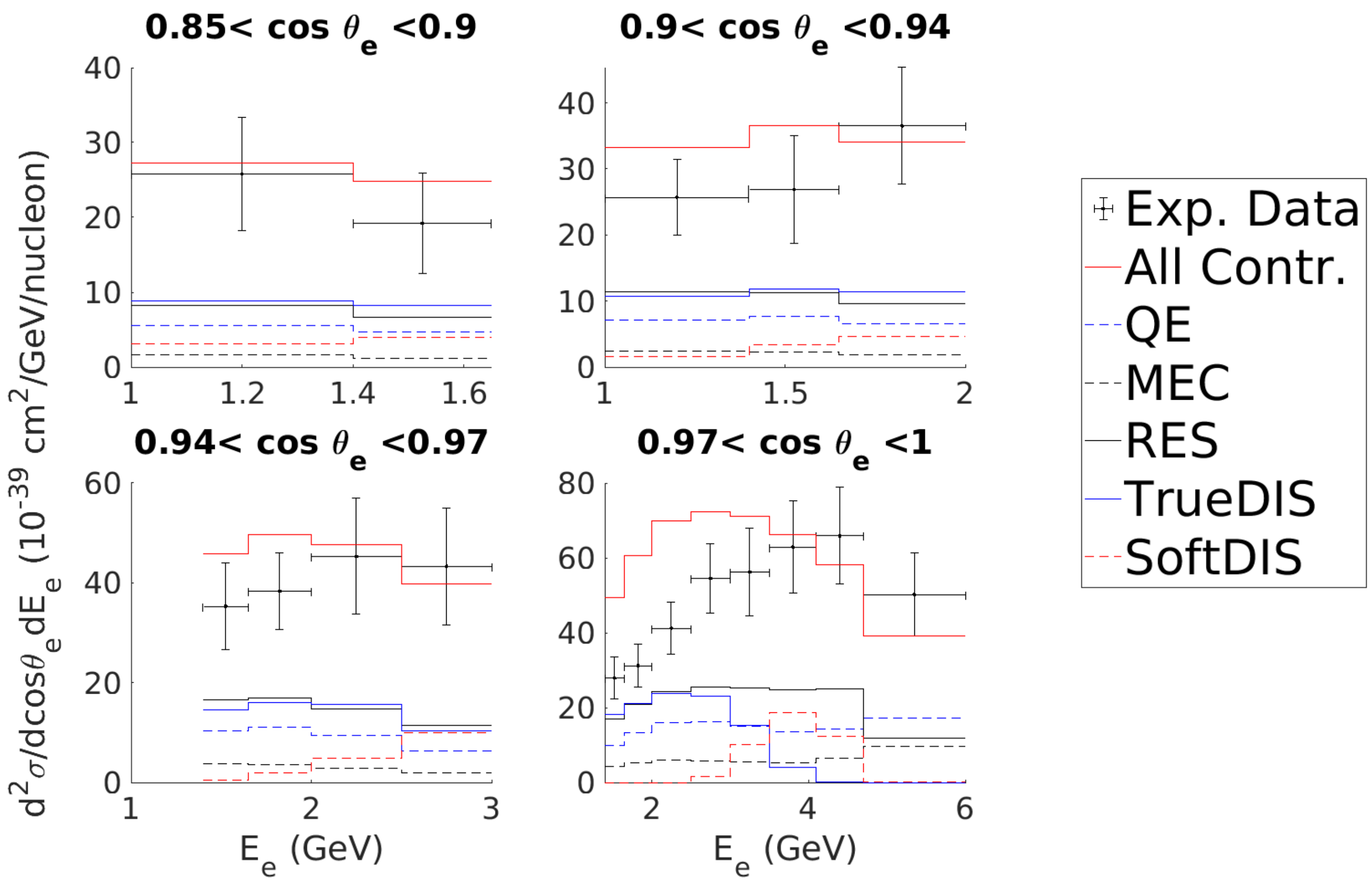


Preliminary Results

Results: MicroBooNE



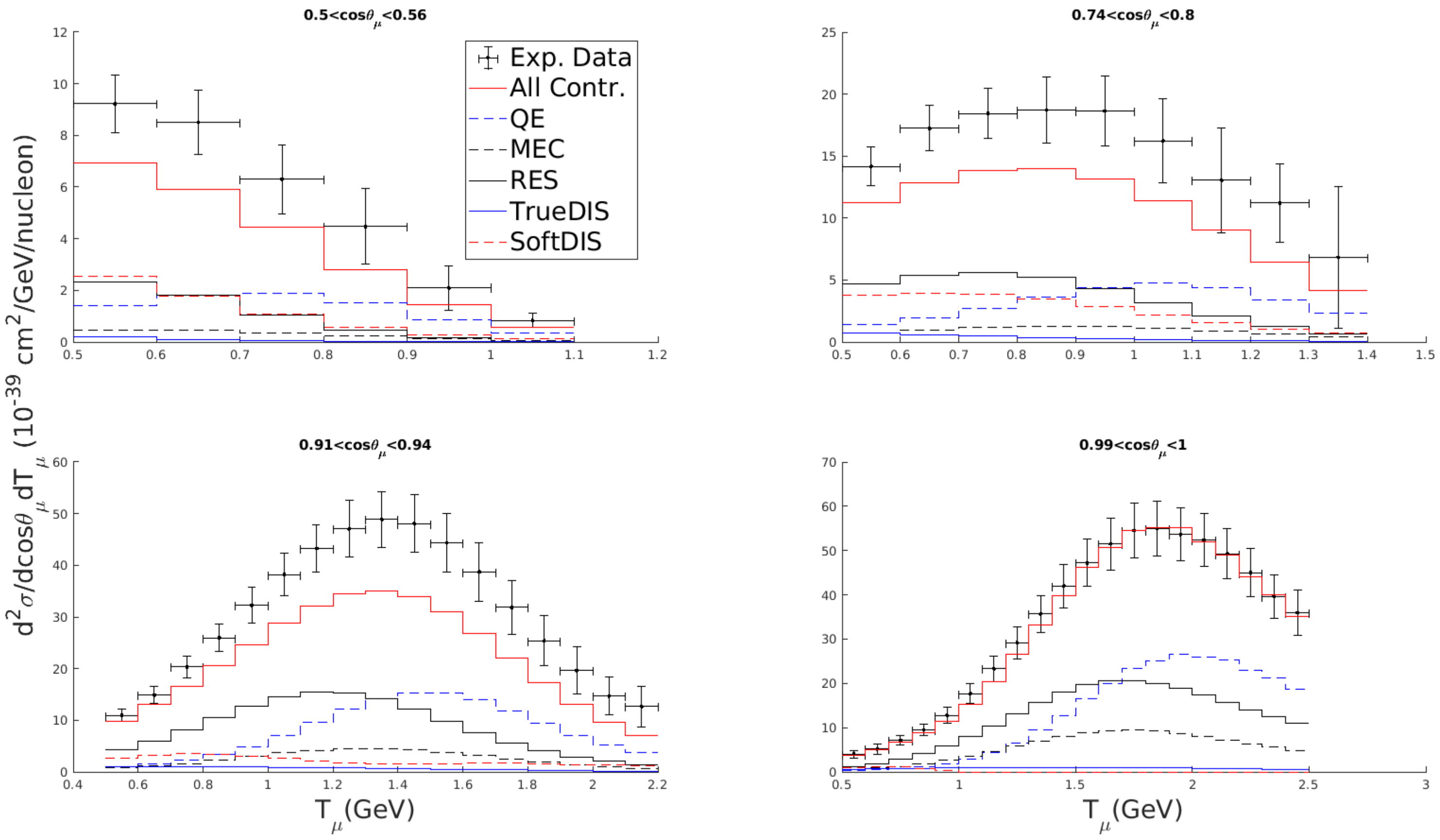
Results: NOvA



NOvA CC $\nu_e, < E_{\nu_e} > \sim 2.4\ GeV$

Preliminary Results

Results: NOvA

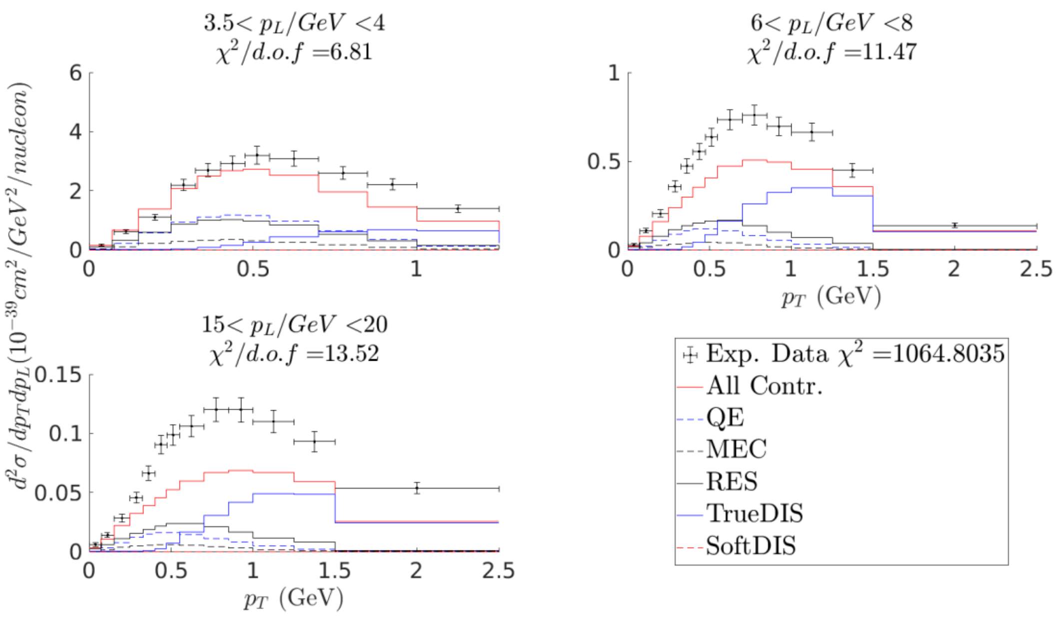


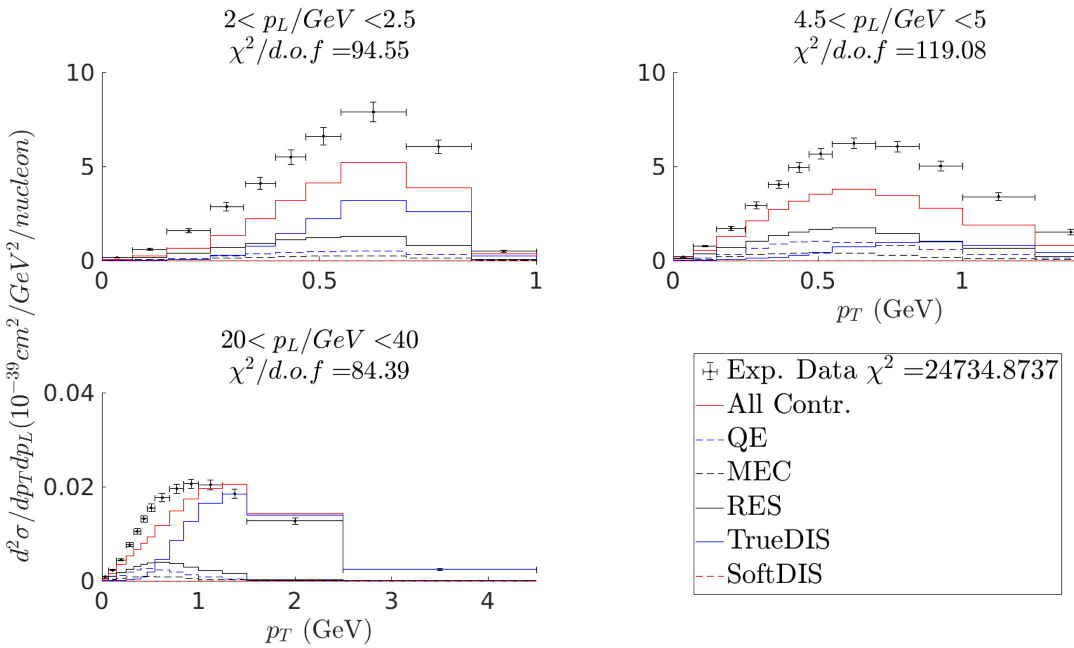
NOvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 2.0\ GeV$

Preliminary Results

Results: MINERvA

[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].





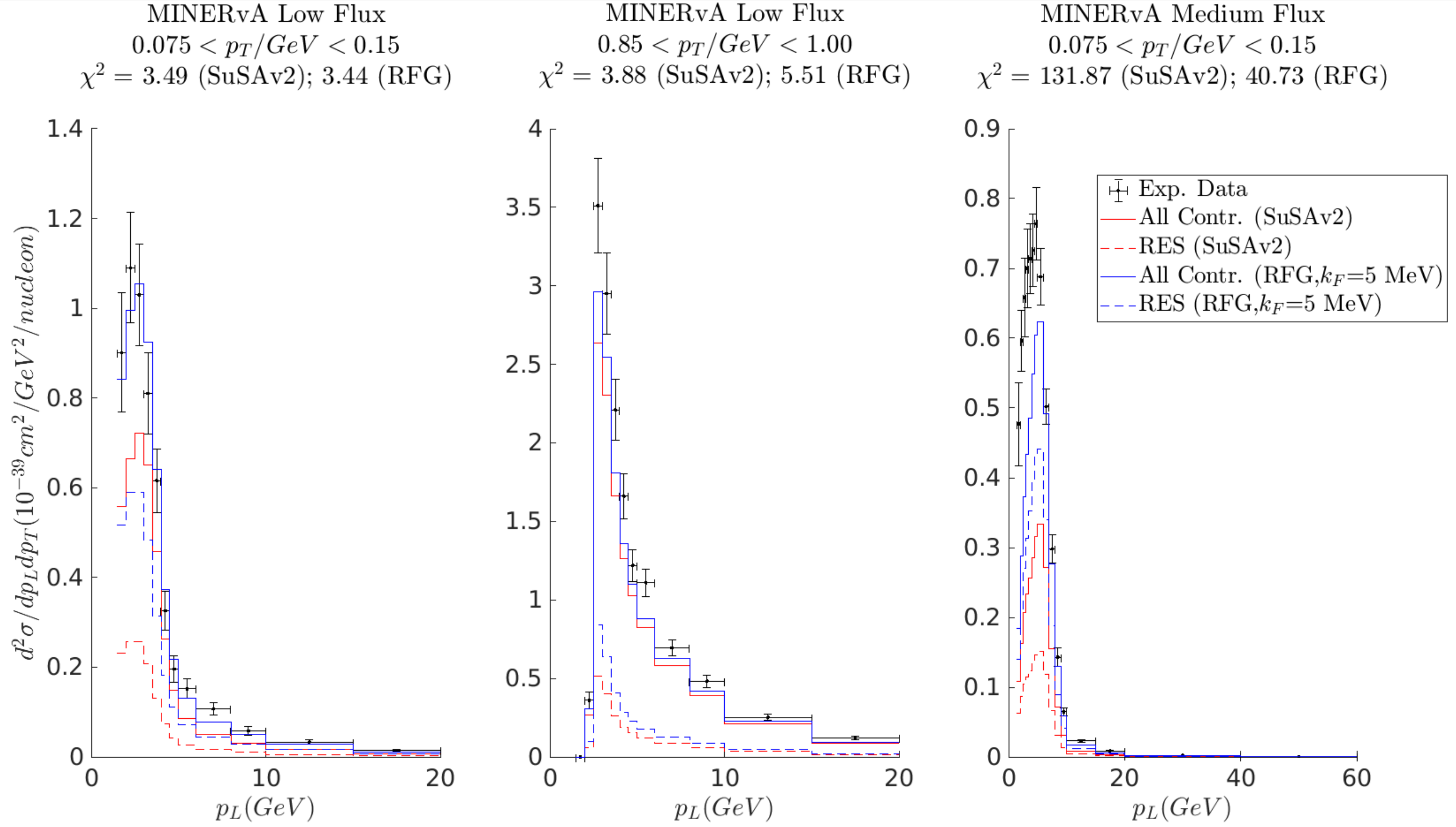
MINERvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 3.5\ GeV$ (Low)

$\chi^2 = 495$ (MnGENIEv1) $\chi^2 = 422$ (GENIE 2.8.4)

MINERvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 6.0\ GeV$ (Medium)

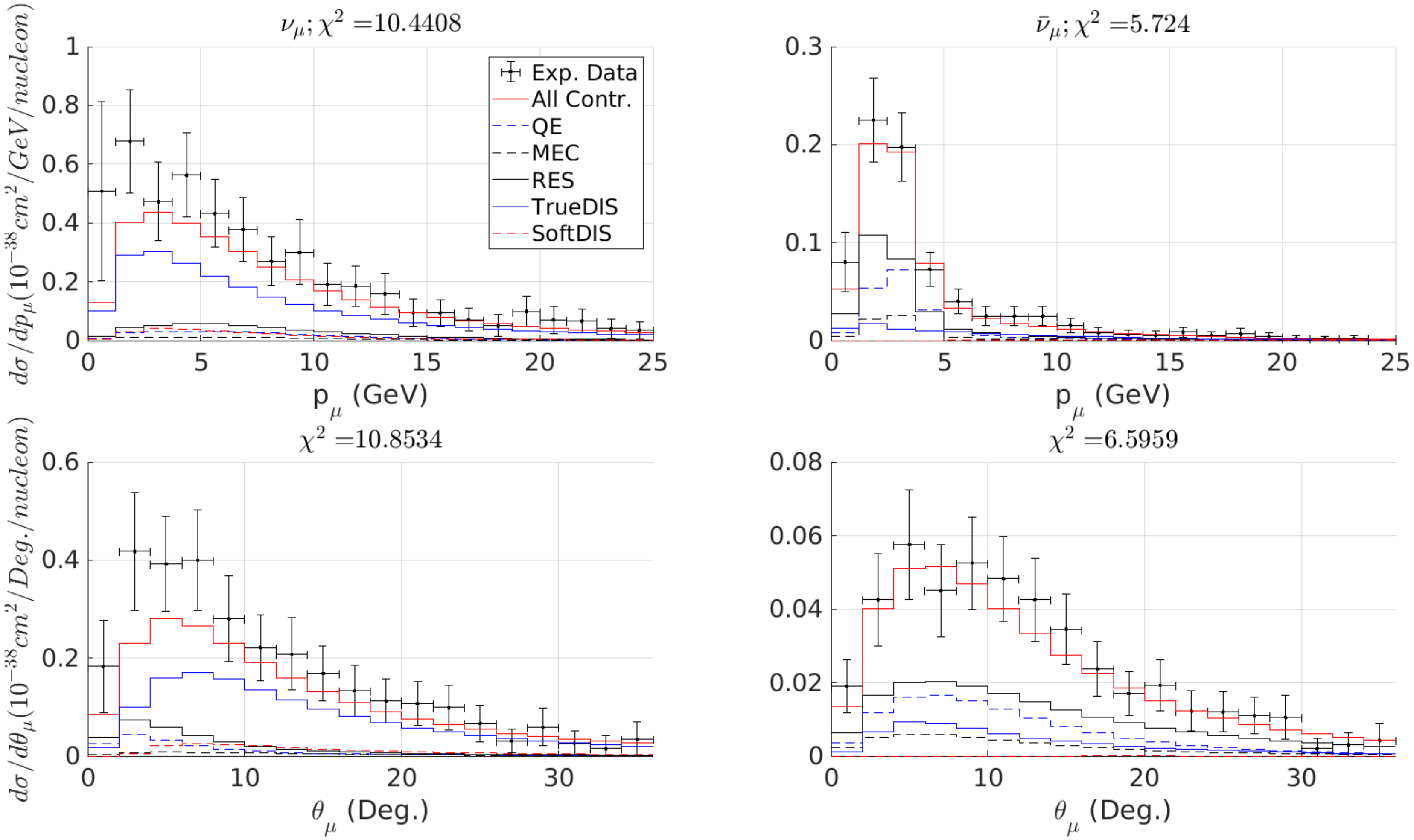
$\chi^2 = 8241$ (GENIE 2.12.6) $\chi^2 = 6786$ (MINERvA Tune v1)

Results: MINERvA



[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

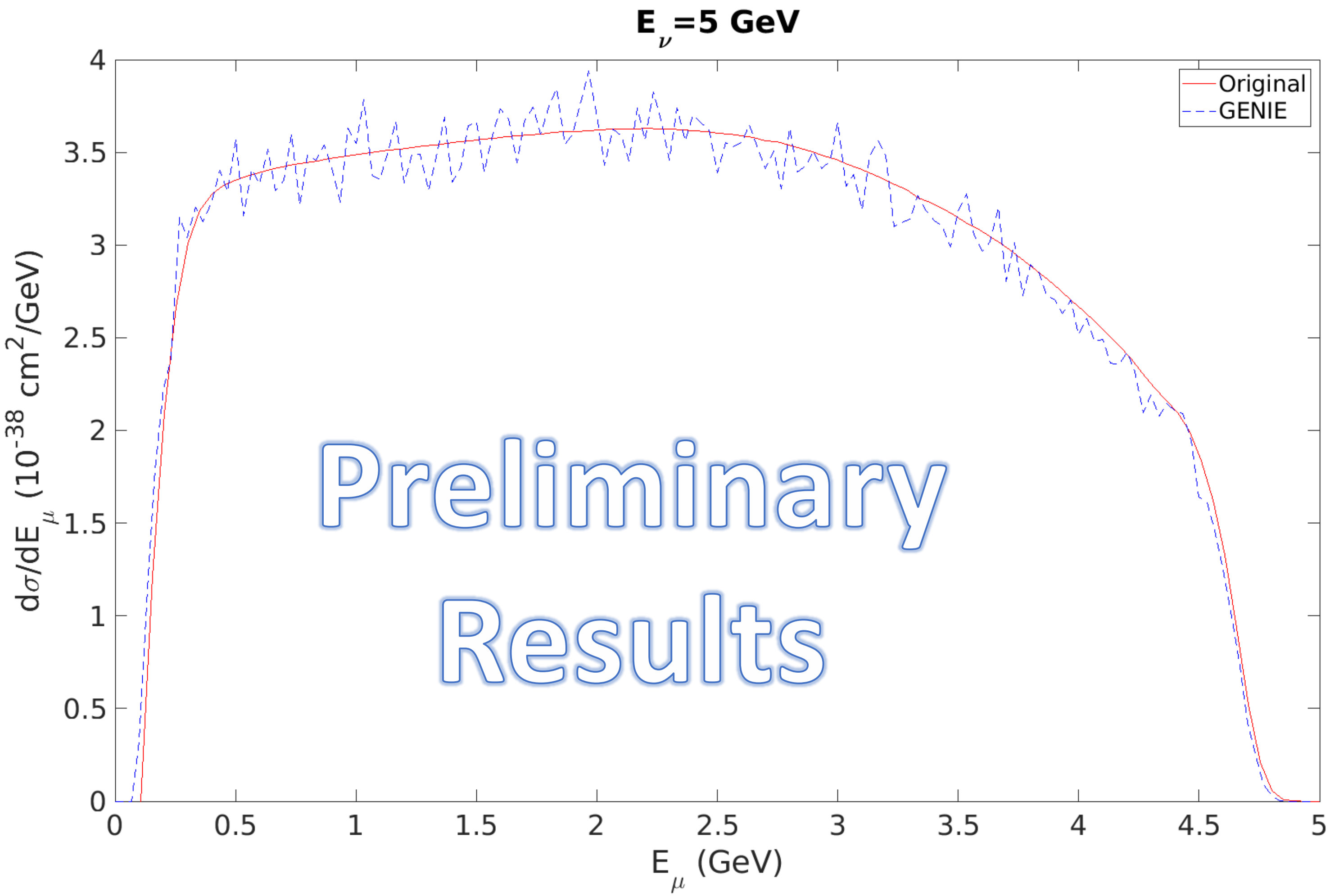
Results: ArgoNEUT



[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

ArgoNEUT CC $\nu_\mu, < E_{\nu_\mu} > \sim 9.6\ GeV$; CC$\bar{\nu}_\mu, < E_{\nu_\mu} > \sim 3.6\ GeV$

Implementation of the model in GENIE



The SuSAv2-inelastic model has been implmented in the GENIE generator.

In the left, we show the comparison between the results of the original code and the results from GENIE.

In collaboration with

Fermilab

Summary and Conclusion

- The superscaling model were tested and reproduced well electron scattering data across the whole energy spectrum. This model was also extended to the weak interaction and reproduced well data from T2K, MicroBooNE and ArgoNEUT [J. Gonzalez-Rosa et al., Phys. Rev. D 105, 093009 (2022)].

- Our predictions have been compared with available data for charged current muon neutrino-nucleus reactions from T2K, MINERvA, MicroBooNE and ArgoNEUT experiments [J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

- For T2K, QE channel dominates in most of kinematical situations. At forward angles, the contributions of SoftDIS and TrueDIS get larger and become crucial to explain the experiment. The overestimation at lower momentum can be corrected using Relativistic Mean Field

Summary and Conclusion

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- Similar comments also apply to MicroBooNE. The discrepancies between data and theoretical predictions are consistent with the studies based on Monte Carlo analyses and other theoretical calculations. We tend to underestimate the triple and single differential cross section in the preliminary results.
- In the case of NOvA, we overestimate the results at very forward angles for electrons and underestimate the results for muons .
- In the case of neutrinos for MINERvA, the predictions are below the data in the region where the cross sections reach their maxima. The description of ArgoNEUT data is good.
- The present study shows clearly the applicability of these models to describe weak processes. Further studies are needed with new models implemented.

Thanks for your attention

Back Up: Inelastic Hadronic Tensor

Considering the following inelastic hadronic tensor:

$$G^{\mu\nu}_{inel} = -\left[W_1(\tau,\rho_X) + \frac{1}{2}W_2(\tau,\rho_X)D(\kappa,\tau,\rho_X)\right]\left(g^{\mu\nu} + \frac{\kappa^\mu\kappa^\nu}{\tau}\right)$$

$$+W_2(\tau,\rho_X)\left[1 + \tau\rho_X^2 + \frac{3}{2}D(\kappa,\tau,\rho_X)\right]\frac{a^\mu a^\nu}{\tau} \mp i\, W_3(\tau,\rho_X)\varepsilon^{\mu\nu\alpha\beta}\left[\zeta_F\left(\frac{1+\psi_X^2}{2} + \lambda\rho_X\right)\frac{a_\alpha\kappa_\beta}{\kappa} - \rho_X\kappa_\alpha\kappa_\beta\right] + 4W_4(\tau,\rho_X)\kappa^\mu\kappa^\nu .$$

where, $a^\mu = (\kappa, 0,0,\lambda), \kappa^\mu = (\lambda,0,0,\kappa)$,

$\rho_X = 1 + \frac{1}{4\tau}(\mu_X^2 - 1)$ and

$$D(\kappa,\tau,\rho_X) = \zeta_F(1 - \psi_X^2)\left[1 + \zeta_F\psi_X^2 - \frac{\lambda}{\kappa}\psi_X\sqrt{\zeta_F(2 + \zeta_F\psi_X^2)} + \frac{\tau}{3\kappa^2}\zeta_F(1 - \psi_X^2)\right].$$

More information in [J. Gonzalez-Rosa et al., Phys. Rev. D 105, 093009 (2022)]

Back Up: Inelastic Structure Functions

We can write the neutrino inelastic structure function in terms of QCD:

$$F_2^{\nu N} = \upsilon W_2^{\upsilon} = Q + \bar{Q} = x(u(x) + d(x) + \bar{u}(x) + \bar{d}(x)),$$

$$xF_3^{\nu N} = x\upsilon W_3^{\upsilon} = Q - \bar{Q} = x\left(u(x) + d(x) - \bar{u}(x) - \bar{d}(x)\right).$$

In a similar way, if we look at the electron inelastic structure functions:

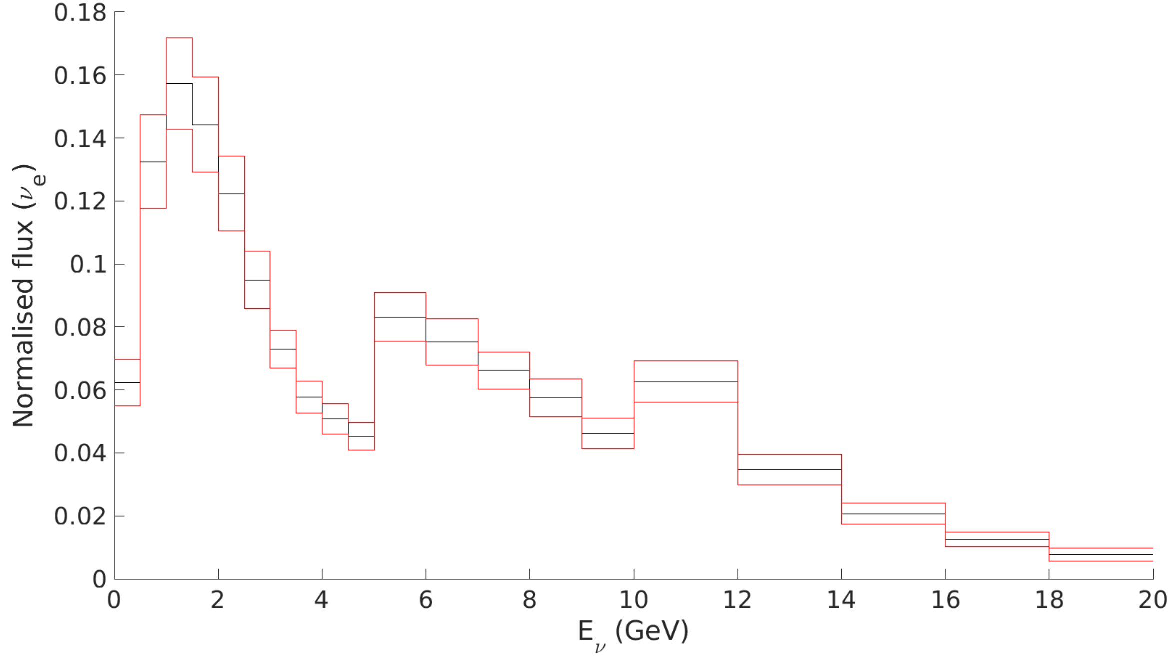
$$F_2^{eN} = \frac{1}{2}\left(F_2^{ep} + F_2^{2n}\right) = \frac{5x}{18}\left(u(x) + \bar{u}(x) + d(x) + \bar{d}(x)\right),$$

we will obtain the following aproximations:

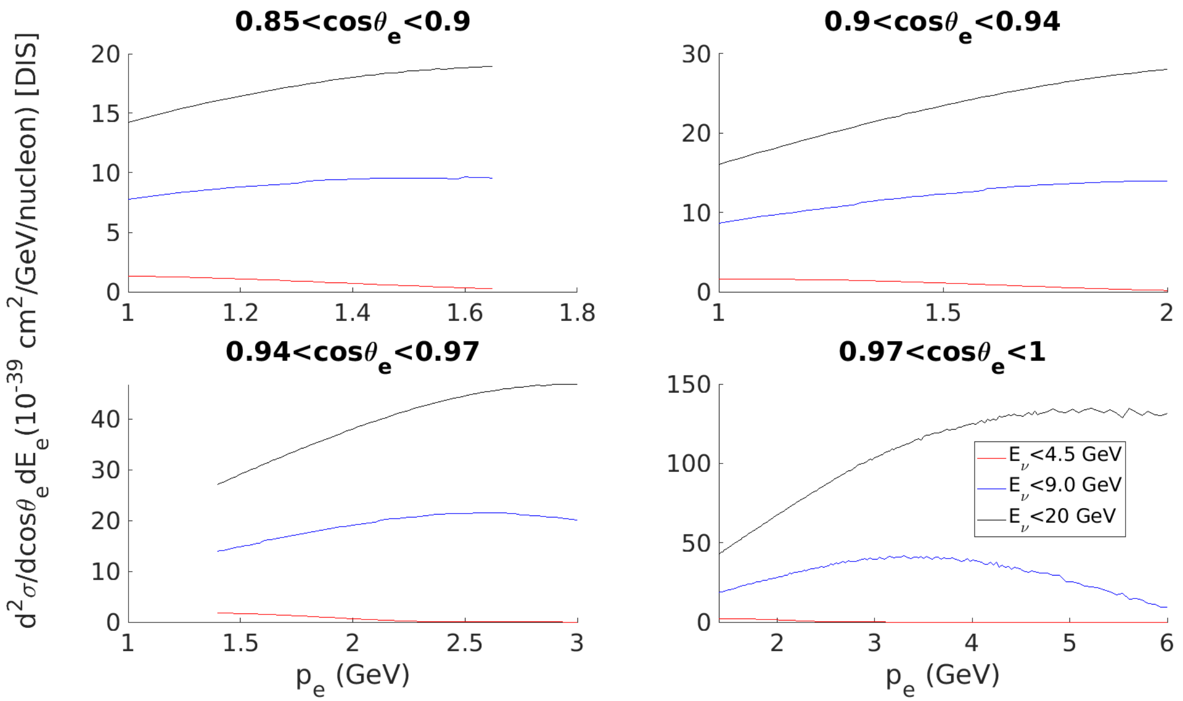
$$F_2^{\upsilon N} \approx \frac{18}{5} F_2^{eN}, \qquad xF_3^{\upsilon N} = F_2^{\upsilon N} - 2\bar{Q}(x).$$

More information in
[J. Gonzalez-Rosa et al., Phys. Rev. D 105, 093009 (2022)]

Back Up: NOvA



Normalised flux (ν_e)
E_ν (GeV)



0.85<cosθ_e<0.9
0.9<cosθ_e<0.94
0.94<cosθ_e<0.97
0.97<cosθ_e<1
$d^2\sigma/d\cos\theta_e dE_e (10^{-39}$ cm^2/GeV/nucleon) [DIS]
p_e (GeV)
E_ν<4.5 GeV
E_ν<9.0 GeV
E_ν<20 GeV