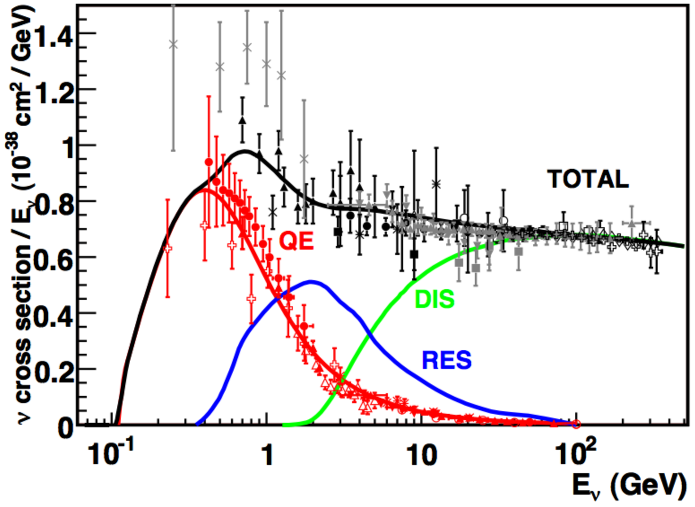
Study of neutrino-nucleus scattering using the superscaling approach: The SuSAv2-DCC model.

J. Gonzalez-Rosa (jgrosa@us.es). PhD Student.

Supervised by J. A. Caballero and G. D. Megias.

Departamento de Física atómica, molecular y nuclear, Universidad de Sevilla, 41080 Sevilla, Spain.

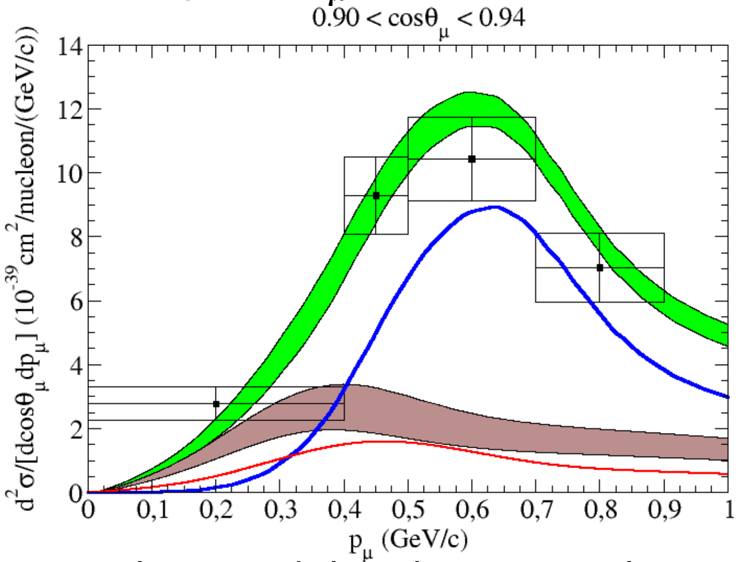
Introduction



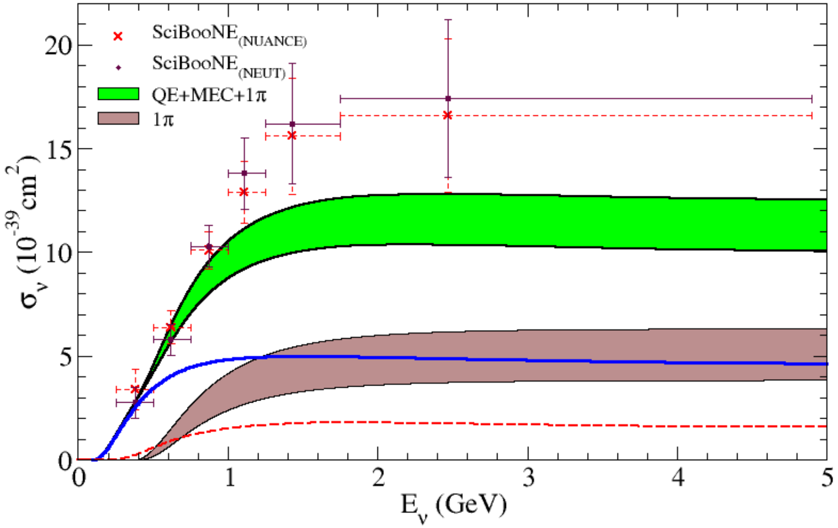
- Quasielastic region (QE).
- Resonance (RES).
- Deep Inelastic Scattering (DIS).

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

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



Total Inclusive Cross Section



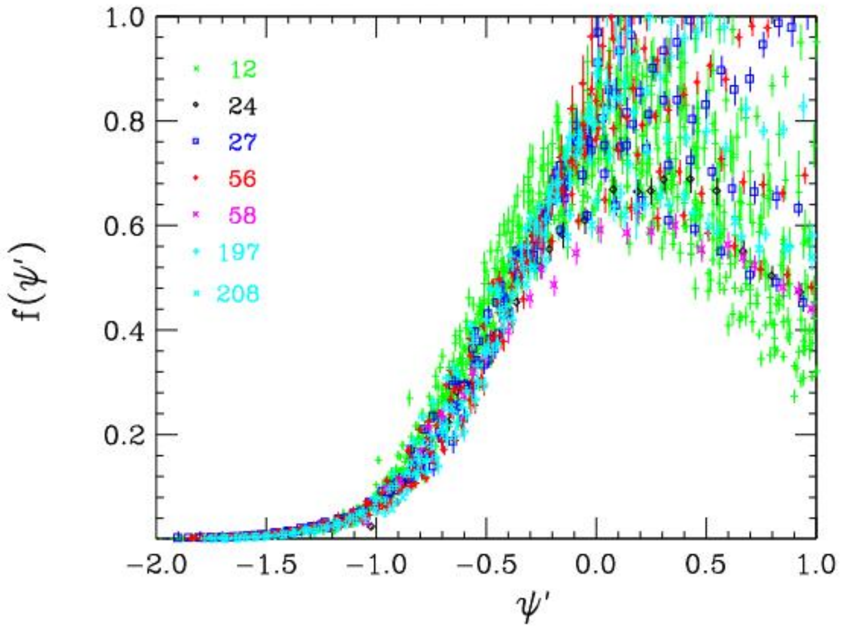
Superscaling model with QE + 2p2h + 1π [G. D. Megías et al., Phys. Rev. D **94**, 093004 (2016)].

Introduction

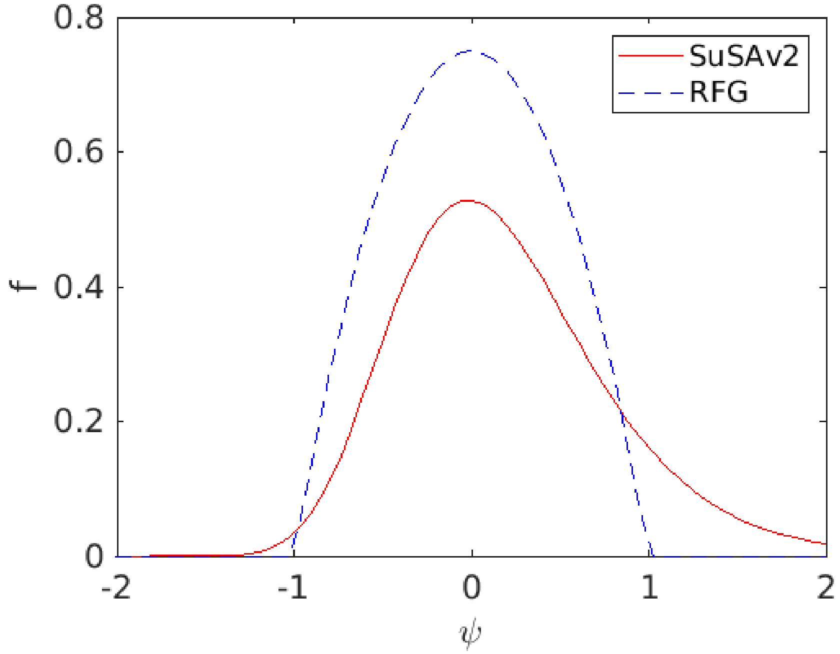
The scaling function does not depend explicitly on the transferred momentum or the nuclear species [J. E. Amaro et al., J. Phys. G 47, 124001 (2020), G. D. Megias, PhD Thesis (2017)].

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

SuSAv2 model takes into account the complexities of nuclear structure.



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



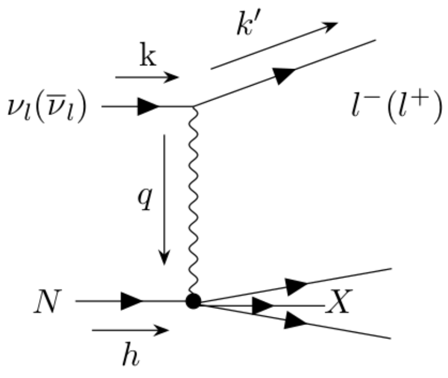
Comparison between SuSAv2-QE and Relativistic Fermi Gas (RFG) scaling function.

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.

$$R_{inel}^{K}(\kappa,\tau) = \frac{N}{\eta_F^2 \kappa} \xi_F \int_{\mu_X^{min}}^{\mu_X^{max}} d\mu_X f^{model}(\psi_X') U^k$$

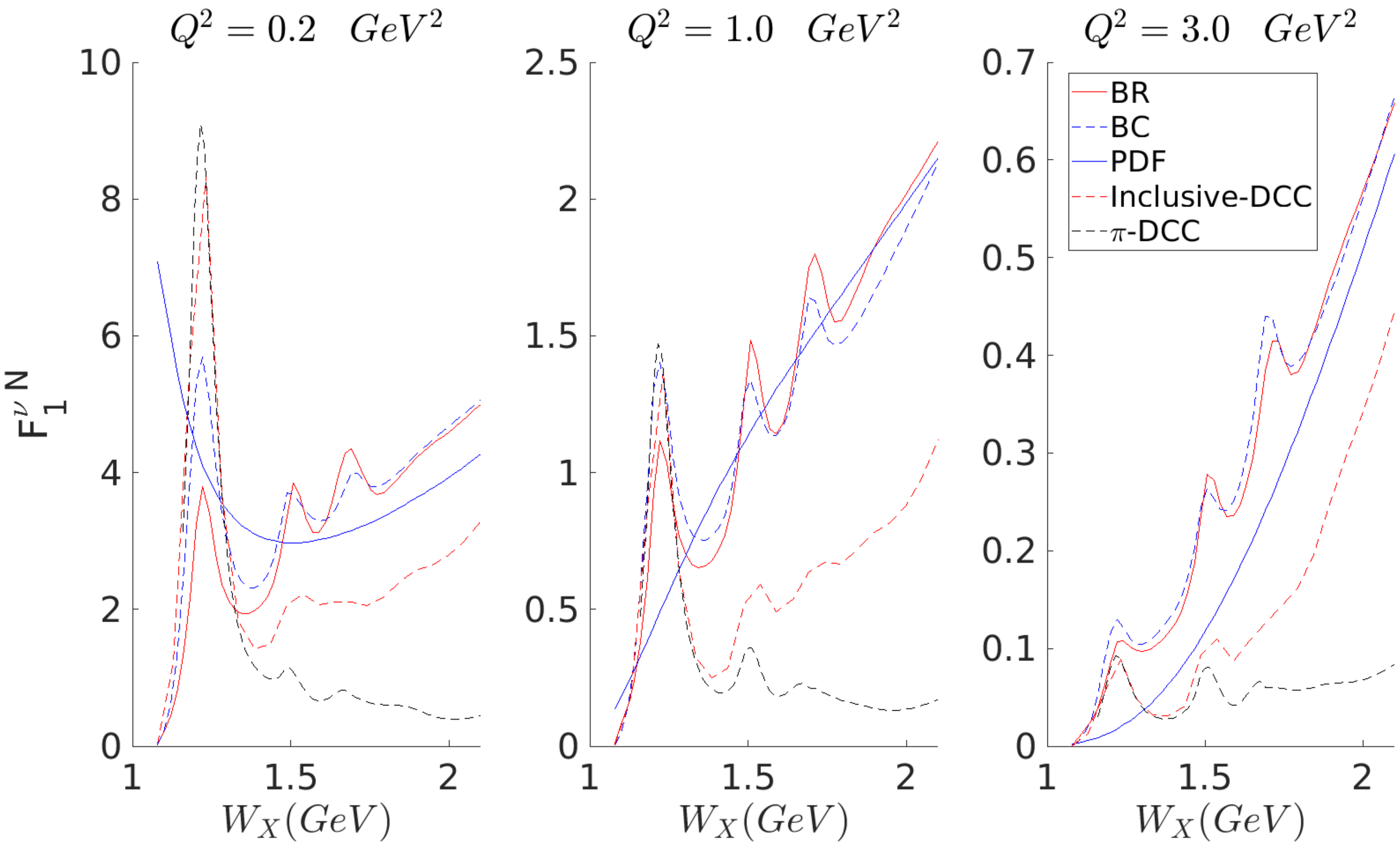


Inelastic Feynmann Diagram

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)

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

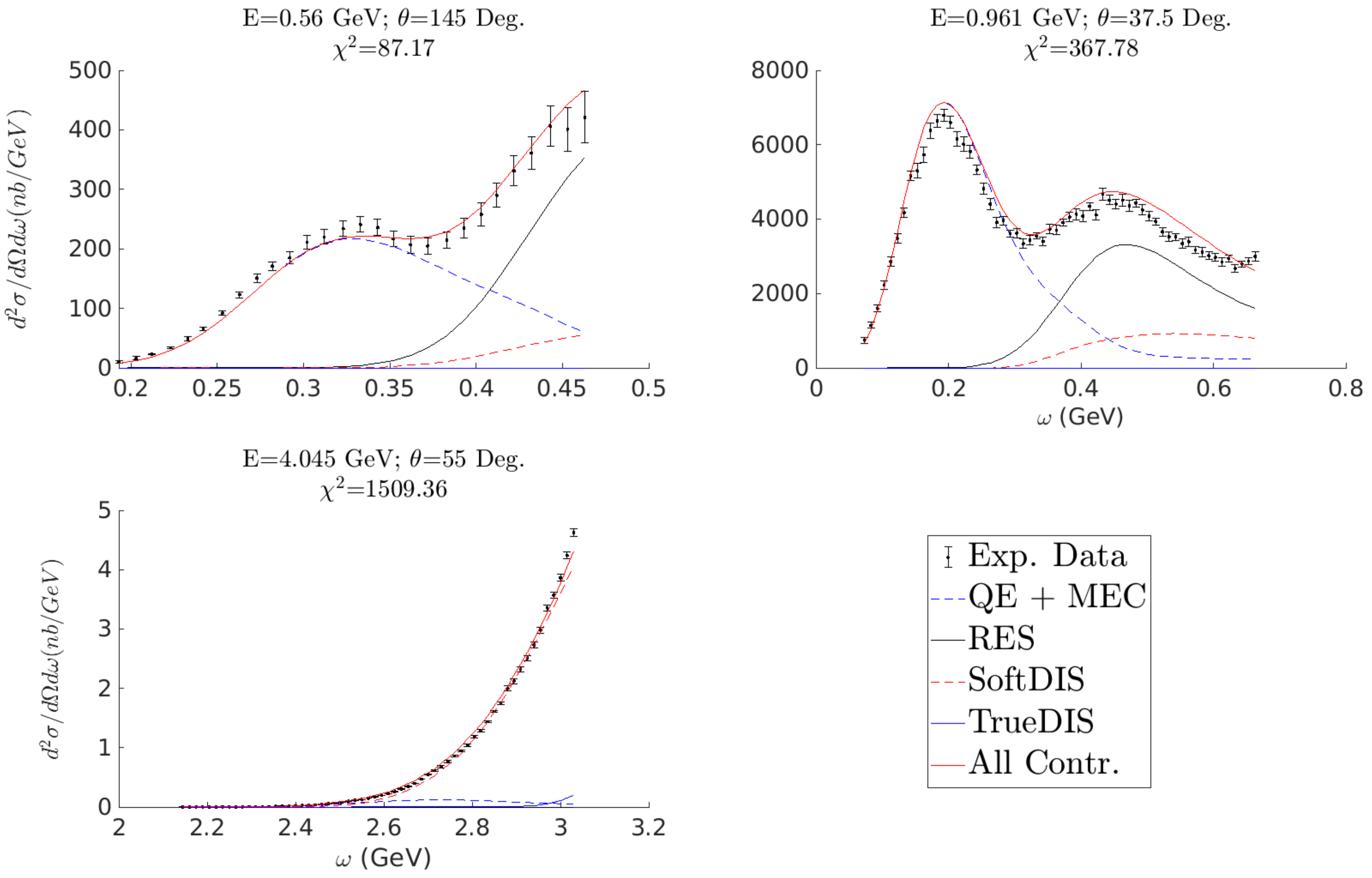
Dynamical Coupled Channels

- 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

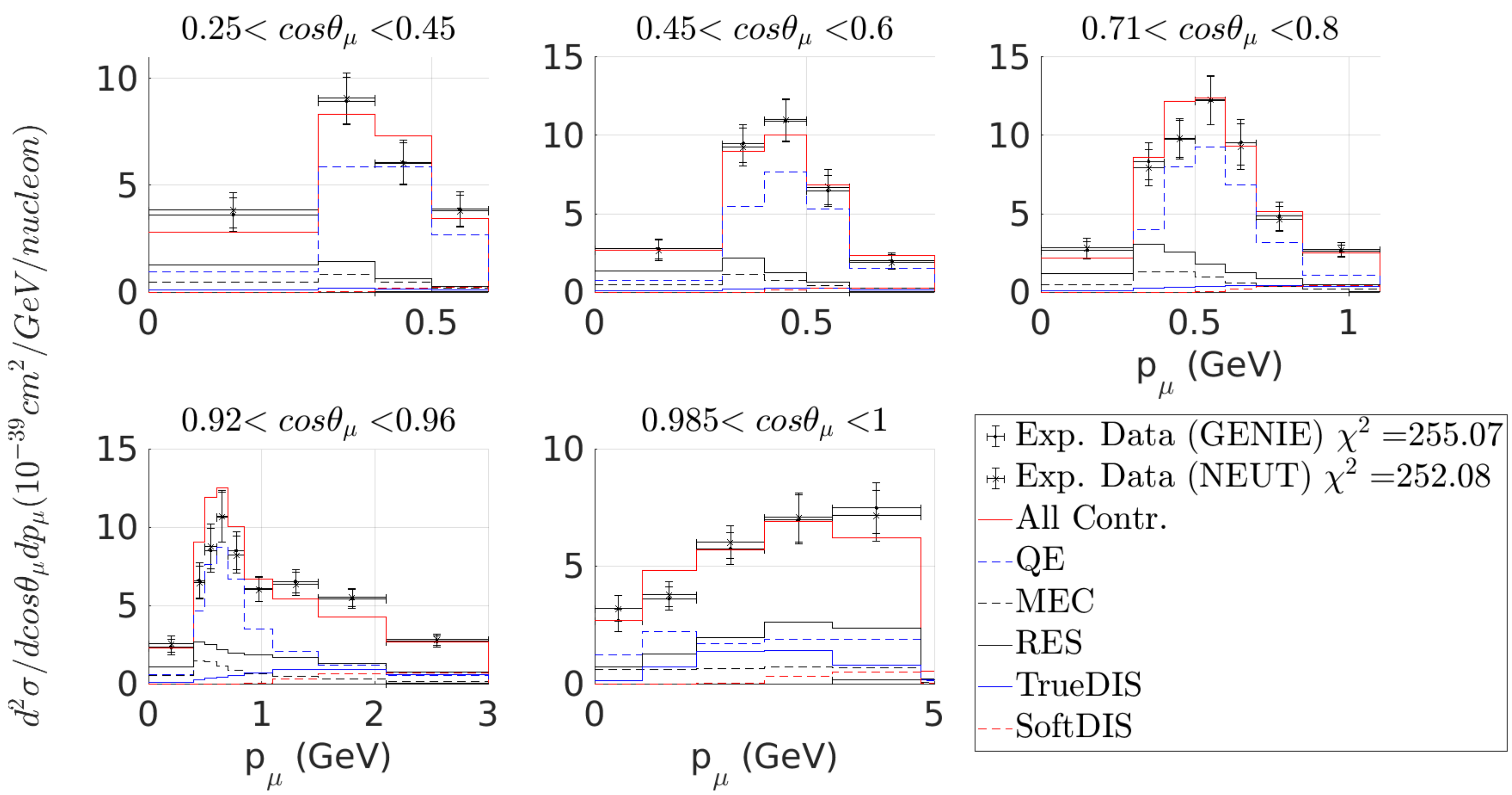
Results: Electron scattering



- At low exchange energy (ω), the cross section is dominated by quasielastic interaction.
- At higher exchange energy, inelastic interaction like resonance or deep inelastic scattering become more important.
- At higher electron energy, all relevant contributions are inelastic ones.

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

Results: T2K



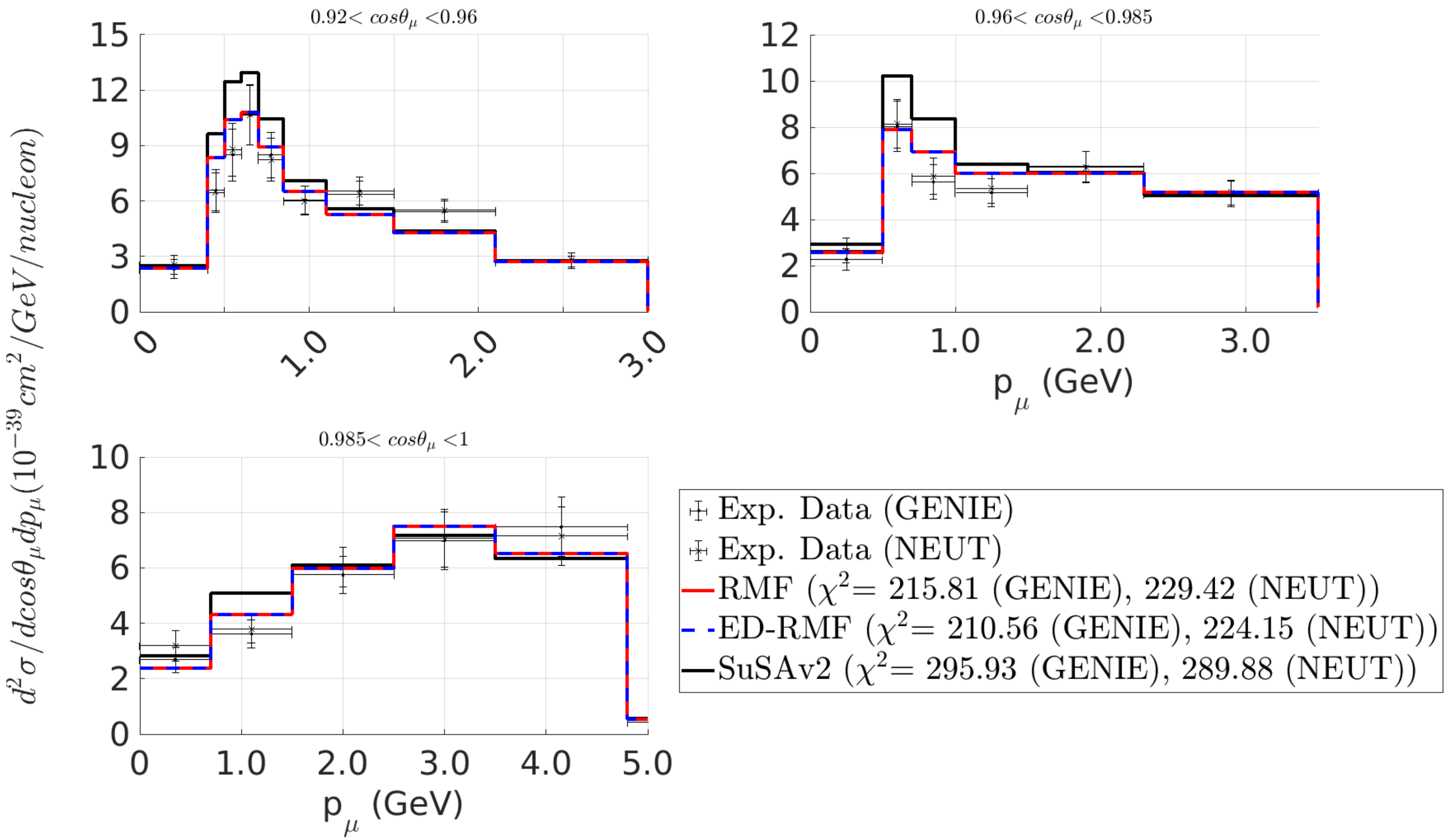
$\chi^2 = 218.3$ (GENIE) $\chi^2 = 192.0$ (NEUT)

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

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

- Quasielastic contribution governs these results.
- At higher muon momentum, inelastic interaction becomes necessary to explain the cross section.
- At very forward angles, cross section is overestimated due the quasielastic contribution from the SuSAv2 model.

Results: T2K (RMF)



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

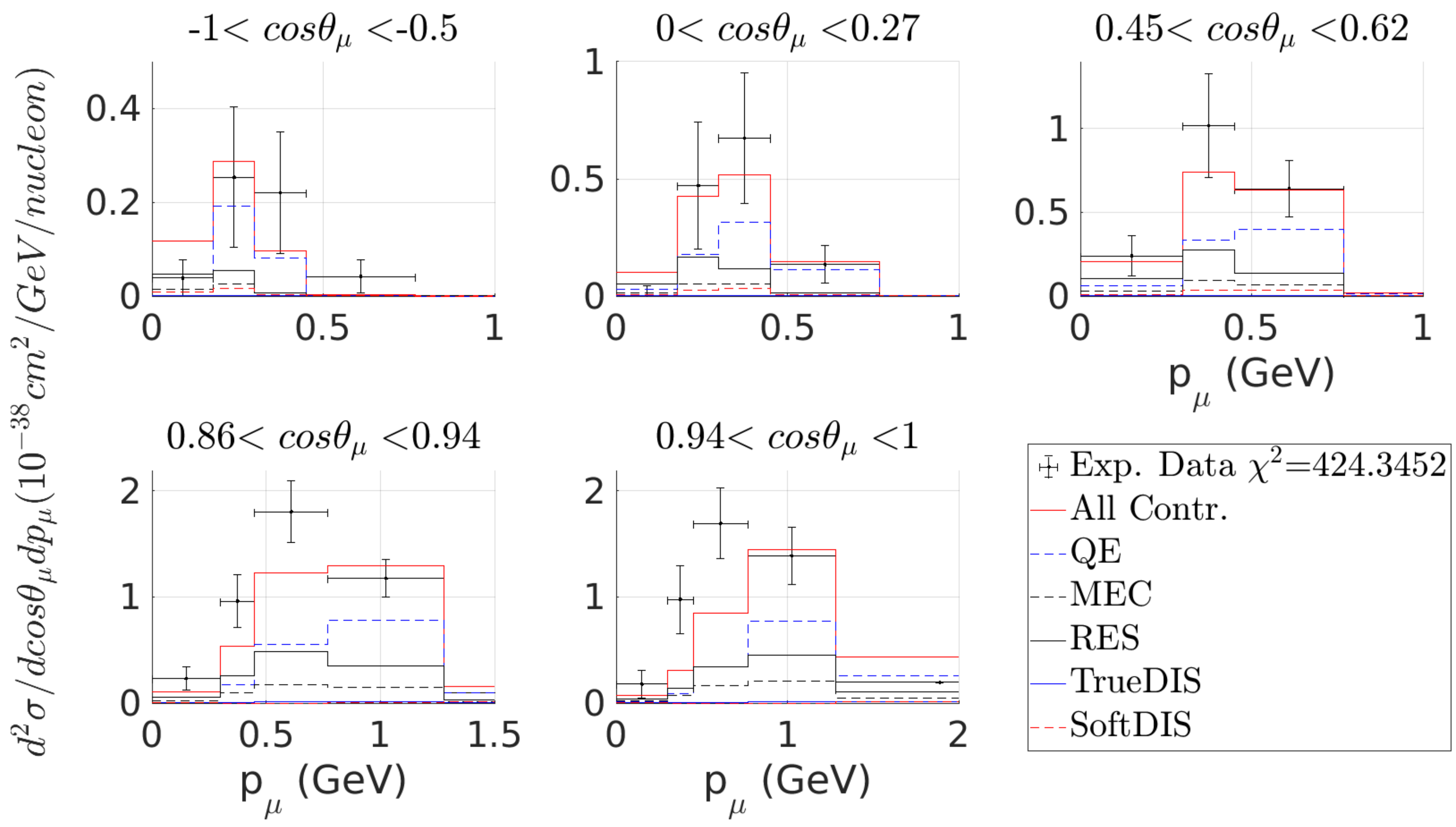
[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

- QE contribution using different models: RMF, ED-RMF and SuSAv2.
- The overestimation is corrected using RMF.

$\chi^2 = 218.3$ (GENIE)

$\chi^2 = 192.0$ (NEUT)

Results: MicroBooNE



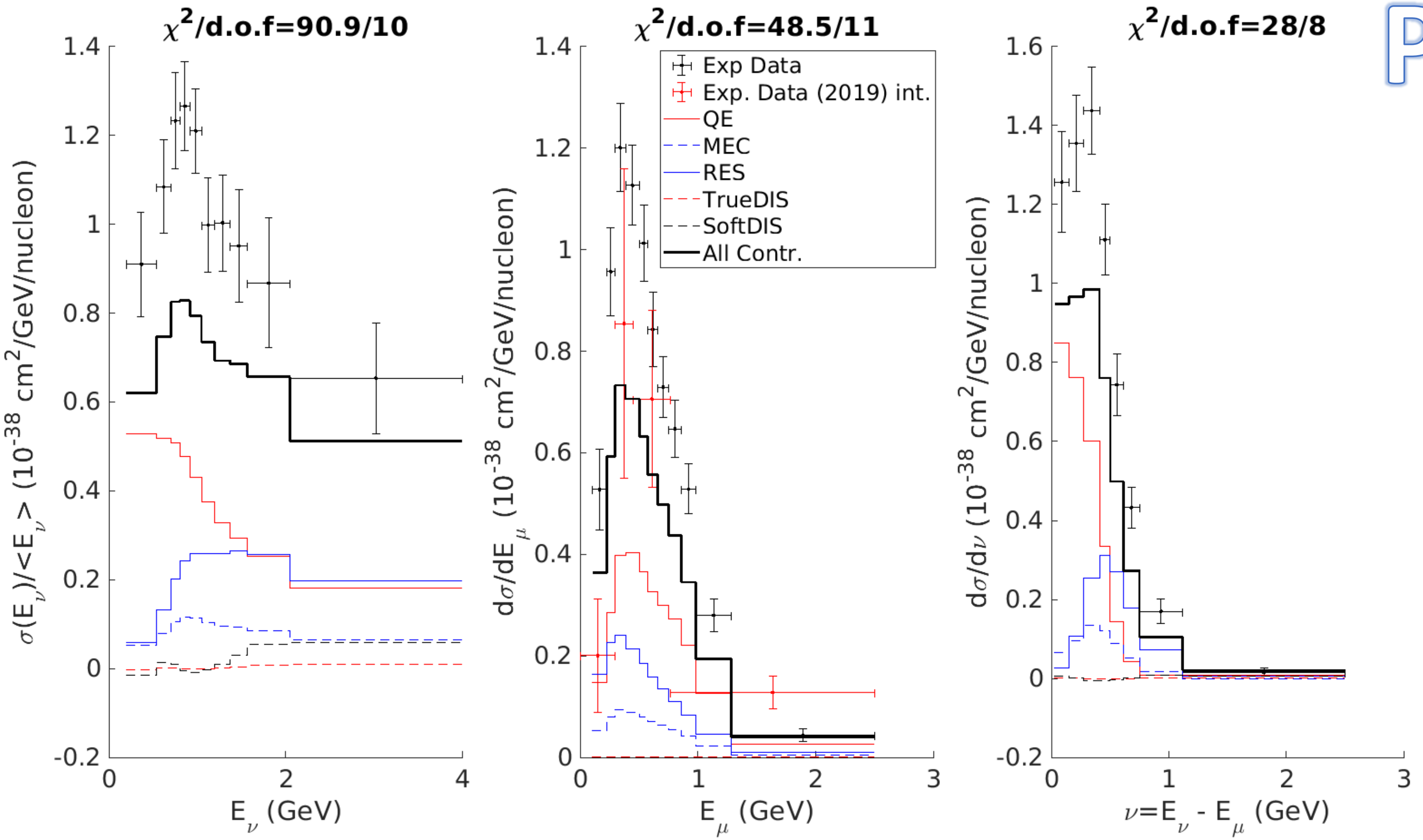
MicroBooNE CC ν_μ, $< E_{\nu_\mu} > \sim 0.8$ GeV

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

$\chi^2 = 103.9$
(GENIEv3)

- Quasielastic contribution dominates the cross section.
- The prediction has a shift to the left at backward scattering angle and to the right at forward angles.

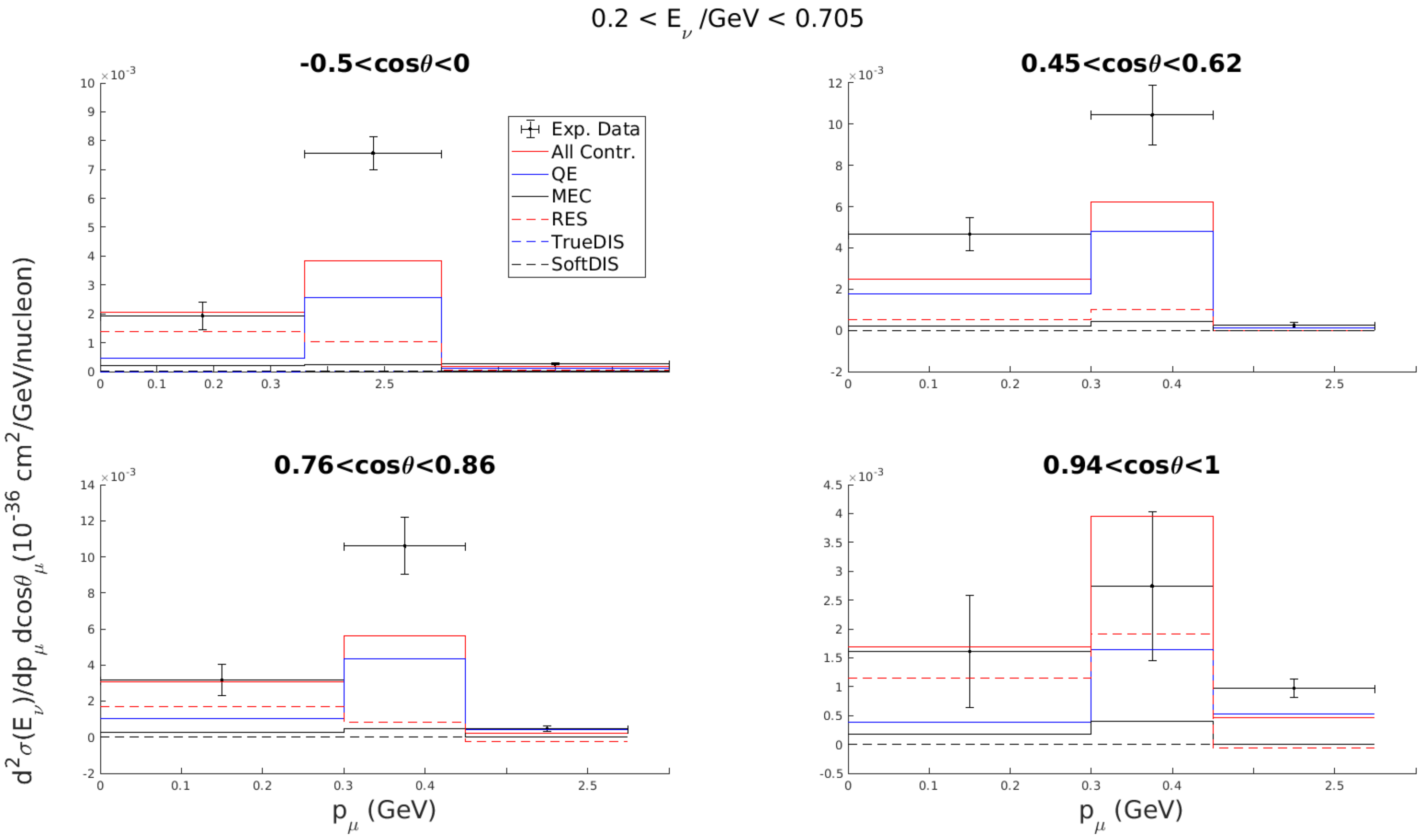
Results: MicroBooNE



Preliminary Results

- The experimental total cross section shown in these plots is higher than the previous one.
- We tend to underestimate the experimental data, specilally when the cross section peaks.

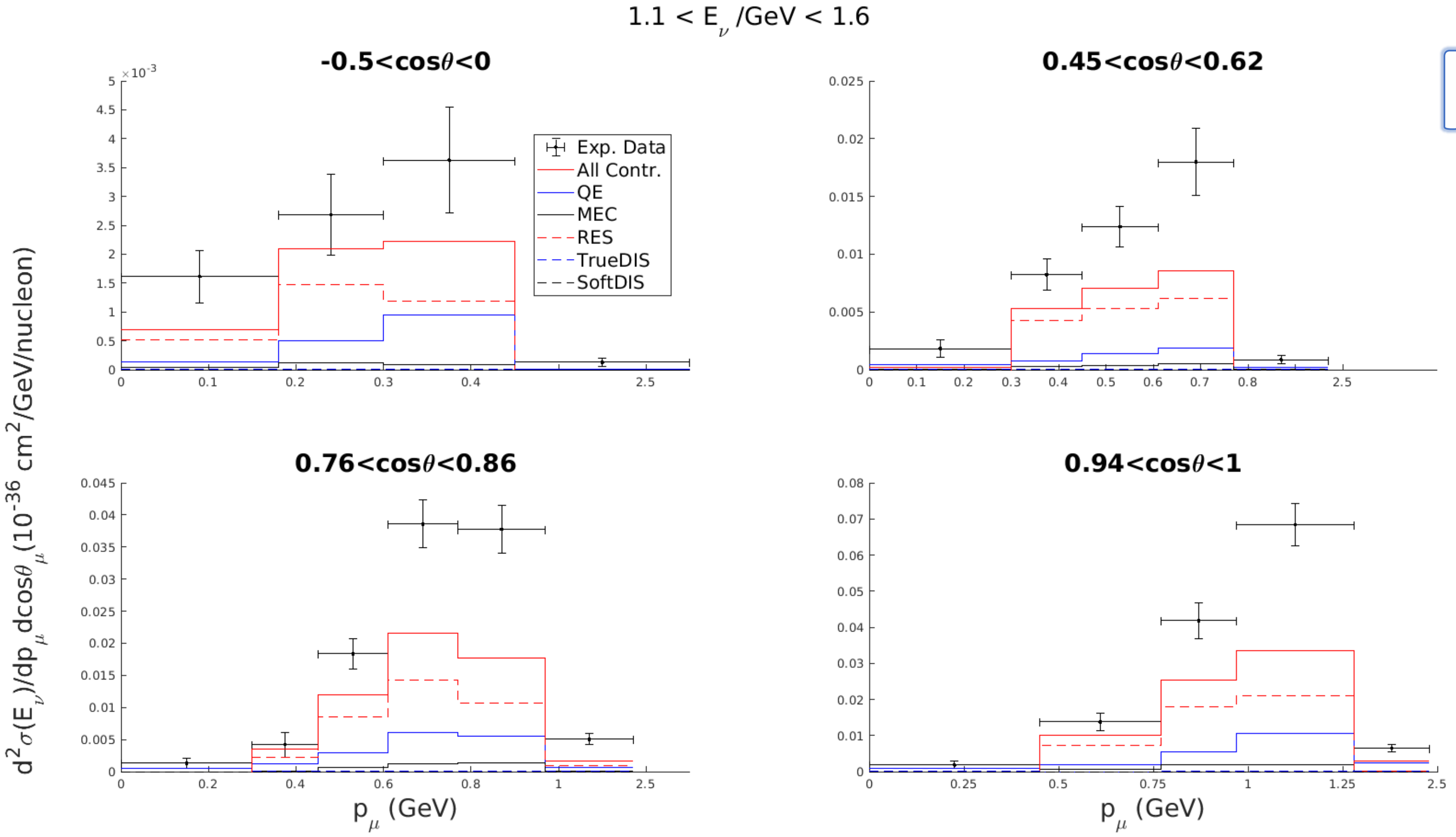
Results: MicroBooNE



Preliminary Results

- At these kinematics, the quasielastic contribution dominates.
- The prediction underestimate the data, in general.

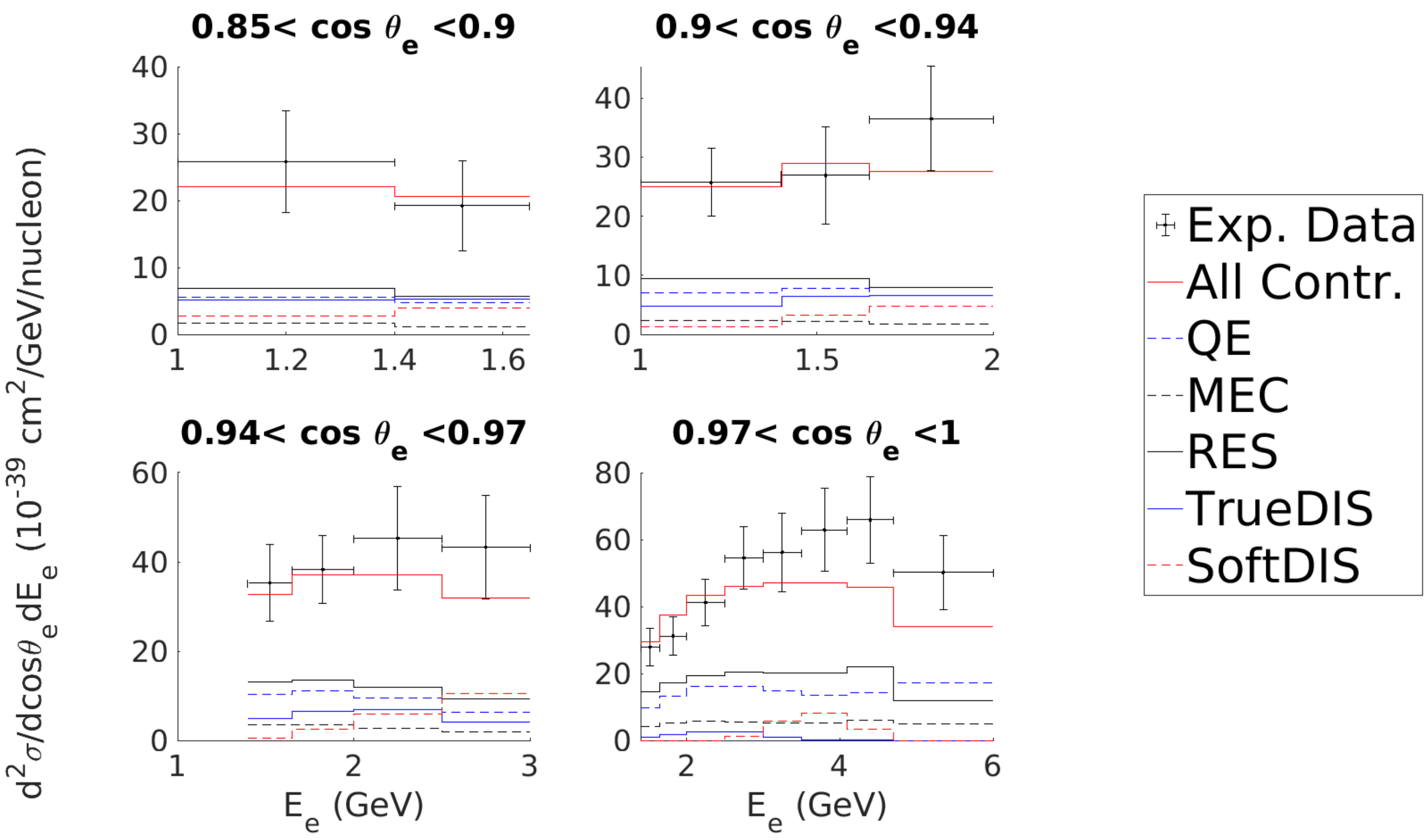
Results: MicroBooNE



Preliminary Results

- At these kinematics, the resonance contribution is the most important one.
- The prediction underestimate the data, in general.

Results: NOvA

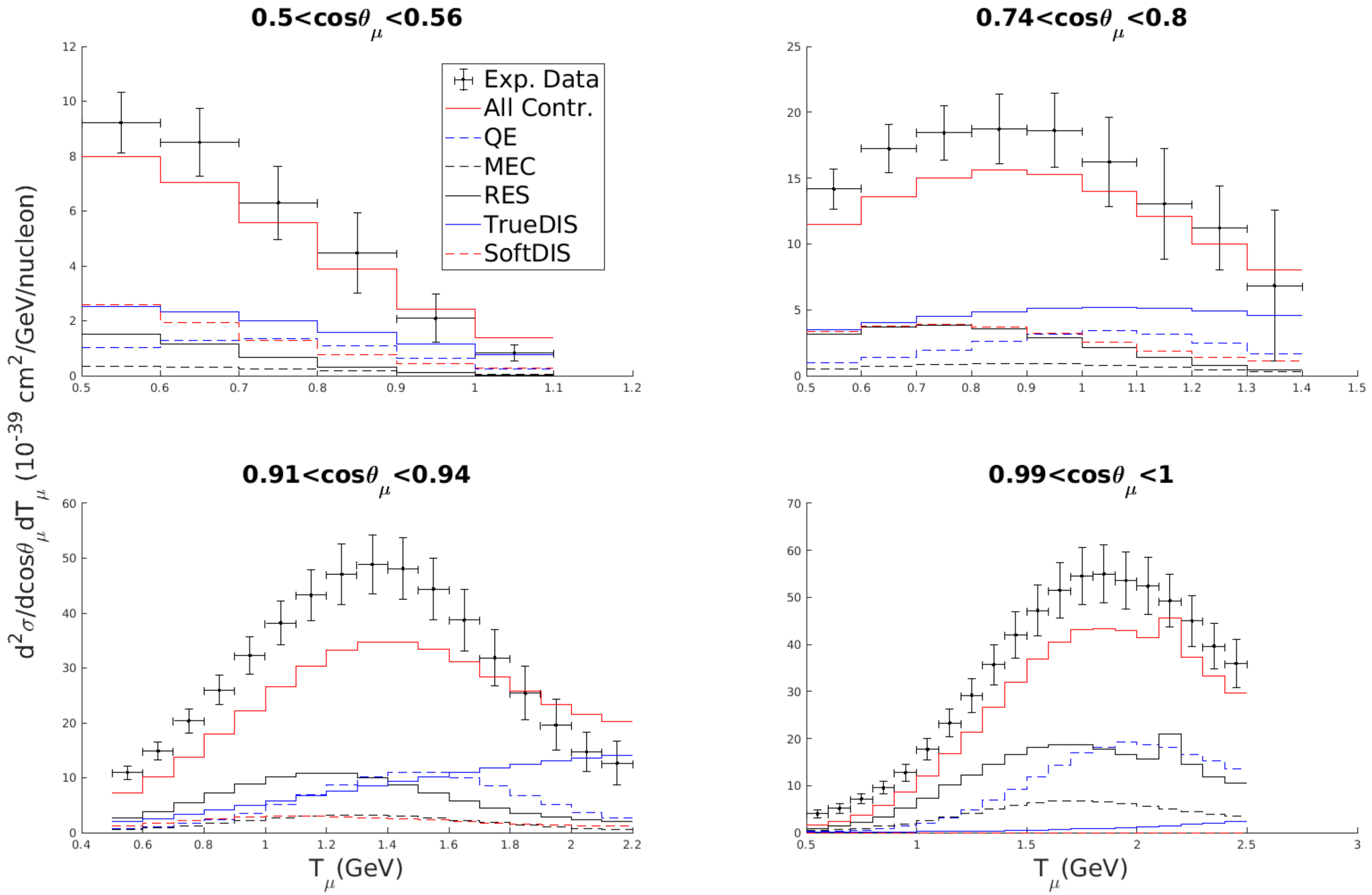


Preliminary Results

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

- In general, we reproduce the cross section.
- We need to add the contributions of the other elements.In this plot, we are considering that the target nucleus is carbon.

Results: NOvA



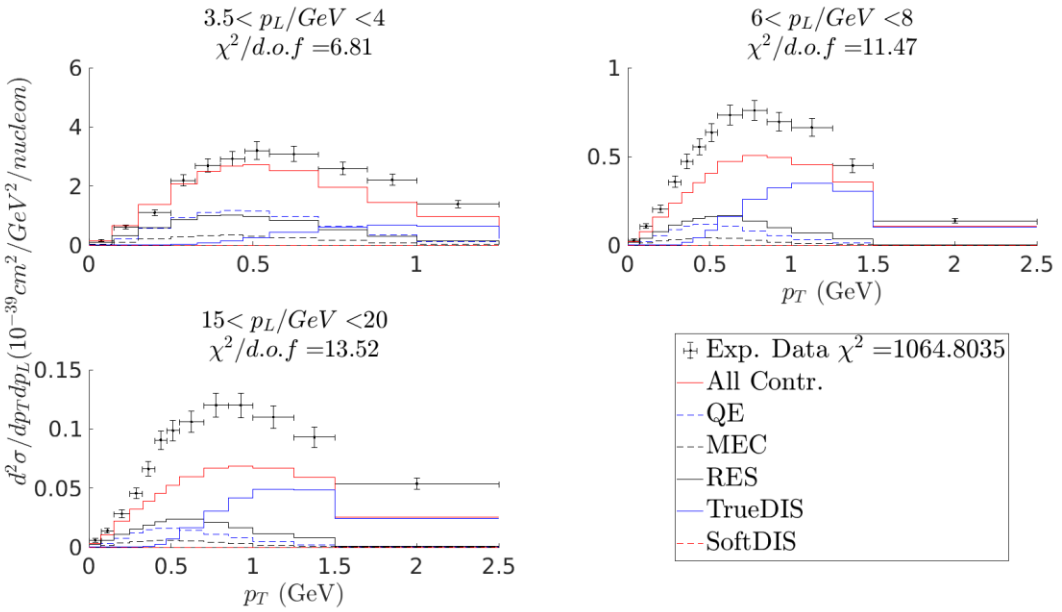
Preliminary Results

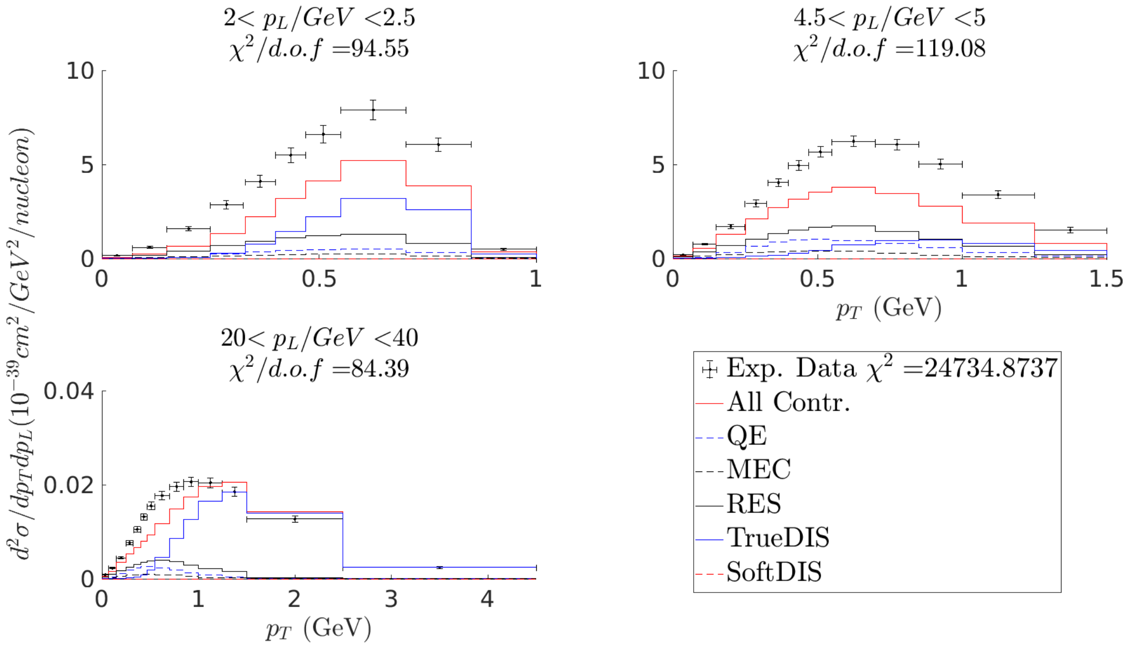
NOvA CC $\nu_\mu, < E_{\nu_\mu} > \sim 4.0\ GeV$

- In general, we underestimate the cross section in the peak. There is some overestimation at higher kinetic energy.
- We need to add the contributions of the other elements. In this plot, we are considering that the target nucleus is carbon.

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)

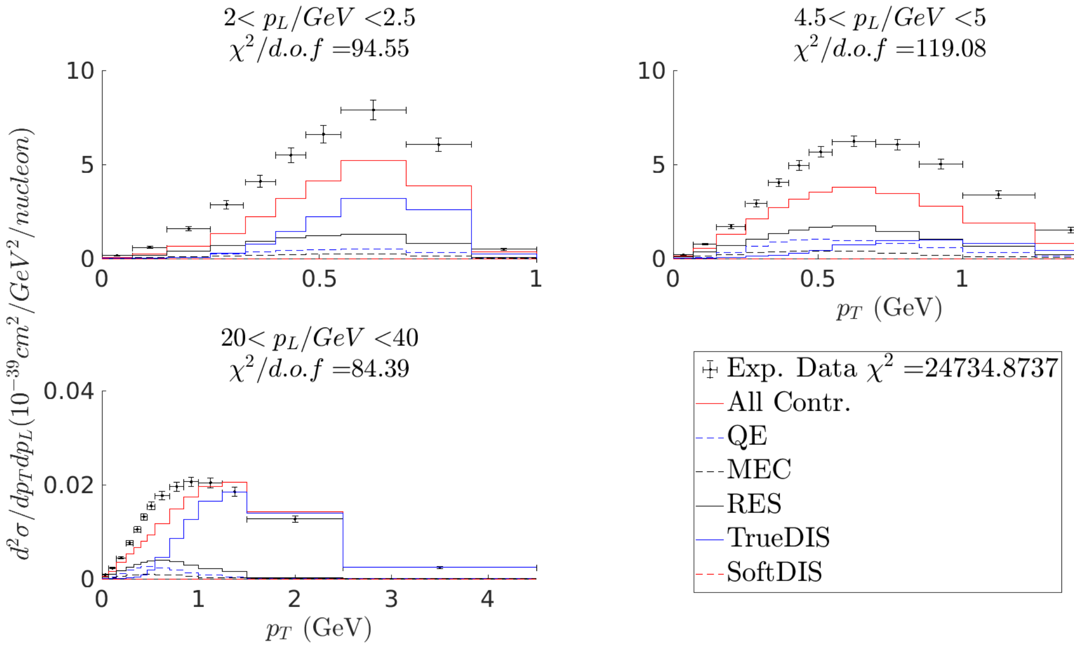
$\chi^2 = 495$ (MnGENIEv1) $\chi^2 = 422$ (GENIE 2.8.4)

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

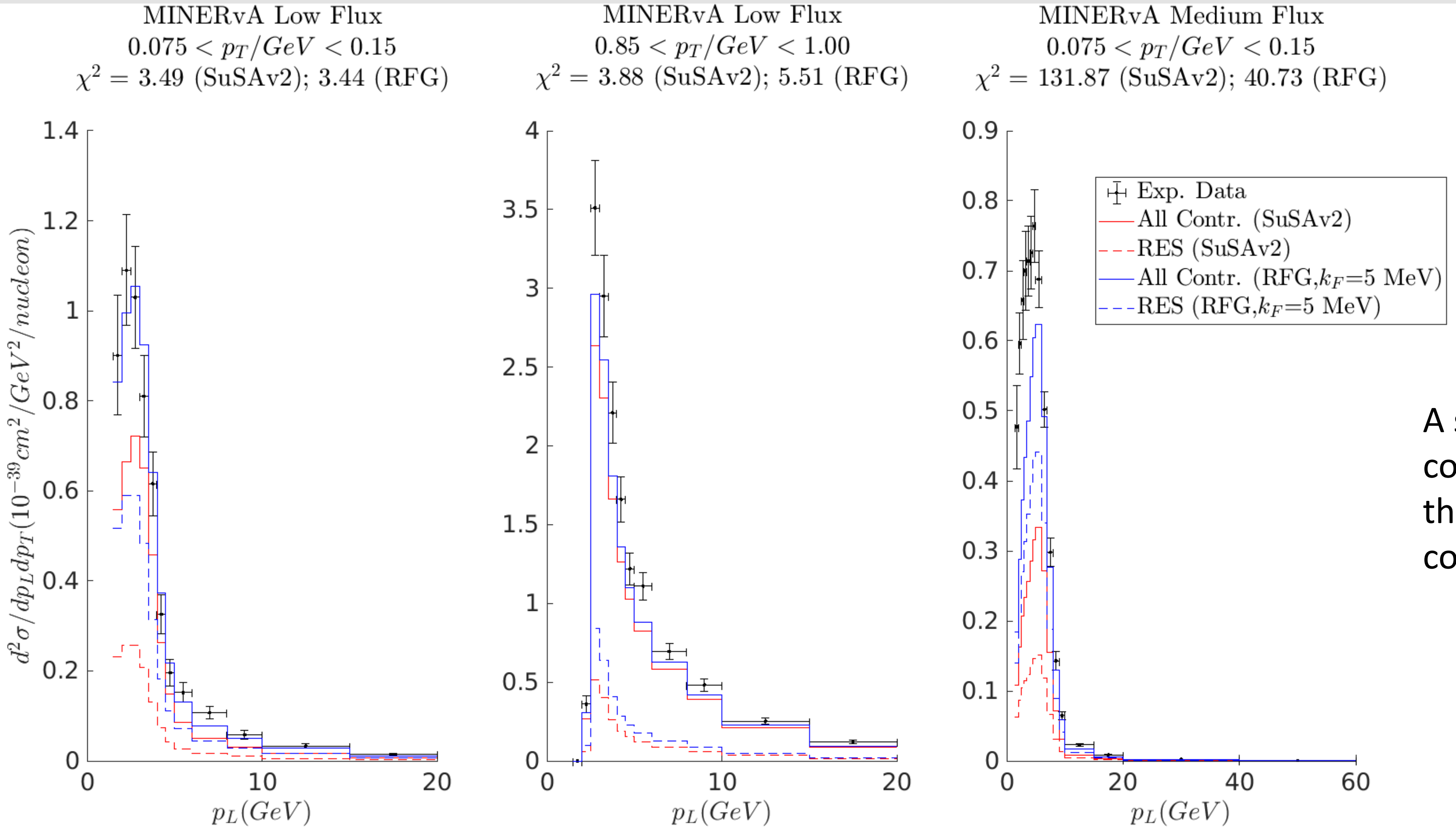
- At low longitudinal momentum, we are closer to the experimental data.
- When the resonance contrubution becomes more important in the kinematics we tend to underestimate the data.
- The zones dominated by deep inelastic scattering are also closer to the experimental results.



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)

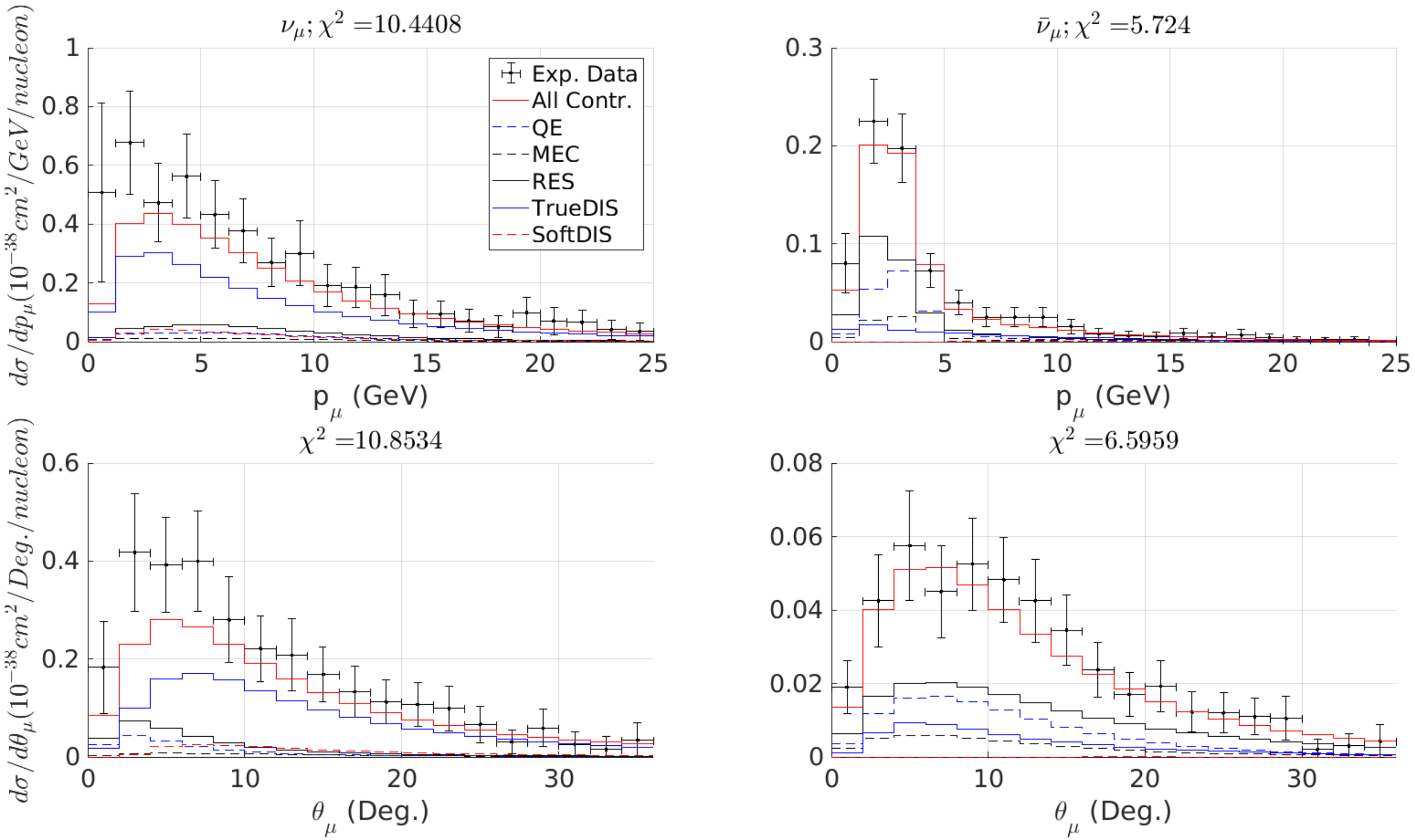
Results: MINERvA



A single-nucleon contribution is closer to the data than a nuclear contribution.

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

Results: ArgoNEUT

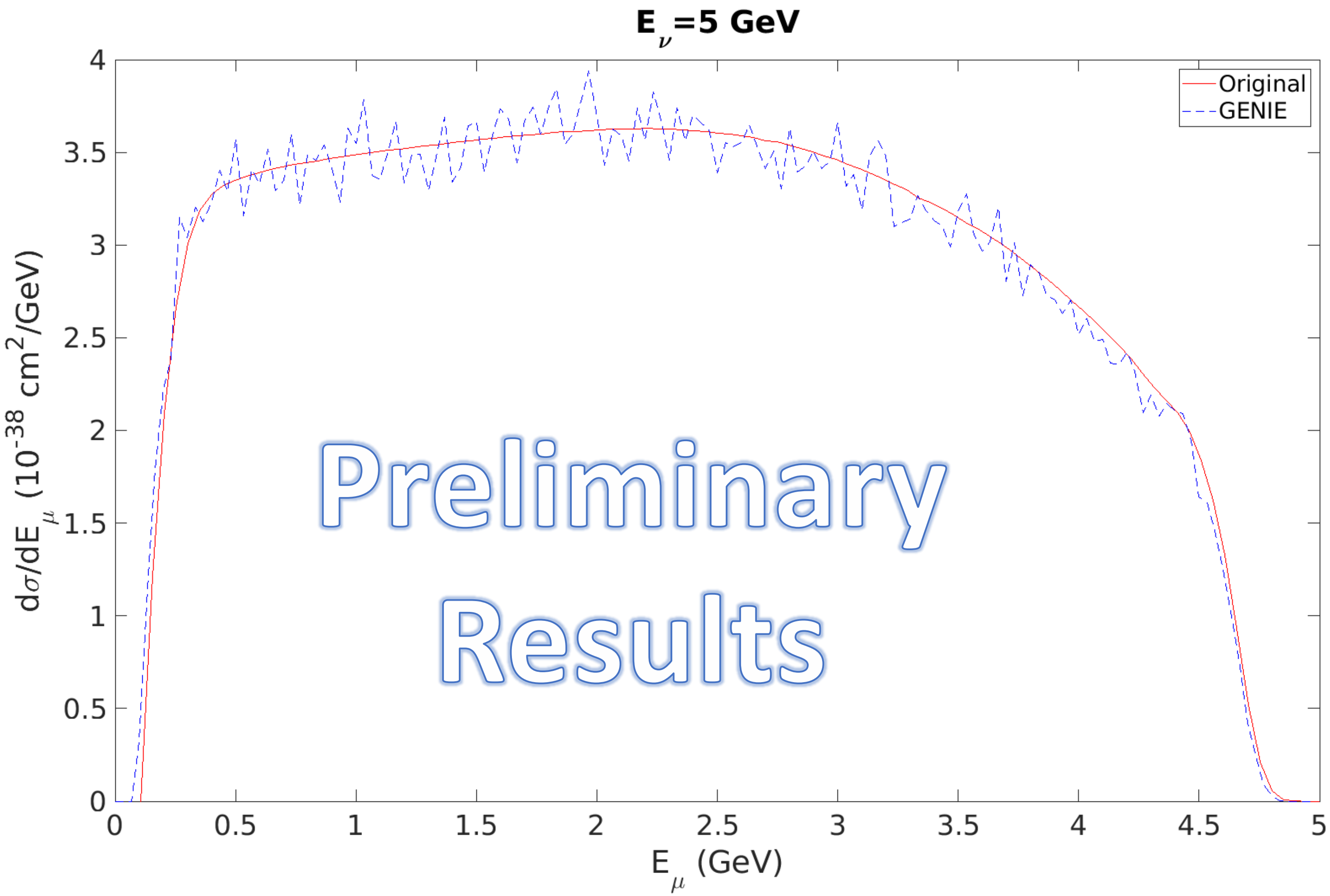


ArgoNEUT CC $\nu_\mu, < E_{\nu_\mu} > \sim 9.6\ GeV$; CC$\bar{\nu}_\mu, < E_{\nu_\mu} > \sim 3.6\ GeV$

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

There is a underestimation at very forward angles in the case of neutrinos scattering.

Implementation of the model in GENIE



The SuSAv2-inelastic model has been implemented 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

.

- 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 match the results 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:

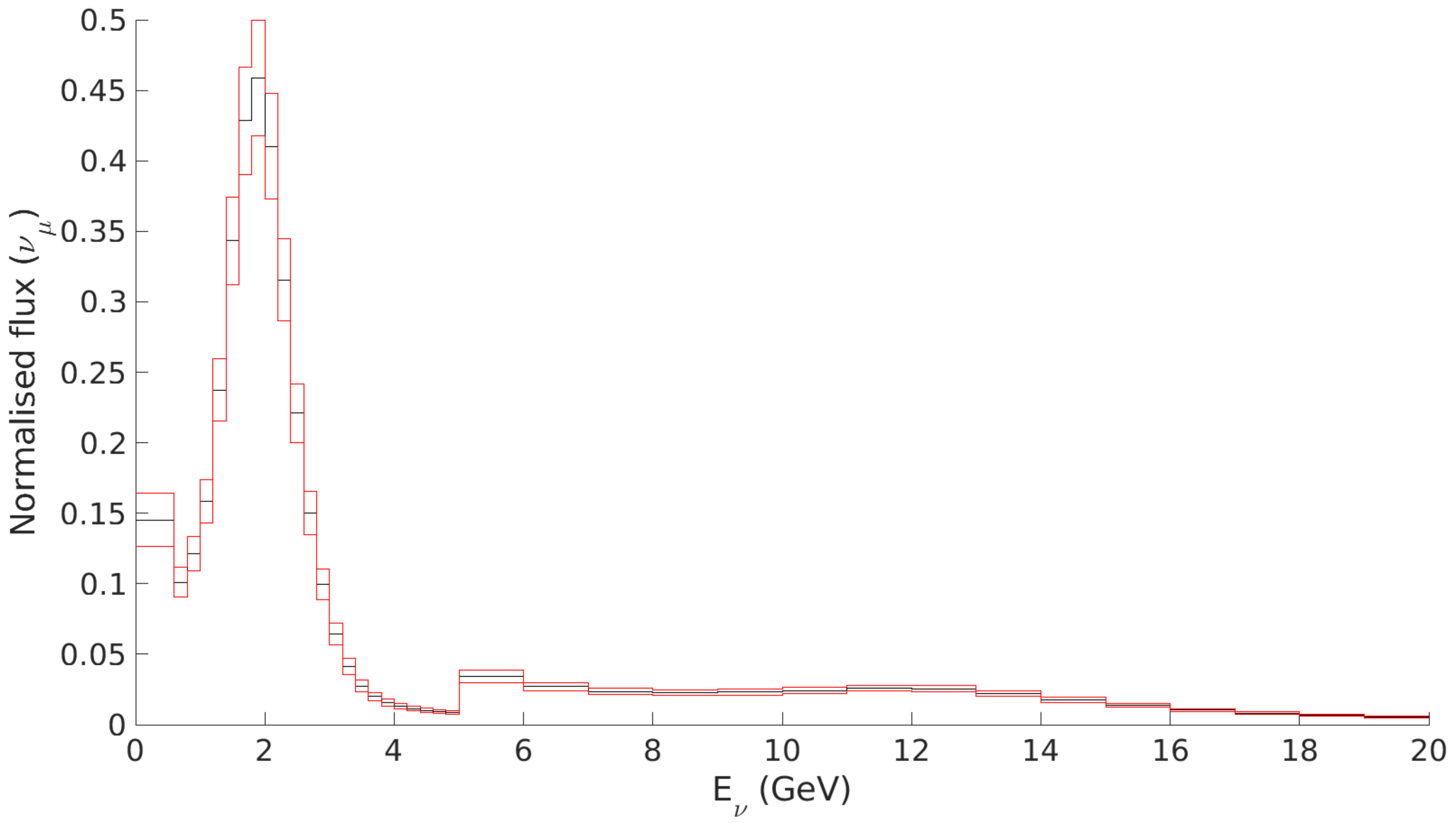
$$F_2^{eN} = \frac{1}{2}\left(F_2^{ep} + F_2^{2n}\right) = \frac{5x}{18}\left(u(x) + \bar{u}(x) + d(x) + \bar{d}(x)\right),$$

we will obtain the following aproximations:

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

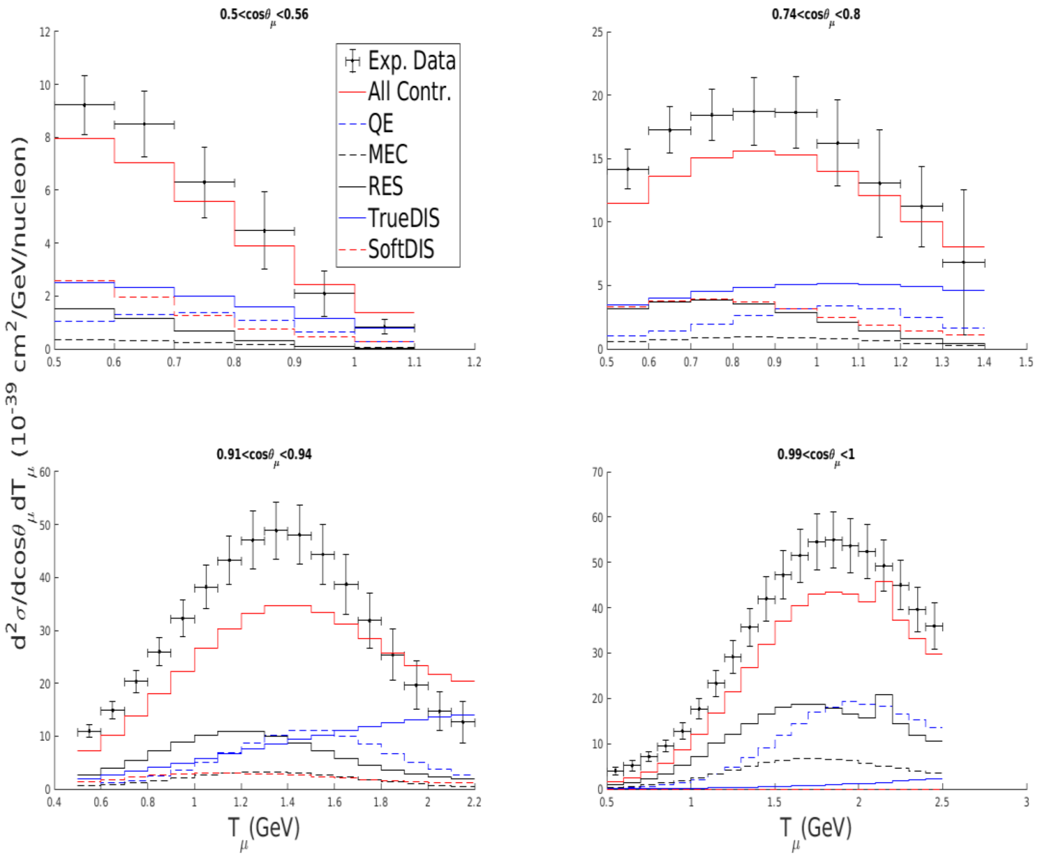
More information in [J. Gonzalez-Rosa et al., Phys. Rev. D 105, 093009 (2022)]

Back Up: NOvA

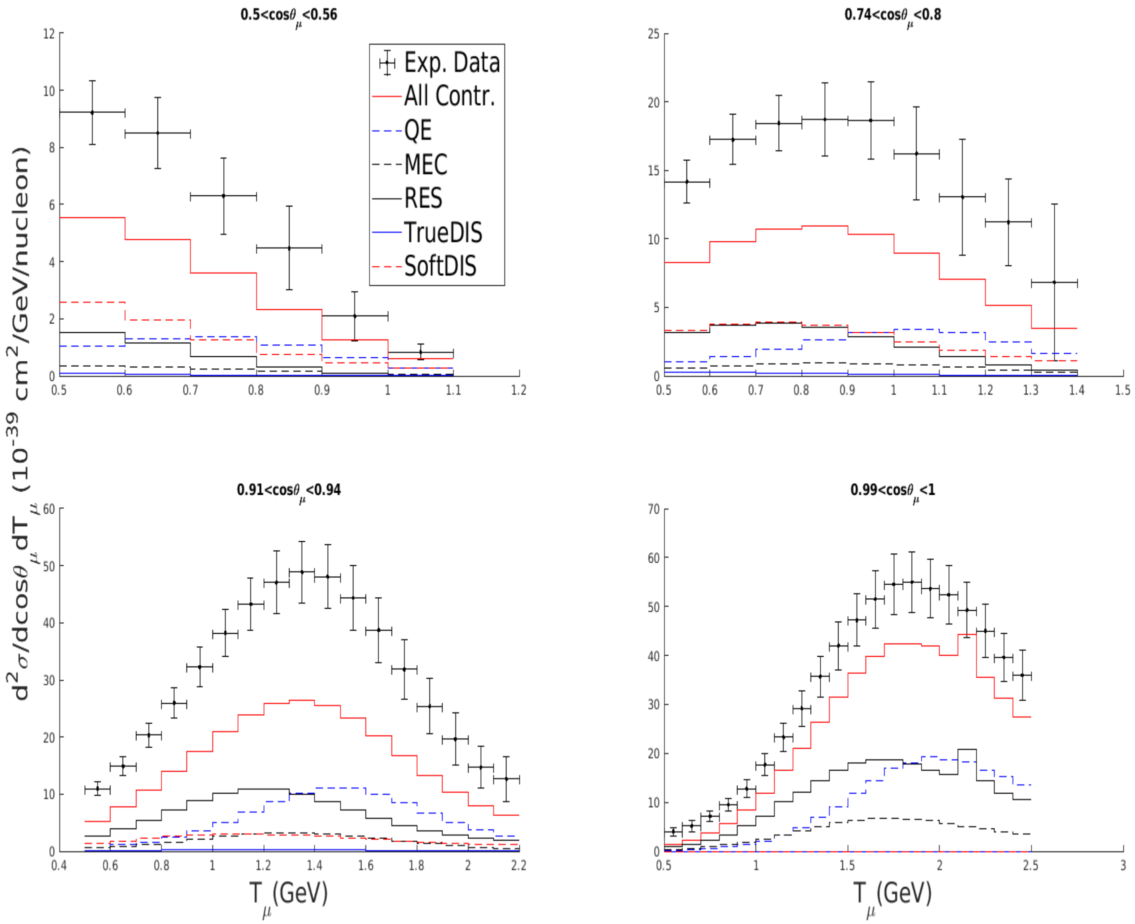


Normalised flux (ν_μ)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
16
18
20
E_ν (GeV)

Back Up: NOvA



NOvA Muon – All Flux



NOvA Muon – Flux Limited to Ev < 5 GeV