Understanding Uncertainties in Neutrino Experiments

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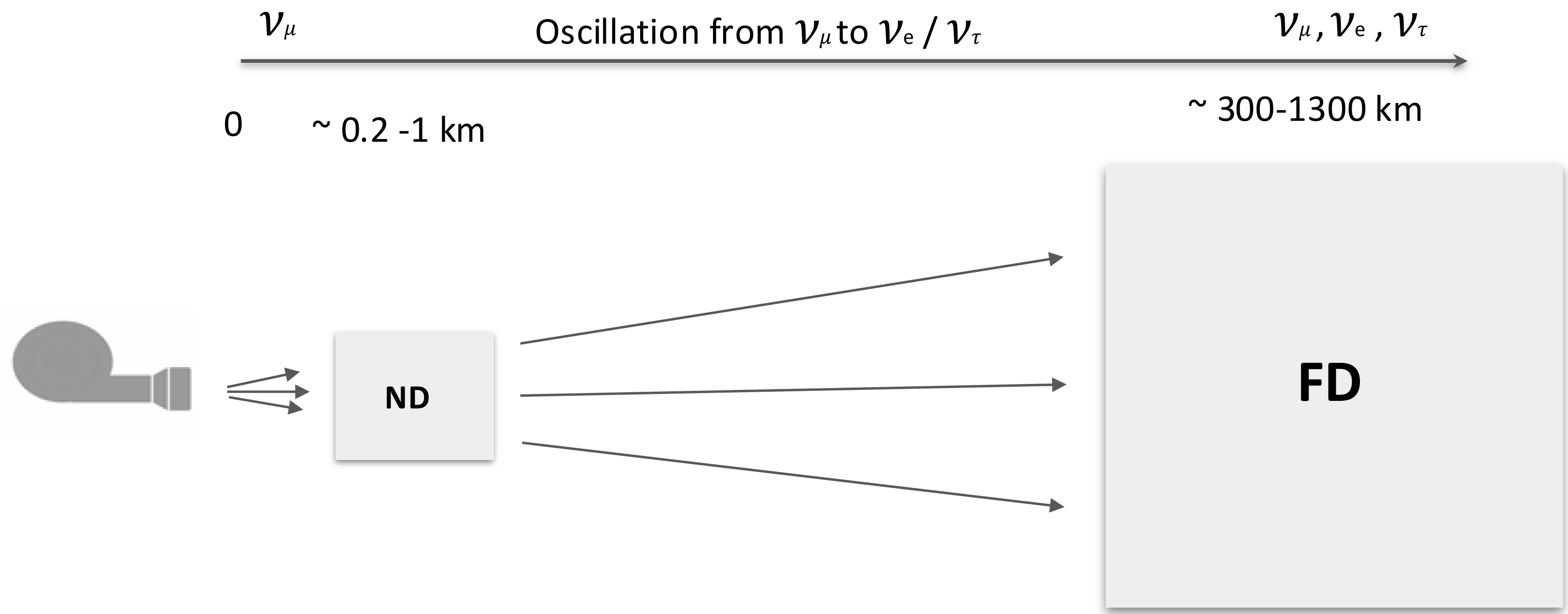
Plan of the Talk

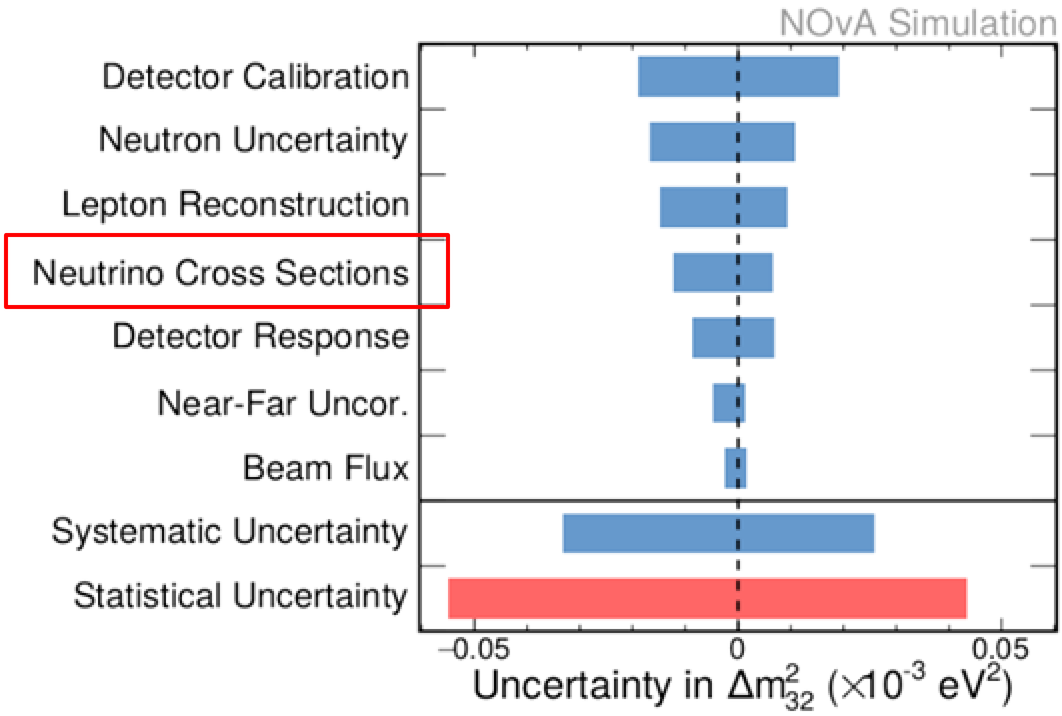
- Introduction
- CCQE analysis
- KDAR Neutrino
- Neutral pion production
- Outlook


ν_μ
Oscillation from ν_μ to ν_e / ν_τ
ν_μ , ν_e , ν_τ
0
~ 0.2 -1 km
~ 300-1300 km
ND
FD

Neutrino Uncertainty

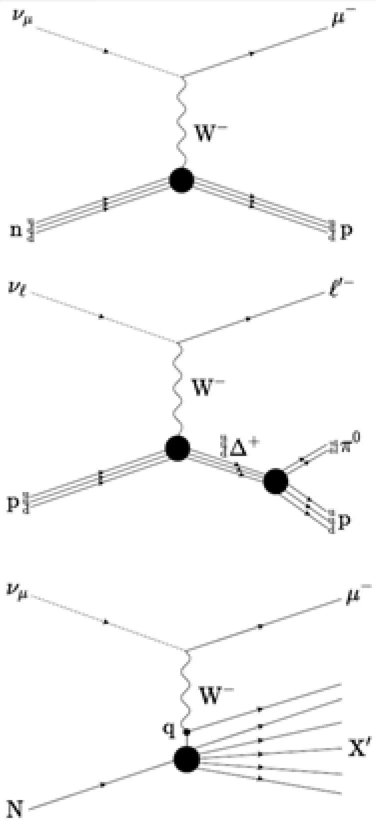
- Neutrino Cross section uncertainty is one of the crucial parameters.

- Essential for precision measurements and search for New Physics.



A Himmel talk 2023

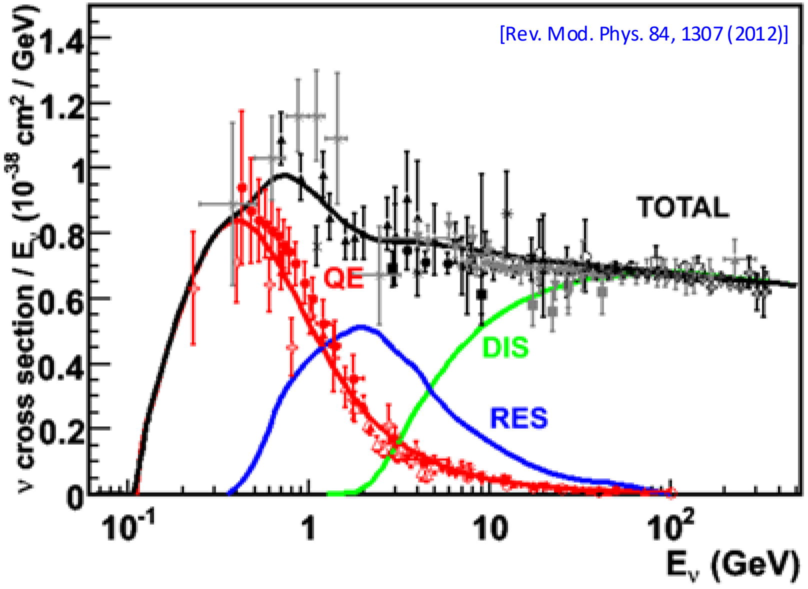
Neutrino Interactions



Quasi-Elastic (QE)

Resonance (RES)

Deep Inelastic Scattering (DIS)

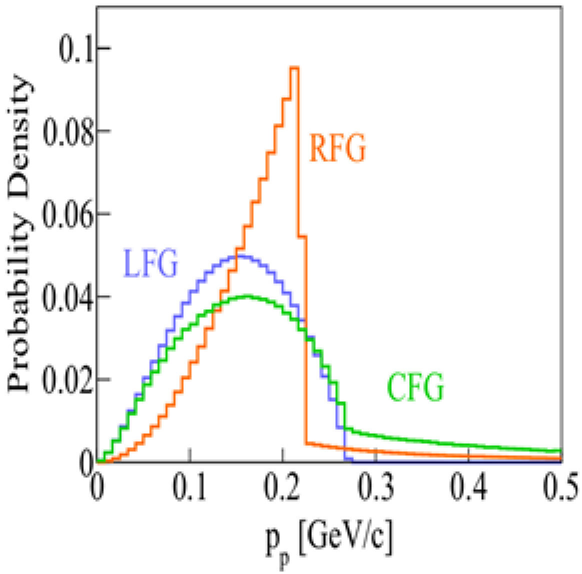


Different cases

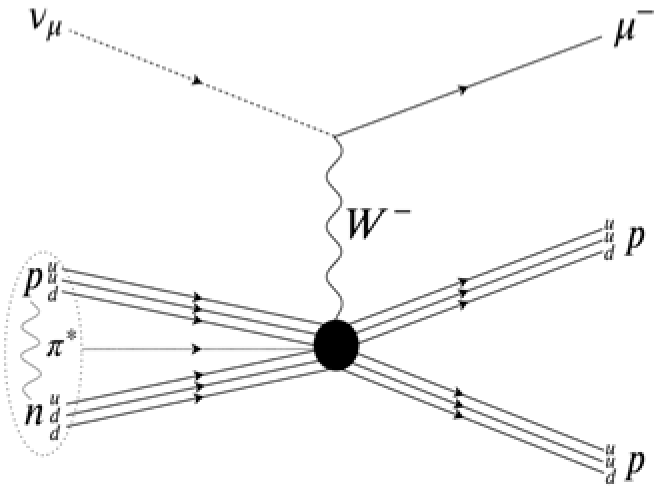
Initial State effect (IS)

→ Fermi Motion

[EPJST 230 (2021) 24, 4449-4467]



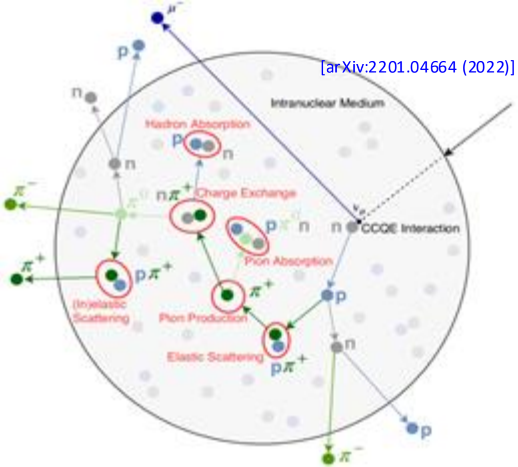
Meson Exchange current (MEC)



Multi nucleon knockout

Final State Interactions (FSI)

[arXiv:2201.04664 (2022)]



→ (in)elastic scattering
→ pion production
→ absorption
→ charge exchange

ν_μ CCQE Scattering on Argon & Carbon

Uncertainty in Quasi-elastic Interaction

- ν_μ CC-QE interaction: $\nu_\mu\, n \rightarrow \mu^- \, p$
- Final state of a pure CCQE consists of 1 muon and 1 proton.
- Nuclear effects alter the final state leading to misidentification of CCQE.

FSI causes:

- Pions can be produced : QE misidentified as RES.
- Other nucleon knockout along with proton: QE misidentified as MEC.
- Pions produced in RES can be absorbed: RES misidentified as QE.
- 2 nucleons produced in MEC can go through pion production and absorption leading to 1 proton in final state: MEC misidentified as QE.

- Pion production is the dominant background for CCQE channel.

Needs a proper Event Selection!!

Event Selection for CCQE

High Purity CCQE event Selection : $\nu_\mu + A \rightarrow 1\,\mu^- + 1\,p + X\,n$

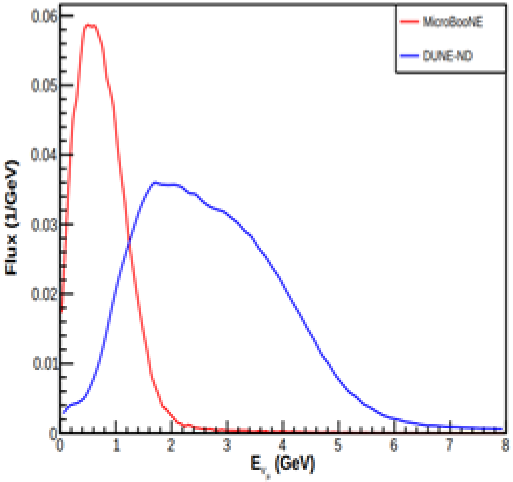
(1 muon + 1 proton + 0 pion + any number of neutron)

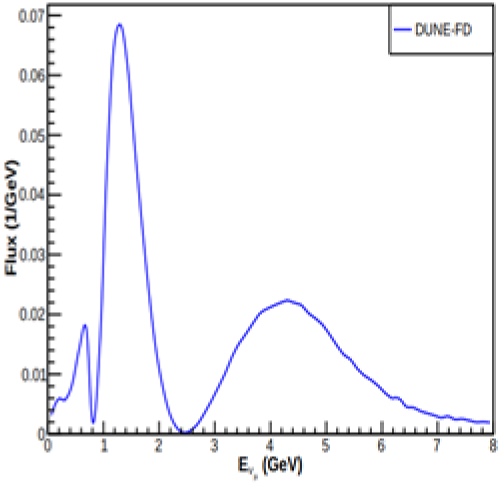
- The selection (1μ 1p xn 0π) has been studied for DUNE (ND & FD) and MicroBooNE detector using Argon and Carbon target.

- The purity of the selection has been checked by reconstructing the neutrino energy.

- The DUNE ND & FD and MicroBooNE $\boldsymbol{\nu}_\mu$ flux are used for simulation in GENIE and NuWro.

[*Nucl.Phys.B* 1008 (2024) 116703]





[arXiv:2103.04797 (2021), DOI: 10.2172/1333130 (2012)]

Energy Reconstruction Mechanism

- Neutrino energy is reconstructed by the **Calorimetric method** based on the energy conservation given by,

$$E_\nu = E_l + \epsilon_n + \sum_i (E_{p'_i} - M) + \sum_j E_{h'_j}$$

Where,
E_l : Muon energy
$E_{p'_i}$: Nucleon energy
M : Nucleon mass
$E_{h'_j}$: Any other meson energy
ϵ_n : Nucleon separation energy

- For a better accuracy in analysis, separation energy is considered as a distribution instead of a constant value.

$$P(E) = \frac{1}{N} \sum_\alpha n_\alpha G(E - E_\alpha, \sigma_\alpha)$$

Where, $N = \sum_\alpha n_\alpha$: Total no. of neutrons

[*Nucl.Phys.B* 1008 (2024) 116703]

[PhysRevC.95.065501 (2016)]

Subshell	E_α (MeV)	σ_α (MeV)	No. neutron n_α
$1s_{1/2}$	40.8	9.1	2
$1p_{3/2}$	20.3	5	4

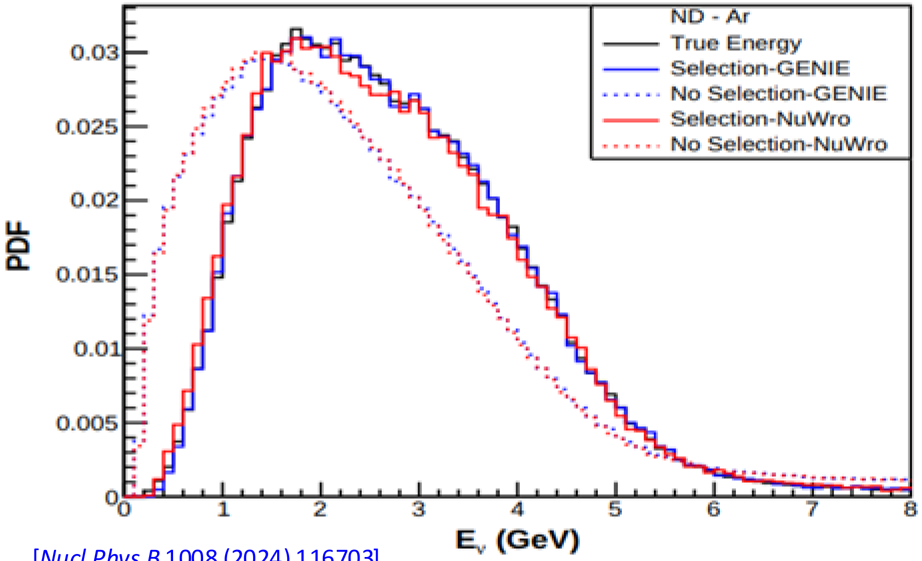
Neutron Shell Structure in C-12

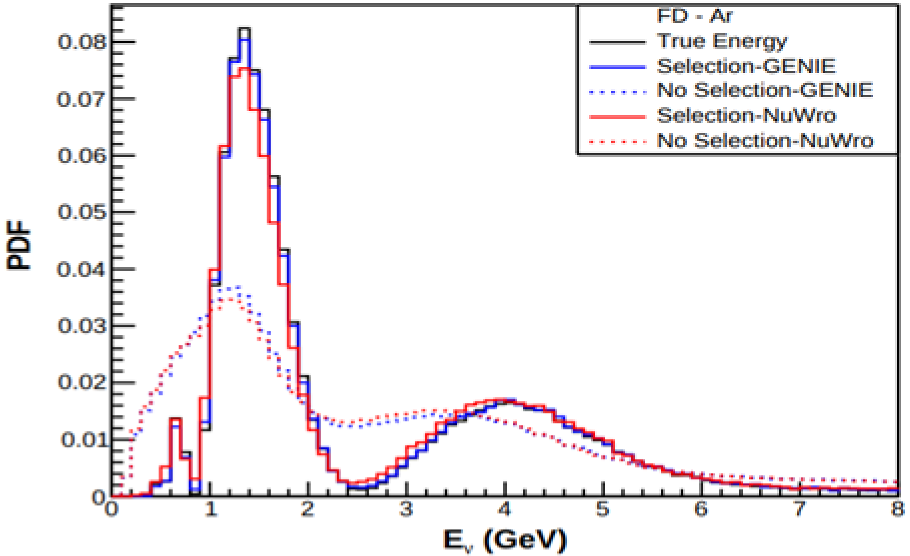
Subshell	E_α (MeV)	σ_α (MeV)	No. neutron n_α
$1s_{1/2}$	62	6.25	2
$1p_{3/2}$	40	3.75	4
$1p_{1/2}$	35	3.75	2
$1d_{5/2}$	18	1.25	6
$2s_{1/2}$	13.15	1	2
$1d_{3/2}$	11.45	0.75	4
$1f_{7/2}$	5.56	0.75	2

Neutron Shell Structure in Ar-40

Energy Reconstruction - DUNE

- The reconstructed energy for ND without the selection is shifted by ≈ 0.4 GeV towards lower energies, compared to the true energy.
- The reconstructed energy is distorted with flattening of the minima around 2.4 GeV for FD without selection. Also, the event rate is significantly low at the maxima at 1.4 GeV.
- **Improvement in E_{reco}** with the selection with $E_{reco} - E_{true} < 100$ MeV.

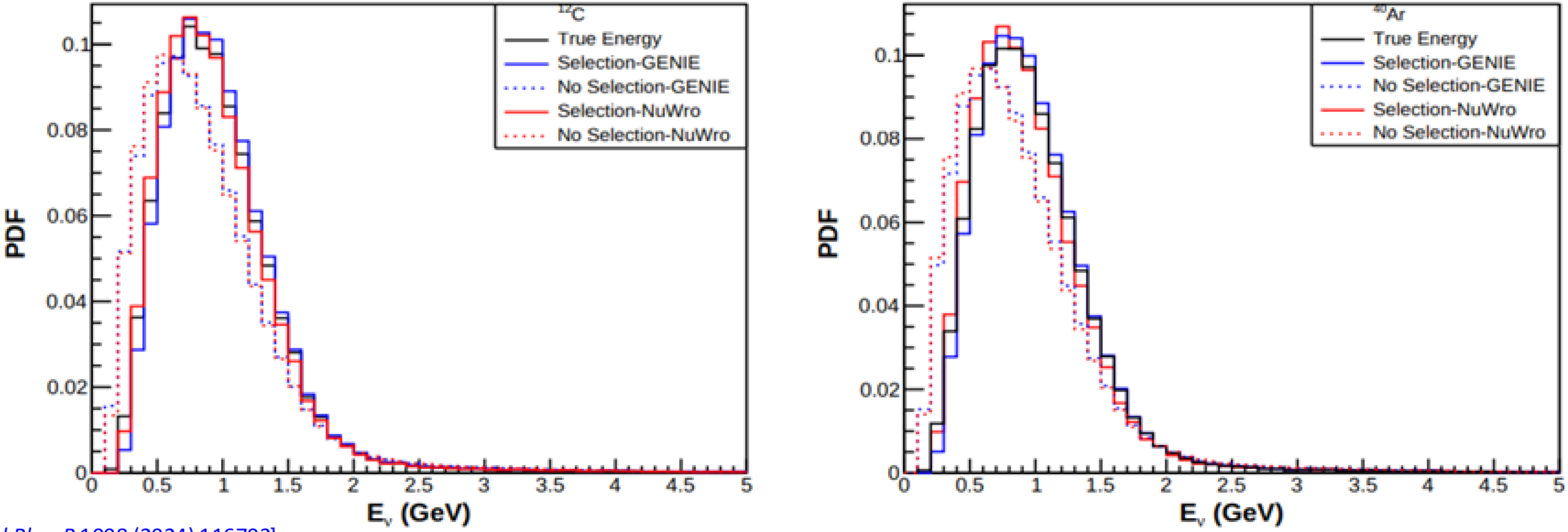




[*Nucl.Phys.B* 1008 (2024) 116703]

Energy Reconstruction - MicroBooNE

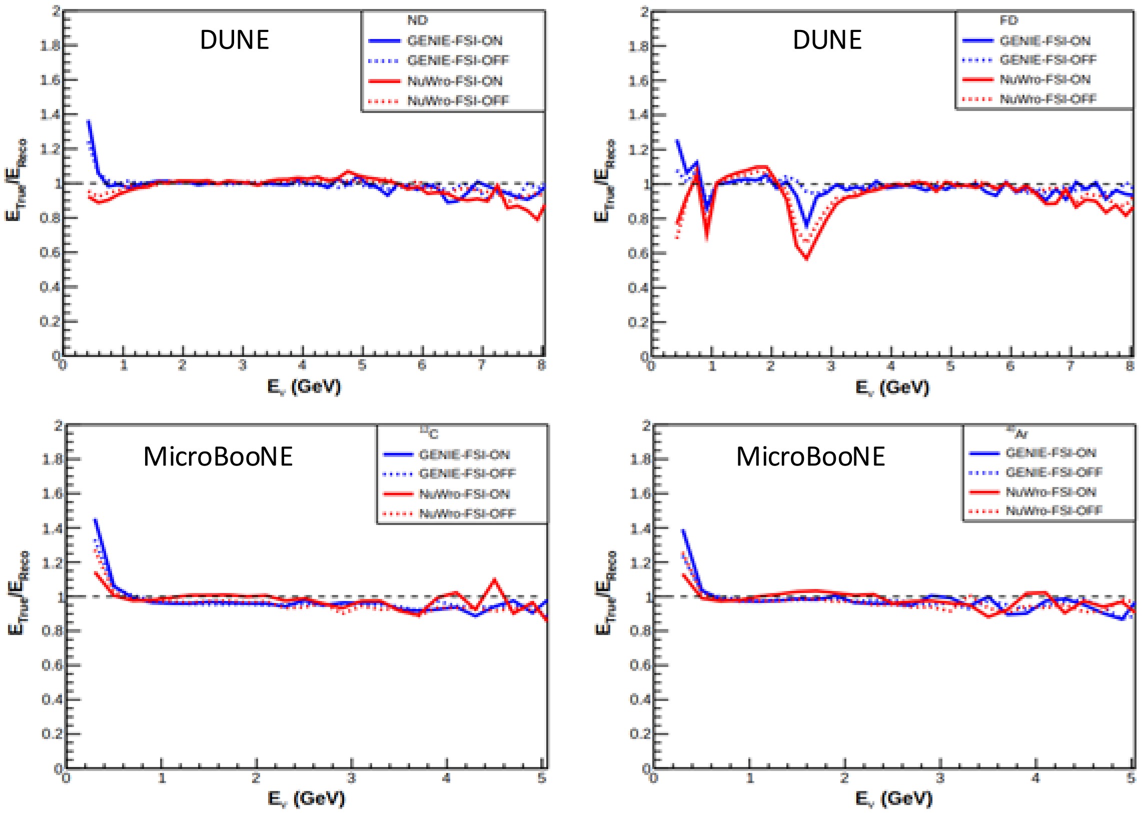
- The reconstructed energy for both Argon and Carbon is shifted by ≈ 0.2 GeV towards lower energies, compared to the true energy.
- The reconstructed energy agrees well with the true energy by considering the selection.
- The shift between reconstructed and true energy reduced to less than 100 MeV.



[*Nucl.Phys.B* 1008 (2024) 116703]

Purity of the Selection

- The ratio deviates from 1 in the lower energy region (< 1 GeV) due to nuclear effects.
- Deviation in maxima and minima region for DUNE FD.
- When FSI is off, the ratio is closer to 1 in lower energy region indicating the effect of the FSI to the uncertainty in the reconstruction.
- Other nuclear effects cause the deviation even without FSI.



[*Nucl.Phys.B* 1008 (2024) 116703]

Significance of the CCQE Selection

- The selection reduced the shift between reconstructed and true energy to less than 100 MeV which is the required energy resolution for physics potential studies on LBNE.
- The ratio deviating from unity even without FSI indicate the other nuclear effects should be studied in energy reconstruction.
- This work shows that the calorimetric method can be used for energy reconstruction with a proper selection criteria.
- The ratio of true and reconstructed energy distribution in the high-energy regions indicates the viability of this method in higher-energy neutrino experiments.

[*Nucl.Phys.B* 1008 (2024) 116703]

KDAR ν_μ Scattering on Carbon

KDAR Neutrino

- Charged kaons at rest decay to mono-energetic neutrino through two body decay.

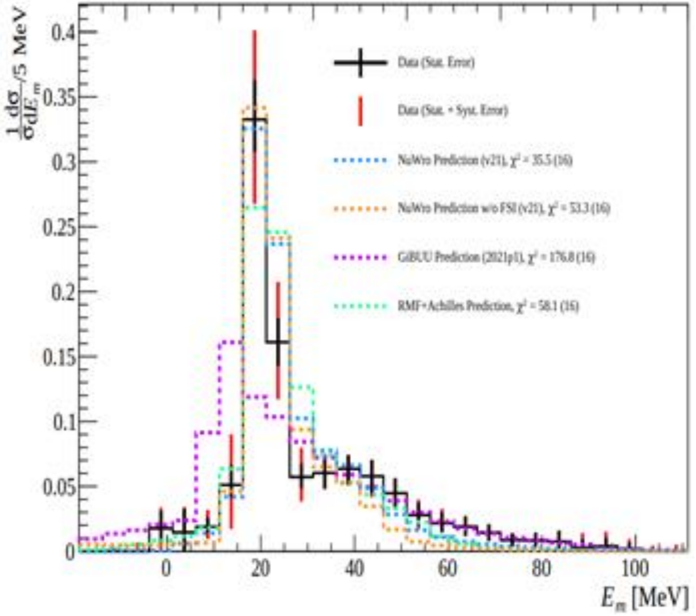
$$K^+ \rightarrow \mu^+ + \nu_\mu$$ (BR = 0.636), E_ν = 235.5 MeV

- Known neutrino energy provides a unique opportunity to study nuclear effects in low-energy regime.
- We did a Monte Carlo study on missing energy in KDAR ν_μ C-12 CC scattering using JSNS2 measurement.

$$E_{miss} = \omega - \sum T_h$$
$$= E_{\nu_\mu} - m_\mu - T_\mu - \sum T_h$$
$$= E_{\nu_\mu} - m_\mu - E_{viss}$$

ω is the energy transfer.
($\omega = E_{\nu_\mu} - E_\mu = E_{\nu_\mu} - m_\mu - T_\mu$)

: h = hadrons
: E_{viss} = visible energy



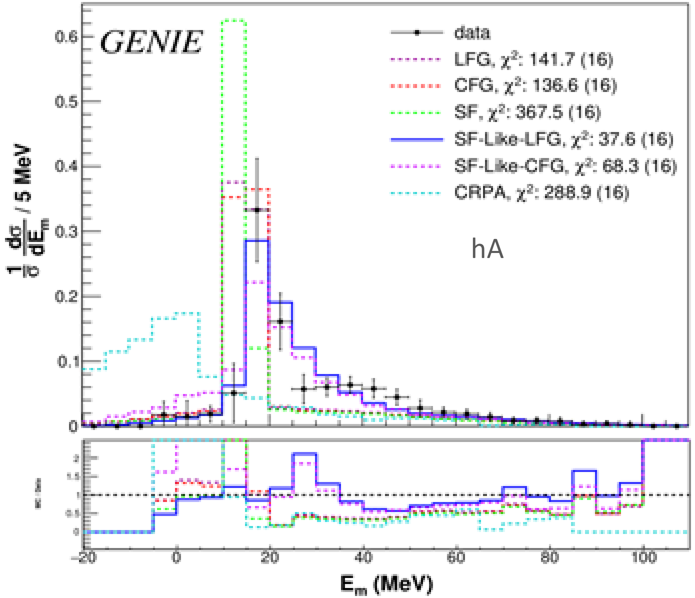
[Phys Rev Lett.134.081801 (2025)]

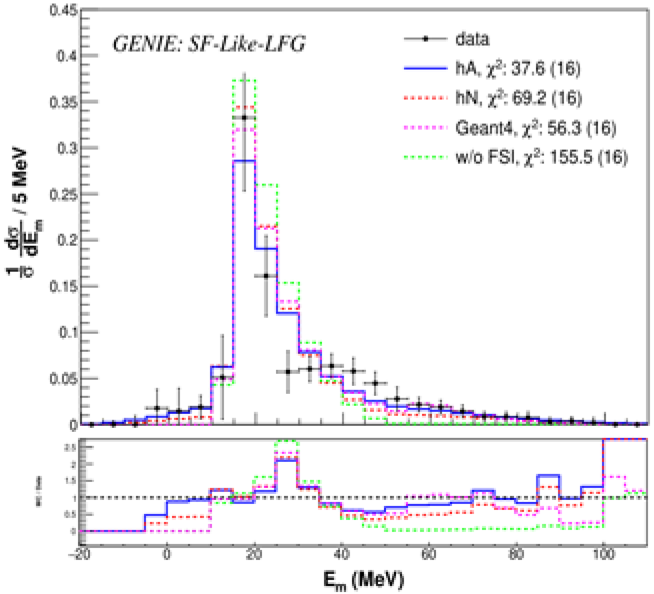
- Event selection considered: 1μ 1p xn 0π (CCQE)
- MC used: GENIE, NuWro, GiBUU

Missing Energy Reconstruction-GENIE

- The peak around 15 MeV is due to nucleon separation energy and predicted by SF-Like-LFG and SF-Like-CFG. MC/data deviates from 1 around 30 MeV for all the nuclear models.
- CRPA shows a shift towards negative missing energy. Similar shift has been observed in lepton energy spectrum in PhysRevD.106.073001 (2022), to be explored further in future.

- The hA model with the SF-like-LFG nuclear model provides better agreement.



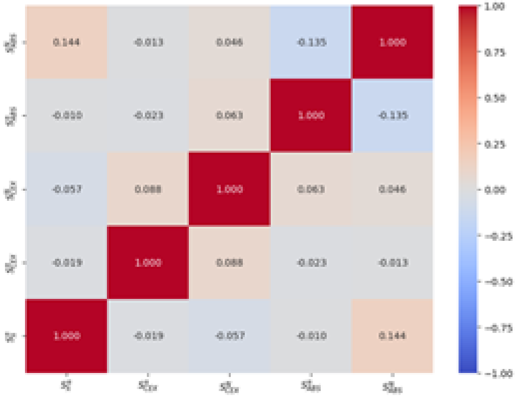


[arXiv:2508.07772 (2025)]

GENIE FSI Tuning

- GENIE reweighting package v1.0.4 is used for tuning.

Parameter	Nominal	Range	All-parameter (Best-fit)	Selected-parameter (Best-fit)	Final tune
S^{π}_{λ}	1.0 ± 0.2	(0.0, 3.0)	1.24 ± 0.56	1.12 ± 0.53	✓
S^{N}_{λ}	1.0 ± 0.2	(0.0, 3.0)	0.03 ± 0.32	1.0	
S^{π}_{CEX}	1.0 ± 0.5	(0.0, 3.0)	2.03 ± 0.50	0.58 ± 0.52	✓
S^{N}_{CEX}	1.0 ± 0.5	(0.0, 3.0)	1.57 ± 0.44	2.74 ± 0.46	✓
S^{π}_{INEL}	1.0 ± 0.4	(0.0, 3.0)	1.38 ± 0.53	1.0	
S^{N}_{INEL}	1.0 ± 0.4	(0.0, 3.0)	1.31 ± 0.43	1.0	
S^{π}_{ABS}	1.0 ± 0.2	(0.0, 3.0)	0.86 ± 0.47	1.60 ± 0.48	✓
S^{N}_{ABS}	1.0 ± 0.2	(0.0, 3.0)	2.07 ± 0.55	0.62 ± 0.53	✓

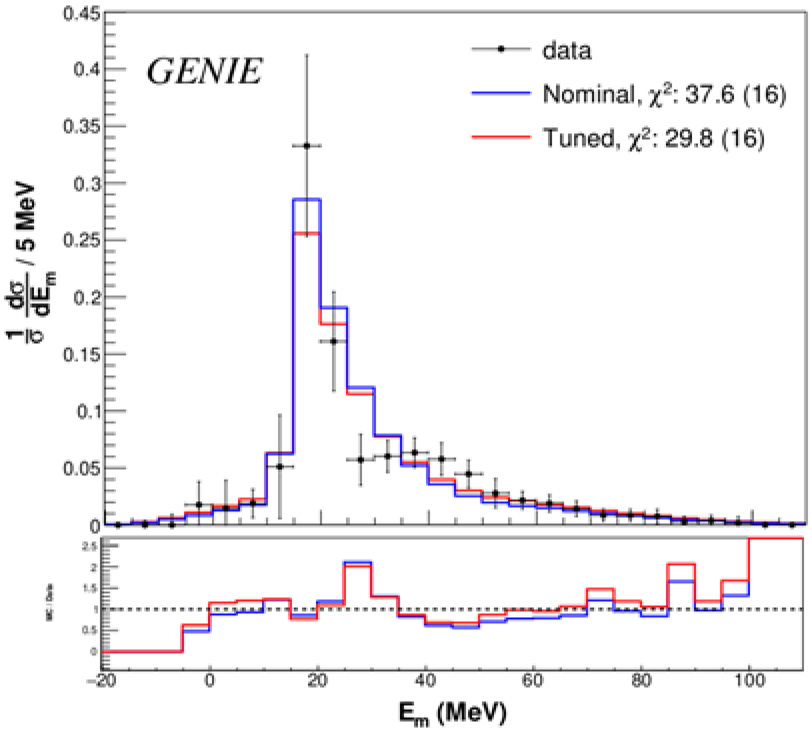


- Selected parameters: out of 1σ of nominal values in all-parameters (best-fit).
- MFP of nucleon (λ_N) is removed from tuning: reduction in λ_N decreases cross-section around the peak ~ 15 MeV and vice versa.

[arXiv:2508.07772 (2025)]

GENIE FSI Tuning

- χ^2 is reduced significantly to 29.8 (16).
- MC/data shows an improvement being close to 1 compared to the nominal distribution.
- Deep around 25 MeV remained unexplained.
- The tuning of the hA FSI model improved the cross section, but it is not enough to improve the shape of the E_m distribution.



[arXiv:2508.07772 (2025)]

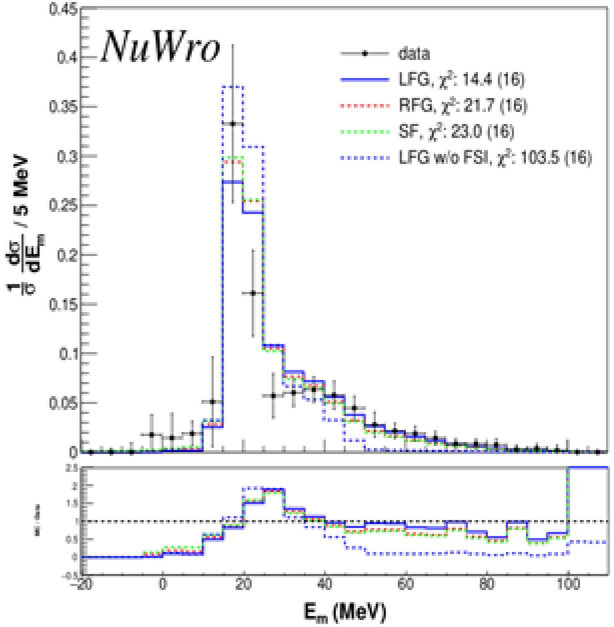
Missing Energy Reconstruction-NuWro & GiBUU

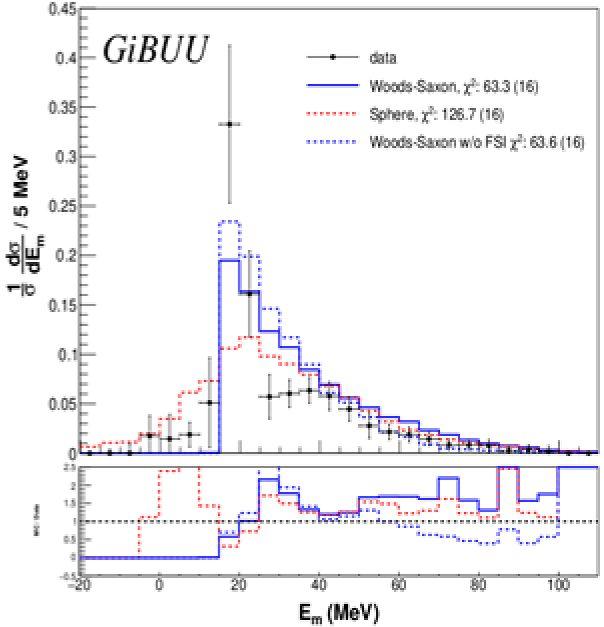
- NuWro predicts the peak around 15 MeV; however MC/data < 1 in lower missing energy regions below 15 MeV. LFG predicts the best fit to the data, with $\chi2$ = 14.4 (16).

- GiBUU does not explain the peak; however, the Woods-Saxon model exhibits a small peak due to the constant nucleon separation energy of 15 MeV.

- GiBUU predicts a broad missing energy spectrum.

- WS model provides a better prediction compared to the spherical density model.



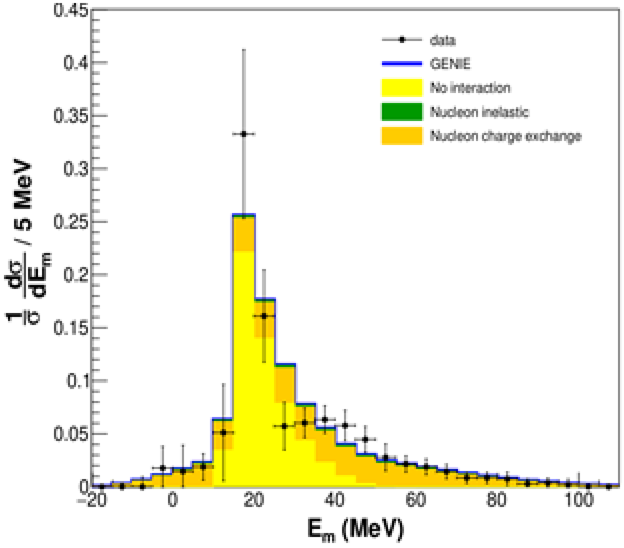


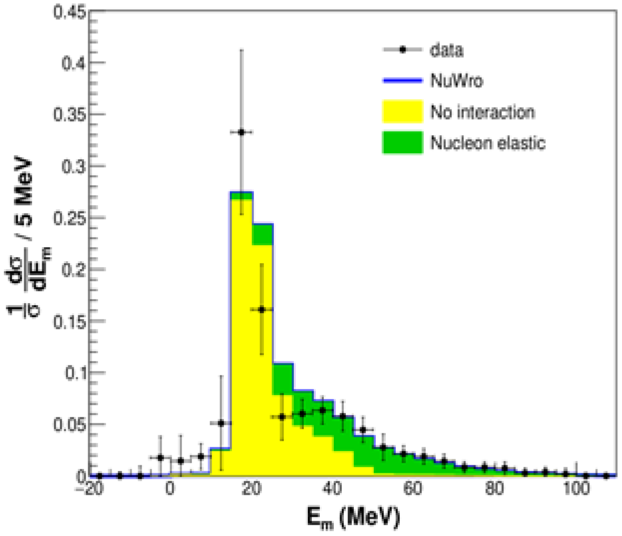
[arXiv:2508.07772 (2025)]

NuWro vs. GENIE

- The similarity between NuWro and GENIE without FSI suggests that NuWro's improved agreement could be due to qualitative differences in its FSI modeling.
- Significant contribution from FSI component - nucleon elastic scattering in NuWro.
- Elastic component is replaced with the no-FSI component in the GENIE hA FSI model to explain the MINERvA data [Nature 614, 48 (2023)].

- Nucleon elastic FSI could be one of the reasons behind the improved prediction in NuWro, in contrast to GENIE.

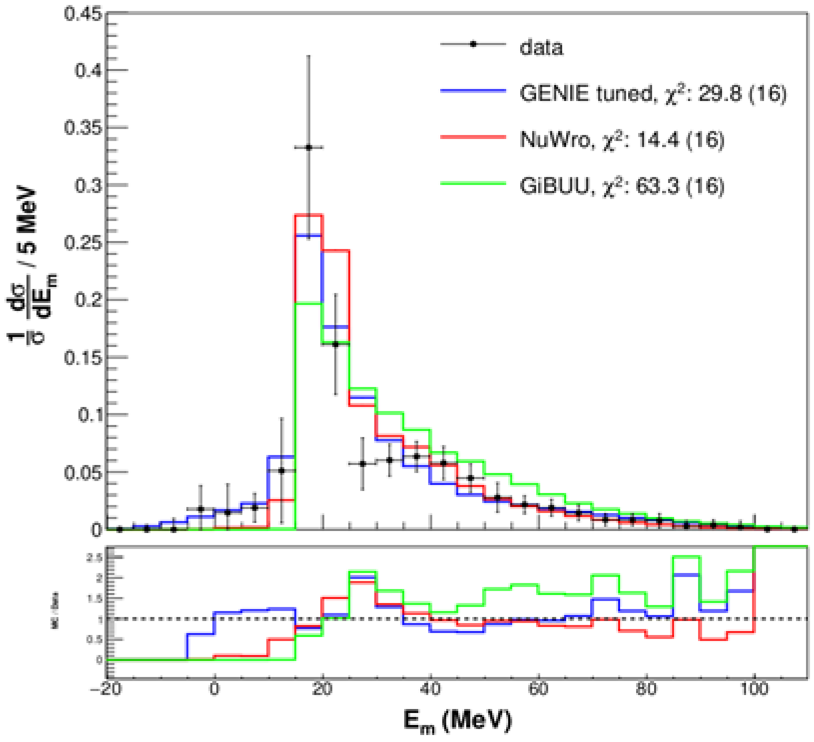




[arXiv:2508.07772 (2025)]

MC Comparison

- NuWro provides an overall better fit.
- GENIE tuned is better in the lower missing energy below ~ 20 MeV than NuWro.
- GiBUU shows a broader spectrum.
- The nucleon removal energy causes the peak at ~ 15 MeV observed in GENIE and GiBUU.
- All MCs show MC/data > 1 in the region, Em ~ 20 - 30 MeV.
- SF-like-LFG in GENIE, LFG in NuWro, and Woods-Saxon model in GiBUU provide the best-fit predictions.

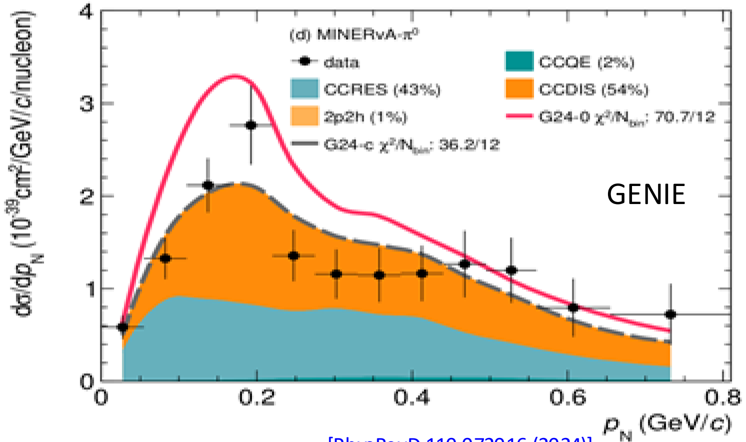


[arXiv:2508.07772 (2025)]

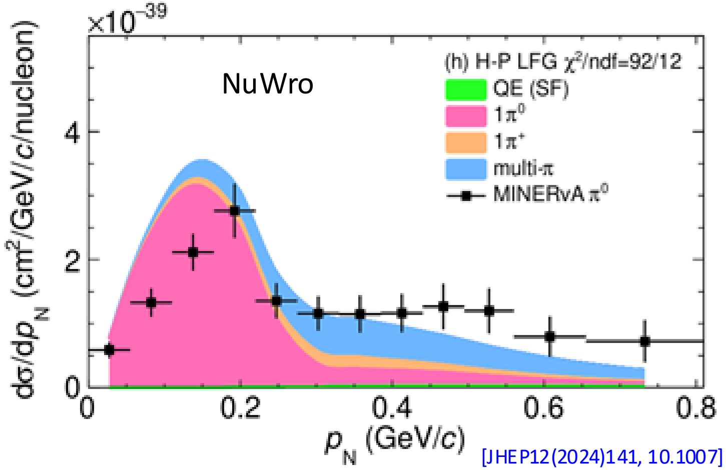
Neutral pion production in MINER$\boldsymbol{\nu}$A

Fermi Motion Discrepancy

- The nucleons inside the nucleus are not at rest, they have the Fermi motion.
- According to the Local Fermi-Gas model, the momentum is less than the Fermi momentum (~ 250 MeV).
- However, there is a higher momentum tail due to the correlation between nucleons.
- The recent MINERνA measurements of neutral pion production gives the momentum of target nucleon which doesn't look to be properly explained by popular MC generators.



[PhysRevD.110.072016 (2024)]



[JHEP12(2024)141, 10.1007]

Reconstruction of Target nucleon Momentum

Momentum conservation:

- Transverse Component: $0 = \vec{p}_T^{\,l'} + \vec{p}_T^{\,N'} - \delta\vec{p}_T$
- Longitudinal Component: $E_\nu = p_L^{l'} + p_L^{N'} - \delta p_L$

Energy Conservation: $E_\nu + M_A = E_{l'} + E_{N'} + E_{A'}$

where,

$p^{l'}\,(p^{N'})$: Momentum of lepton (nucleon)

$E_{l'}(E_{N'})$: Energy of lepton (nucleon)

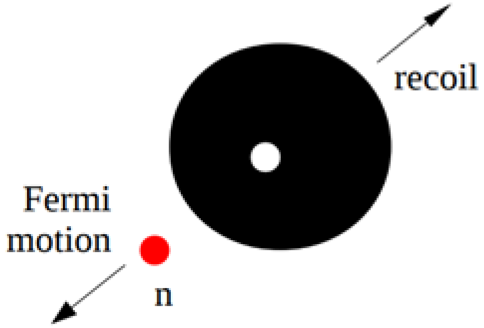
Solving above equations;

$$\delta p_L = \frac{R}{2} - \frac{m_{A'}^2 + \delta p_T^2}{2R}$$

where, $R \equiv m_A + p_L^{l'} + p_L^{N'} - E_{l'} - E_{N'}$

The momentum of the struck nucleon can be calculated,

$$\boxed{p_n = \sqrt{\delta p_T^2 + \delta p_L^2}}$$

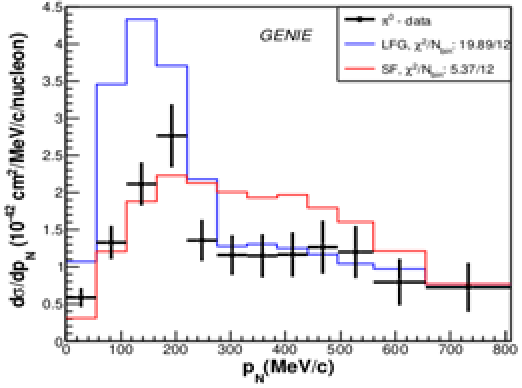


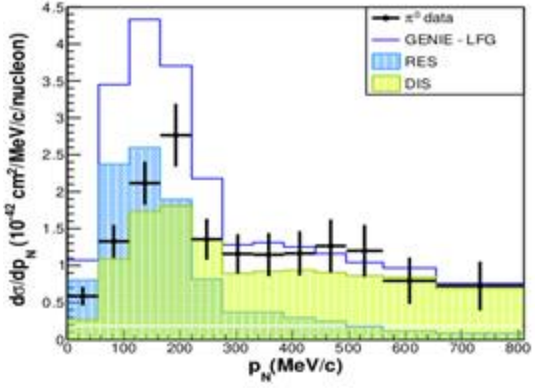
$\vec{p}_n = -\vec{p}_{A-1}$

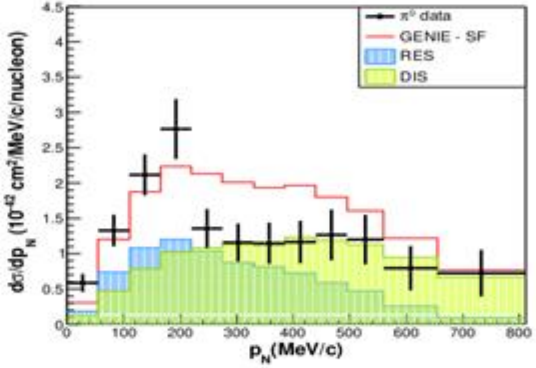
[Phys. Rev. C94, 015503 (2016)]

Analysis using default MC model - GENIE

- The prediction agrees with data in higher momentum region but overpredicts in lower region for LFG.
- The prediction behaves as opposite for the spectral function (SF).
- Both LFG & SF can’t explain the data in the region ~ 250 MeV/c.
- LFG provides a better shape than SF and considered for further analysis.
- For LFG, higher contribution from DIS leads to over-prediction in the lower momentum region.



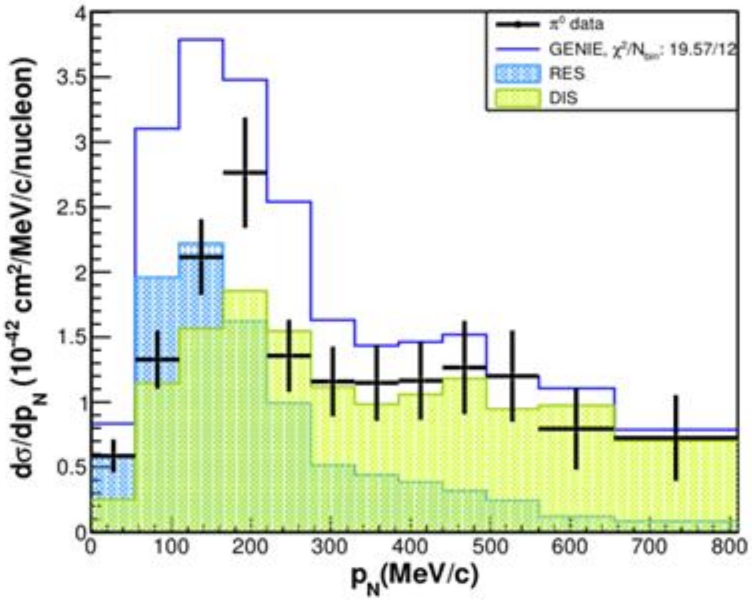




[Phys.Rev.D 111 (2025) 9, 093002]

Analysis using alternative MC models- GENIE

- Initial state of target nucleon is described by the nuclear models.
- The nucleons are correlated inside the nucleus quantified by the SRC-fraction.
- SRC-fraction is considered as an effective parameter and is taken as 0.15 [PhysRevD.110.072016 (2024)].
- Resonance is the dominant channel for pion production, RES axial mass is considered to be effective to the analysis and set to 1.08 GeV [PhysRevD.110.072016 (2024)].
- Improvement in shape of the prediction!

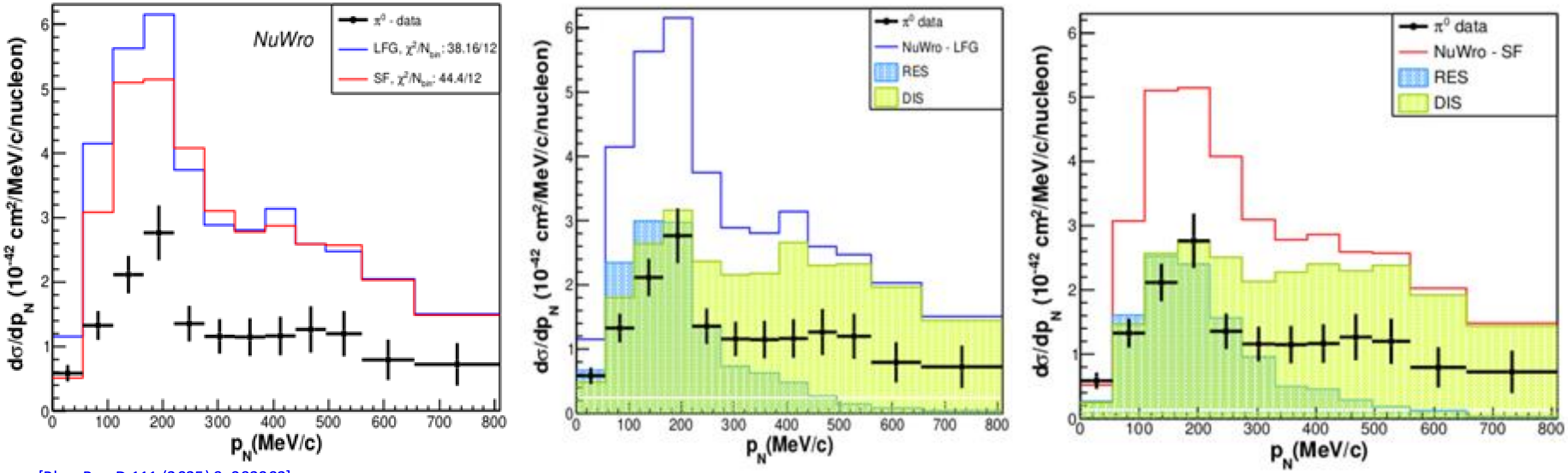


- Over-prediction in lower momentum region could be due to high DIS component in that region!

[Phys.Rev.D 111 (2025) 9, 093002]

Analysis using default MC model - NuWro

- The prediction is higher than the data by a factor of ≈ 50% for both LFG & SF.
- The extra factor in the prediction could be due to the greater contribution of DIS to the neutral pion production.
- LFG prediction is better than that of SF, so considered for the further analysis.
- The Higher multiplicity of pions could be the main reason for the over-prediction.



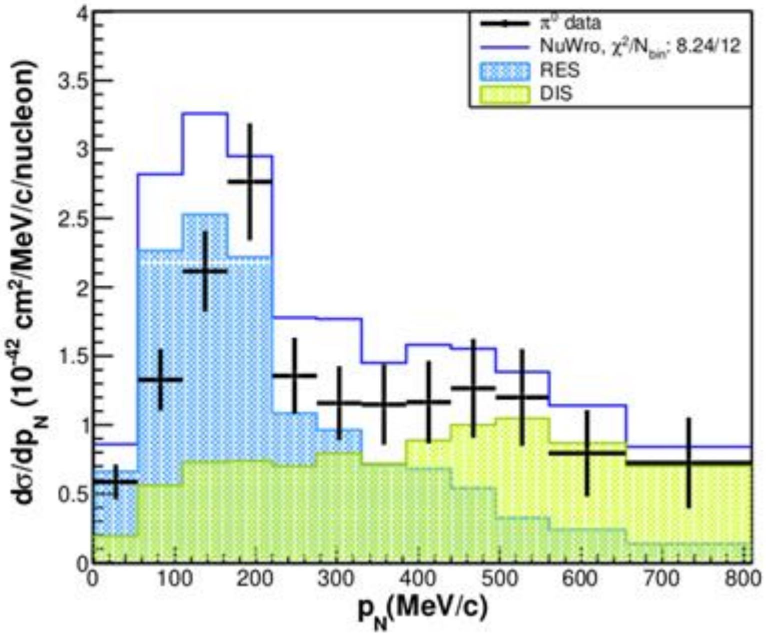
[Phys.Rev.D 111 (2025) 9, 093002]

Analysis using alternative MC models- NuWro

- The Formation Zone (FZ) effect controls the pion production in NuWro.

FZ effect: It is the finite time or distance a hadron requires after being produced before it can undergo further interaction in the nuclear medium.

- FZ effect for particles produced in primary interaction leads to a higher multiplicity of pions [PhysRevC.86.015505 (2012)].
- In the analysis, it's disabled for the primaries and only applied to particles produced in FSI.
- Prediction shows a better overall shape with reduced $\chi 2$ and reduced the DIS component.



- Over-prediction in lower momentum region is observed similar to GENIE!

[Phys.Rev.D 111 (2025) 9, 093002]

Summary of the Analysis

- The alternative models match the overall shape of the data and hold up well at higher neutron momentum in both GENIE and NuWro.

- However, the RES contribution below the Fermi peak (~ 220 MeV/c) leaves no room for the DIS component, causing an overestimation in the lower momentum region.

- This could help future MINERvA measurements with higher statistics and cross-section studies of pion production in neutrino experiments.

[Phys.Rev.D 111 (2025) 9, 093002]

Second Resonance

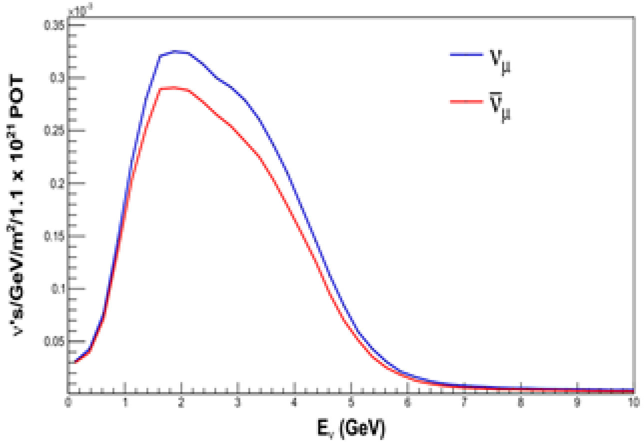
Formalism

- 40% of the interactions come from the resonant interaction channel at DUNE.
- This work quantifies the contributions of second resonance regions to the cross-section measurements at DUNE by reconstructing hadron energy and Q2.
- First RES region: Δ (1232)
- Second RES regions: P11(1440), D13(1520), and S11(1535).
- Hadron energy and Q2 can be reconstructed by,

$$E_H = \sum_i (E_{n_i} - M) + \epsilon_n + \sum_j E_{m_j}$$

$$Q^2 = 2E_\nu(E_l - p_l \cos\theta_l) - m_l^2$$

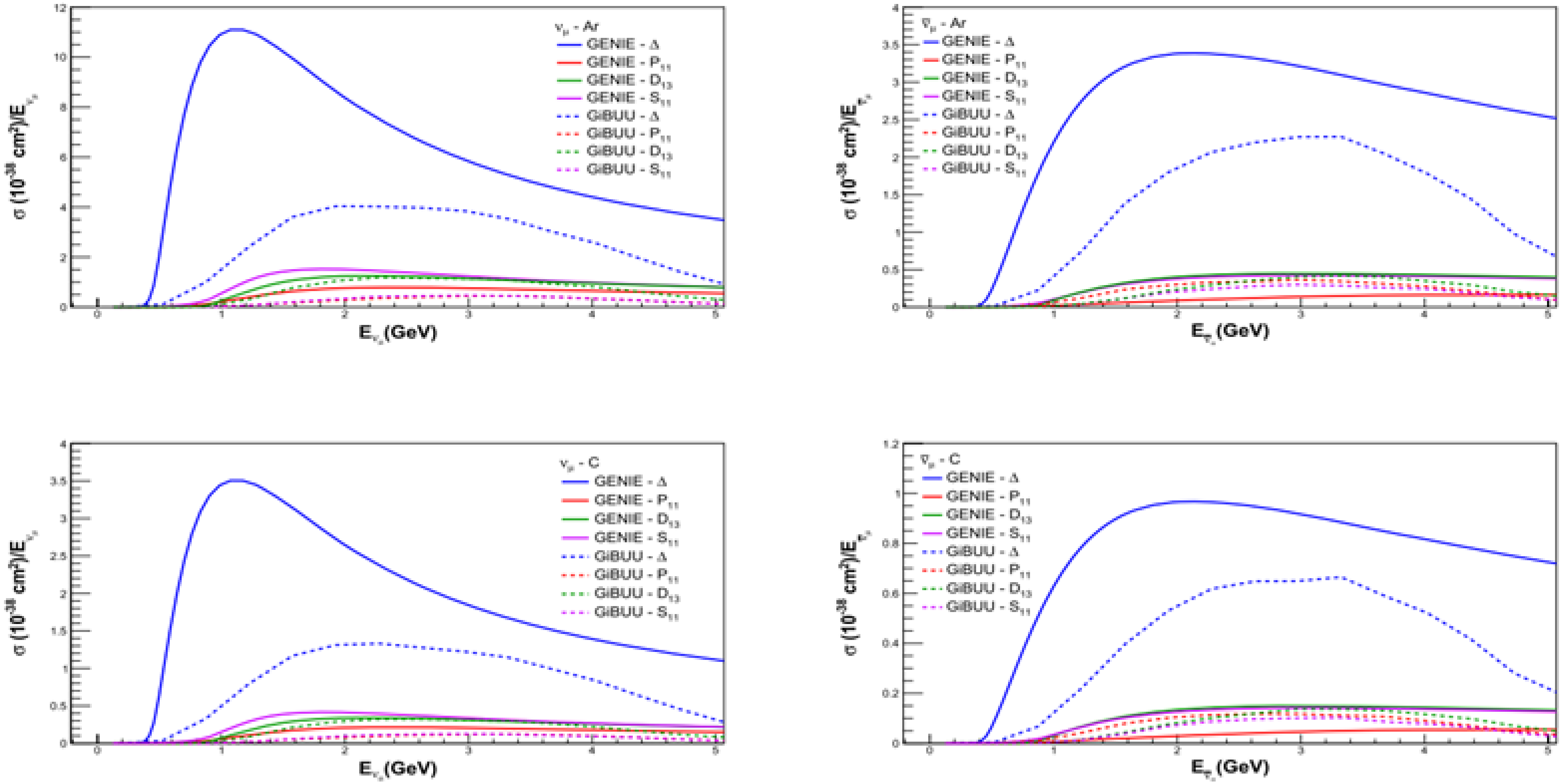
l, n, m are lepton, nucleon and meson.



[arXiv:2103.04797 (2021)]

- MC used: GENIE, GiBUU
- Flux used: DUNE ND ν_μ $\bar{\nu}_\mu$

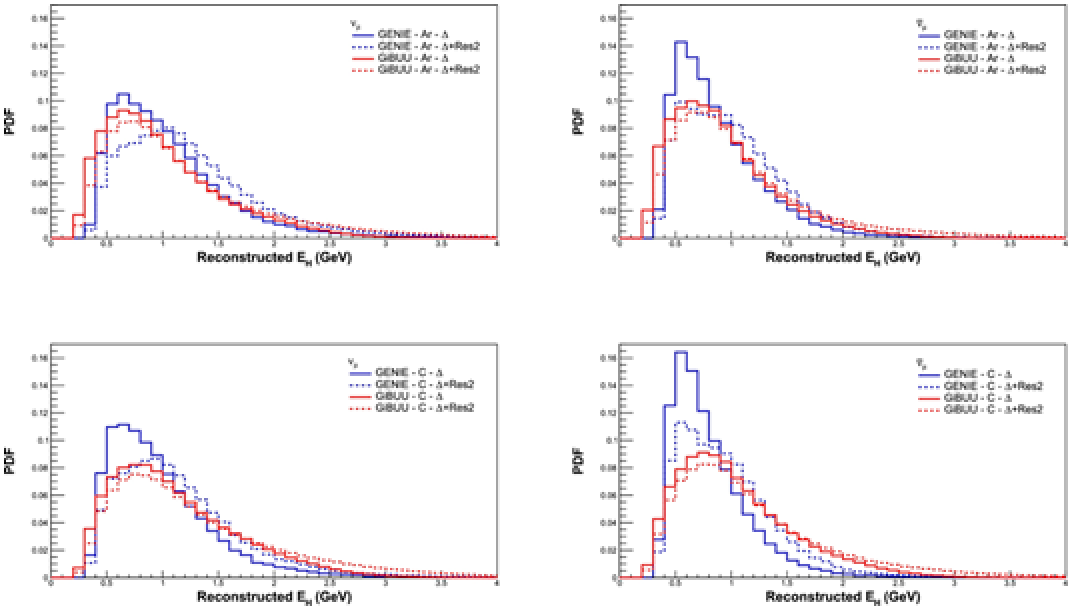
CCRES Cross-Section



Hadron Energy Reconstruction

- 2nd RES shifted the distribution:
  In GENIE:
  → Neutrino: ~ 130 MeV for Argon
  : ~ 115 MeV for Carbon
  → Anti-neutrino : ~105 MeV (both)

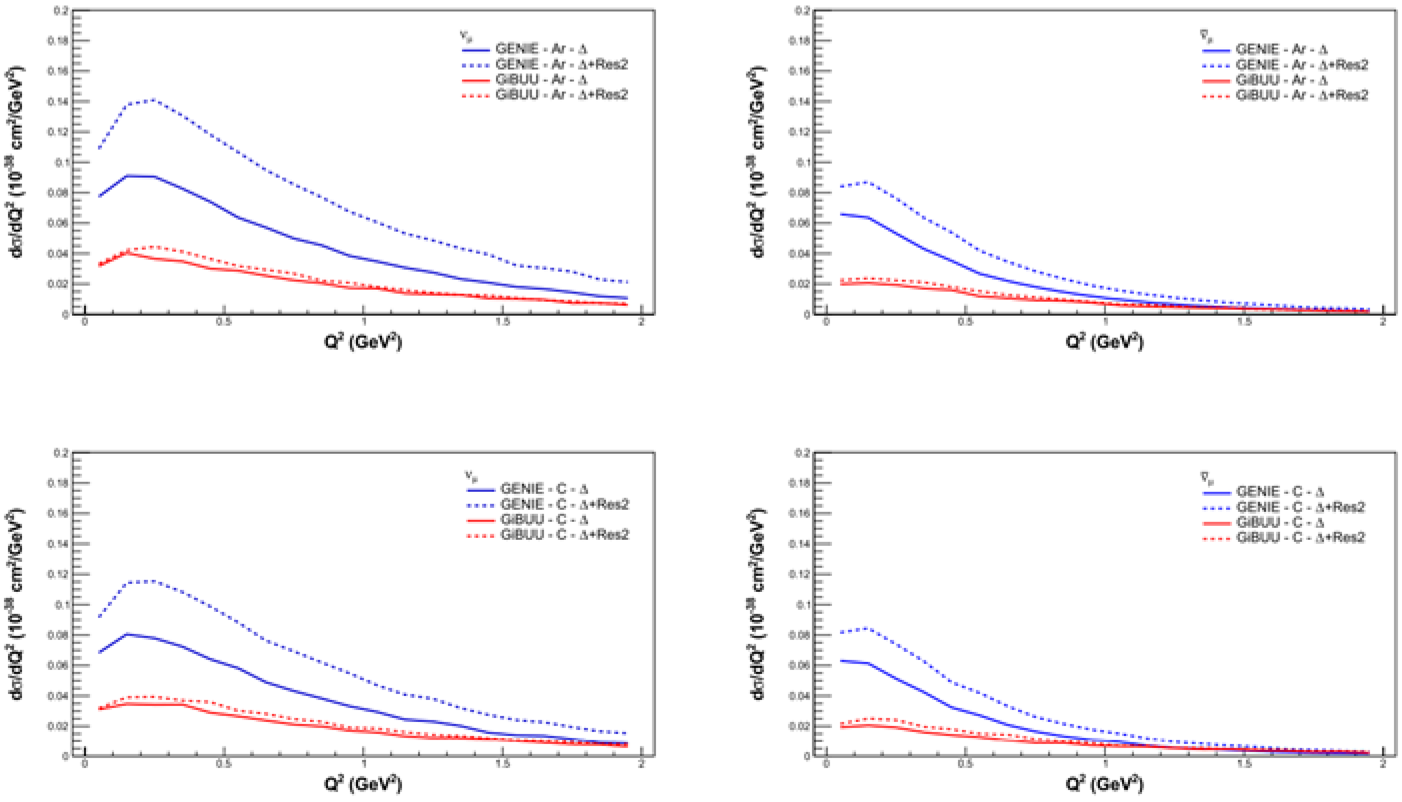
  In GiBUU:
  → Neutrino: ~ 160 MeV for Argon
  : ~ 170 MeV for Carbon
  → Anti-neutrino : ~145 MeV (both)



- Similar pattern shown in Q2 distribution.

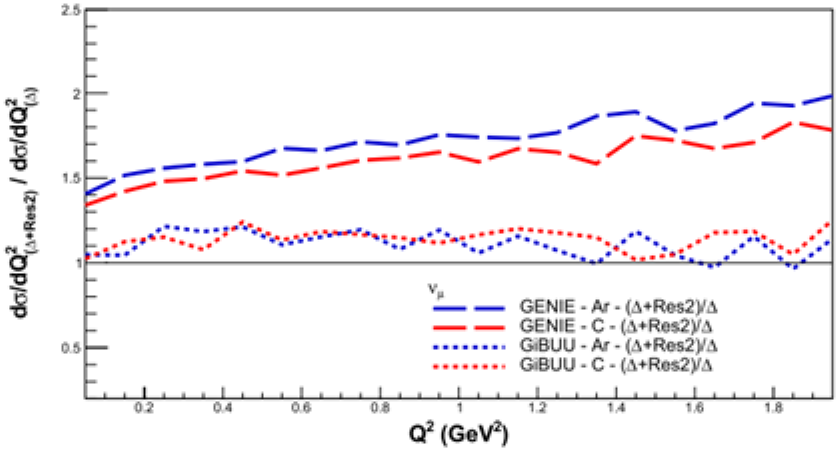
- This is due to the explicit dependence of this kinematic variable on the reconstructed baryonic and mesonic energies.

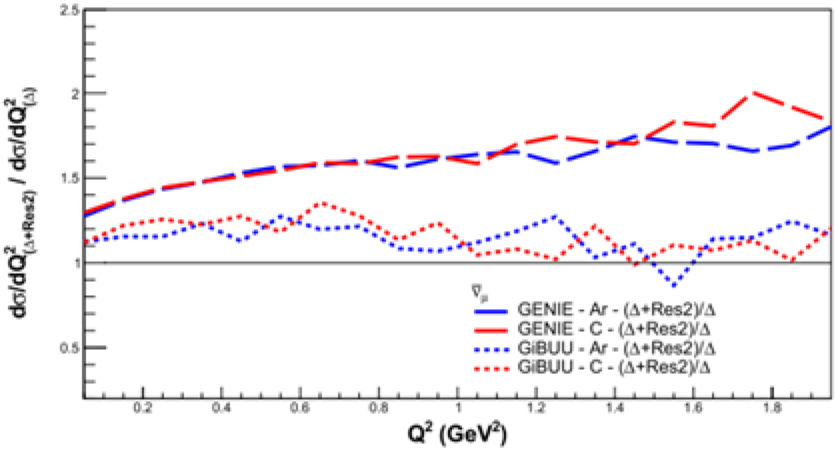
Q2 Reconstruction



Quantification of Second RES

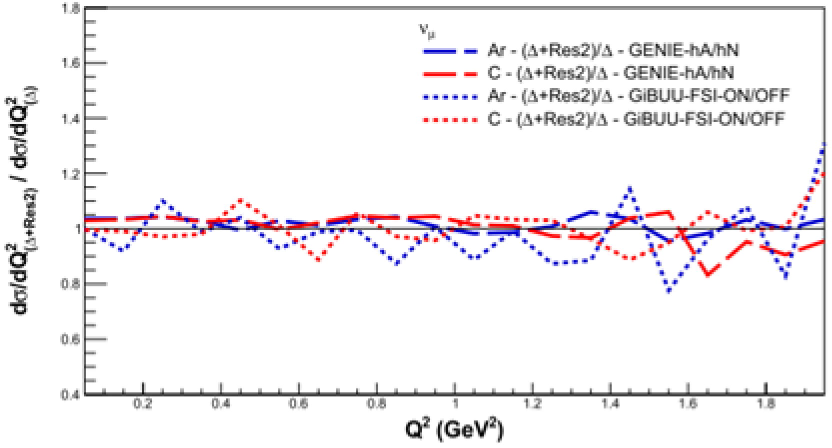
- The ratio deviates from 1 and increases with higher Q2 value in GENIE.
- GiBUU also shows a deviation from unity.
- Second resonance contribution with respect to Δ-resonance has a significant effect with the higher momentum transfer for both the neutrino and antineutrino.

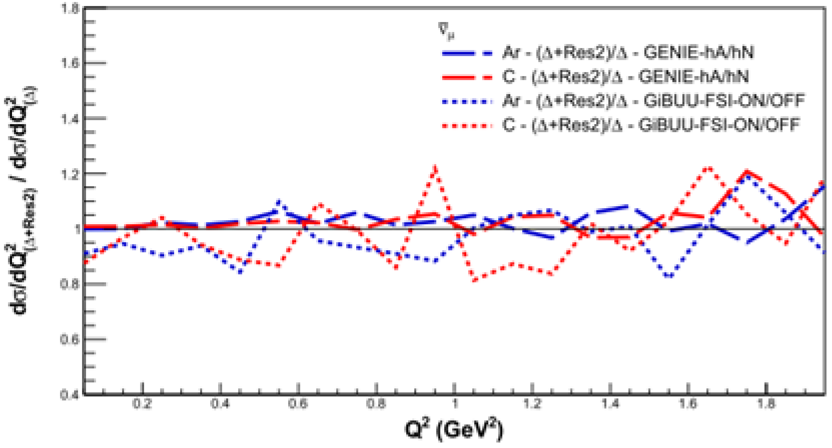




Quantification of Second RES

- The differences between the FSI models for GENIE are observed as Q2 increases.
- A significant variation can be seen above Q2 ≈ 1.6 GeV2 for Carbon.
- In GiBUU, the effect of FSI has larger uncertainties for antineutrino than neutrino.





Outlook

- Precision measurement & new physics
- ν-A understanding
- ν Generators
- Exciting opportunities

Thank you!