UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Neutrino Physics Center

Benchmarking State-of-the-Art Theory and Empirical Models of Pionless Neutrino-Argon Scattering in GENIE

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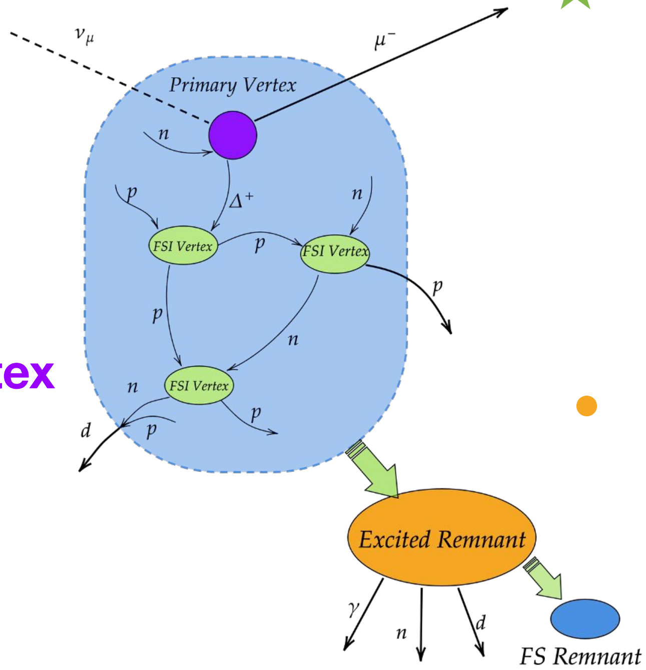
Neutrino-nucleus interactions

★ **Nuclear structure**
- Nucleon density
- Momentum distribution
- Nuclear potential

★ **Primary neutrino vertex**
- Quasielastic
- 2p2h
- Resonance
- Deep inelastic
- …



★ **Final state interactions**
- Hadrons coming from neutrino primary vertex can re-scatter with other nucleons inside a nucleus.

● **De-excitation of remnant nucleus**
- ABLA
- GEMINI
- MARLEY*
- …

Local Fermi Gas

- Nucleon density distribution
  - Woods-Saxon (A > 20)

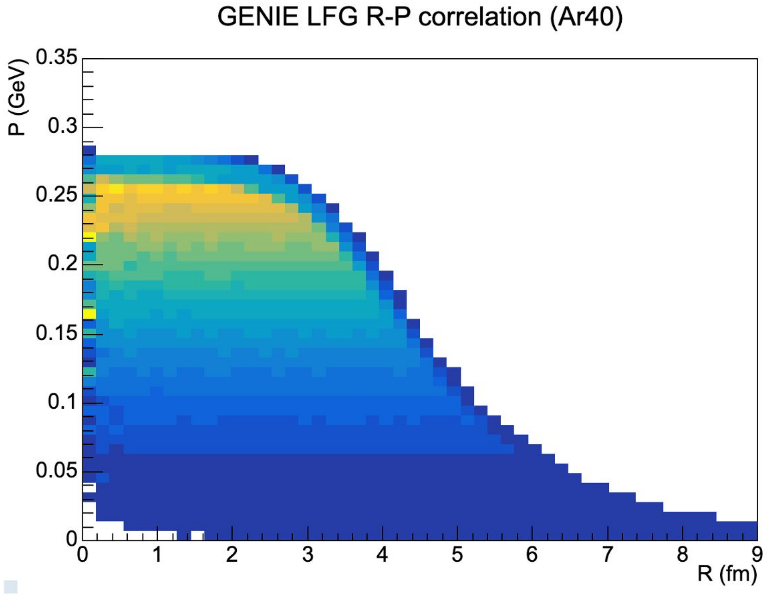
$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

  - Harmonic Oscillator (20 > A > 4)

$$\rho(r) = \rho_0 \left[1 + \alpha\left(\frac{r}{b}\right)^2\right] \exp\left[-\left(\frac{r}{b}\right)^2\right]$$

- Local Fermi Gas

$$p_F = \left(3\pi^2 N \rho(r)\right)^{1/3}$$

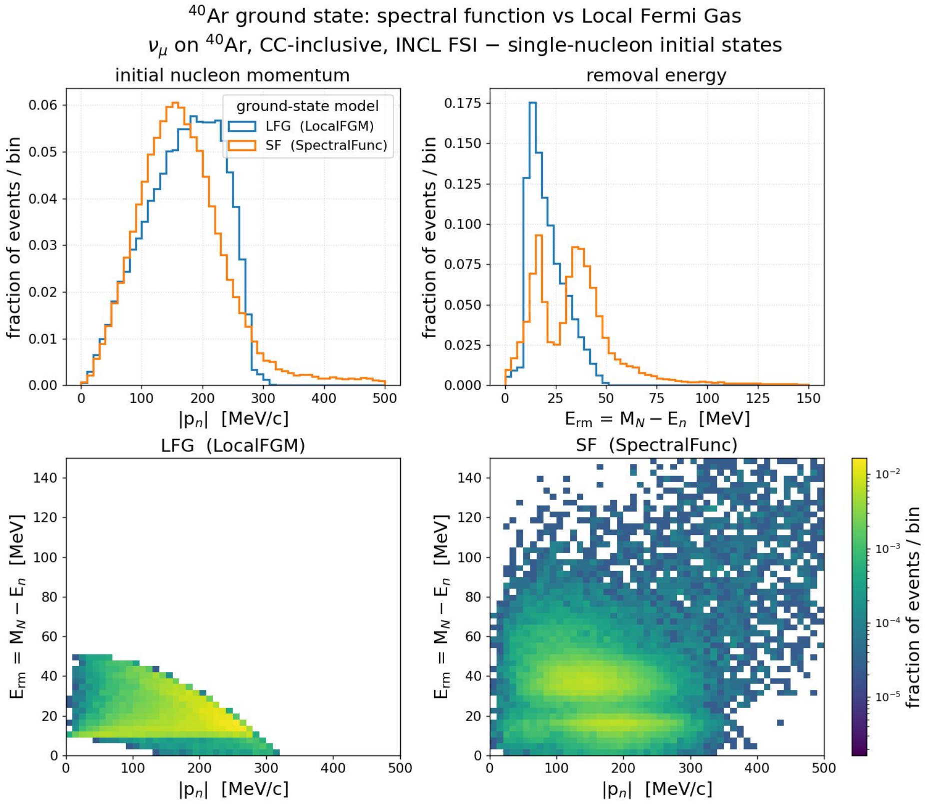


Nuclear structure

- Spectral function model

$$P_\tau(\mathbf{k},E) = \sum_n \left|\langle 0|[|k\rangle|\Psi_n^{A-1}\rangle]\right|^2 \delta\left(E + E_0 - E_n^{A-1}\right)$$
$$= P_{\mathrm{MF}}(\mathbf{k},E) + P_{\mathrm{corr}}(\mathbf{k},E)$$

- Recently implement in GENIE
  - 12C, 16O, 40Ar and 56Fe
- Isospin asymmetry of Argon spectral function
  - Proton spectral function from (e, e'p) on **Argon**
  - Neutron spectral function from (e, e'p) on **Titanium**



Phys. Rev. D 107, 012005
Phys. Rev. D 105, 112002

Axial form factor

- Axial form factor in the one body current

$$j^{\mu}_{1b} = \gamma^{\mu} F_1^V\left(\tilde{Q}^2\right) + i\sigma^{\mu\nu}\frac{\tilde{q}_\nu}{2M}F_2^V\left(\tilde{Q}^2\right) + \gamma^{\mu}\gamma^5 F_A\left(\tilde{Q}^2\right) + \frac{\tilde{q}^{\mu}}{M}\gamma^5 F_P\left(\tilde{Q}^2\right)$$

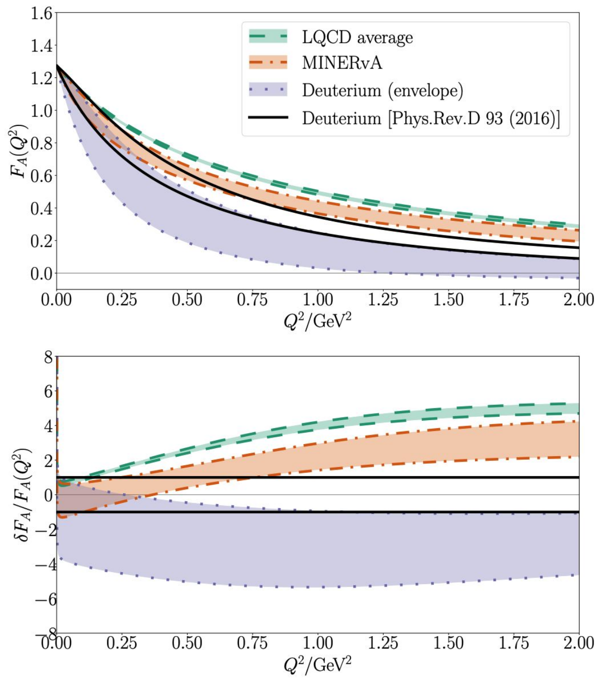
- Dipole parameterization

$$F_A\left(Q^2\right) = g_A\left[1 + Q^2/M_A^2\right]^{-2}.$$

- z-expansion parameterization

$$F_A(z) = \sum_{k=0}^{\infty} a_k z^k \qquad z = \frac{\sqrt{t_c + Q^2} - \sqrt{t_c - t_0}}{\sqrt{t_c + Q^2} + \sqrt{t_c - t_0}}.$$

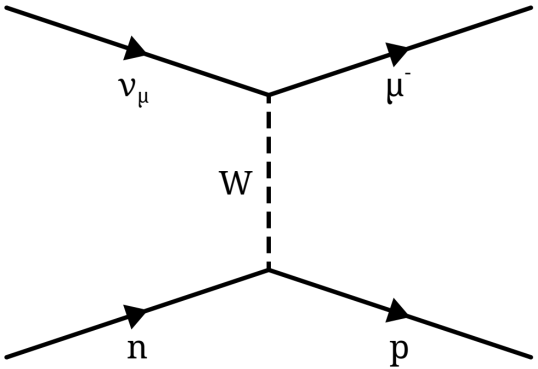
- GENIE implements the recent results from LQCD calculation and MINERvA data.



Aaron S. Meyer arxiv:2601.02676

Primary vertex

- We simulate charged-current QEL, RES, MEC and DIS interactions.
  - SF Unified QEL and Nieves QEL with RPA off
  - Berger Sehgal RES model
  - Bodek-Yang model
  - SuSAv2 MEC model
- Model combination inconsistencies
  - SuSAv2 MEC model is developed based on LFG. SuSAv2 + SF is not consistent.
  - The axial form factor affects both QEL and MEC, but since we use a pre-calculated hadron tensor for MEC, changing the axial form factor model does not change the MEC model.
- Consistency limitations are a challenge for event generators in general, not just GENIE



Quasielastic model

- Nieves (Valencia) QEL model — **inclusive charged-current neutrino-nucleus reactions**

$$\frac{d^2\sigma_{\nu l}}{d\Omega\left(\hat{k}'\right)dE_l'} = \frac{\left|\vec{k'}\right|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

  - The double differential cross section with respect to the outgoing lepton kinematical variables
  - The model was built incorporating the local Fermi gas model.
  - The model apply RPA correction to hadron tensor.
  - Combining SF and RPA effect has been discussed by Nieves, haven’t implemented in GENIE

Quasielastic model

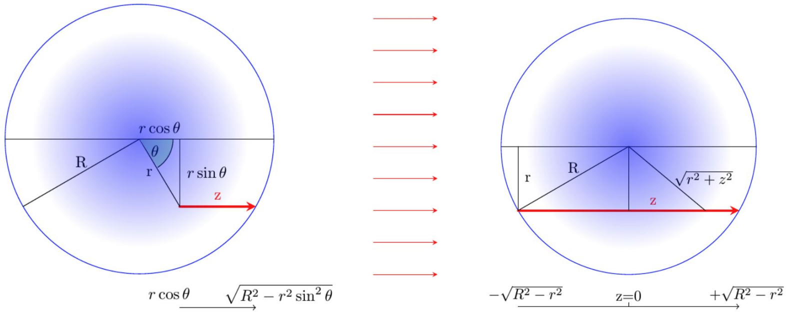
- Fully exclusive leption-nucleus differential cross section, single-nucleon emission

$$d\sigma = \sum_{\tau=n,p} \frac{\mathcal{N}_\tau \mathcal{C}}{32\pi^2 E_{\mathbf{p}} E_{\mathbf{p}'} E_{\mathbf{k}'} E_{\mathbf{k}}} P_\tau(\mathbf{p}, E)$$
$$\times L_{\mu\nu} \tilde{A}^{\mu\nu}_\tau \delta\left(E_{\mathbf{k}} + E_{N_i} - E_{\mathbf{k}'} - E_{\mathbf{p}'}\right) d^3\mathbf{p} dE d^3\mathbf{k}'$$

  - QE scattering within the impulse approximation (AI)
  - Differential cross section with respect to both lepton and nucleon variables
  - It is only single nucleon currents for now. We plan to incorporate two-body currents and interference terms at a later stage.

Final state interactions

- Nuclear physics is a quantum many-body problem: we can neither solve it from first principles nor describe it with statistical methods.
- hA2018 simulates the propagation of hadrons inside nucleus, which is treated as a sphere with density varying continuously as a function of radius (e.g. Woods-Saxon density).
  - Mean free path of hadrons related to nuclear density and momentum
- It is a single-step model.

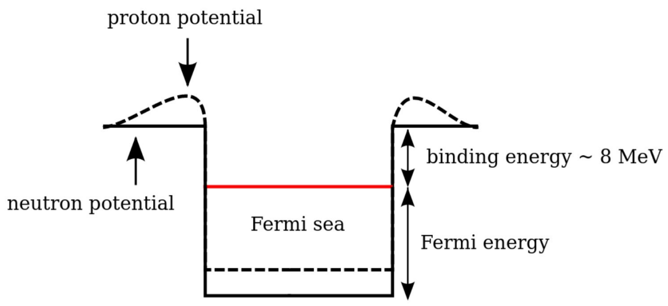


INCL++ model

- Hypothesis used within INCL

$$\lambda/2\pi \ll d < \Lambda < R$$

- The reduced de Broglie wavelength
- Distance between two nucleons inside the target nucleus
- The mean free path of particle in the nucleus
- The radius of the nucleus



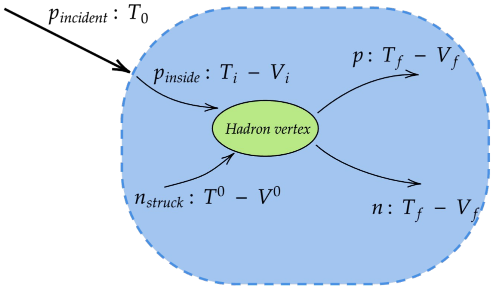
- Potential well for particles

INCL++ model

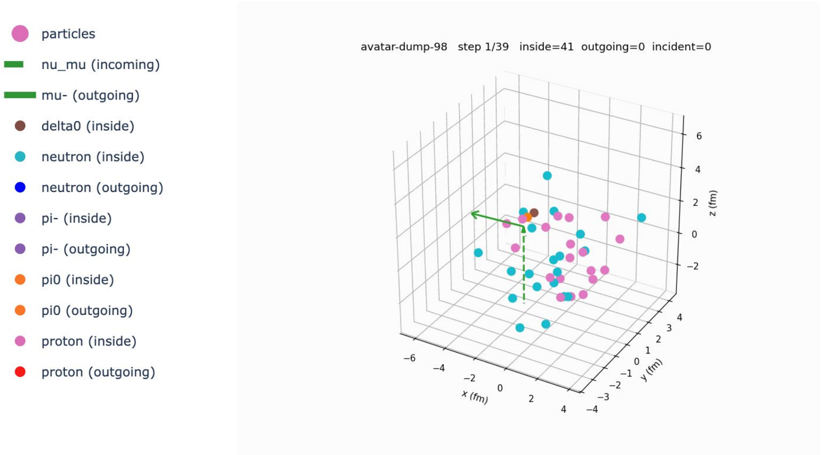
- INCL++ is a time-like intranuclear cascade model (multi-step).
- Hadrons will scatter on spectator nucleons if they reach a close enough distance.

$$d_{\min} = \sqrt{\sigma_{tot}/\pi}$$

- Hadrons in INCL model have nuclear potential (V) and kinetic energy (T)
- Hadronic vertices in INCL get energy conservation through potential energies



$$T_i - V_i + T^0 - V^0 = T_f^p - V_f^p + T_f^n - V_f^n$$

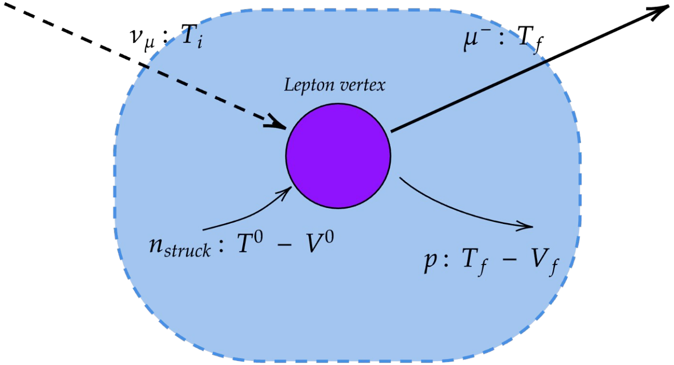


Key issue in interface GENIE with INCL++

- Connect the isospin-, momentum-, and position-dependent potential in INCL with GENIE nuclear model
  - Approach 1: use the full INCL nuclear model in GENIE
    - A consistent treatment of nuclear model from primary lepton vertex to the hadron rescattering vertices
  - Approach 2: combine the GENIE and INCL nuclear models
    - Use variety of GENIE treatments for the primary vertex, e.g., local Fermi gas, spectral function, …

Approach 1

- Apply INCL approach for GENIE lepton primary vertex
- Leptons have no nuclear potential energies either inside or outside nucleus
  - Coulomb potential is currently neglected for charged leptons
- We take an approach that is otherwise similar to hadronic vertices in INCL



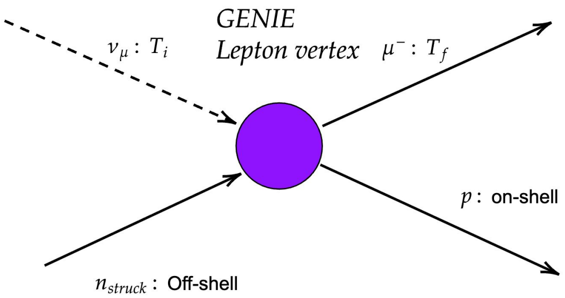
Energy conservation

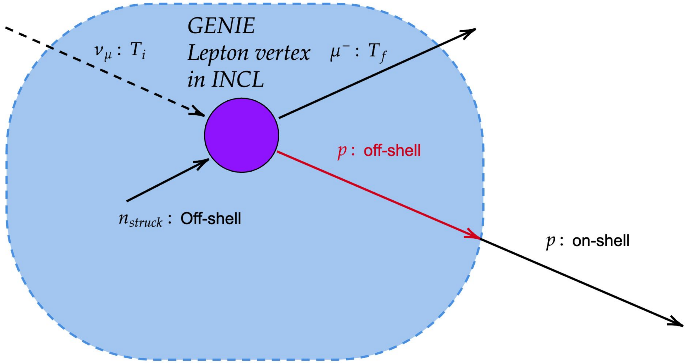
$$T_i^{\nu} + T^0 - V^0 = T_f^{\mu} + T_f^{n} - V_f^{n}$$

This is the first time both the initial and final states are treated as off-shell inside the nucleus in GENIE

Approach 2

- Put the GENIE-style lepton vertex into INCL to trigger the FSI cascade
  - Constructed a method to connect the two models consistently with energy–momentum conservation and momentum- and position-dependent potentials.
  - Convert the on-shell final state from genie into INCL++ style off-shell in-medium particle





Baseline model

- AR23
  - LFG + SF like nn correlation
  - Valencia model for 1p1h, z-expansion form factor from deuterium data
  - hA 2018 FSI model
  - SuSAv2 2p2h model
- MicroBooNE tune
  - LFG model
  - Valencia model for 1p1h, Dipole form factor, tuned Ma of CCQE to t2k data
  - hA 2018 FSI model
  - Nieves 2p2h model fit to t2k data

Model configuration and simulation

- We start from GENIE's AR23 tune (used by DUNE, SBN) with changes
  - LFG with SF-like correlation -> LFG default
  - Nieves QEL model with RPA off and bug fix (see backup for the latter)
- Comparisons of model ingredients
  - LFG model v.s. SF model
  - Deuterium axial form factor v.s. LQCD axial form factor
  - hA2018 v.s. INCL++ final state interaction
- We compare simulation results with MicroBooNE pionless measurements
  - CC0π1p Phys. Rev. Lett. 131 (10) (2023)
  - CC0πNp Phys. Rev. D 112 (11) (2025) 112004

Comparisons - best empirical

- Comparing the most theory-driven model and best empirical model.
- Focus on the nuclear ground state and final state interactions
- Most theoretical model close to AR23
- Best empirical close to MicroBooNE Tune

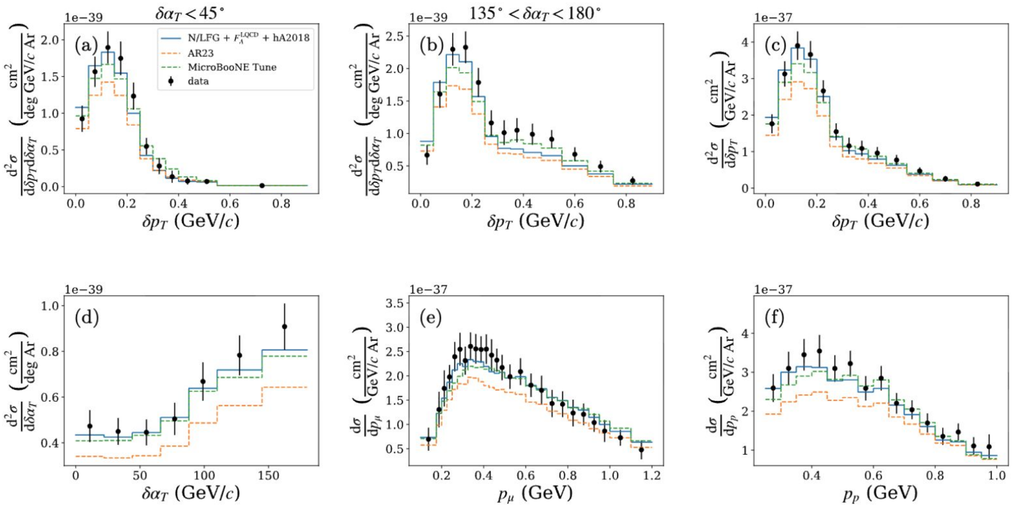


Table 1: χ^2/ndf (p-value) relative to MicroBooNE data for Fig. 1.

Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
N/LFG + F_A^{LQCD} + hA2018	35.98/49 (0.92)	6.78/13 (0.91)	3.47/7 (0.84)	16.29/26 (0.93)	16.05/15 (0.38)
AR23	38.05/49 (0.87)	10.63/13 (0.64)	7.56/7 (0.37)	28.96/26 (0.31)	24.07/15 (0.06)
MicroBooNE Tune	42.61/49 (0.73)	7.31/13 (0.89)	3.96/7 (0.78)	24.59/26 (0.54)	17.38/15 (0.30)

Comparisons - most theory

- Comparing the most theory-driven model and best empirical model.
- Focus on the nuclear ground state and final state interactions
- Most theoretical model close to AR23
- Best empirical close to MicroBooNE Tune

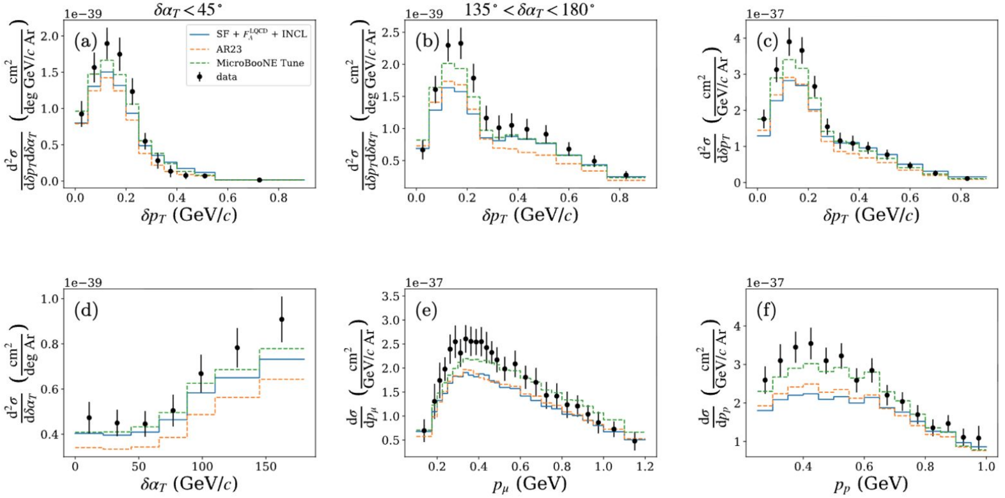
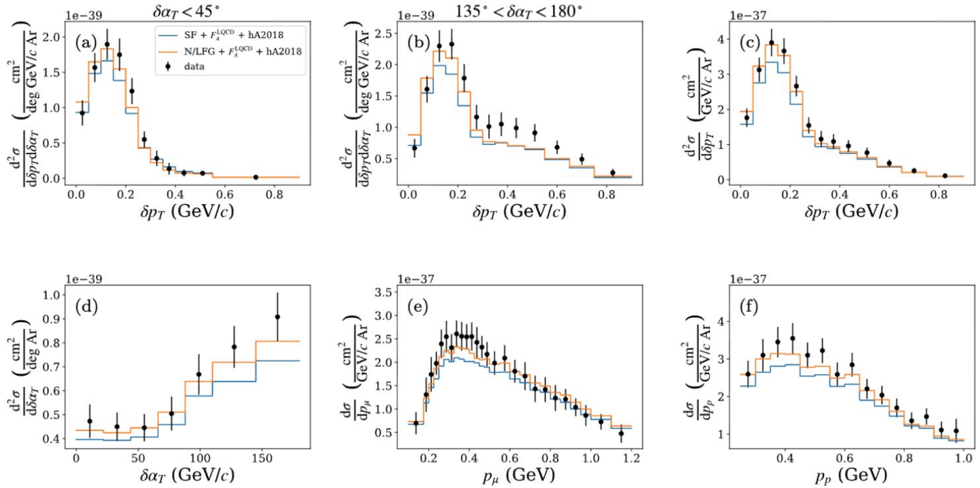


Table 1: χ^2/ndf (p-value) relative to MicroBooNE data for Fig. 1.

Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
SF + F_A^{LQCD} + INCL	66.61/49 (0.05)	15.72/13 (0.26)	5.47/7 (0.60)	23.91/26 (0.58)	32.25/15 (0.01)
AR23	38.05/49 (0.87)	10.63/13 (0.64)	7.56/7 (0.37)	28.96/26 (0.31)	24.07/15 (0.06)
MicroBooNE Tune	42.61/49 (0.73)	7.31/13 (0.89)	3.96/7 (0.78)	24.59/26 (0.54)	17.38/15 (0.30)

The nuclear ground state model

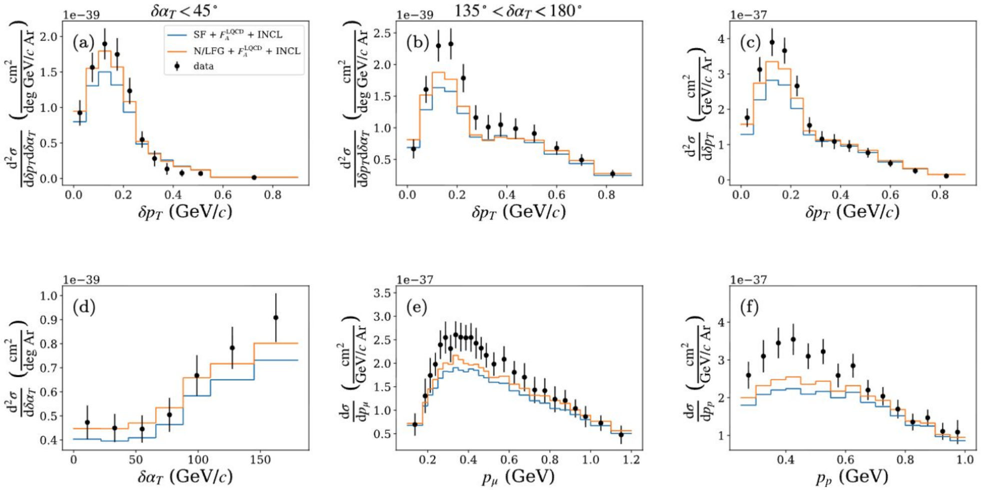
- LFG has a slightly larger overall cross section than SF.
- The χ² scores cannot distinguish between LFG / SF very well when using hA2018 FSI.
- Although SF and LFG are very different in theory, the MicroBooNE data have limited sensitivity.



Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
SF + F_A^{LQCD} + hA2018	34.25/49 (0.95)	6.36/13 (0.93)	5.19/7 (0.64)	18.82/26 (0.84)	15.59/15 (0.41)
N/LFG + F_A^{LQCD} + hA2018	35.98/49 (0.92)	6.78/13 (0.91)	3.47/7 (0.84)	16.29/26 (0.93)	16.05/15 (0.38)

The nuclear ground state model

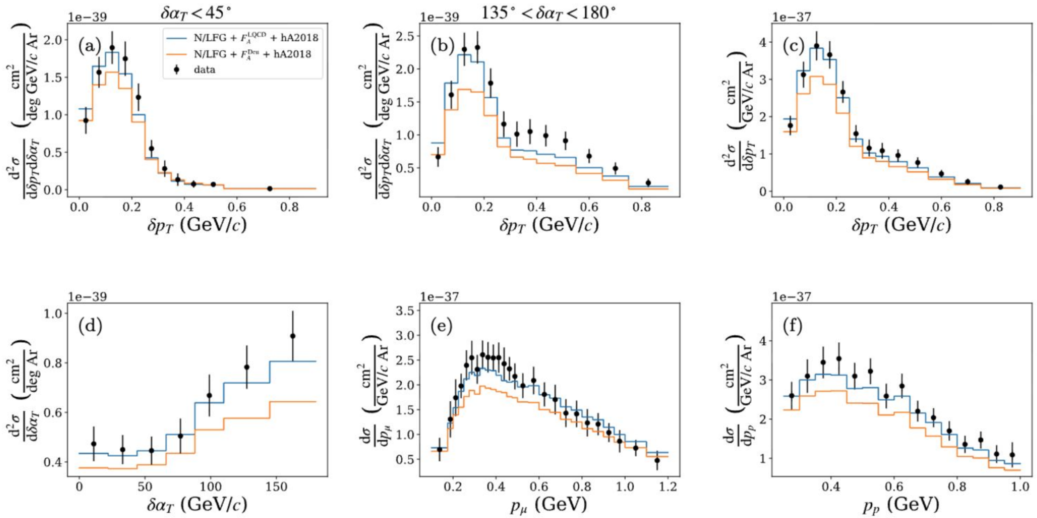
- When using the INCL FSI model, there is a weak preference for the LFG model.



Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
SF + F_A^{LQCD} + INCL	66.61/49 (0.05)	15.72/13 (0.26)	5.47/7 (0.60)	23.91/26 (0.58)	32.25/15 (0.01)
N/LFG + F_A^{LQCD} + INCL	56.01/49 (0.23)	9.09/13 (0.77)	5.75/7 (0.57)	17.66/26 (0.89)	26.94/15 (0.03)

The axial form factor

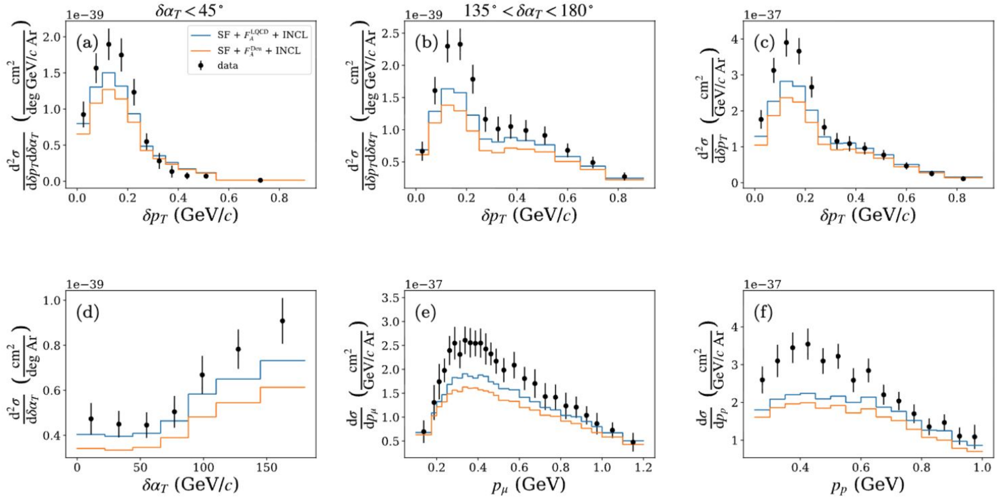
- Keep nuclear ground state model and FSI model
  - LFG + hA2018
- Vary axial form factor from LQCD to deuterium fit.



Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
N/LFG + F_A^{LQCD} + hA2018	35.98/49 (0.92)	6.78/13 (0.91)	3.47/7 (0.84)	16.29/26 (0.93)	16.05/15 (0.38)
N/LFG + F_A^{Deu} + hA2018	44.21/49 (0.67)	9.59/13 (0.73)	10.19/7 (0.18)	20.89/26 (0.75)	19.95/15 (0.17)

The axial form factor

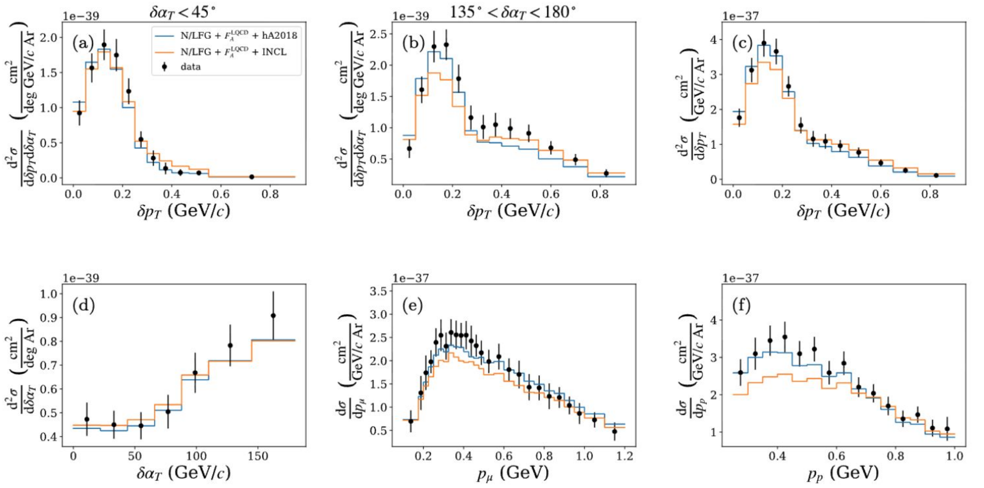
- Keep nuclear ground state model and FSI model
  - SF + INCL
- Vary axial form factor from LQCD to deuterium fit.
- The axial form factor impacts the overall normalization.
- LQCD increases the cross section by ~10% compared to the deuterium fit.



Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
SF + F_A^{LQCD} + INCL	66.61/49 (0.05)	15.72/13 (0.26)	5.47/7 (0.60)	23.91/26 (0.58)	32.25/15 (0.01)
SF + F_A^{Deu} + INCL	81.91/49 (0.00)	23.94/13 (0.03)	10.01/7 (0.19)	35.08/26 (0.11)	38.83/15 (0.00)

The final state interaction model

- INCL has stronger FSI effects than hA2018 model.
    - INCL has a larger cross section in high δpT and smaller cross section in low δpT,
- δαT cannot distinguish between INCL / hA2018.
- Proton momentum discriminates between INCL / hA2018 well.
- The χ² scores favor hA2018 over INCL for these data.



Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
N/LFG + F_A^{LQCD} + hA2018	35.98/49 (0.92)	6.78/13 (0.91)	3.47/7 (0.84)	16.29/26 (0.93)	16.05/15 (0.38)
N/LFG + F_A^{LQCD} + INCL	56.01/49 (0.23)	9.09/13 (0.77)	5.75/7 (0.57)	17.66/26 (0.89)	26.94/15 (0.03)

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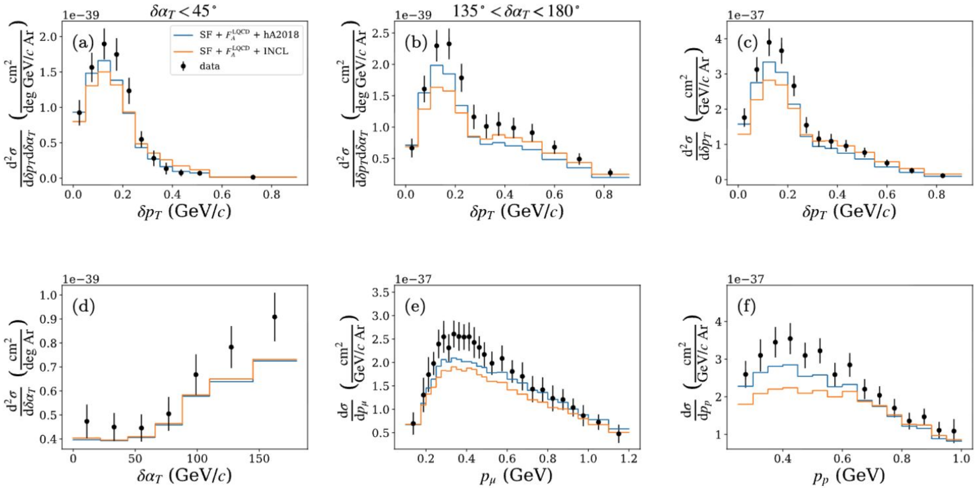


Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
SF + $F_A^{\rm LQCD}$ + hA2018	34.25/49 (0.95)	6.36/13 (0.93)	5.19/7 (0.64)	18.82/26 (0.84)	15.59/15 (0.41)
SF + $F_A^{\rm LQCD}$ + INCL	66.61/49 (0.05)	15.72/13 (0.26)	5.47/7 (0.60)	23.91/26 (0.58)	32.25/15 (0.01)

Summary

- We study different neutrino-nucleus interaction model ingredients in GENIE and compare to MicroBooNE data.
- We focus on measurements in the CC0π1p and CC0πNp channels
  - The data can't reliably discriminate between the LFG and SF ground states.
  - The LQCD-based axial form factor achieves better agreement than the deuterium fit.
  - The hA2018 FSI model generally performs better for these data than INCL++.
- MicroBooNE data tend to favor a higher cross-section normalization across various model configurations
- This work provides a benchmark of current GENIE models, including the most theoretical options available and popular empirical alternatives

MEC model

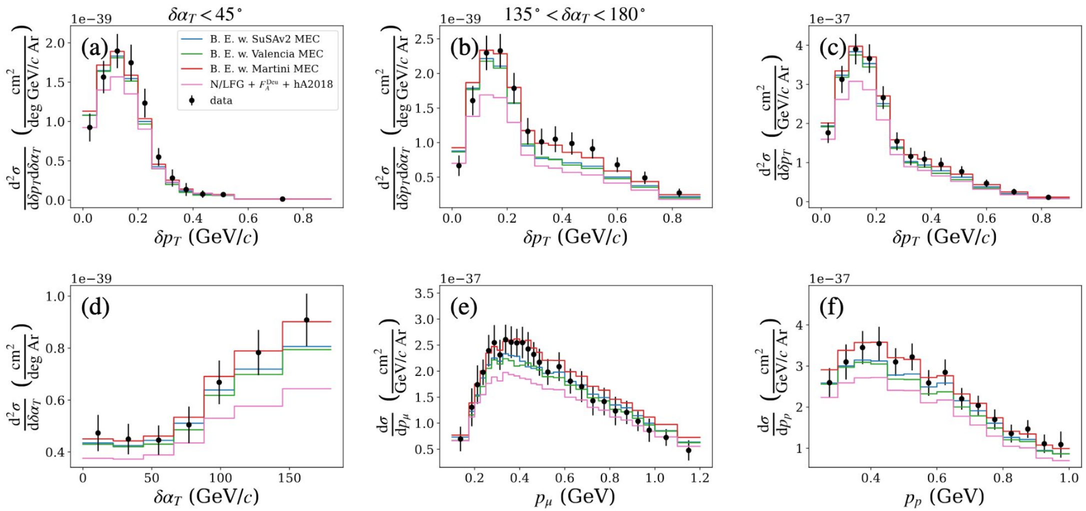
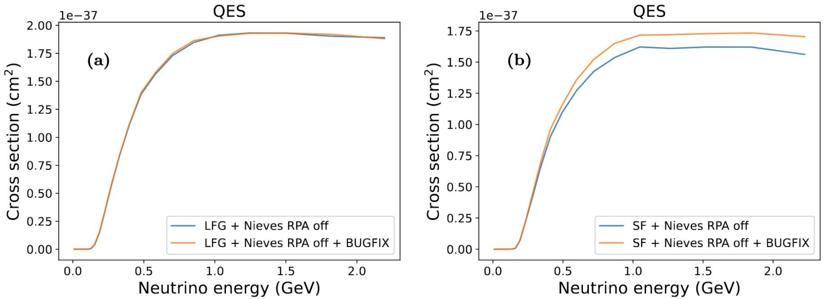


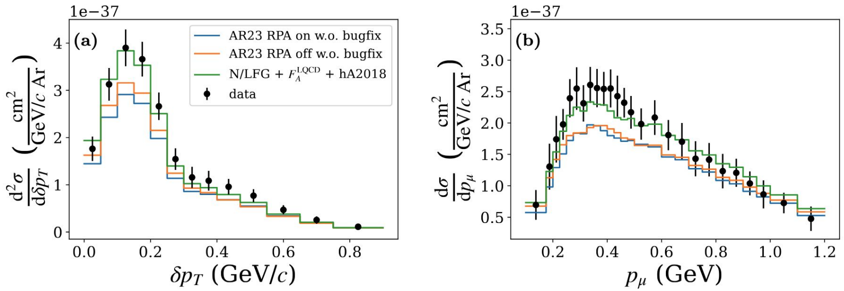
Table B.2: χ^2/ndf (p-value) of MC and reference simulations relative to MicroBooNE data.

Configuration	δp_T vs. $\delta\alpha_T$ [a]	δp_T	$\delta\alpha_T$	p_μ	p_p
B.E. (N/LFG+F_A^{LQCD}+hA2018)	35.98/49 (0.92)	6.78/13 (0.91)	3.47/7 (0.84)	16.29/26 (0.93)	16.05/15 (0.38)
B.E. with Valencia MEC	37.55/49 (0.88)	7.89/13 (0.85)	3.28/7 (0.86)	15.52/26 (0.95)	17.52/15 (0.29)
B.E. with Martini *et al.* MEC	32.50/49 (0.97)	3.99/13 (0.99)	1.43/7 (0.98)	10.29/26 (1.00)	11.42/15 (0.72)
N/LFG + F_A^{Deu} + hA2018	44.21/49 (0.67)	9.59/13 (0.73)	10.19/7 (0.18)	20.89/26 (0.75)	19.95/15 (0.17)

BUG fix in Nieves model

- Nieves model provide the hadron tensor in nucleus rest frame, reduced to 5 independent nonzero terms.
- GENIE needs to work in the nucleon rest frame, this requires a Lorentz boost that was previously missing
- Impact becomes more noticeable for SF nuclear model





Impact of cluster production in INCL++

- INCL achieves better agreement with cluster production turned off

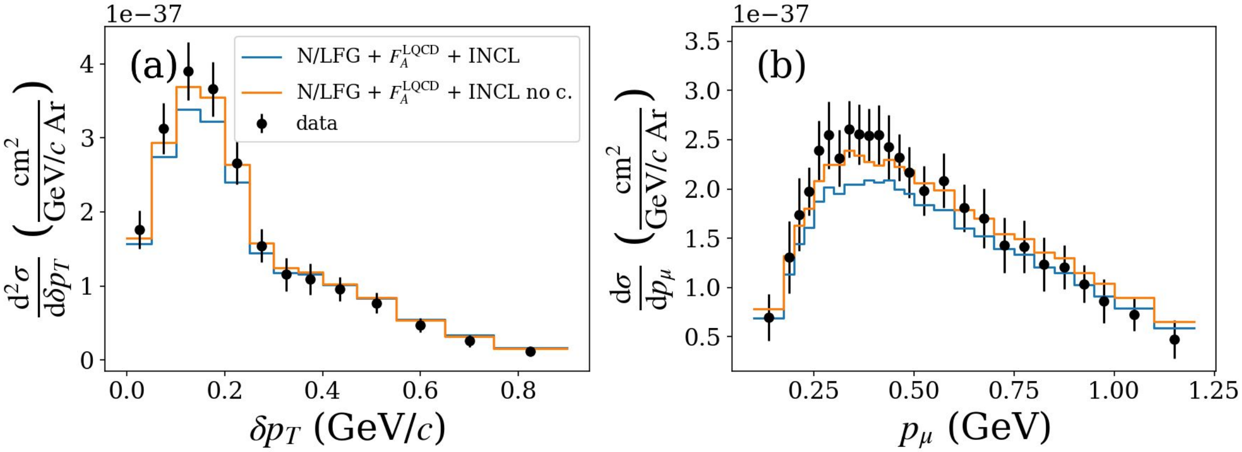


TABLE VI. χ^2/ndf (p-value) of MC and reference simulations relative to MicroBooNE data.

Configuration	δp_T vs. $\delta\alpha_T$	δp_T	$\delta\alpha_T$	p_μ	p_p
B. E. w. SuSAv2 MEC	43.18/49 (0.71)	4.44/13 (0.99)	5.73/7 (0.57)	17.49/26 (0.89)	14.79/15 (0.47)
N/LFG + F_A^{LQCD} + INCL no c.	44.48/49 (0.66)	3.66/13 (0.99)	4.21/7 (0.76)	16.41/26 (0.93)	16.99/15 (0.32)
N/LFG + F_A^{LQCD} + INCL	52.58/49 (0.34)	7.46/13 (0.88)	4.35/7 (0.74)	17.31/26 (0.90)	26.21/15 (0.04)

Table of χ² scores

- LFG + LQCD + hA2018 is the best fit to data.

Table 1: χ^2/ndf (p-value) of MC and reference simulations relative to MicroBooNE data.

Configuration	δp_T vs. $\delta\alpha_T$ [a]	δp_T	$\delta\alpha_T$	p_μ	p_p
N/LFG + F_A^{LQCD} + hA2018 [b]	35.98/49 (0.92)	6.78/13 (0.91)	3.47/7 (0.84)	16.29/26 (0.93)	16.05/15 (0.38)
SF + F_A^{LQCD} + hA2018	34.25/49 (0.95)	6.36/13 (0.93)	5.19/7 (0.64)	18.82/26 (0.84)	15.59/15 (0.41)
N/LFG + F_A^{Deu} + hA2018	44.21/49 (0.67)	9.59/13 (0.73)	10.19/7 (0.18)	20.89/26 (0.75)	19.95/15 (0.17)
N/LFG + F_A^{LQCD} + INCL	56.01/49 (0.23)	9.09/13 (0.77)	5.75/7 (0.57)	17.66/26 (0.89)	26.94/15 (0.03)
SF + F_A^{Deu} + hA2018	43.52/49 (0.69)	11.91/13 (0.54)	11.12/7 (0.13)	30.98/26 (0.23)	24.93/15 (0.05)
SF + F_A^{LQCD} + INCL [c]	66.61/49 (0.05)	15.72/13 (0.26)	5.47/7 (0.60)	23.91/26 (0.58)	32.25/15 (0.01)
N/LFG + F_A^{Deu} + INCL	68.42/49 (0.03)	16.33/13 (0.23)	8.73/7 (0.27)	27.98/26 (0.36)	31.56/15 (0.01)
SF + F_A^{Deu} + INCL	81.91/49 (0.00)	23.94/13 (0.03)	10.01/7 (0.19)	35.08/26 (0.11)	38.83/15 (0.00)
MicroBooNE Tune	42.61/49 (0.73)	7.31/13 (0.89)	3.96/7 (0.78)	24.59/26 (0.54)	17.38/15 (0.30)
AR23	38.05/49 (0.87)	10.63/13 (0.64)	7.56/7 (0.37)	28.96/26 (0.31)	24.07/15 (0.06)

[a] The χ^2/ndf (p-value) in this column include contributions from intermediate $\delta\alpha_T$ bins not shown in Fig. 1.
[b] Best empirical tune.
[c] Most theoretical tune.

Tail in delta pT

- NN correlation
- 2p2h
- FSI rescattering