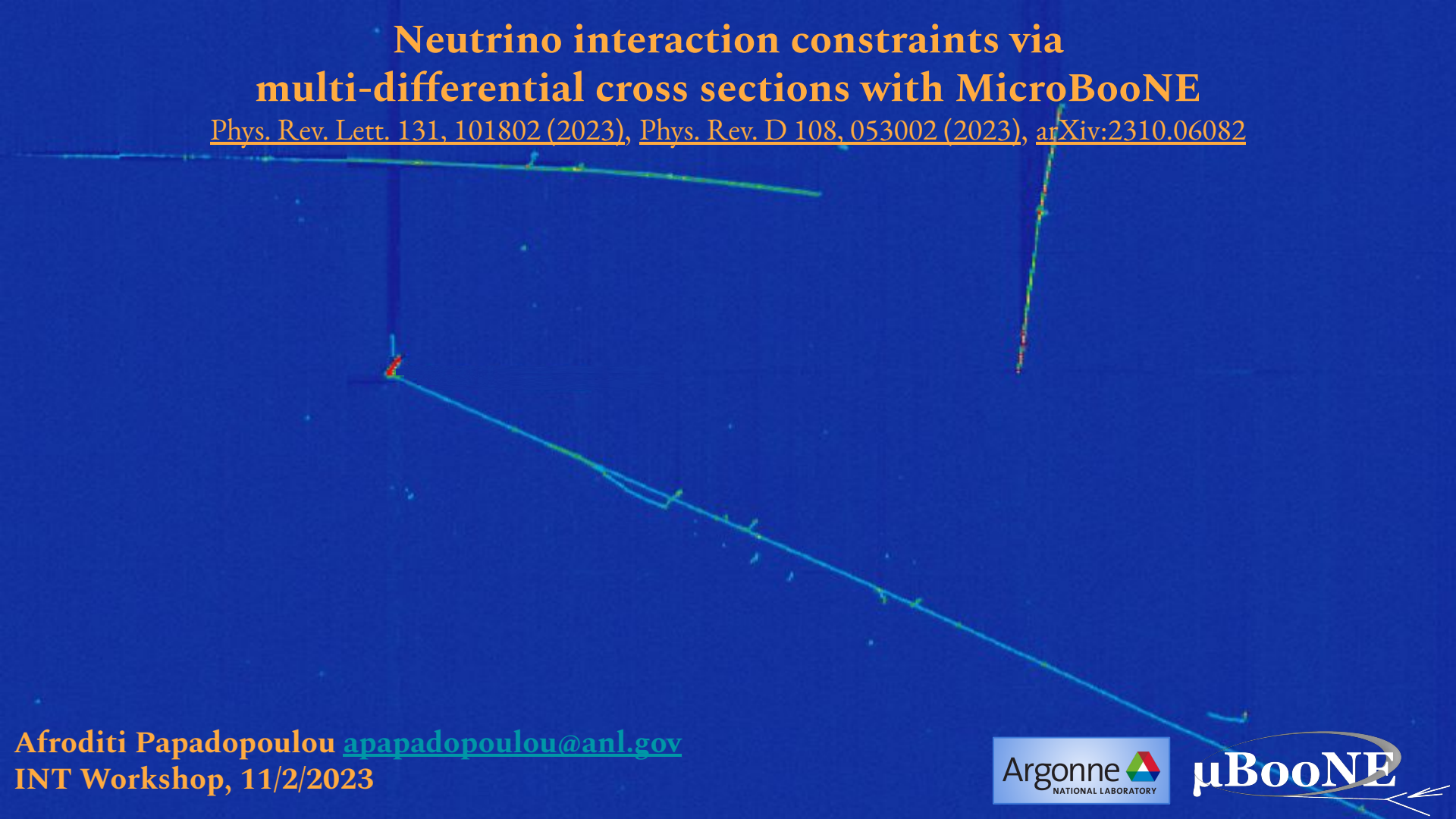
Neutrino interaction constraints via multi-differential cross sections with MicroBooNE

Phys. Rev. Lett. 131, 101802 (2023), Phys. Rev. D 108, 053002 (2023), arXiv:2310.06082



Afroditi Papadopoulou apapadopoulou@anl.gov

INT Workshop, 11/2/2023

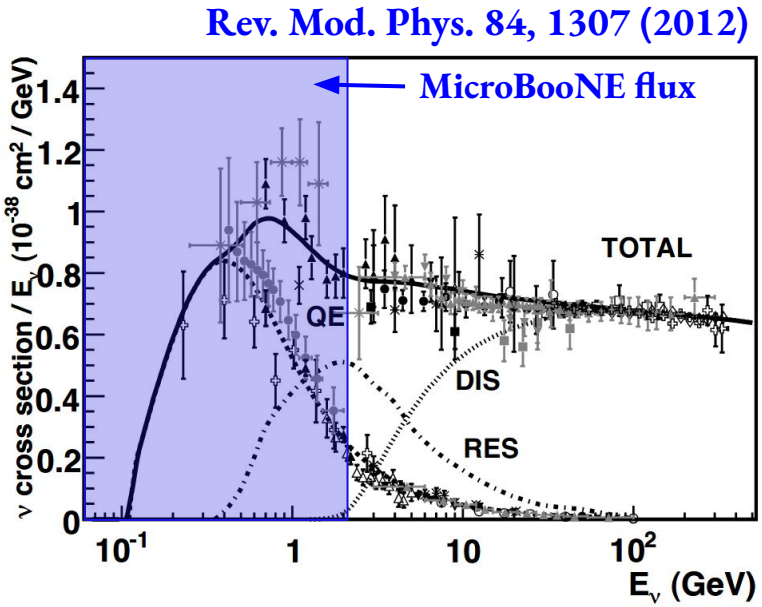
Argonne NATIONAL LABORATORY

μBooNE

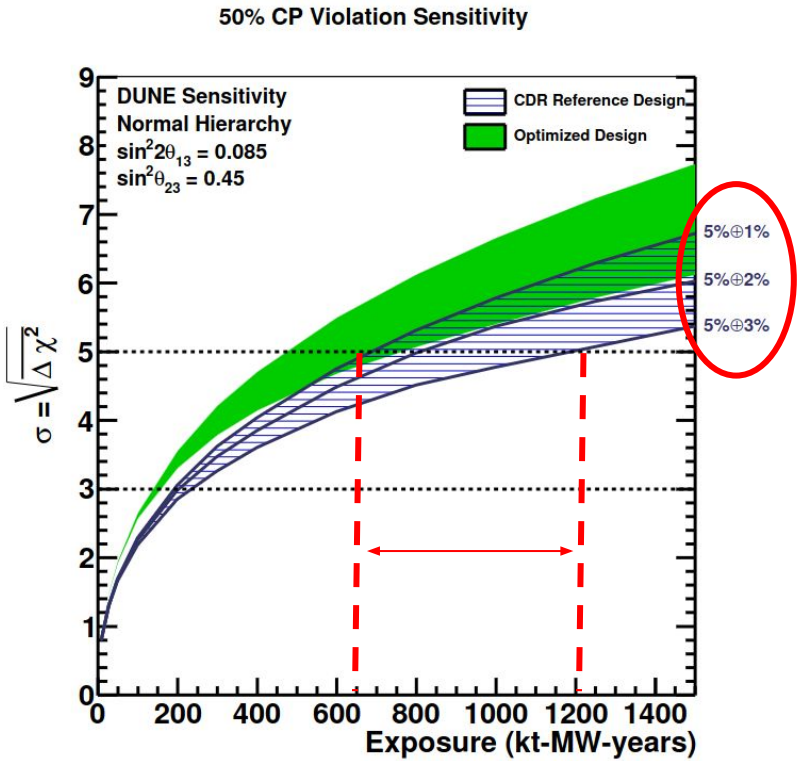
Neutrino Interaction Challenge

- Broad neutrino spectra
- Various complex interaction mechanisms

Any mismodeling in neutrino event generator simulation predictions can limit experimental sensitivity



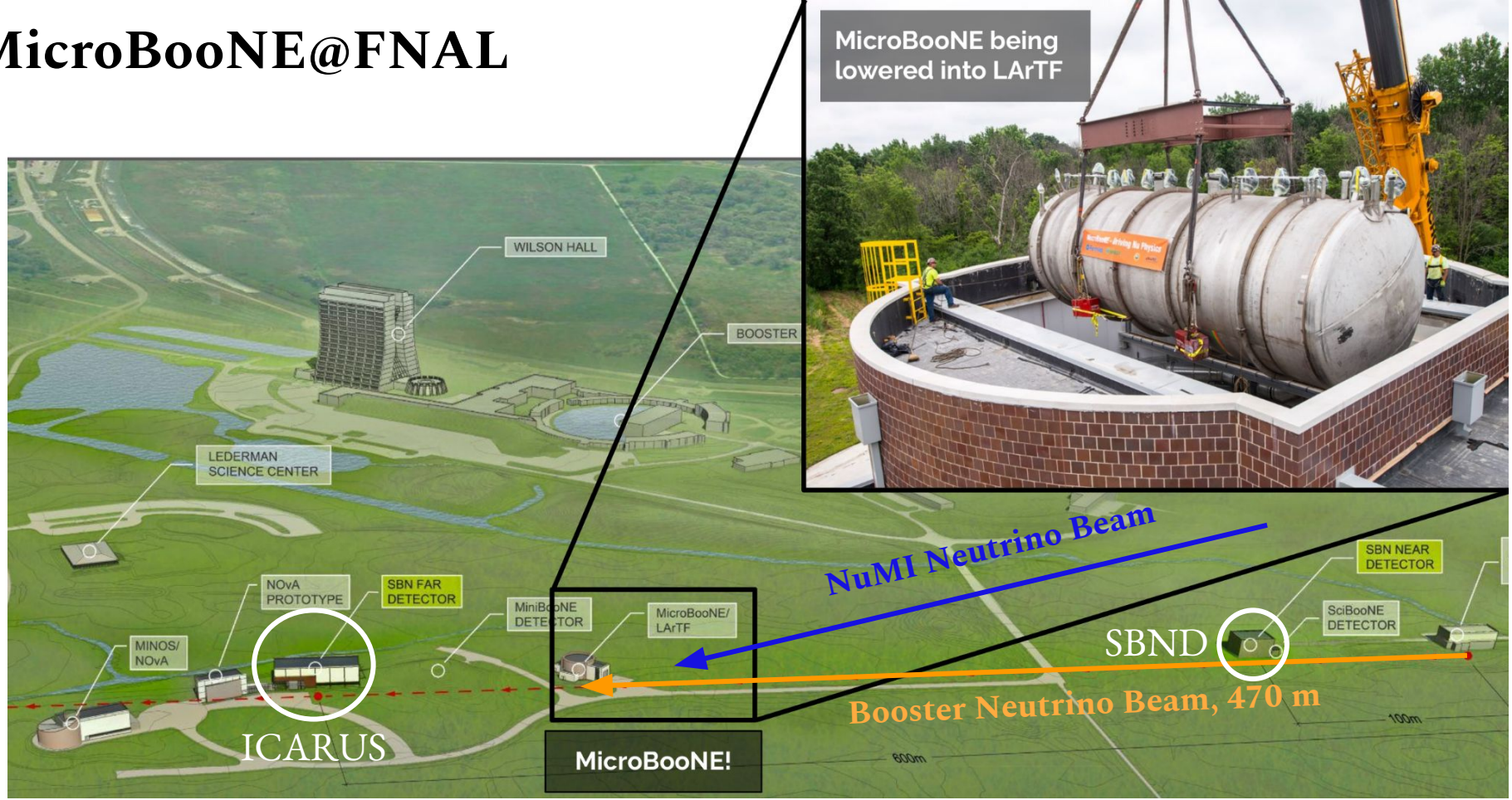
Future Experiments



- Mismodeling can impact required run time of forthcoming flagship experiments
- But … head start with Short-Baseline Neutrino (SBN) Program (MicroBooNE, SBND, ICARUS)

DUNE CDR, arXiv:1512.06148

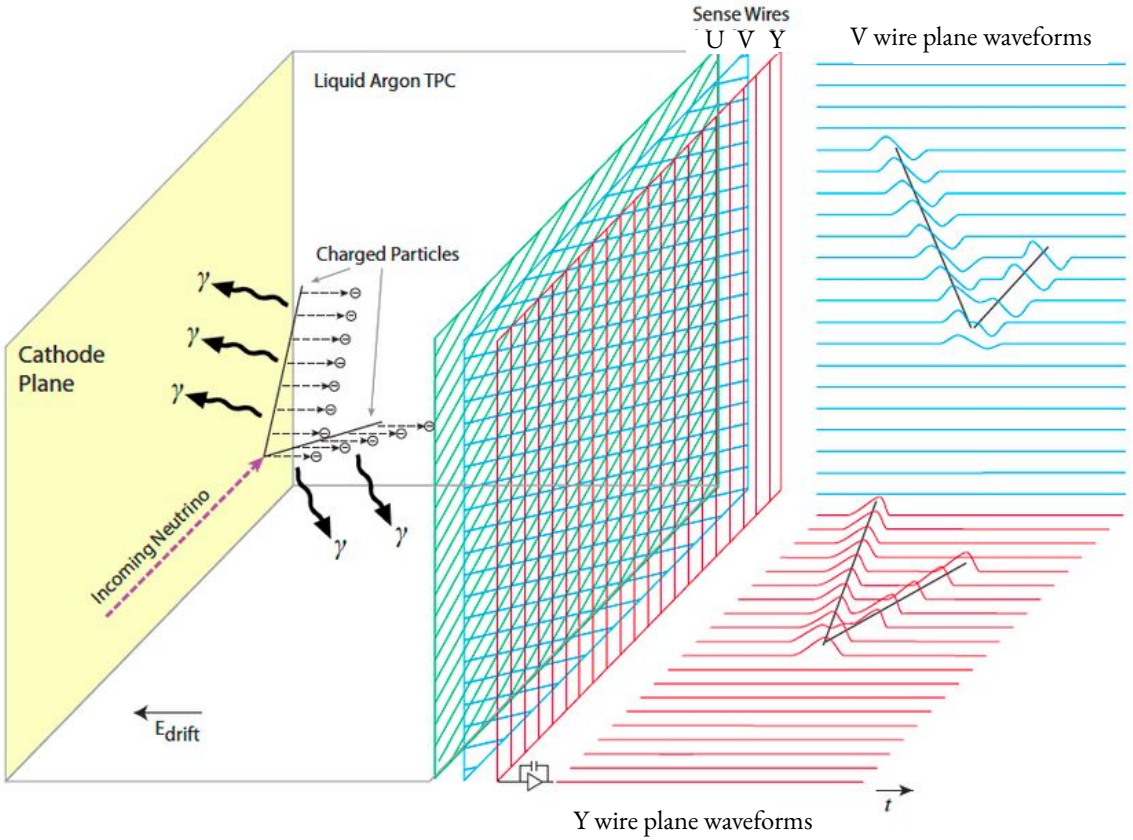
MicroBooNE@FNAL

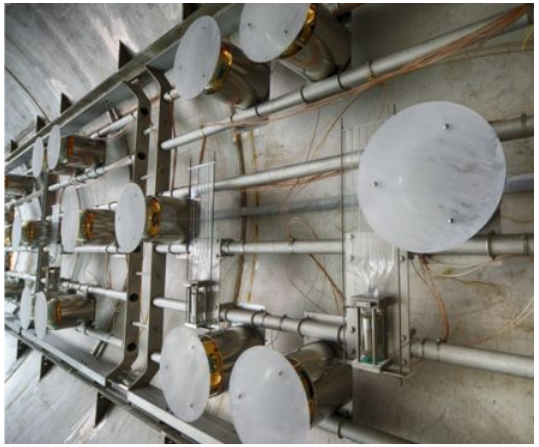


85 tonne Liquid Argon Time Projection Chamber (LArTPC)

JINST 12, P02017 (2017)

LArTPC Operation Principle



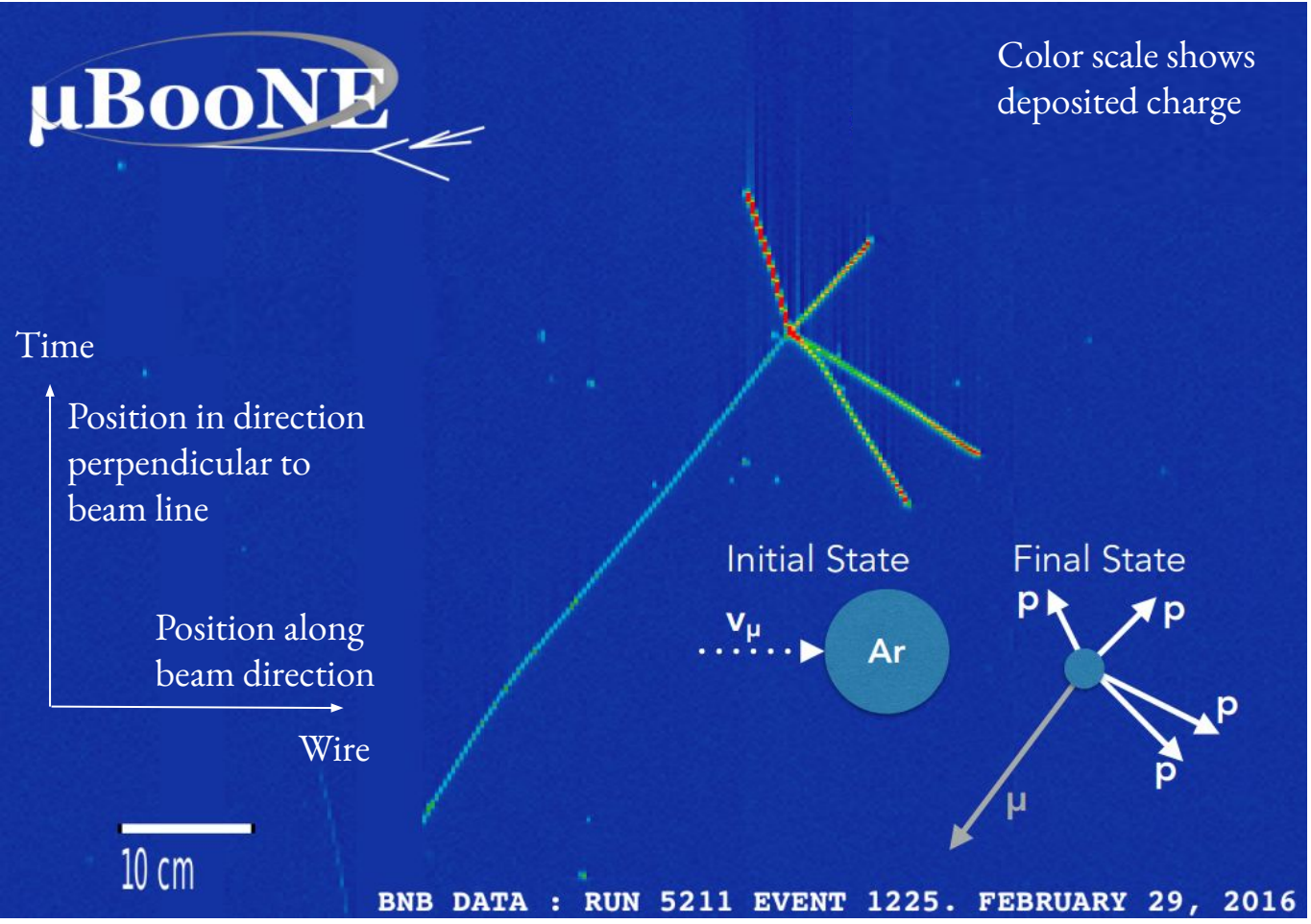


MicroBooNE

- 3 wire planes
- 8192 gold coated wires
- 3 mm wire spacing
- 32 PMTs

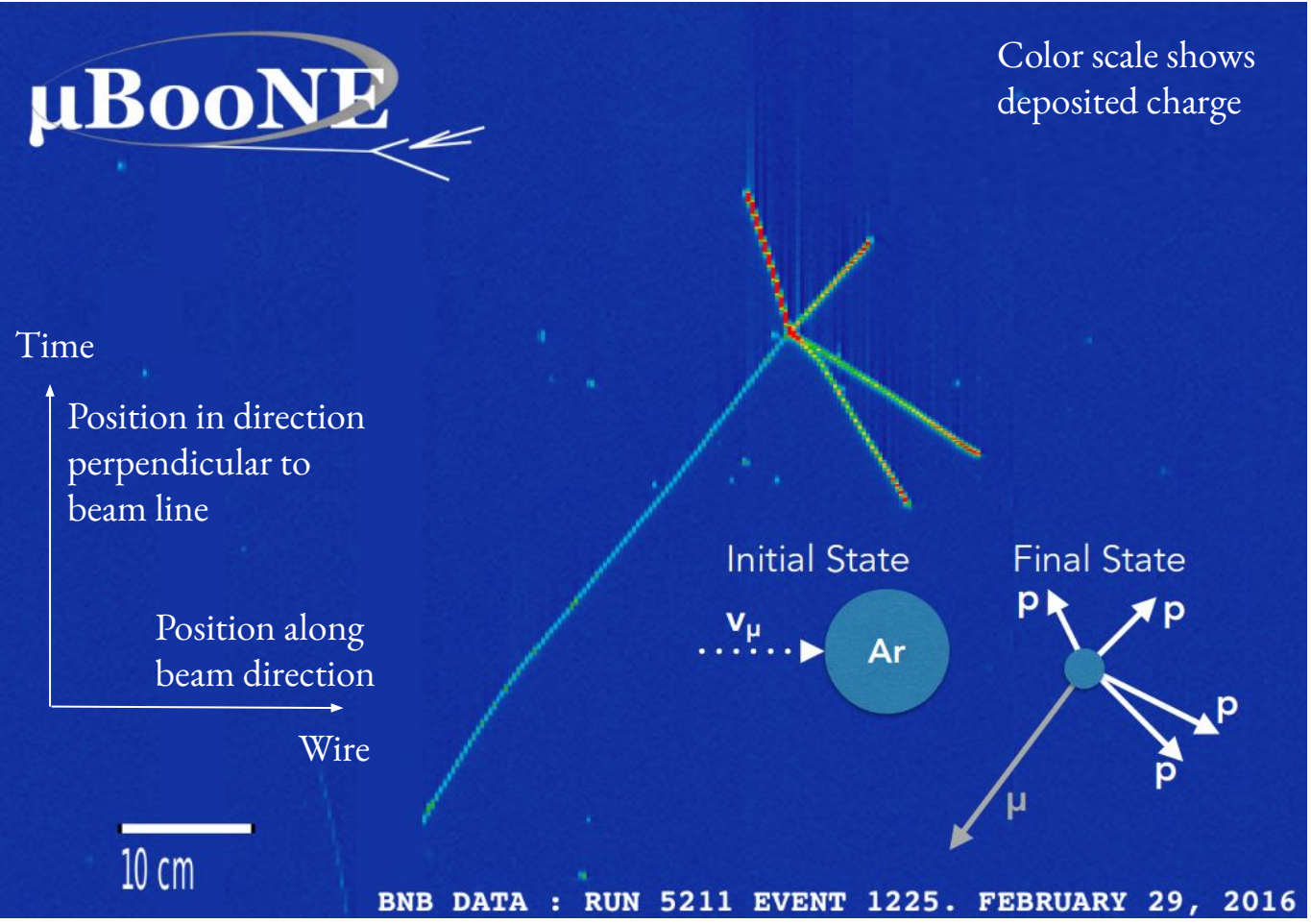
[JINST 12, P02017 (2017)]

MicroBooNE Data Events



- Excellent spatial resolution
- Low detection thresholds
- Precise calorimetric information
- Powerful particle identification

MicroBooNE Data Events



- Largest available neutrino-argon data set with ~500k recorded neutrino interactions
- 15 released and more than 30 active MicroBooNE cross section analyses
- Multiple topologies investigated

Already Public Results

CC inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 3D CC E_ν @ BNB
  arXiv:2307.06413 , submitted to PRL
- 1D ν_e CC inclusive @ NuMI
  Phys. Rev. D105, L051102 (2022)
  Phys. Rev. D104, 052002 (2021)

Pion production

- ν_μ NCπ^0 @ BNB
  Phys. Rev. D 107, 012004 (2023)

Rare channels

- η production @ BNB, submitted to PRL
  arXiv:2305.16249
- Λ production @ NuMI
  Phys. Rev. Lett. 130, 231802 (2023)

CC0π

- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Transverse Imbalance @ BNB
  Phys. Rev. Lett. 131, 101802 (2023)
  Phys. Rev. D 108, 053002 (2023)
- 1D & 2D ν_μ CC1p0π Generalized Imbalance @ BNB
  arXiv:2310.06082, submitted to PRD
- 1D ν_μ CC1p0π @ BNB
  Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CC2p @ BNB
  arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB
  Phys. Rev. D102, 112013 (2020)

15 cross section publications
and way more to come!

Already Public Results

CC inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 3D CC E_ν @ BNB
  arXiv:2307.06413 , submitted to PRL
- 1D ν_e CC inclusive @ NuMI
  Phys. Rev. D105, L05110
  Phys. Rev. D104, 052002

Pion production

- ν_μ NCπ^0 @ BNB
  Phys. Rev. D 107, 012004 (2023)

Rare channels

- η production @ BNB, submitted to PRL
  arXiv:2305.16249
- Λ production @ NuMI
  Phys. Rev. Lett. 130, 231802 (2023)

CC0π

- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Transverse Imbalance @ BNB
  Phys. Rev. Lett. 131, 101802 (2023)
  Phys. Rev. D 108, 053002 (2023)
- 1D & 2D ν_μ CC1p0π Generalized Imbalance @ BNB
  arXiv:2310.06082, submitted to PRD
  arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB
  Phys. Rev. D102, 112013 (2020)

Opportunity to extensively benchmark neutrino event generator predictions

15 cross section publications
and way more to come!

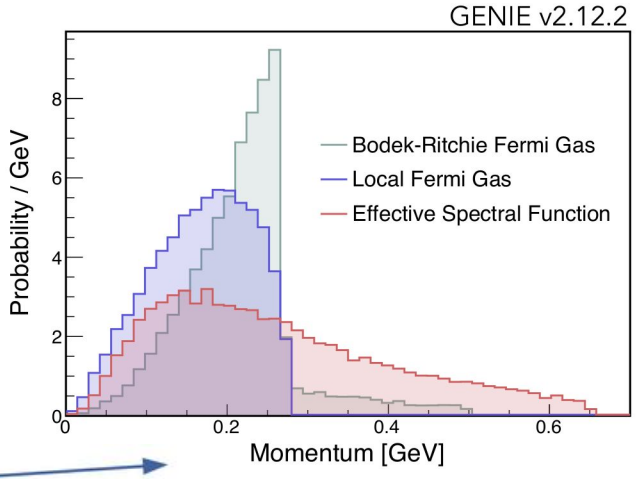
Nuclear Effects in Event Generators

Rev. Mod. Phys. 89, 045002 (2017)

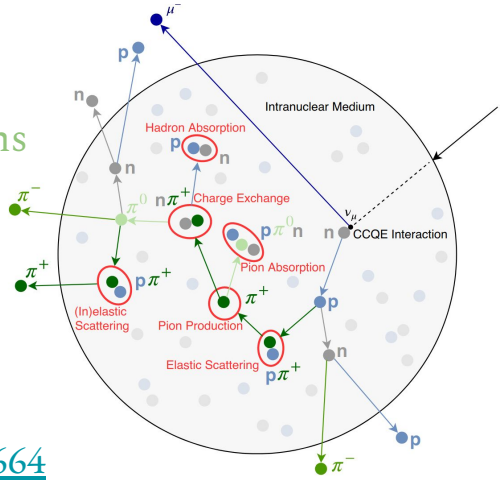
- Fermi motion
- Final state interactions
- Meson exchange currents
- …

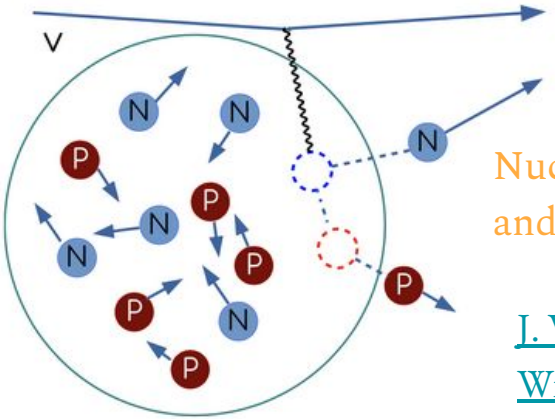
} Known unknowns that need to be accurately simulated

Struck nucleon motion in argon



Hadron reinteractions



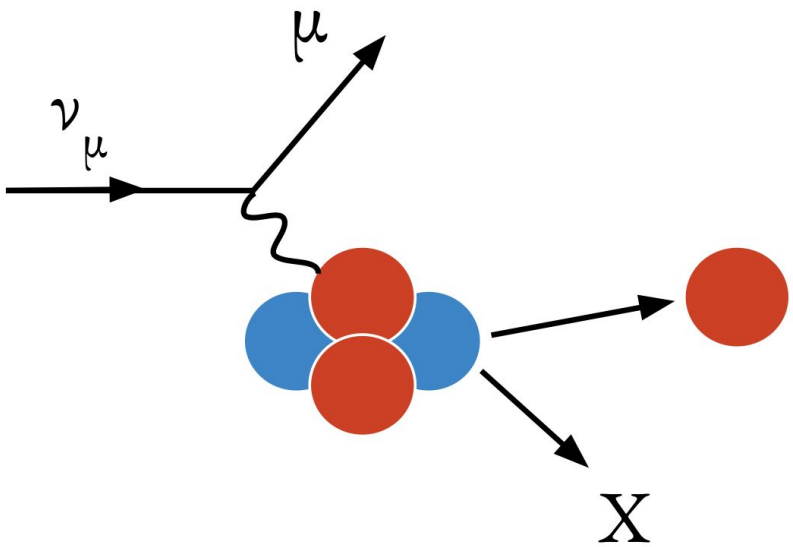


Nucleon-nucleon relative angle and momenta

J. Wolcott
Wine & Cheese Seminar

arXiv:2201.04664

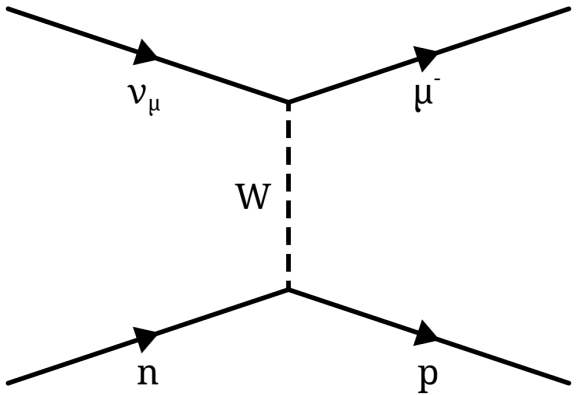
Double-Differential Single-Proton Knockout

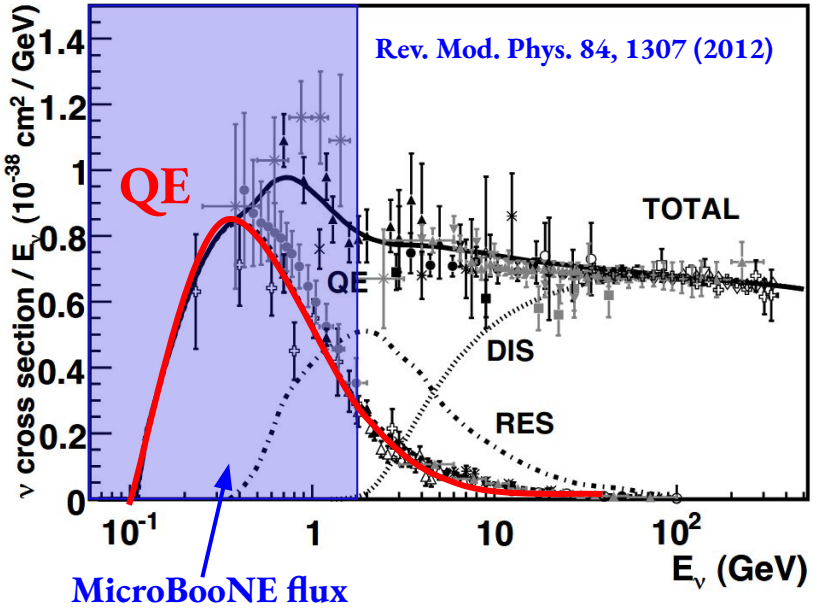


- First double-differential single-proton cross section measurement on argon
- Identified kinematic variables and phase-space regions with sensitivity to nuclear effects
- Uses ~50% of available MicroBooNE data sets & Booster Neutrino Beam (BNB)

Phys. Rev. Lett. 131, 101802 (2023)
Phys. Rev. D 108, 053002 (2023)
arXiv:2310.06082

Single-Proton Knockout





- Dominated by Charged Current Quasi-elastic (CCQE) interactions
- Simple single muon-proton events
- Dominant at MicroBooNE energies

CC1p0π Quasielastic-like Signal Definition

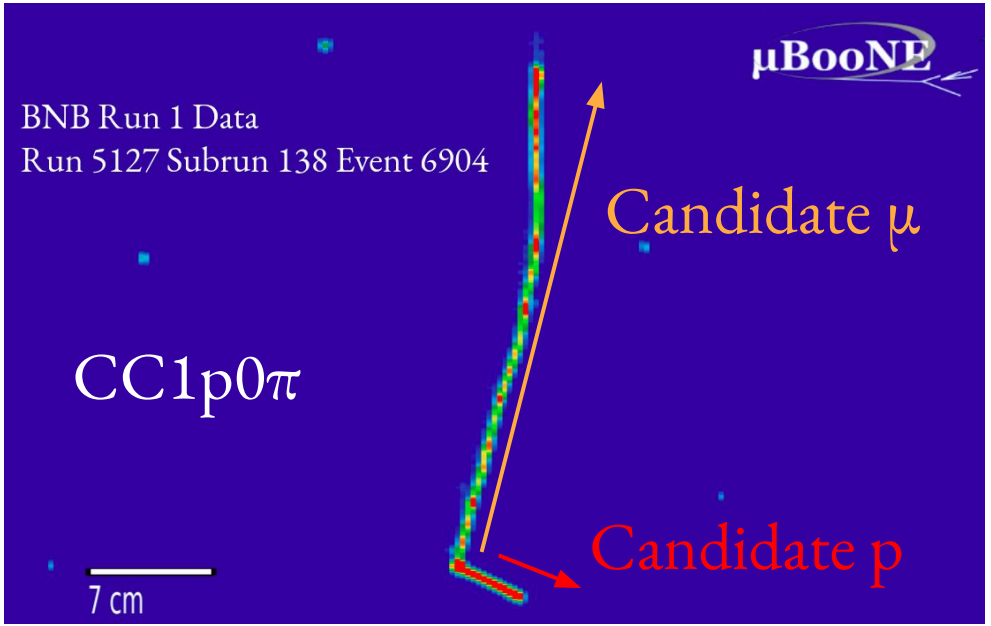
Ranges driven by minimum track length, track containment, hadronic reinteractions, and systematics

- 1 muon
  $100 < P_{\mu} < 1200$ MeV/c
- 1 proton
  $300 < P_{p} < 1000$ MeV/c
- No $\pi^{\pm}$ with $P_{\pi} > 70$ MeV/c
- No π^{0} or heavier mesons
- Any number of neutrons

9051 CC1p0π candidate data events

CC1p0π ~10% efficiency

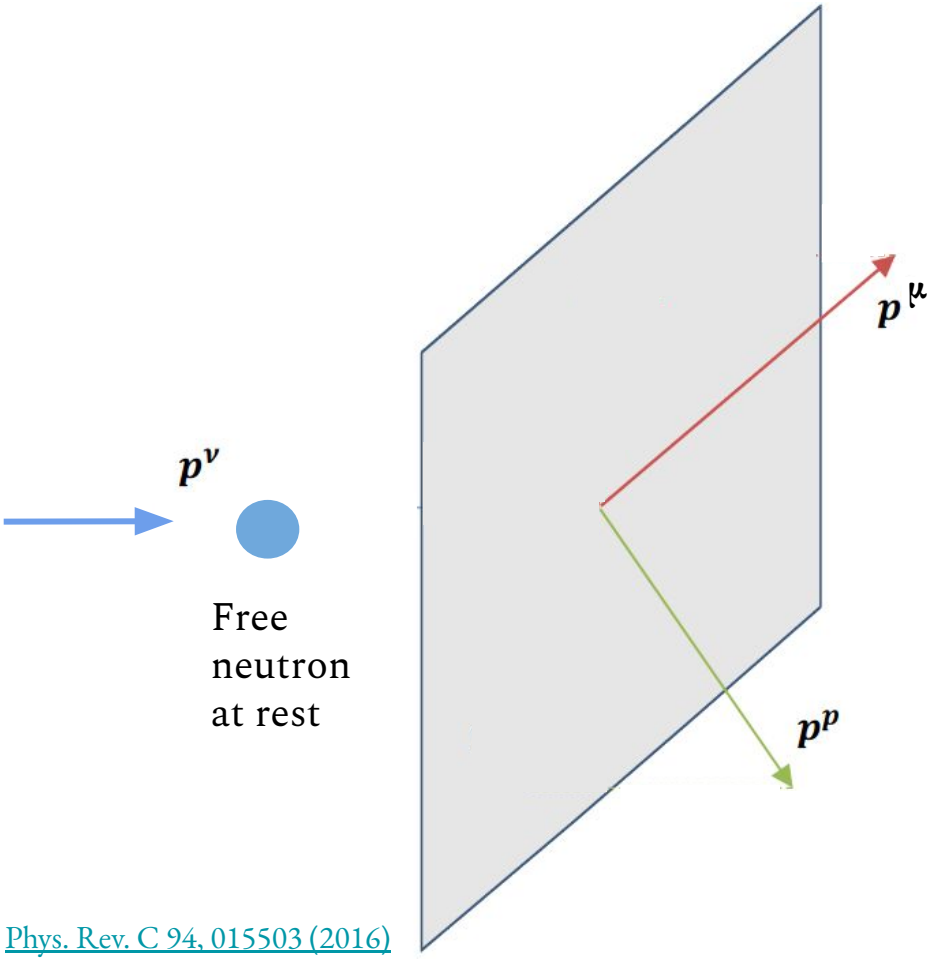
~70% purity



[Phys. Rev. Lett. 131, 101802 (2023)]
[Phys. Rev. D 108, 053002 (2023)]
[arXiv:2310.06082]
* [Phys. Rev. D 105, 072001 (2022)]

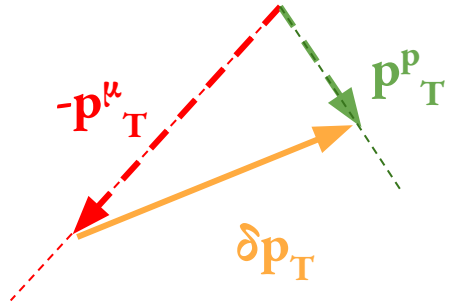
MC: GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

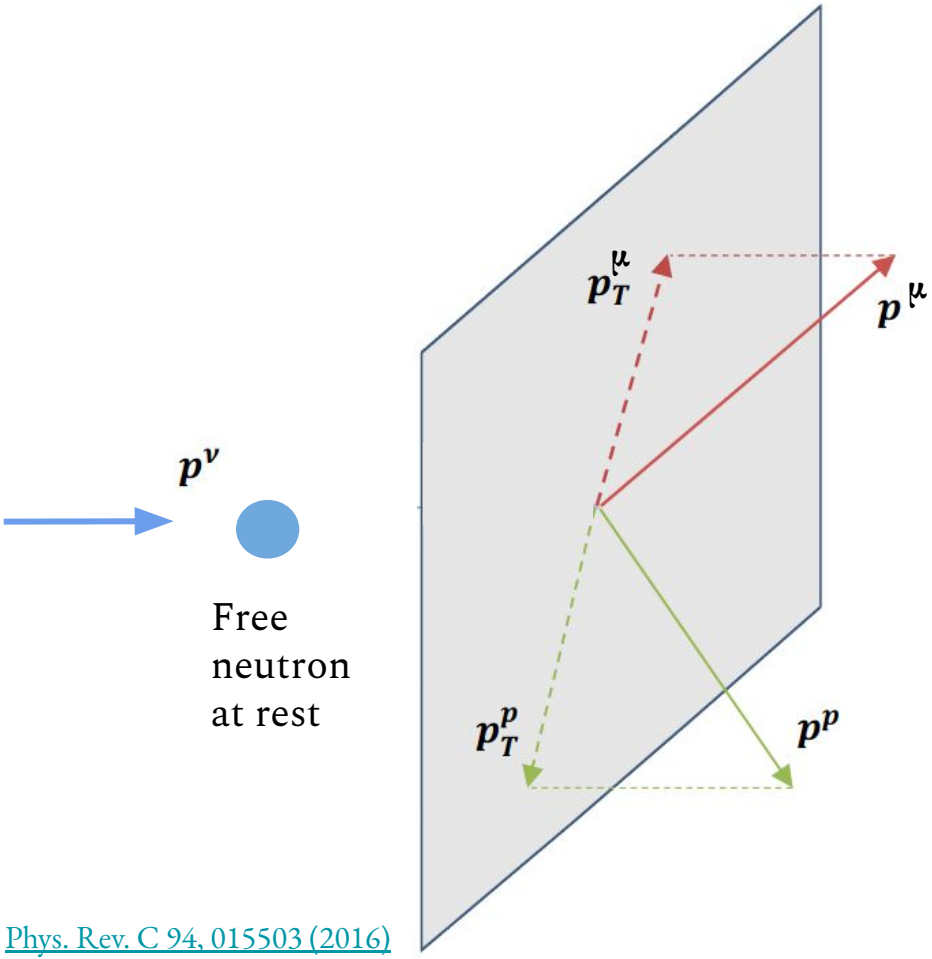
Transverse Kinematic Imbalance (TKI)



Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)





Free neutron at rest

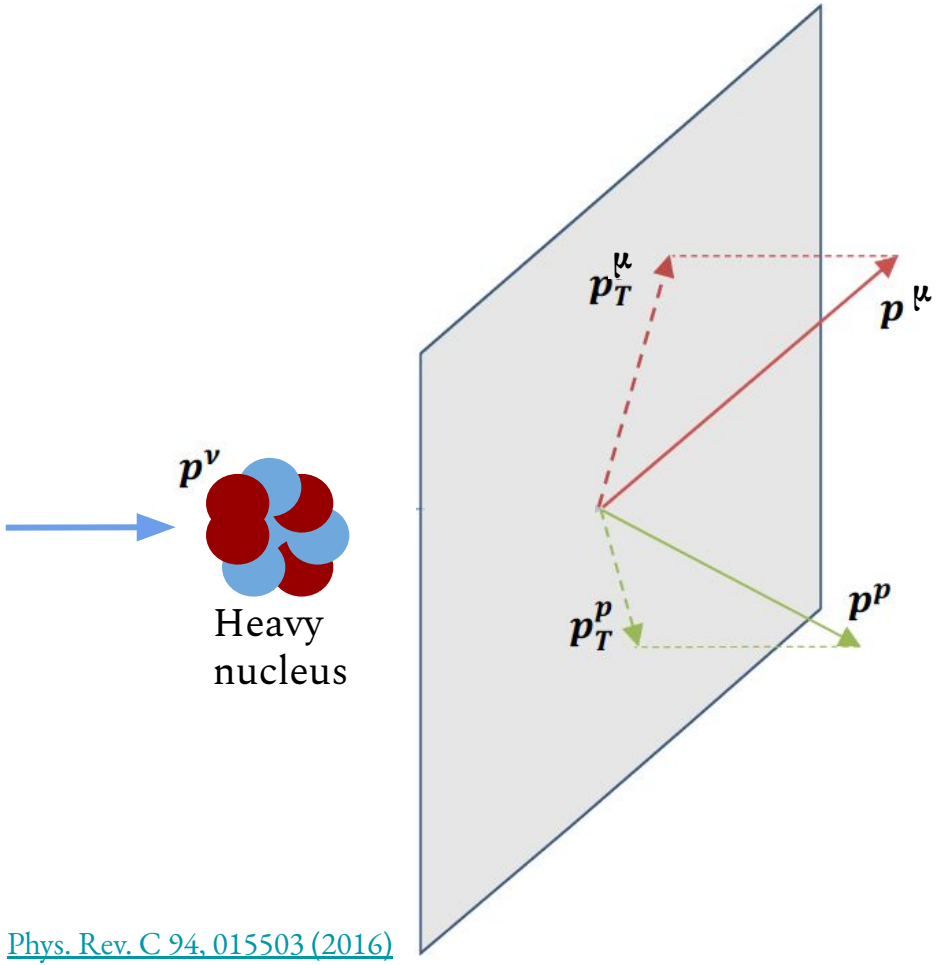
Transverse missing momentum
$\delta p_T = | \mathbf{p}_T^{\mu} + \mathbf{p}_T^{p} | = 0$

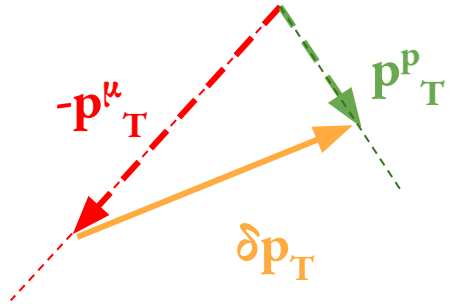
Transverse projections equal and opposite due to momentum conservation

Incoming neutrino energy independent

Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)





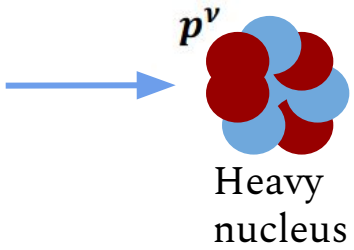
Transverse missing momentum
$\delta p_T = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} | > 0$

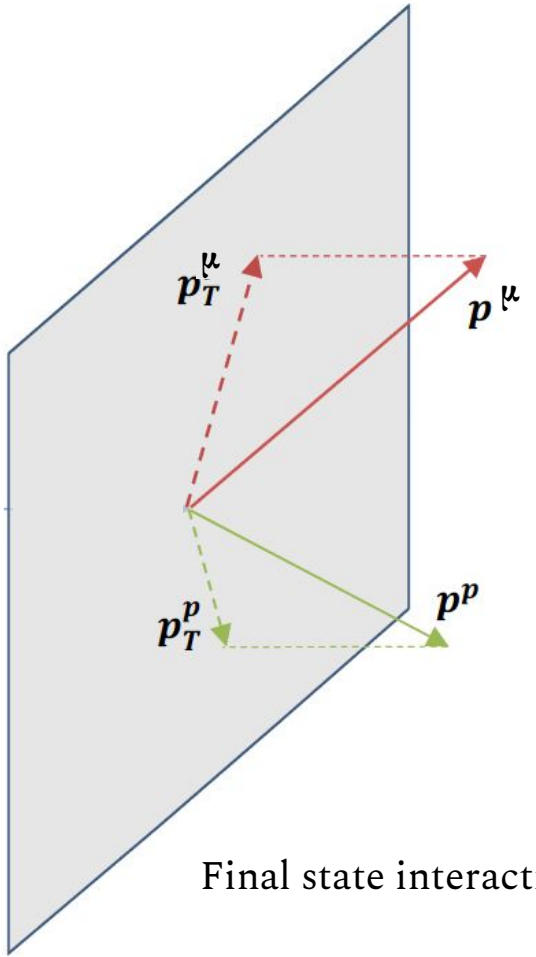
Broad distribution due to initial nucleon motion and other nuclear effects

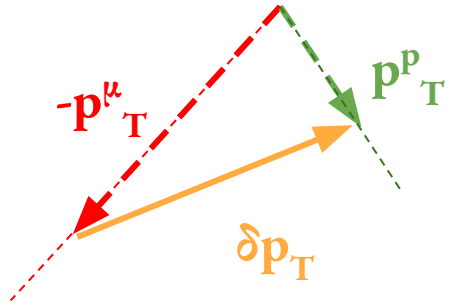
Incoming neutrino energy independent

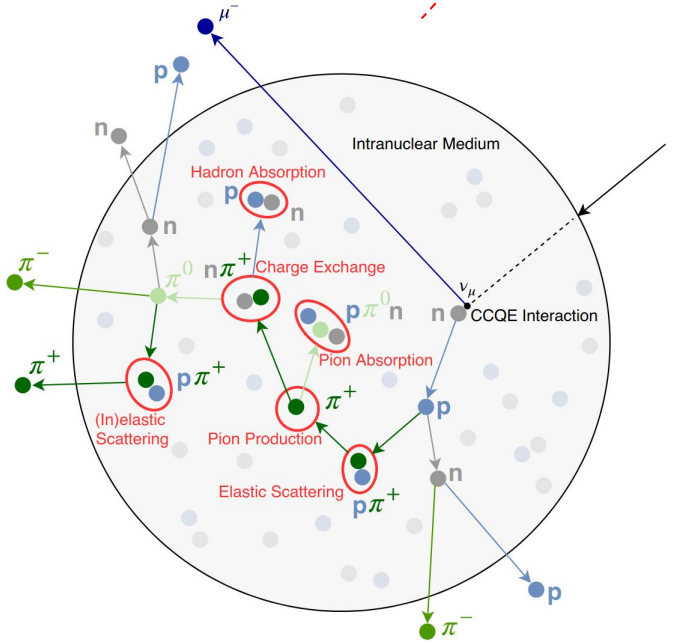
Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)







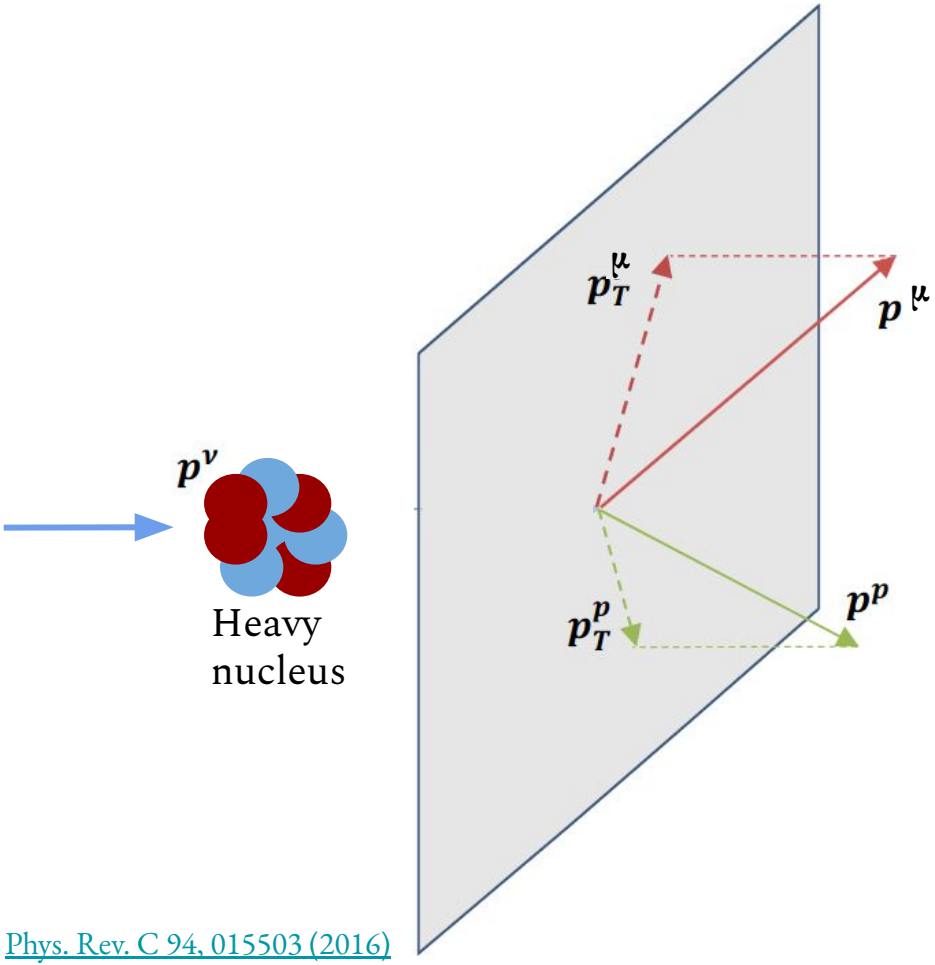


Final state interactions (FSI)

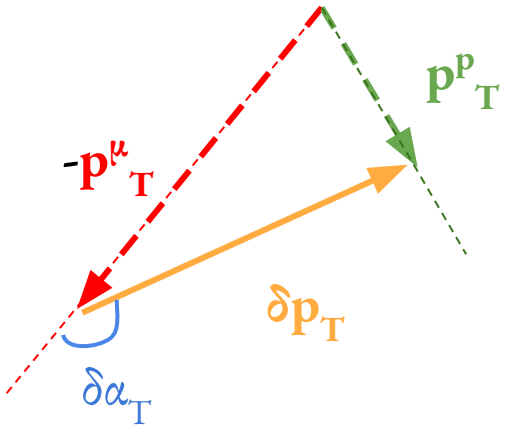
[Phys. Rev. C 94, 015503 (2016)]

[arXiv:2201.04664]

Transverse Kinematic Imbalance (TKI)

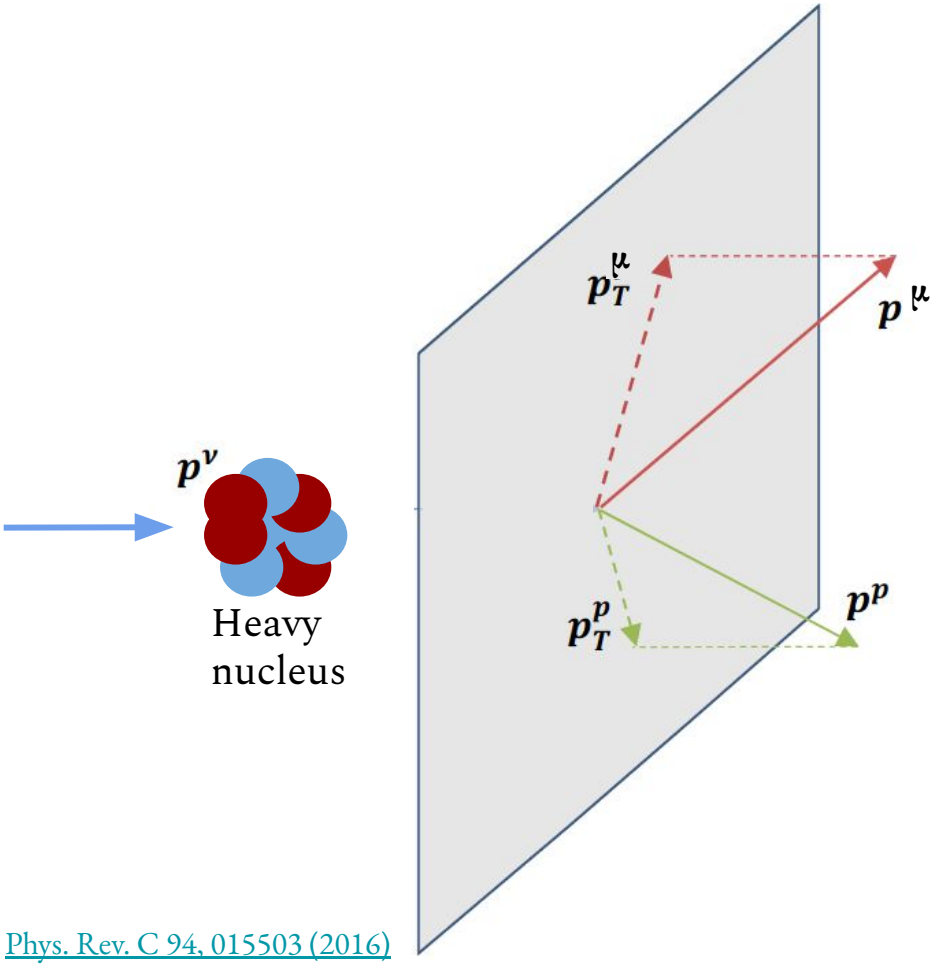


Orientation of the imbalance ($\delta\alpha_T$) also meaningful

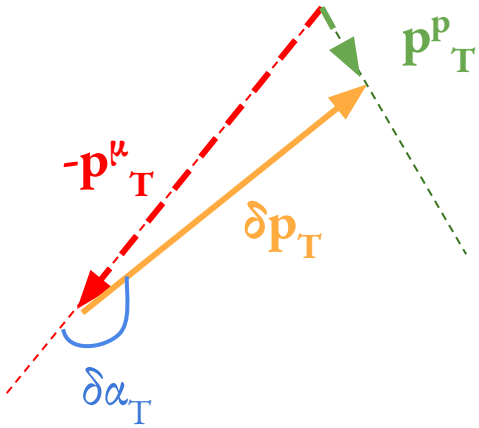


Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)

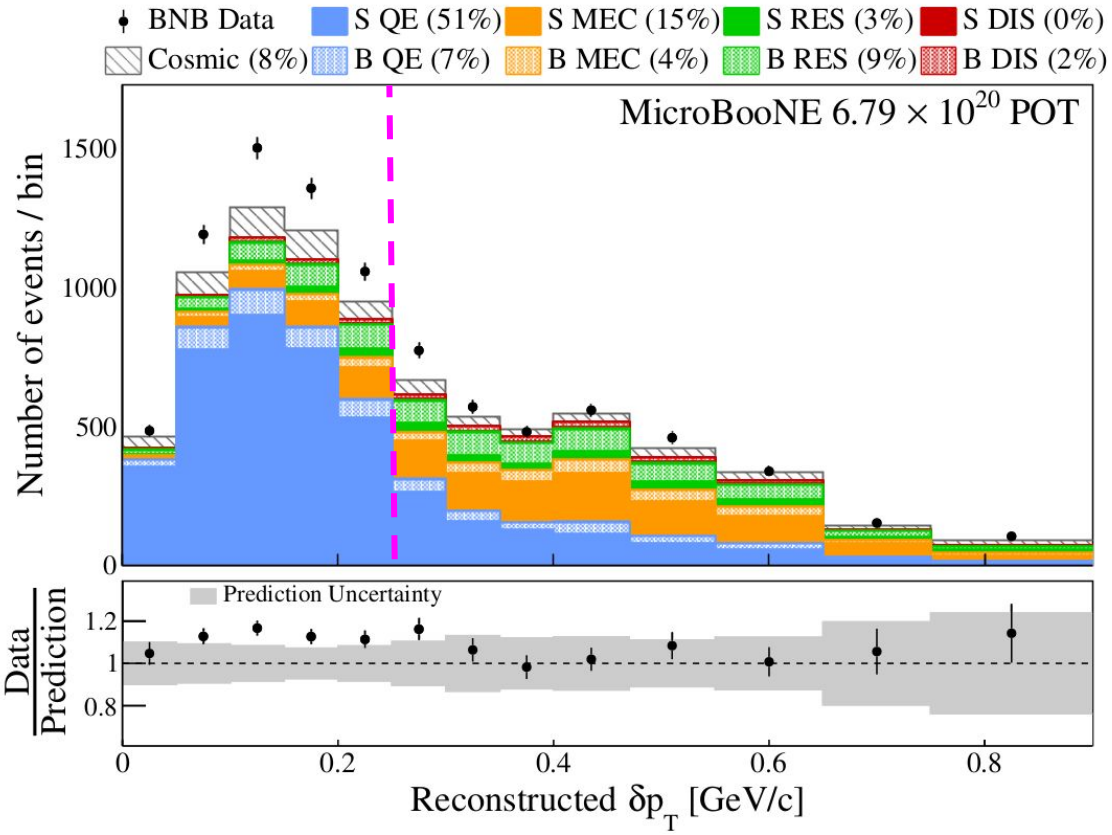


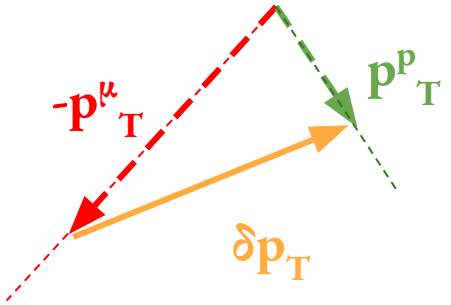
Lower proton momentum due to FSI leads to larger $\delta\alpha_T$ (closer to 180°)



Phys. Rev. C 94, 015503 (2016)

Transverse Missing Momentum δp_T





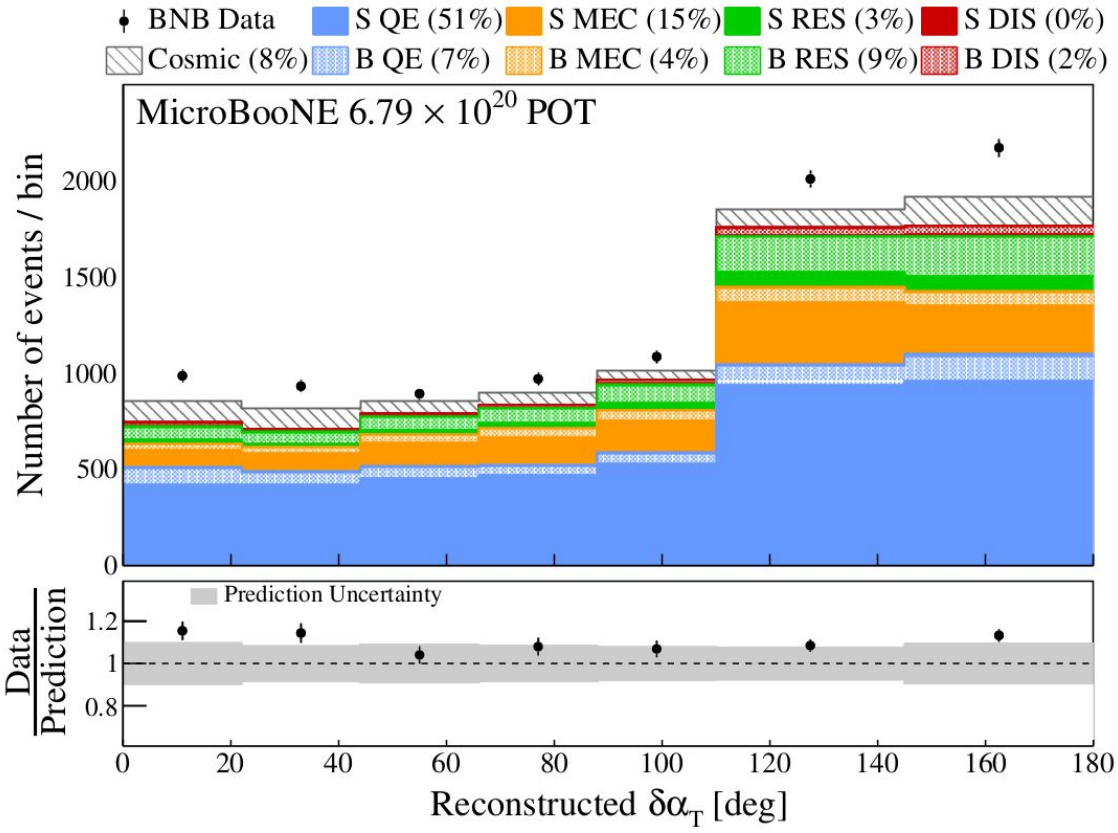
- S = Signal, B = Background
- **QE** dominance in peak below Fermi momentum (~250 MeV/c)
- **MEC**/**RES** mainly in high momentum tail

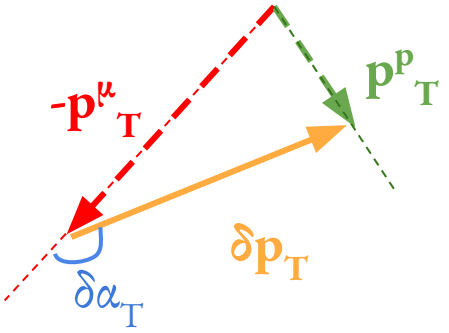
[Phys. Rev. D 108, 053002 (2023)]

* [Phys. Rev. D 105, 072001 (2022)]

GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

Transverse Orientation $\delta\alpha_T$





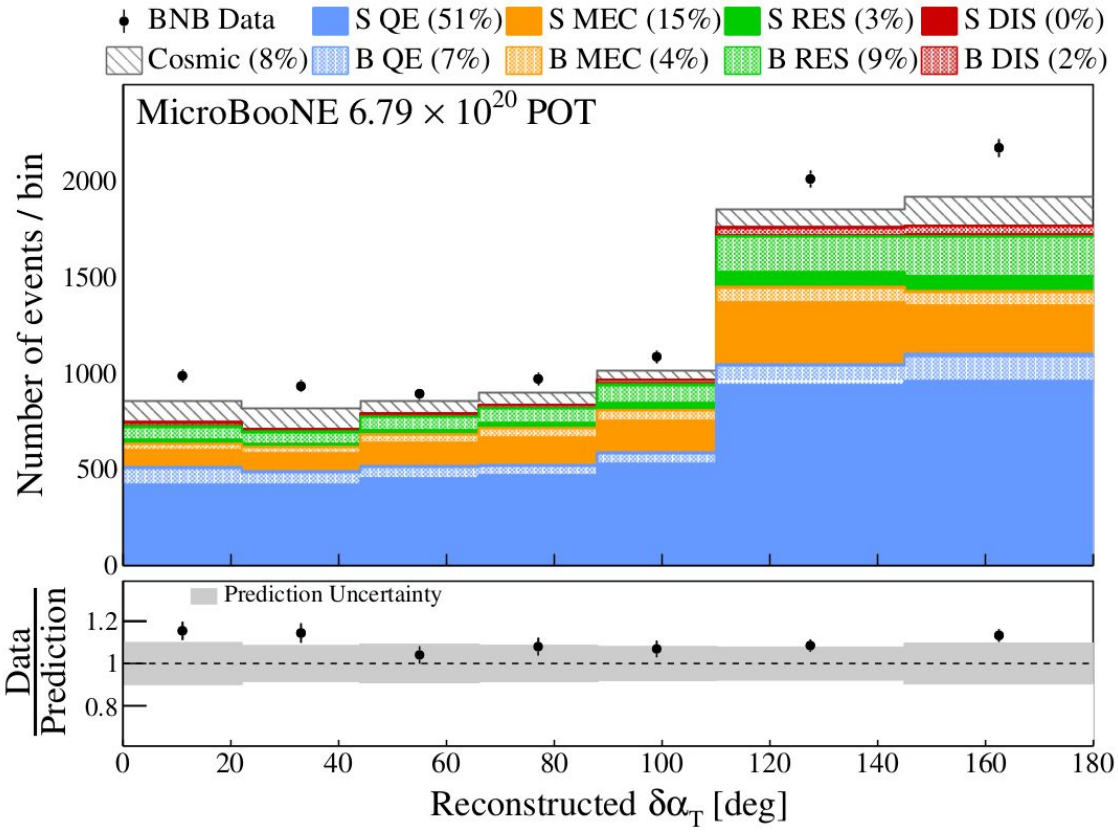
- $\delta\alpha_T$ asymmetry due to proton FSI
- **MEC**/**RES** fractional contribution enhanced in ~180° region

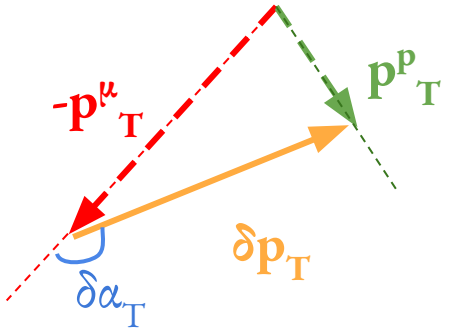
Phys. Rev. D 108, 053002 (2023)

* Phys. Rev. D 105, 072001 (2022)

GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

Transverse Orientation $\delta\alpha_T$

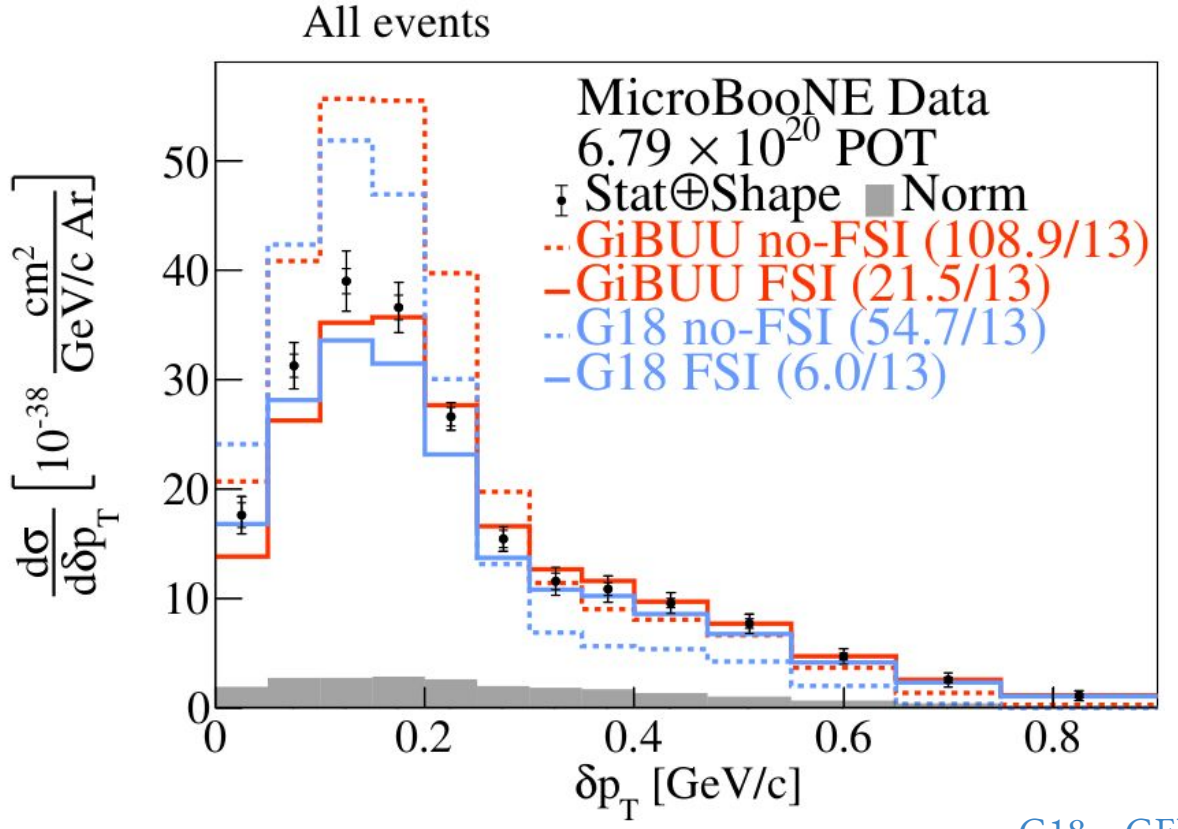


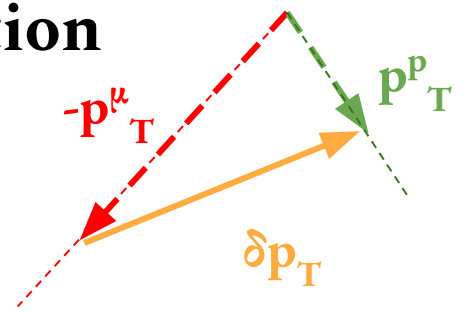


Need to move from event distributions to cross sections→ *unfolding*
More details in backup slides

Phys. Rev. D 108, 053002 (2023)
* Phys. Rev. D 105, 072001 (2022)

Transverse Missing Momentum δp_T Cross Section





- First neutrino-argon differential cross section in δp_T
- FSI reduces strength of the peak
- Small changes in the tail
- Data favors FSI addition

Phys. Rev. Lett. 131, 101802 (2023)

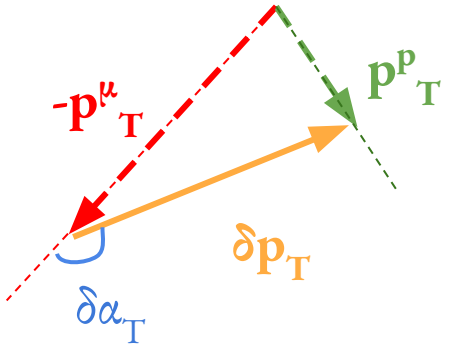
* Phys. Rev. D 105, 072001 (2022)

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

GiBUU = GiBUU 2021

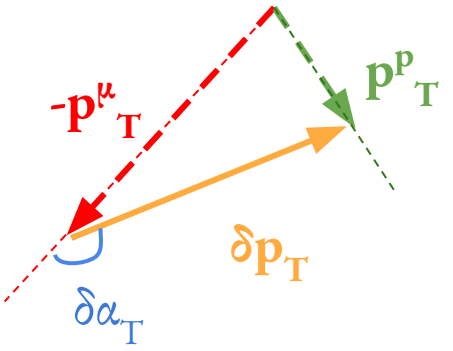
High Statistics→Into the Multiverse!

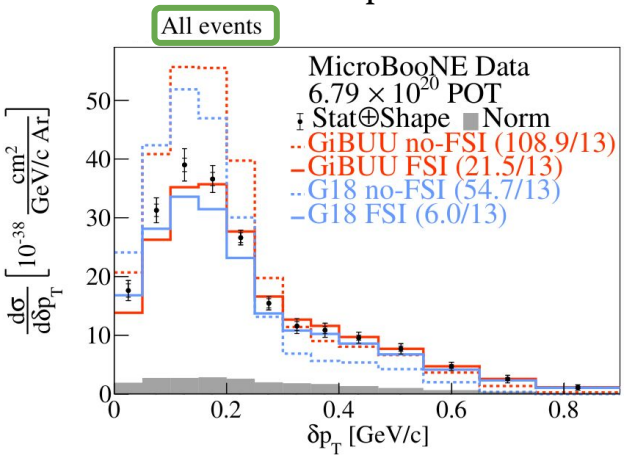
- **Extension to 2D** for the first time on argon
- Probe regions with greater model discrimination power



High Statistics→Into the Multiverse!

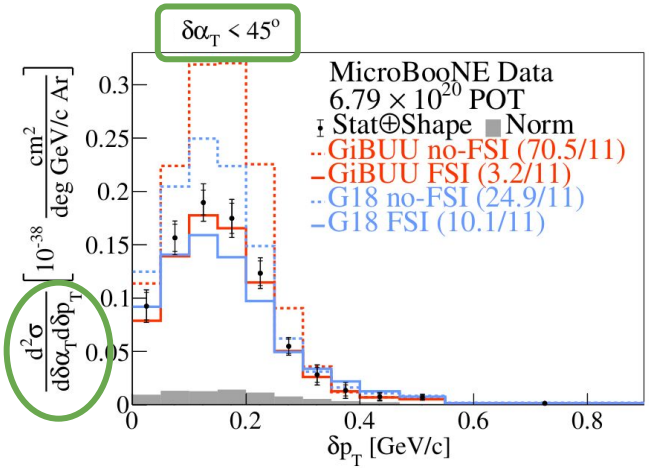
- **Extension to 2D** for the first time on argon
- Probe regions with greater model discrimination power

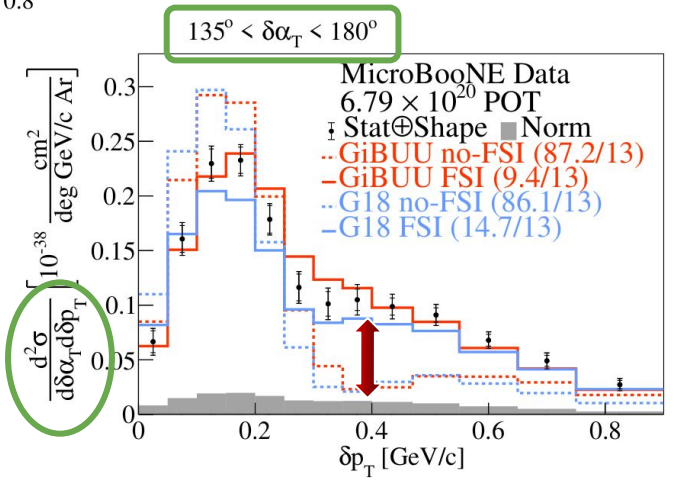




QE-dominated

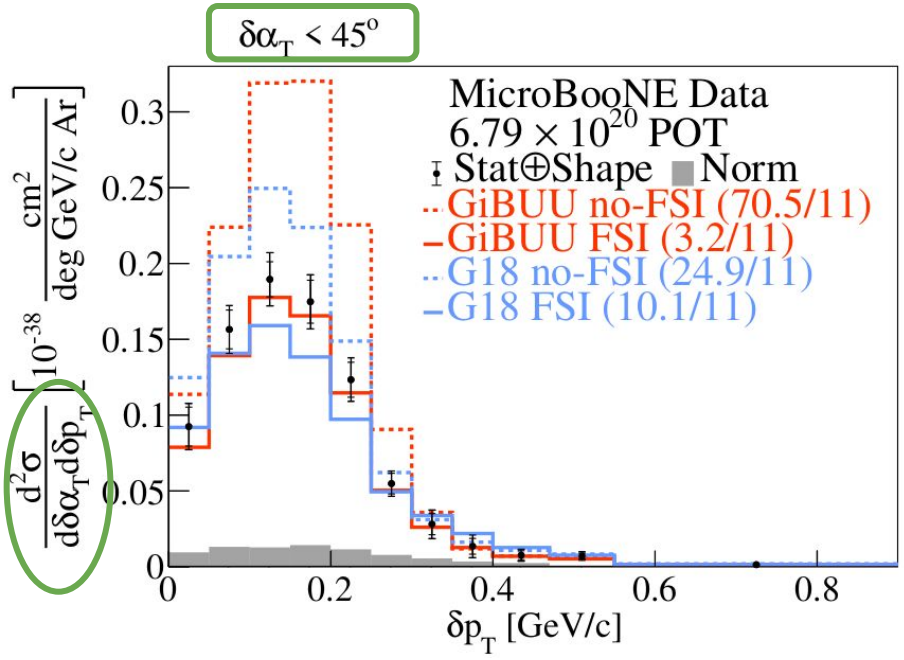
MEC/RES/FSI-dominated

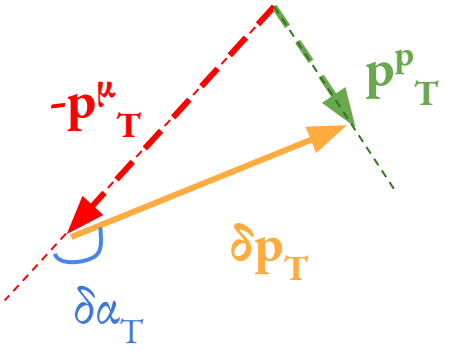




High Statistics→Into the Multiverse!

QE-dominated region





- Addition of FSI reduces peak strength
- No high transverse missing momentum tail
- Ideal part of phase-space to study Fermi motion
- Results consistent with local Fermi gas distribution

Phys. Rev. Lett. 131, 101802 (2023)

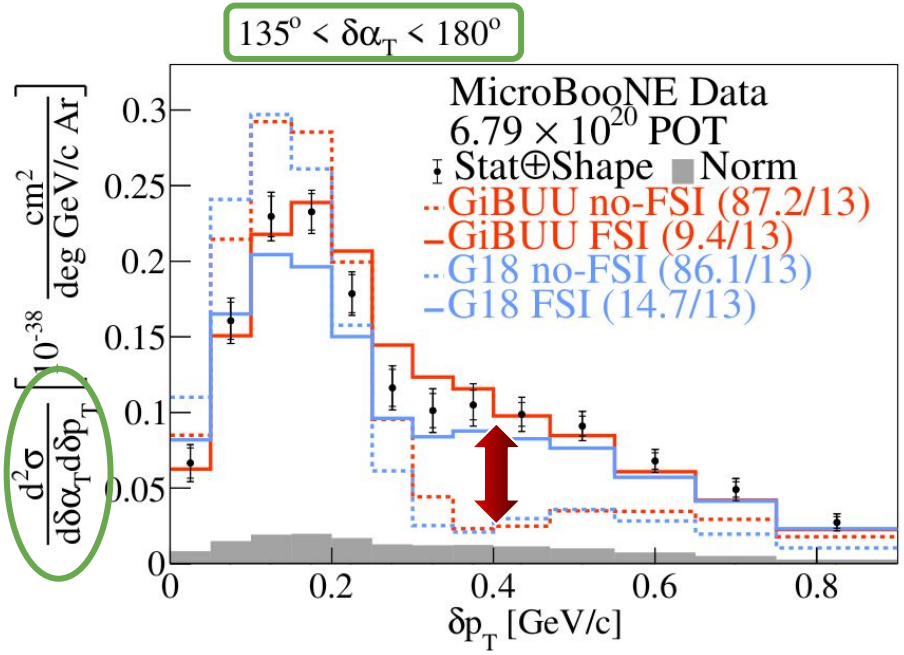
* Phys. Rev. D 105, 072001 (2022)

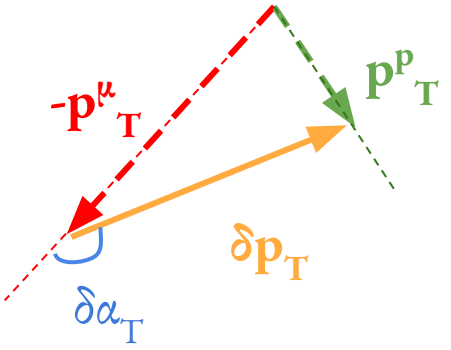
G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

GiBUU = GiBUU 2021

High Statistics→Into the Multiverse!

MEC/RES/FSI-dominated





- FSI predictions in good agreement with data
- Minimal no-FSI contributions at high δp_T
- High $\delta\alpha_T$ & high δp_T part of phase-space ideal to test FSI / multinucleon effects

Phys. Rev. Lett. 131, 101802 (2023)

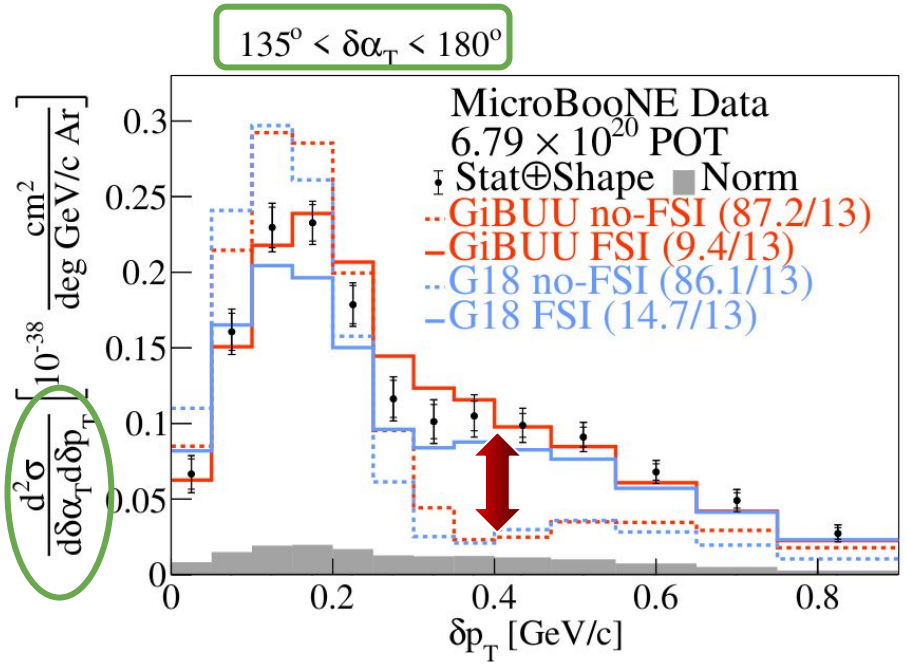
* Phys. Rev. D 105, 072001 (2022)

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

GiBUU = GiBUU 2021

CC1p0π TKI Summary

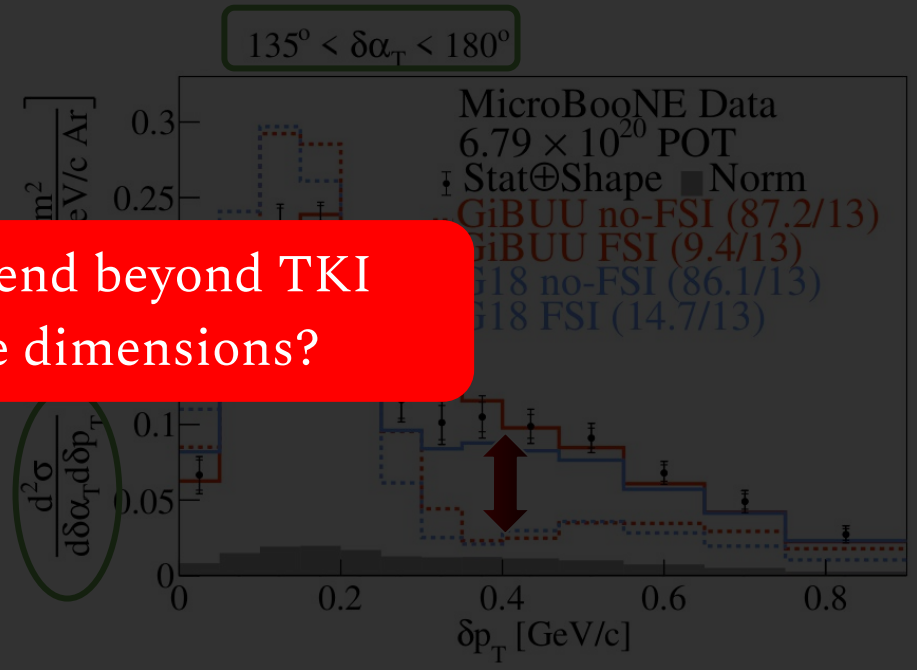
- First single- and double- differential neutrino-argon cross section measurements in TKI
- Fermi motion studied with 2D measurement in δp_T with $\delta\alpha_T < 45^o$
- FSI & multinucleon effects studied with 2D measurement in δp_T with $135^o < \delta\alpha_T < 180^o$
- Way more single- and double-differential results in Phys. Rev. Lett. 131, 101802 (2023) and Phys. Rev. D 108, 053002 (2023)!



CC1p0π TKI Summary

- First single- and double- differential neutrino-argon cross section measurements in TKI
- Fermi motion studied w
  in δp_T with $\delta\alpha_T < 45^\circ$
- FSI & multinucleon effects studied with 2D measurement in δp_T with $135^\circ < \delta\alpha_T < 180^\circ$
- Way more single- and double-differential results in Phys. Rev. Lett. 131, 101802 (2023) and Phys. Rev. D 108, 053002 (2023)!

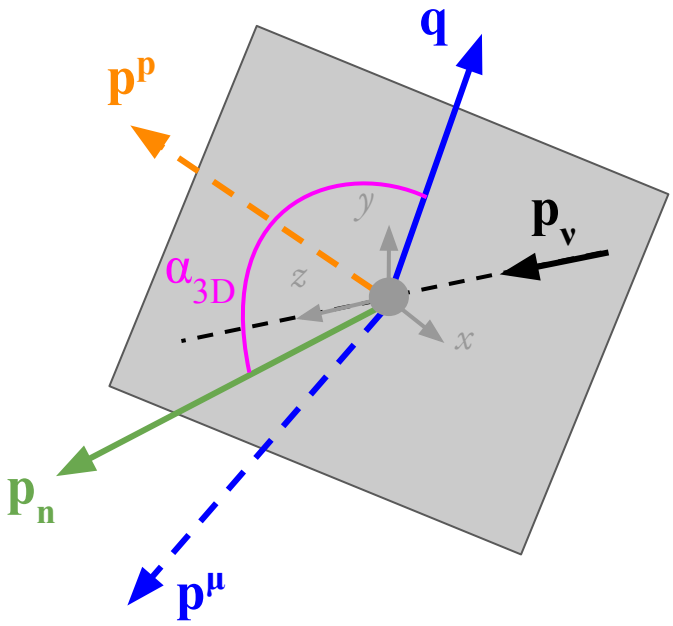
But why not extend beyond TKI by using three dimensions?



Generalized Kinematic Imbalance (GKI)

Phys. Rev. C 95, 065501 (2017)
arXiv:2310.06082

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy

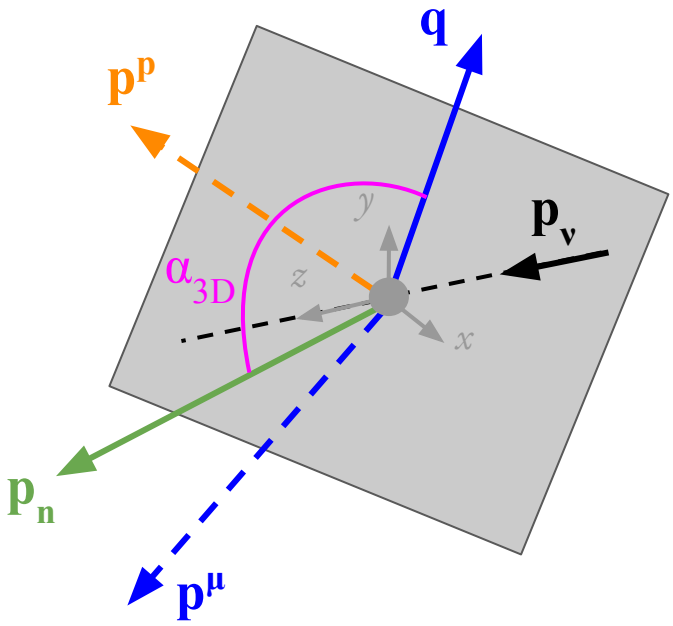


Generalized Kinematic Imbalance (GKI)

Phys. Rev. C 95, 065501 (2017)
arXiv:2310.06082

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy

BE = 30.9 MeV



$$E_{\text{cal}} = E_\mu + K_p + B$$

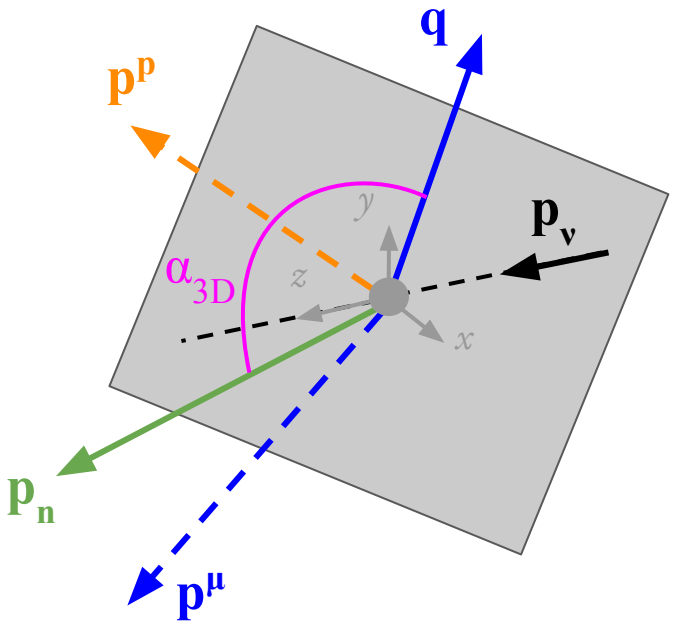
$$p_L = p_L^\mu + p_L^p - E_{\text{cal}}$$

$$\vec{q} = E_{\text{cal}}\hat{z} - \vec{p}_\mu$$

Generalized Kinematic Imbalance (GKI)

Phys. Rev. C 95, 065501 (2017)
arXiv:2310.06082

- Extension to 3D by considering longitudinal component of missing momentum and calorimetric assumption on the incoming energy
- Extensively tested again several event generators and model configurations

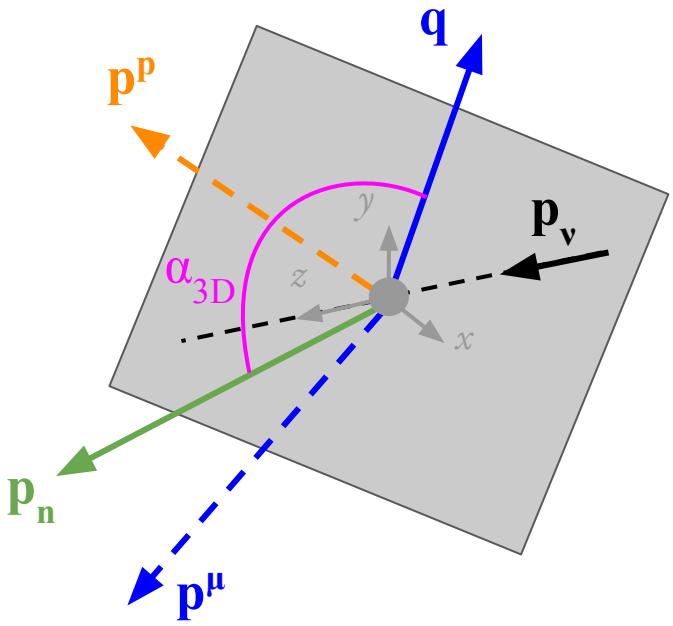


Name	Generator / Configuration
Gv2	GENIE v2.12.10
G18	GENIE v3.0.6 G18_10a_02_11a
G18T	G18 with tune
G21	GENIE v3.2.0 G21_11b_00_000
GiBUU	GiBUU 2021
NuWro	NuWro v19.02.1
NEUT	NEUT v5.4.0

Generalized Kinematic Imbalance (GKI)

Phys. Rev. C 95, 065501 (2017)
arXiv:2310.06082

- Extension to 3D by considering longitudinal component of missing moment and calorimetric assumption on the incoming energy
- Extensively tested again several event generators and model configurations



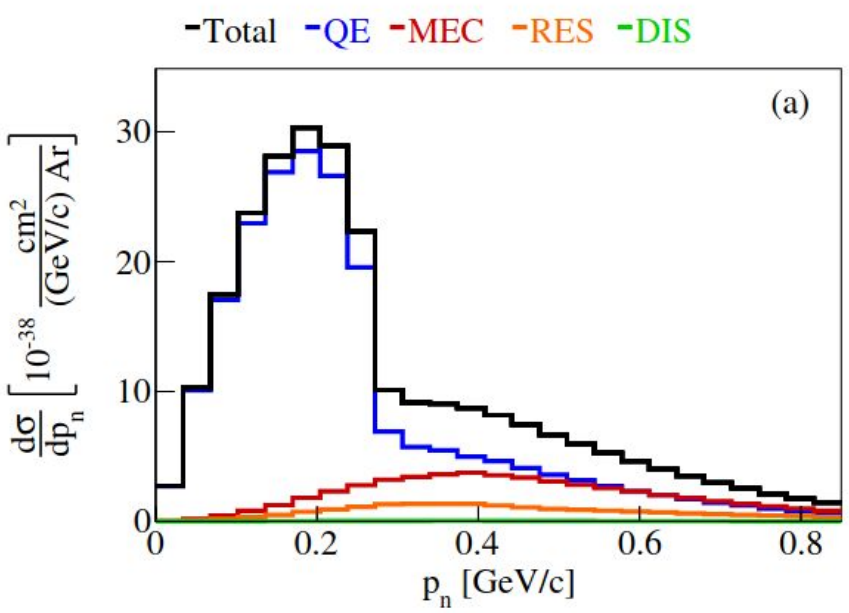
Name	Generator / Configuration
Gv2	GENIE v2.12.10
G18	GENIE v3.0.6 G18_10a_02_11a
G18T	G18 with tune
G21	GENIE v3.2.0 G21_11b_00_000
GiBUU	GiBUU 2021
NuWro	NuWro v19.02.1
NEUT	NEUT v5.4.0

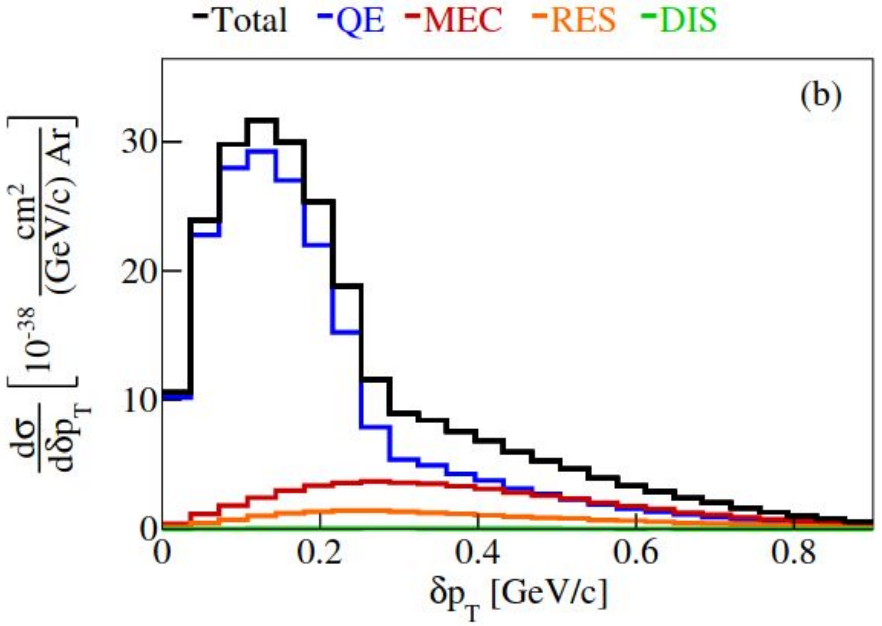
Selected comparisons shown next

Missing momentum

GENIE v3.0.6 G18_10a_02_11a

arXiv:2310.06082

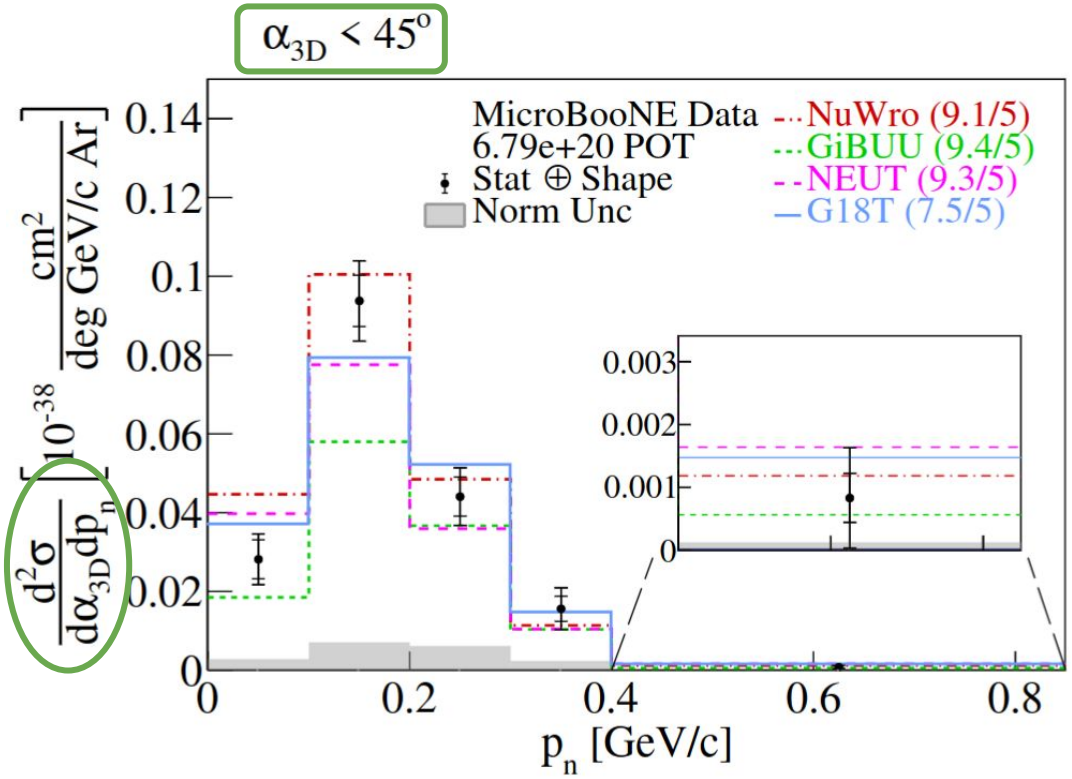




- If free nucleon, both variables would have been zero
- On Argon, broad distribution due to Fermi motion
- QE dominance due to CC1p0π signal definition
- p_n pushes non-QE component to higher values

Into the GKI multiverse!

QE-dominated region

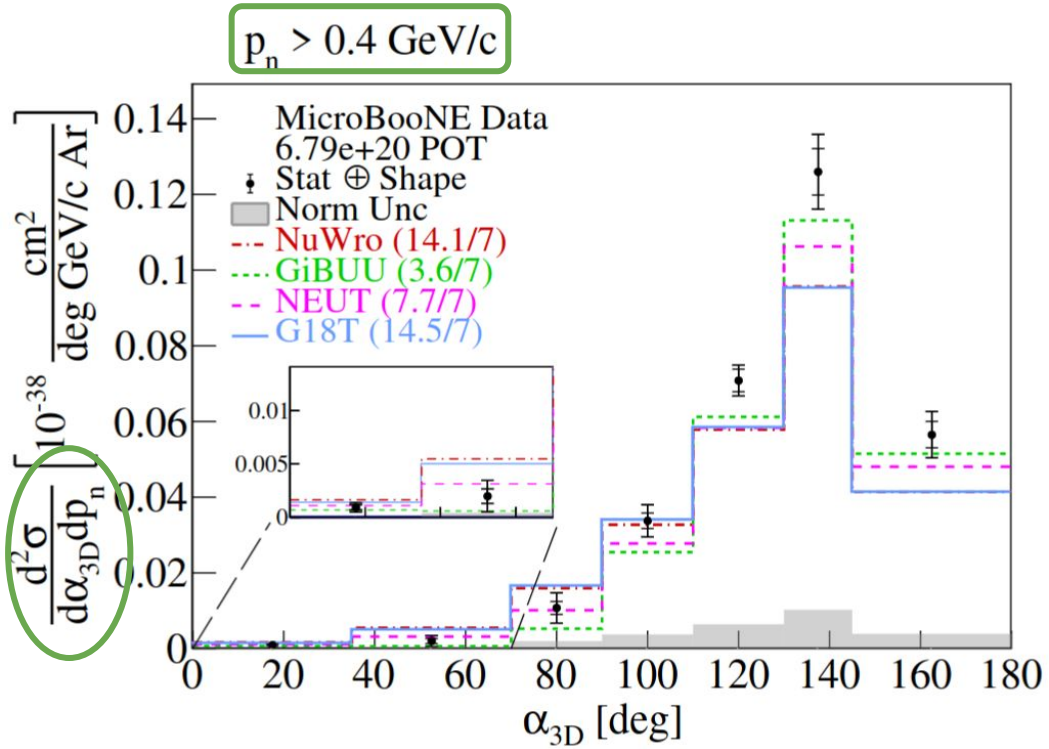


- Tail significantly suppressed
- Consistent with local Fermi gas
- G18T results in lowest χ^2

arXiv:2310.06082

Into the GKI multiverse!

MEC/RES/FSI-dominated

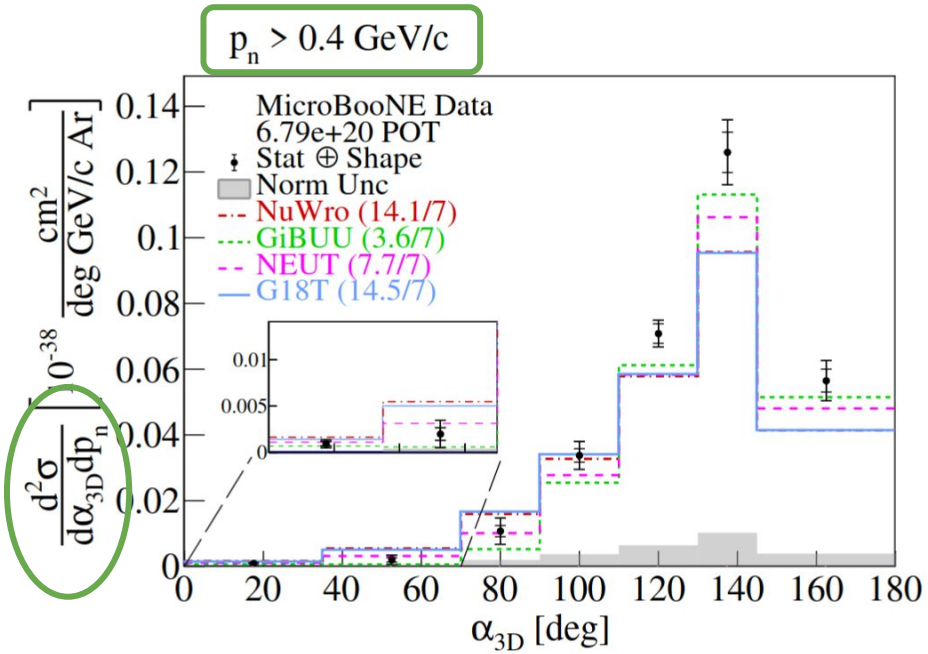


- Sharply peaked distribution to the right
- Driven by FSI
- GiBUU yields best result

arXiv:2310.06082

CC1p0π GKI Summary

- Introduction of generalized kinematic imbalance (GKI) variables in 3D space
- Enhanced sensitivity to nuclear effects
- First single- and double-differential cross section GKI measurement ever with MicroBooNE
- G18T results in good description in QE-dominated regions
- GiBUU yields best performance in FSI-dominated regions
- Way more results in arXiv:2310.06082!




μBooNE
Thank you!