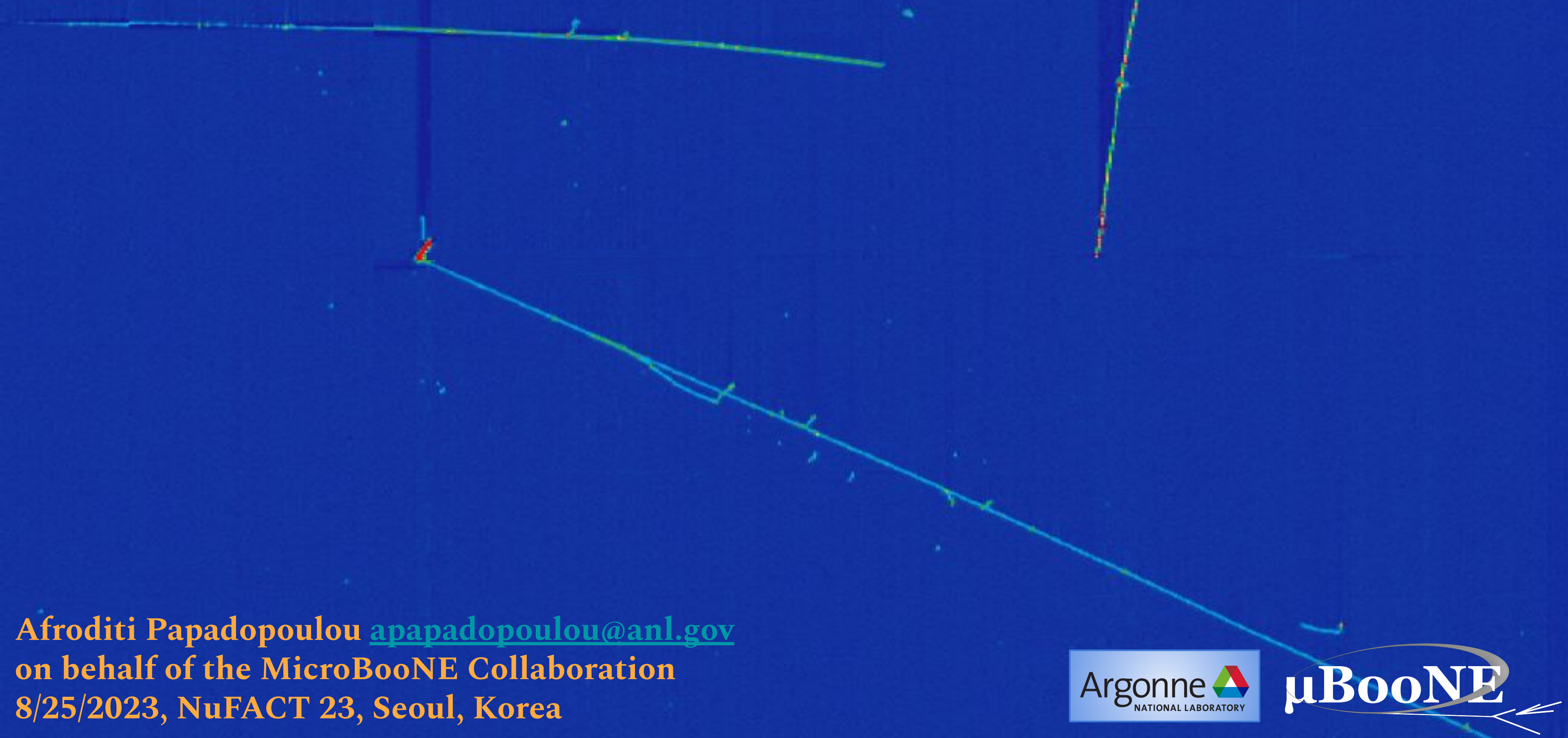
The MicroBooNE cross section program with a special focus on the transverse kinematic imbalance analysis

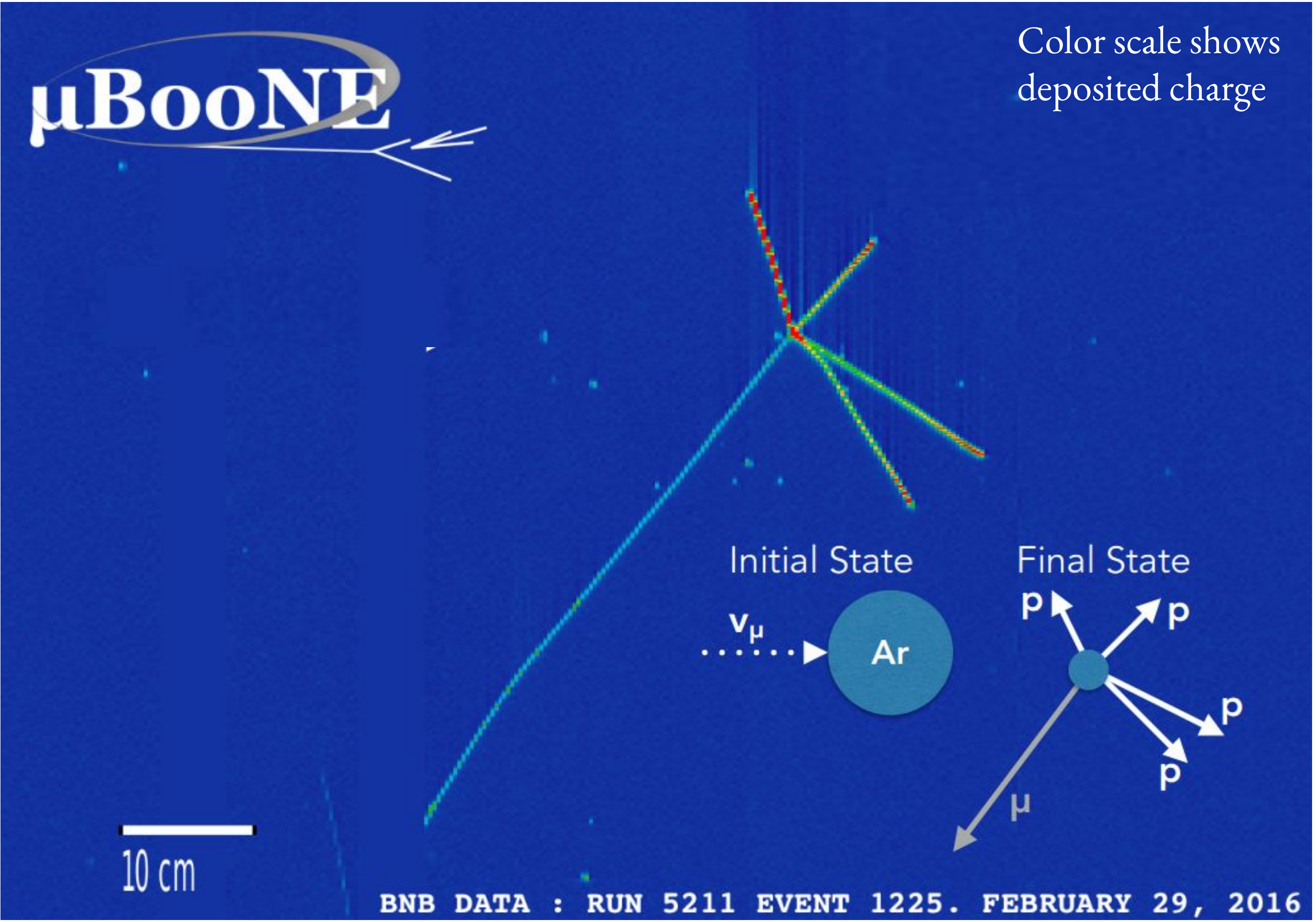


Afroditi Papadopoulou apapadopoulou@anl.gov
on behalf of the MicroBooNE Collaboration
8/25/2023, NuFACT 23, Seoul, Korea

Argonne NATIONAL LABORATORY

μBooNE

MicroBooNE Data Events



- Largest available neutrino-argon data set with ~500k recorded neutrino interactions
- Over 10 released and more than 30 active MicroBooNE cross section analyses
- Multiple topologies investigated

More details in Avinay, Lee & Meghna's talks

Already Public Results

CC inclusive

- 1D & 2D 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
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Pion production

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

CC0π

- 1D ν_e CCNp0π @ BNB
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  arXiv:2301.03706 (accepted to PRD)
  submitted to PRL & PRD
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Rare channels

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

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- 1D ν_μ CC inclusive @ BNB
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  Phys. Rev.
  Phys. Rev.

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  arXiv:2301.03700, arXiv:2301.03706
  submitted to PRL & PRD

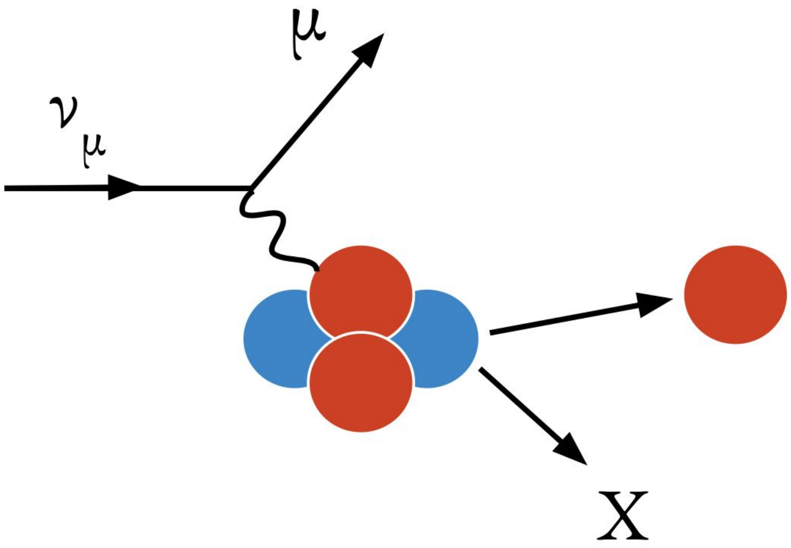
Phys. Rev. D102, 112013 (2020)

Rare channels

- η production @ BNB
  arXiv:2305.16249
- Hyperon (Λ,Σ) production @ NuMI
  arXiv:2212.07888, accepted to PRL

Opportunity to extensively benchmark neutrino event generator cross section predictions necessary for precision measurements

Double-Differential Single-Proton Knockout



- First double-differential single-proton cross section measurement on argon
- Targeting nuclear effects
- Identified kinematic variables and phase-space regions with sensitivity to Fermi motion & final state interactions

arXiv:2301.03700 (accepted to PRL)
arXiv:2301.03706 (accepted to PRD)

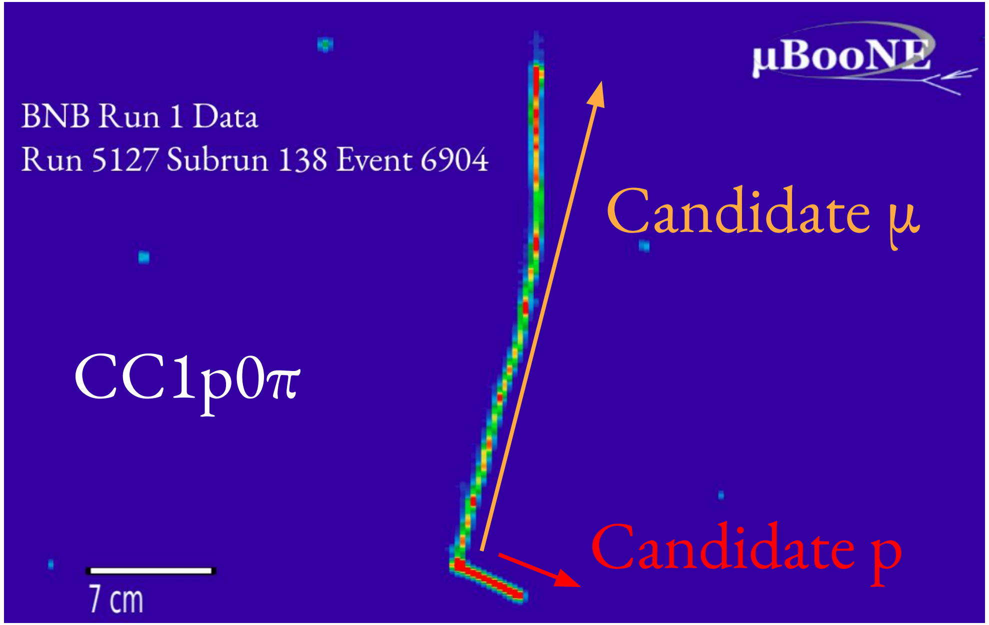
CC1p0π Quasielastic-like Signal Definition

- 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

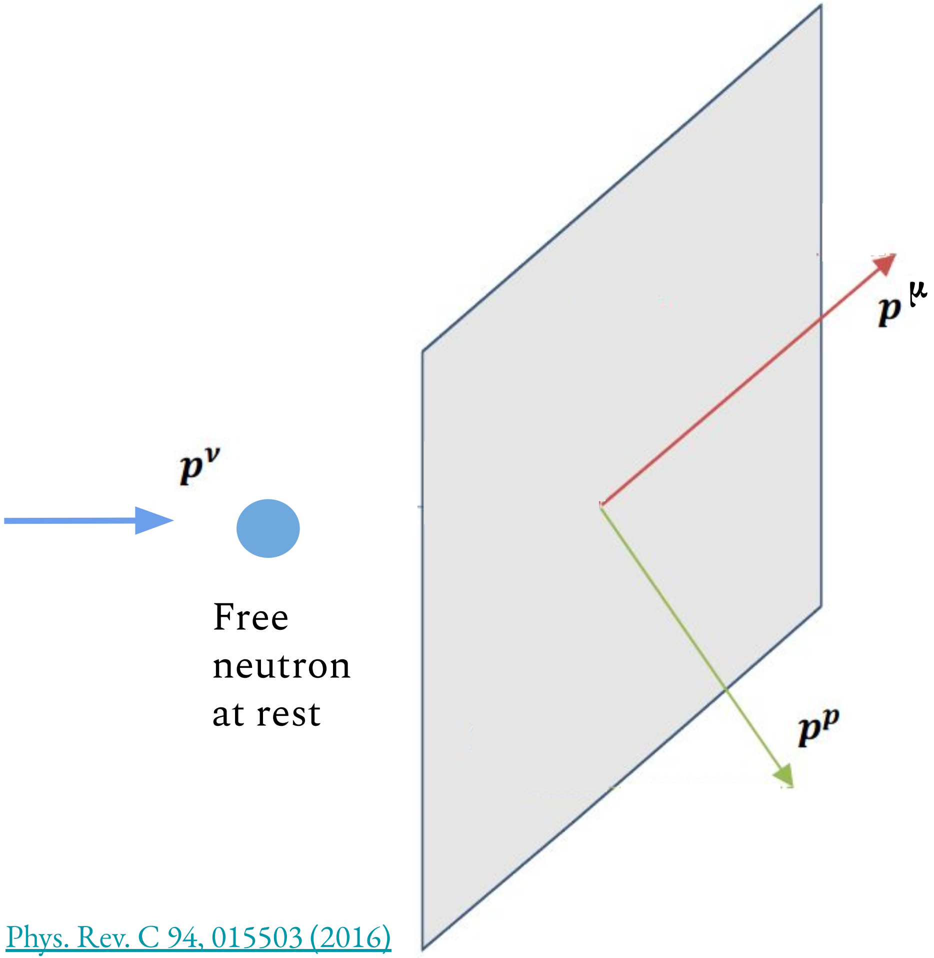
~70% purity



arXiv:2301.03706, arXiv:2301.03700
(accepted to PRL and PRD)
* Phys. Rev. D 105, 072001 (2022)

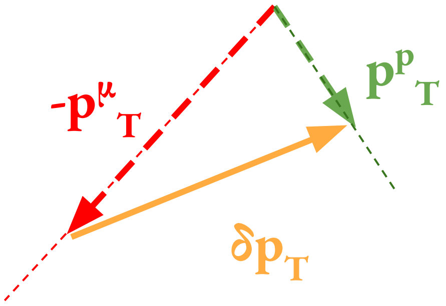
MC: GENIE v3.0.6 G18_10a_02_11b + tune*
Nieves QE & MEC, Berger Sehgal RES

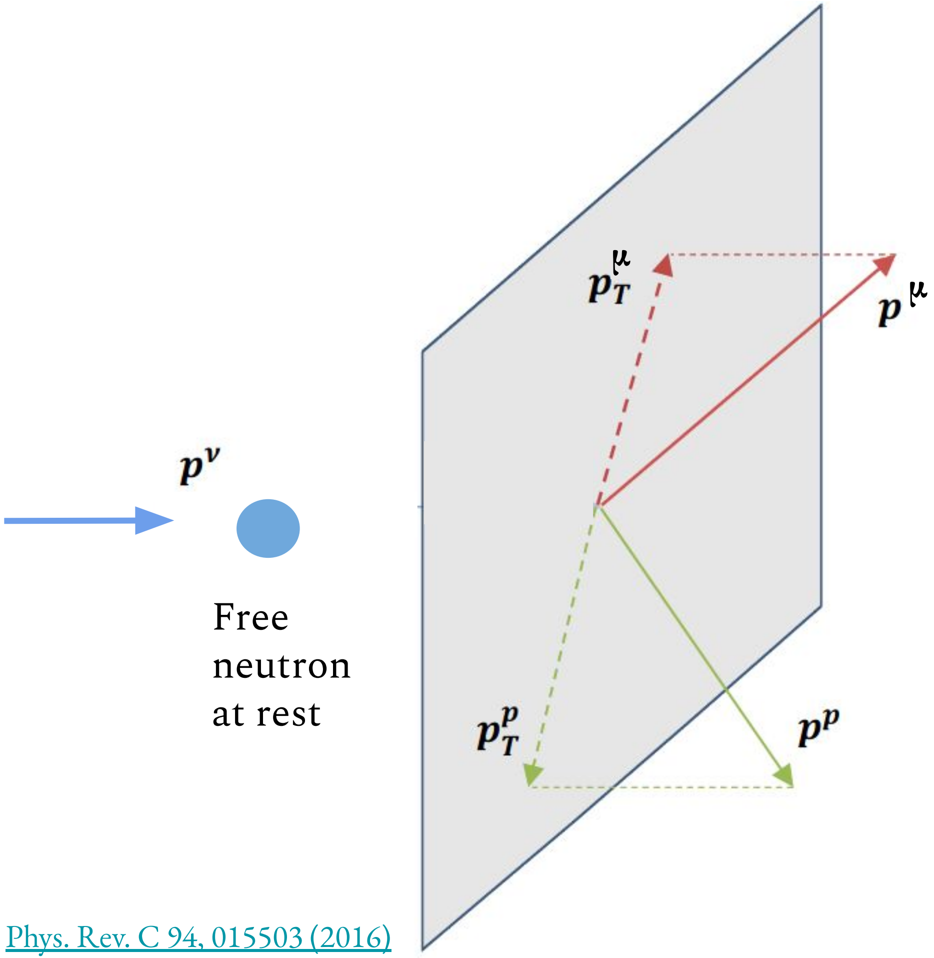
Transverse Kinematic Imbalance (TKI)



Phys. Rev. C 94, 015503 (2016)

Transverse Kinematic Imbalance (TKI)



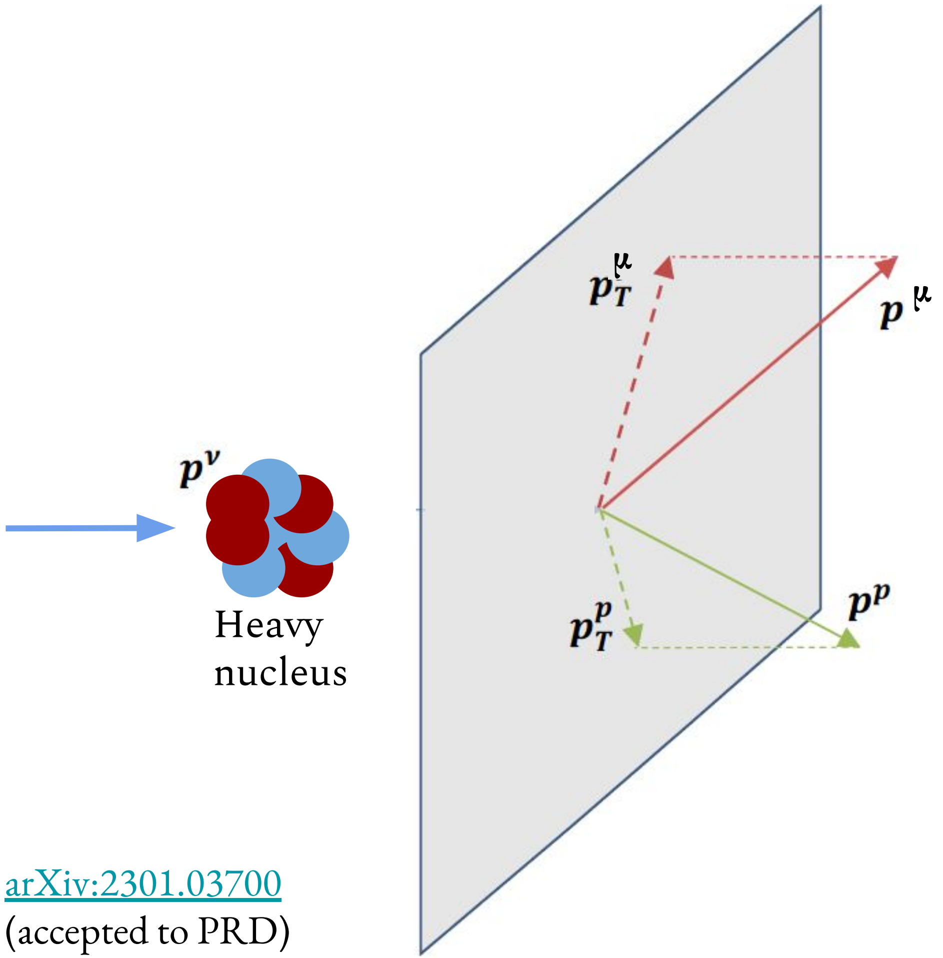


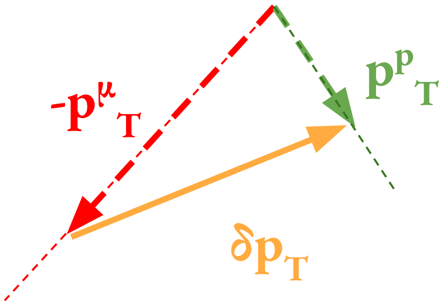
Transverse missing momentum
$\delta p_T = |\, \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} \,| = 0$

Transverse projections equal and opposite due to momentum conservation

Phys. Rev. C 94, 015503 (2016)

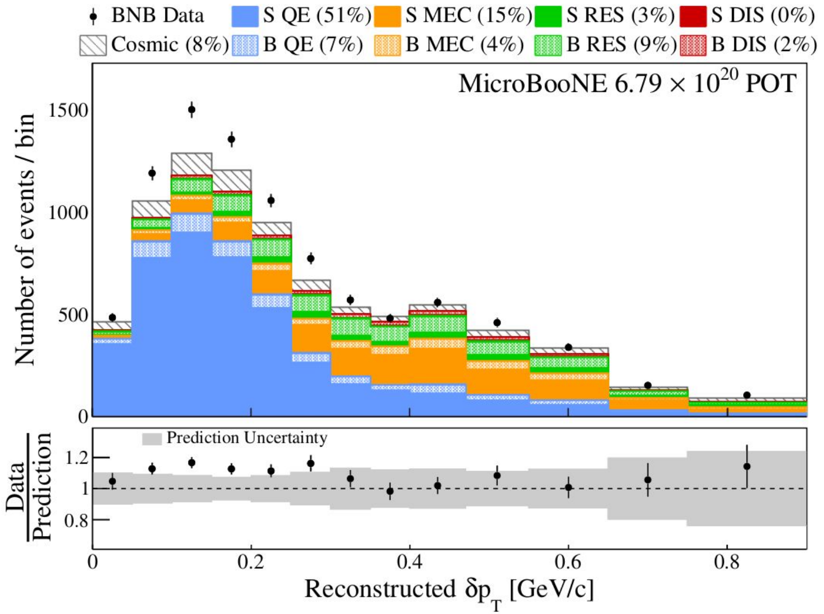
Transverse Kinematic Imbalance (TKI)





Transverse missing momentum

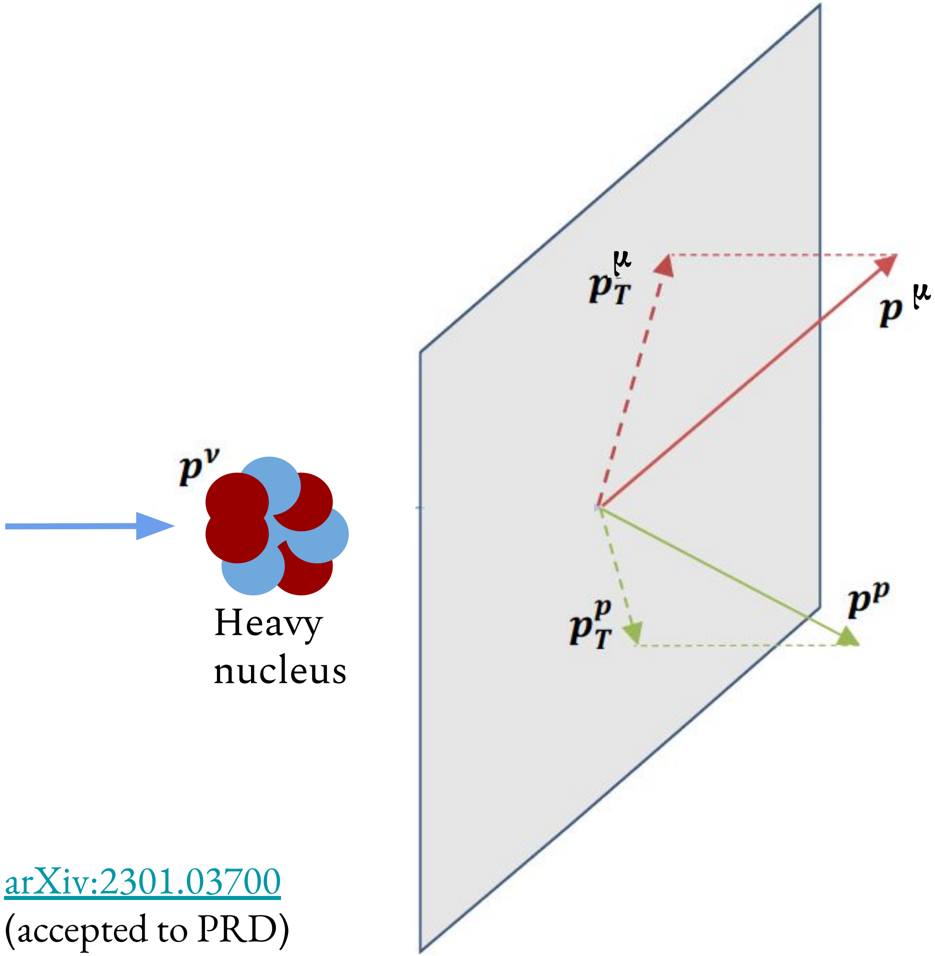
$\delta p_T = |\, \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} \,| > 0$

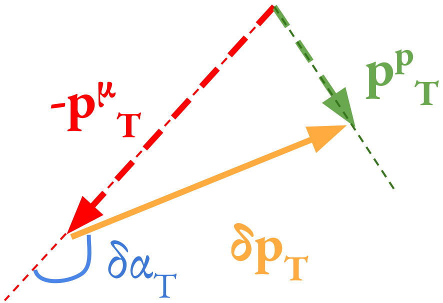


[arXiv:2301.03700](https://arxiv.org/abs/2301.03700)

(accepted to PRD)

Transverse Kinematic Imbalance (TKI)

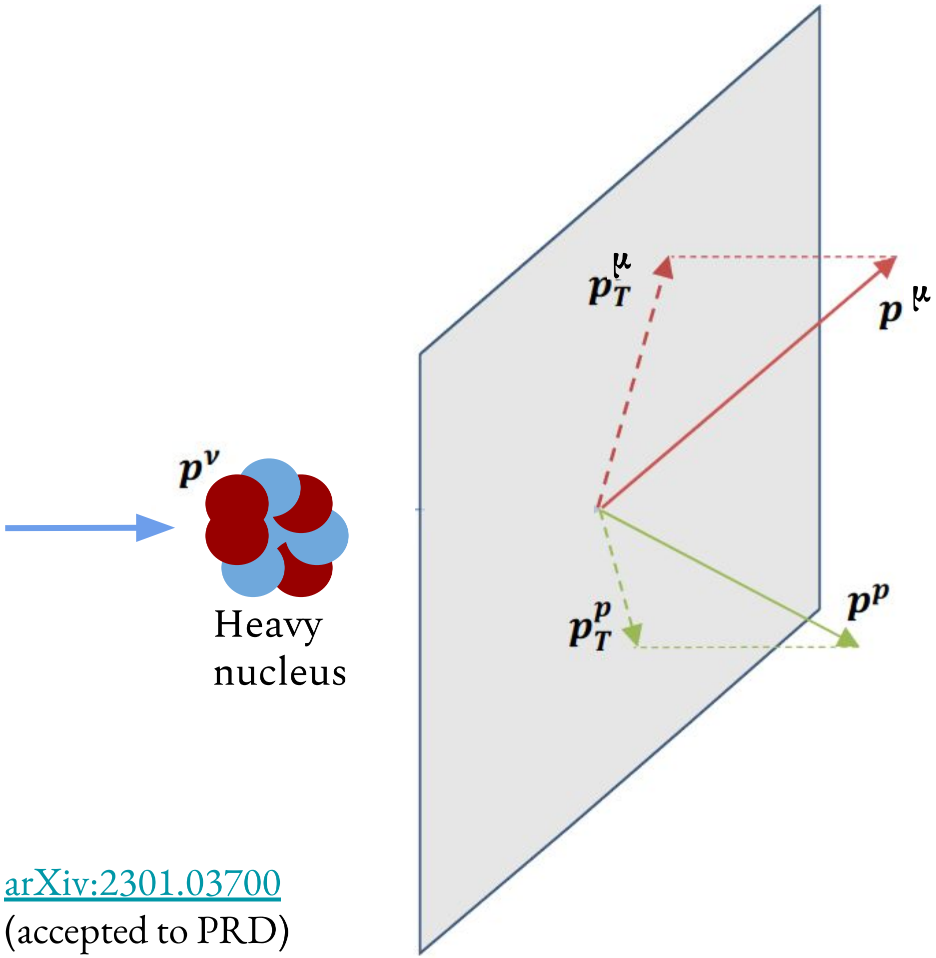


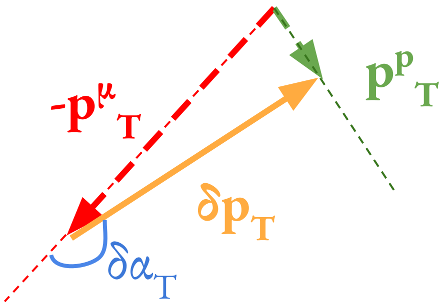


Orientation of the imbalance ($\delta\alpha_T$) also meaningful

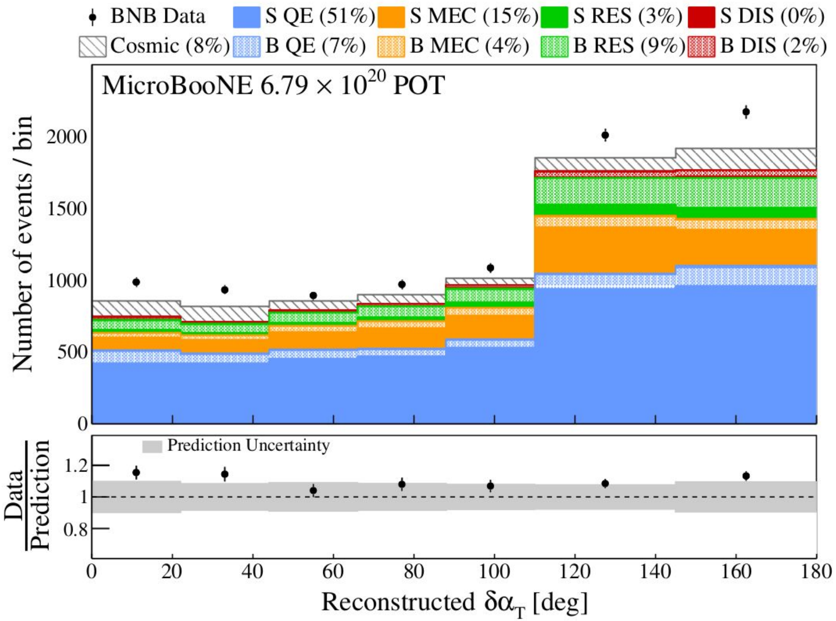
arXiv:2301.03700
(accepted to PRD)

Transverse Kinematic Imbalance (TKI)



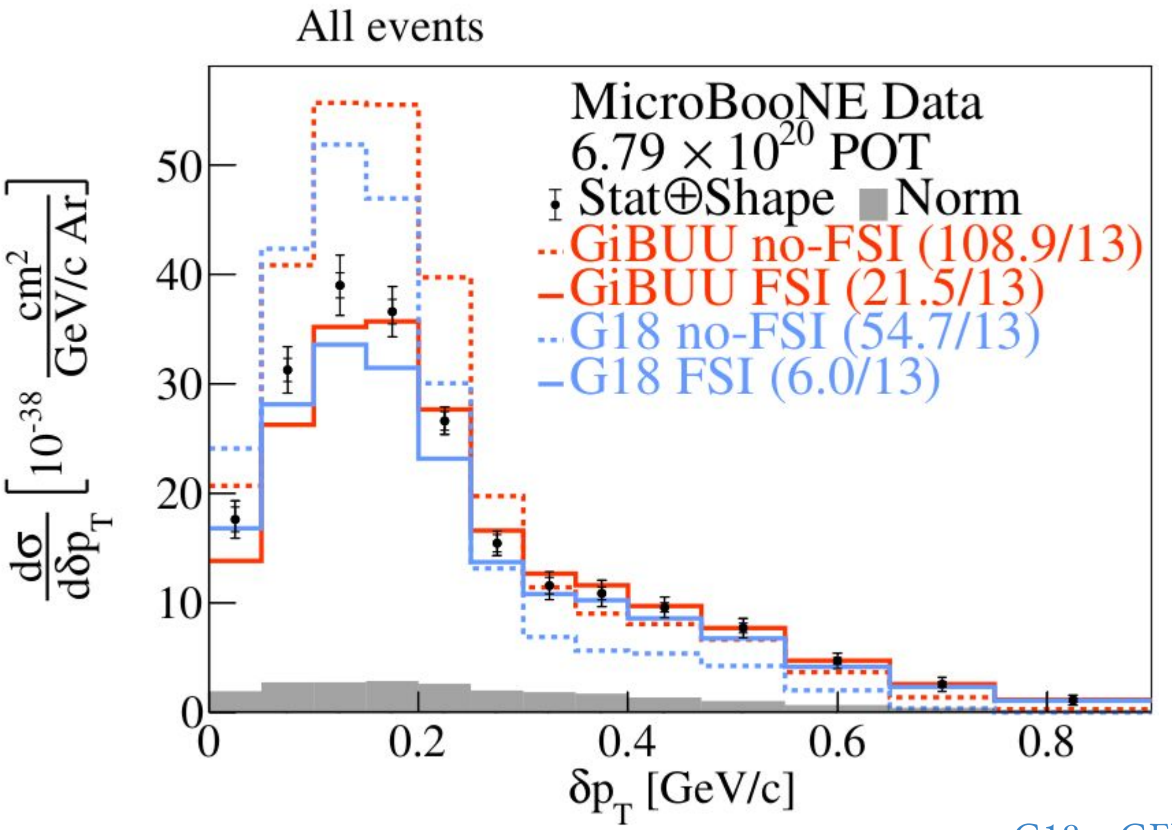


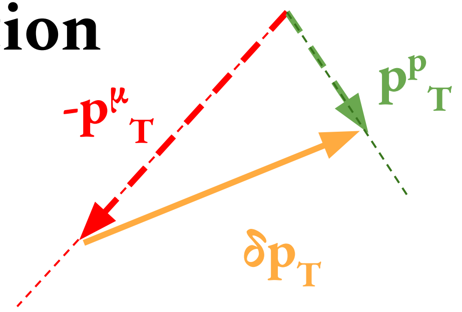
Lower proton momentum due to FSI leads to larger $\delta\alpha_T$ (closer to 180°)



arXiv:2301.03700
(accepted to PRD)

Transverse Missing Momentum δp_T Cross Section





- FSI reduces strength of the peak
- Small changes in the tail
- Data favors FSI addition

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

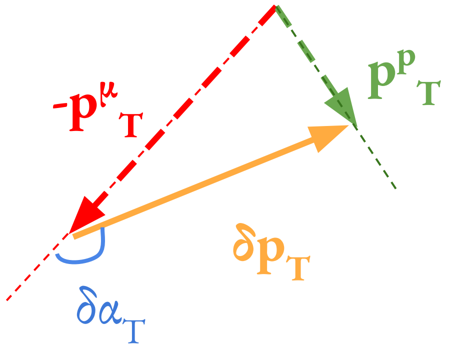
GiBUU = GiBUU 2021

arXiv:2301.03706 (accepted to PRL)

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

High Statistics→Into the Multiverse!

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



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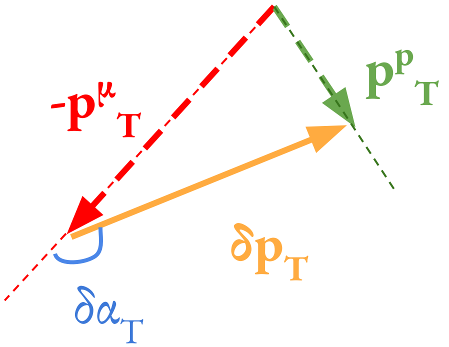
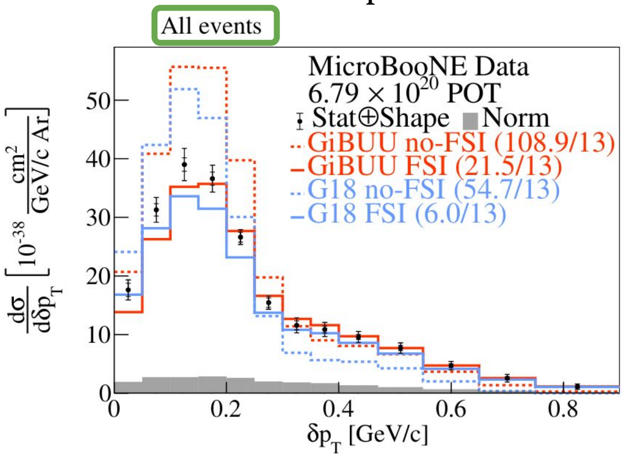
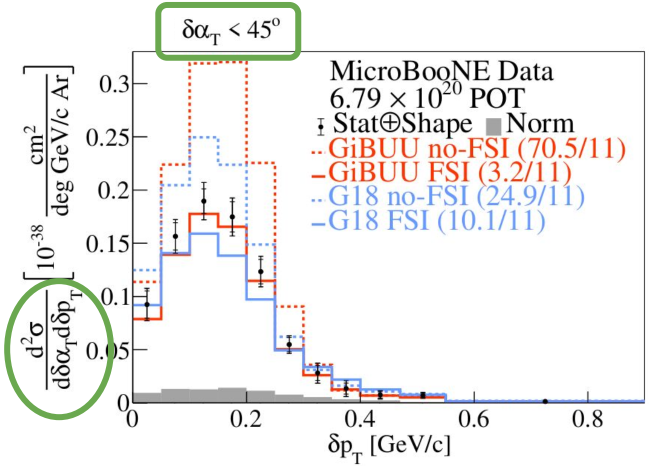
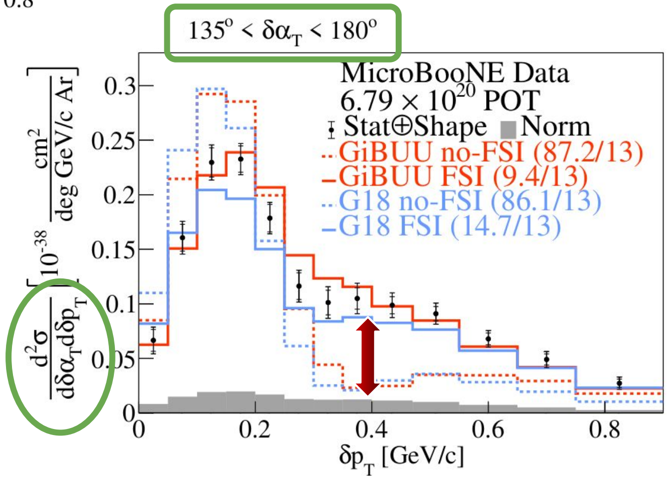




QE-dominated

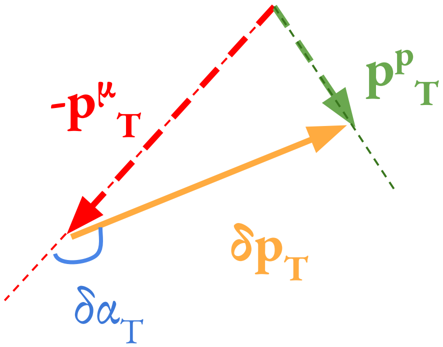
MEC/RES/FSI-dominated

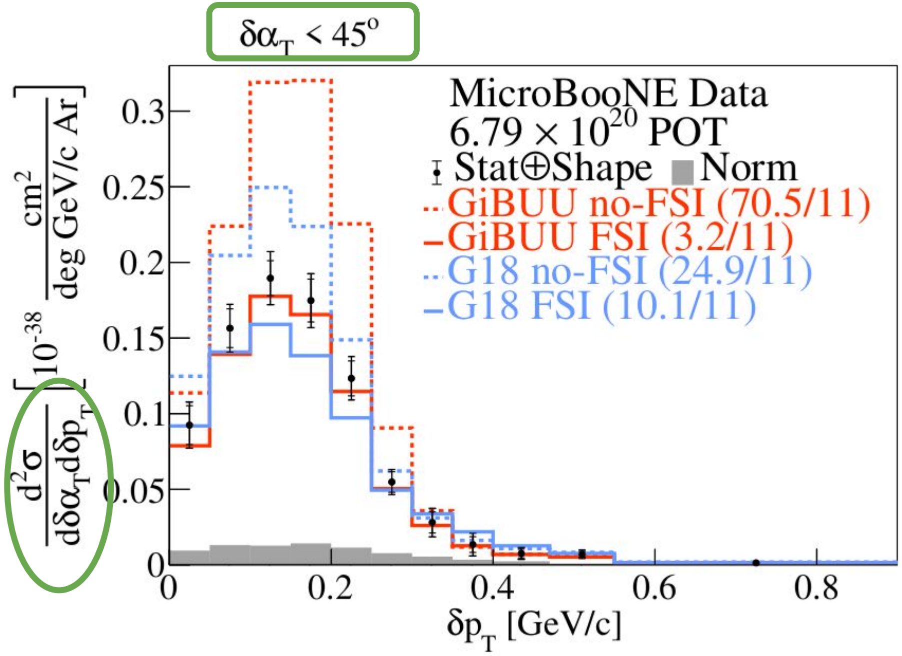




High Statistics→Into the Multiverse!

QE-dominated region





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

arXiv:2301.03706 (accepted to PRL)

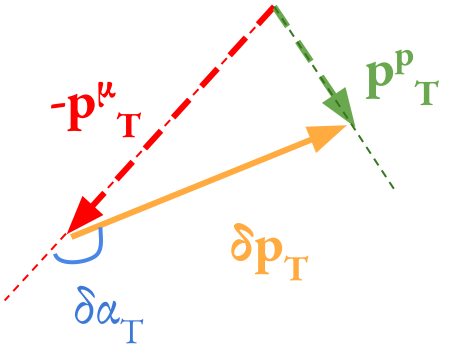
* Phys. Rev. D 105, 072001 (2022)

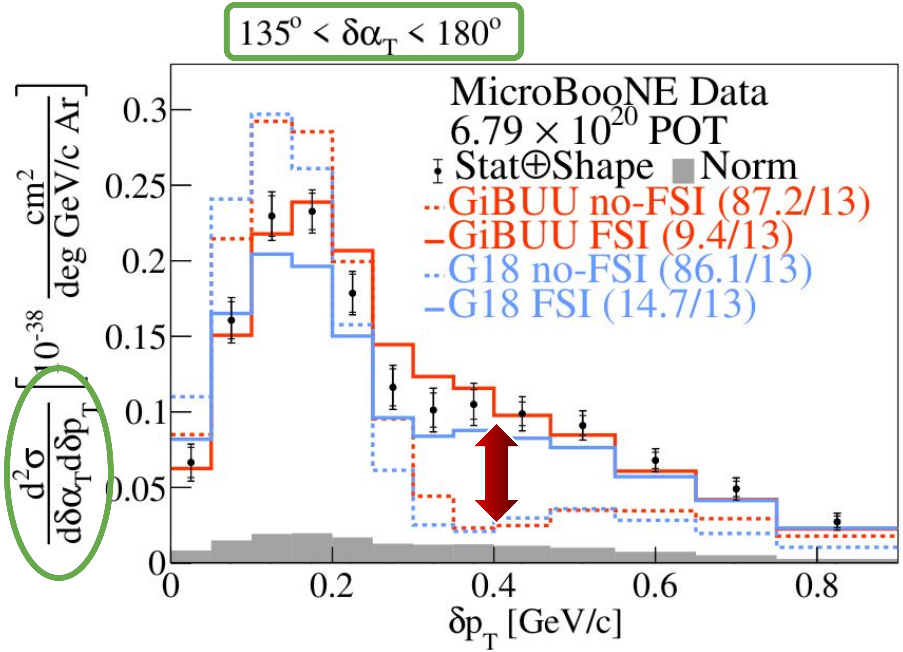
G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

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

arXiv:2301.03706 (accepted to PRL)

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

G18 = GENIE v3.0.6 G18_10a_02_11b + tune*

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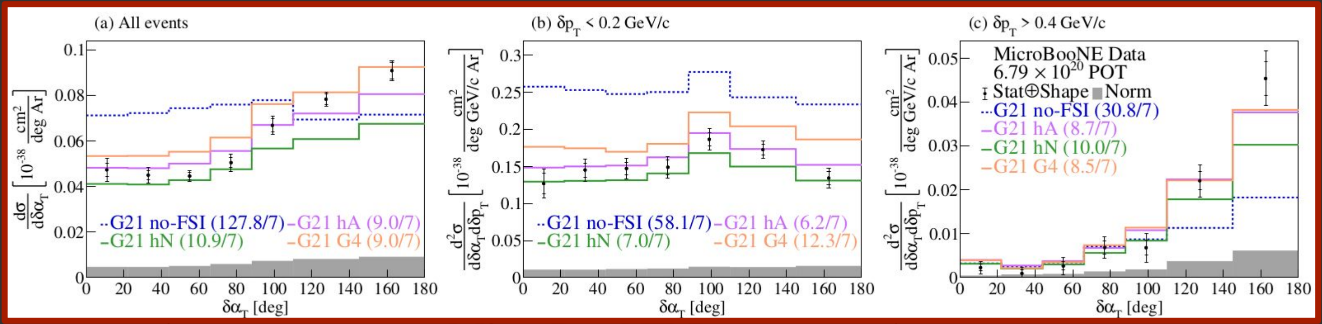
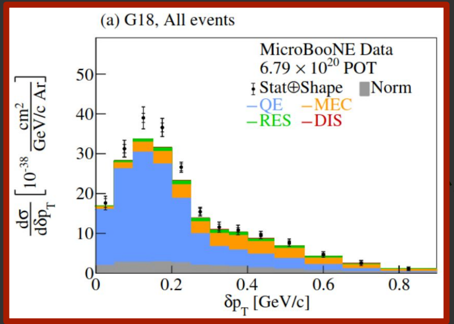
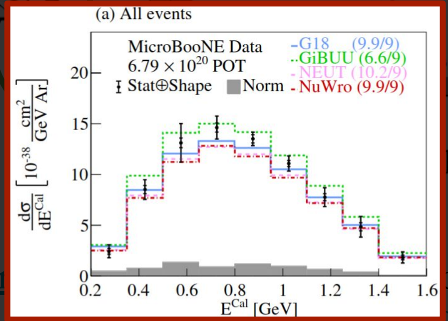


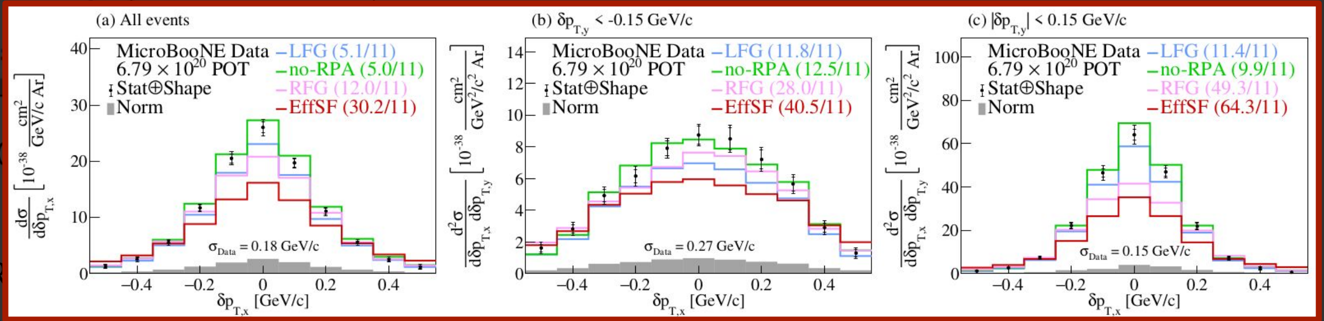


Way more details in arXiv:2301.03706 & arXiv:2301.03706

See also poster on TKI

But far from the end of the MicroBooNE cross section story!





to test FSI / multinucleon effects

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

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CC inclusive

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Rare channels

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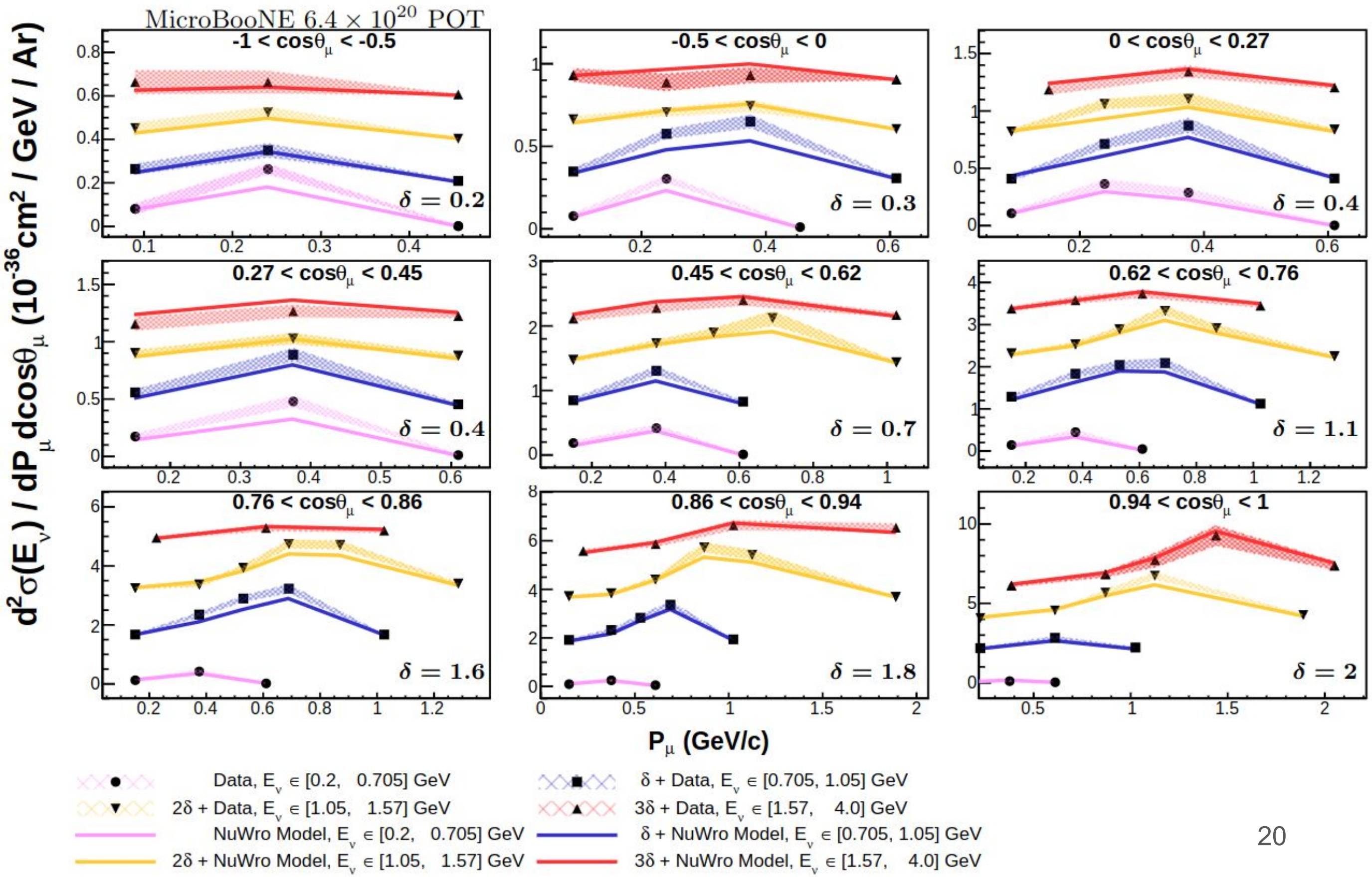
  arXiv:2305.16249, submitted to PRL
- Λ production @ NuMI
  Phys. Rev. Lett. 130, 231802 (2023)

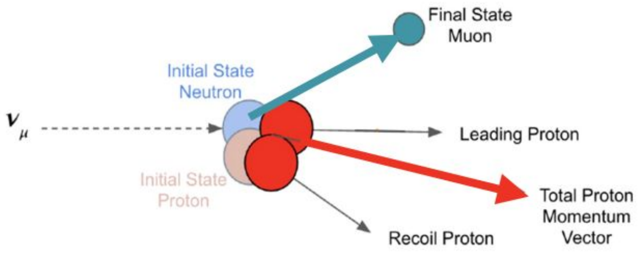
ν_μ CC Inclusive 3D

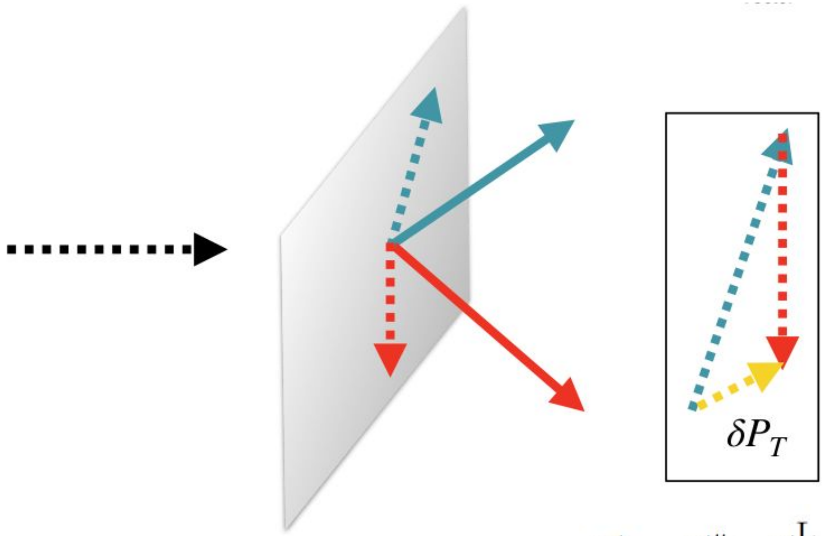
- Extension of Phys. Rev. Lett. 128, 151801
- First triple-differential cross section result on argon
- Extensive validation of model accounting for missing energy
- All event generators yield disagreements in different parts of the phase-space



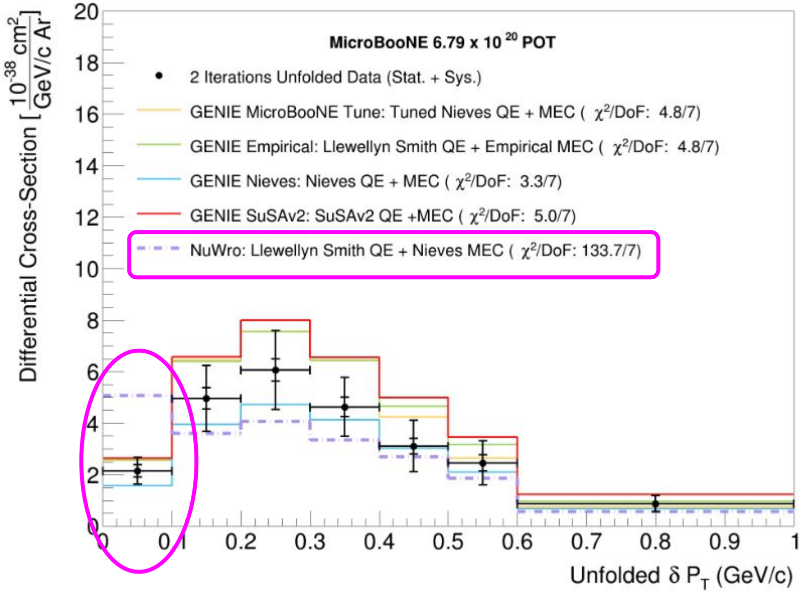
arXiv:2307.06413 submitted to PRL

ν_μ CC2p0π





$$\delta\vec{P}_T = \vec{P}_T^{\mu} + \vec{P}_T^{L} + \vec{P}_T^{R}$$

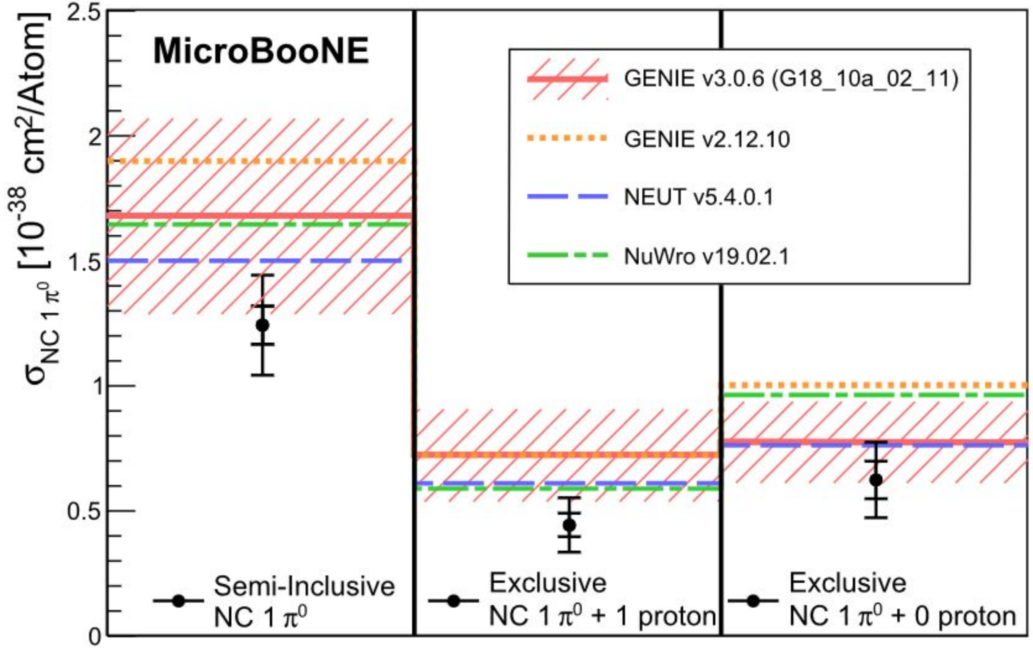


- Dominated by MEC events (~80%)
- NuWro overprediction at low values due to back-to-back proton orientation
- GENIE predictions result in better agreement

arXiv:2211.03734
submitted to PRL

NC π^0

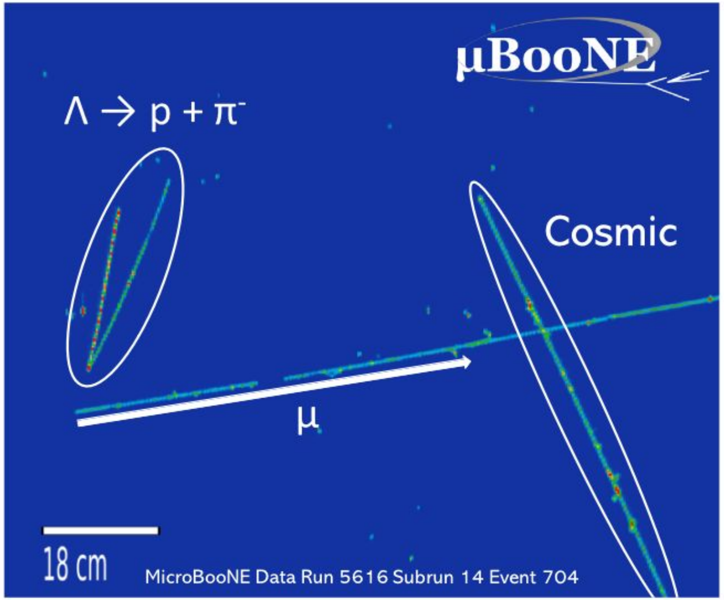
- First measurement on argon
- Measure 0p and 1p channels (and their combination)
- Background constraint for electron & photon analyses
- NEUT yields overall best agreement

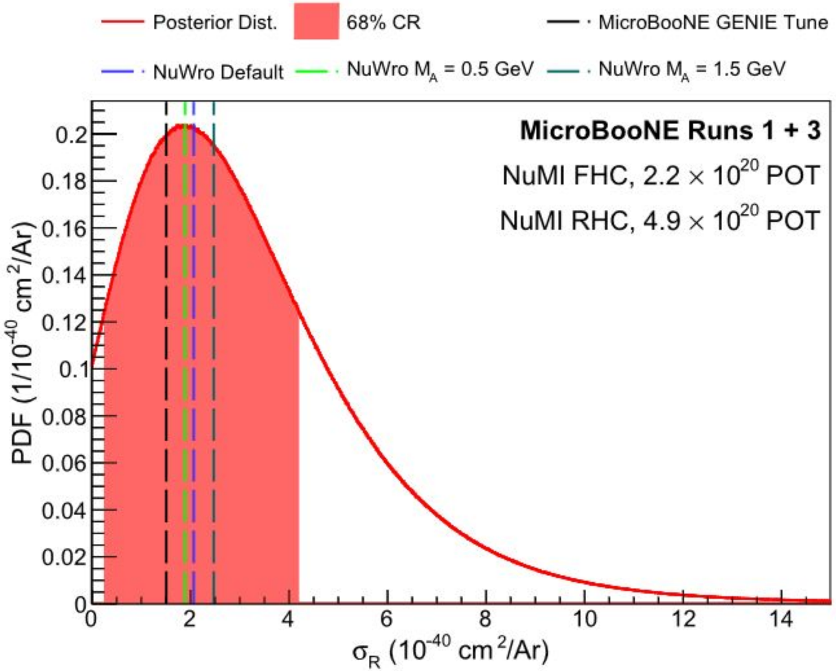


Phys. Rev. D 107, 012004

Λ Baryon Production

- First measurement with a modern detector
- Very rare process - 5 observed events
- Identified Λ baryons through invariant mass and separated vertex



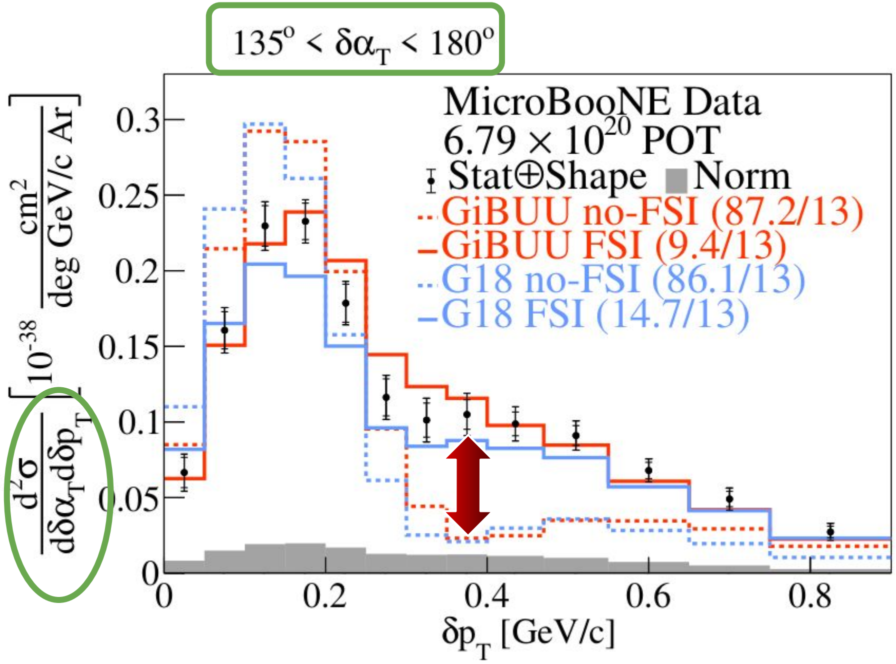


Phys. Rev. Lett. 130, 231802

See David's talk on η analysis

Summary

- Diverse and comprehensive cross section program with novel measurements
- Exploring lots of different channels and variety of analysis techniques
- Sensitivity to expose inconsistencies between modeling approaches
- Haven't yet analyzed our full data set (x2 stats)



Wealth Of Cross Section Results To Follow!

CC inclusive

- ν_μ CC inclusive @ NuMI
- ν_e/ν_μ ratios @ BNB, NuMI
- 3D E_ν, E_μ, hadronic energy @ NuMI & BNB
- anti-ν_e @ NuMI

CC0π

- 2D ν_μ CC1p0π Generalized Kinematic Imbalance @ BNB
- ν_μ CC0π inclusive @ BNB
- 2D ν_μ CCNp0π @ BNB
- 1D ν_e CC0πNp @ NuMI
- 1D ν_μ NC1p0π @ BNB

Pion production

- ν_μ CC1π^+ @ BNB, NuMI
- ν_μ CCNπ @ NuMI
- 1D ν_μ CCπ^0 @ BNB
- 2D ν_μ CC/NC π^0 @ BNB
- 2D $\nu_{e,\mu}$ NCπ^0 @ BNB

Rare & novel channels

- ν_μ CC Kaon @ BNB, NuMI
- MeV-scale Physics in MicroBooNE
- Neutrons @ BNB

Thank you!

Backup Slides

TABLE IV. Tuned parameter values and uncertainties after fitting to T2K CC0π data for the nominal simulation and three tunes that build to the final four parameter tune. Note that postfit χ^2 values are quoted here only for the 58 bins included in the fit (excluding the highest muon momentum bin in each cos θ bin), and using diagonal elements of the covariance matrix only. In the text and figures, pre- and postfit χ^2 comparisons are also quoted for the full T2K dataset of 67 bins. "Norm." is an abbreviation for normalization.

	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K $\chi^2_{\text{diag}}/\text{N}_{\text{bins}}$
Nominal (untuned)	0.961242 GeV	1	100%	0	106.7/58
Fit MaCCQE + CC2p2h Norm.	1.14 ± 0.07 GeV	1.61 ± 0.19	100% (fixed)	0 (fixed)	71.8/58
Fit MaCCQE + CC2p2h Norm + CCQE RPA Strength	1.18 ± 0.08 GeV	1.12 ± 0.38	(64 ± 23)%	0 (fixed)	69.7/58
Fit MaCCQE + CC2p2h Norm + CCQE RPA Strength + CC2p2h Shape	1.10 ± 0.07 GeV	1.66 ± 0.19	(85 ± 20)%	$1^{+0}_{-0.74}$	52.5/58

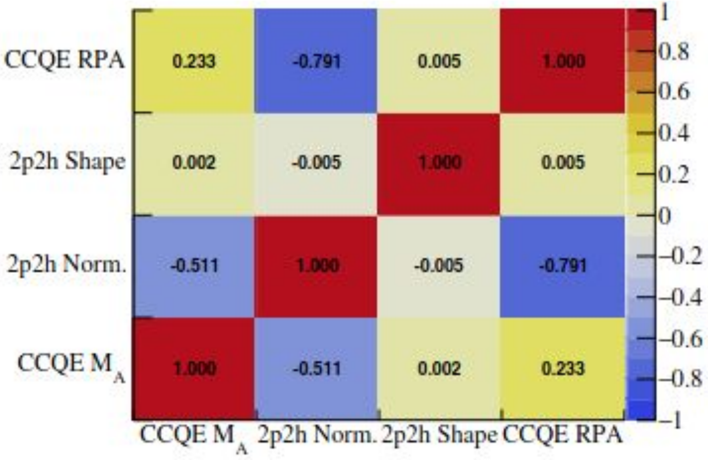
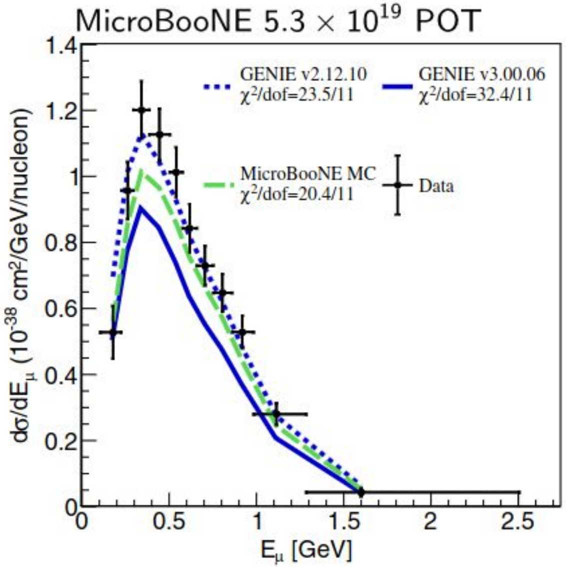


FIG. 7. Correlations between parameters after fitting to T2K CC0π data.

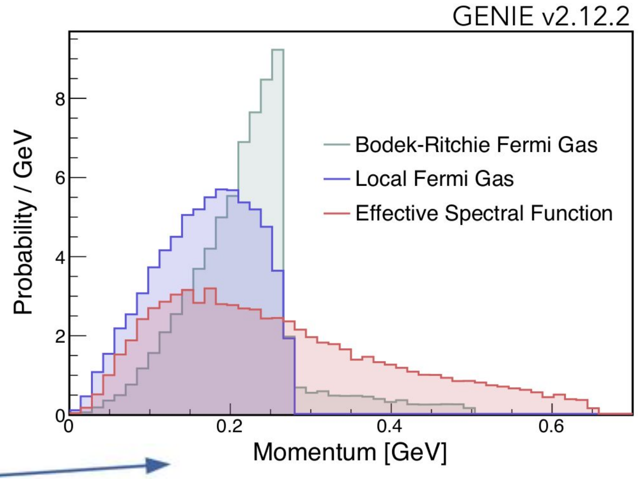


Phys. Rev. D 105, 072001 (2022)

Nuclear Effects in Event Generators

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

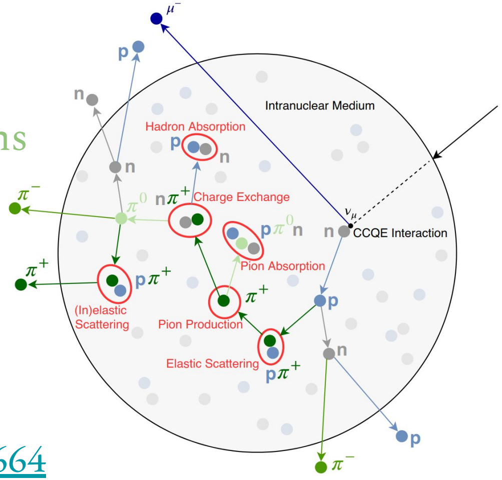
Struck nucleon motion in argon

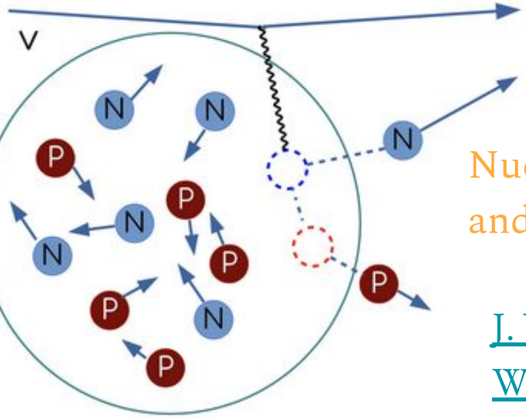


- Fermi motion
- Final state interactions
- Meson exchange currents
- …

} Known unknowns that need to be accurately simulated

Hadron reinteractions



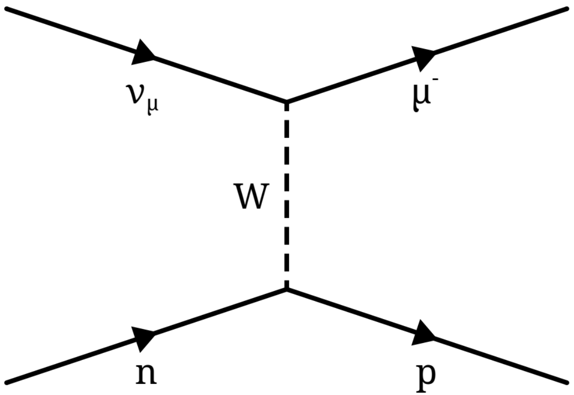


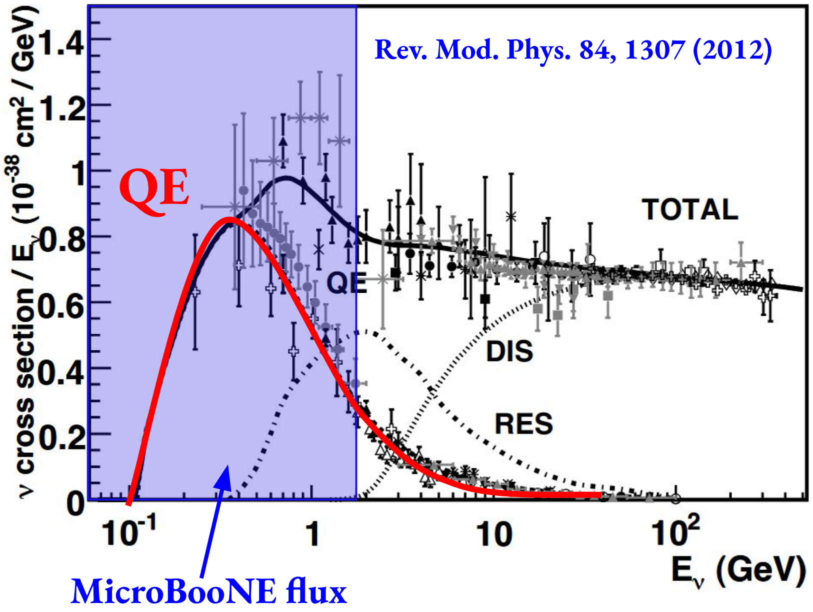
Nucleon-nucleon relative angle and momenta

J. Wolcott
Wine & Cheese Seminar

arXiv:2201.04664

Single-Proton Knockout





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

TKI Neutrino Measurements

Experiment	Target	References
T2K	CH	Phys.Rev.D 103 11, 112009 (2021) Phys. Rev. D 98, 032003 (2018)
MINERvA	CH	Phys. Rev. Lett. 121, 022504 (2018) Phys. Rev. D 101, 092001 (2020) Phys. Rev. D 102, 072007 (2020)

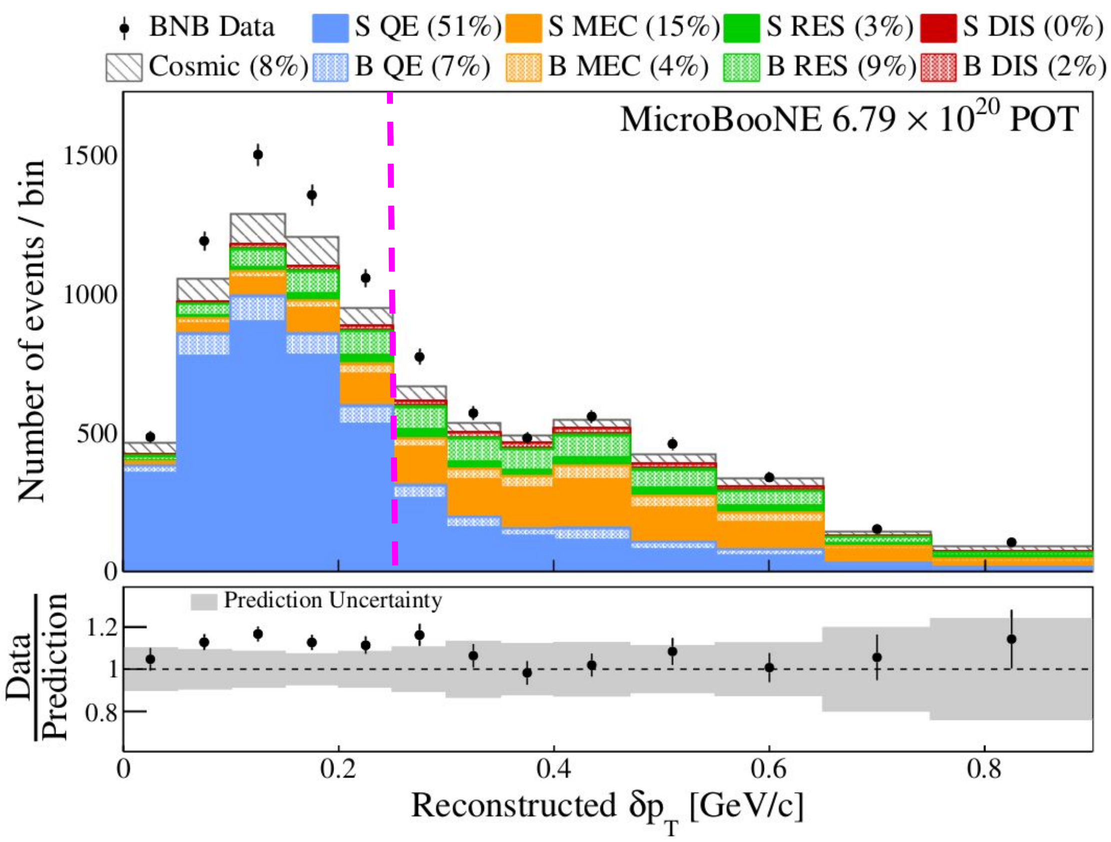
But none on argon up to now!

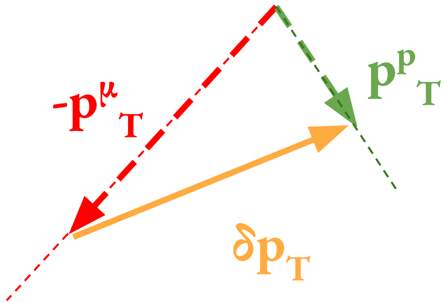
TKI Neutrino Measurements

Experiment	Target	References
T2K	CH	Phys.Rev.D 103 11, 112009 (2021) Phys. Rev. D 98, 032003 (2018)
MINERvA	CH	Phys. Rev. Lett. 121, 022504 (2018) Phys. Rev. D 101, 092001 (2020) Phys. Rev. D 102, 072007 (2020)
MicroBooNE	Ar	arXiv:2301.03706 (accepted to PRL) arXiv:2301.03700 (accepted to PRD)

First single- and double-differential single-proton cross section measurements on argon in transverse kinematic imbalance

Transverse Missing Momentum δp_T





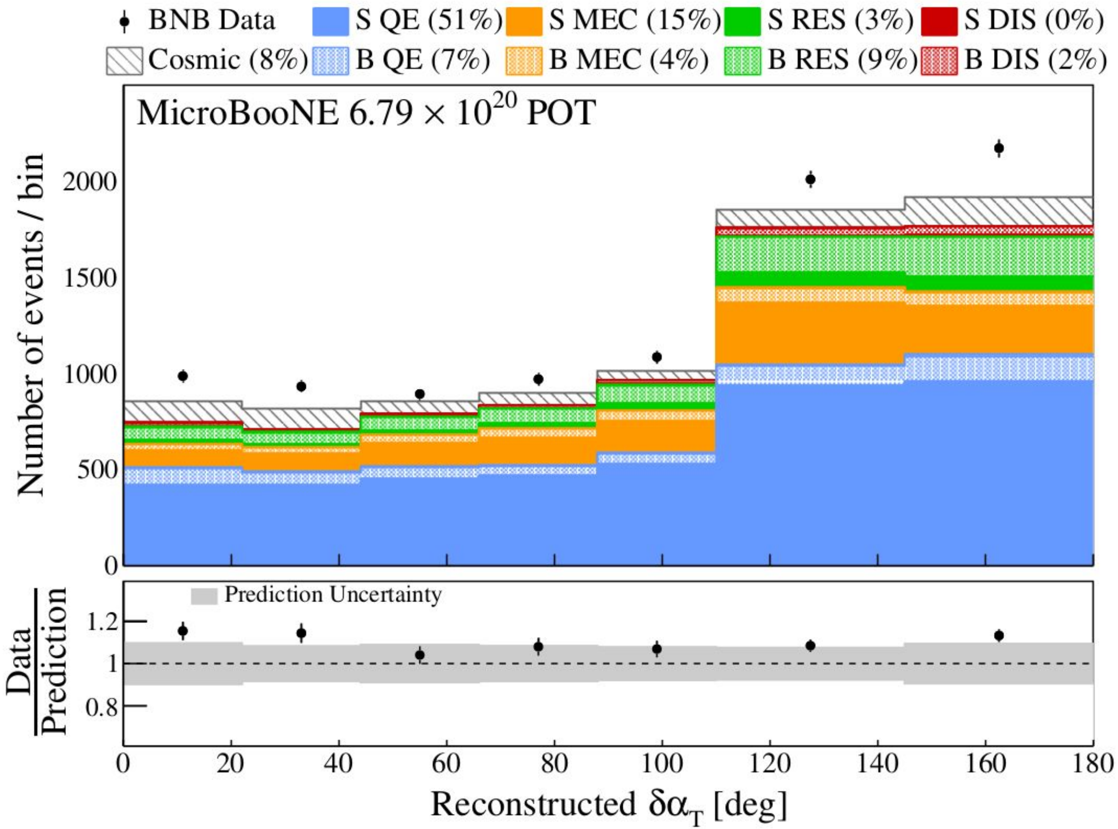
- S = Signal, B = Background
- **QE** dominance in peak below Fermi momentum (~250 MeV/c)
- **MEC**/**RES** mainly in high momentum tail

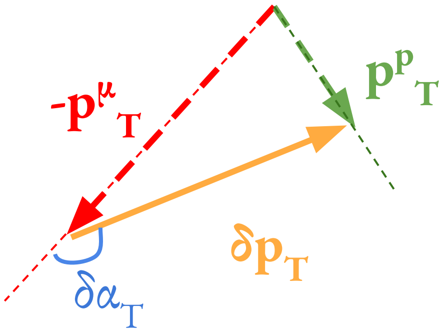
arXiv:2301.03700 (accepted to PRD)

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

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

Transverse Orientation $\delta\alpha_T$





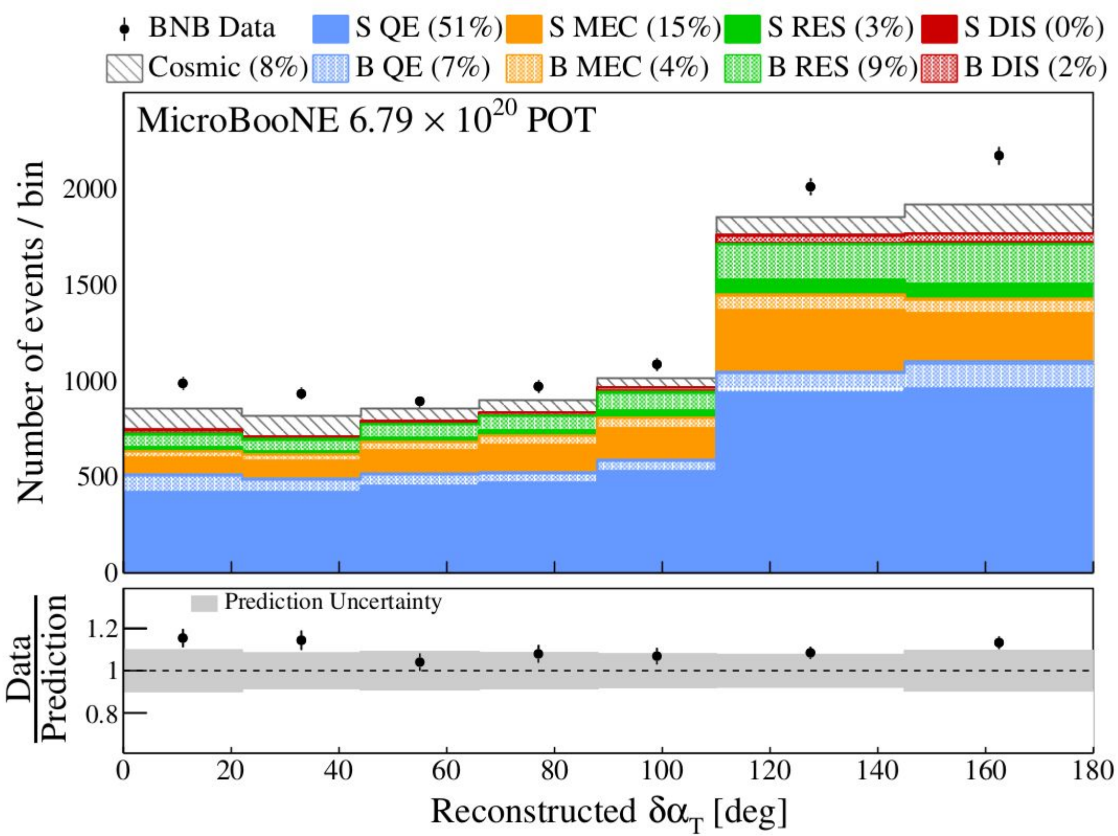
- $\delta\alpha_T$ asymmetry due to proton FSI
- **MEC**/**RES** fractional contribution enhanced in ~180° region

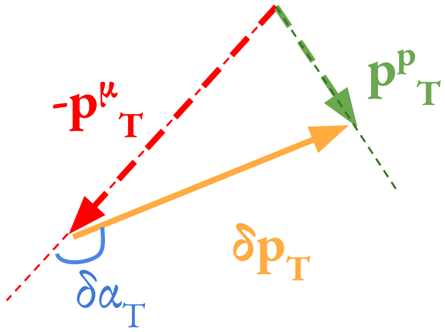
arXiv:2301.03706 (accepted to PRD)

* [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→ *Wiener-SVD unfolding*
JINST **12** P10002 (2017)
More details in backup slides

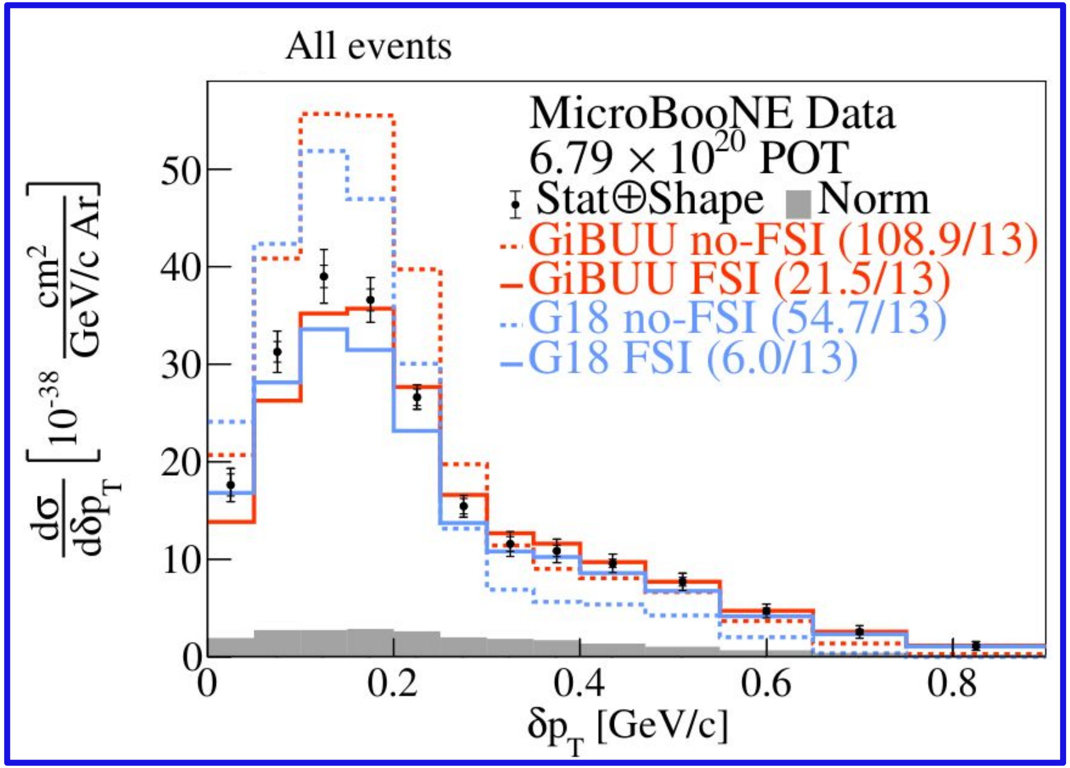
arXiv:2301.03706 (accepted to PRD)
* Phys. Rev. D 105, 072001 (2022)

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Output quantities in regularized space

- Unfolded data spectrum
- Smearing Matrix A_C
  *Applied on theory predictions and included in data release



arXiv:2301.03706

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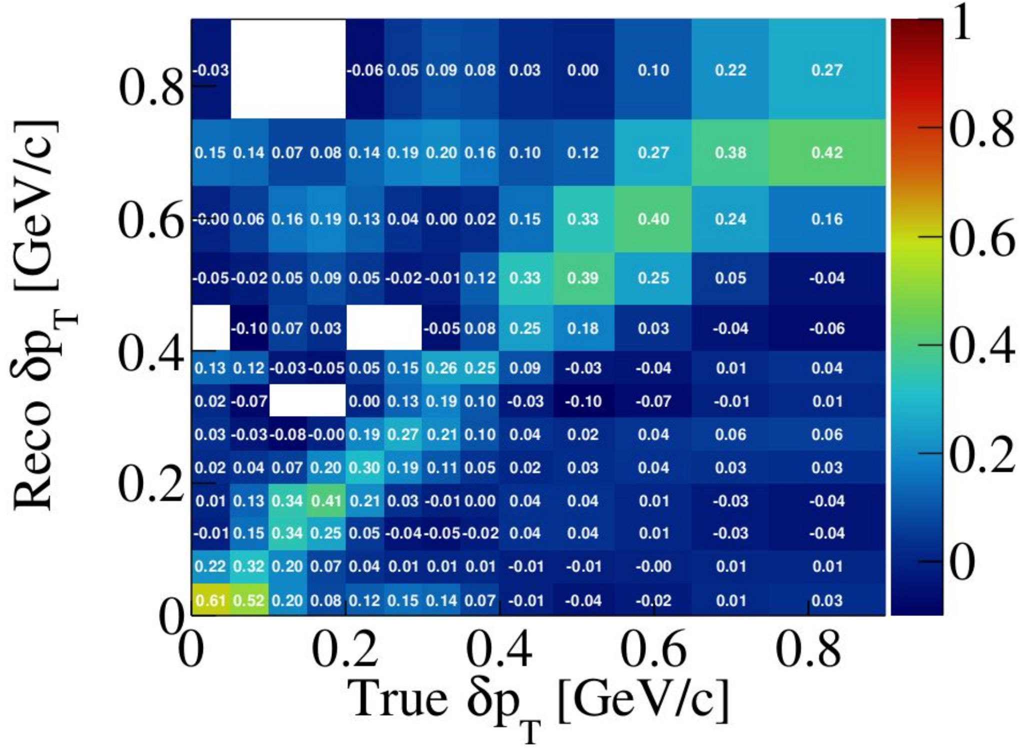


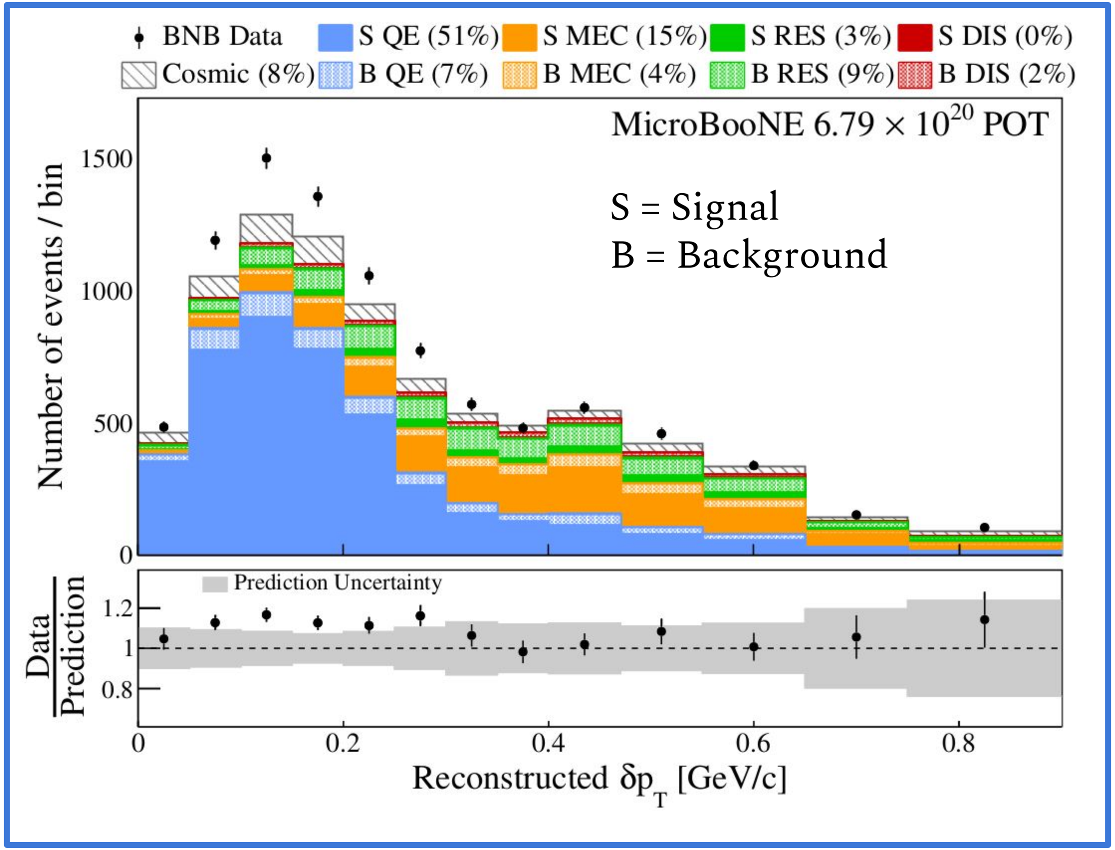
arXiv:2301.03706

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Input Quantities

- Measurement (Data)
- Background (Cosmics + MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)



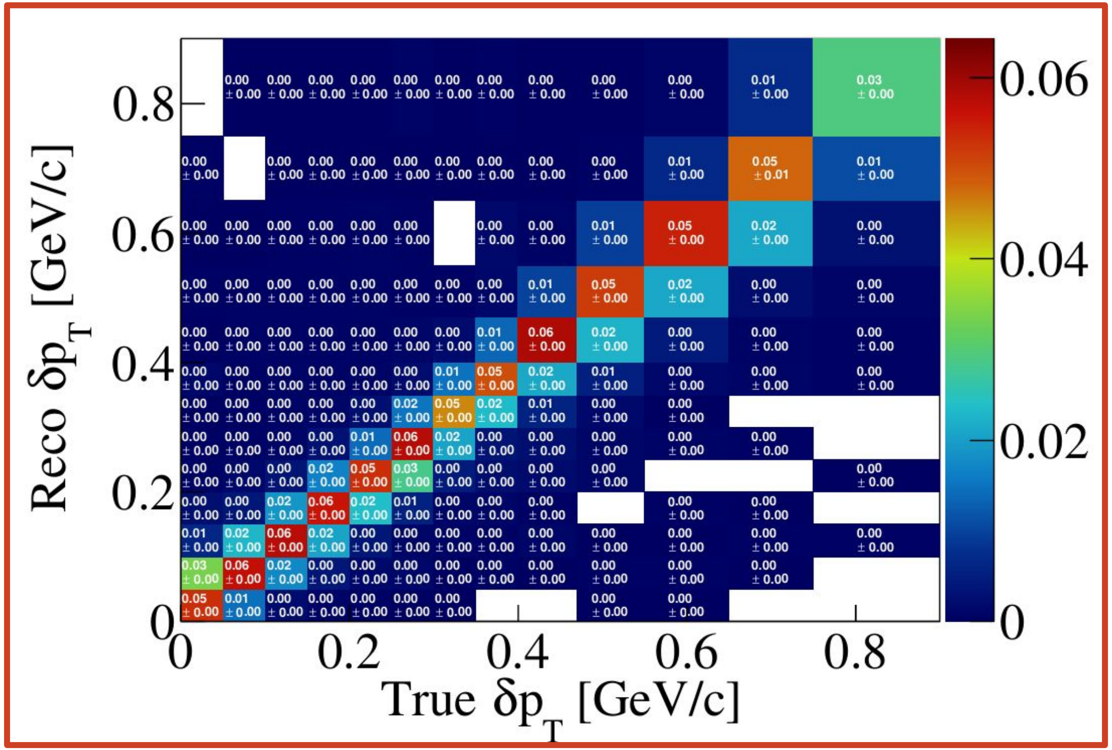
arXiv:2301.03700

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)



Probability that a generated event is reconstructed and selected

Diagonal matrix with flat ~6% efficiency

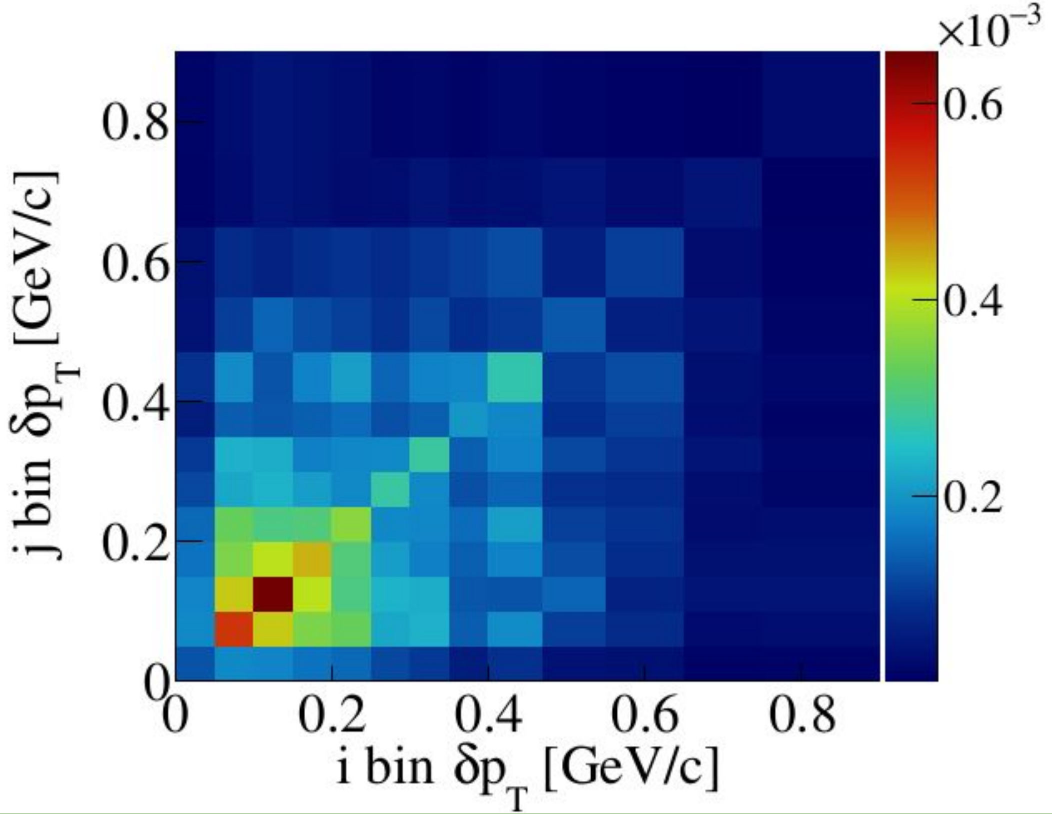
arXiv:2301.03700

Cross Section Extraction with Wiener SVD Unfolding

JINST **12** P10002 (2017)

Input Quantities

- Measurement (Data)
- Background (MC)
- Response Matrix (MC)
- Total Covariance Matrix (MC)

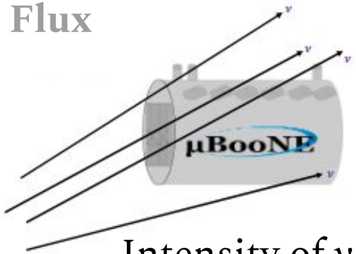


Includes information on statistical and systematic uncertainties

arXiv:2301.03700

Uncertainties

Flux



(7.3%)

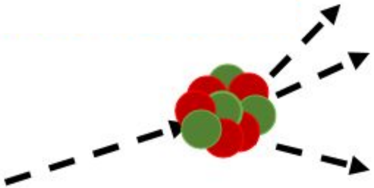
Intensity of ν source

Detector

(4.9%)

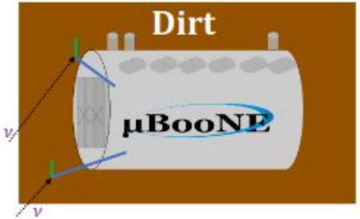
TPC & light variations

Cross section



(6%)

Modeling accuracy



(0.2%)

Out-of-cryostat ν interactions

Reinteractions

(1%)

Hadron rescattering

POT counting

(2%)

Protons-on-target precision

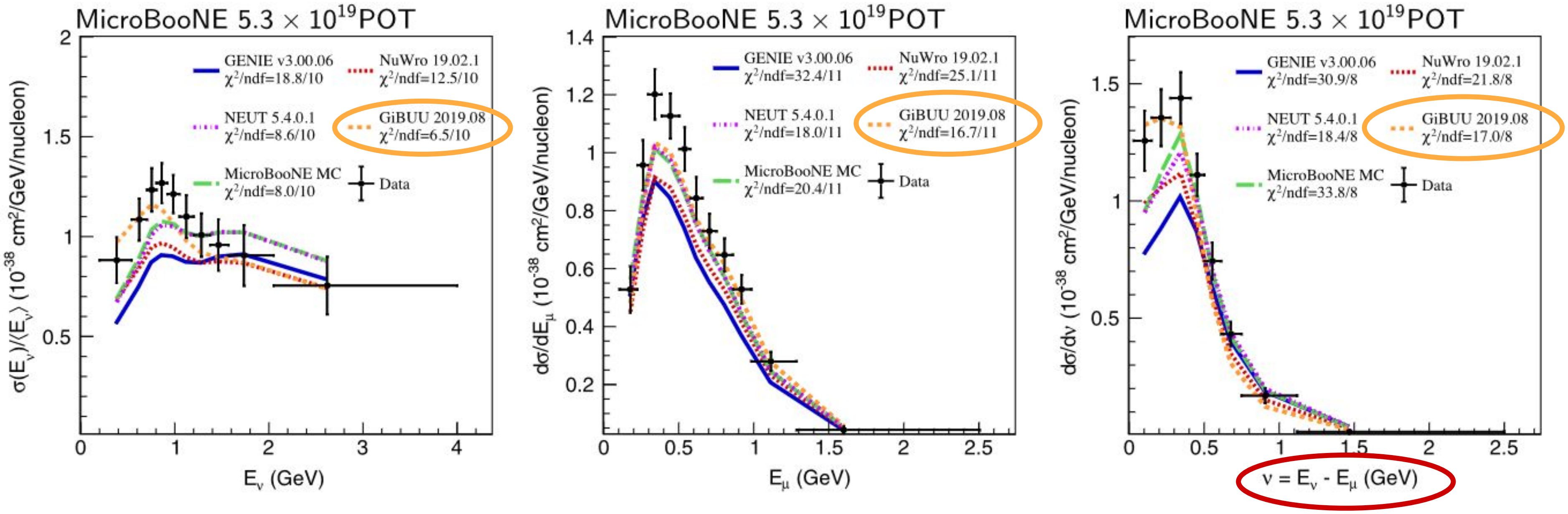
- \+ Statistical (1.5%)
- \+ Number of argon targets (1%)

Total (**11%**)

Systematics-dominated analysis

ν_μ CC Inclusive 1D

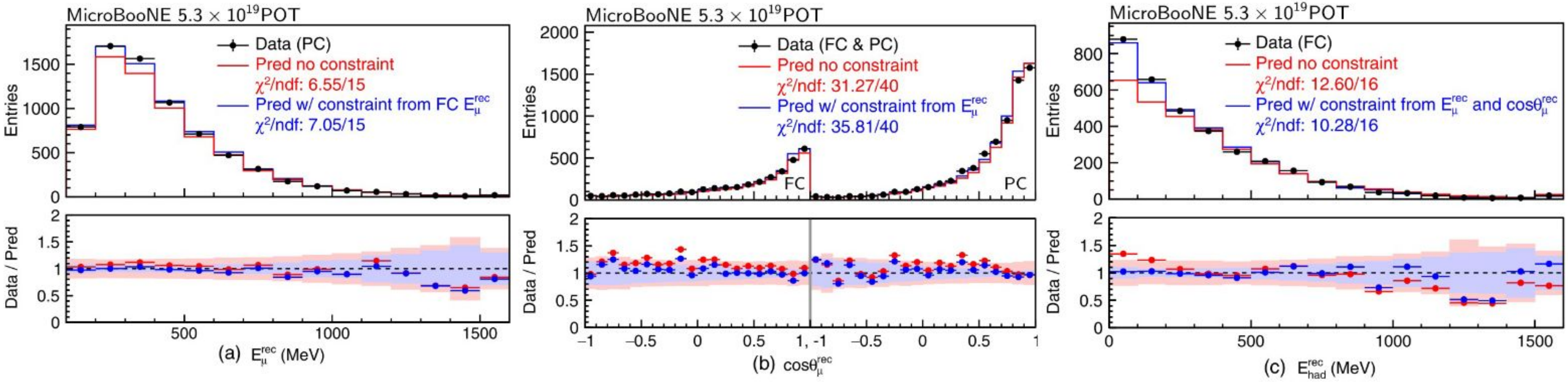
- Unfolding using Wiener-SVD JINST **12** P10002 (2017)
- First ever measurement of cross section as a function of energy transfer
- GiBUU results in best performance



Phys. Rev. Lett. 128, 151801

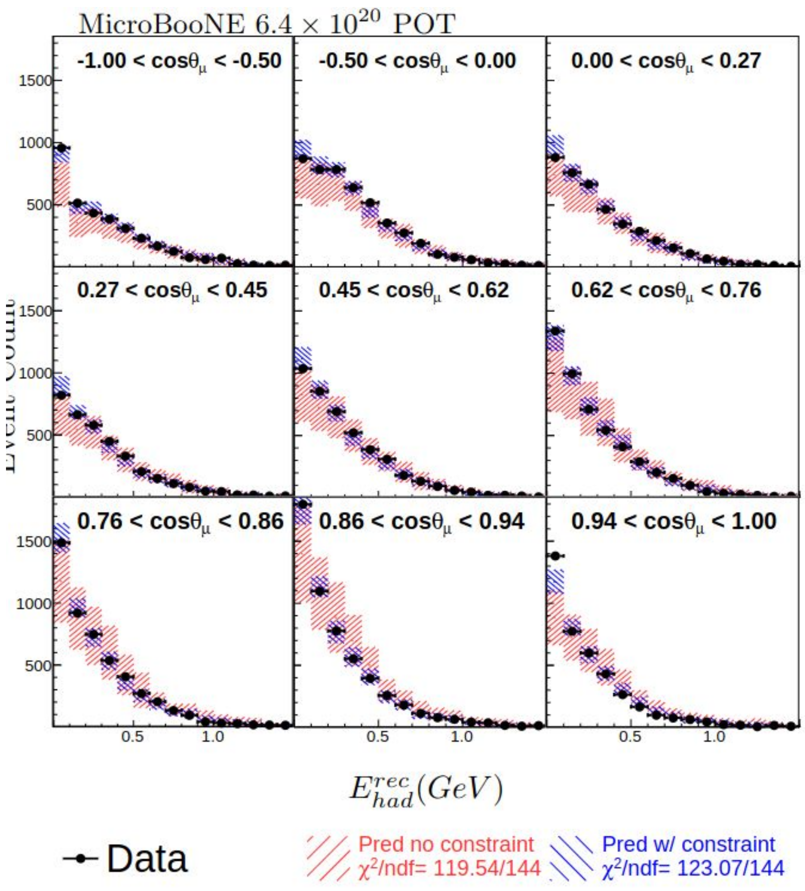
ν_μ CC Inclusive 1D

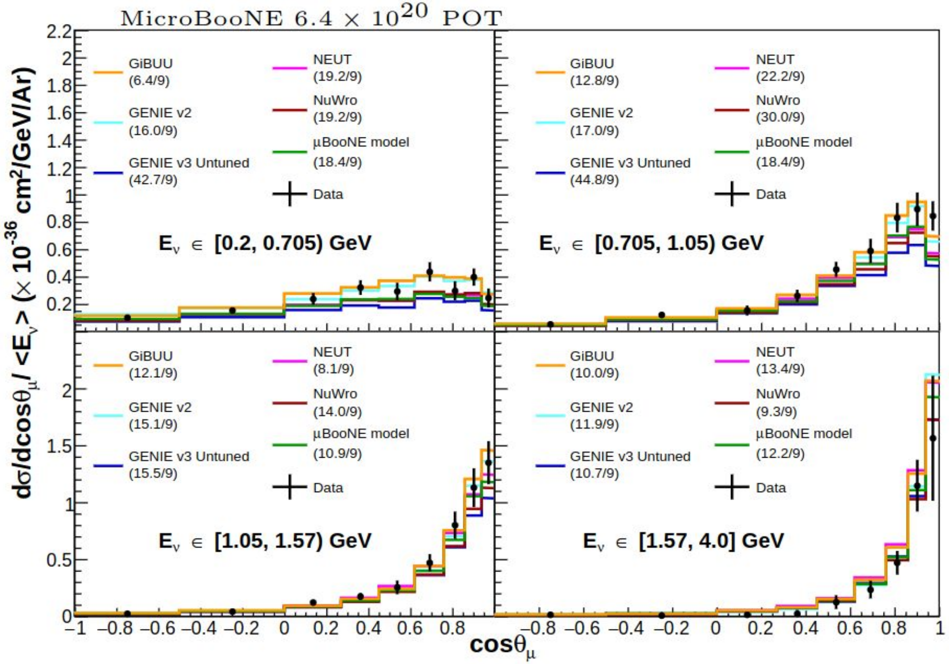
- Observe the visible hadronic energy, muon energy and direction
- Use them to test model validity due to missing hadronic energy



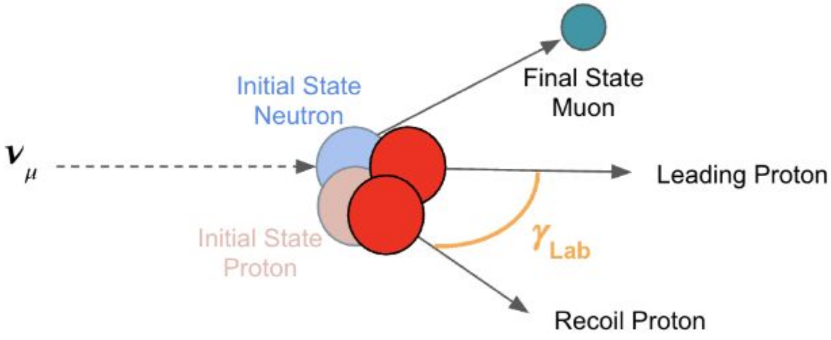
Phys. Rev. Lett. 128, 151801

ν_μ CC Inclusive 3D



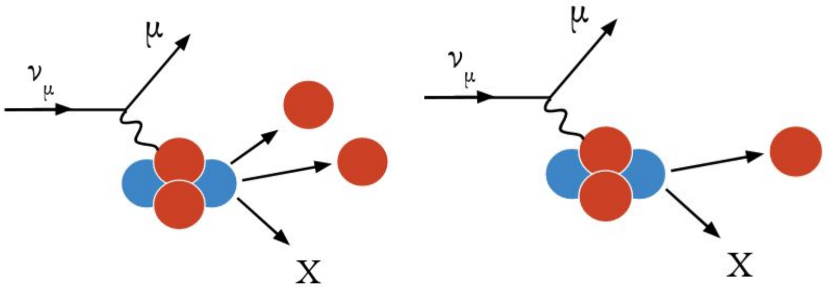


ν_μ CC2p0π



- First neutrino-argon cross sections for an exclusive 2p final state
  - Various observables studied

- γ_{Lab}: angle between the two protons
  - Sensitive to modeling choices for MEC and QE

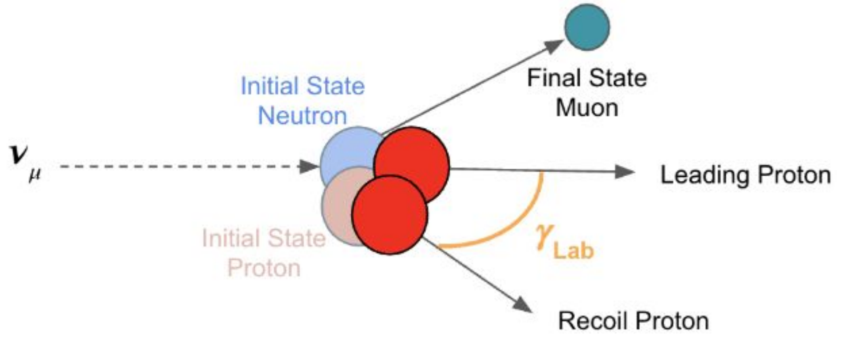


Meson Exchange Current (MEC)

Quasi-elastic (QE)

MICROBOONE-NOTE-1117-PUB

ν_μ CC2p0π



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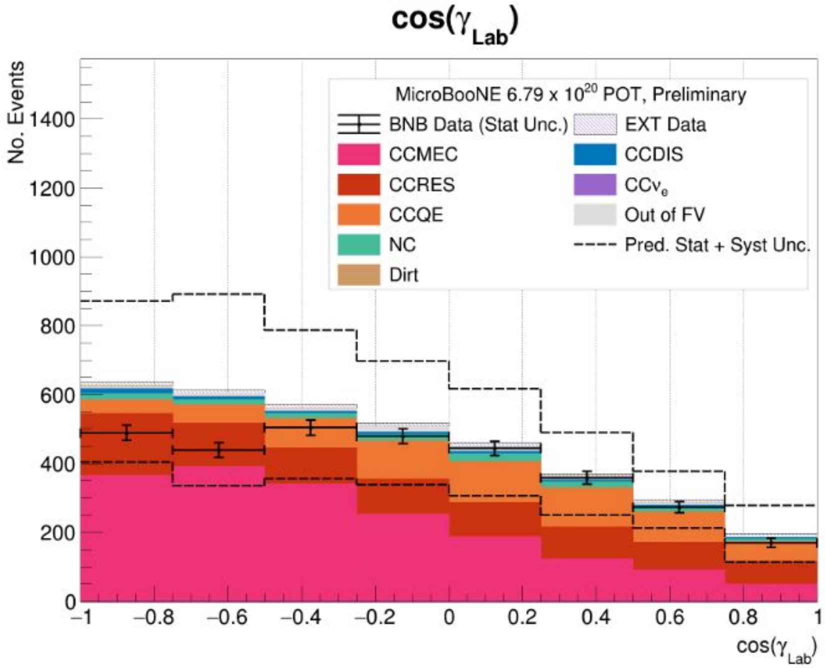
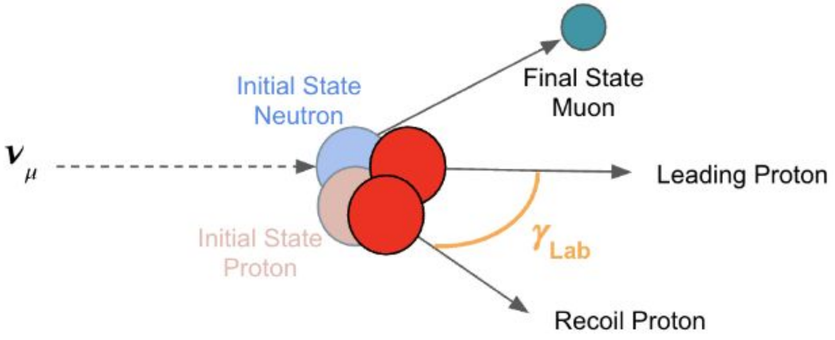


MICROBOONE-NOTE-1117-PUB

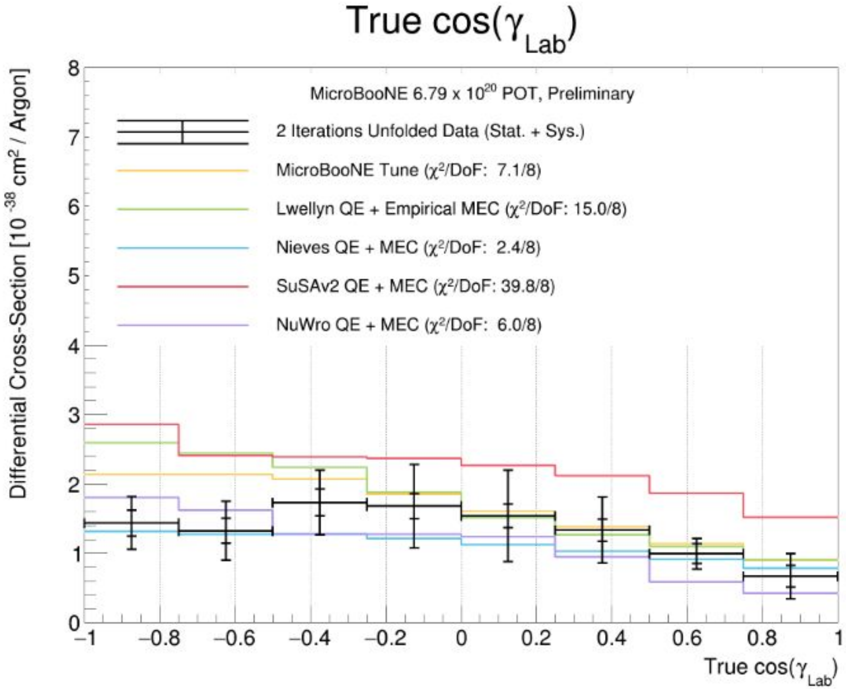
ν_μ CC2p0π



- First neutrino-argon cross sections for an exclusive 2p final state
  - Various observables studied

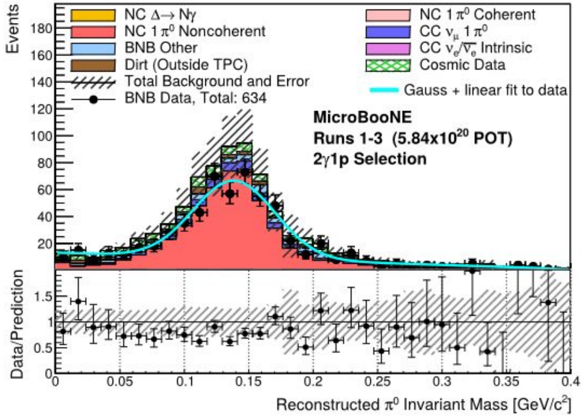
- γ_{Lab}: angle between the two protons
  - Sensitive to modeling choices for MEC and QE

- Data-MC shape & normalization differences identified

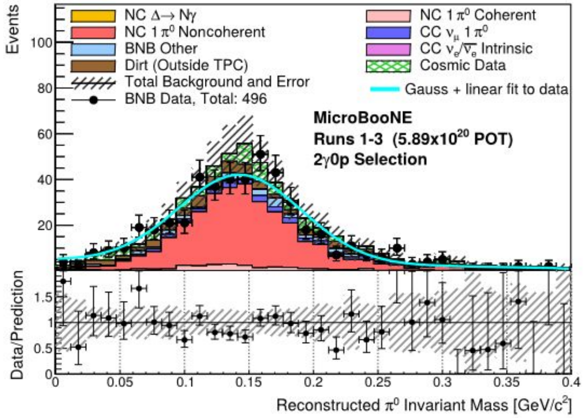


MICROBOONE-NOTE-1117-PUB

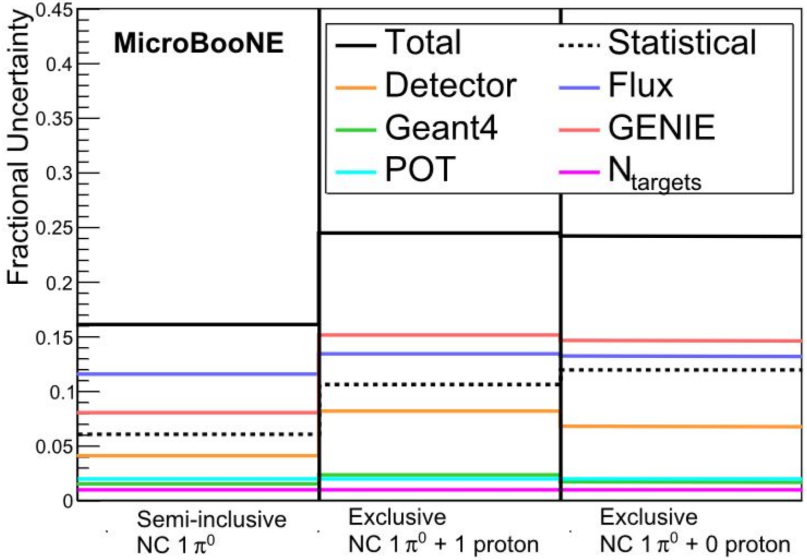
NC π^0



(a) $2\gamma 1p$



(b) $2\gamma 0p$

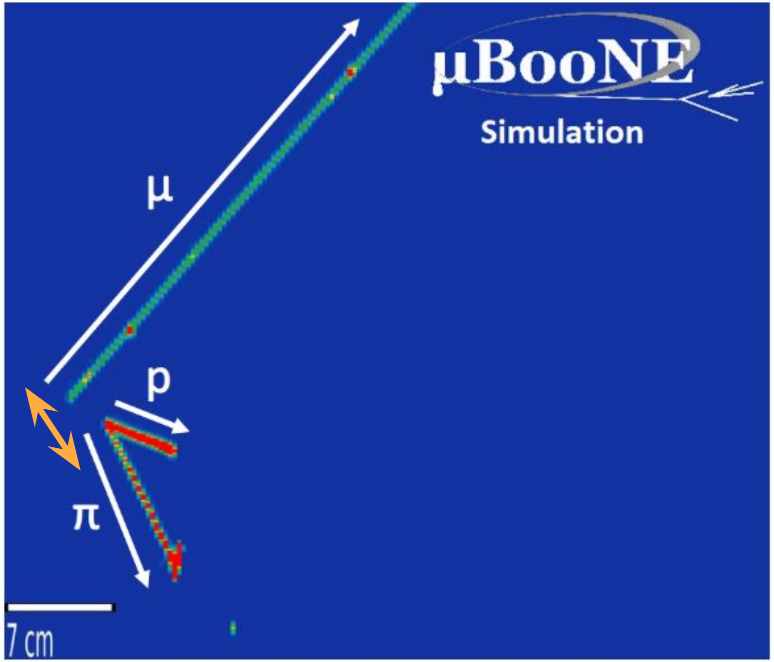


Λ Production

Event Selection

- Selection identifies a muon candidate and a proton-pion candidate pair
- Proton-pion "island" activity separated from muon candidate
- Proton-pion kinematics consistency with Λ baryon decay

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$



Also see poster by [C.Thorpe]

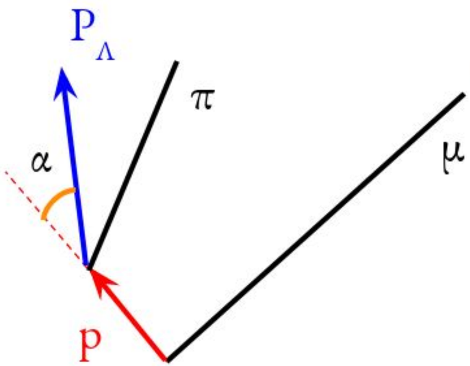
MICROBOONE-NOTE-1097-PUB

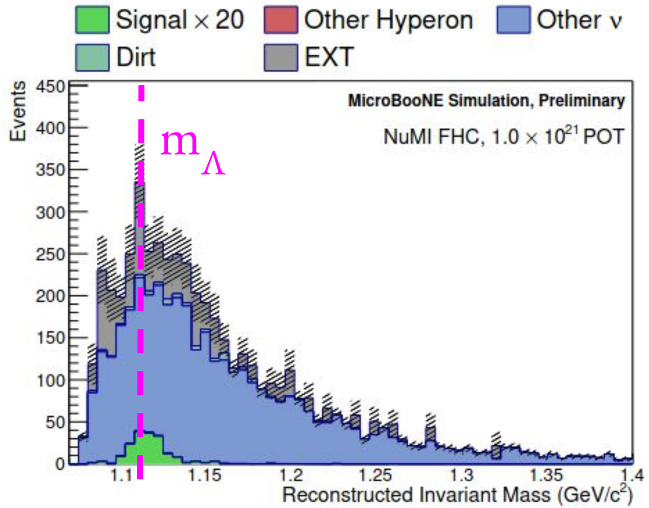
Λ Production

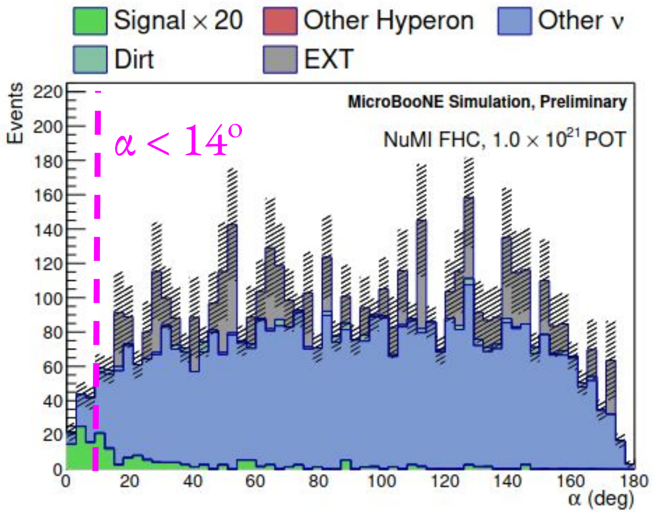
Λ baryon decay consistency

- Keeping events with
  1.09 < invariant mass W < 1.14 GeV/c^2
  and angular deviation $\alpha < 14^o$

- After selection
  Signal = 2.5 events
  Bkg = 2.8 events
  when initially
  Signal = ~40 events
  Bkg = ~2M events



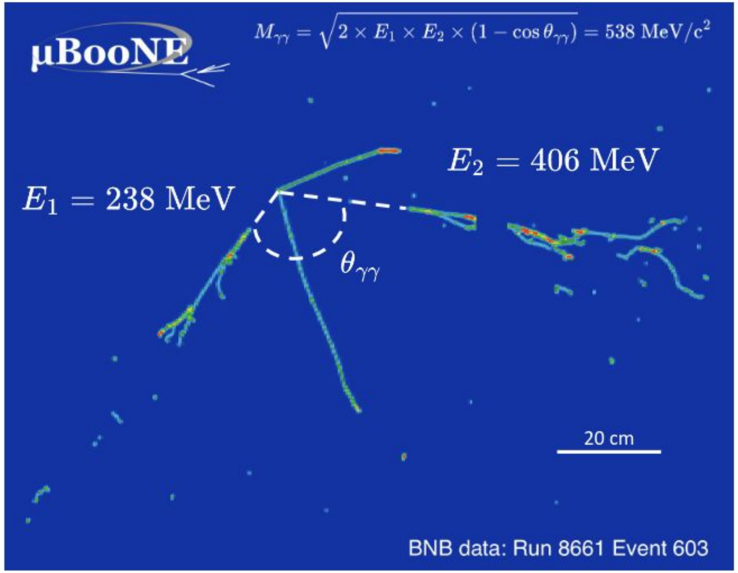


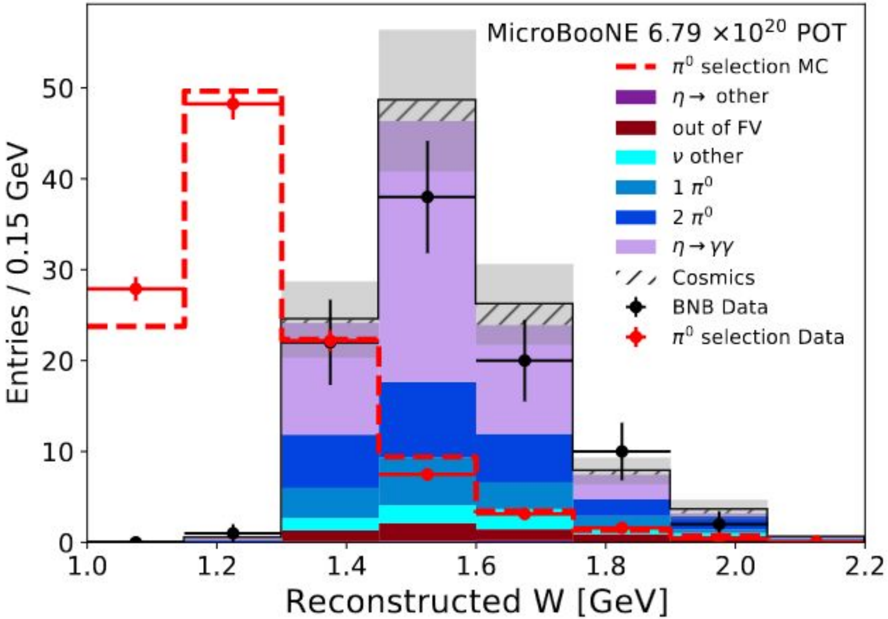


Also see poster by C.Thorpe
MICROBOONE-NOTE-1097-PUB

η Meson Production

- Unique probe of higher resonances such as N(1535)
- Identified via decay to 2γ with invariant mass of 548 MeV
- Include protons to estimate reconstructed invariant mass of hadronic system





arXiv:2305.16249, submitted to PRL

See David's talk