Exploring Neutrino Interaction Physics with MicroBooNE

Steven Gardiner, Fermi National Accelerator Laboratory
on behalf of the MicroBooNE Collaboration

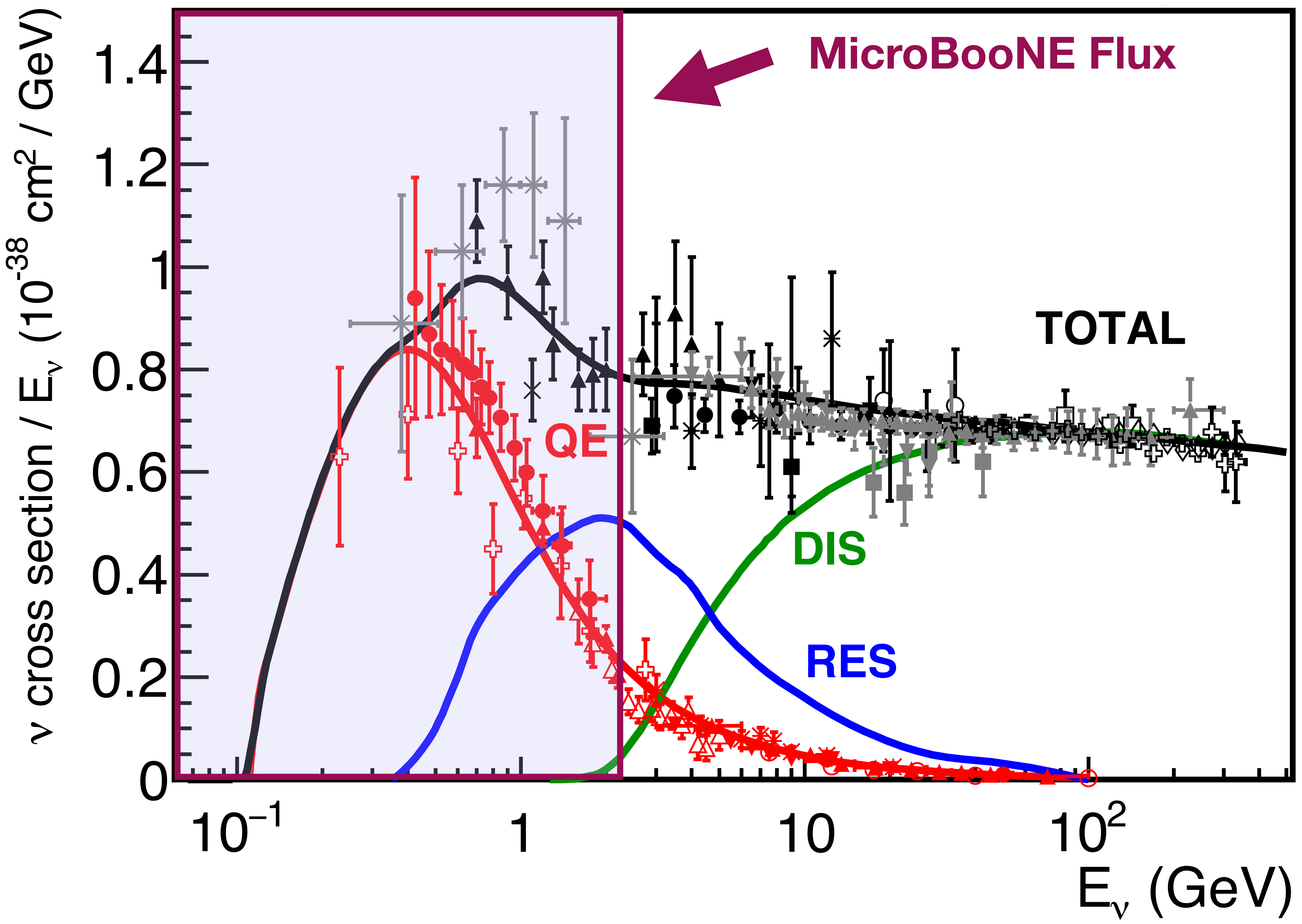
XXX International Conference on Neutrino Physics

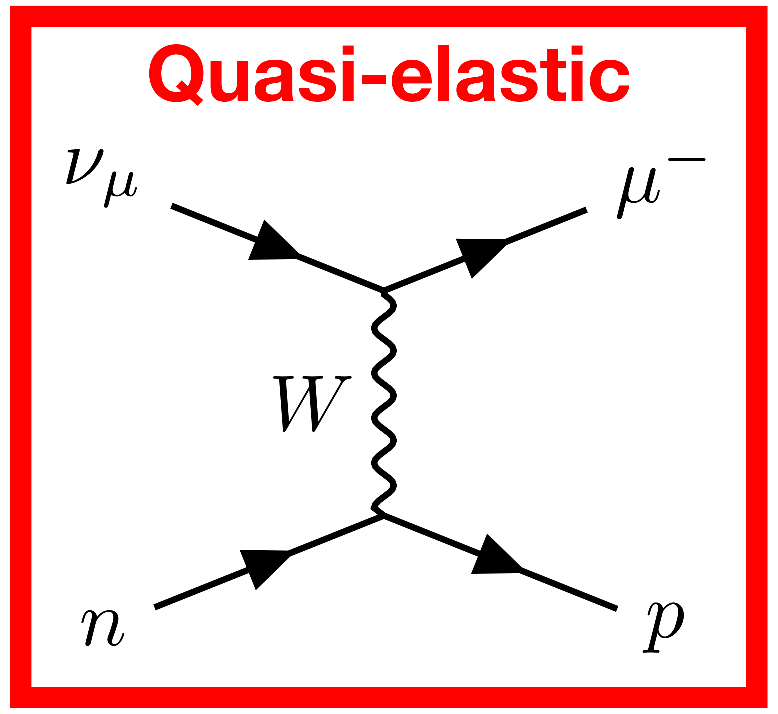
4 June 2022

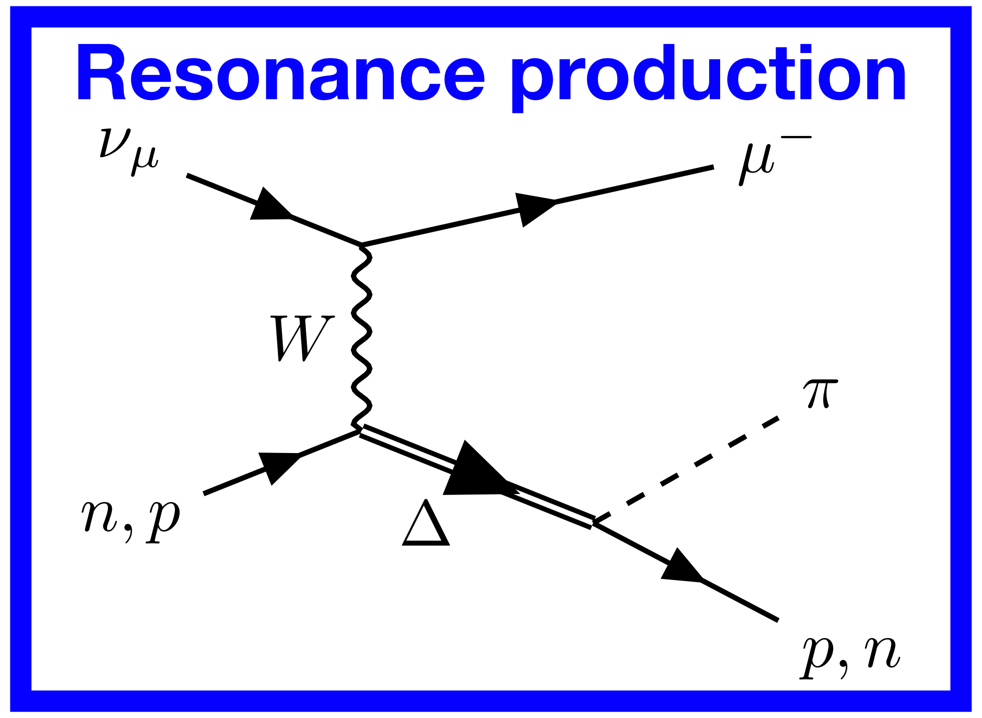
Discovery science with neutrinos requires understanding their interactions

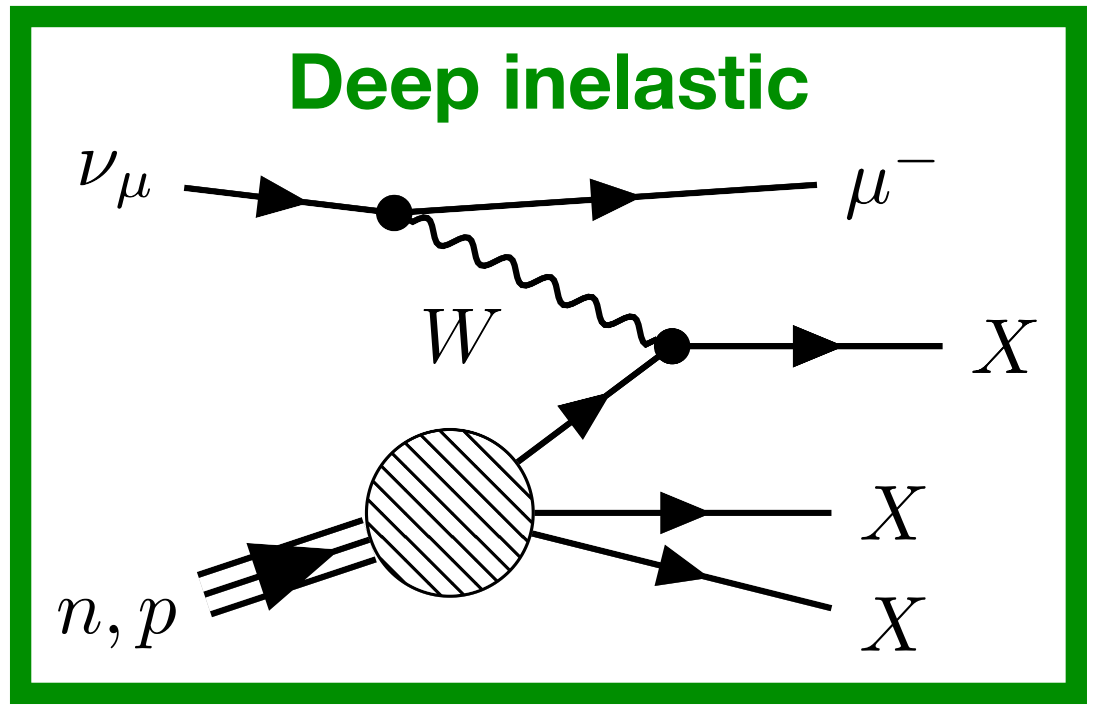
- Broad energy scale
- Various interaction mechanisms
- Must be accurately simulated to correctly interpret data

Rev. Mod. Phys. 84, 1307 (2012)









MicroBooNE’s expanding cross-section program is providing much-needed data with an argon target

- **Liquid argon time projection chamber** (LArTPC) at Fermilab
  - Low-threshold, fully active tracking calorimeter
  - Detector technology shared by SBN and DUNE
- Largest neutrino-argon data set (~0.5 M events in 5 years)
- 30 active cross-section analyses

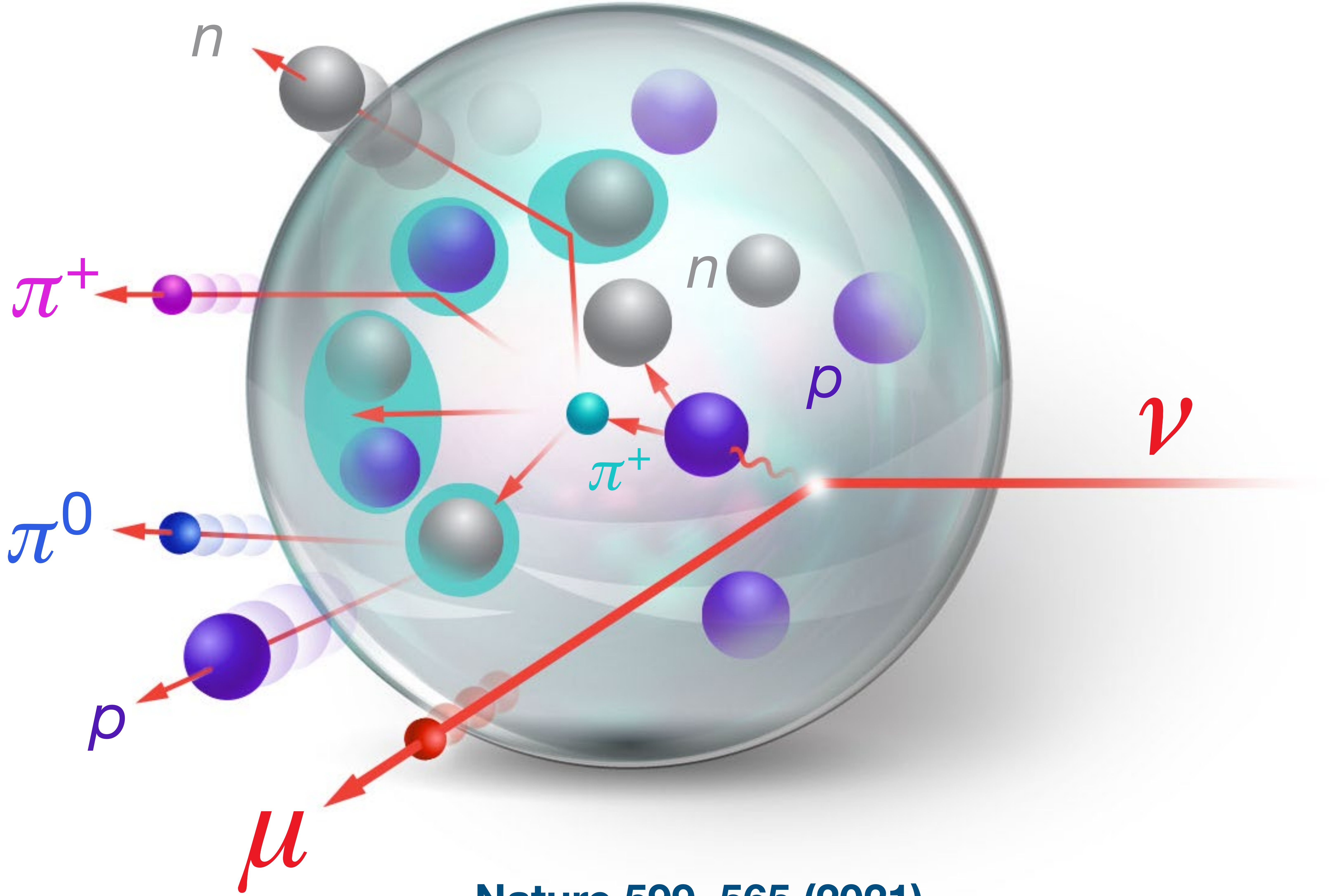
Answering key nuclear modeling questions with MicroBooNE data

3 examples in this talk

1. Neutral-current (NC) π^0 backgrounds to ν_e appearance

2. Hadronic energy for neutrino calorimetry

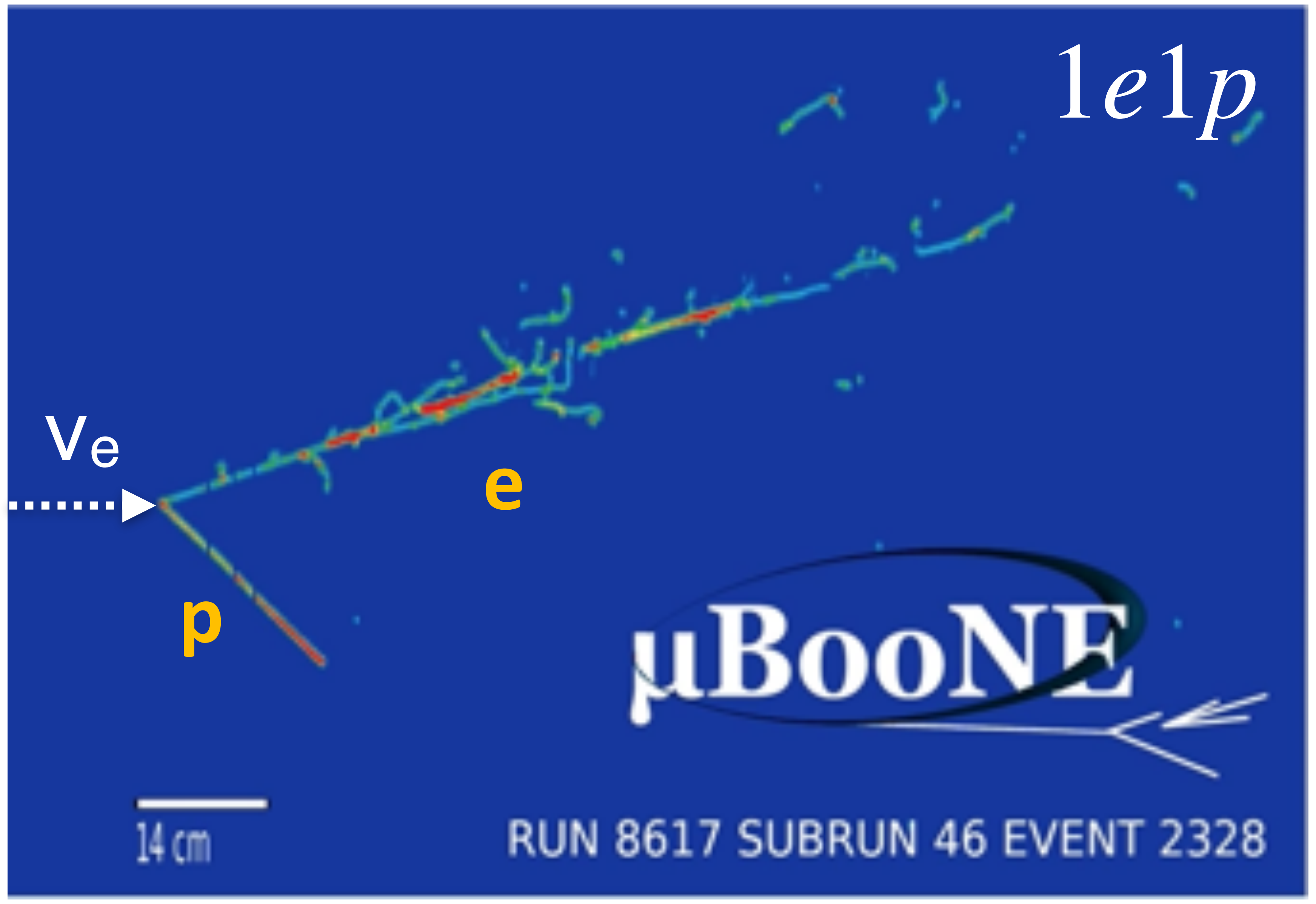
3. Nuclear effects in quasielastic-like (QE-like) events

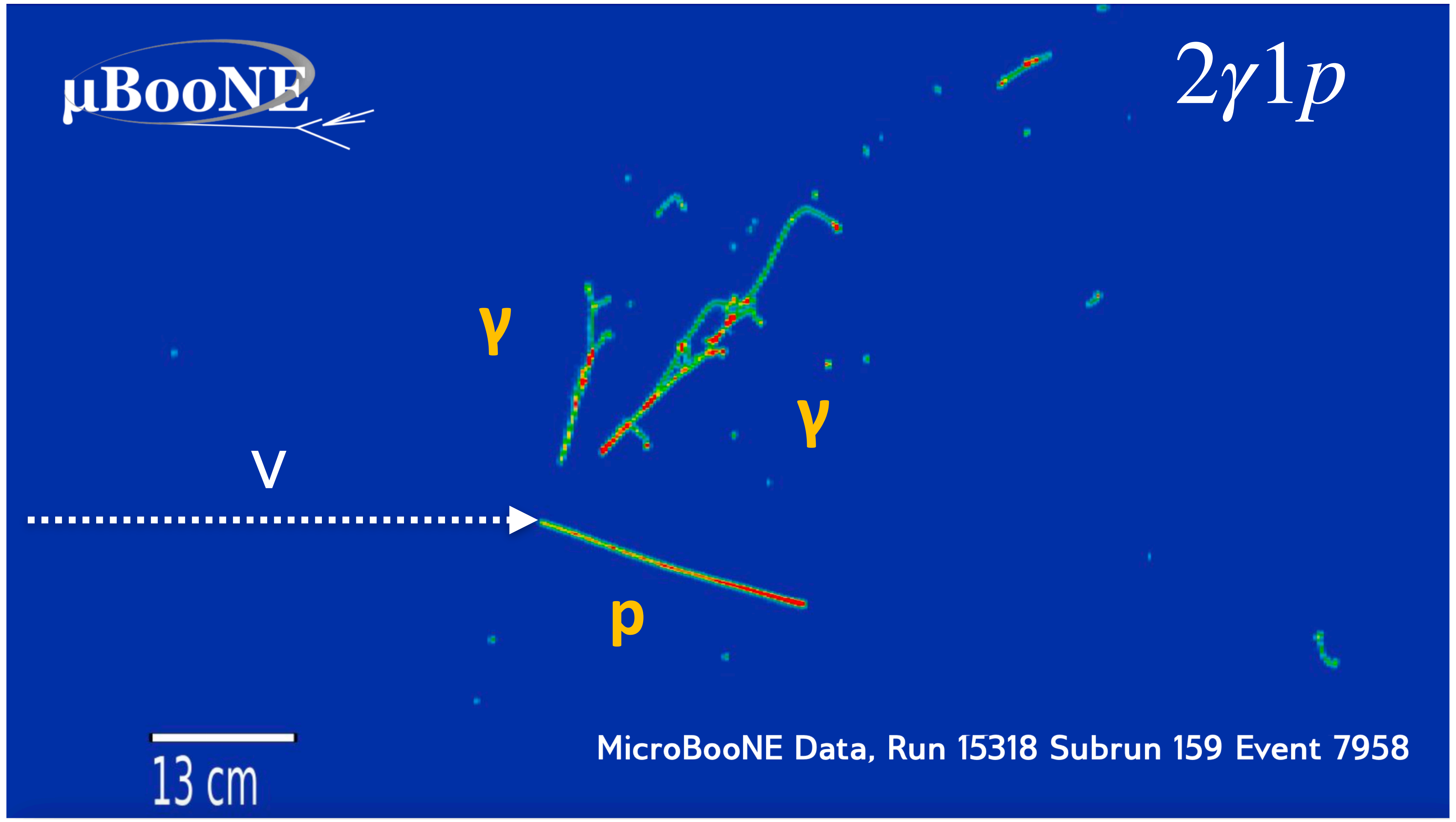


Nature 599, 565 (2021)

NC π^0 events are an important background to ν_e appearance

- $\pi^0 \rightarrow \gamma\gamma$ looks like e- if one shower is missed
  - Mimics ν_e interaction
- LArTPCs provide powerful γ/e- discrimination, but it is not perfect
- Remaining π^0 background must be estimated via simulation
- **How well-modeled are the NC π^0 interactions?**

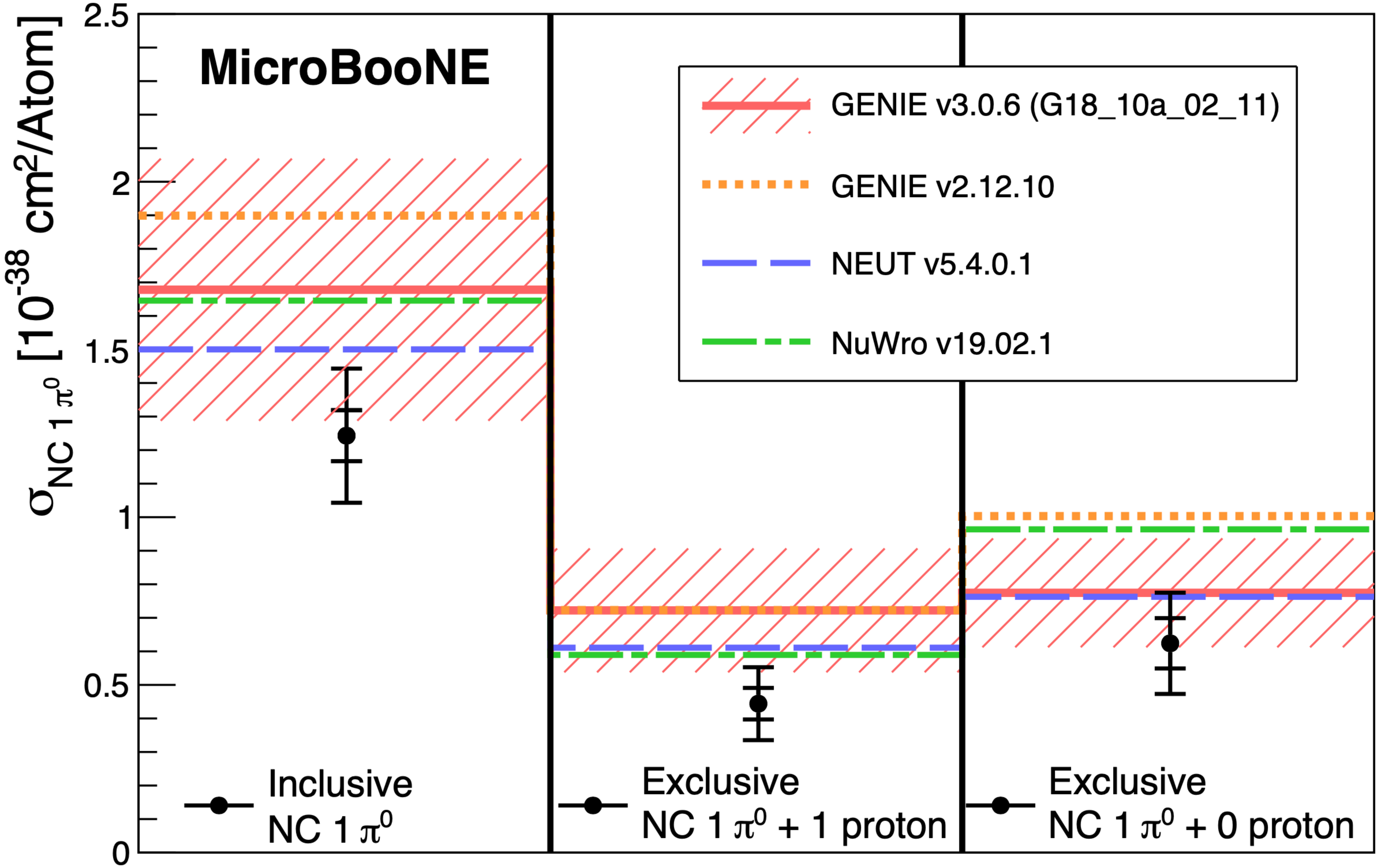




MicroBooNE NC 1π^0 total cross sections

- First NC 1π^0 inclusive on argon with $\langle E_\nu \rangle \approx 1$ GeV
- First exclusive NC 1π^0 measurements in the 0p and 1p channels (any target)
- Deficits seen compared to all models studied
  - ~1σ in terms of GENIE v3 uncertainty band
- Results also useful for non-ν_e BSM searches (see talk by **Hanyu Wei**)

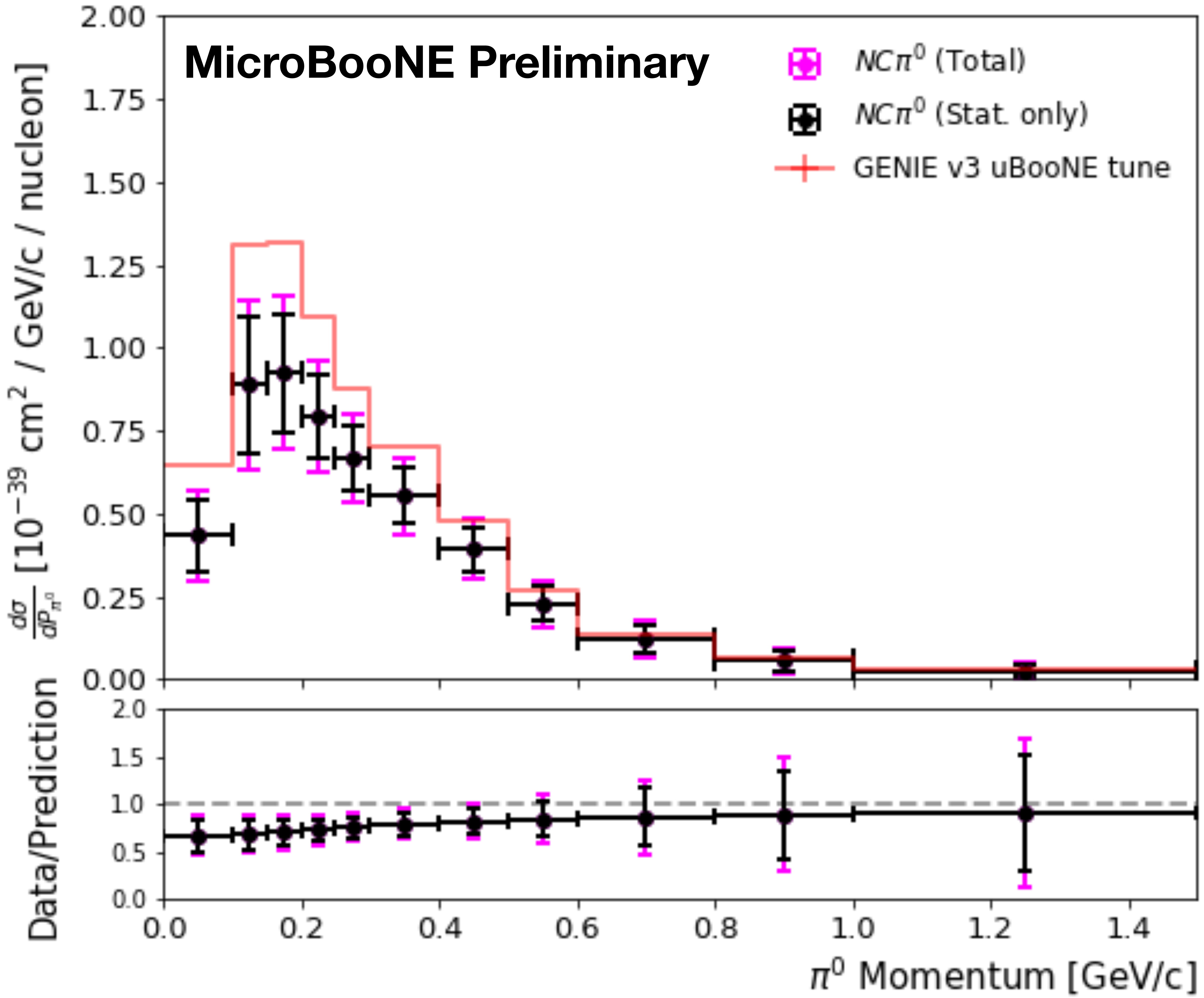
[arXiv:2205.07943](https://arxiv.org/abs/2205.07943), submitted to PRD



N. Oza, Poster #756

Differential NC π^0 cross sections

- Analysis for NC $(\geq 1)\pi^0$ well underway
  - ~1σ deficit apparent over much of the phase space
- Preliminary result statistics-limited
  - Few % of available data
- Much more coming soon!



G. Scanavini, [Poster #759]

[MICROBOONE-NOTE-1111-PUB]

Hadronic energy modeling is crucial for neutrino calorimetry

- Oscillation measurements require understanding **energy-dependent event rates**

"Easy" **Hard**

$$E_\nu = E_\ell + \omega$$

- $E_{cal} \approx E_\nu$: add up everything, correct for missing energy

$$\omega = E_{\mathrm{had}} + E_{\mathrm{miss}}$$

- E_{miss} can be a large fraction of the total

Hadronic energy modeling is crucial for neutrino calorimetry

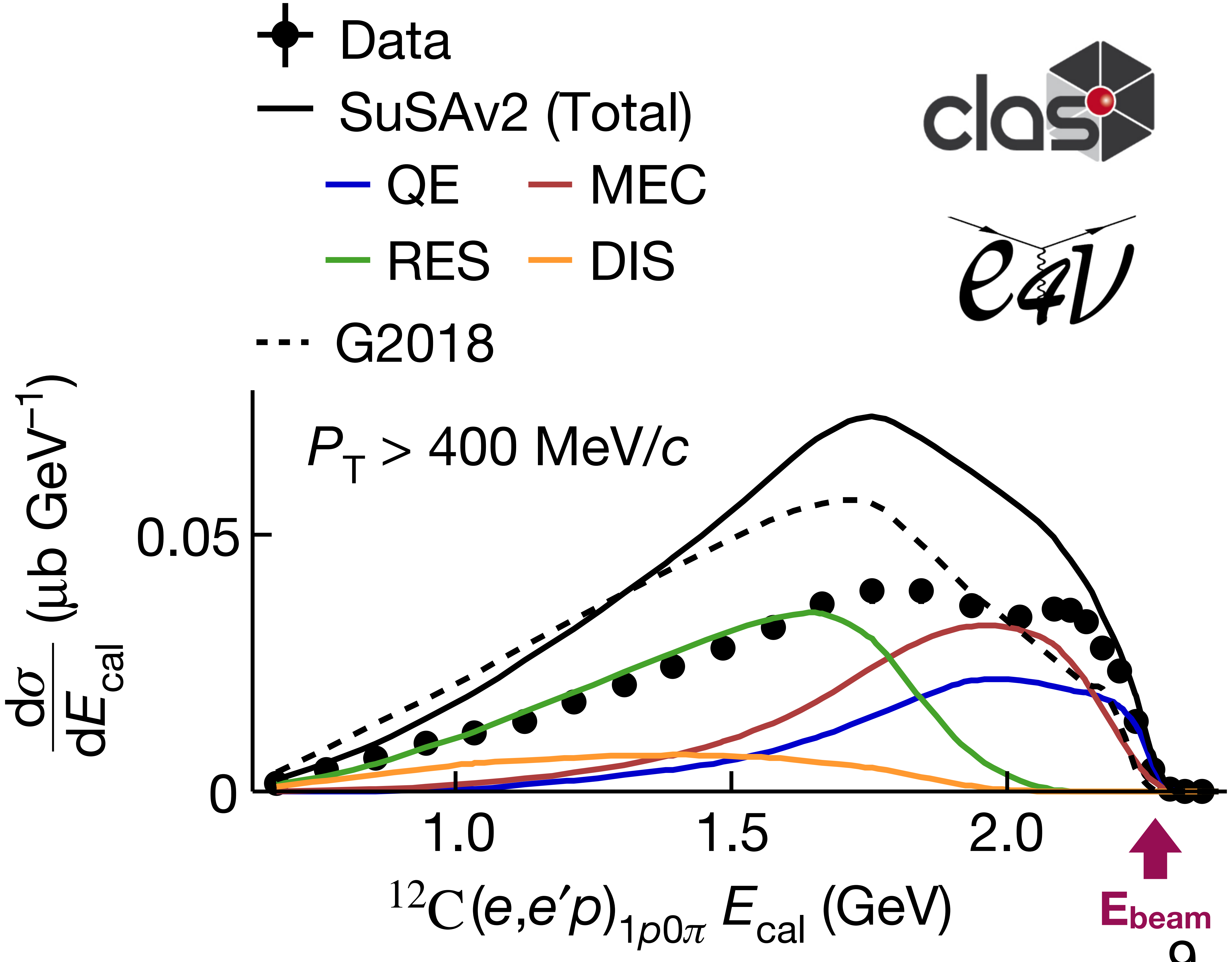
- Oscillation measurements require understanding **energy-dependent event rates**

“Easy” **Hard**

$$E_\nu = E_\ell + \omega$$

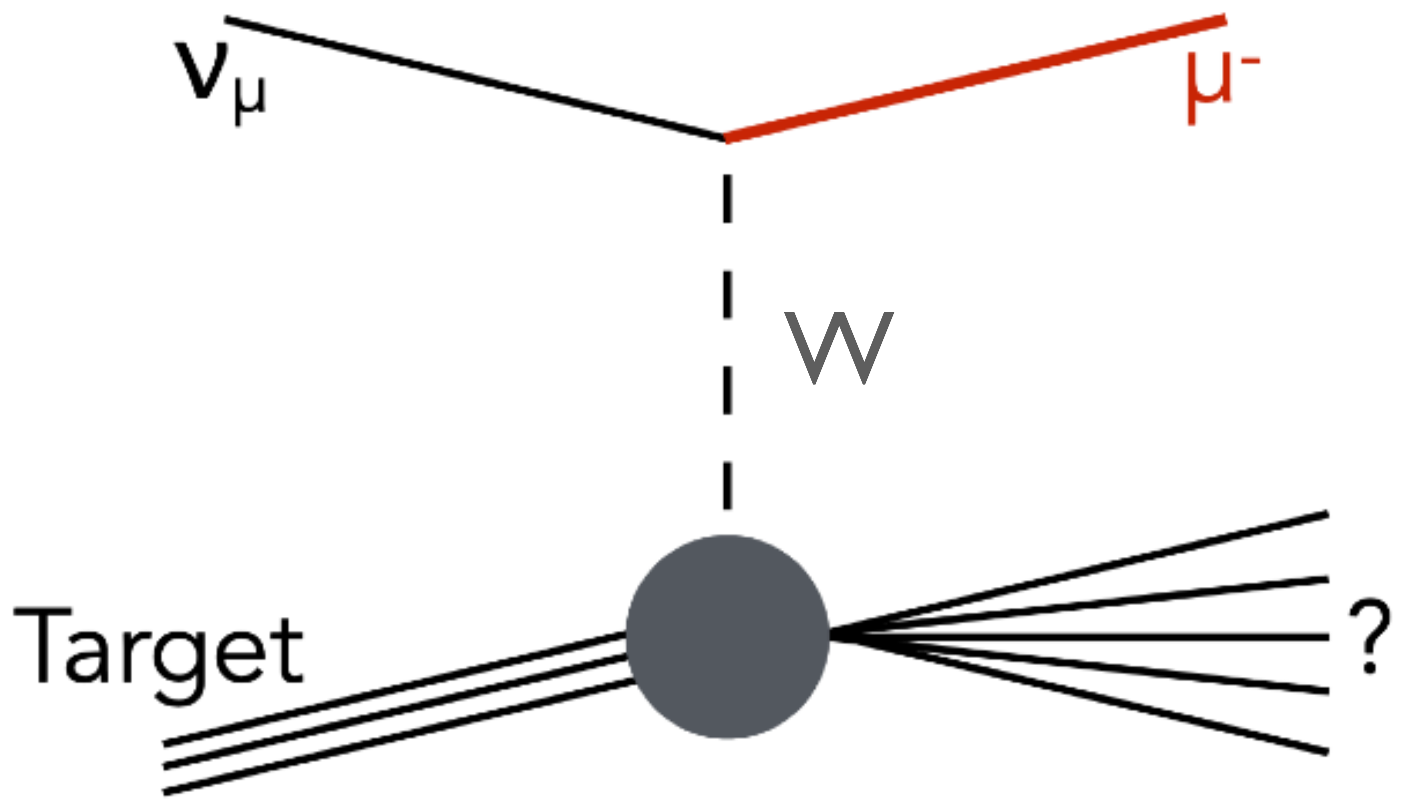
- $E_{cal} \approx E_\nu$: add up everything, correct for missing energy
- Current simulations do not describe the bias well
  - Benchmarked with **electron beam data** (monoenergetic, high-statistics)

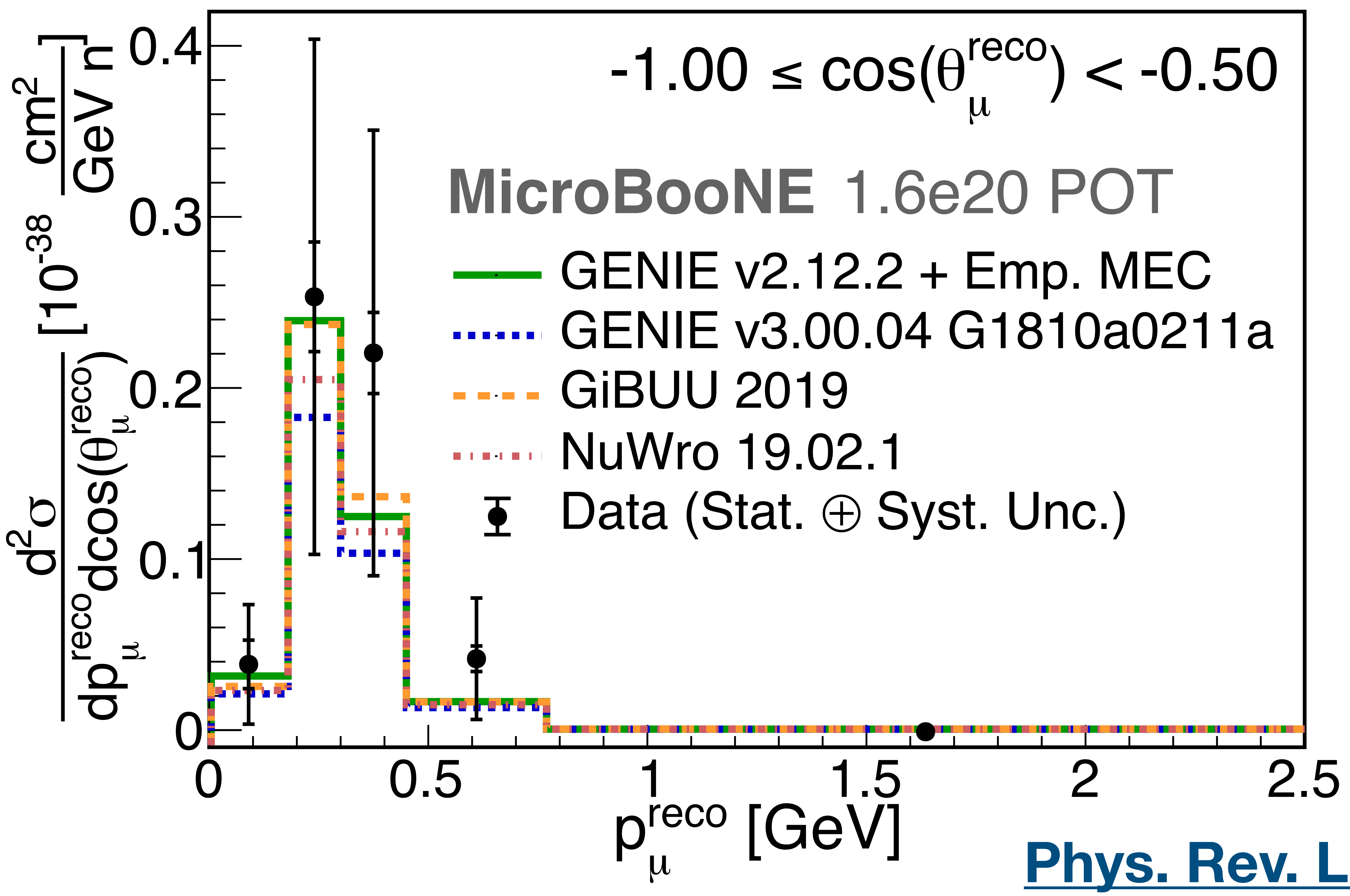
CLAS and e4v Collaborations, [Nature 599, 565 (2021)]
(See talk by **Or Hen**)

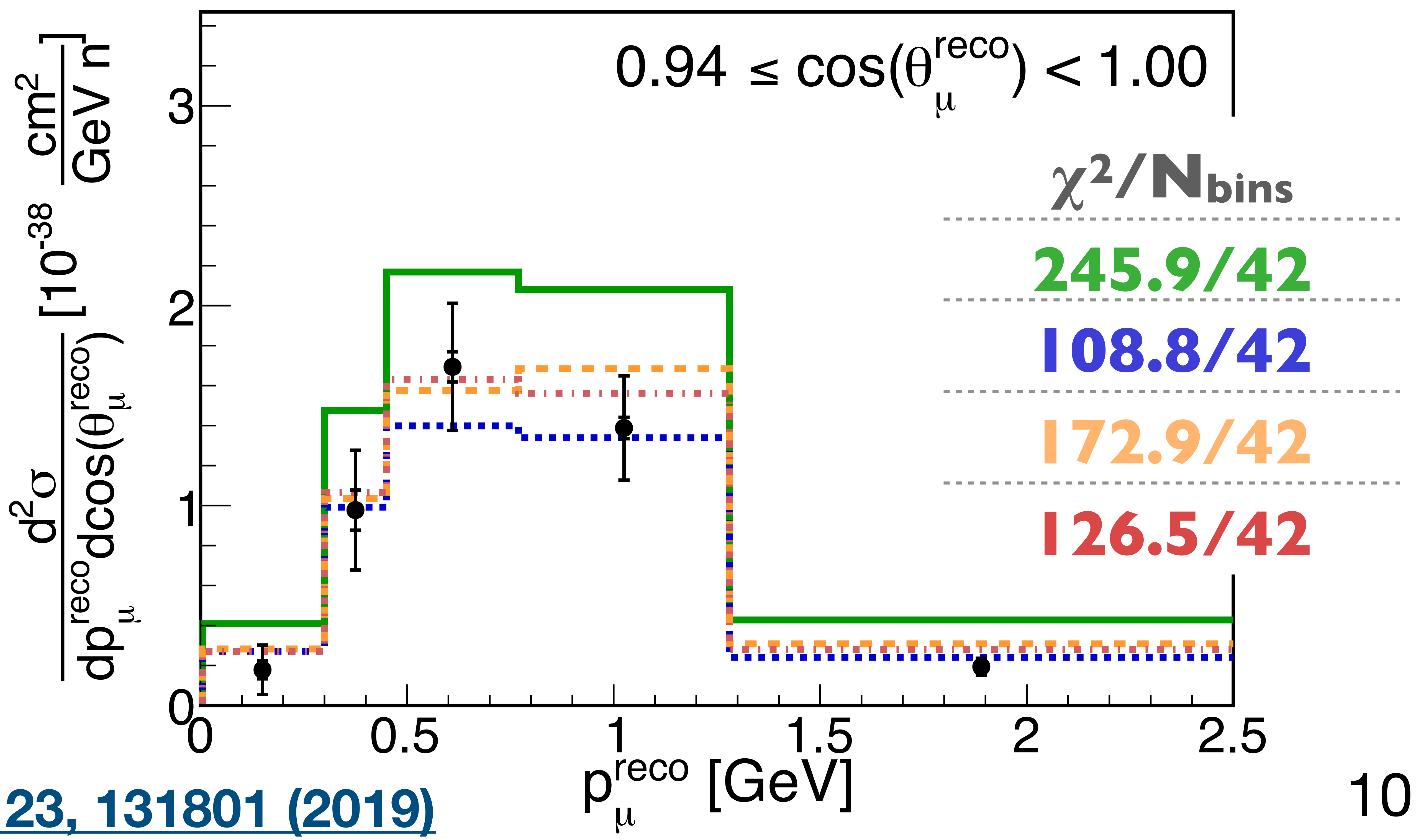


Neutrino 2020 era: lepton kinematics in CC inclusive

- Shed light on the "easy" part of the model: **E_ℓ**
- Recent work has pursued the "hard" part: **ω**







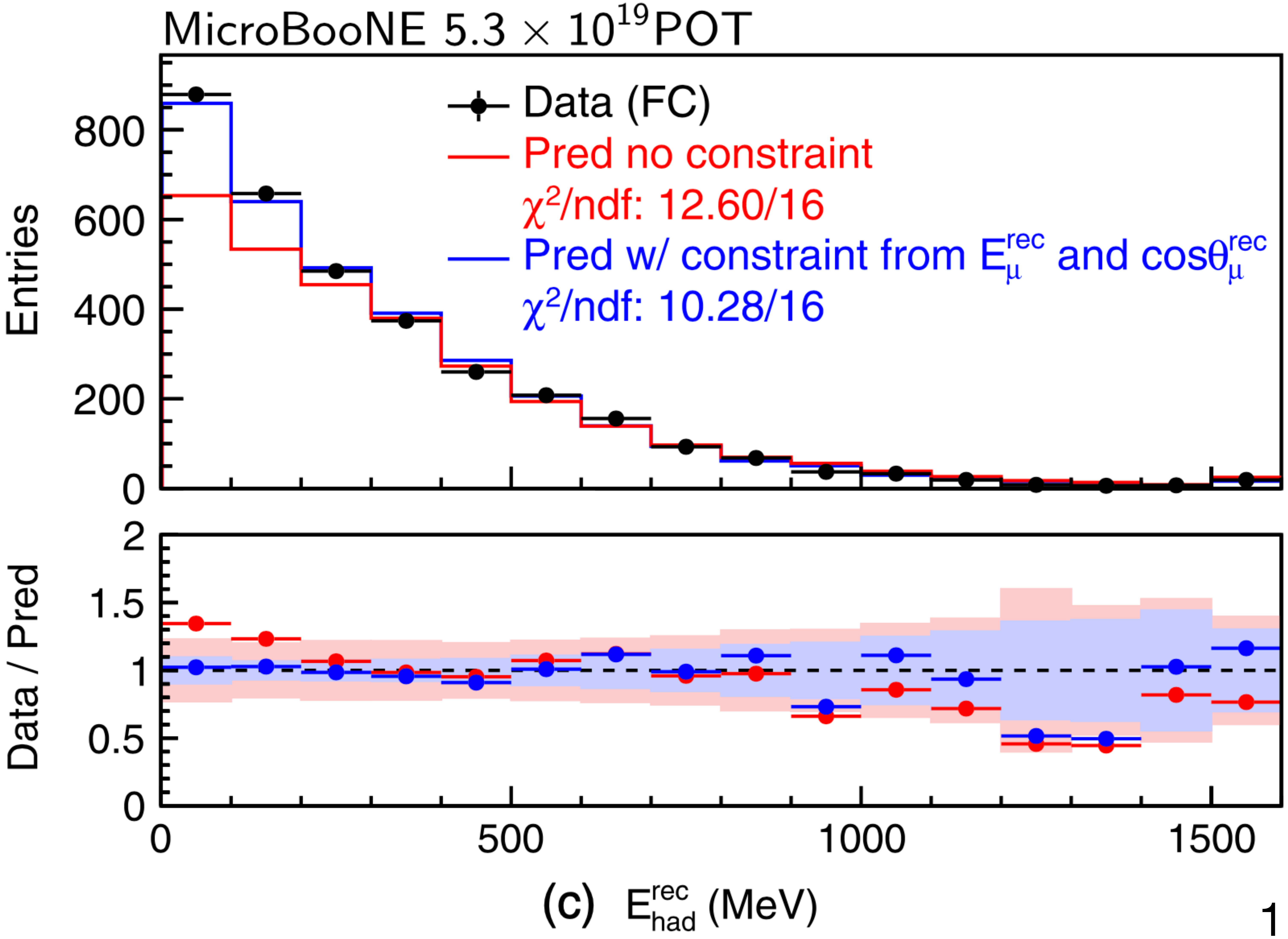
Phys. Rev. Lett. 123, 131801 (2019)

Enabling measurements of E_ν and ω with MicroBooNE

- Key observables, but a reliable model is needed to extract them from data

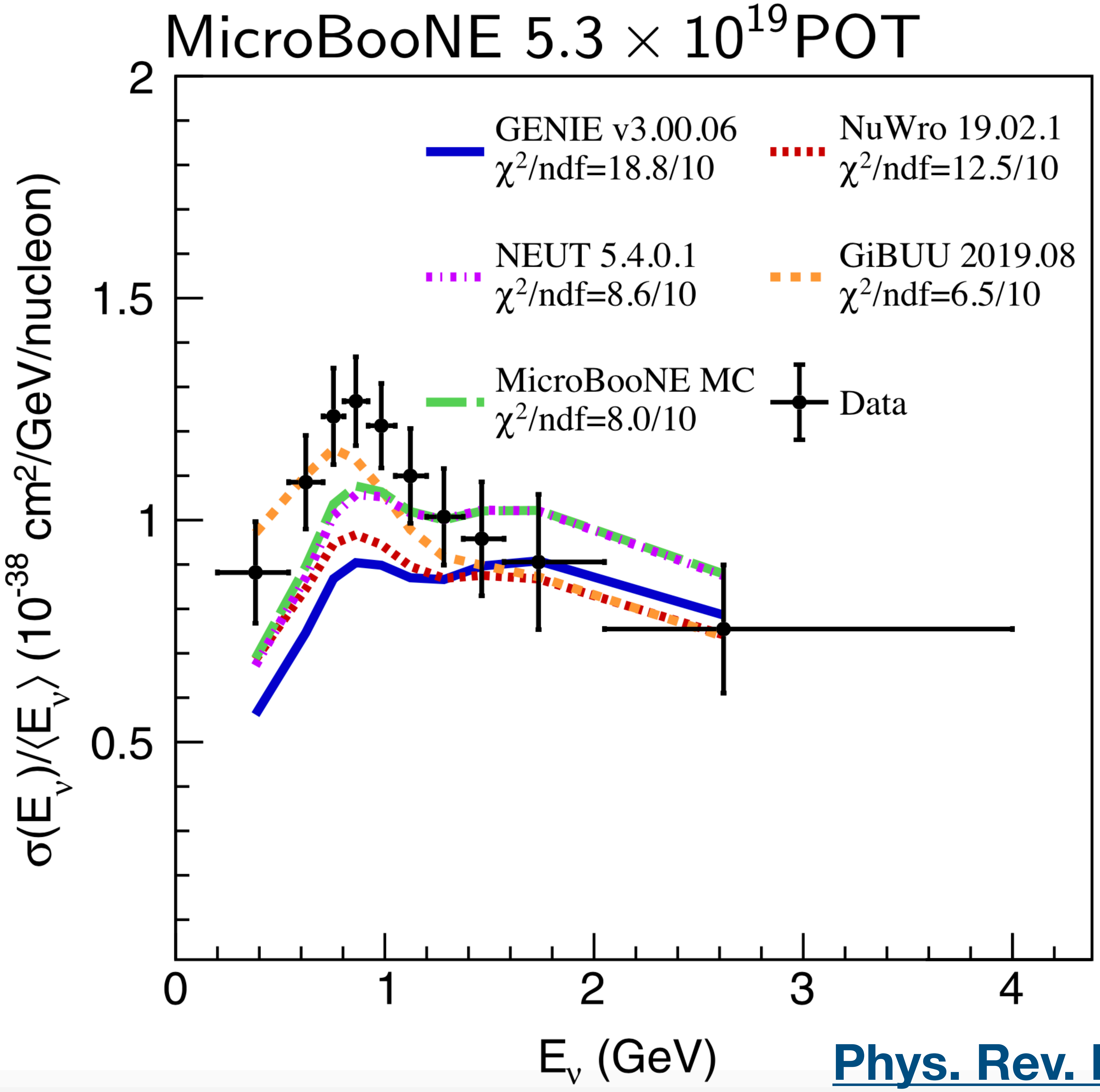
- Suitability validated with a novel constraint procedure
  - Refine $E_{\mathrm{had}}^{\mathrm{rec}}$ prediction using muon kinematics
  - Sensitive to ~15% mismodeling of missing energy

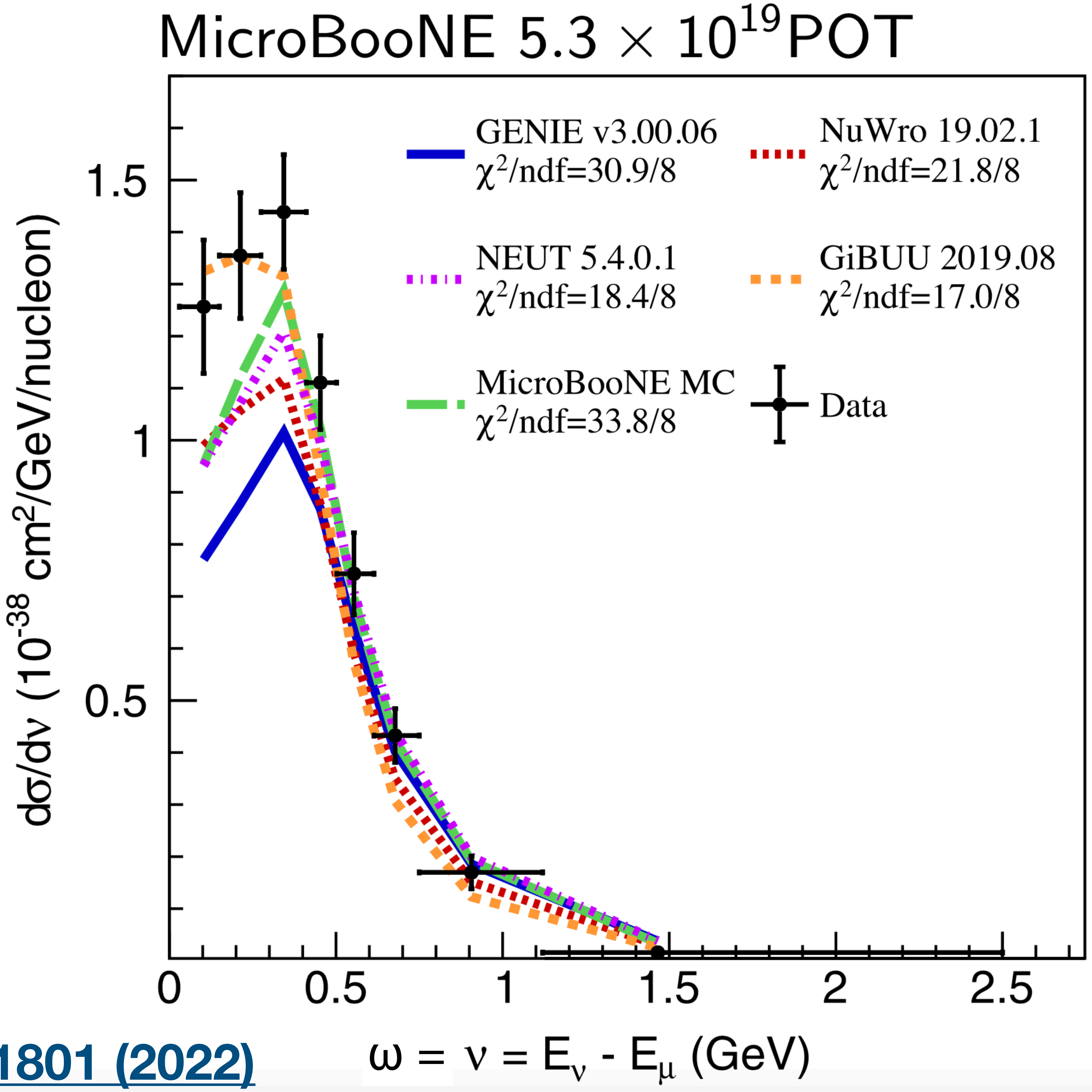
Phys. Rev. Lett. 128, 151801 (2022)



Initial results already discriminate between models

- Preference for GiBUU at low E_ν and ω
- Foundation for multi-differential measurements (L. Cooper-Troendle, **Poster #766**)

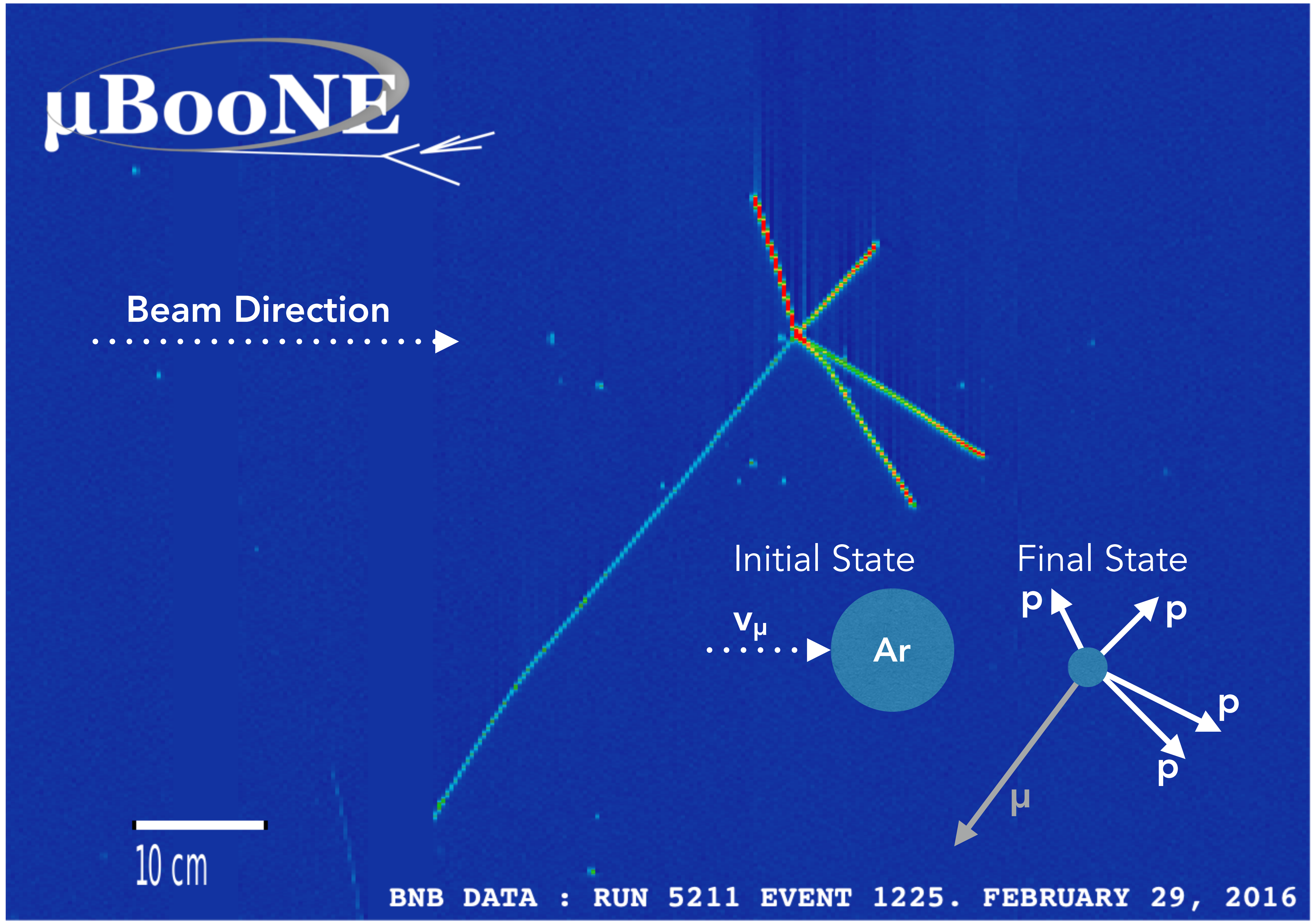




Phys. Rev. Lett. 128, 151801 (2022)

LArTPCs enable greater understanding of QE-like interactions

- Real-world analyses are sensitive to full final-state modeling
  - Efficiency corrections, backgrounds, etc.
- High-quality proton reconstruction in LArTPCs
  - Probe nuclear physics of ν_μ CC 0π events with unprecedented detail



Proton momentum thresholds

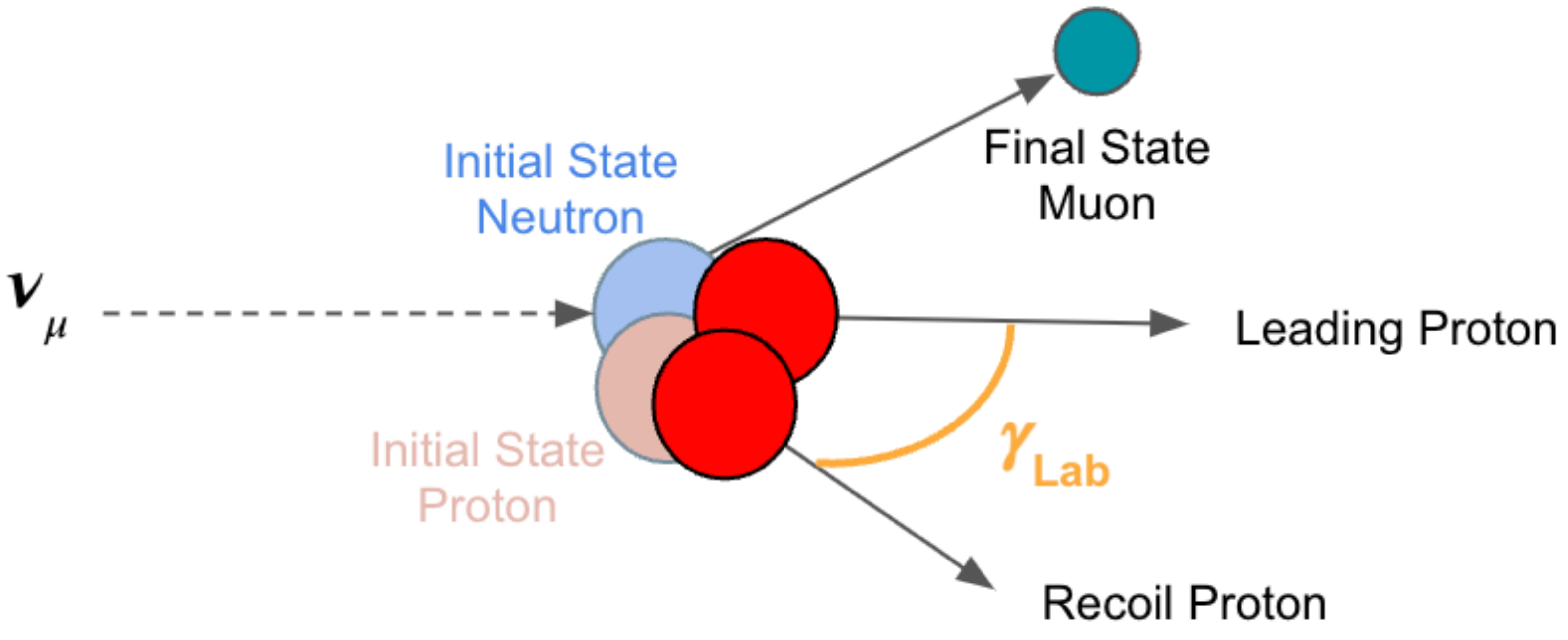
T2K: 500 MeV/c
Phys. Rev. D 99, 012004 (2019)

MINERvA: 450 MeV/c
Phys. Rev. D 98, 032003 (2018)

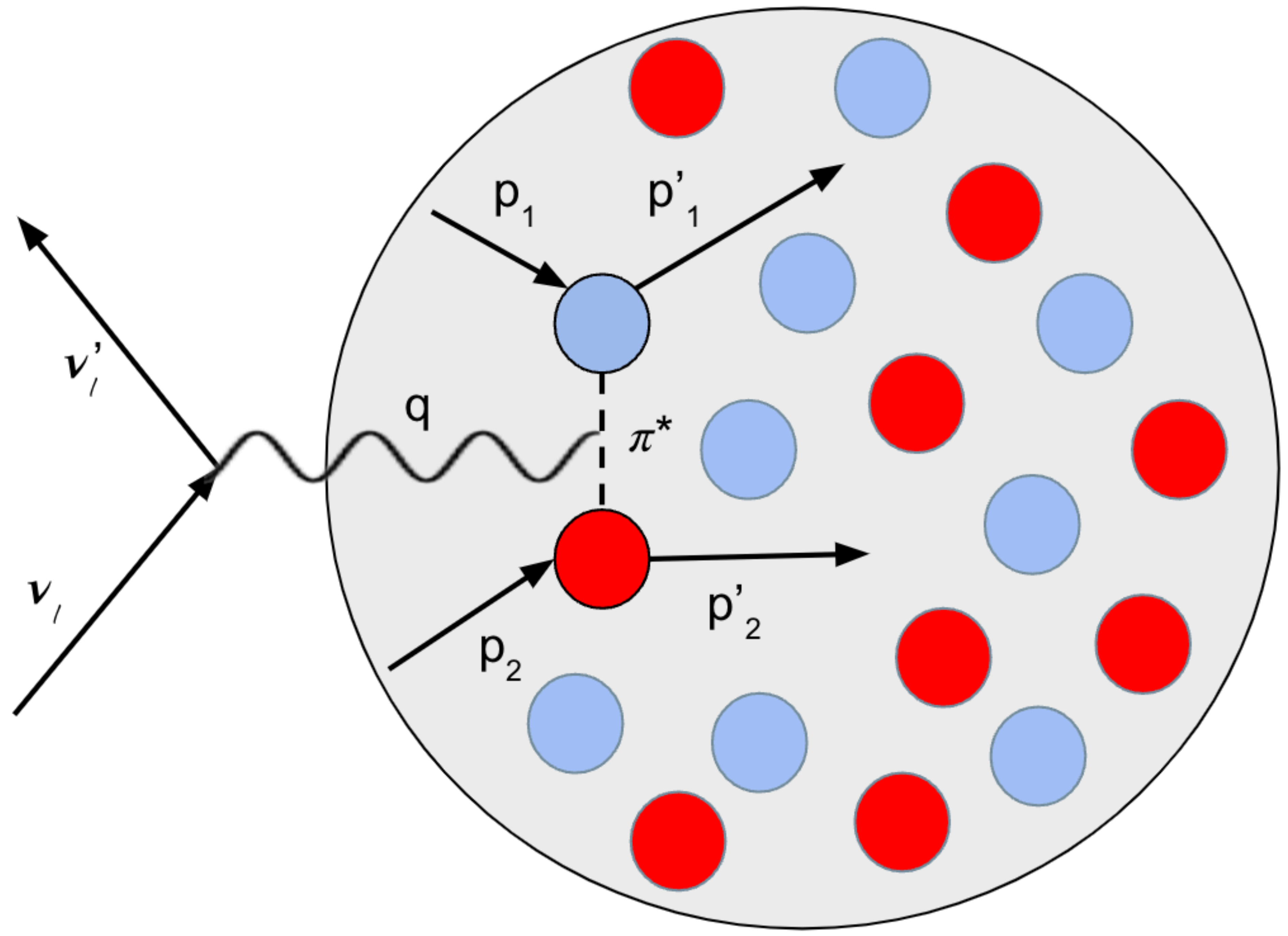
MicroBooNE: 300 MeV/c
Phys. Rev. D 102, 112013 (2020)

ν_μ CC 0π 2p

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



Meson exchange currents (MEC)



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

S. Sword-Fehlberg, [Poster #723]

[MICROBOONE-NOTE-1117-PUB]

ν_μ CC 0π 2p

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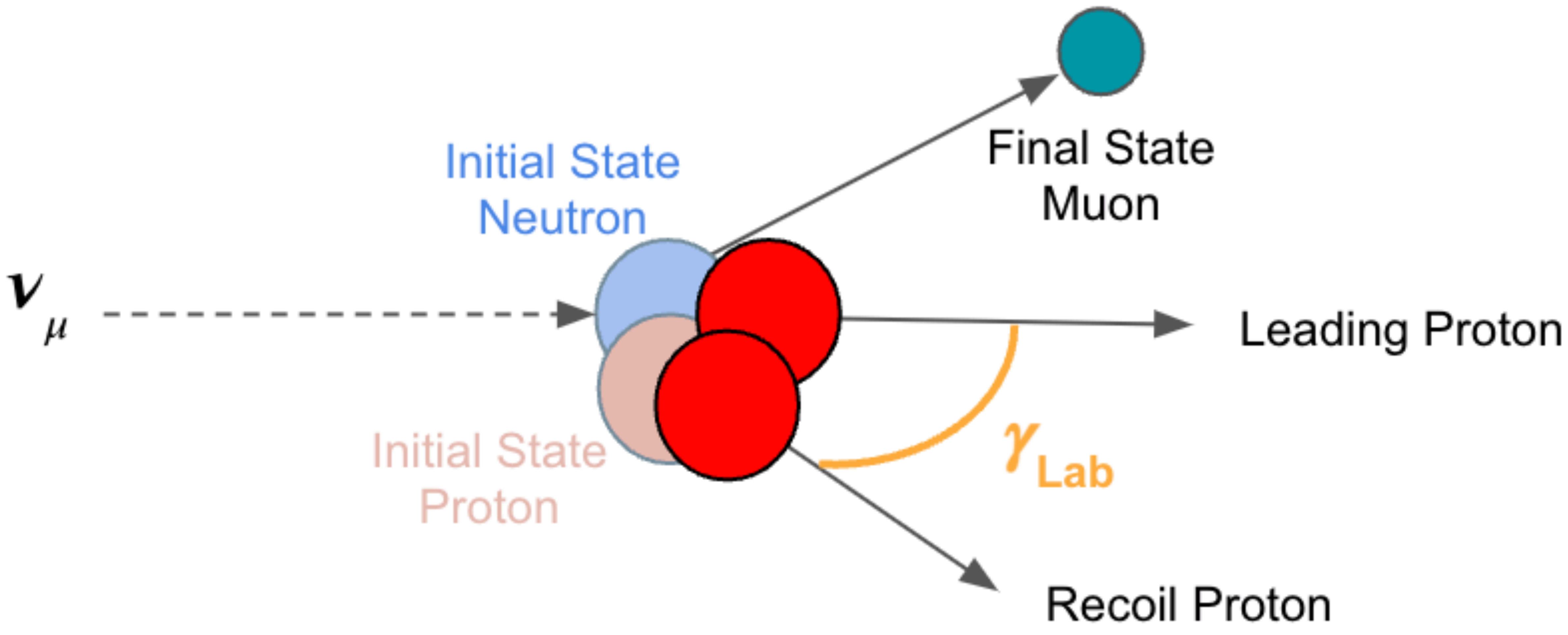

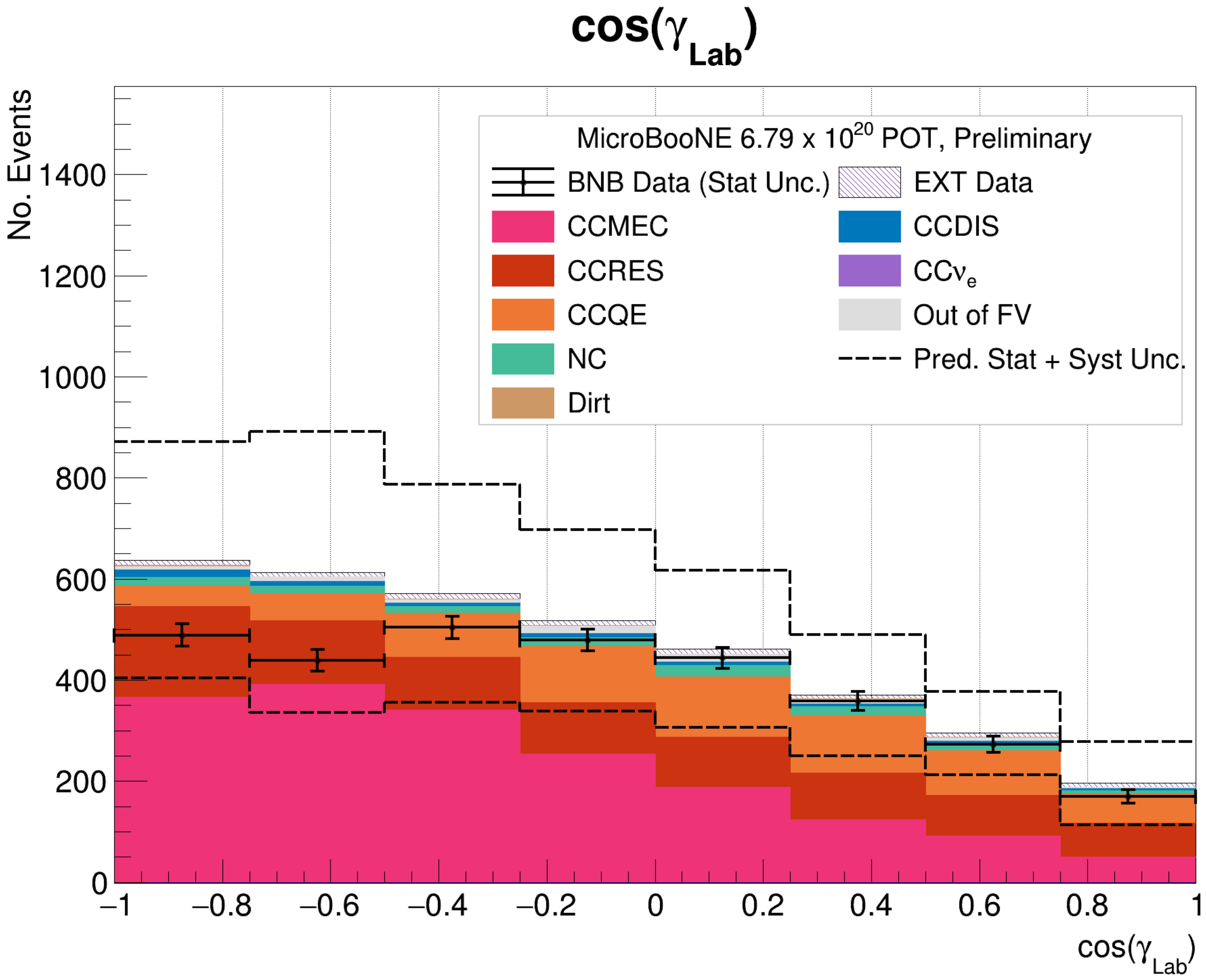

S. Sword-Fehlberg, Poster #723

MICROBOONE-NOTE-1117-PUB

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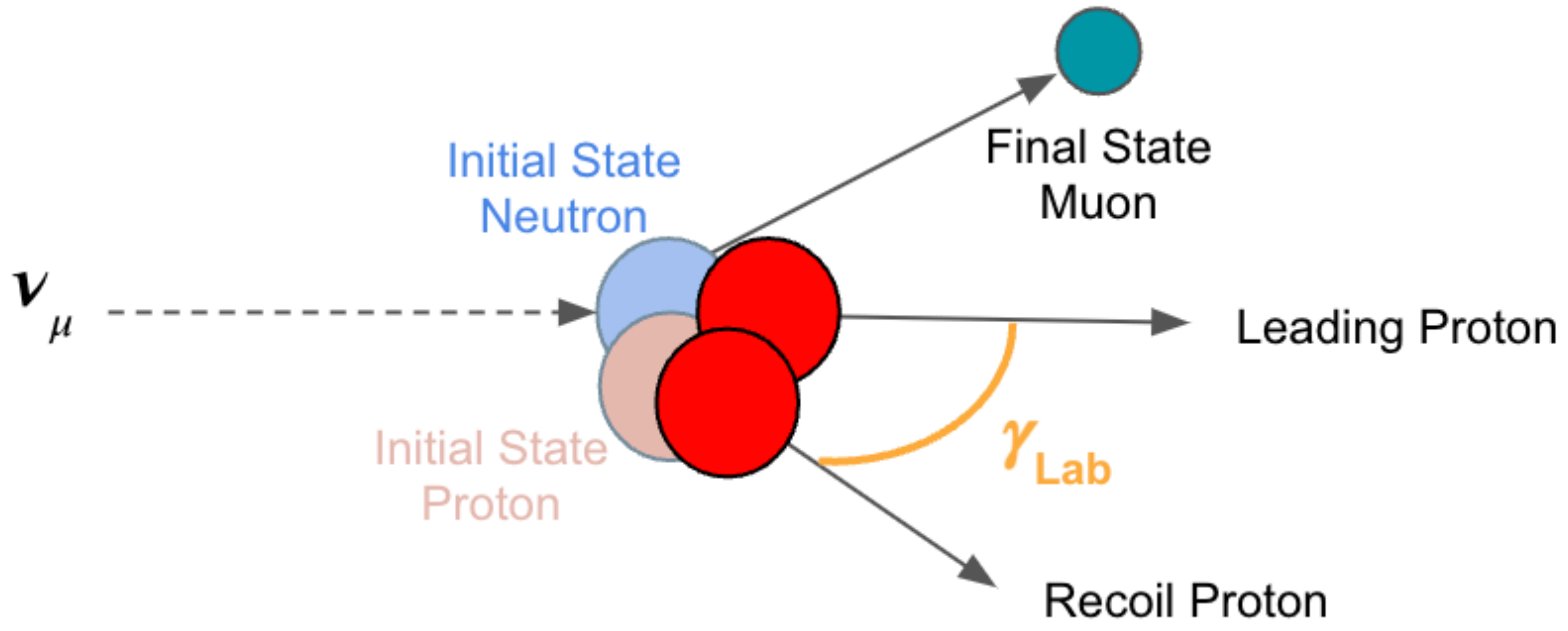
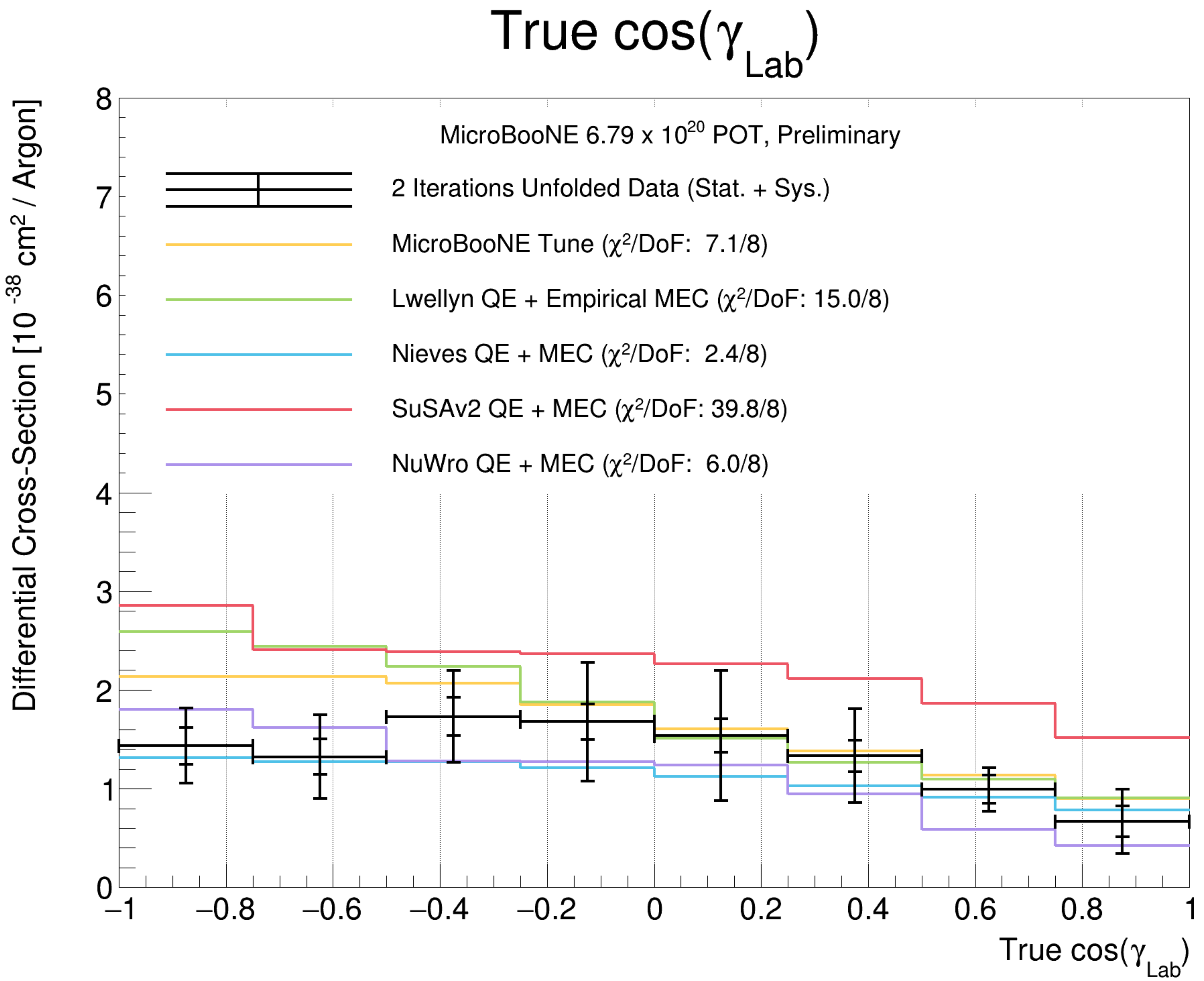
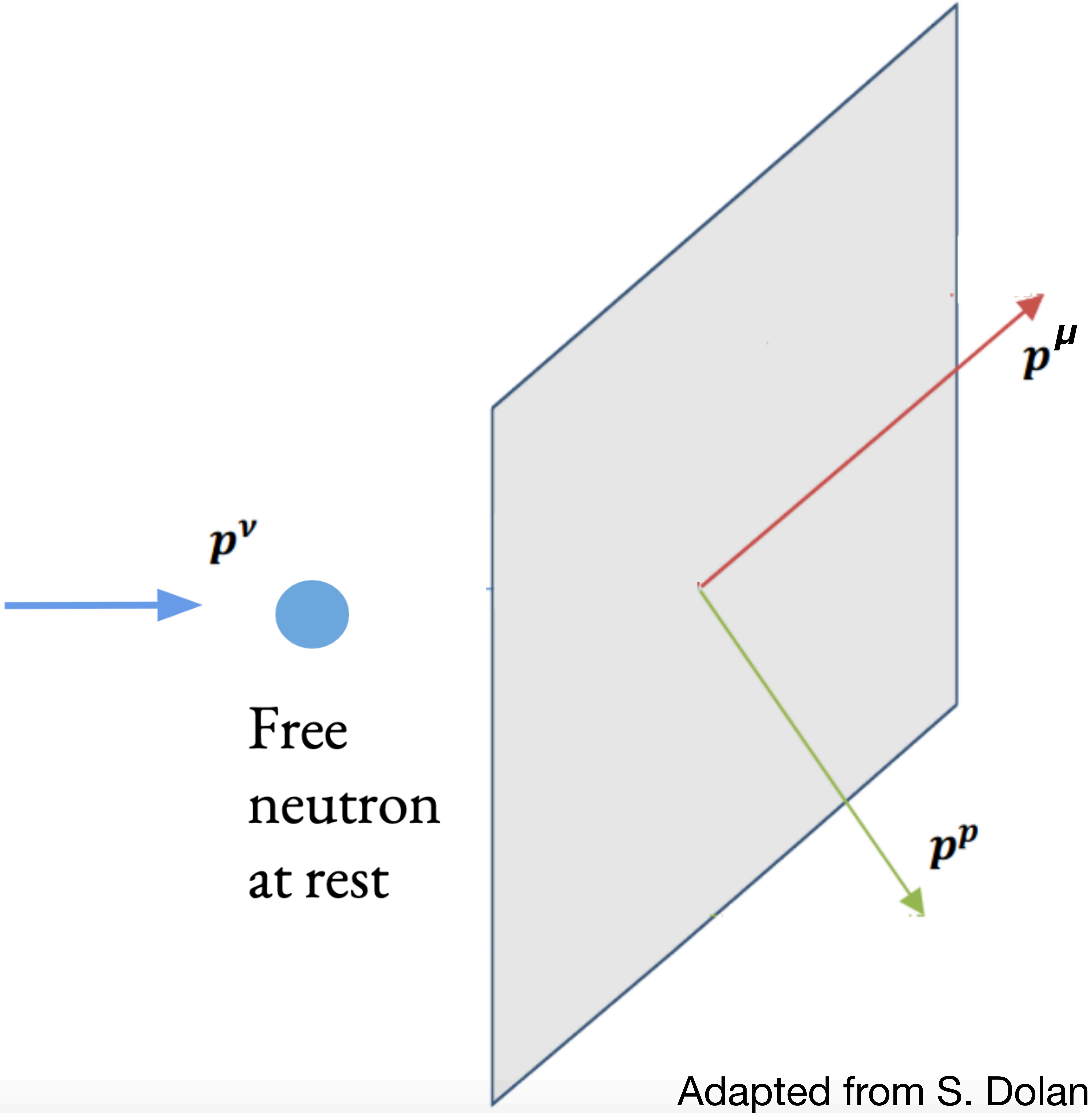




S. Sword-Fehlberg, Poster #723

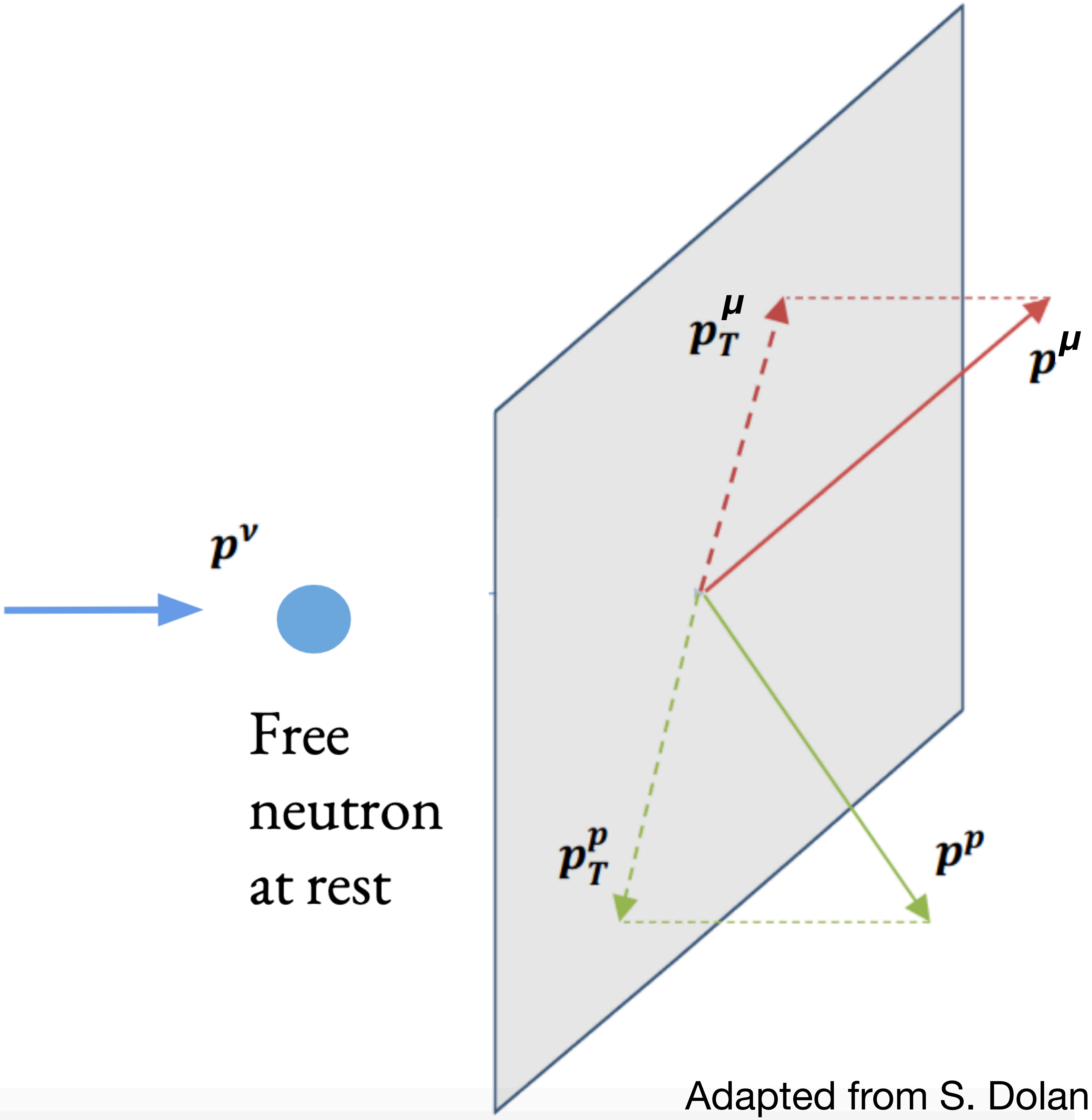
MICROBOONE-NOTE-1117-PUB

Transverse kinematic imbalance (TKI)



Adapted from S. Dolan, "[Exploring nuclear effects with transverse imbalances]"

Transverse kinematic imbalance (TKI)

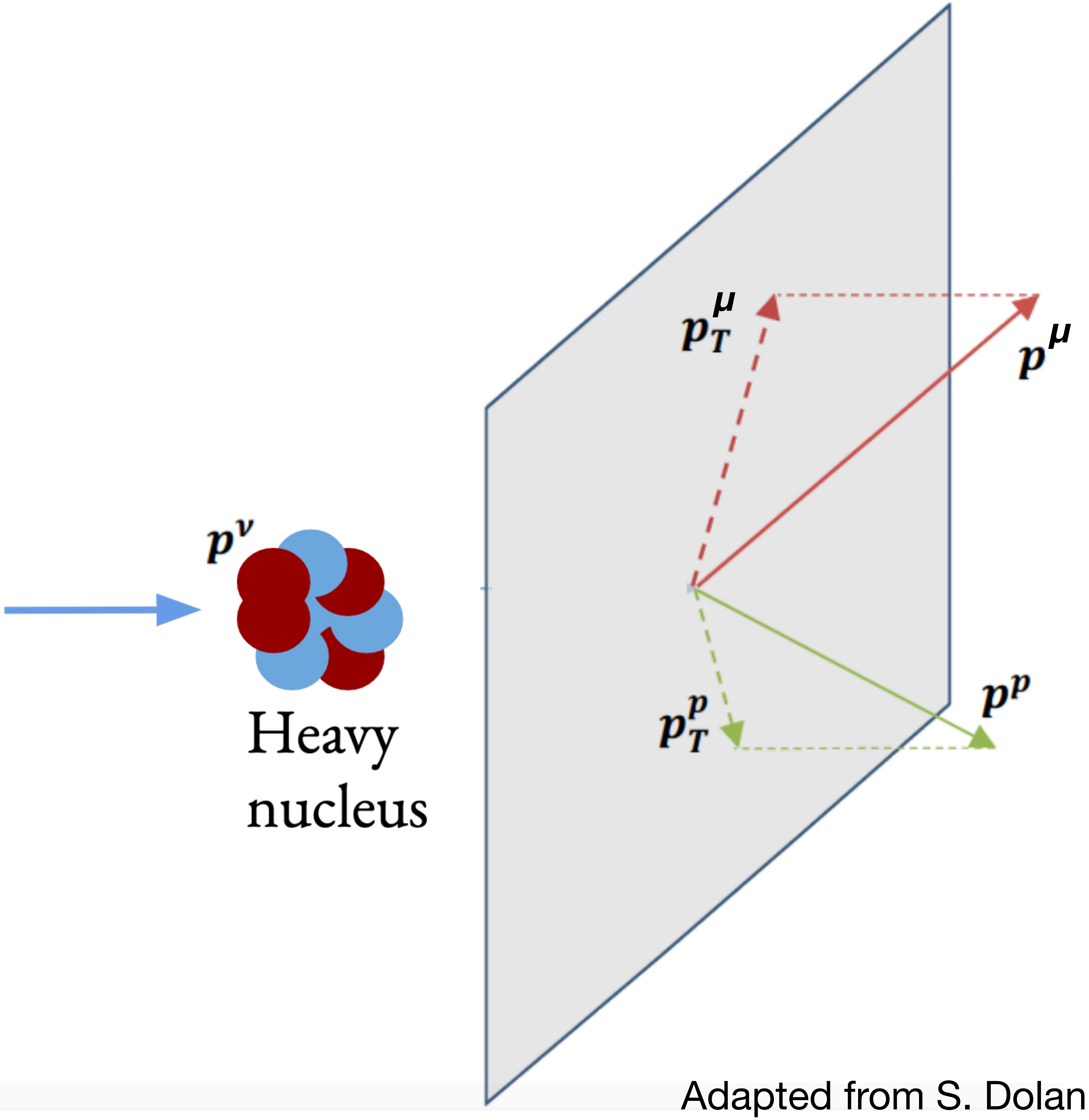


$$\delta p_T = \left| \mathbf{p}_T^{\mu} + \mathbf{p}_T^{p} \right| = 0$$

Transverse projections
trivially equal and opposite
(momentum conservation)

Adapted from S. Dolan, "**Exploring nuclear effects with transverse imbalances**"

Transverse kinematic imbalance (TKI)

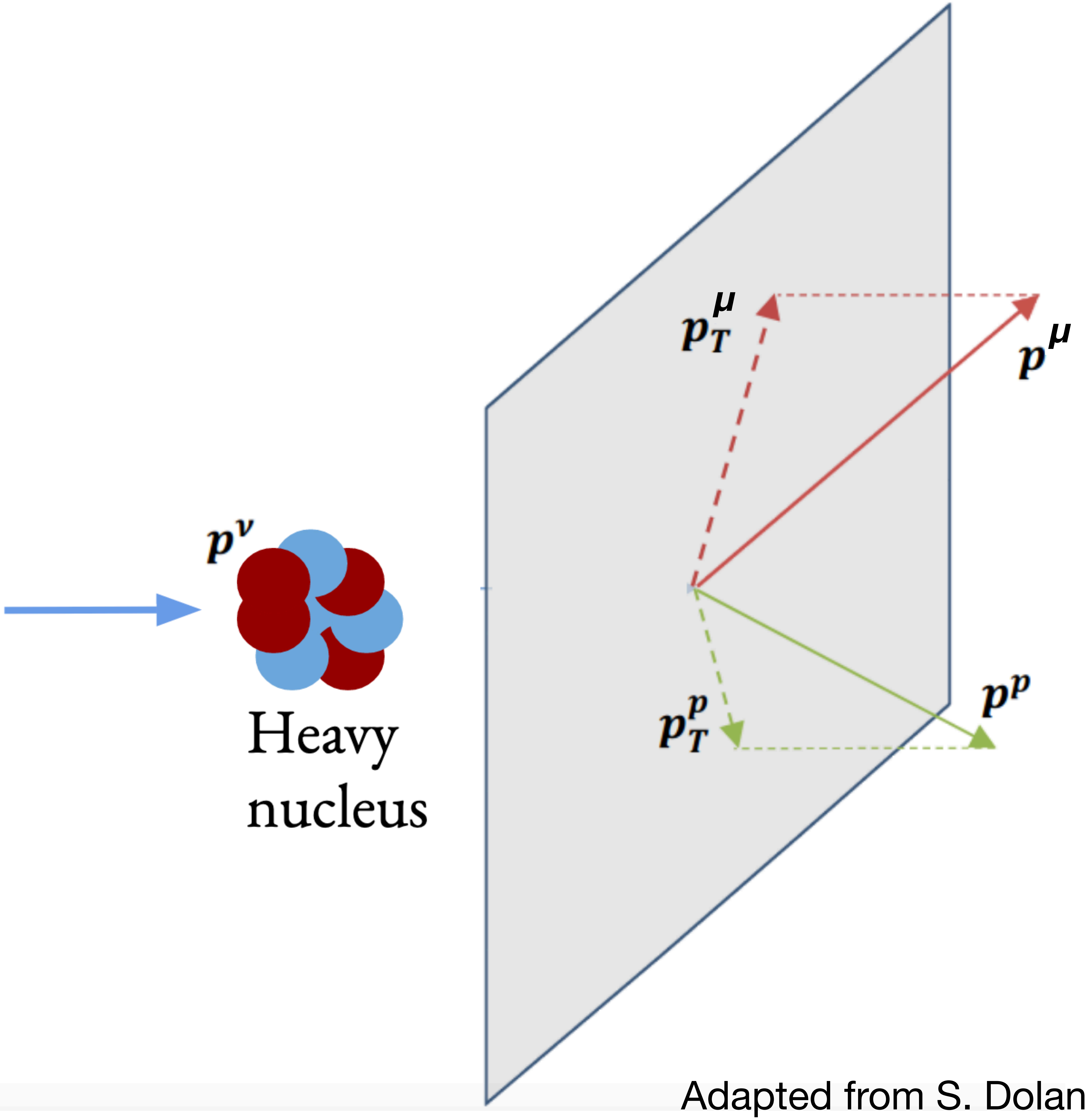


$$\delta p_T = \left| \mathbf{p}_T^\mu + \mathbf{p}_T^p \right| > 0$$

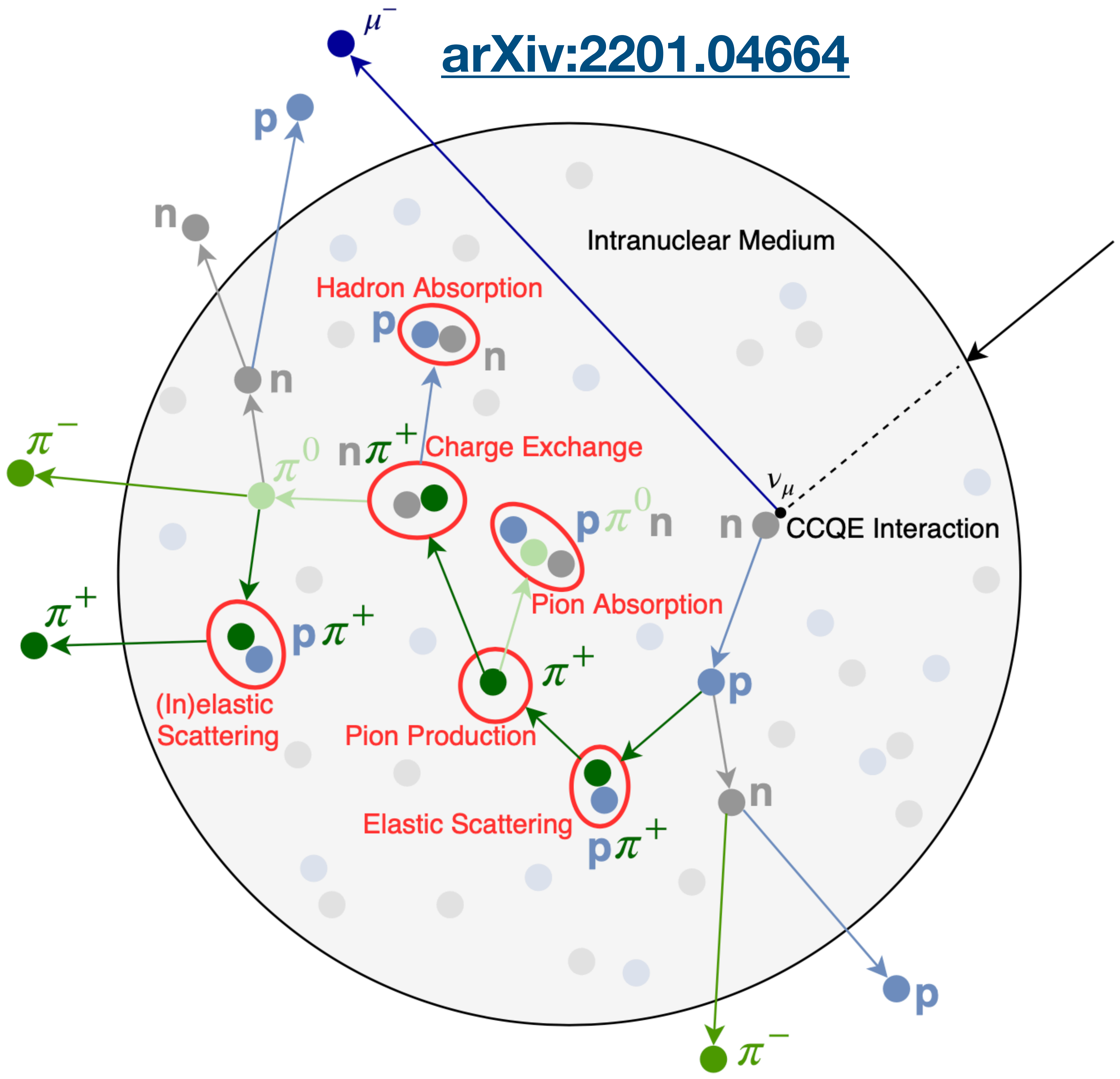
Imbalance due to initial nucleon motion and other nuclear effects

Adapted from S. Dolan, "Exploring nuclear effects with transverse imbalances"

Transverse kinematic imbalance (TKI)



Hadronic final-state interactions (FSI)



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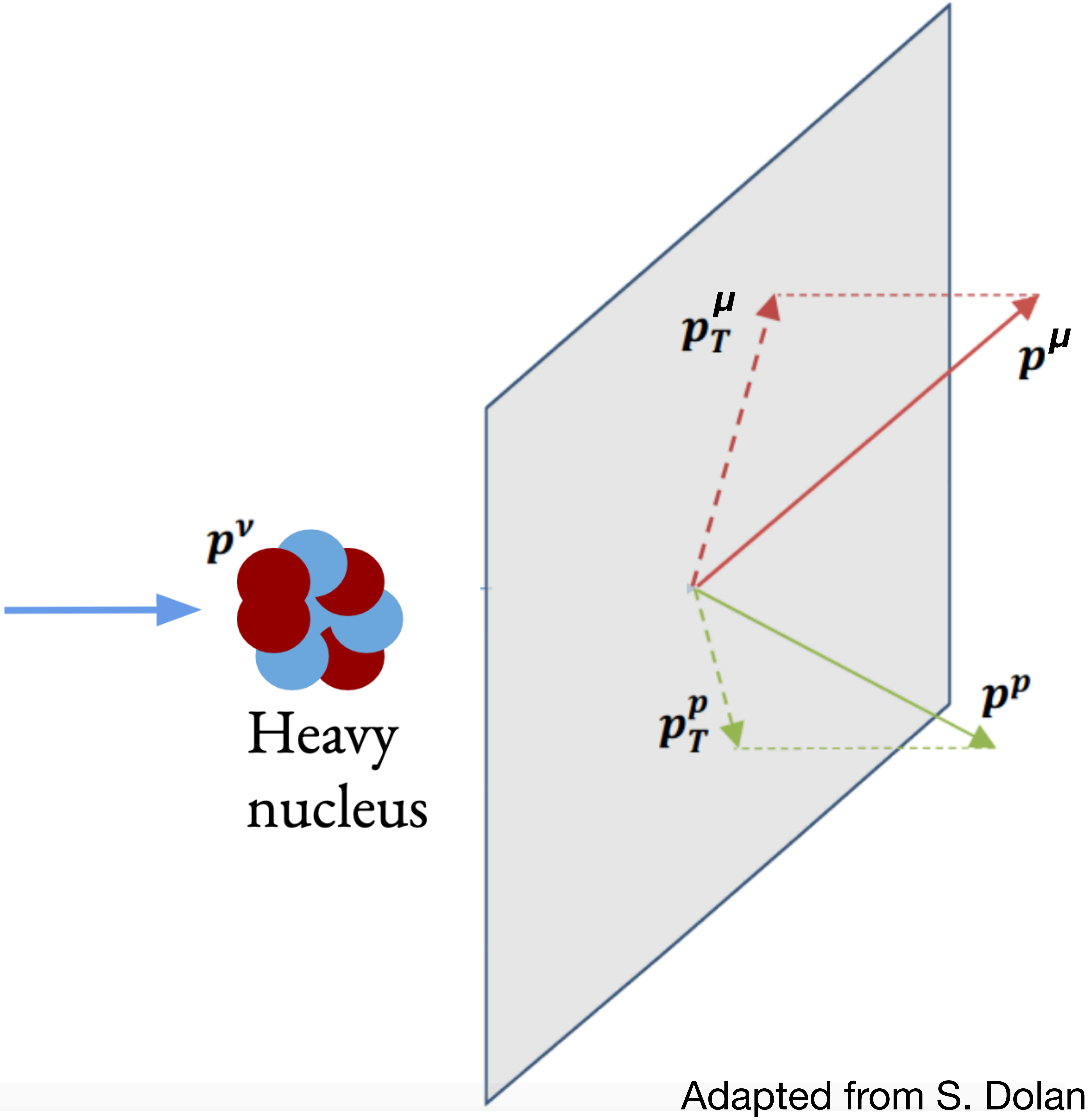
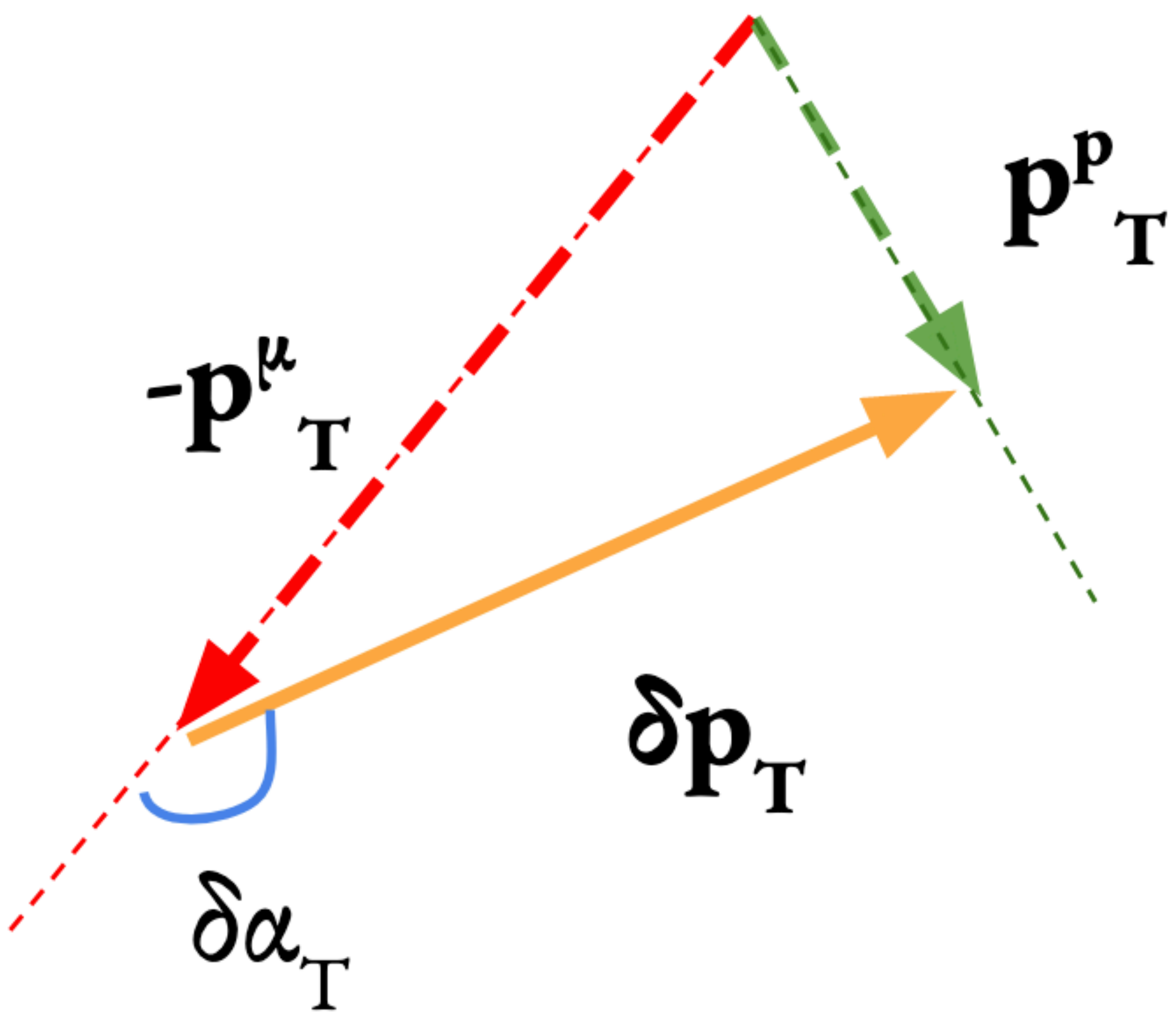
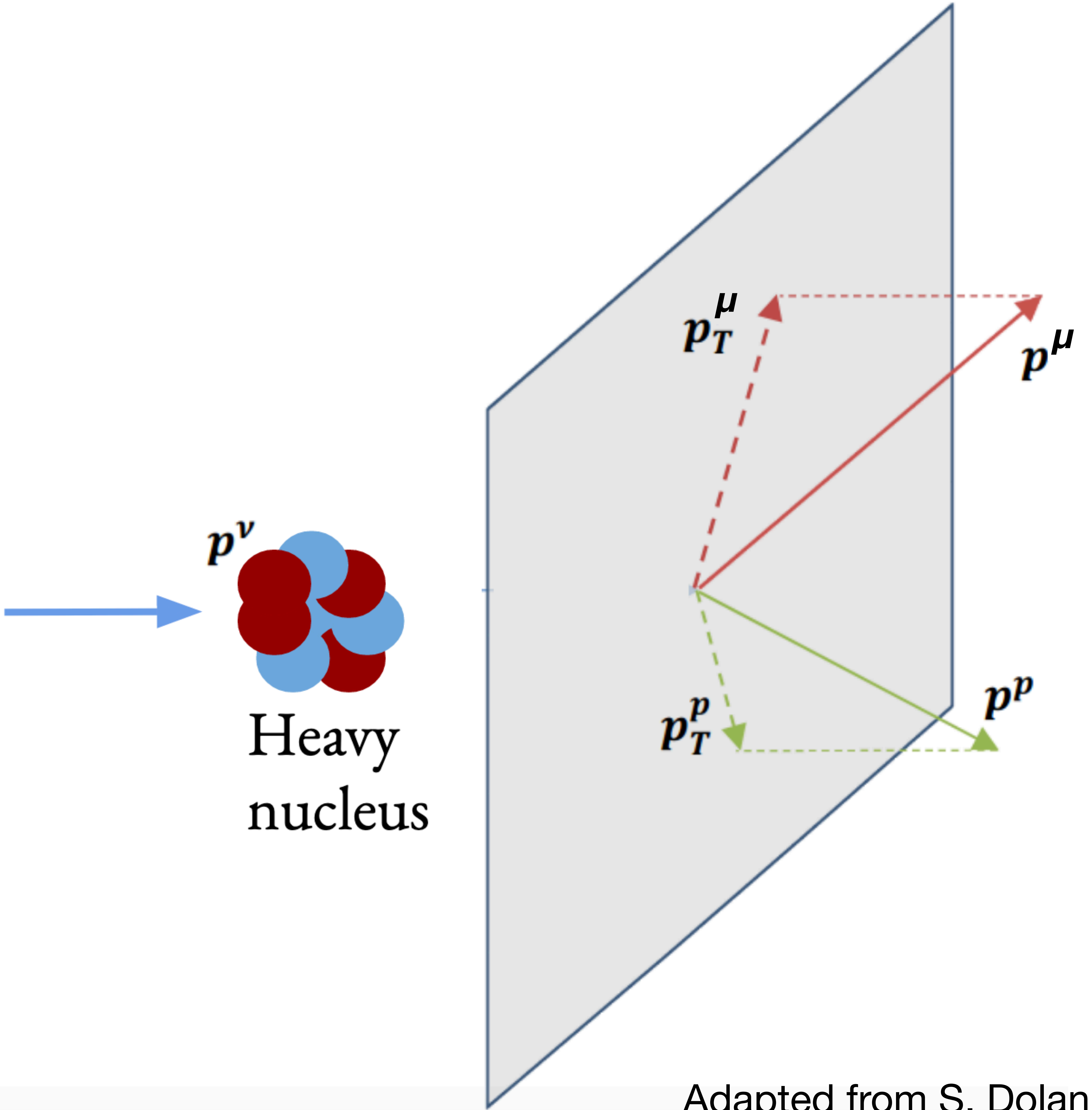


Orientation of the imbalance ($\delta\alpha_T$) also meaningful

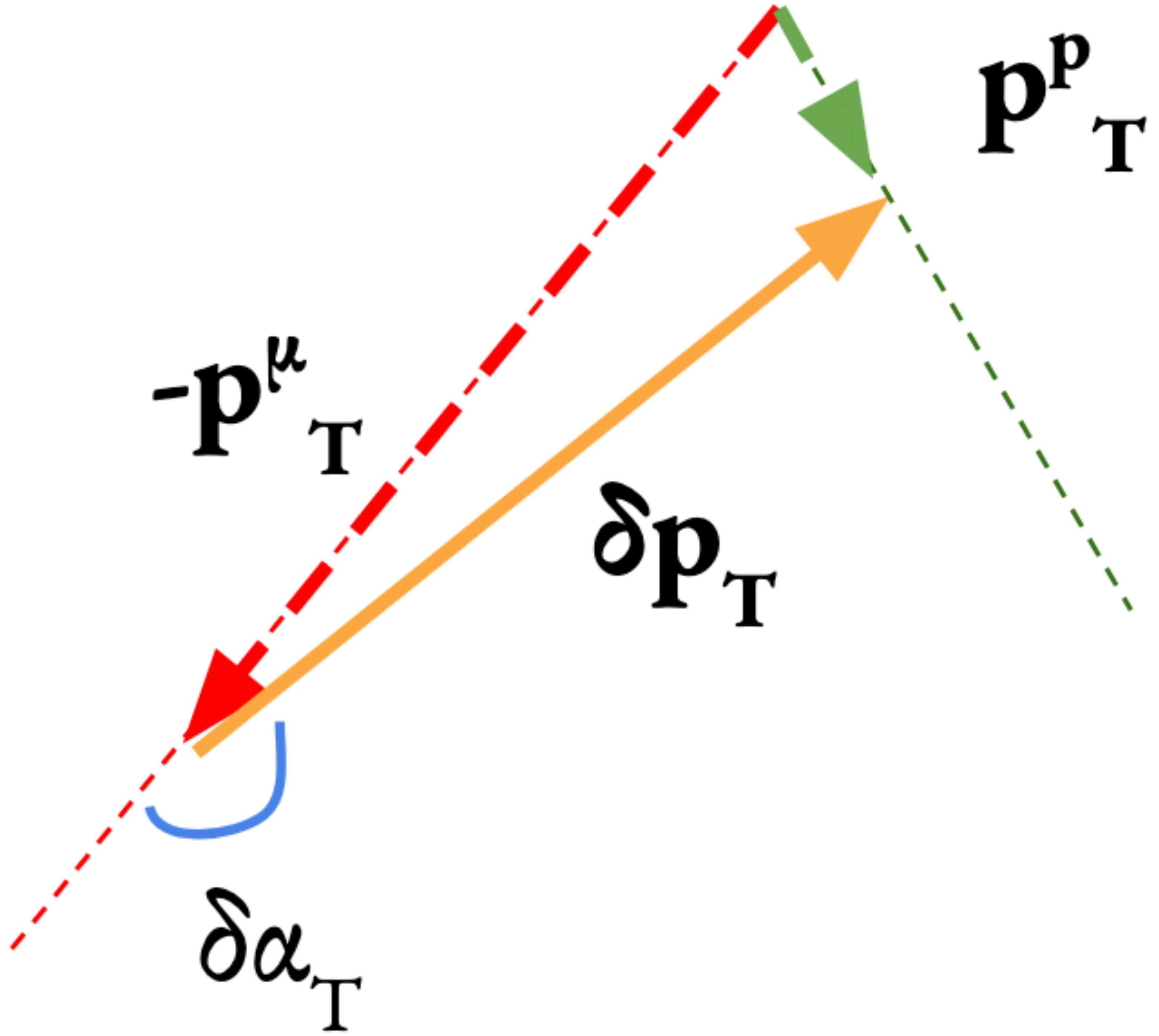


Adapted from S. Dolan, "**Exploring nuclear effects with transverse imbalances**"

Transverse kinematic imbalance (TKI)



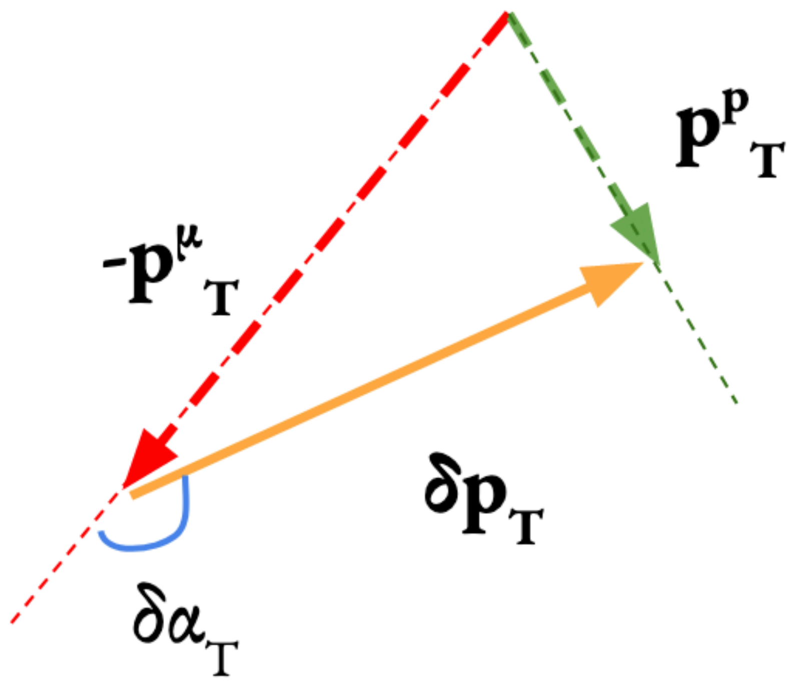
High $\delta\alpha_T$ values correspond to **proton deceleration** due to FSI

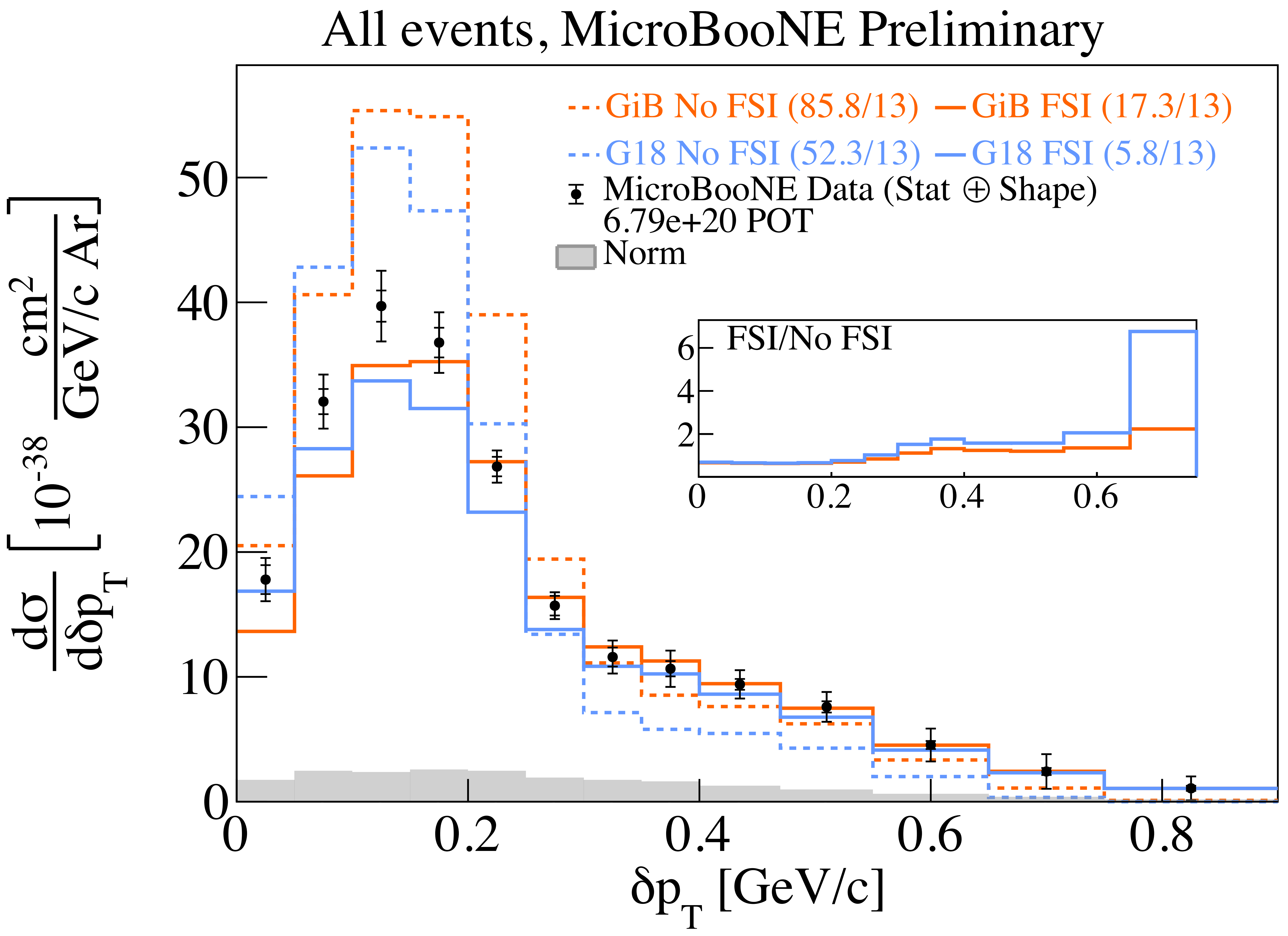


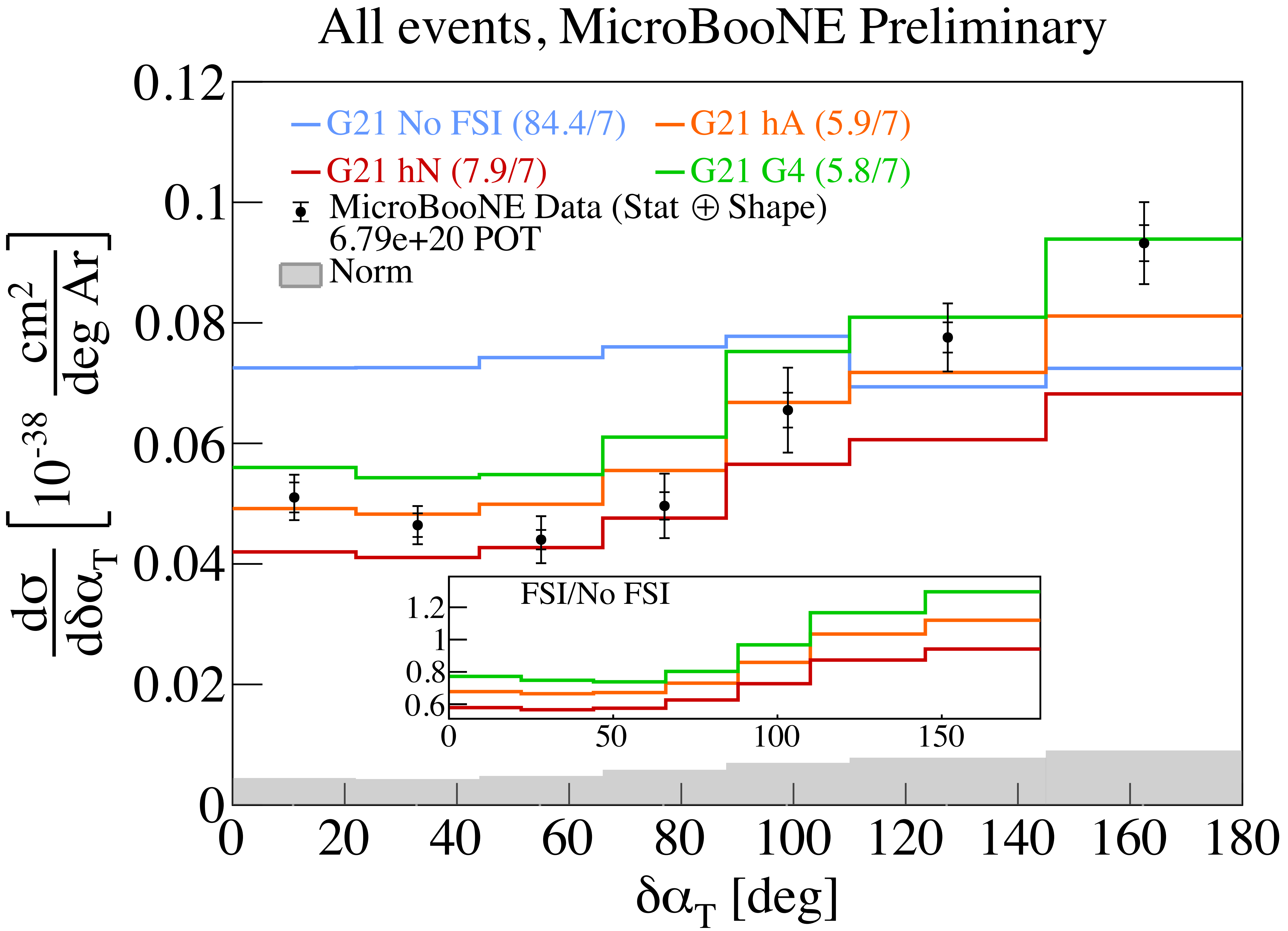
Adapted from S. Dolan, "**Exploring nuclear effects with transverse imbalances**"

TKI variables in ν_μ CC 0π 1p events

- First neutrino-argon differential cross sections in TKI variables
- Sensitive to details of proton FSI modeling



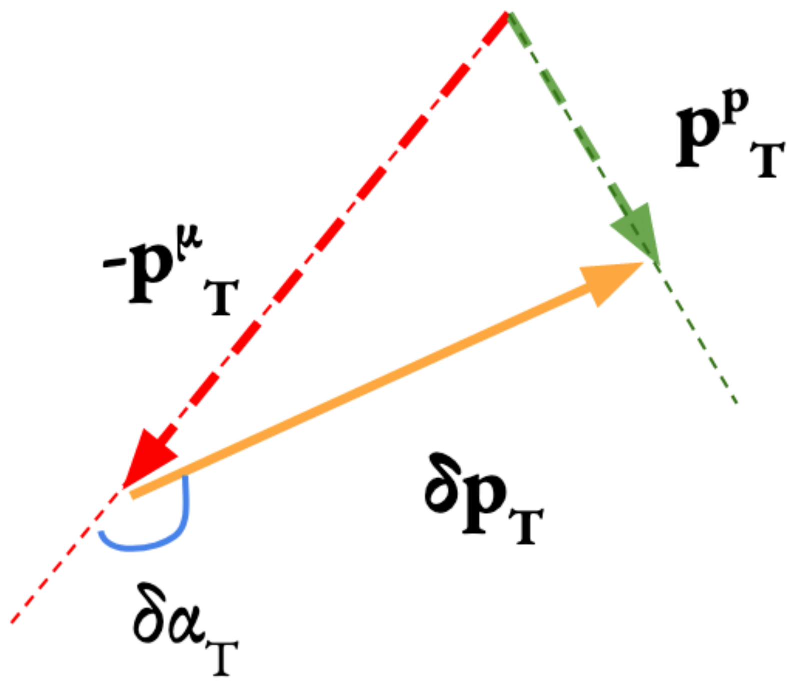


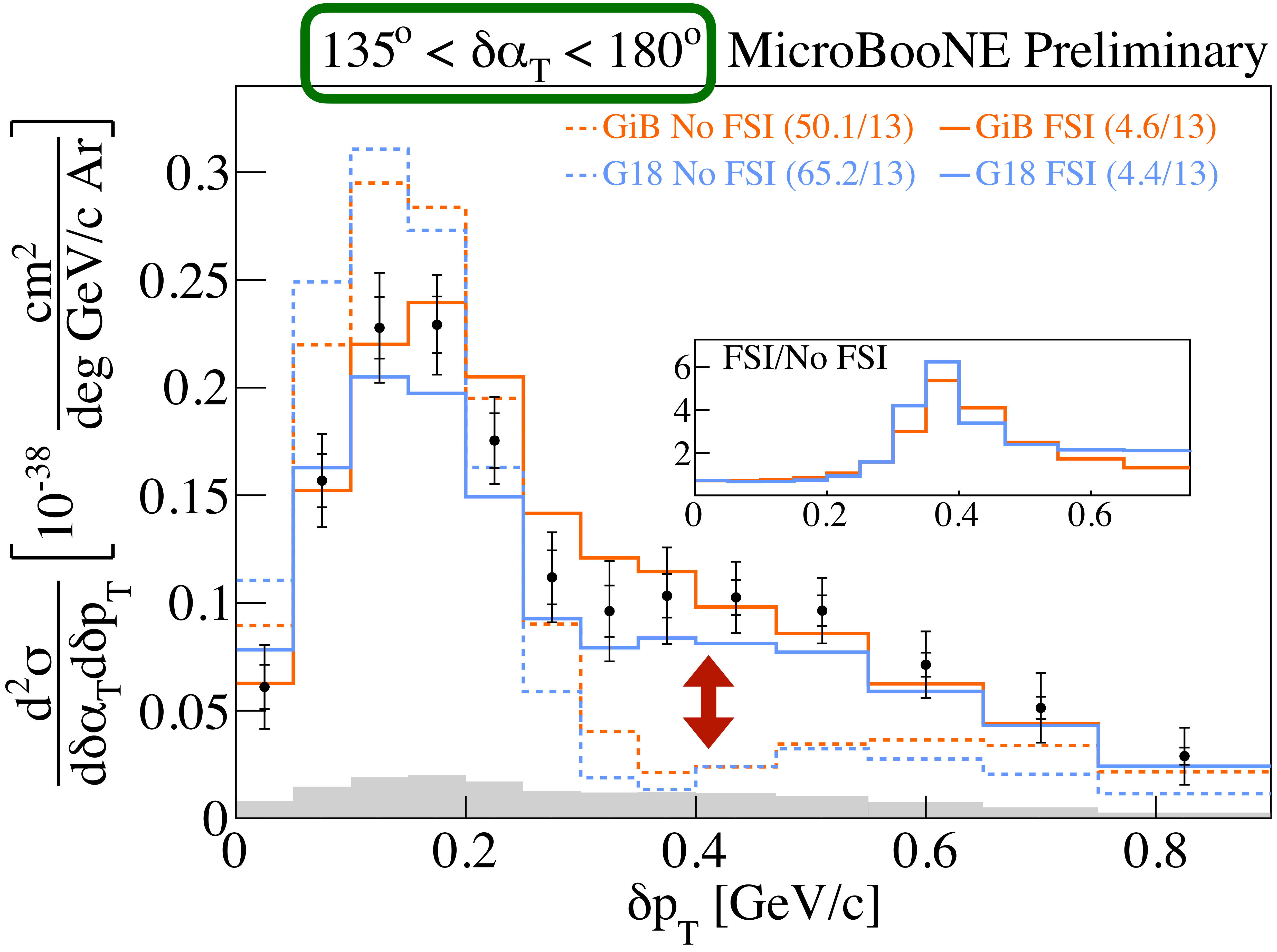


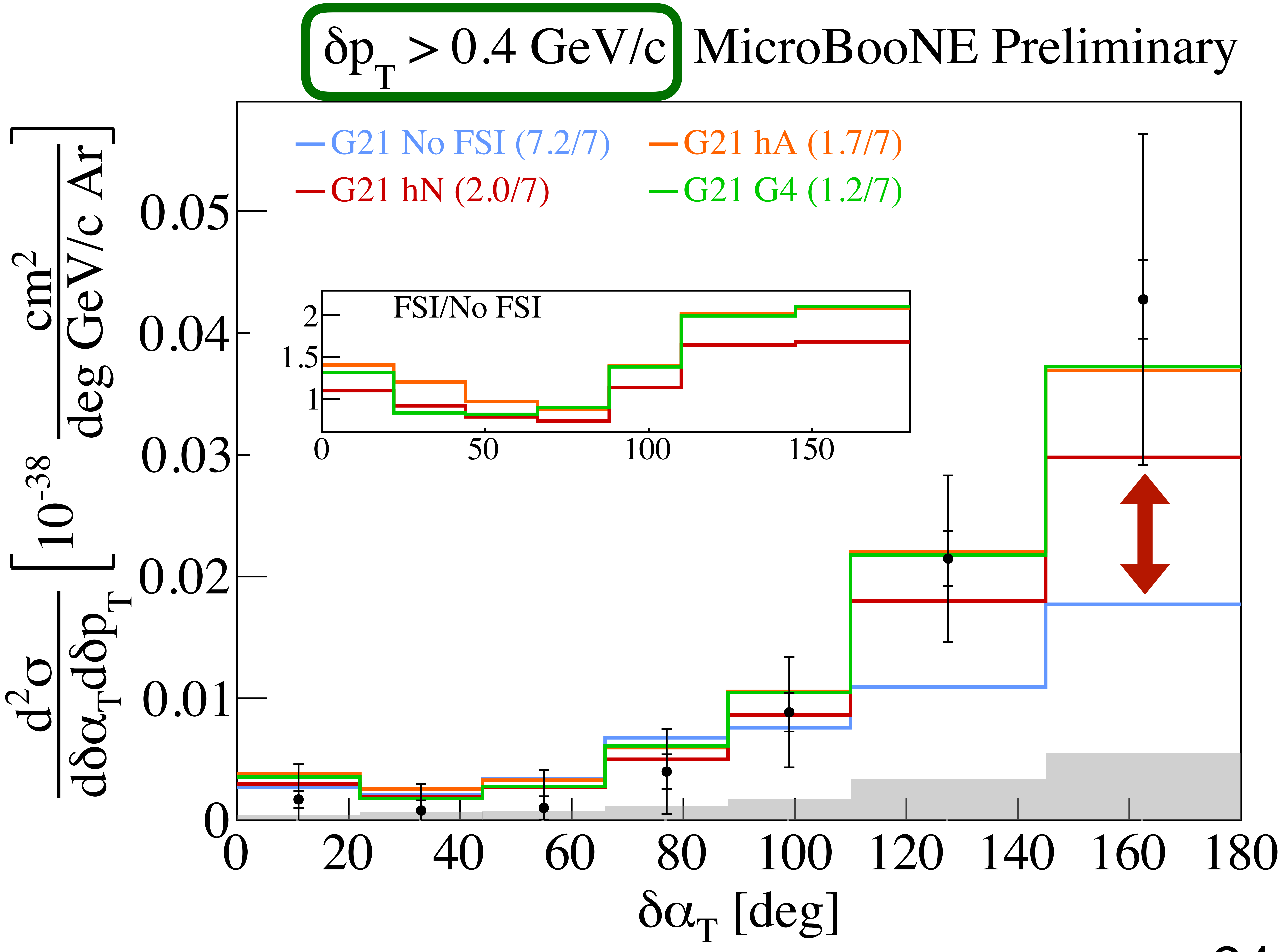
A. Papadopoulou, Poster #723 **MICROBOONE-NOTE-1108-PUB**

TKI variables in ν_μ CC 0π 1p events

- **Extension to 2D** for the first time (any neutrino target)
- Probe regions with greatest model discrimination power







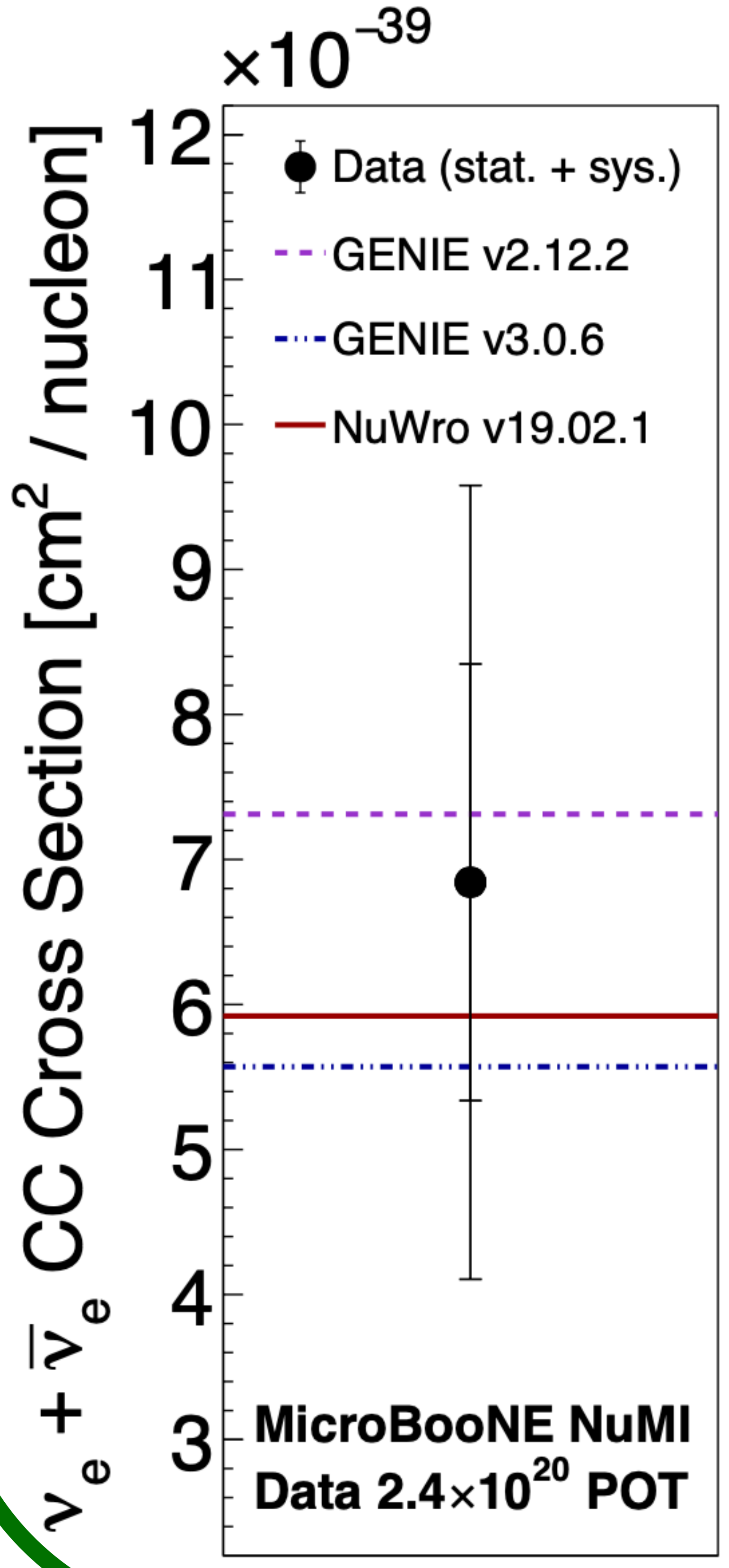
A. Papadopoulou, Poster #723 MICROBOONE-NOTE-1108-PUB

Measurements of electron neutrinos

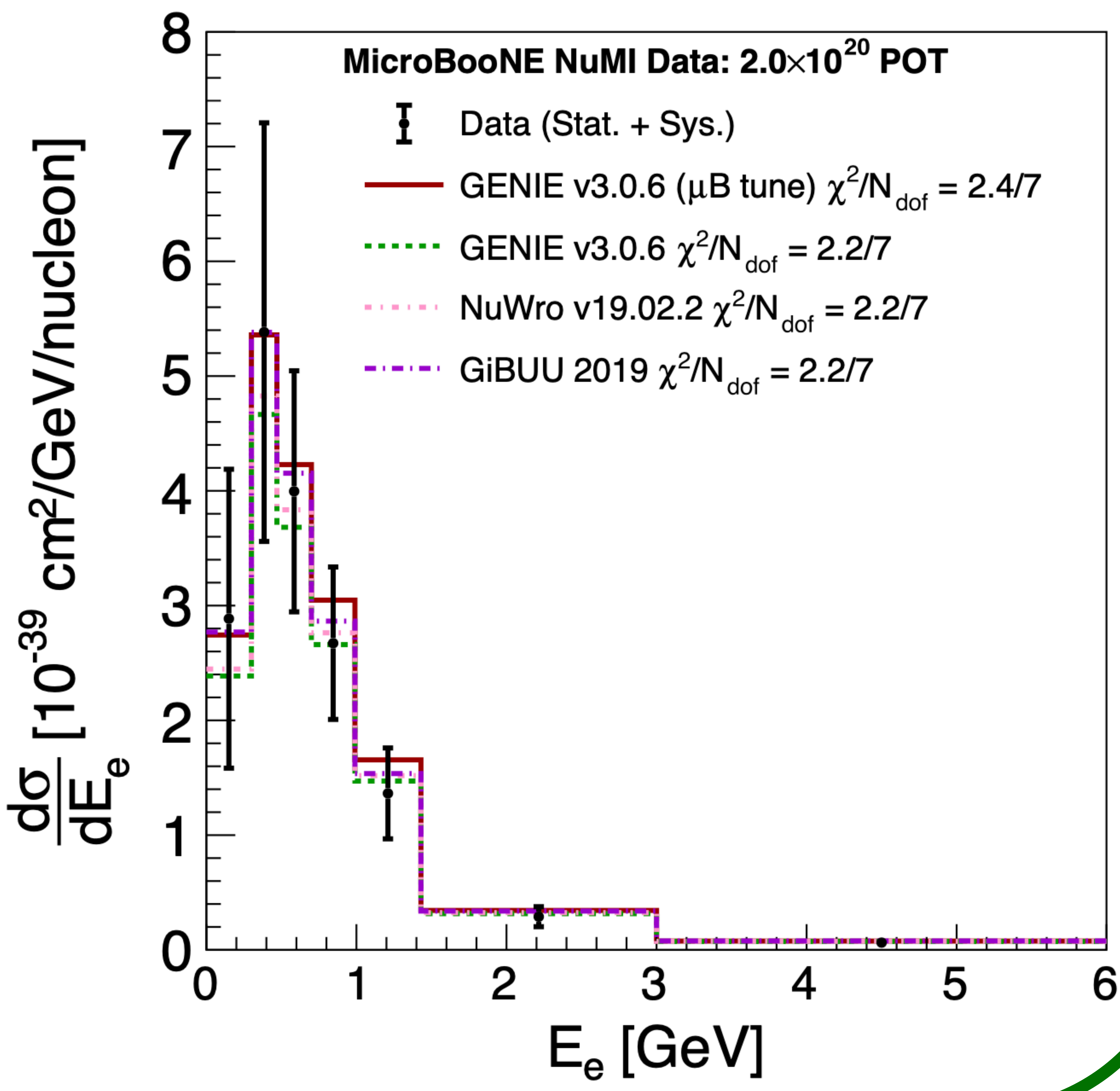
- Much exciting progress in detecting and understanding ν_e interactions in liquid argon

Charged-current inclusive

Phys. Rev. D 104, 052002 (2021)



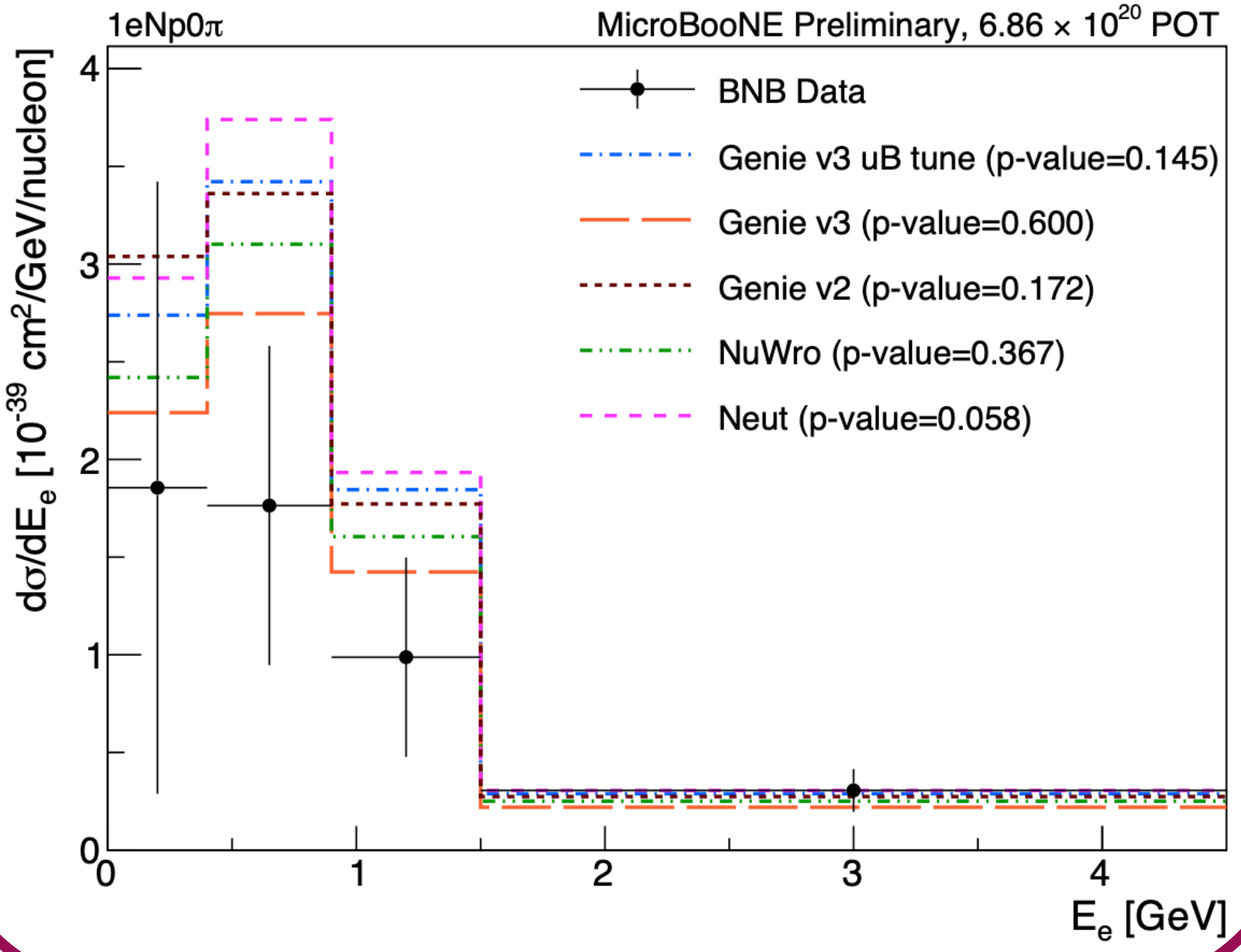
Phys. Rev. D 105, L051102 (2022)



CC 0π (≥1)p

S. Berkman, Poster #734

MICROBOONE-NOTE-1109-PUB



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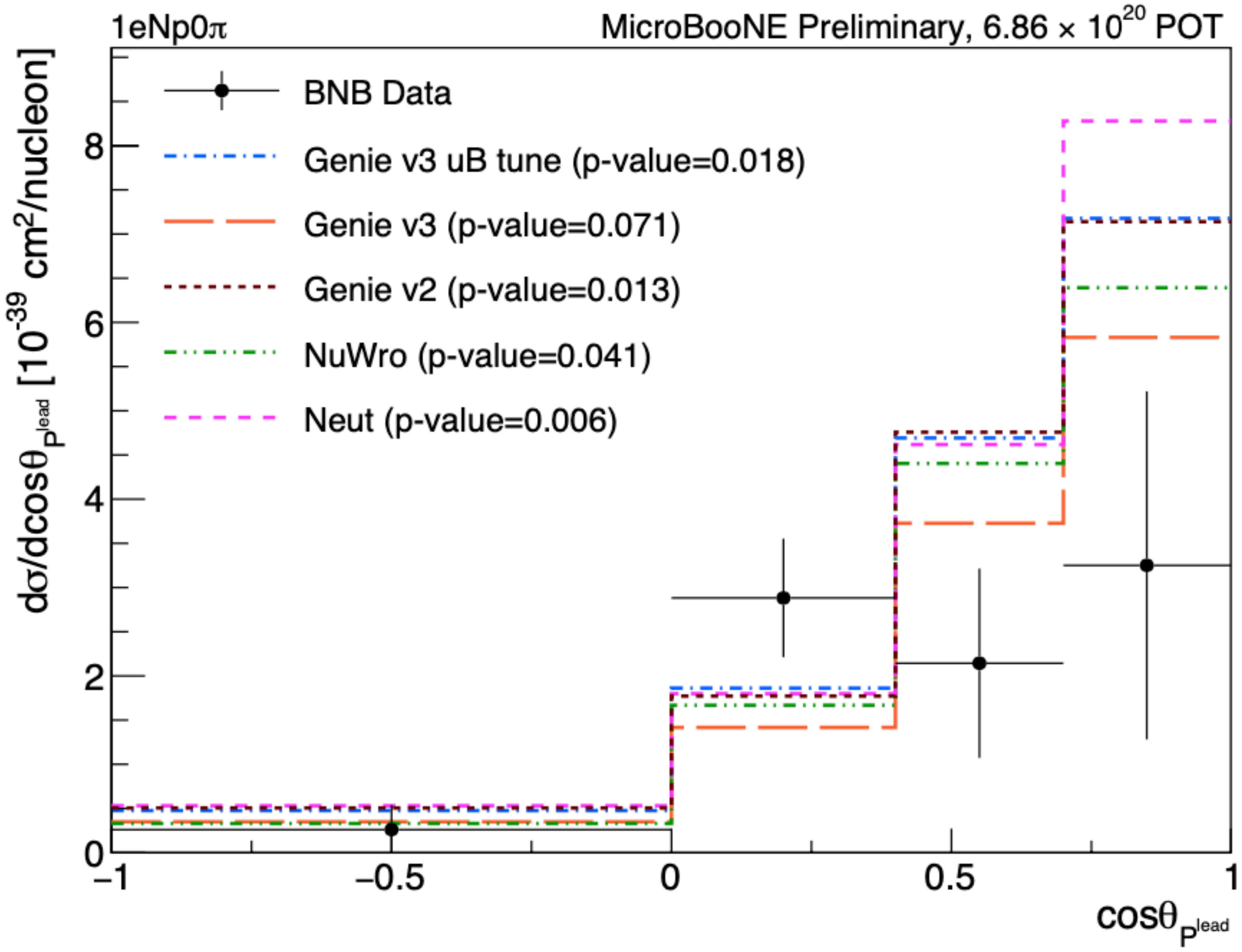
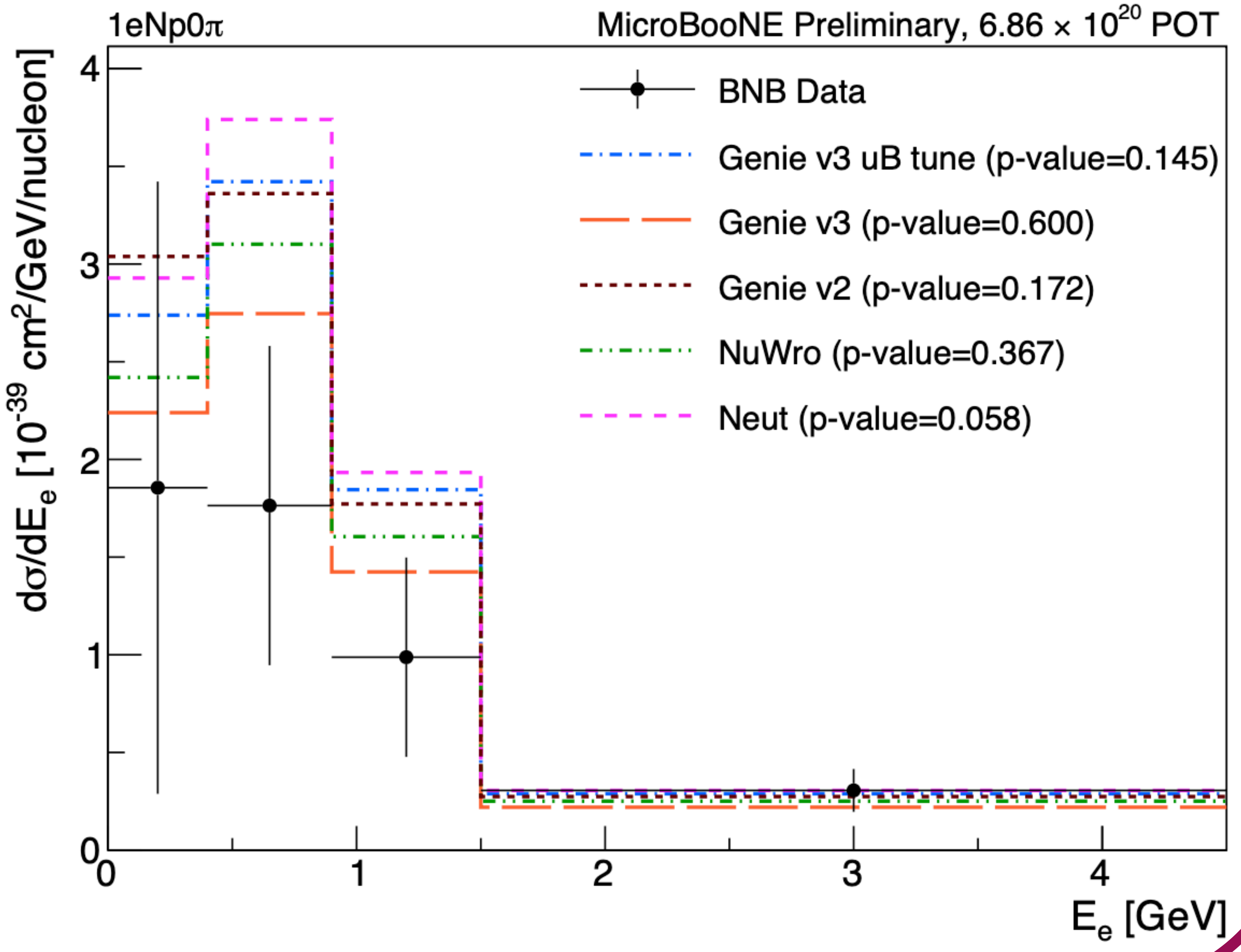


Energy and angle measurements reported for e- and leading p

CC 0π (≥1)p

S. Berkman, Poster #734

MICROBOONE-NOTE-1109-PUB



MicroBooNE cross-section results since Neutrino 2020

Publications

Phys. Rev. D 102, 112013 (2020)
ν_μ CC 0π (≥1)p

Phys. Rev. D 104, 052002 (2021)
Total $\nu_e + \bar{\nu}_e$ CC inclusive

Phys. Rev. D 105, L051102 (2022)
Differential $\nu_e + \bar{\nu}_e$ CC inclusive

Phys. Rev. Lett. 128, 151801 (2022)
Energy-dependent ν_μ CC inclusive

Phys. Rev. D 105, 072001 (2022)
MicroBooNE GENIE Tune

arXiv:2205.07943, submitted to PRD
Total NC $1\pi^0$

Posters at this conference

M. Bhattacharya, Poster #773
MICROBOONE-NOTE-1107-PUB
ν_μ CC $1\pi^0$

G. Scanavini, Poster #759
MICROBOONE-NOTE-1111-PUB
NC (≥1)π^0

S. Berkman, Poster #734
MICROBOONE-NOTE-1109-PUB
ν_e CC 0π

S. Sword-Fehlberg, Poster #723
MICROBOONE-NOTE-1117-PUB
ν_μ CC 0π 2p

A. Papadopoulou, Poster #748
MICROBOONE-NOTE-1108-PUB
ν_μ CC 0π 1p TKI

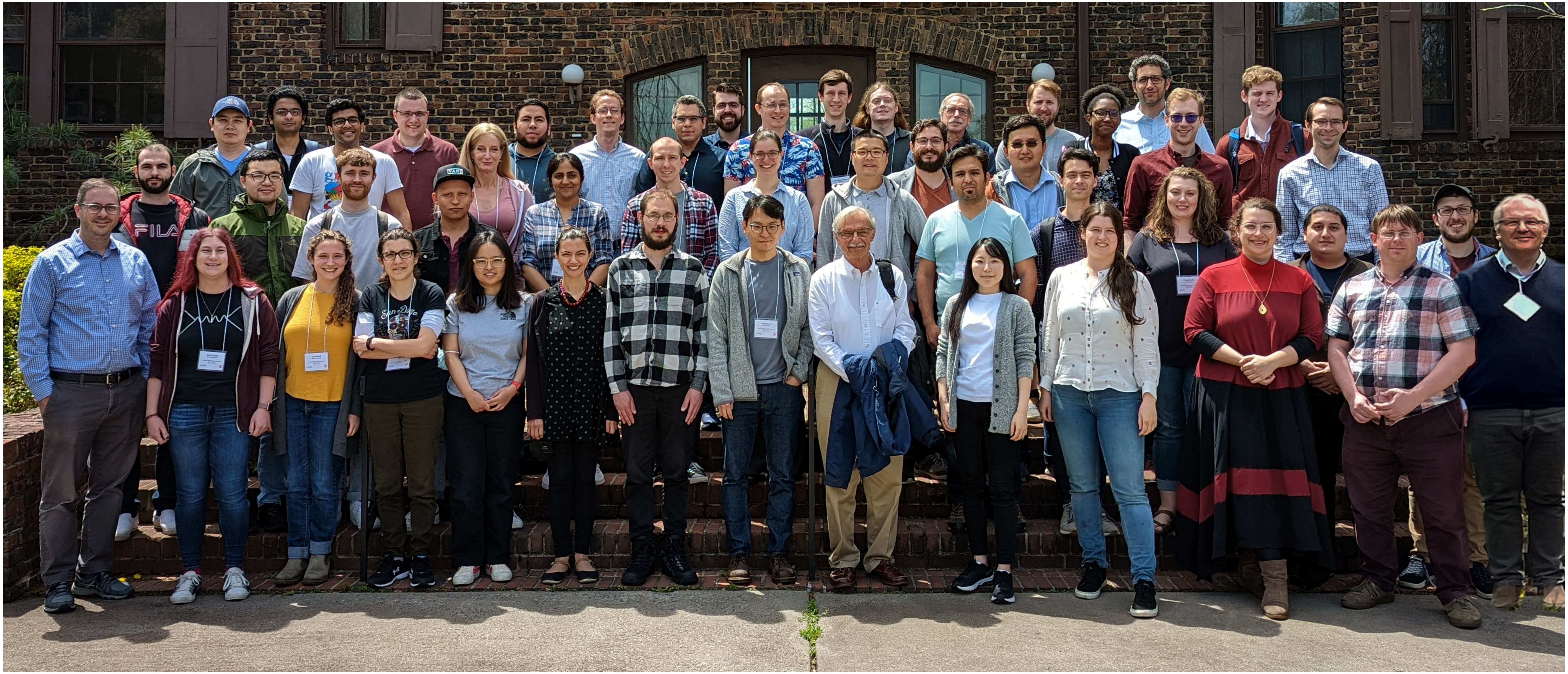
C. Thorpe, Poster #708
MICROBOONE-NOTE-1112-PUB
$\bar{\nu}_\mu$ CC Λ

L. Cooper-Troendle, Poster #766
MICROBOONE-NOTE-1110-PUB
Methods for 3D ν_μ CC inclusive

N. Oza, Poster #756
arXiv:2205.0794
Total NC $1\pi^0$

J. Barrow, Poster #772
$\mu 4 \nu$

And much more coming soon from our 30 active analyses!



μBooNE

Special thanks to our funding agencies, Fermilab, and all involved in making our neutrino cross-section science possible!

http://microboone.fnal.gov/public-notes/

Backup