Latest Cross Section Results from μBooNE

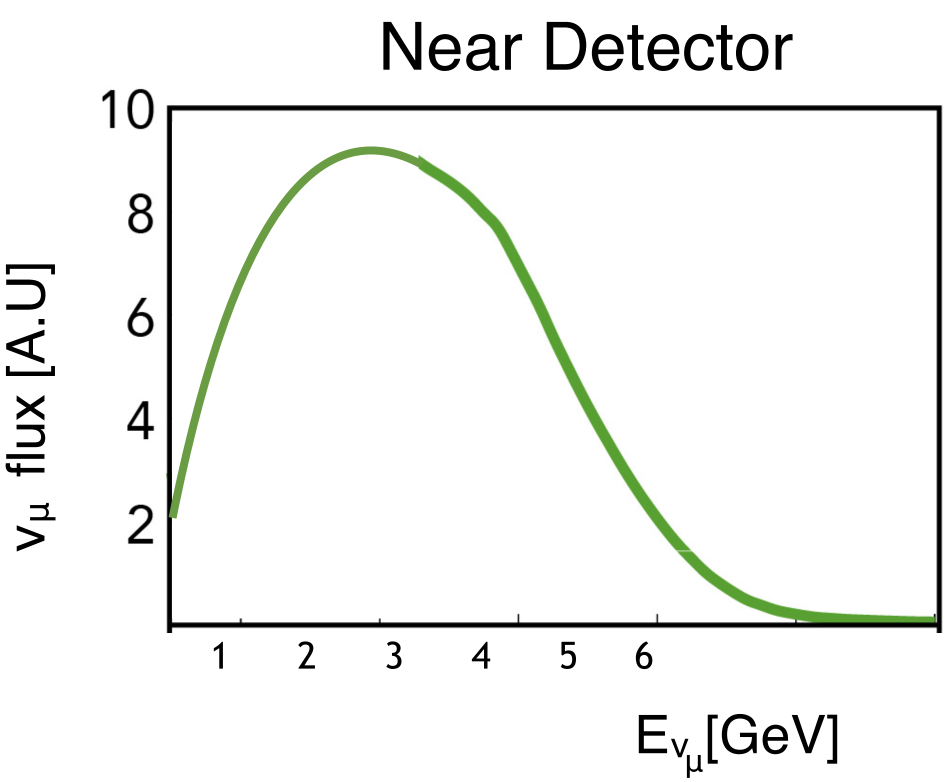
Lepton Interactions with Nucleons and Nuclei

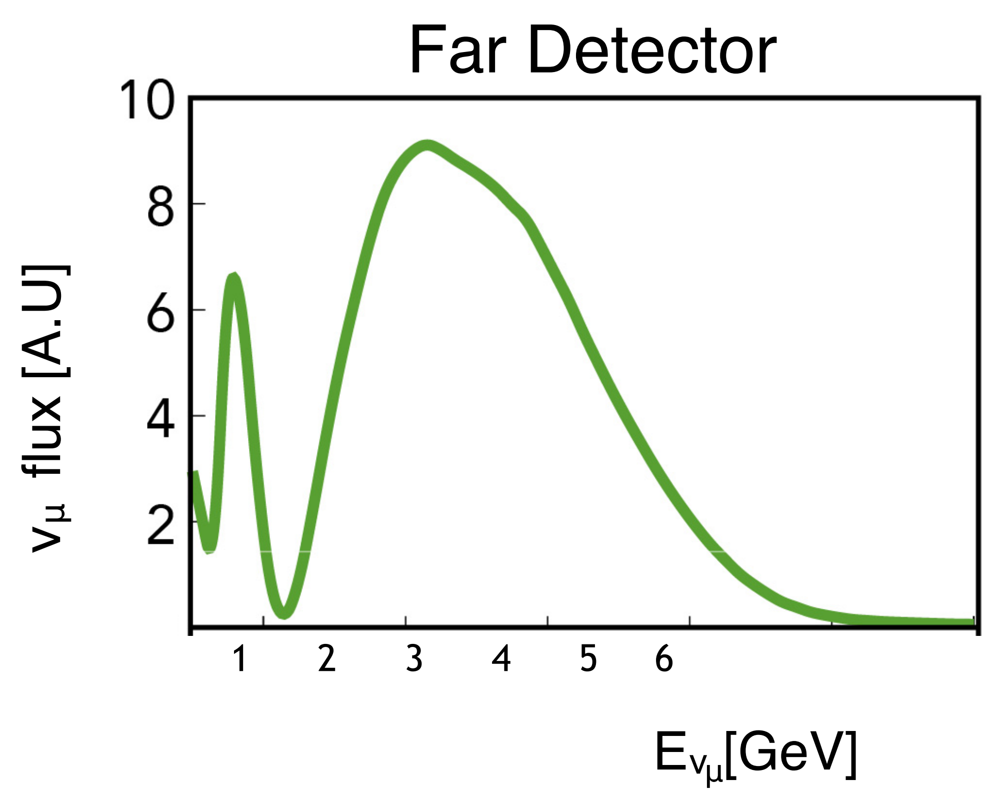
September 7th 2023

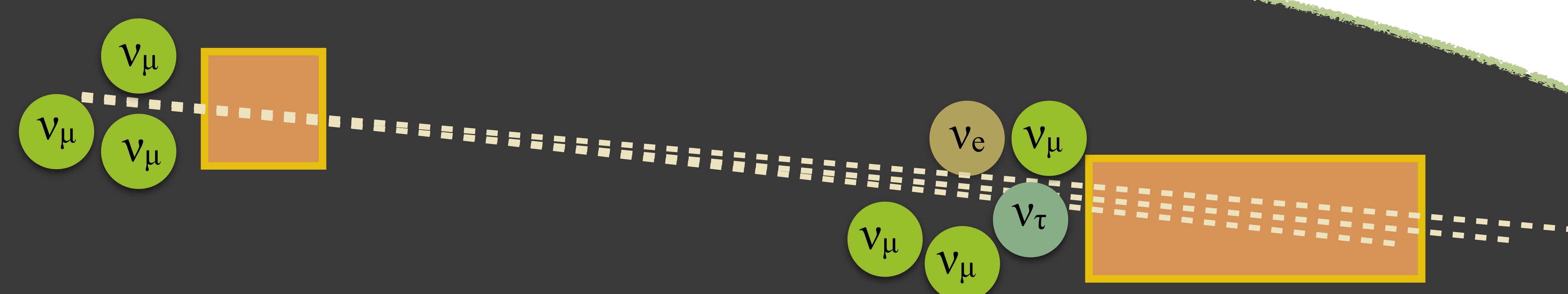
Adi Ashkenazi
adishka@tauex.tau.ac.il

TEL AVIV UNIVERSITY

Towards Precision measurements of Oscillations



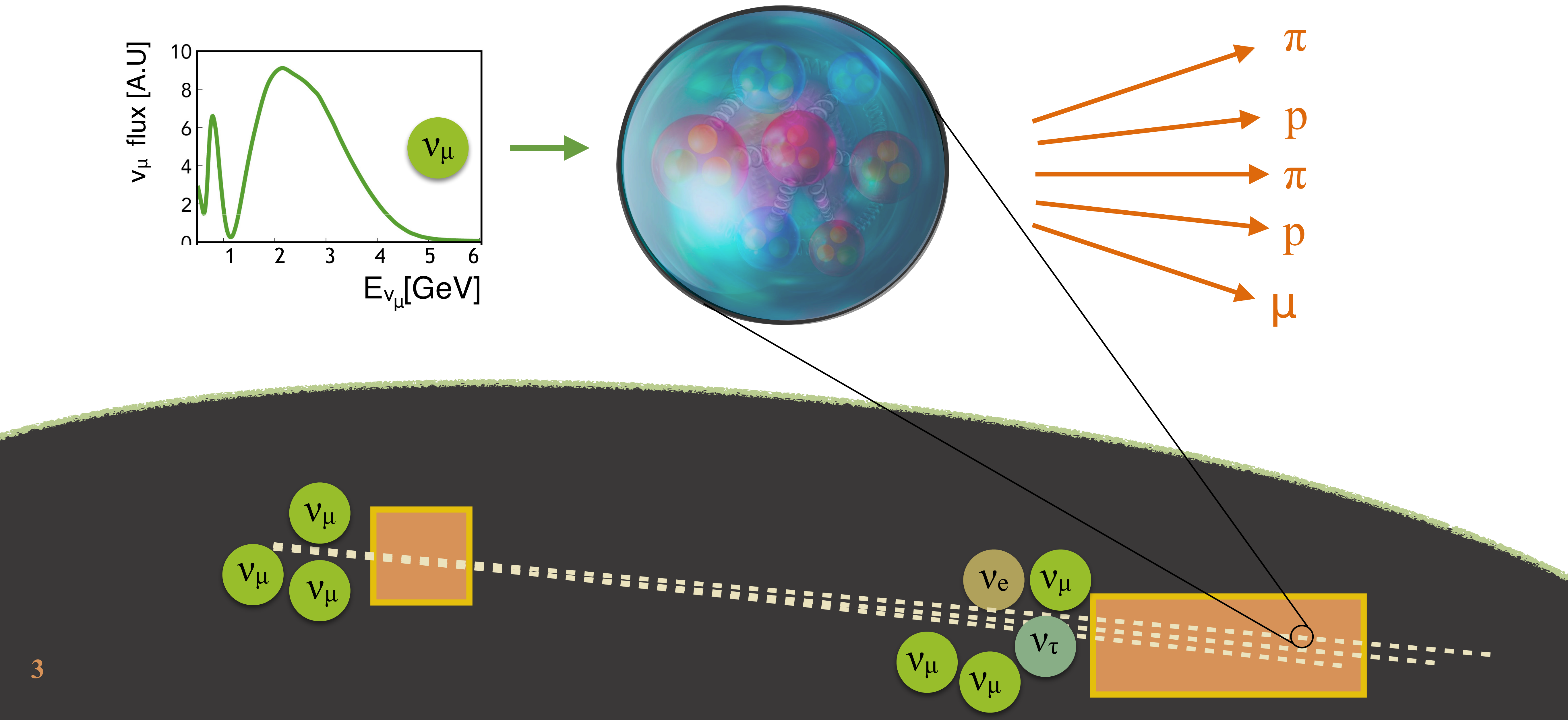




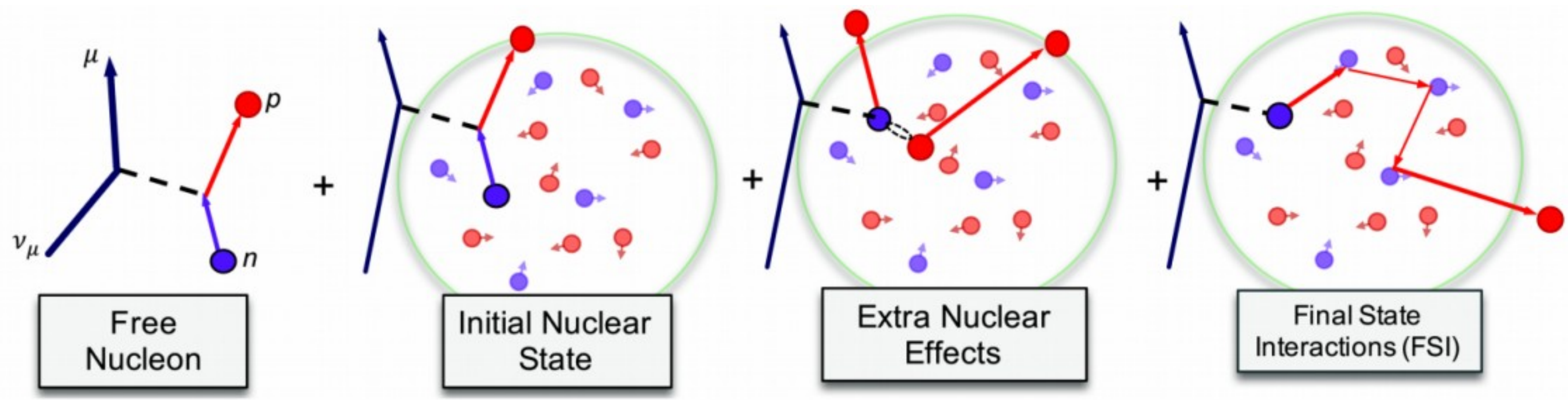
The nuclear challenge in precision measurements

Incoming true flux | Modelling Input | Measurement

$$\int \Phi(E,L) \quad \sigma(E) f_\sigma(E,E_{rec}) \, dE \propto N\,(Erec, L)$$



Lepton-Nucleus Interaction Modelling



Neutrino event generators simulating νA interaction

Genie

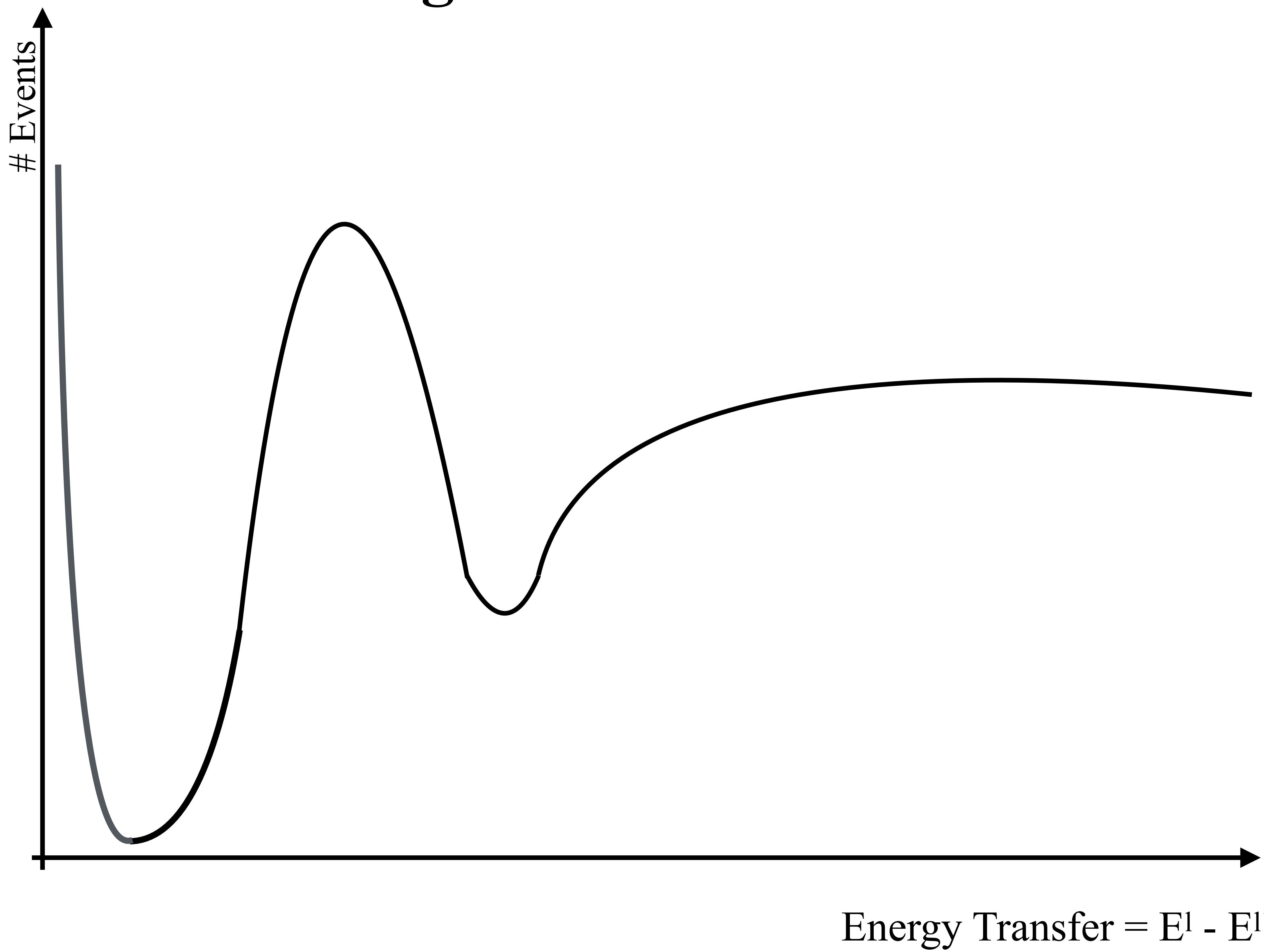
NuWro
Wroclaw Neutrino Event Generator

NEUT

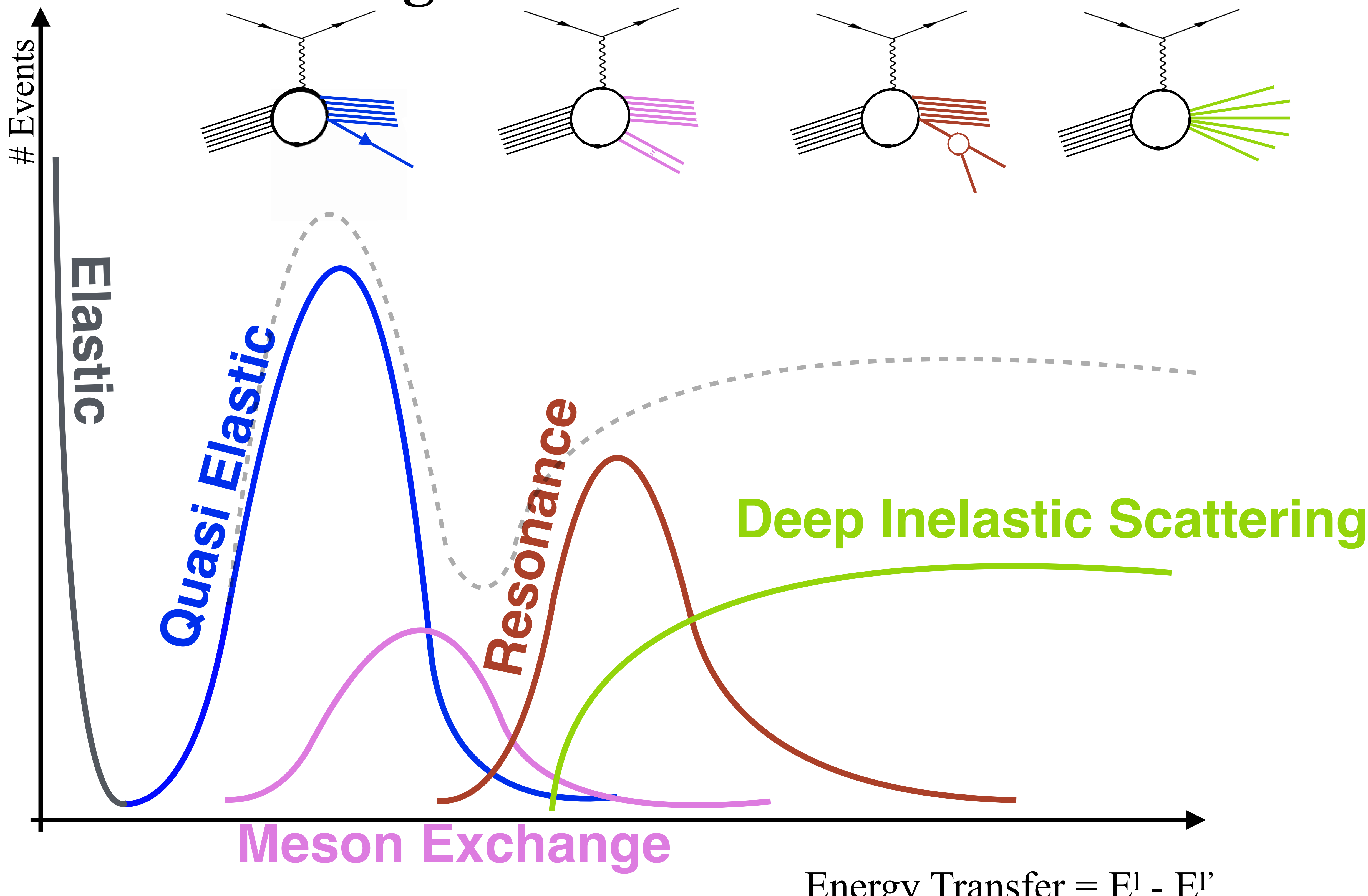
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

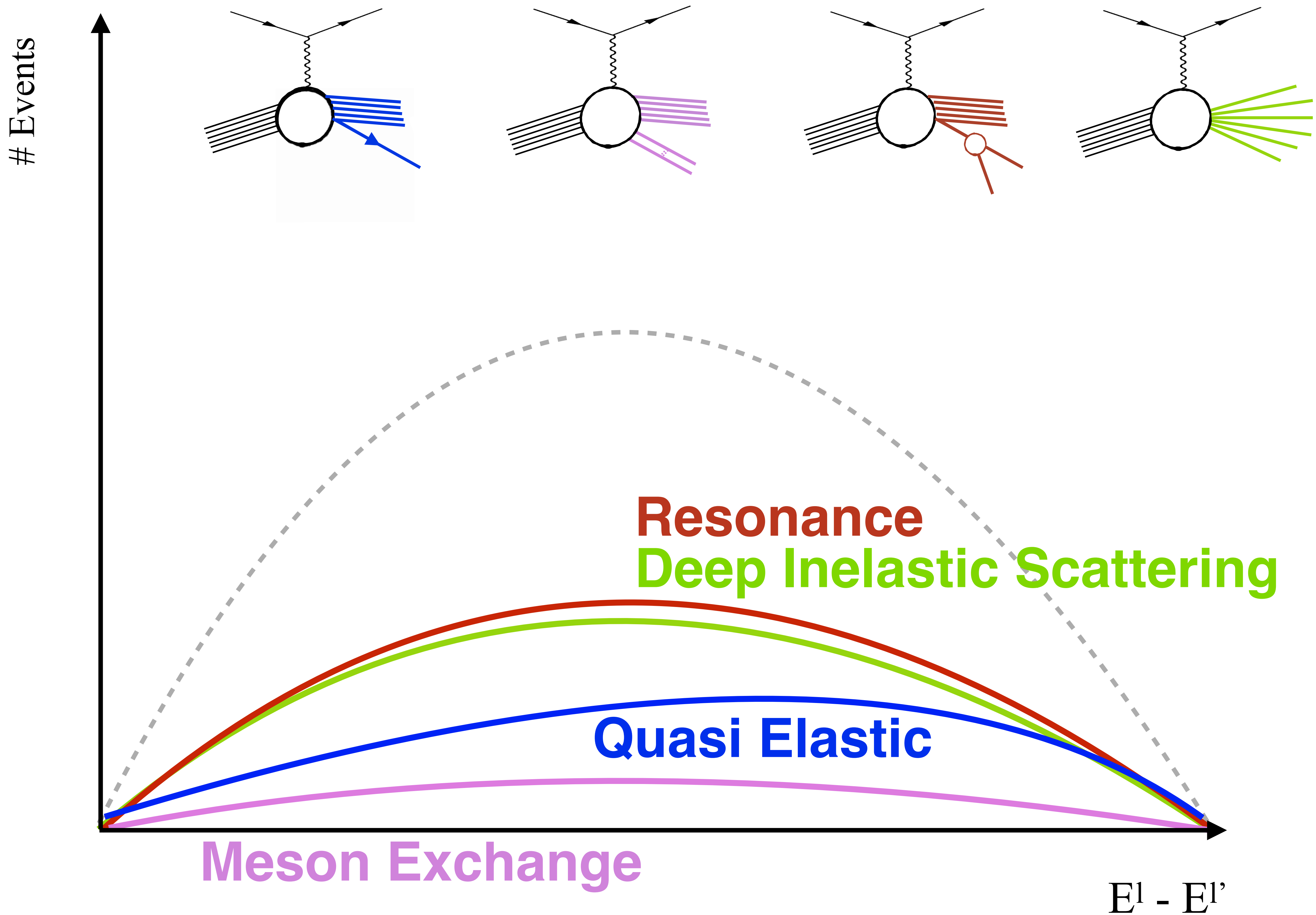
Lepton - nuclei interaction processes for mono-energetic flux



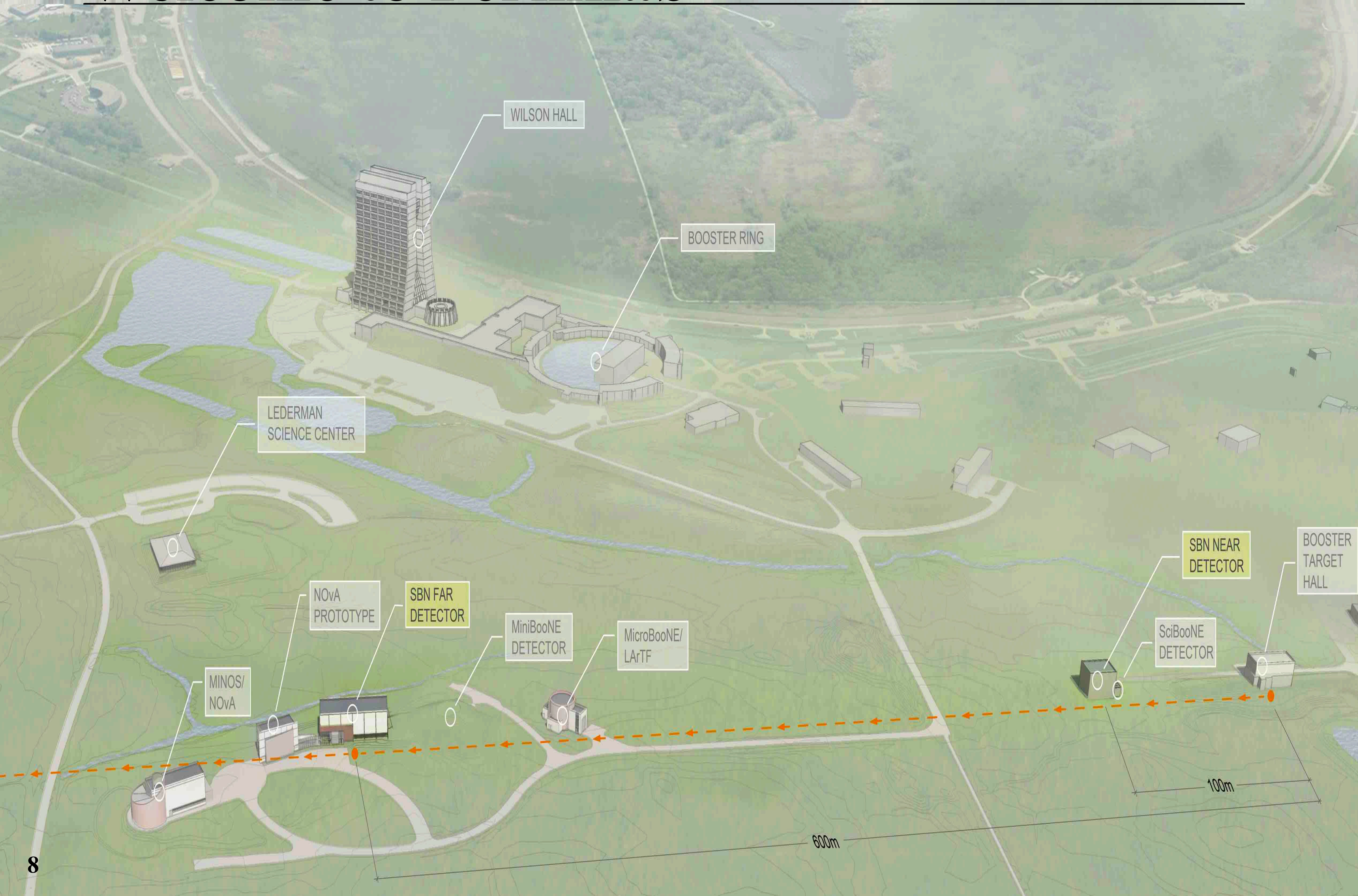
Lepton - nuclei interaction processes for mono-energetic flux



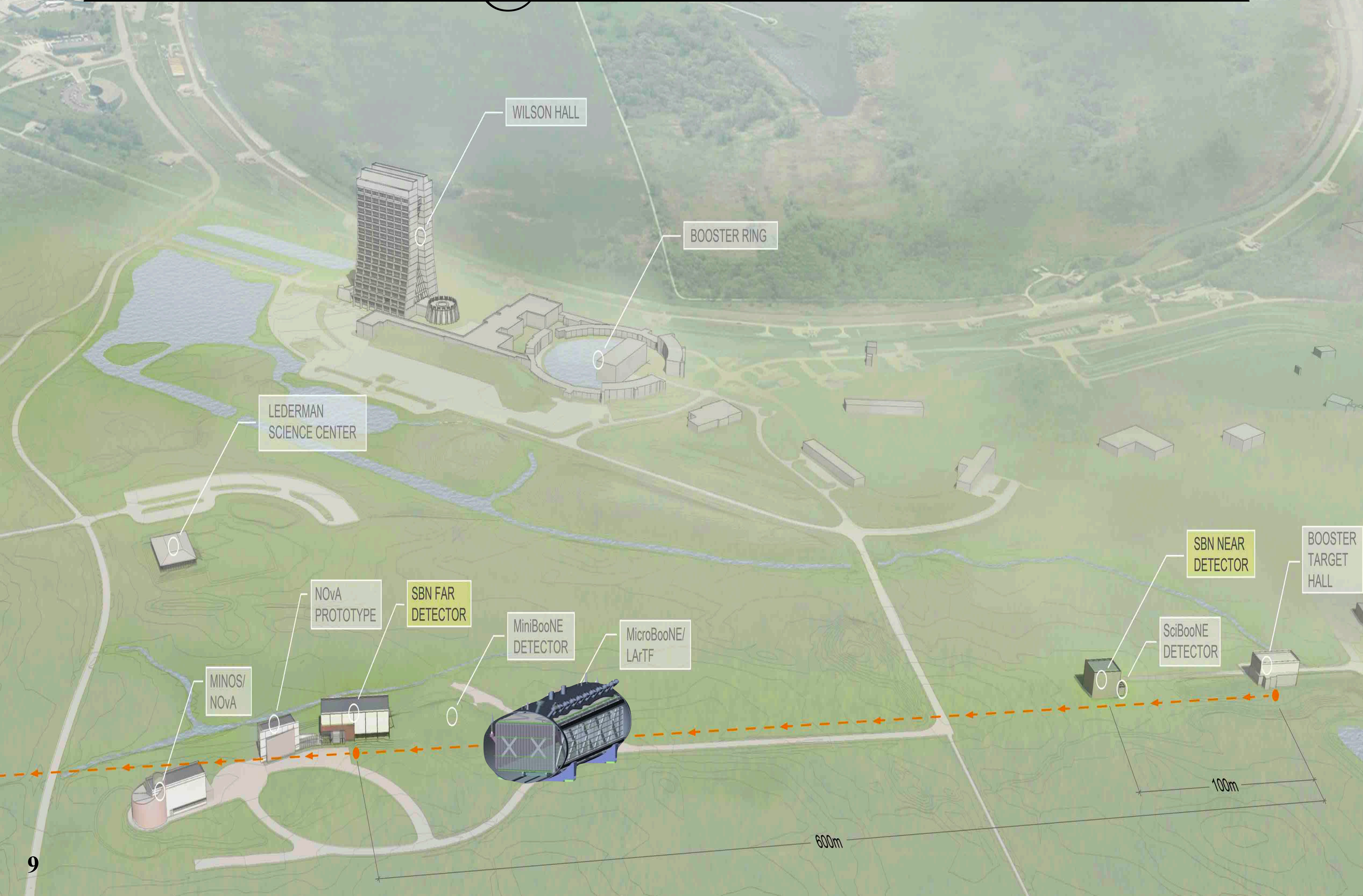
ν Experiments Fluxes Challenge our Understanding



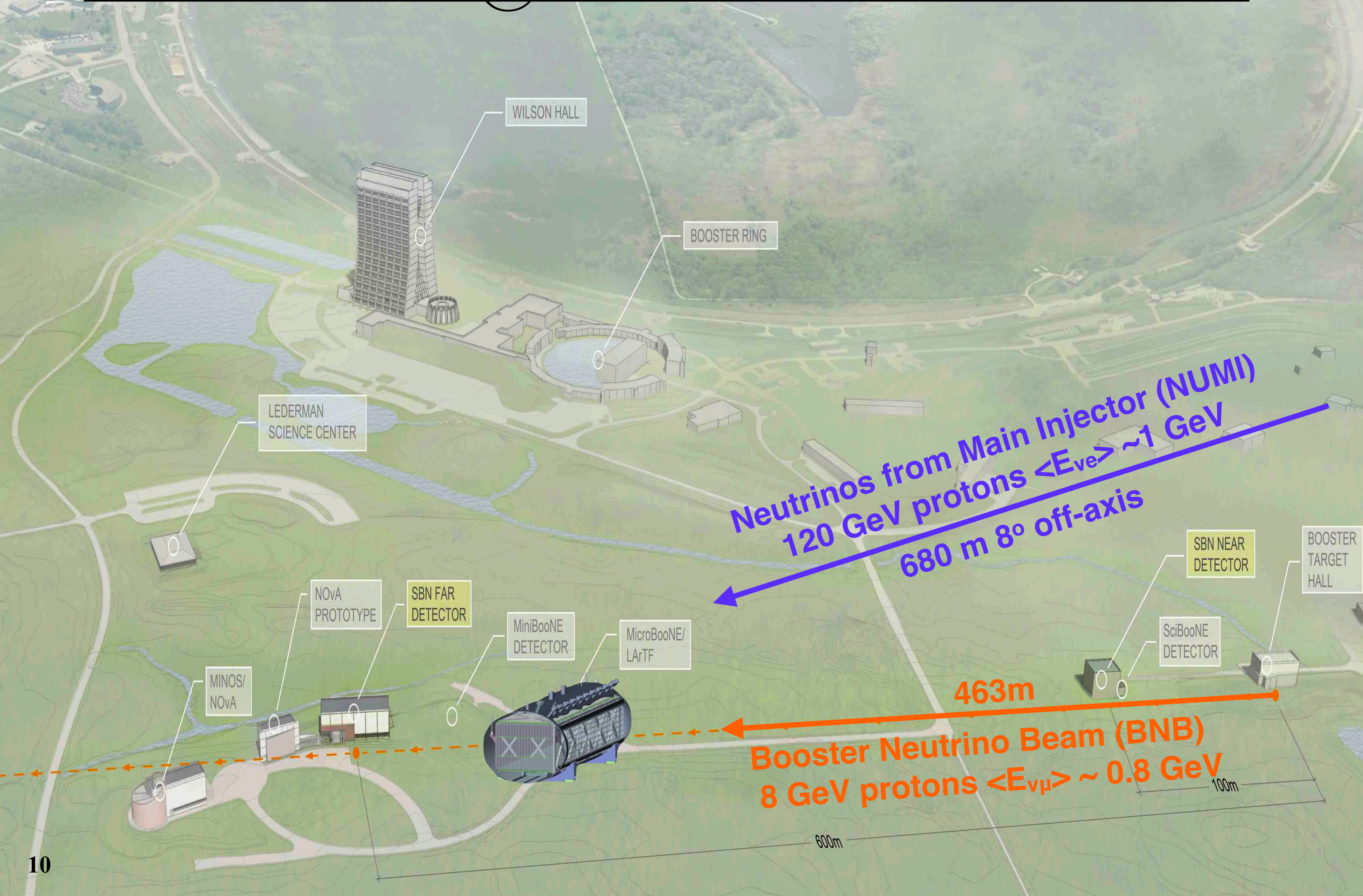
Welcome to Fermilab



MicroBooNE @ the Short Baseline



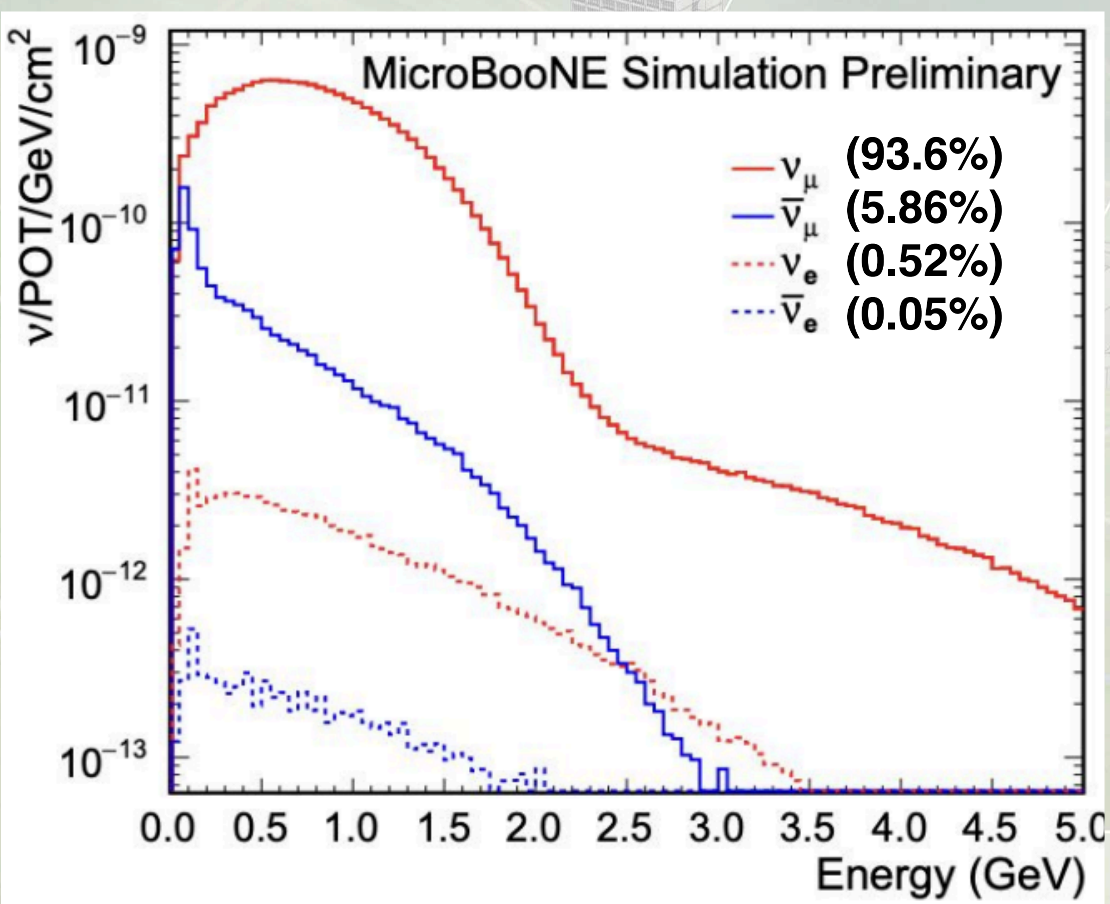
MicroBooNE @ the Short Baseline

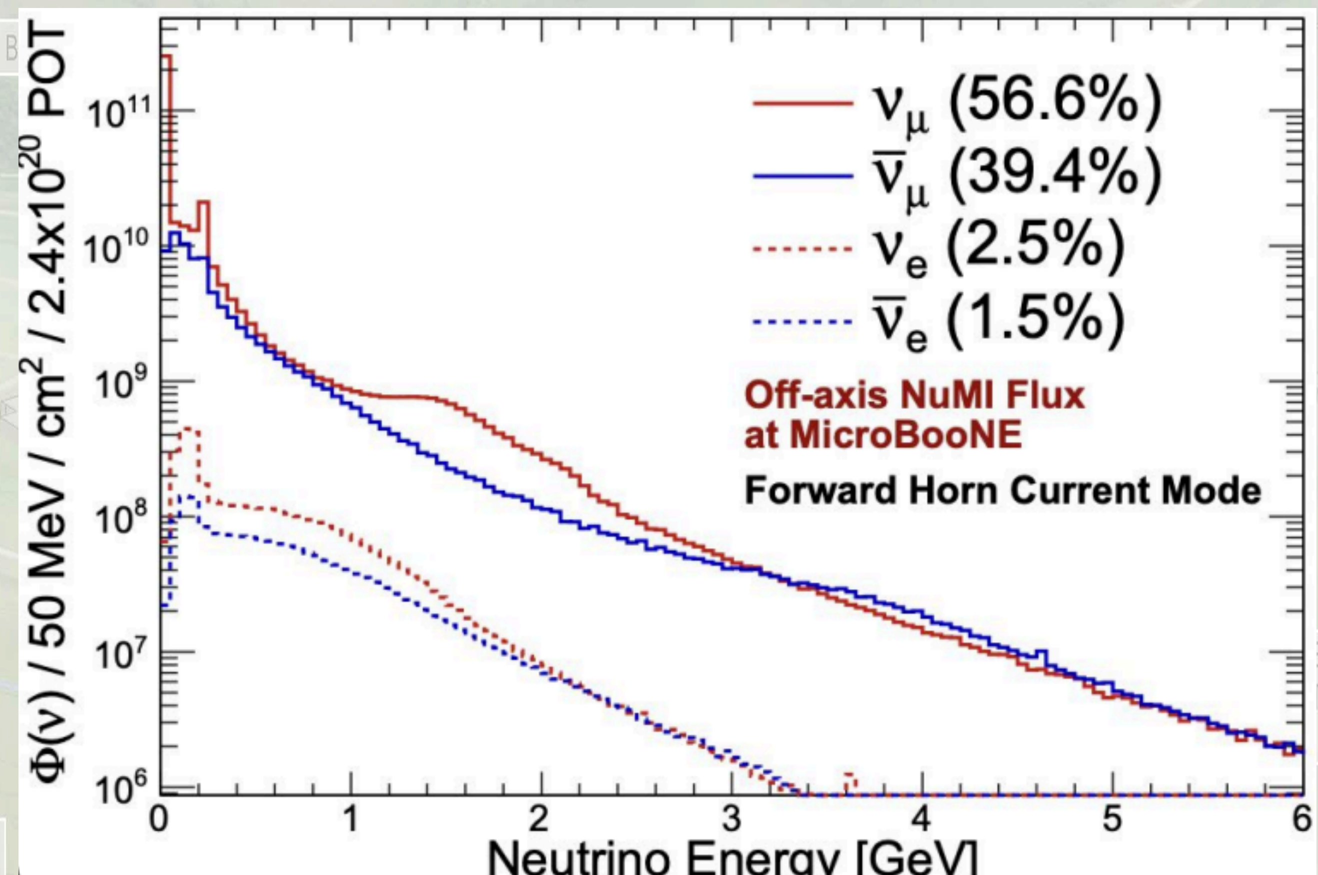


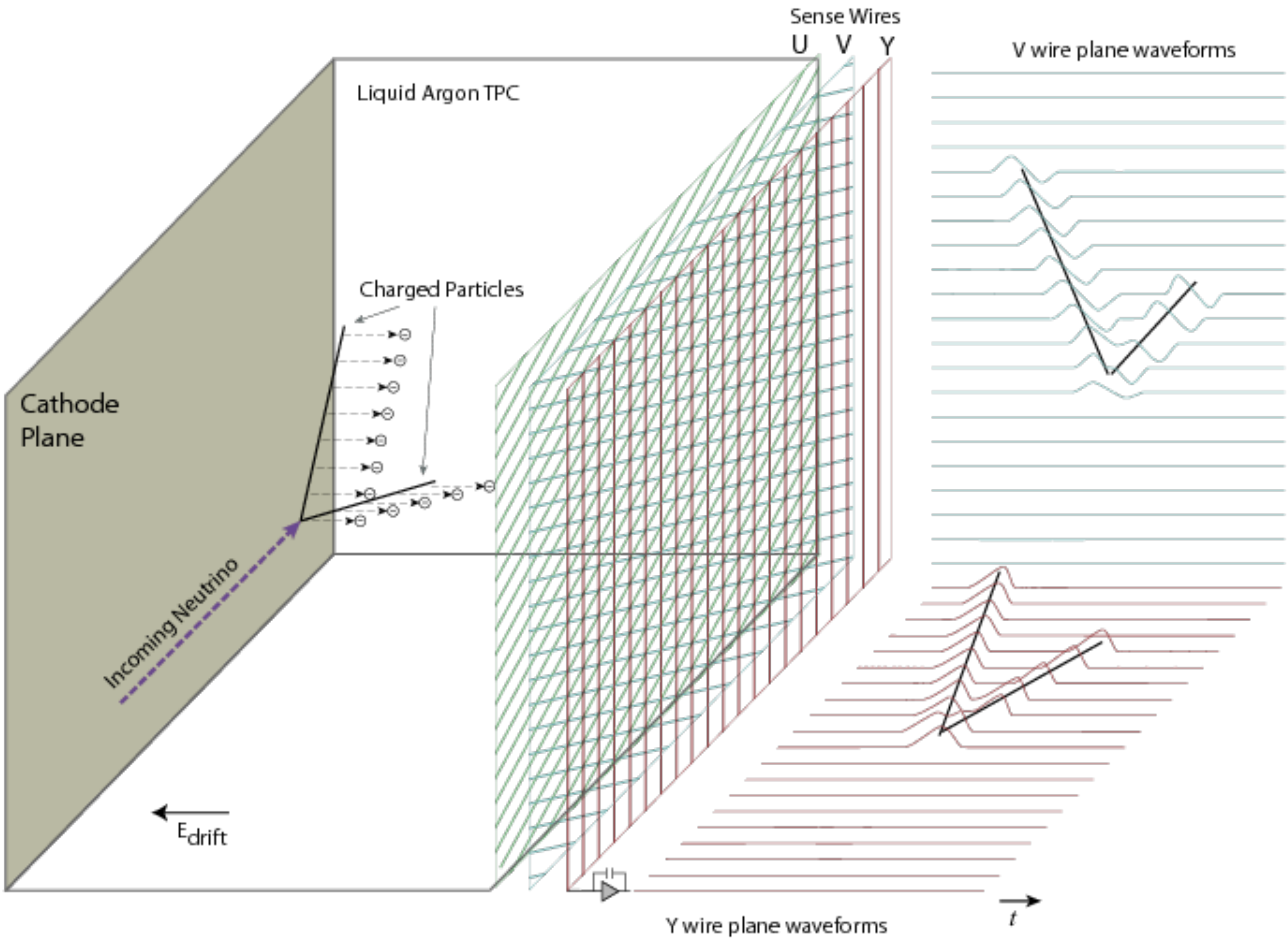
MicroBooNE's Beams

Booster Neutrino Beam (BNB)
8 GeV protons $\langle E_{\nu\mu} \rangle \sim 0.8$ GeV

Neutrinos from Main Injector (NUMI)
120 GeV protons $\langle E_{\nu e} \rangle \sim 1$ GeV







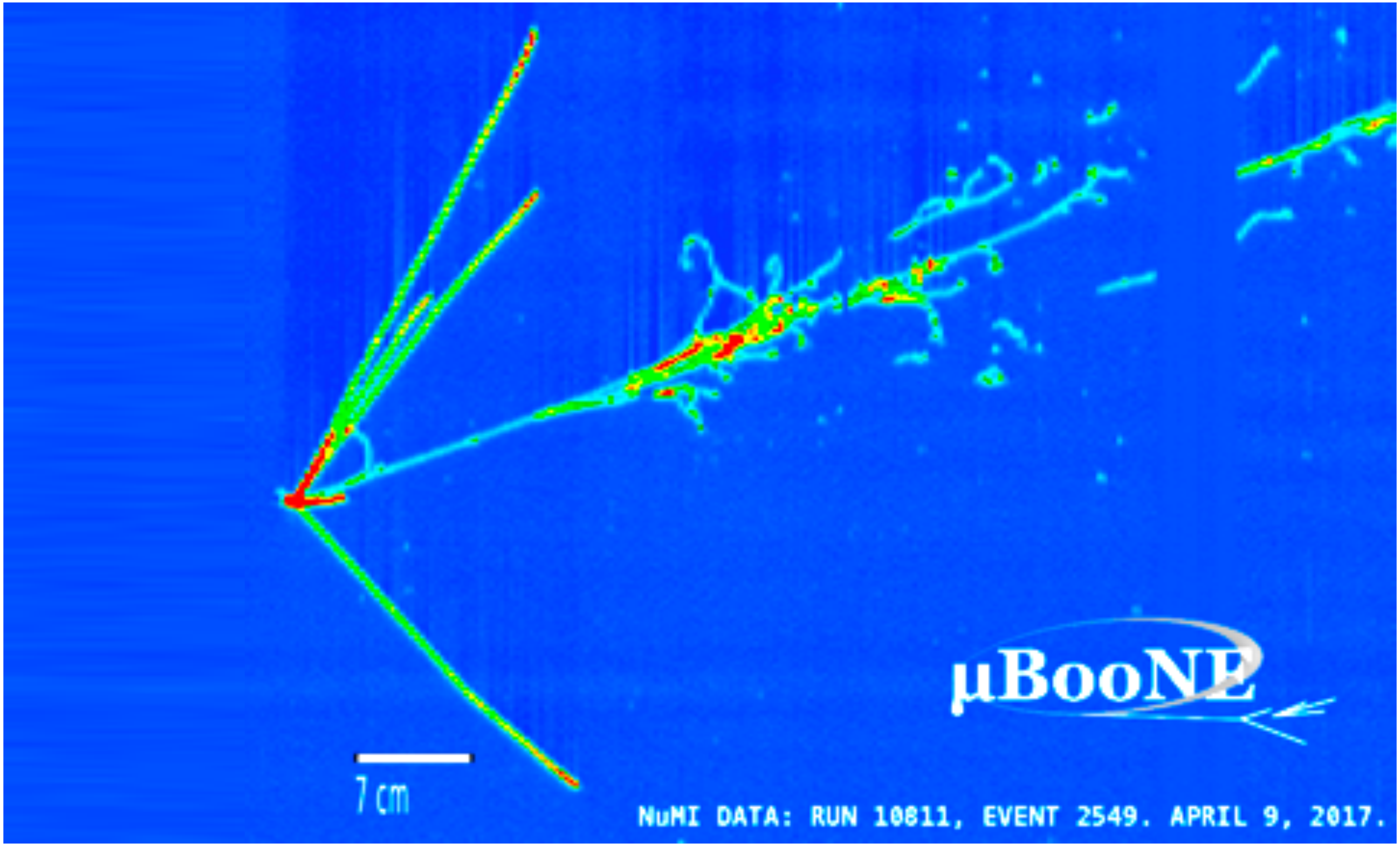
LAr Time Projection Chamber   Active mass : 85 tons

Triggered by PMTs, 3 wire planes with 3 mm spacing

impeccable spatial resolution, calorimetric measurement

μBooNE

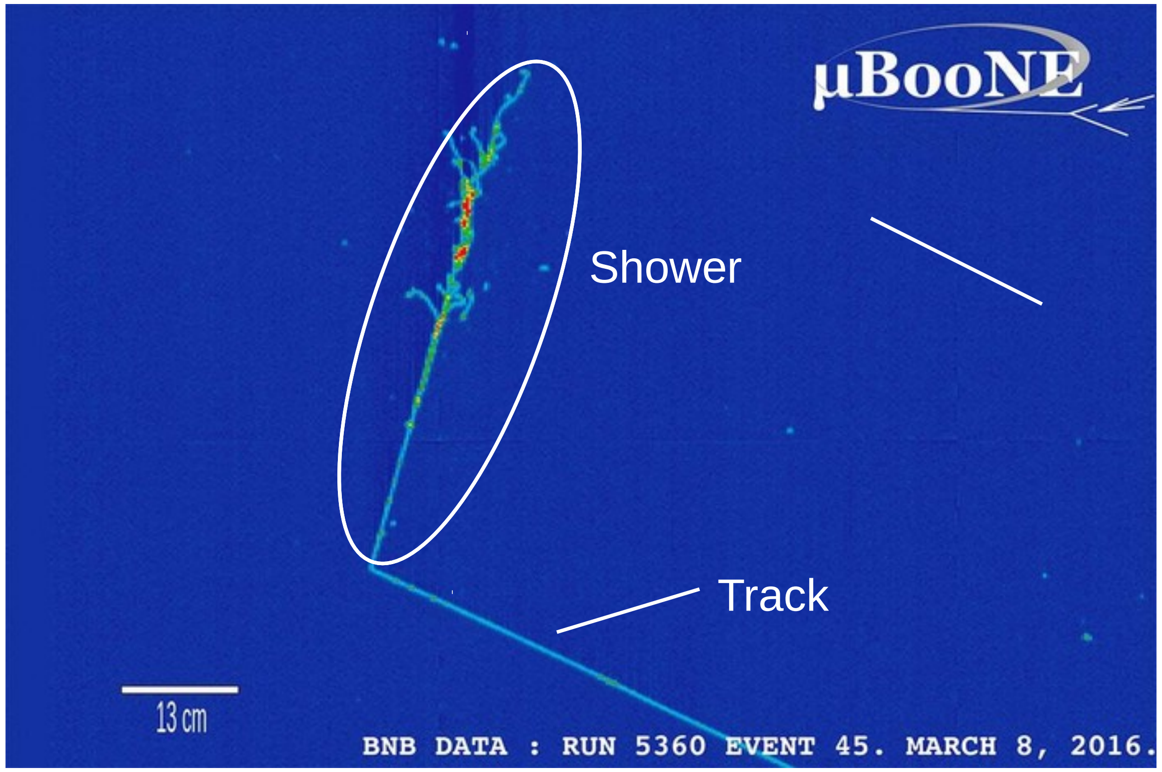
μBooNE Detector Performance

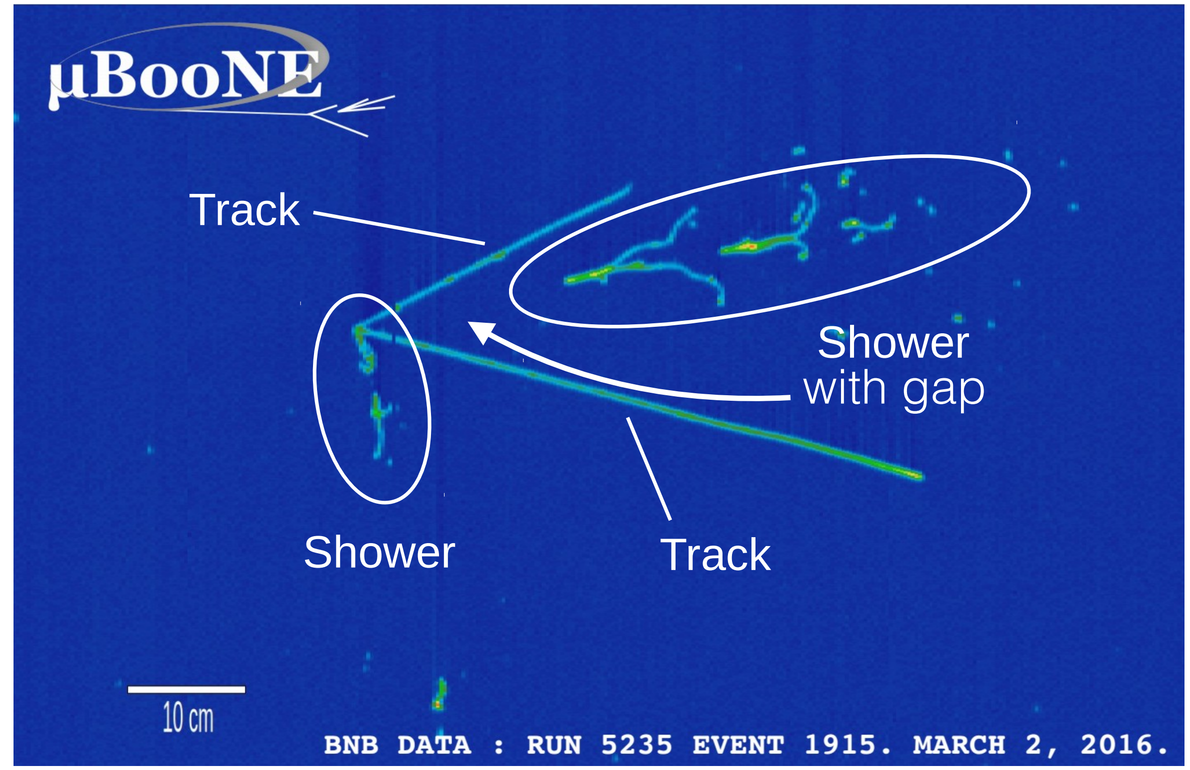


4π acceptance, impeccable spatial resolution, sub-cm order tracking

Calorimetric measurement for PID

μBooNE Detector Performance





Particle Identification

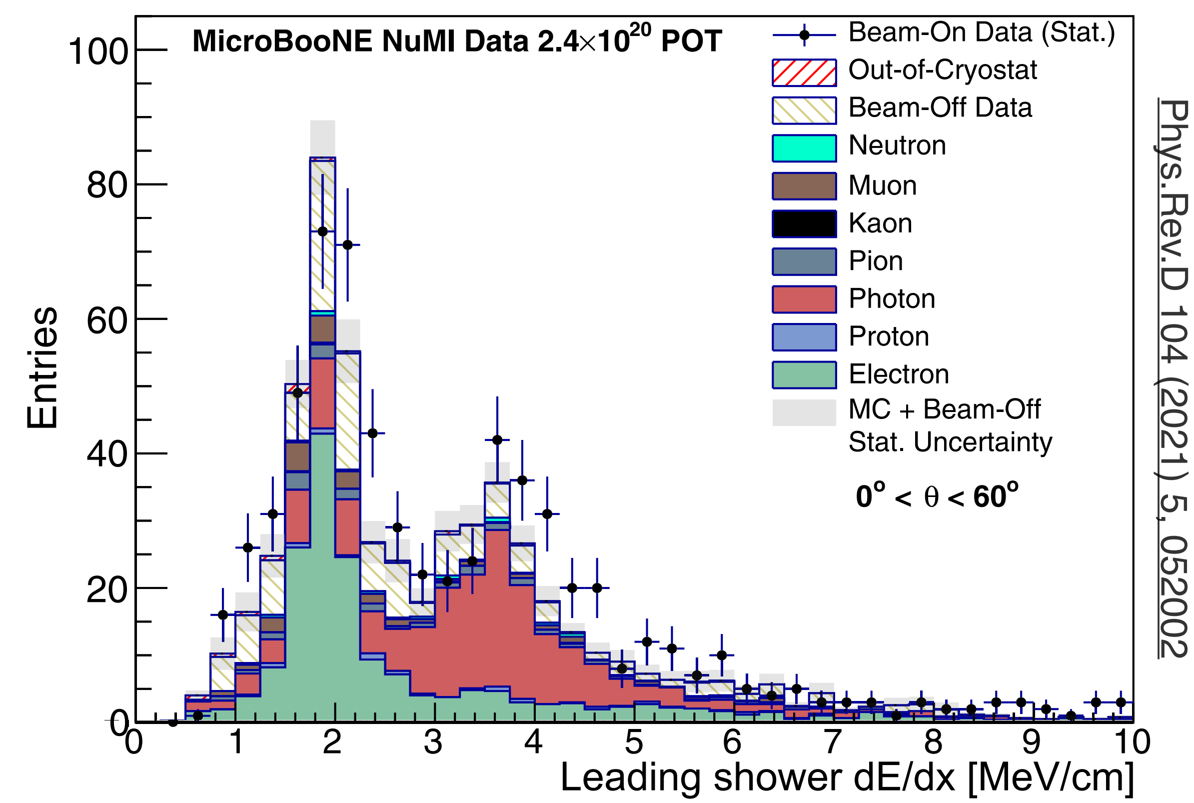
μ, π, K, p tracks

e, γ shower

with impressive separation based on:

Distance to vertex

dE/dx



Collection plane 0° < θ < 60°

µBooNE Cross Section Analyses

- Comparing to various event generators

  Including a self-developed tune in Genie

  CCQE and CCMEC tuned to T2K $\nu_\mu CC0\pi$ data Phys.Rev.D 105 (2022) 7, 072001

- A novel approach to estimate detector related systematic uncertainties Eur.Phys.J.C 82 (2022) 5, 454

- GEANT4 based beam and target simulation, constrained with NA49 data

- Using off-beam data to estimate background - overlay method

- Exploring various reconstruction chains

μBooNE Cross Section Analyses

Inclusive

1D & 2D ν_μ CC inclusive @ BNB
Phys. Rev. Lett. 123, 131801 (2019)

1D ν_μCC 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)

π

ν_μNCπ0 @ BNB
Phys. Rev. D 107, 012004 (2023)

0π

1D ν e CCNp0π @ BNB
Phys. Rev. D 106, L051102 (2022)

1D & 2D ν μ CC1p0π Kinematic Imbalance @ BNB
arXiv:2301.03700 (accepted to PRL)
arXiv:2301.03706 (accepted to PRD)

1D ν μ CC1p0π @ BNB
Phys. Rev. Lett. 125, 201803 (2020)

1D ν μ CC2p @ BNB
arXiv:2211.03734, submitted to PRL

1D ν μ CCNp0π @ BNB
Phys. Rev. D102, 112013 (2020)

Rare

η production @ BNB
arXiv:2305.16249, submitted to PRL

Λ production @ NuMI
Phys. Rev. Lett. 130, 231802 (2023)

μBooNE Cross Section Analyses

Today

Inclusive

1D & 2D ν_μ CC inclusive @ BNB
Phys. Rev. Lett. 123, 131801 (2019)

1D ν_μCC 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)

π

ν_μNCπ0 @ BNB
Phys. Rev. D 107, 012004 (2023)

0π

1D ν_e CCNp0π @ BNB
Phys. Rev. D 106, L051102 (2022)

1D & 2D ν_μCC1p0π Kinematic Imbalance @ BNB
arXiv:2301.03700 (accepted to PRL)
arXiv:2301.03706 (accepted to PRD)

1D ν_μCC1p0π @ BNB
Phys. Rev. Lett. 125, 201803 (2020)

1D ν_μCC2p @ BNB
arXiv:2211.03734, submitted to PRL

1D ν_μCCNp0π @ BNB
Phys. Rev. D102, 112013 (2020)

Rare

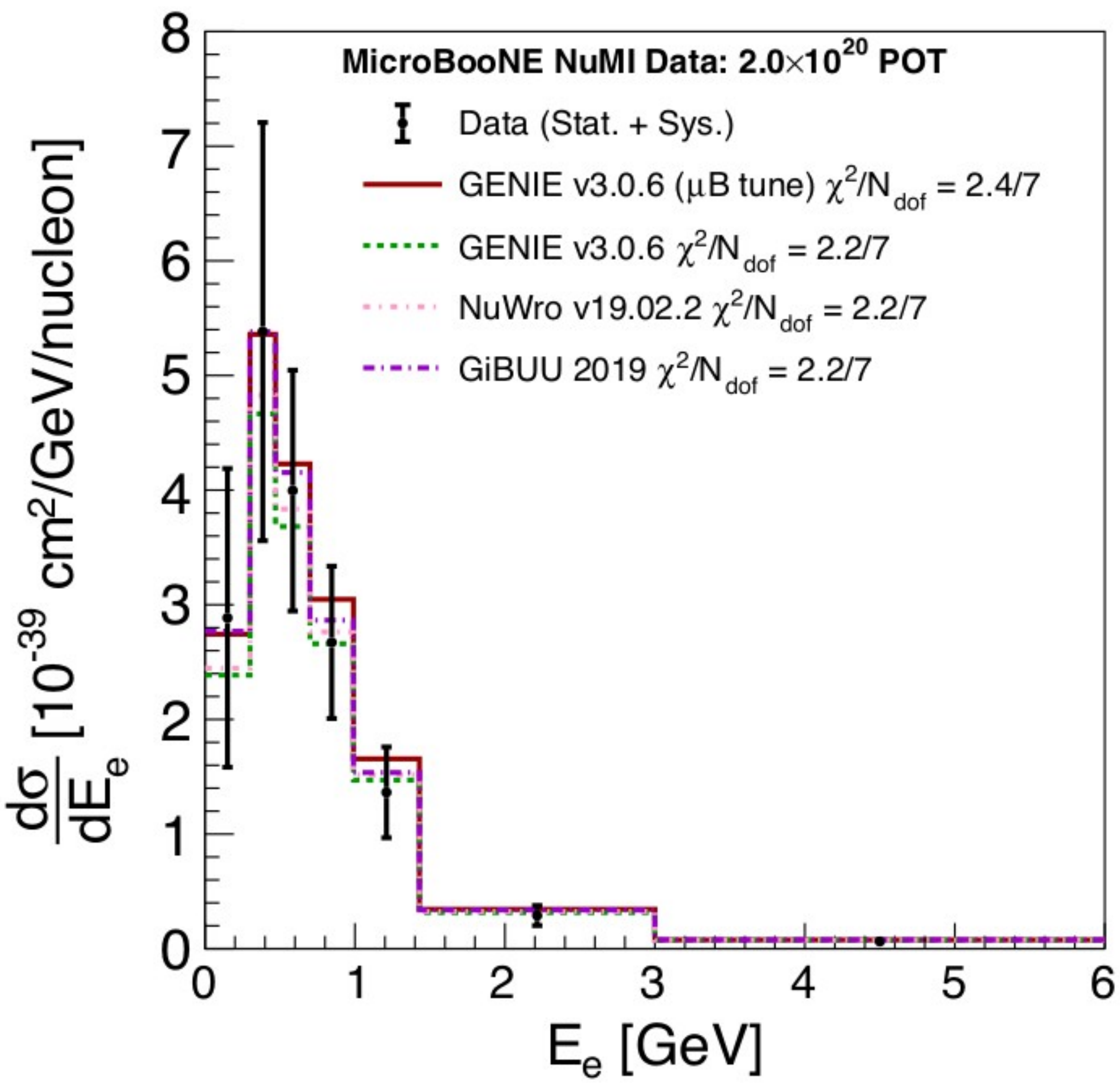
η production @ BNB
arXiv:2305.16249, submitted to PRL

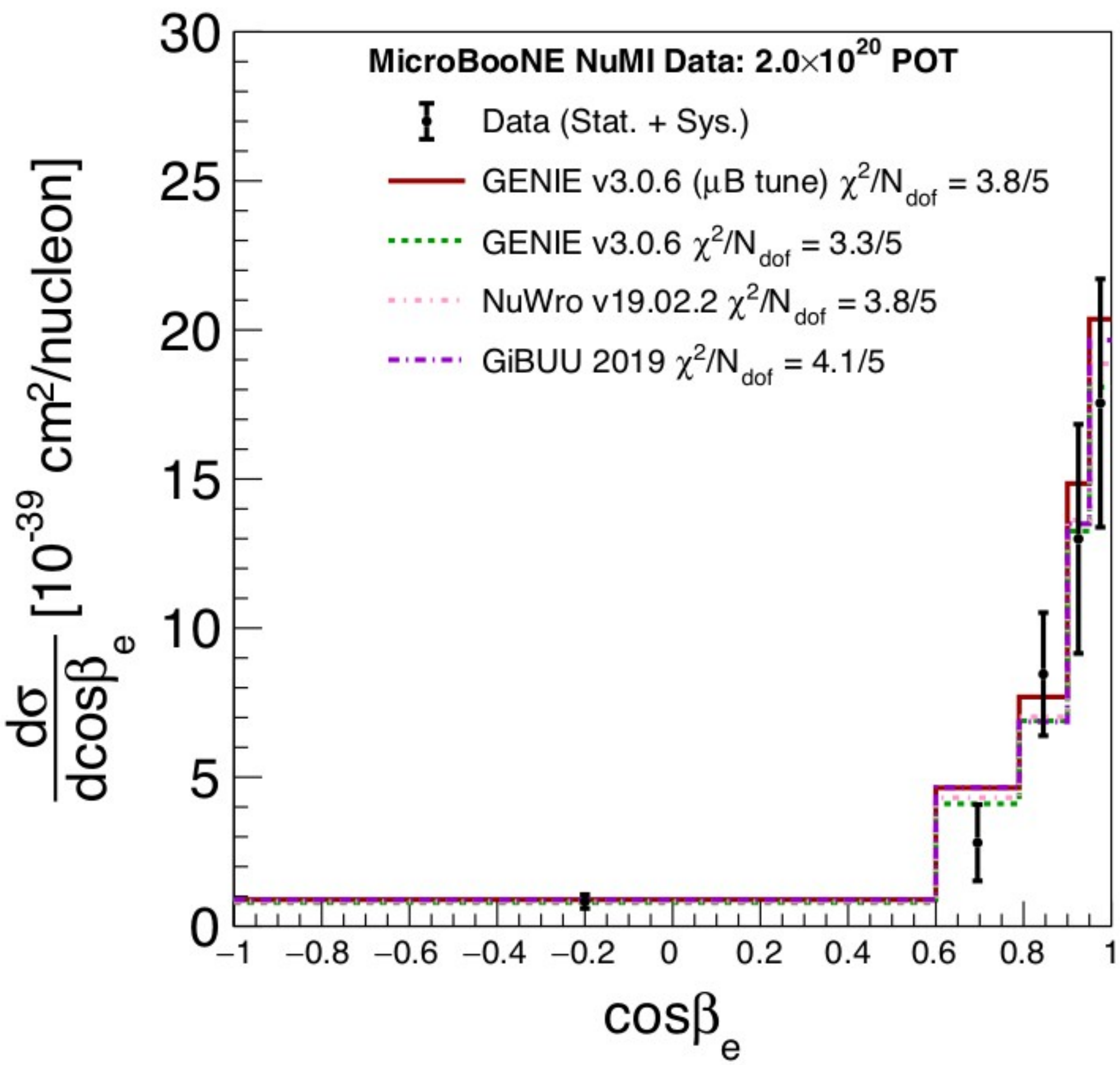
Λ production @ NuMI
Phys. Rev. Lett. 130, 231802 (2023)

Inclusive Results

Inclusive ν_e using NUMI beam

First ν_e differential cross section





Based on 243 selected events

purity of 72%

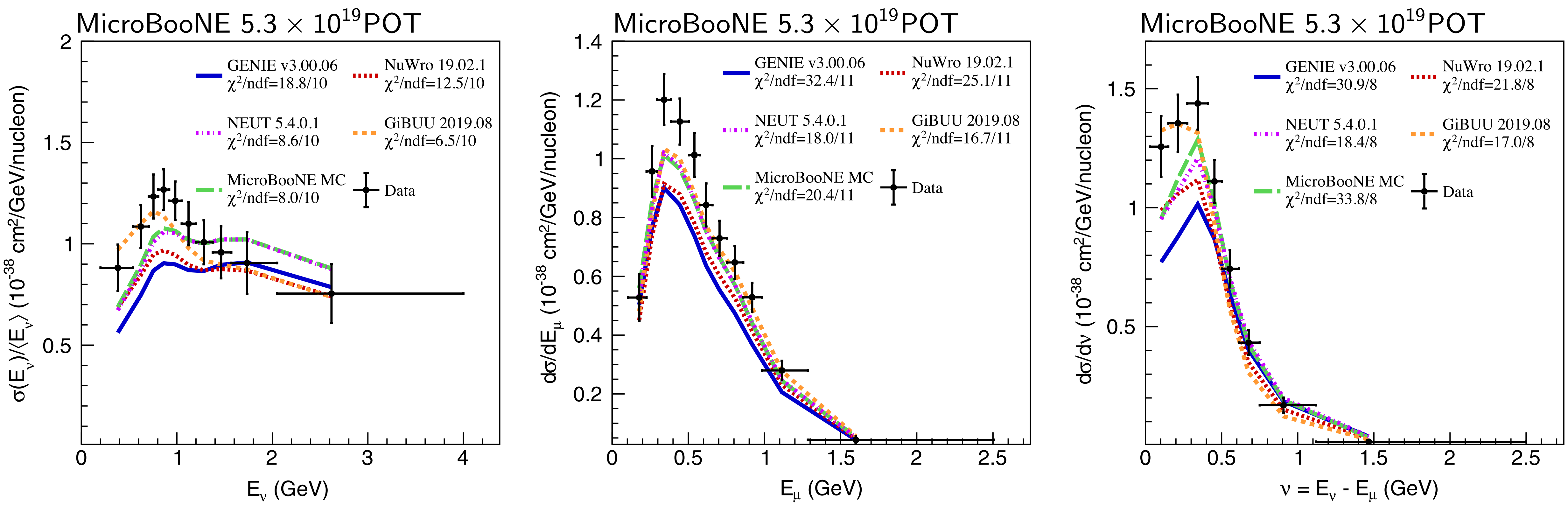
efficiency 21%

Phys. Rev. D 104, 052002 Phys. Rev. D 105, 051102

Inclusive ν_μ using BNB

Presenting first differential cross section for E_ν and $\nu = E_\nu - E_\mu$

Using Wiener-SVD unfolding



GiBUU is favored at low energy, but overall gives lower prediction

Could be due underestimation of after Δ resonance

Based on 11528 selected events

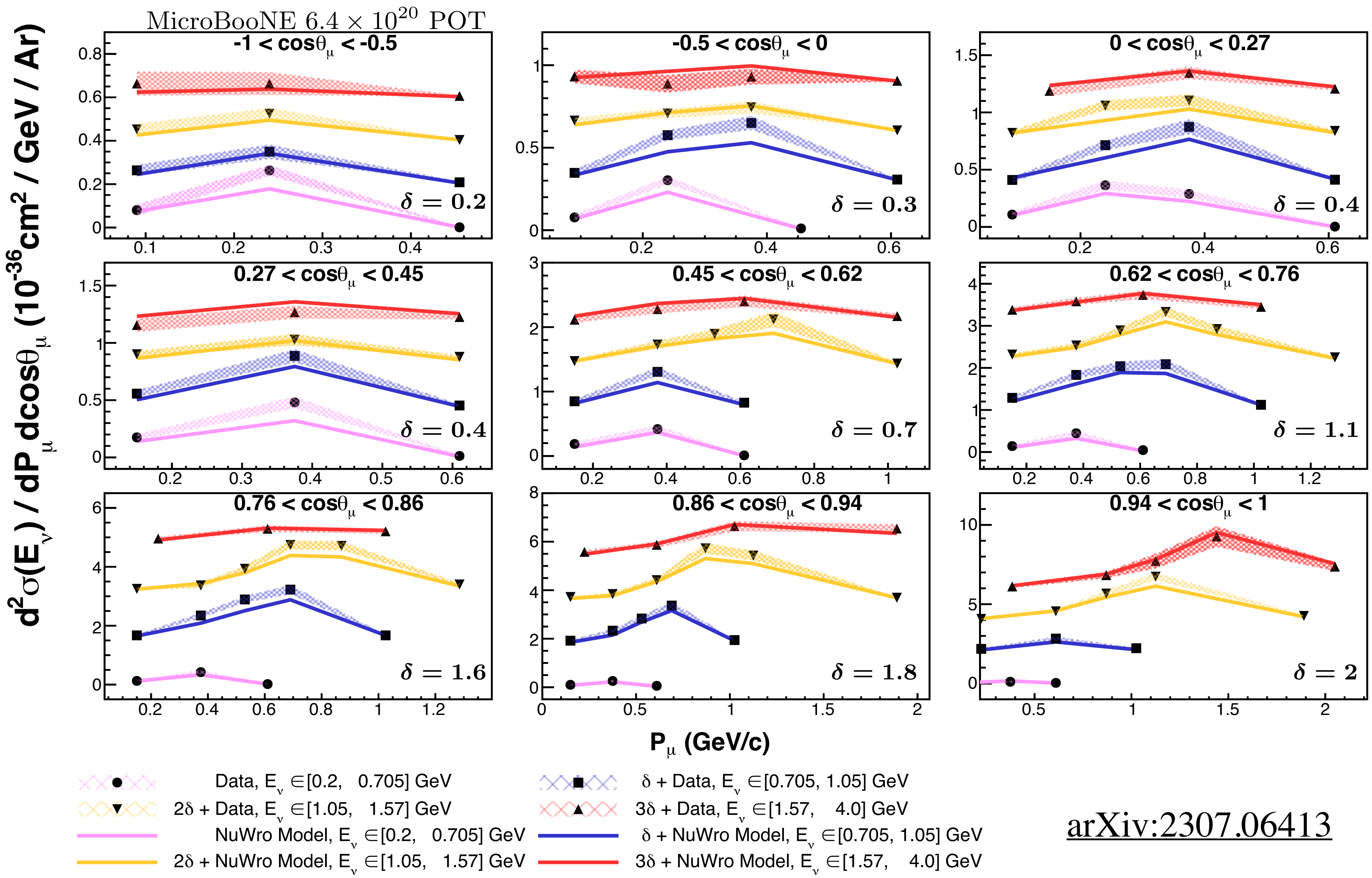
purity of 92%

efficiency 68%

Phys. Rev. Lett. 128, 151801

Inclusive ν_μ using BNB in 3D

First triple differential cross section on argon



arXiv:2307.06413

Different event generators yield disagreement in different part of phase-space

GiBUU and NEUT favored at low energies, NuWro at higher

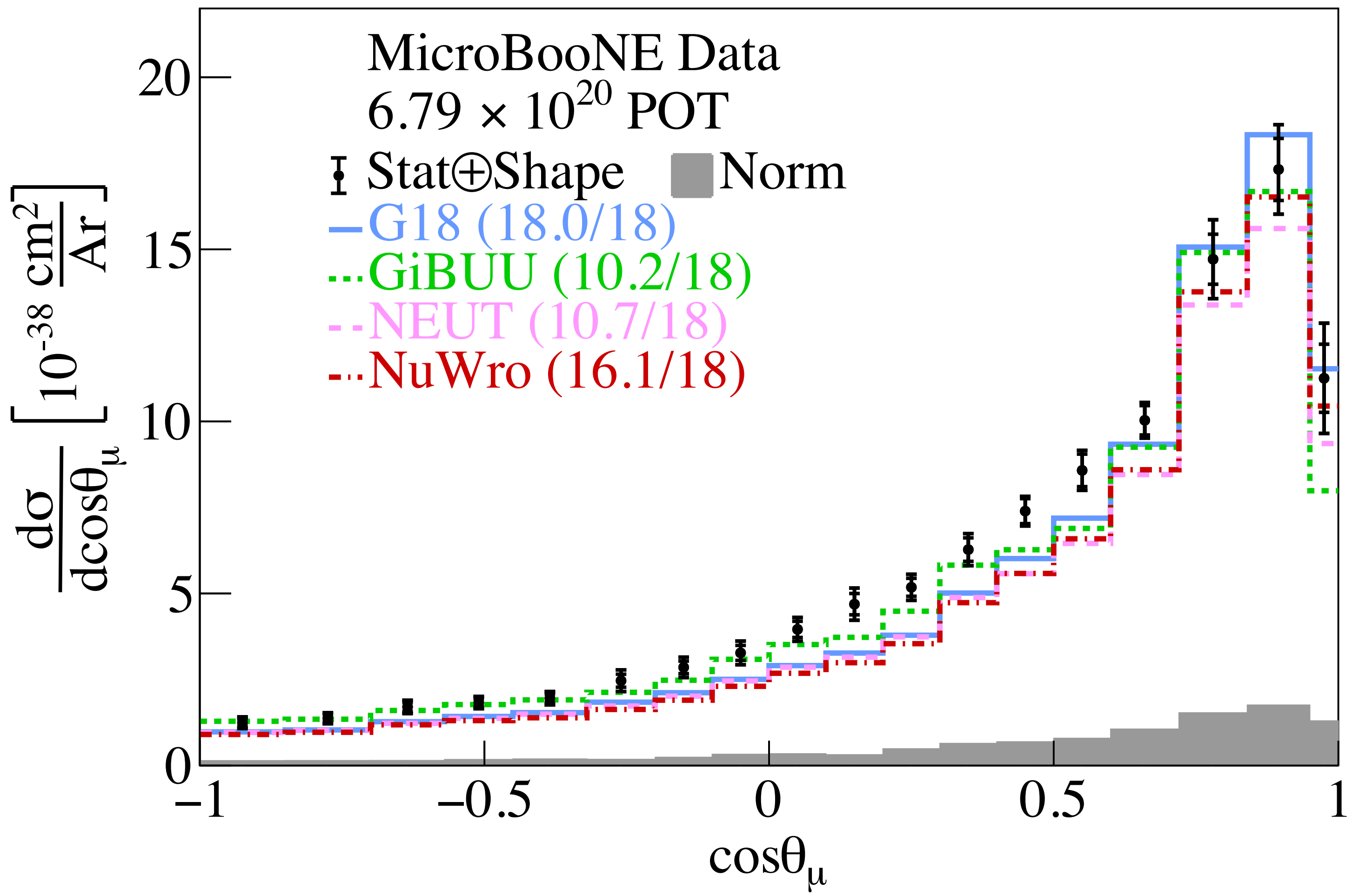
µBooNE

0π Results

ν_μCC 1p0π

A simple topology with a potential to unveil the underlying nuclear physics

Significant improvement from previous results



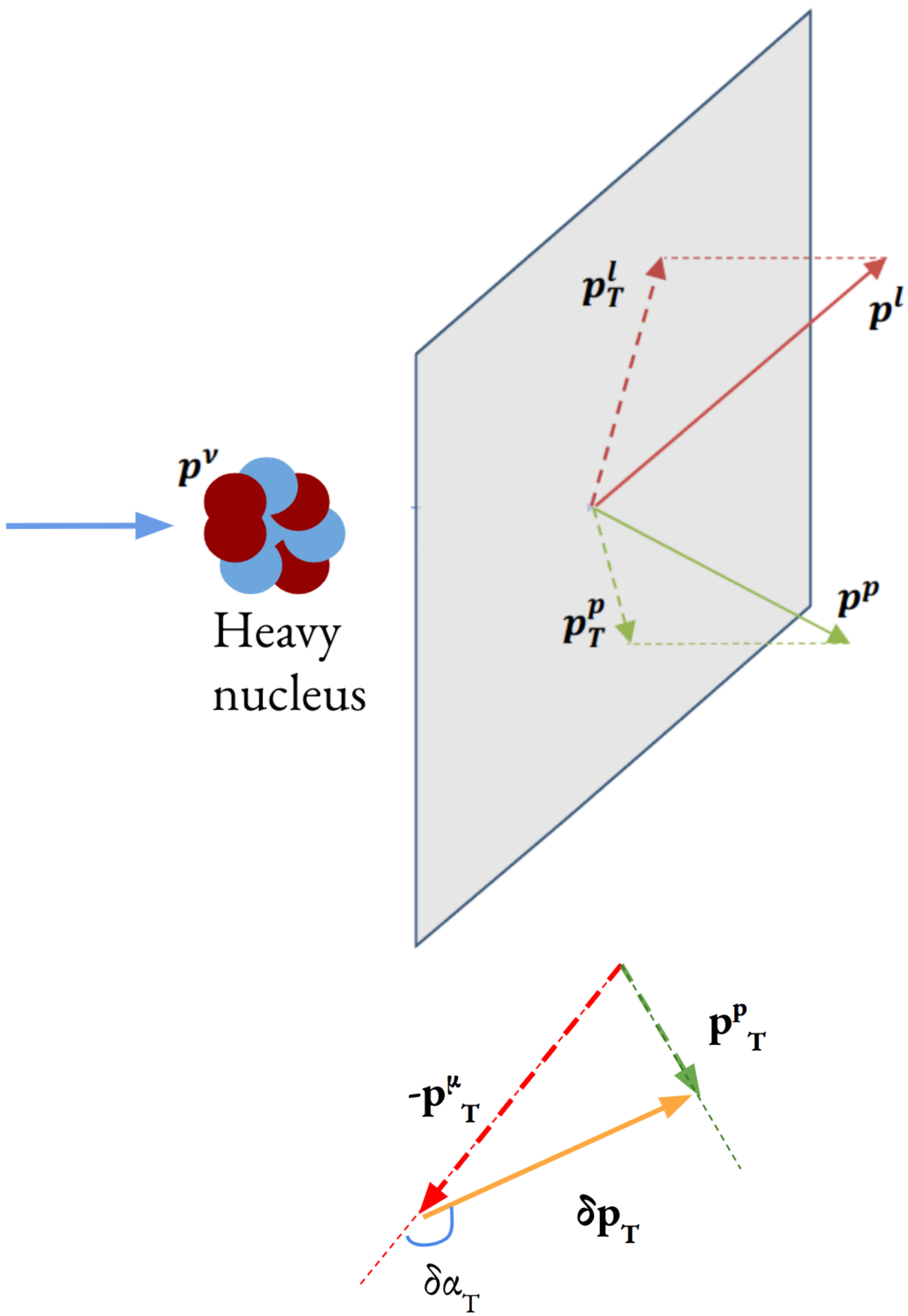
Based on 9051 events

purity of 70%

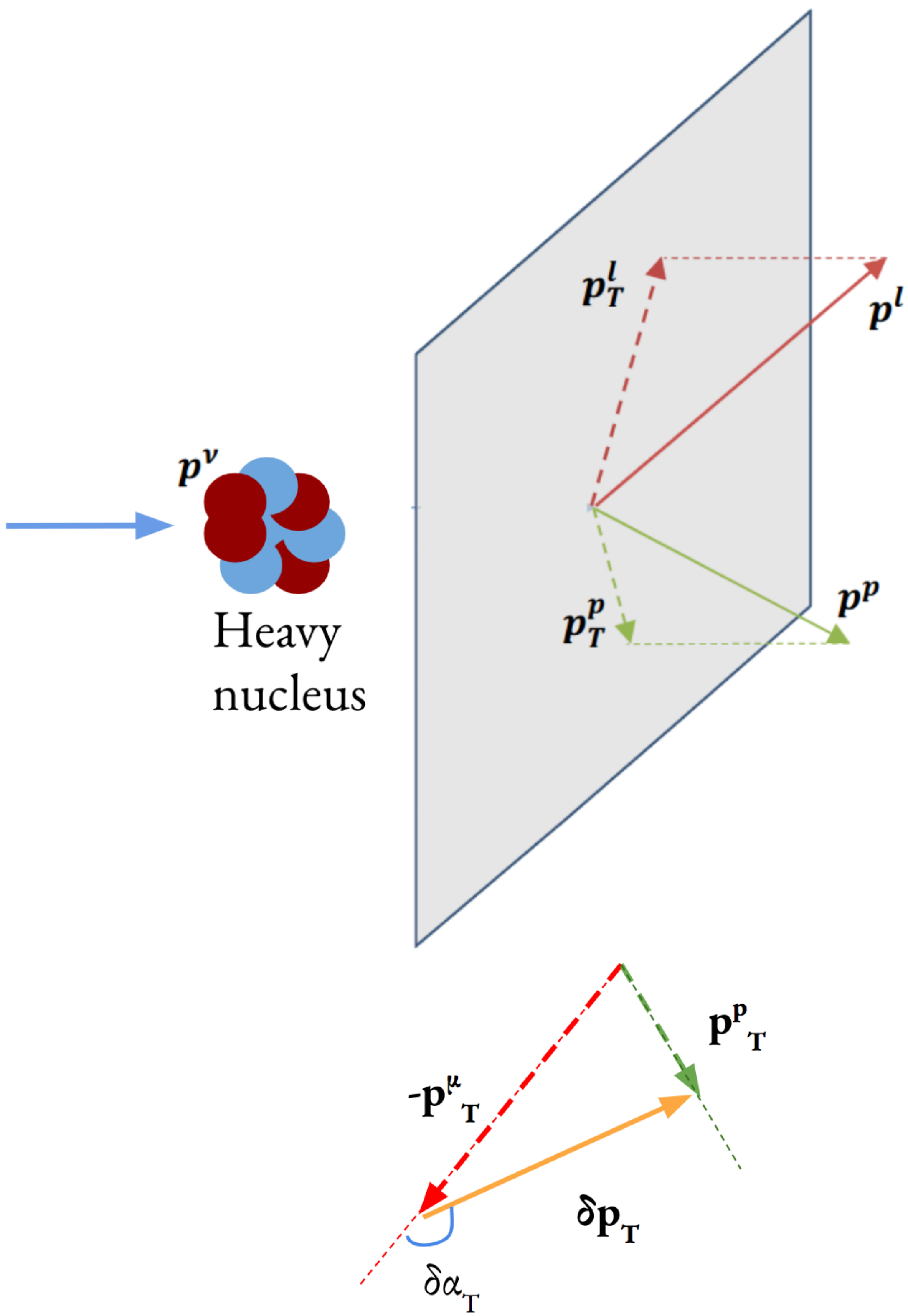
efficiency 10%

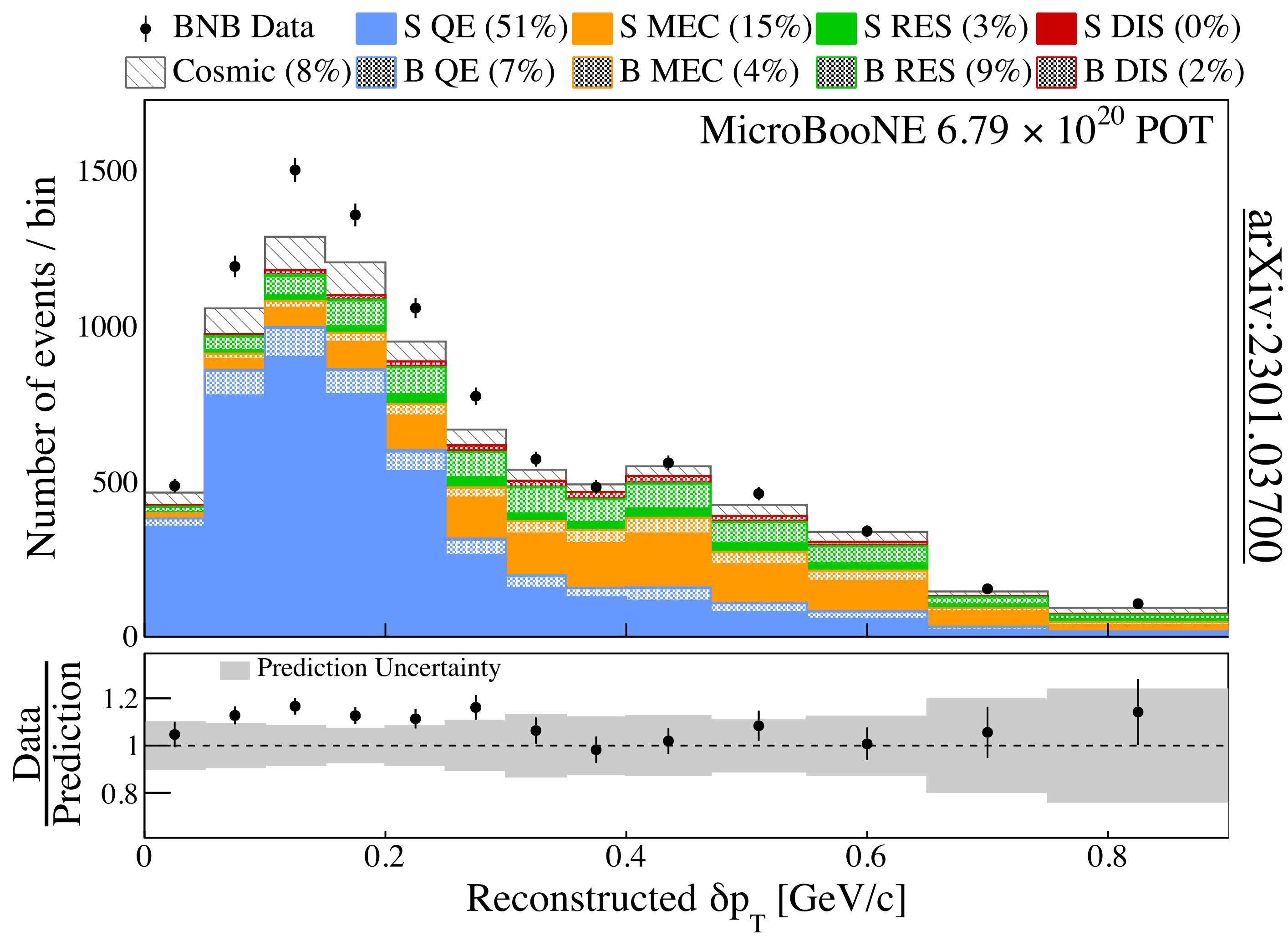
arXiv:2301.03700 , arXiv:2301.03706 do we already have PRL/PRD cite?

ν_μCC 1p0π Transverse Kinematic Imbalance



ν_μCC 1p0π Transverse Kinematic Imbalance

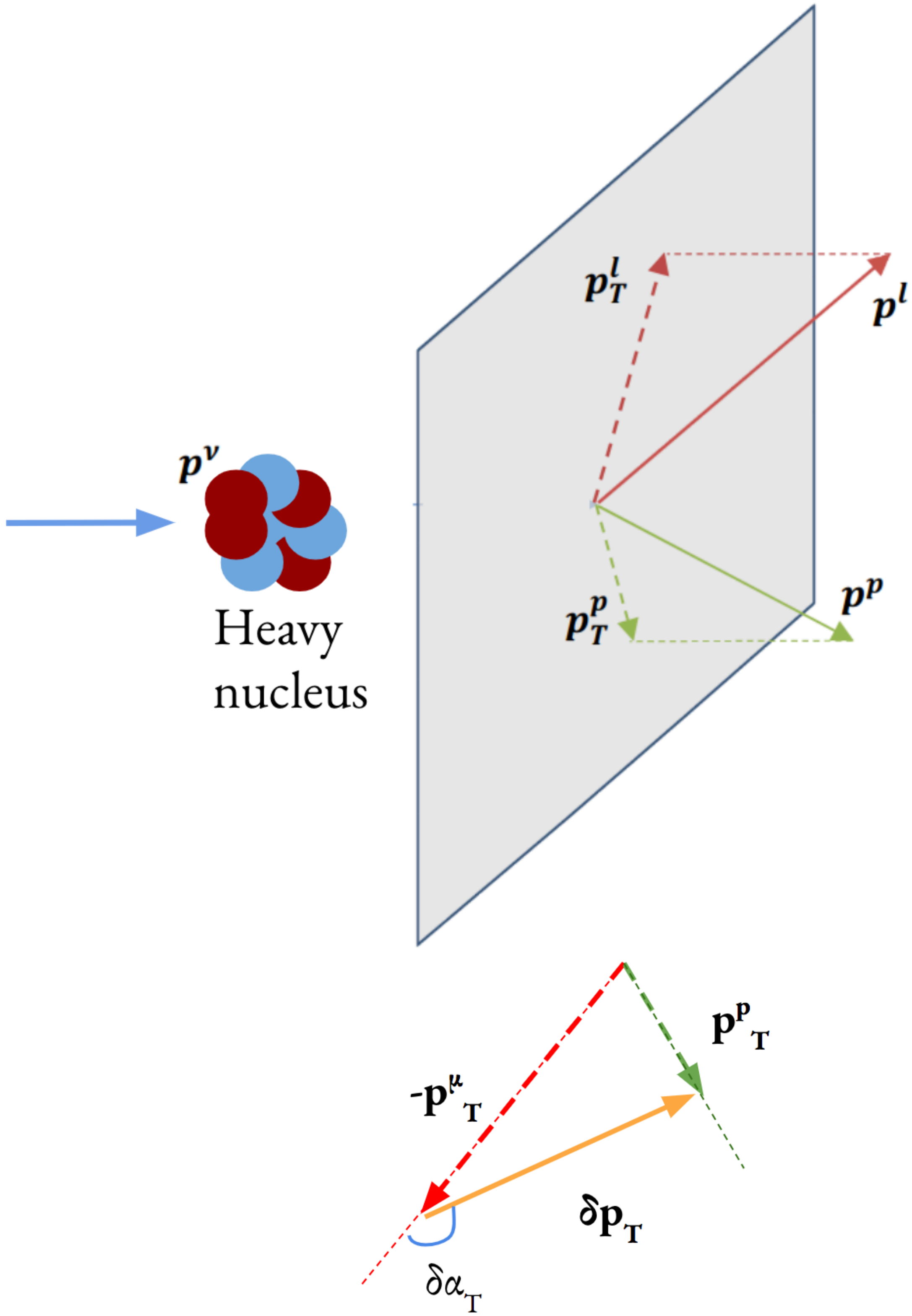


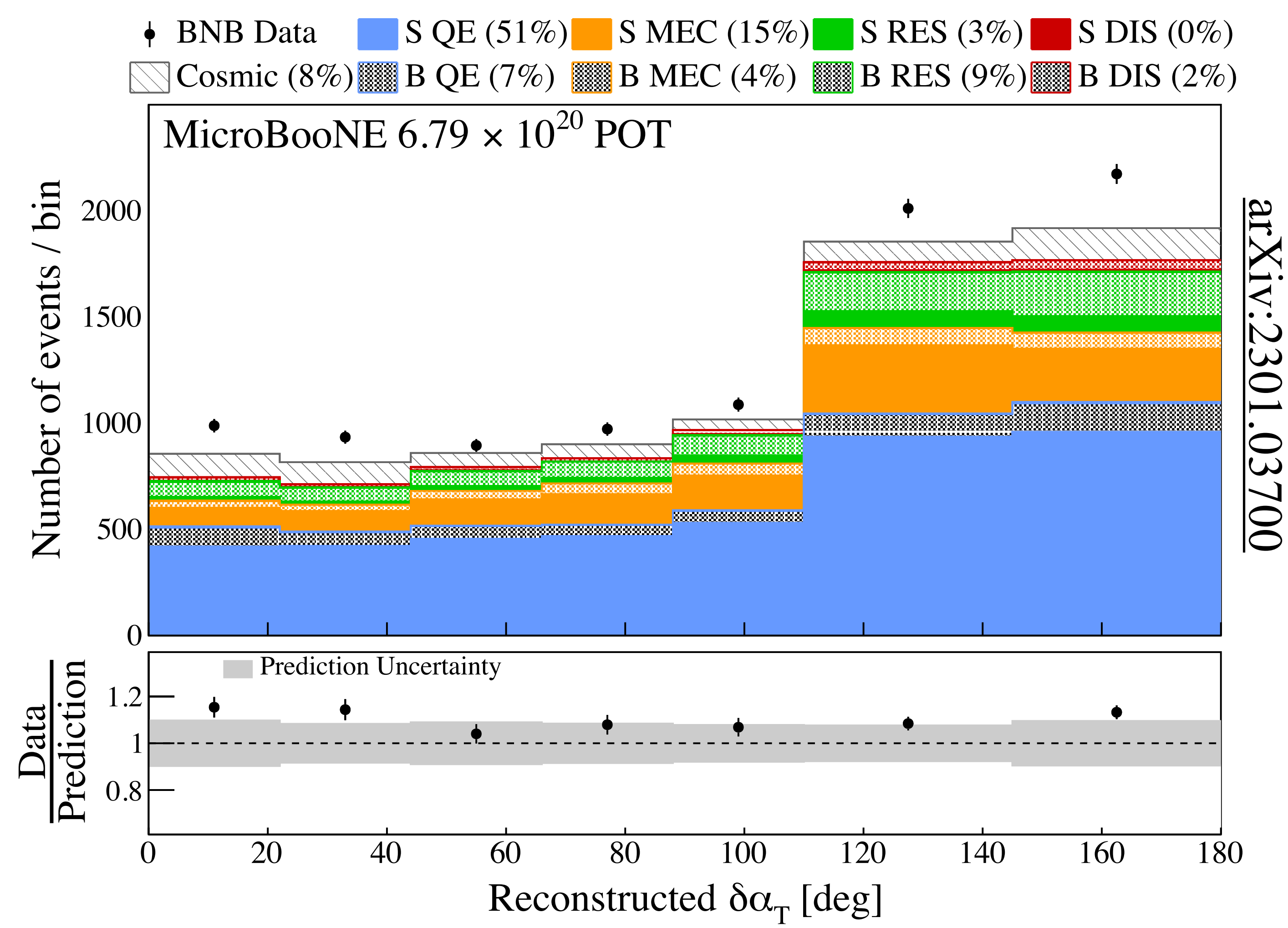


$$\delta p_T = \left|\vec{p}_T{}^{\mu} + \vec{p}_T{}^{p}\right|$$

Sensitive to
hit nucleon momentum

ν_μCC 1p0π Transverse Kinematic Imbalance





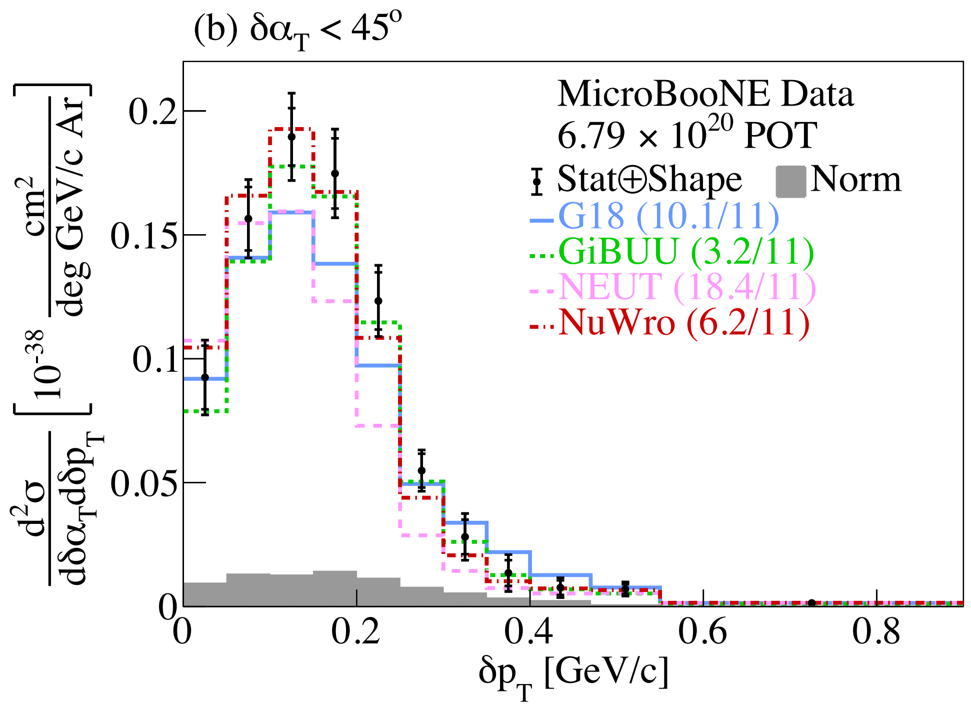
$\delta\alpha_T$

Sensitive to

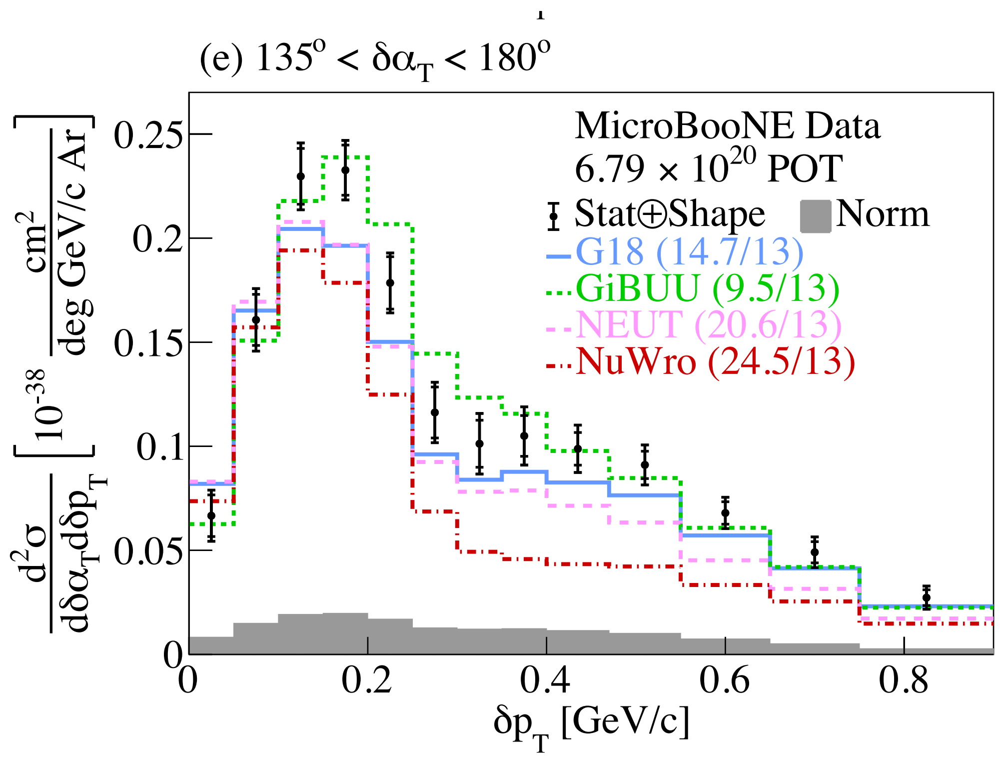
Final State Interactions

ν_μCC 1p0π

Double differential cross section study the impact of nuclear effects



For events with high αT, the various predictions differ due to FSI effect

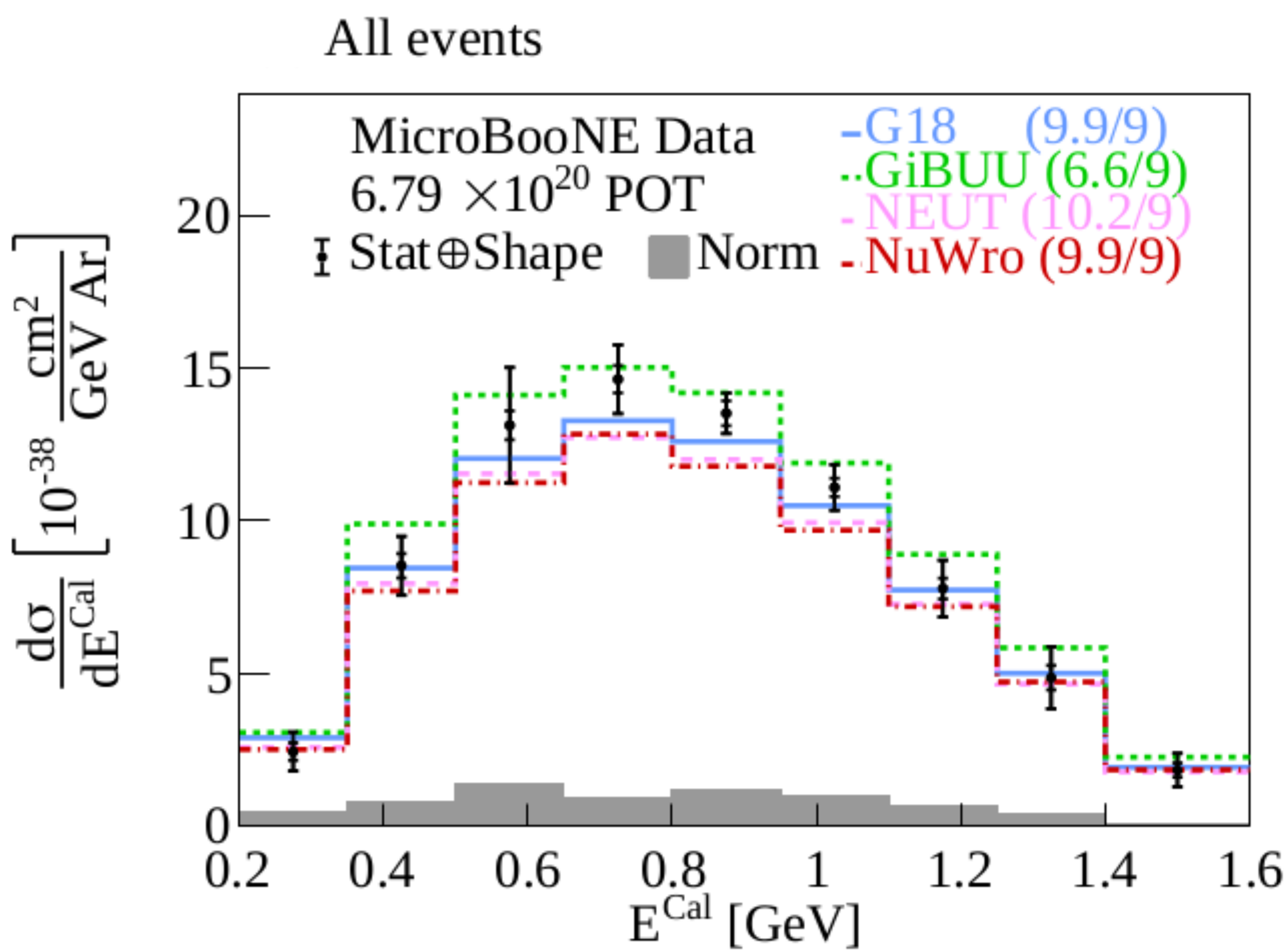


many more in arXiv:2301.03700 , arXiv:2301.03706

ν_μCC 1p0π

Double differential cross section study the impact of nuclear effects on energy reconstruction

With increasing transverse momentum the various prediction differ

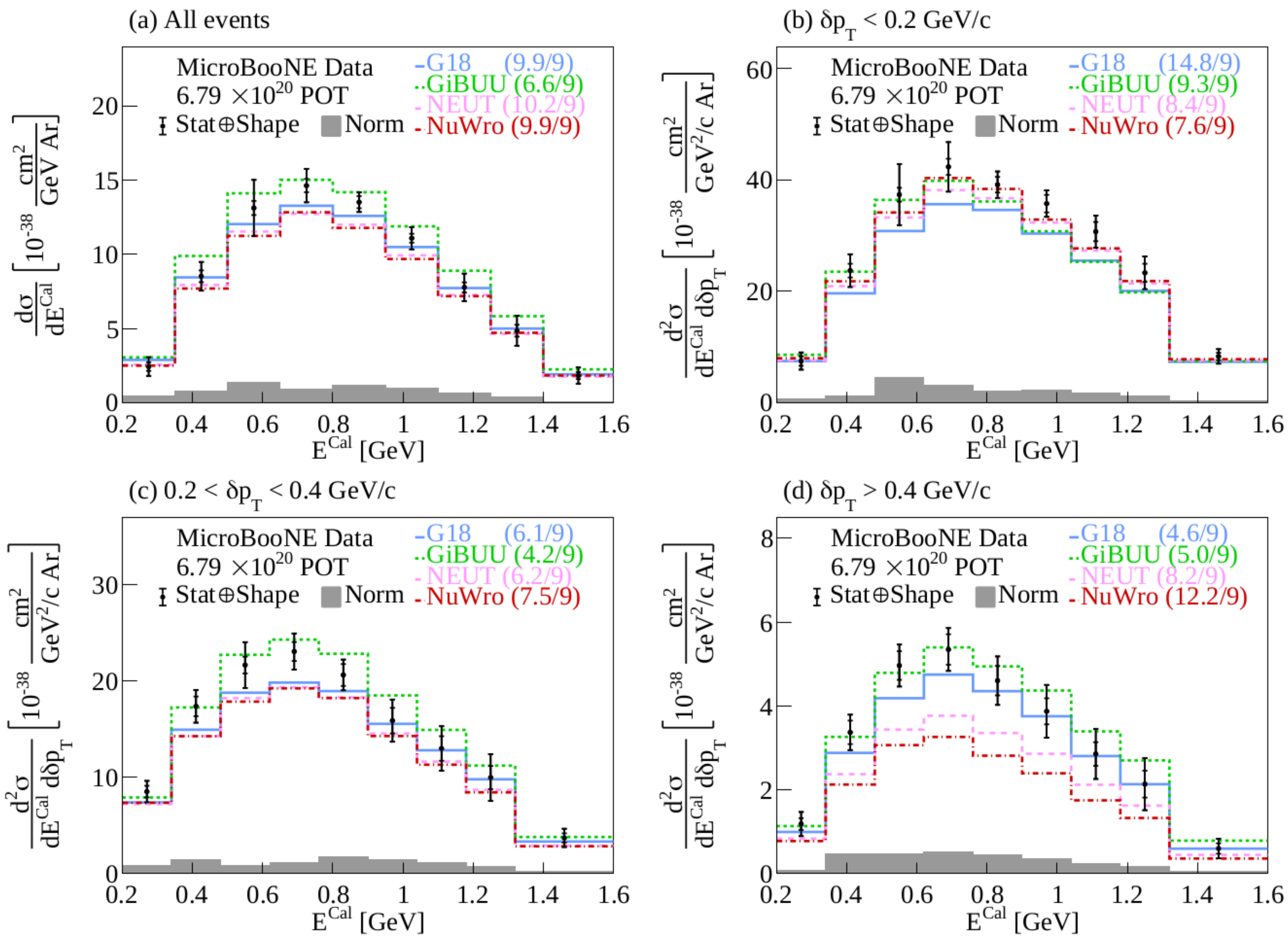


many more in arXiv:2301.03700 , arXiv:2301.03706

ν_μCC 1p0π

Double differential cross section study the impact of nuclear effects on energy reconstruction

With increasing transverse momentum the various predictions differ

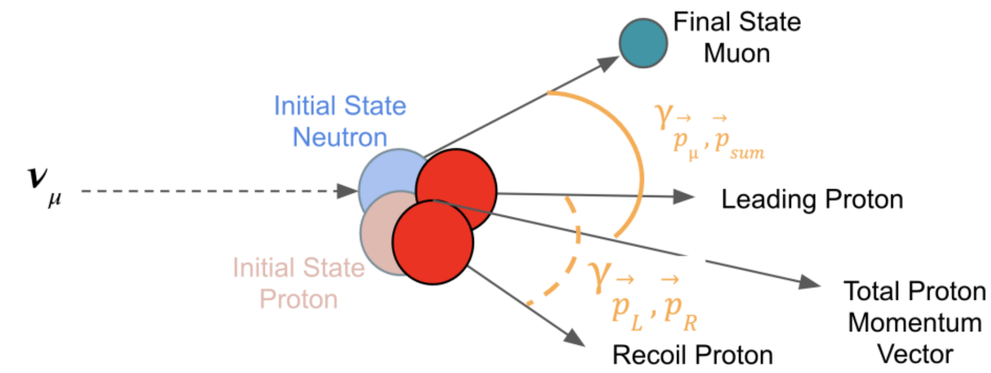


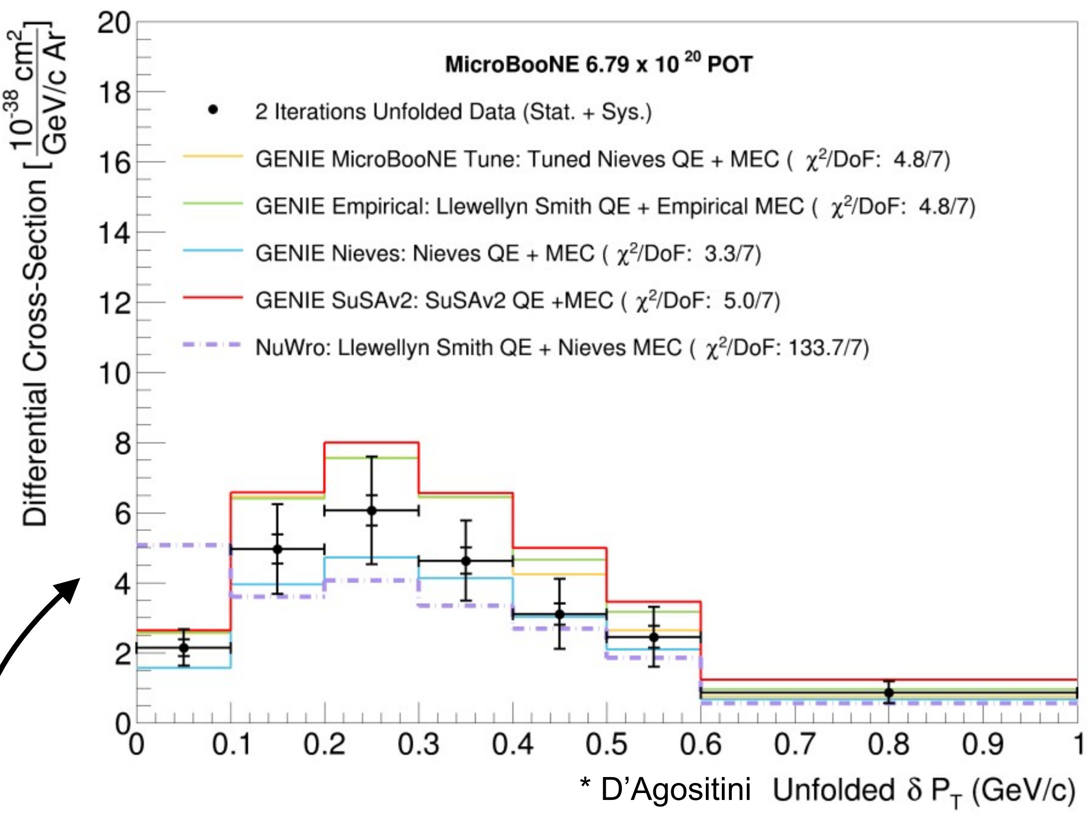
many more in arXiv:2301.03700 , arXiv:2301.03706

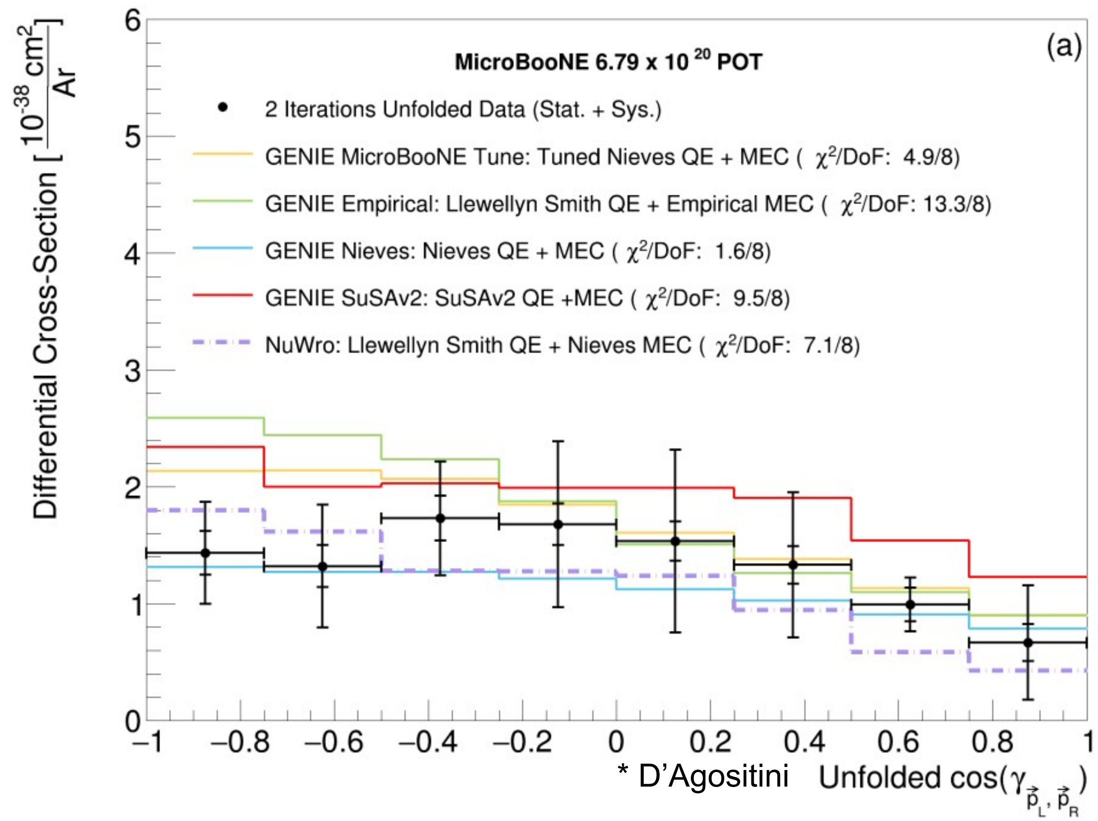
ν_μCC 2p0π

First high statistics analysis of its kind

Dominated by MEC events







NuWro prediction differs due to back to back nucleon orientation

purity of 65.4%

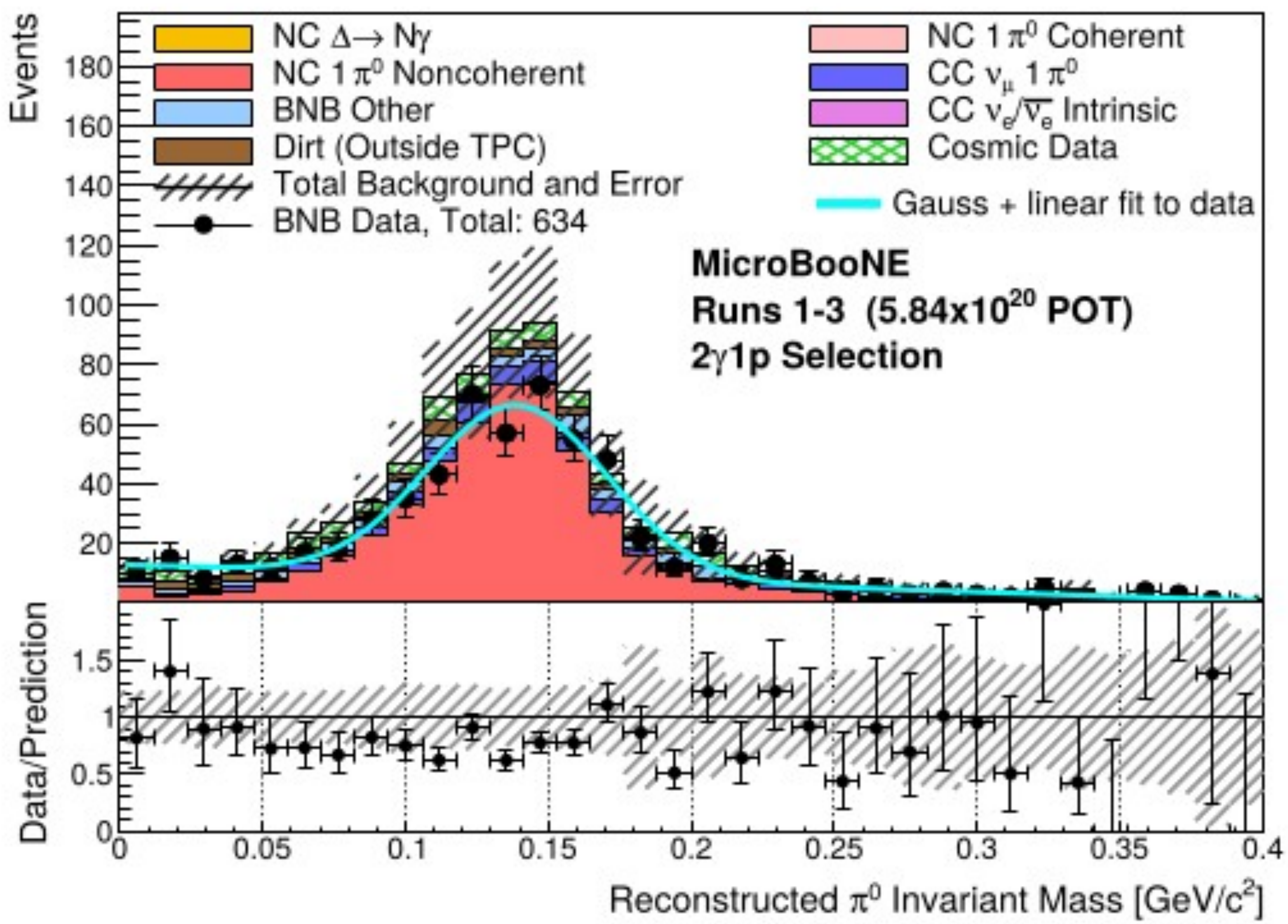
efficiency 13%

arXiv:2211.03734

μBooNE 0π Results

NC π^0

Extensively studied as background to LEE
Identify neutral pions by their invariant mass



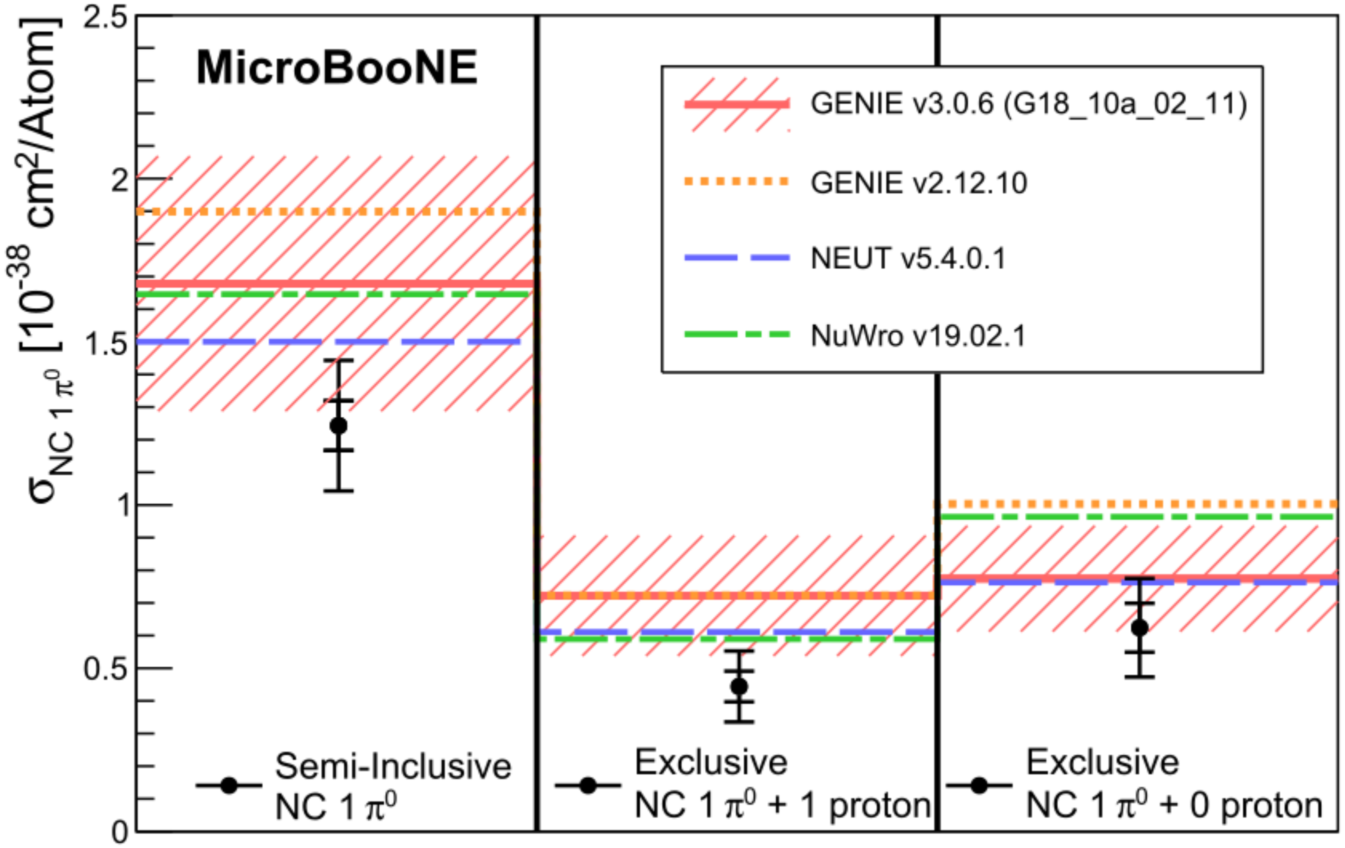
Phys. Rev. D 107, 012004

NC π^0

Measured cross section in 1p2γ and 0p2γ chanels

Good agreement, justifying its use as a constraint

NEUT model is favored



$\sigma = \ 1.243 \pm 0.185(\text{syst}) \pm 0.076(\text{stat})\ \ [10^{-38}\ \text{cm}^2/\text{Ar}]$

Based on 1130 events

purity: 52.9% for $0p1\pi^0$, 63.5% for $1p1\pi^0$

efficiency: 6% for $0p1\pi^0$ and 10.7% for $1p1\pi^0$

Phys. Rev. D 107, 012004

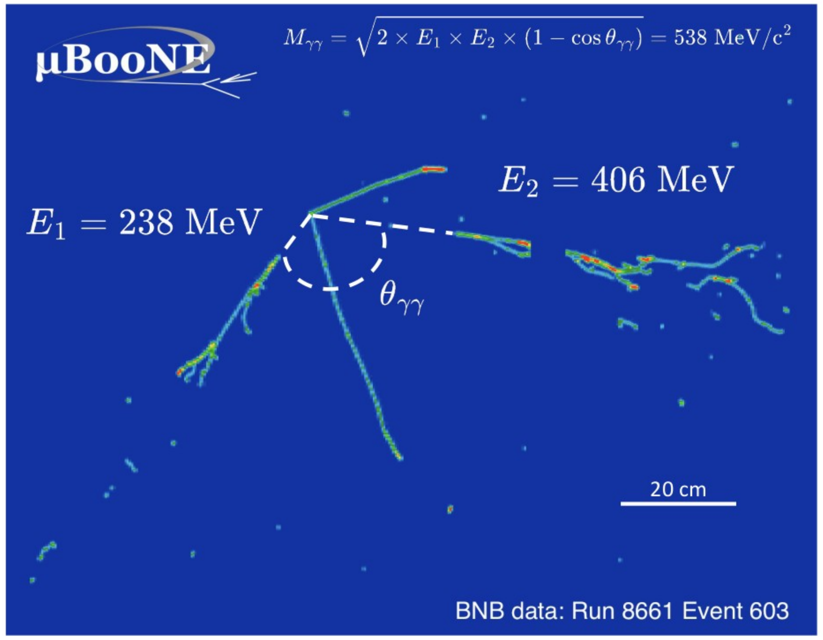
Rare Production

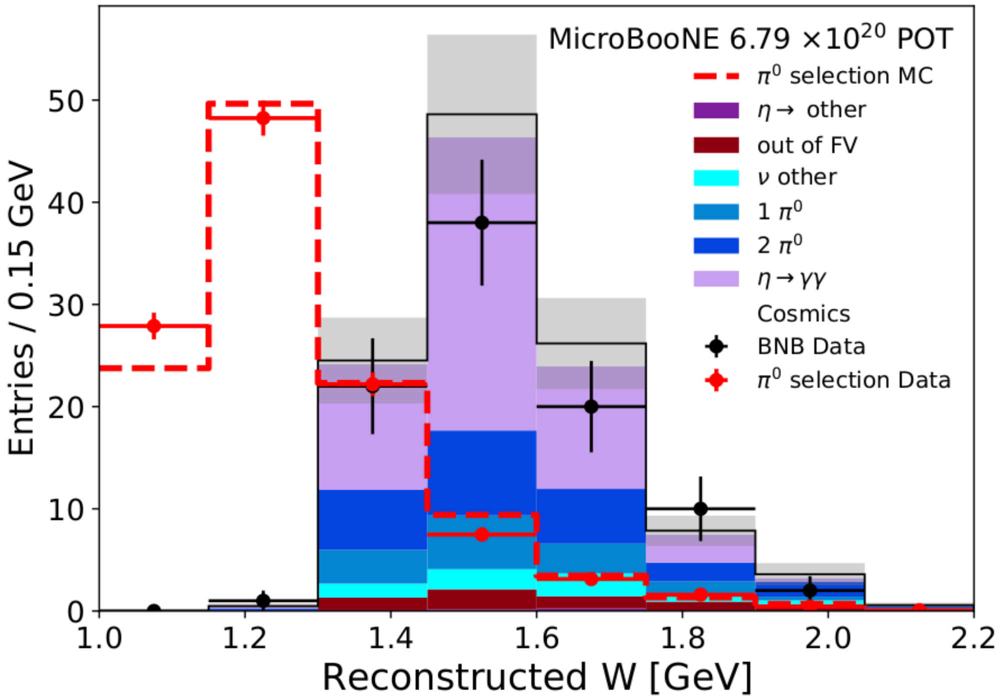
η Production

A unique channel to probe higher- mass resonances such as N(1535), N(1650), N(1710)

A Complimentary standard candle to π^0

Identified by $m_{\gamma\gamma}$ around 548 MeV





σ = $3.22 \pm 0.84\ (\text{stat.}) \pm 0.86\ (\text{syst.})\ 10^{-41} \text{cm}^2/\text{nucleon}$.

Based on 93 events

purity: 49.9%

efficiency: 13.6%

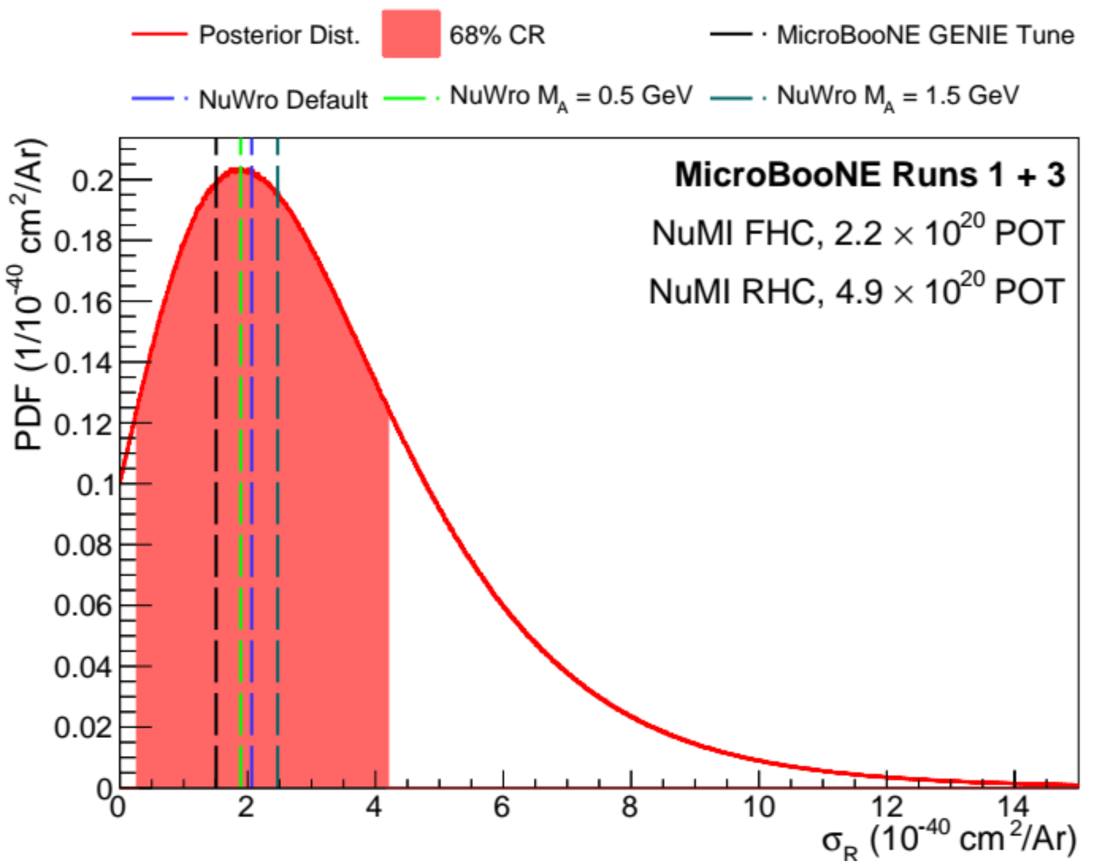
arXiv:2305.16249

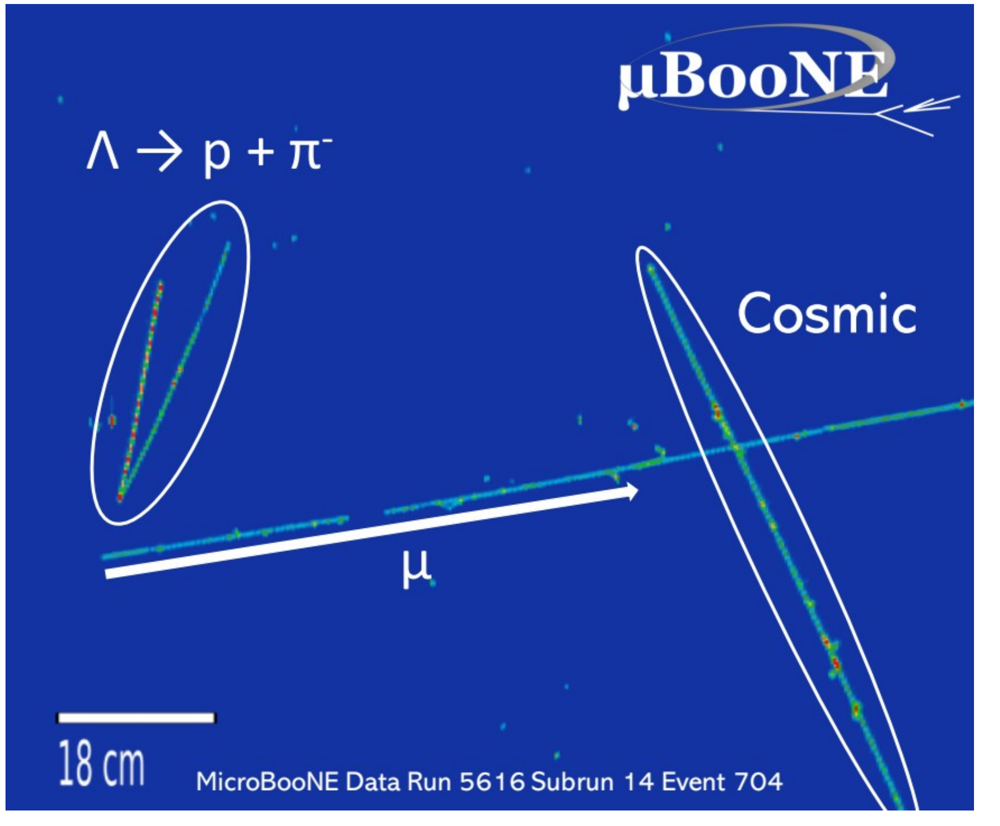
Λ production using NUMI beam

First measurement with a modern detector

Rare interaction analysis based on 5 events

Identification using invariant mass and separated vertex





$\sigma = \ 2.0^{+2.2}_{-1.7} \times 10^{-40} \ \text{cm}^2/\text{Ar}$

Based on 5 selected events

purity: **47%**

efficiency: 6.1%

Phys. Rev. Lett. 130, 231802

µBooNE Collaboration

Ongoing Analyses

Inclusive

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

0π

- 2D ν_μCC1p0π
- Generalized Kinematic Imbalance @ BN
- ν_μCC0π inclusive @ BNB
- 2D ν_μCCNp0π @ BNB
- 1D ν_eCC0πNp @ NuMI
- 1D ν_μNC1p0π @ BNB

π

- ν_μCC1π^+ @ BNB, NuMI
- ν_μCCNπ @ NuMI
- 1D ν_μCCπ^0 @ BNB
- 2D ν_μCC/NCπ^0 @ BNB
- 2D $\nu_{e,\mu}$NCπ^0 @ BNB

Rare

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

μBooNE

Summary

MicroBooNE is still running a diverse and comprehensive cross section program.

Showcasing different channels, analysis techniques

By using:

- an improved cross section model
- LArTPC simulation with new estimated uncertainties
- The state of the art beam simulation

MicroBooNE is sensitive enough to expose inconsistencies between models and dive into the unknown of the νAr interaction

Stay tuned as 40% of our data is still to come!

μBooNE

Thank you for your attention