LATEST NEUTRINO-ARGON SCATTERING RESULTS FROM MICROBOONE

Kirsty Duffy, Fermi National Accelerator Laboratory

HEP Seminar, Imperial College London

10th March 2021

55 cm

Run 3469 Eve

Most neutrino experiments rely on **understanding neutrino interactions with nuclei**, to reconstruct neutrino flavour and energy

The success of future liquid argon experiments relies on a good understanding of these effects on **argon nuclei**

MicroBooNE is the world's **only running liquid-argon experiment taking data in a neutrino beam** — uniquely placed to answer these questions

I will use **"neutrino interactions"** and **"neutrino cross sections"** interchangeably in this talk

Most neutrino experiments rely on **understanding neutrino interactions with nuclei**, to reconstruct neutrino flavour and energy

The success of future liquid argon experiments relies on a good understanding of these effects on **argon nuclei**

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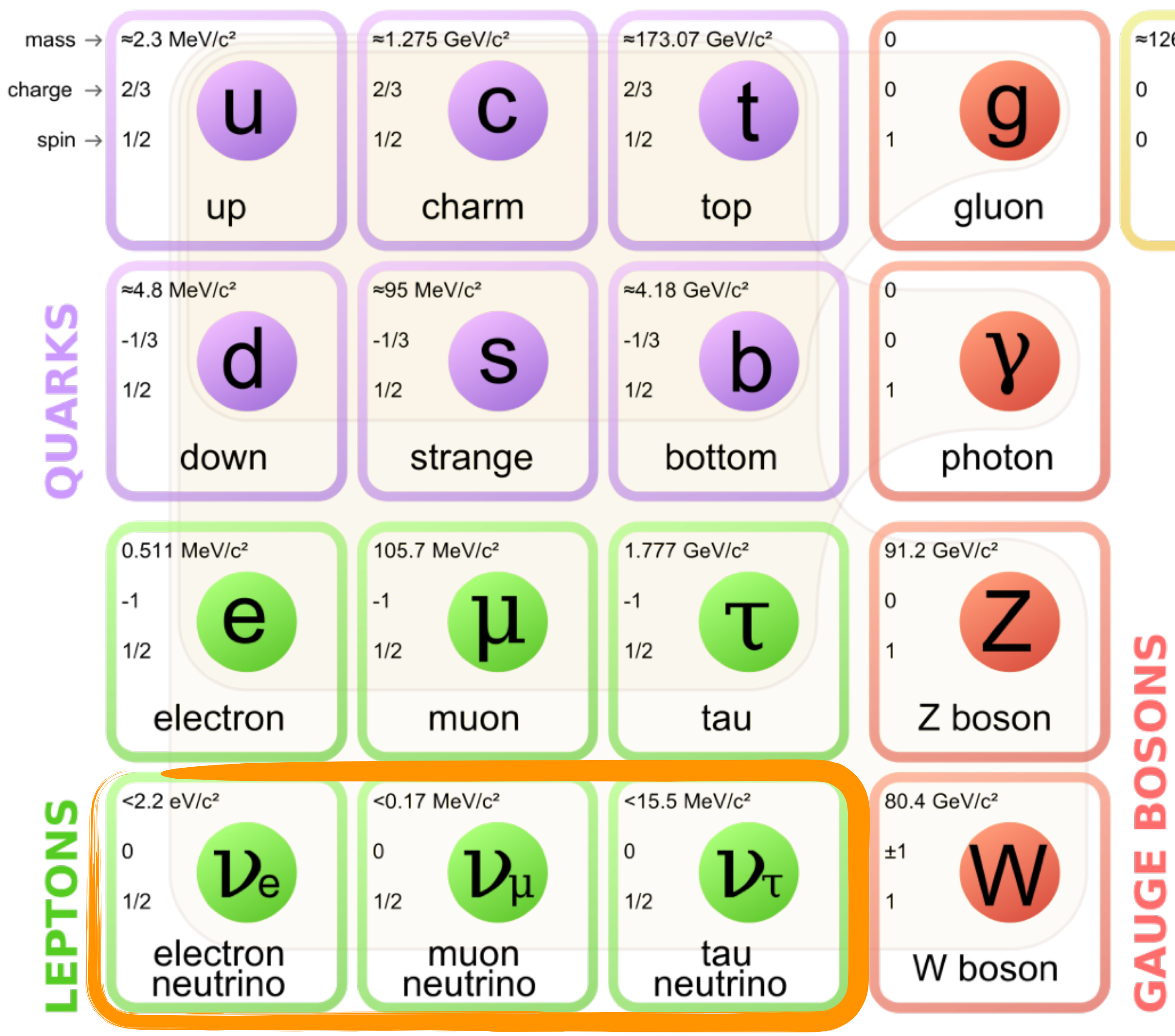
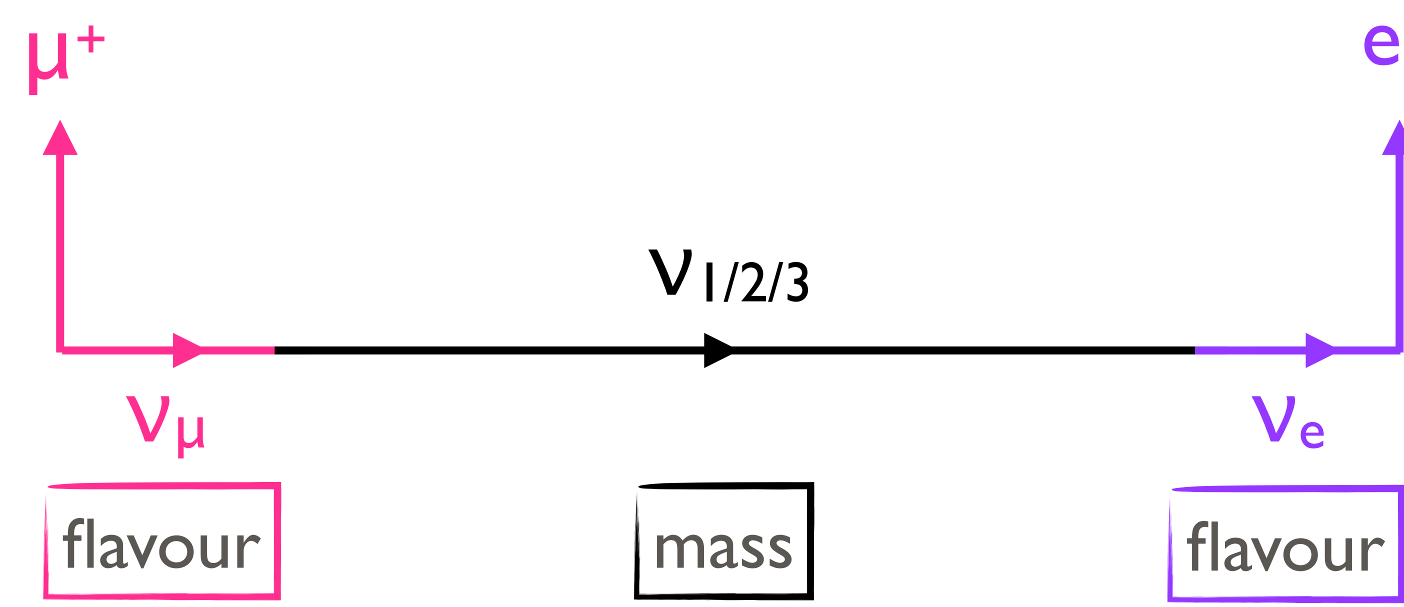
NEUTRINOS: WHAT WE KNOW



- Fundamental particles in the Standard Model
- Very small (non-zero) mass
- Interact via weak force
- "Paired" with charged leptons

NEUTRINOS: WHAT WE KNOW

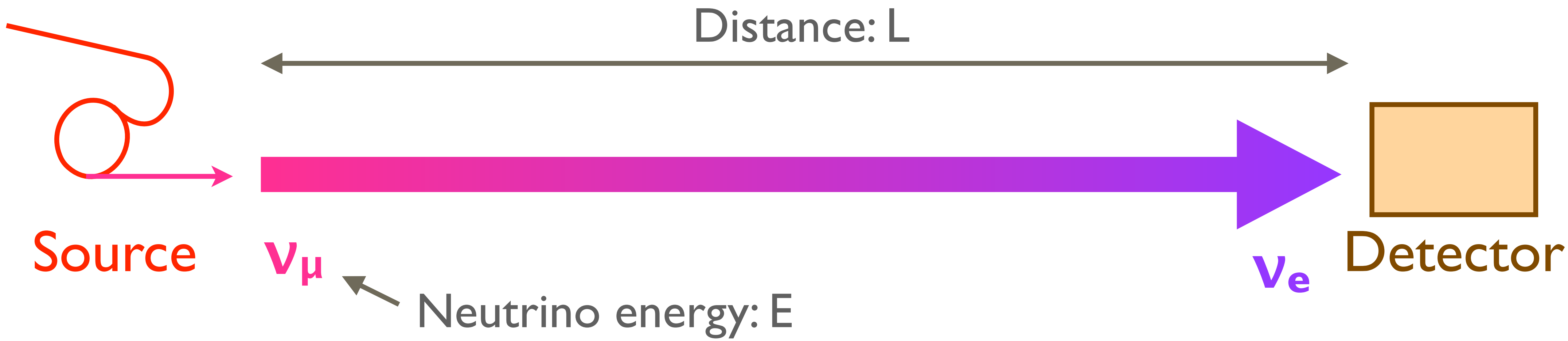
- Two sets of eigenstates: flavour (interaction) and mass (propagation)
- Related by **PMNS* matrix**
  → 3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$
  → 1 CP-violating phase, δ_{CP}
- Allows for neutrino flavour change



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

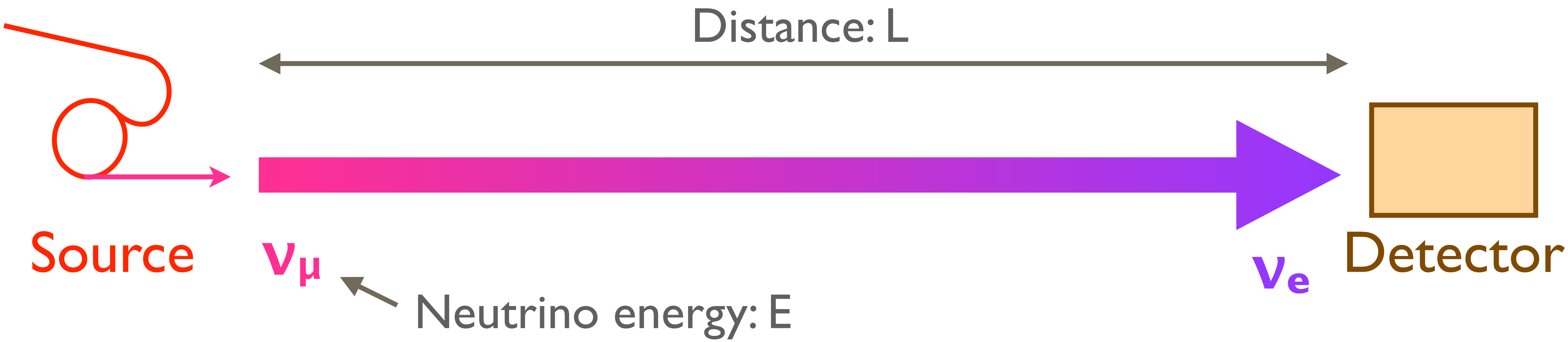
flavour mass

*Named after physicists Pontecorvo, Maki, Nakagawa, and Sakata



Muon neutrino disappearance

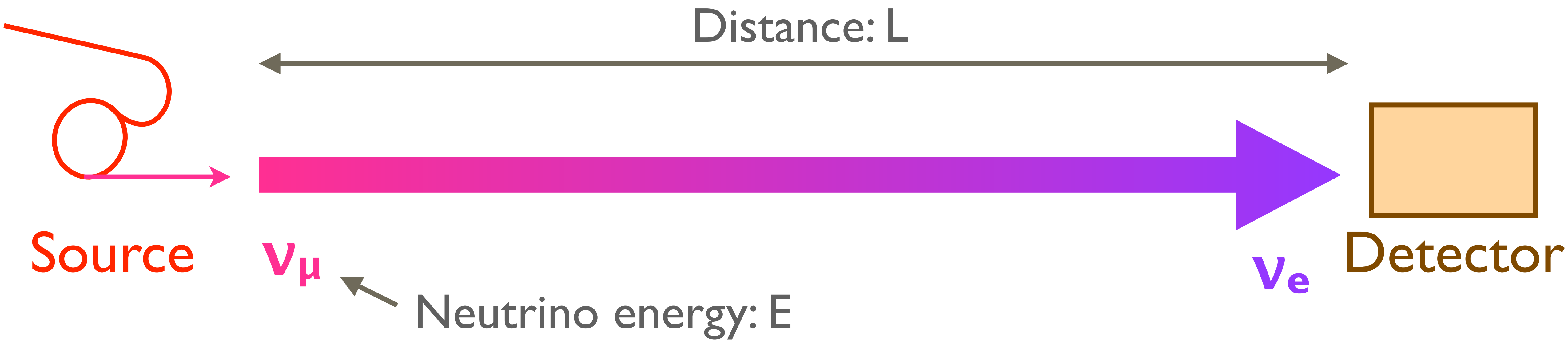
Electron neutrino appearance



Probability to detect a neutrino of a given flavour **oscillates** as:

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$



Probability to detect a neutrino of a given flavour **oscillates** as:

$$\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

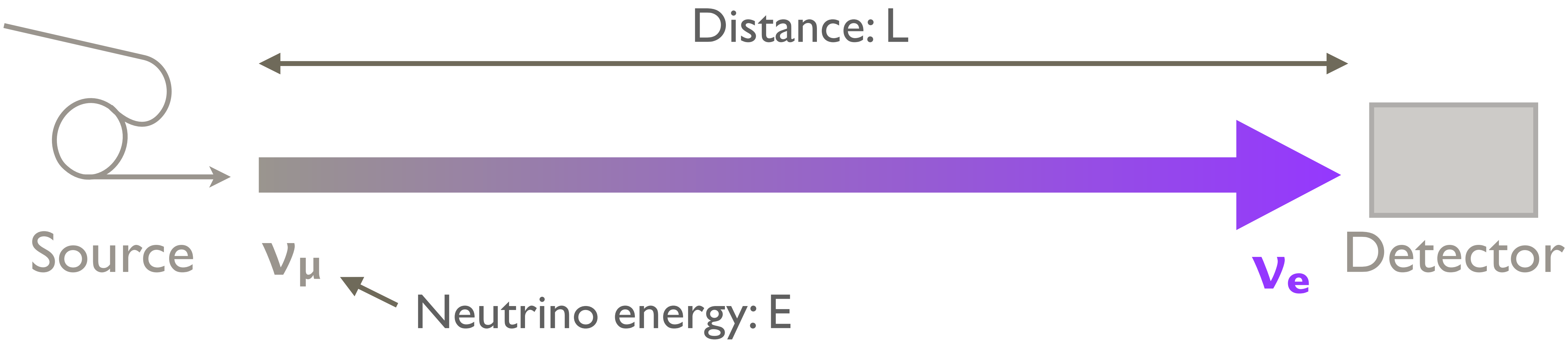
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Reason number 1 why neutrinos are exciting:

Neutrino oscillation

→ Neutrinos have mass

→ Physics beyond the Standard Model!



Electron neutrino appearance

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq$ **Something**

$(+)-$ [**Something else** **x** $\sin\delta_{CP}$]

$\bar{\nu}$ ν

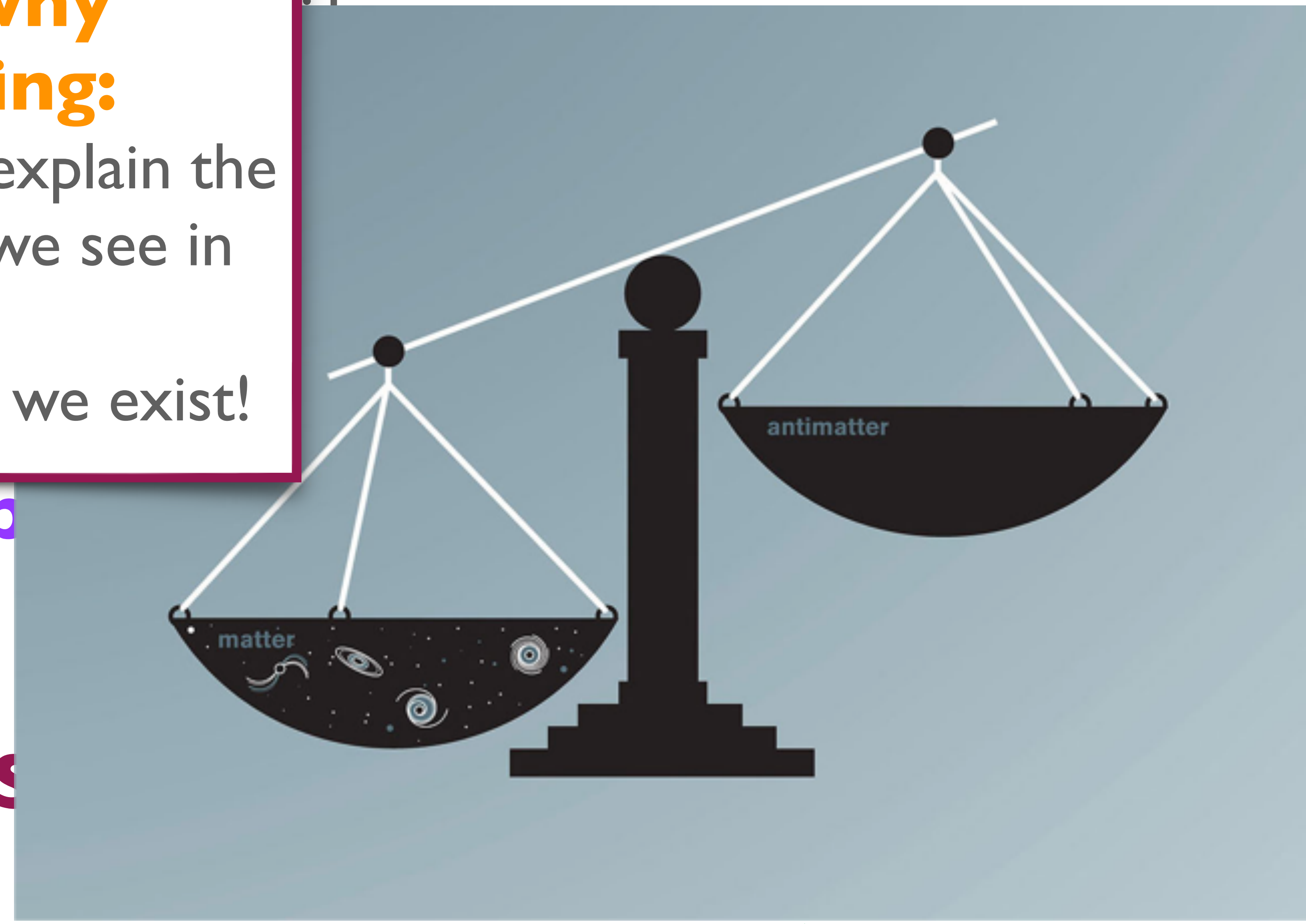
$+\,$(CP-even, solar, matter effect terms)

Reason number 2 why neutrinos are exciting:

CP violation in neutrinos might explain the matter-antimatter asymmetry we see in the universe

→ neutrinos could explain why we exist!

Electron neutrino app



$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq$$

$(+)-$ [**Something else** x $-\sin \delta_{CP}$]

$\bar{\nu}$ ν

$+$ (CP-even, solar, matter effect terms)

CURRENT MEASUREMENTS

NOvA and **T2K** experiments are measuring neutrino oscillations over long baselines

Both have large uncertainties due to cross-section modeling

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

T2K Nature 580, 339-344 (2020)

LOOKING FORWARD

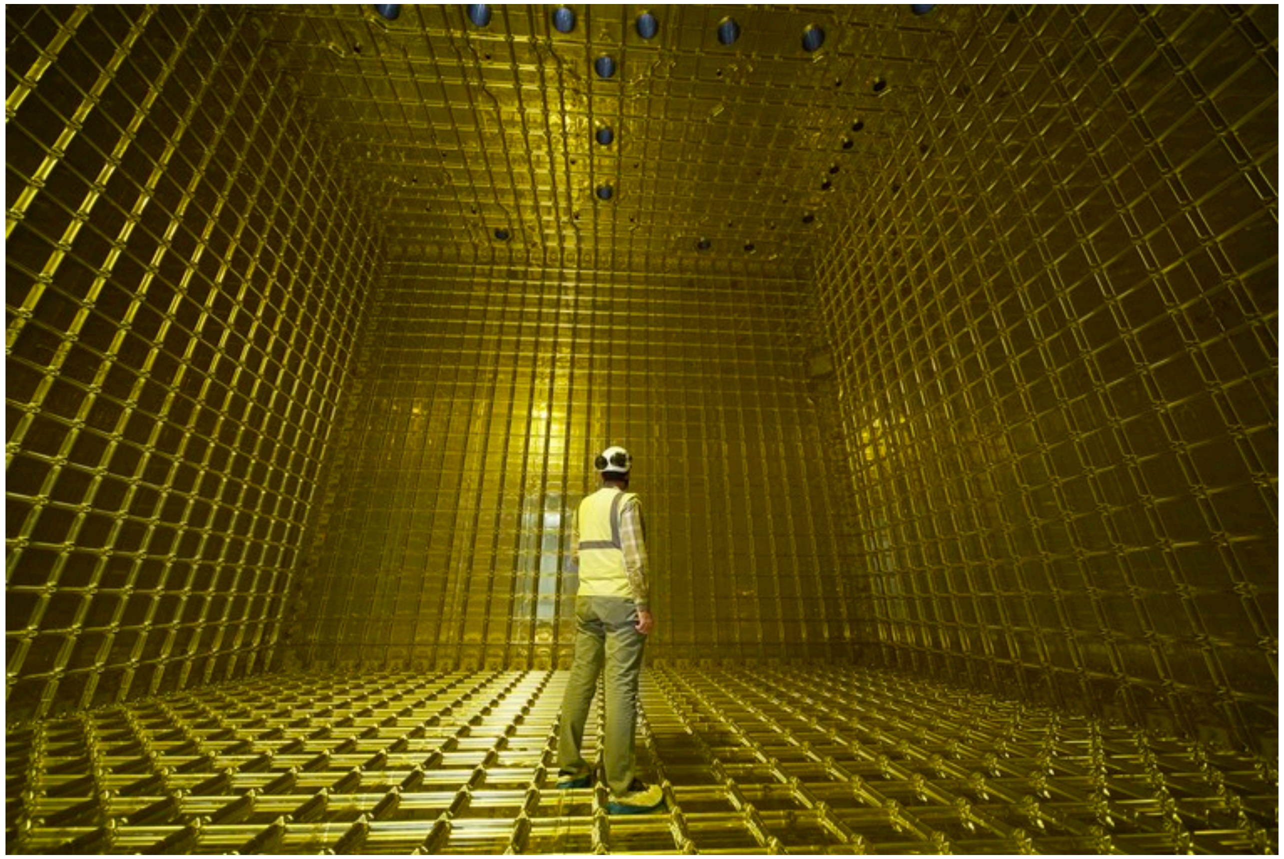
Next-generation experiments **DUNE** and **Hyper-Kamiokande** will measure neutrino oscillations with unprecedented precision

Deep **U**nderground **N**eutrino **E**xperiment

→ 40kton **L**iquid **Ar**gon

→ build on current and future US LAr program:

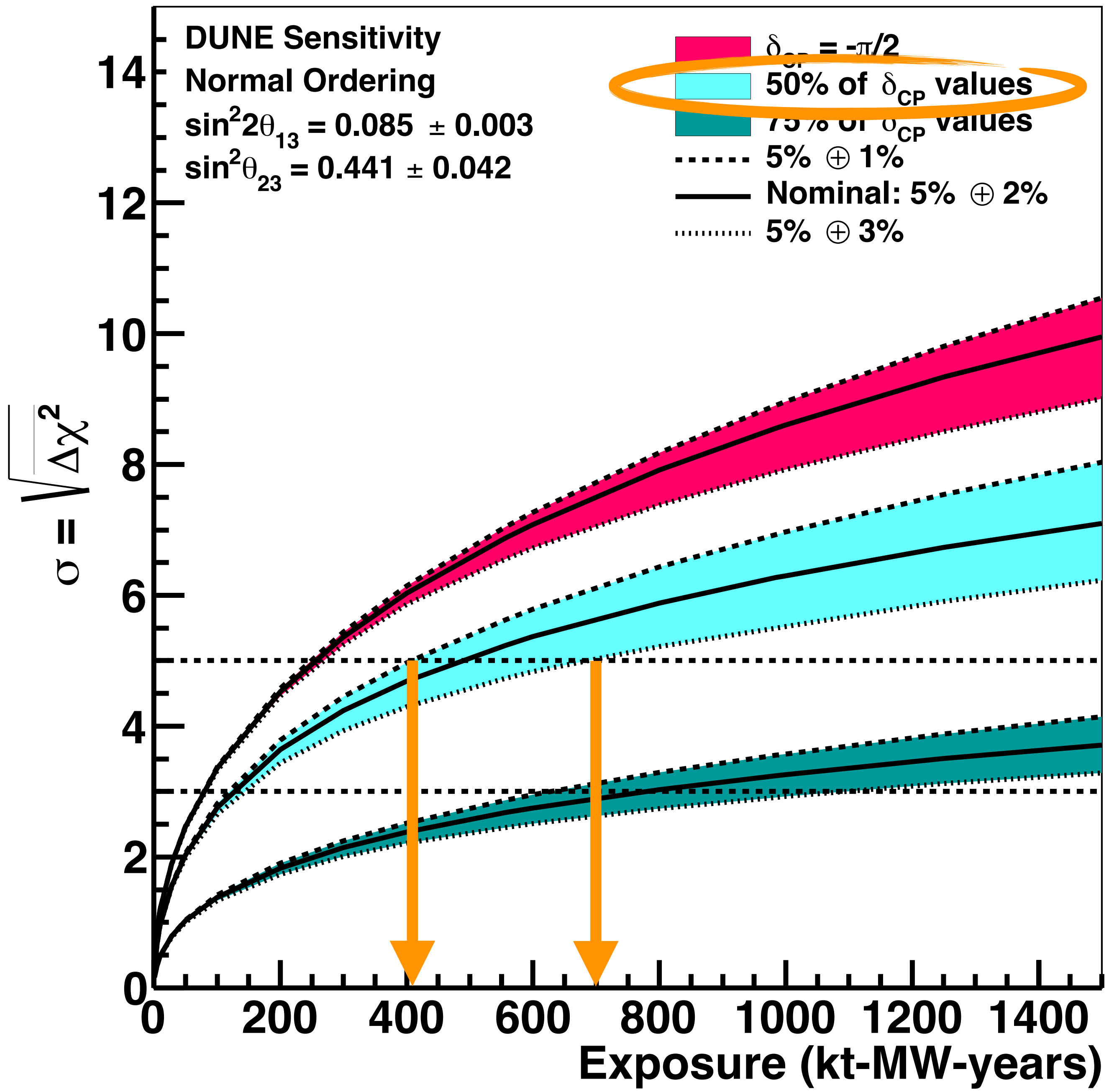
- → ArgoNeuT, LArIAT
- → **MicroBooNE**
- → ProtoDUNEs
- → SBND, ICARUS



LOOKING FORWARD

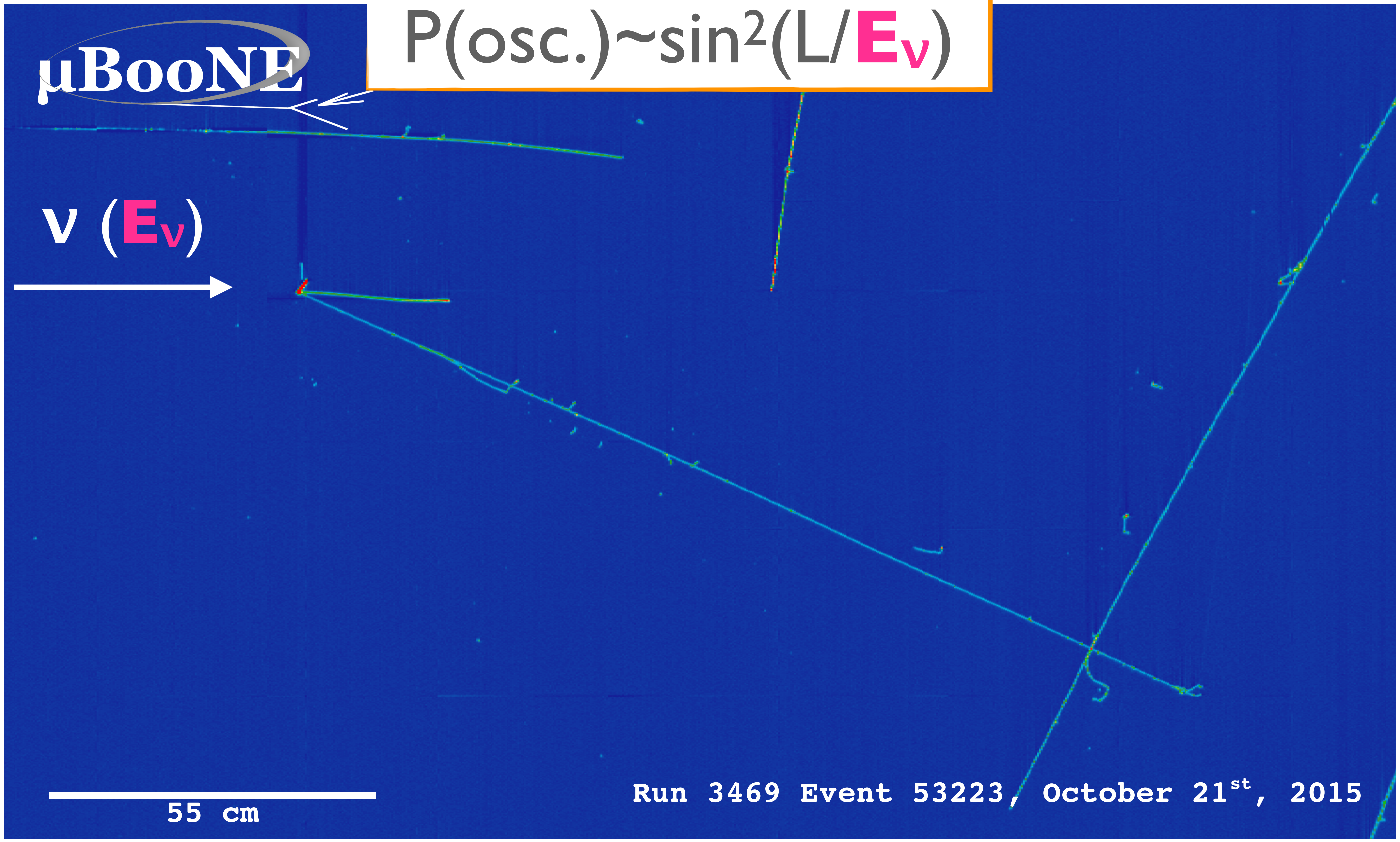
A **better understanding** of neutrino interactions is **vital for DUNE's success**

2% reduction in uncertainty
→ 300 kt-MW-years
→ ~6 years real time
→ $150m operations cost

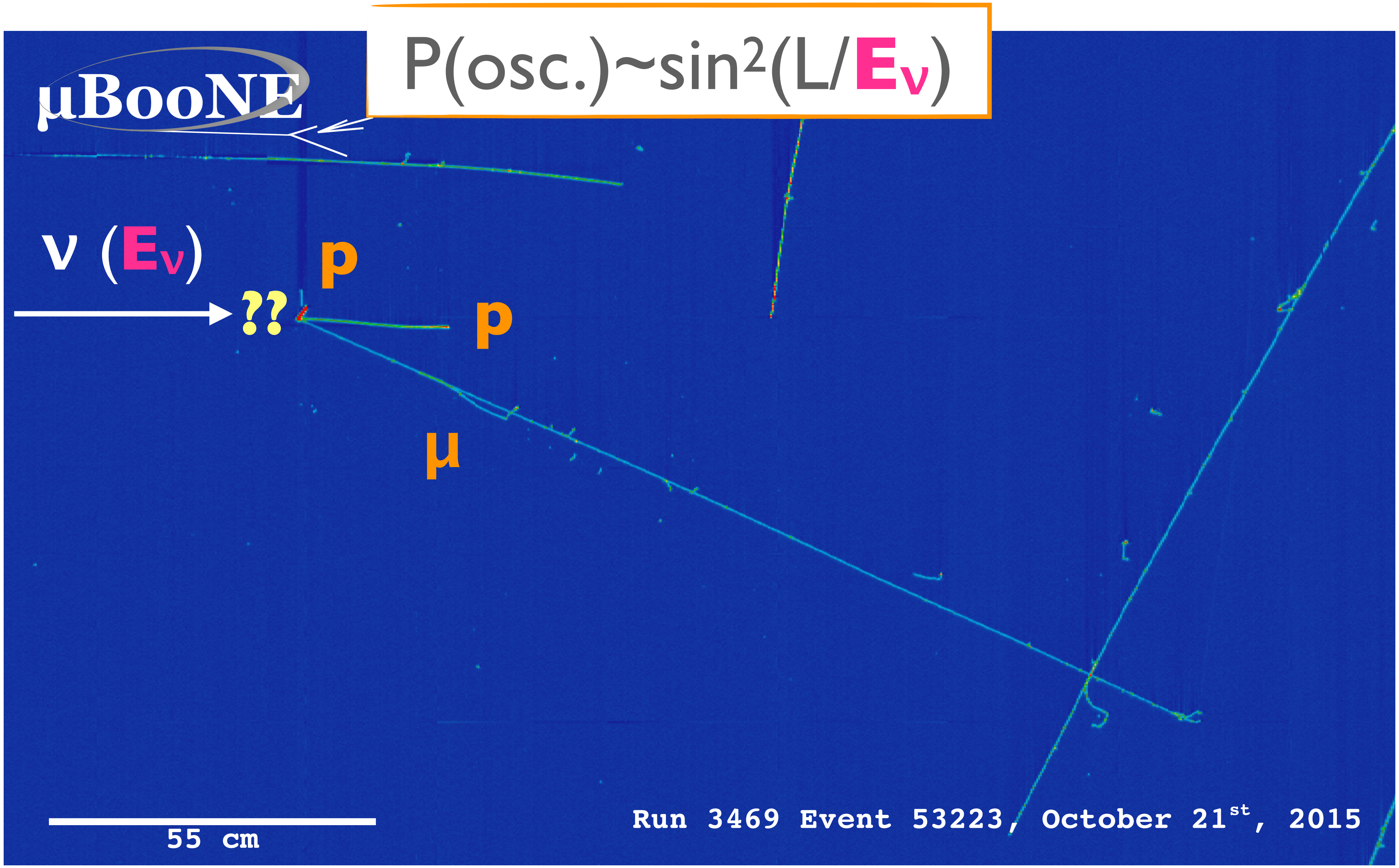


NEUTRINO INTERACTIONS

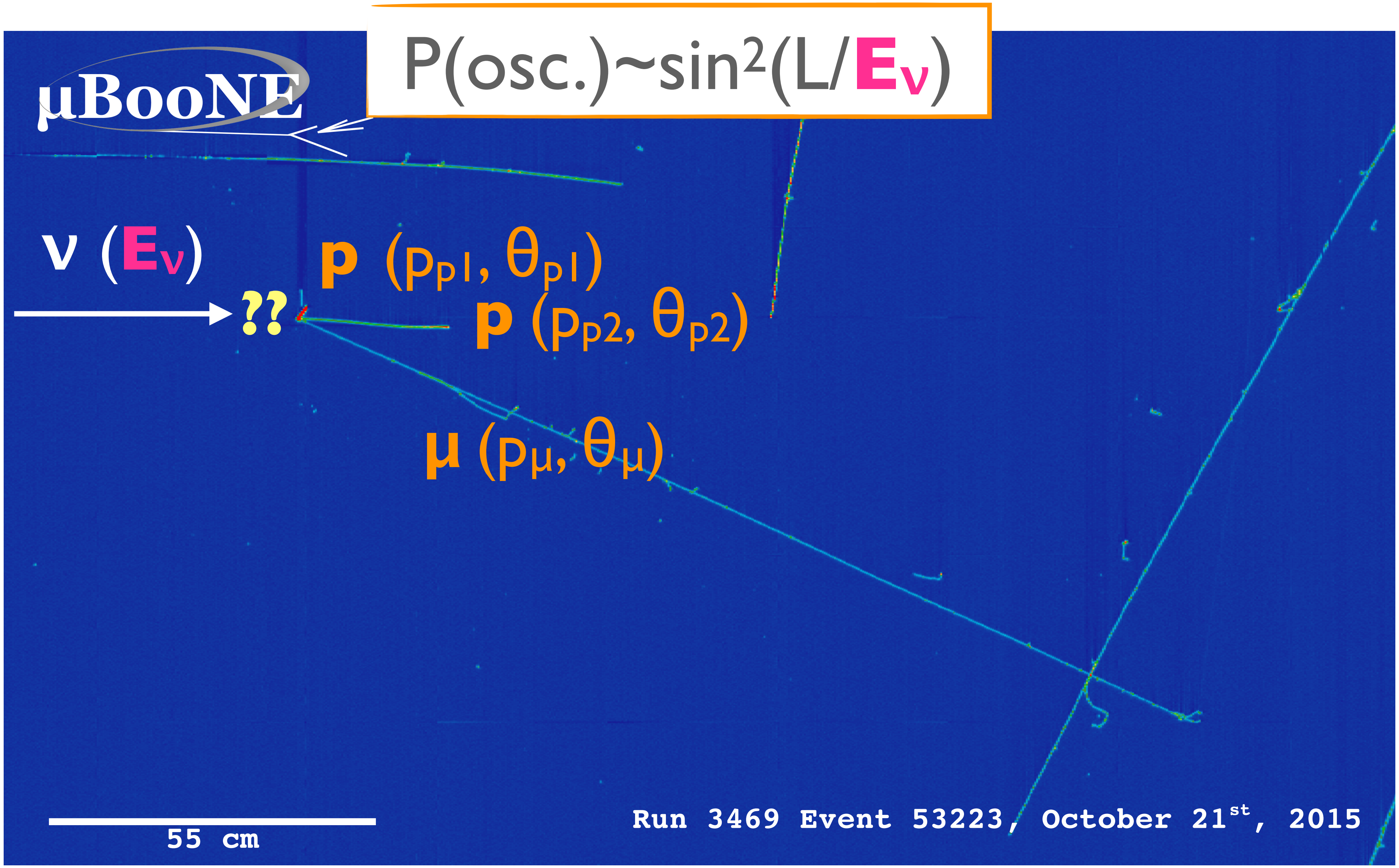
$P(osc.) \sim \sin^2(L/E_\nu)$



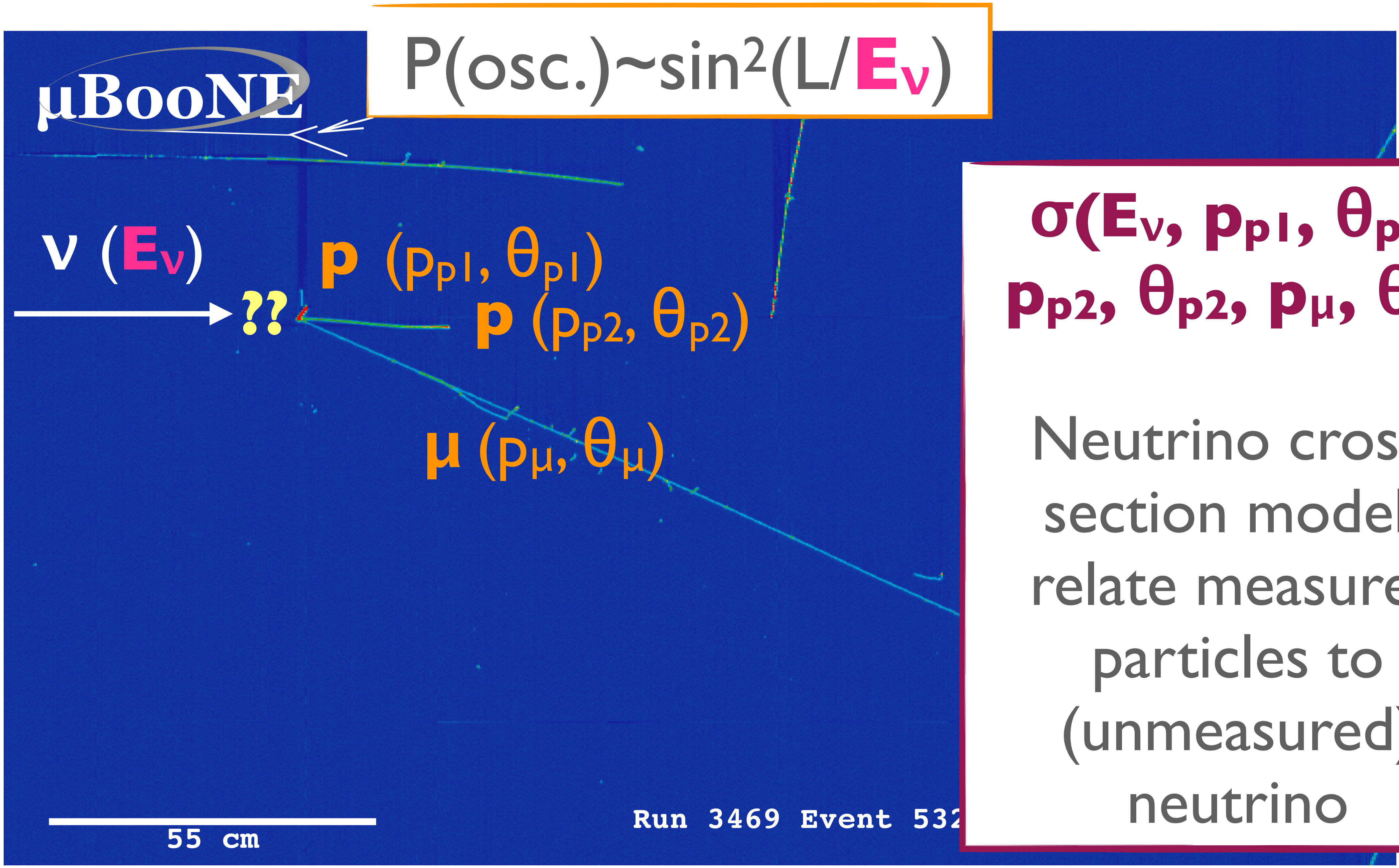
NEUTRINO INTERACTIONS



NEUTRINO INTERACTIONS



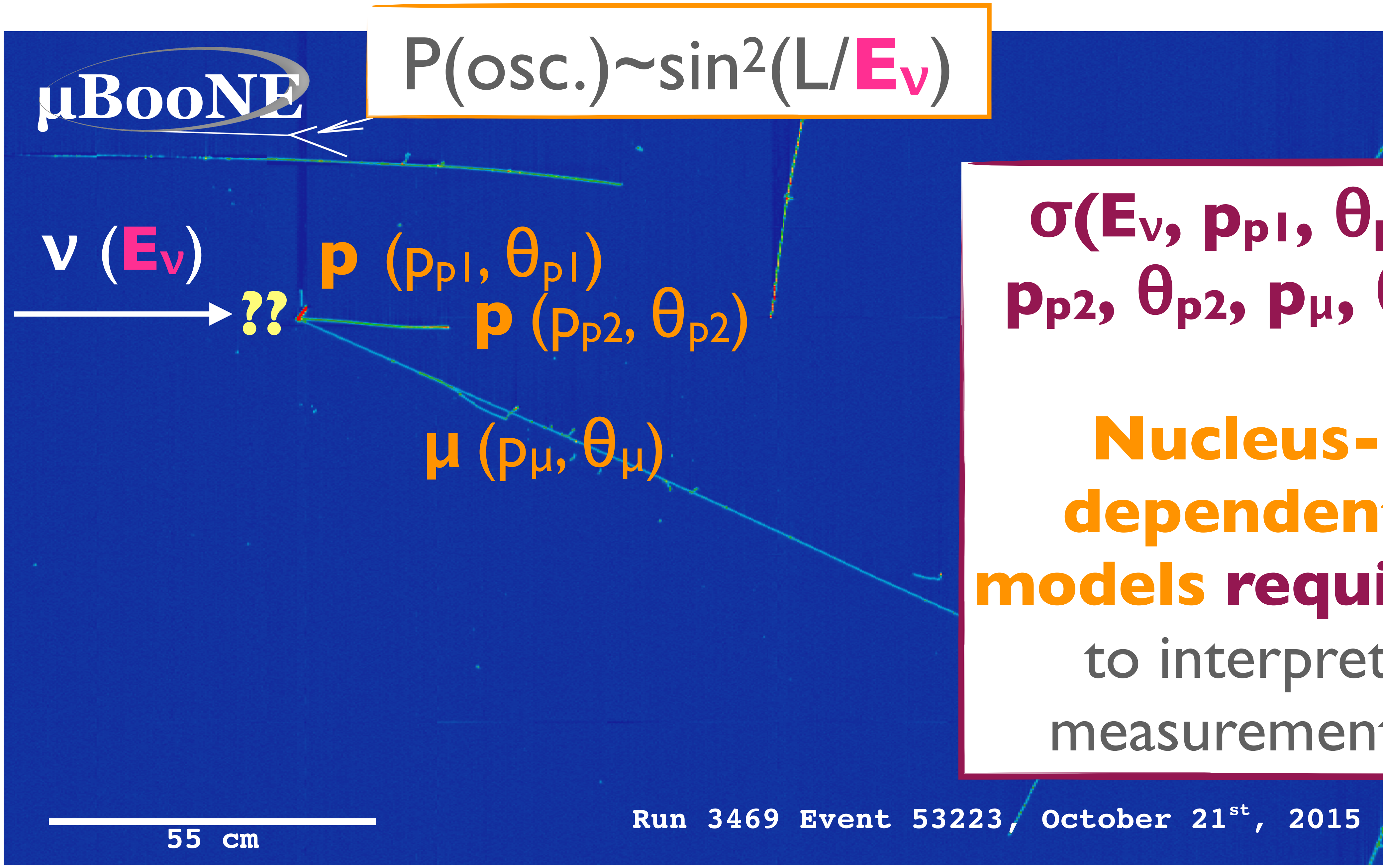
NEUTRINO INTERACTIONS



σ(Eν, pp1, θp1, pp2, θp2, pμ, θμ)

Neutrino cross-section models relate measured particles to (unmeasured) neutrino

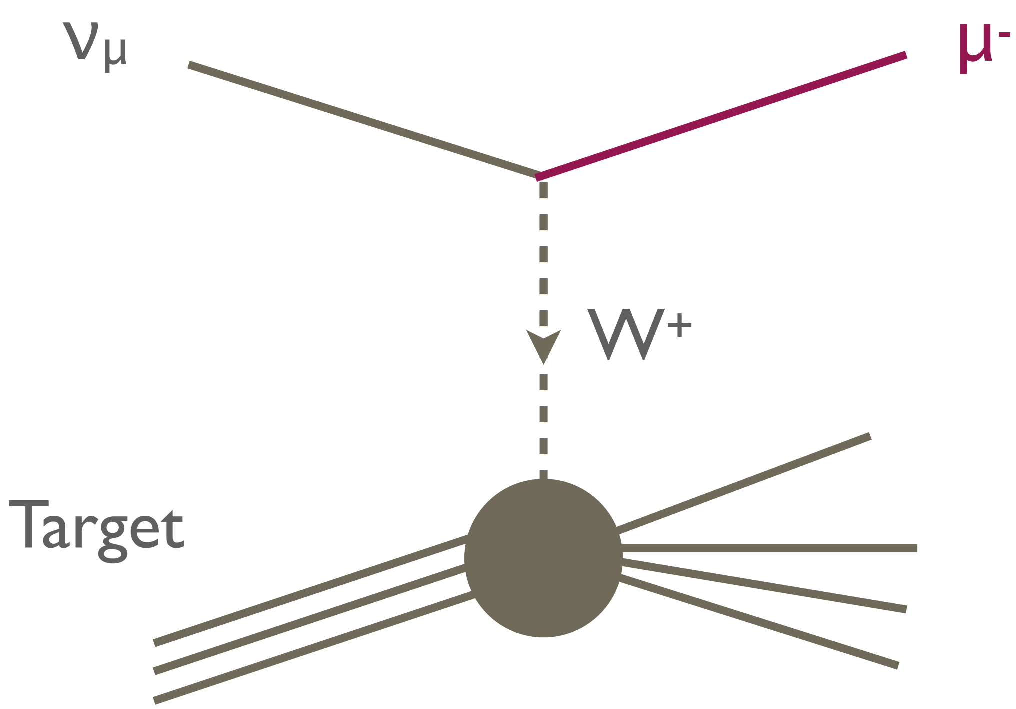
NEUTRINO INTERACTIONS

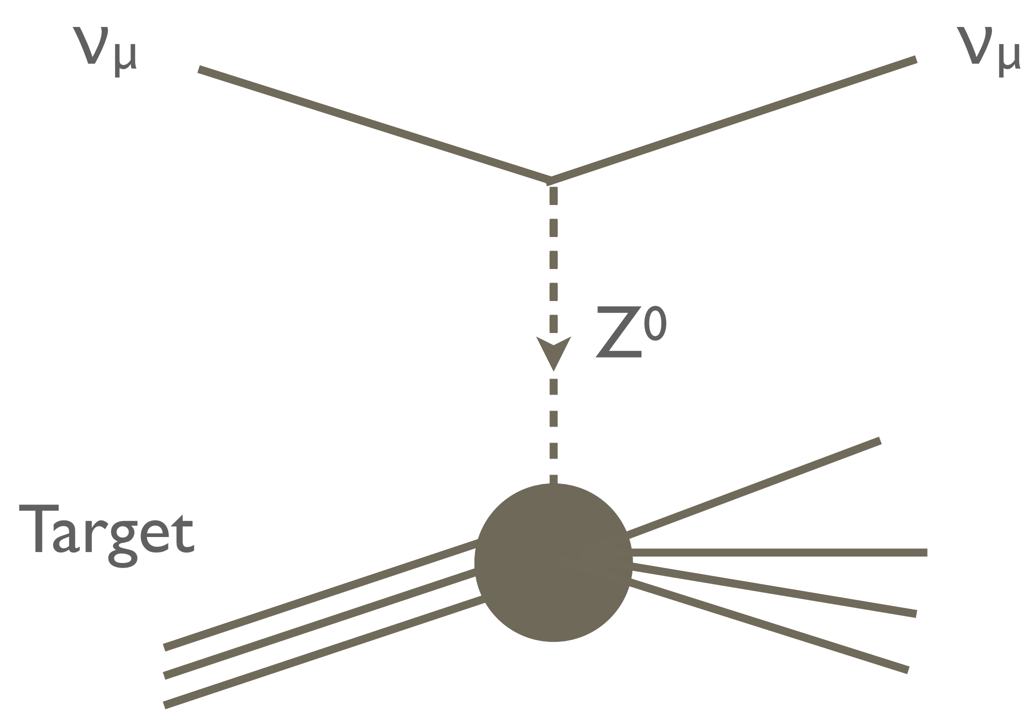


σ(Eν, pp1, θp1, pp2, θp2, pμ, θμ)

Nucleus-dependent models required to interpret measurements

NEUTRINO INTERACTIONS





Charged-current

→ Exchange of W boson

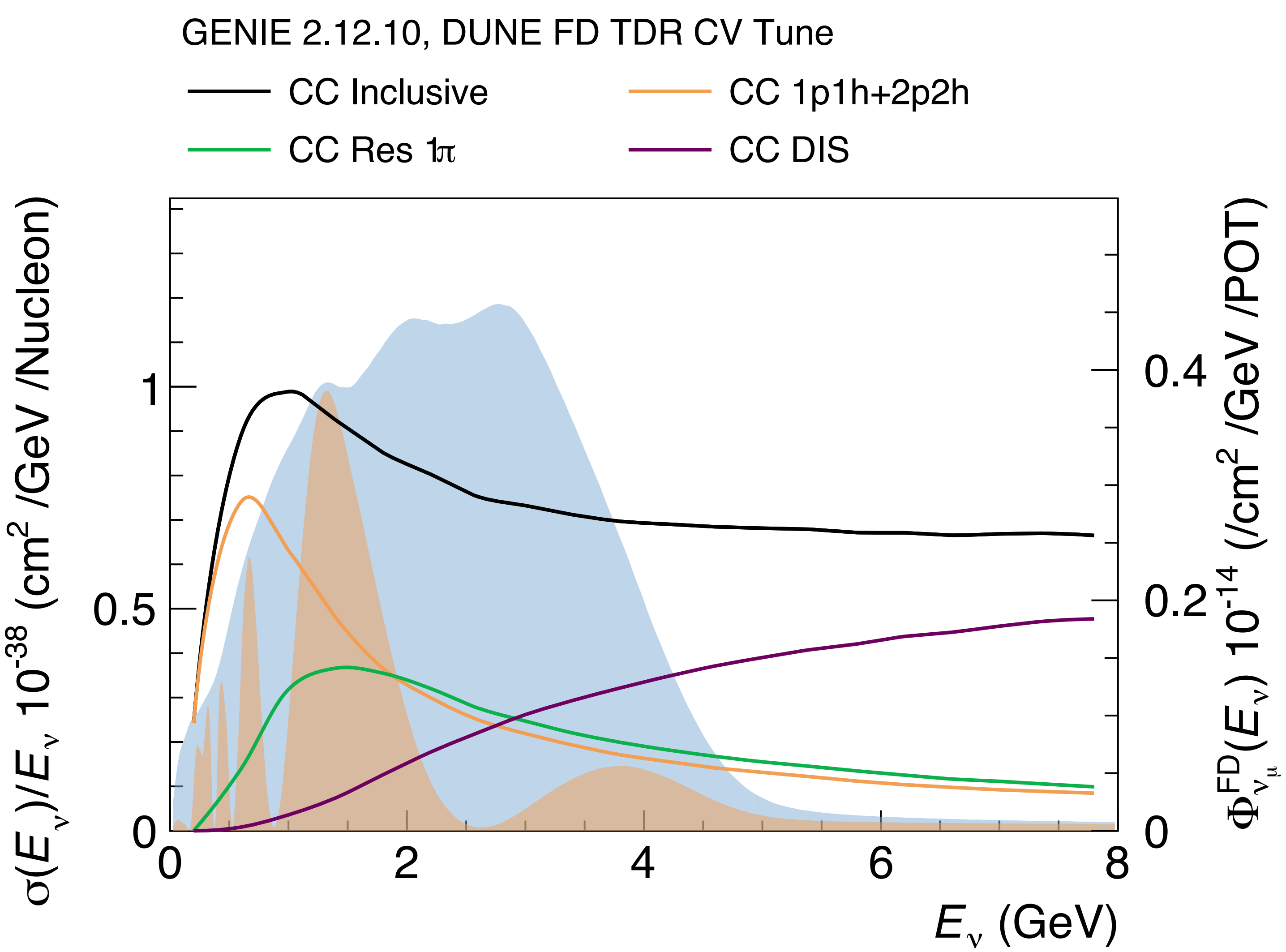
→ Lepton produced with same flavour as ν

Neutral-current

→ Exchange of Z boson

→ Independent of ν flavour

NEUTRINO INTERACTIONS



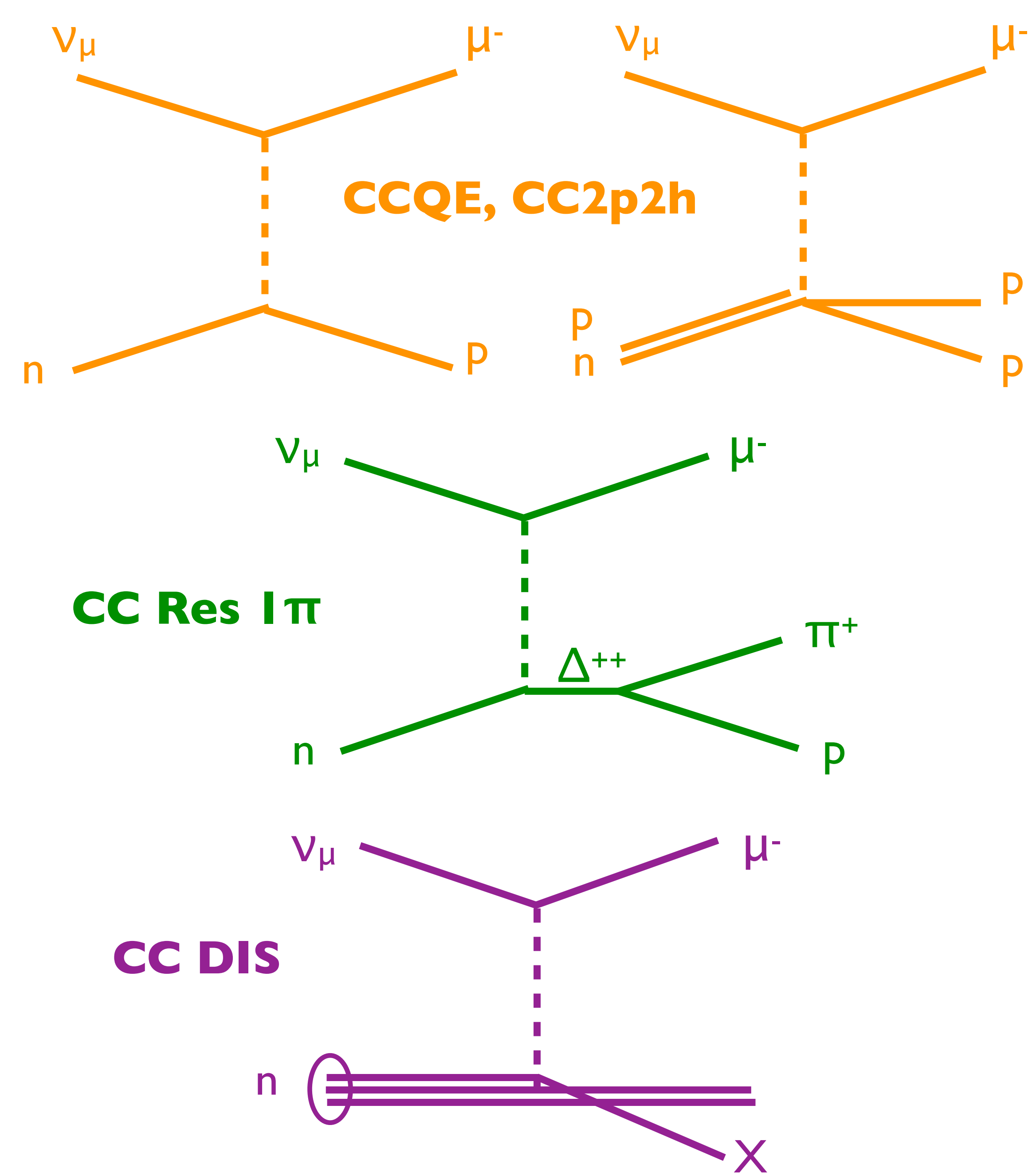
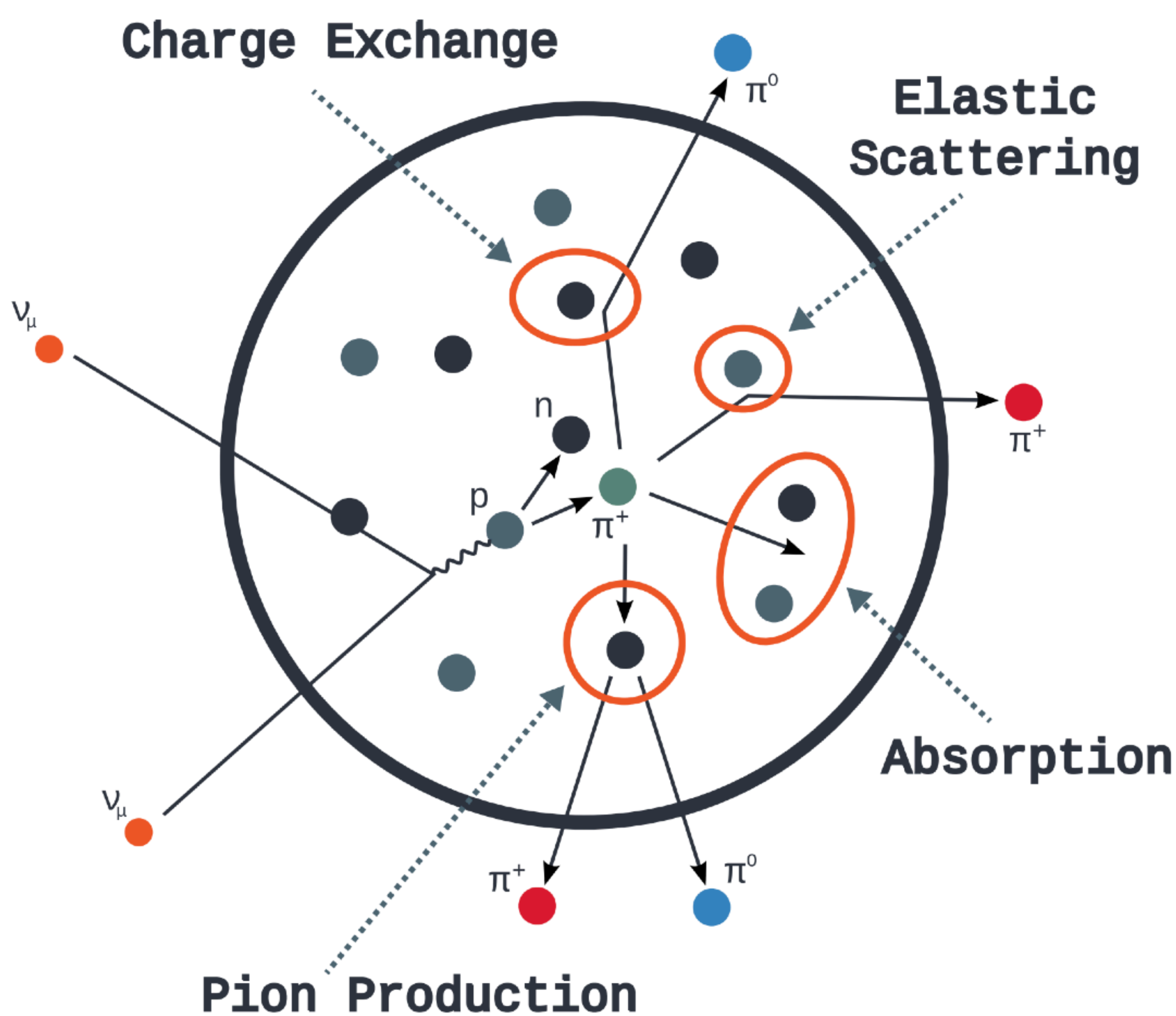


Figure: L. Pickering
Oscillation parameters from NuFit 4.1

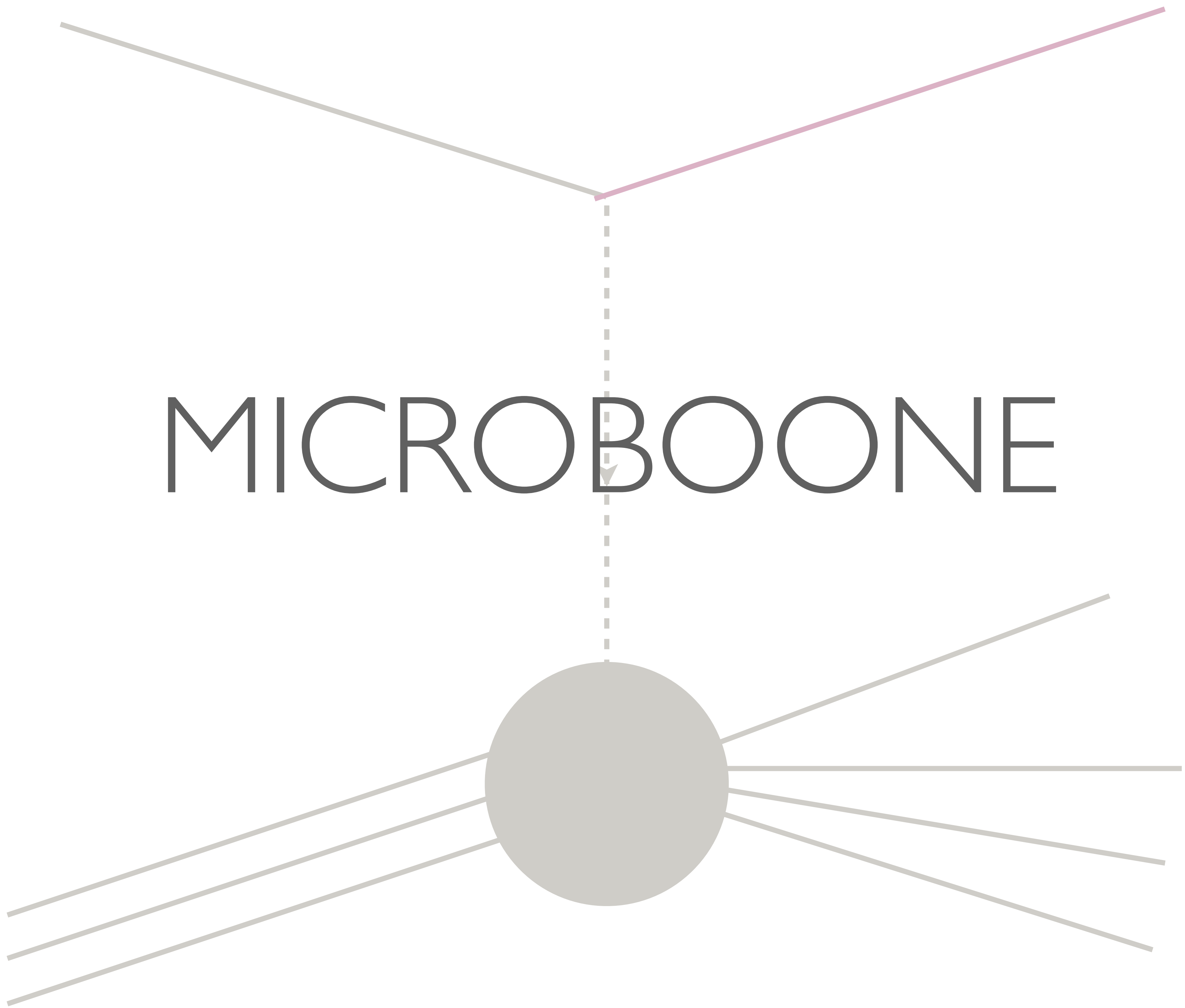
NUCLEAR EFFECTS

Image: T. Golan



- Particles may re-interact as they exit nucleus
  → particles can be lost
  → particles you see may not be from neutrino interaction
- Neutrino isn't interacting with a nucleon at rest → initial state of interaction unknown
- Nuclear effects depend on nucleus — argon data is vital!

MICROBOONE




MicroBooNE - Driving Nu Physics


LONDON
UNITED
RATP GROUP
Hammersmith 10

MicroBooNE is a 170 ton Liquid Argon Time Projection Chamber (LArTPC)

Main physics goals:

- LArTPC detector R&D for future experiments
- Measure neutrino-Ar cross sections
- Search for new neutrino oscillations at short distances
- Exotic beam-dump/astrophysical neutrino signals

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FERMILAB'S NEUTRINO BEAMS

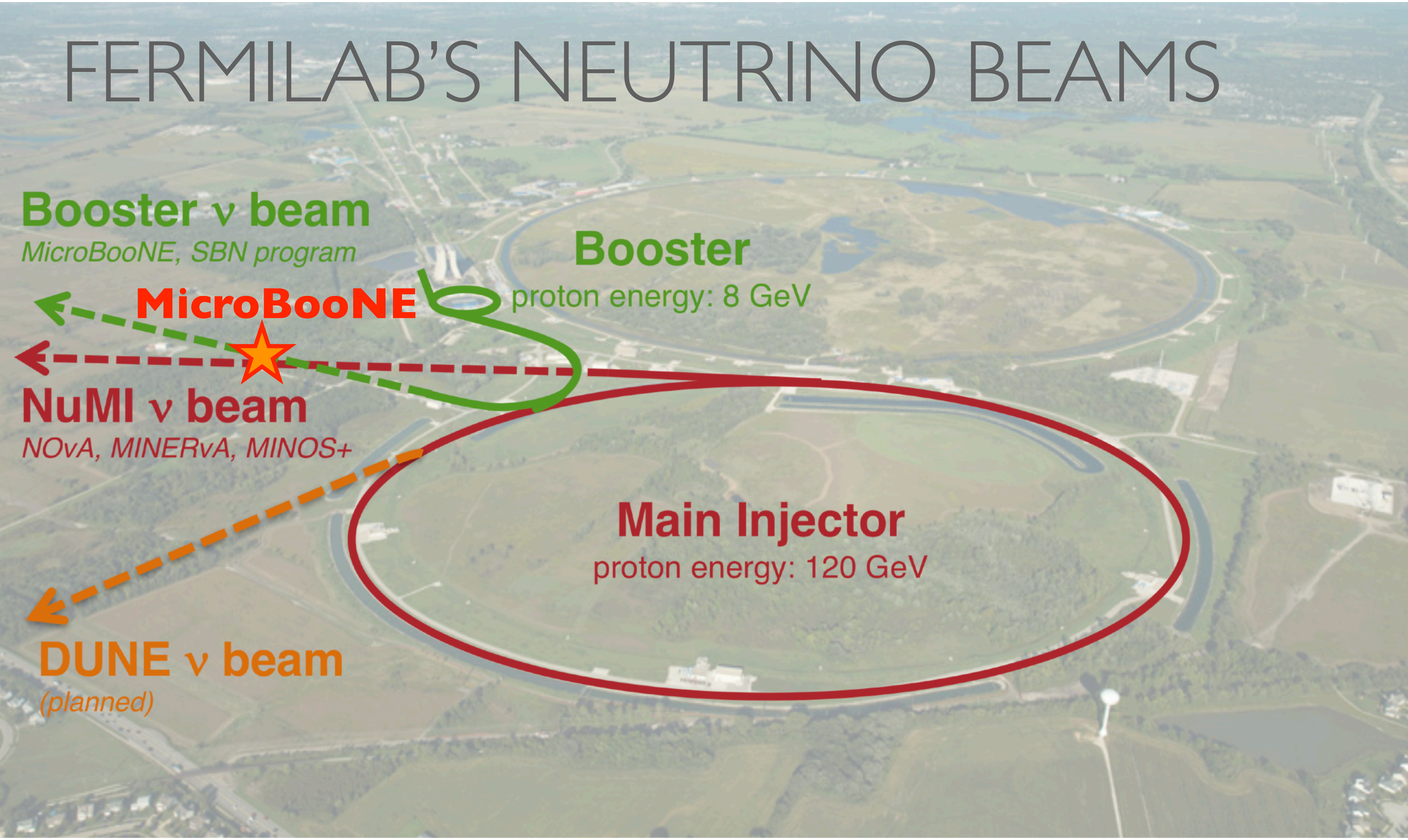
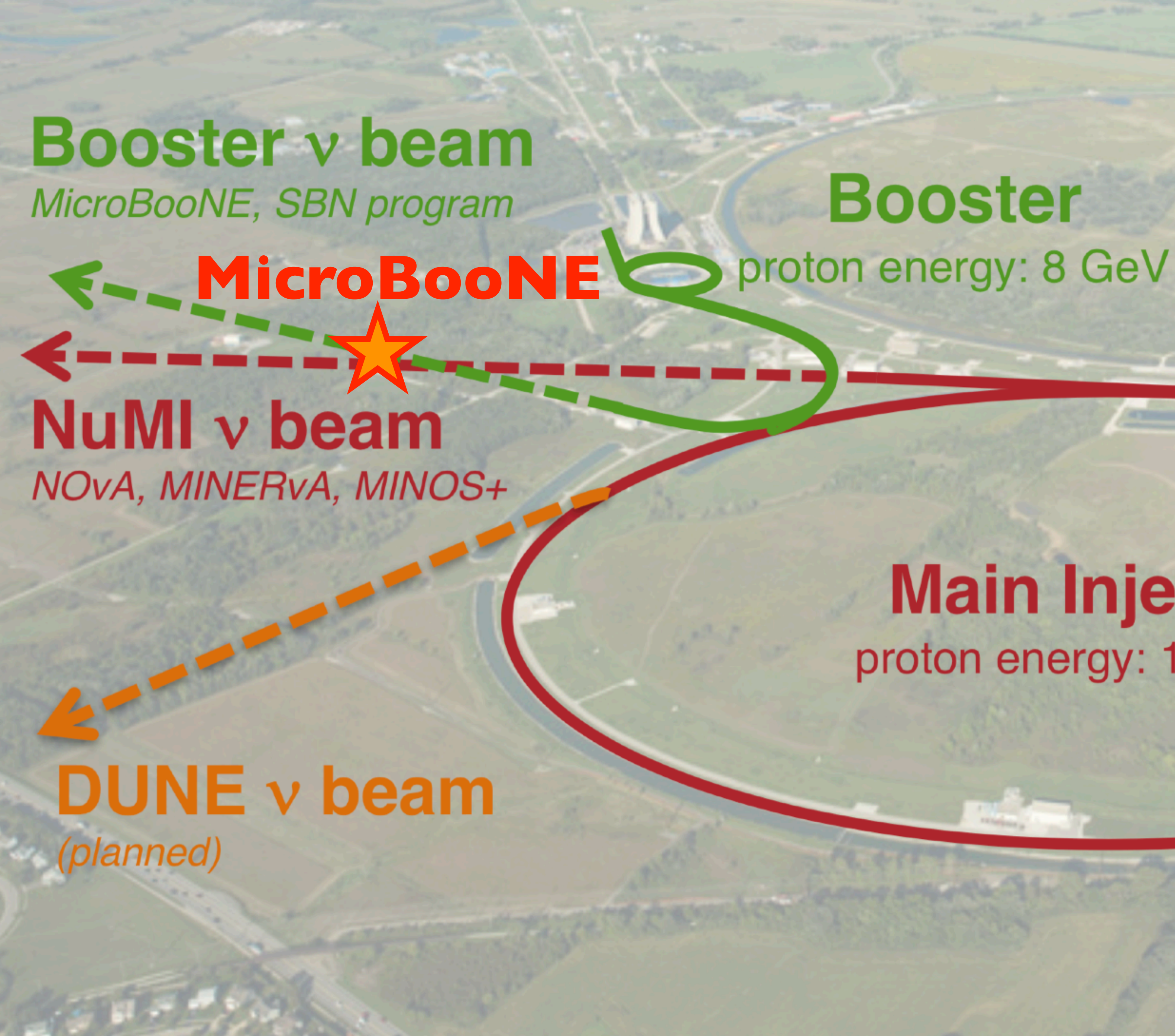


Image: G. Zeller

FERMILAB'S NEUTRINO BEAMS



Booster Neutrino Beam (BNB): 463m

>99% $\nu_\mu/\bar{\nu}_\mu$ at peak

$\langle E_\nu \rangle$ = 850 MeV

NuMI Neutrino Beam (NuMI): ~680m

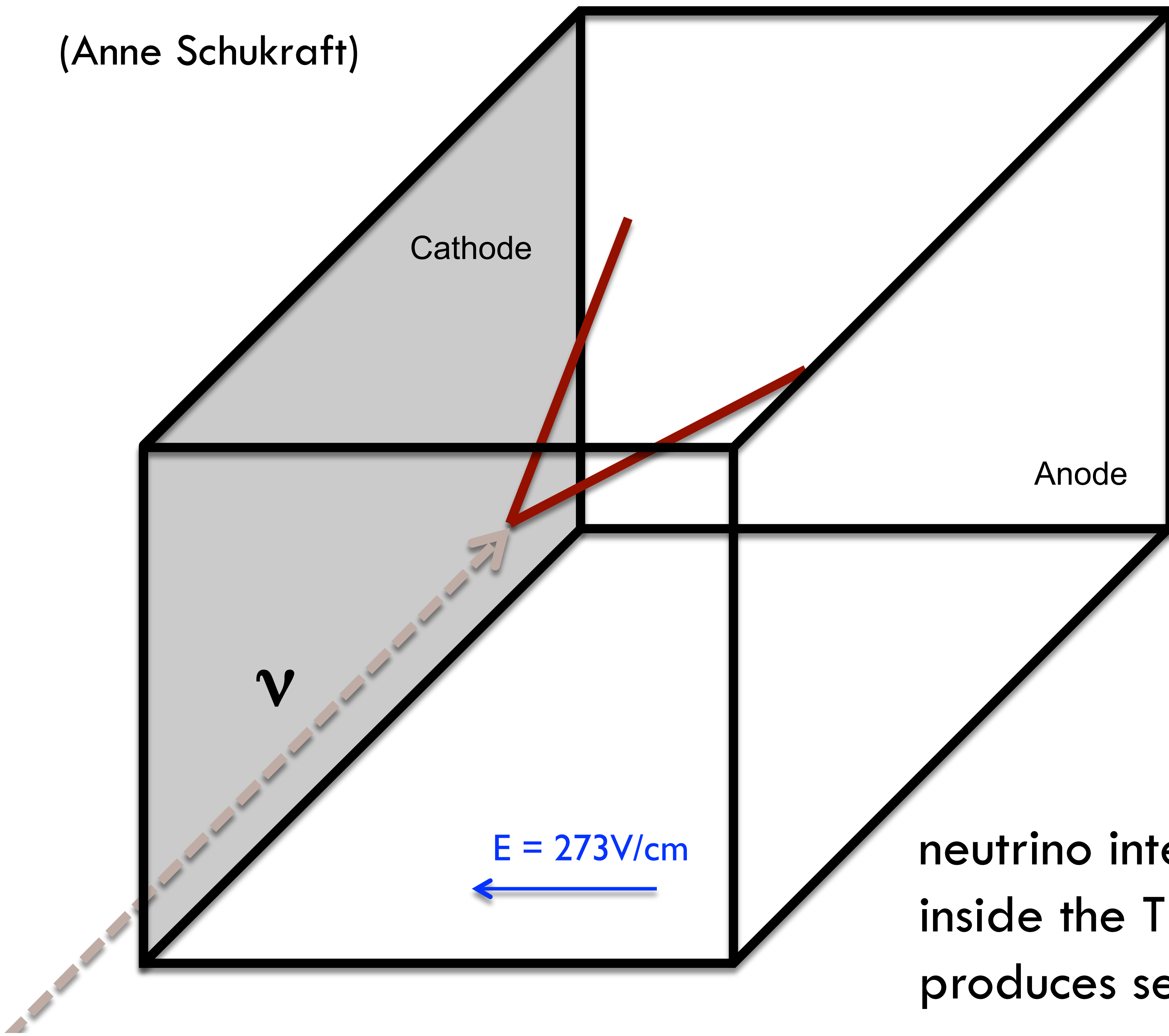
8° off axis → 5% ν_e

Image: G. Zeller

μBooNE

LIQUID ARGON TPC

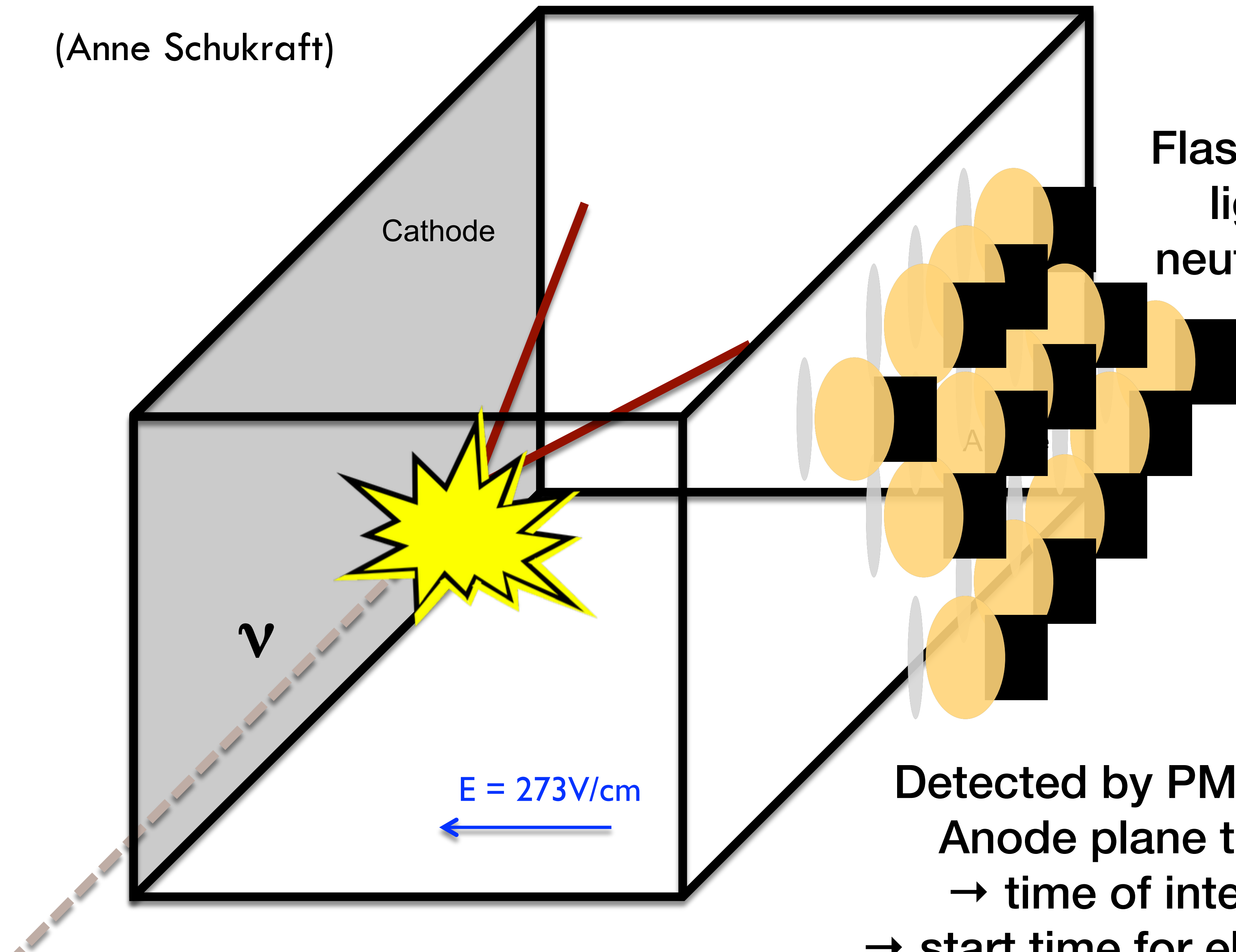
(Anne Schukraft)



neutrino interacts with the argon inside the TPC volume and produces secondary particles

LIQUID ARGON TPC

(Anne Schukraft)

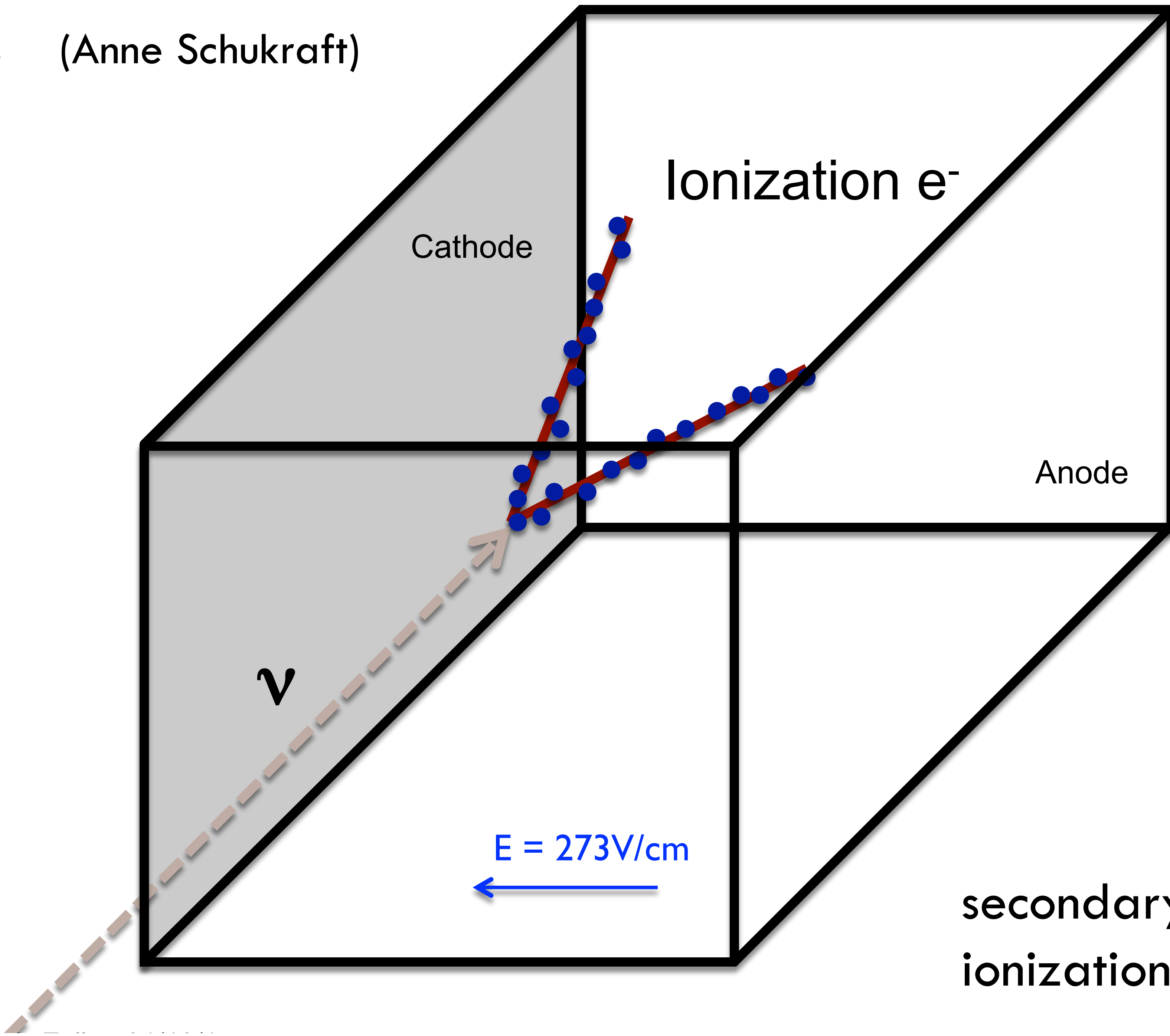


Flash of scintillation light at time of neutrino interaction

Detected by PMTs behind Anode plane to get t0
→ time of interaction
→ start time for electron drift

LIQUID ARGON TPC

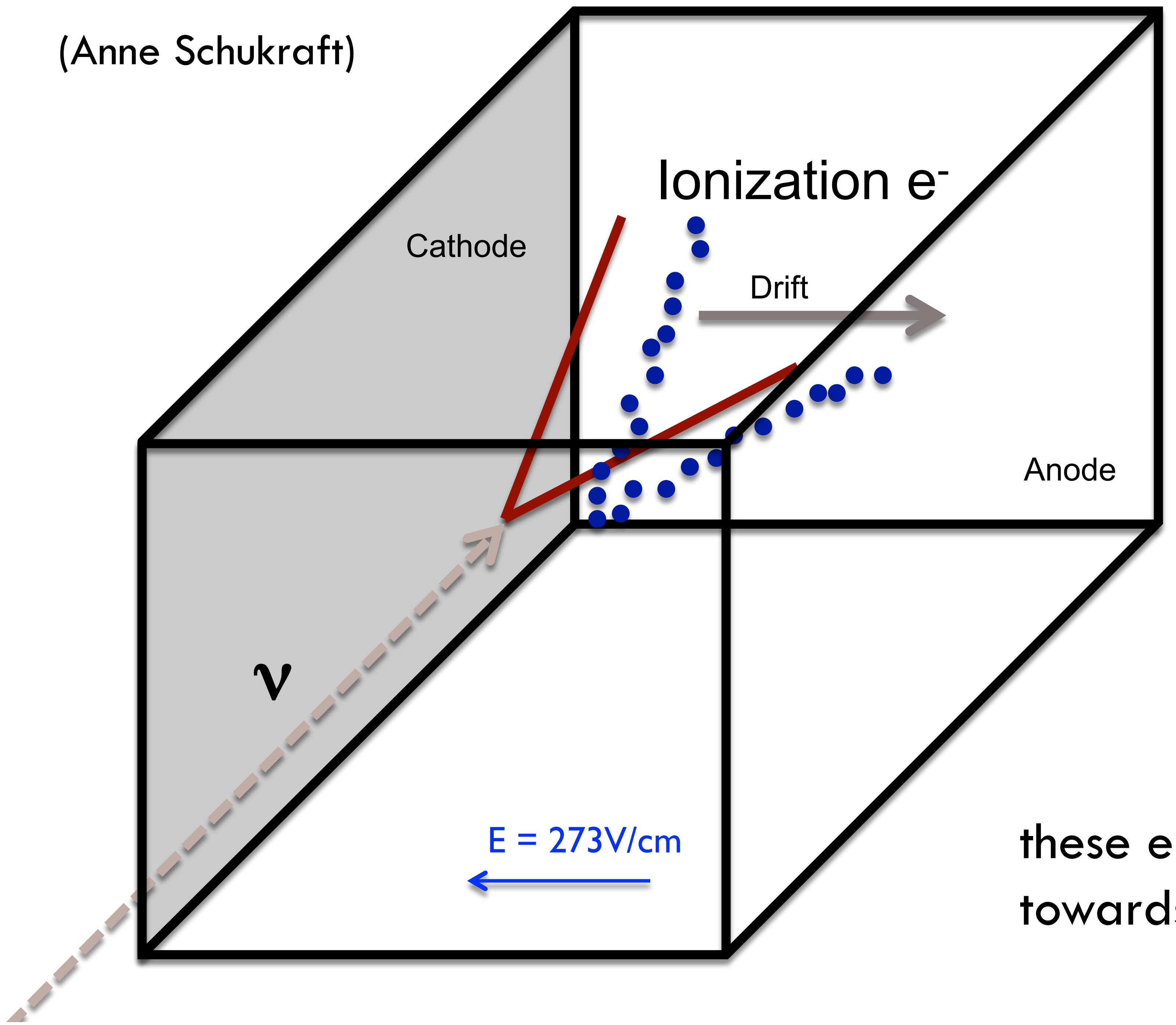
(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

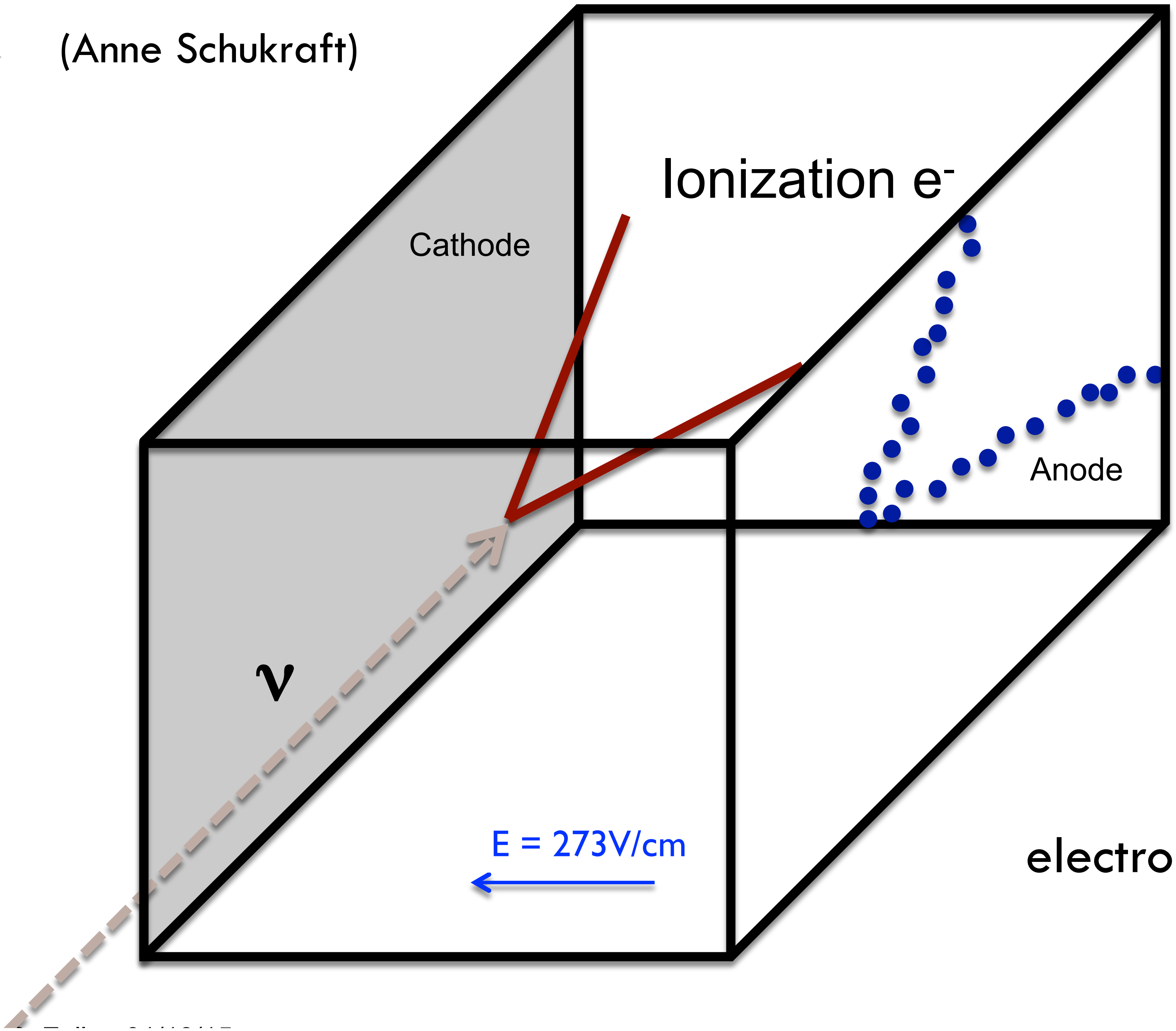
(Anne Schukraft)



these electrons drift towards the anode

LIQUID ARGON TPC

(Anne Schukraft)

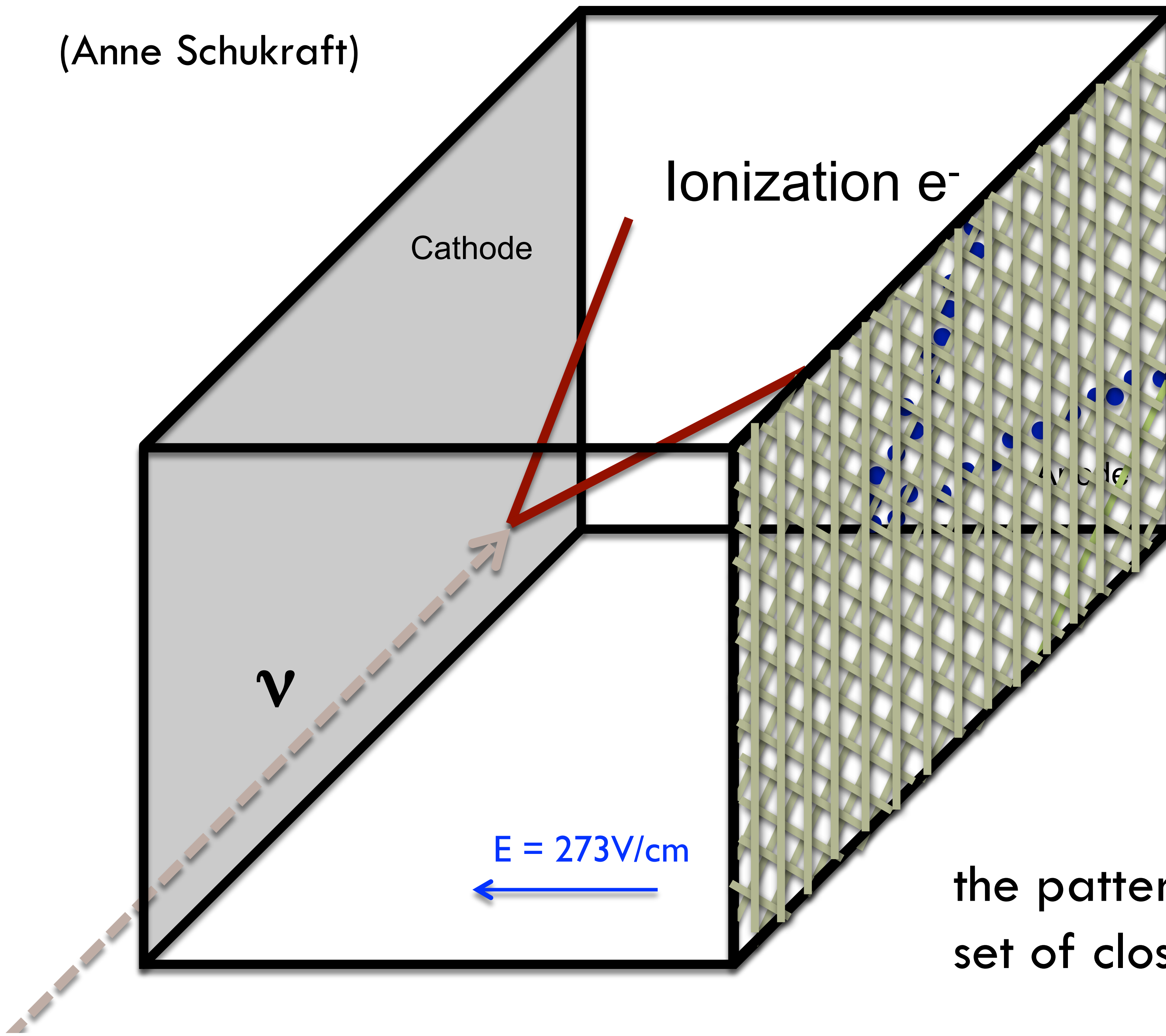


electrons arrive at anode

LIQUID ARGON TPC

(Anne Schukraft)

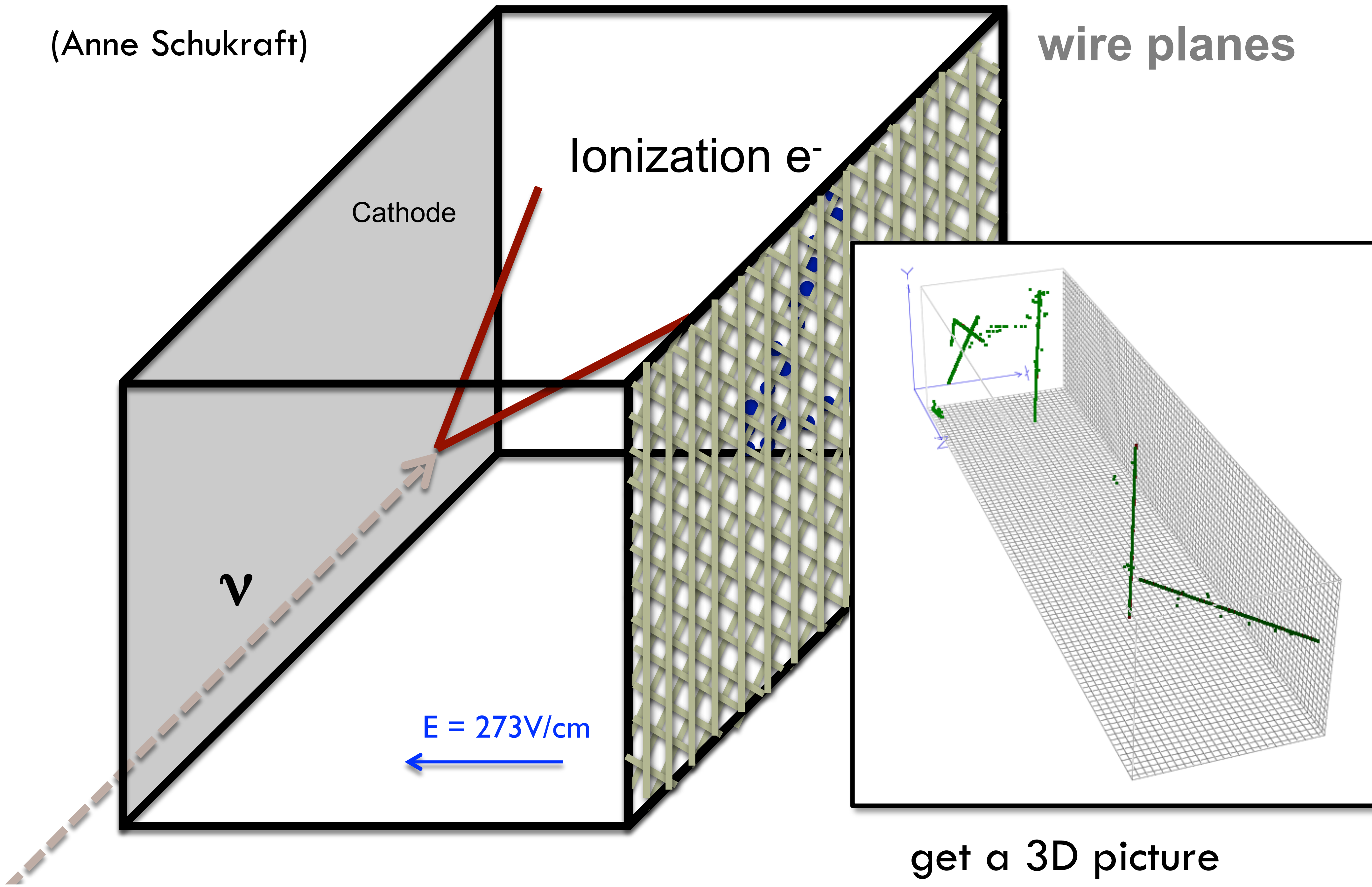
wire planes



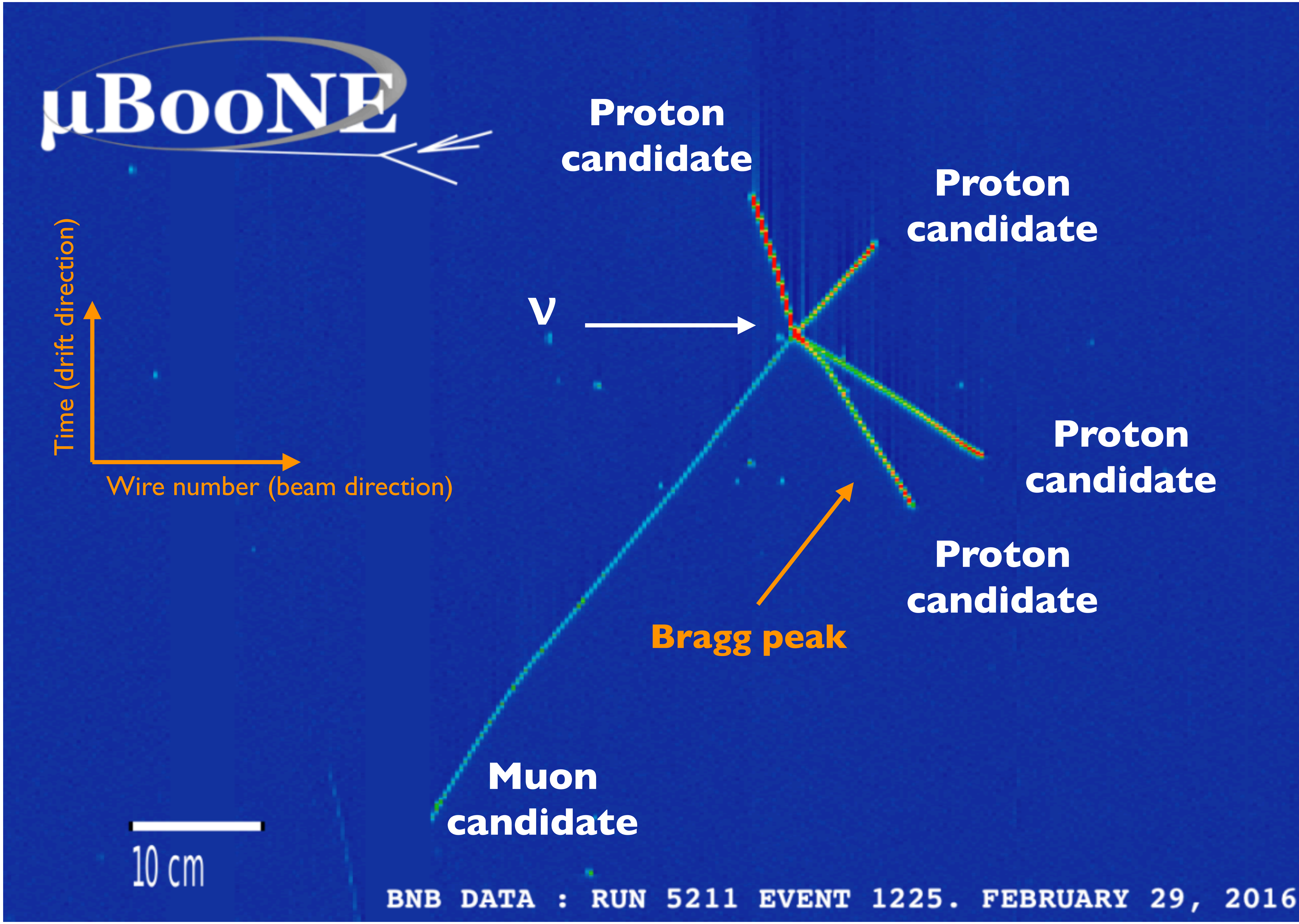
the pattern is recorded on a set of closely spaced wires

LIQUID ARGON TPC

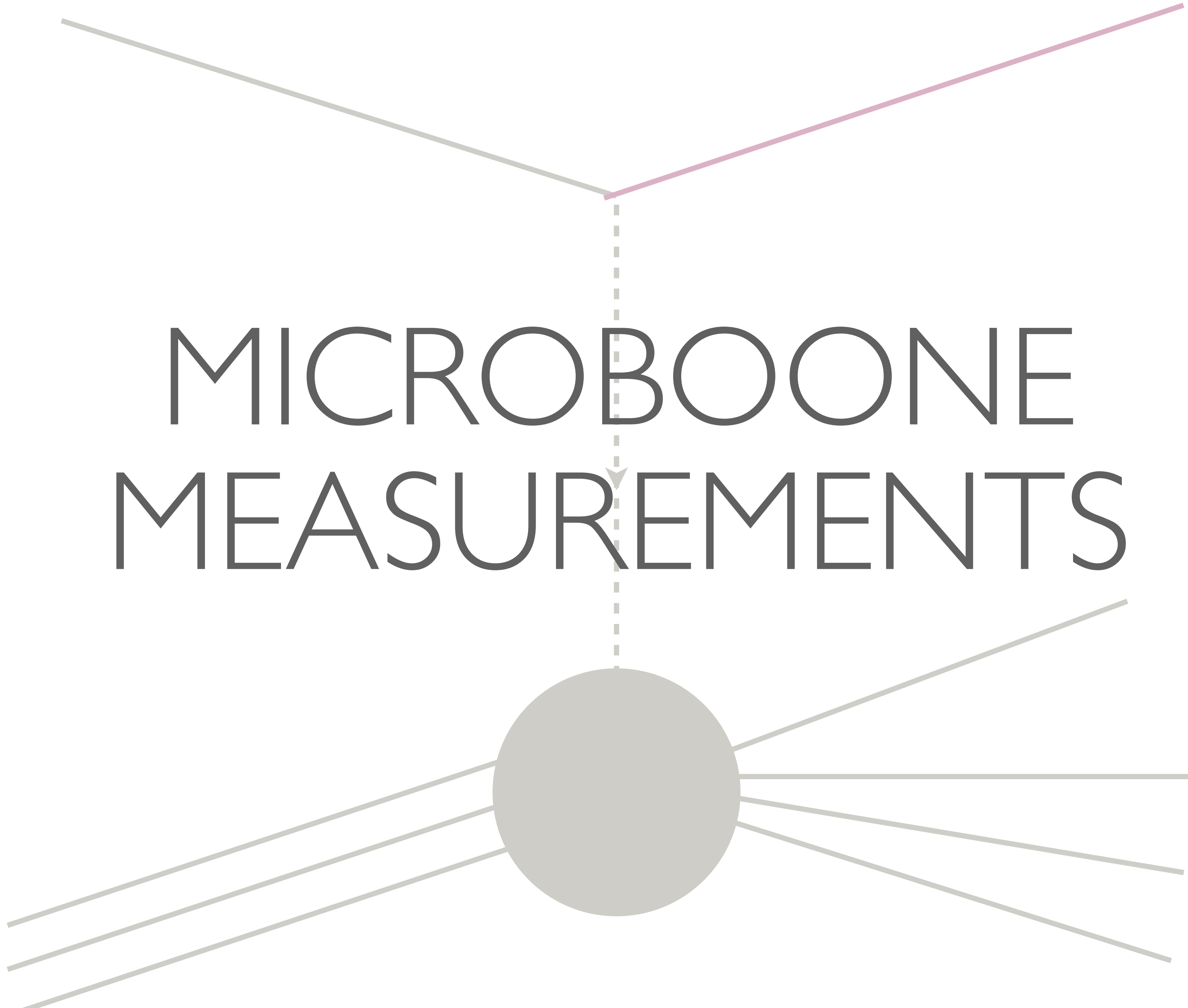
(Anne Schukraft)



get a 3D picture

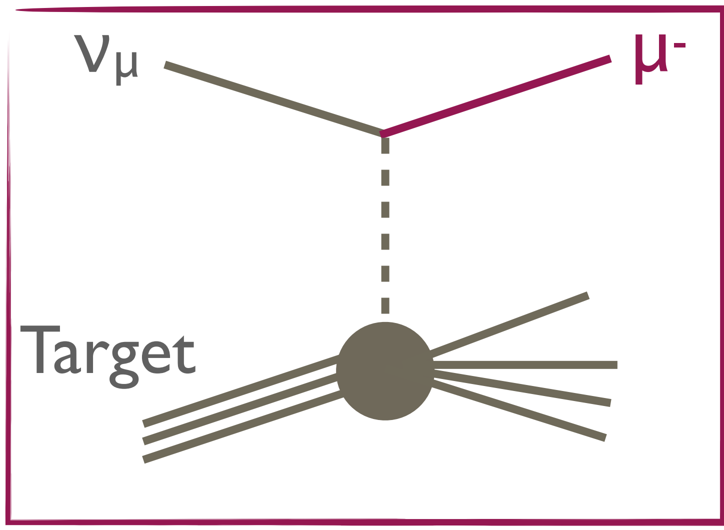

μBooNE
Proton candidate
Proton candidate
ν
Time (drift direction)
Wire number (beam direction)
Proton candidate
Proton candidate
Bragg peak
Muon candidate
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

MICROBOONE MEASUREMENTS



TODAY'S CROSS SECTION MEASUREMENTS

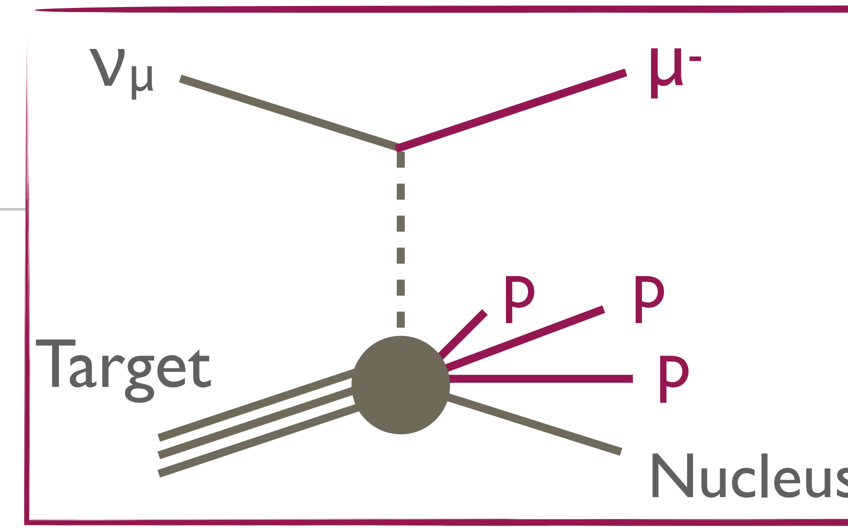
ν_μ CC inclusive



BNB

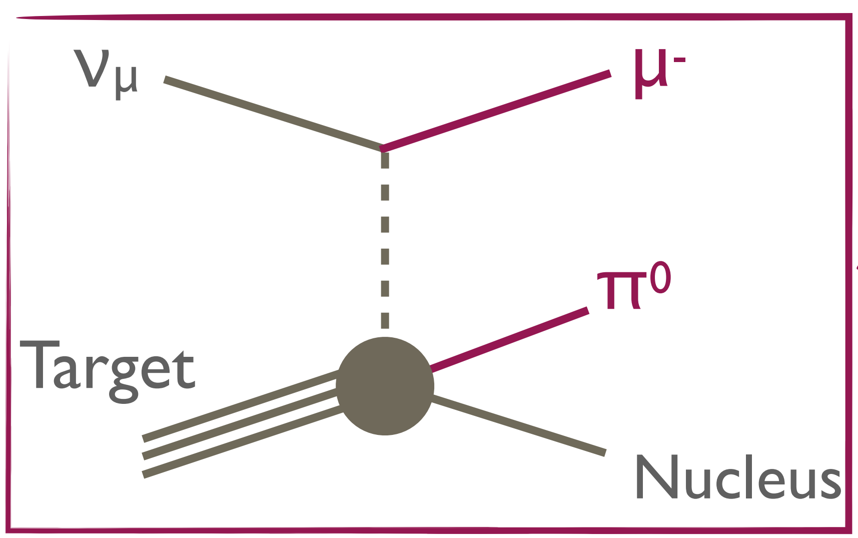
ν_μ CC0π Np

ν_μ CCQE-like



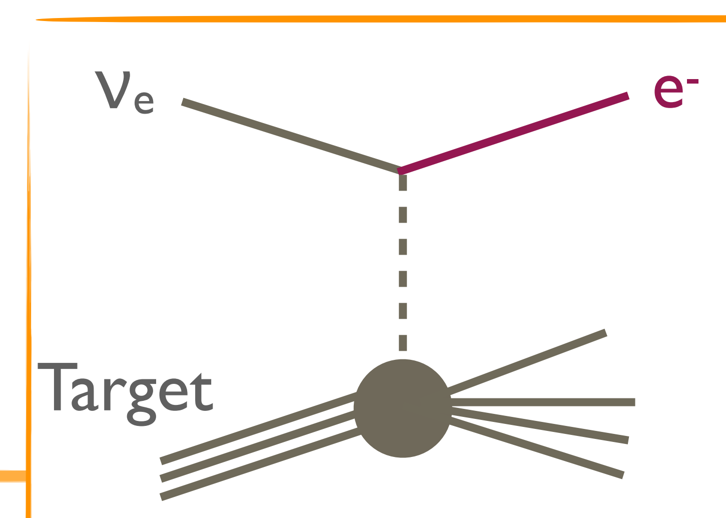
BNB

ν_μ CC π^0



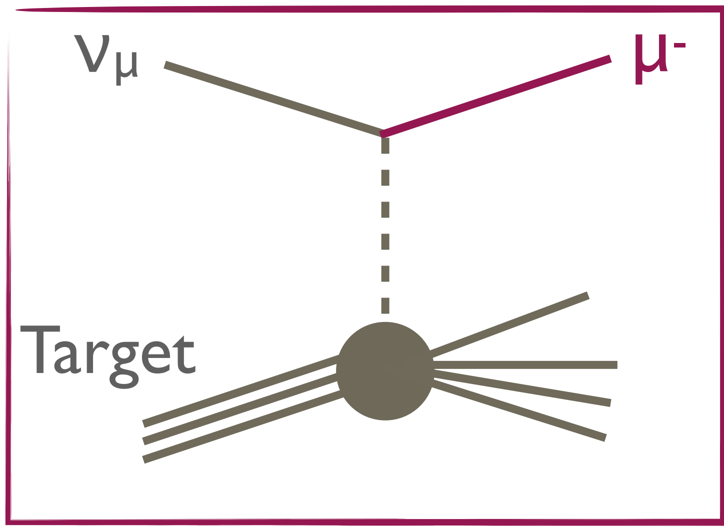
BNB

ν_e CC inclusive



NuMI

TODAY'S CROSS SECTION MEASUREMENTS



BNB

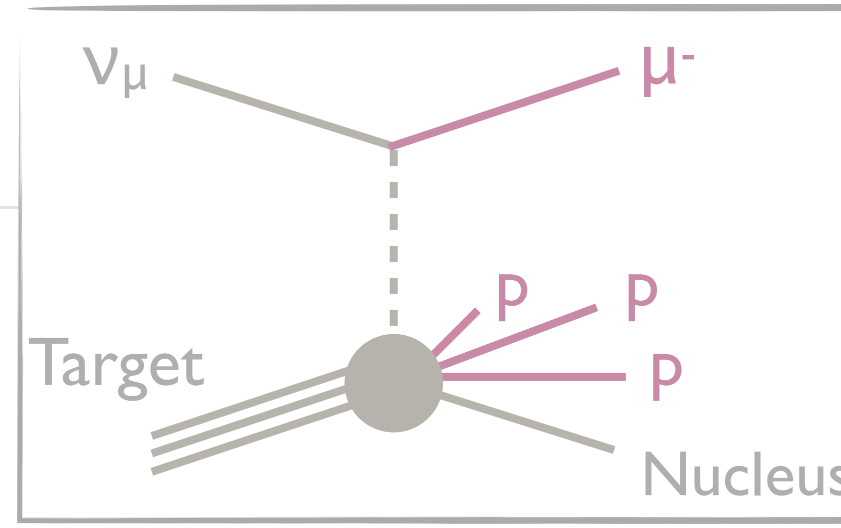
ν_μ CC inclusive

ν_μ CC0π Np

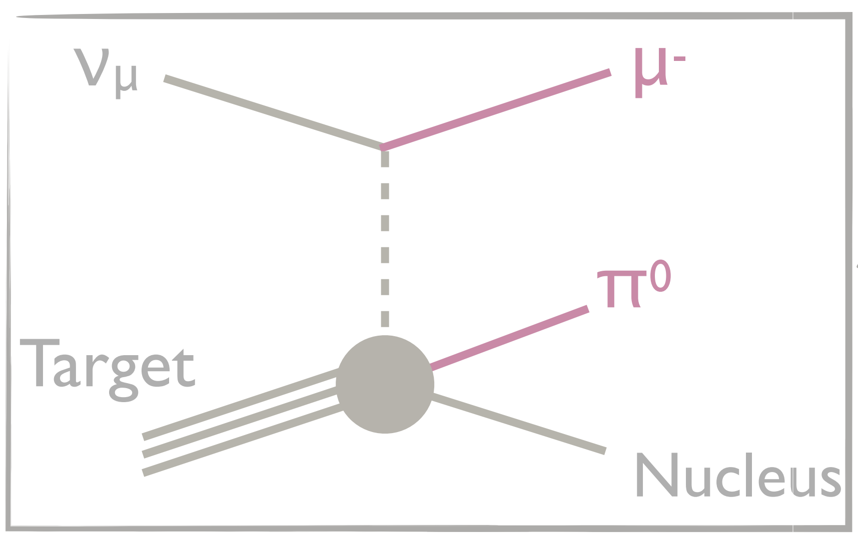
ν_μ CCQE-like

ν_μ CC π^0

ν_e CC inclusive



BNB



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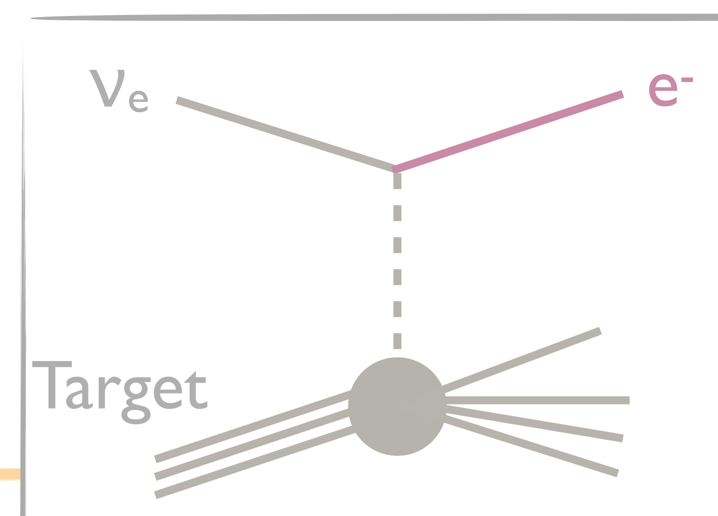


NuMI

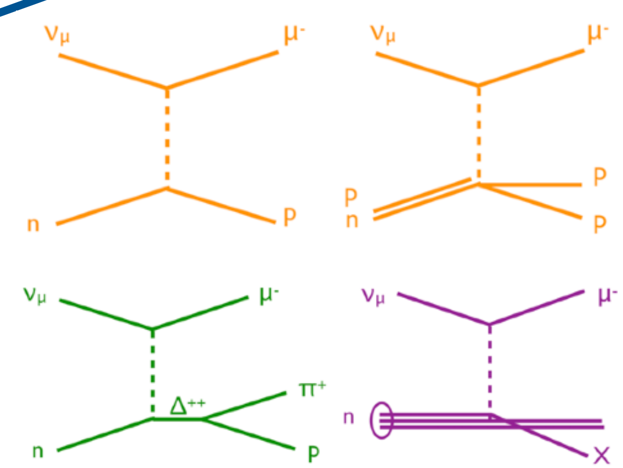
CC-INCLUSIVE

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

- Measure cross-section for **charged-current (CC)** **inclusive** muon neutrino interactions

Outgoing μ^- in final state

…and anything else



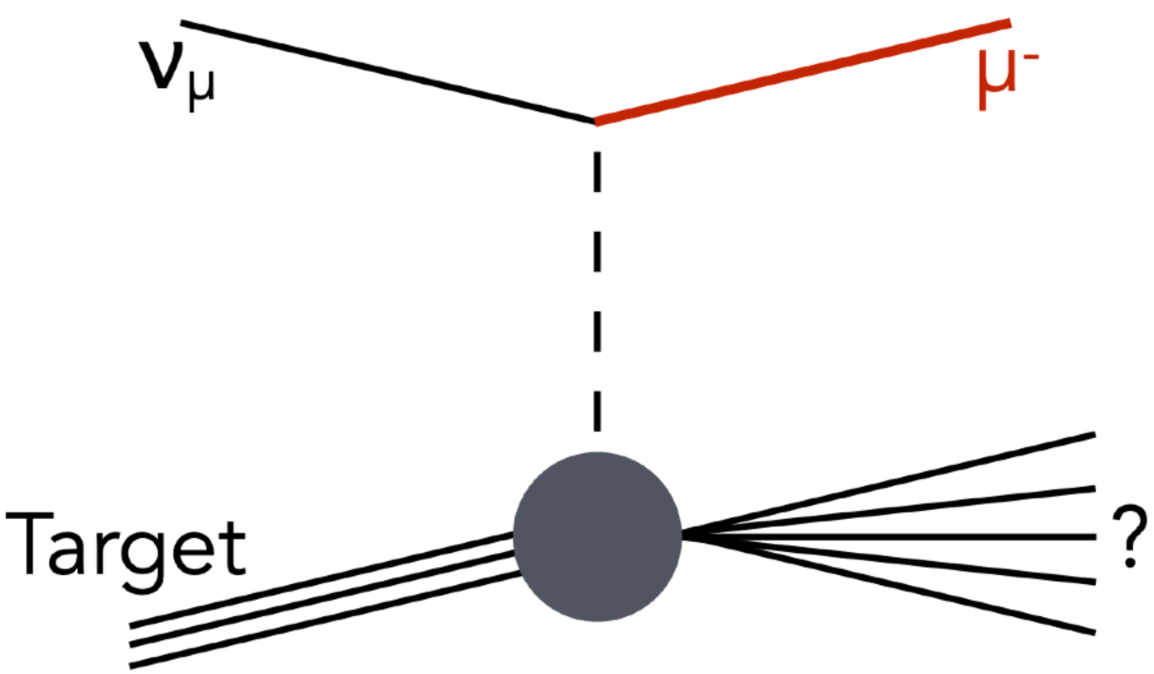


Figure from M. del Tutto

- Large statistics
- Includes many different interaction types — overall test of how well we model all processes
- Pre-selection to study other channels

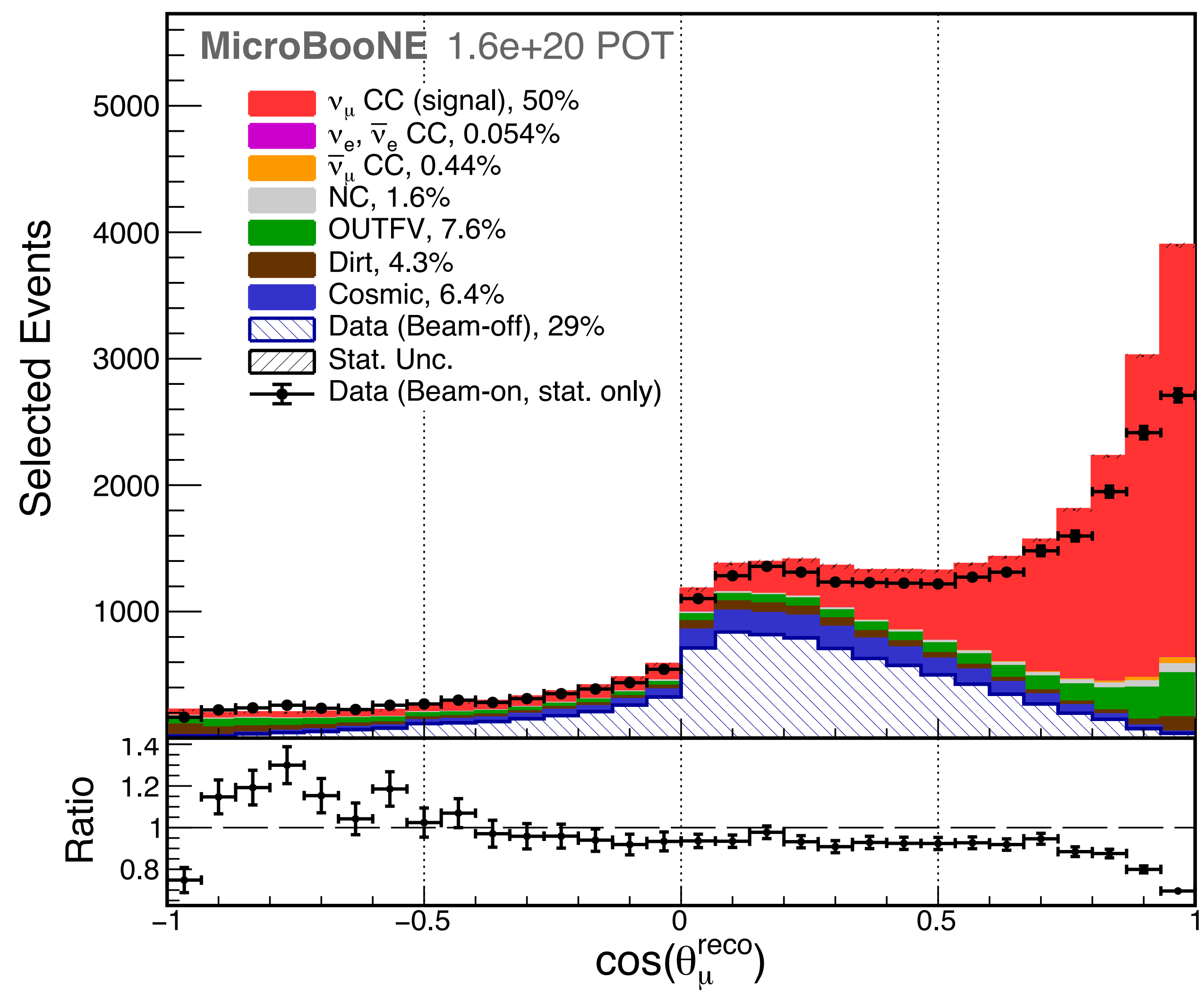
CC INCLUSIVE CROSS SECTION MEASUREMENT

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

Signal (CC-inclusive) events: 50.4%

Largest background: **cosmic rays** (29%) → directly measured with beam-off data

First ever double-differential cross section measurement on argon: compare to worldwide interaction generators



µBooNE

CROSS SECTION

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

Double-differential cross section defined as:

$$\left\langle \frac{d^2\sigma}{dp_\mu^{\text{reco}} d\cos\theta_\mu^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu \cdot \Delta\cos\theta_\mu)_i}$$

- No. selected events in bin i (data) → N_i
- No. background events in bin i (MC, cosmic data) → B_i
- Overall efficiency (selection and acceptance) in bin i (MC) → $\tilde{\epsilon}_i$
- No. target nucleons → N_{target}
- Muon neutrino flux (integrated over all energies) → Φ_{ν_μ}
- Width of bin i → $(\Delta p_\mu \cdot \Delta\cos\theta_\mu)_i$

UNCERTAINTIES

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

Calculate uncertainty on **total** CC-inclusive cross section

Source of uncertainty	Relative uncertainty [%]
Beam flux	12.4
Cross section modeling	3.9
Detector response	16.2
Dirt background	10.9
Cosmic ray background	4.2
MC statistics	0.2
Stat	1.4
Total	23.8

Flux uncertainty ~12%

Inclusive measurement → not strongly dependent on cross section model

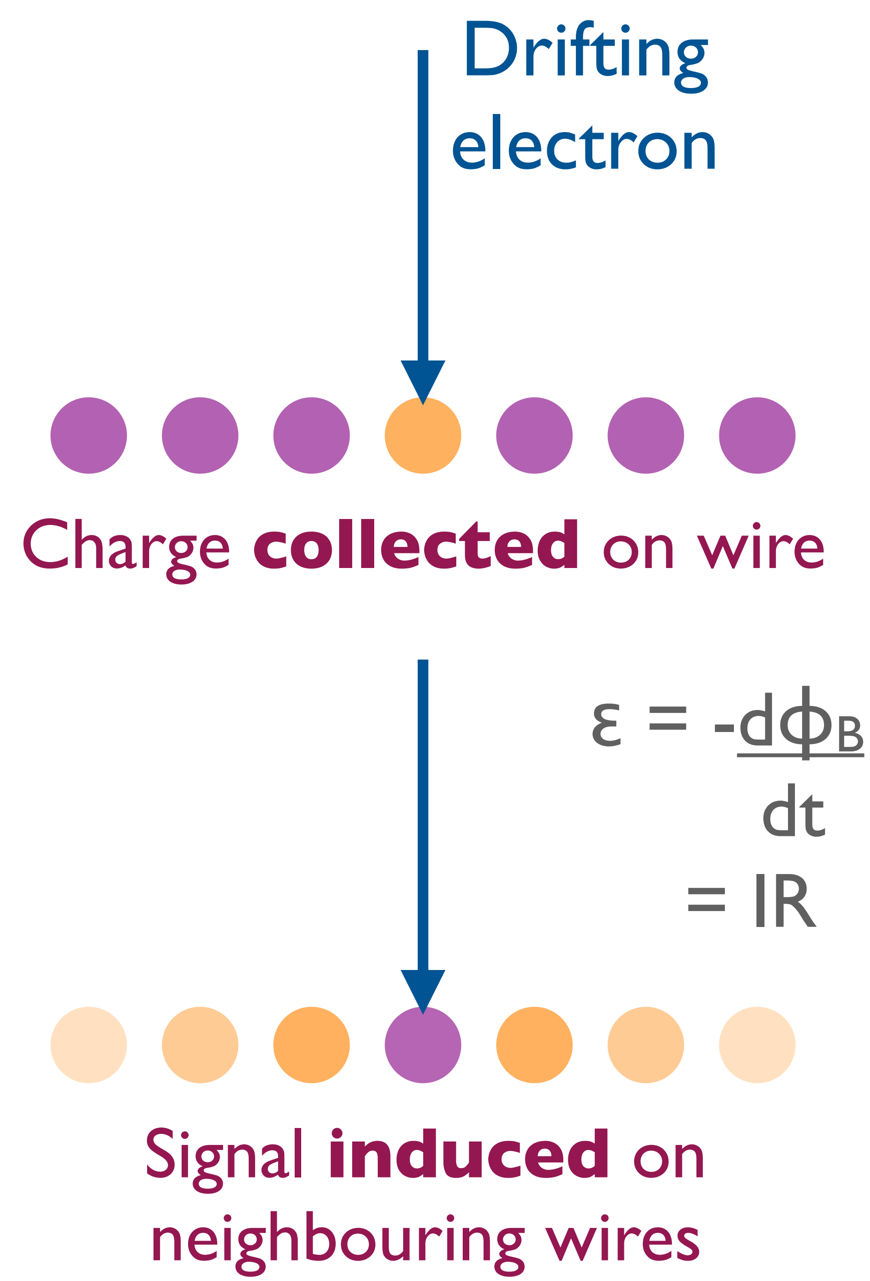
Total uncertainty dominated by detector response

INDUCED CHARGE

JINST 13 P07006 (2018)

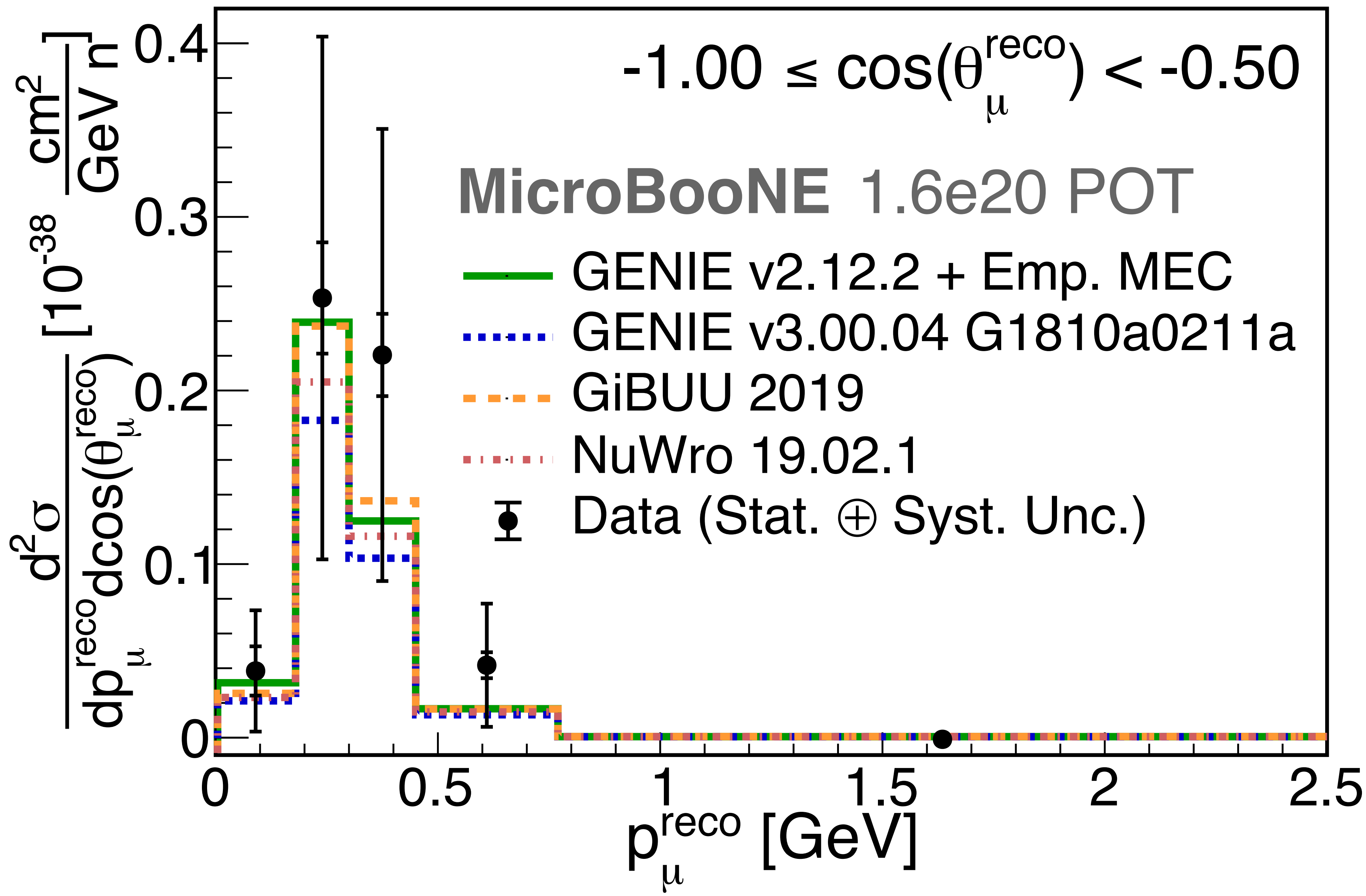
JINST 13 P07007 (2018)

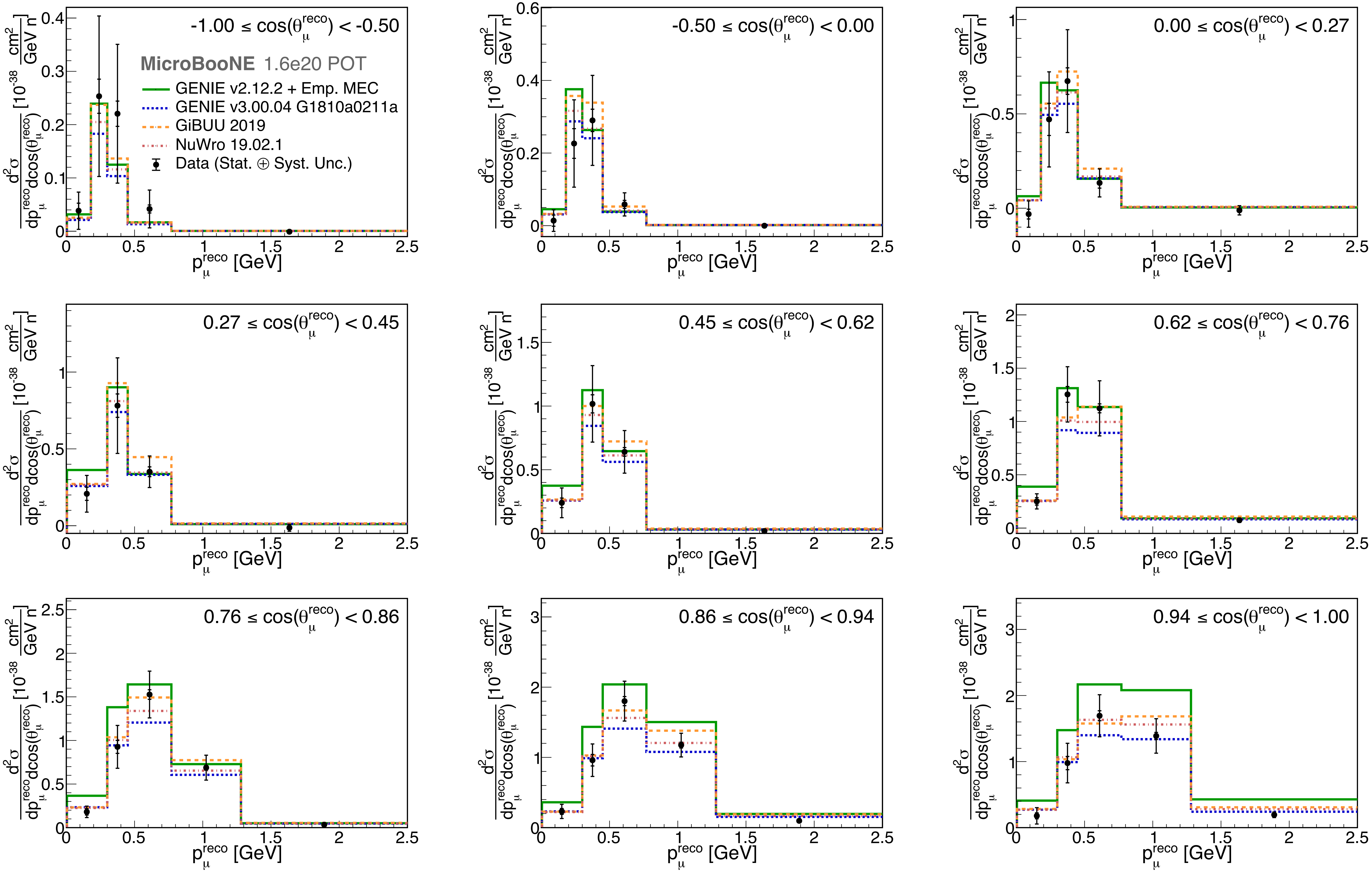
- Detector response → 16% uncertainty on total cross section
- Largest single contribution: 13% due to modeling of **induced charge**
  - MC assumes drift electrons cause signal on only one wire
  - Not true! Nearby wires see **charge by induction**
  - Because of this, **detector response depends on track angle**
  - Easy to fix — include in simulation and account for in reconstruction!



RESULTS

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

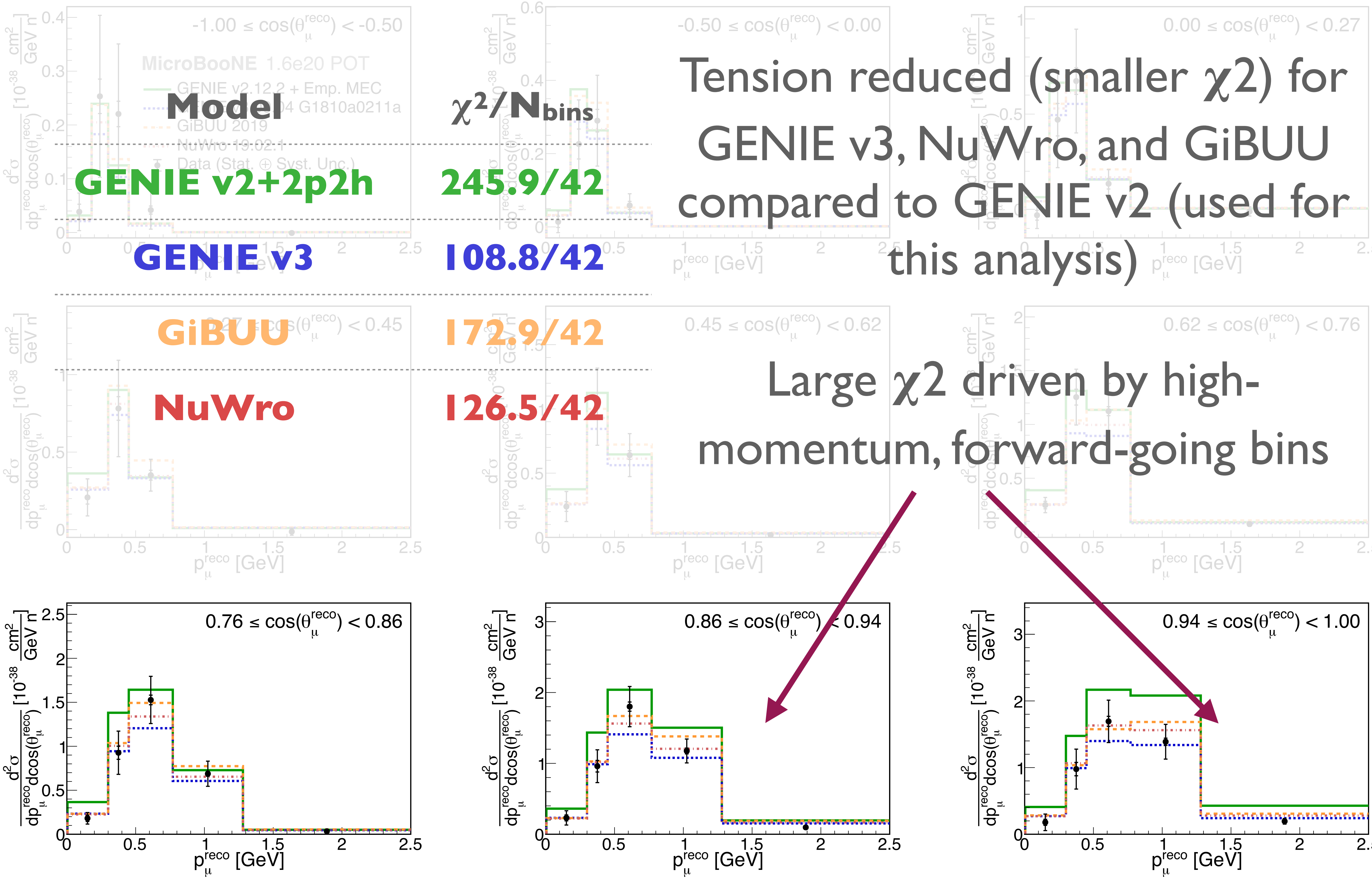



-1.00 ≤ cos(θ_μ^reco) < -0.50
-0.50 ≤ cos(θ_μ^reco) < 0.00
0.00 ≤ cos(θ_μ^reco) < 0.27
0.27 ≤ cos(θ_μ^reco) < 0.45
0.45 ≤ cos(θ_μ^reco) < 0.62
0.62 ≤ cos(θ_μ^reco) < 0.76
0.76 ≤ cos(θ_μ^reco) < 0.86
0.86 ≤ cos(θ_μ^reco) < 0.94
0.94 ≤ cos(θ_μ^reco) < 1.00
MicroBooNE 1.6e20 POT
GENIE v2.12.2 + Emp. MEC
GENIE v3.00.04 G1810a0211a
GiBUU 2019
NuWro 19.02.1
Data (Stat. ⊕ Syst. Unc.)
p_μ^reco [GeV]
d²σ / dp_μ^reco dcos(θ_μ^reco) [10⁻³⁸ cm²/GeV n]

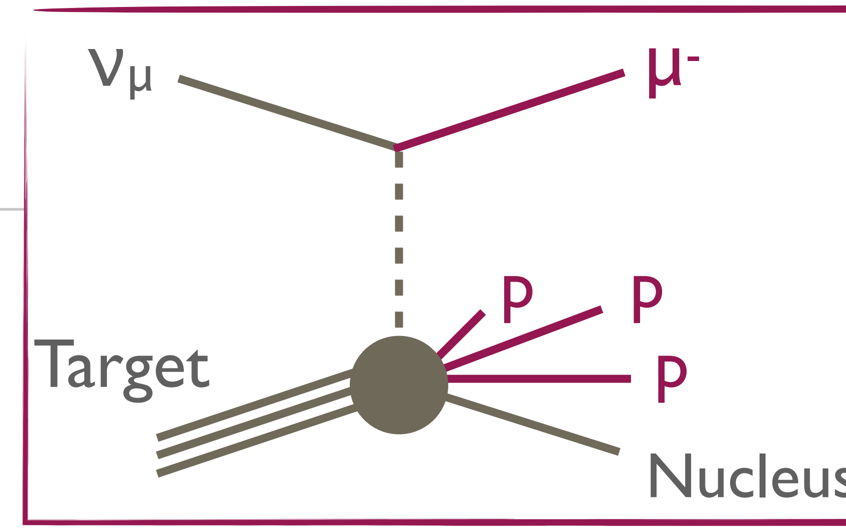
Model	χ^2/N_{bins}
GENIE v2+2p2h	245.9/42
GENIE v3	108.8/42
GiBUU	172.9/42
NuWro	126.5/42

Tension reduced (smaller $\chi 2$) for GENIE v3, NuWro, and GiBUU compared to GENIE v2 (used for this analysis)

Large $\chi 2$ driven by high-momentum, forward-going bins

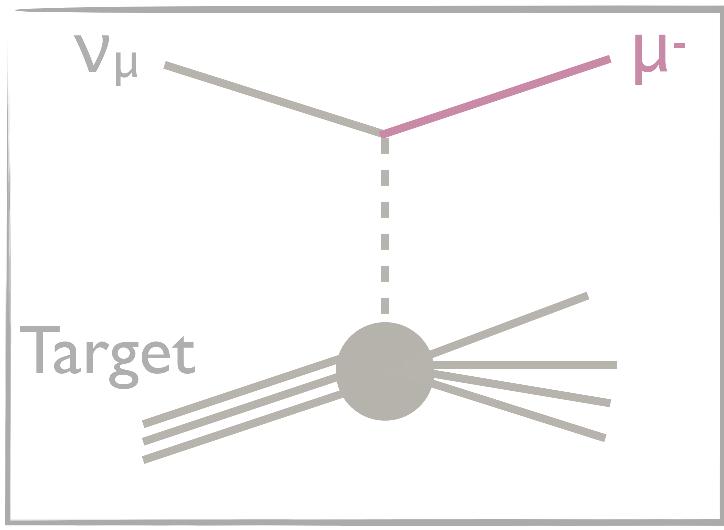


TODAY'S CROSS SECTION MEASUREMENTS



BNB

ν_μ CC inclusive

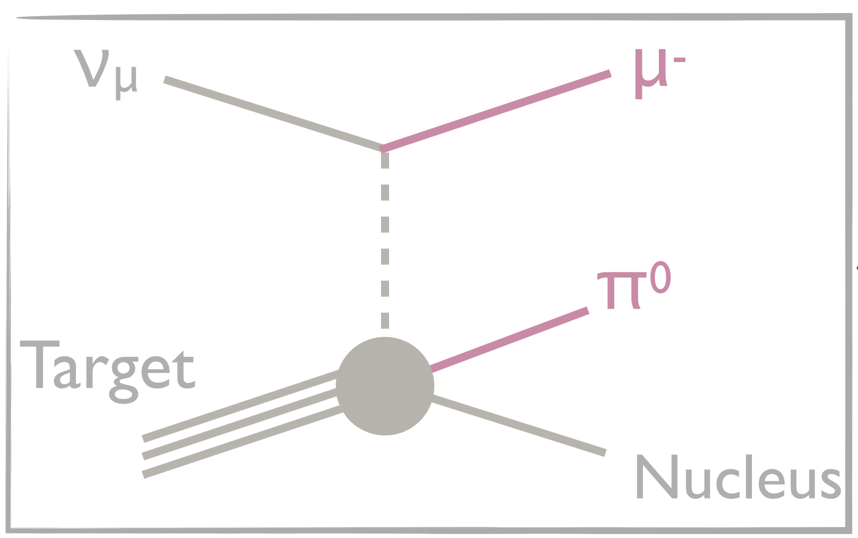


BNB

ν_μ CC0π Np

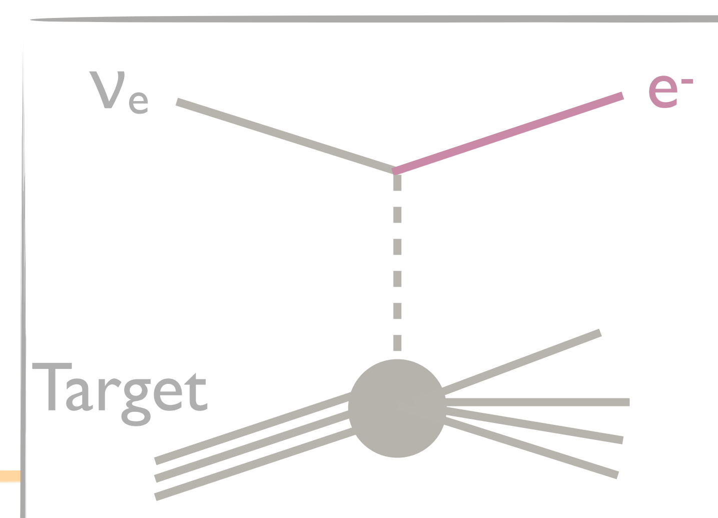
ν_μ CCQE-like

ν_μ CC π^0



BNB

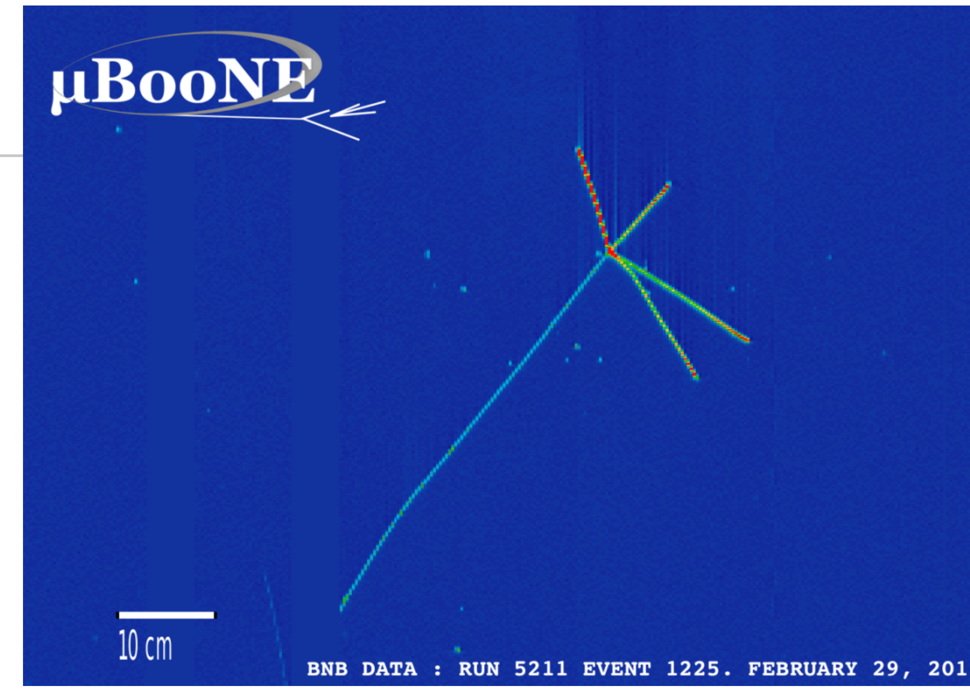
ν_e CC inclusive



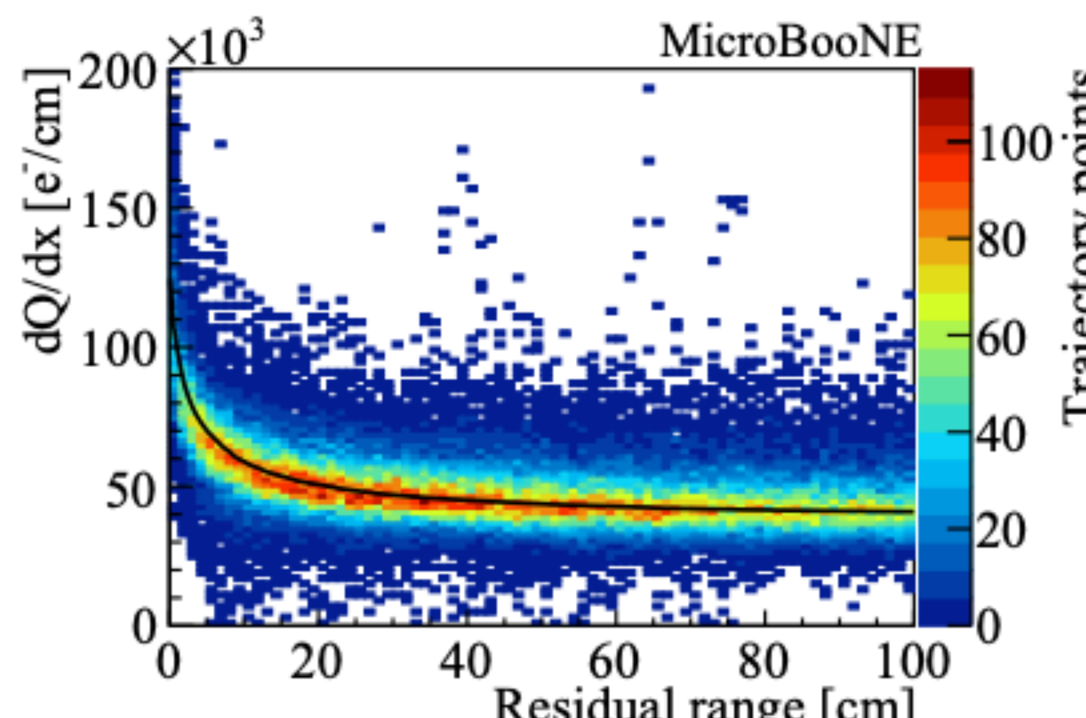
NuMI

LArTPC STRENGTH: LOW PROTON THRESHOLDS

Phys. Rev. Lett. 125, 201803 (2020)
Phys. Rev. D 102, 112013 (2020)
JINST 15, P03022 (2020)



- Measuring proton kinematics gives us more information about the interaction
- **Low thresholds** → access to new information about nuclear effects, probe e.g. 2p2h scattering
  - MicroBooNE: **300 MeV/c**
  - ArgoNeuT: **200 MeV/c** Phys. Rev. D 90, 012008 (2014)
  - T2K: 500 MeV/c Phys. Rev. D 98, 032003 (2018)
  - MINERvA: 450 MeV/c Phys. Rev. D 99, 012004 (2019)
- Protons **identified by Bragg peak** in last 30 cm of track

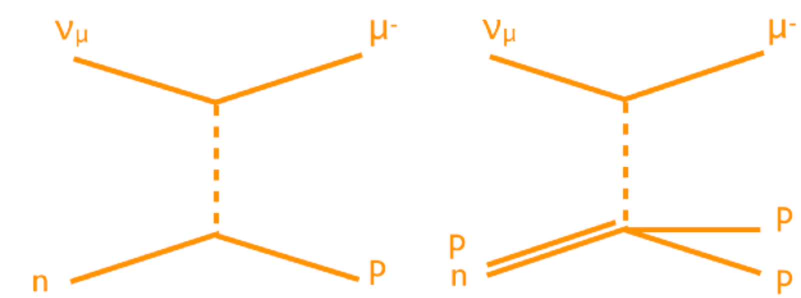


MEASUREMENTS WITH PROTONS

ν_μ CC interaction

↓

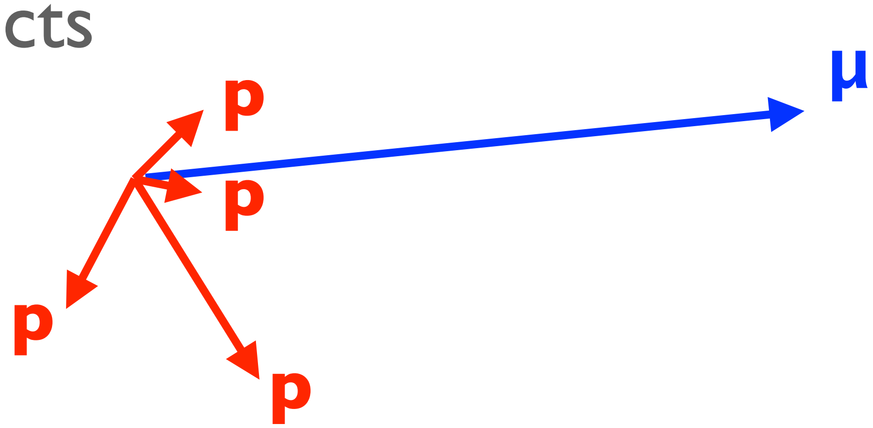
No pions



1 or more proton candidates

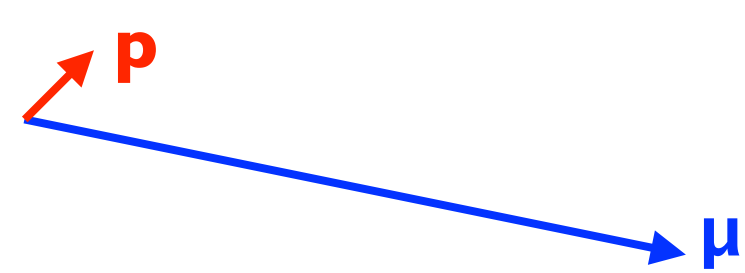
→ CCQE and CC2p2h (and other processes with FSI)

→ general probe of nuclear effects



Exactly 1 proton candidate: CCQE-like kinematics

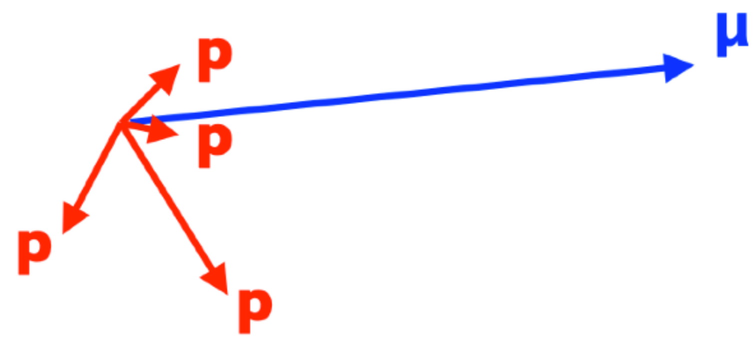
→ try to isolate CCQE or CCQE-like interactions



CC0πNp (N≥1) CROSS SECTION

Phys. Rev. D 102, 112013 (2020)

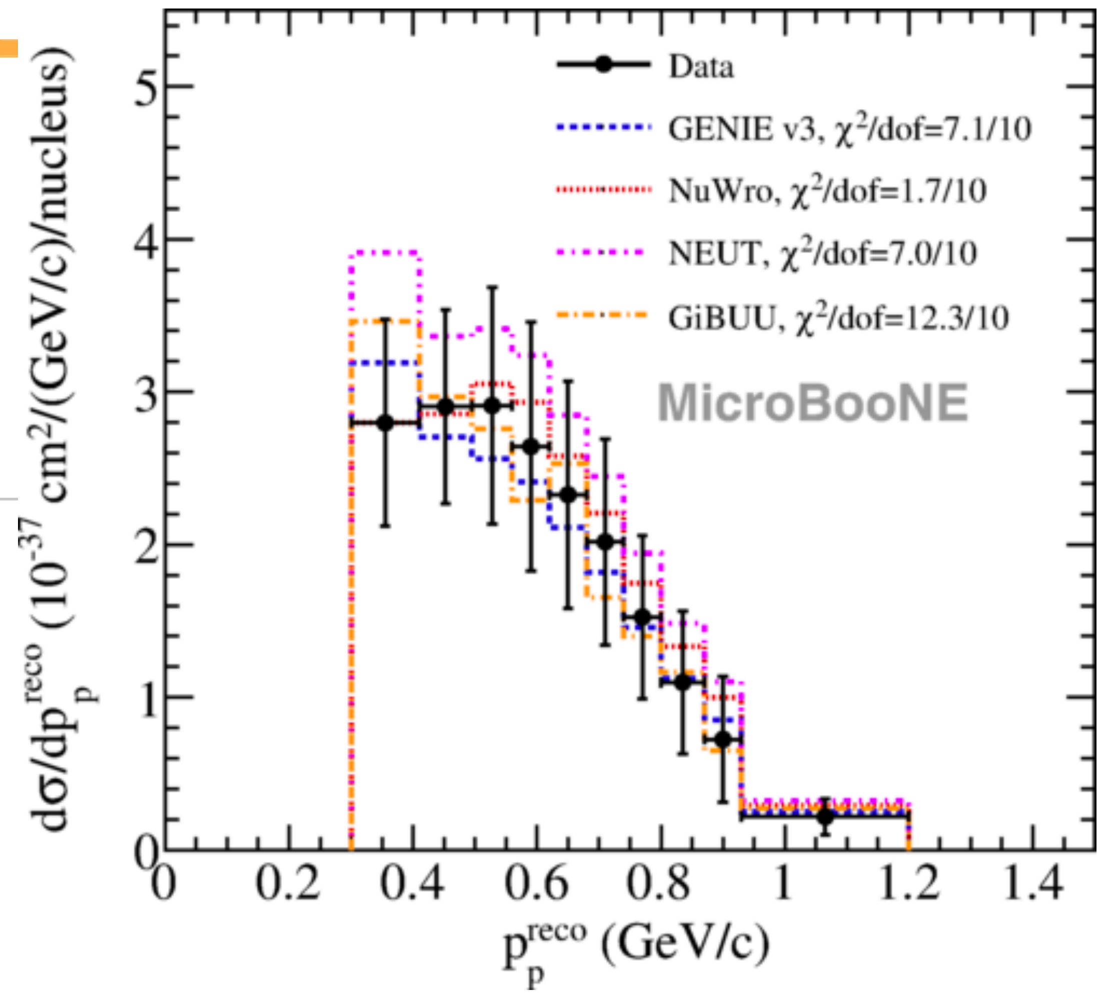
Signal:

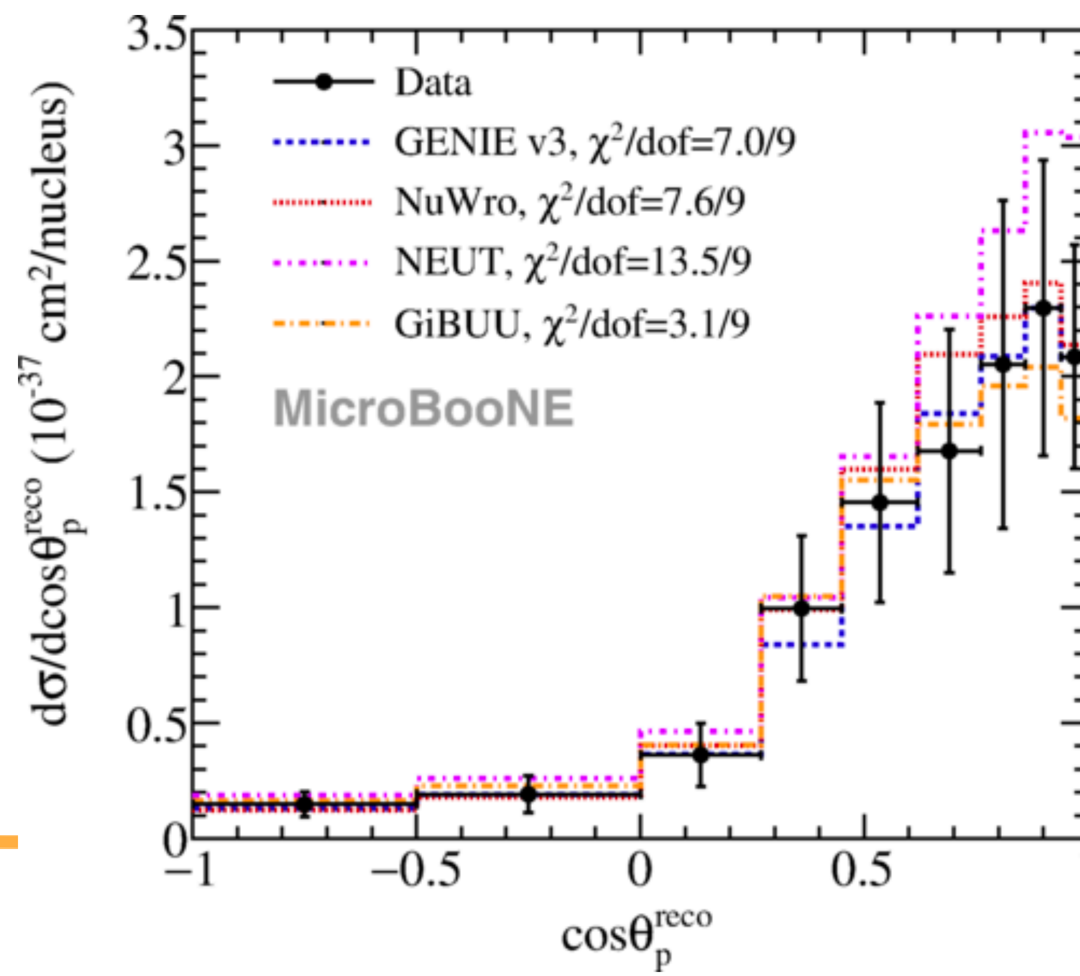


- 1 muon (p_{μ}>100 MeV/c)
- At least 1 proton (300<p_{p}<1200 MeV/c)
- No pions

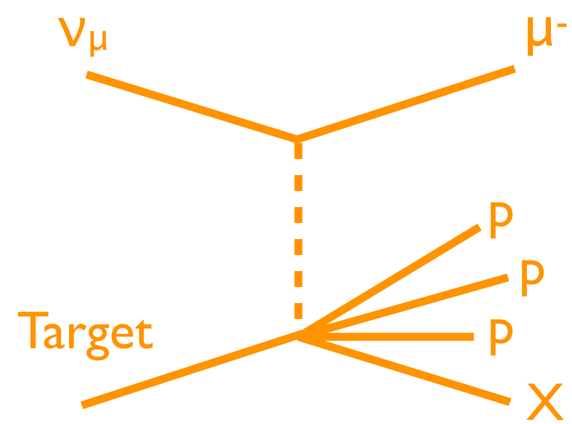
→ **71% purity, 29% efficiency**

- Proton momentum and angle show **reasonable agreement** with generators
- Lowest bin in proton momentum has not been seen before — **Low thresholds = new information** about proton kinematics

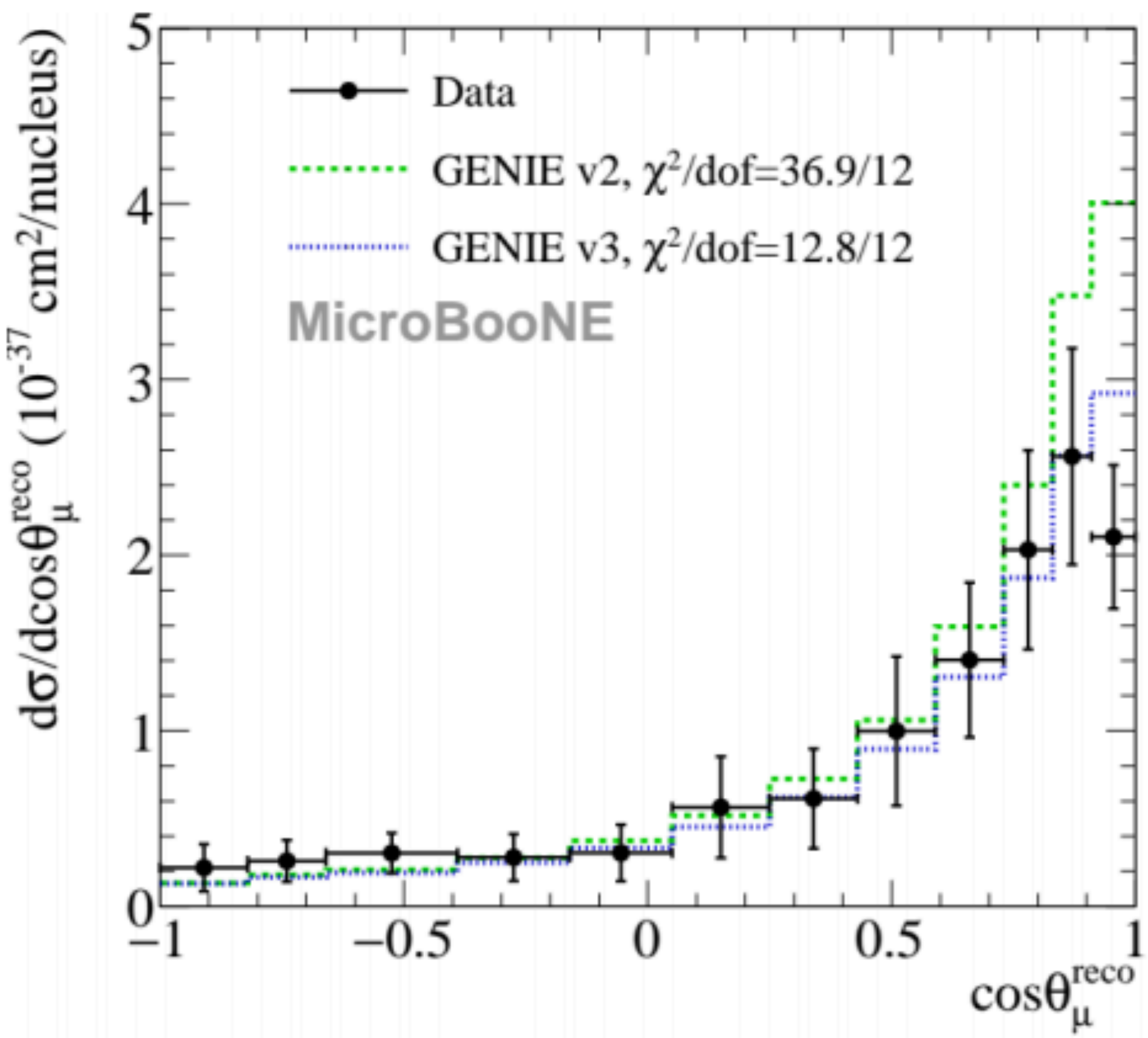


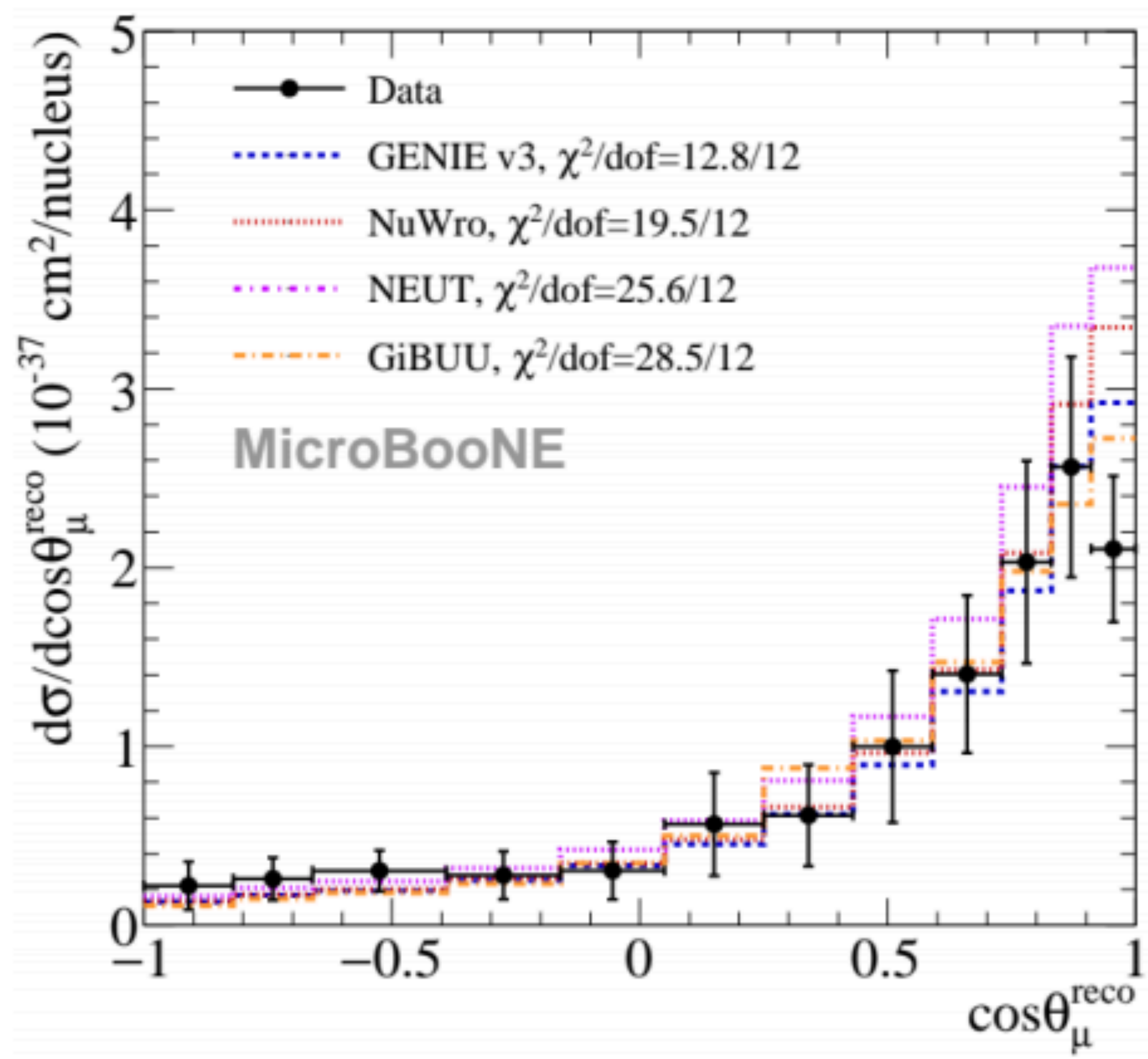


CC0πNp (N≥1) CROSS SECTION



Phys. Rev. D 102, 112013 (2020) also includes measurement as a function of muon momentum, muon-proton opening angle

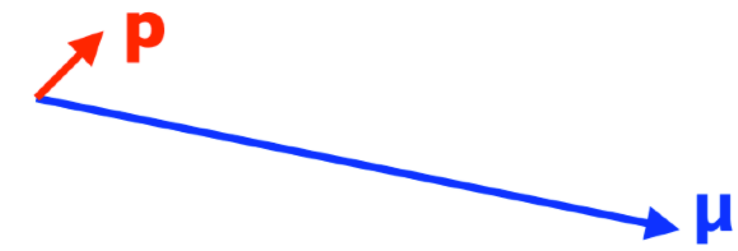




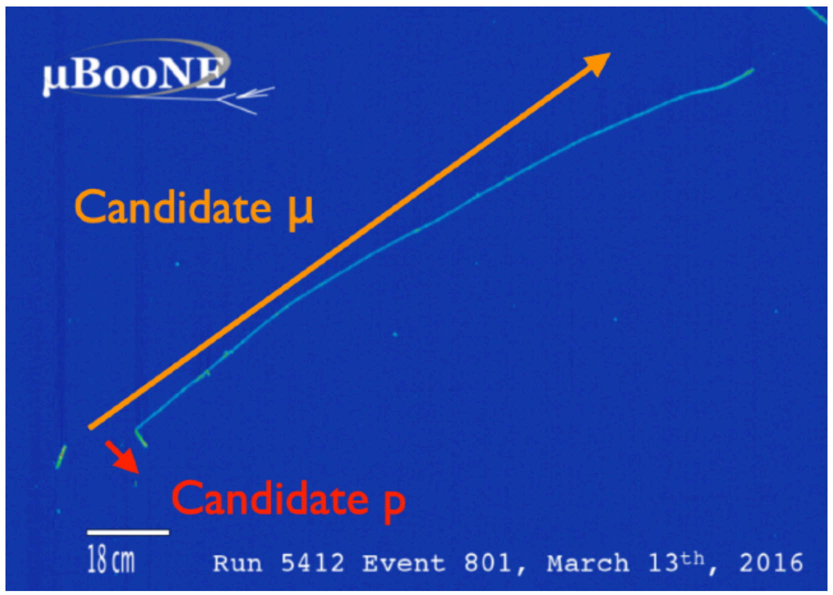
- Big over-prediction at forward-going angles
- Models with RPA do much better, but not quite enough

CCQE-LIKE CROSS SECTION

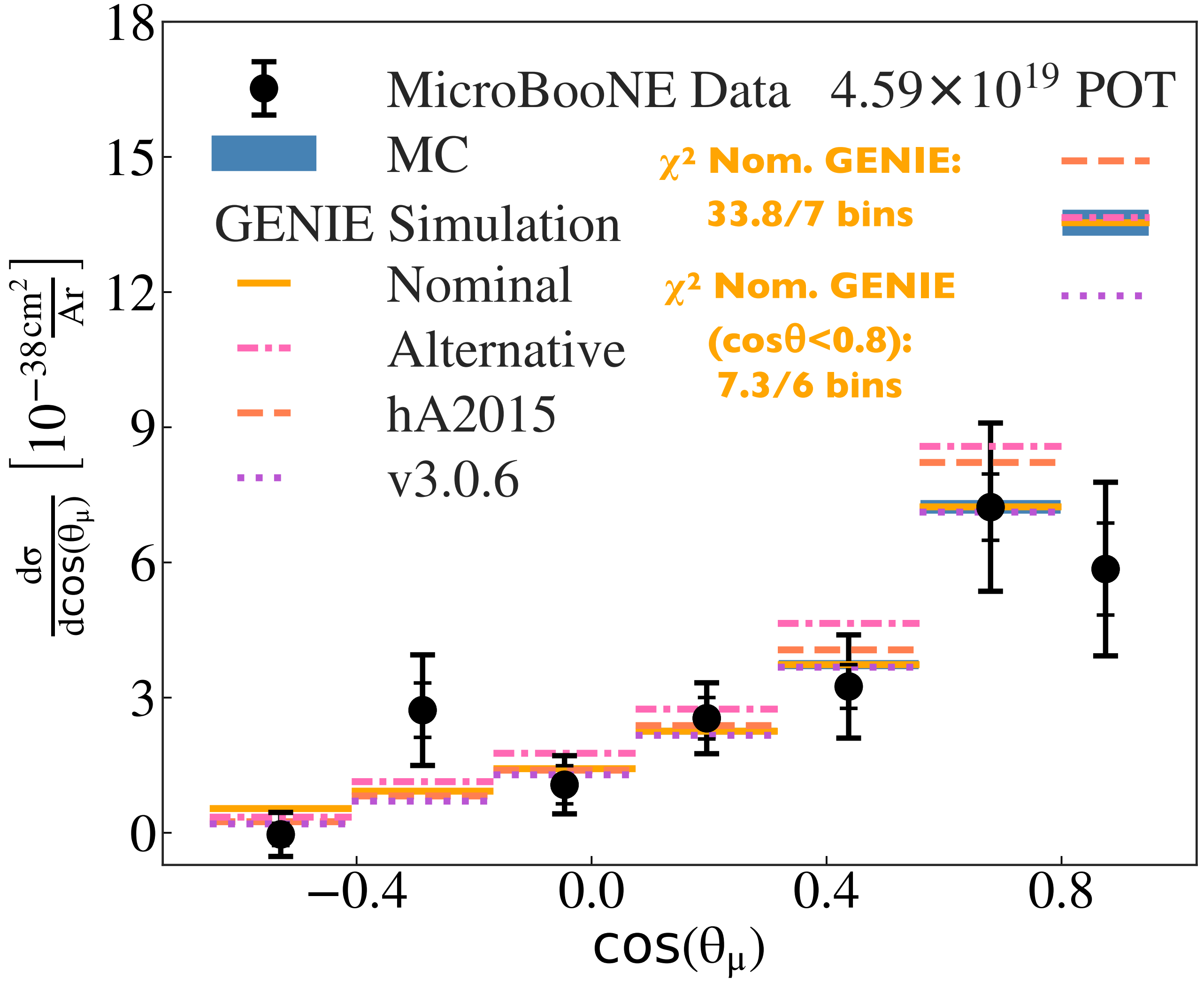
Eur. Phys. J. C 79 673 (2019)   Phys. Rev. Lett. 125, 201803 (2020)



First extraction of ν_μ-^{40}Ar CCQE-like cross section using a surface LArTPC



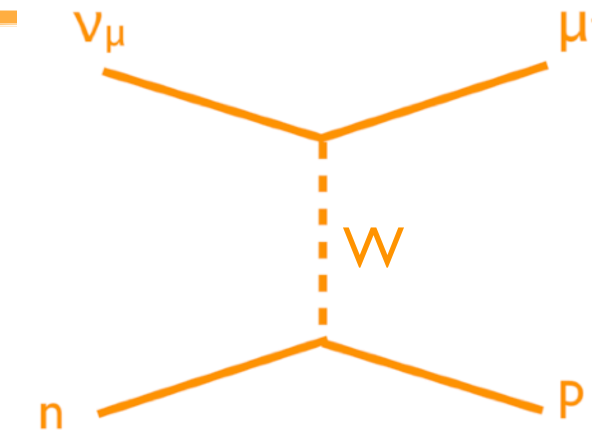
→ ~84% CC1p0π (~81% CCQE) purity, ~20% efficiency



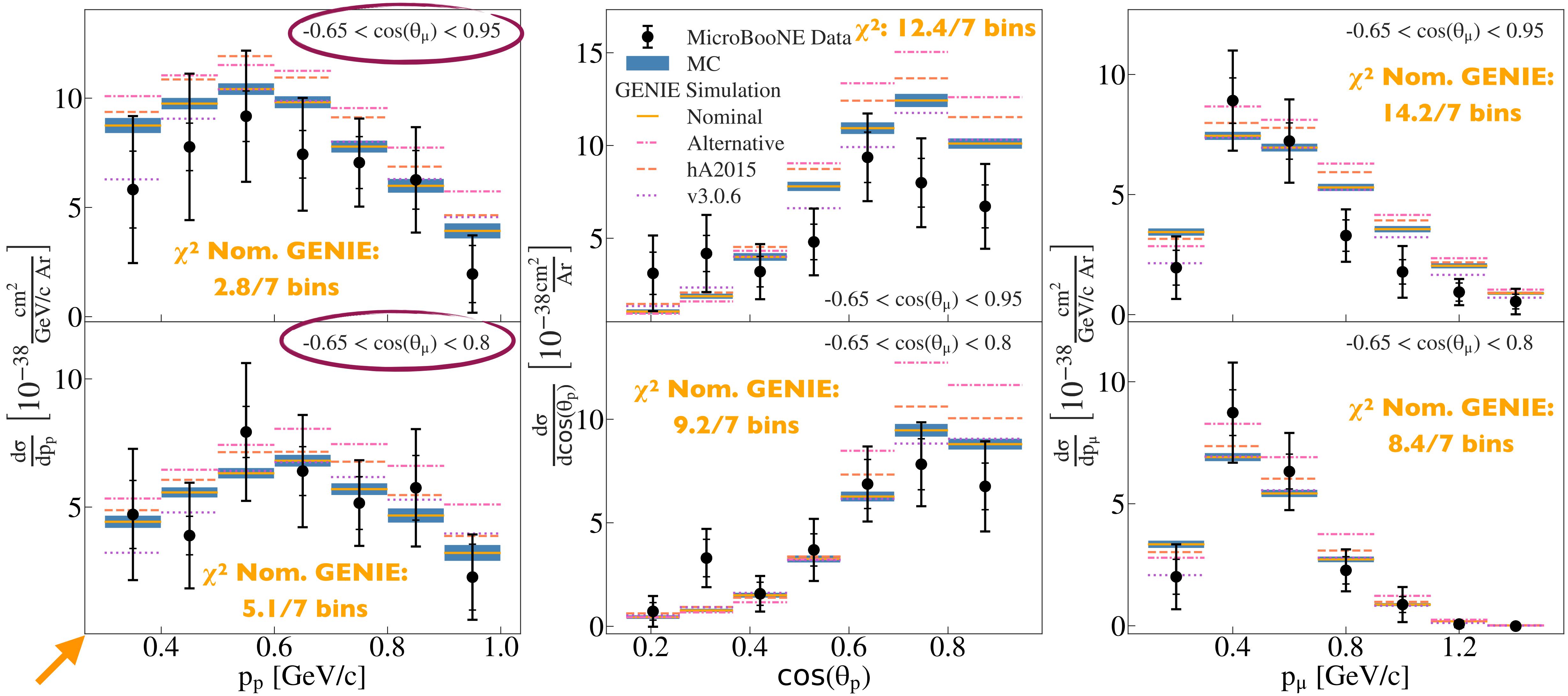
Good agreement with models, except at very **forward muon scattering** angles

μBooNE

CCQE-LIKE CROSS SECTION



Eur. Phys. J. C 79 673 (2019)   Phys. Rev. Lett. 125, 201803 (2020)



Proton momentum threshold 300 MeV/c

Across all kinematic variables, agreement is improved if forward muon angles are excluded

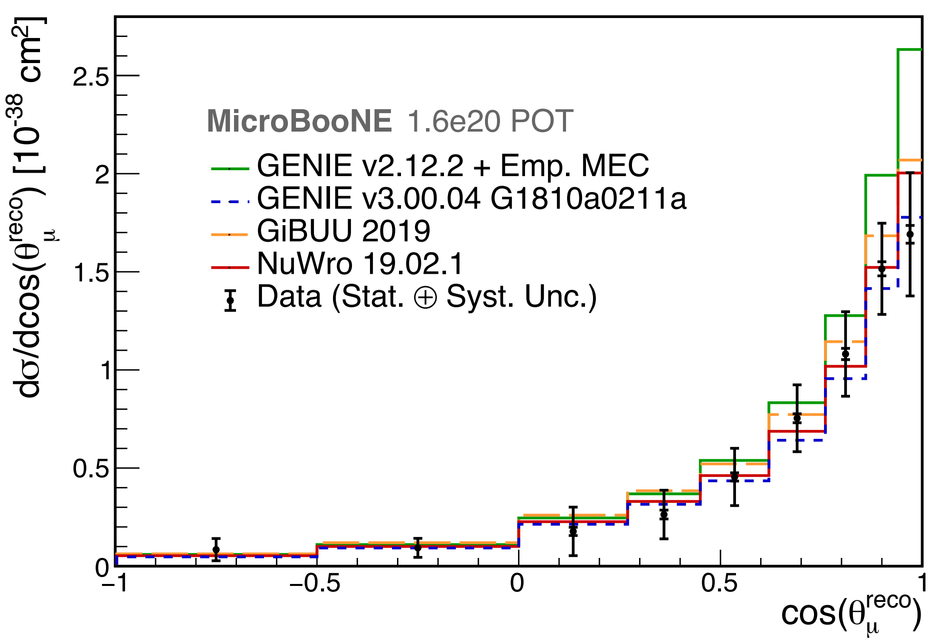
μBooNE

THAT FORWARD-ANGLE BIN: A CONSISTENT STORY

Phys. Rev. Lett. 123, 131801 (2019) Phys. Rev. D 102, 112013 (2020) Eur. Phys. J. C 79 673 (2019) Phys. Rev. Lett. 125, 201803 (2020)

All three compare to the same GENIE models → cross-comparison

GENIE v3

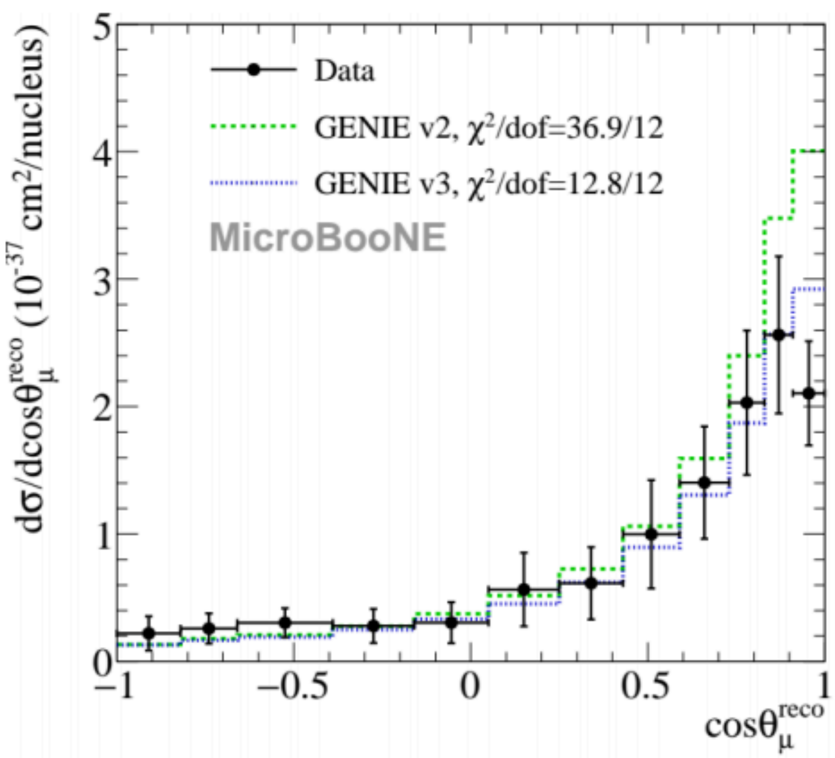


CC Inclusive

Inclusive

Some deficit

GENIE v2 GENIE v3

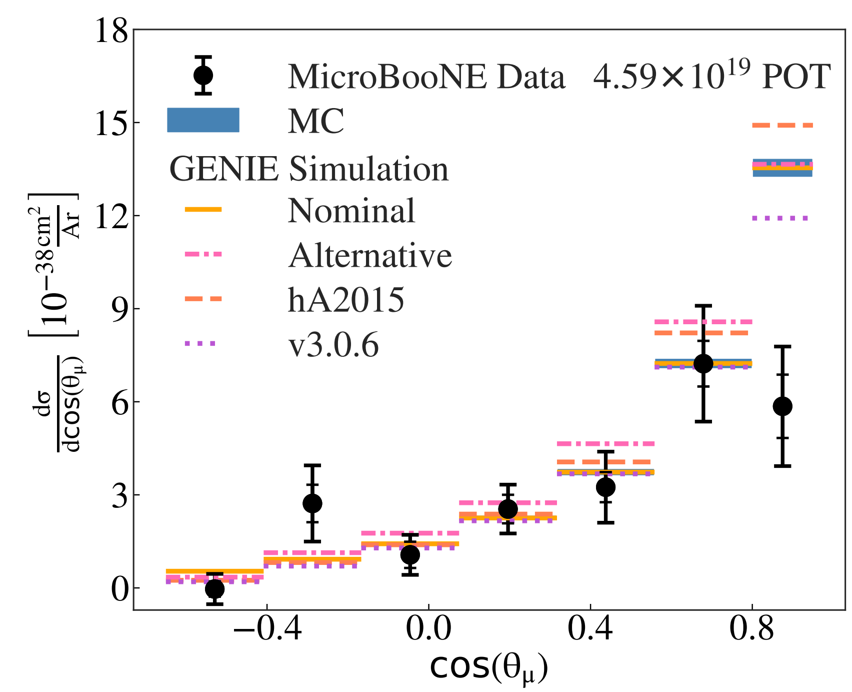


CC0πNp

More exclusive

Turnover in data

GENIE v2 GENIE v3



CCQE-like

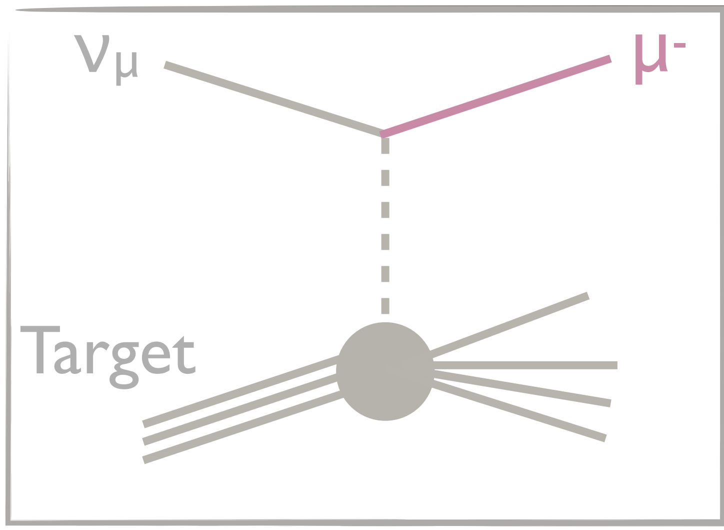
Even more exclusive

Even more deficit

μBooNE

TODAY'S CROSS SECTION MEASUREMENTS

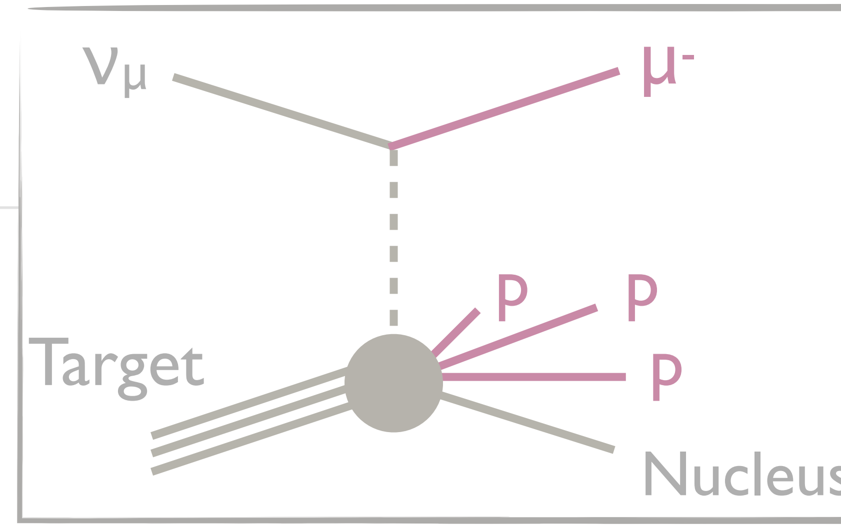
ν_μ CC inclusive



BNB

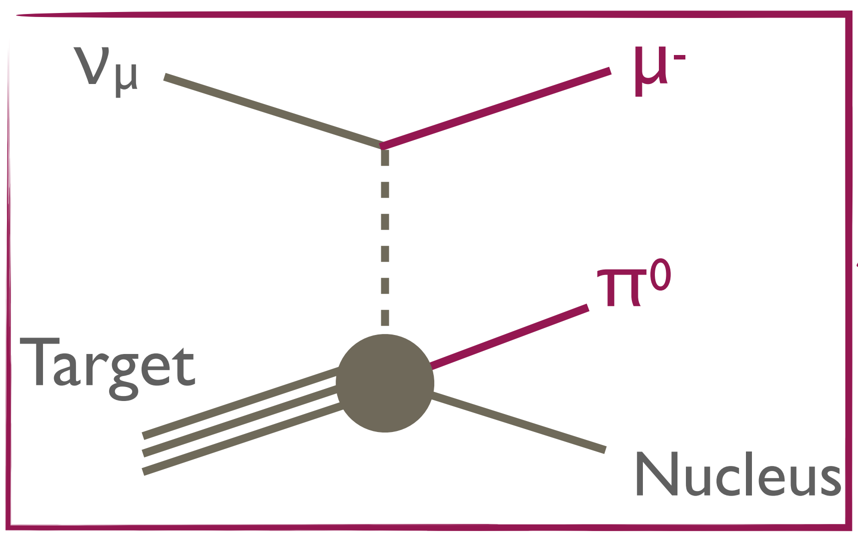
ν_μ CC0π Np

ν_μ CCQE-like



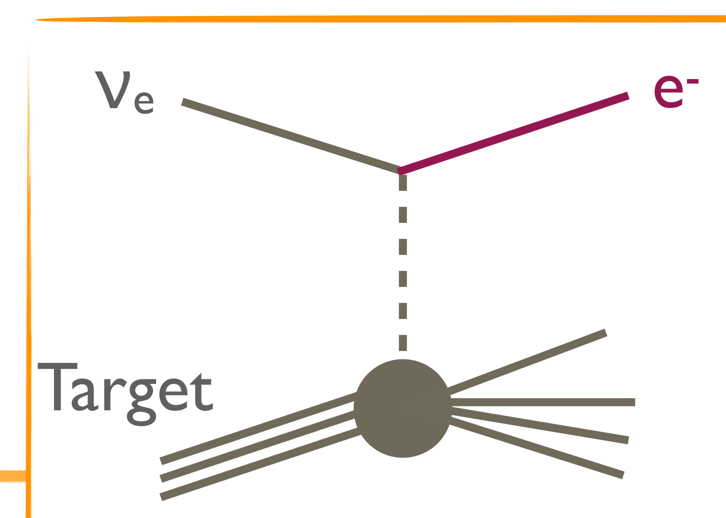
BNB

ν_μ CC π^0



BNB

ν_e CC inclusive

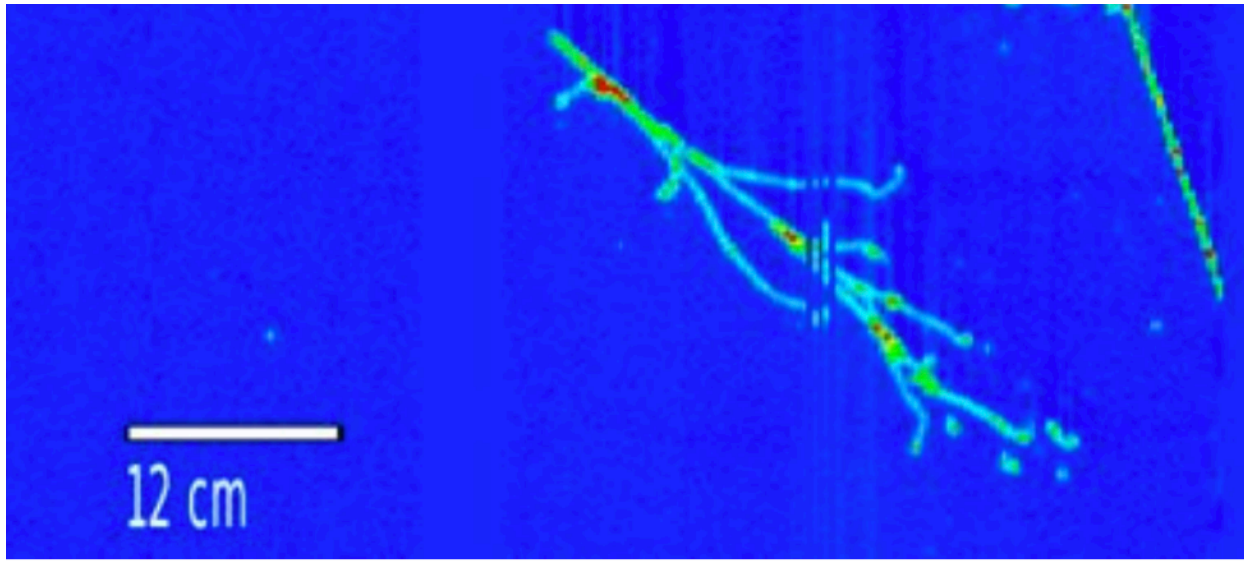


NuMI

LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 99, 091102(R) (2019)

- **Electrons and photons produce showers in LArTPCs**
  → important to understand for ν_e appearance searches in SBN and DUNE



LARTPC STRENGTH: ELECTRONS AND PHOTONS

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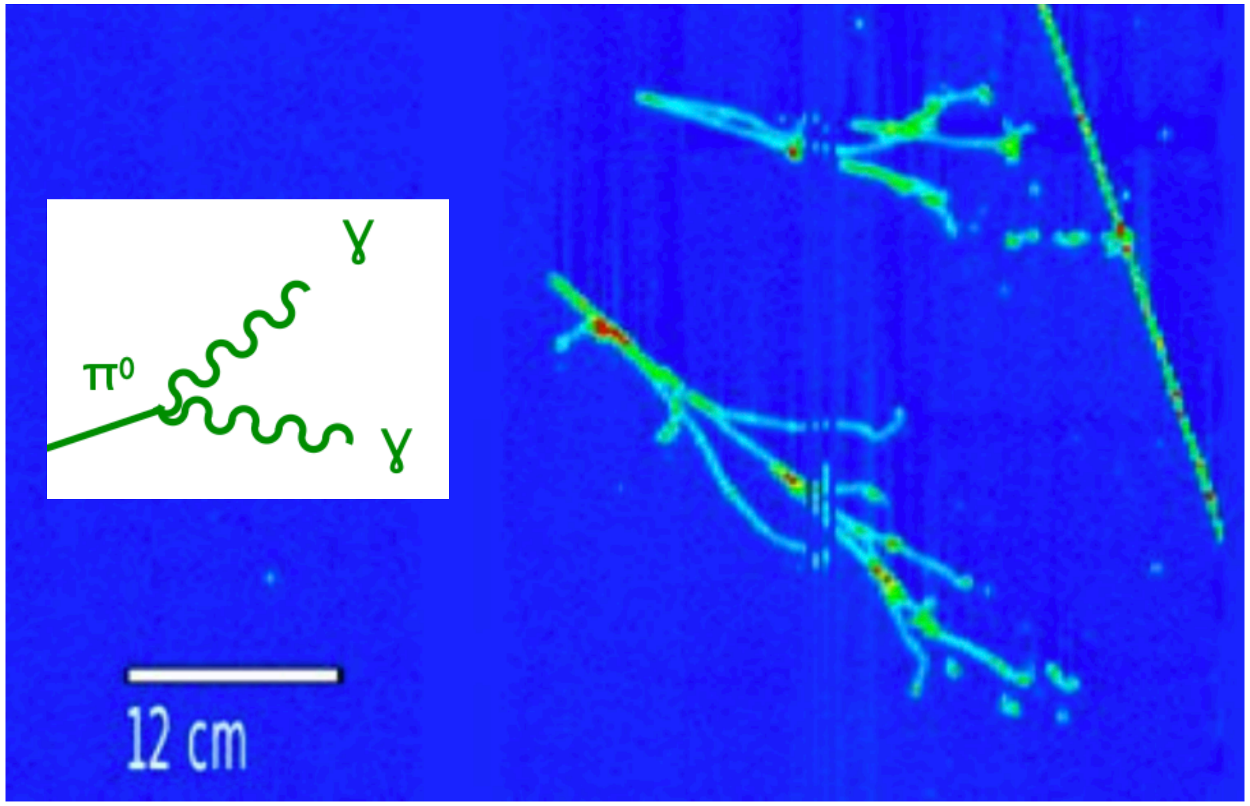
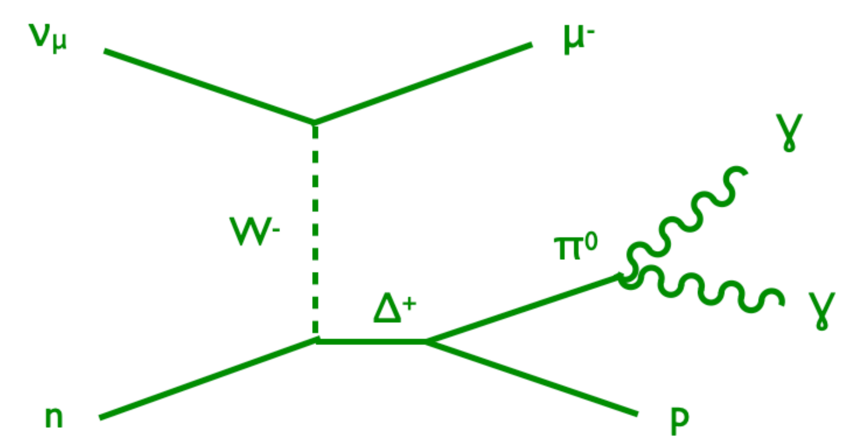
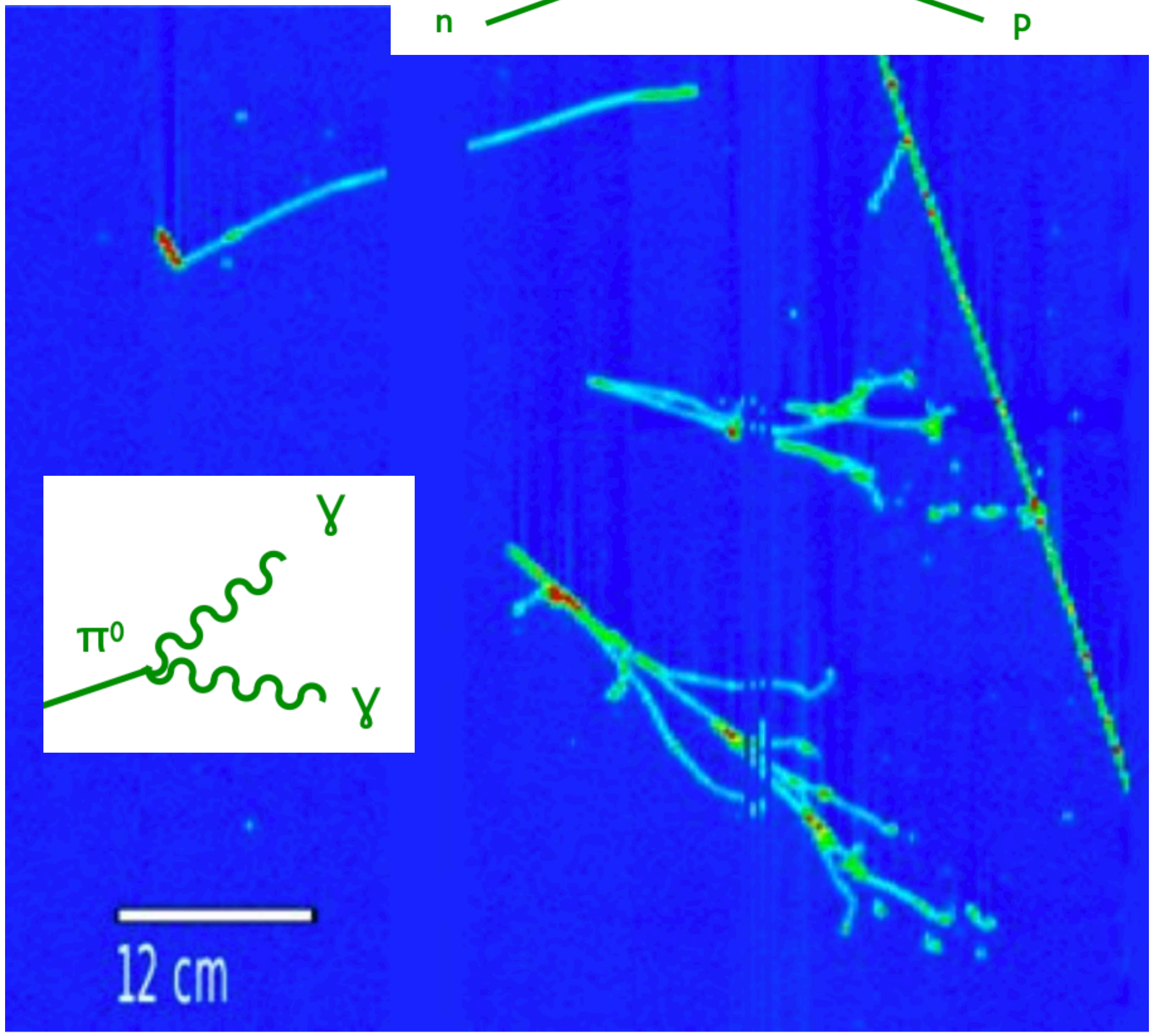


LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 99, 091102(R) (2019)

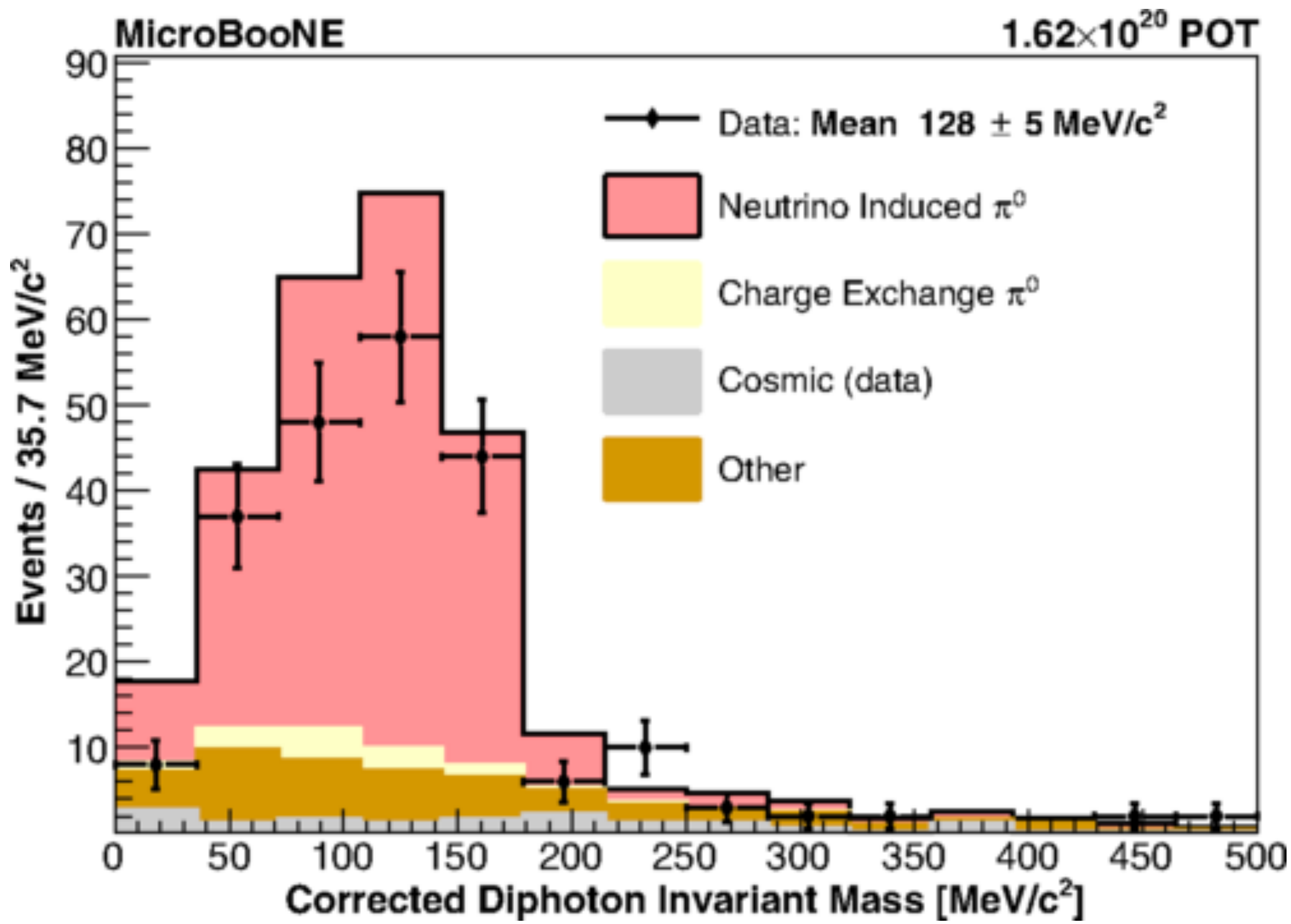


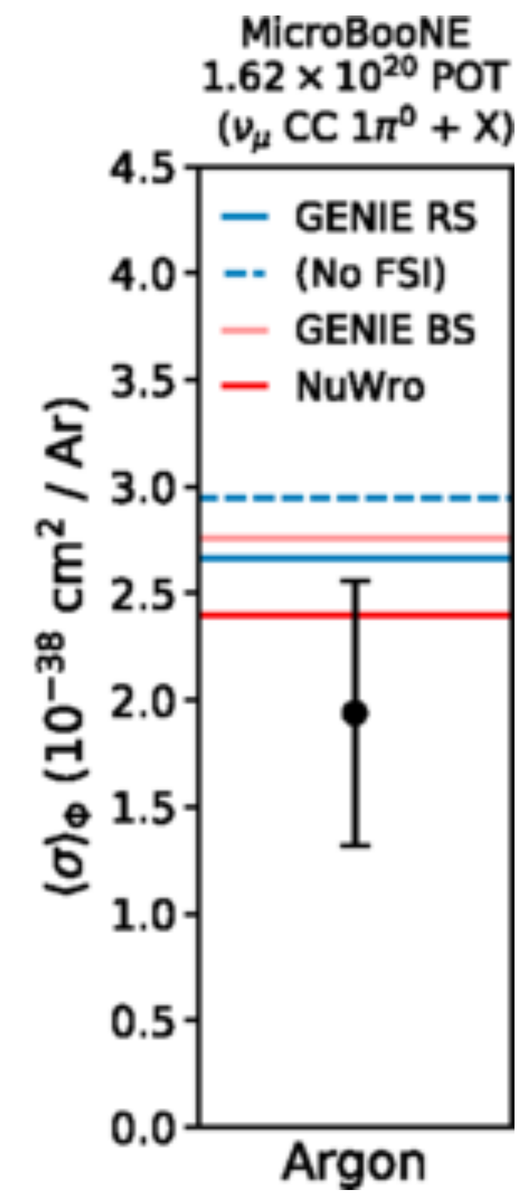
- **Electrons and photons produce showers in LArTPCs** → important to understand for ν_e appearance searches in SBN and DUNE
- π^0 interactions are a background (although often can be distinguished by energy deposition)
  - → **measurement of CCπ^0 production cross section**
  - → **verify shower reconstruction** by reconstructing π^0 mass peak



CCπ⁰ CROSS SECTION MEASUREMENT

Phys. Rev. D 99, 091102(R) (2019)

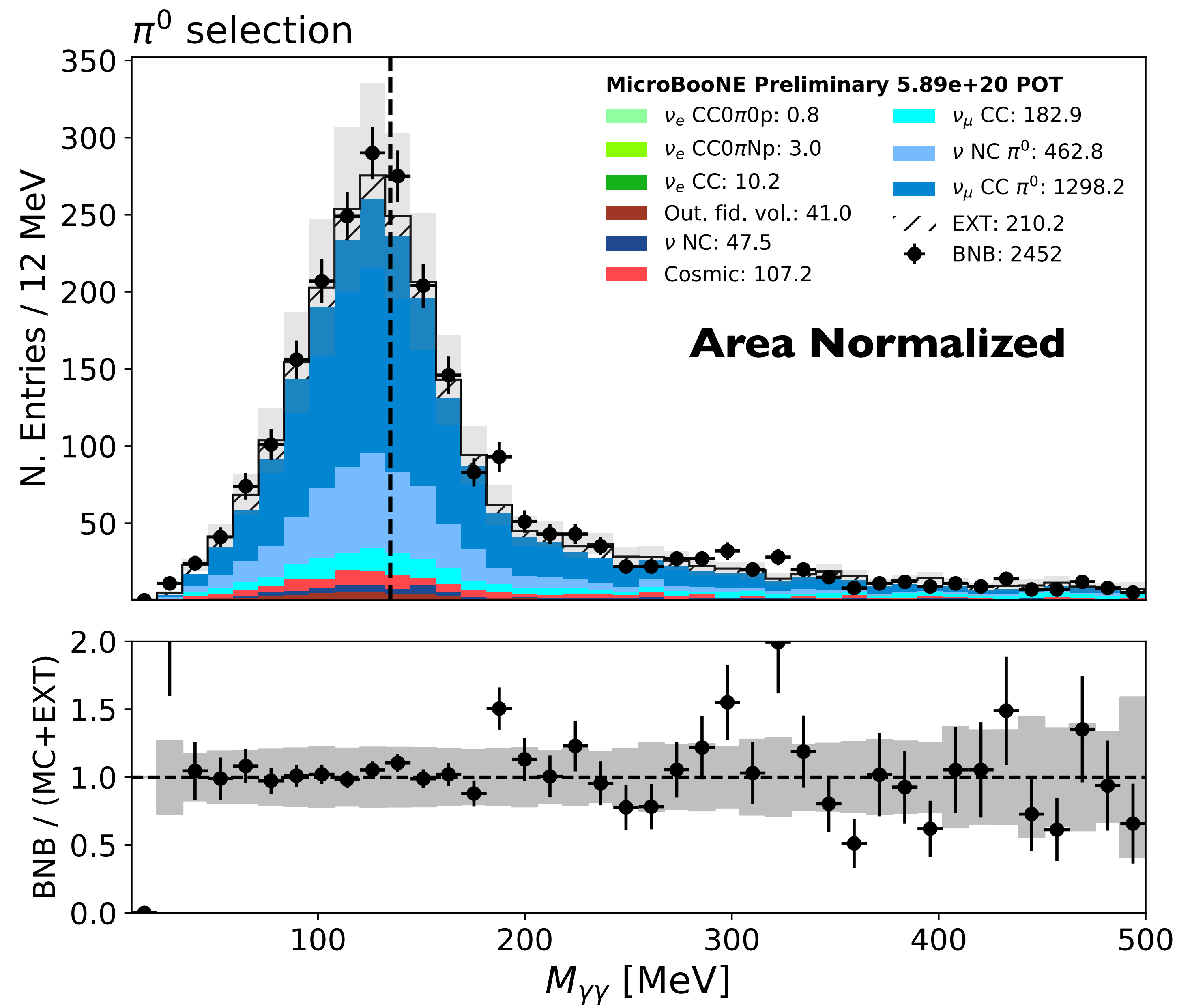




π^0 MEASUREMENTS: FUTURE PROSPECTS

MICROBOONE-NOTE-1085-PUB

- With improvements in detector simulation and reconstruction, current selections have **higher statistics** and **improved resolution**
- Working towards:
  → **Differential CCπ^0** cross section measurement
  → **NCπ^0** cross section measurement
  → **CC/NC** comparisons

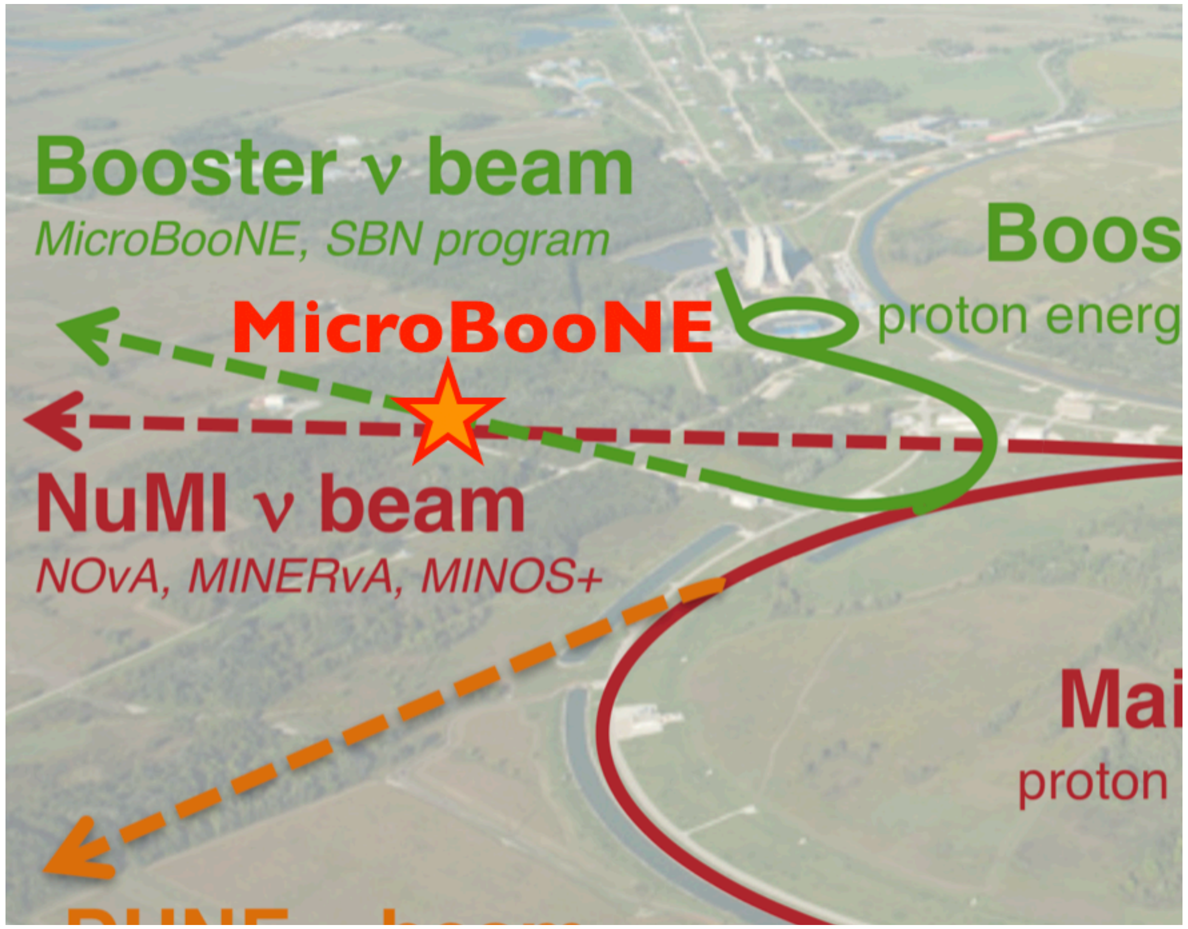


CHANGING TRACK

- Electron neutrinos are hard to study: oscillation experiments' neutrino beams are intentionally mostly ν_μ

- But electron neutrinos are what we want to measure in an oscillation analysis! Important to study and understand

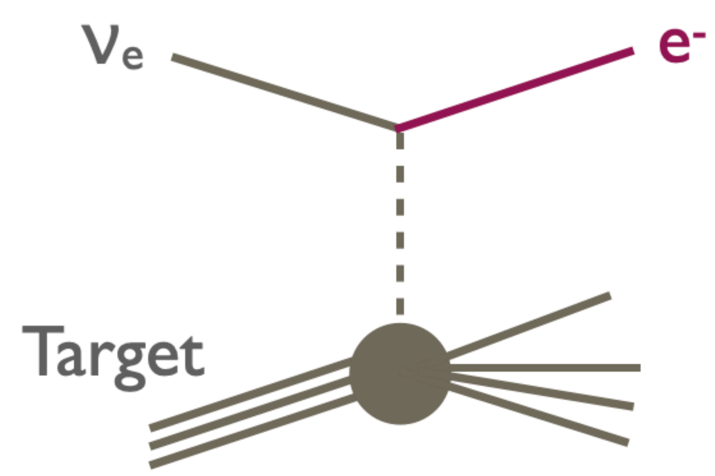
- Off-axis NuMI flux: ~5% ν_e

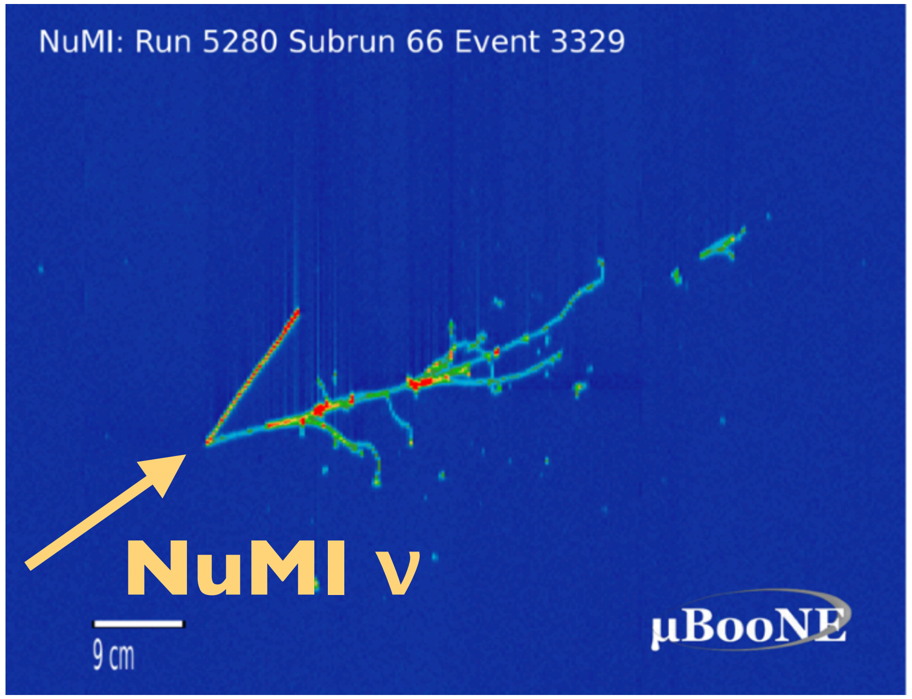


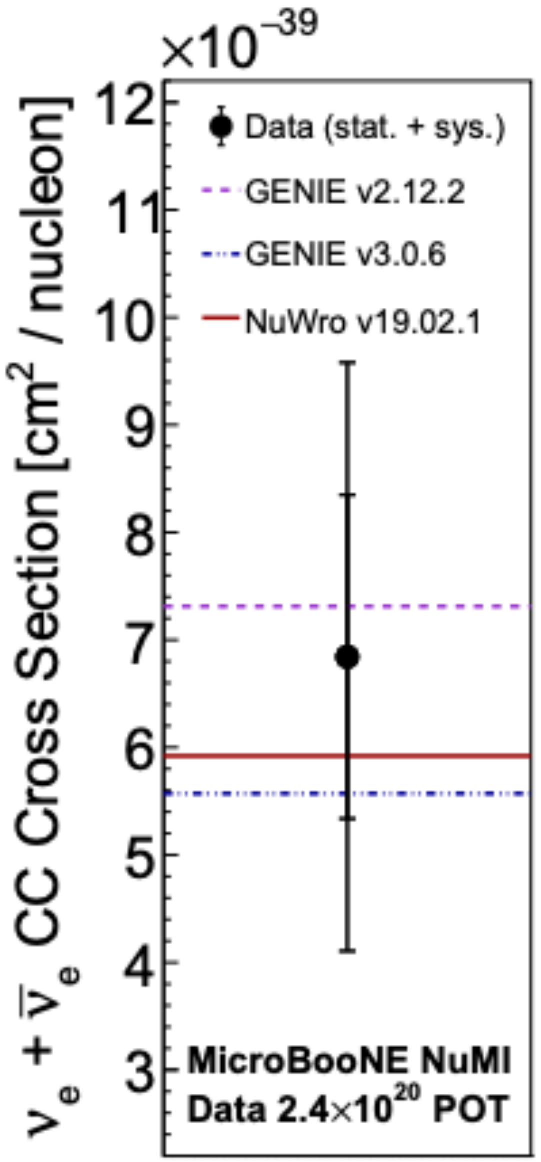
ELECTRON NEUTRINO CROSS SECTION MEASUREMENT

arXiv:2101.04228[hep-ex]

- **ν_e+$\bar{\nu}_e$ inclusive cross-section** measurement with NuMI beam:
  - Purity 40%, efficiency 9%
  - Purity excluding cosmics > 65%
  - →**~214 events** in 2.4x10^{20} POT
- First demonstration of selecting ν_e in a surface LArTPC



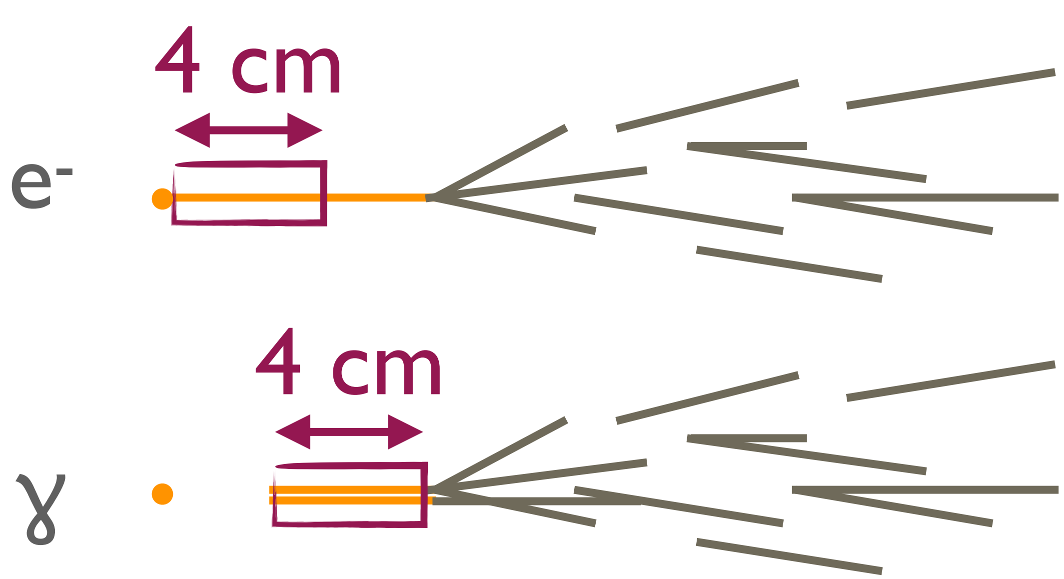


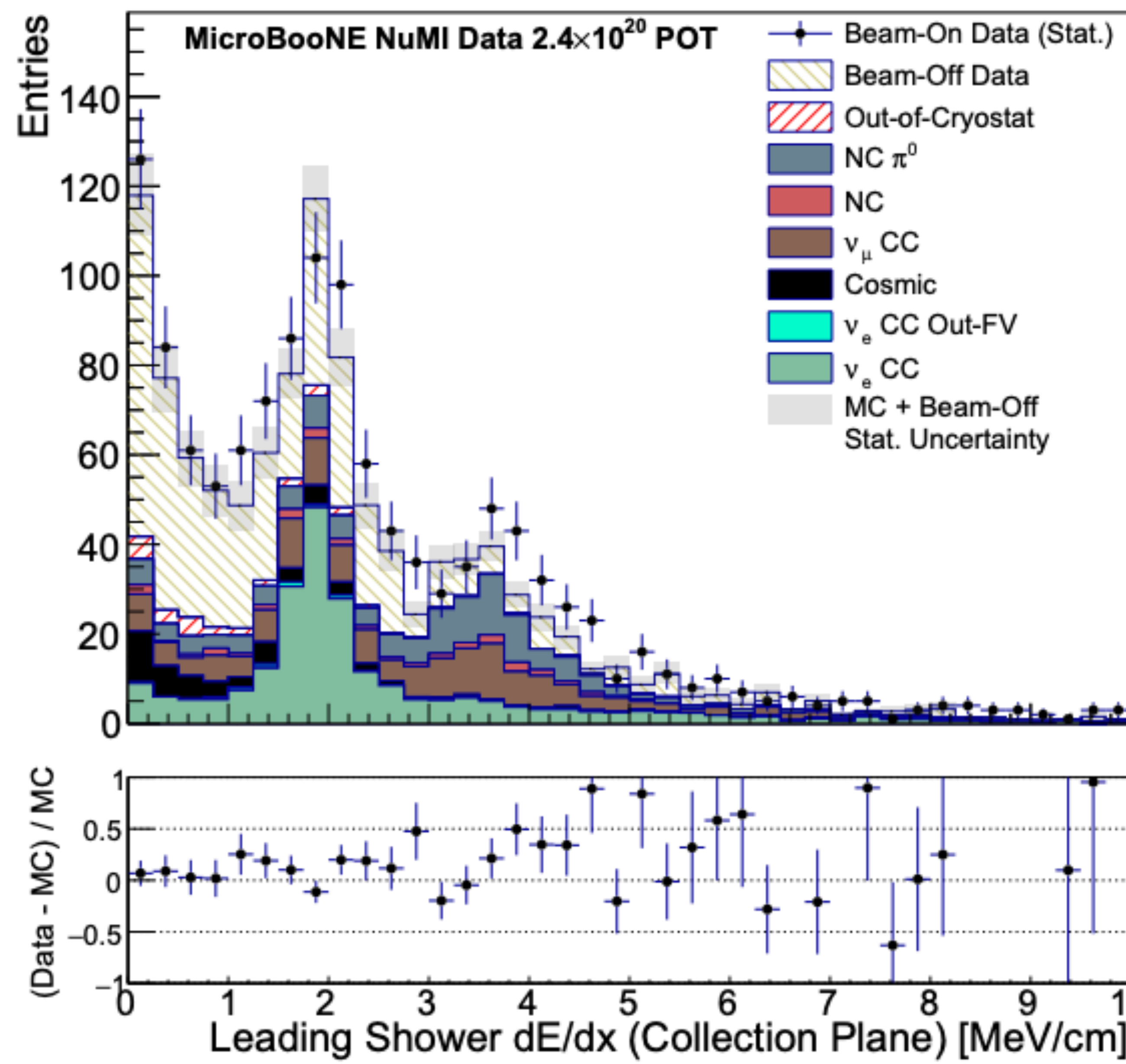


ELECTROMAGNETIC SHOWERS

arXiv:2101.04228[hep-ex]

- Select ν_e by looking for showers
- Distinguish from photons using dE/dx at start of shower
- One of the key capabilities of LAr detectors — in action!



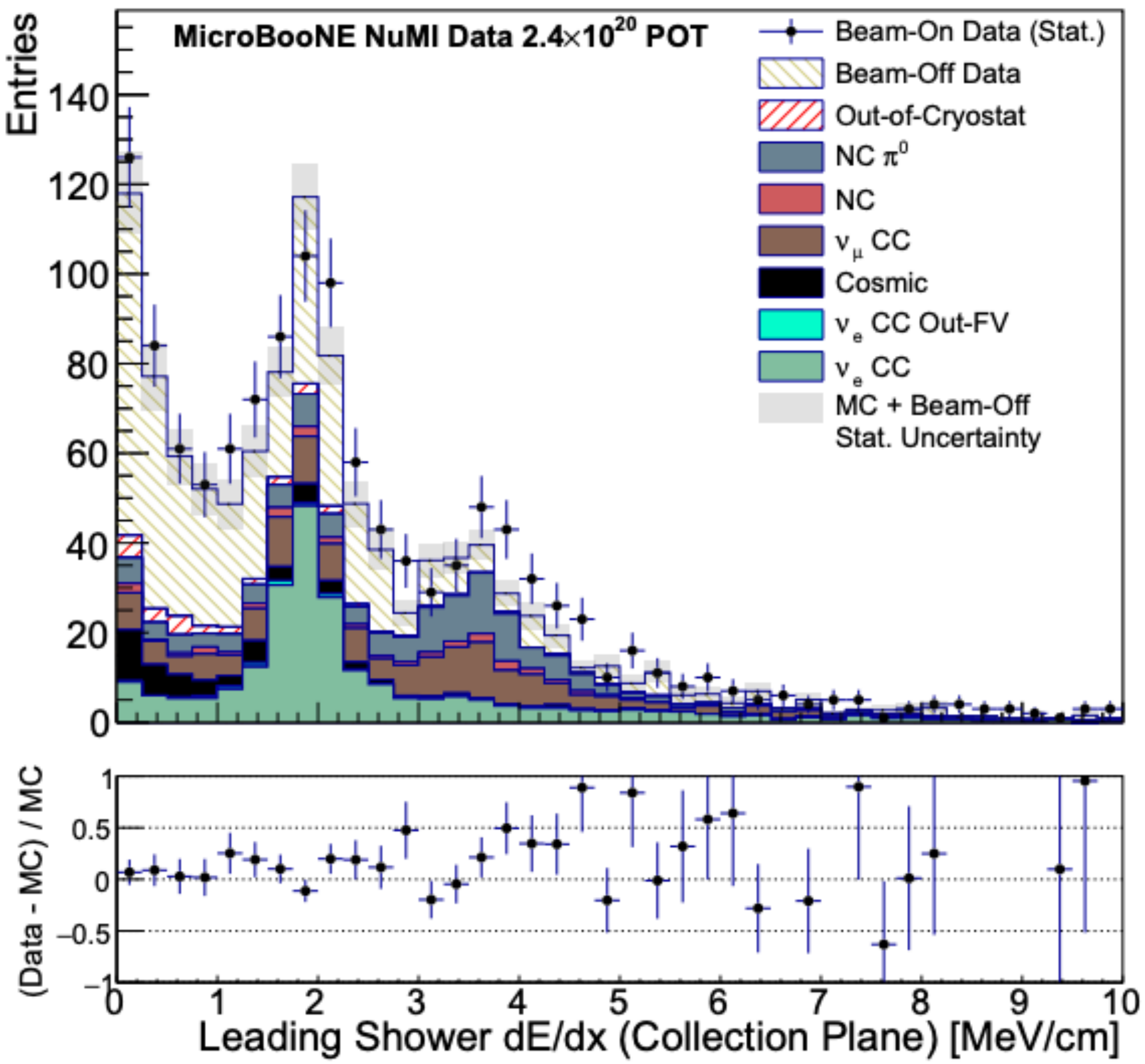


μBooNE

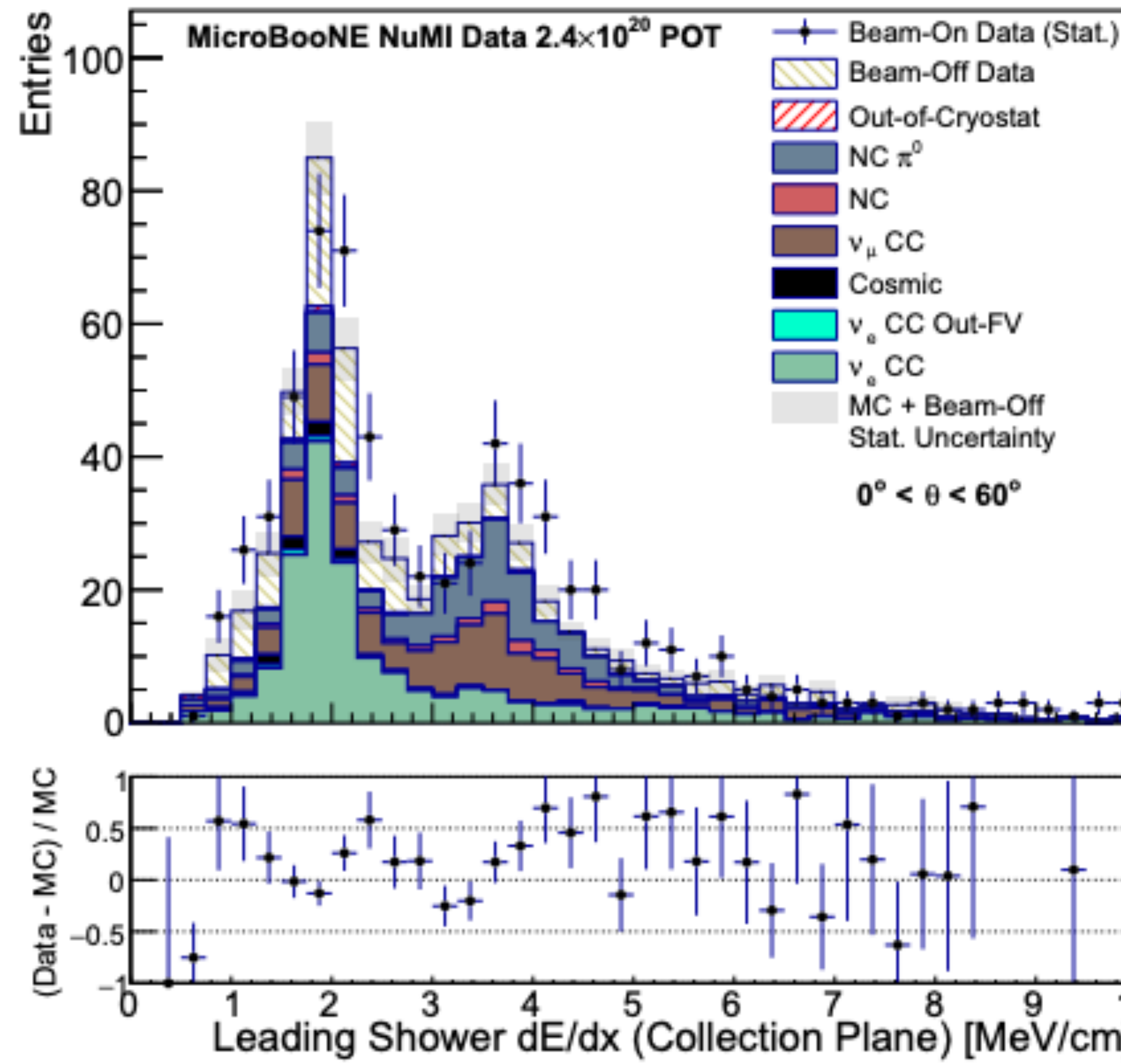
ELECTROMAGNETIC SHOWERS

arXiv:2101.04228[hep-ex]

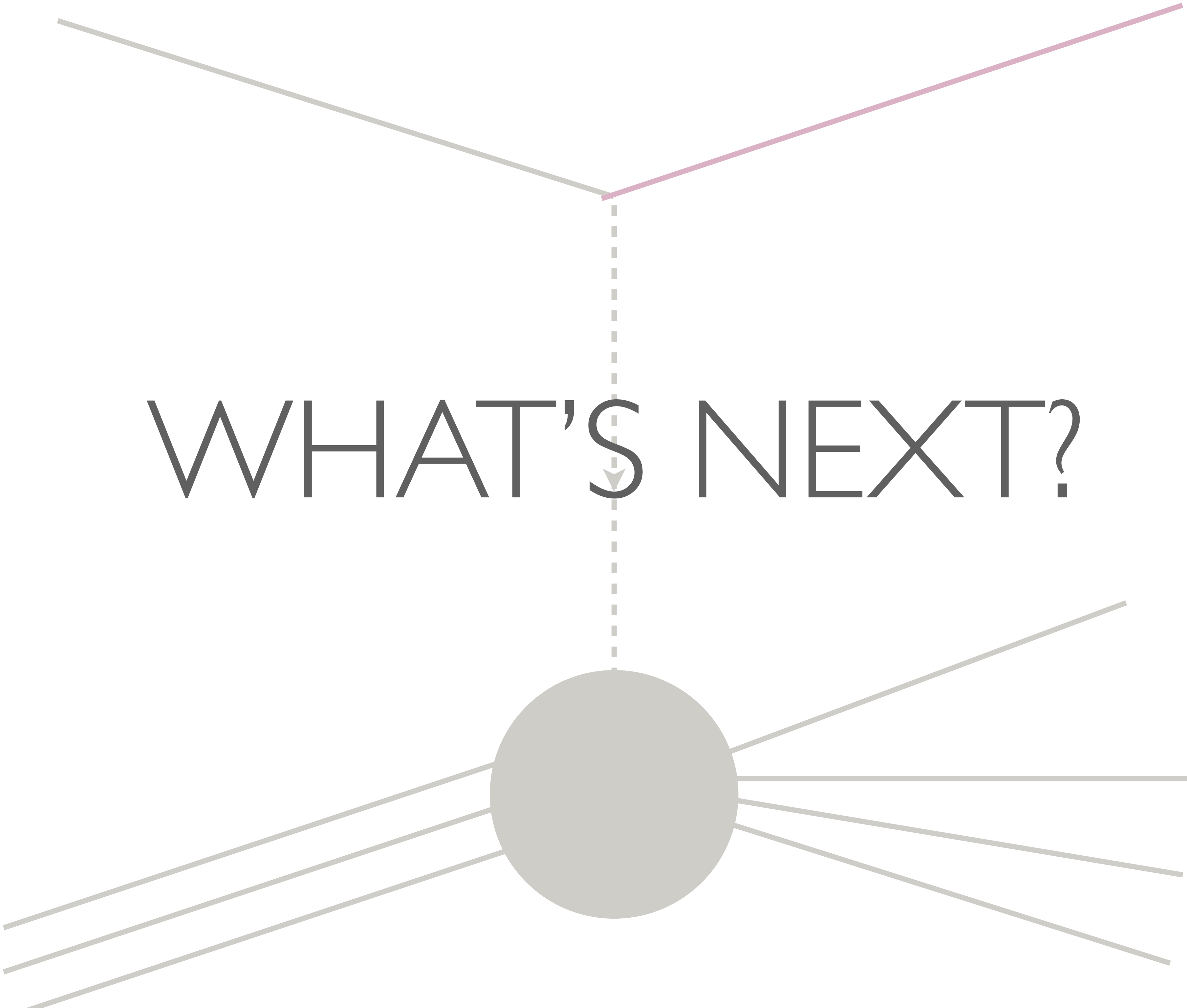
All showers



0 < θ < 60°: Perpendicular to wires

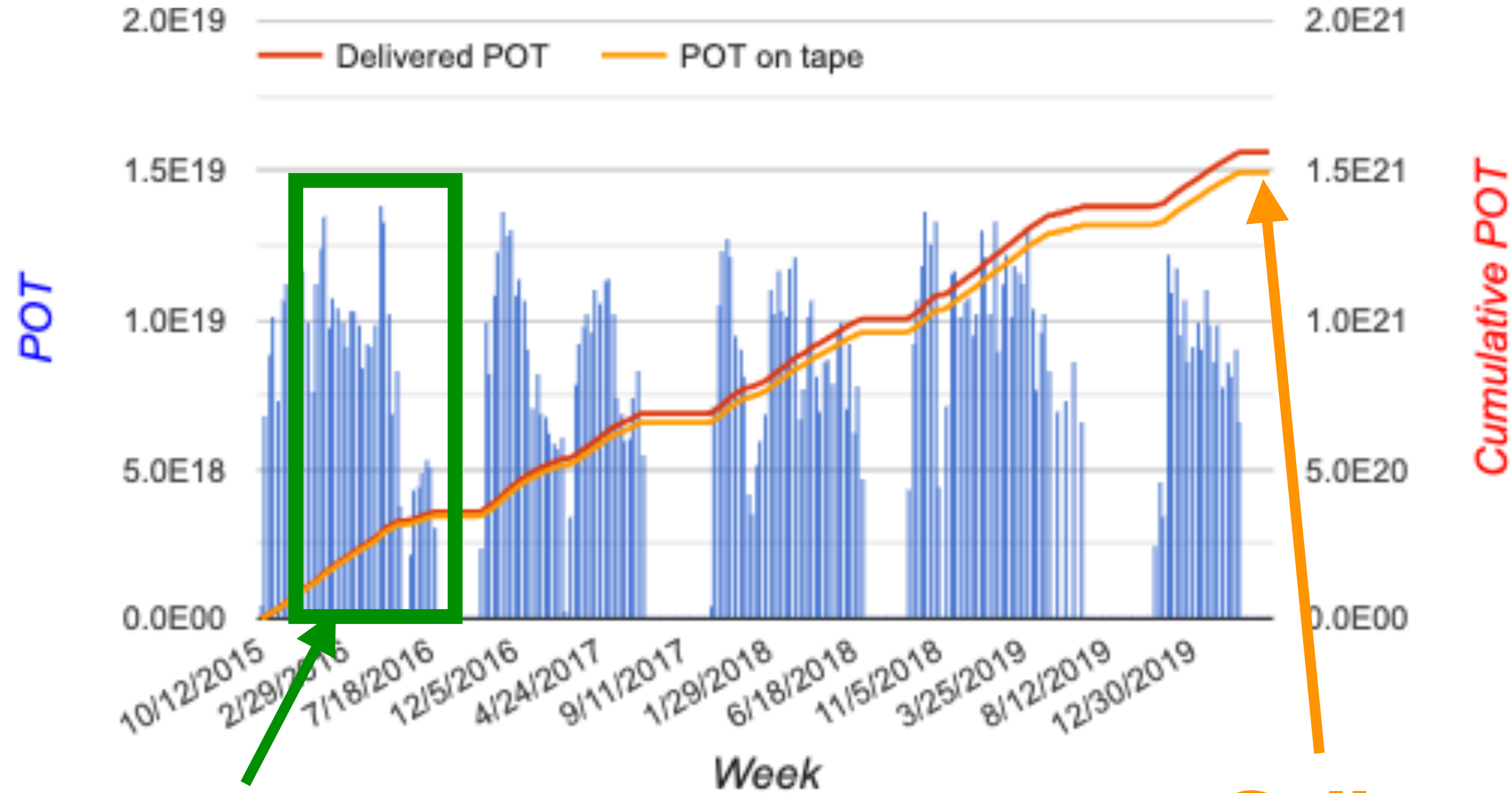


WHAT'S NEXT?



(A LOT) MORE DATA

BNB Data collection: Protons on Target (POT)



These analyses:
~1.6x10^{20} POT
(protons on target)

Collected to date:
1.5x10^{21} POT

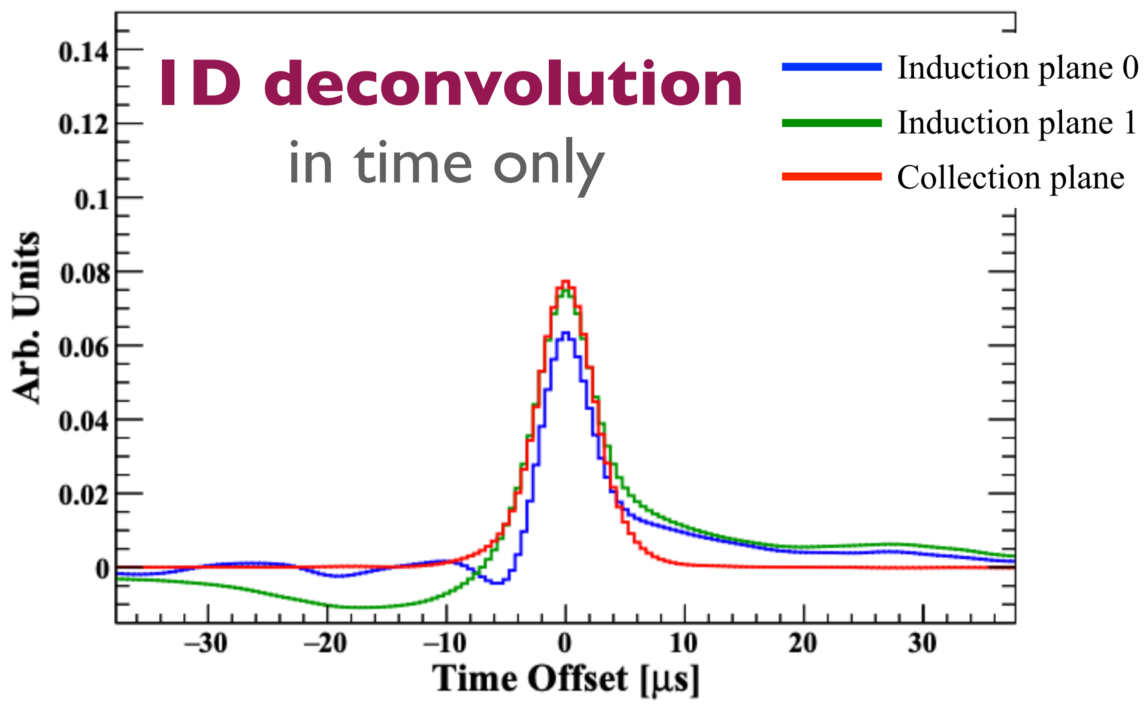
μBooNE

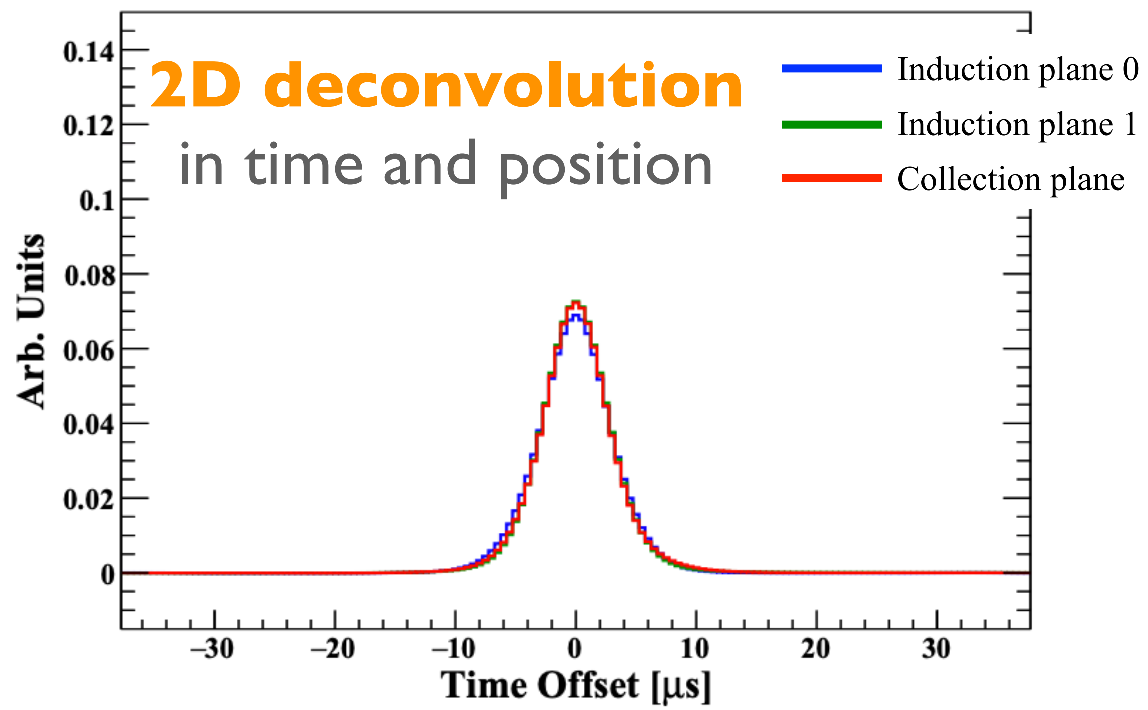
BETTER DATA AND MODELING

JINST 13 P07006 (2018)

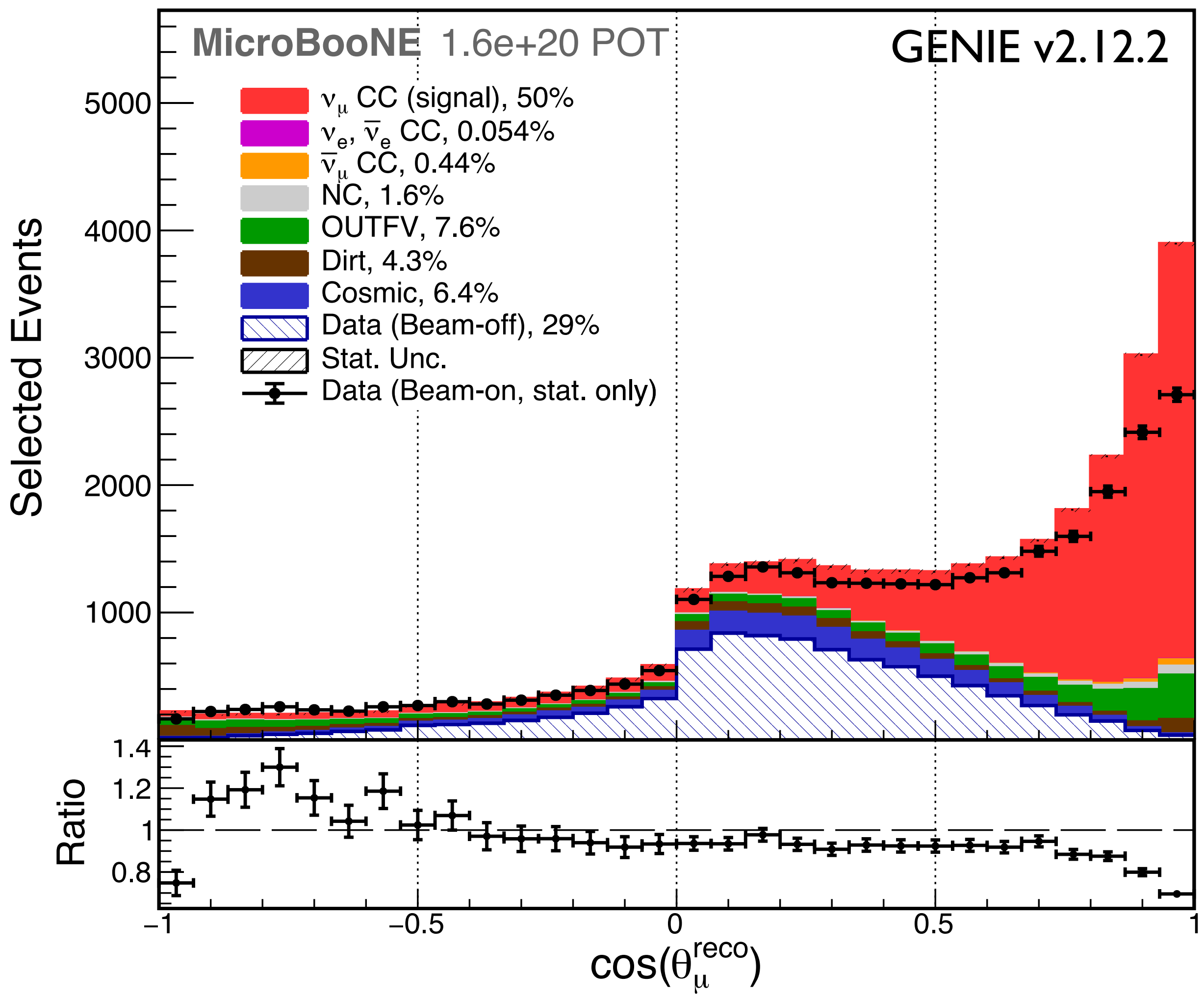
JINST 13 P07007 (2018)

- MicroBooNE Collaboration has made **huge improvements** in our understanding of the detector in the past few years
- Detailed understanding of detector is **key to our R&D mission** for future LAr program
- **Improved signal processing** (2D deconvolution) accounts for interfering wire signals on all three planes
- Tracking is hard when particles go parallel to wires. Precise calorimetry on all planes → 3D tracking → **4π particle identification**





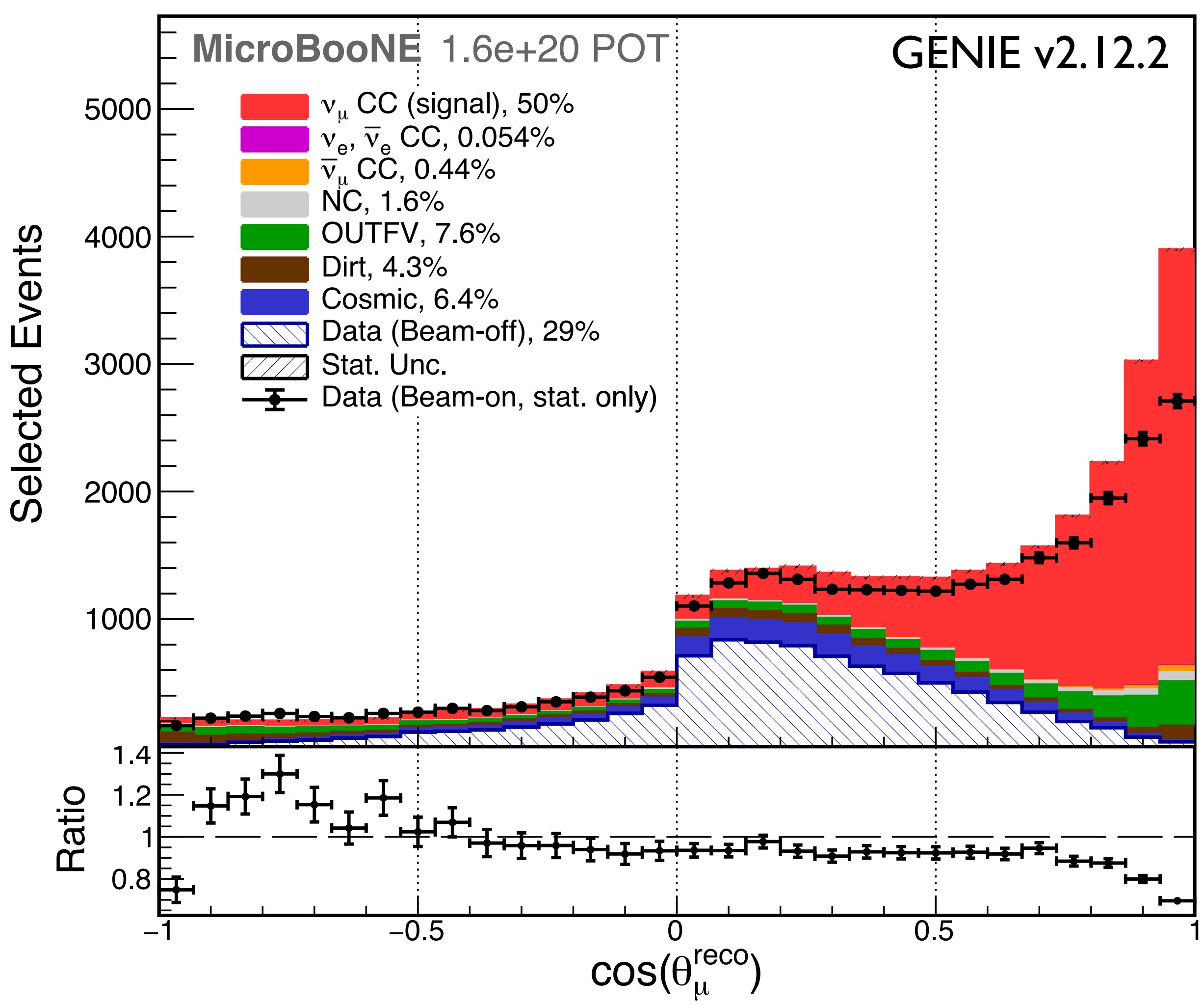
IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS



Previous Measurement

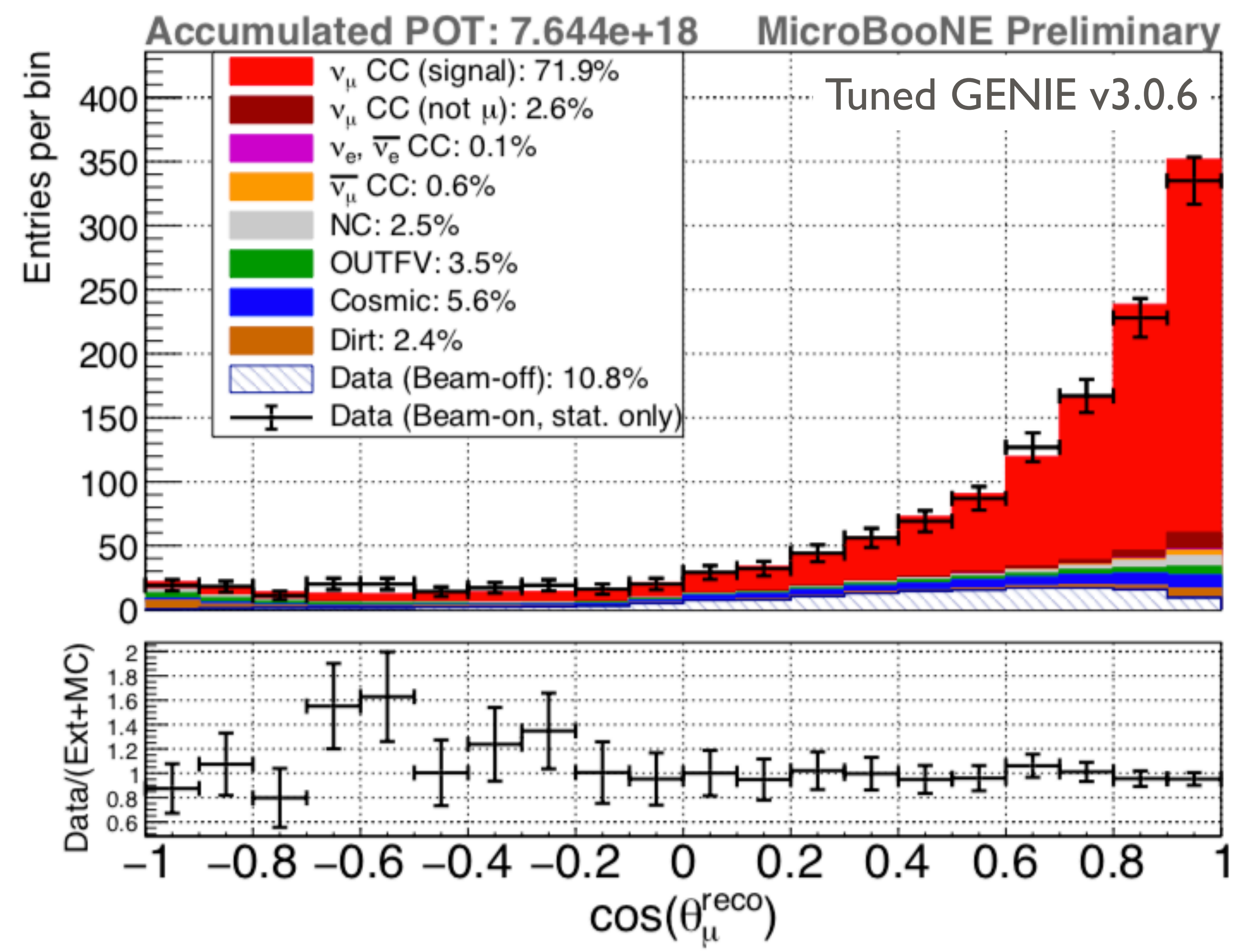
PRL 123, 131801 (2019)

IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS



Previous Measurement

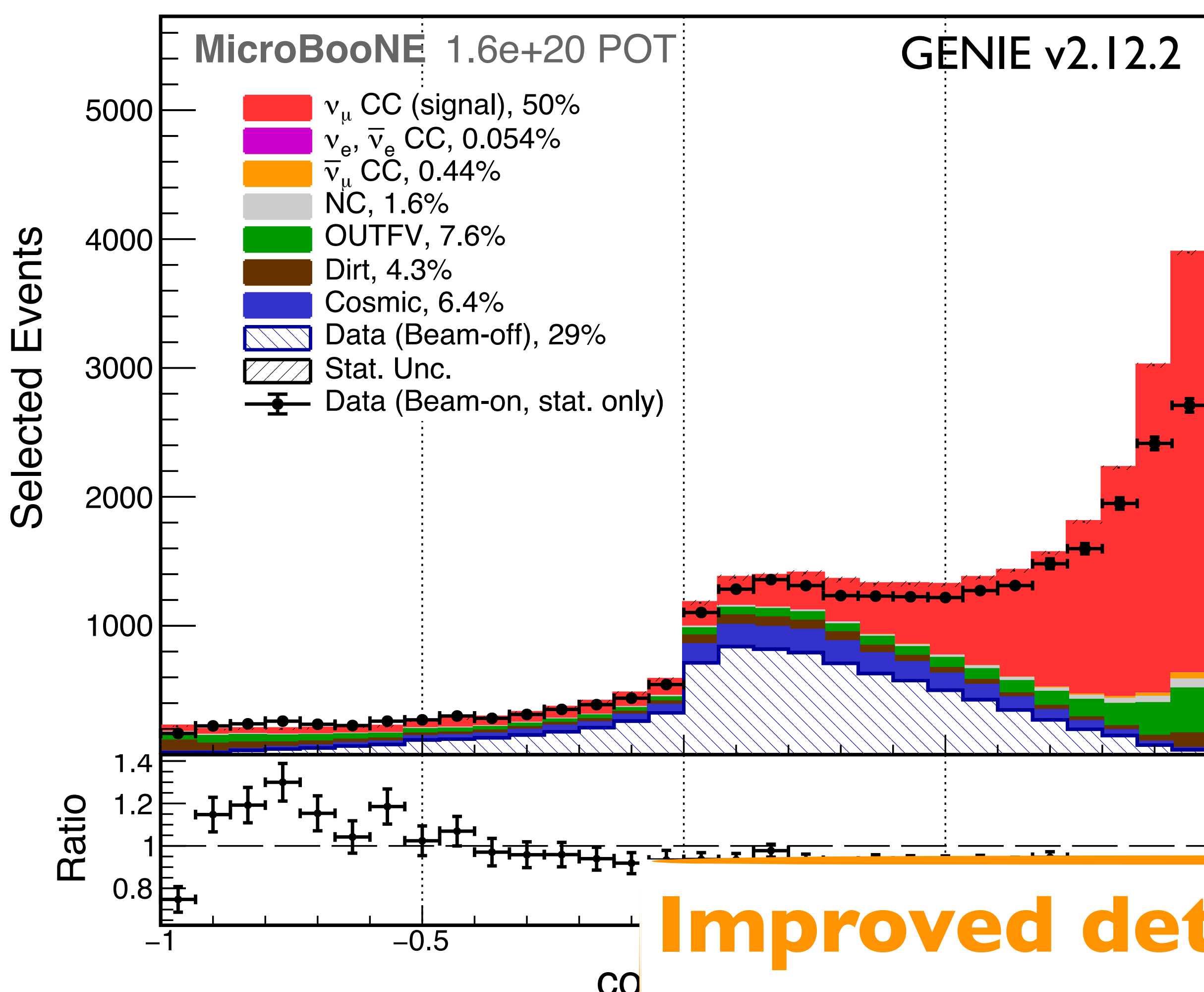
PRL 123, 131801 (2019)

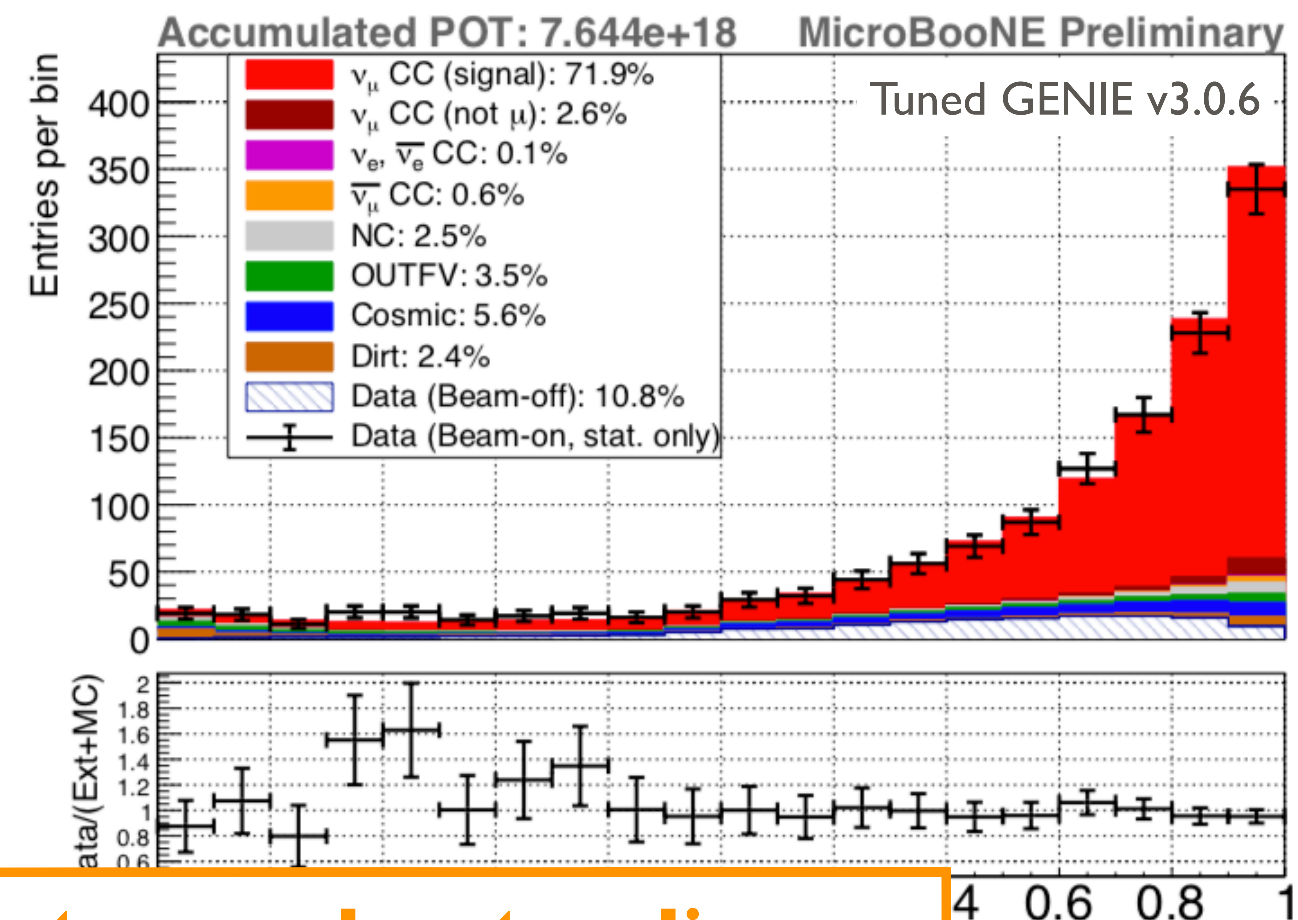


Current Measurement

MICROBOONE-NOTE-1069-PUB

IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS





Previous M… …ent

PRL 123,

Improved detector understanding, reconstruction → higher purity

ν_μCC (signal) purity: 50% → 71.9%

Entering backgrounds: 33.3% → 13.2%

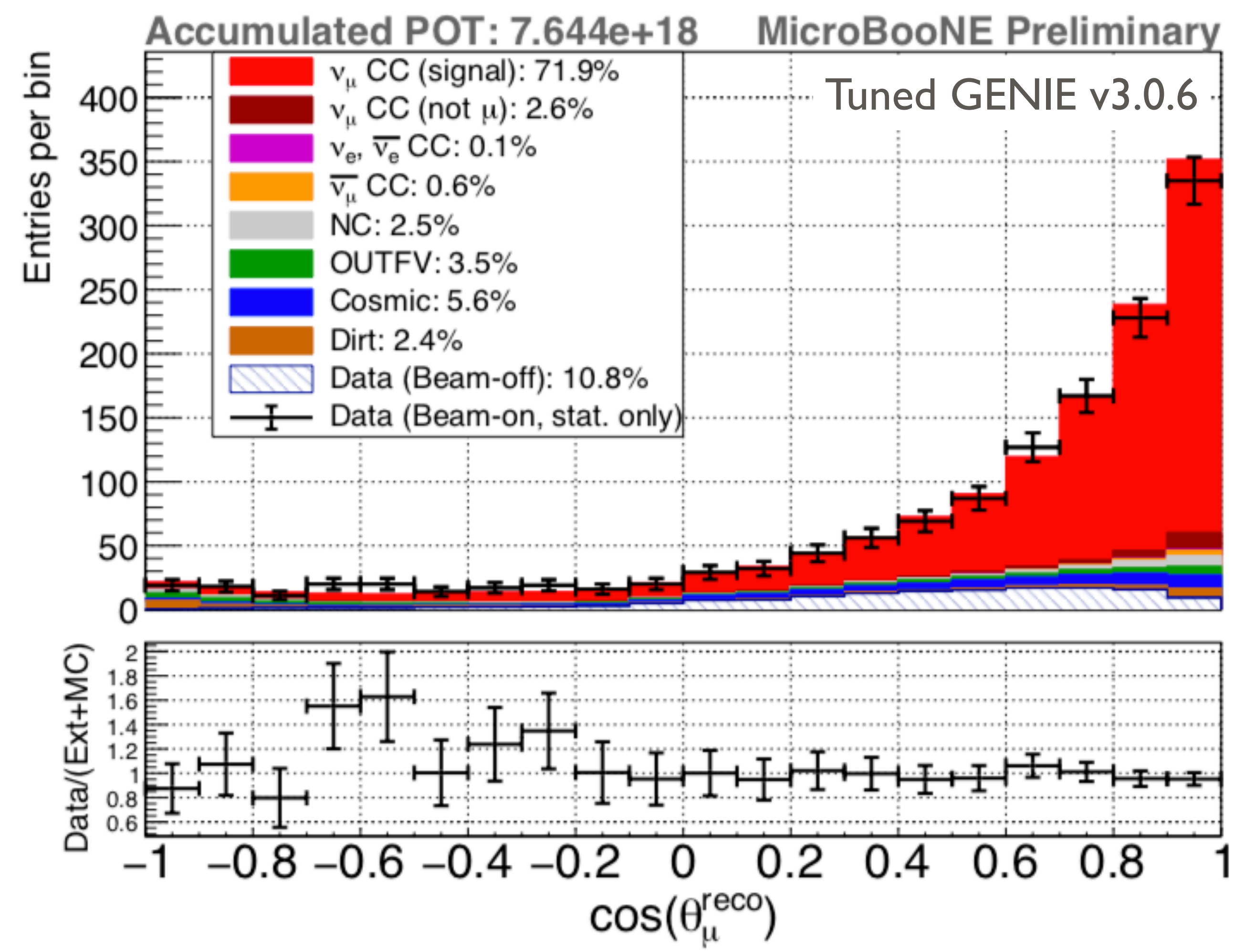
IMPROVED INTERACTION MODELING ENABLES BETTER MEASUREMENTS

Better data-simulation agreement from improved neutrino interaction modeling

- GENIE v2.12.2 → GENIE v3.0.6
- **Tuned** CCQE and CC2p2h models to T2K ν_μ CC0π data
- T2K data is on a carbon target → tuning seems to give **good agreement with MicroBooNE's argon-target data**

PRL 123, 131801 (201

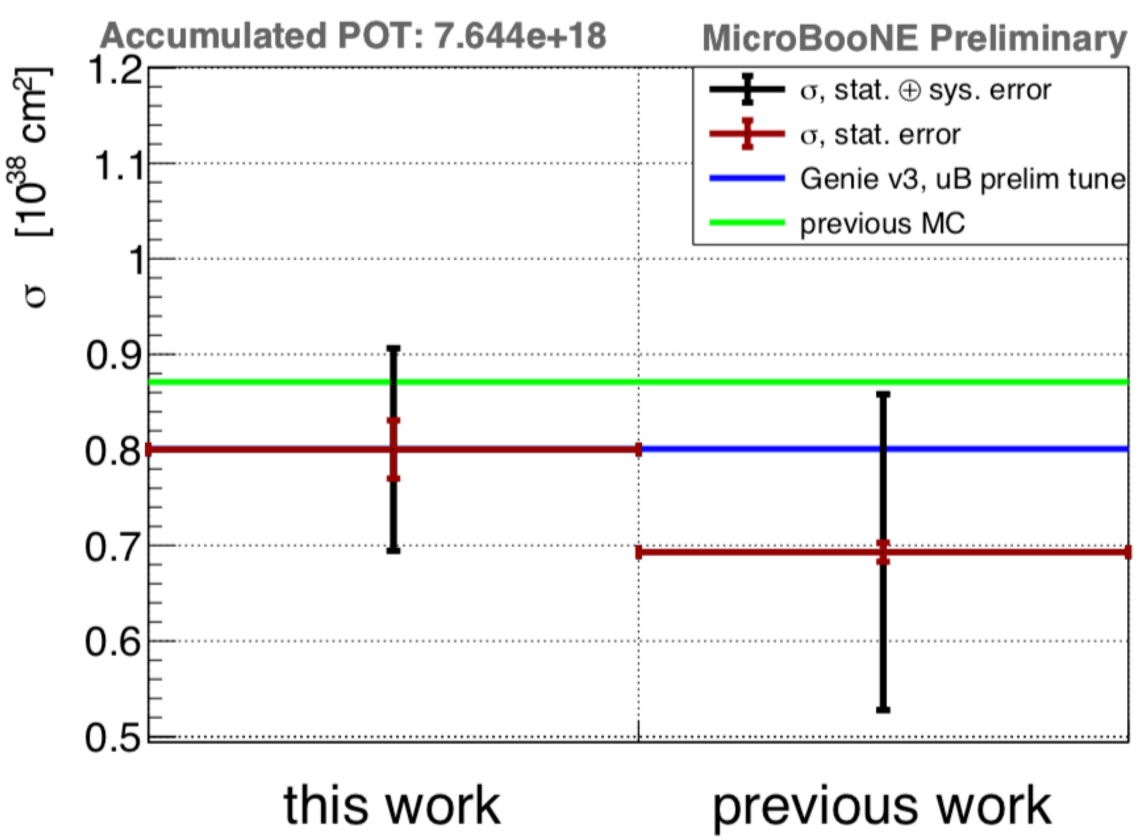
MICROBOONE-NOTE-1074-PUB



GENIE v3.0.6 models used:
QE/2p2h → **J. Nieves, J.E. Amaro, M. Valverde** Phys. Rev. C 70, 055503 (2004) and **R. Gran, J. Nieves, F. Sanchez. M. Vicente-Vacas** Phys. Rev. D 88, 113007 (2013)
RES/COH → **C. Berger, L. Sehgal** Phys. Rev. D 76, 113004 (2007), Phys. Rev. D 79, 053003 (2009)
FSI → work by **L. Salcedo, E. Oset, M. Vicente-Vacas, C. Garcia-Recio** Nucl. Phys. A 484, 557-592 (1988) and **V. Pandharipande, S.C. Pieper** Phys. Rev. C 45, 791-798 (1992)

DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1075-PUB , MICROBOONE-NOTE-1069-PUB



Flux-integrated cross section **consistent with previous measurement**

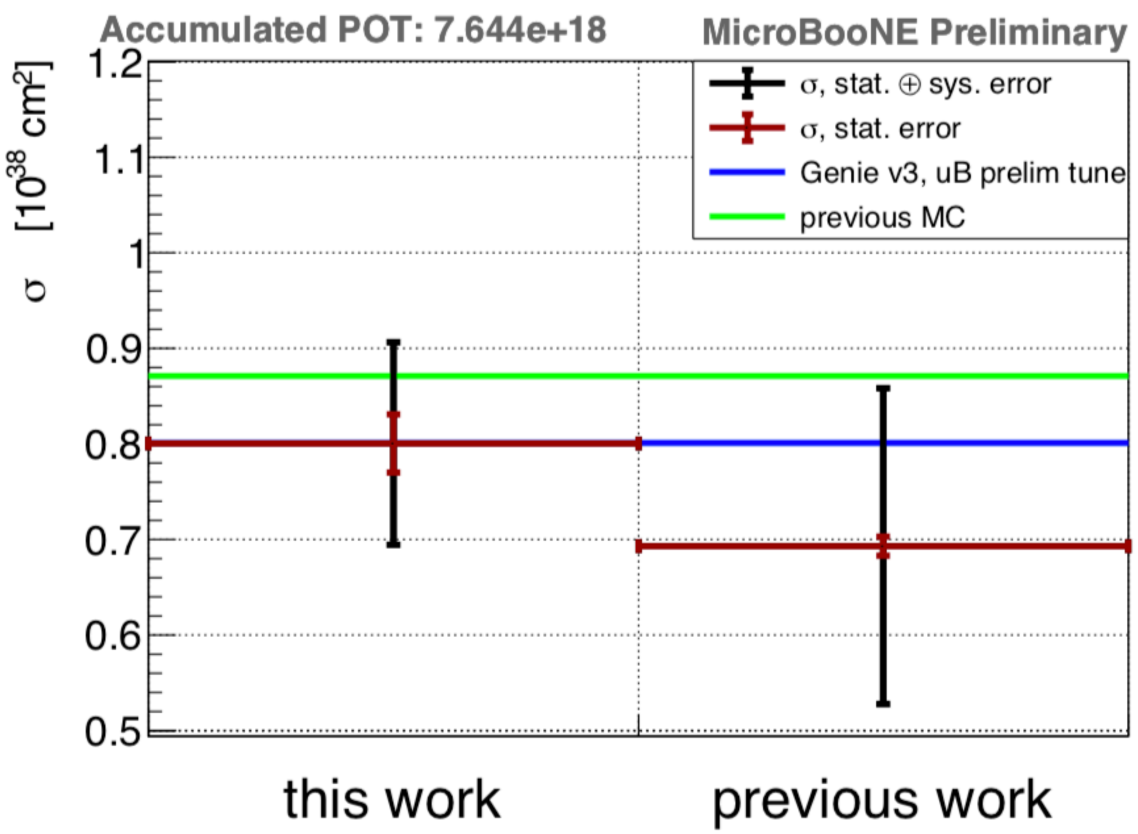
Drastically reduced systematic uncertainties

Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	-
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

PRL 123, 131801 (2019)

DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1075-PUB MICROBOONE-NOTE-1069-PUB



Flux-integrated cross section **consistent with previous measurement**

Drastically reduced systematic uncertainties

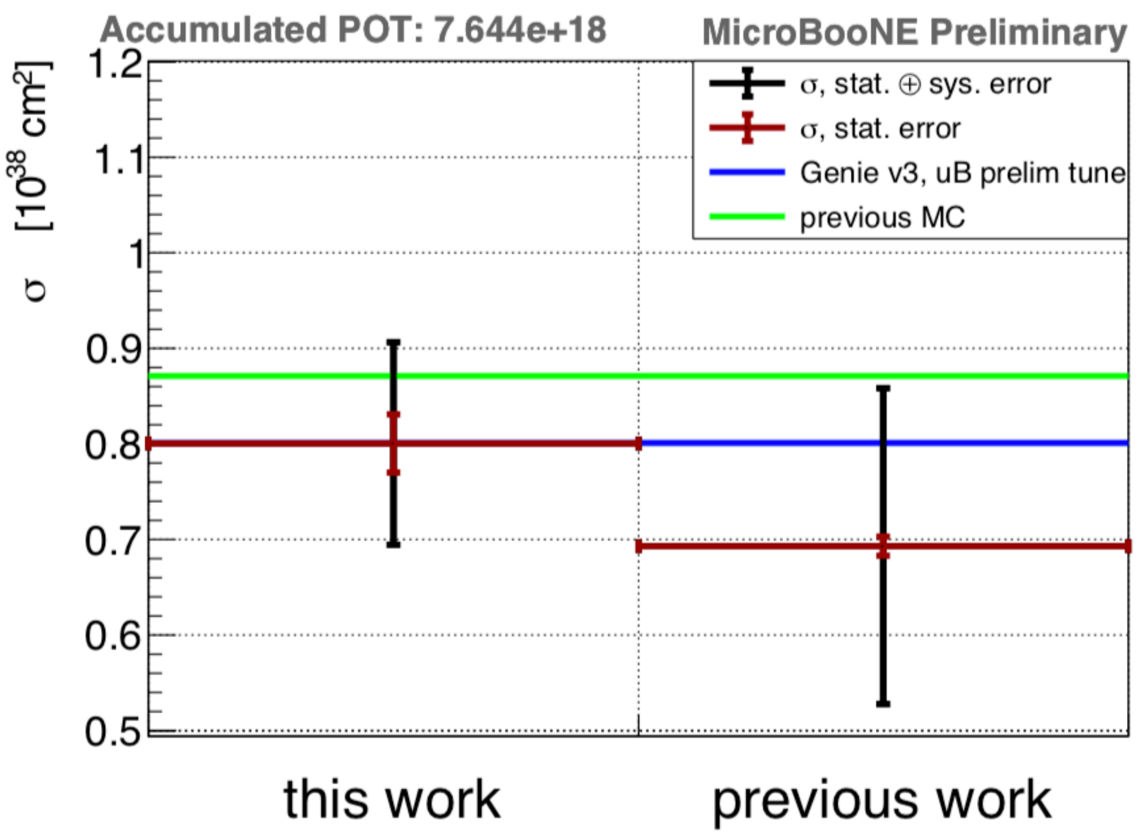
Largest reduction in uncertainties comes from improved detector understanding

Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	-
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

PRL 123, 131801 (2019)

DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1075-PUB , MICROBOONE-NOTE-1069-PUB



Flux-integrated cross section **consistent with previous measurement**

Drastically reduced systematic uncertainties

Instead of cosmic ray simulation, now use overlay: simulated neutrino interactions overlaid on real cosmic data → no uncertainty in cosmic ray model

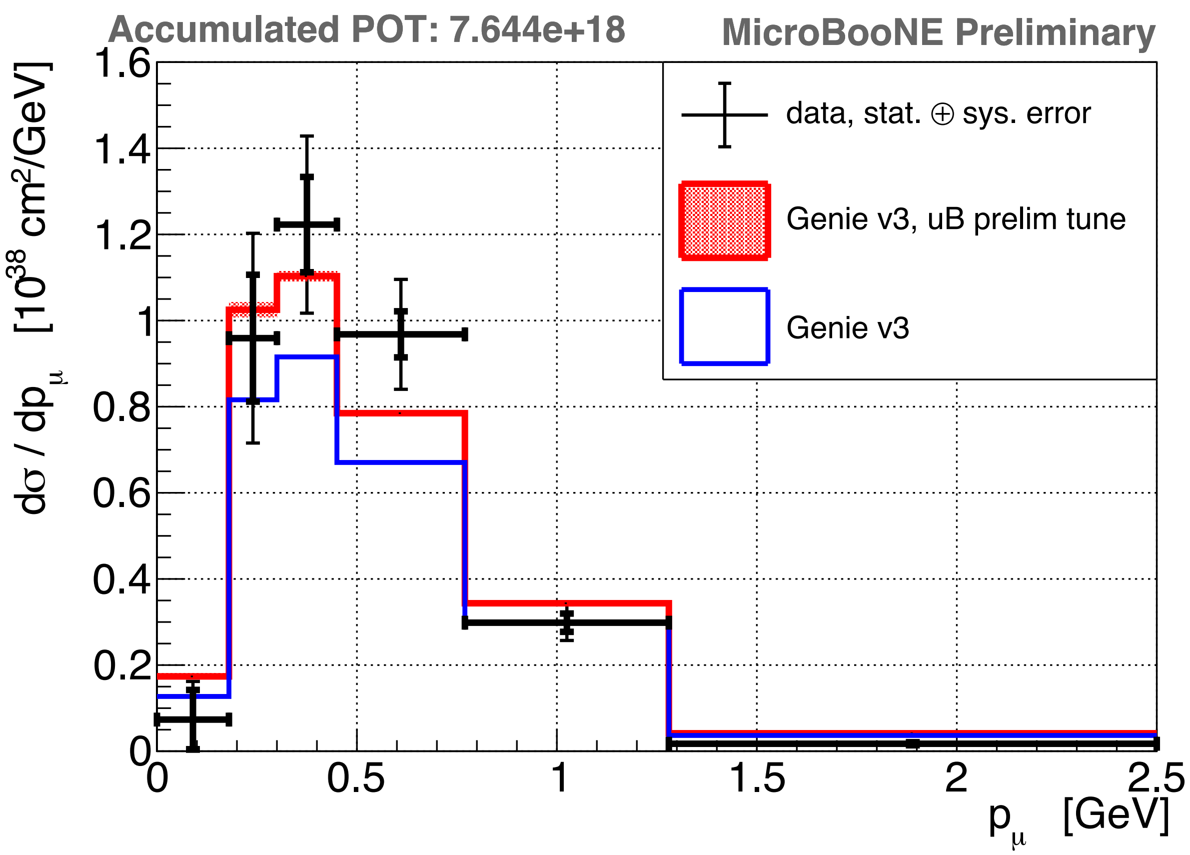
Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	-
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

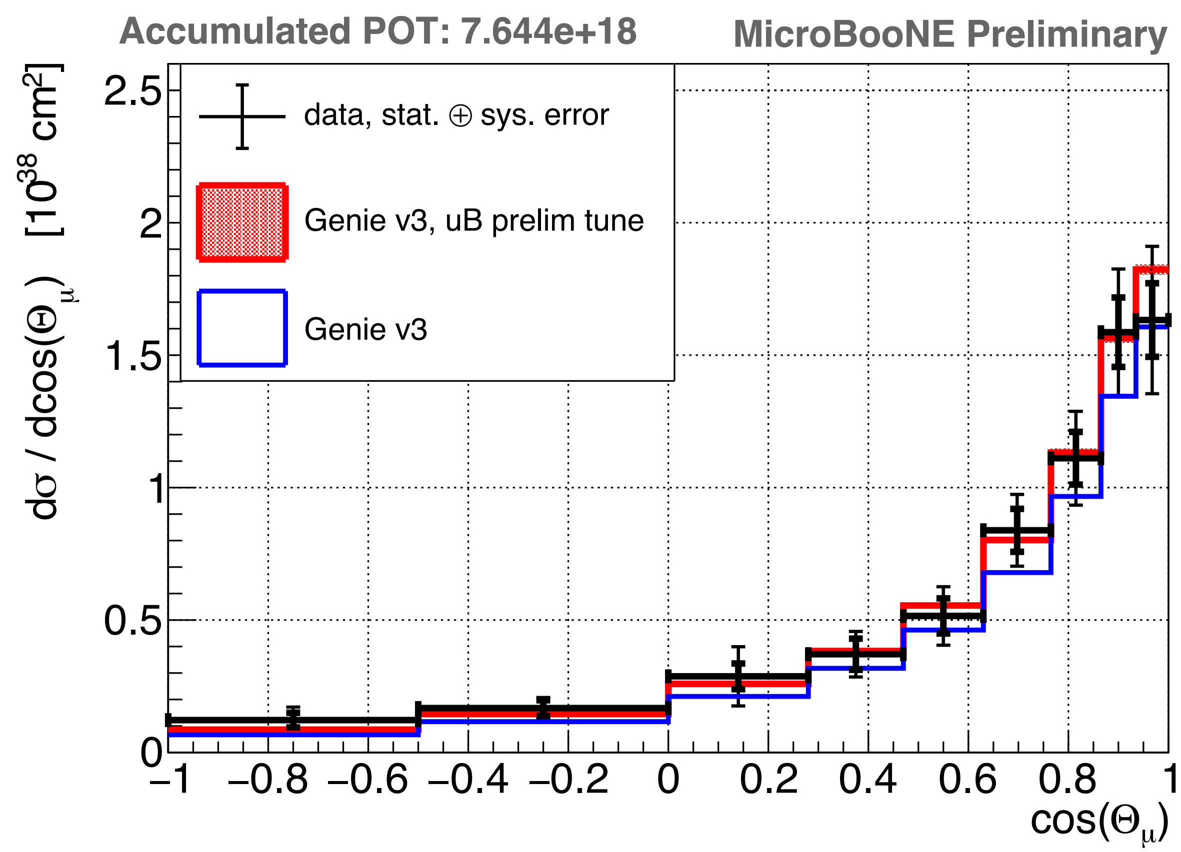
PRL 123, 131801 (2019)

µBooNE

IMPROVED CROSS SECTION MEASUREMENT

MICROBOONE-NOTE-1074-PUB MICROBOONE-NOTE-1075-PUB MICROBOONE-NOTE-1069-PUB





Single-differential cross section as a function of reconstructed muon momentum and angle → **very good agreement with previous measurement,** but **reduced uncertainties**

Future development towards **double-differential** cross-section measurement

Many measurements of ν-Ar scattering

- ν_μ CC inclusive cross section

Single-differential cross section
Phys. Rev. Lett. 108 161802 (2012)

Updated single-differential cross section
Phys. Rev. D 89, 112003 (2014)

- ν_μ exclusive channels

ν_μ and $\bar{\nu}_\mu$ NCπ^0 production
Phys. Rev. D 96, 012006 (2017)

ν_μ and $\bar{\nu}_\mu$ CCπ^+ production
Phys. Rev. D 98, 052002 (2018)

ν_μ and $\bar{\nu}_\mu$ Coherent CCπ^+ production
Phys. Rev. Lett. 113, 261801 (2014)

ν_μ and $\bar{\nu}_\mu$ CC2p production
Phys. Rev. D 90, 012008 (2014)

- Other measurements

Many measurements of ν-Ar scattering

- ν_μ CC inclusive cross section

ArgoNeuT: Single-differential cross section
Phys. Rev. Lett. 108 161802 (2012)

ArgoNeuT: Updated single-differential cross section
Phys. Rev. D 89, 112003 (2014)

MicroBooNE: Double-differential cross section
Phys. Rev. Lett. 123, 131801 (2019)

MicroBooNE: Single-differential cross section with updated detector and interaction models
MICROBOONE-NOTE-1069-PUB

- ν_μ exclusive channels

MicroBooNE: Charged-particle multiplicity
Eur. Phys. J. C79, 248 (2019)

MicroBooNE: ν_μ CCQE-like scattering Eur. Phys. J. C 79 673 (2019)
Phys. Rev. Lett. 125, 201803 (2020)

MicroBooNE: ν_μ CC0πNp (N≥1) scattering
Phys. Rev. D 102, 112013 (2020)

ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ CC2p production
Phys. Rev. D 90, 012008 (2014)

MicroBooNE: ν_μ CCπ^0 production
Phys. Rev. D99, 091102(R) (2019)

ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ NCπ^0 production
Phys. Rev. D 96, 012006 (2017)

ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ CCπ^+ production
Phys. Rev. D 98, 052002 (2018)

ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ Coherent CCπ^+ production
Phys. Rev. Lett. 113, 261801 (2014)

MicroBooNE: ν_μ CC kaon production
MICROBOONE-NOTE-1071-PUB

MicroBooNE: ν_μ NC 1p production
MICROBOONE-NOTE-1067-PUB

- Other measurements

ArgoNeuT: ν_e and $\bar{\nu}_e$ scattering (inclusive)
Phys. Rev. D 102, 011101(R) (2020)

MicroBooNE: ν_e and $\bar{\nu}_e$ total cross section (inclusive)
arXiv:2101.04228[hep-ex]

ArgoNeuT: MeV-scale physics Phys. Rev. D 99, 012002 (2019)

MicroBooNE: MeV-scale physics
MICROBOONE-NOTE-1076-PUB

ArgoNeuT: Limits on millicharged particles
Phys. Rev. Lett. 124, 131801 (2020)

MORE MEASUREMENTS!

A **large number** of **new measurements** are in progress, including:

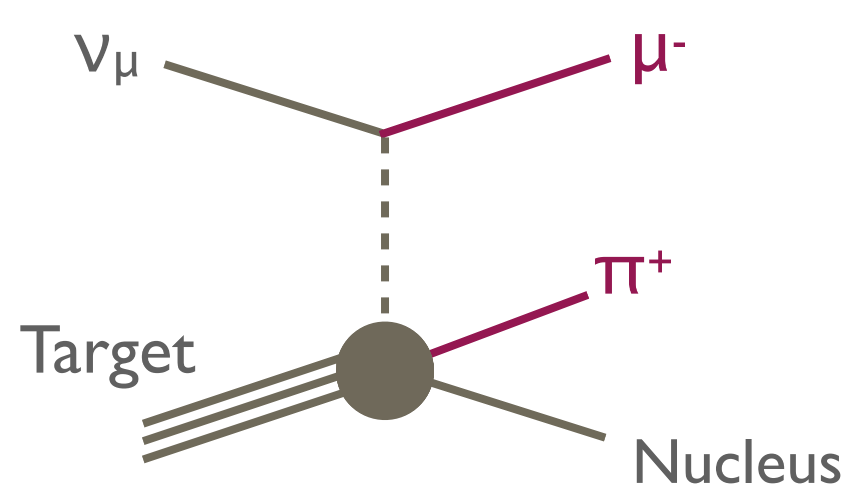
- ν_μ CC $0\pi2p$
- ν_μ CC $0\pi Np$ transverse variables
- ν_μ CC $0\pi1p$ transverse variables
- ν_μ CC π^0 (update)
- ν_μ CC $1\pi^+$
- ν_μ CC-Coherent $1\pi^+$
- ν_μ NC π^0
- ν_μ NC 1γ
- ν_μ CC $0\pi0p$
- ν_μ CC inclusive (update)
- ν_μ CC inclusive hadronic energy
- ν_μ NC Elastic p
- ν_μ CC $1K^\pm$
- ν_μ hyperon production
- ν_μ CC eta production
- KDAR ν_μ
- ν_e CC inclusive (update)
- ν_e CC $0\pi Np$

MORE MEASUREMENTS!

A **large number** of **new measurements** are in progress, including:

- ν_μ CC 0π2p
- ν_μ CC 0πNp transverse variables
- ν_μ CC 0π1p transverse variables
- ν_μ CC π^0 (update)
- ν_μ CC 1π^+
- ν_μ CC-Coherent 1π^+
- ν_μ NC π^0
- ν_μ NC 1γ
- ν_μ CC 0π0p
- ν_e CC 0πNp

- Charged pions → dominant interaction modes at DUNE



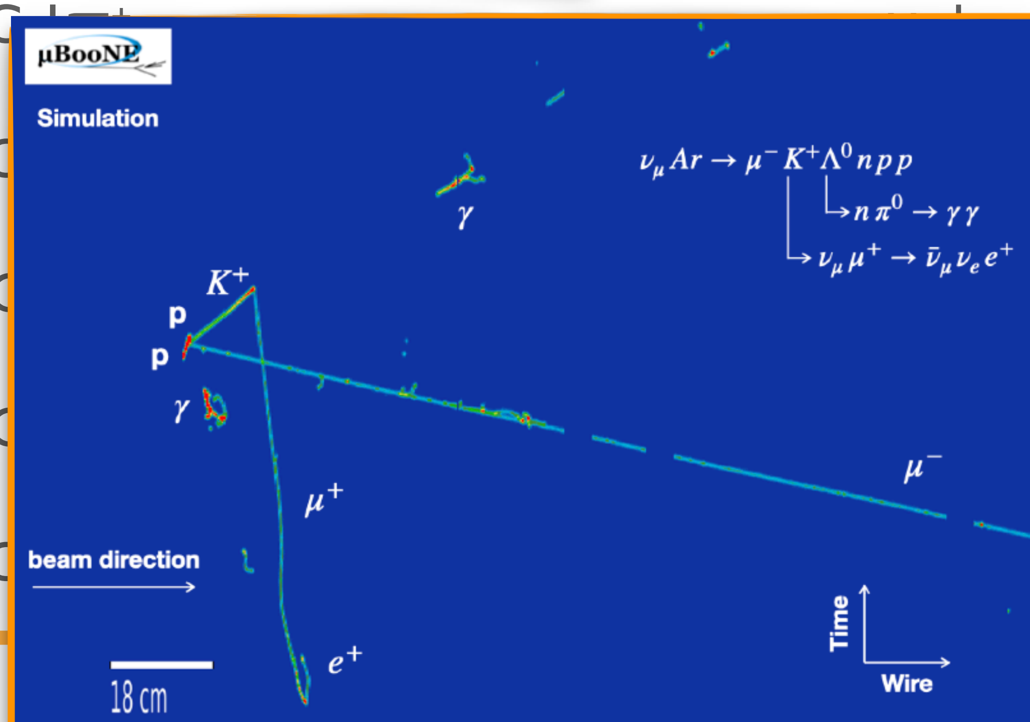
- Development work focused on distinguishing charged pions from muons

MORE MEASUREMENTS!

- Rare interactions: charged kaon production
- Very little world data
- Background to proton decay search at DUNE: $p \rightarrow K^+\nu$

A… **…easurements** are in progress, including:

- ν_μ CC inclusive (update)
- …les
- ν_μ CC inclusive hadronic energy
- …es
- ν_μ NC Elastic p
- ν_μ CC 1$K^\pm$
- ν_μ CC…
- …eron production
- ν_μ CC…
- …eta production
- ν_μ NC…
- ν_μ
- ν_μ NC…
- …inclusive (update)
- ν_μ CC…
- …0πNp

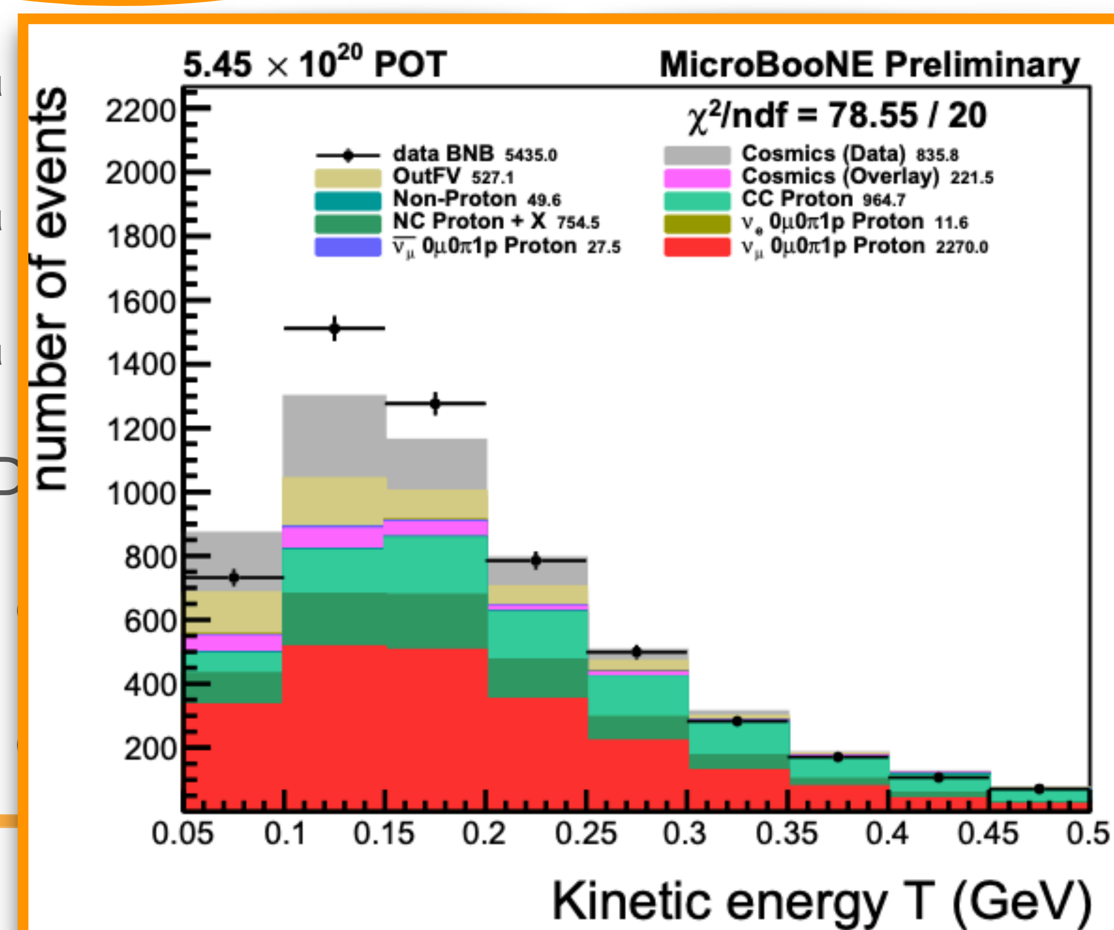


- Signal: single, isolated proton
- Already have an NC1p selection and preliminary cross section extraction
- Select events with $Q^2 \sim 2m_pT_p$ = 0.1 GeV^2, **significantly lower** than previous measurements
- Future development towards **NC elastic scattering** cross section → measure strange component of neutral-current axial form factor

EMENTS!

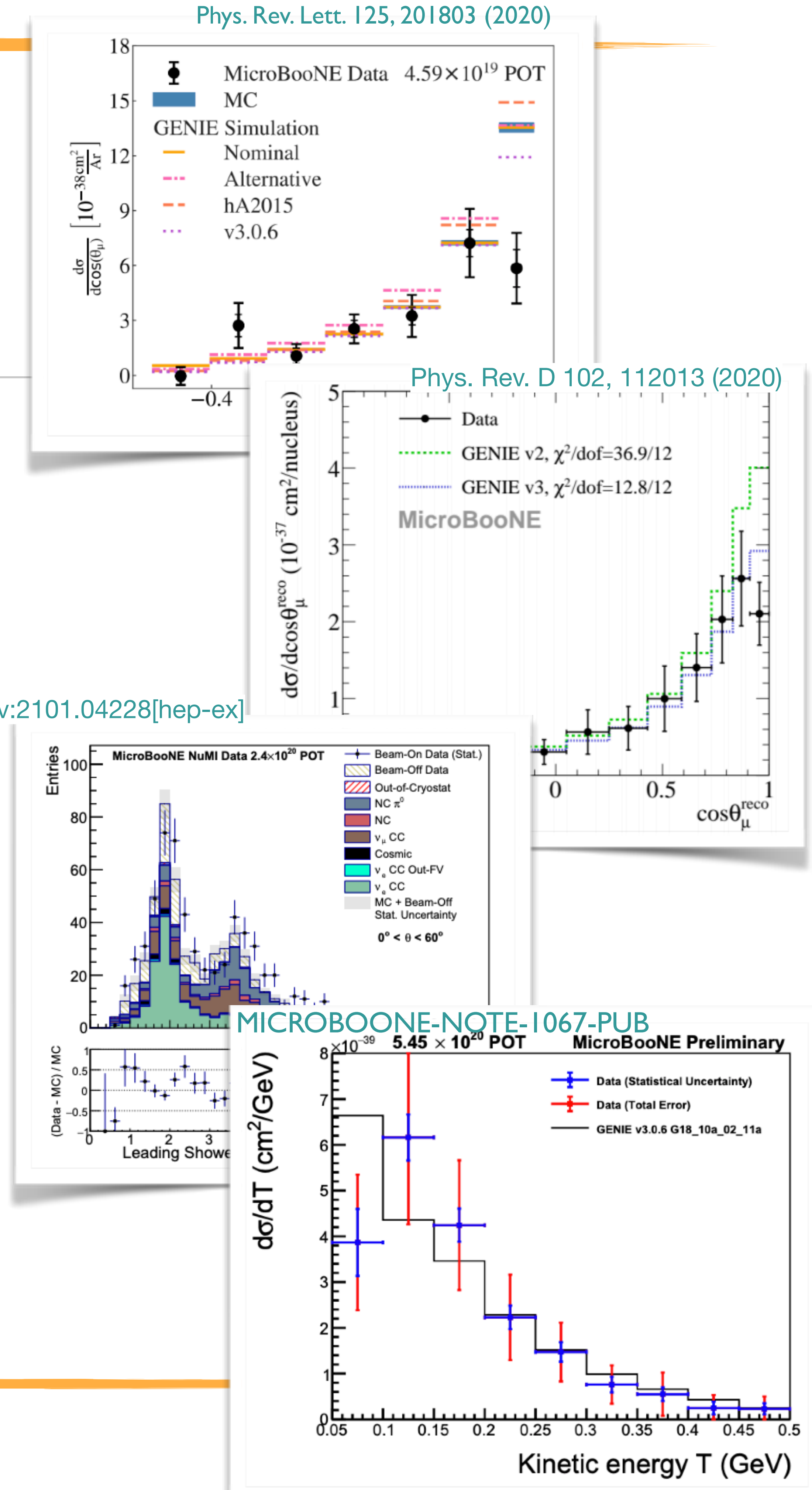
urements are in progress, including:

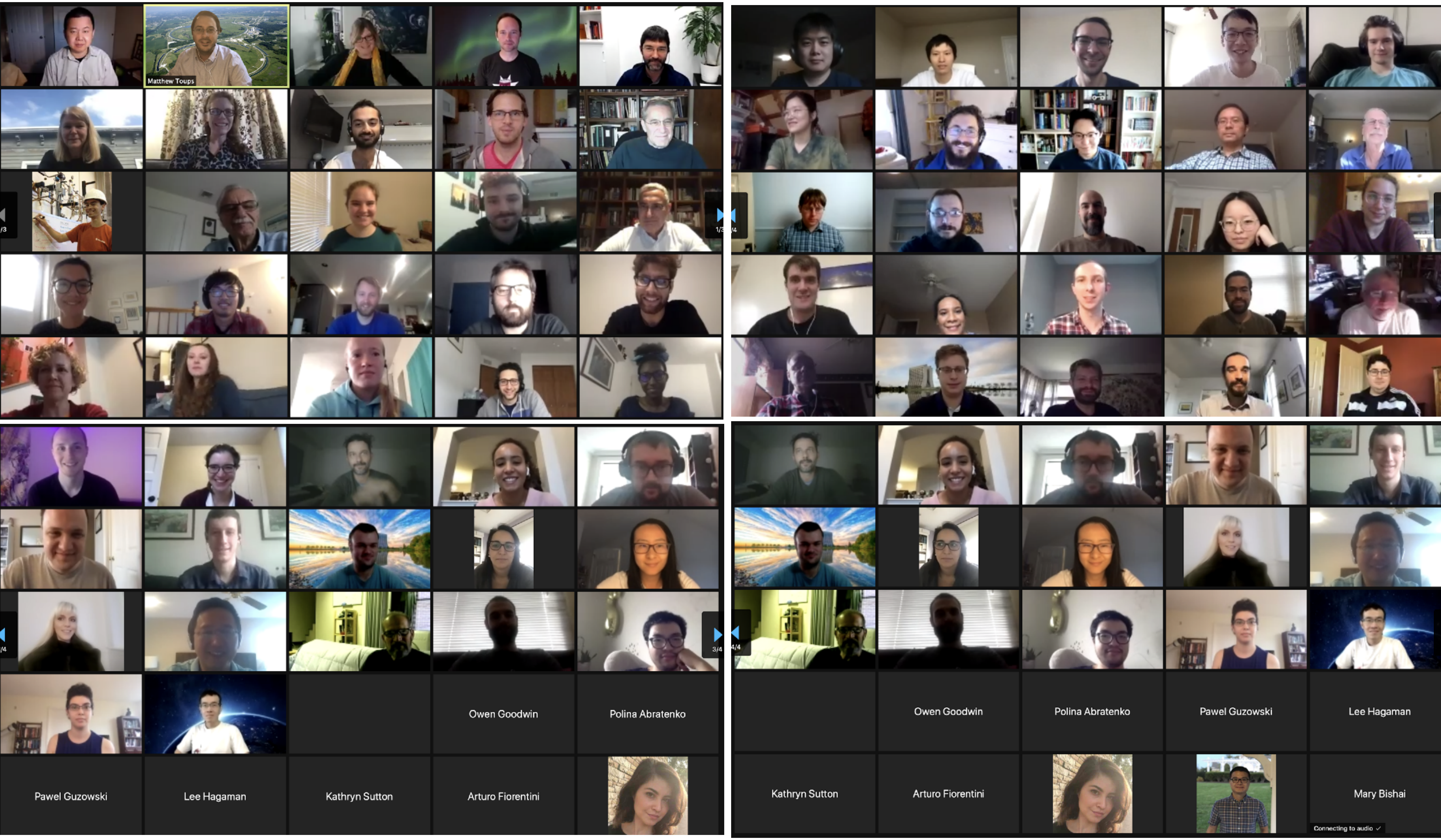
- ν_μ CC inclusive (update)
- ν_μ CC inclusive hadronic energy
- ν_μ NC Elastic p
- ν_μ
- ν_μ
- ν_μ
- KD
- ν_e
- ν_e



SUMMARY

- Cross-section measurements on argon are **vital** for the success of the SBN program and eventually DUNE
- MicroBooNE has demonstrated **4π acceptance** and ability to measure particles with **very low thresholds**
- We are already able to make **precise, accurate measurements of exclusive final states**
- **Huge progress** over the past few years: first time we can confront **models tuned to carbon** with high-statistics argon data
- More (and more precise) measurements expected in the future → **stronger tests** of our models

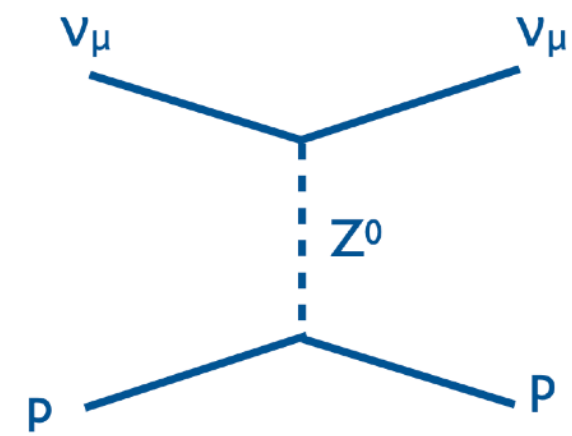




THANK YOU

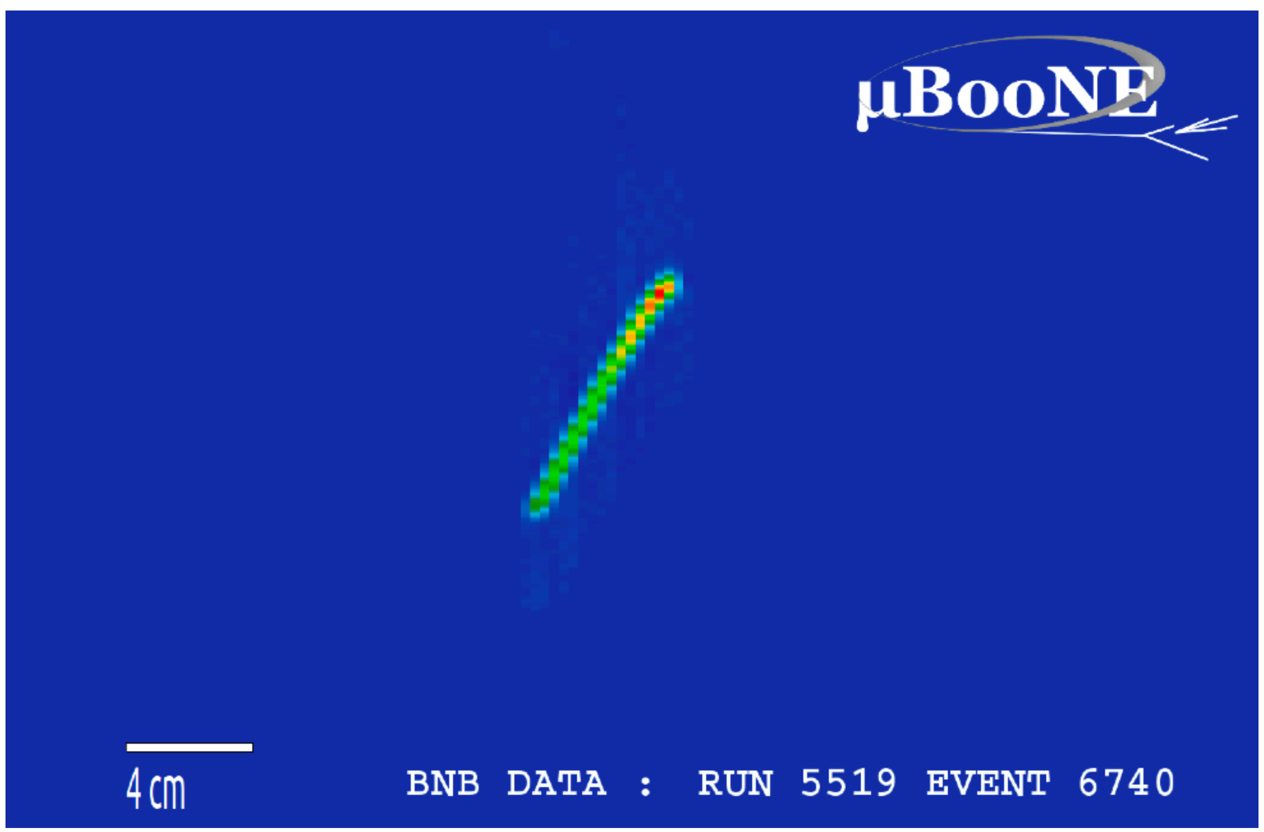
μBooNE

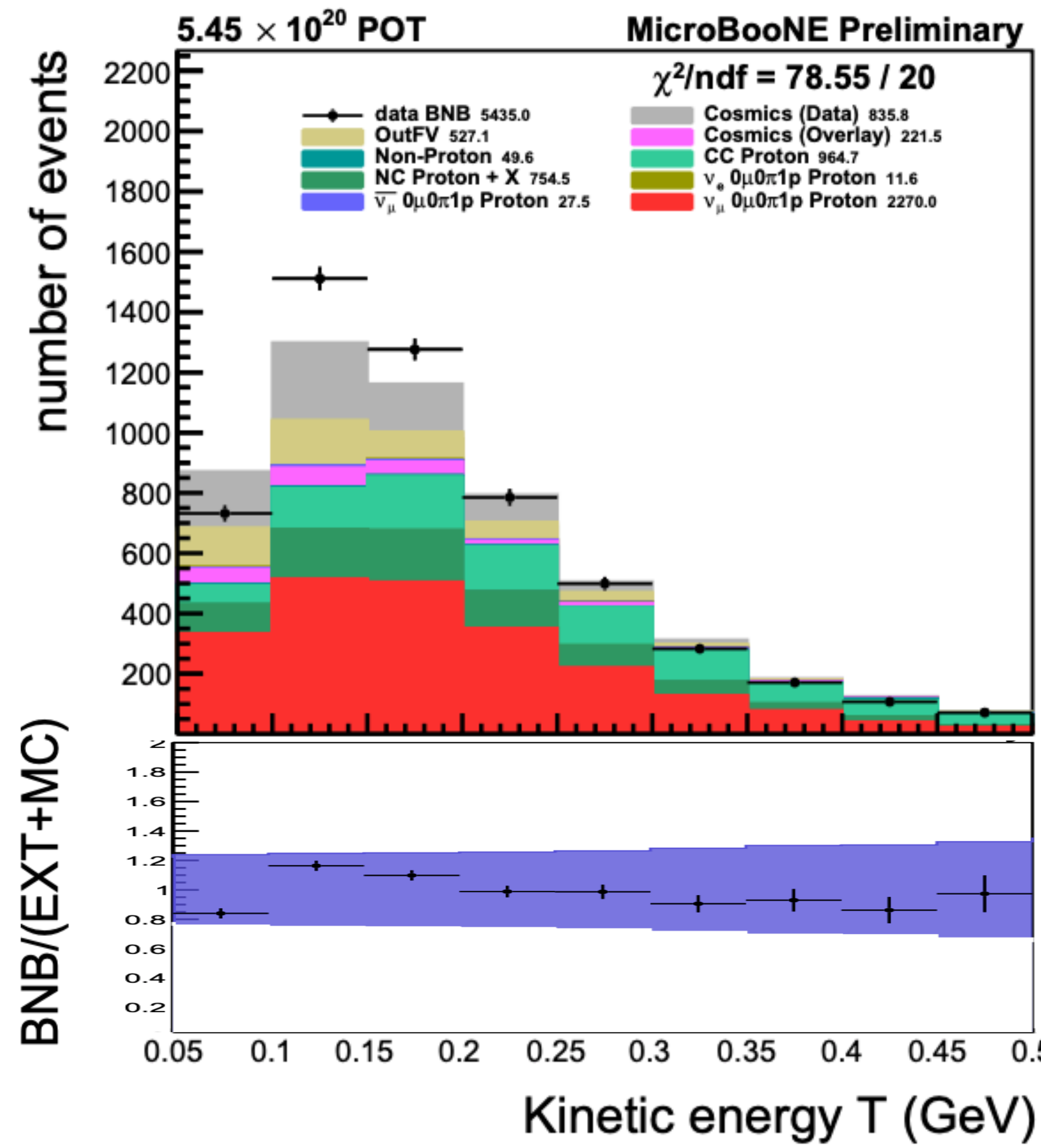
NC1P CROSS SECTION MEASUREMENT



MICROBOONE-NOTE-1067-PUB

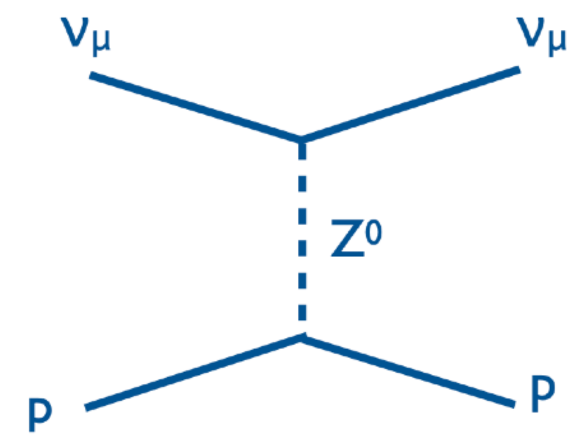
- Measure cross section for neutral-current single proton production
- Signal: 1 isolated proton



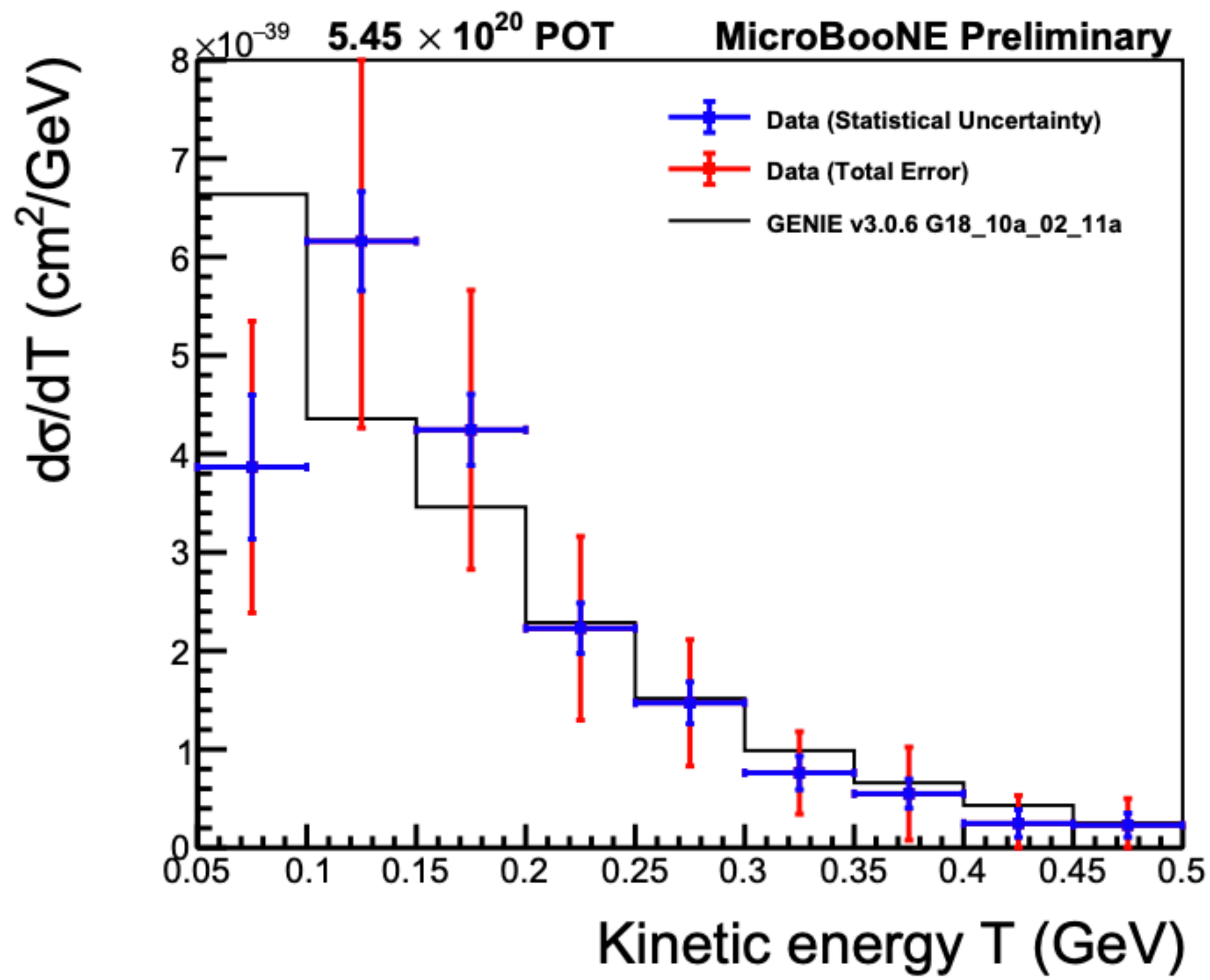


NC1P CROSS SECTION MEASUREMENT

MICROBOONE-NOTE-1067-PUB



- Measurement includes events with $Q^2 \sim 2m_p T_p = 0.1$ GeV^2, **significantly lower** than previous measurements
- Future development towards a measurement of **NC elastic scattering** cross section → measure strange component of neutral-current axial form factor

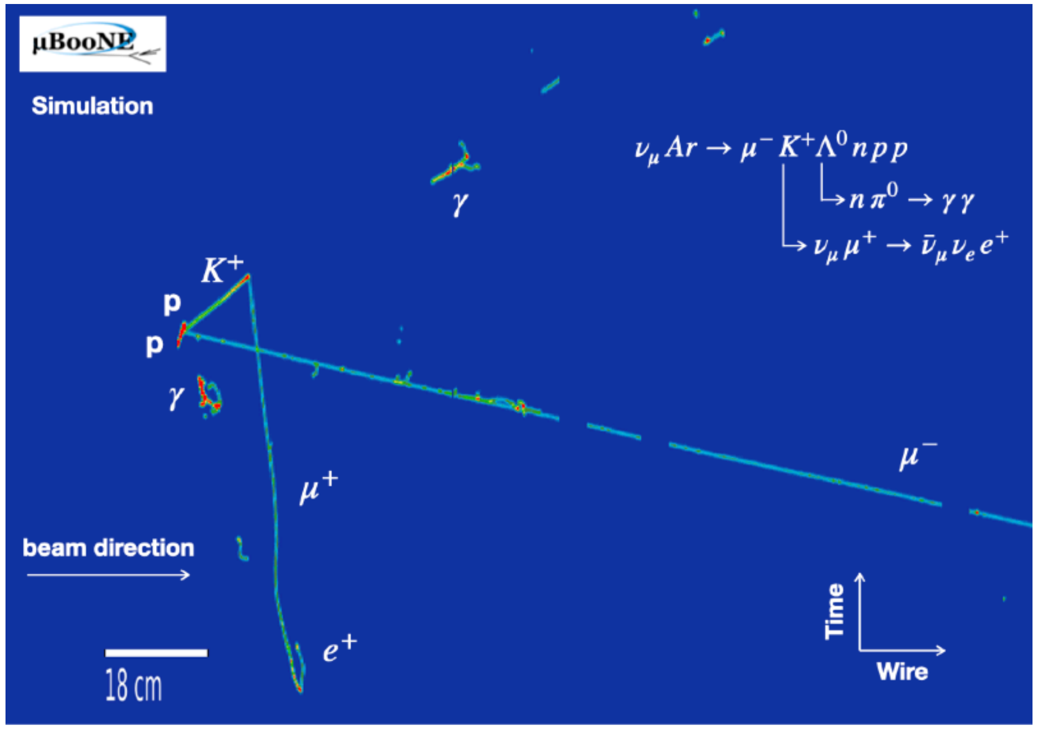


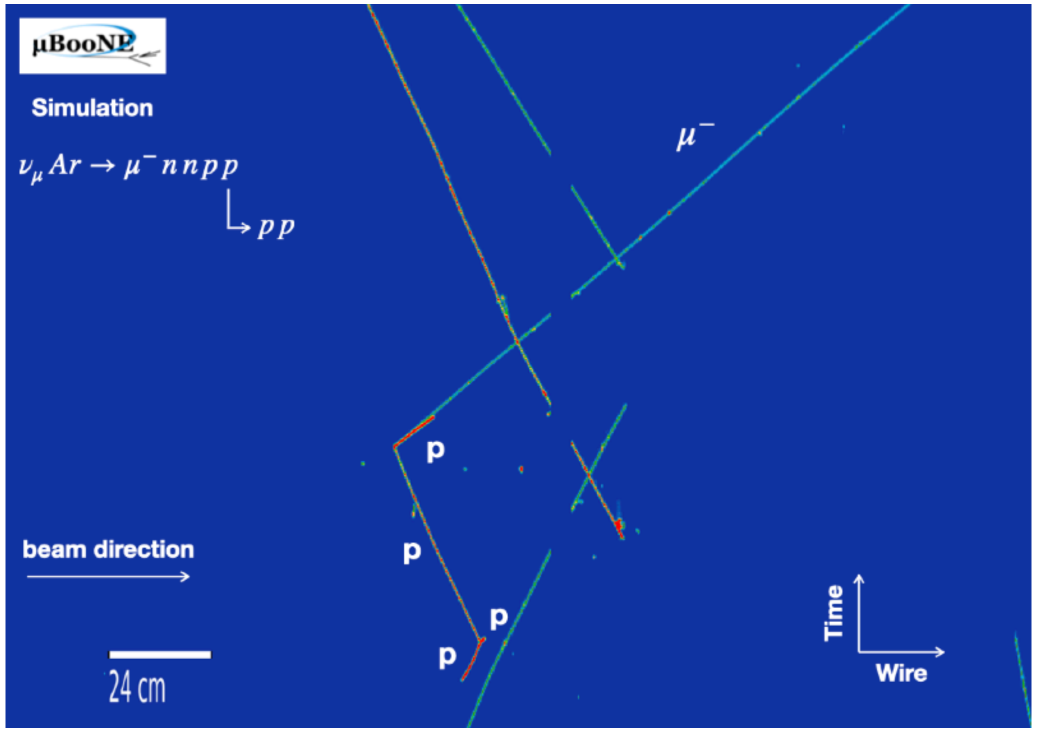
CC KAON PRODUCTION SELECTION

A. Fiorentini, poster 369, poster session 3

MICROBOONE-NOTE-1071-PUB

- **CC kaon production**: rare process, few existing measurements, background for **proton decay** $p \rightarrow K^+\nu$ searches in DUNE
- Selection developed on simulation: look for K^+ track from neutrino interaction and μ^+ from K^+ decay
- 67.7% purity and 7% efficiency → expect to select 12 candidate interactions in $1.3\text{x}10^{21}$ POT MicroBooNE data set
- Aim: cross section measurement and study of K^+ in LArTPC

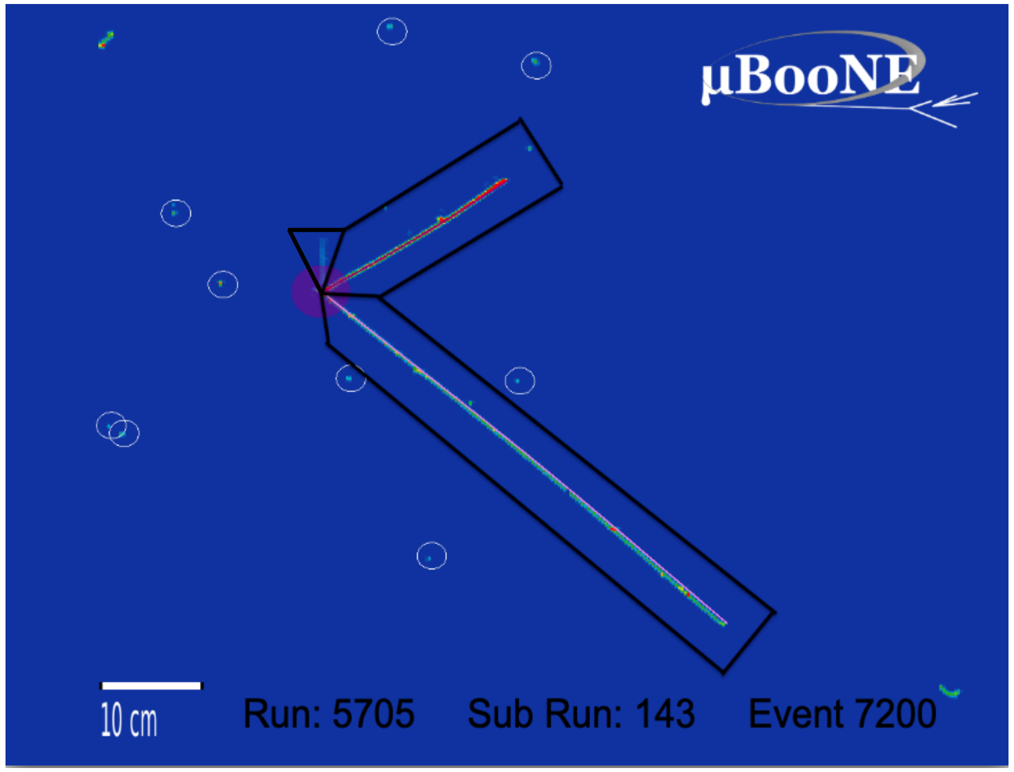


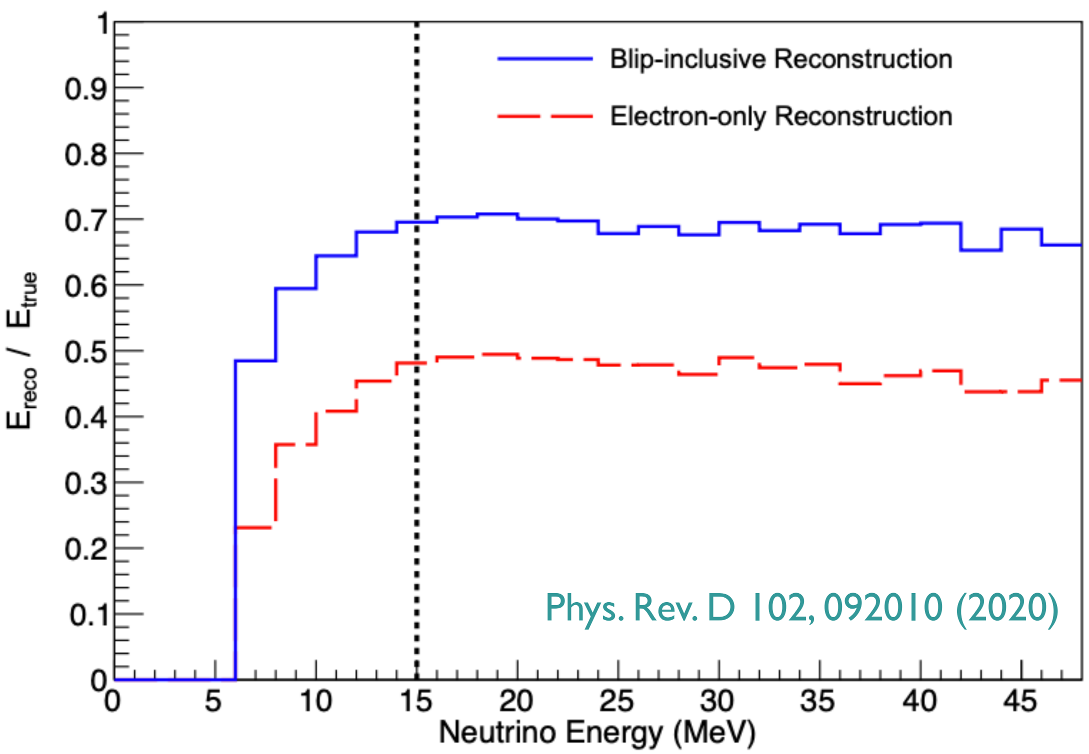


PUSHING THE LIMITS

Phys. Rev. D 102, 092010 (2020)
Phys. Rev. Lett. 124, 131801 (2020)
Phys. Rev. D 99, 012002 (2019)
MICROBOONE-NOTE-1076-PUB

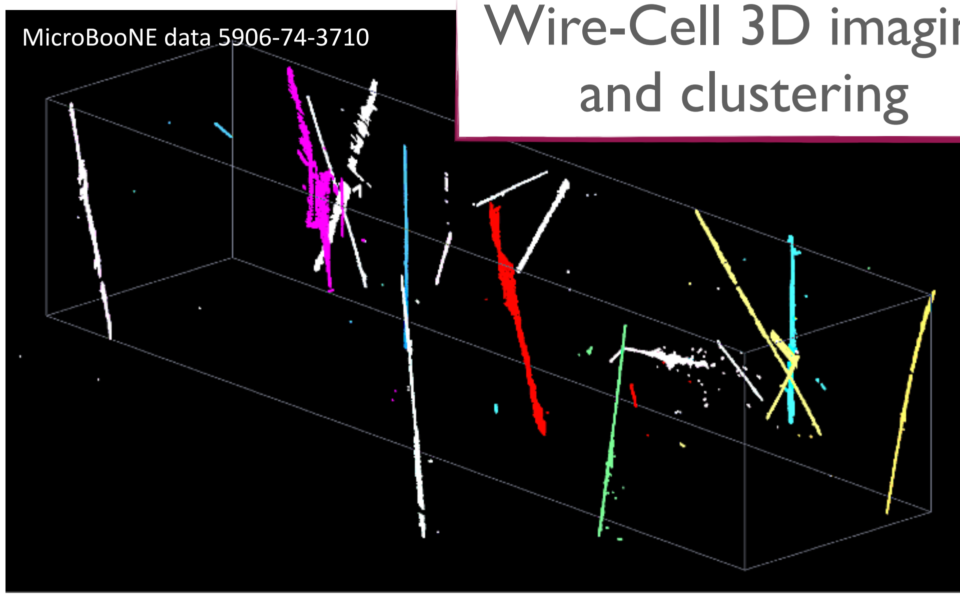
- Both ArgoNeuT and MicroBooNE have demonstrated ability to reconstruct **energy depositions from sub-MeV particles** (ArgoNeuT: 300 keV, MicroBooNE: 100 keV)
- Generally **photons** from nucleus de-excitation or **neutron** re-interactions → can give **substantial improvements** in calorimetry and energy reconstruction
- Used in ArgoNeuT to place constraints on BSM physics search for millicharged particles



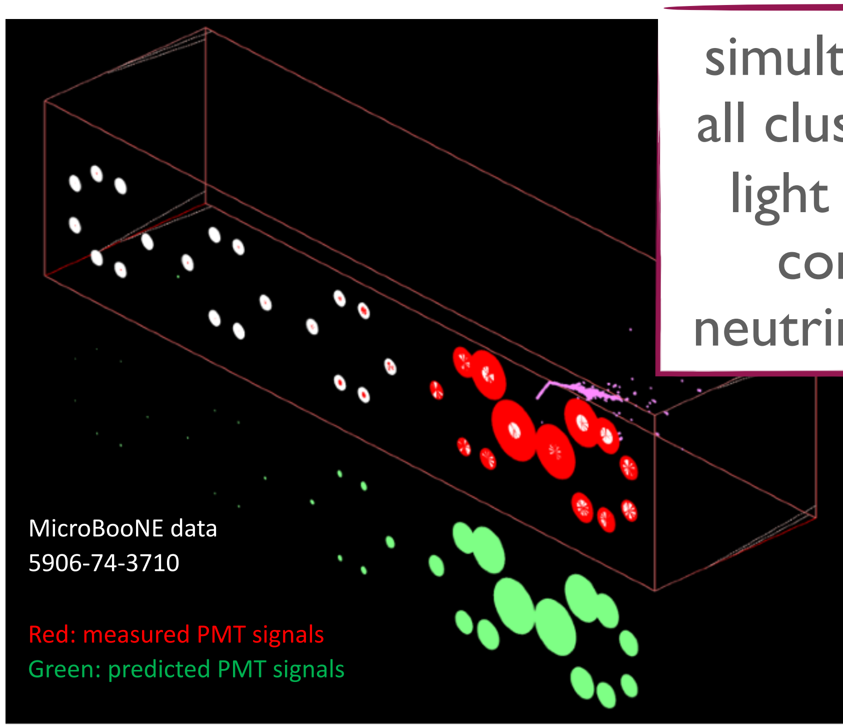


IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

arXiv:2011.01375[physics.ins-det] arXiv:2012.07928[hep-ex]

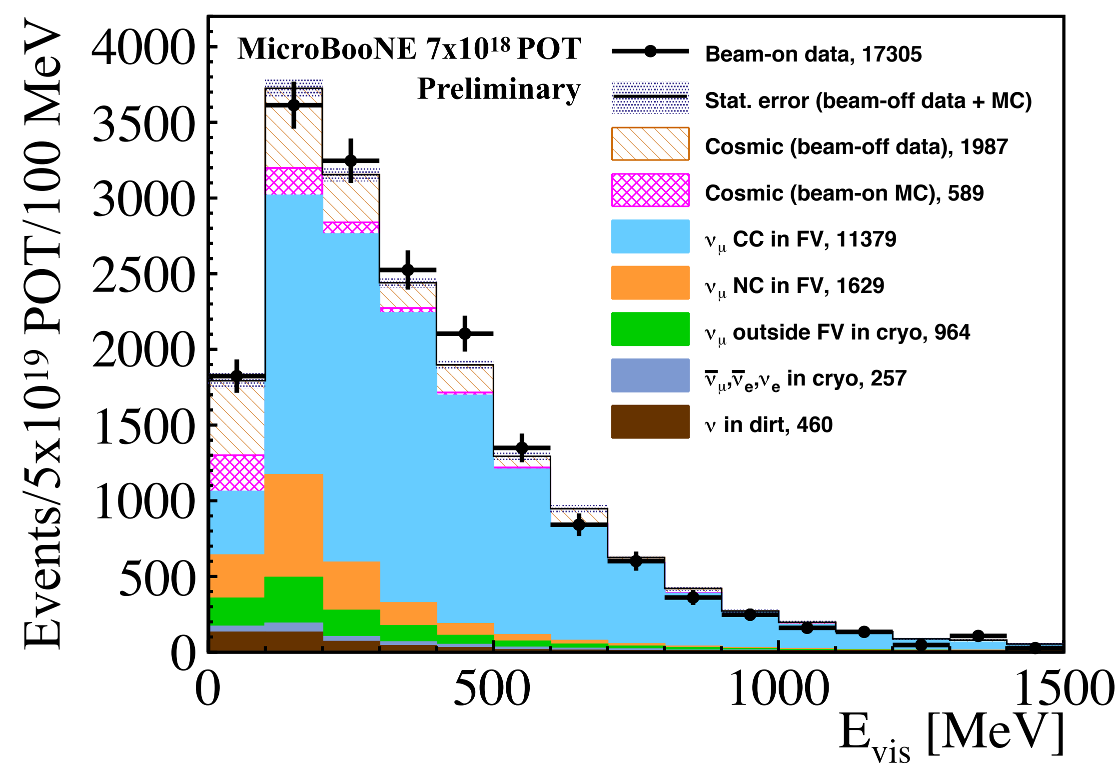


Wire-Cell 3D imaging and clustering



simultaneously match all clusters in event to light → find cluster consistent with neutrino-induced flash

- Cosmic rejection power (without kinematic requirements) **increased by factor of 8** compared to previous publications
- **High efficiency**: 80.4% for ν_μCC (87.6% for ν_eCC)
- **Increased statistics**: 11.3k events,compared to 4.3k events in same data set for 2019 CC inclusive measurement



COSMIC REJECTION

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

- **Check if in time with beam flash**
- **Check if compatible with beam flash in terms of position and light intensity**
- **Check if track goes all the way through the detector**
- **Check if track is a cosmic crossing anode/cathode (known t0)**
- **Check for Bragg peak/ decay electron indicating muon enters and stops**

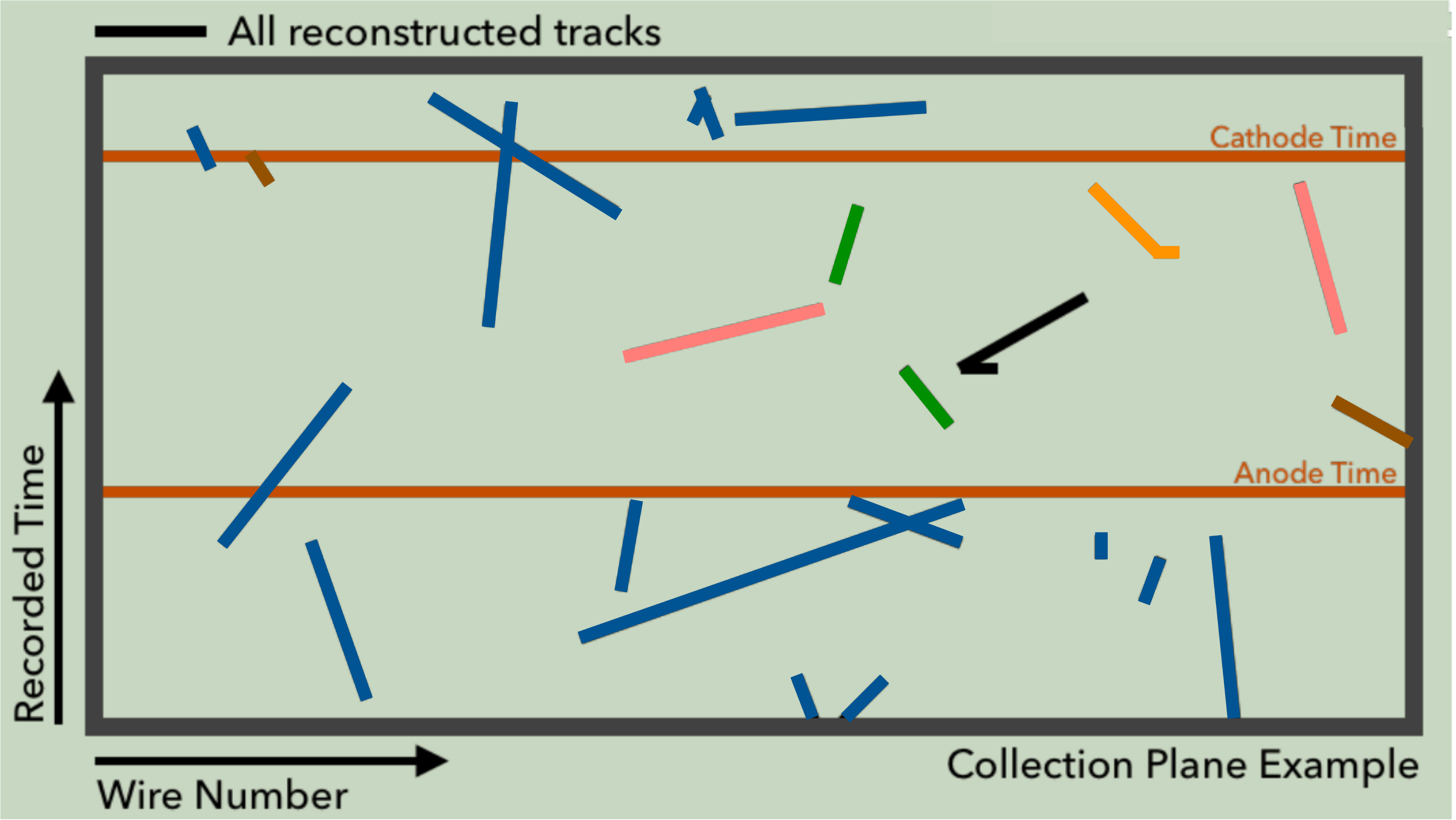
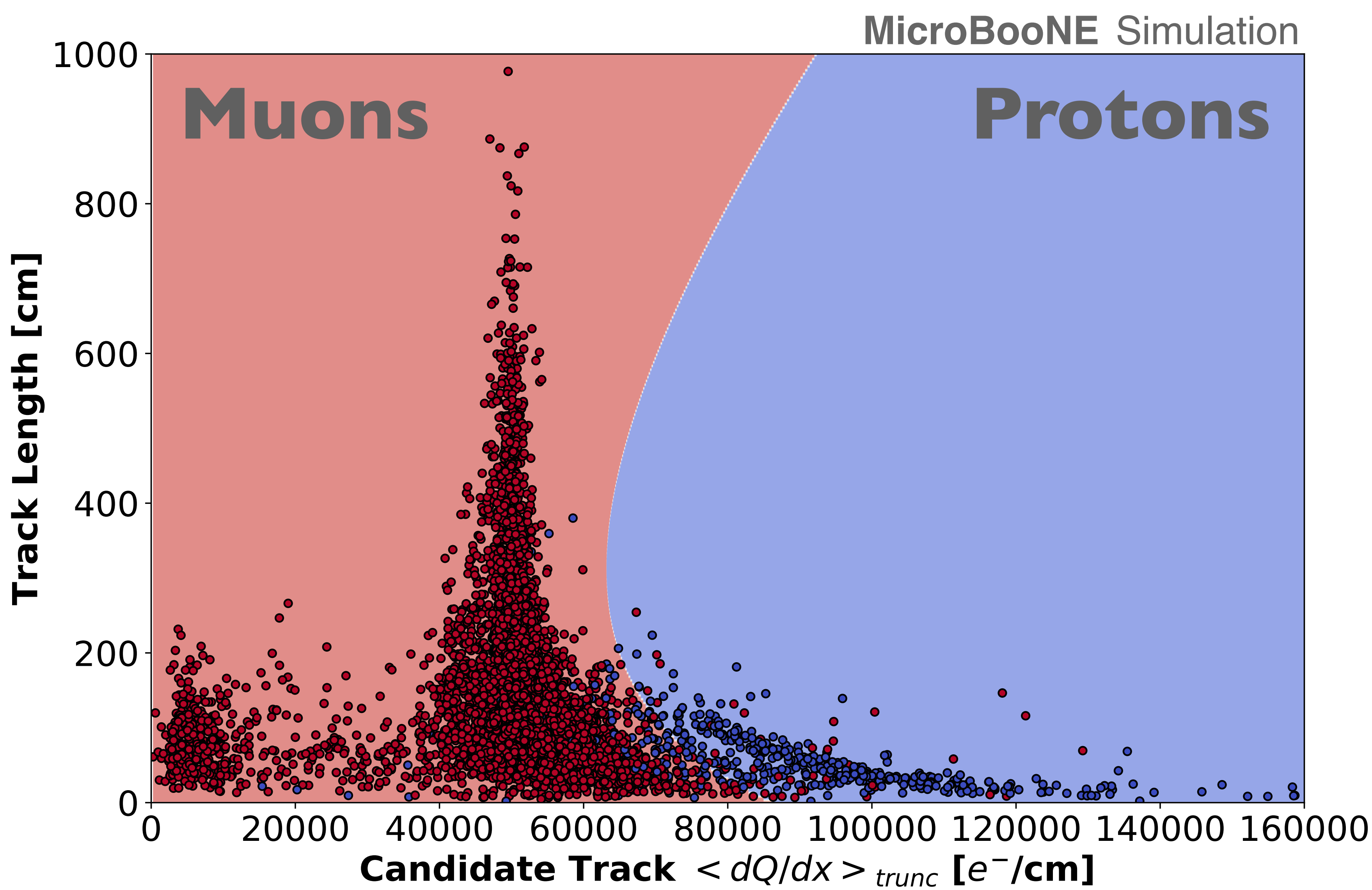


Figure from M. del Tutto

SELECTING CC EVENTS

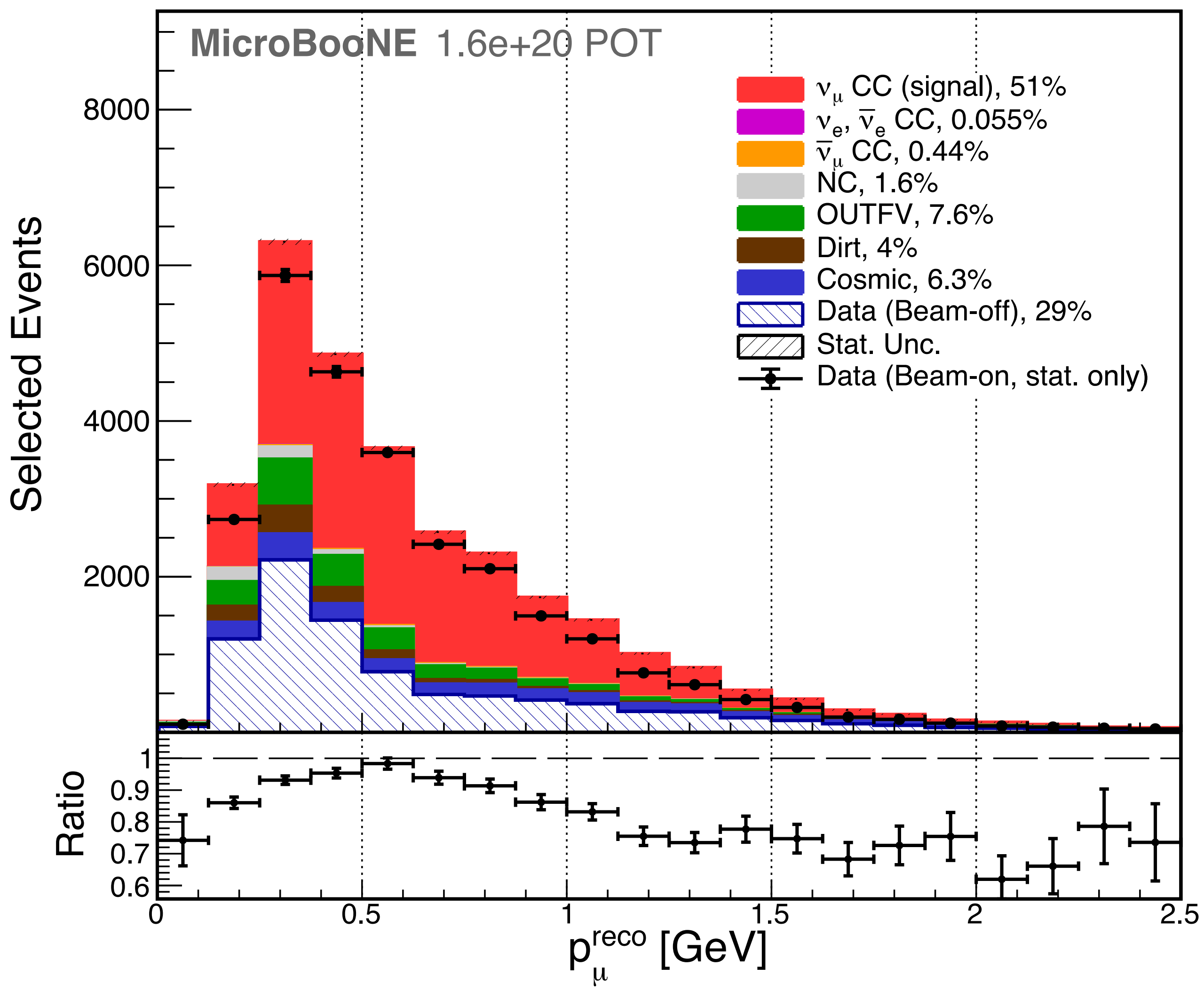
Phys. Rev. Lett. 123, 131801 (2019)

- Charged-current events selected by presence of muon
- Longest track in event is muon candidate → use dQ/dx and track length to reject protons



SELECTED EVENTS

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



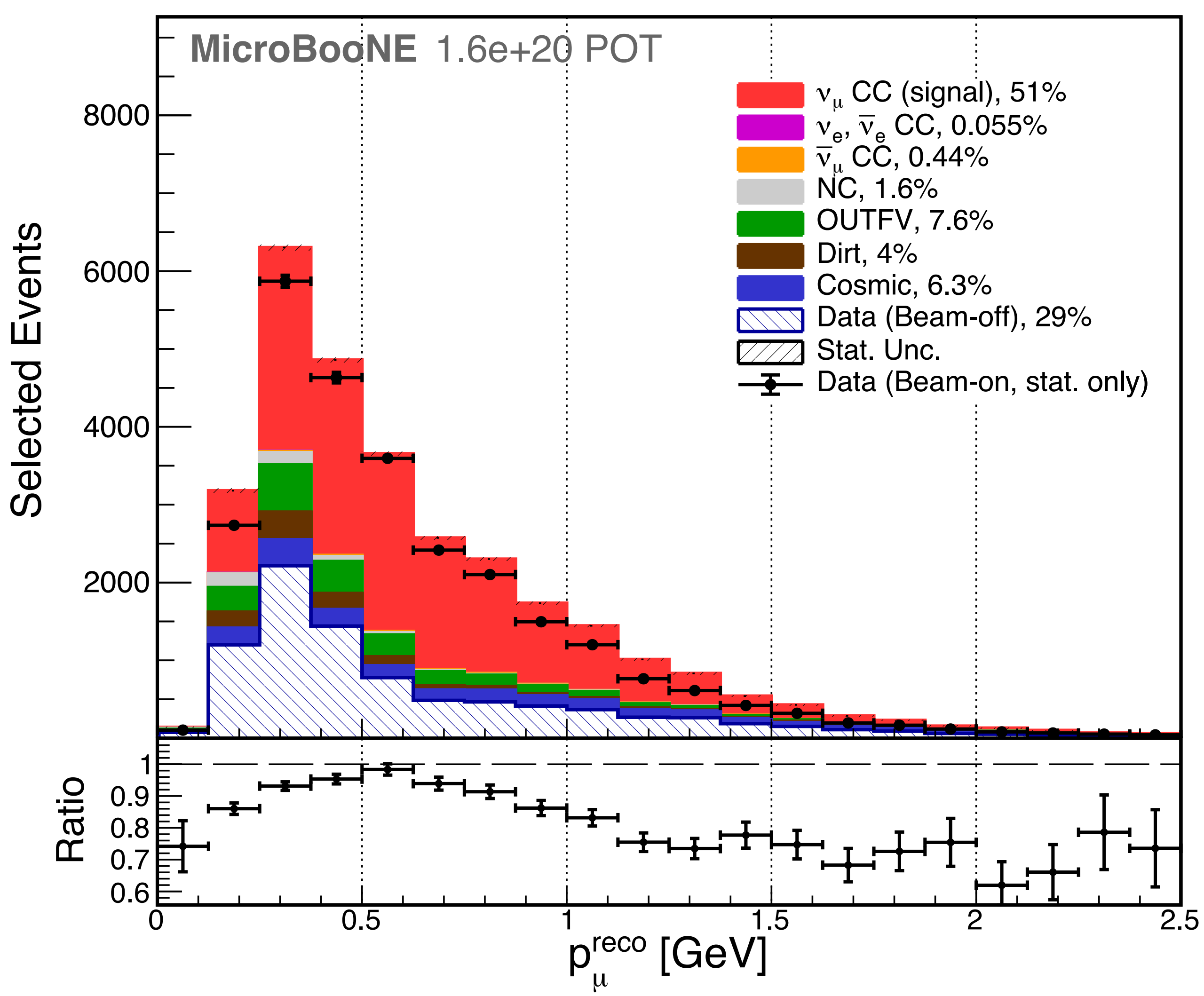
Signal (CC-inclusive) events: 50.4%

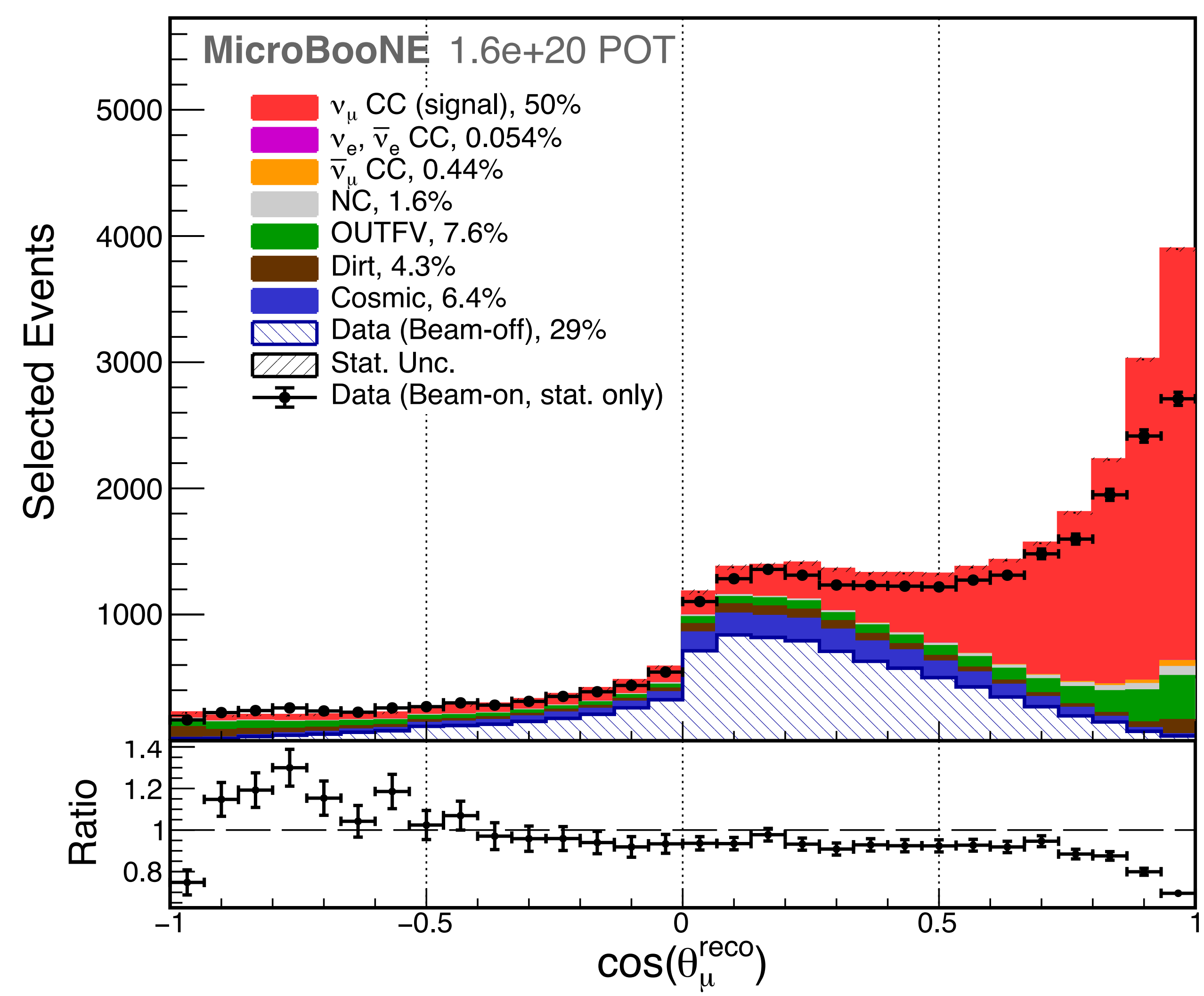
Largest background: **cosmics** (29%) → directly measured with beam-off data

Other backgrounds from **neutrino interactions outside fiducial volume** and **cosmic interactions in time with neutrino beam**

SELECTED EVENTS

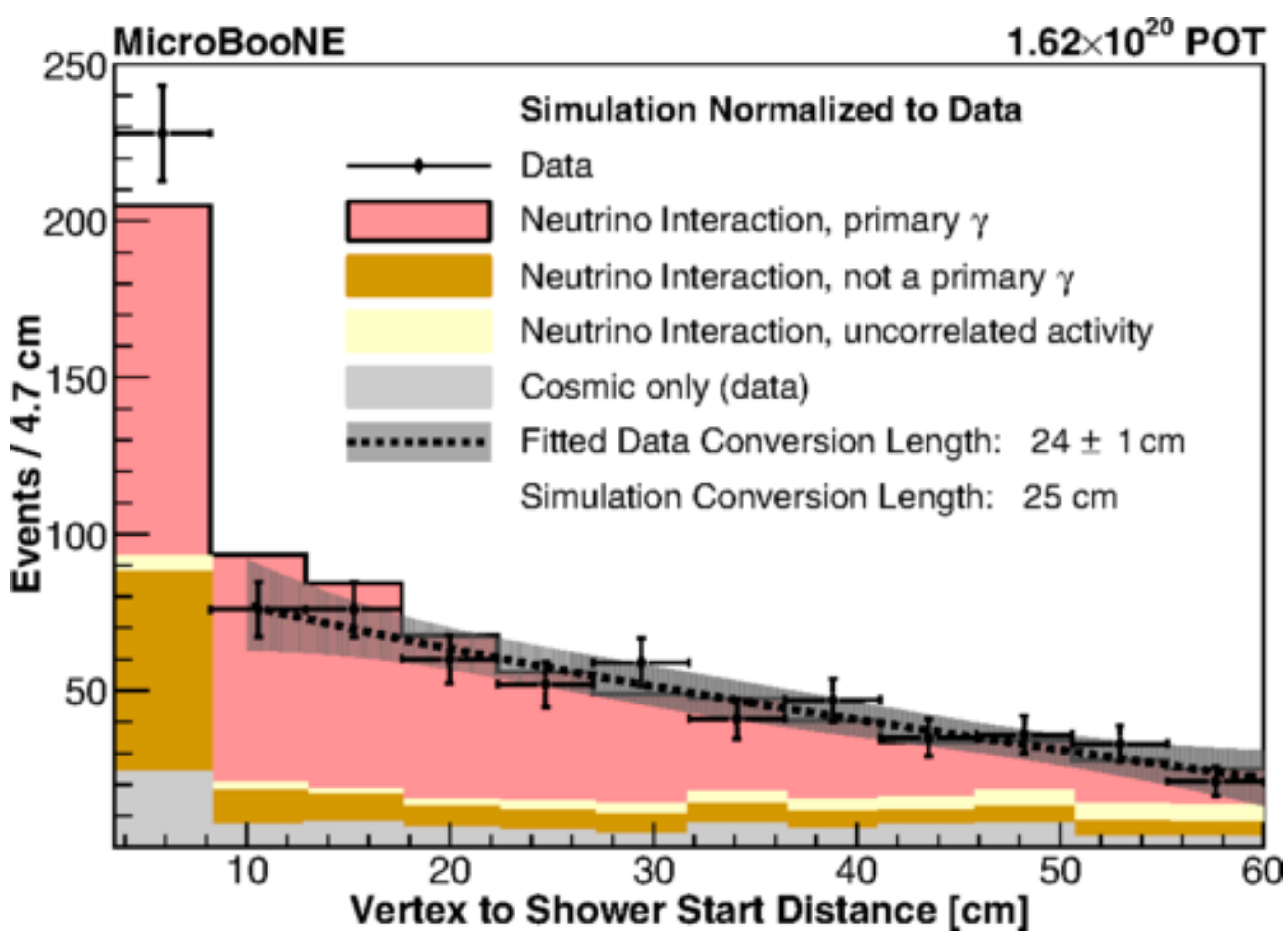
Phys. Rev. Lett. 123, 131801 (2019)





Largest ever sample of neutrino interactions on argon

CCPI0: PHOTON CONVERSION



Phys. Rev. D 99, 091102(R) (2019)

- Look at single photons passing $CC\pi^0$ selection
- Measure mean free path to validate:
  1) that we have selected photons
  2) that we have the interaction vertex right
- ✔ Data agrees with simulation within uncertainties

μBooNE

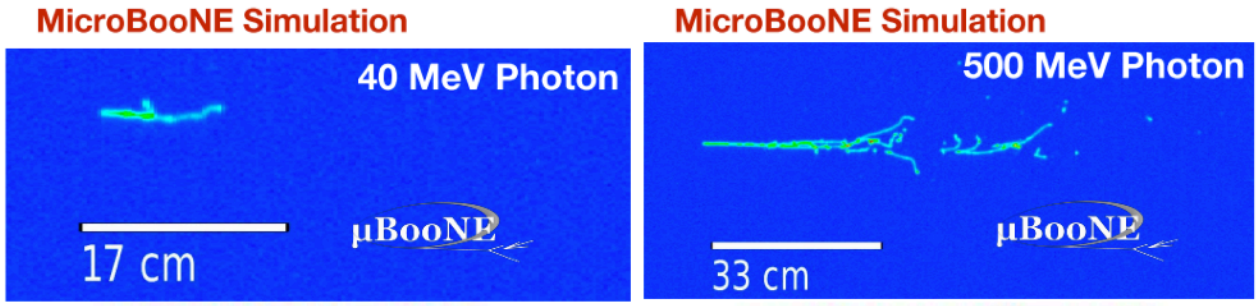
CCPI0 SELECTIONS

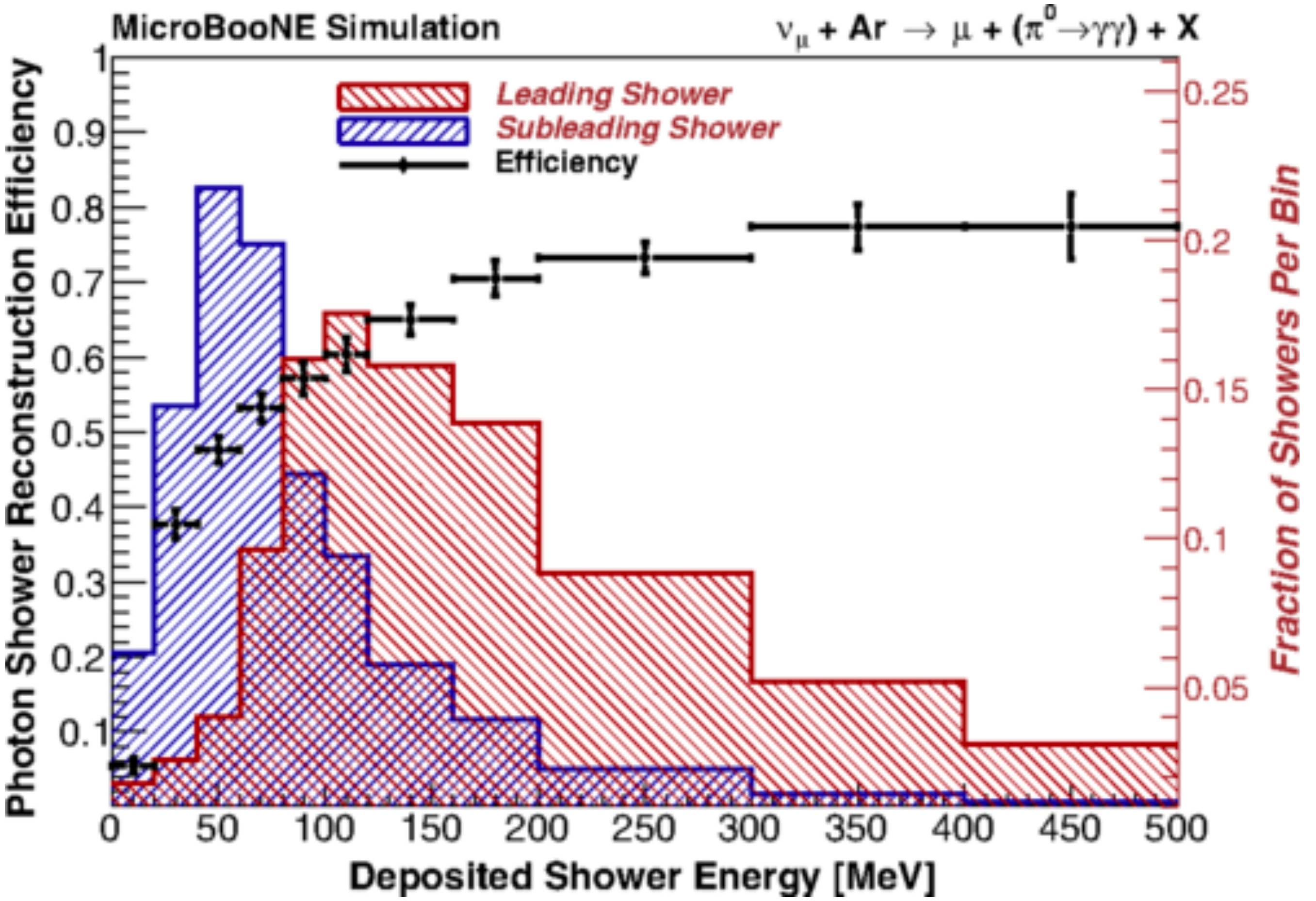
Phys. Rev. D 99, 091102(R) (2019)

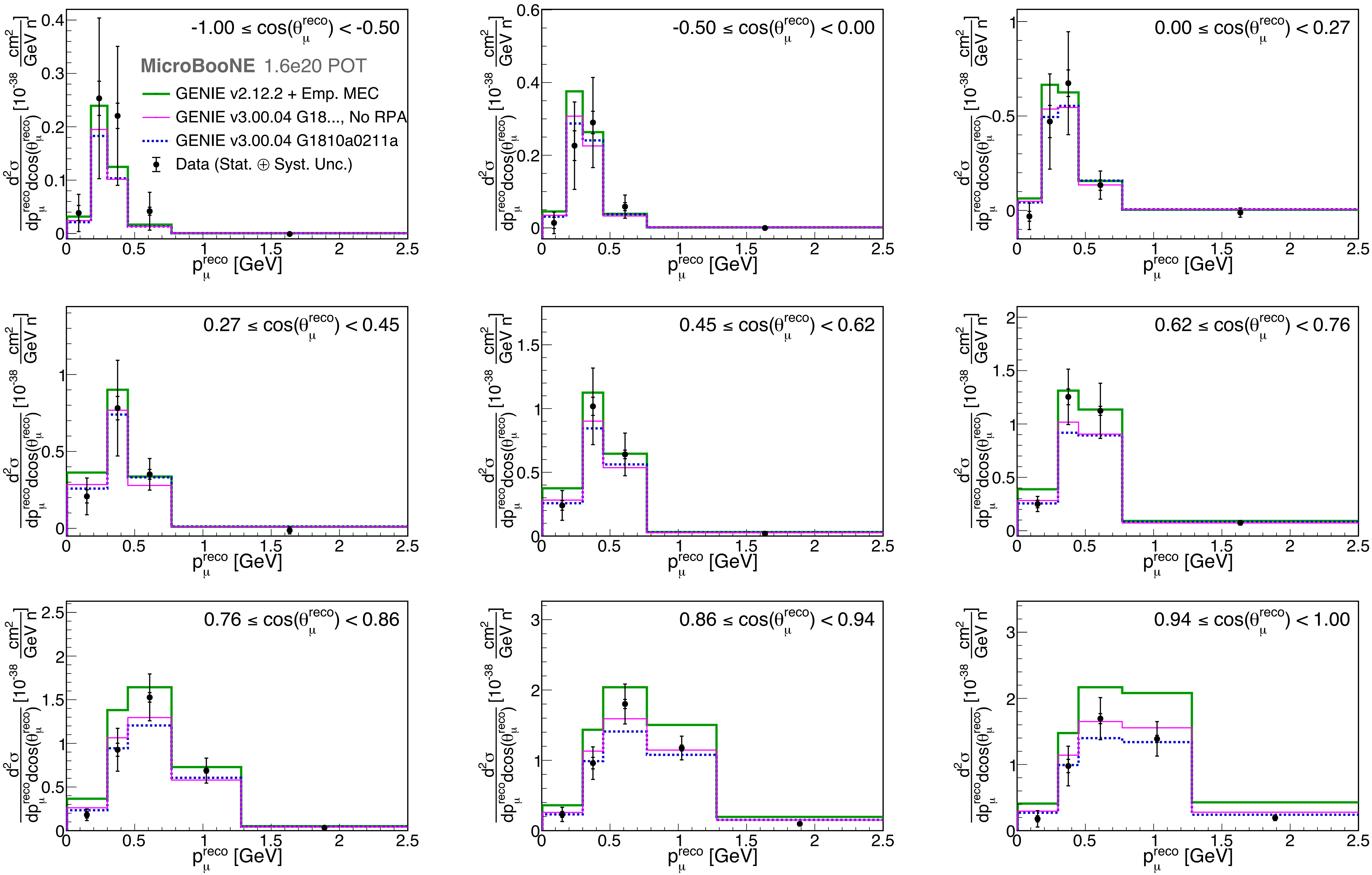
Low-energy photons appear more track like
→ low reconstruction efficiency
→ requiring that we reconstruct both π^0 photons limits statistics

Two-shower selection
→ validate π^0 hypothesis by invariant diphoton mass

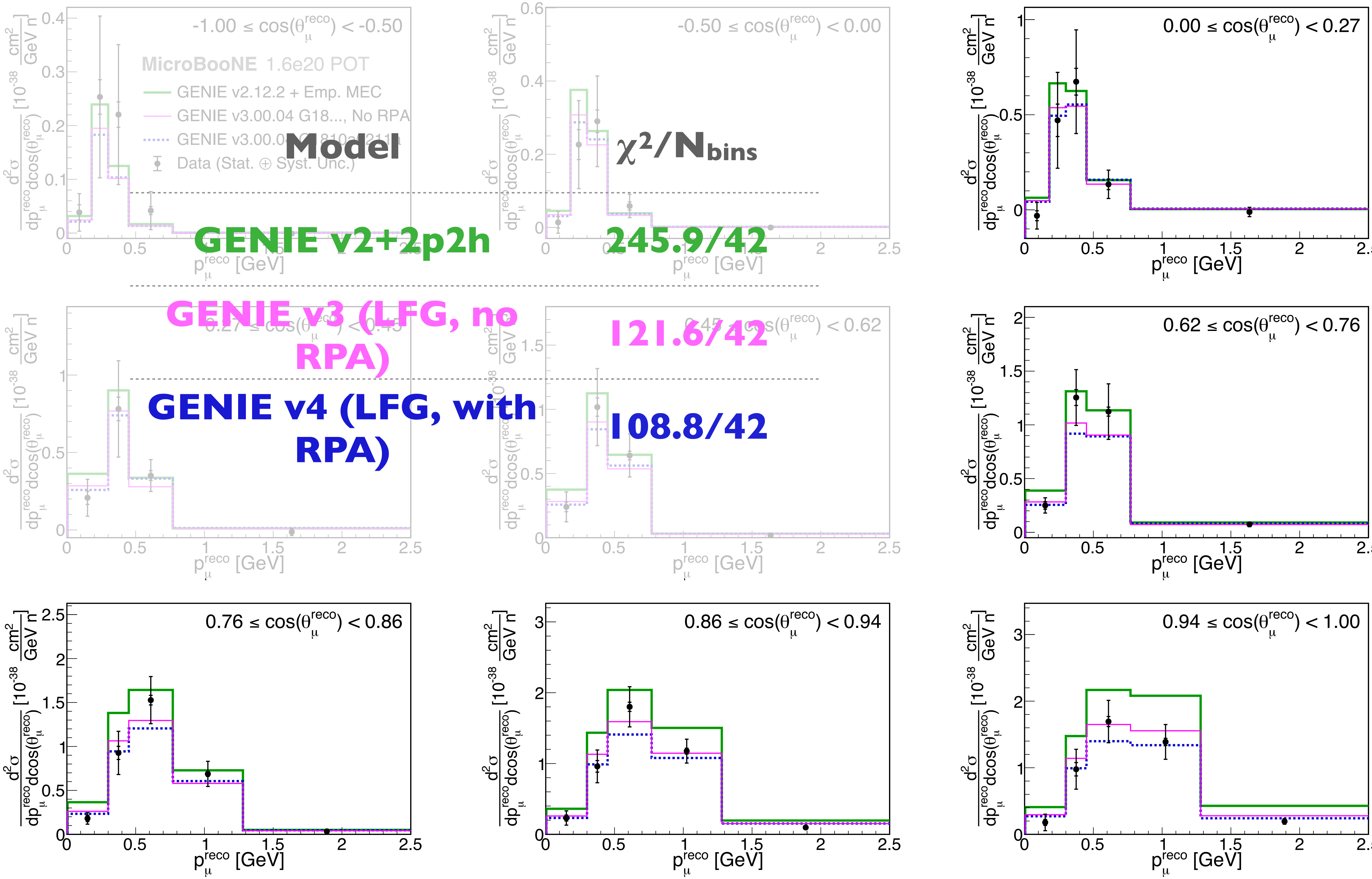
Single shower selection
→ validate photon hypothesis
→ maximize statistics for cross section measurement





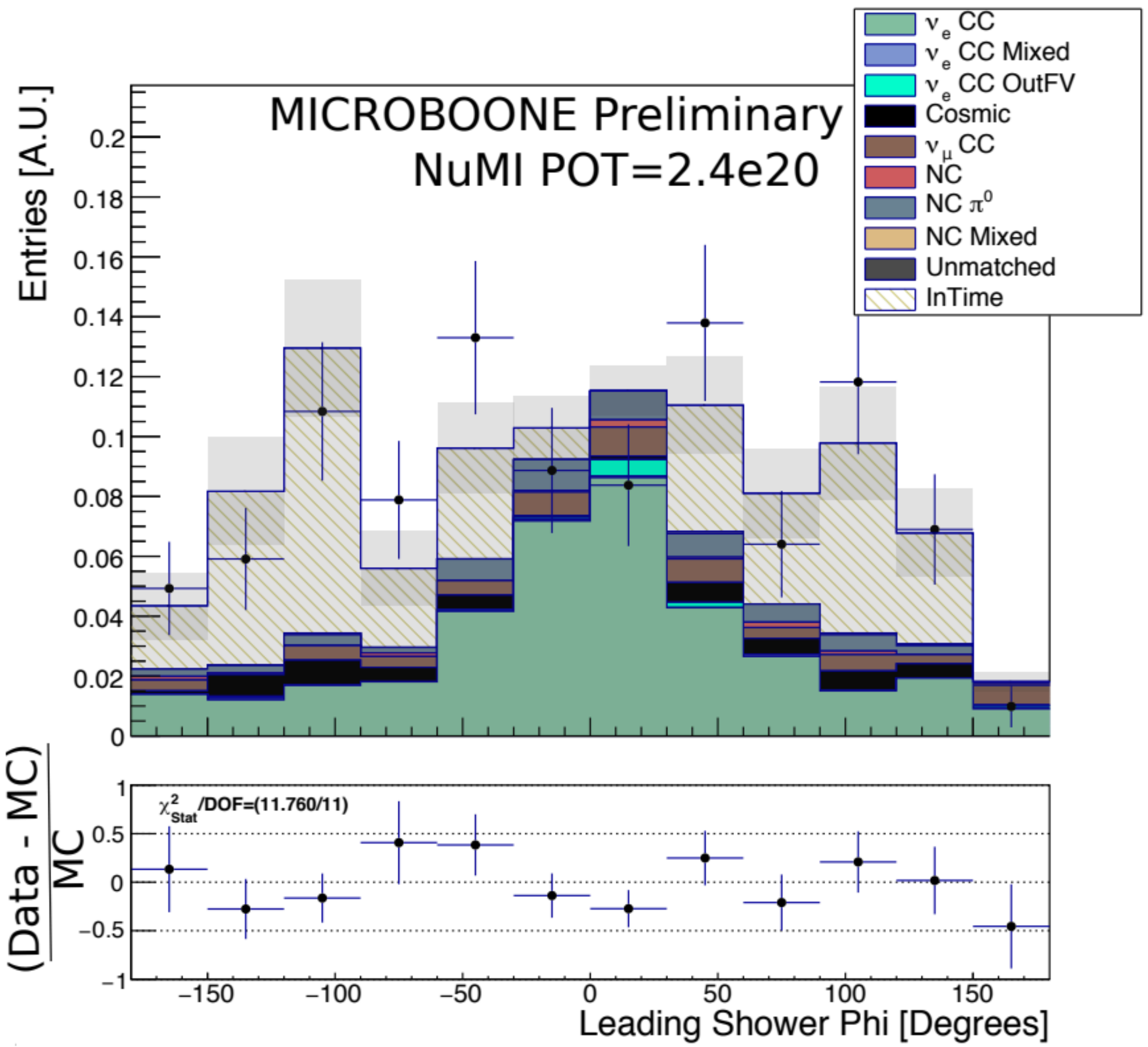


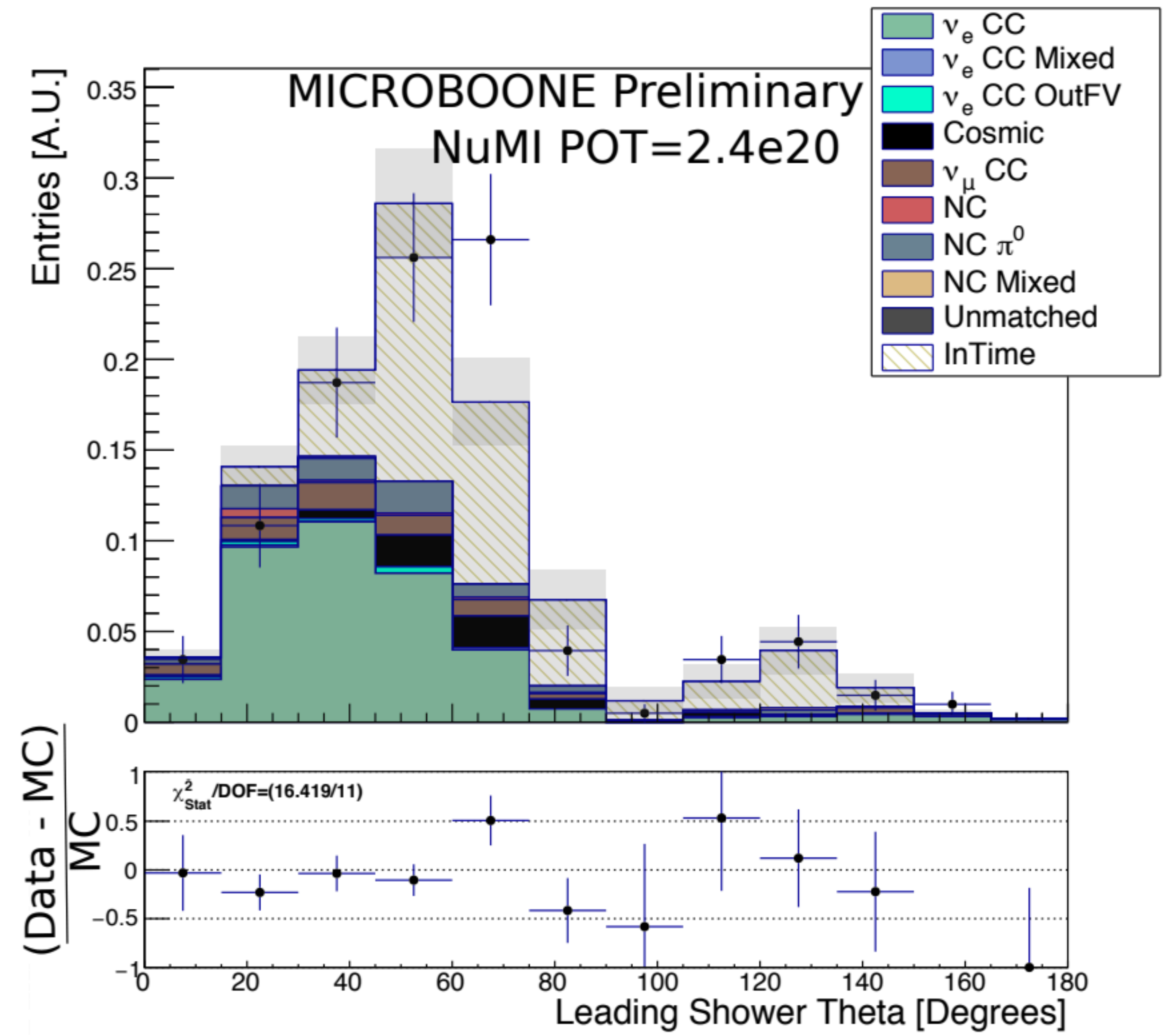
-1.00 ≤ cos(θ_μ^reco) < -0.50
-0.50 ≤ cos(θ_μ^reco) < 0.00
0.00 ≤ cos(θ_μ^reco) < 0.27
0.27 ≤ cos(θ_μ^reco) < 0.45
0.45 ≤ cos(θ_μ^reco) < 0.62
0.62 ≤ cos(θ_μ^reco) < 0.76
0.76 ≤ cos(θ_μ^reco) < 0.86
0.86 ≤ cos(θ_μ^reco) < 0.94
0.94 ≤ cos(θ_μ^reco) < 1.00
MicroBooNE 1.6e20 POT
GENIE v2.12.2 + Emp. MEC
GENIE v3.00.04 G18..., No RPA
GENIE v3.00.04 G1810a0211a
Data (Stat. ⊕ Syst. Unc.)
p_μ^reco [GeV]



Model	χ^2/N_{bins}
GENIE v2+2p2h	245.9/42
GENIE v3 (LFG, no RPA)	121.6/42
GENIE v4 (LFG, with RPA)	108.8/42

NUE SELECTED EVENTS





ν_e selection efficiency: 9%, purity: 40%

CROSS SECTION

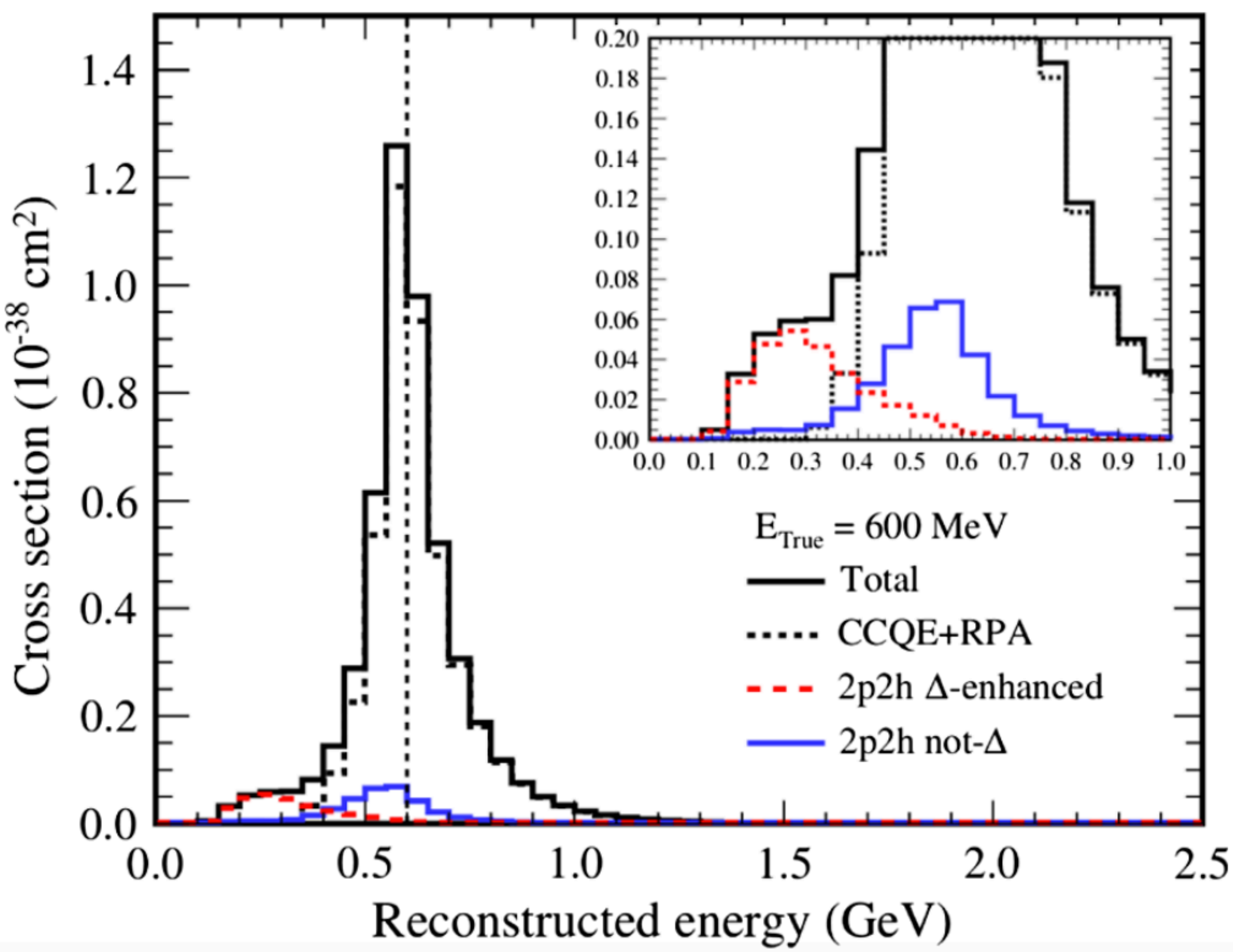
arXiv: 1905.09694 [hep-ex]
Accepted to PRL

Note: cross section presented in **reconstructed** p_μ—$\cos\theta_\mu$ space

$$\left\langle \frac{d^2\sigma}{dp_\mu^{reco}\, d\cos\theta_\mu^{reco}} \right\rangle_i$$

- Unlike other cross section measurements we do not unfold to true muon momentum and angle
  - → unfolding introduces bias, inflates uncertainties
- Instead, present result in **reconstructed** muon momentum and angle
- Publish detector smearing and efficiency
  - → theoretical predictions can be **forward folded** (i.e. smeared by our known detector effects)
  - → produce a realistic prediction of what we expect to see in our detector
  - → directly compare to data

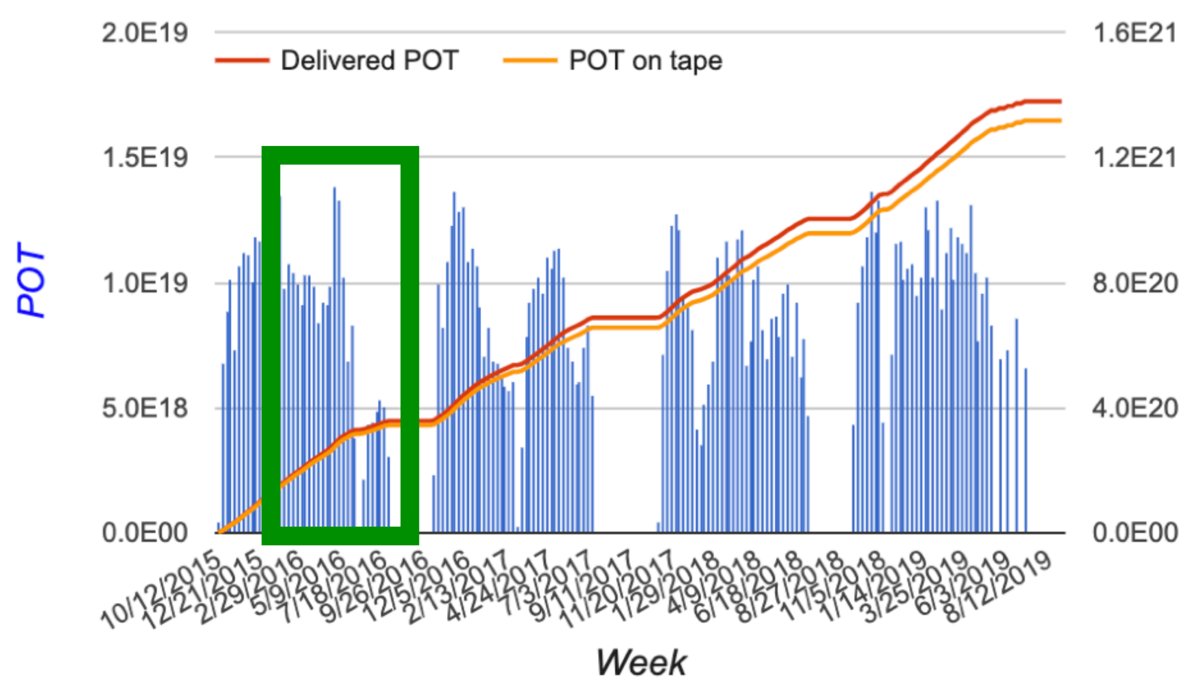
NEUTRINO INTERACTIONS AND RECONSTRUCTING NEUTRINO ENERGY

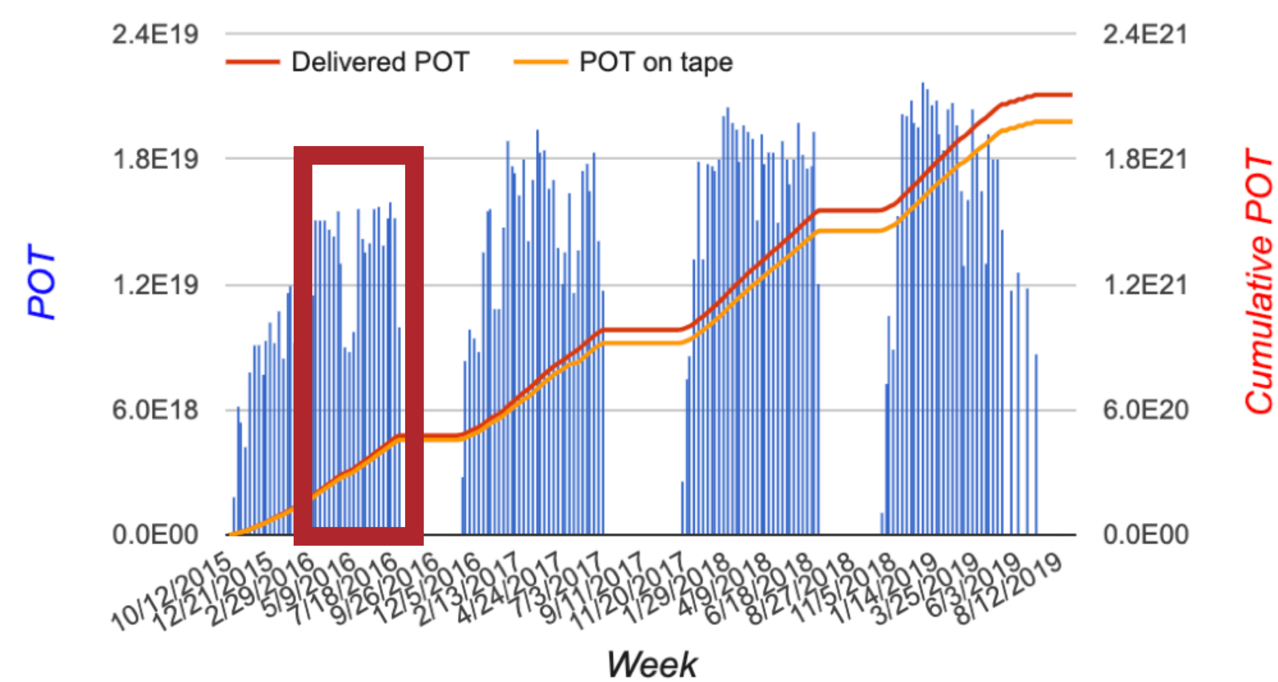


Phys. Rev. D 96, 092006 (2017)

- Reconstructing neutrino energy requires assumptions
  - **CCQE formula**: assume all events are CCQE, reconstruct energy from lepton — what if it's not CCQE?
  - **Calorimetric**: measure deposited energy of all particles — what about neutrals/particles you miss?
- Assuming the wrong interaction model:
  - → **bias** in reconstructing neutrino energy
  - → **bias** in oscillation parameters

MICROBOONE'S DATA





BNB

1.38×10^{21} POT delivered

(1.32×10^{21} POT on tape)

This talk: Run 1 = 1.6×10^{20} POT

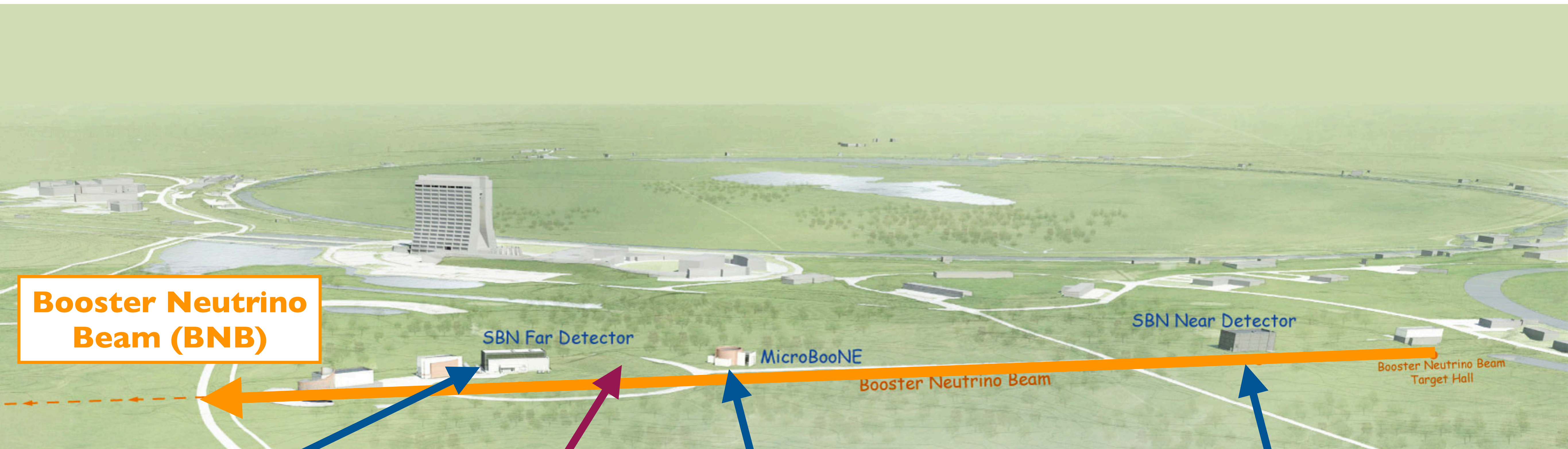
NuMI

2.1×10^{21} POT delivered

(1.98×10^{21} POT on tape)

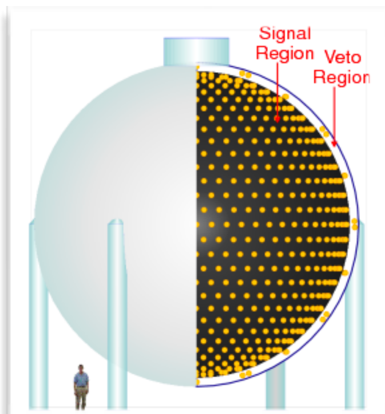
This talk: 2.4×10^{20} POT

SHORT-BASELINE NEUTRINOS AT FERMILAB



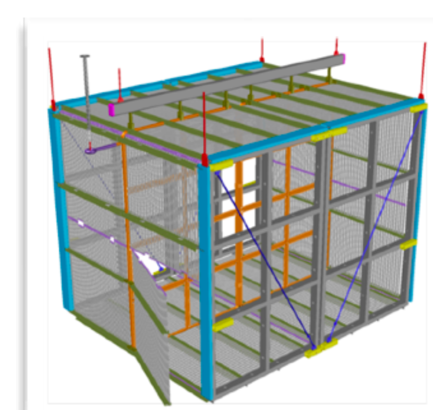
ICARUS

MiniBooNE



MicroBooNE

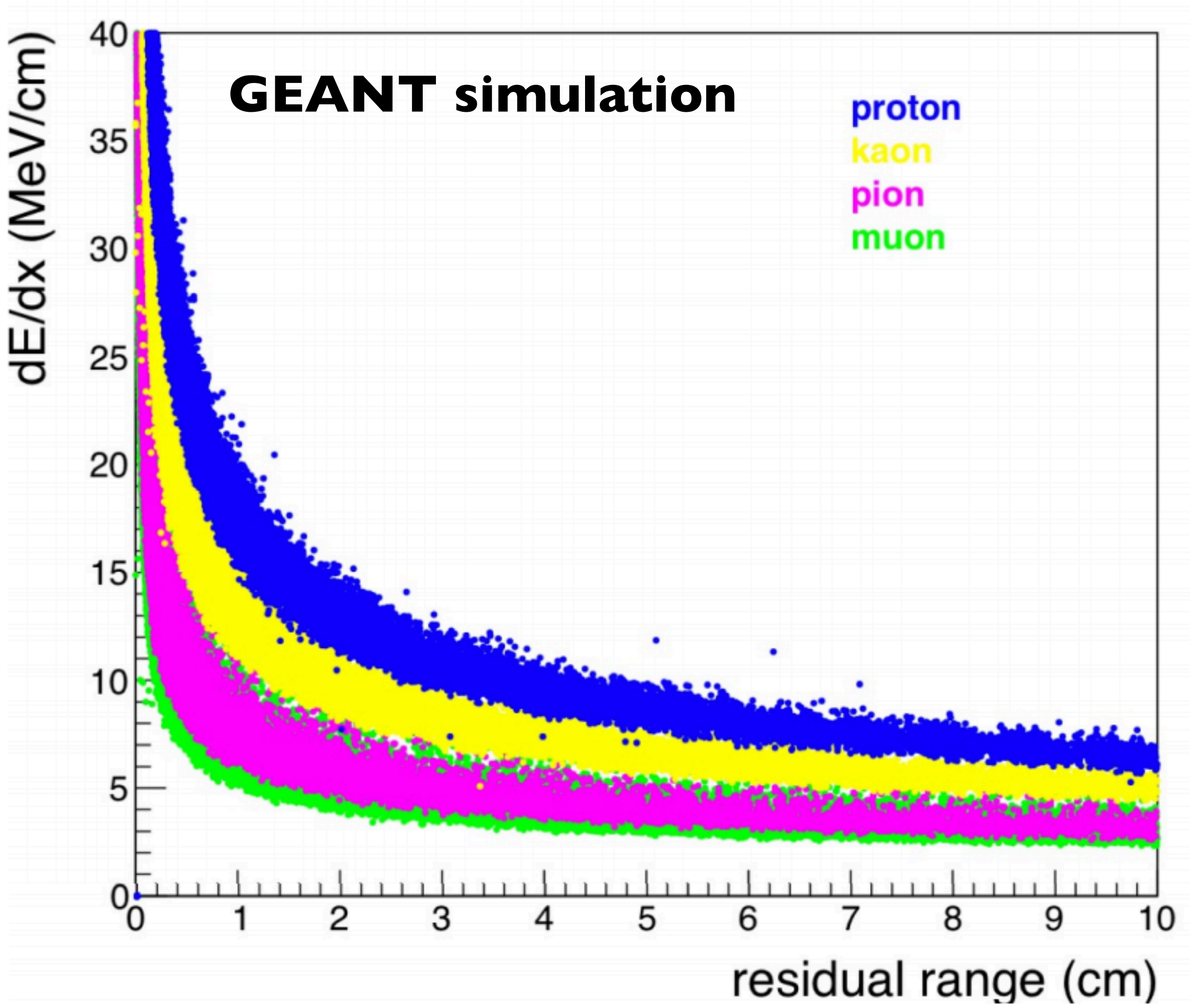
SBND

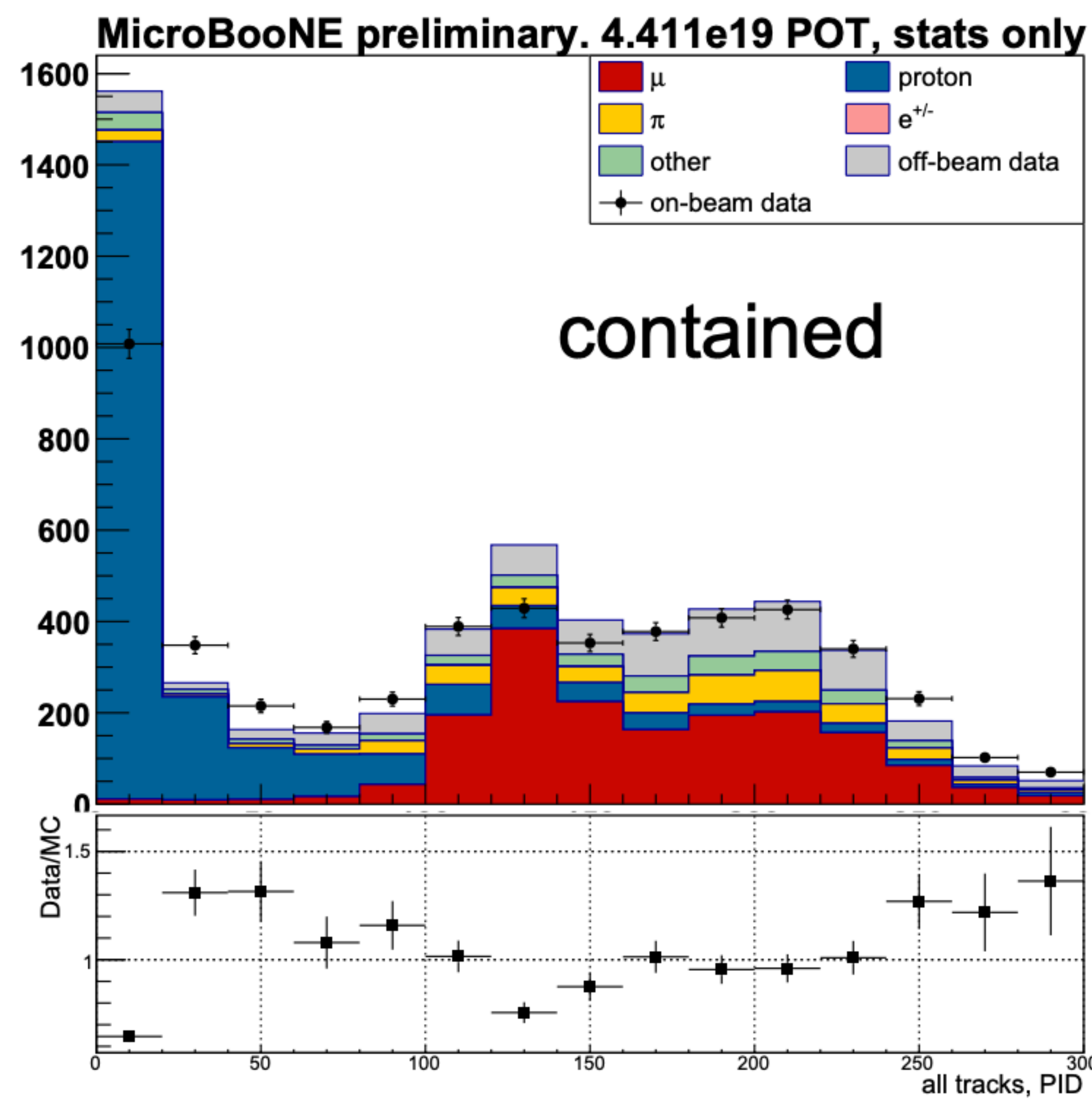


IDENTIFYING π^+

MICROBOONE-NOTE-1056-PUB

Separate charged pions from protons using deposited energy in track per unit length

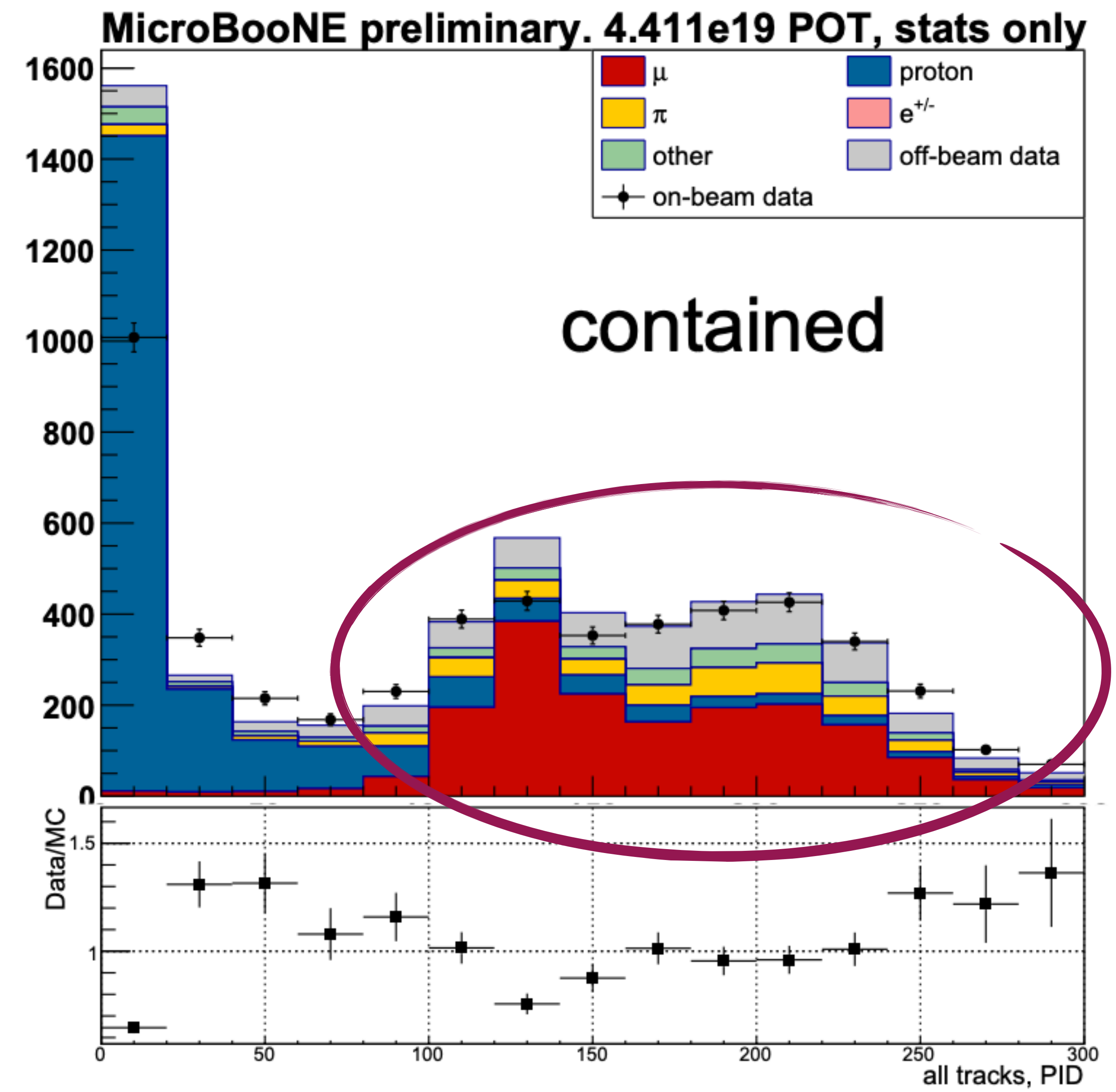




IDENTIFYING π^+

MICROBOONE-NOTE-1056-PUB

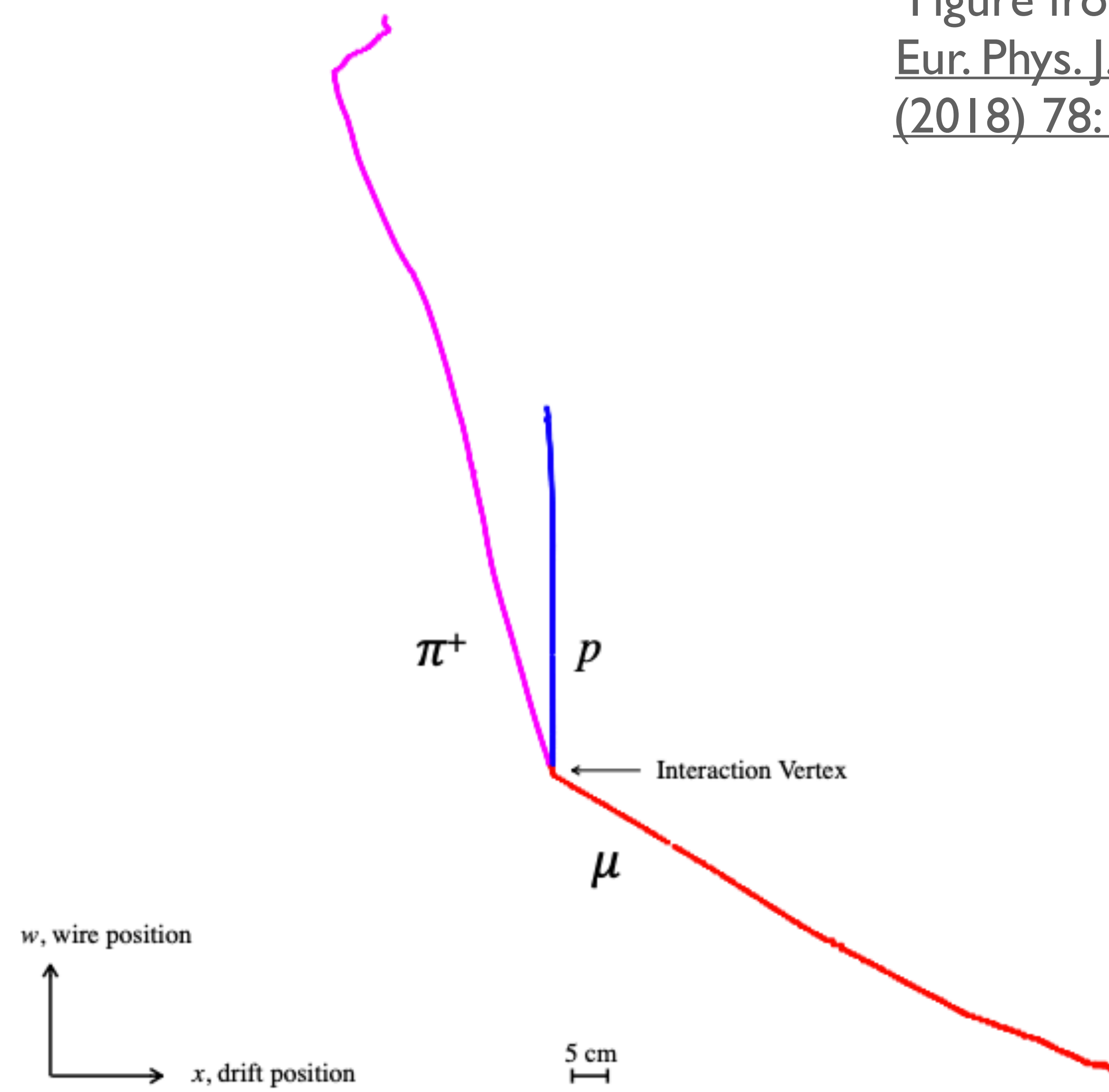
- Separating **charged pions** from **muons** is harder → at our energies, dE/dx profile is ~identical
- So how can we distinguish charged pions from muons in a CC1pi+ measurement?



RECONSTRUCTING π^+

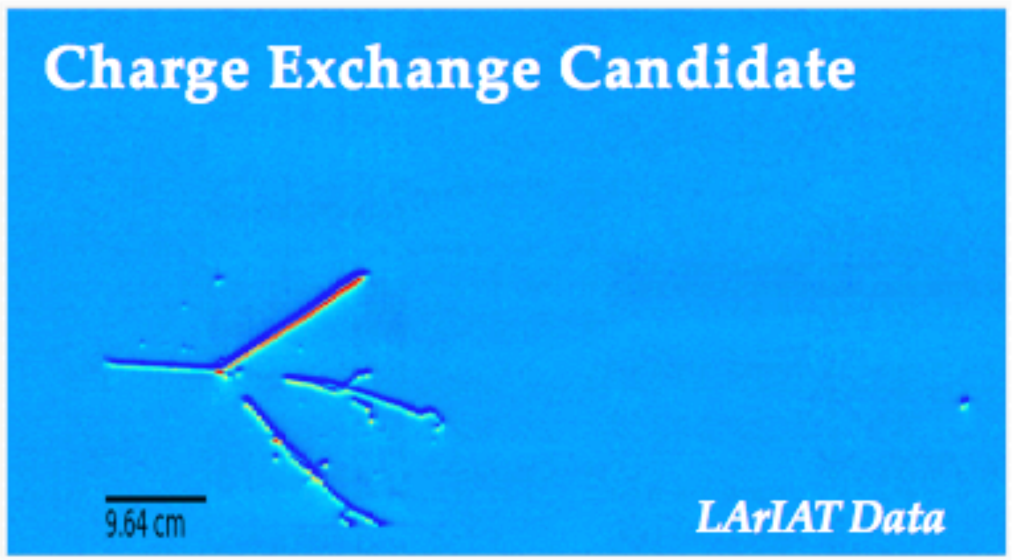
- Charged pions can be difficult to reconstruct
  - Large amount of scattering: may be reconstructed as a shower, rather than a track
  - Secondary vertices often missed: pion and daughters can be merged

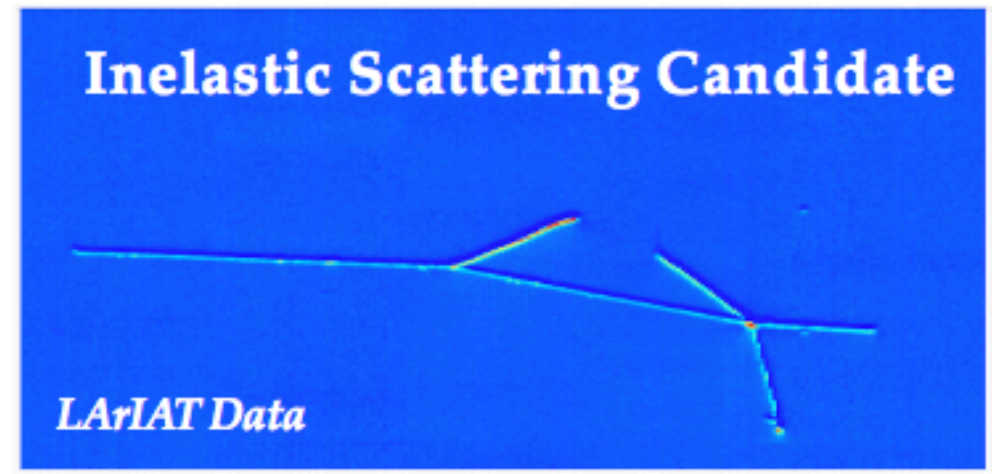
Figure from [Eur. Phys. J. C (2018) 78: 82]

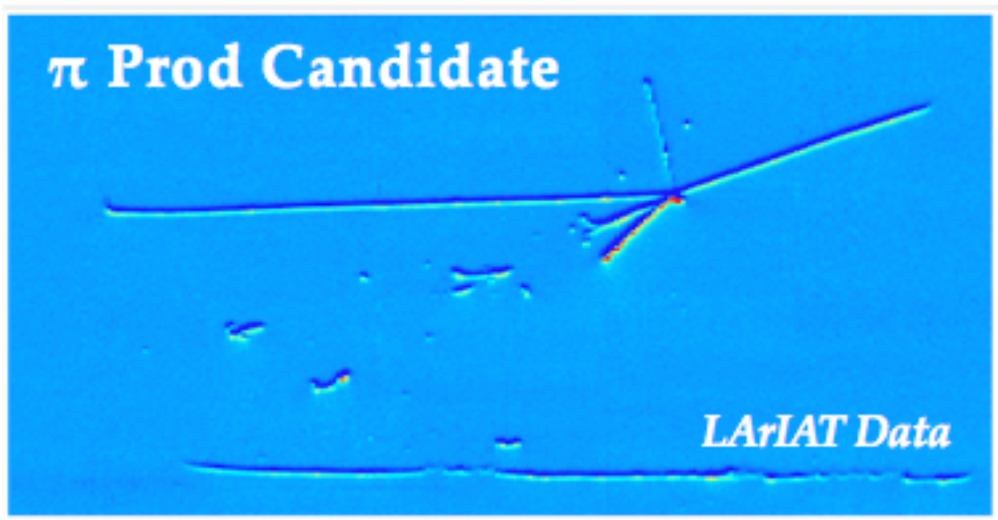


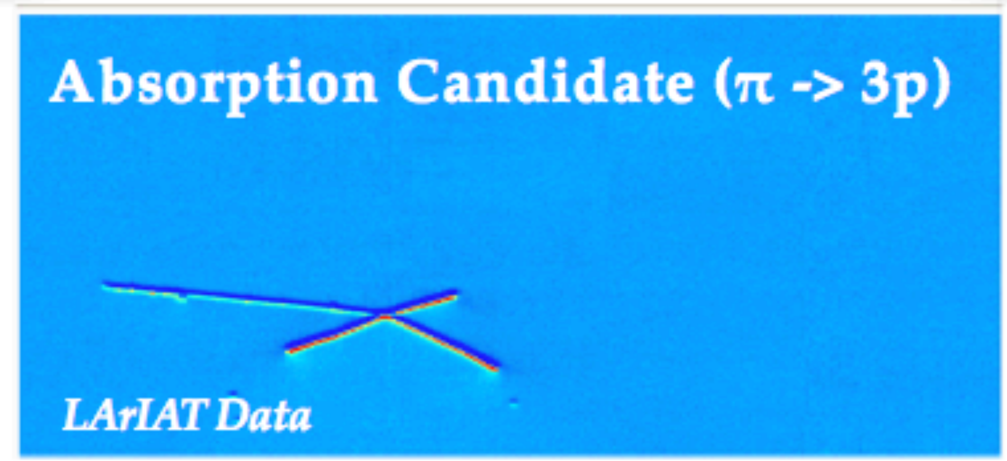
Slide source: Elena Gramellini, Fermilab Neutrino Seminar

HADRONIC INTERACTIONS





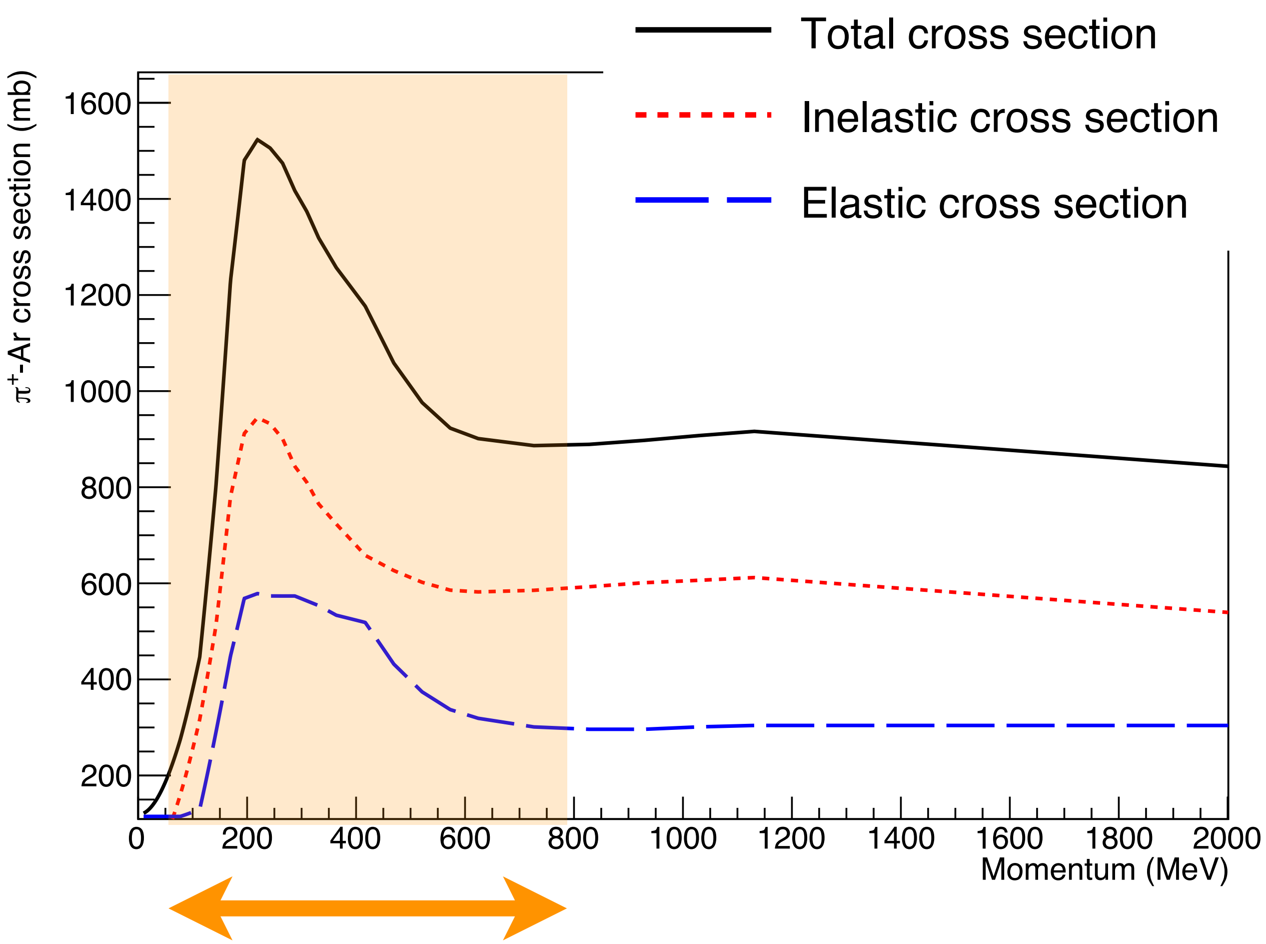


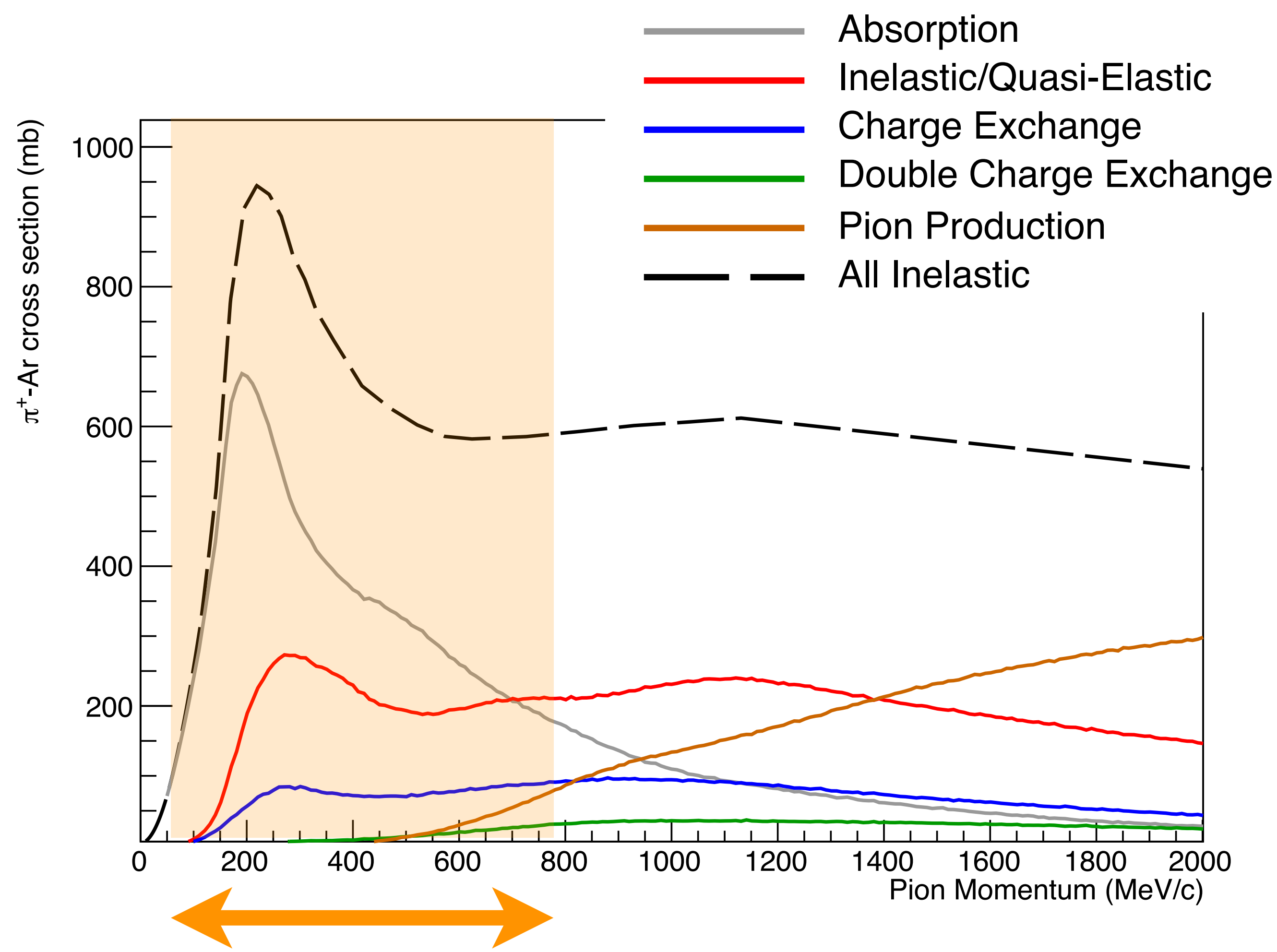


LArIAT Data

π^+ INTERACTIONS

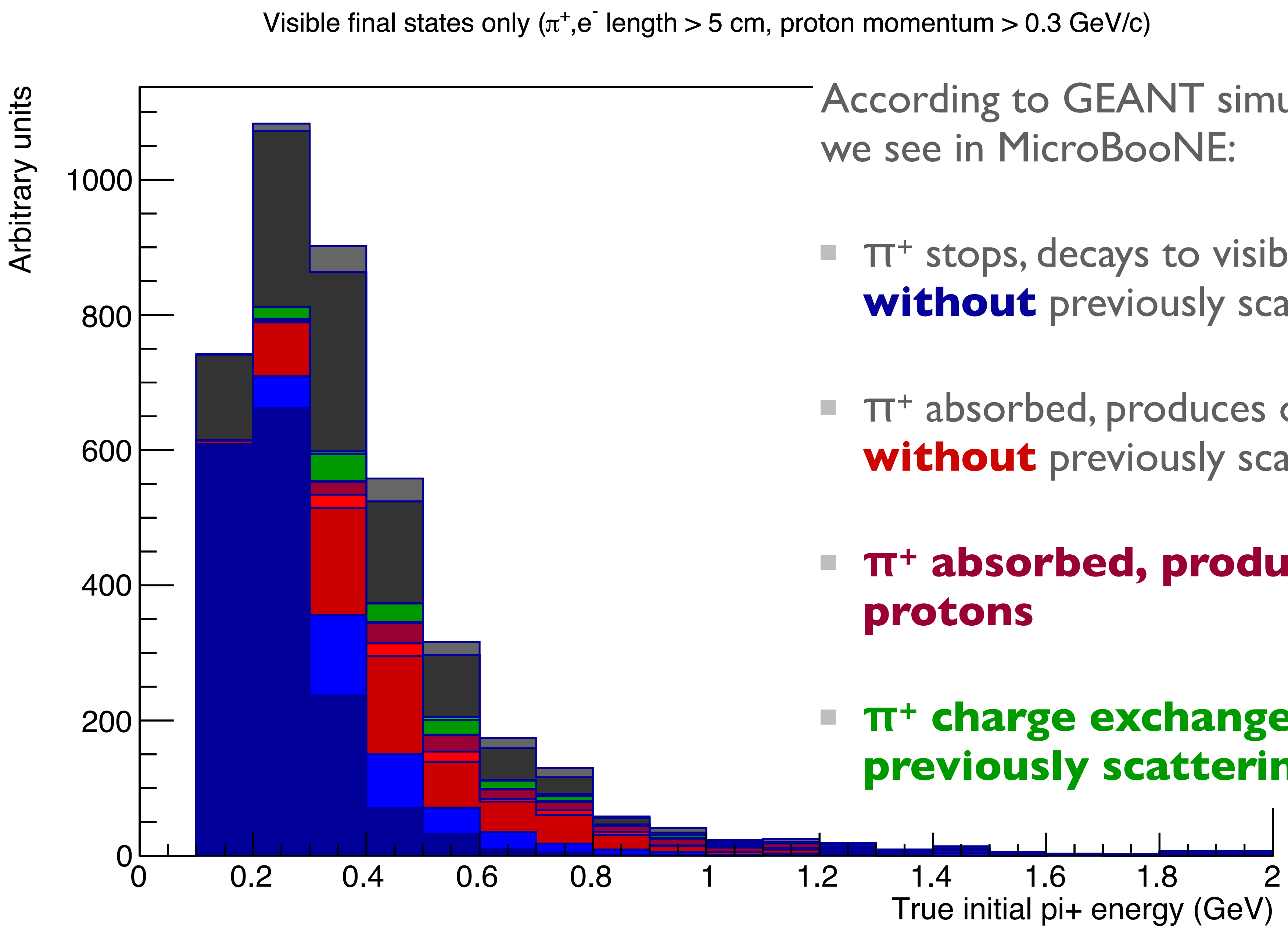
Plots made using GEANTReWeight (J. Calcutt)





Roughly speaking, GENIE predicts π^+ produced in MicroBooNE will fall in **this energy range**

PUTTING IT ALL TOGETHER



According to GEANT simulation expect majority of what we see in MicroBooNE:

- π^+ stops, decays to visible Michel electron (**with** or **without** previously scattering)
- π^+ absorbed, produces one visible proton (**with** or **without** previously scattering)
- **π^+ absorbed, produces multiple visible protons**
- **π^+ charge exchange: produces π^0 without previously scattering**