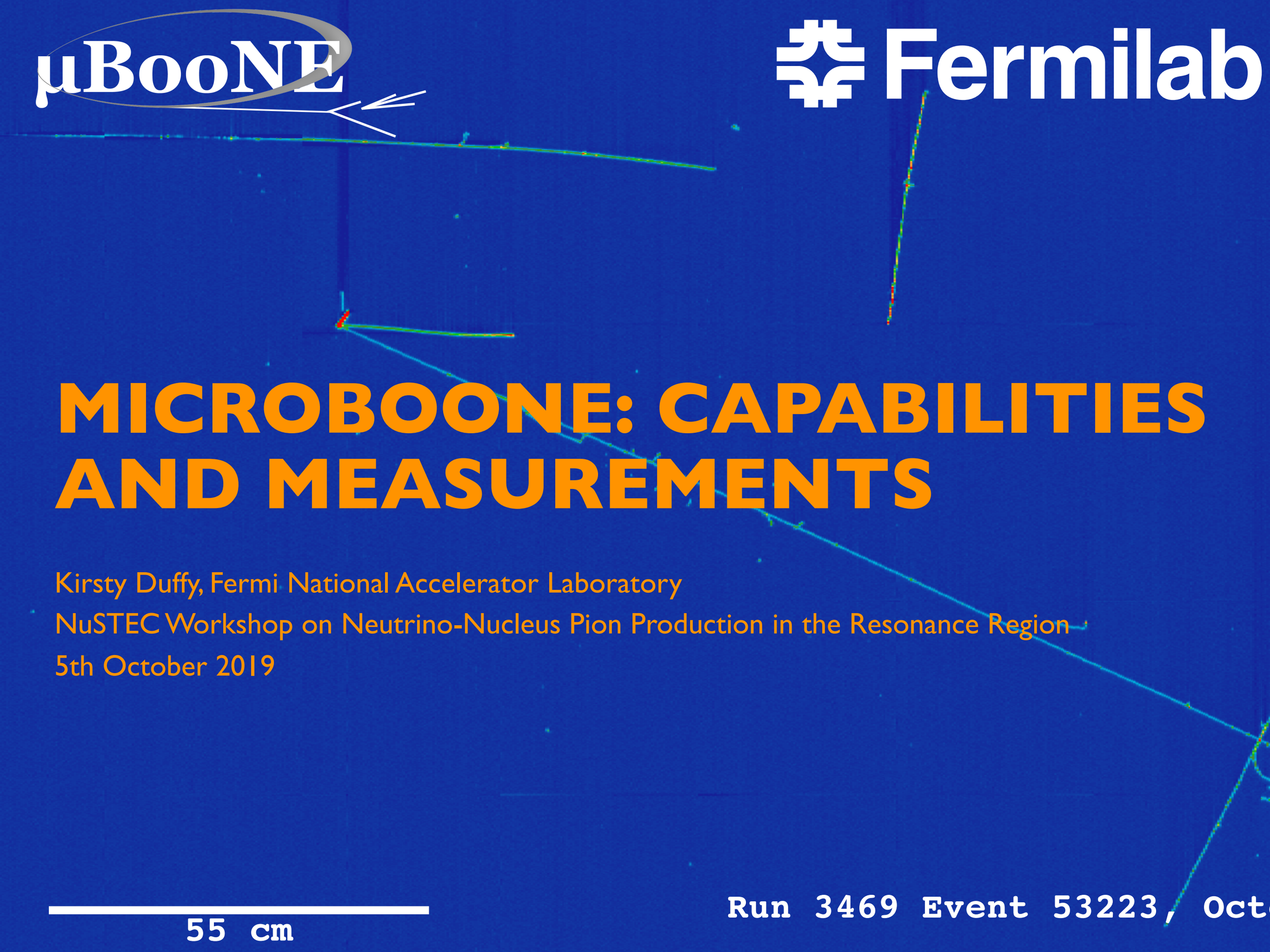
MICROBOONE: CAPABILITIES AND MEASUREMENTS

Kirsty Duffy, Fermi National Accelerator Laboratory

NuSTEC Workshop on Neutrino-Nucleus Pion Production in the Resonance Region

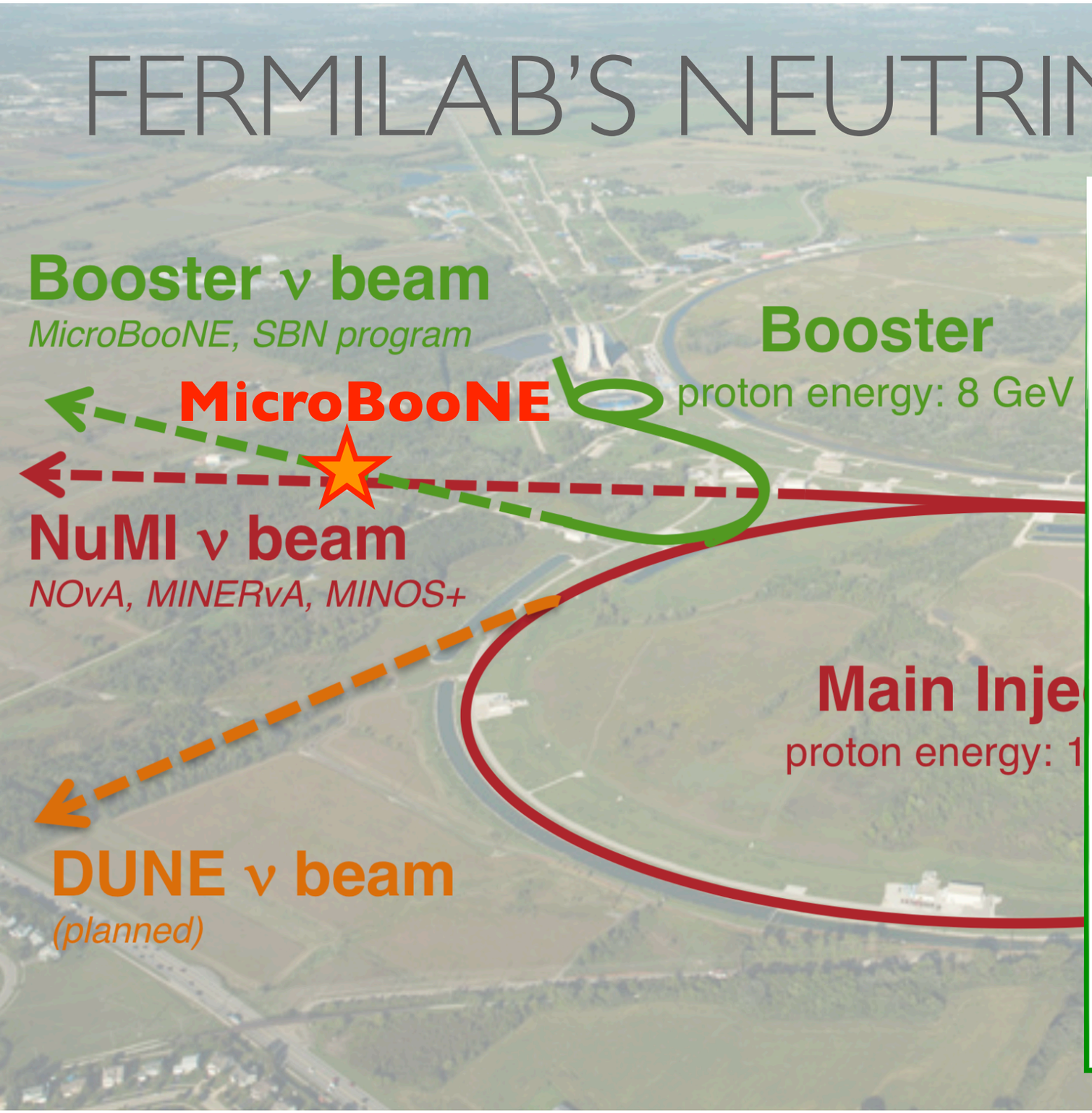
5th October 2019



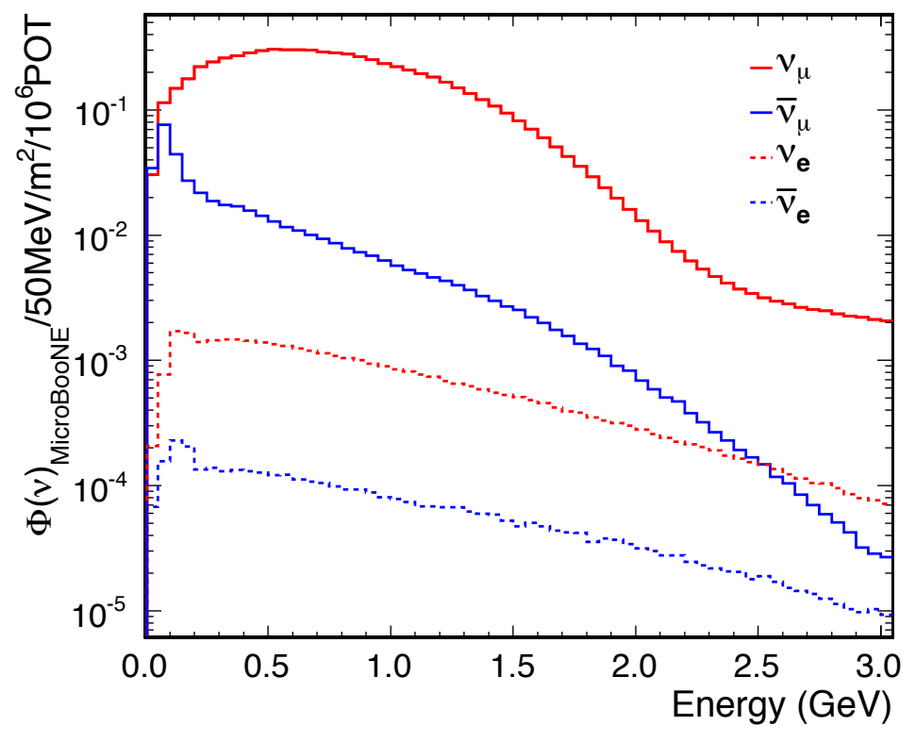
MicroBooNE: a 170 ton Liquid Argon Time Projection Chamber (LArTPC)

2.5 x 2.3 x 10.4 m TPC volume

FERMILAB'S NEUTRINO BEAMS



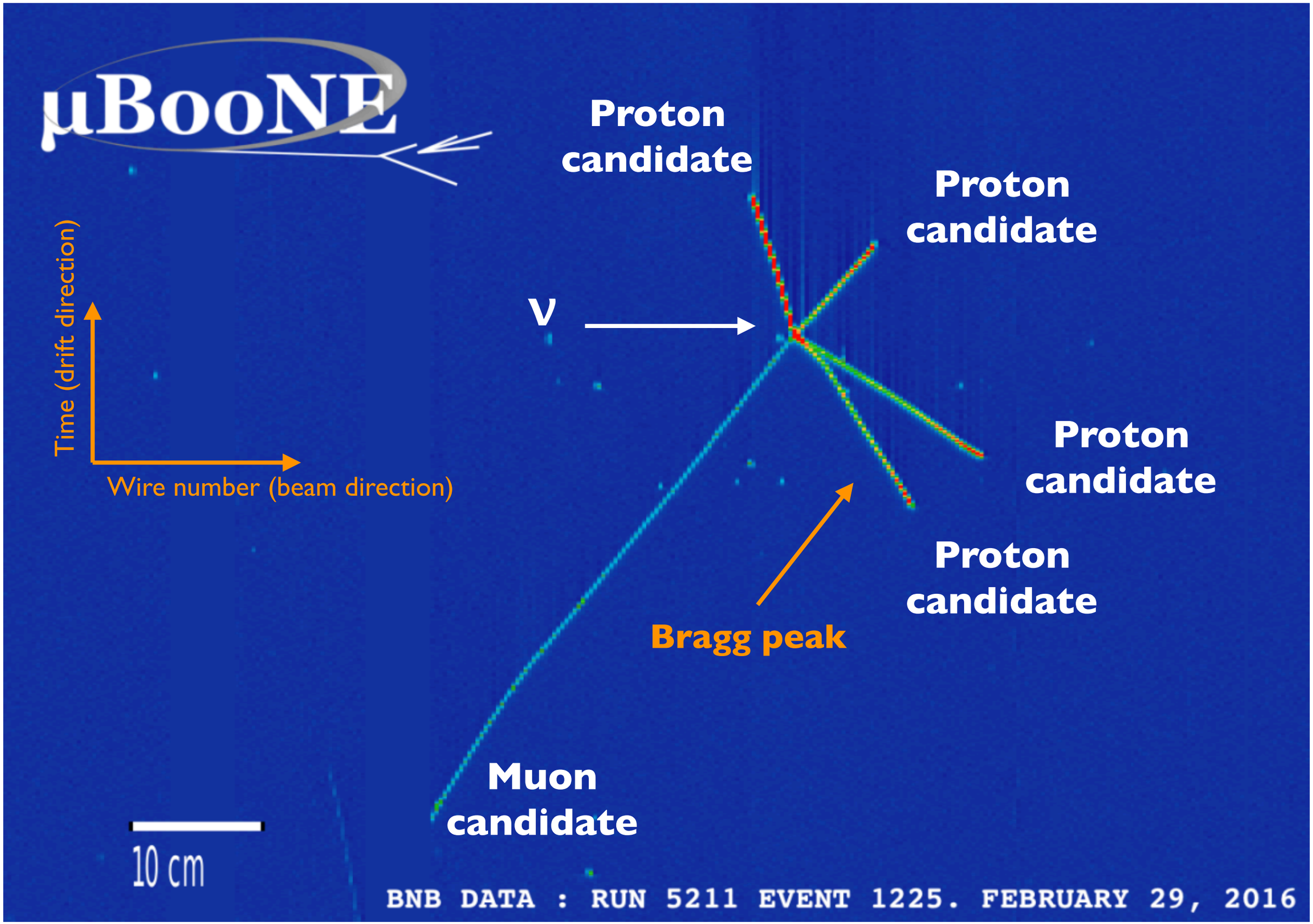
Booster Neutrino Beam (BNB): 463m



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

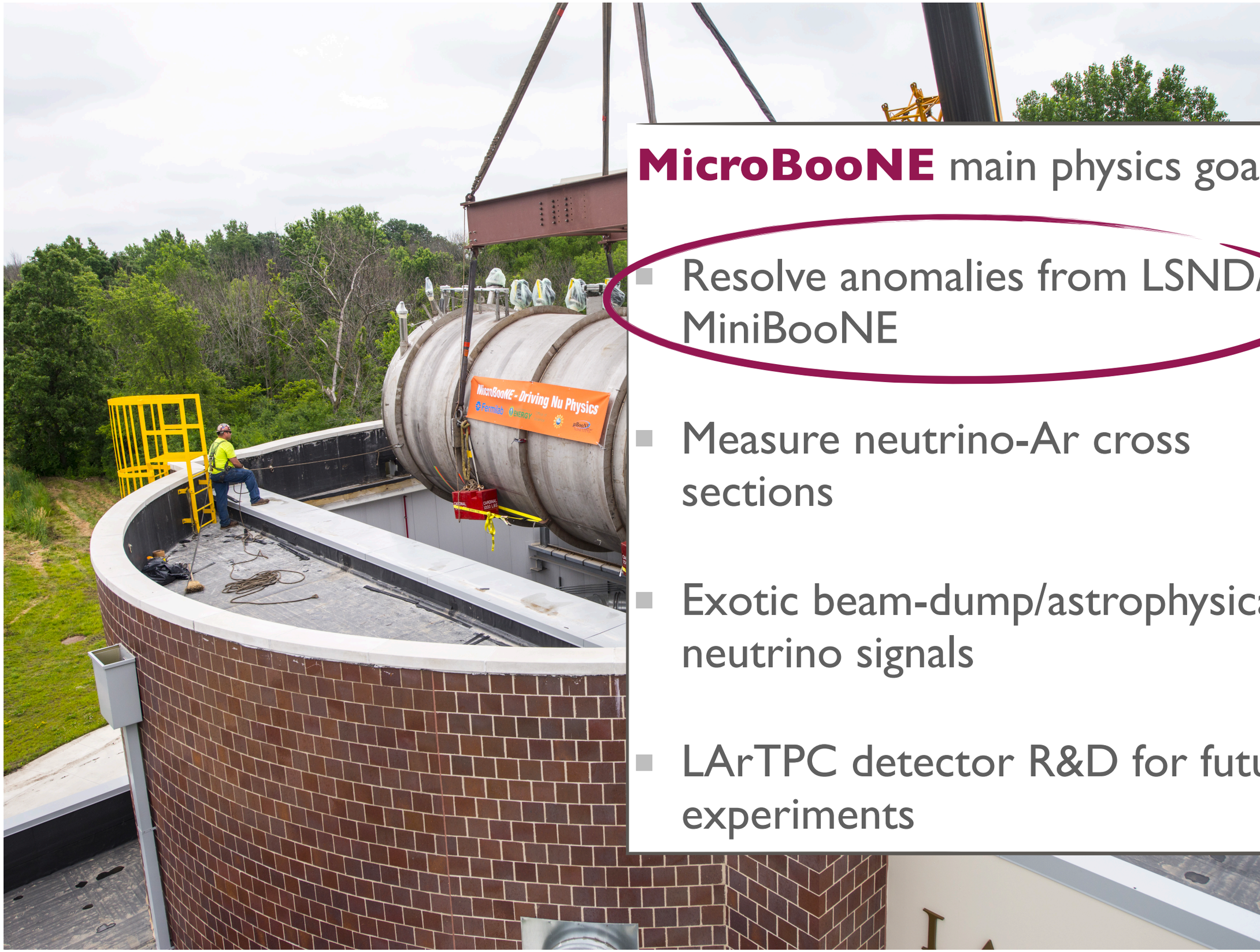
$\langle E_\nu \rangle$ = 850 MeV

Image: G. Zeller


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 main physics goals:

- Resolve anomalies from LSND/ MiniBooNE
- Measure neutrino-Ar cross sections
- Exotic beam-dump/astrophysical neutrino signals
- LArTPC detector R&D for future experiments



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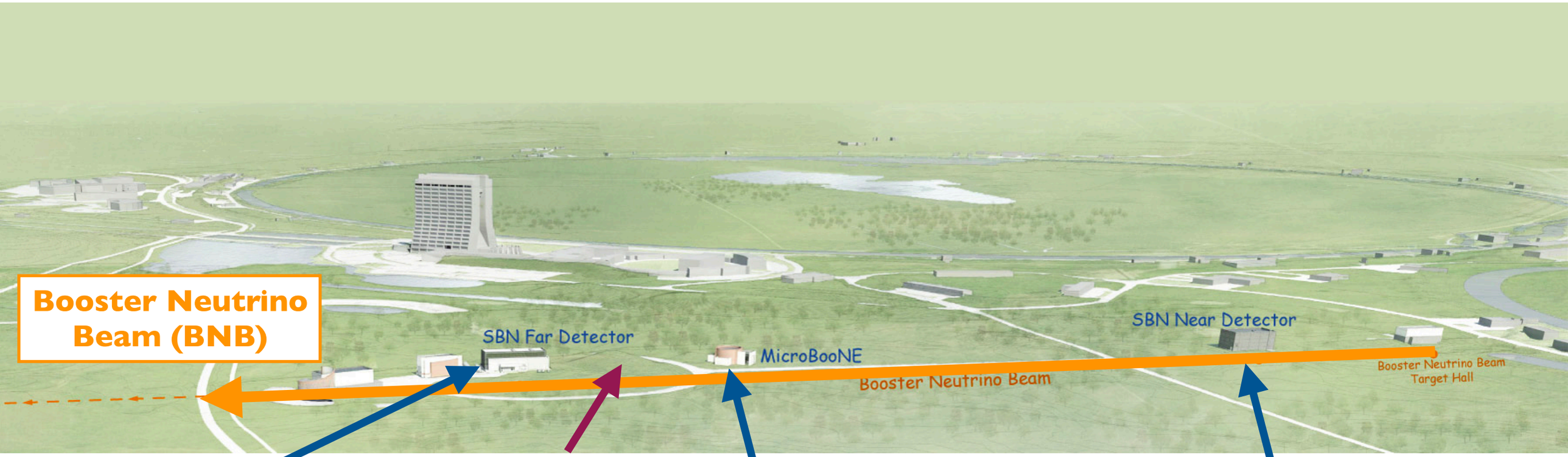
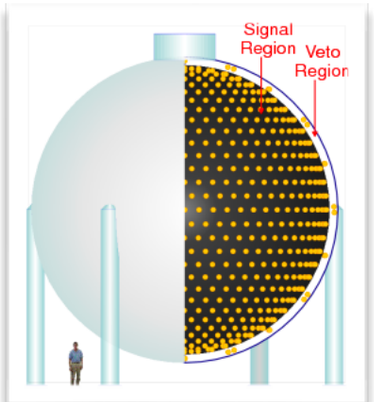
SHORT-BASELINE NEUTRINOS AT FERMILAB



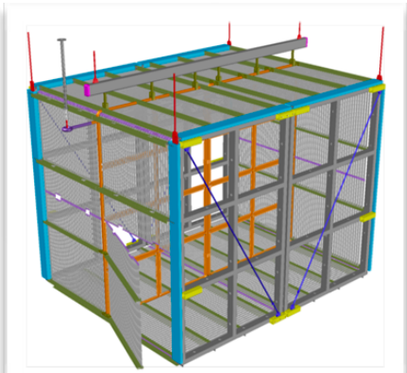
ICARUS

MiniBooNE

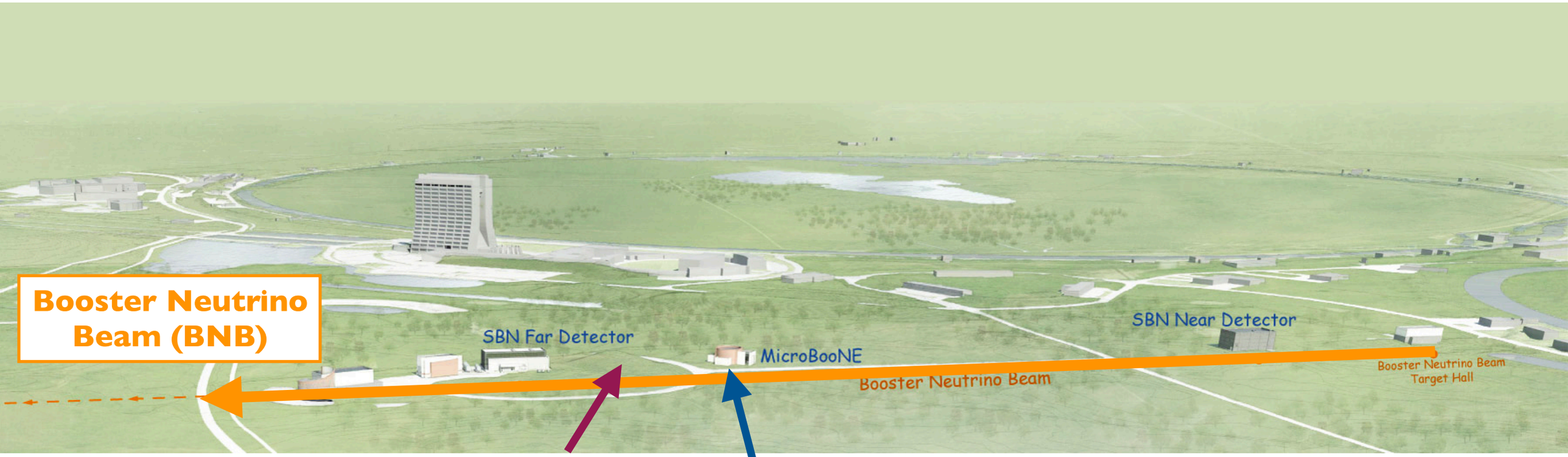


MicroBooNE

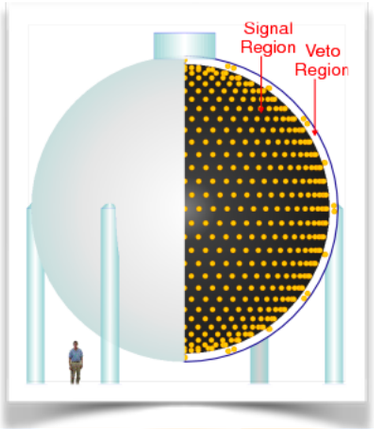
SBND



SHORT-BASELINE NEUTRINOS AT FERMILAB

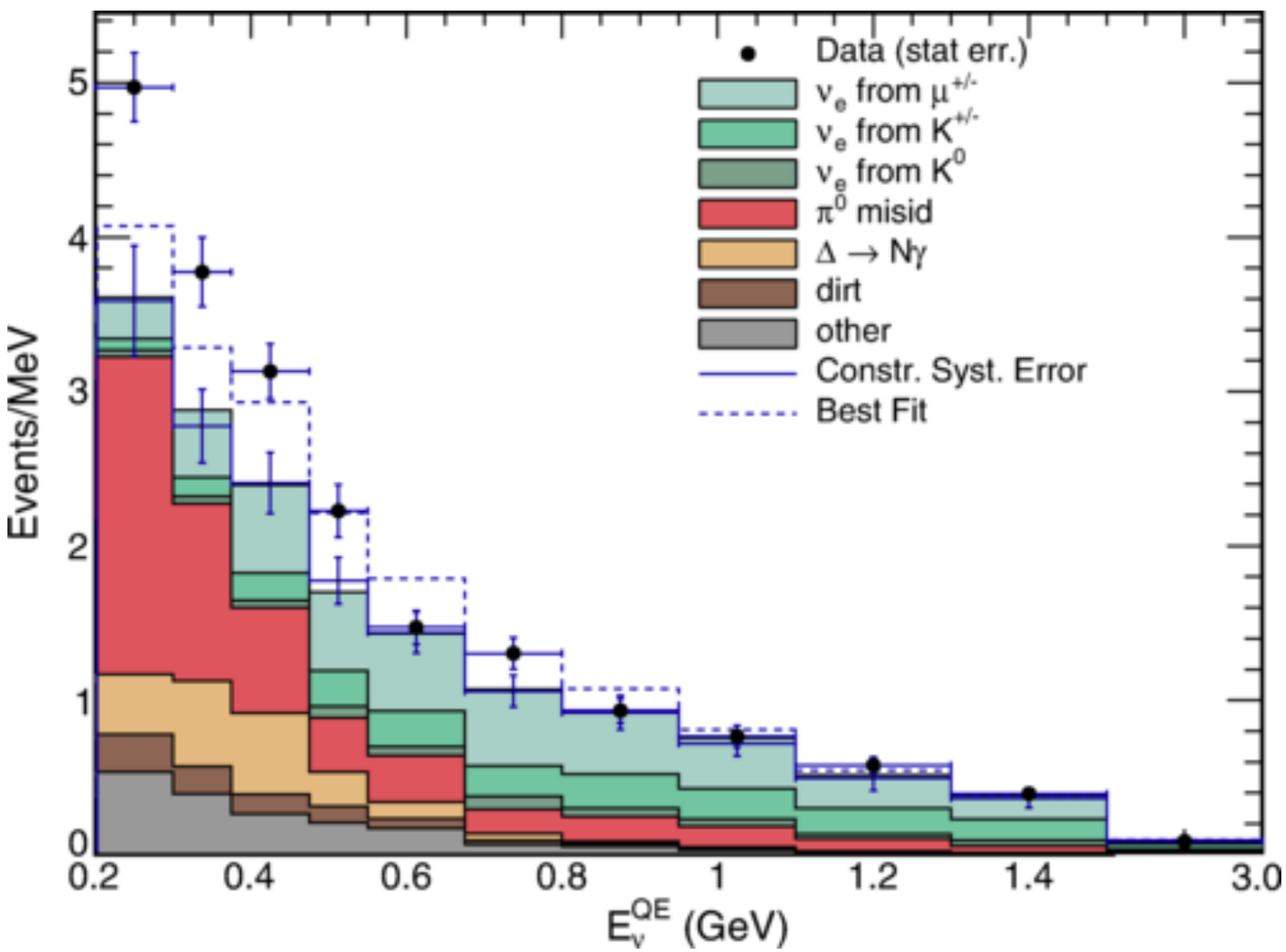


MiniBooNE



MicroBooNE

LOW-ENERGY EXCESS: MINIBOONE



- Most recent result published in 2018:
- 4.7σ excess of measured ν_e and $\bar{\nu}_e$ over prediction at low energies
  - → "Low Energy Excess" (LEE)
- Largest background from photons (π^0 or $\Delta \rightarrow N\gamma$) because MiniBooNE could not distinguish between $e^{\pm}$ and γ (mineral oil Cherenkov detector)

Phys. Rev. Lett. 121, 221801

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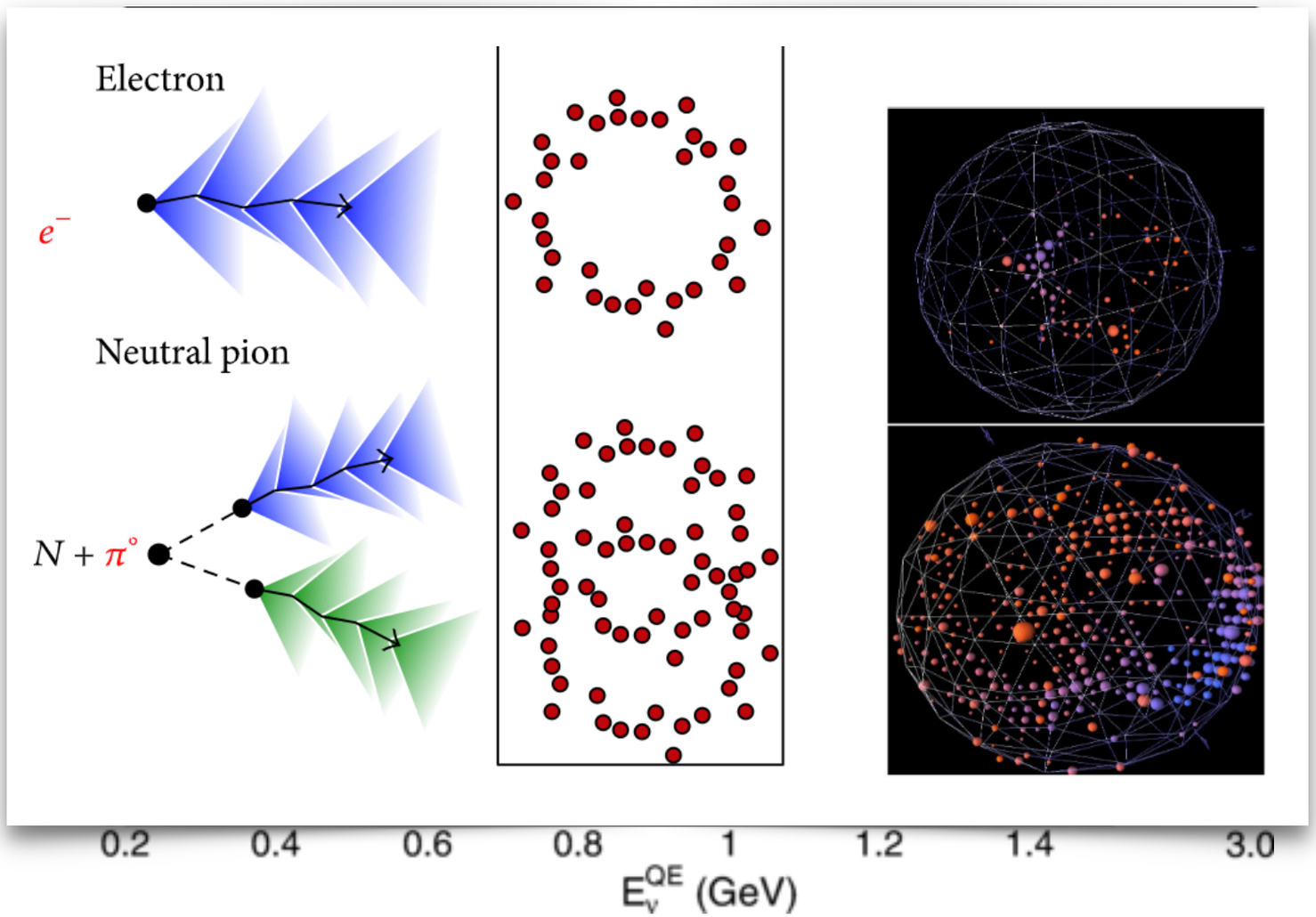

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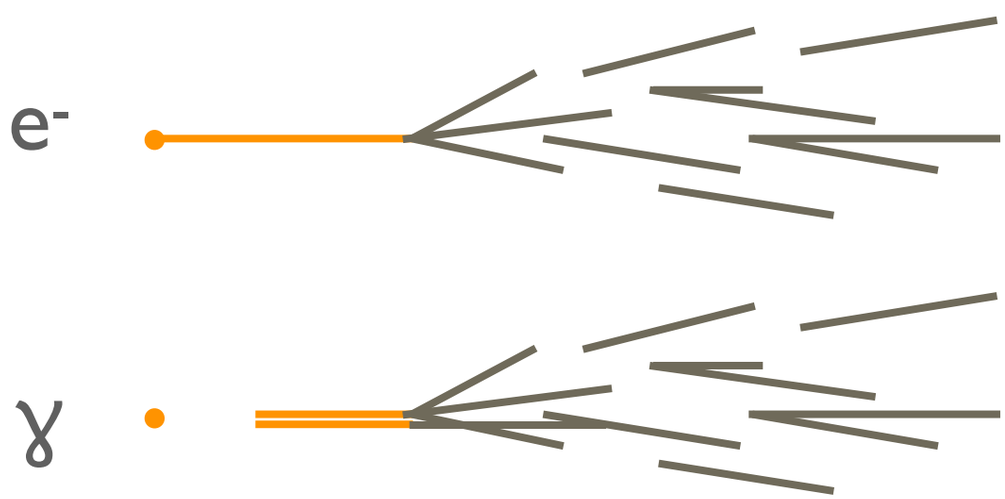
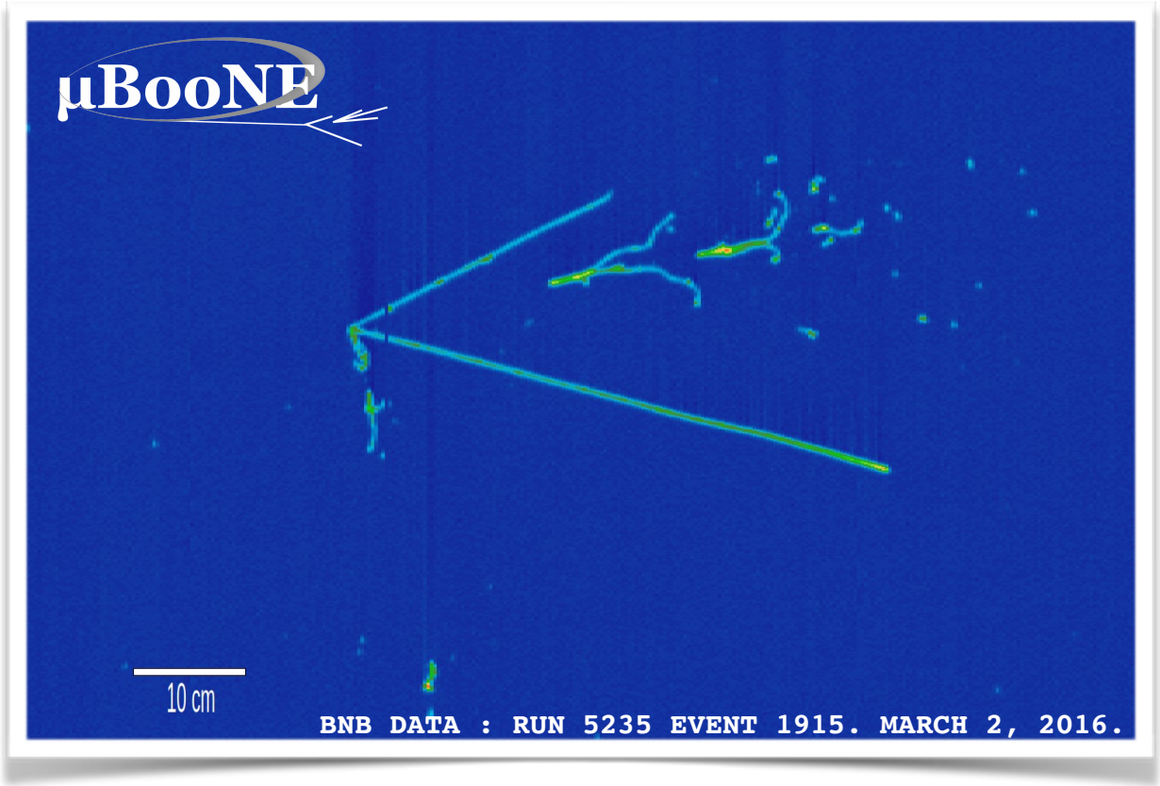
Phys. Rev. Lett. 121, 221801

LOW-ENERGY EXCESS: MICROBOONE

MicroBooNE (LArTPC) can distinguish electrons from photons → resolve nature of MiniBooNE low-energy excess

1) Shower start





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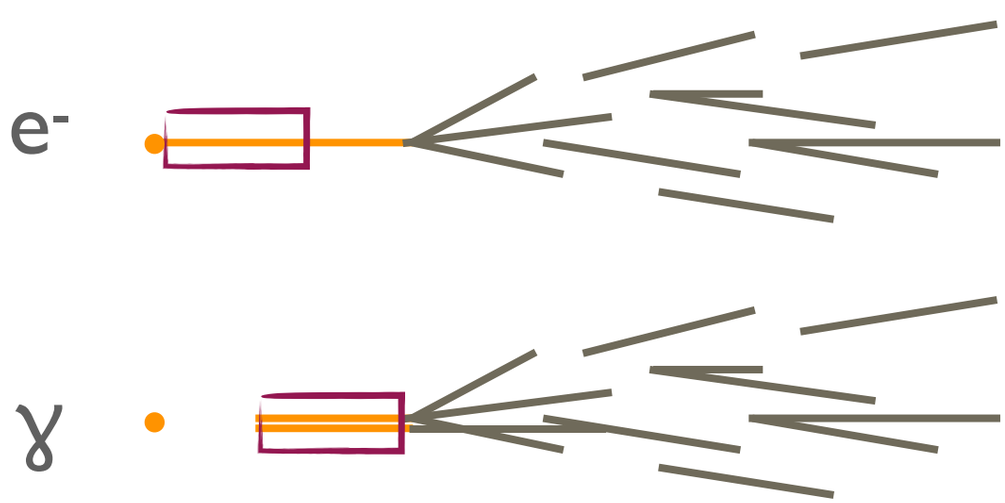
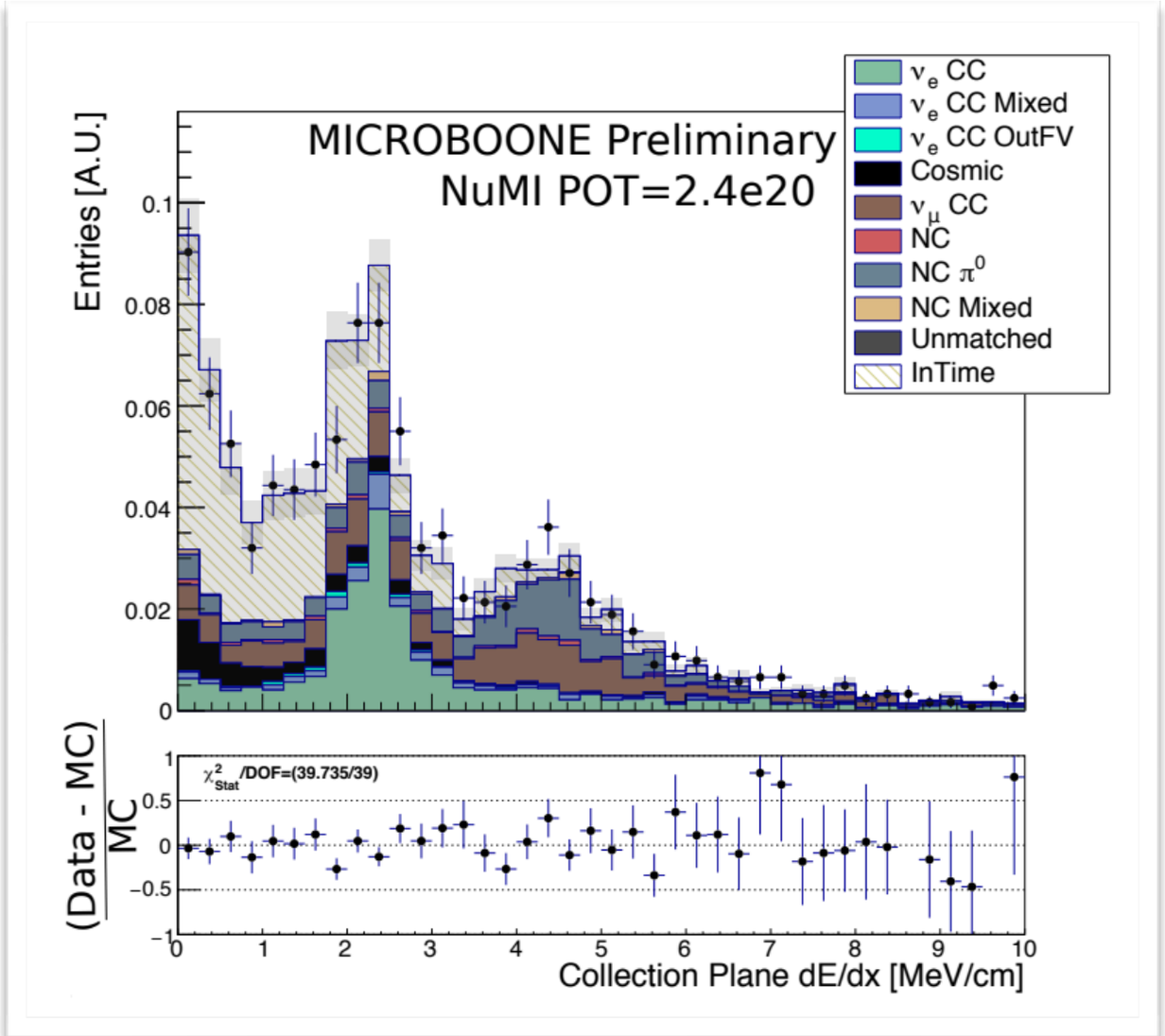


2) dE/dx



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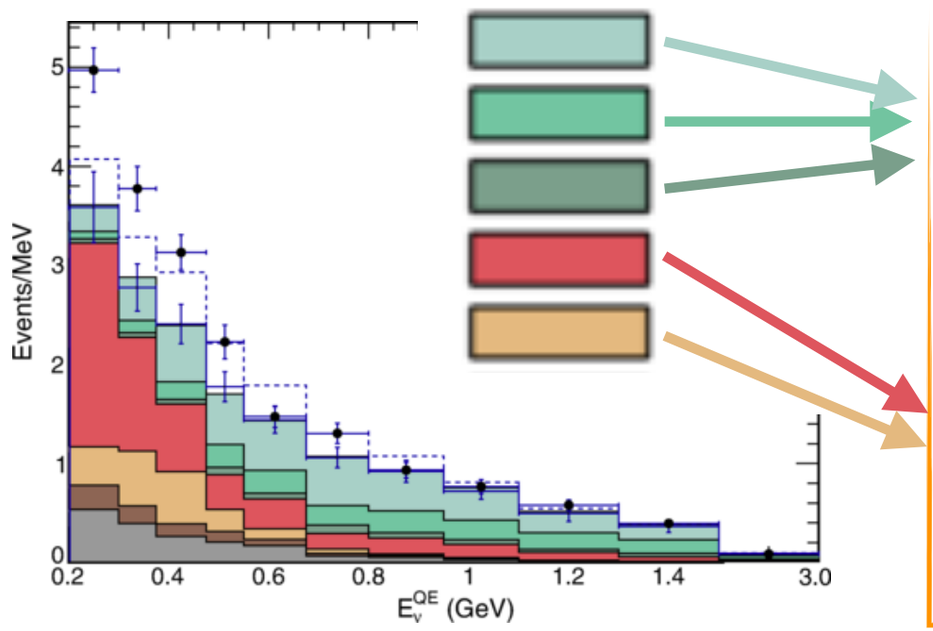


Signal channels

Electron-like → 1e1p
→ 1eNp (N>=1)
→ 1e

Photon-like → 1γ0p
→ 1γ1p

Sideband background constraints

ν_μ CC interactions → constrain neutrino flux and cross-section uncertainties (common between ν_e and ν_μ)

CC π^0, NC π^0 → constrain π^0 background

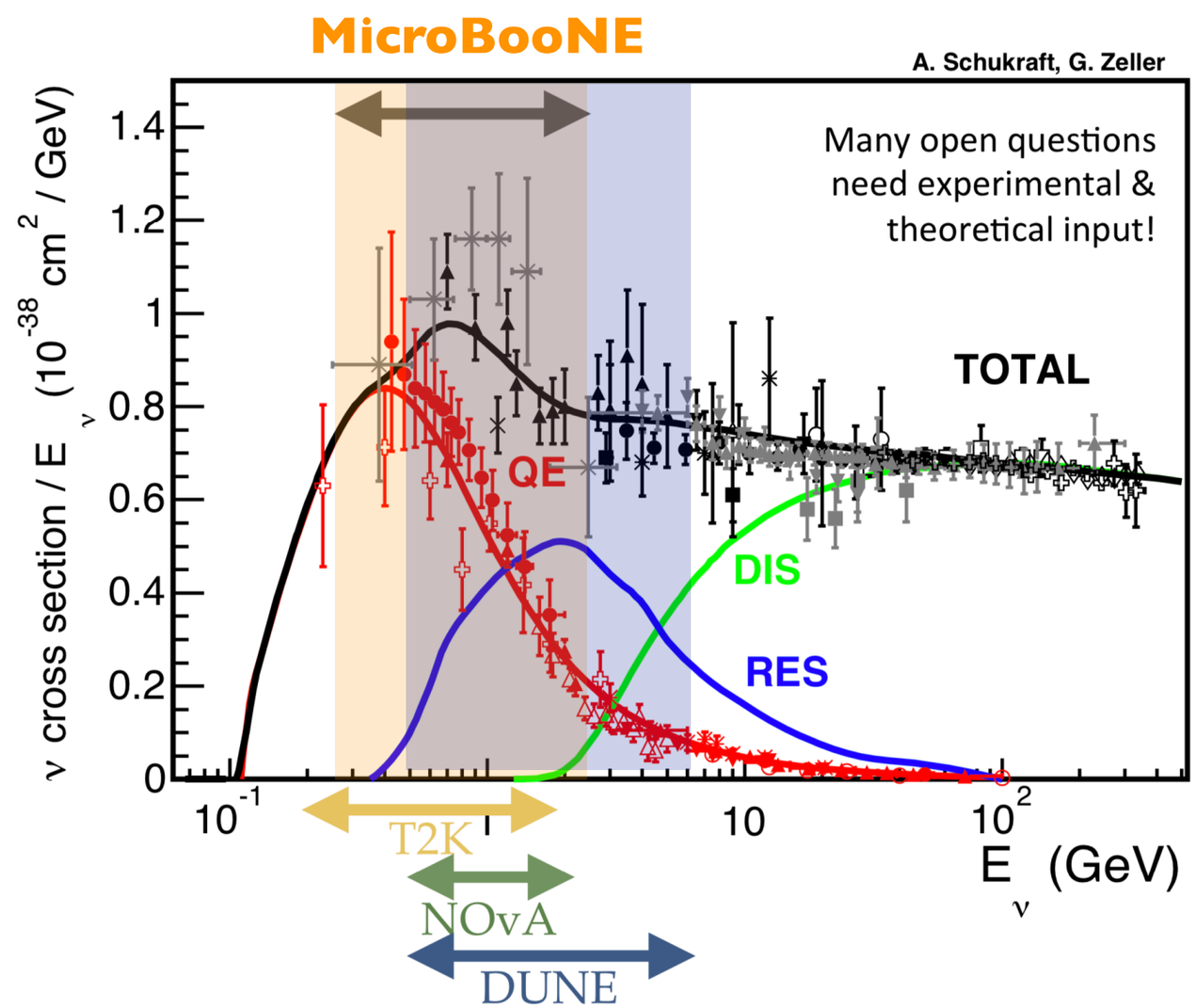
RESONANT INTERACTIONS IN MICROBOONE LEE

Resonant interactions form significant parts of the signal and backgrounds to MicroBooNE's LEE analysis, in ways that are also strongly dependent on FSI

- **Signal**
  - **CC0pi** → large component (O(15%), but model dependent) from resonant pion production with pion absorbed
- **Background**
  - **Neutral pions** (80% of background in γ-like signal)
    - → constrain with a sideband of our own data: $CC\pi^0$ and $NC\pi^0$ selections
    - Need models to describe the data well enough that our sideband will be valid
    - Cross-section measurements: $CC\pi^0$ (published, to be updated), $NC\pi^0$ (planned)
  - **Charged pions**
    - Inclusive ν_e searches → $NC\pi^+$ background to ν_μ CC0π sideband
    - ν_e searches requiring a proton require a ν_μ CC0π1p sideband → $NC\pi^-p$ background ($NC\pi^+p$ suppressed). Current estimate O(%), no current hope to constrain or measure in our data — will have to rely on model

EXTRA MOTIVATION: DUNE

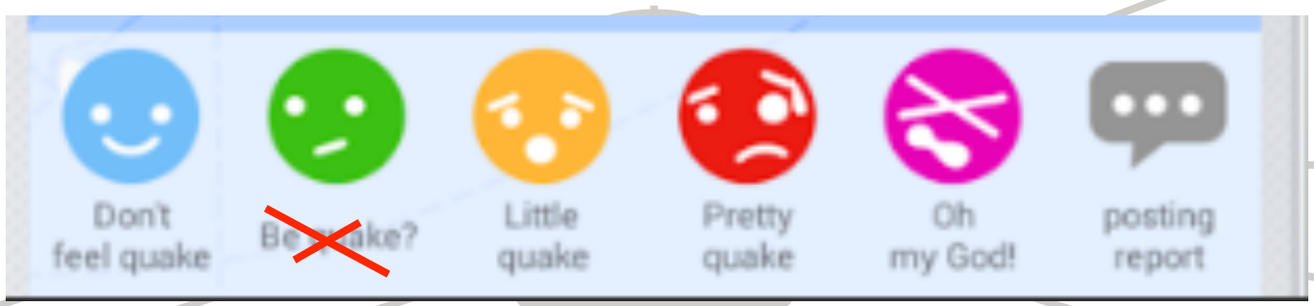
- CC pion production will be an oscillation signal channel for DUNE (and many backgrounds similar to MicroBooNE LEE)
- → MicroBooNE measurements (on argon) will be an important input
- But watch out: different energies, different types of interactions



Cross-section measurements today:

- Measurements that aren't specifically in the resonance region
- Measurements of neutral pions
- Measurements of charged pions

NOT-PION-SPECIFIC MEASUREMENTS



Be Pions?

CC-INCLUSIVE

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

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

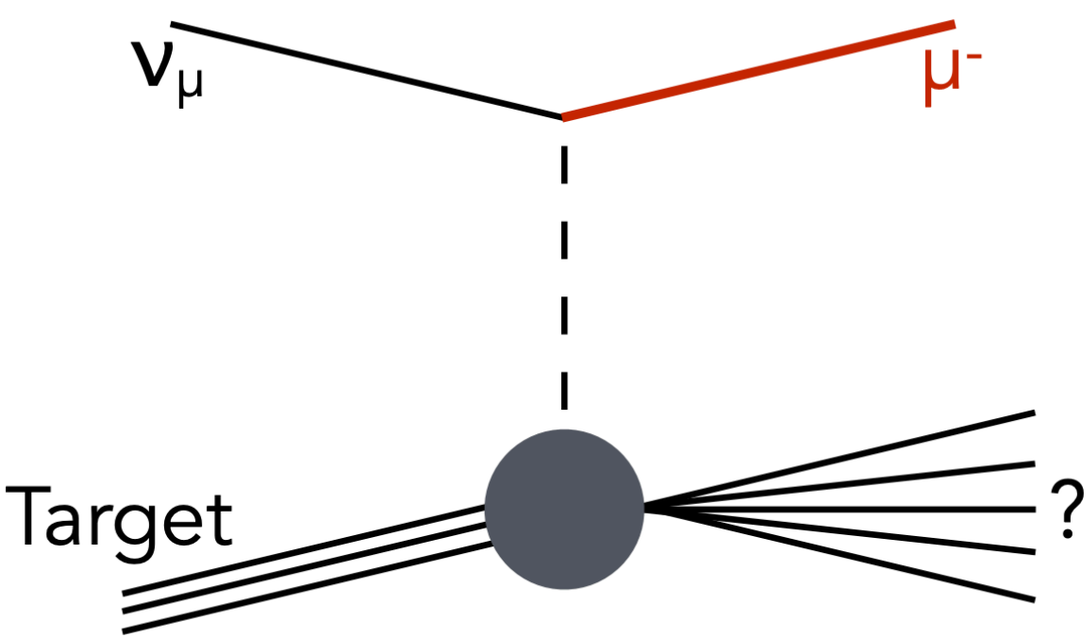


Figure from M. del Tutto

Event selection summary:

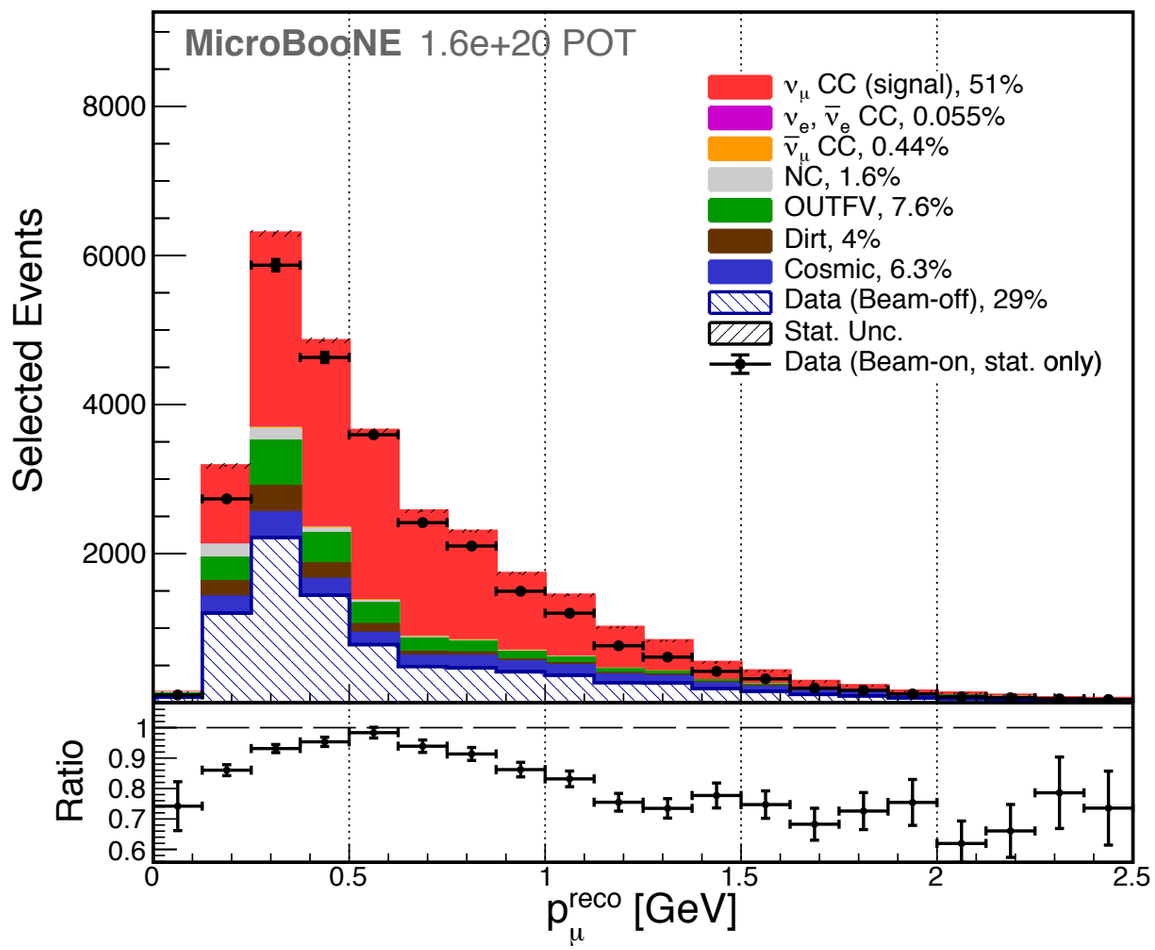
- Identify neutrino interaction using topological/calorimetric information to reject cosmic tracks
- Identify muon candidate as longest track in event — dE/dx must be consistent with a MIP

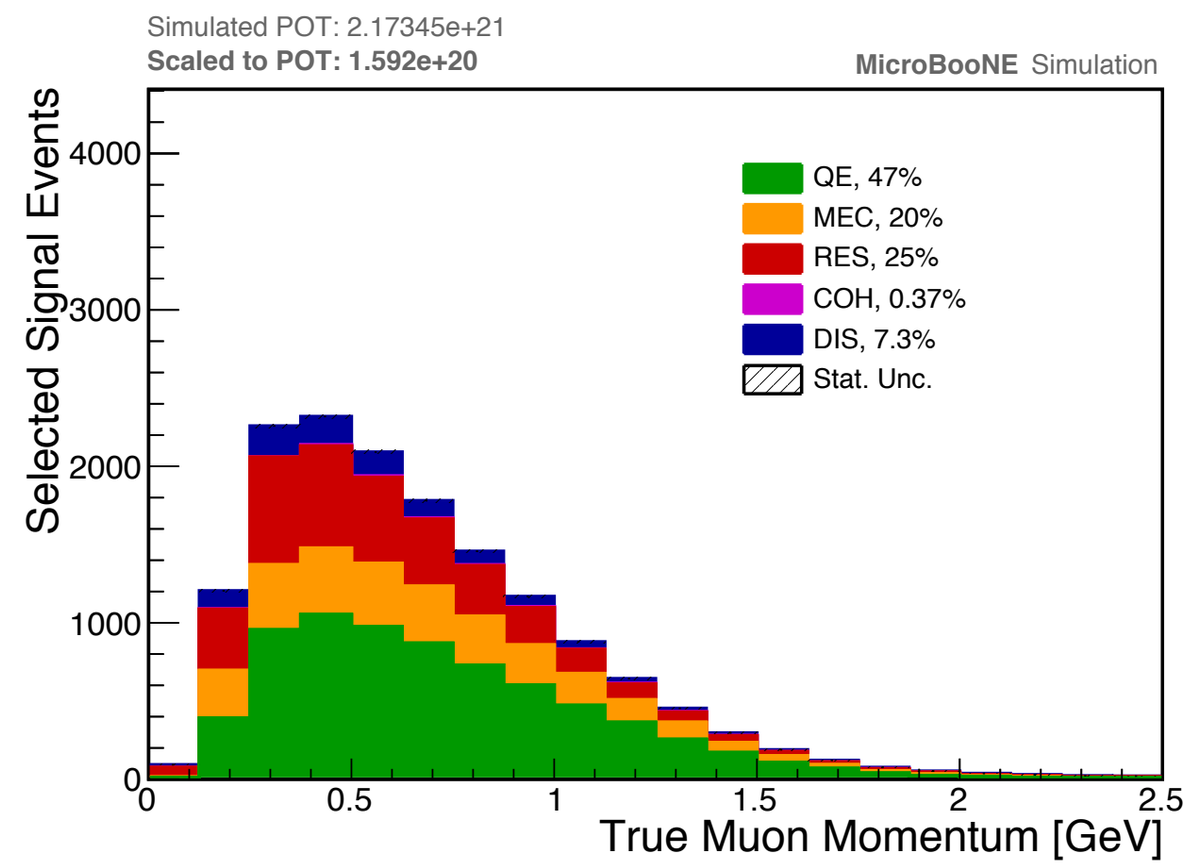
SELECTED EVENTS

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

Signal (CC-inclusive) events: 50.4%

Estimate 25% **resonant interactions**





SELECTED EVENTS

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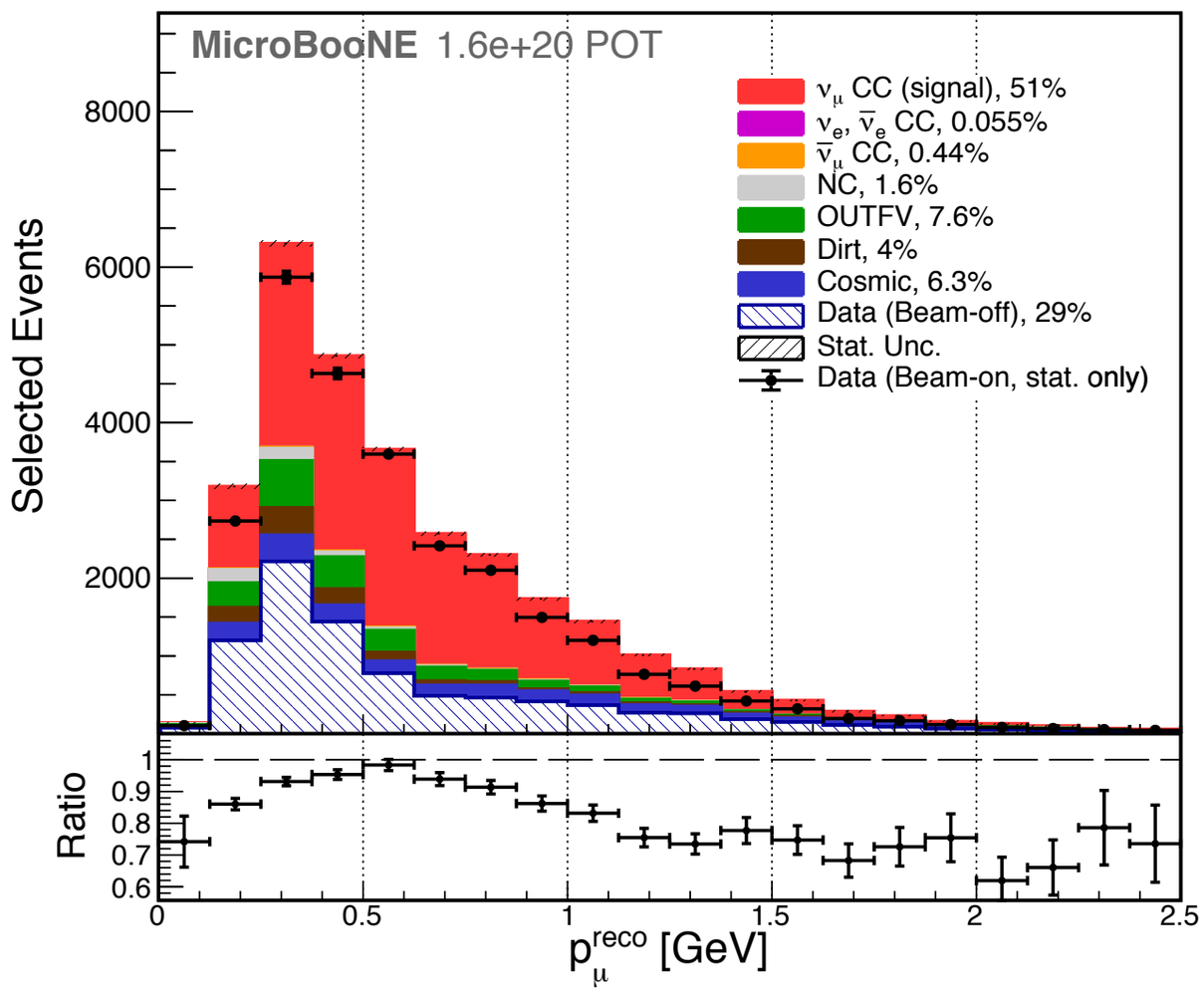
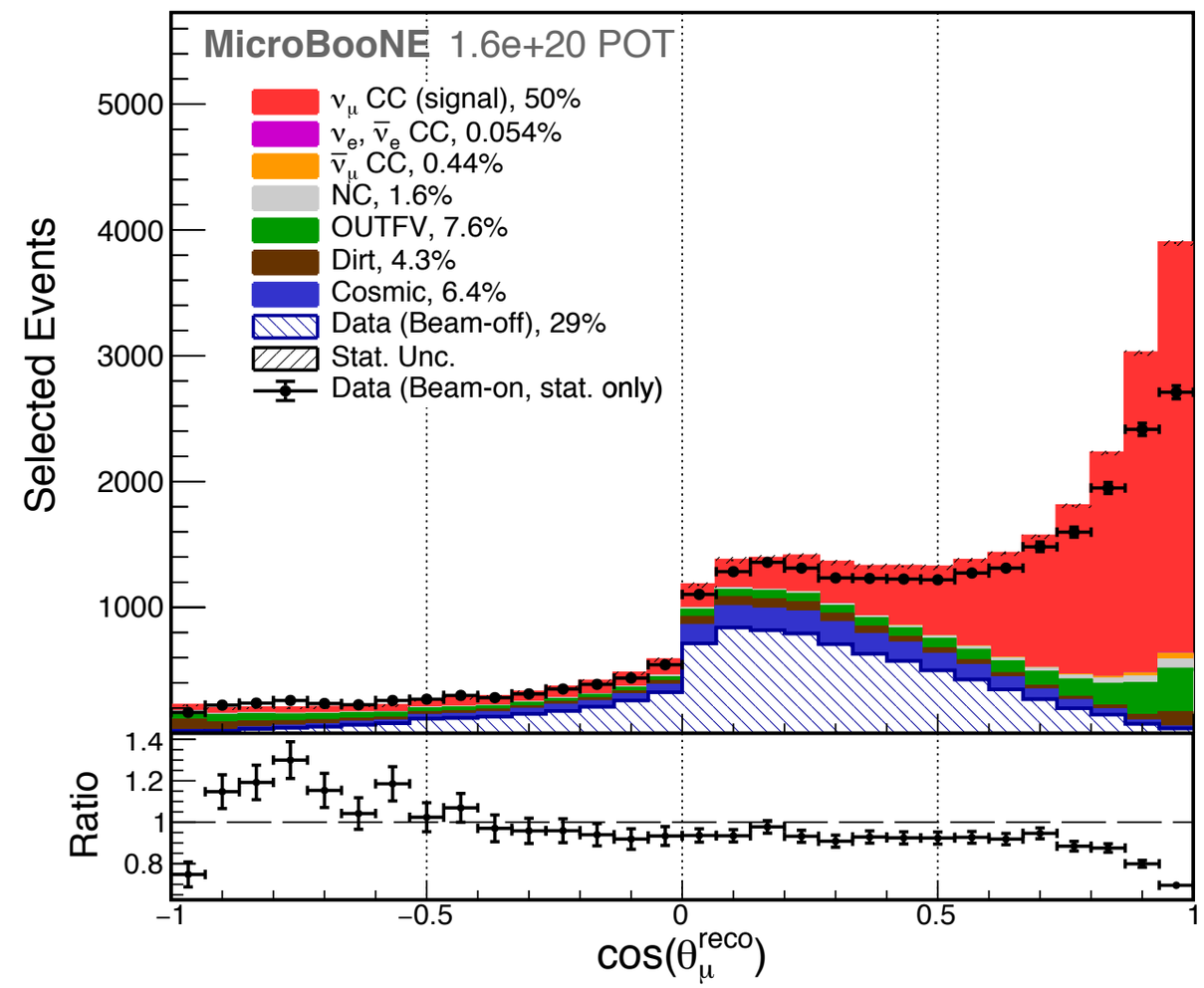




Largest ever sample of neutrino interactions on argon

CROSS SECTION

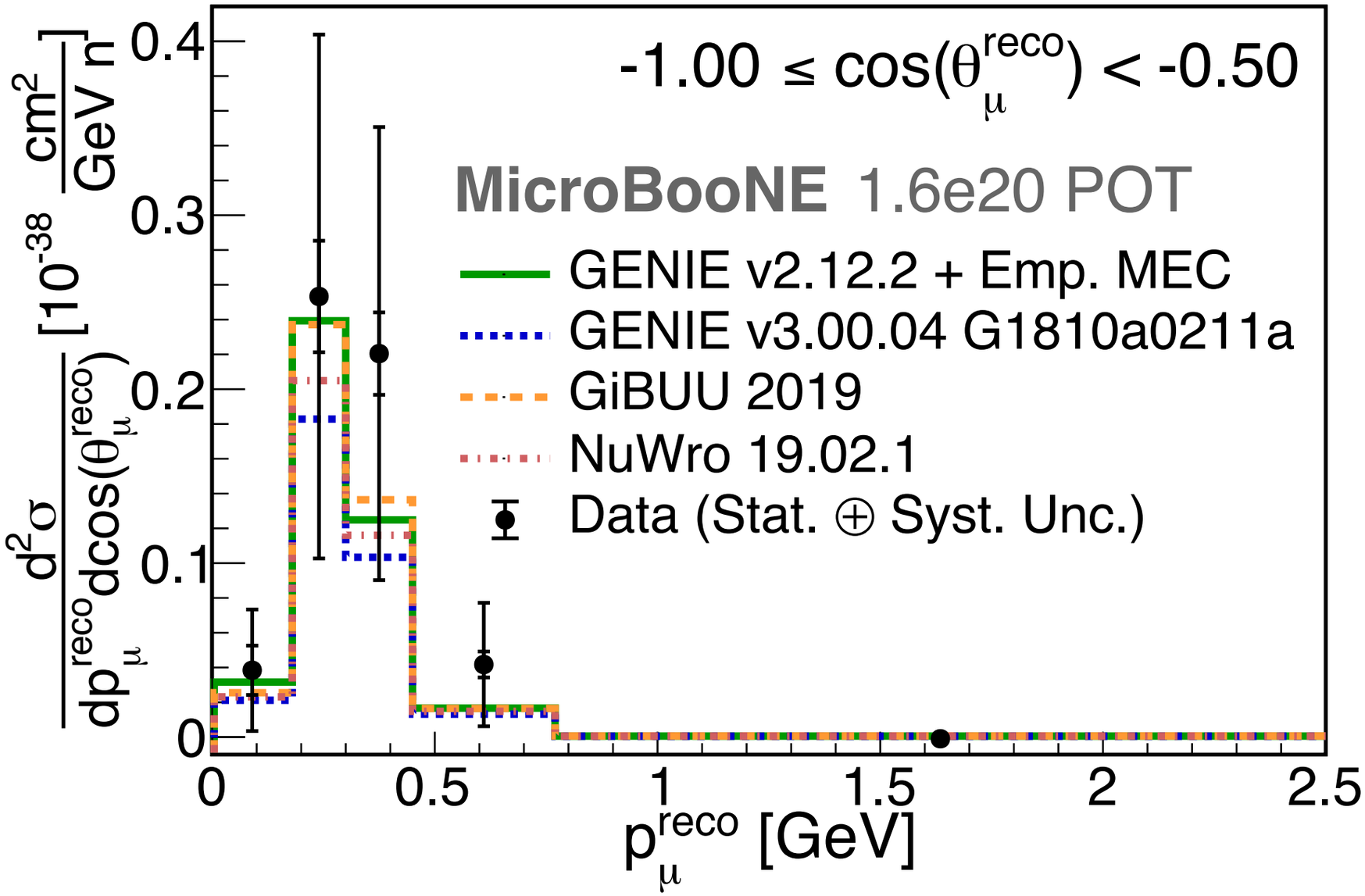
Phys. Rev. Lett. 123, 131801 (2019)

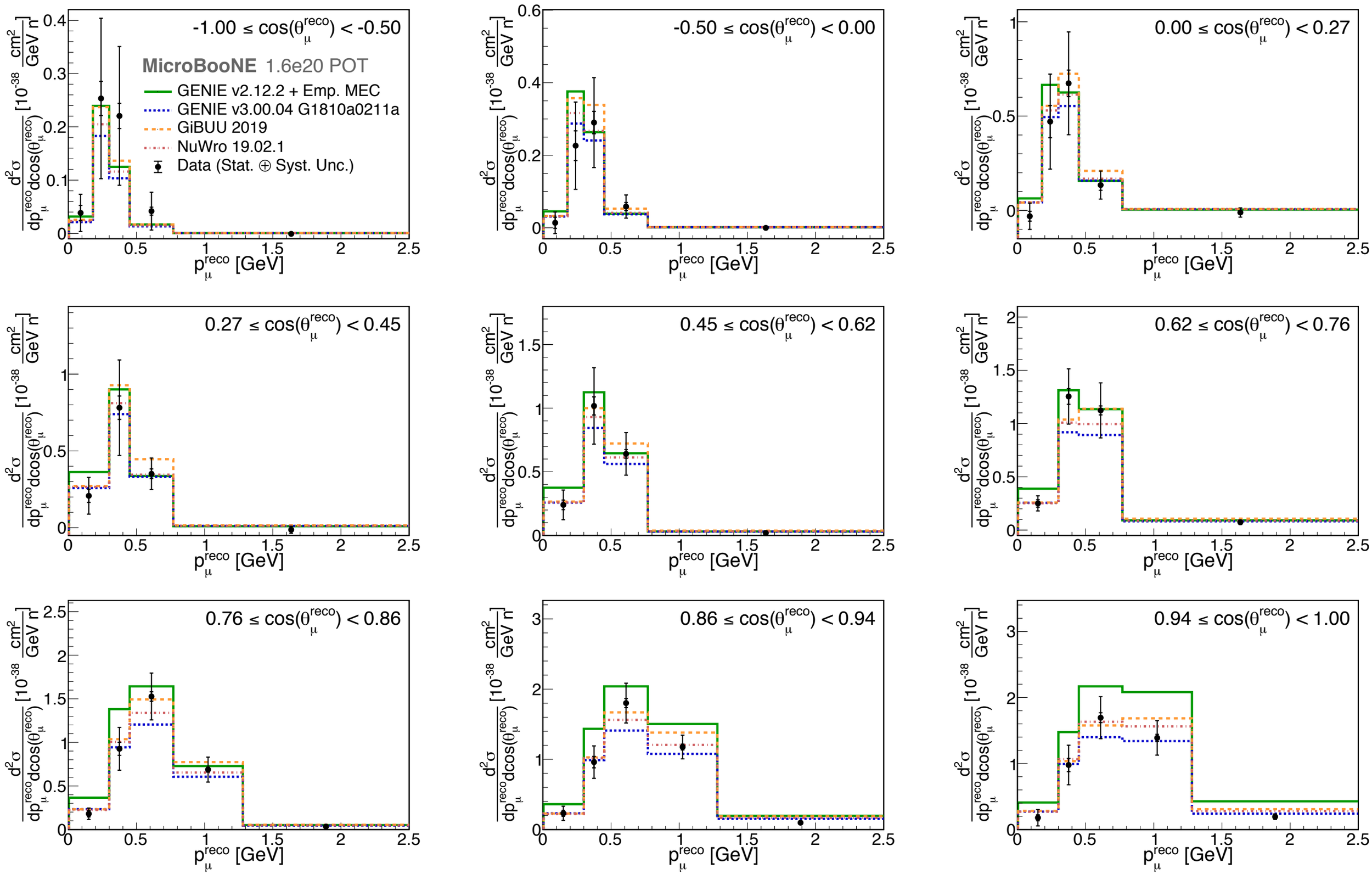
- Unlike other cross section measurements we do not unfold to true muon momentum and angle
  - → unfolding introduces bias, inflates uncertainties
- Instead, present result in **reconstructed** muon momentum and angle
- Publish detector smearing and efficiency
  - → theoretical predictions can be **forward 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

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

RESULTS

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

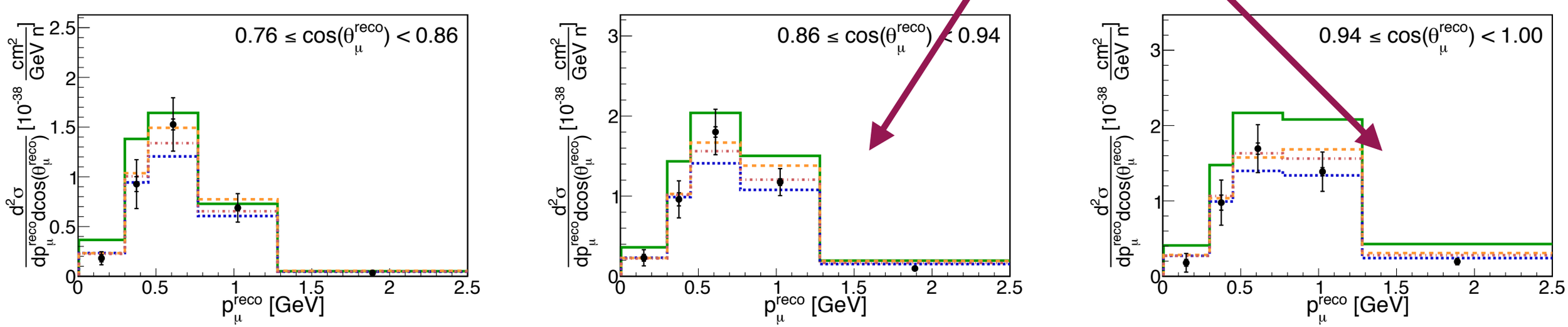


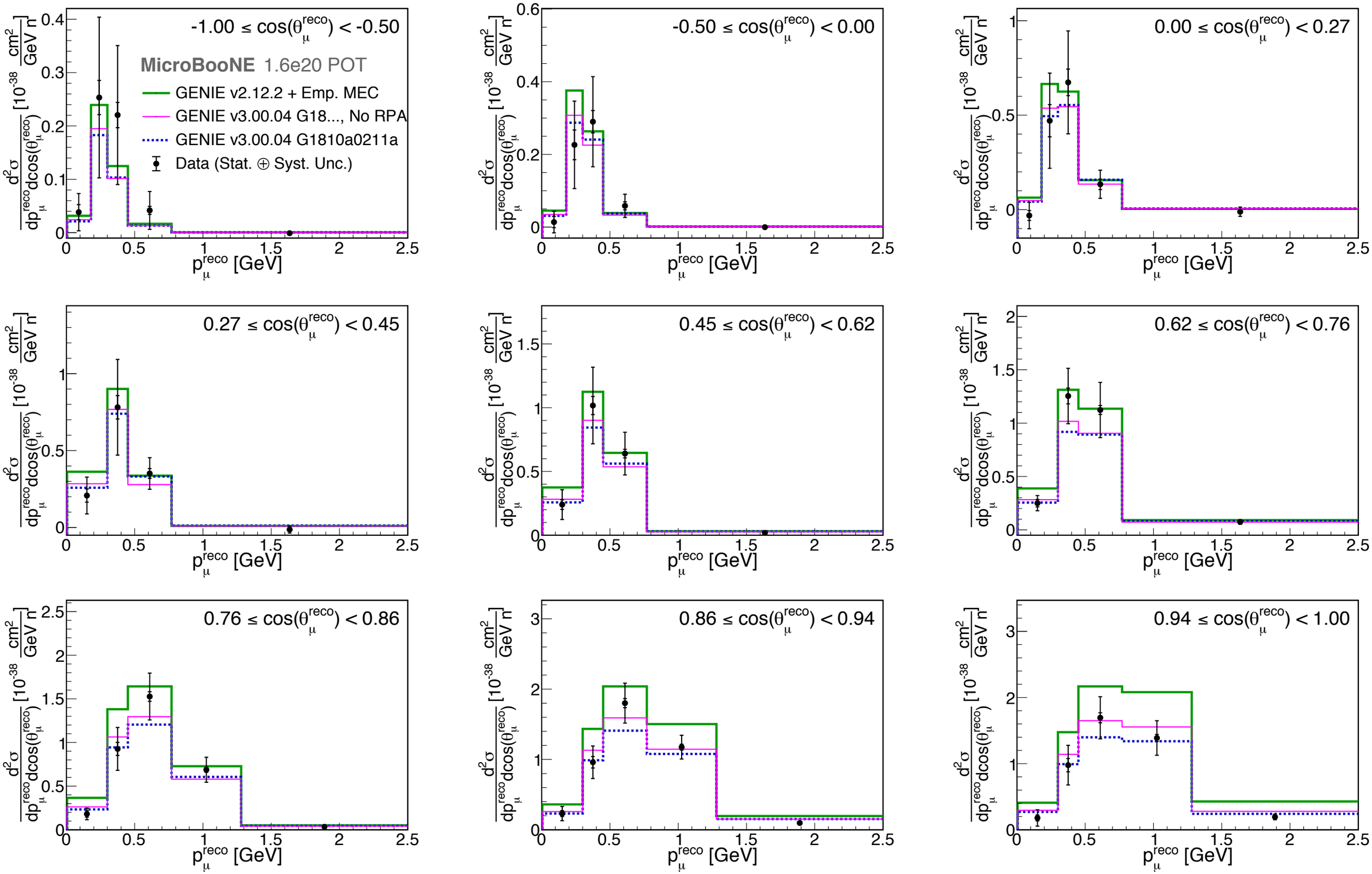

-1.00 ≤ cos(θ_μ^reco) < -0.50
MicroBooNE 1.6e20 POT
GENIE v2.12.2 + Emp. MEC
GENIE v3.00.04 G1810a0211a
GiBUU 2019
NuWro 19.02.1
Data (Stat. ⊕ Syst. Unc.)
-0.50 ≤ cos(θ_μ^reco) < 0.00
0.00 ≤ cos(θ_μ^reco) < 0.27
0.27 ≤ cos(θ_μ^reco) < 0.45
0.45 ≤ cos(θ_μ^reco) < 0.62
0.62 ≤ cos(θ_μ^reco) < 0.76
0.76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

Model	χ^2/N_{bins}
GENIE v2+MEC	**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 (largely QE and MEC processes)




-1.00 ≤ cos(θ_μ^reco) < -0.50
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.)
-0.50 ≤ cos(θ_μ^reco) < 0.00
0.00 ≤ cos(θ_μ^reco) < 0.27
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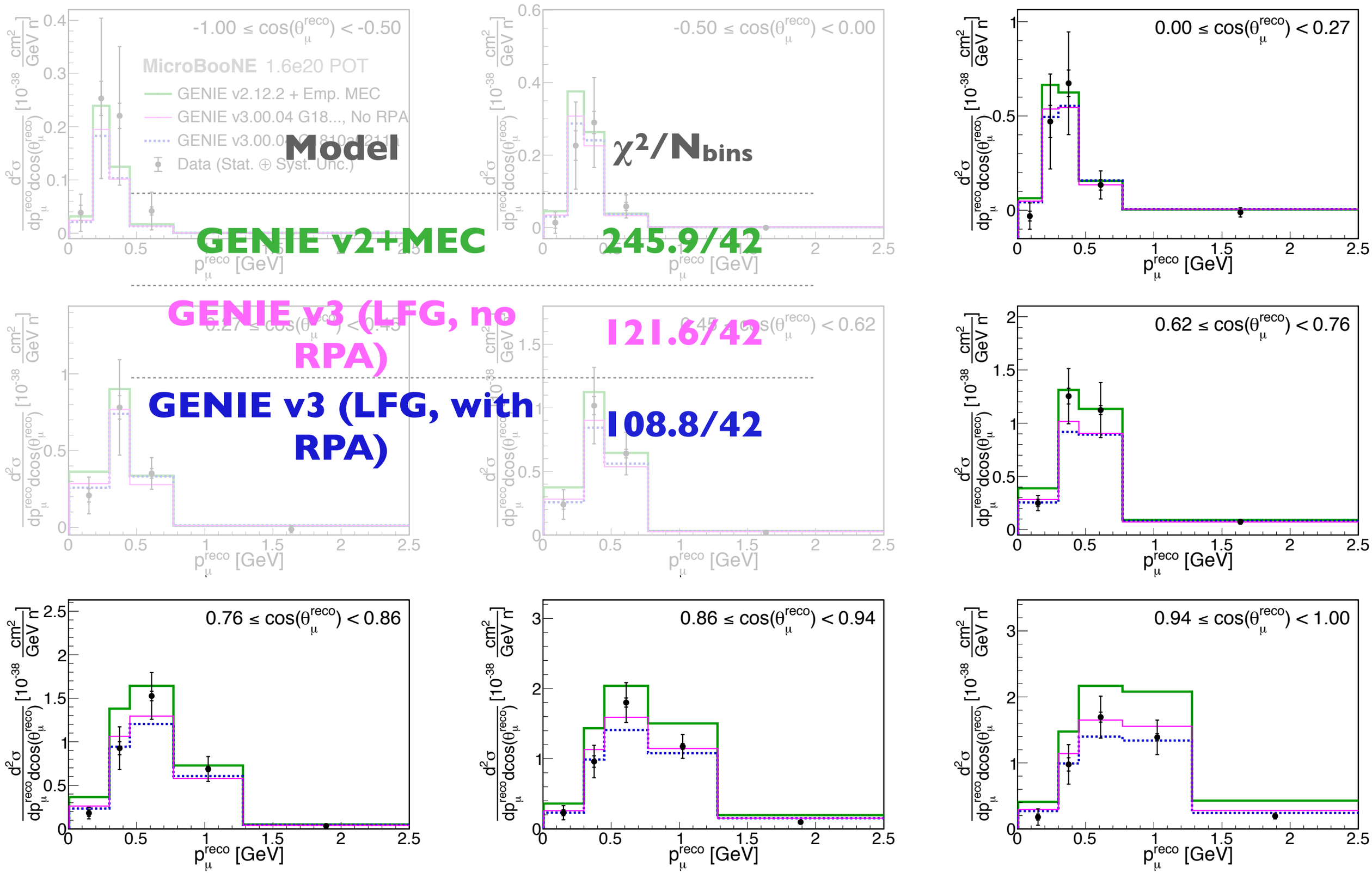
d²σ / dp_μ^reco dcos(θ_μ^reco) [10^-38 cm² / GeV n]
p_μ^reco [GeV]


-1.00 ≤ cos(θ_μ^reco) < -0.50
MicroBooNE 1.6e20 POT
GENIE v2.12.2 + Emp. MEC
GENIE v3.00.04 G18..., No RPA
Data (Stat. ⊕ Syst. Unc.)
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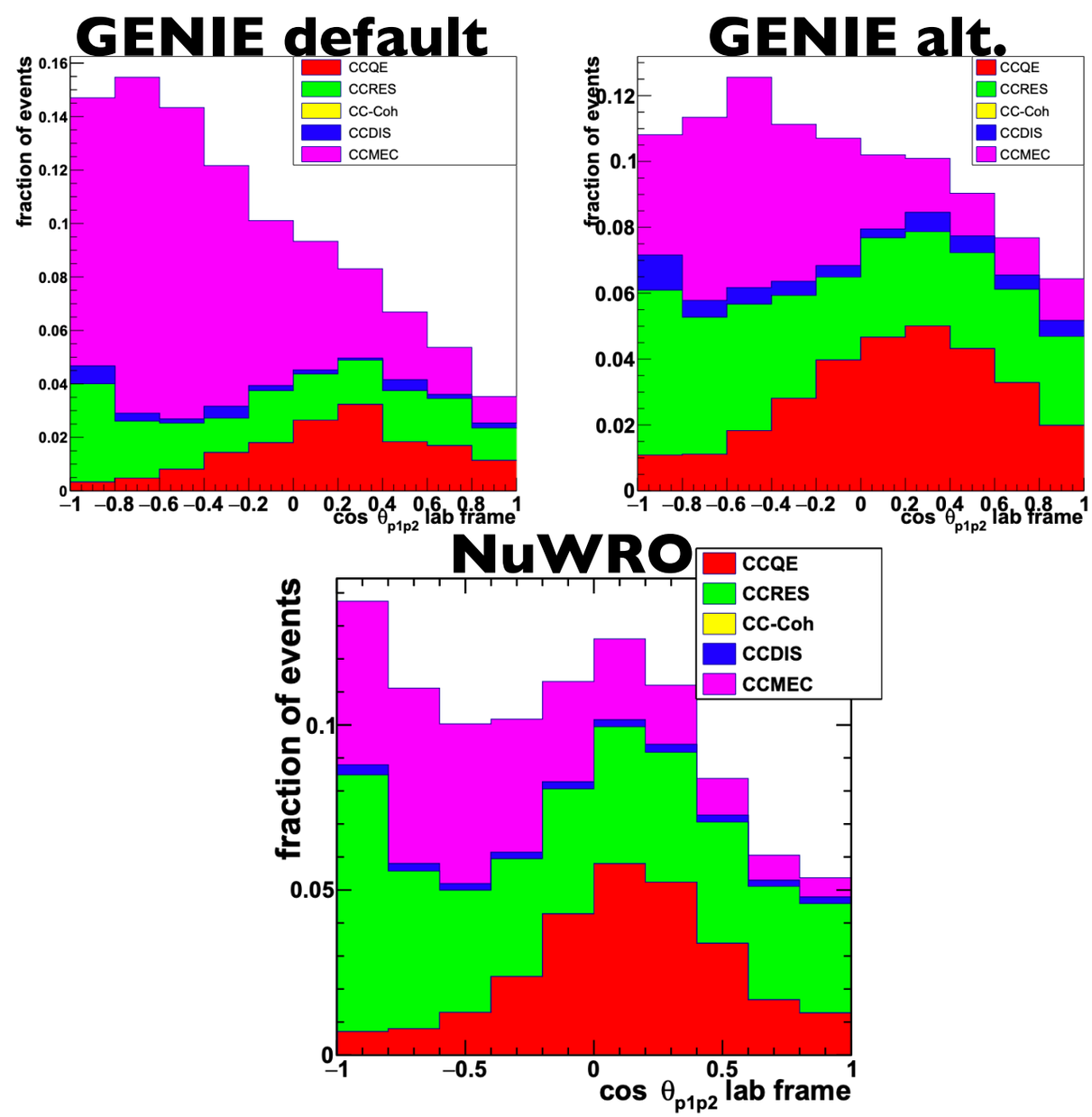
p_μ^reco [GeV]
Model
χ²/N_bins
GENIE v2+MEC
245.9/42
GENIE v3 (LFG, no RPA)
121.6/42
GENIE v3 (LFG, with RPA)
108.8/42

MICROBOONE-NOTE-1056-PUB

UPCOMING MEASUREMENTS

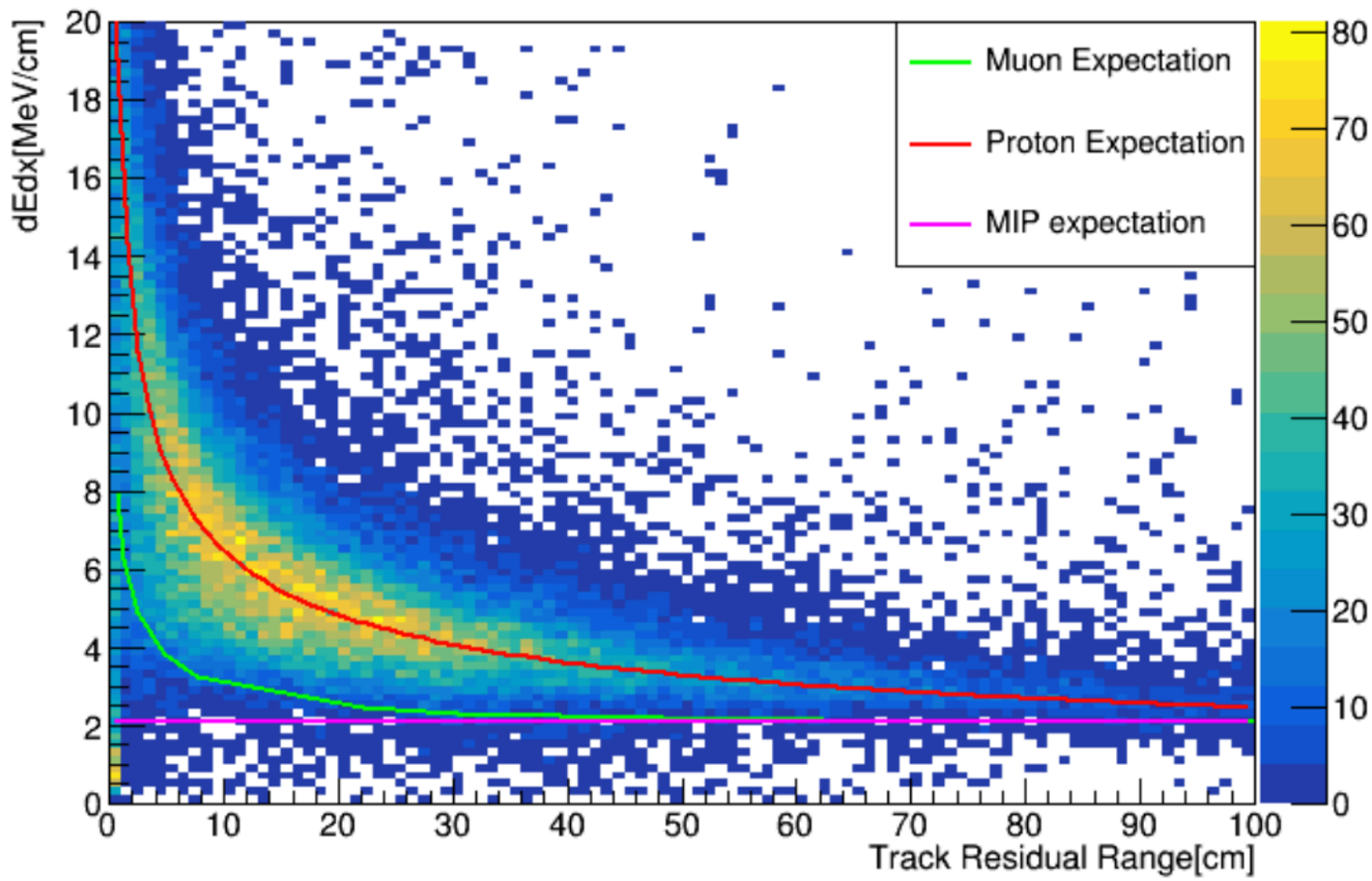
CC0π multi-proton measurements

- Pion-less measurements with protons are useful probes of nuclear effects
- Large disagreements between different (reasonable) models
- Because of FSI, on MicroBooNE → potentially large resonant contribution



SELECTING PROTONS

MICROBOONE-NOTE-1056-PUB



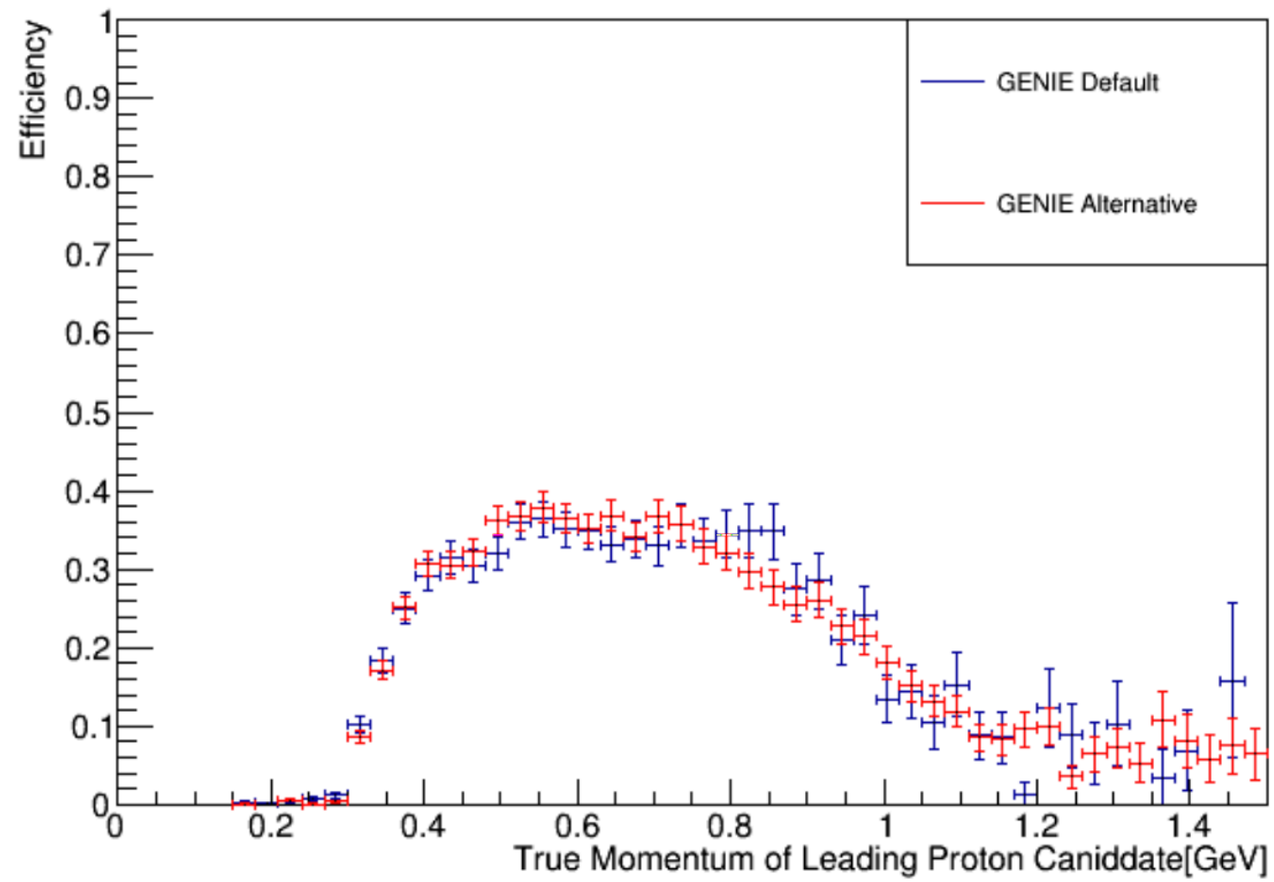
Compare dE/dx profile in last 30cm of track to proton Bethe-Bloch expectation

→ **calculate χ^2 to find tracks consistent with proton hypothesis**

PROTON THRESHOLD

MICROBOONE-NOTE-1056-PUB

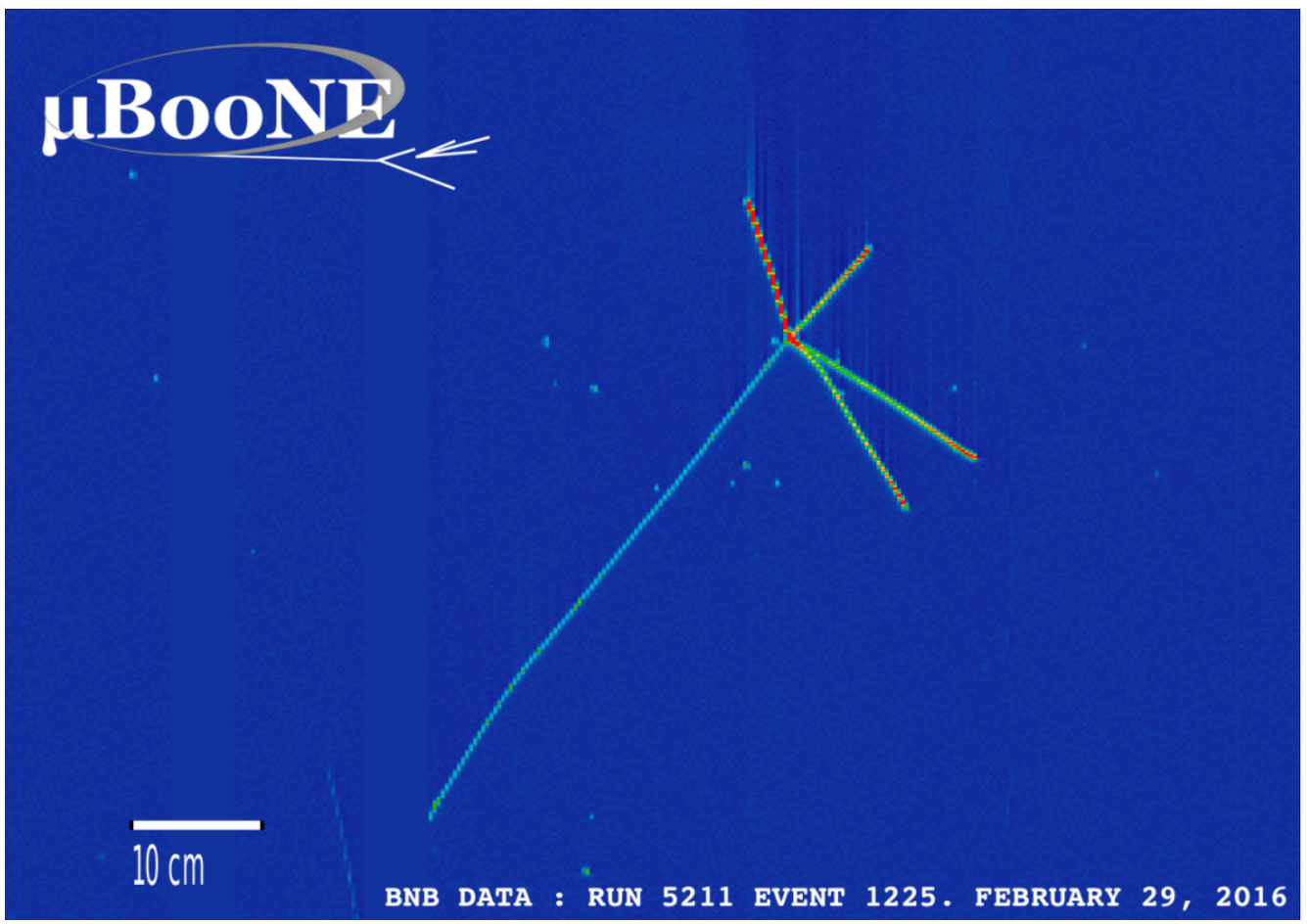
- LArTPCs have significantly lower thresholds than other detector technologies → measurement of lower-momentum protons than ever before
- Current MicroBooNE threshold 300 MeV/c
  → 47 MeV KE
  → 1.5 cm track
- Compare to other experiments:
  - MINERvA: 120 MeV KE (Phys. Rev. D 97. 052002 (2018))
  - T2K: 450 MeV/c (Phys. Rev. D 98, 032003 (2018))



Current threshold limited by reconstruction — expected to improve (ArgoNeuT: 21 MeV KE)

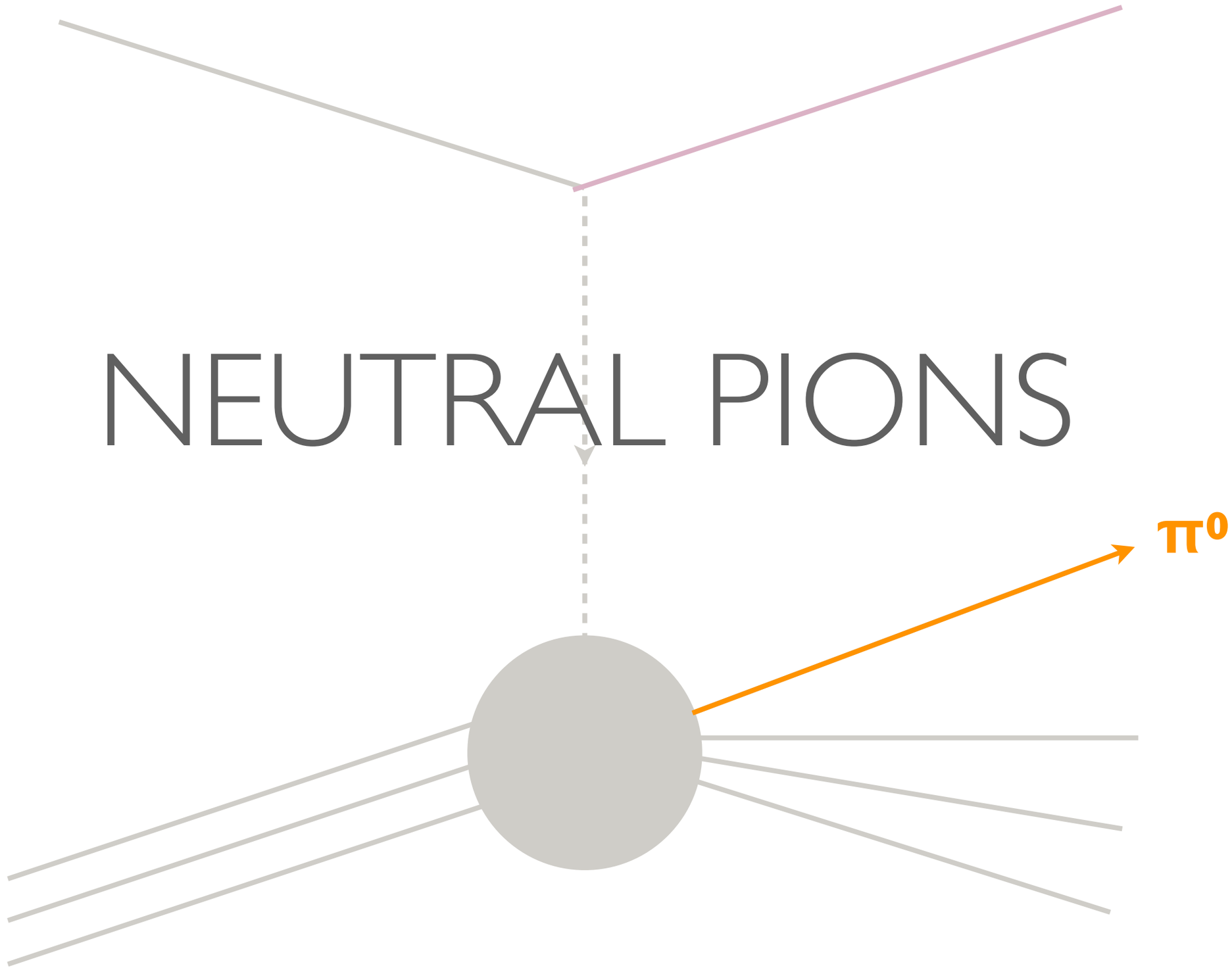
UPCOMING MEASUREMENTS

In progress (near future)



- **CC0π2p, CC0πNp (N>=1)**
  - Selections described in MICROBOONE-NOTE-1056-PUB
- Further future: Single Transverse Variables
- **All of these measurements will need to be interpreted using good resonance and FSI models**

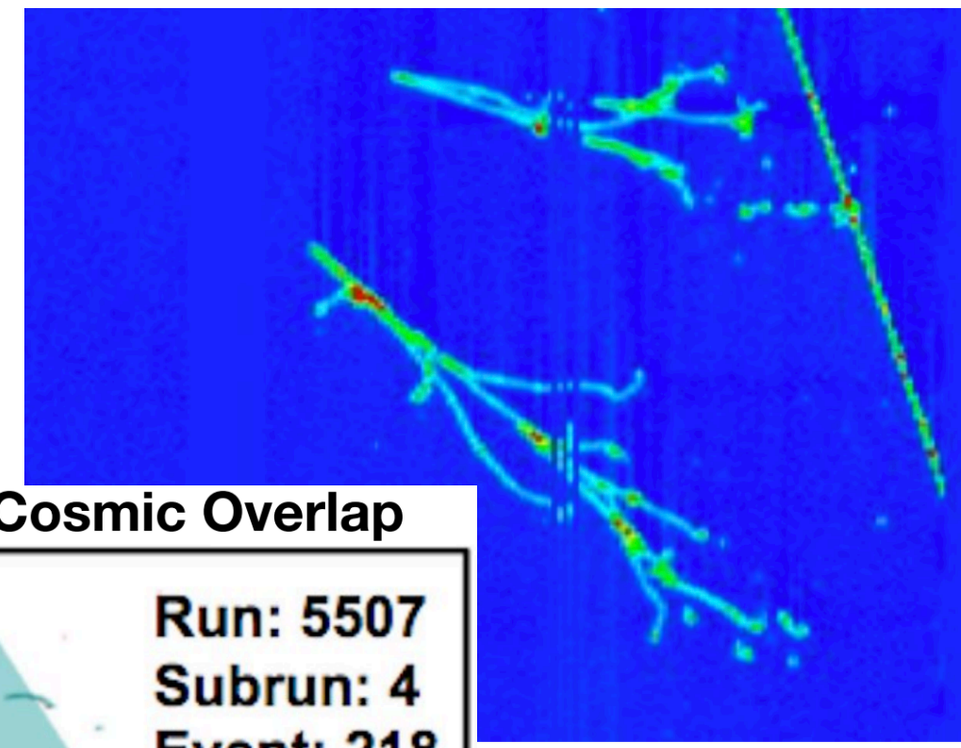
NEUTRAL PIONS

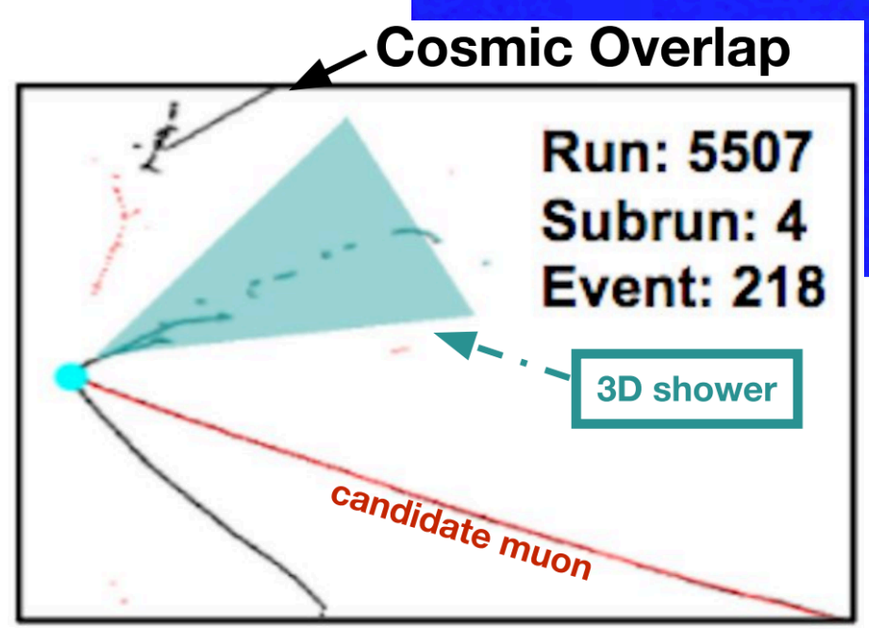


π^0 IN MICROBOONE

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

- Photons (and electrons) produce showers in MicroBooNE
- Shower reconstruction is difficult: trade-off between completeness and purity (much more than track reconstruction) → direct impact on energy reconstruction
- Current approach: conservative to guard against cosmic charge being added to our showers



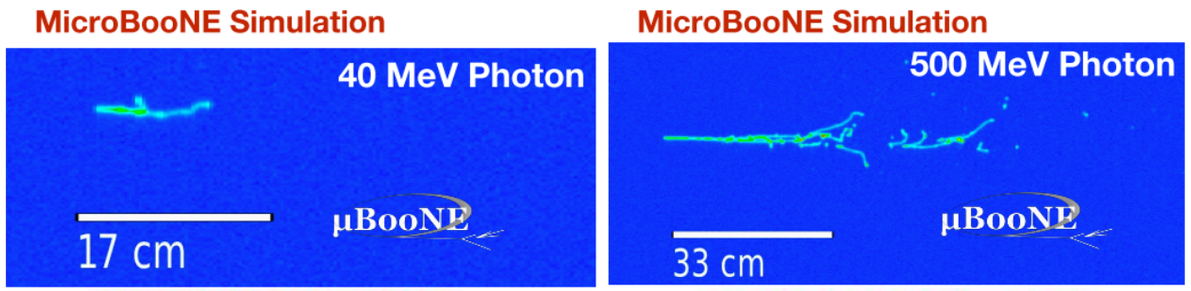


A. Hackenburg, Yale U., Ph.D. Thesis

π^0 IN MICROBOONE

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

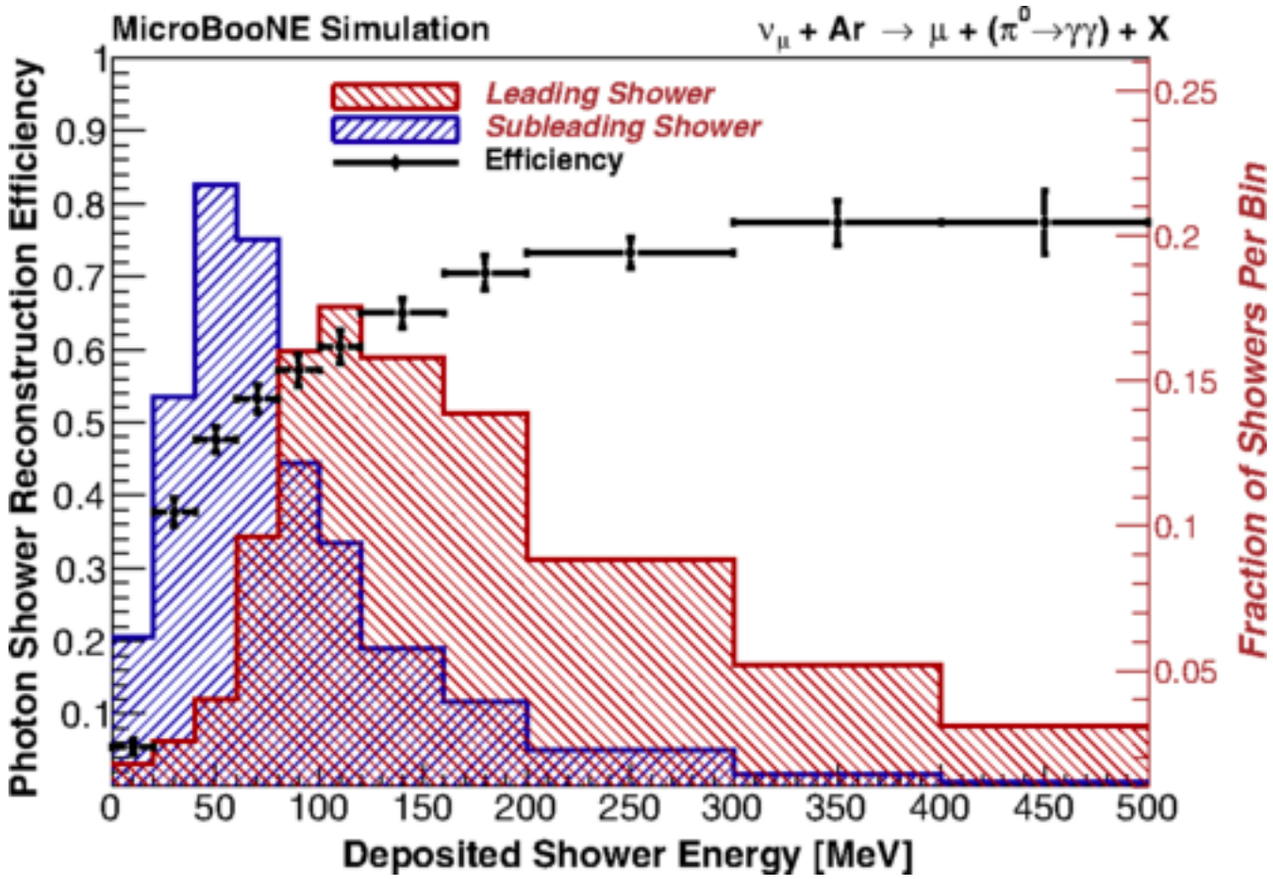
Low-energy photons appear more track like



→ low reconstruction efficiency

→ makes it difficult to identify both photons from a π^0

→ requiring that we reconstruct both π^0 photons limits statistics, and may sculpt phase space



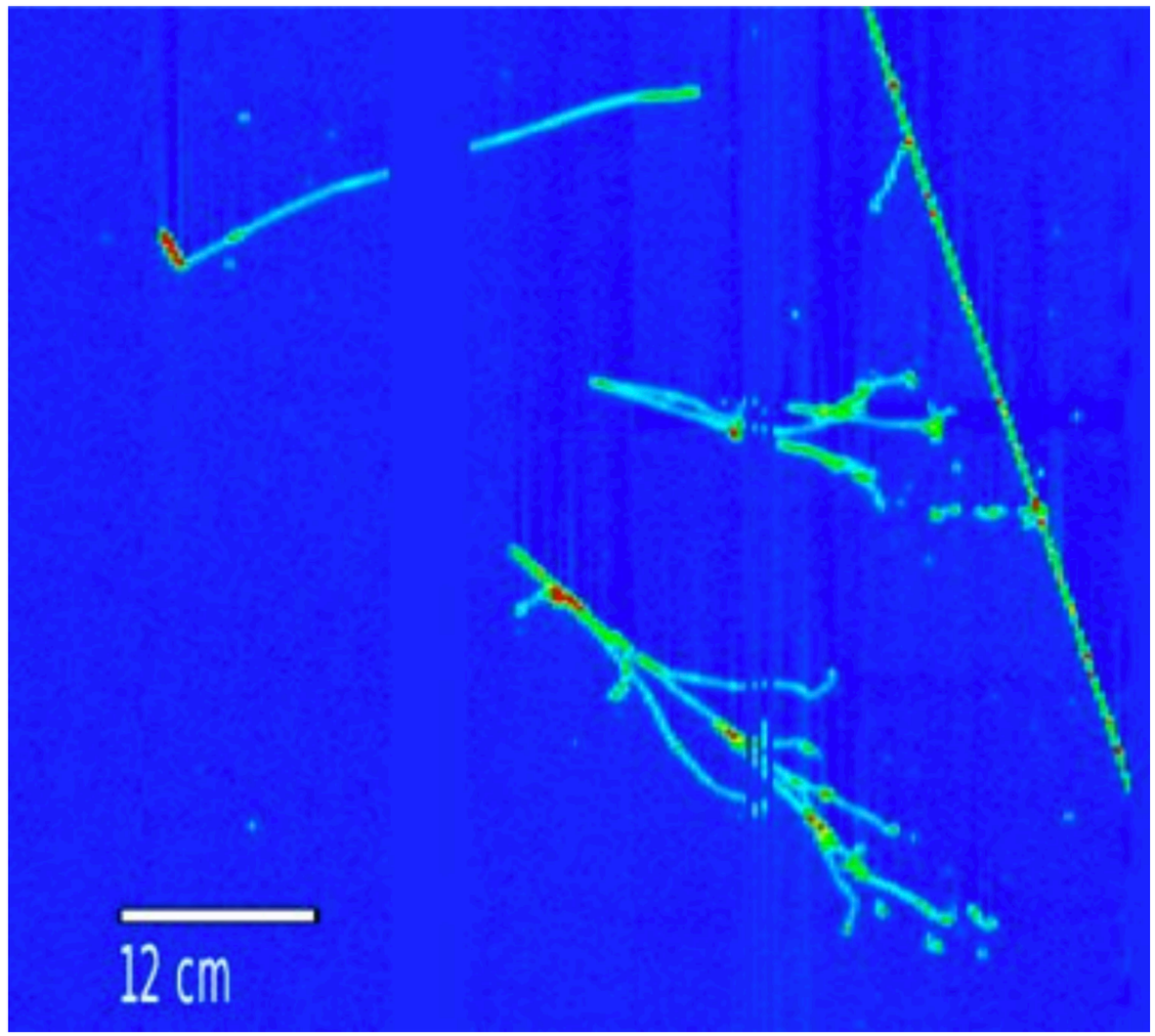
CCπ^0 MEASUREMENT

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

- Easier to select CCπ^0 interactions than NCπ^0 because muon gives us the interaction point
- Excellent testing ground for shower energy and angle resolution → towards NCπ^0 measurement

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

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

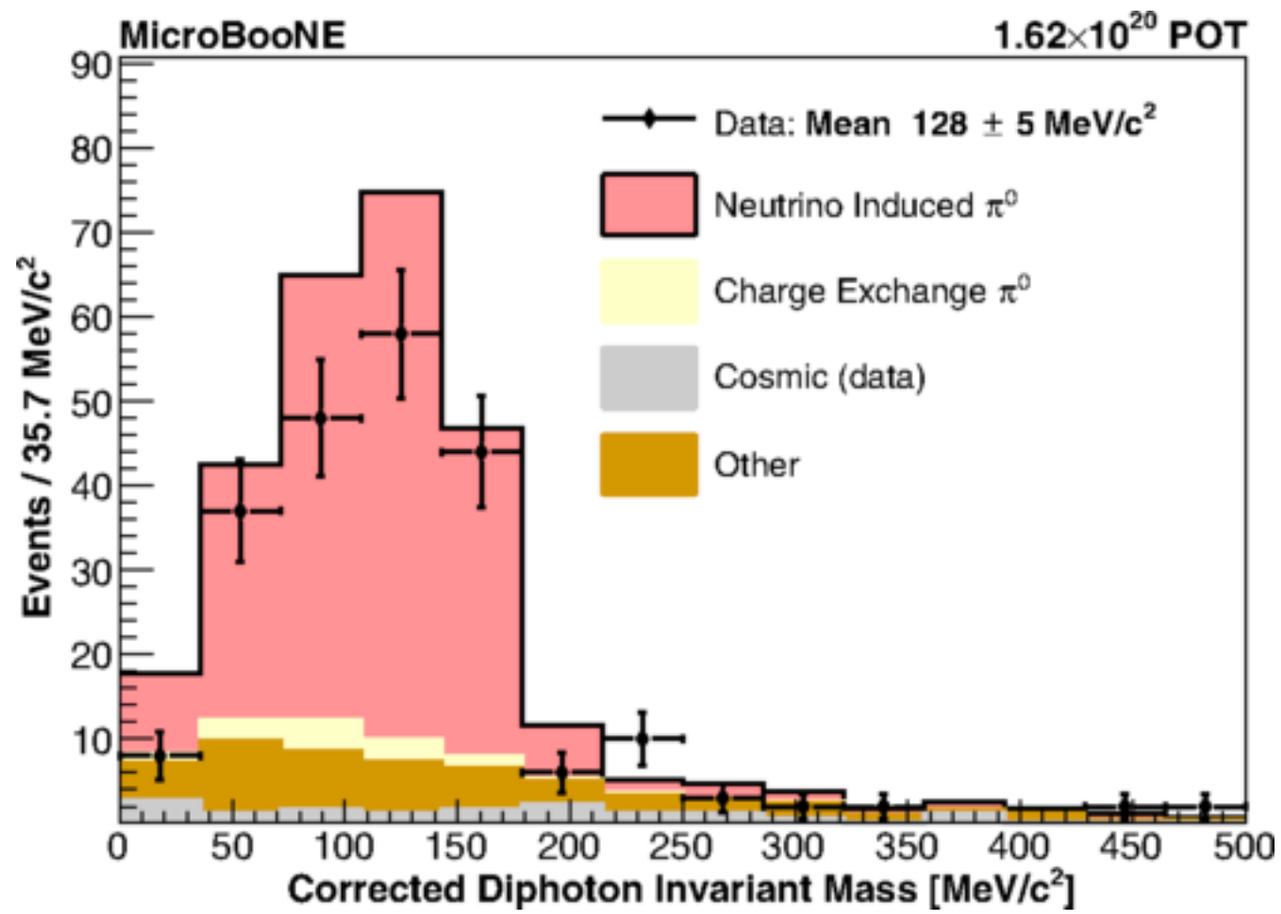


FINDING π^0s

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

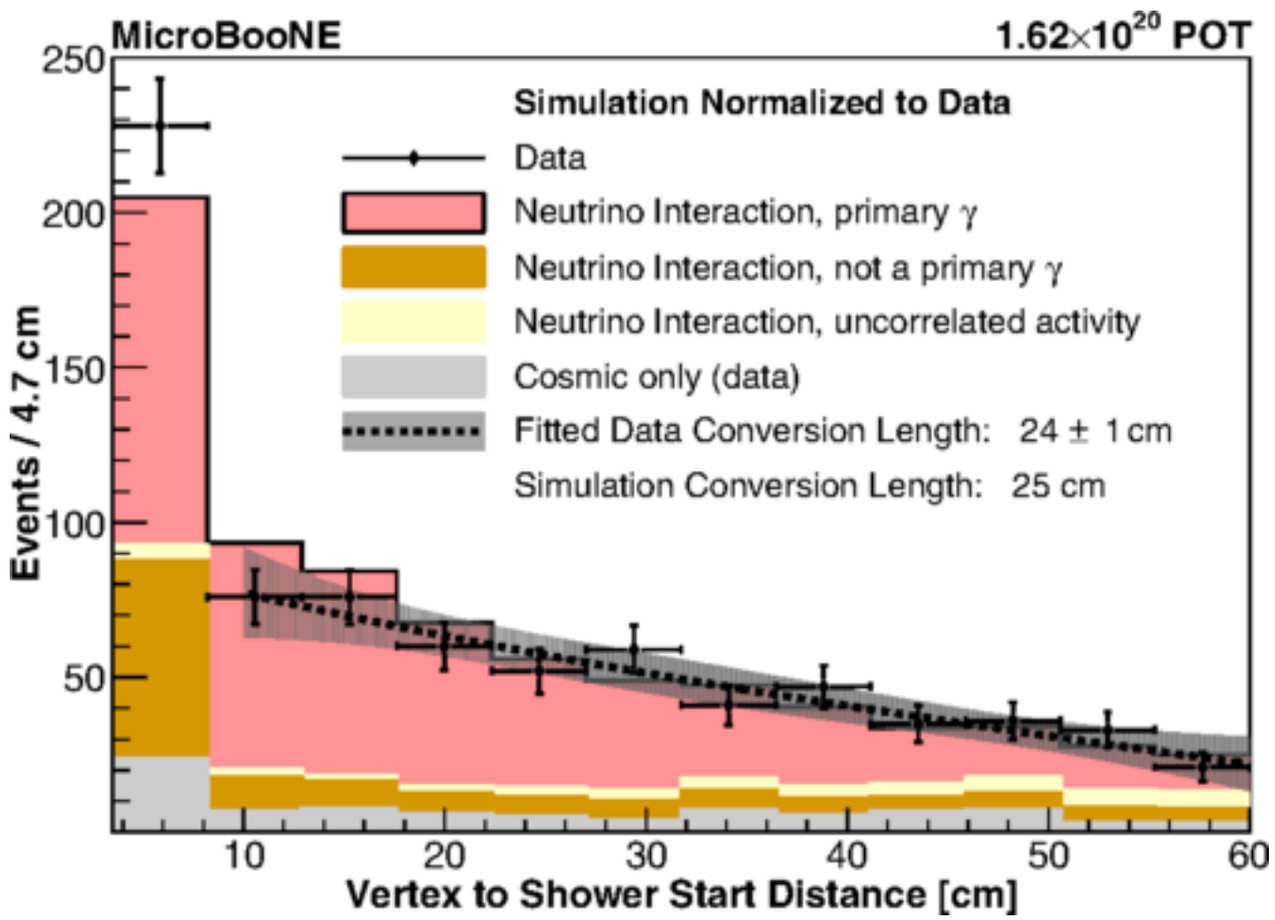
Two-shower selection

- Select π^0 events by looking for two showers → two photons on top of CC-inclusive selection
- Convince ourselves that we really have found π^0s by calculating invariant mass of the two photons: if the photons come from a π^0 then should be ~π^0 mass (135 MeV)
- Note: we do not cut on π^0 mass



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

CCπ^0: PHOTON CONVERSION

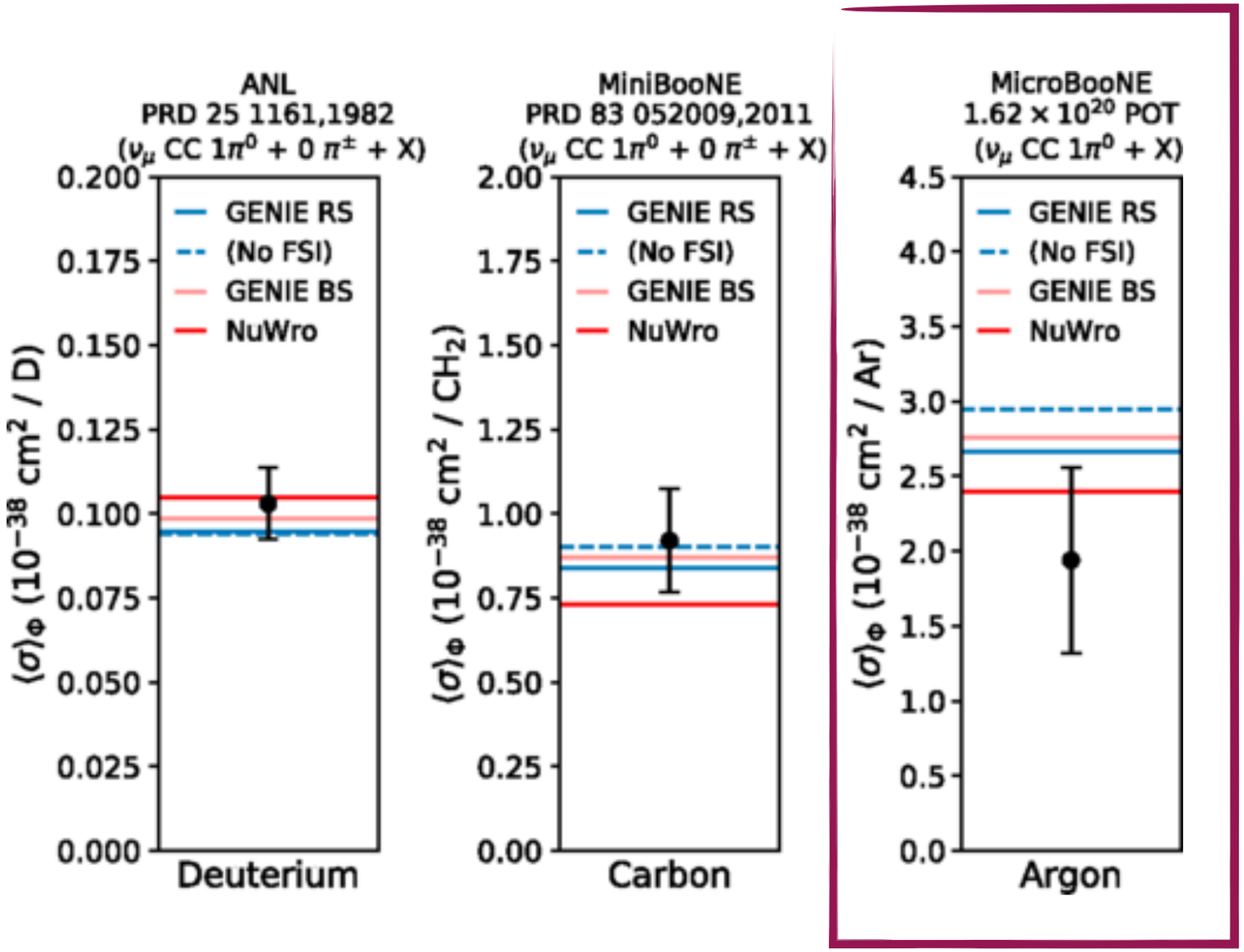


Single-shower selection

- Look at single photons passing CC-inclusive selection
- Measure mean conversion length to validate:
  1) that we have selected photons
  2) that we have the interaction vertex right
- ✔ Data agrees with simulation within uncertainties

CCπ^0 CROSS SECTION

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



- First ever CCπ^0 cross section measurement on argon
- Measurement in agreement with models within 1.2σ
- → current nuclear scaling consistent with our measurement

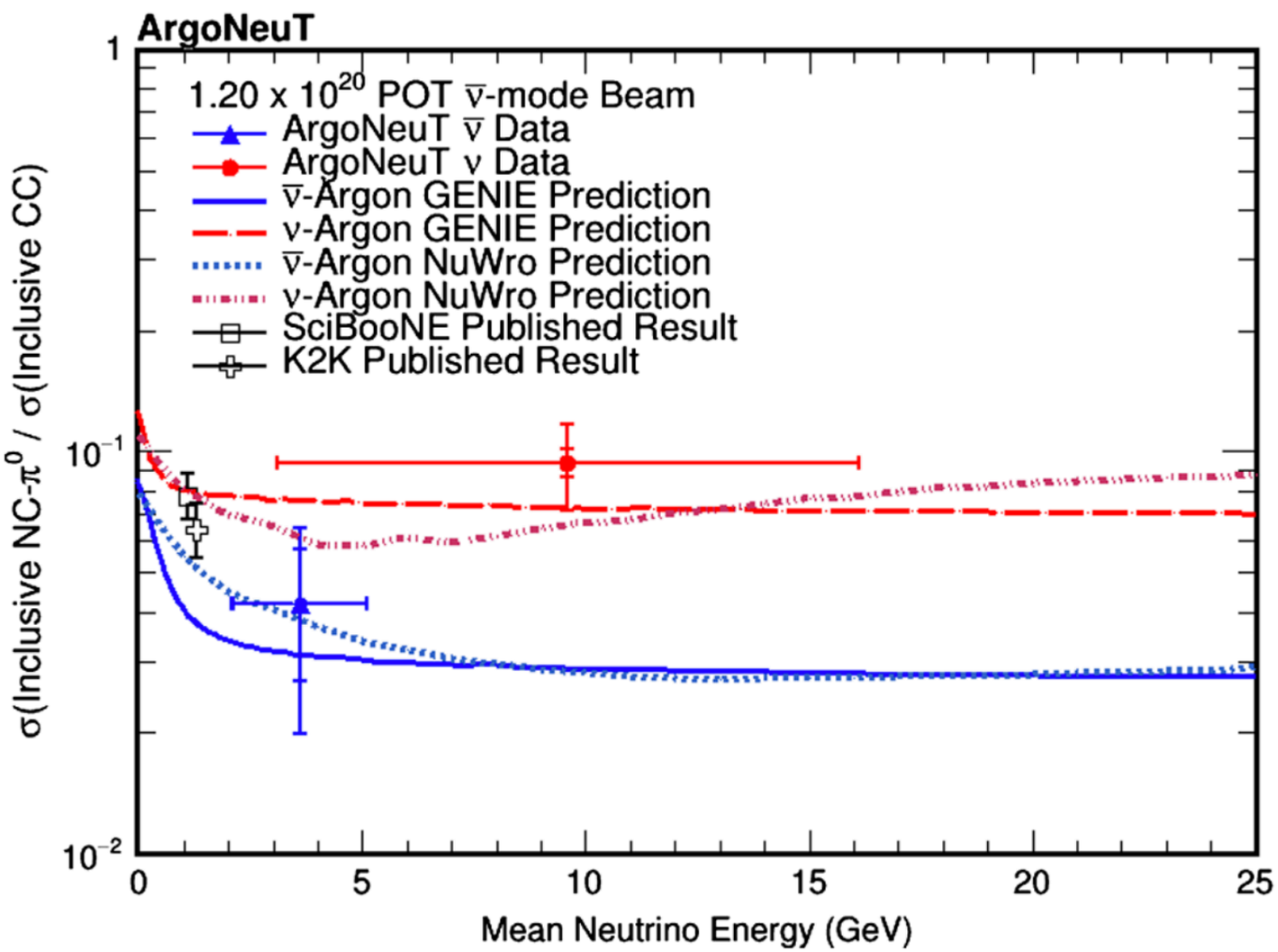
LOOKING FORWARD

In progress (near future)

- In the near future, plan to **update this measurement**:
  - Updated detector model and systematics
  - ~10x statistics
  - **Differential cross section** as a function of π^0 momentum and angle, muon momentum and angle
- Main analyzer **Supraja Balasubramanian** (at this workshop!)

NCπ⁰: MEASUREMENTS ON ARGON

NC1π⁰ ArgoNeuT measurement



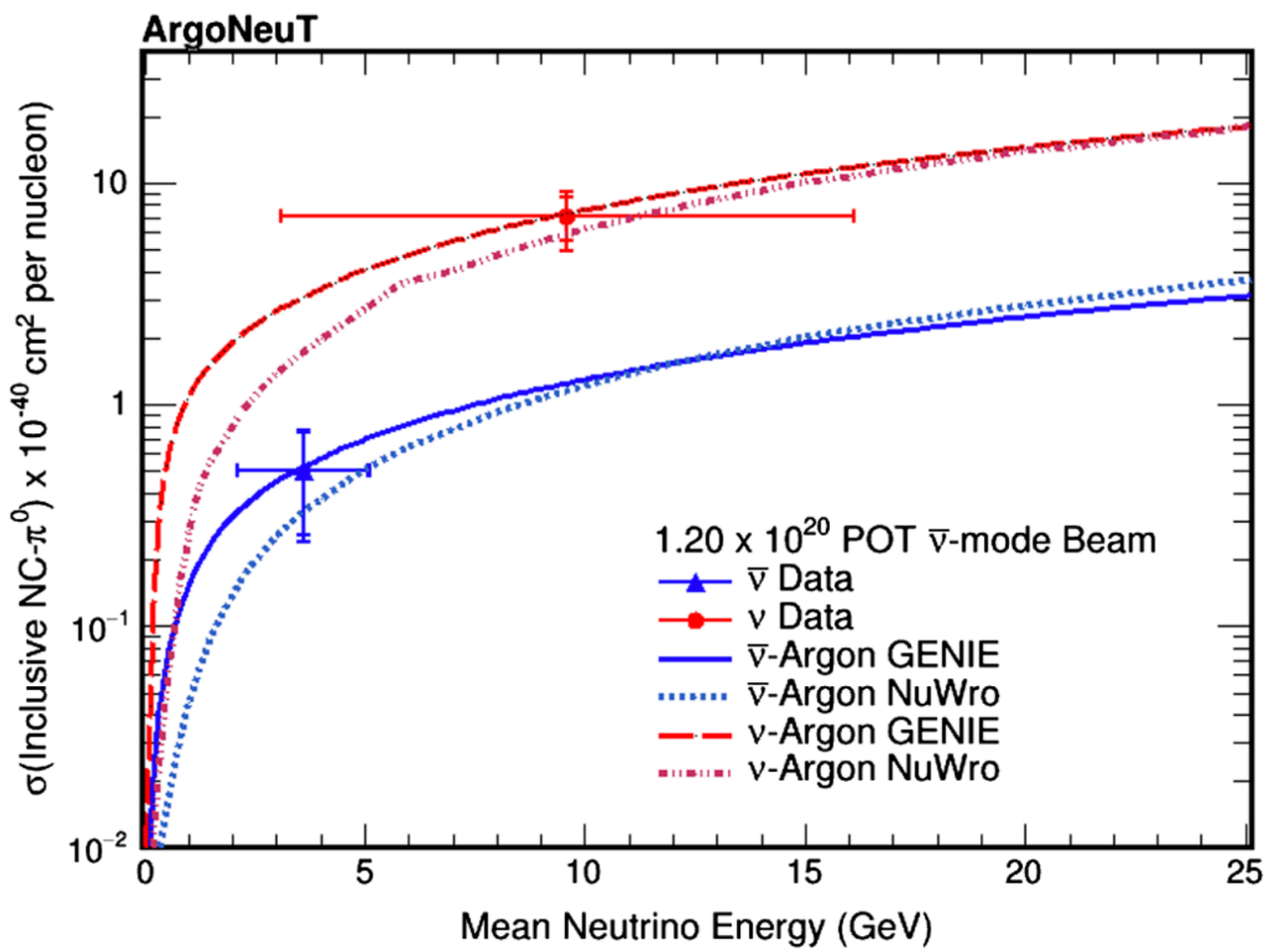
PRD 96, 012006 (2017)

- ArgoNeuT: flux-integrated NCπ⁰ measurement PRD 96, 012006 (2017)
- Measure ratio of σ(NCπ⁰) to σ(CC):
  - Good agreement with generators
  - Integrated result is slightly higher than previous results at lower energy

NCπ^0: MEASUREMENTS ON ARGON

NC1π^0 ArgoNeuT measurement

- Flux-integrated cross section measurement shows good agreement with generators

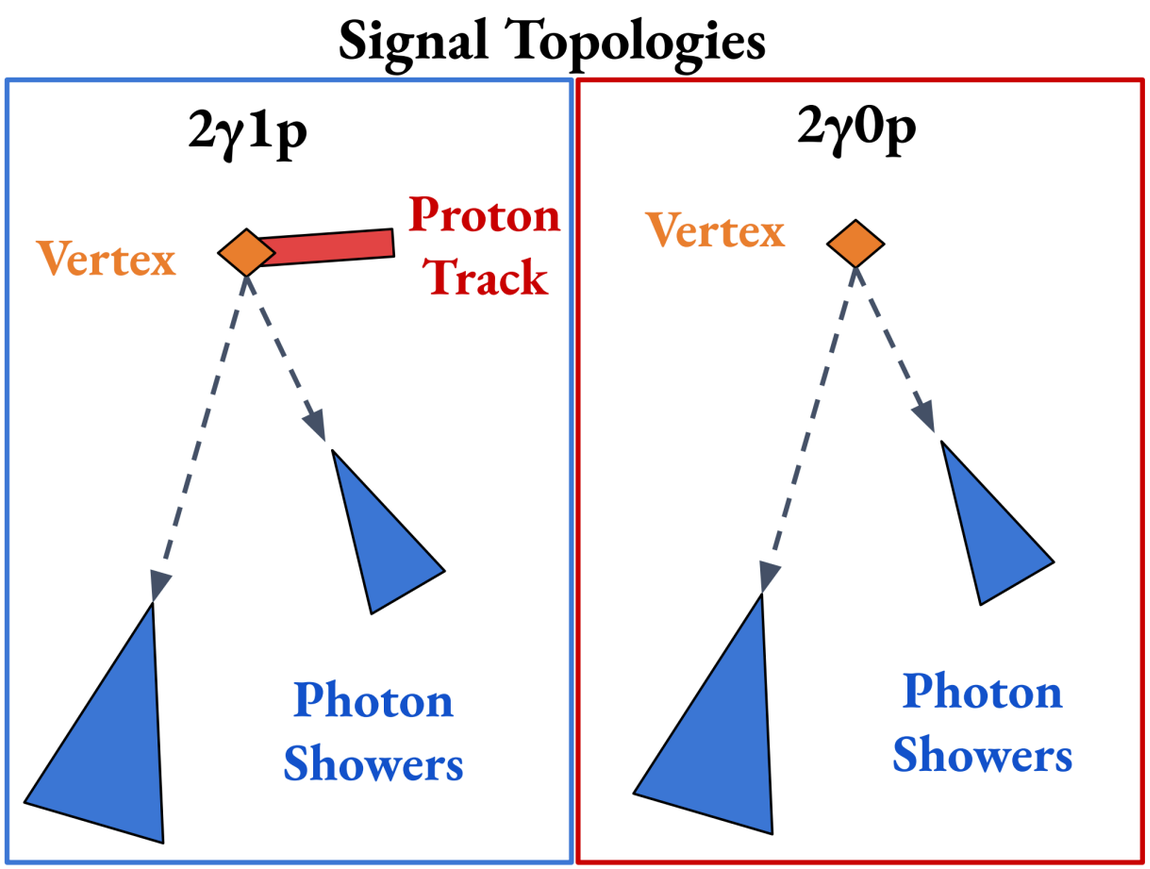


PRD 96, 012006 (2017)

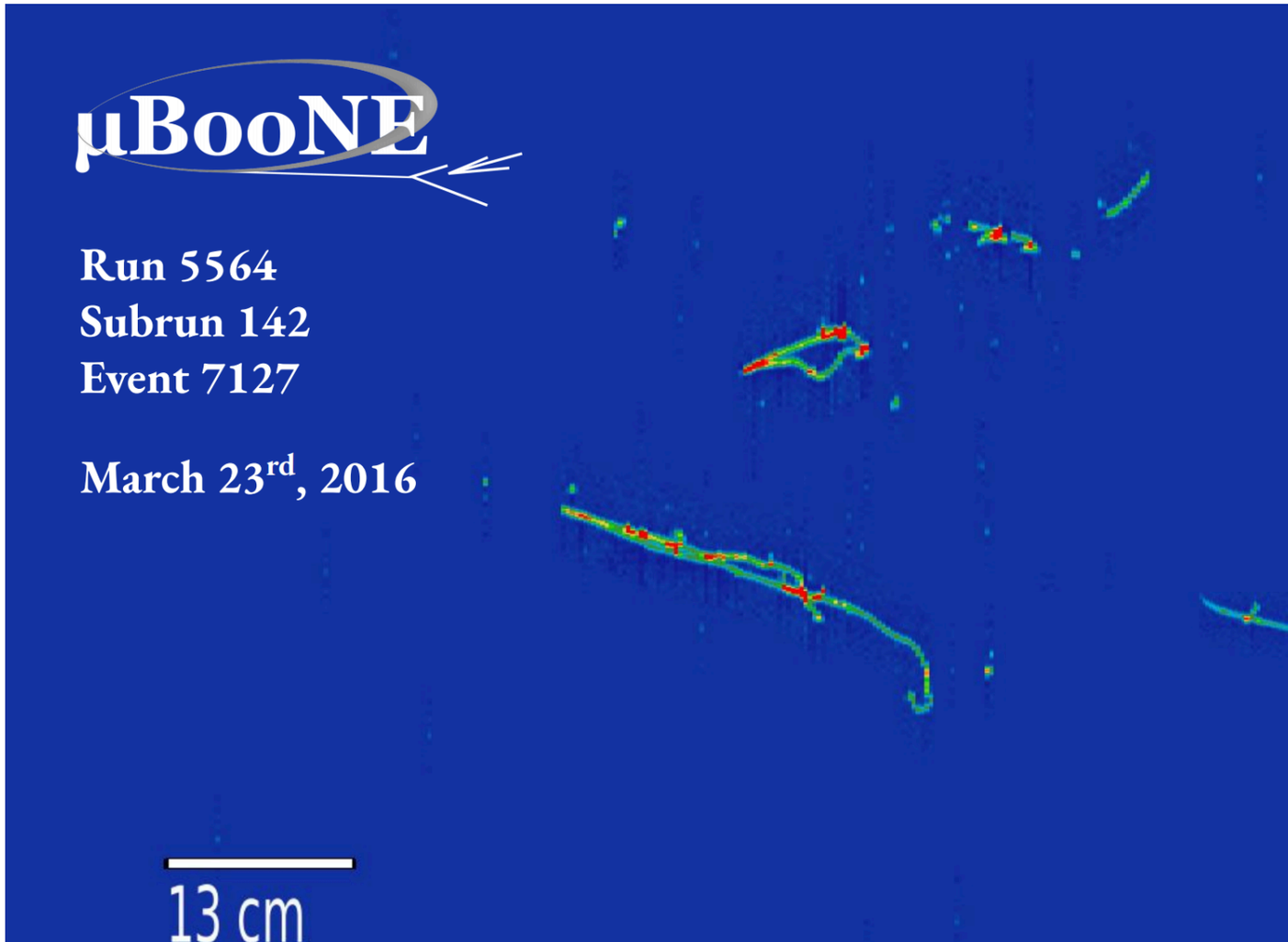
NCπ^0: MICROBOONE ANALYSIS

In progress (near future)

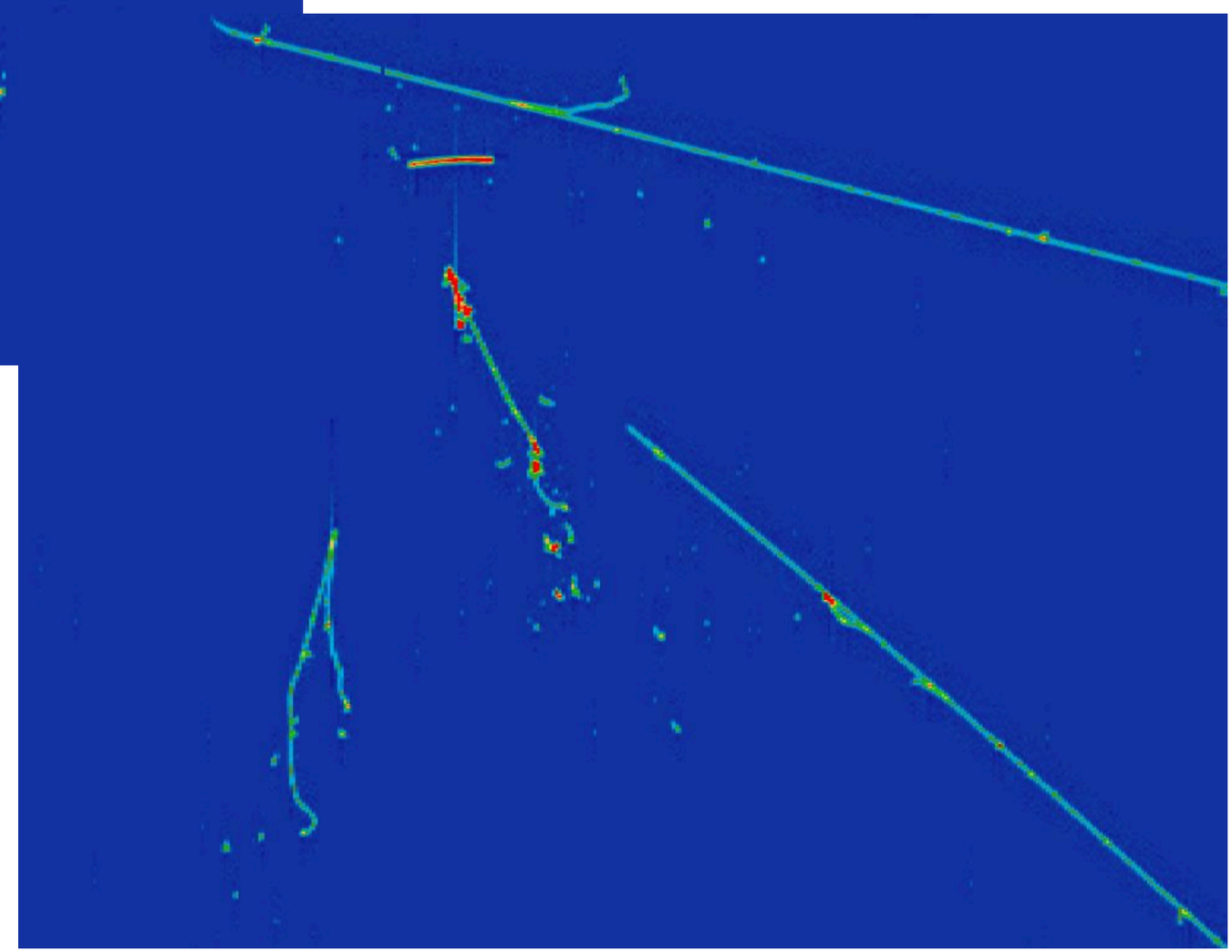
- MicroBooNE photon-like LEE analysis will use π^0 sideband to constrain background
- Have a fairly mature selection for two channels: 2ɣ0p, 2ɣ1p (see A. Mogan, DPF 2019)
- Expect several hundred events in final selection with low background contamination: ~60% pure, currently largest background CCπ^0 (~45%)



A. Mogan, DPF 2019

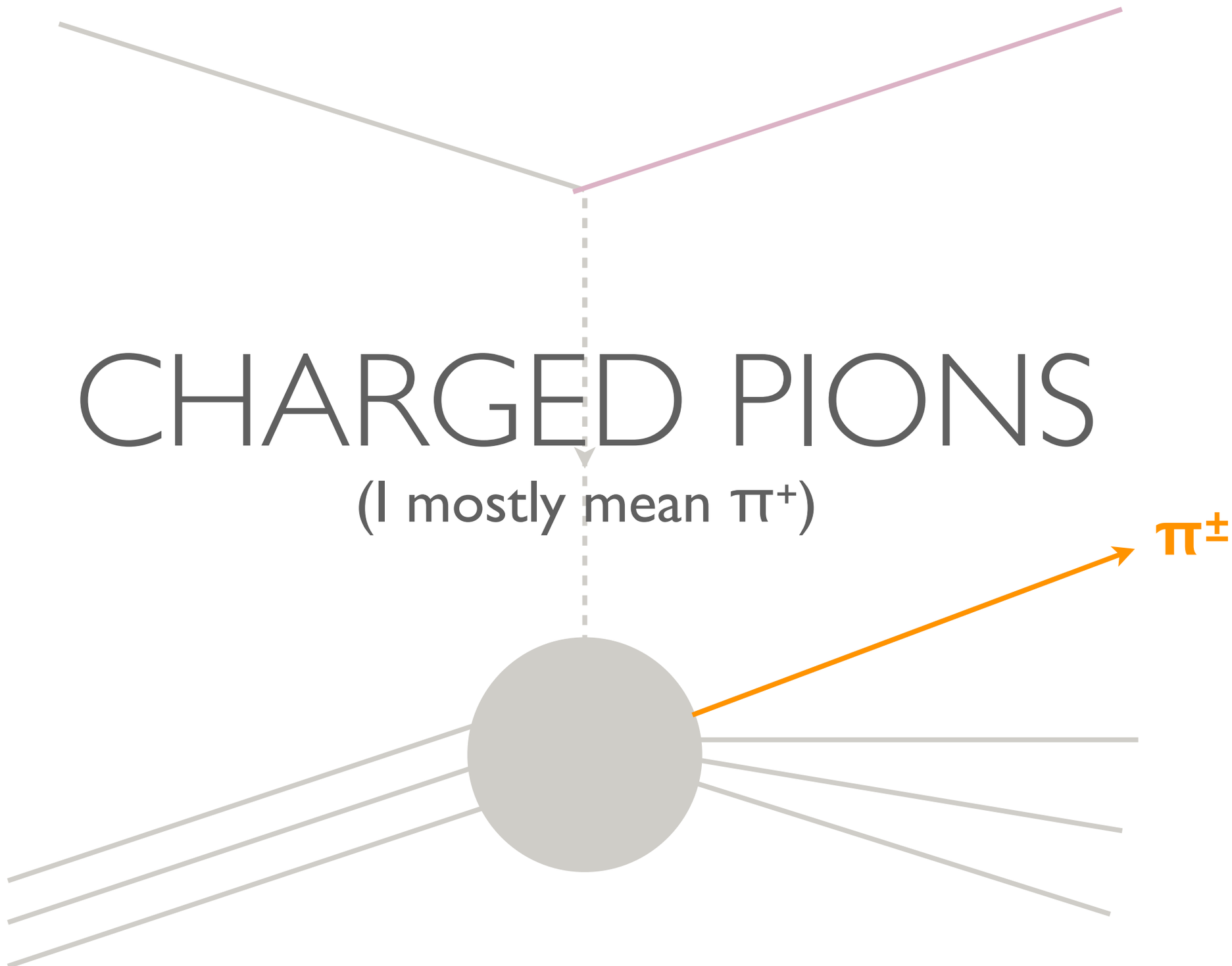


In progress (near future)



CHARGED PIONS

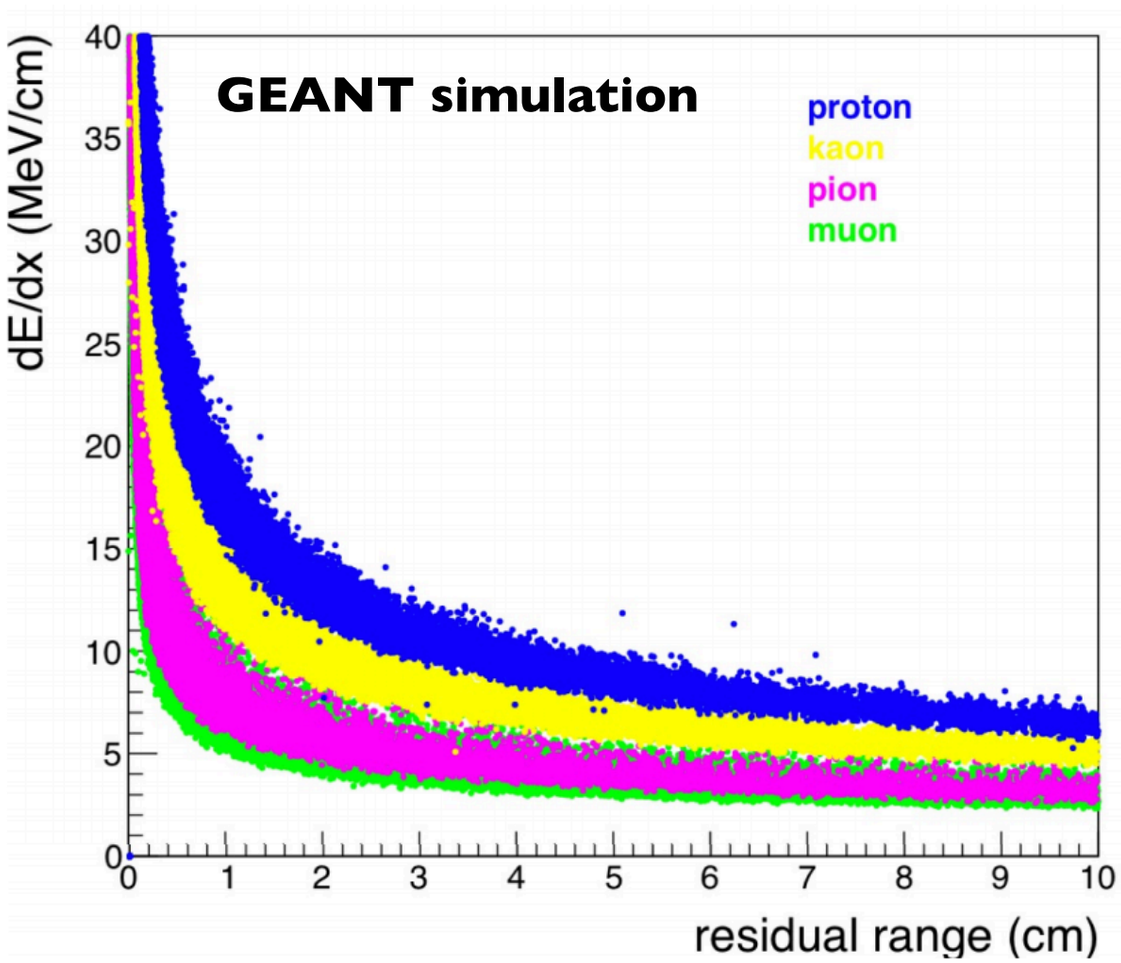
(I mostly mean π^+)

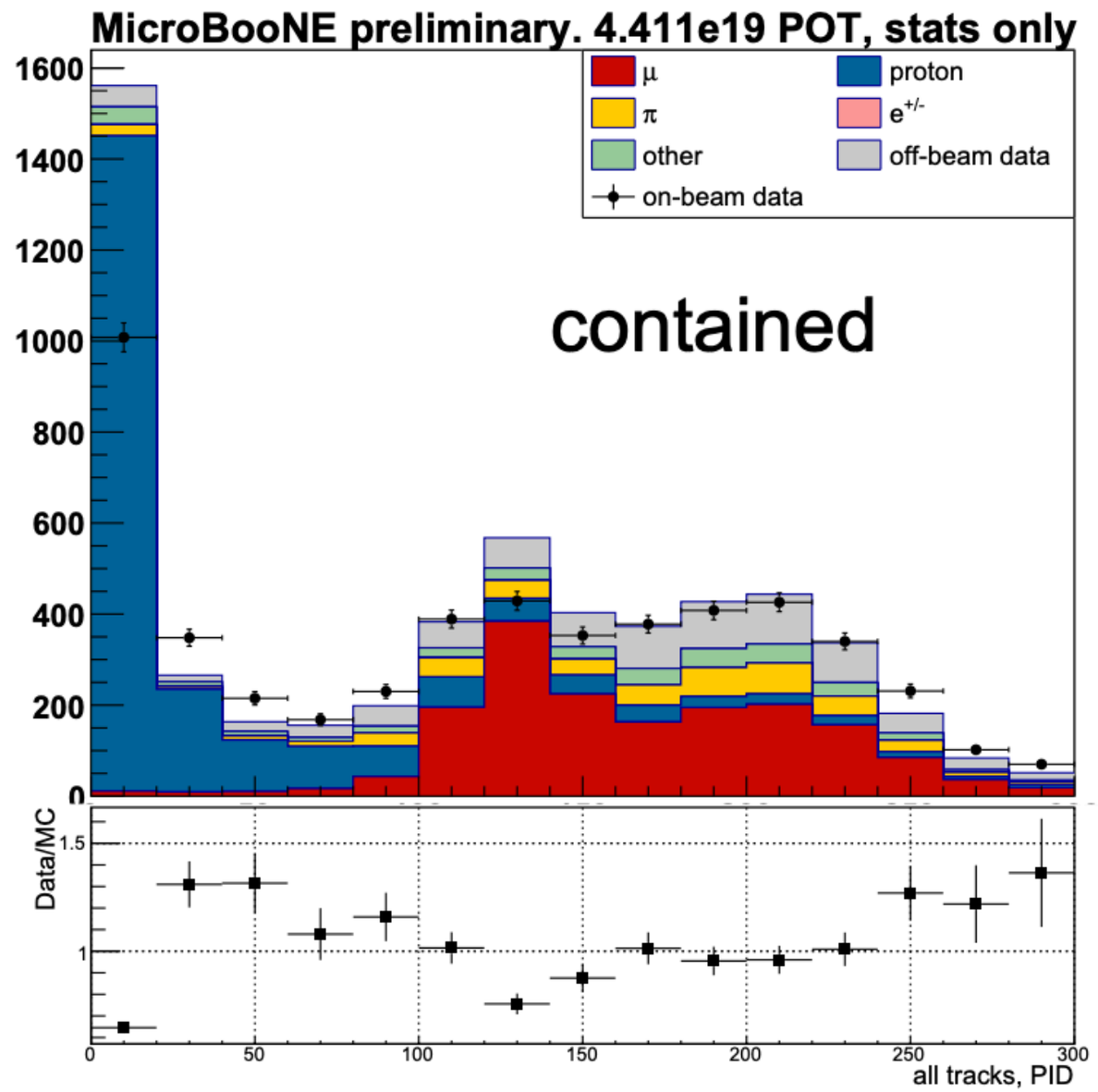


IDENTIFYING π^+

MICROBOONE-NOTE-1056-PUB

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

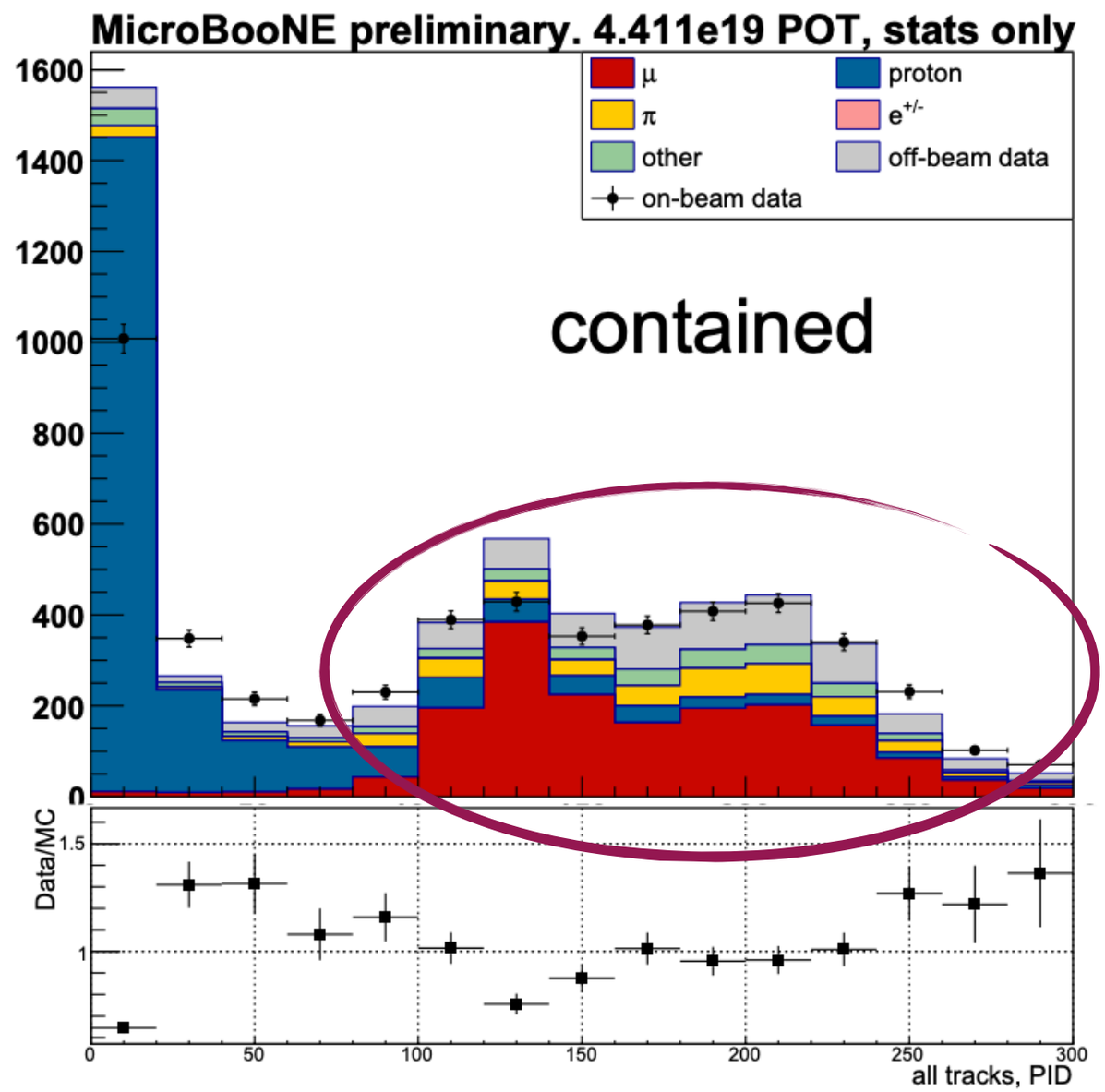




IDENTIFYING π^+

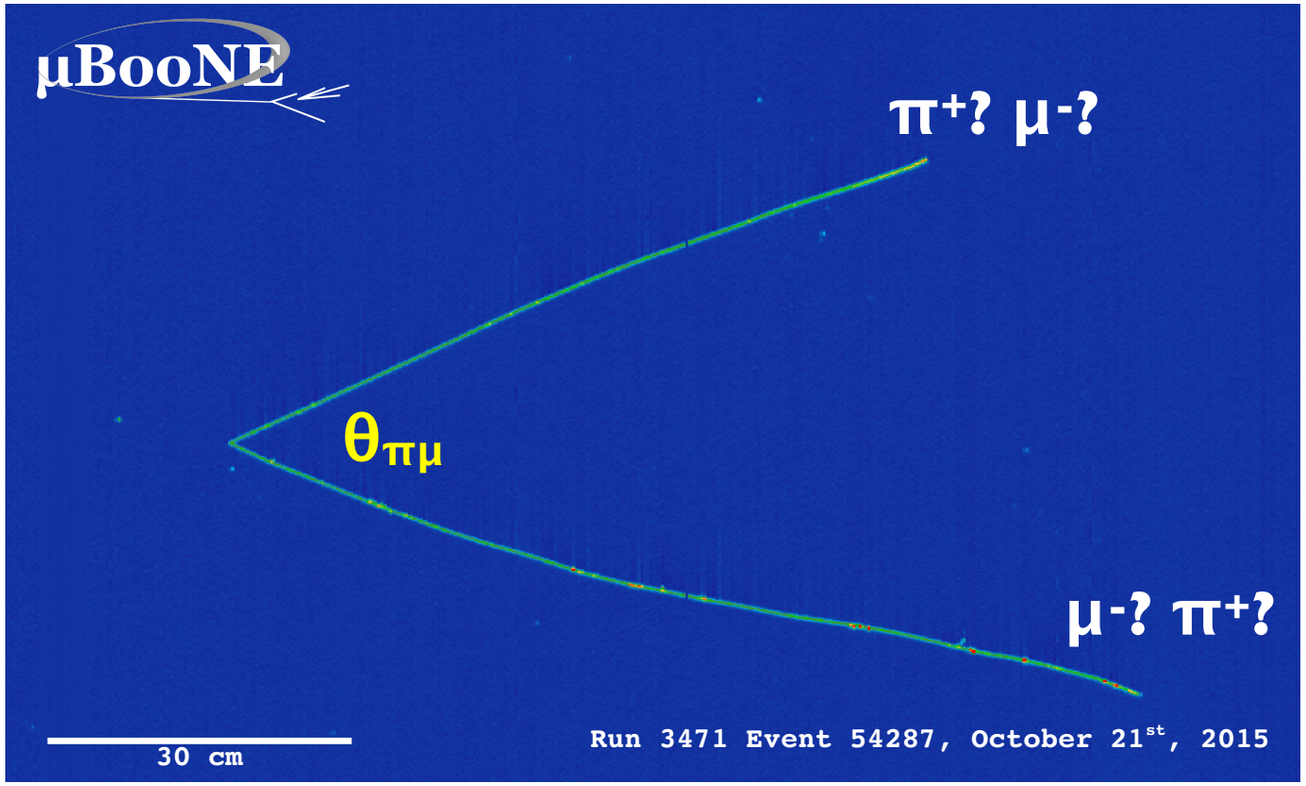
MICROBOONE-NOTE-1056-PUB

- 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?



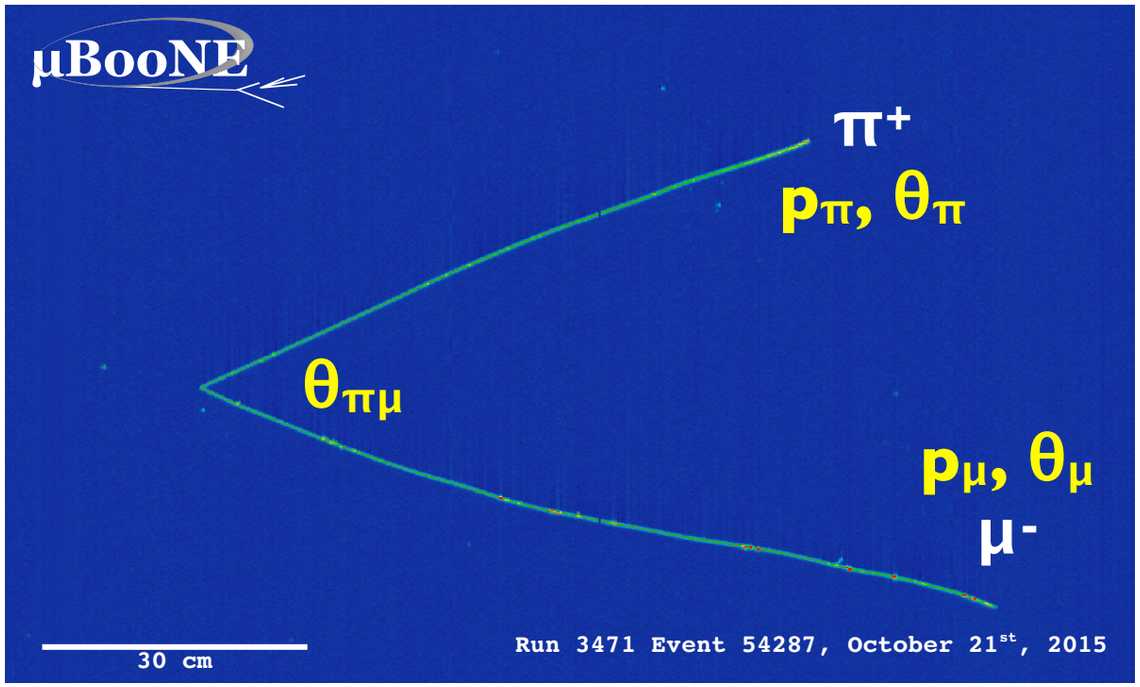
OPTION 1: WE DON'T

- Simple selection: two tracks start at vertex, both inconsistent with being a proton → muon and charged pion candidates
- No further particle ID
- Limits the measurements you can make to just opening angle
- **We don't plan to do this**



OPTION 2: TRACK LENGTH AND/OR CONTAINMENT

- We expect in CC1pi+ interactions*:
  - >70% μ^- has higher momentum than π^+
  - >90% π^+ stops in detector

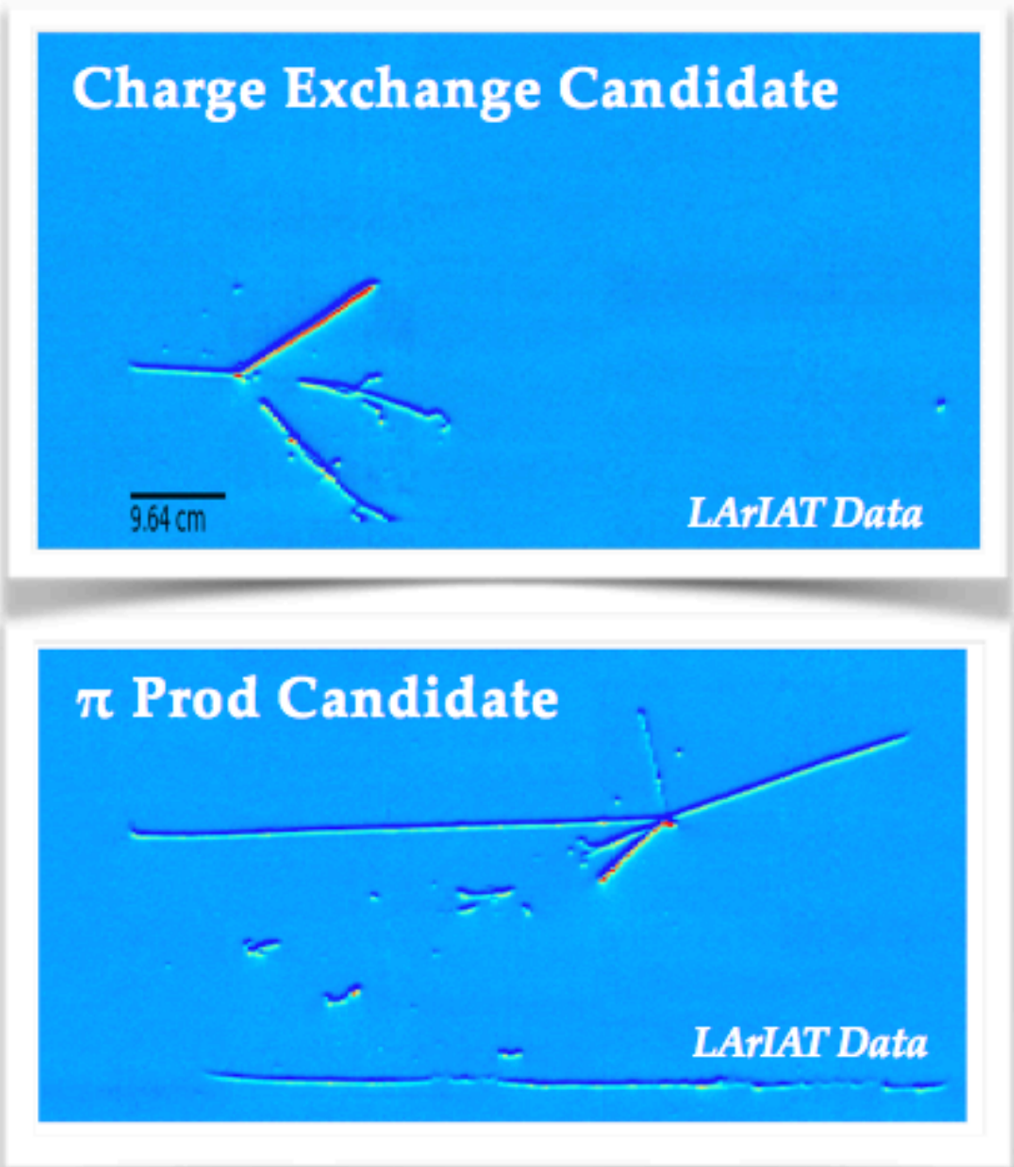


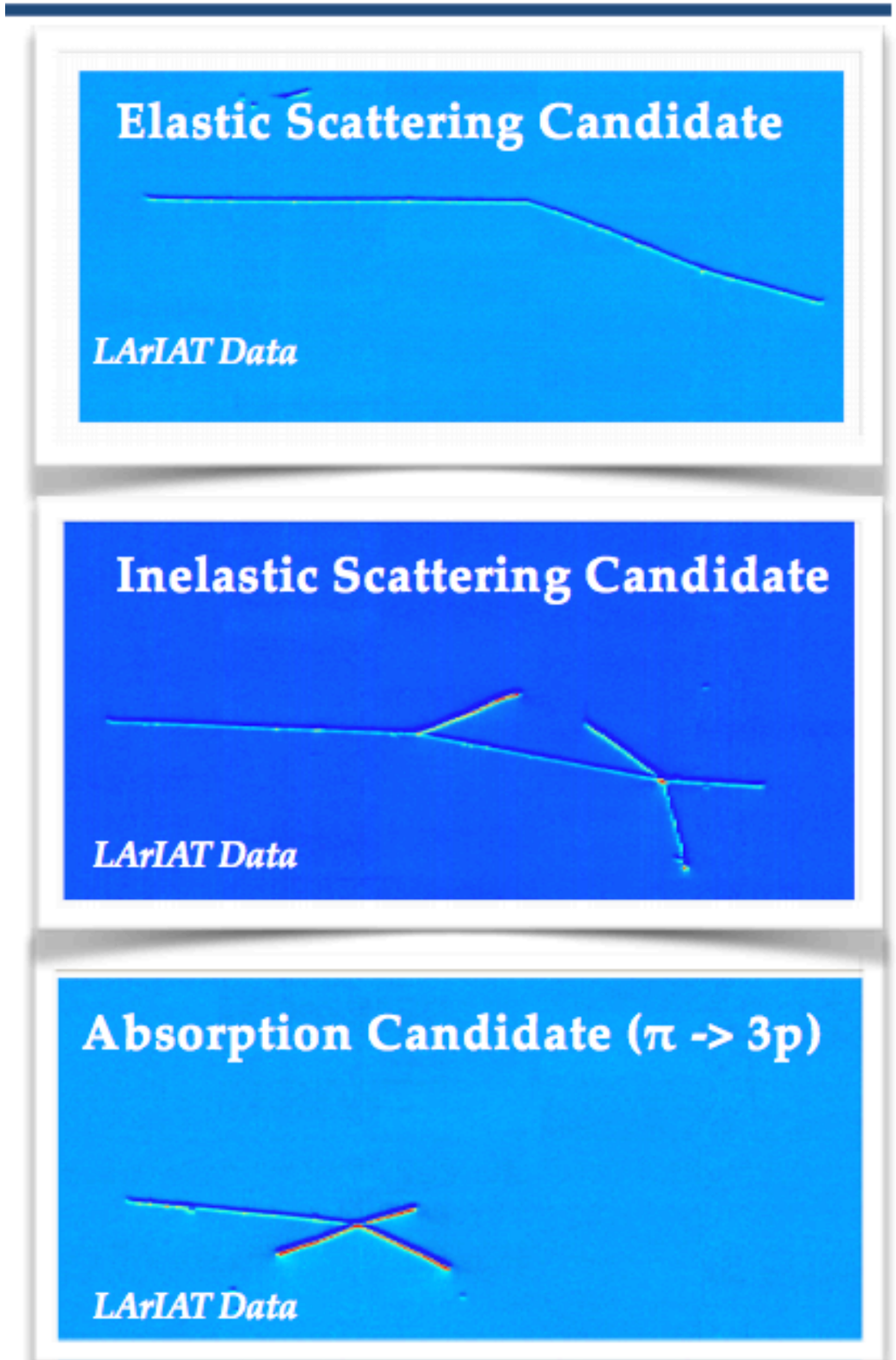
- **We may consider this** as a fallback if other methods don't work (for reasons I'll go into)

*GENIE v3.0.6, tune G18_10a_02_11a (Berger-Sehgal model, axial FF tuned to MiniBooNE)

Slide source: Elena Gramellini, Fermilab Neutrino Seminar

OPTION 3: HADRONIC INTERACTIONS

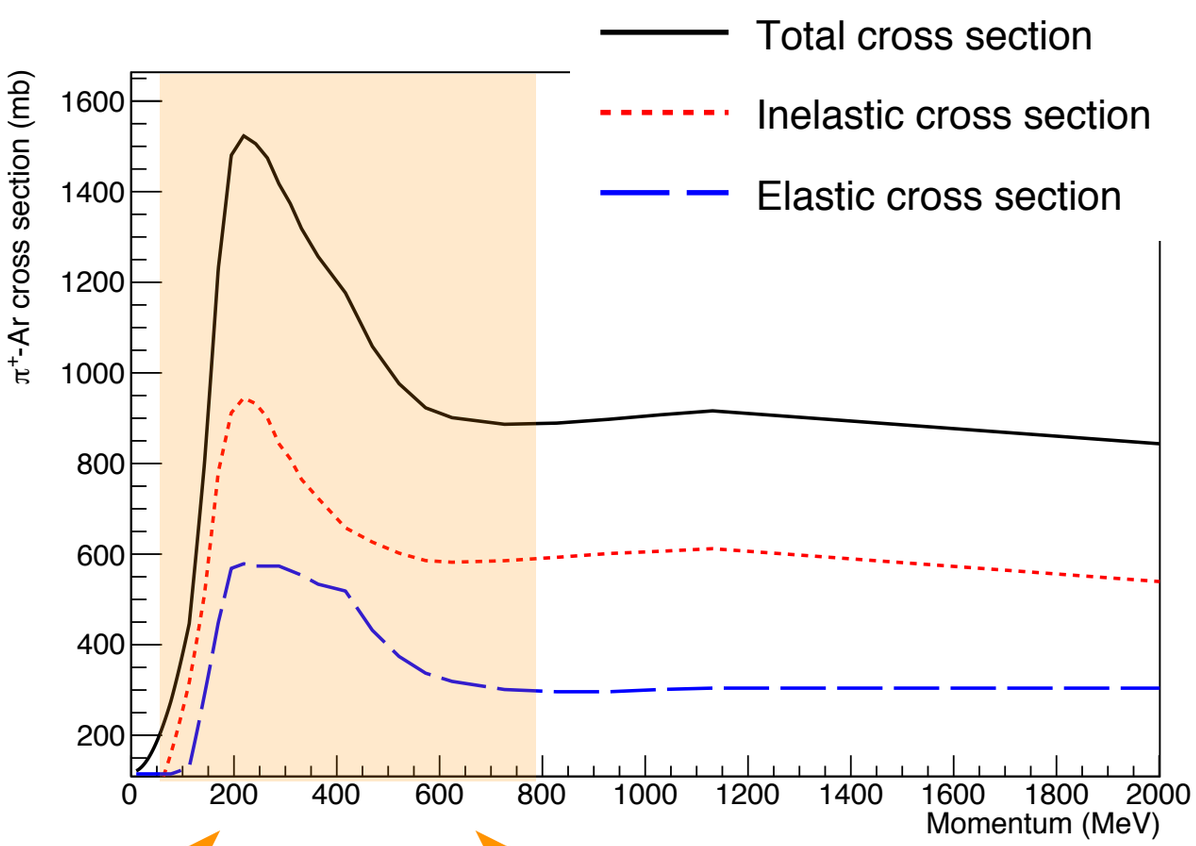


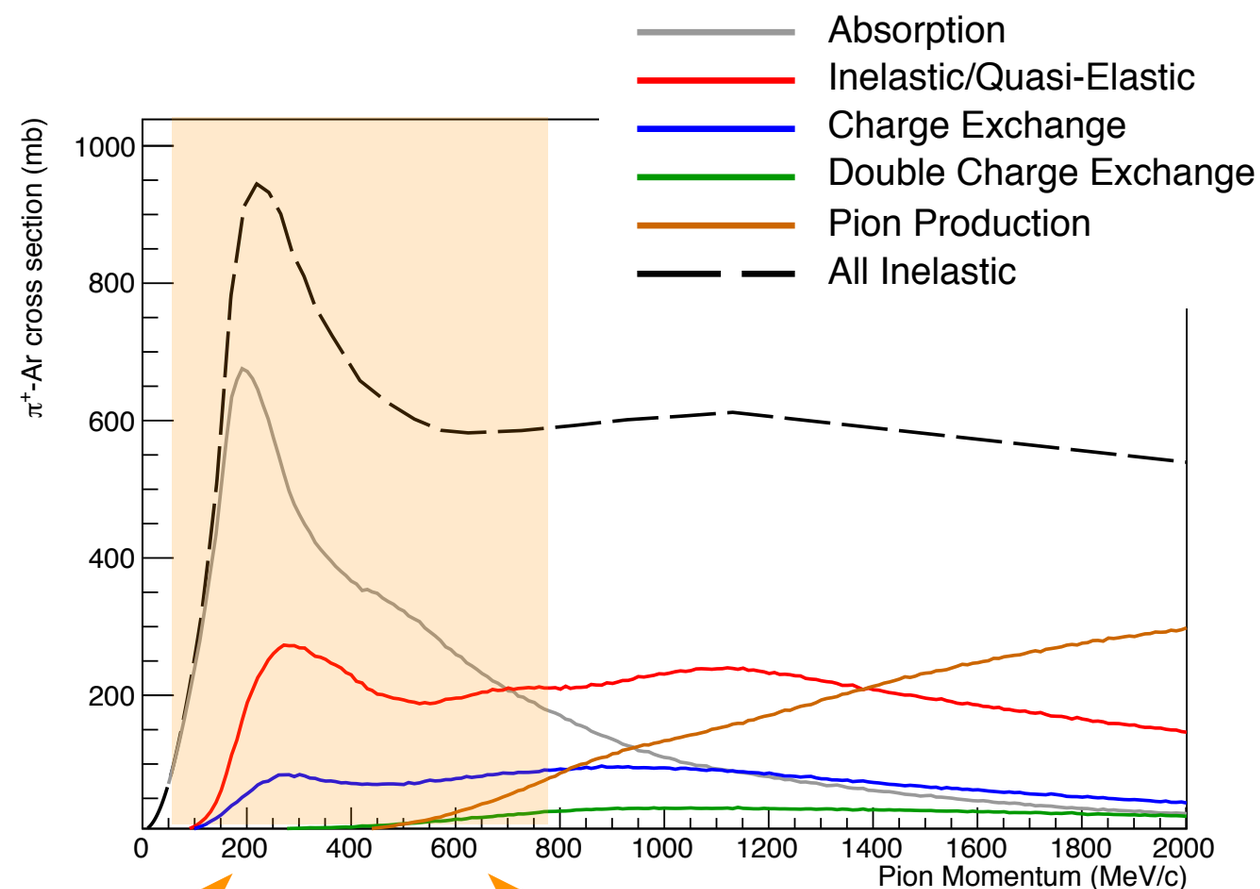


LArIAT Data

π^+ INTERACTIONS

Plots made using GEANTReWeight (J. Calcutt)

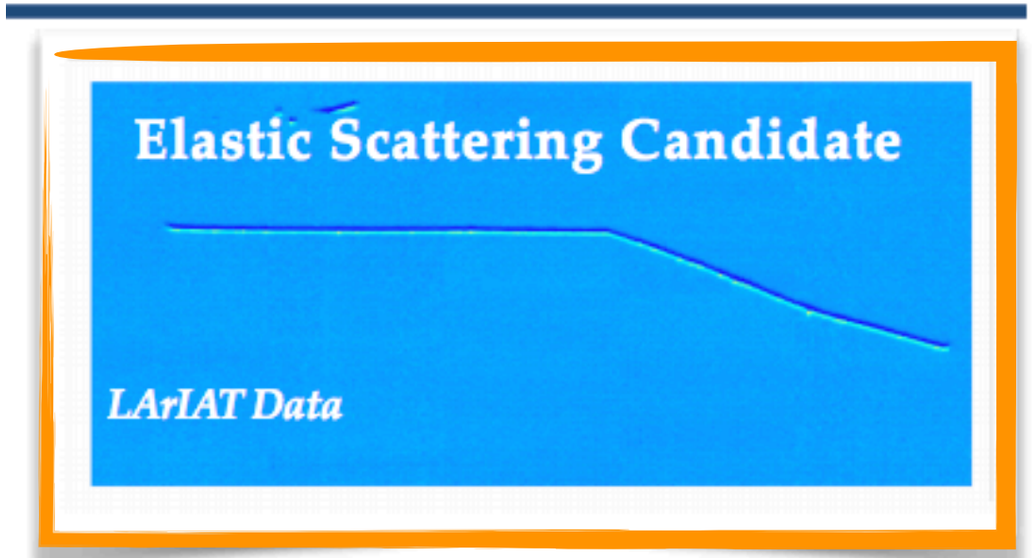


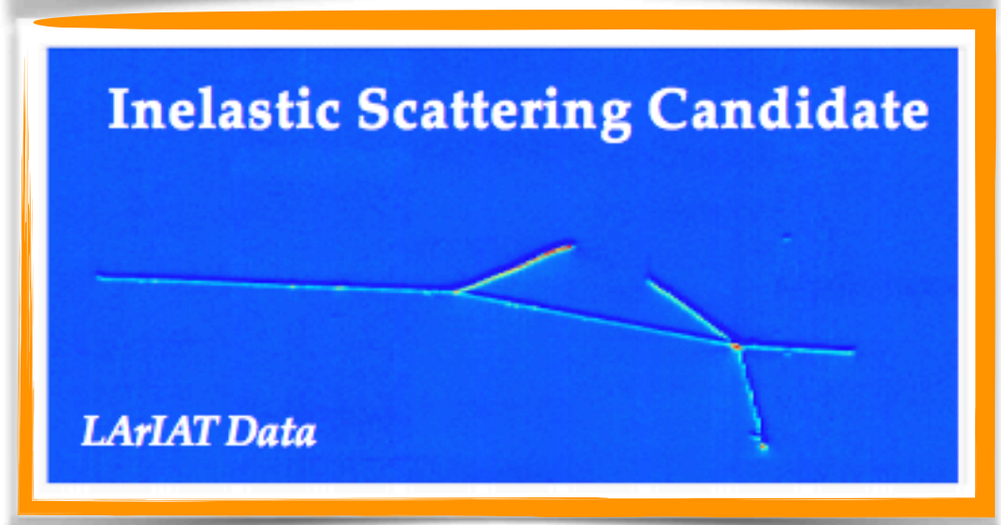


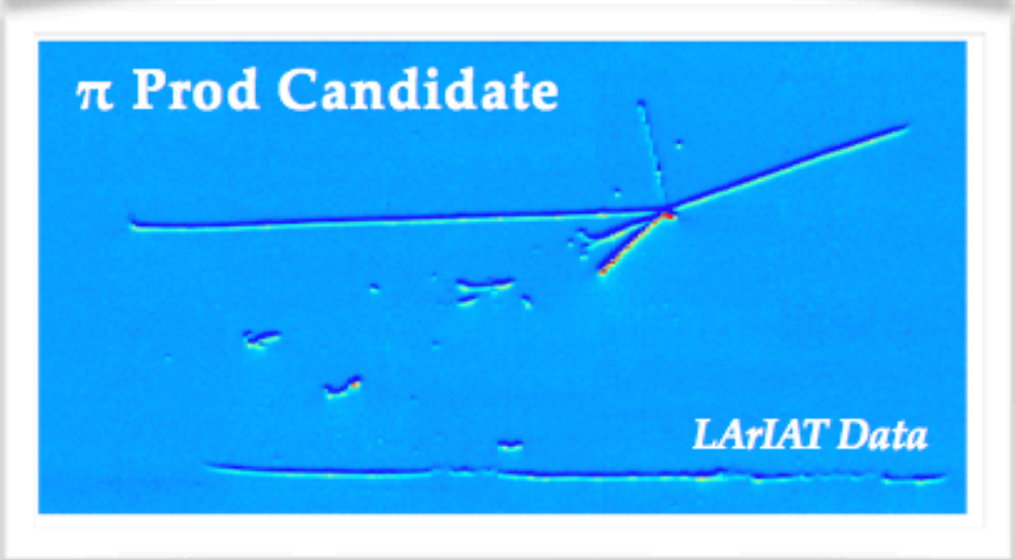
Roughly speaking, GENIE predicts π^+ produced in MicroBooNE will fall in **this energy range**

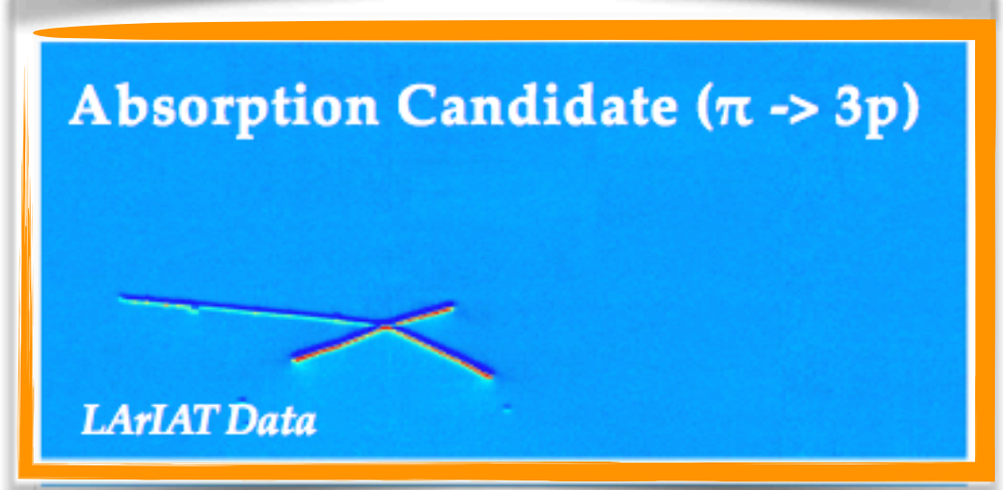
Slide source: Elena Gramellini, Fermilab Neutrino Seminar

OPTION 3: HADRONIC INTERACTIONS





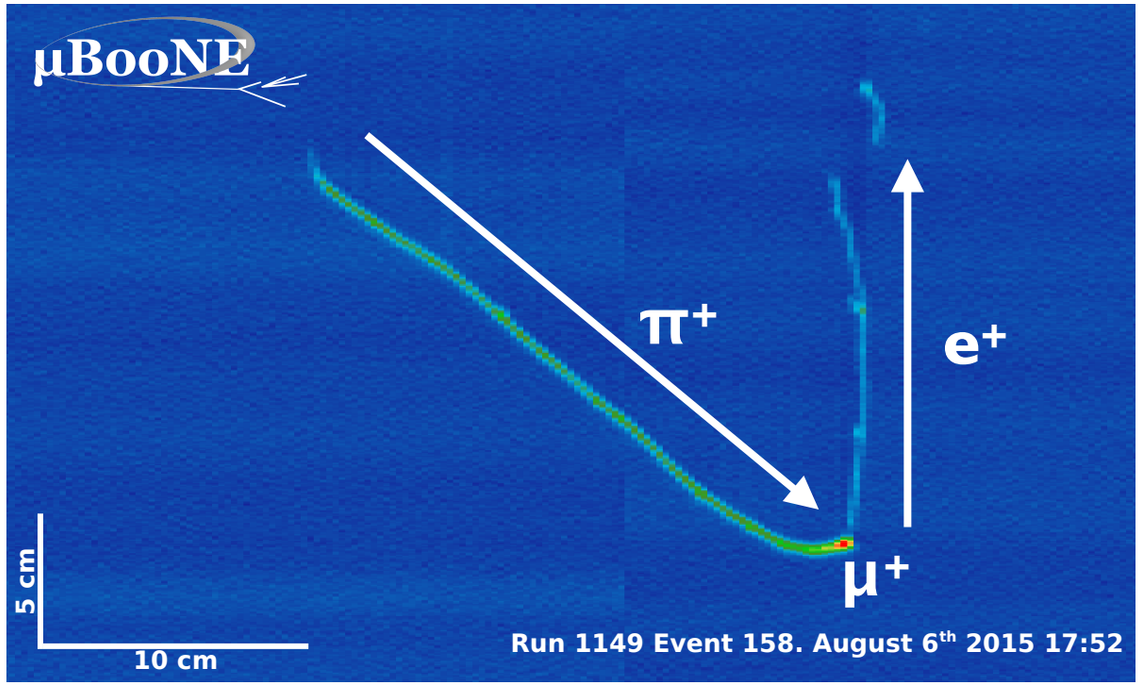




LArIAT Data

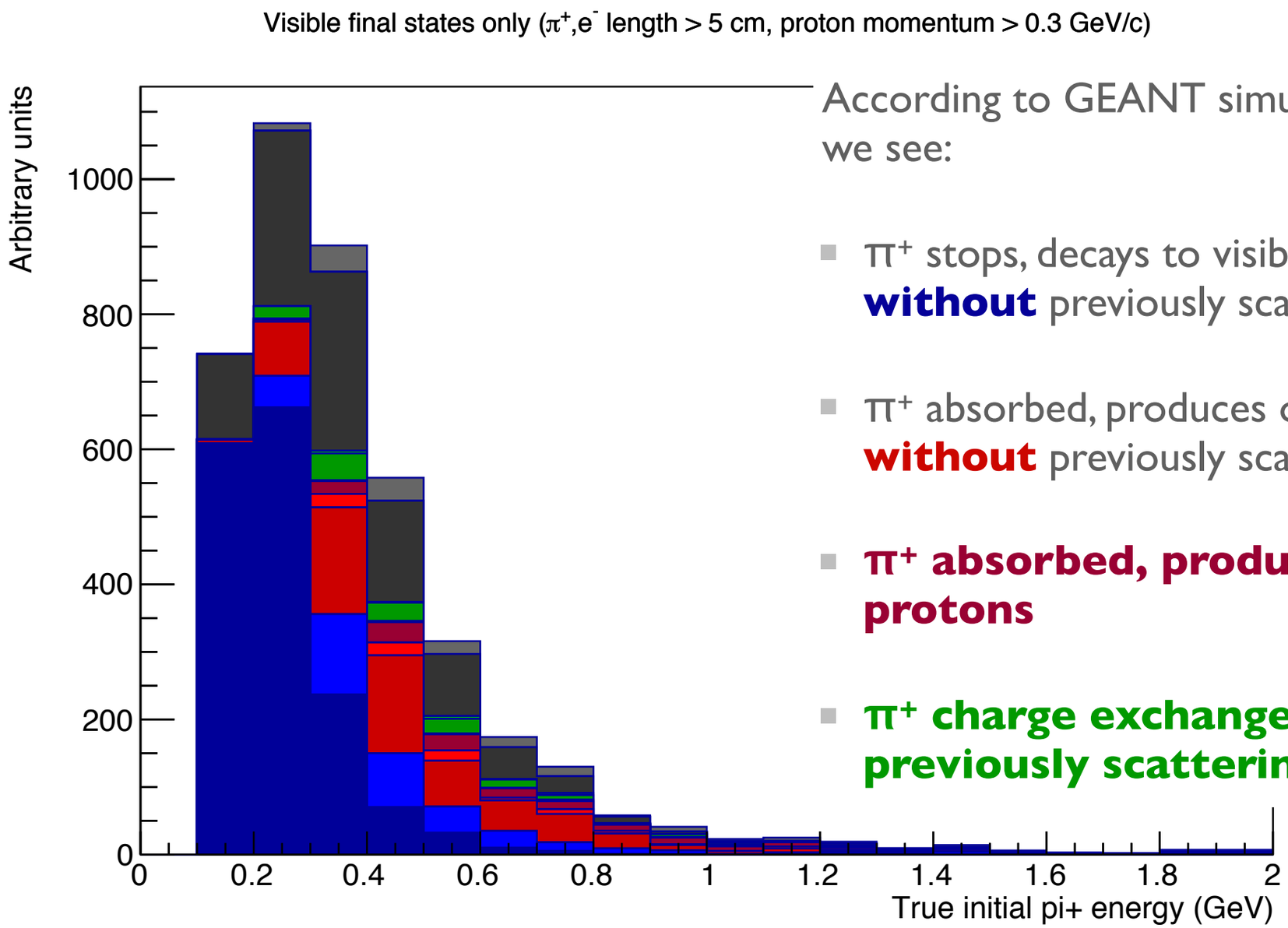
OPTION 4: MICHEL ELECTRON

- GEANT4 predicts:
  - >90% of π^+ stop in detector
  - ~55% decay to produce a Michel electron (muon not visible) → ~50% with Michel electron > 5cm
- Look for π+ by presence of Michel electron?



  - Pro: if we see a Michel electron, we know the pion has stopped → measure momentum using track length
  - Con: Efficiency loss of >50%
  - Another con: **this isn't a way to identify π^+ exclusively** — muons can also decay to produce Michel electrons! May be effective when combined with option 2 (track length), but model dependent? **We are considering this**

PUTTING IT ALL TOGETHER



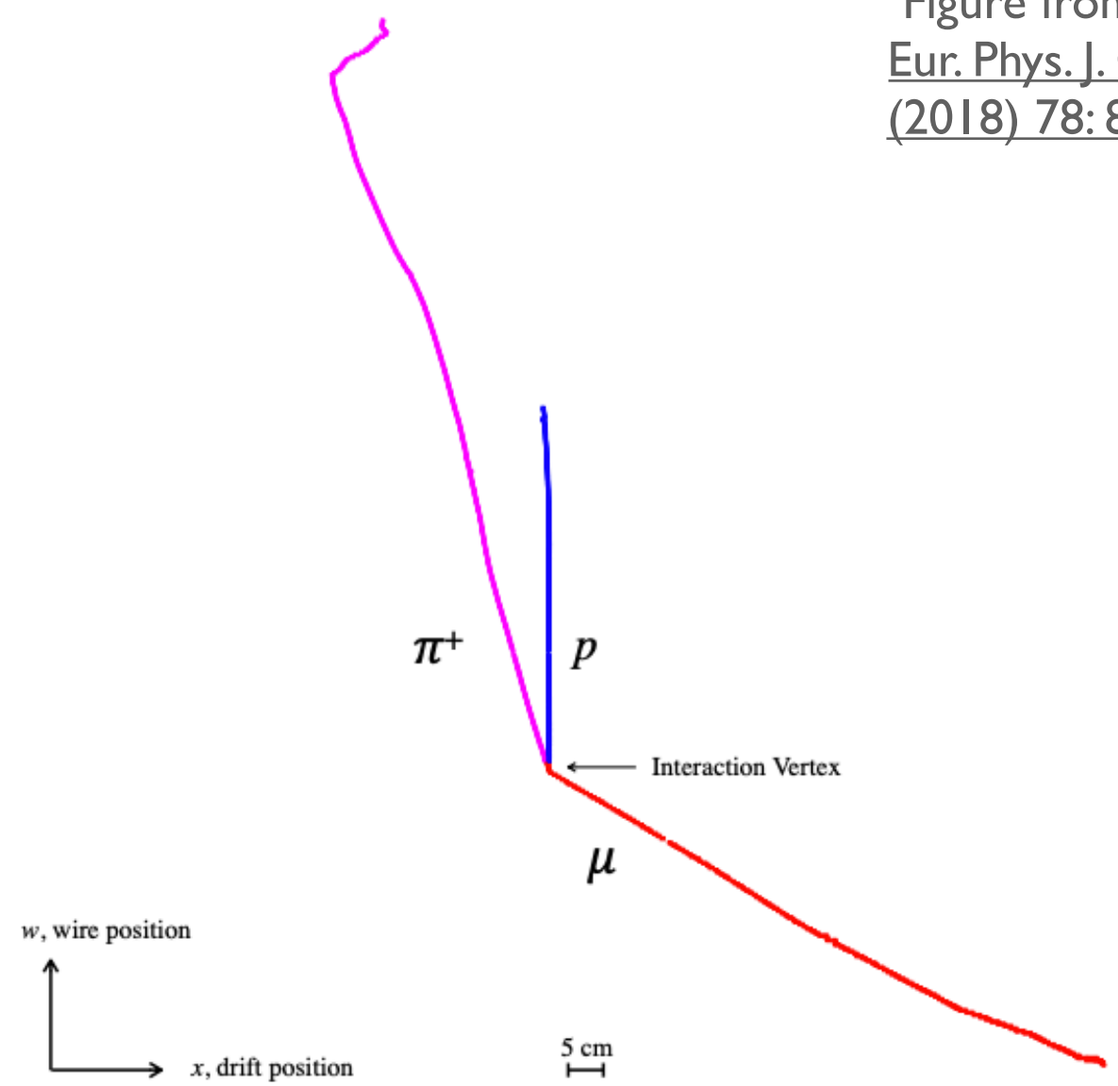
According to GEANT simulation expect majority of what we see:

- 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**

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



A CATCH-22?

If a π^+ stops in the detector with a reconstructable Michel electron:

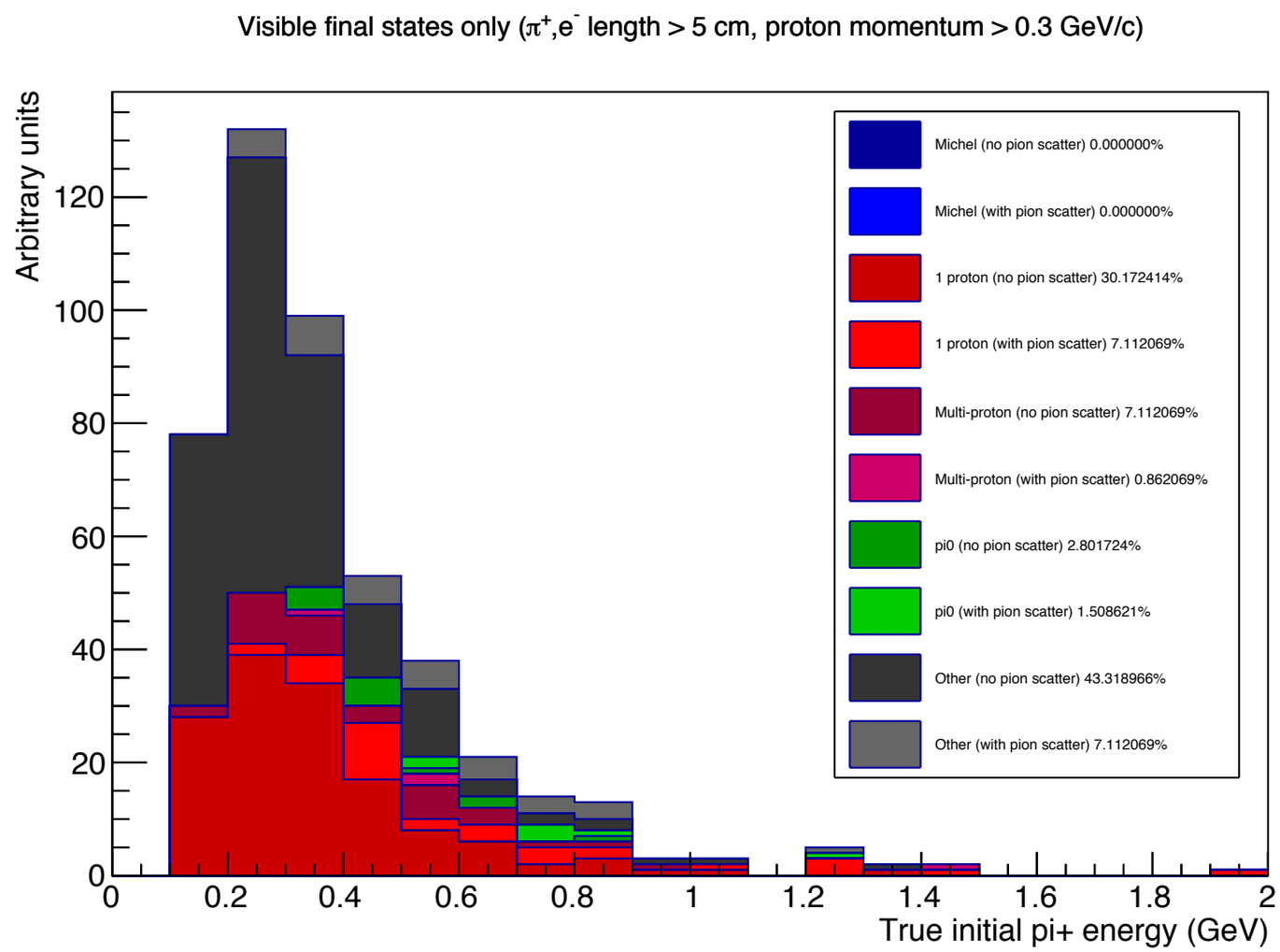
- ✔ We know the pion is at rest
- ✔ Can measure momentum accurately using length
- ✔ Likely fate for charged pions at MicroBooNE energies
- ✘ Cannot positively identify as a charged pion (i.e. not a muon)

If a π^+ interacts hadronically:

- ✔ Can positively identify as a charged pion (i.e. not a muon)
- ✘ More difficult to reconstruct correctly
- ✘ Cannot measure momentum accurately using length
- ✘ Less likely to happen at MicroBooNE energies (efficiency loss)

WHAT ABOUT π^-?

- I've focused on π^+ here because we plan to measure $\nu_\mu CC1\pi^+$ production in MicroBooNE
- π^- are less of a focus for us, but will be more relevant for DUNE. They behave a little differently
- Almost all π^- are captured on Argon → can't identify using scatters or Michel decays. Rely instead on looking for protons after absorption



MEASUREMENTS ON ARGON

- ArgoNEUT: CC1$\pi^{\pm}$ production Phys. Rev. D 98, 052002 (2018)
- Select two-track events: one matched to a track in MINOS (muon candidate)
- Select CC1$\pi^{\pm}$ events using dE/dx of pion candidate, event topology
- Overall purity 35.8% (ν), 55.7% ($\bar{\nu}$)
- 337 selected ν events (285 $\bar{\nu}$)

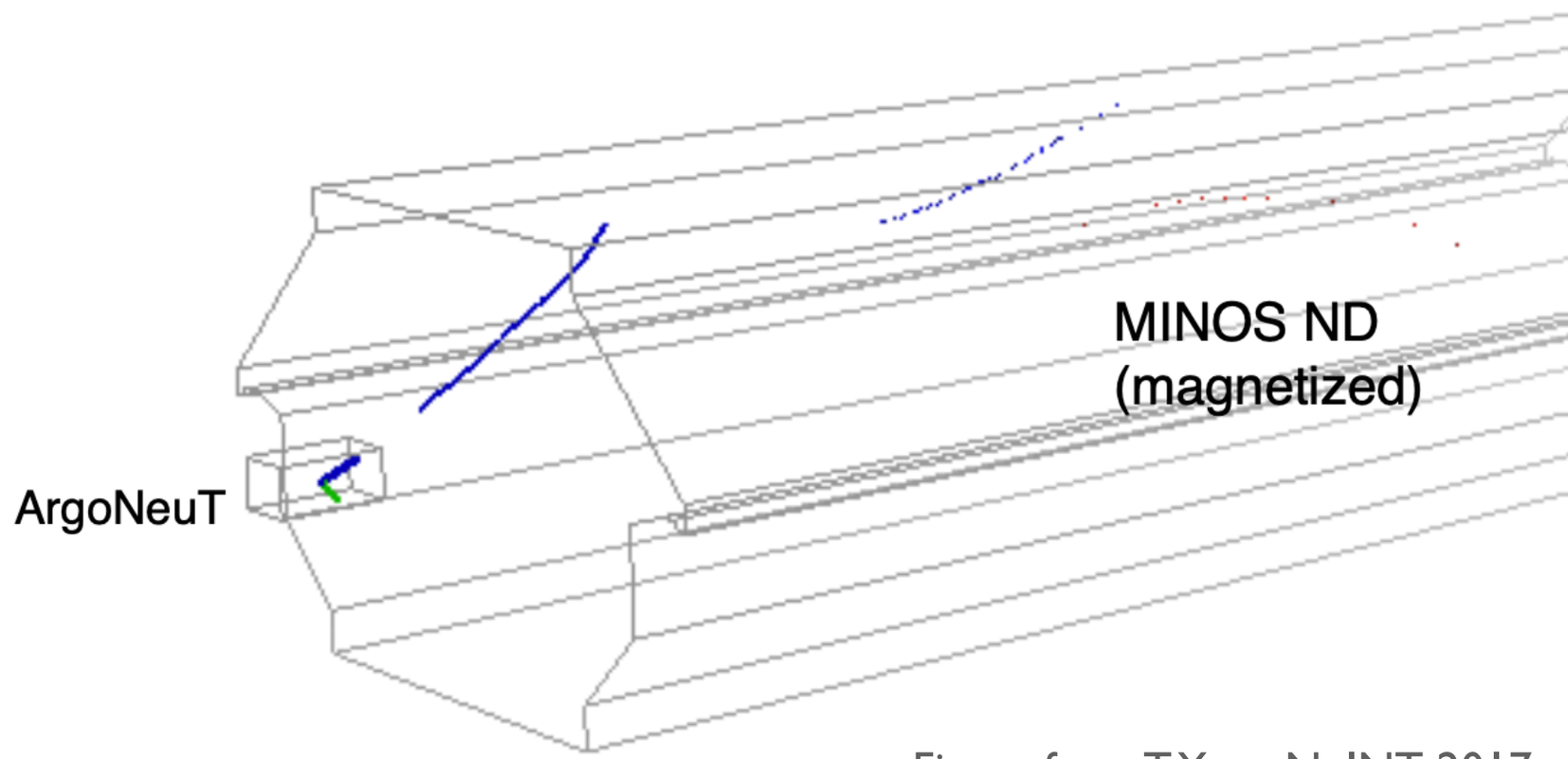
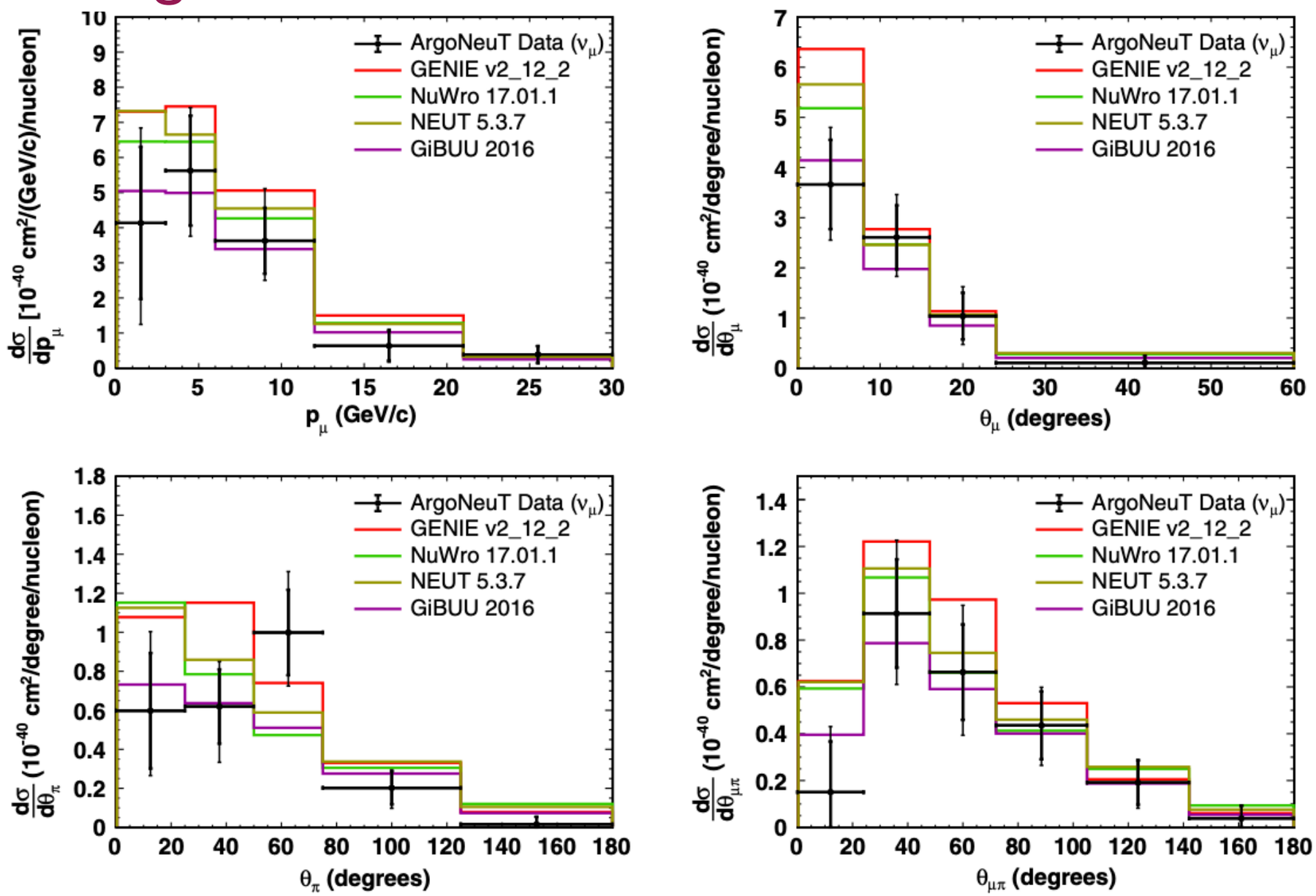


Figure from T. Yang, NuINT 2017

MEASUREMENTS ON ARGON

ν_μ CC1$\pi^\pm$ ArgoNeuT measurement

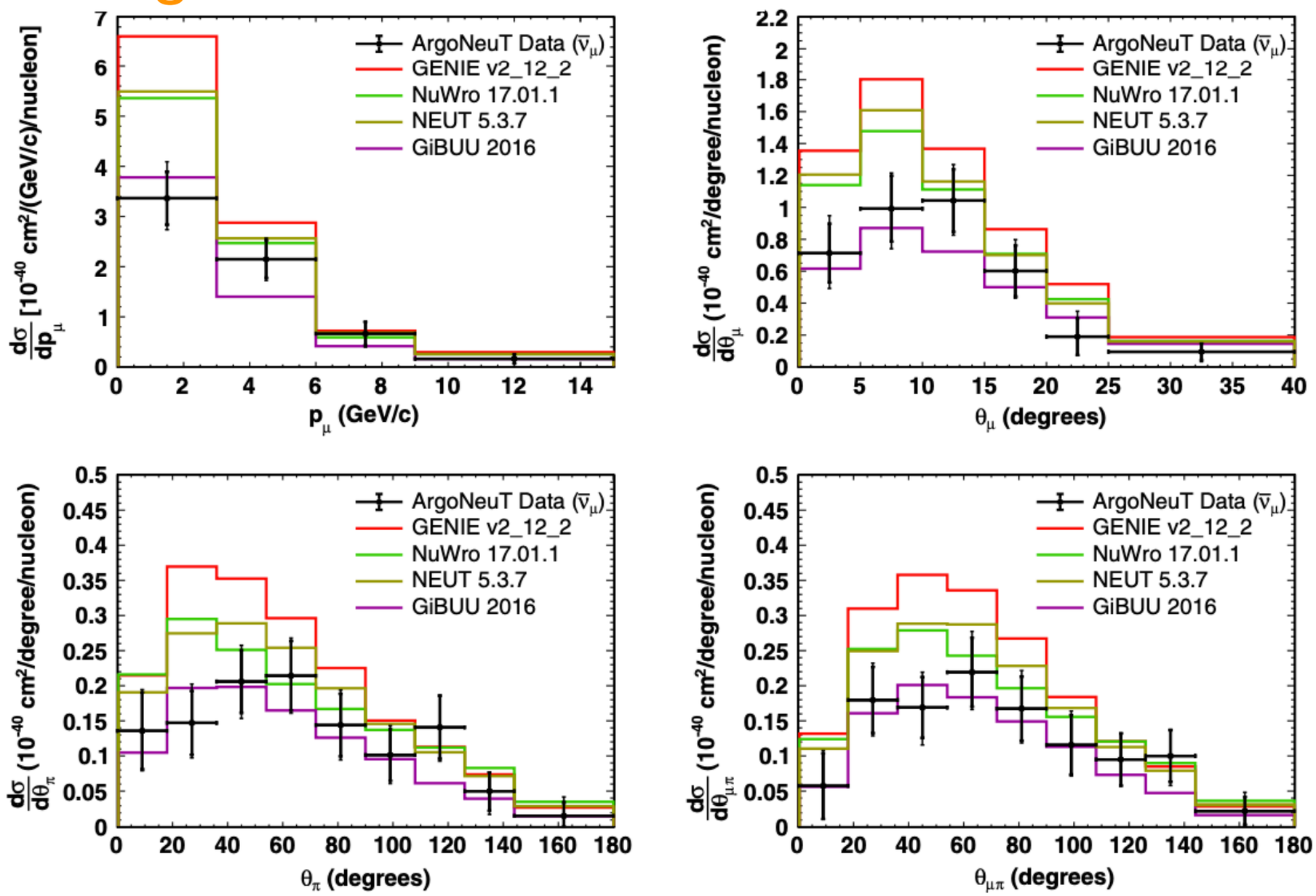
Phys. Rev. D 98, 052002 (2018)



MEASUREMENTS ON ARGON

$\bar{\nu}_\mu$ CC1$\pi^\pm$ ArgoNeuT measurement

Phys. Rev. D 98, 052002 (2018)



TS ON ARGON

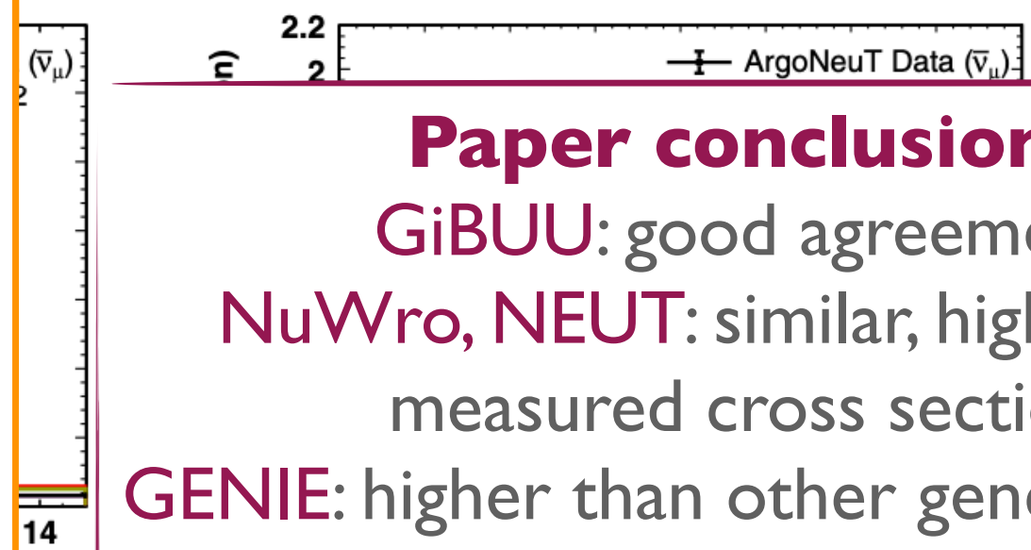
Resonant pion production model
- GENIE, NEUT: Rein-Sehgal
- NuWro: Δ(1232) resonance only

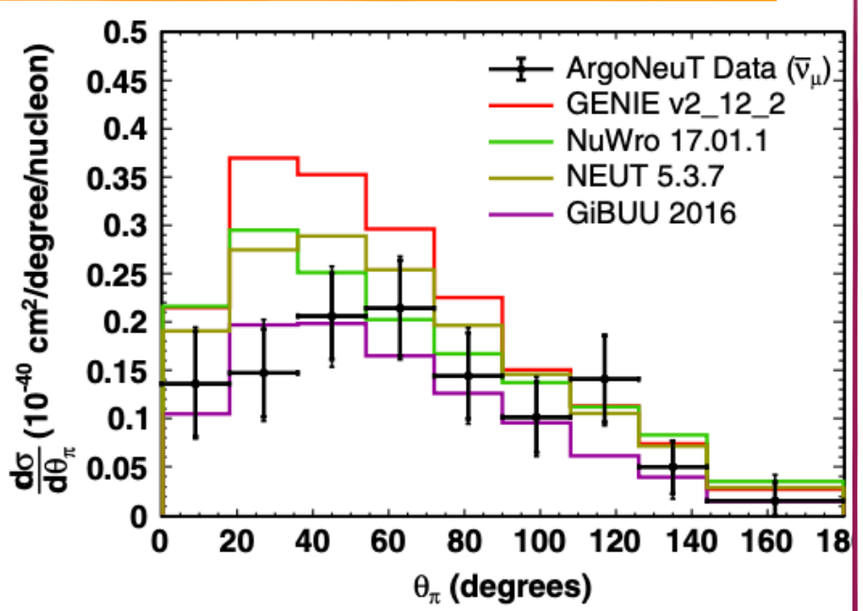
Nonresonant model
- NEUT: Rein-Sehgal
- GENIE, NuWro: Bodek-Yang above resonance region, extrapolate smoothly to converge with resonance model at lower W

FSI
- NEUT, NuWro: Salcedo-Oset cascade
- GENIE: effective cascade model
- GiBUU: quantum-kinetic transport theory

rement

Phys. Rev. D 98, 052002 (2018)





Paper conclusions

GiBUU: good agreement

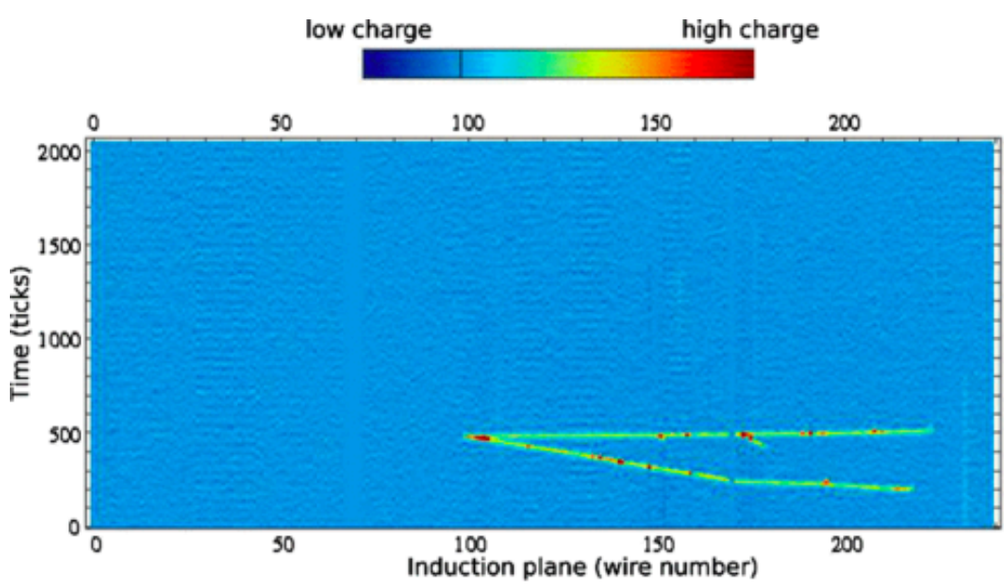
NuWro, NEUT: similar, higher than measured cross section

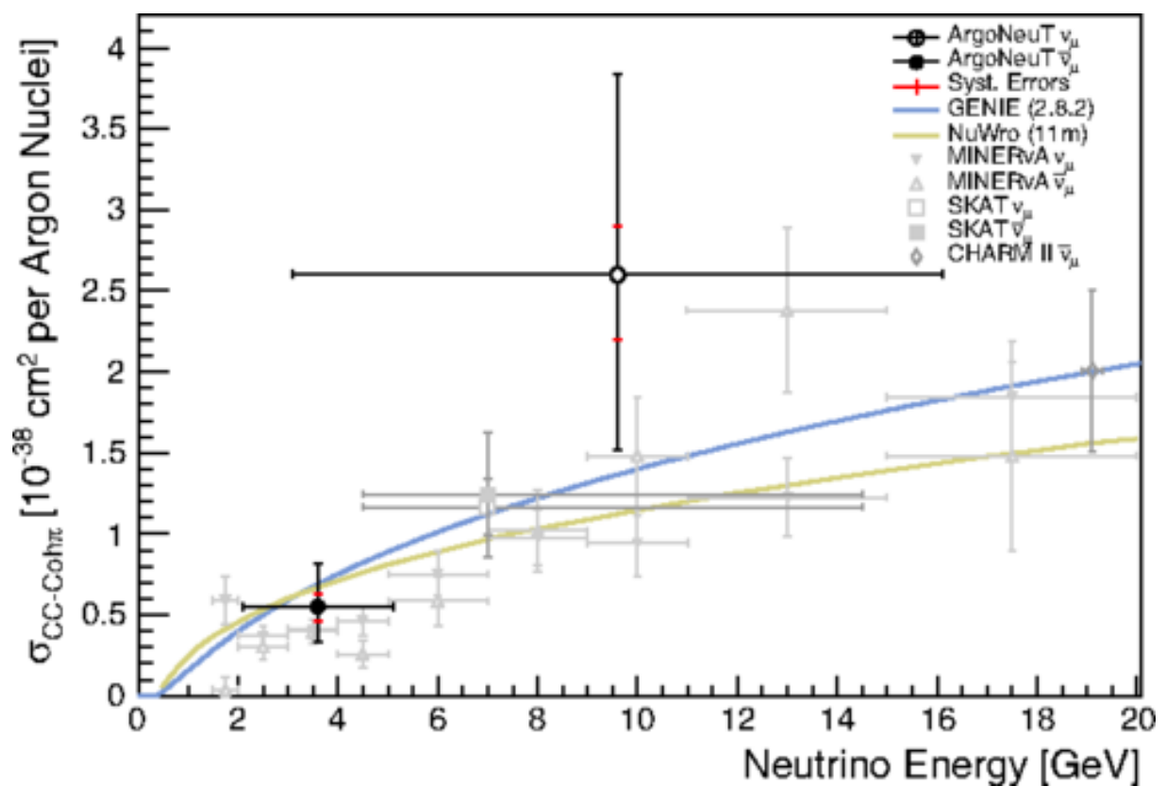
GENIE: higher than other generators and measured cross sections (with reanalysis of bubble chamber data in EPJC (2016) 76: 474 points to GENIE's nonresonant background prediction)

All predictions within 2σ of measurement, except GENIE $\bar{\nu}$ (3.3σ)

MEASUREMENTS ON ARGON

- ArgoNEUT: CC-Coherent π^+ production Phys. Rev. Lett. 113, 261801 (2014)
- General agreement with Rein-Sehgal prediction (low statistics — select 24 ν and 30 $\bar{\nu}$ events, estimate ~7±3 signal events in each)





MICROBOONE ANALYSES

In progress (near future)

- **CC1π^+ (inclusive) measurement**
  - Look for **one muon, one π^+**, no showers ($e/\gamma/\pi^0$)
  - (Preliminary) aim is for **differential measurement**: opening angle, muon momentum/angle, pion momentum/angle
- **CC-Coherent 1π+ measurement**
  - Look for **one muon, one π^+, no vertex activity**, very forward-going
  - Try to avoid cutting on |t| (squared 4-momentum transfer to nucleus) and measure — is that useful?
  - **CC1π+ will be significant background**: use above measurement and/or need good predictions

MICROBOONE ANALYSES

Planned (farther future)

- **CC1π^+1p**
  - More exclusive topology: reconstruct Δ^{++} resonance
  - **What interesting measurements can/should we make with this topology?**
- **CC-multiπ**
  - Interesting for DUNE, who will sit at RES-DIS transition region
  - May be difficult in MicroBooNE — expect very few DIS events at our energies
  - SBND may be able to make measurements (same flux, but ~30x statistics) — **how interesting/necessary is that measurement?**
- A question for you: **what other measurements would you like to see from MicroBooNE?**

SUMMARY

MicroBooNE needs to understand resonant interactions (and FSI) for the success of our own physics program: especially **π^0 backgrounds** and **RES+FSI part of signal**

Our measurements can help, as well as provide input to SBN/DUNE

- Current measurements: CCincl, CCπ^0
- In progress: CC2p, CCNp (N>=1), CCπ^0 differential, NCπ^0, CCπ^+, CC-Cohπ^+
- Coming later: CCNp STV, CCπ^+1p, CCmultiπ

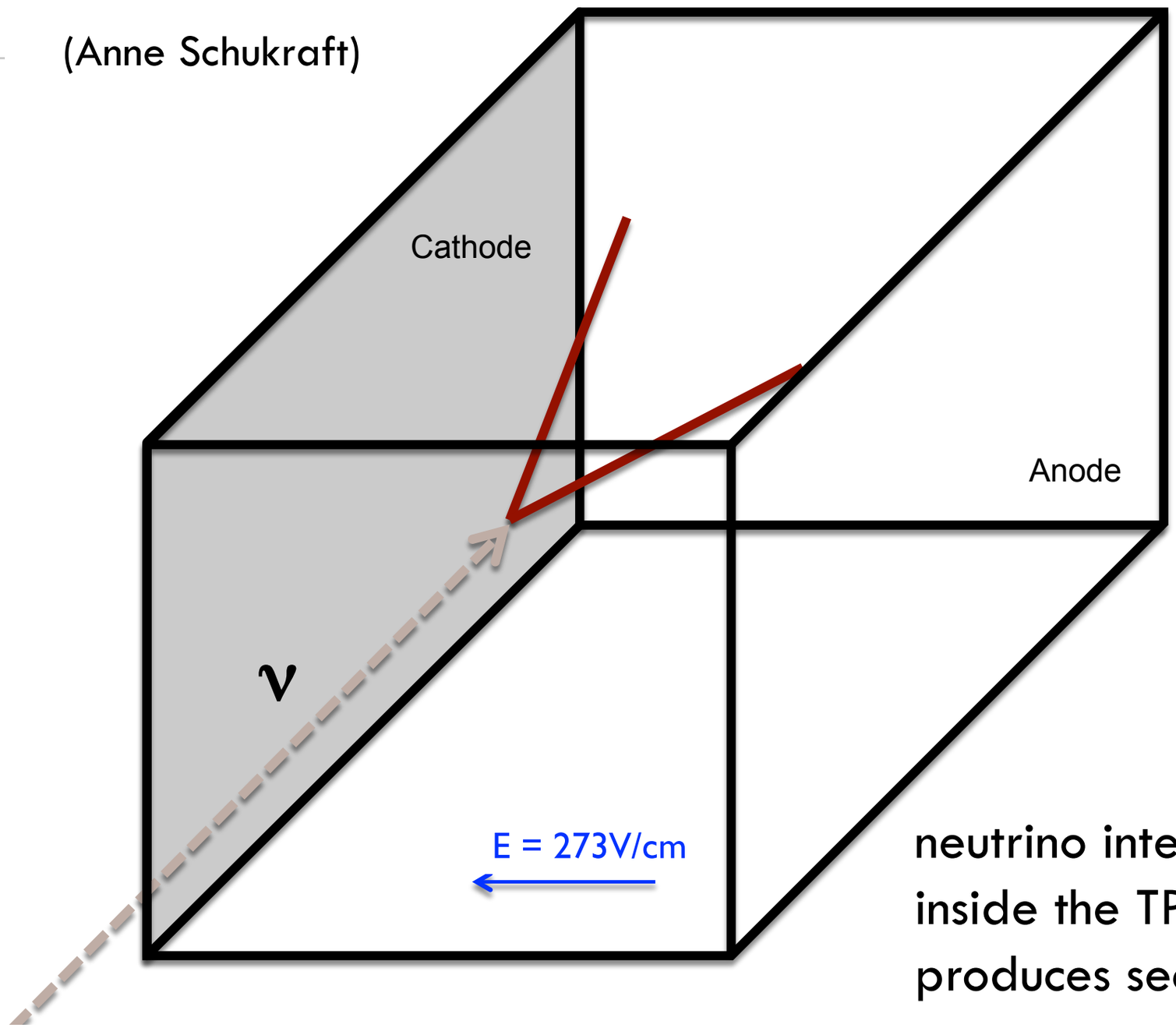
Appreciate input from the community on the most interesting measurements to make

What do we need to make precise measurements?

- **Good predictions of π-Argon cross sections** (FSI, interactions in detector)
- **Good models for neutrino interactions** (particularly CCQE, MEC, RES, FSI) **with realistic and believable uncertainties**

LIQUID ARGON TPC

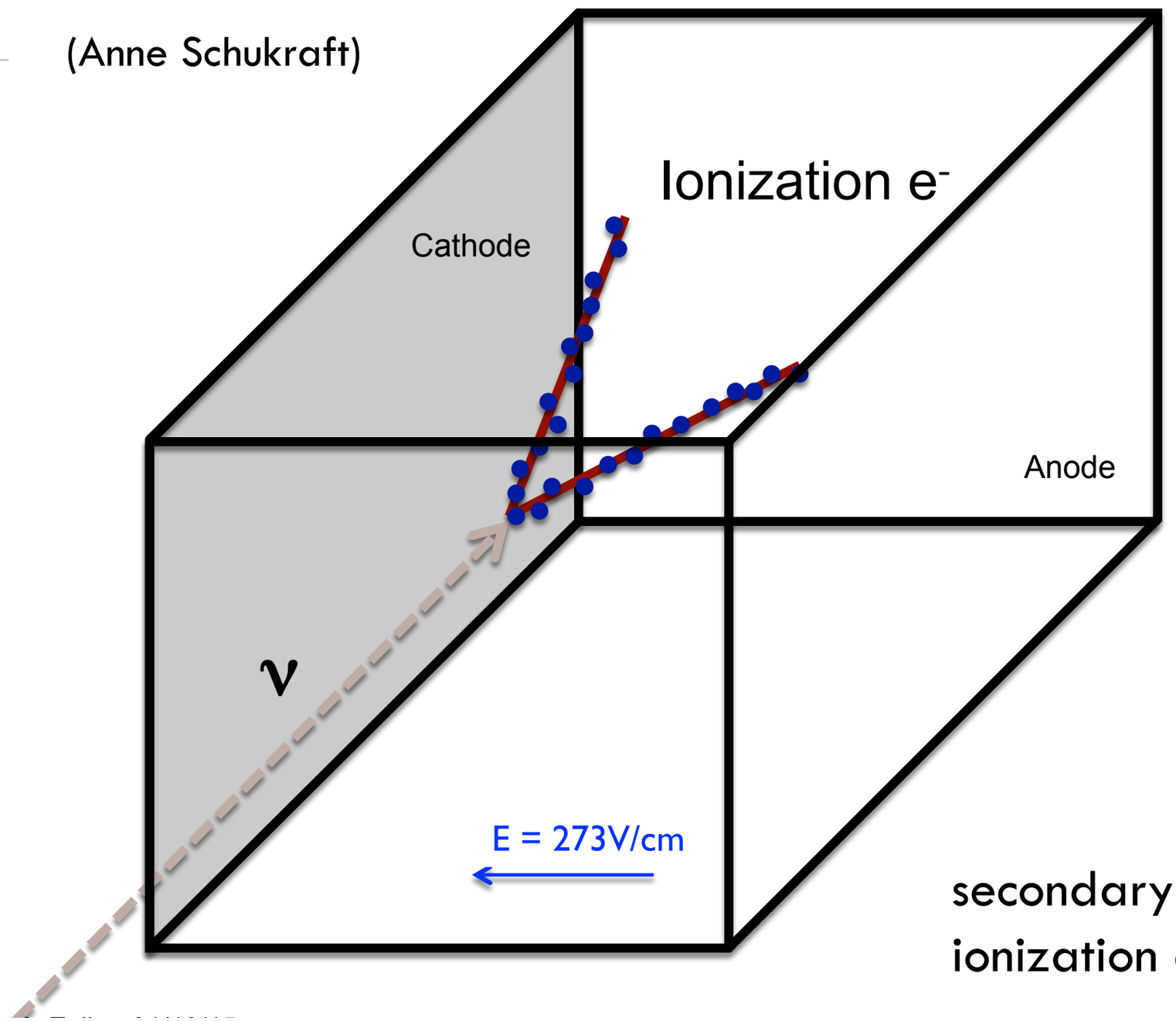
(Anne Schukraft)



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

LIQUID ARGON TPC

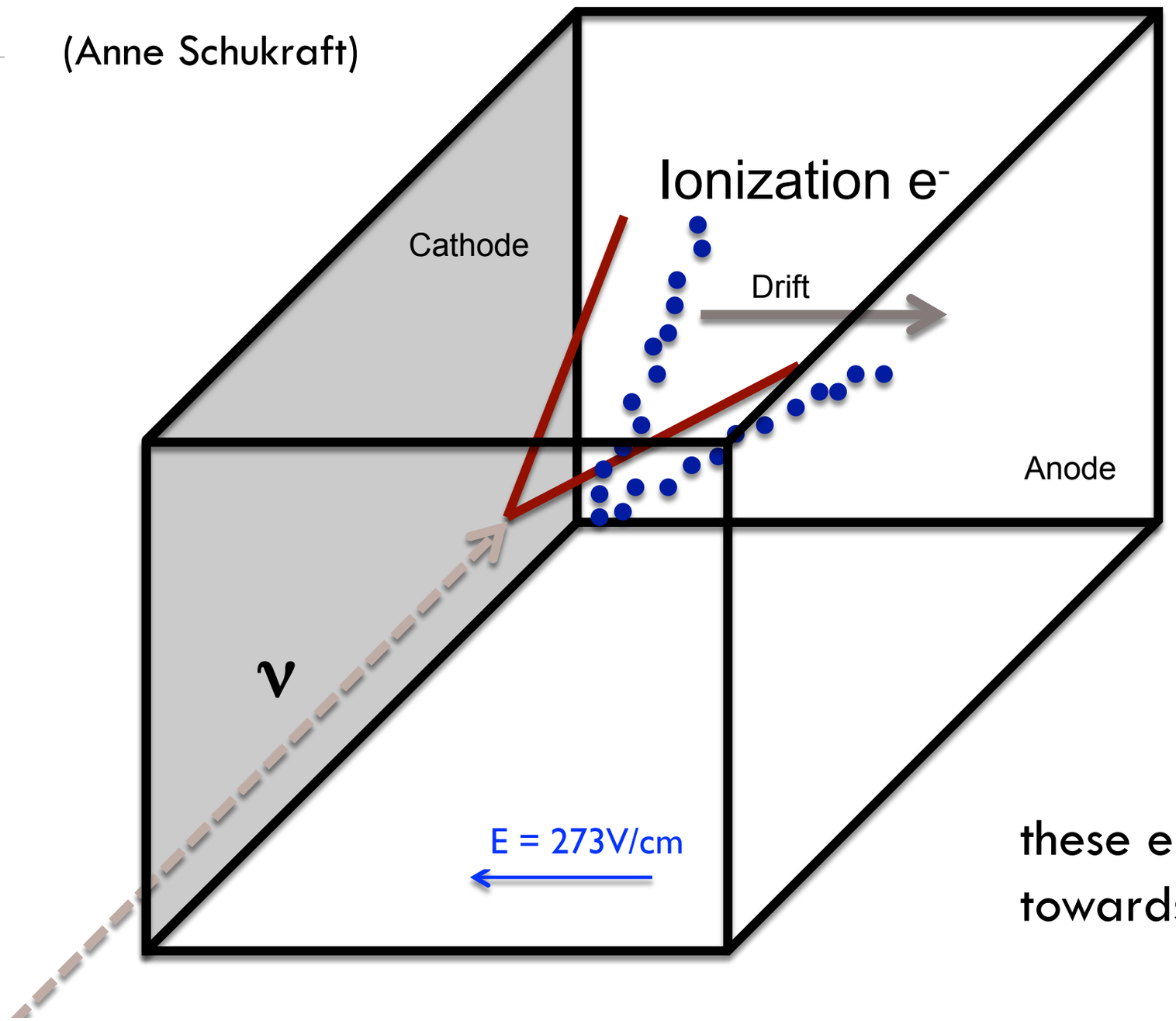
(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

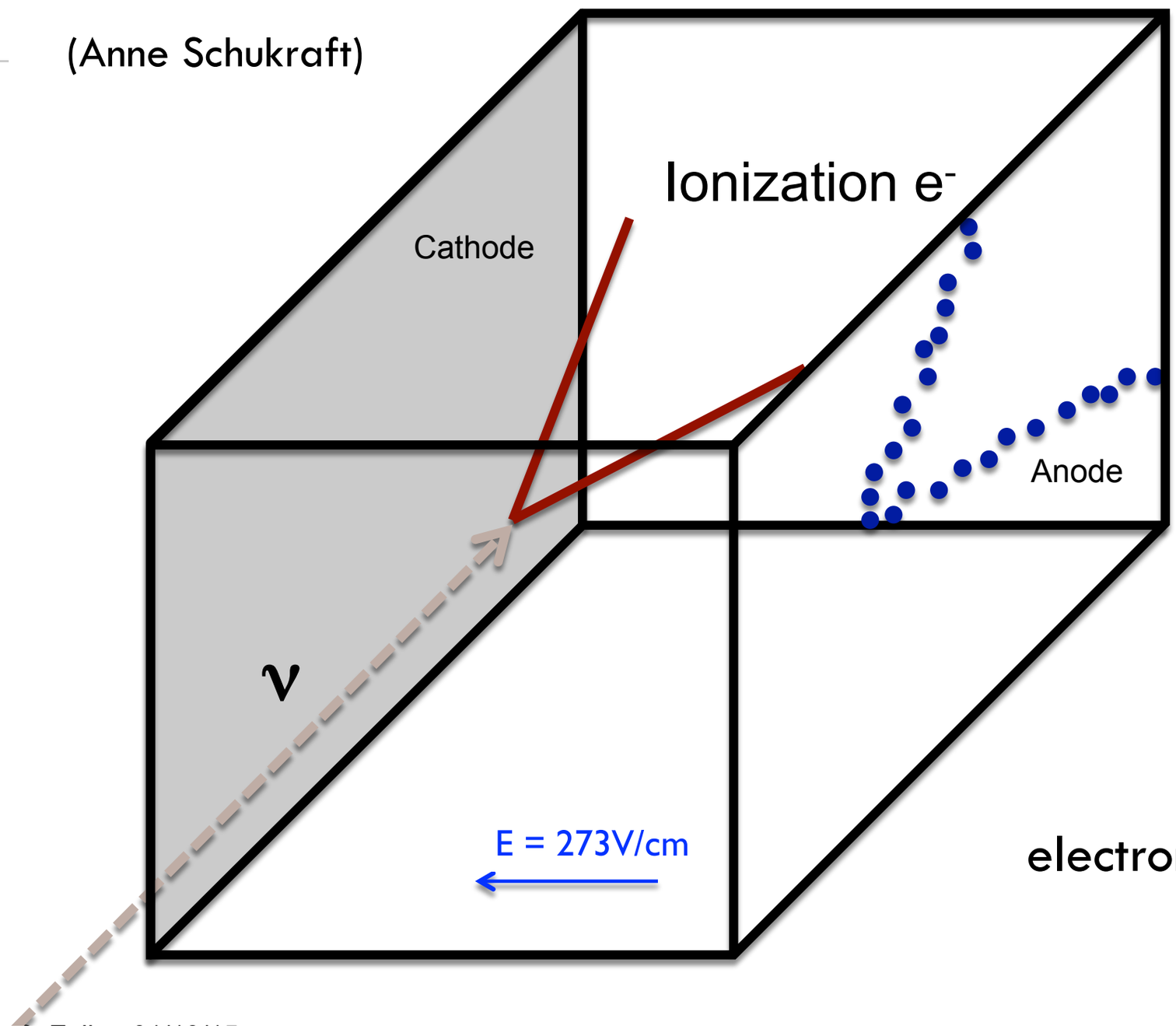
(Anne Schukraft)



these electrons drift towards the anode

LIQUID ARGON TPC

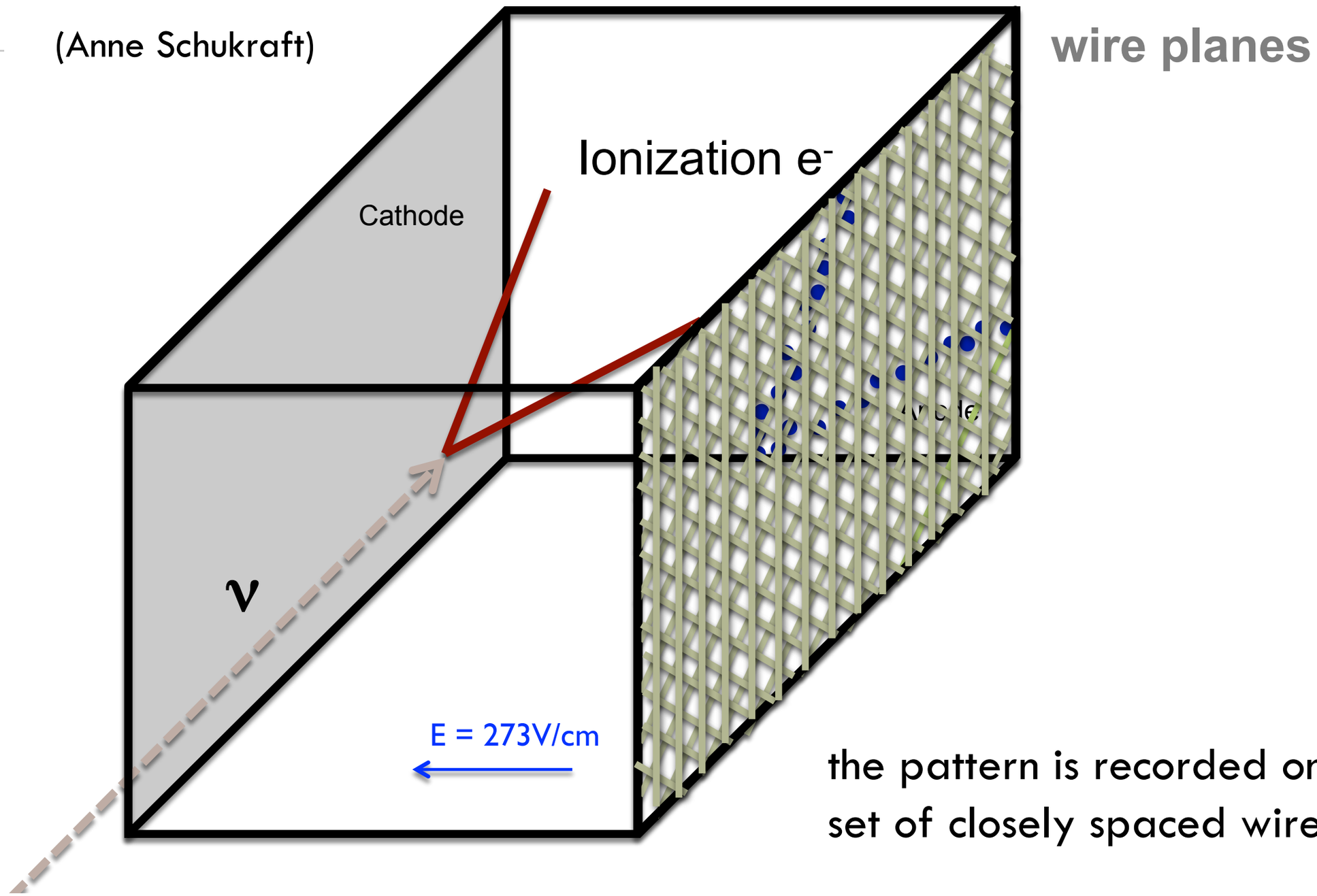
(Anne Schukraft)



electrons arrive at anode

LIQUID ARGON TPC

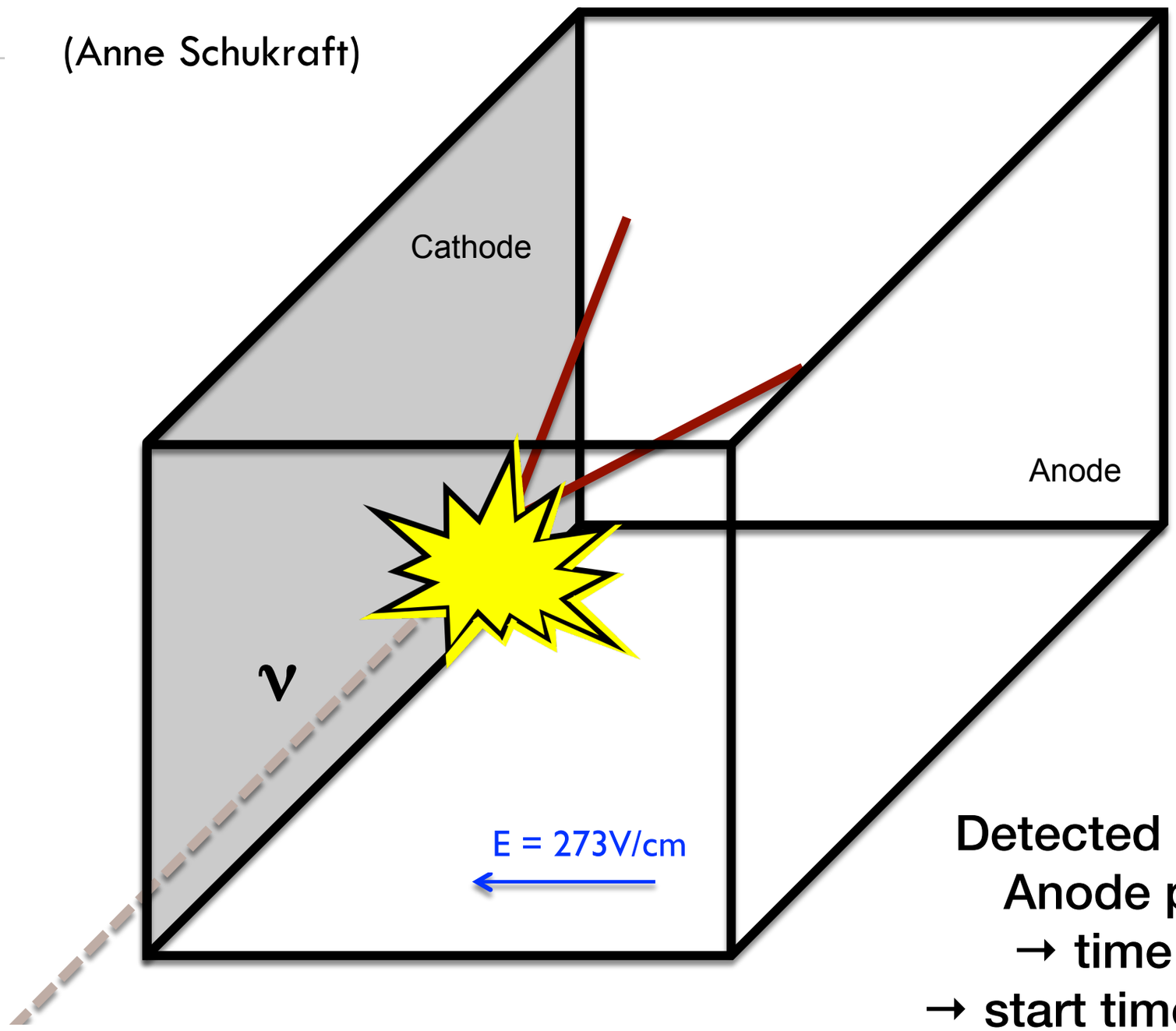
(Anne Schukraft)



the pattern is recorded on a set of closely spaced wires

LIQUID ARGON TPC

(Anne Schukraft)

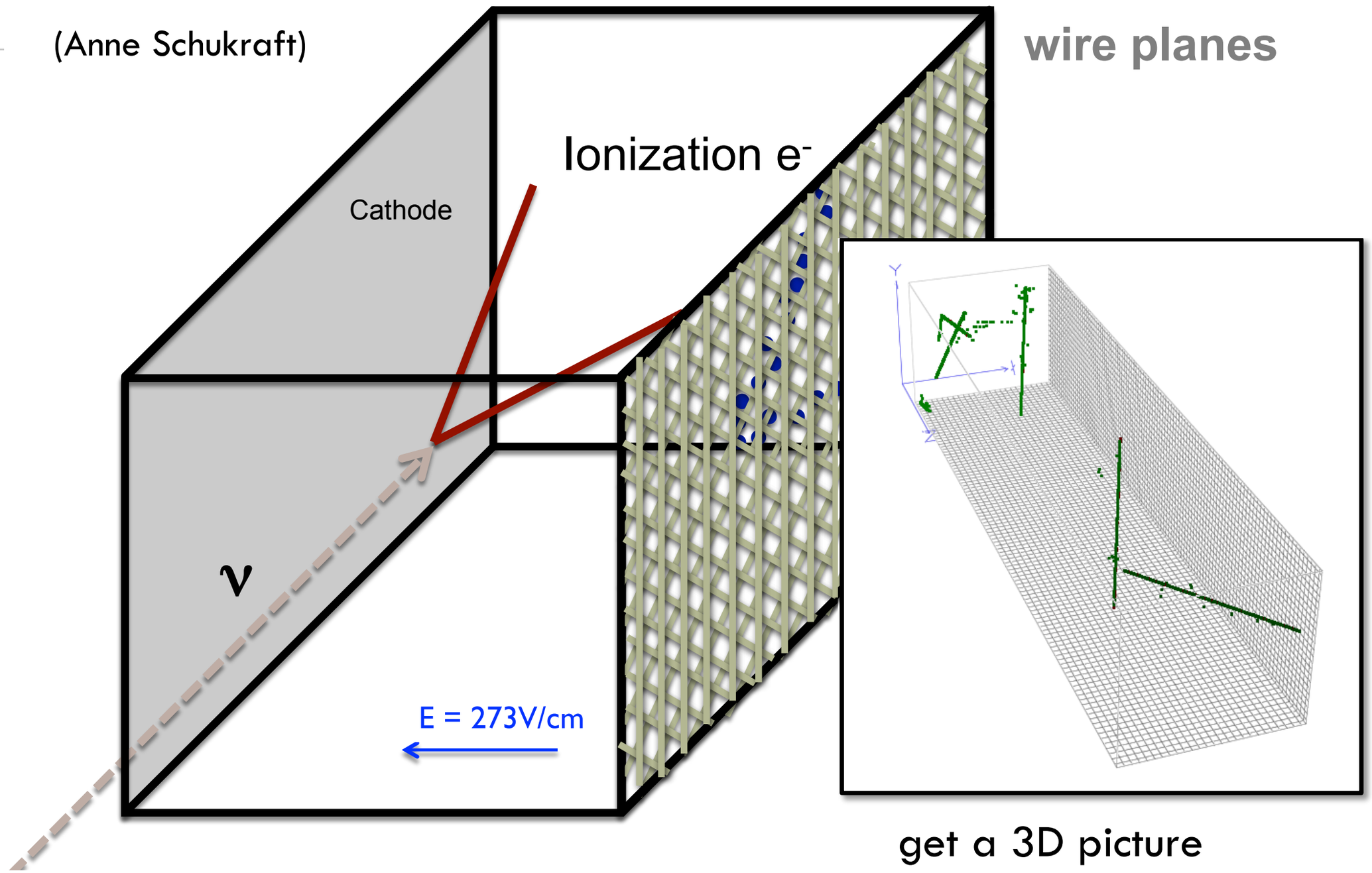


Flash of scintillation light at time of neutrino interaction

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

LIQUID ARGON TPC

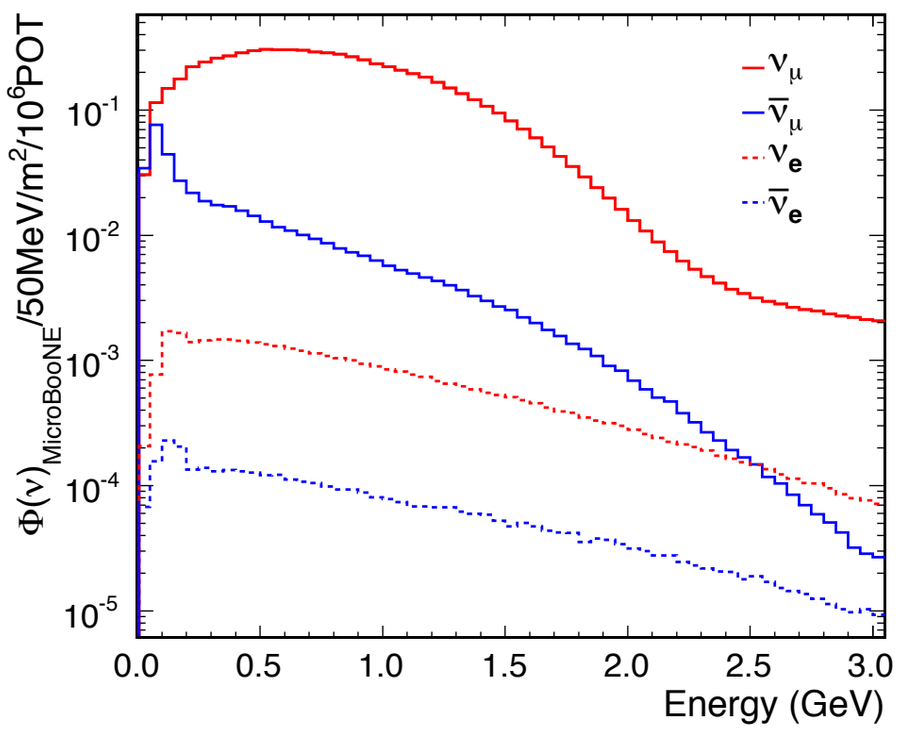
(Anne Schukraft)



FERMILAB'S NEUTRINO BEAMS

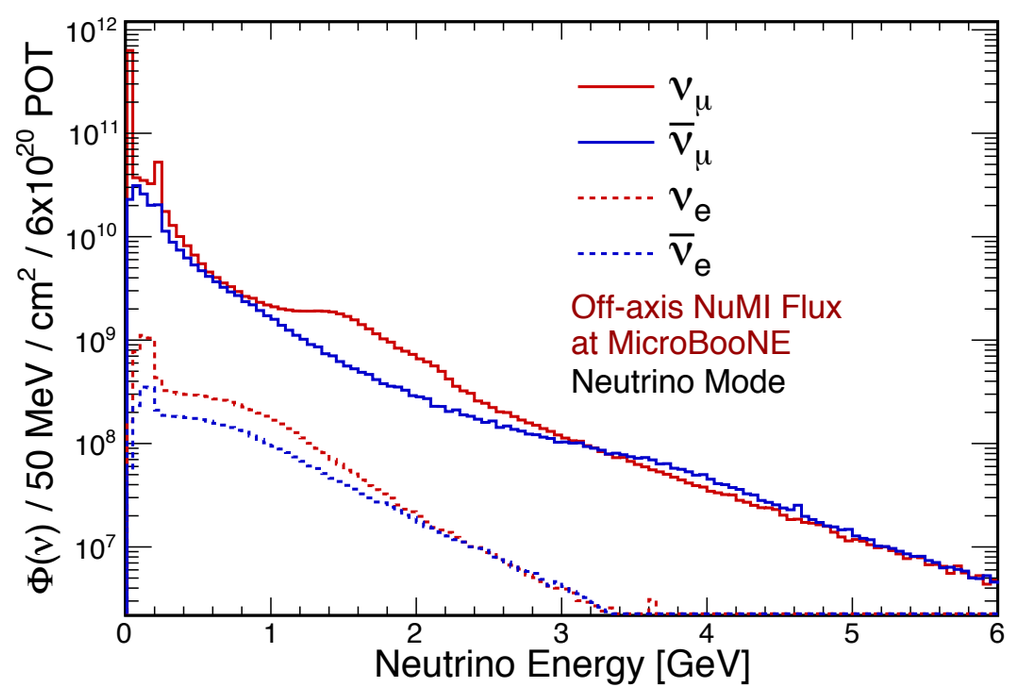
Booster ν
MicroBooNE, SB
Micr
NuMI ν b
NOvA, MINERvA
DUNE ν
(planned)

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

COSMIC REJECTION

arXiv: 1905.09694 [hep-ex]
Accepted to PRL

Large amount of cosmic contamination because of 2.3ms drift time

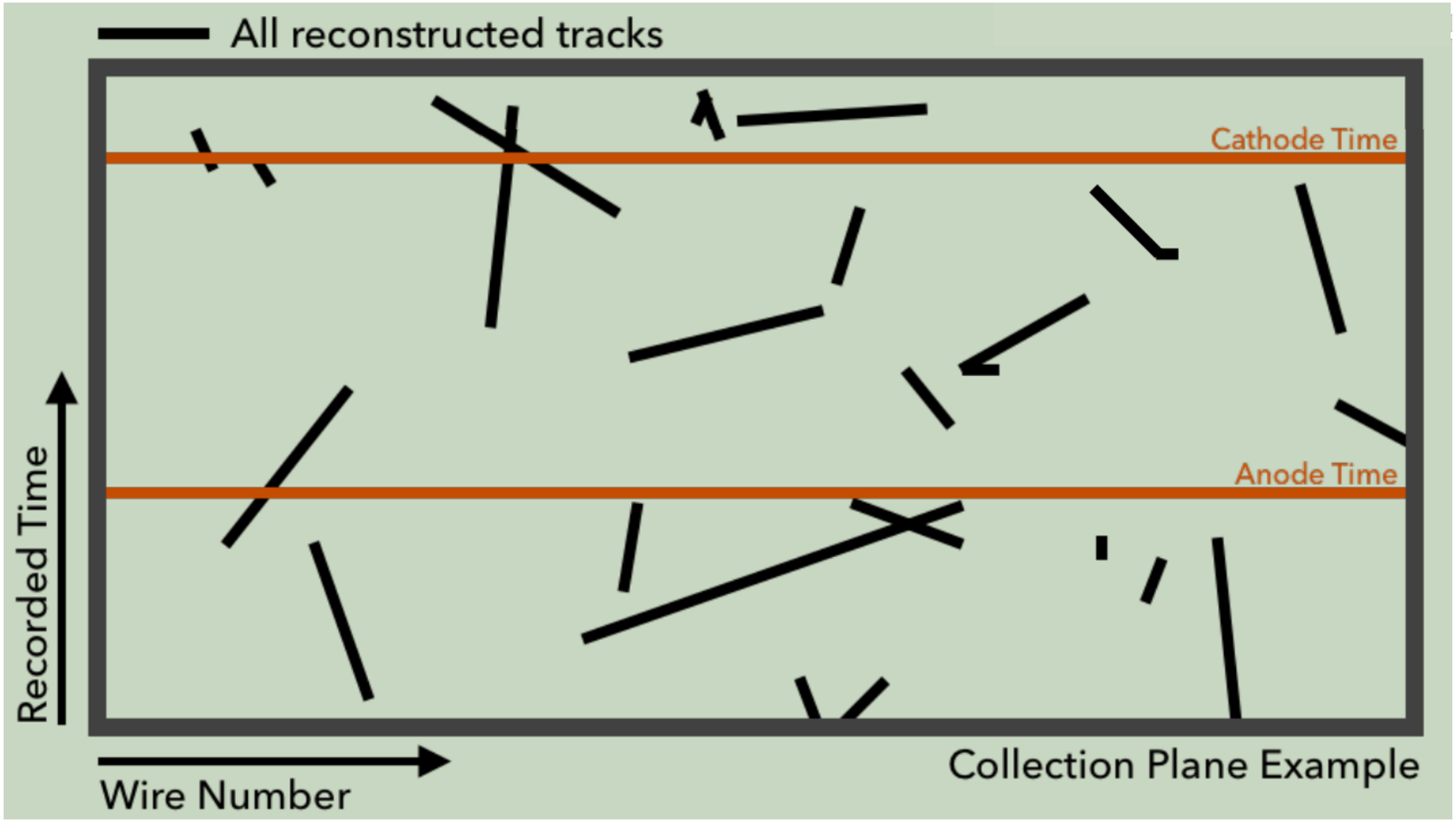


Figure from M. del Tutto

COSMIC REJECTION

arXiv: 1905.09694 [hep-ex]
Accepted to PRL

- **Check if in time with beam flash**

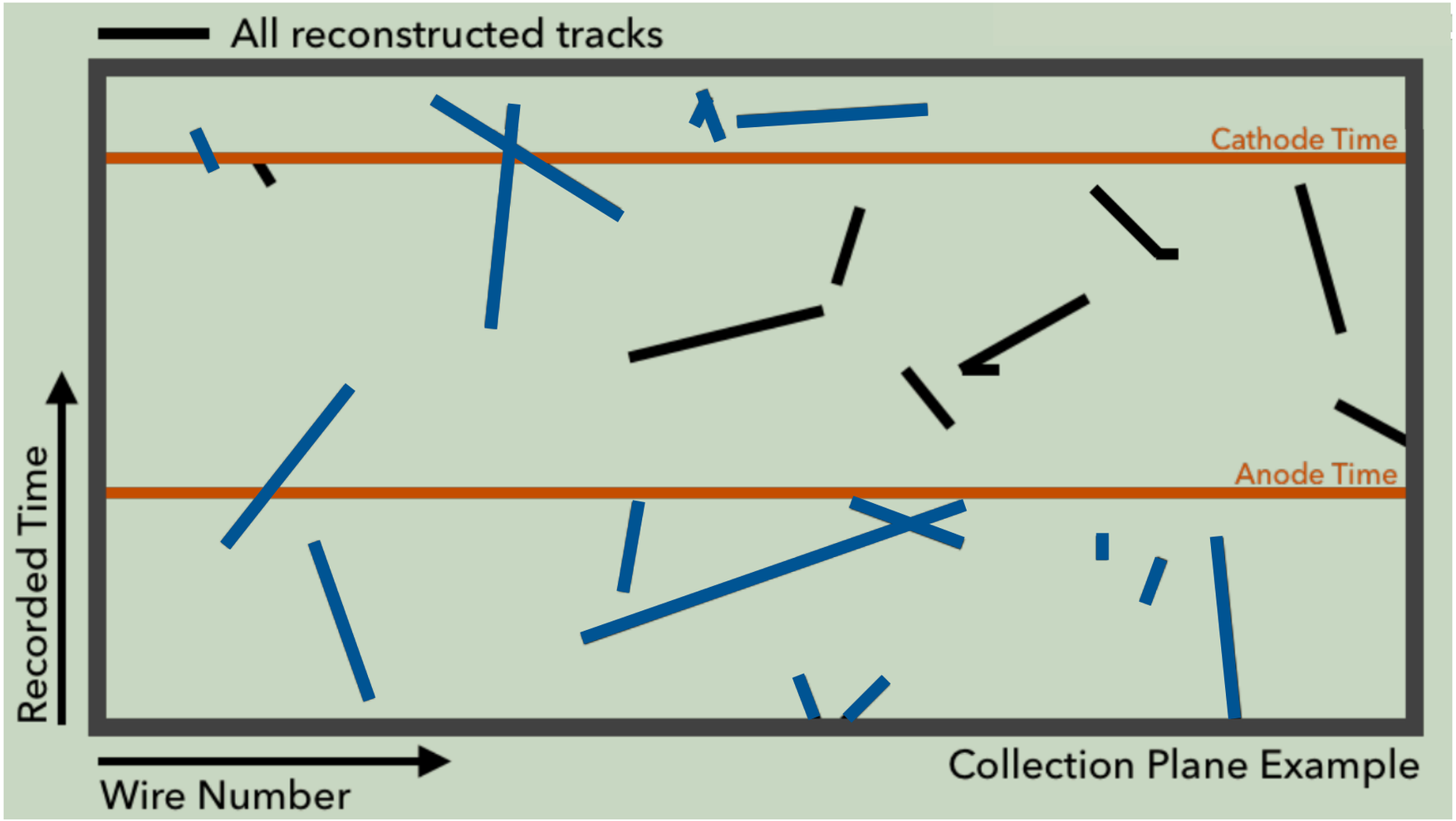


Figure from M. del Tutto

COSMIC REJECTION

arXiv: 1905.09694 [hep-ex]
Accepted to PRL

- **Check if in time with beam flash**
- **Check if compatible with beam flash in terms of position and light intensity**

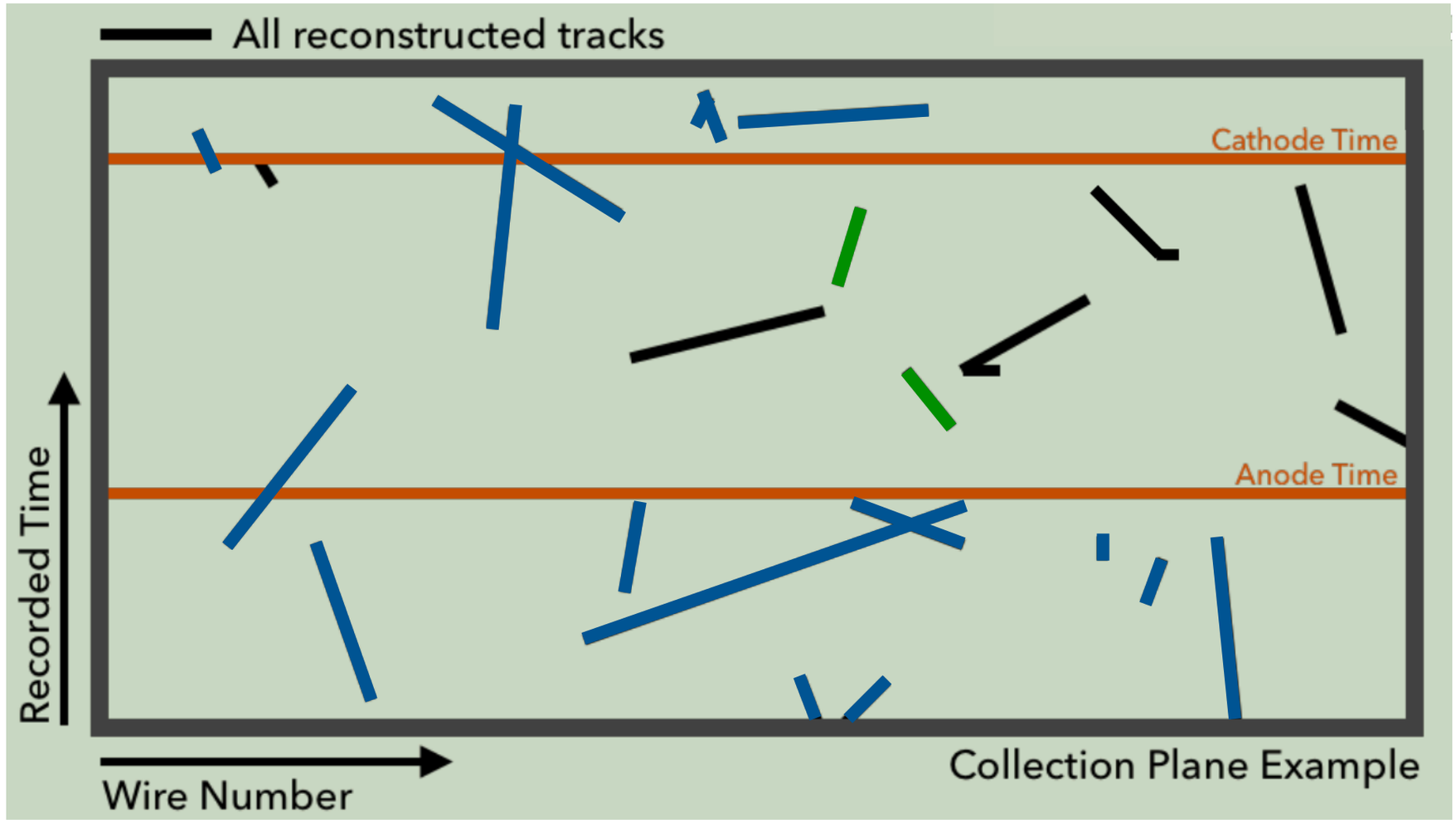


Figure from M. del Tutto

COSMIC REJECTION

arXiv: 1905.09694 [hep-ex]
Accepted to PRL

- **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**

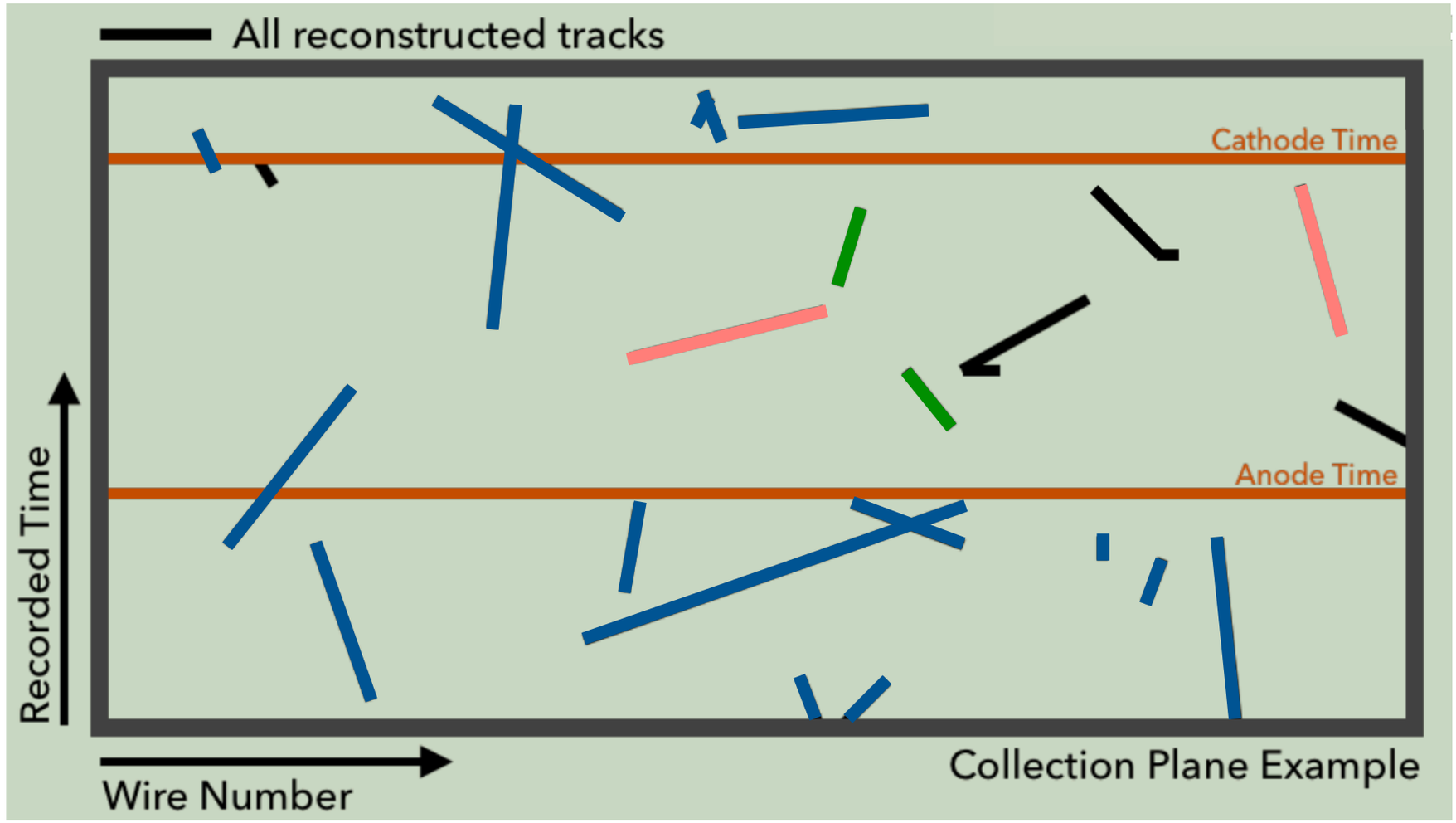


Figure from M. del Tutto

COSMIC REJECTION

arXiv: 1905.09694 [hep-ex]
Accepted to PRL

- **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)**

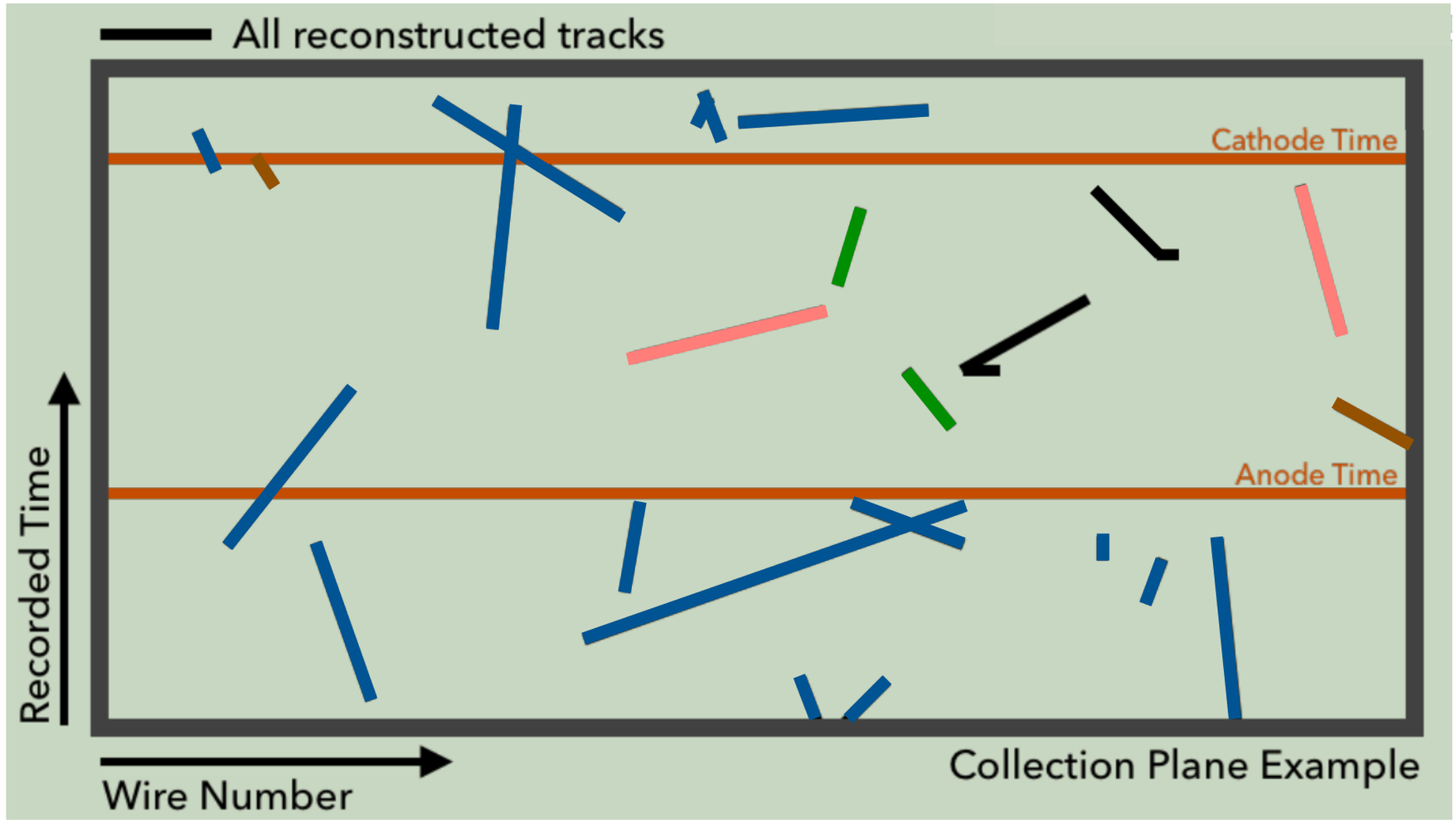


Figure from M. del Tutto

COSMIC REJECTION

arXiv: 1905.09694 [hep-ex]
Accepted to PRL

- **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**

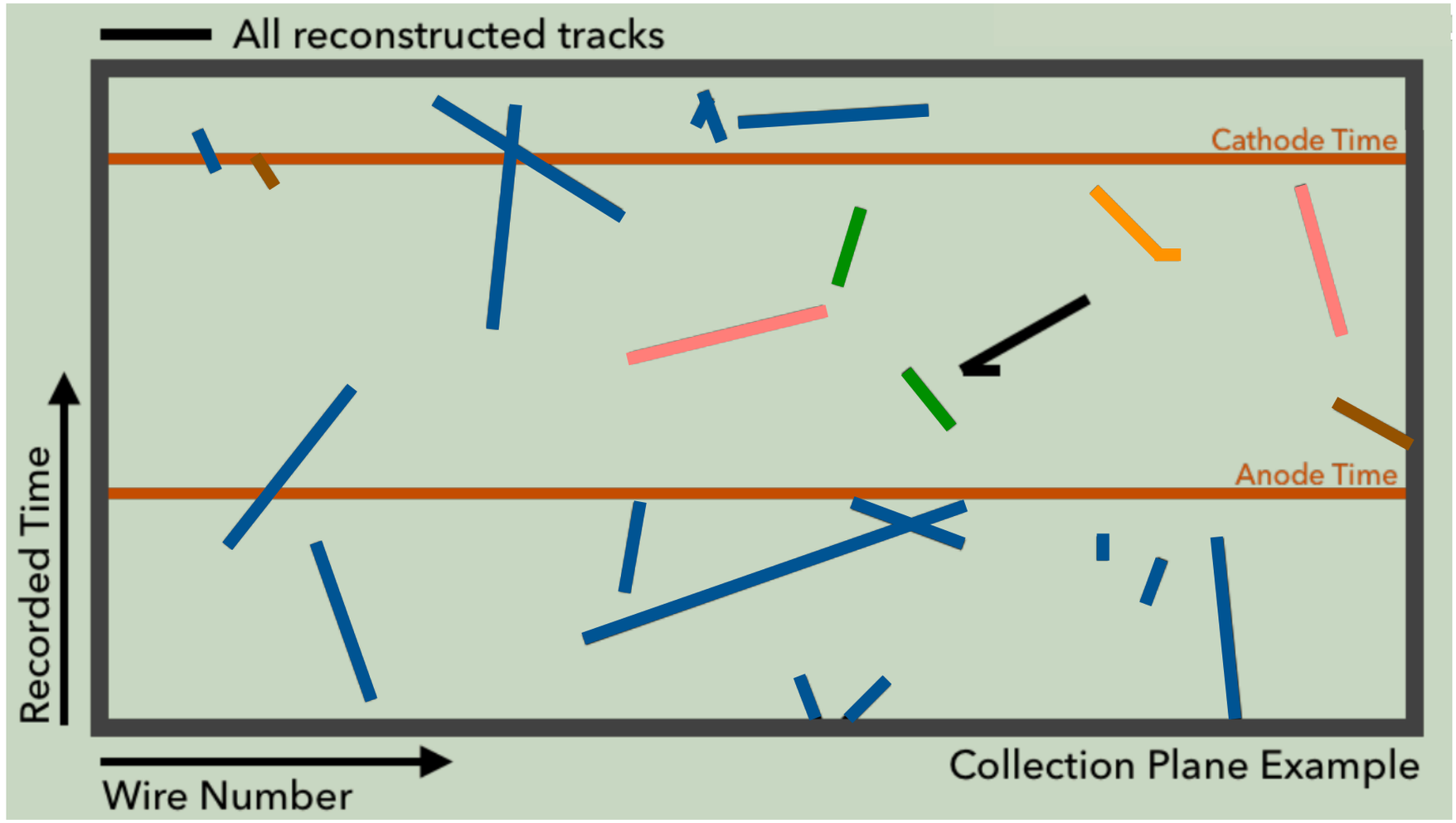
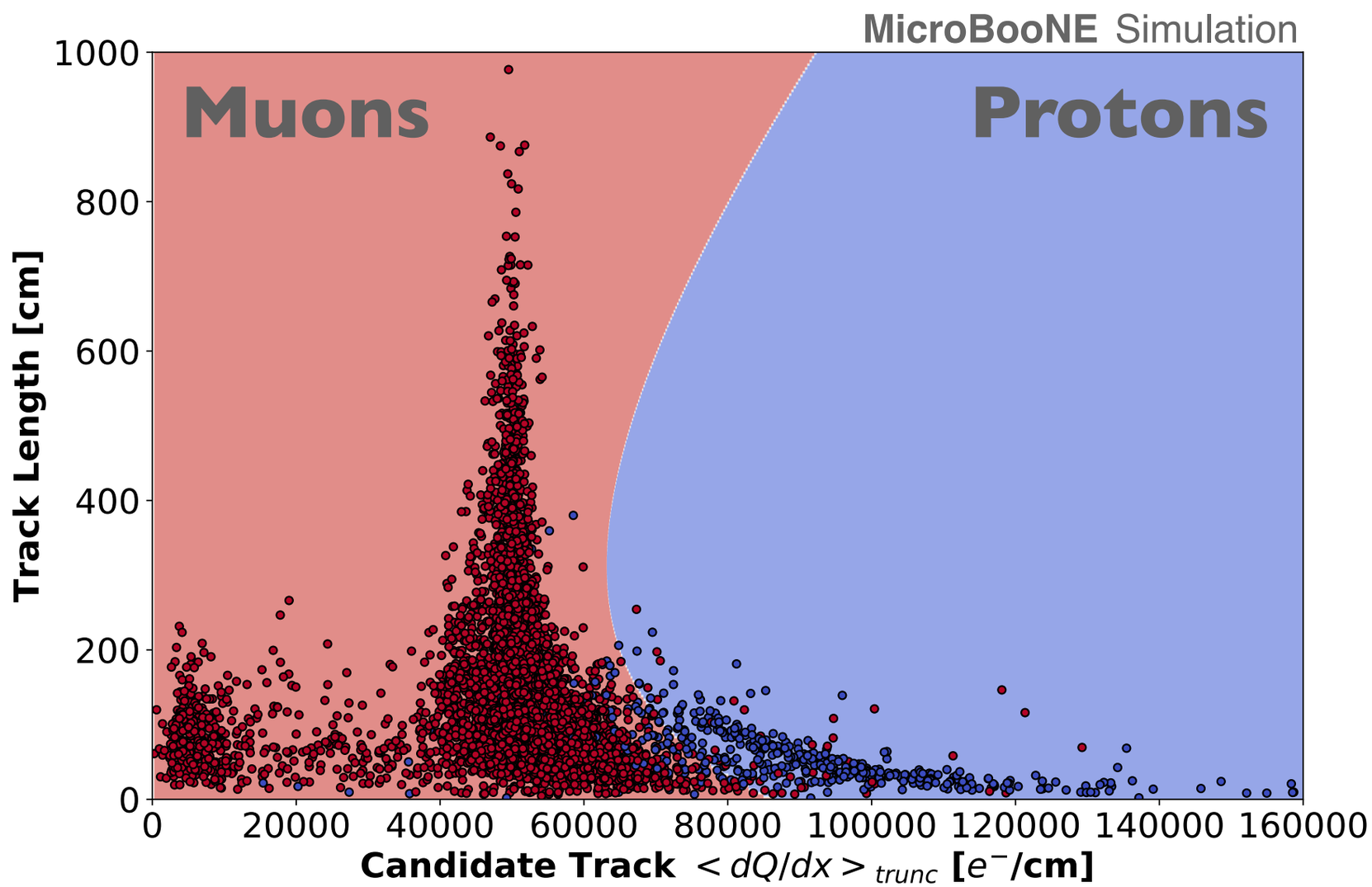


Figure from M. del Tutto

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



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

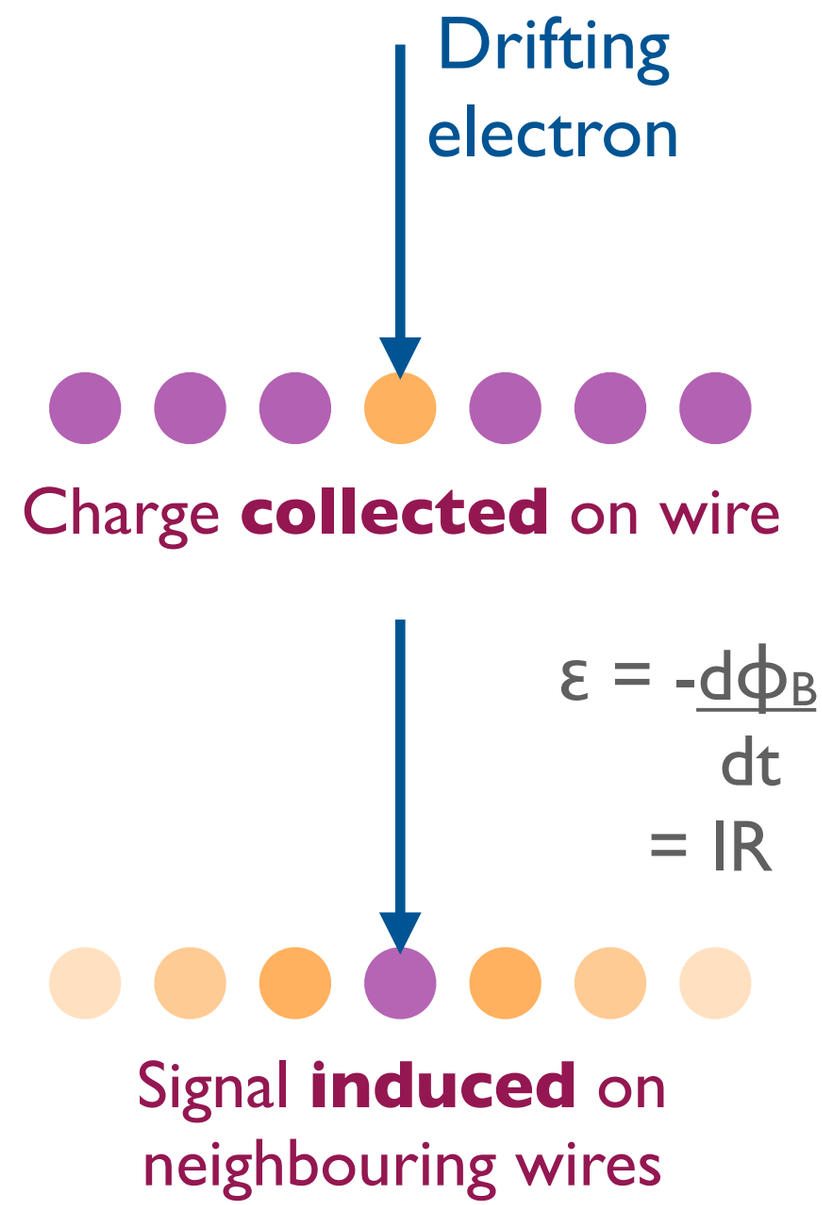
Total uncertainty dominated by detector response

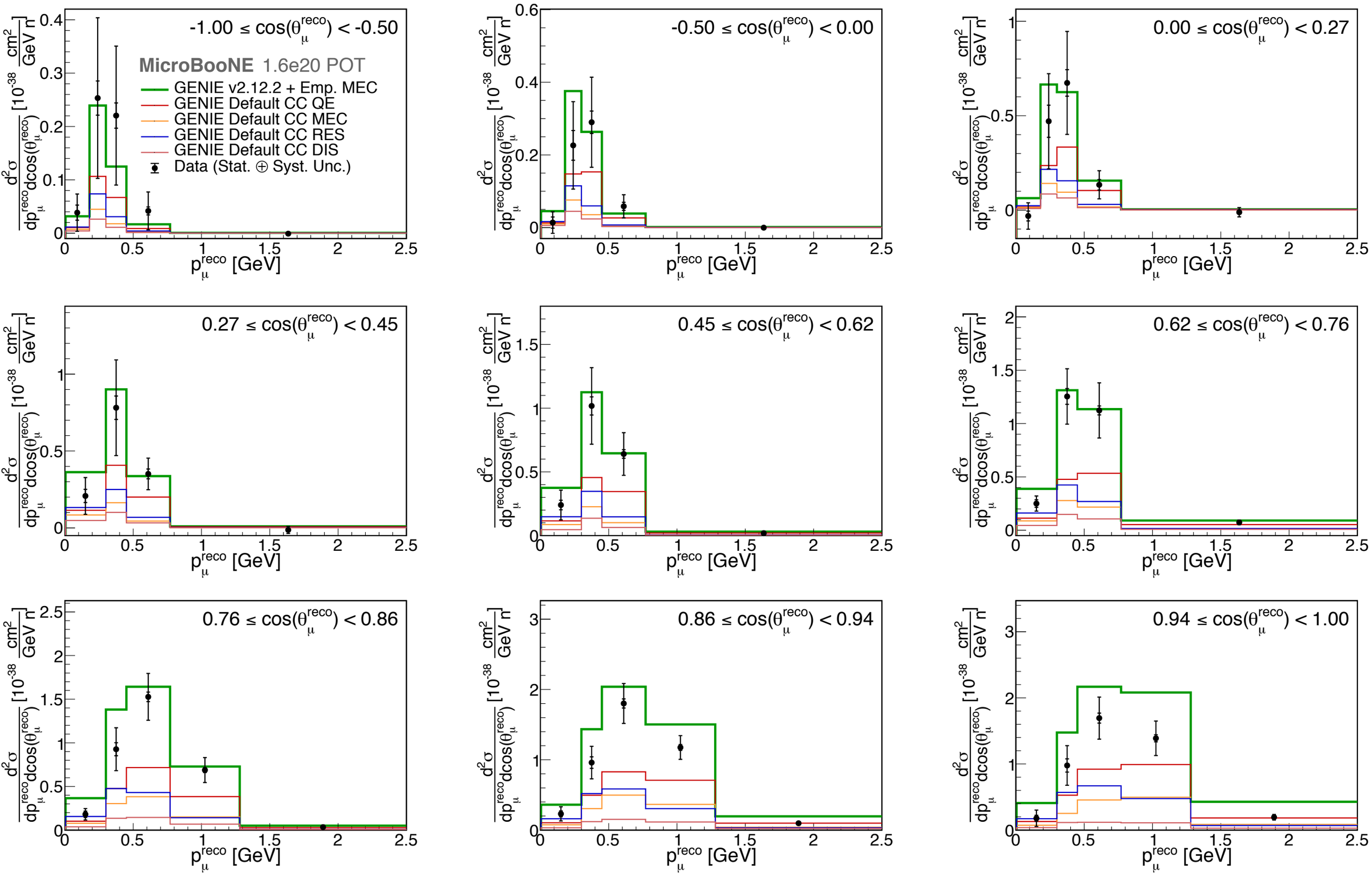
INDUCED CHARGE

JINST 13 P07006 (2018)

JINST 13 P07007 (2018)

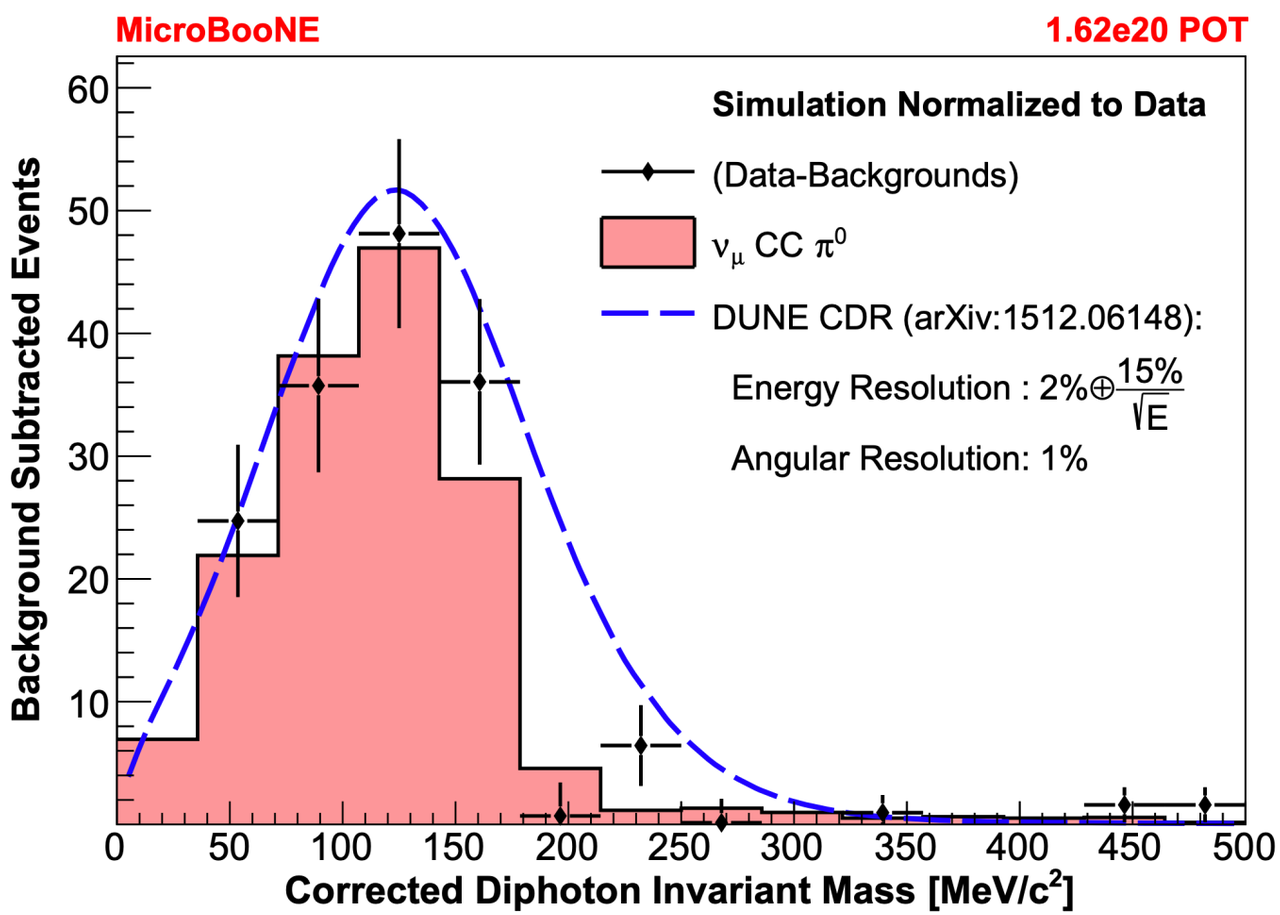
- Detector response → 16% uncertainty on total cross section
- Largest single contribution: 13% due to modeling of **induced charge**
  - MC assumes drift electrons cause signal on only one wire
  - Not true! Nearby wires see **charge by induction**
  - Because of this, **detector response depends on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




MicroBooNE 1.6e20 POT
GENIE v2.12.2 + Emp. MEC
GENIE Default CC QE
GENIE Default CC MEC
GENIE Default CC RES
GENIE Default CC DIS
Data (Stat. ⊕ Syst. Unc.)
-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
d²σ / dp_μ^reco dcos(θ_μ^reco) [10^-38 cm² / GeV n]
p_μ^reco [GeV]

FINDING PI0S

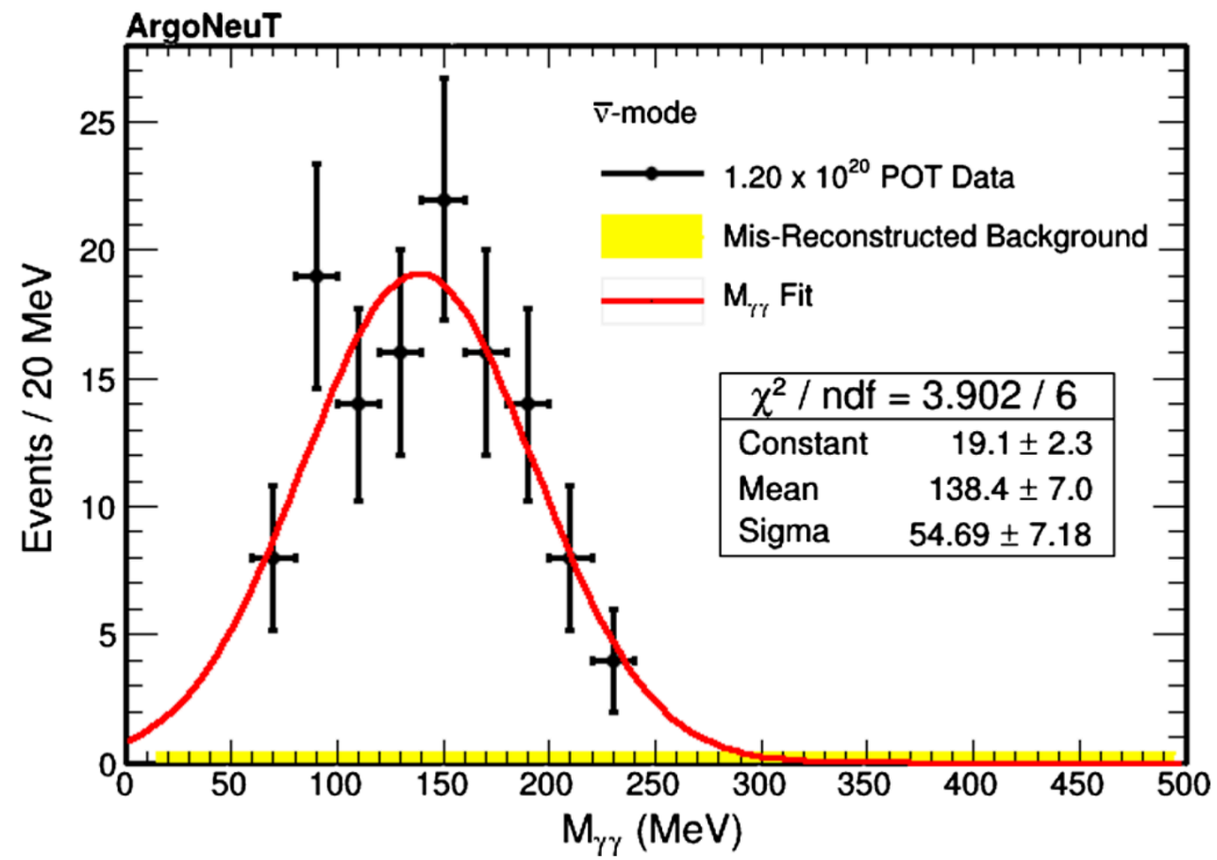
Phys. Rev. D 99, 091102(R) (2019)



- Measure electron and photon energies in the same way (energy of the shower)
- π^0 mass peak → shower energy resolution
- **Good news for DUNE!** LAr technology is already doing better than we thought we needed

NCPI0: MEASUREMENTS ON ARGON

- ArgoNeuT: flux-integrated NCπ^0 measurement PRD 96, 012006 (2017)
- Select events with:
  - 1) No tracks identified as $\mu^\pm$ or $e^\pm$
  - 2) Two showers, with dE/dx consistent with photon (identified by combination of automated reconstruction and hand-scanning)



- Final selection: 64% purity, 123 data events selected
- Confirm NCπ^0 hypothesis by reconstructing diphoton mass

OPTION 3: MCS

- Multiple Coulomb Scattering: charged particle traversing a medium undergoes electromagnetic scattering off atomic nuclei
  - Previously used (in neutrino physics) in emulsion detectors (e.g. DONuT, OPERA) and ICARUS to determine particle momentum. Improved model implemented in MicroBooNE: JINST 12 P10010 (2017)
  - RMS of scattering angle σ (perpendicular to beam direction) related to momentum p:

Constant: 13.6 MeV

$$\sigma = \frac{S_2}{p\beta c} z \sqrt{\frac{l}{X_0}} \left[1 + \epsilon \cdot \ln\left(\frac{l}{X_0}\right) \right]$$

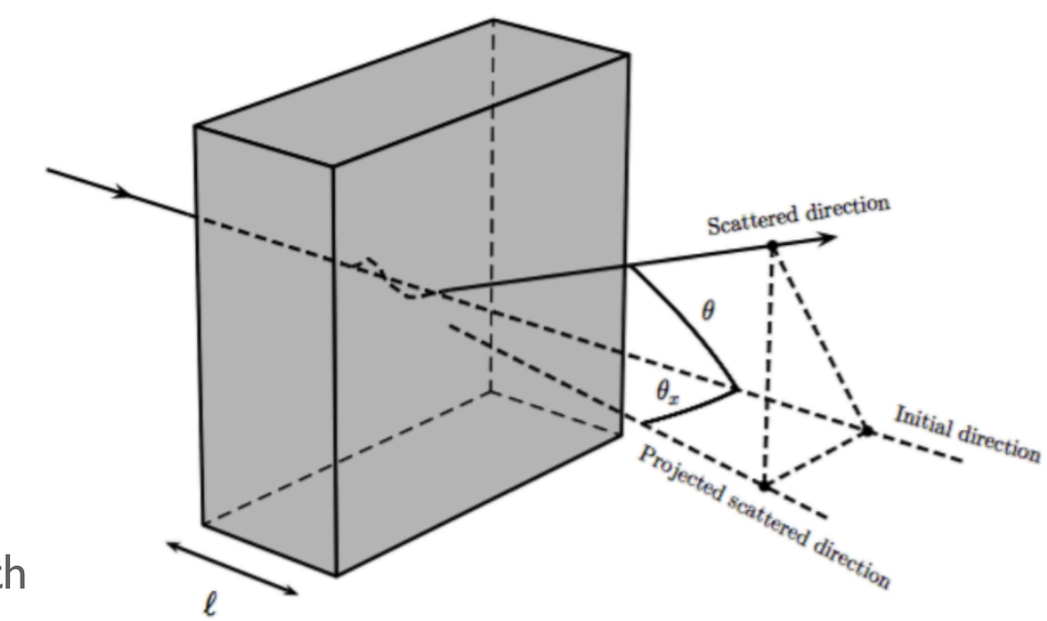
Distance travelled

Particle speed

Magnitude of particle's charge

Constant: 0.038

Radiation length (14cm in LAr)



OPTION 3: MCS

- MCS algorithm splits tracks into segments and measures scattering angles. Could we use that to distinguish π^+ from muons?
- We expect π^+ to scatter more:
  - Muons can scatter electromagnetically on Argon nuclei
  - Pions can scatter electromagnetically **and hadronically** on Argon nuclei
- May be a possibility, but current implementation does not provide enough separation:
  - Most reliable on long tracks — segment length: 14cm, ~radiation length

ARGONEUT CC1PI±

- ArgoNEUT: CC1π± production Phys. Rev. D 98, 052002 (2018)
- According to GENIE, ~50/50 RES/DIS interaction channel (figure from A. Mastbaum)