Recent Cross Section Measurements from MicroBooNE

Steven Gardiner for the MicroBooNE Collaboration

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Lepton Photon Interactions at High Energies

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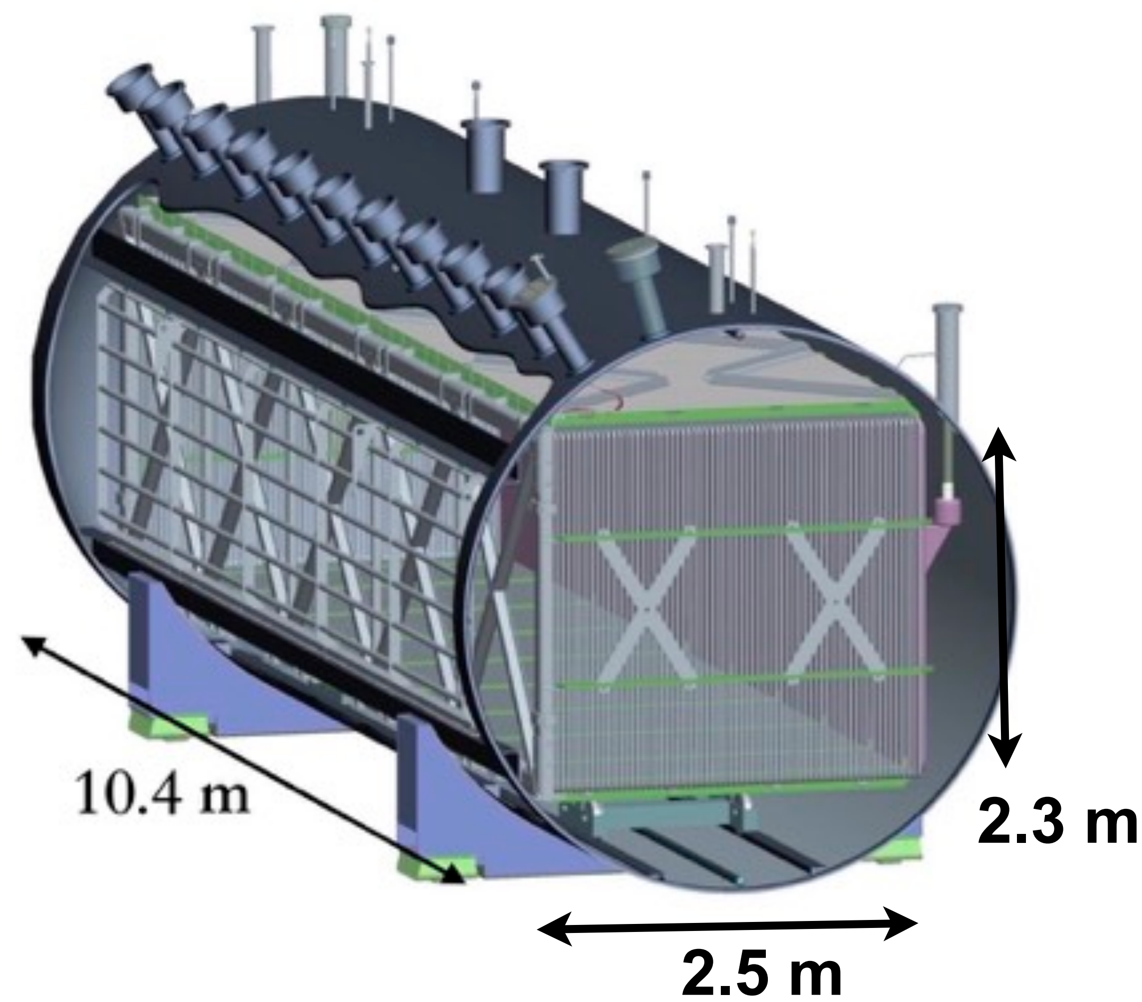
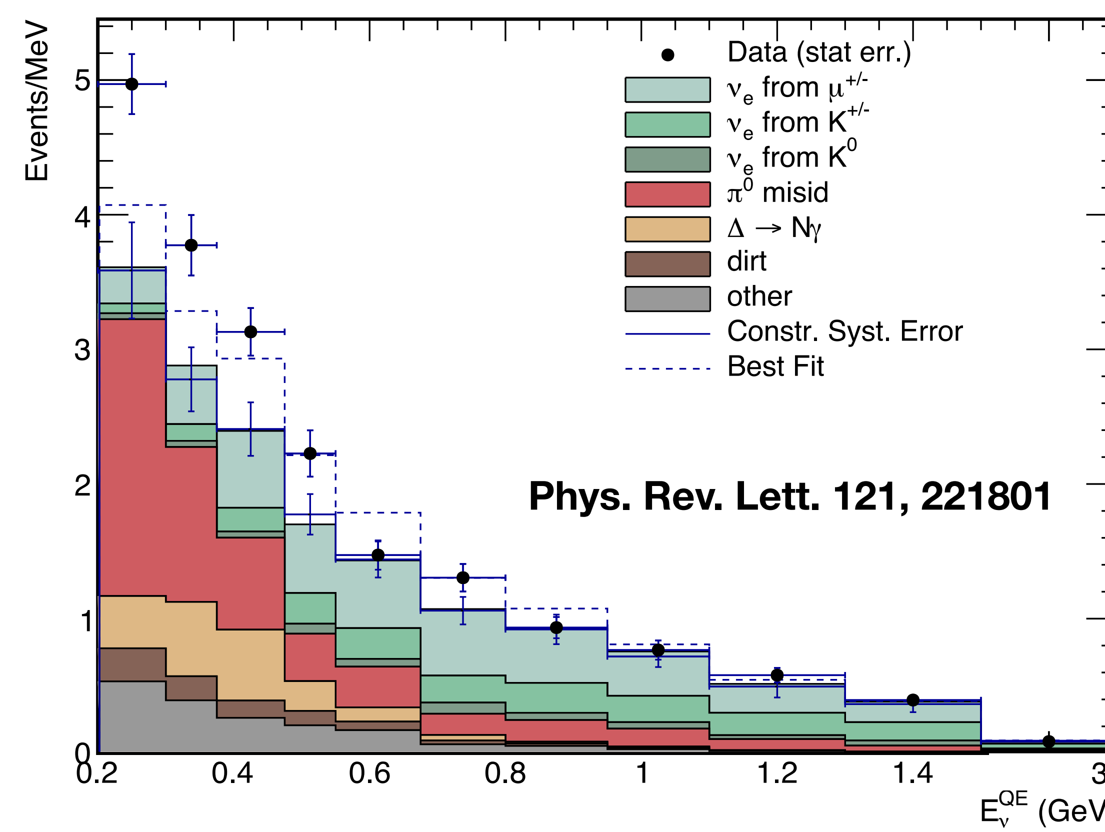
The MicroBooNE Experiment

- **Liquid argon time projection chamber** in the Booster Neutrino Beam at Fermilab (60-ton fiducial mass)

- Primary physics goals
  - **Investigate the origin of the low energy excess (LEE) of electron-like events seen by MiniBooNE**
    - Misidentified γ backgrounds?
    - Sterile neutrinos?
  - Measurements of neutrino-argon cross sections
    - Constrain interaction model systematics for precision oscillation measurements

- Detector R&D for future LArTPC efforts





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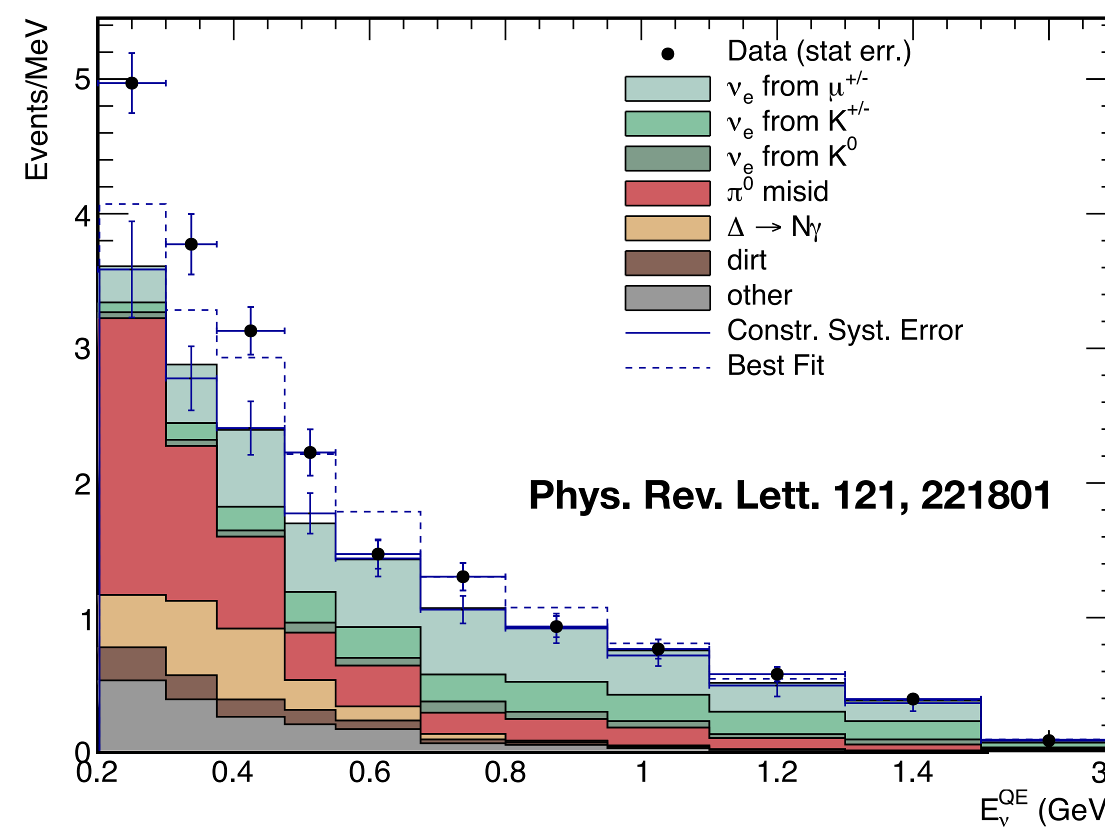

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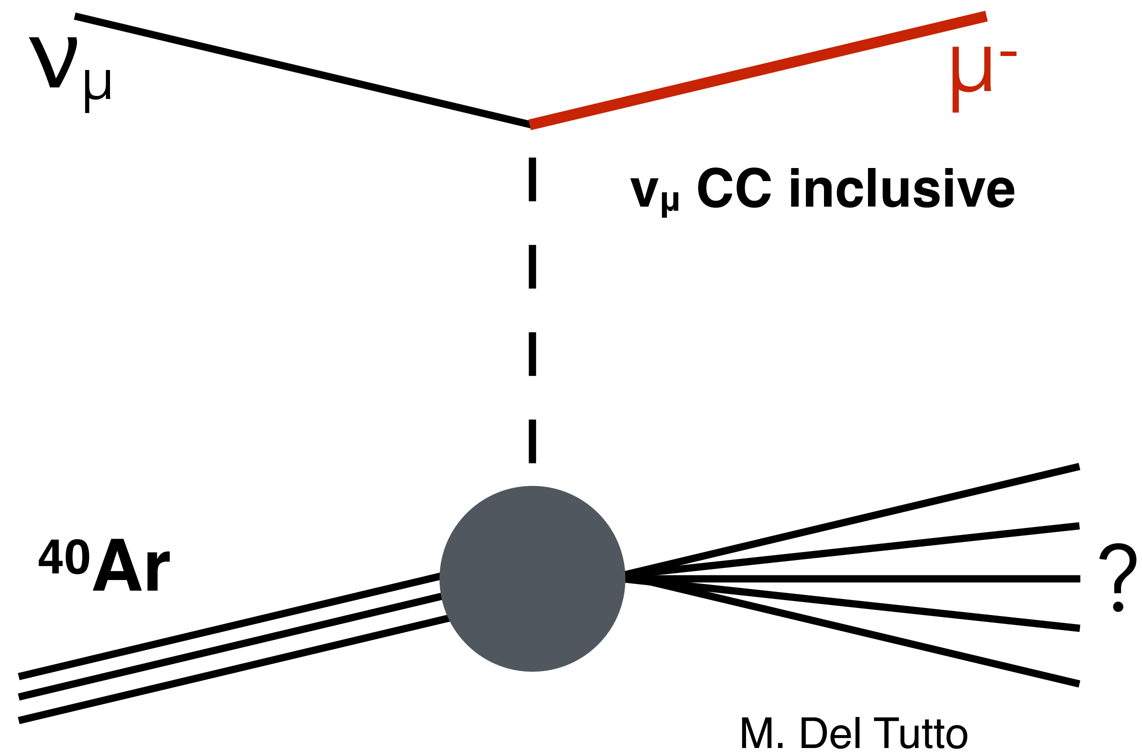
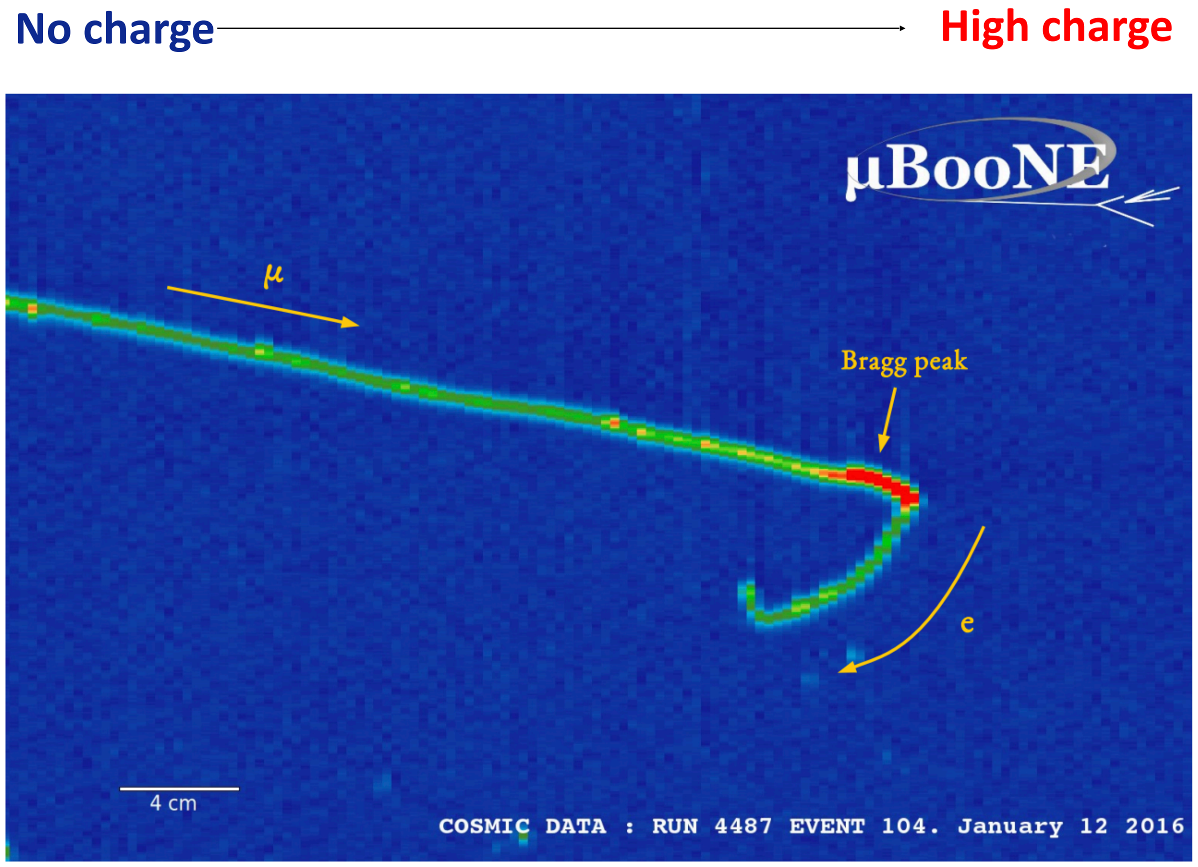
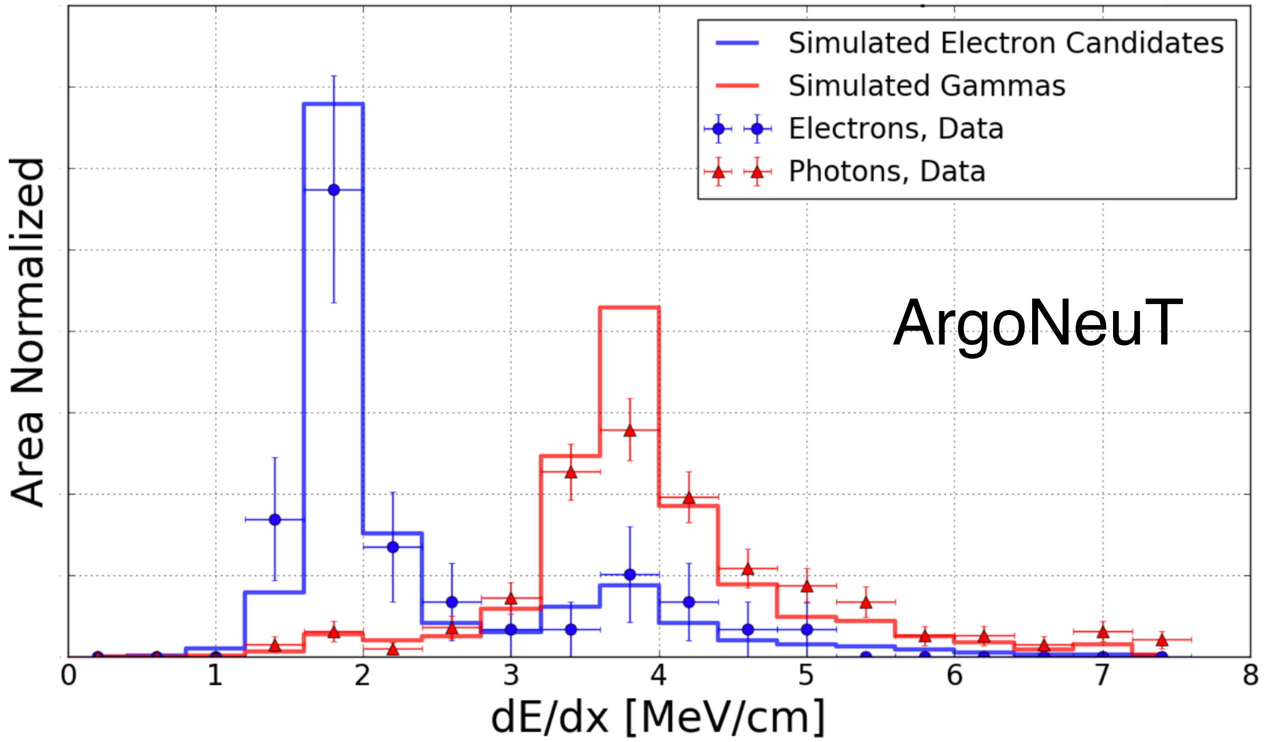


Strengths of LArTPC technology

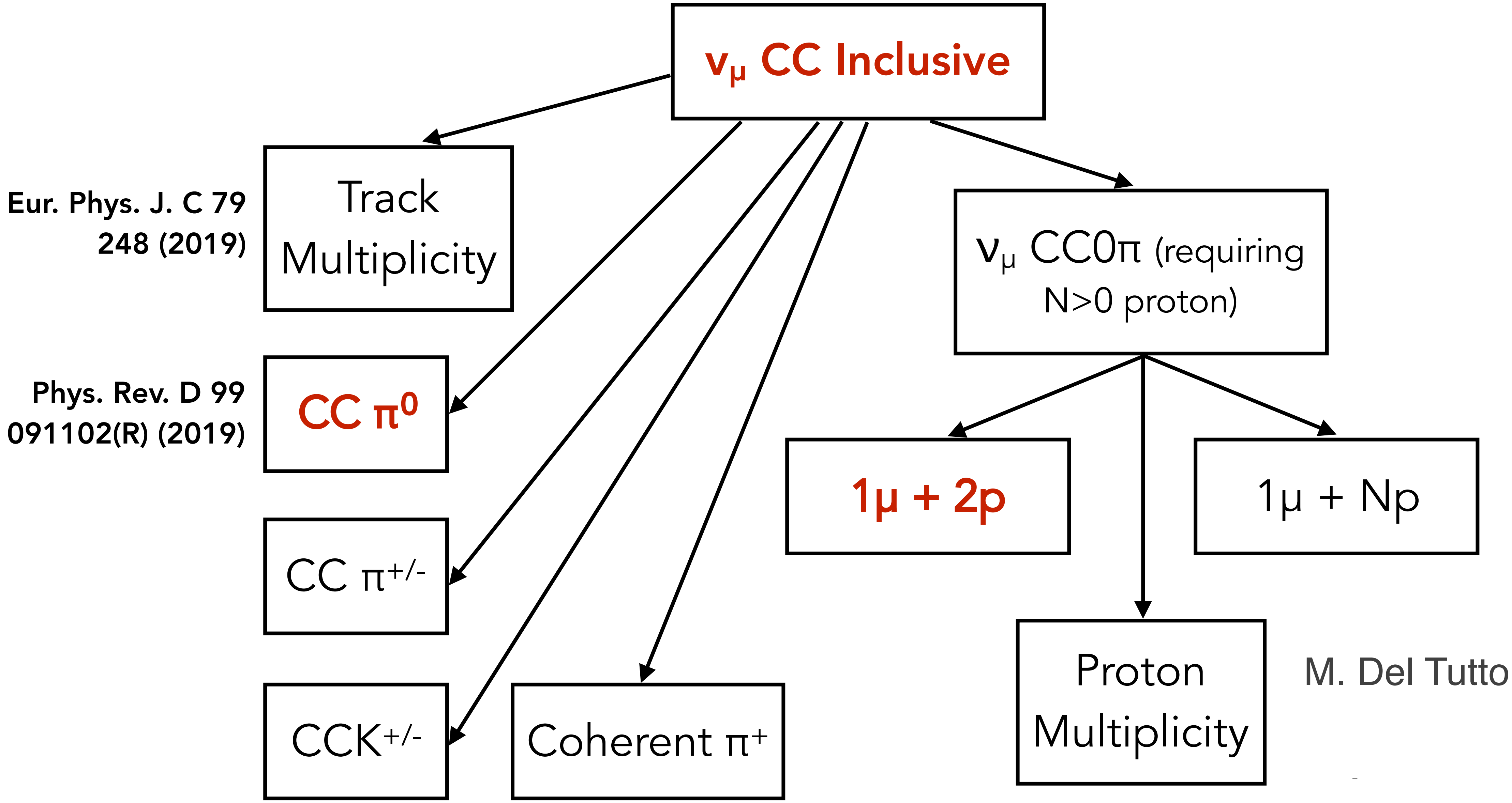
- Low thresholds & full angular coverage
- Tracking with mm scale spatial resolution
- Calorimetry
- Particle identification via dE/dx
  - **e/γ discrimination**
  - Key advantage for oscillation studies using ν_e appearance
- **A challenge**: Limited cross section data for ^{40}Ar





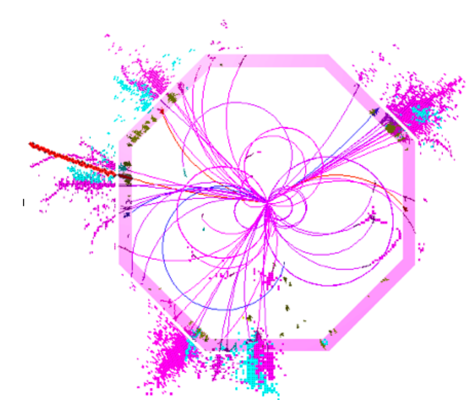
Phys. Rev. D 95, 072005 (2017)

ν_μ CC inclusive: a foundation for other measurements



All three analyses described in this talk make use of the Pandora reconstruction toolkit

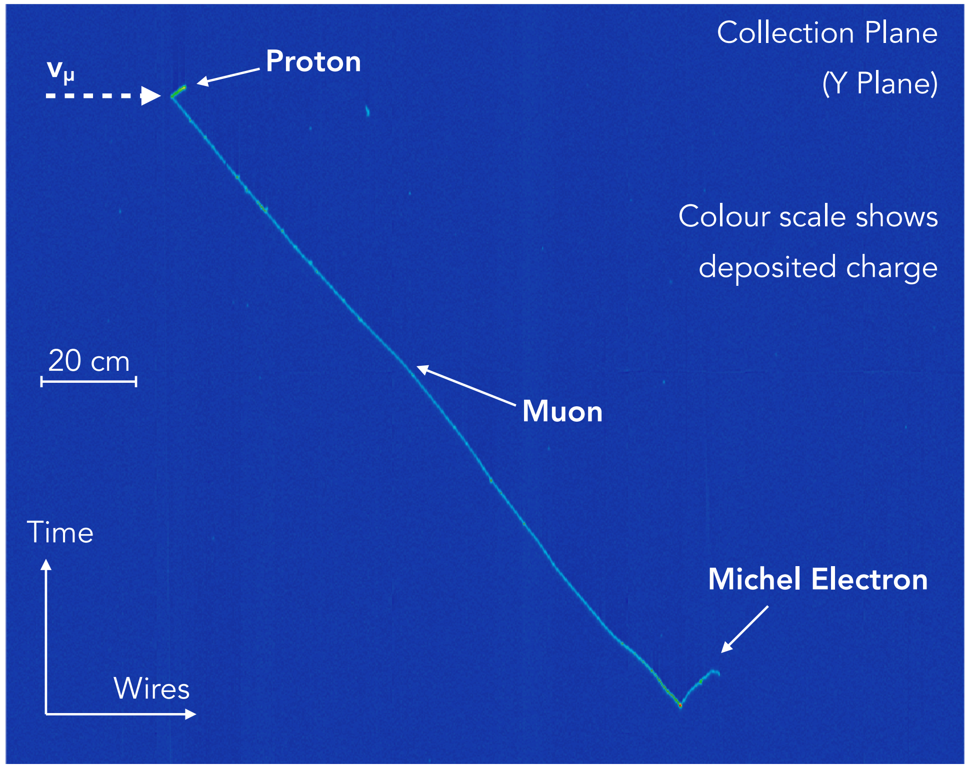
[Eur. Phys. J. C (2018) 78:82]

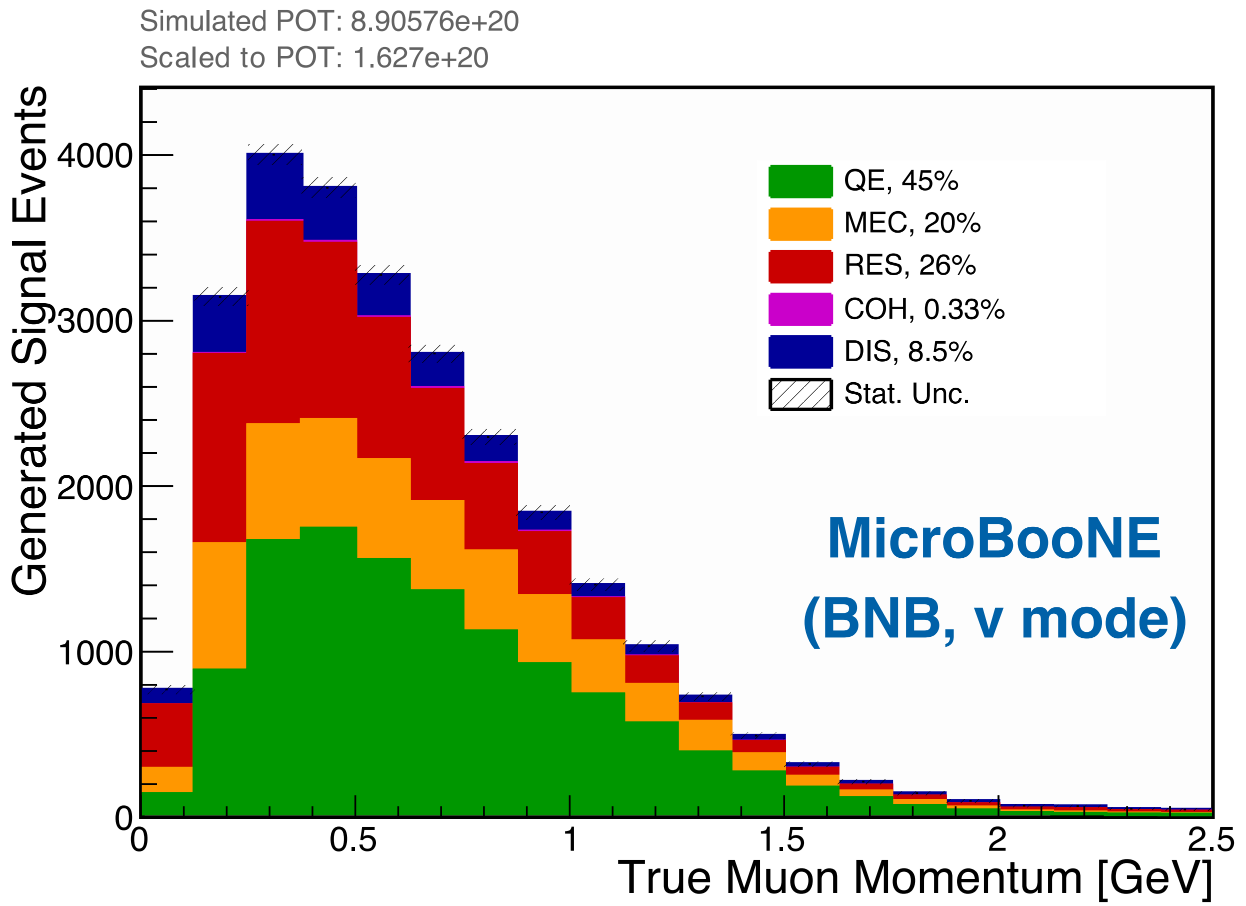


https://github.com/PandoraPFA

ν_μ CC inclusive cross section

- **Simple experimental signature**: one reconstructed muon track
- $\nu_\mu + {}^{40}Ar \rightarrow \mu + \text{anything}$
  - Includes a mixture of underlying reaction modes
  - Comparison to model predictions tests many things at once
  - Provides selection for exclusive cross section measurements
- Complementary to previous CC inclusive measurement by ArgoNeuT at higher mean energy (9.6 GeV vs. 0.8 GeV)





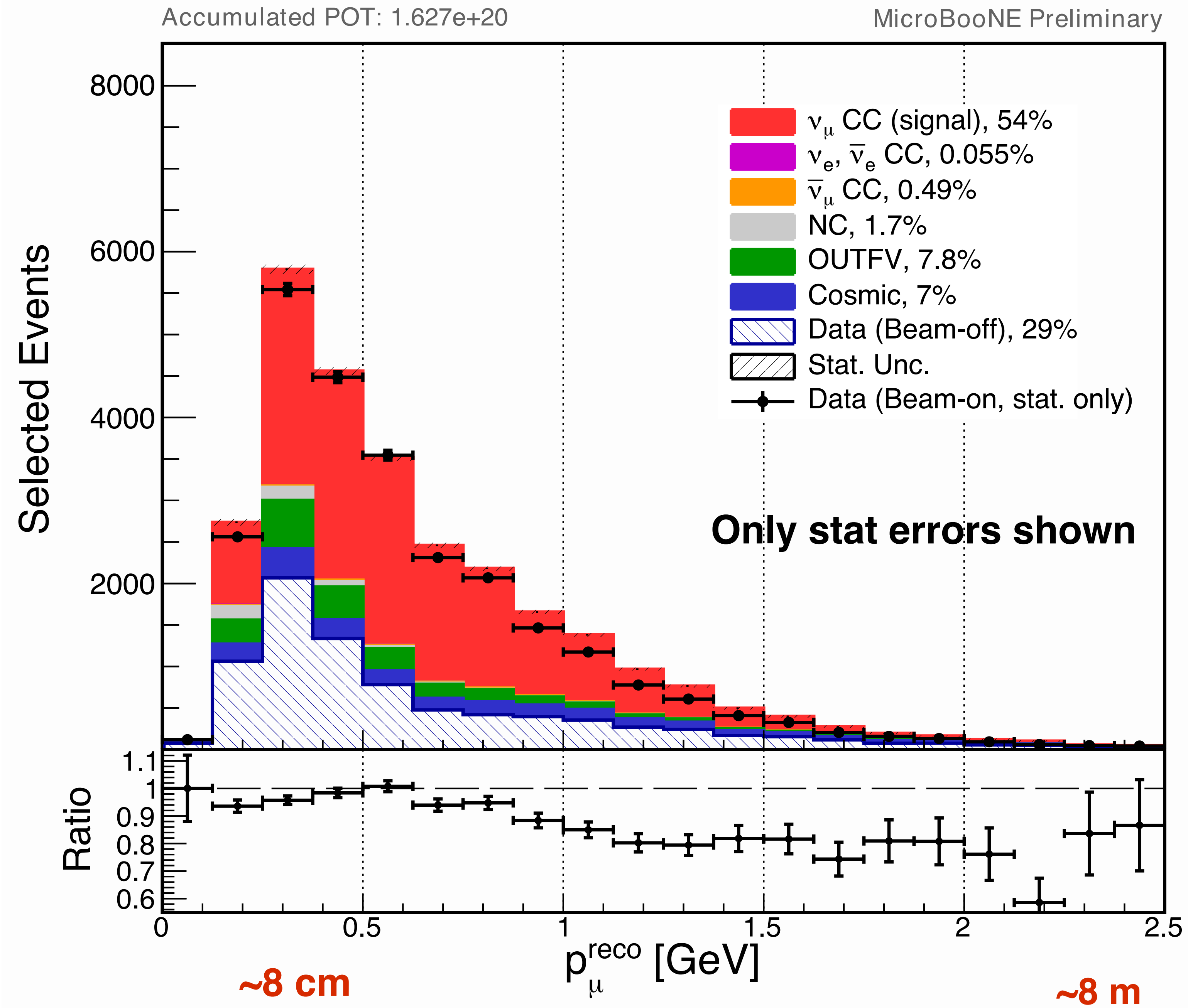
https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1045-PUB.pdf

ν_μ CC inclusive analysis: event selection & reconstruction

- **99.9% cosmic rejection**
  - Often 20+ comics in each 4.8 ms TPC readout window
  - Matching TPC and PMT signals key discrimination technique
- First use of multiple Coulomb scattering to measure p_μ
  - **Contained and exiting muons included**, treated on equal footing
  - Details in [JINST 12, P10010 (2017)]

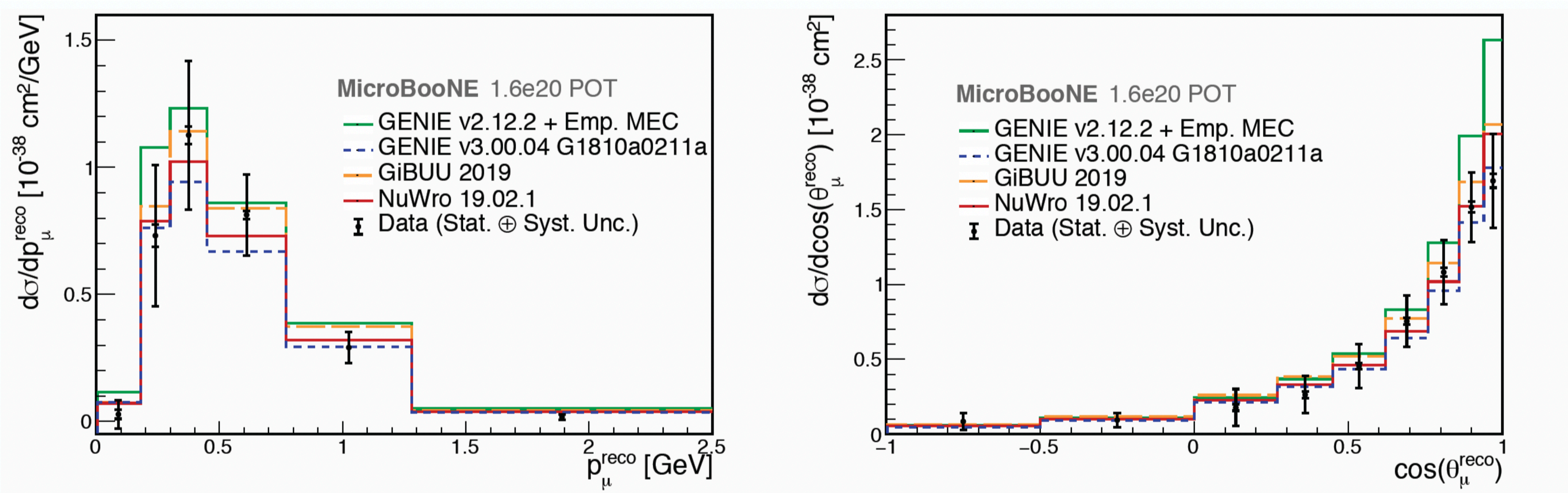
efficiency = 57.2%
purity = 50.4%

https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1045-PUB.pdf



ν_μ CC inclusive cross section results

- Double- and single-differential cross sections for argon (p_μ, $\cos\theta_\mu$)
  - https://arxiv.org/abs/1905.09694
- Binned in terms of reconstructed quantities (model comparisons via forward-folding)
- Tested against several generators: GENIE v2 & v3, GiBUU, NuWro
  - Most tension in high-momentum, forward-angle bins
  - **Recent model improvements** (local Fermi gas, RPA) **favored**
- Best χ^2 = 108.8 / 42 bins for GENIE v3 (versus χ^2 = 245.9 for GENIE v2)
  - **Recent movement has been in the right direction**



https://web.fnal.gov/organization/theory/JETP/2016/FermilabWineAndCheese-MarcoDelTutto.pdf

Fermilab

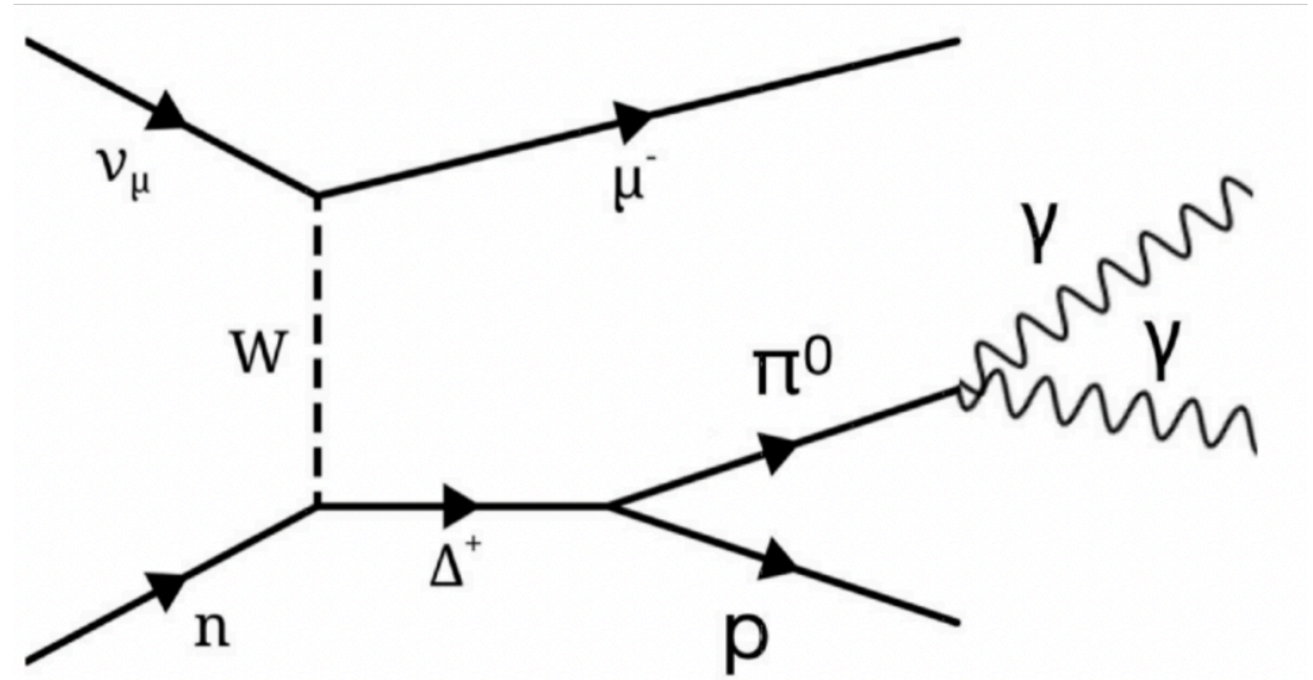
ν_μ CCπ^0 cross section

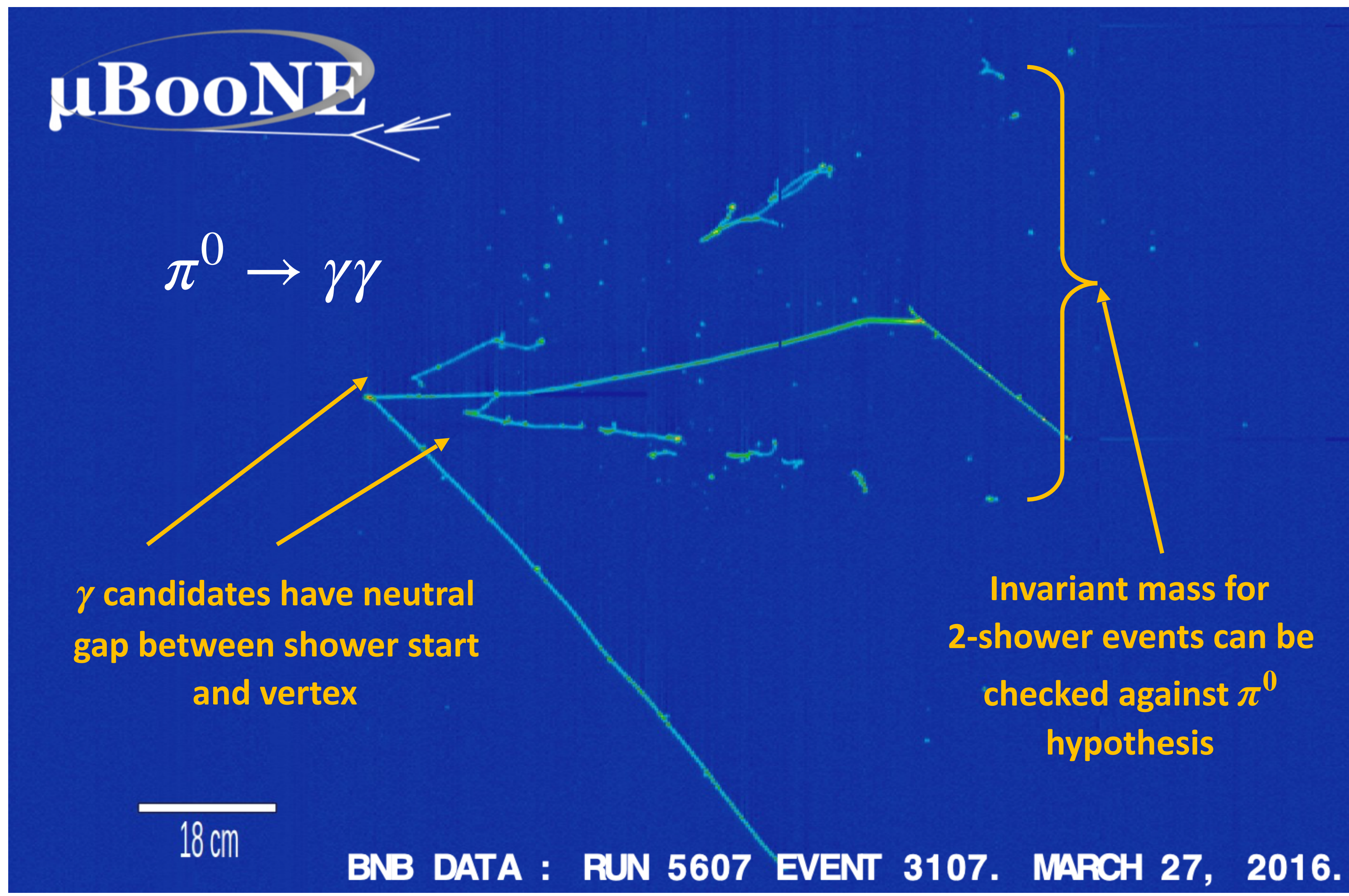
- **Resonant π^0 production**
  - Other processes (e.g., FSIs) also contribute
  - Nearly always decays to 2γ

- Pion production important process to understand for DUNE

- Photons from NC π^0 can be mistaken for ν_e CC events
  - Similar nuclear effects for CC/NC

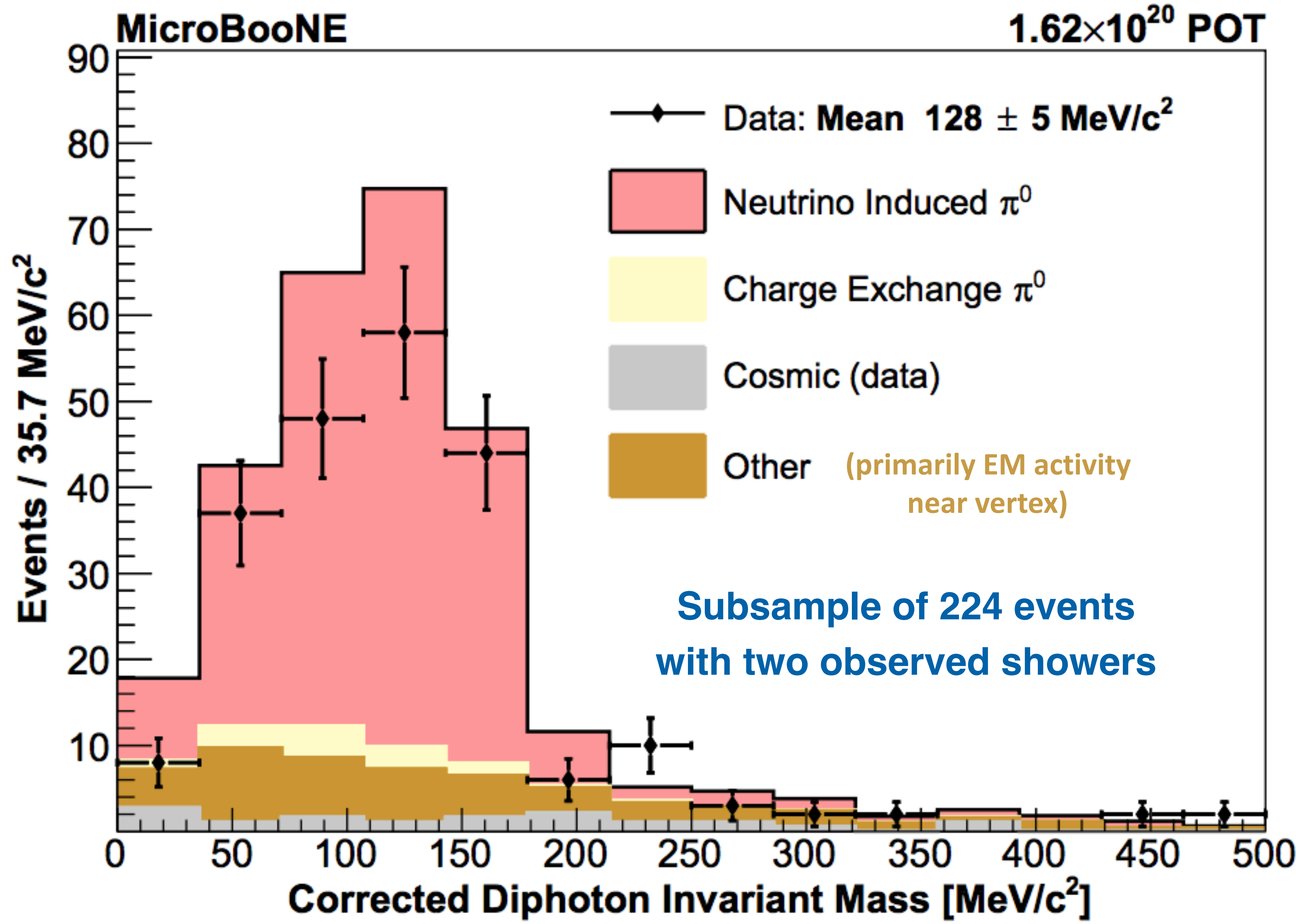
- Events selected from those that pass CC inclusive pre-filter





Validation of CCπ^0 event selection

- Measurement performed using sample of 771 events with at least one reconstructed shower
  - Boosts statistics
  - 95% of BNB GENIE events with $1\gamma \geq 50$ MeV involve π^0 decays
- Mean diphoton invariant mass from 2-shower events agrees with π^0 hypothesis ($m_{\pi^0} = 135$ MeV)
- Cross-check using 224-event subsample with two showers



https://arxiv.org/abs/1811.02700

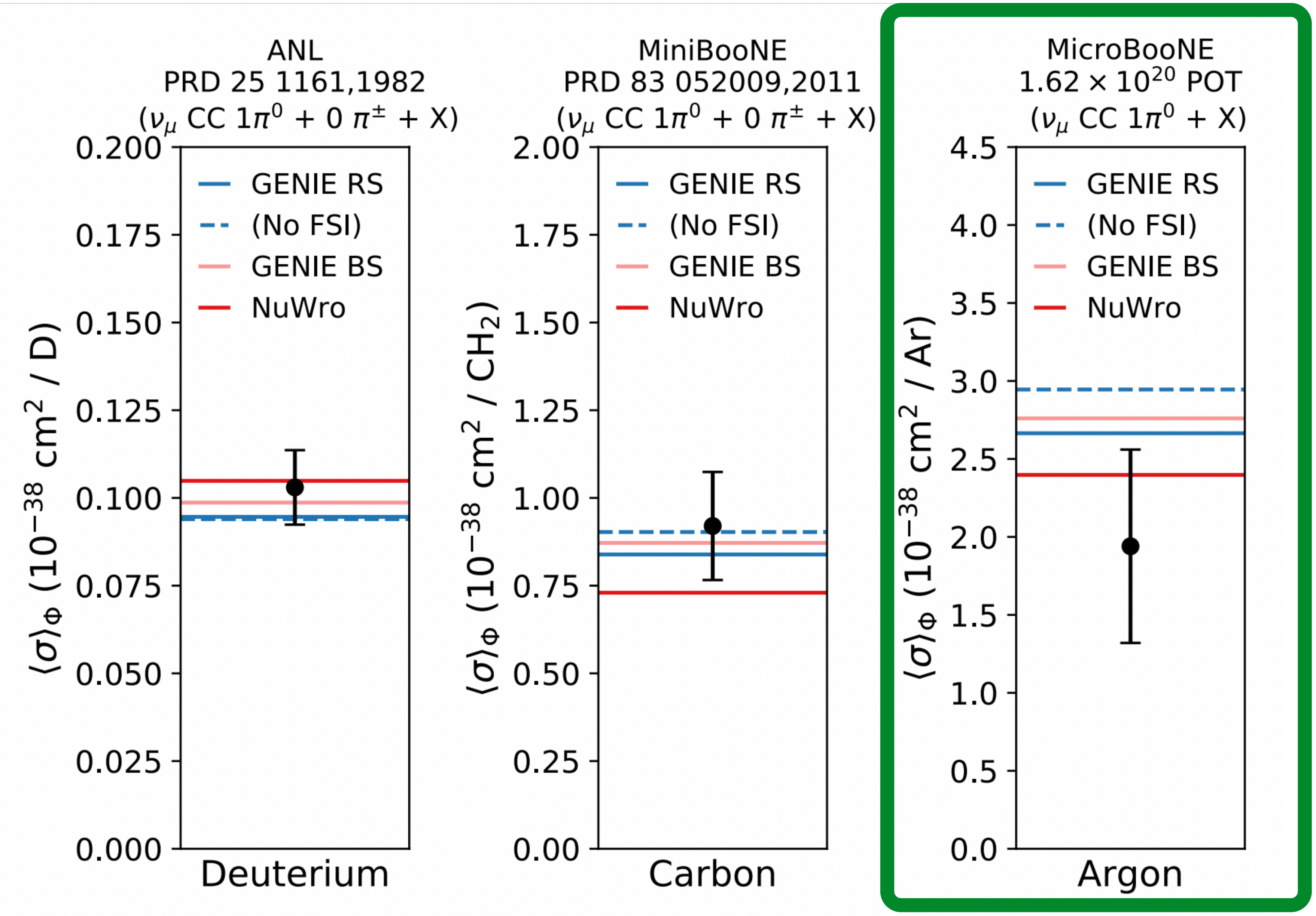
ν_μ CCπ^0 cross section result

https://arxiv.org/abs/1811.02700

- Good agreement with generators across different nuclear masses
- Comparison of GENIE resonant pion production models
  - Rein-Sehgal (RS) with and without FSIs enabled
  - Berger-Sehgal (BS)
- NuWro
  - Adler-Rarita-Schwinger
  - Oset cascade for FSI
- First demonstration of fully-automated shower reconstruction in a LArTPC

Flux-integrated total cross section

$$\langle\sigma\rangle_\Phi = 1.9 \pm 0.2\ \text{(stat)} \pm 0.6\ \text{(syst)} \times 10^{-38}\ \text{cm}^2\ /\ \text{Ar}$$



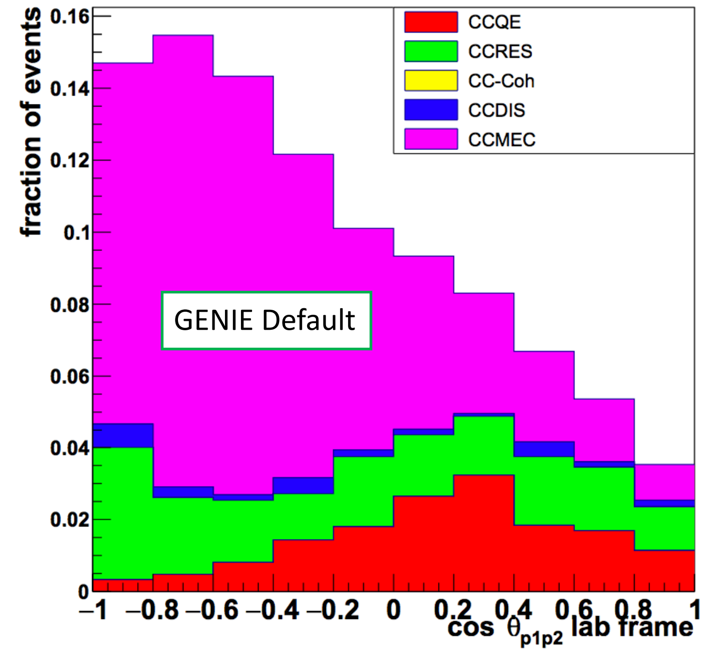
Increasing nuclear target mass ⟶

Investigating protons in CC events

- Low thresholds and precise tracking capabilities of LArTPCs allow for detailed studies of hadronic activity

- Proton multiplicities, momenta, can help shed light on complicated nuclear effects

- **Example**: Angle between protons in CC2p events
  - Shaped by nuclear effects
  - “GENIE Default” = v2.12.10 with empirical MEC
  - “GENIE Alternative” = v2.12.10 with Nieves CCQE & CCMEC



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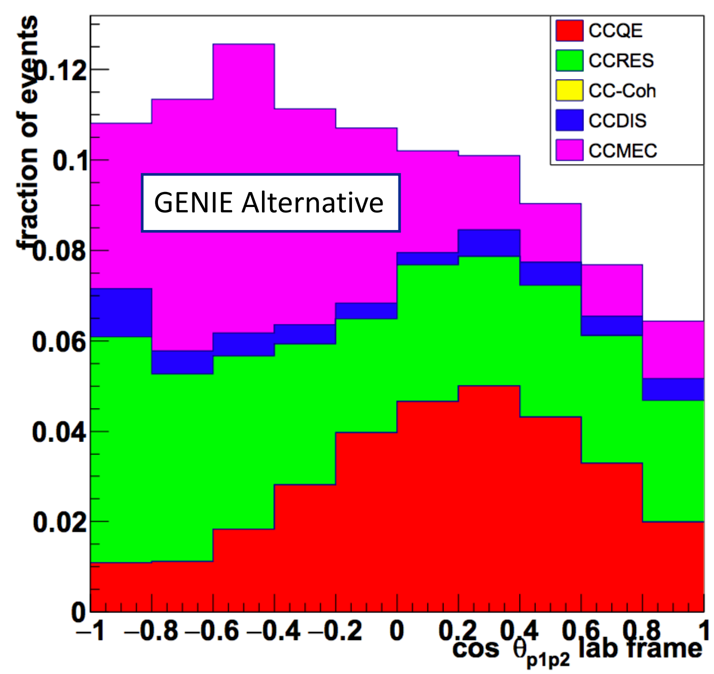
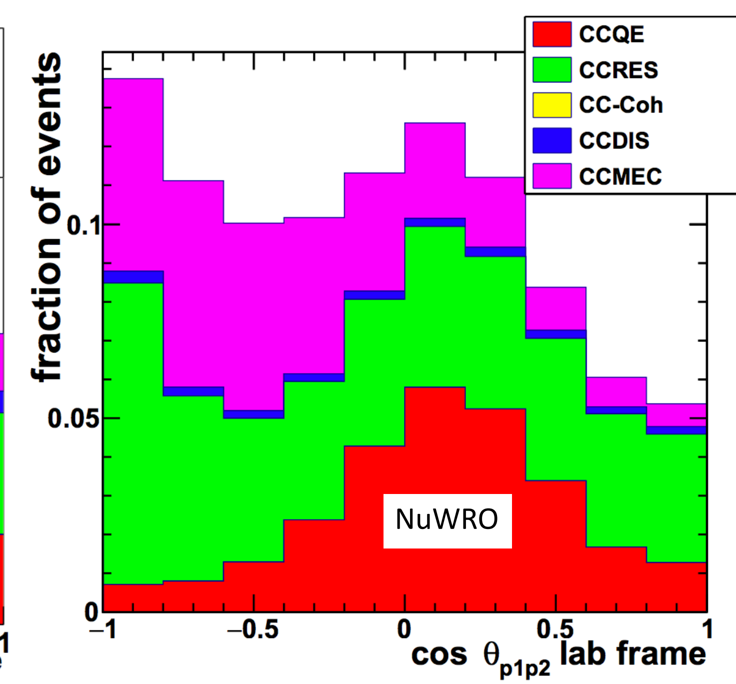
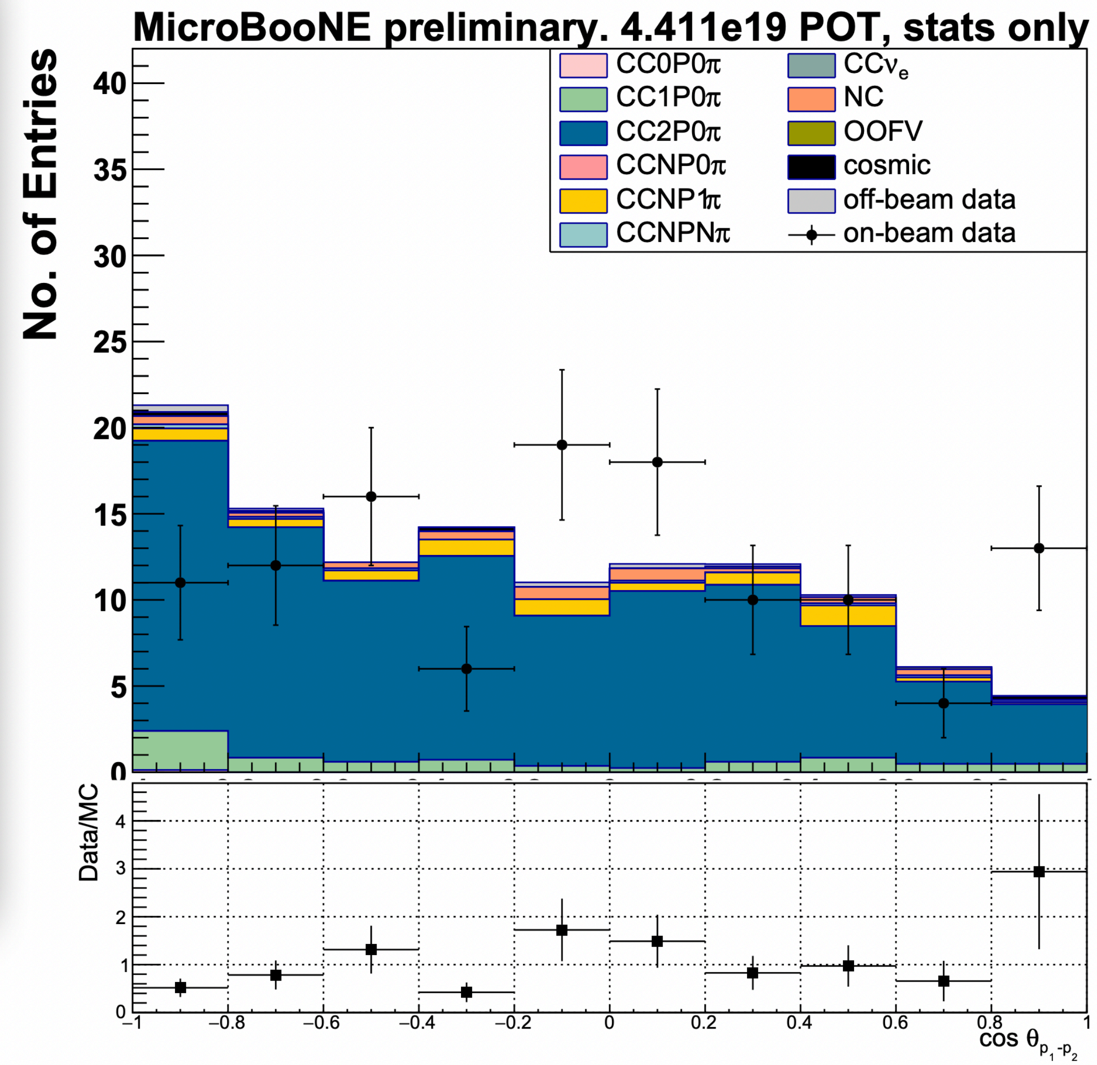


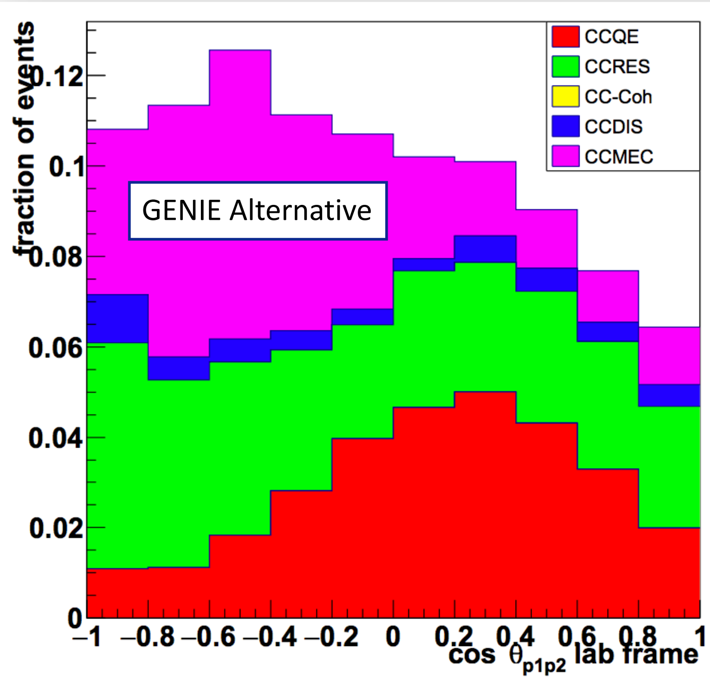


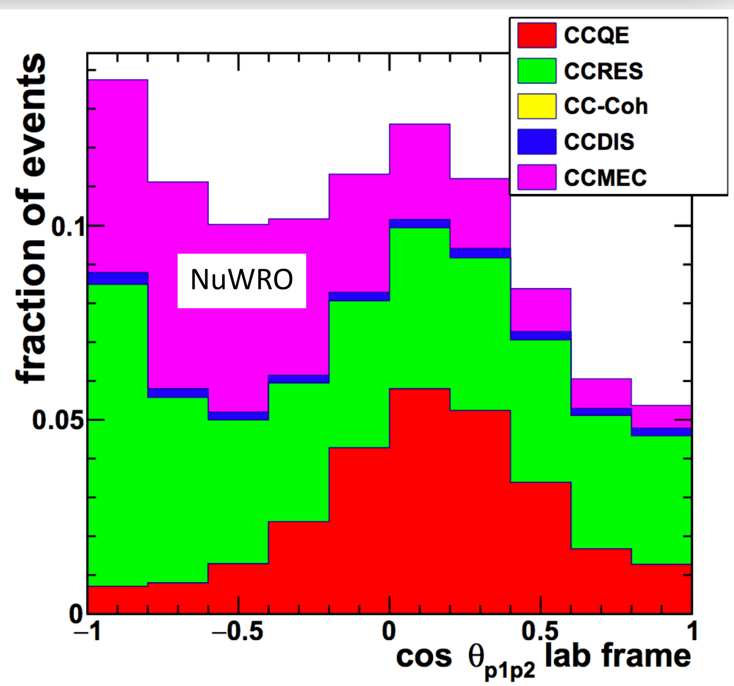
Generator disagreements here are large!
MicroBooNE can help to resolve them

Preliminary data for the CC2p opening angle

https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1056-PUB.pdf

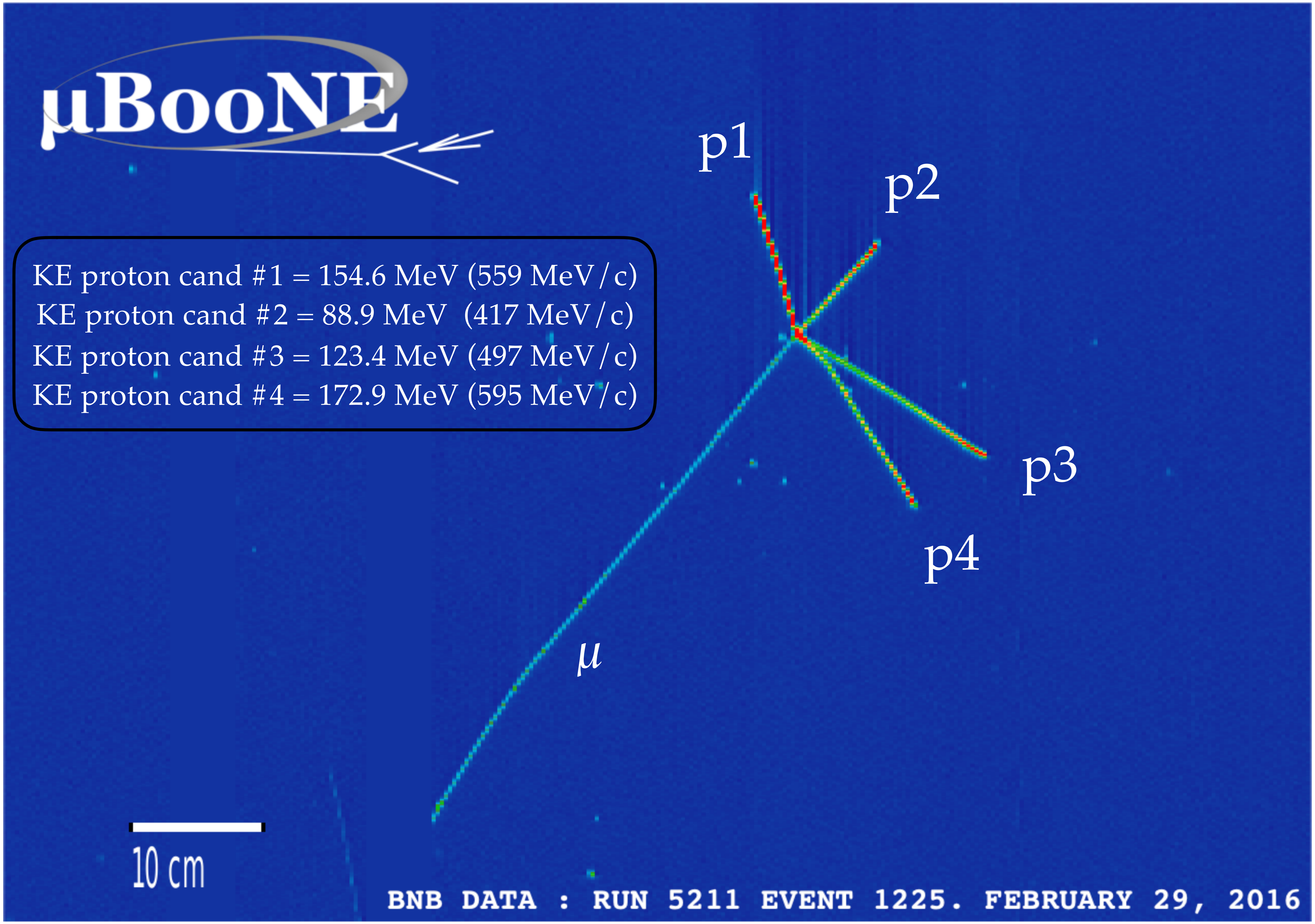






Higher statistics coming soon to constrain these models!

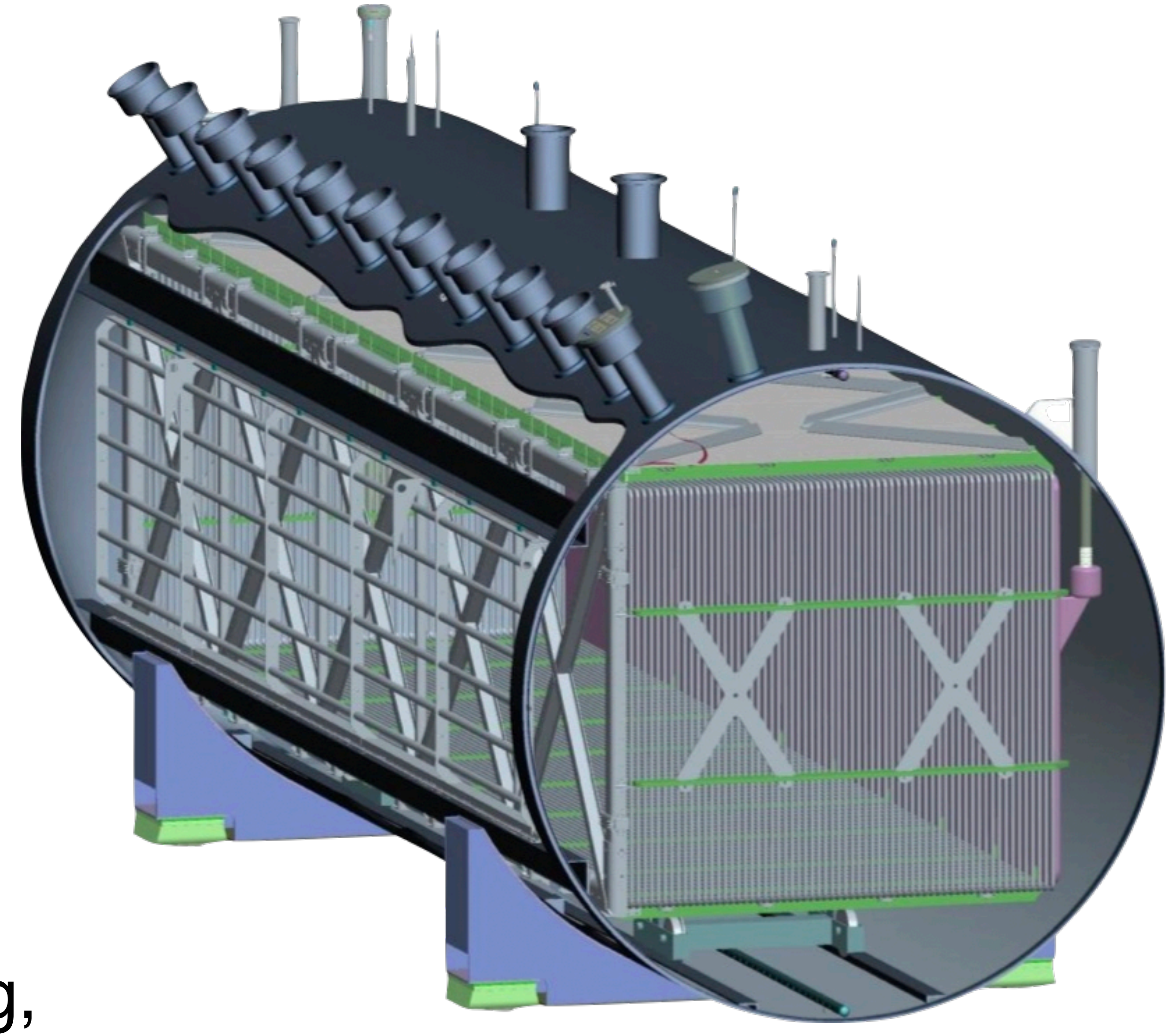
A CC4p event!



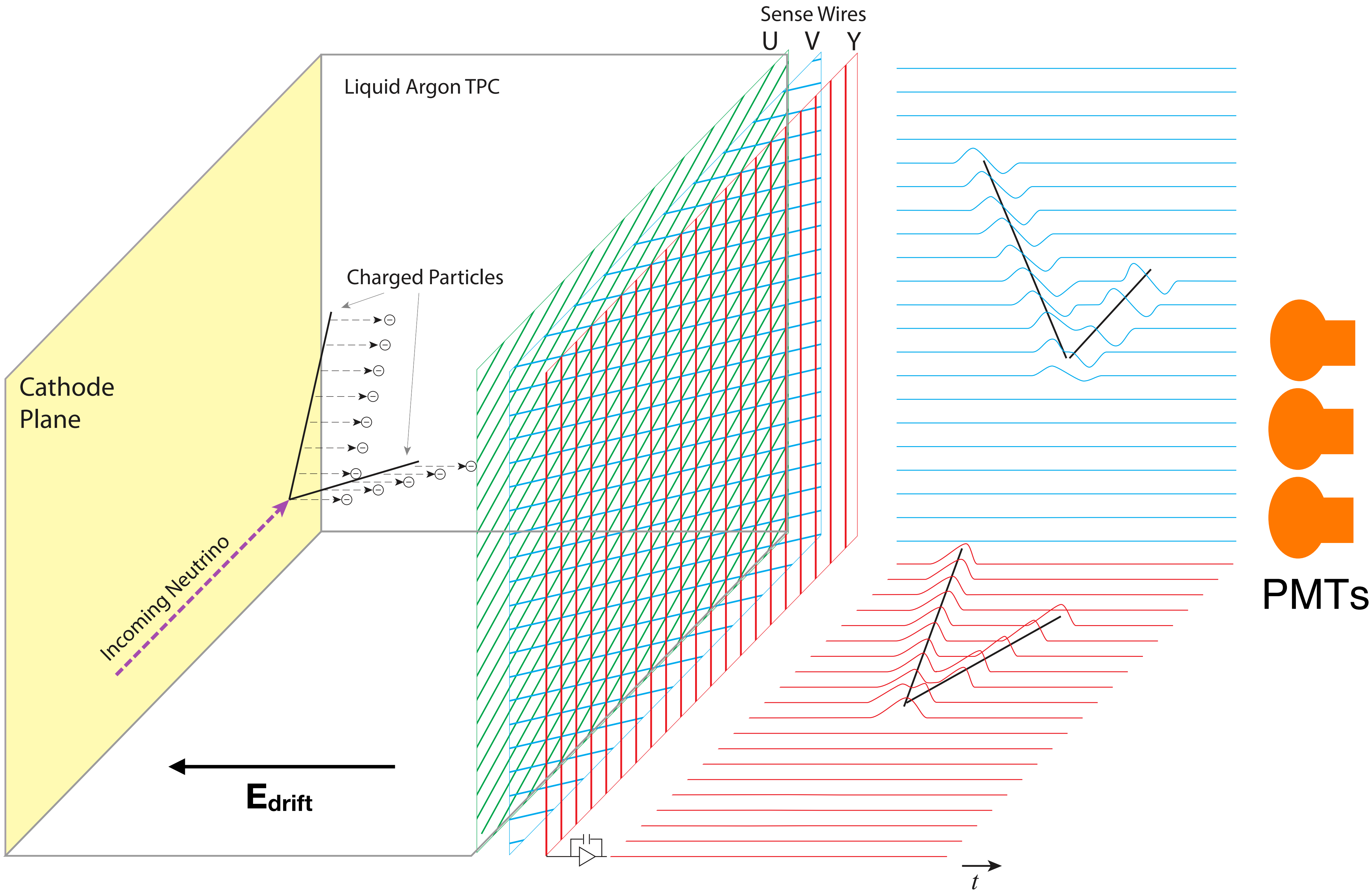
μBooNE
p1
p2
p3
p4
μ
KE proton cand #1 = 154.6 MeV (559 MeV/c)
KE proton cand #2 = 88.9 MeV (417 MeV/c)
KE proton cand #3 = 123.4 MeV (497 MeV/c)
KE proton cand #4 = 172.9 MeV (595 MeV/c)
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

Conclusion

- MicroBooNE is hard at work studying the physics of neutrino-argon interactions
  - ν_μ CC inclusive cross section
  - ν_μ CCπ^0 cross section
  - Proton multiplicities, momenta, angles
  - **Many more results coming soon!**
- Nuclear effects greatly complicate theoretical description of ν-^{40}Ar scattering, but high precision needed to answer key neutrino physics questions
- Current & upcoming MicroBooNE cross section results will provide important model constraints for future oscillation measurements



Liquid argon time projection chambers (LArTPCs)



3D imaging of neutrino events

Cosmic rejection for ν_μ CC inclusive selection

99.9% cosmic rejection

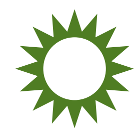
Often 20+ comics in each 4.8 ms TPC readout window!

A track is vetoed as a cosmic ray if . . .


it is through going in the detector

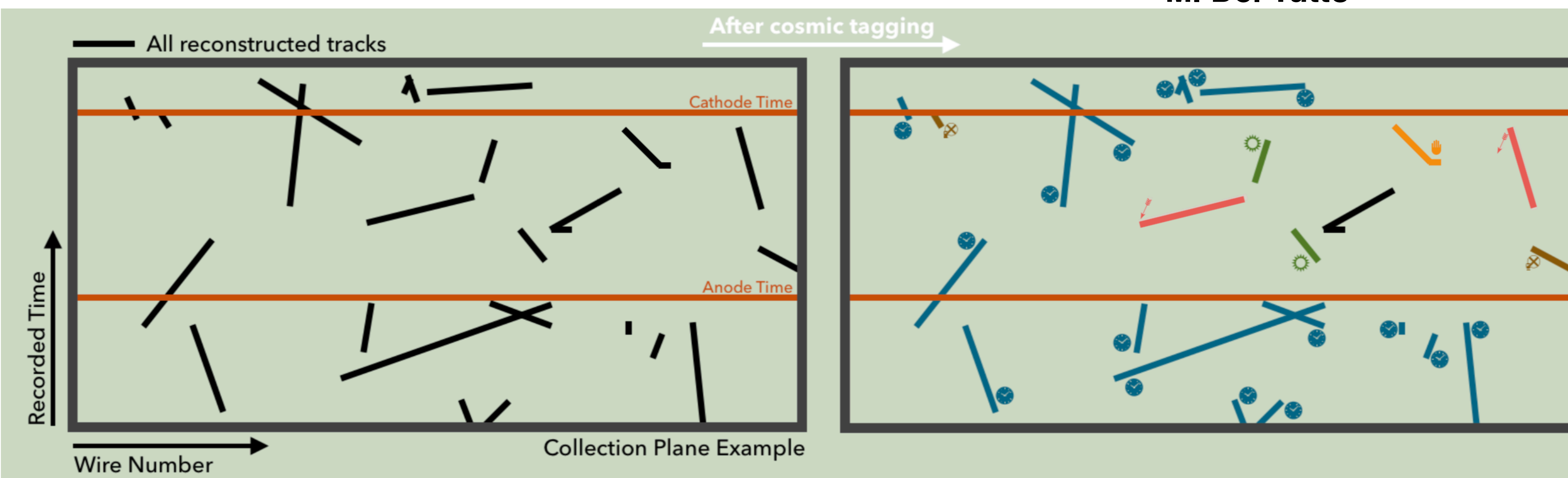

it is not compatible with the neutrino beam time (that lasts for only 1.6 μs compared to the 4.8 ms readout window)


the track is a cosmic crossing the anode or cathode plane (for which we can reconstruct the t_0)

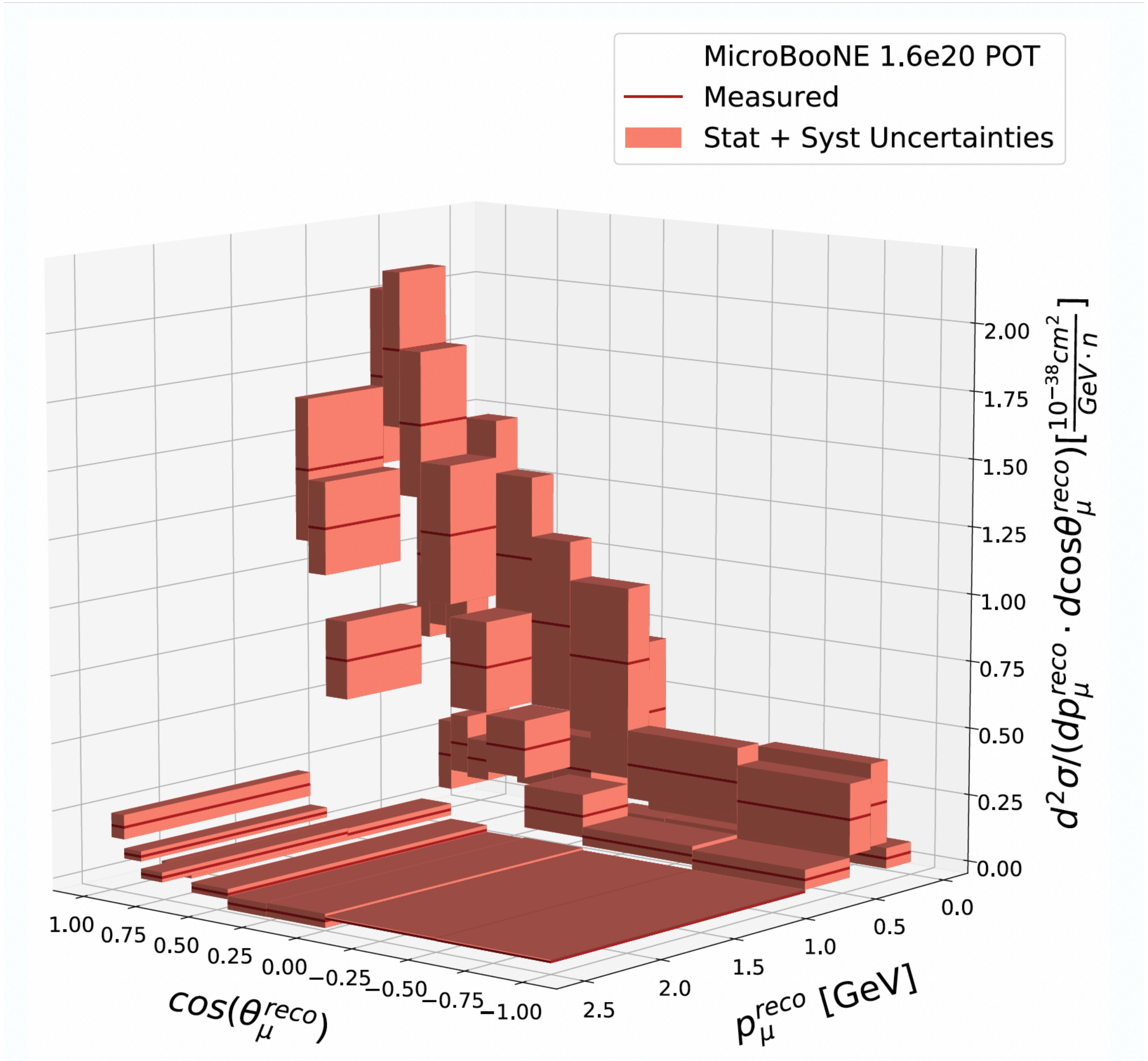

it is not compatible with the flash in the neutrino beam spill in terms of spatial position and light intensity


it is identified as entering and stopping (Bragg peak and/or Michel tagging)

M. Del Tutto



ν_μ CC inclusive cross section results



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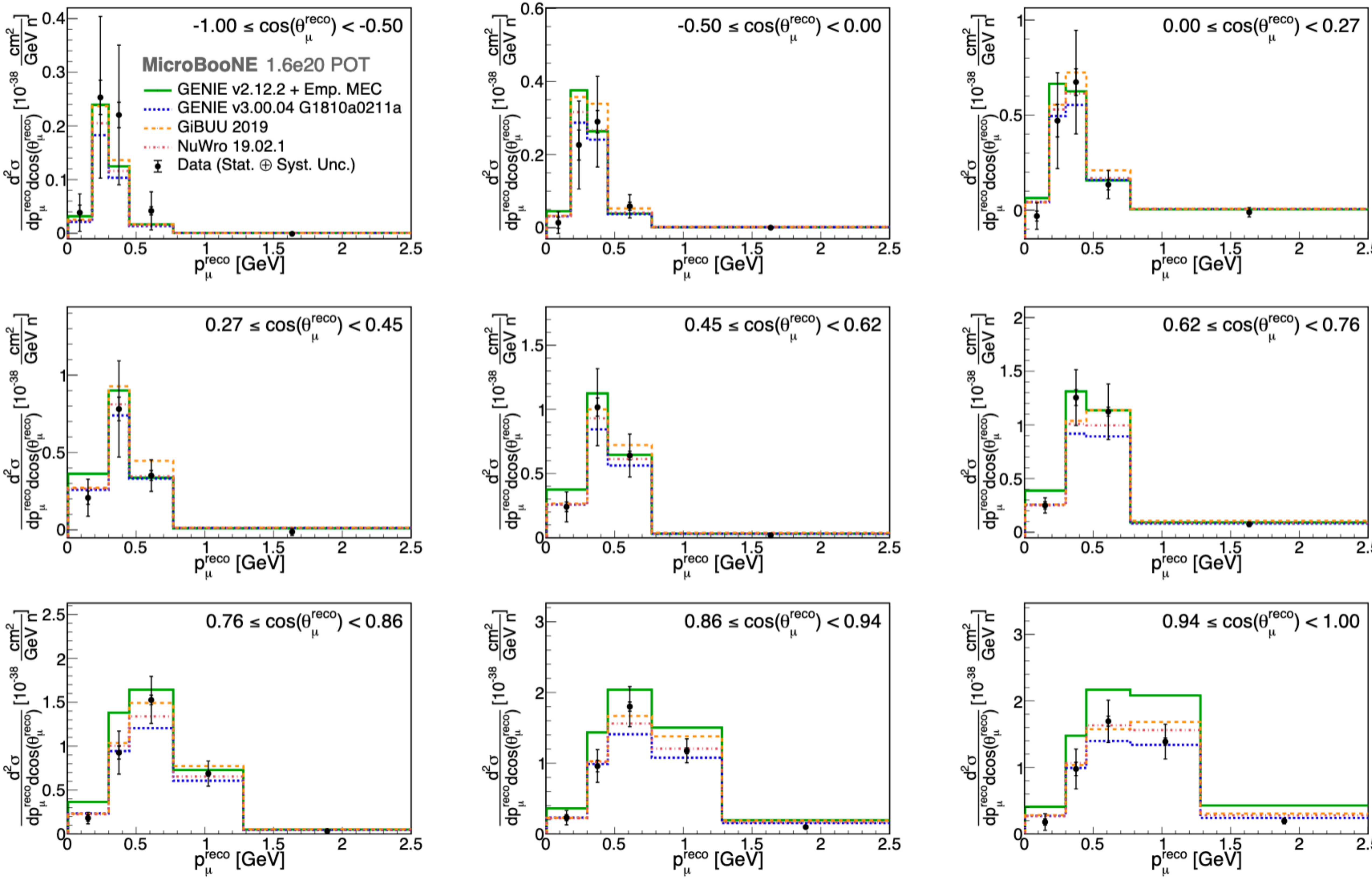
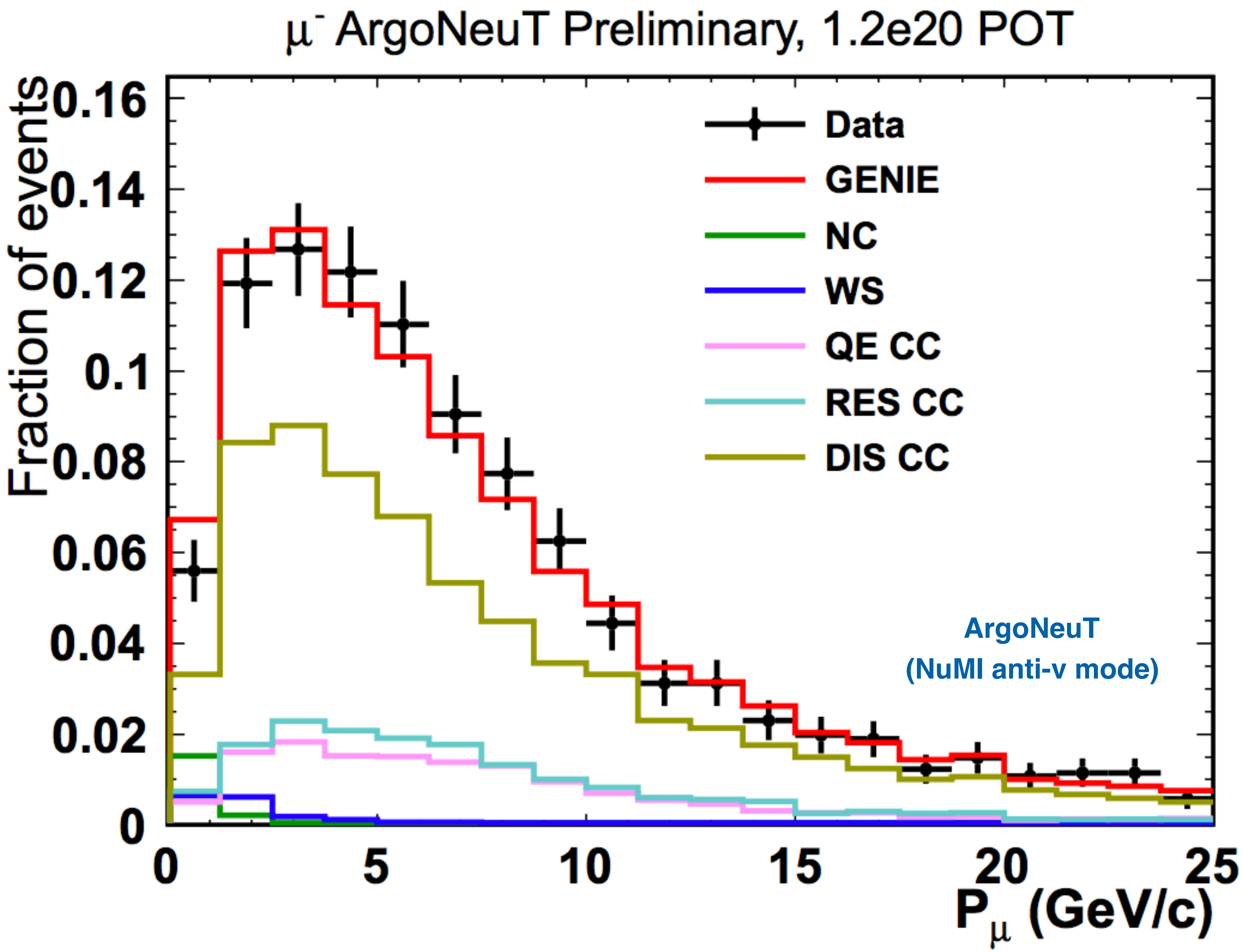
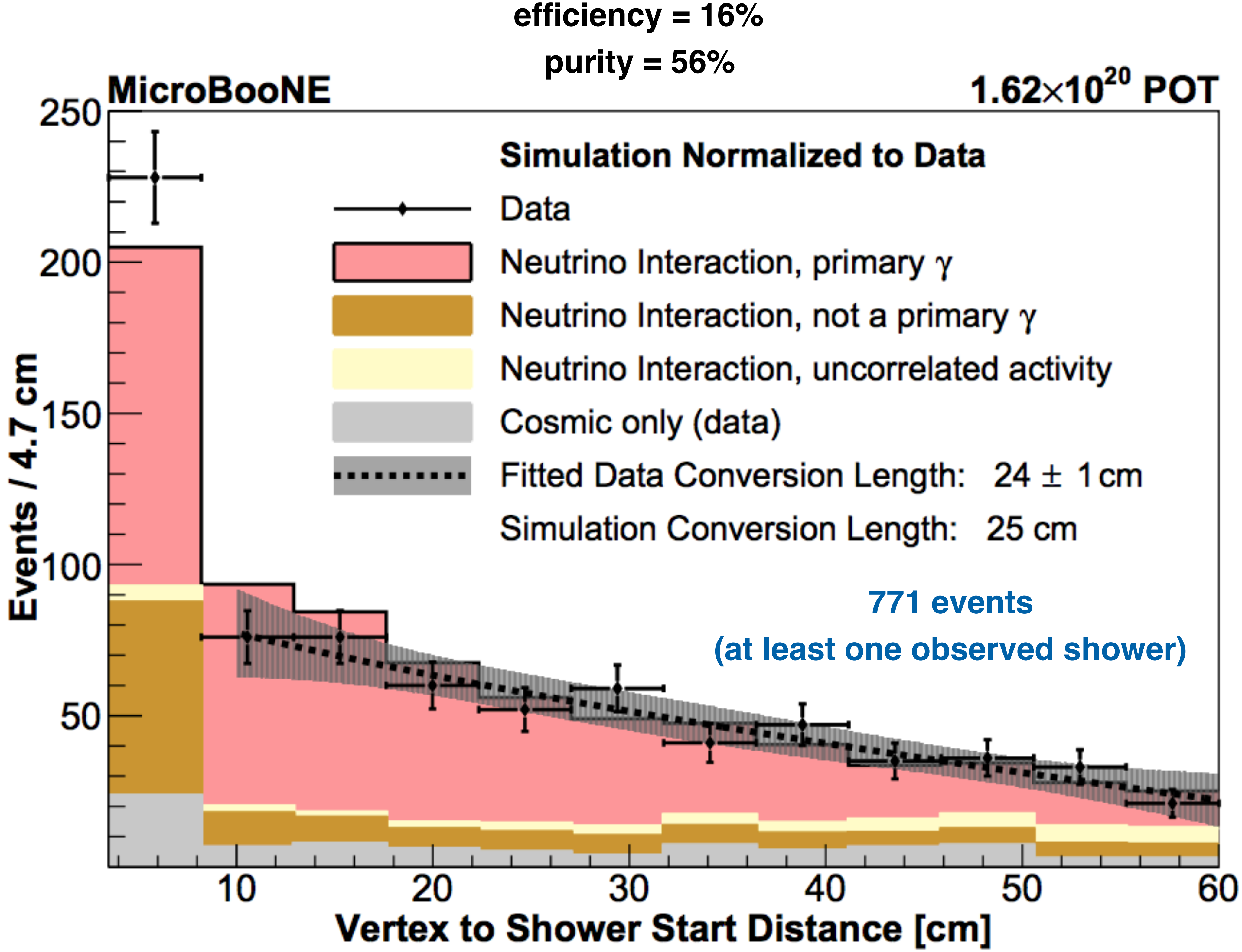


https://arxiv.org/abs/1905.09694

ArgoNeuT ν_μ CC inclusive event distribution



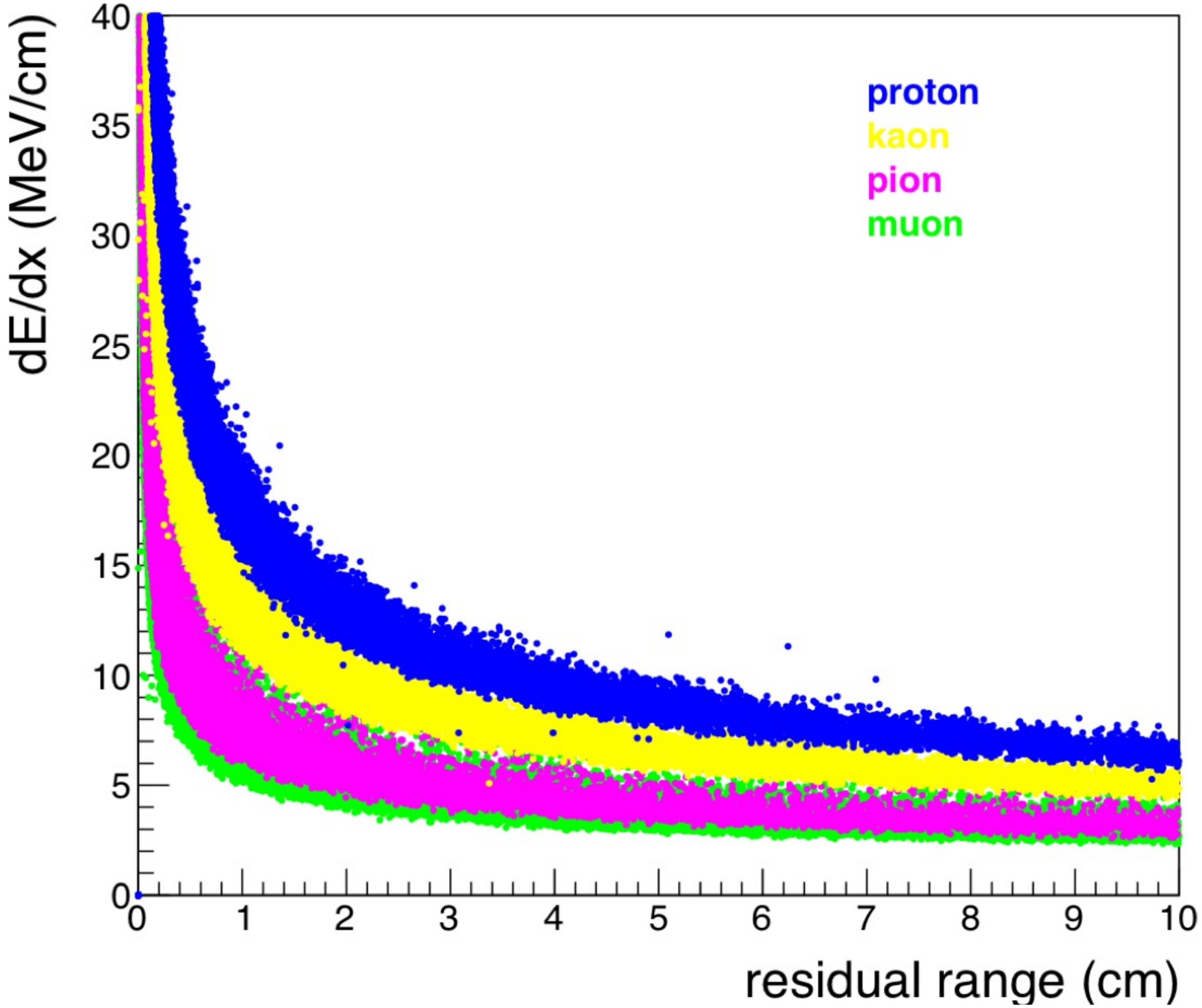
Fit of shower start distances agrees with γ conversion length expected from simulation



Fermilab

Proton candidate selection

- Proton tracks are identified by comparison to theoretical predictions from Geant4 simulations
- "Residual range" = distance between current hit and final hit
- PID metric used to test proton hypothesis
- Accepted candidates are contained and have $PID < 88$



$$PID \equiv \chi^2_{\text{proton}}/ndof = \frac{1}{ndof} \sum_{\text{hits}} \left[\frac{dE/dx_{\text{measured}} - dE/dx_{\text{theory}}}{\sigma_{dE/dx}} \right]^2$$

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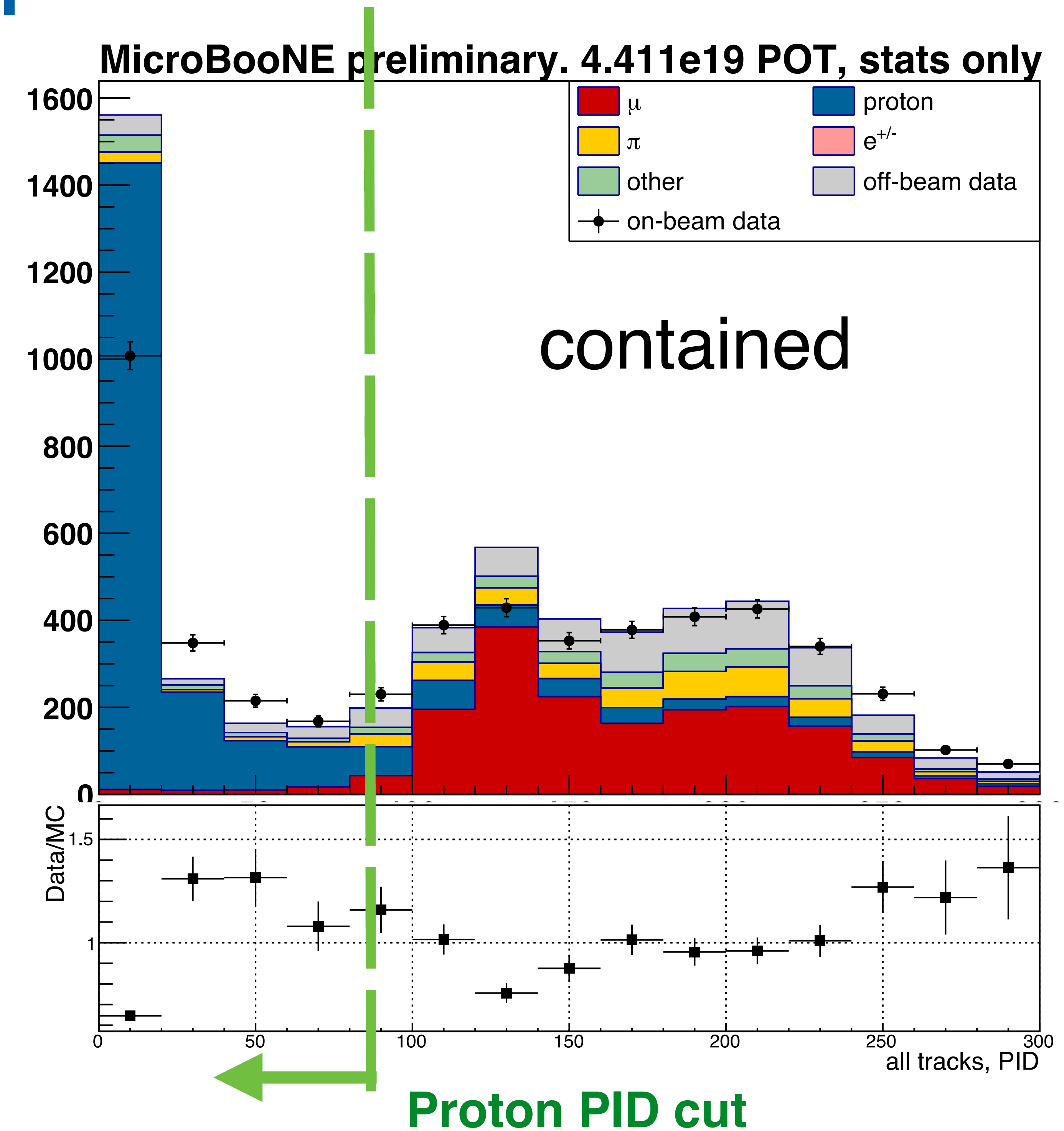

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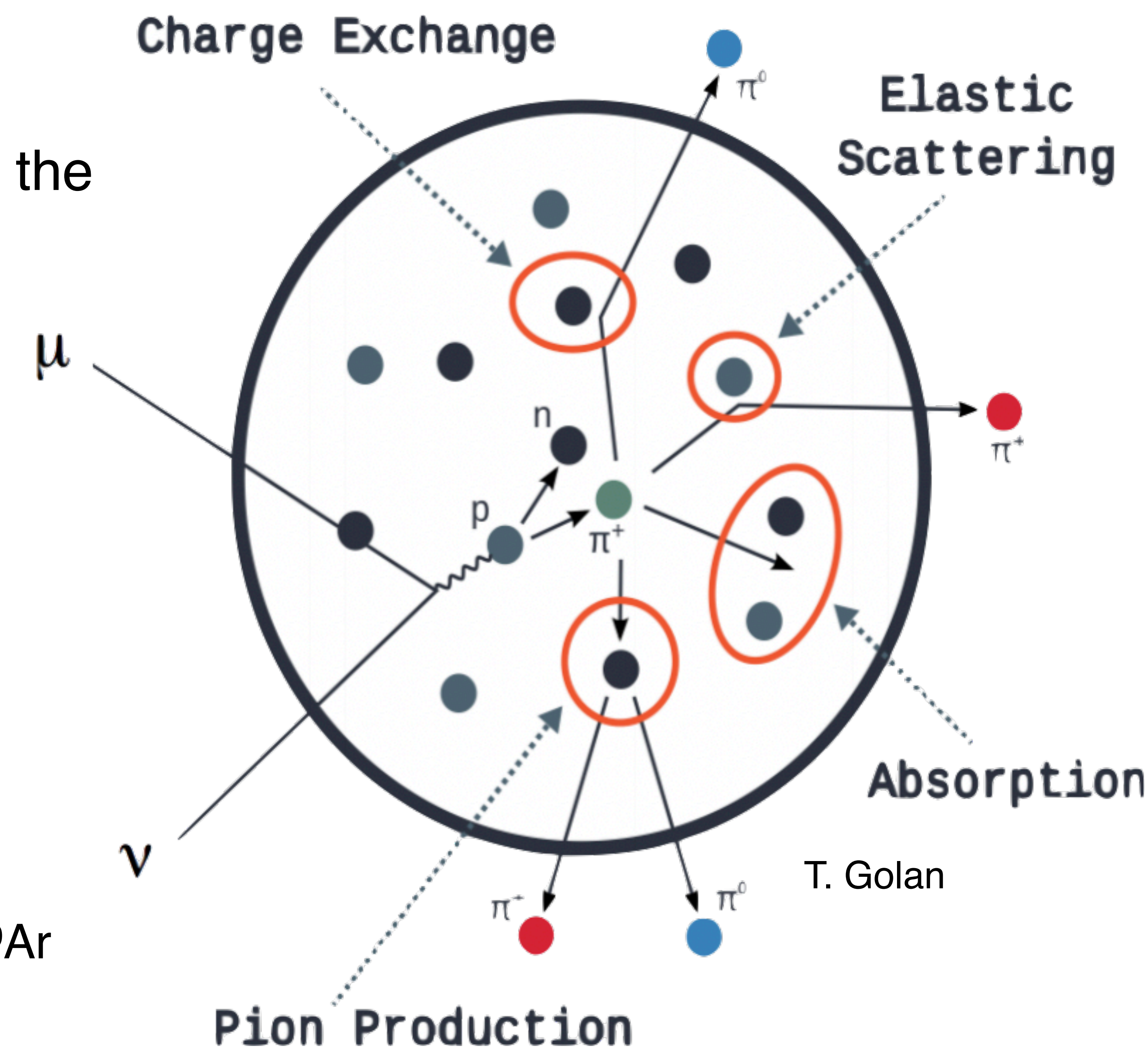
Nuclear effects in neutrino cross sections

- Current accelerator-based oscillation measurements use **nuclear** targets (e.g., ^{40}Ar)

- Many complications compared to the free nucleon case
  - Fermi motion & binding energy
  - Short-range correlations
  - Meson exchange currents
  - Long-range correlations ("RPA")
  - **Final state interactions**

- Challenging theory & sparse data for ^{40}Ar

- MicroBooNE is providing data to improve our understanding of this physics



T. Golan

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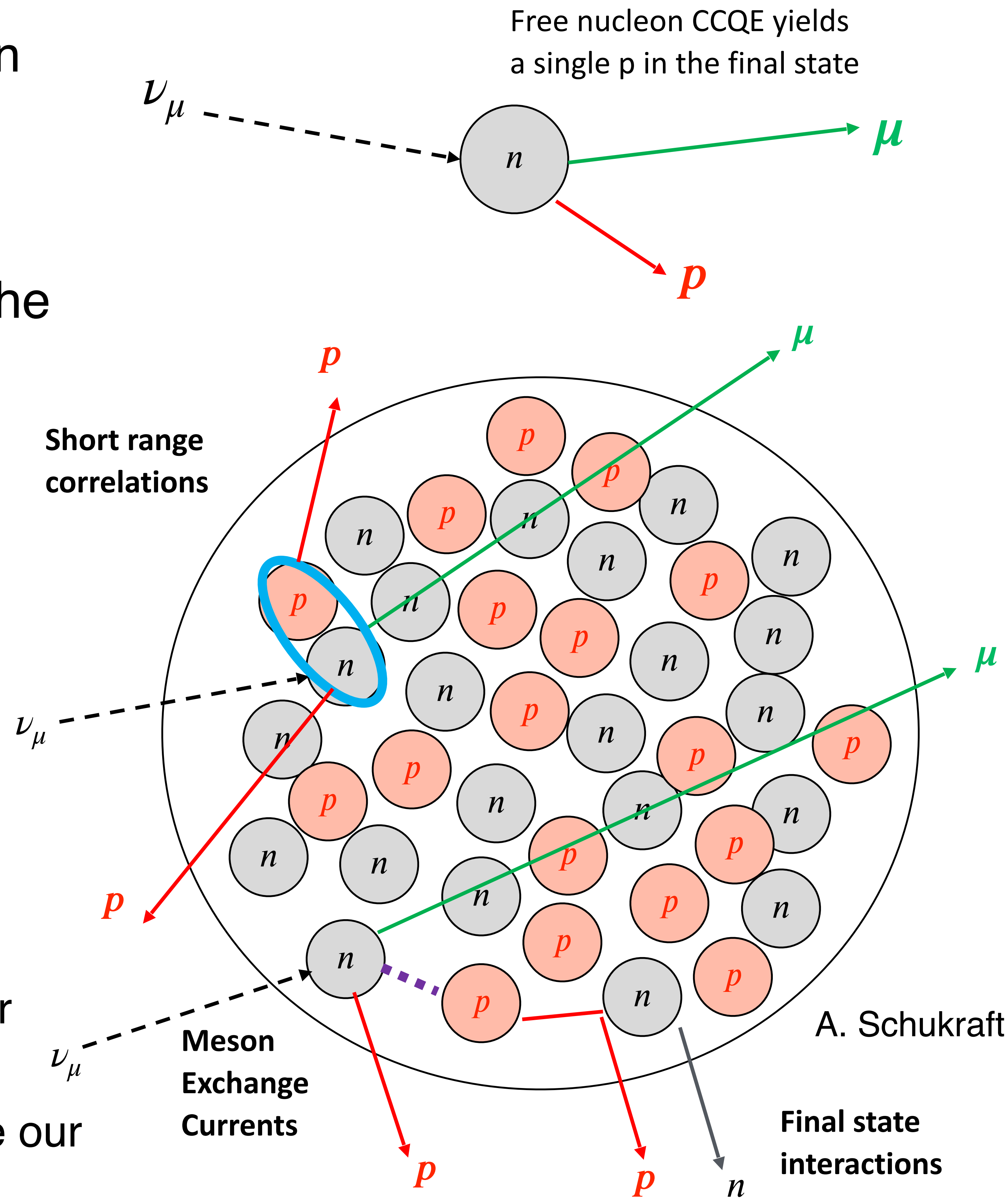

A. Schukraft