MicroBooNE's Neutrino Cross-section Campaign

Meghna Bhattacharya (Fermilab)
On behalf of the MicroBooNE Collaboration

July 23rd, 2022

Snowmass, Seattle

MicroBooNE in a Nutshell

- Liquid Argon Time Projection Chamber at FNAL
  - 85 tonne active volume of Argon
  - 5 years physics runs: 2015-2021
    - Largest ν-Ar dataset collected
- Main physics goals
  - Investigate origin of anomalous low energy excess (LEE) of electron-like events seen by MiniBooNE
  - Measure neutrino-Ar cross sections
  - BSM searches
  - Excellent testbed for LArTPC R&D

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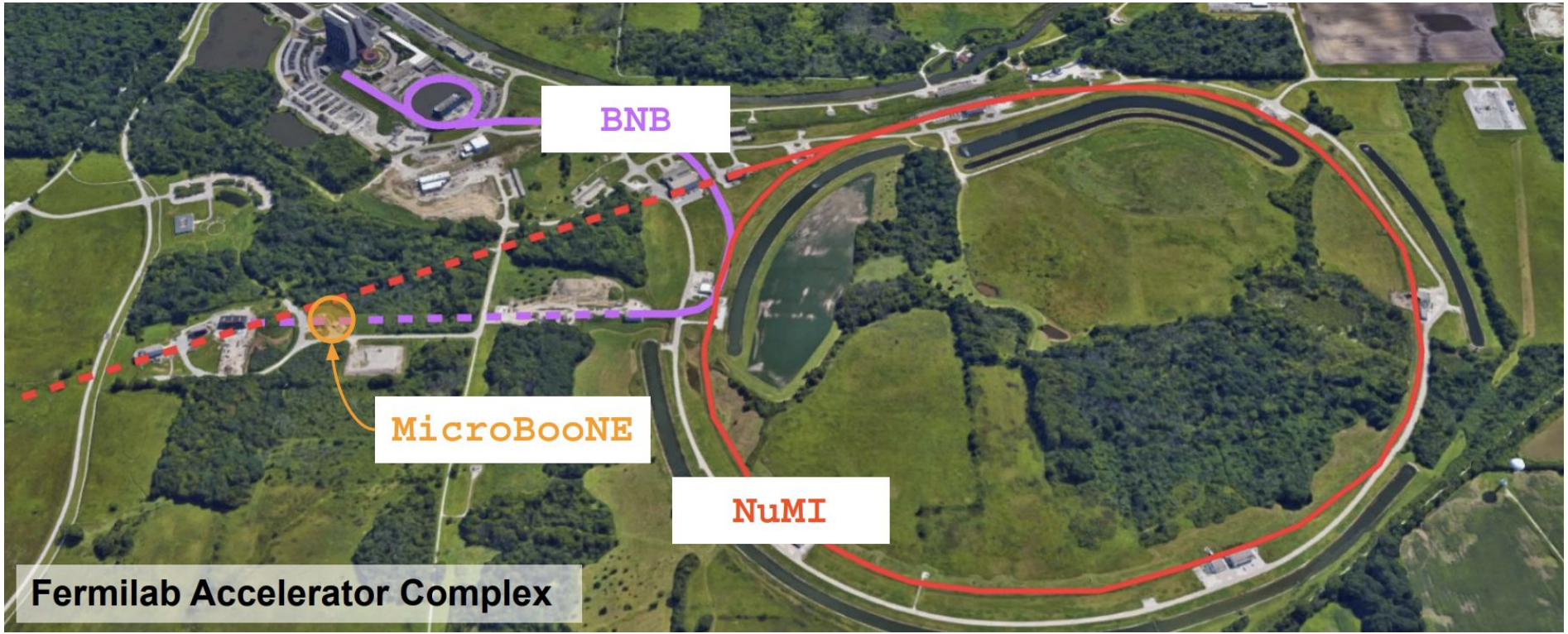
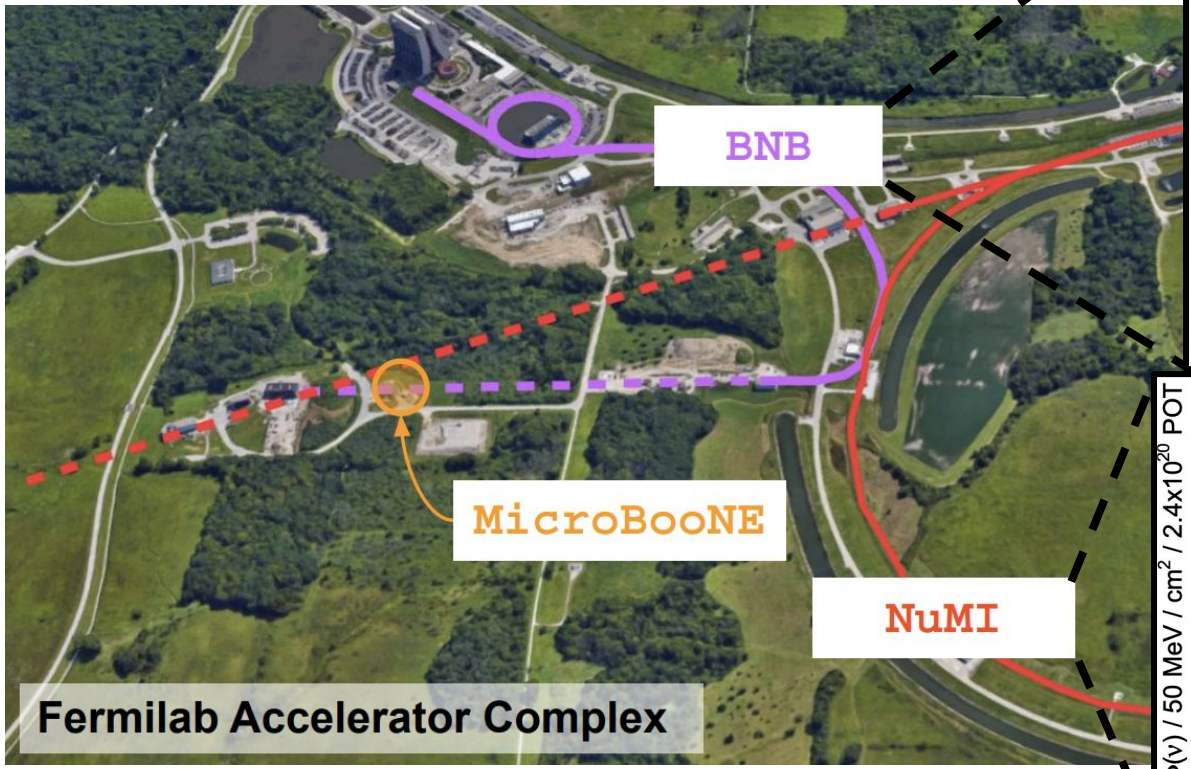
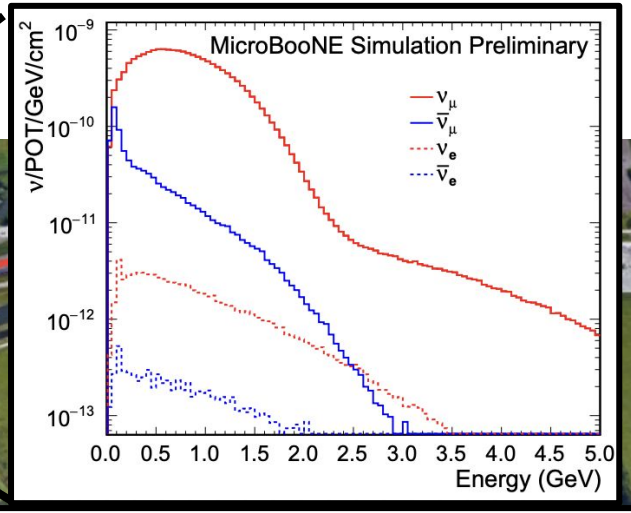
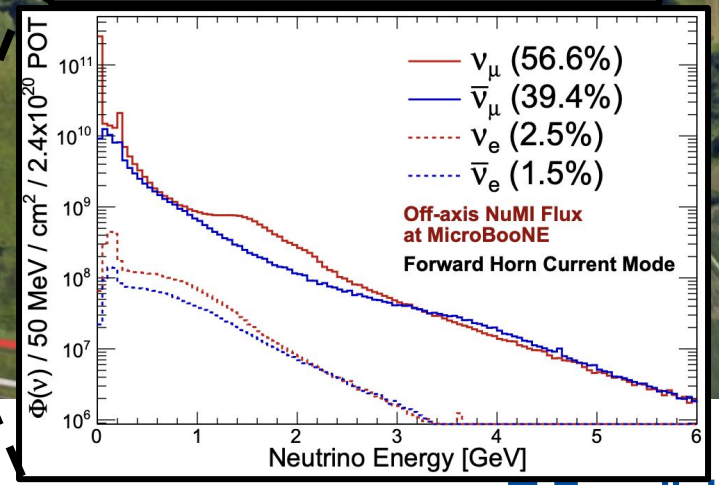
Neutrinos Towards MicroBooNE



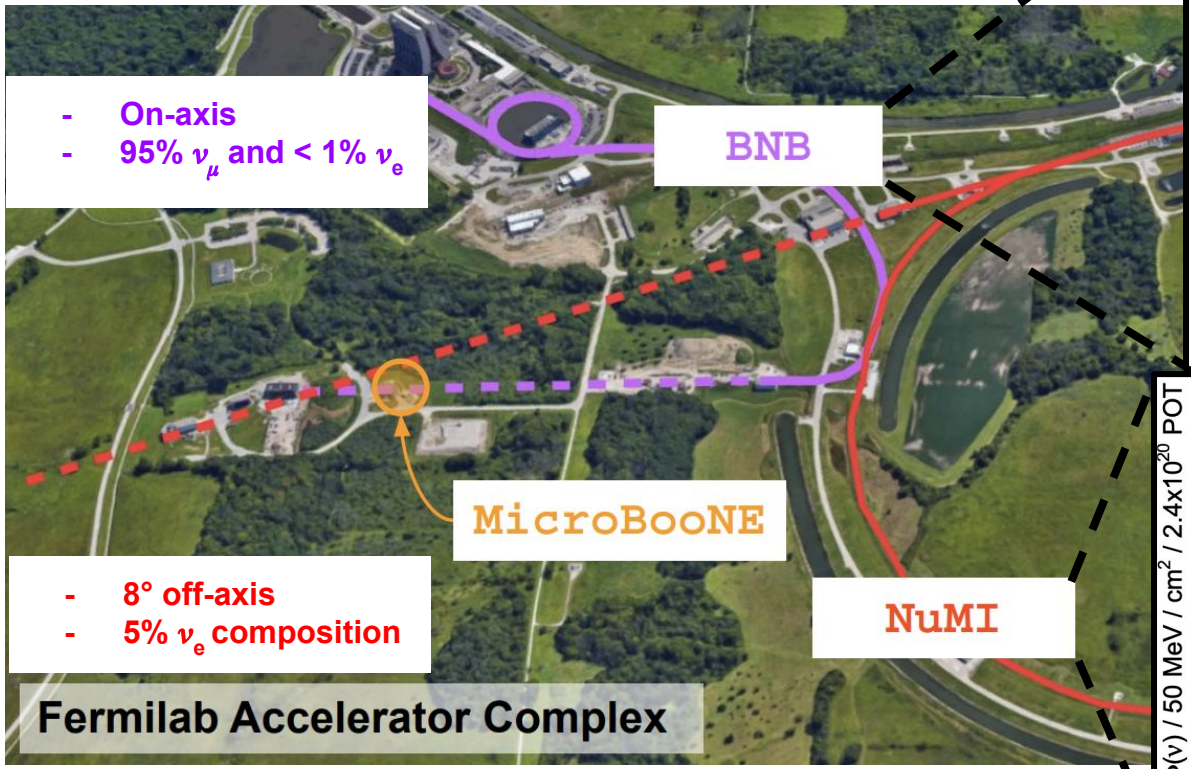
Neutrinos Towards MicroBooNE

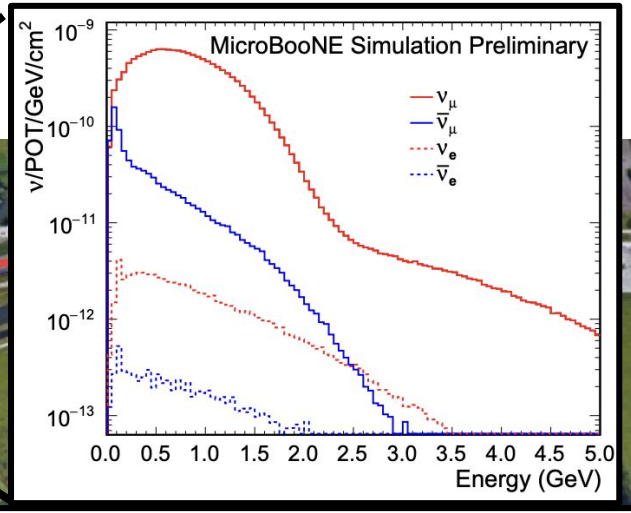


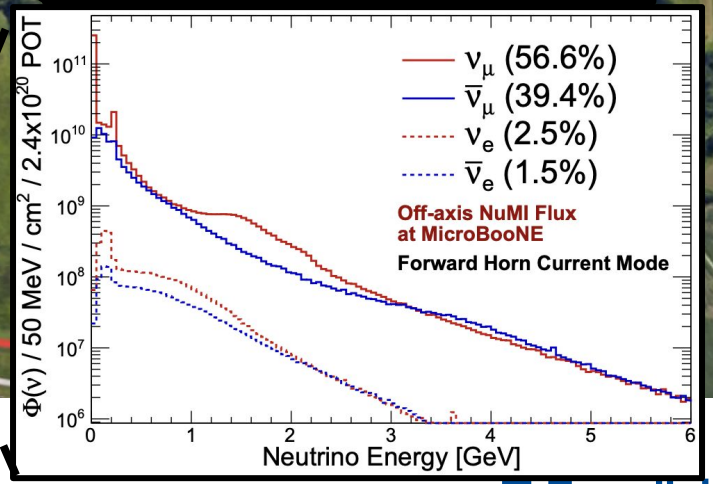




Neutrinos Towards MicroBooNE

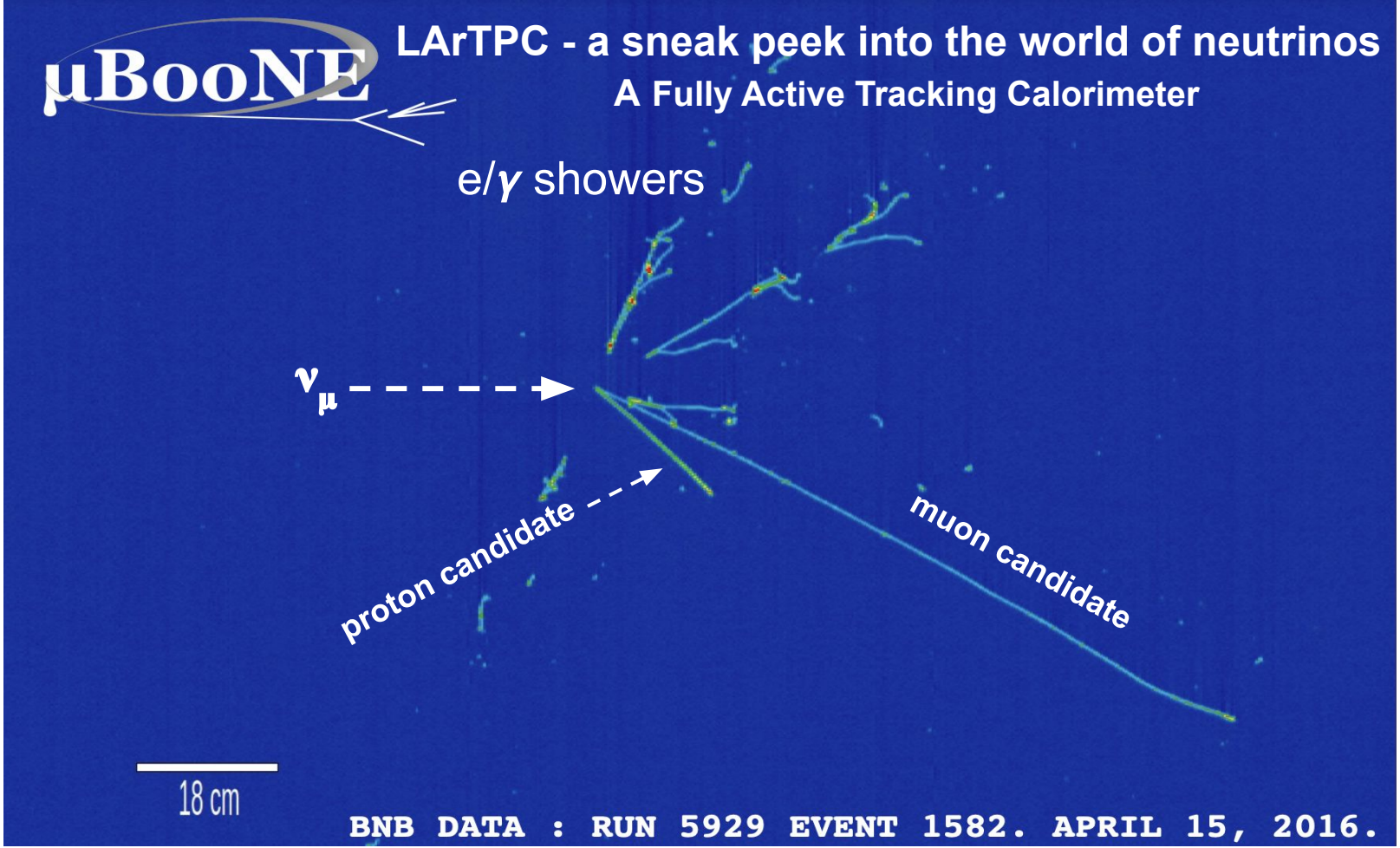






LArTPC - a sneak peek into the world of neutrinos

A Fully Active Tracking Calorimeter



Improvements with LArTPCs - Low proton threshold

- **Measuring proton kinematics provides more information about the interaction**

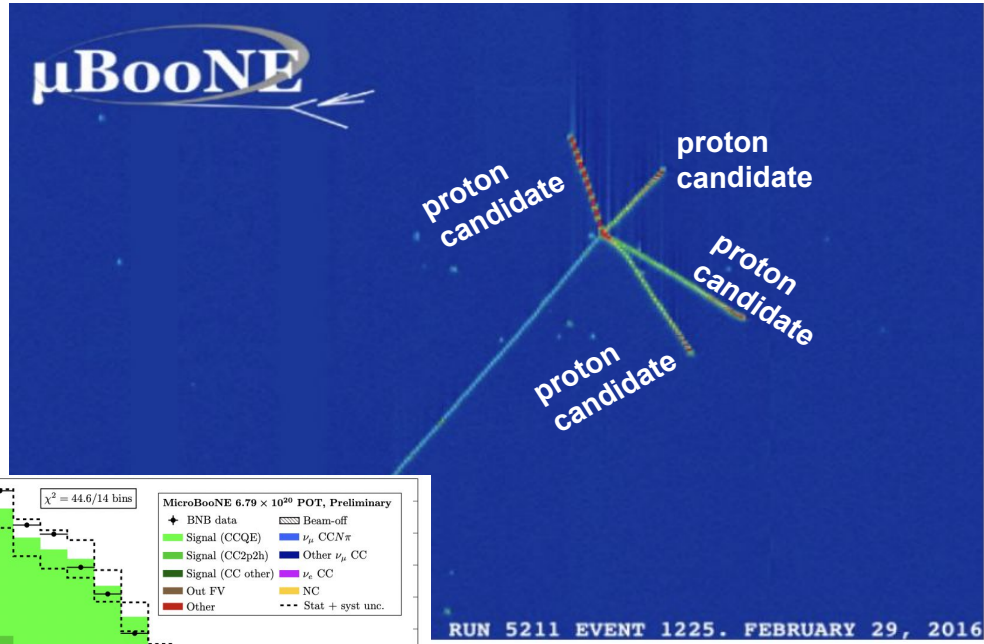
- **Low thresholds**

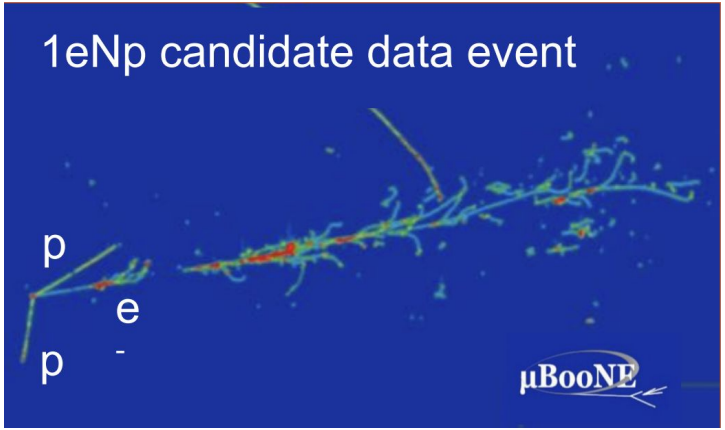
MicroBooNE 300 MeV/c
MICROBOONE-NOTE-1099-PUB

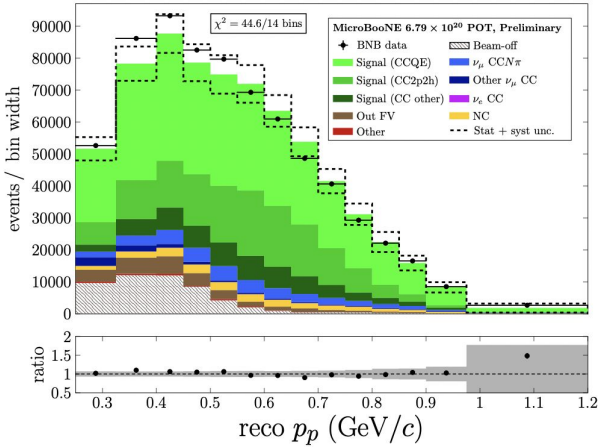
T2K 500 MeV/c
Phys. Rev. D **98**, 032003

ArgoNeuT 200 MeV/c
Phys. Rev. D **90**,012008

MINERvA 450 MeV/c
PhysRevD.99.012004

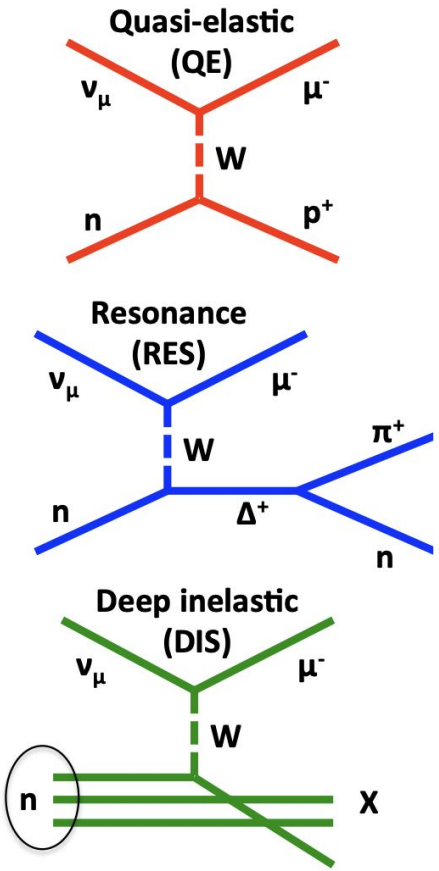


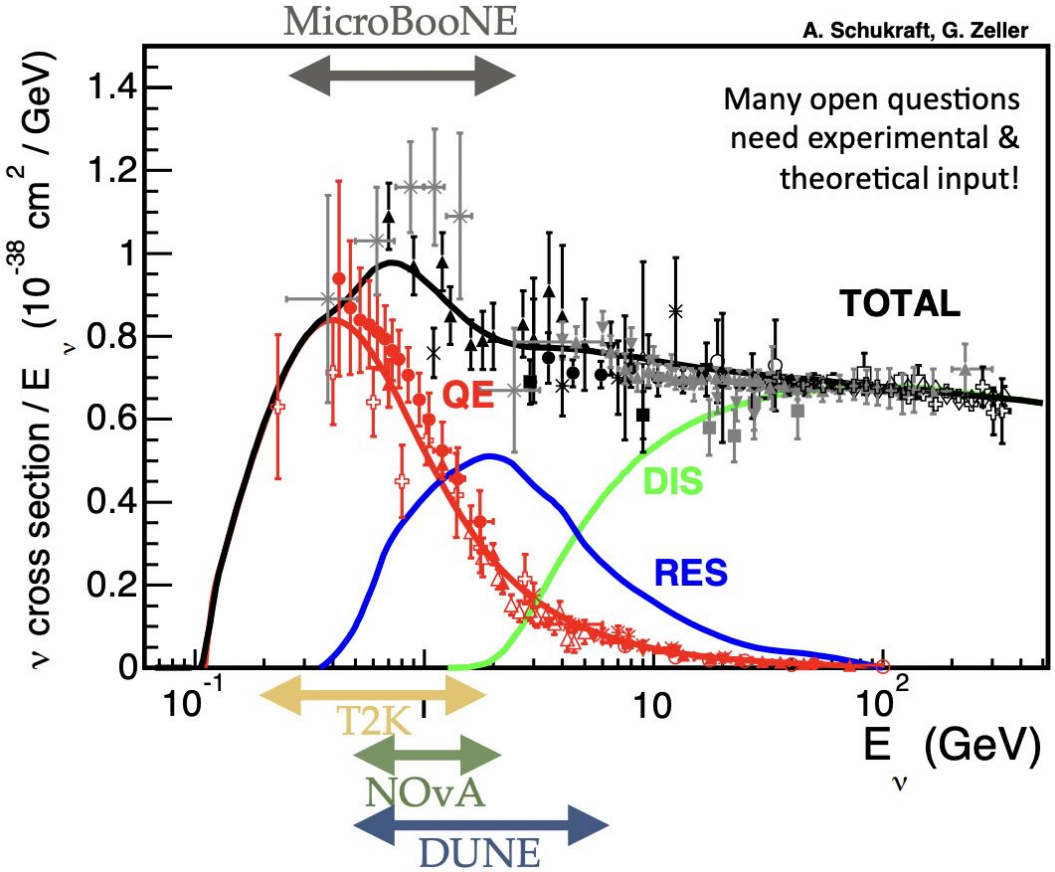




Even lower threshold at MicroBooNE 250 MeV/c
MICROBOONE-NOTE-1099-PUB

Neutrino Interactions





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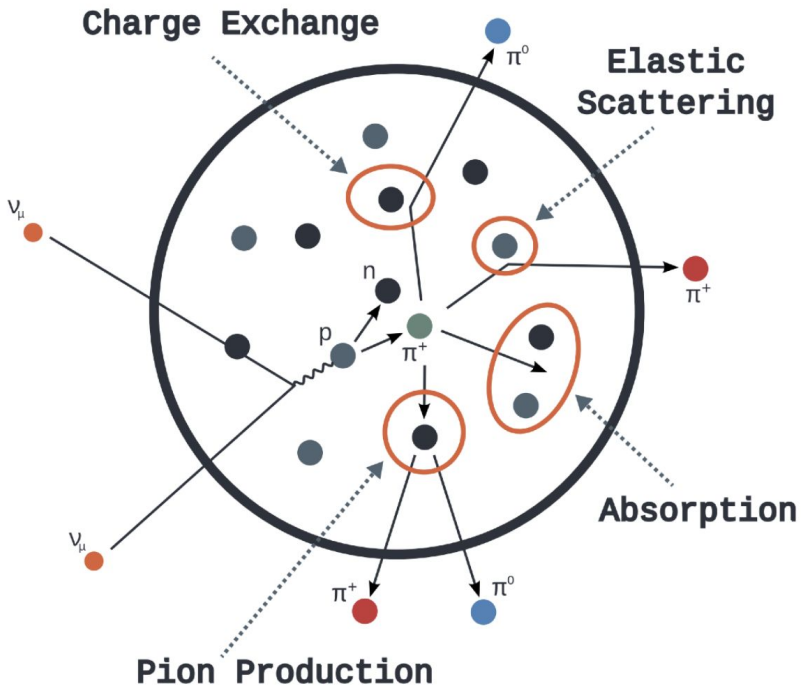
Neutrino Interactions

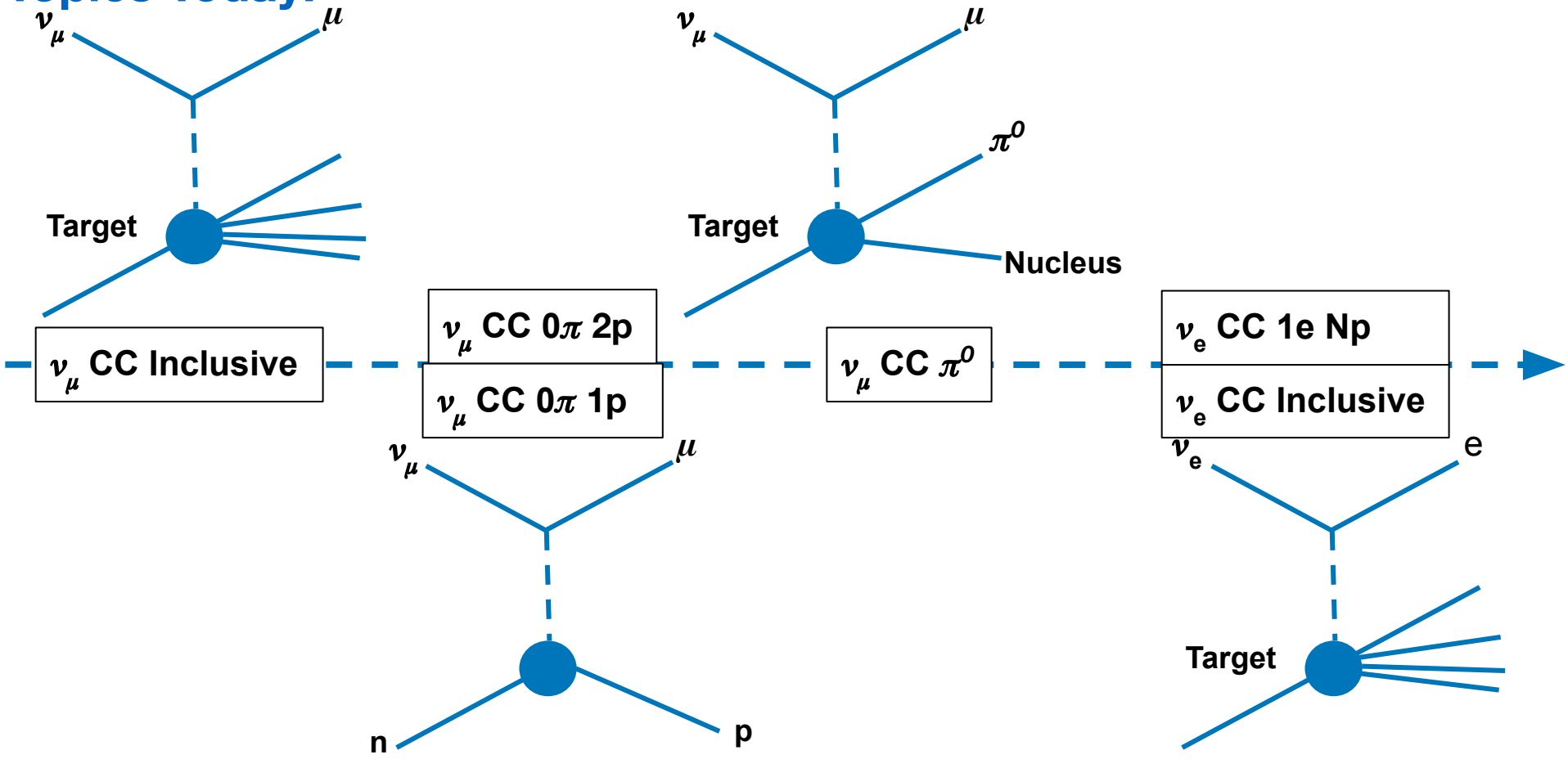
Image: T. Golan



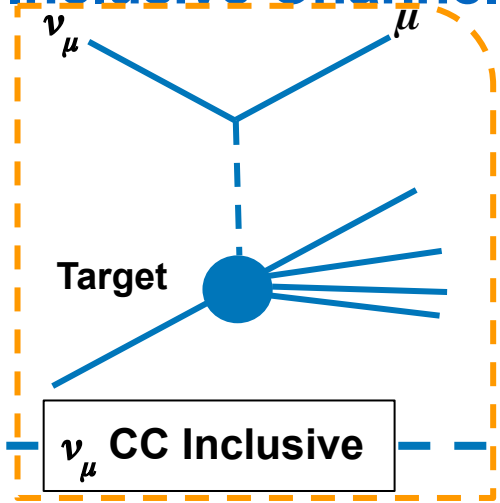
- Experiments need good interaction models
  - Predict final states on a wide range of energies with high precision
- Complex theory
  - Nuclear effects + many interaction processes
- Measurements essential to benchmark and help improve theory

Fermilab

Topics Today:

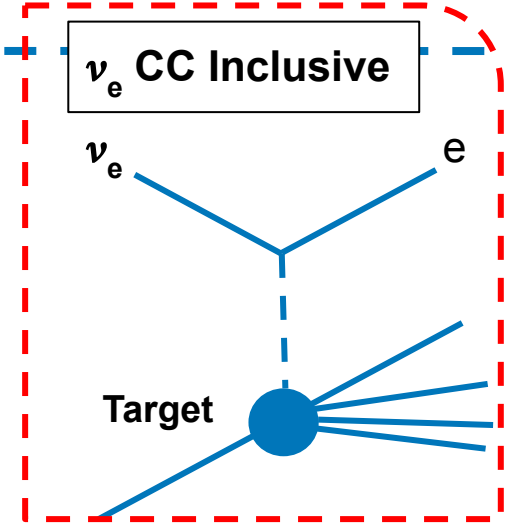


Inclusive Channels :



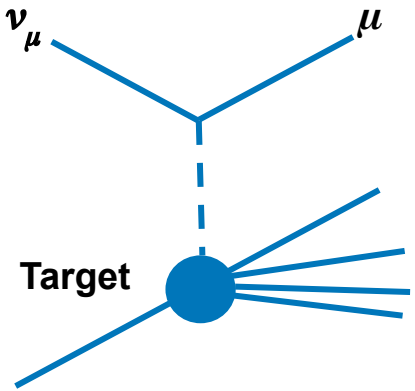
BNB

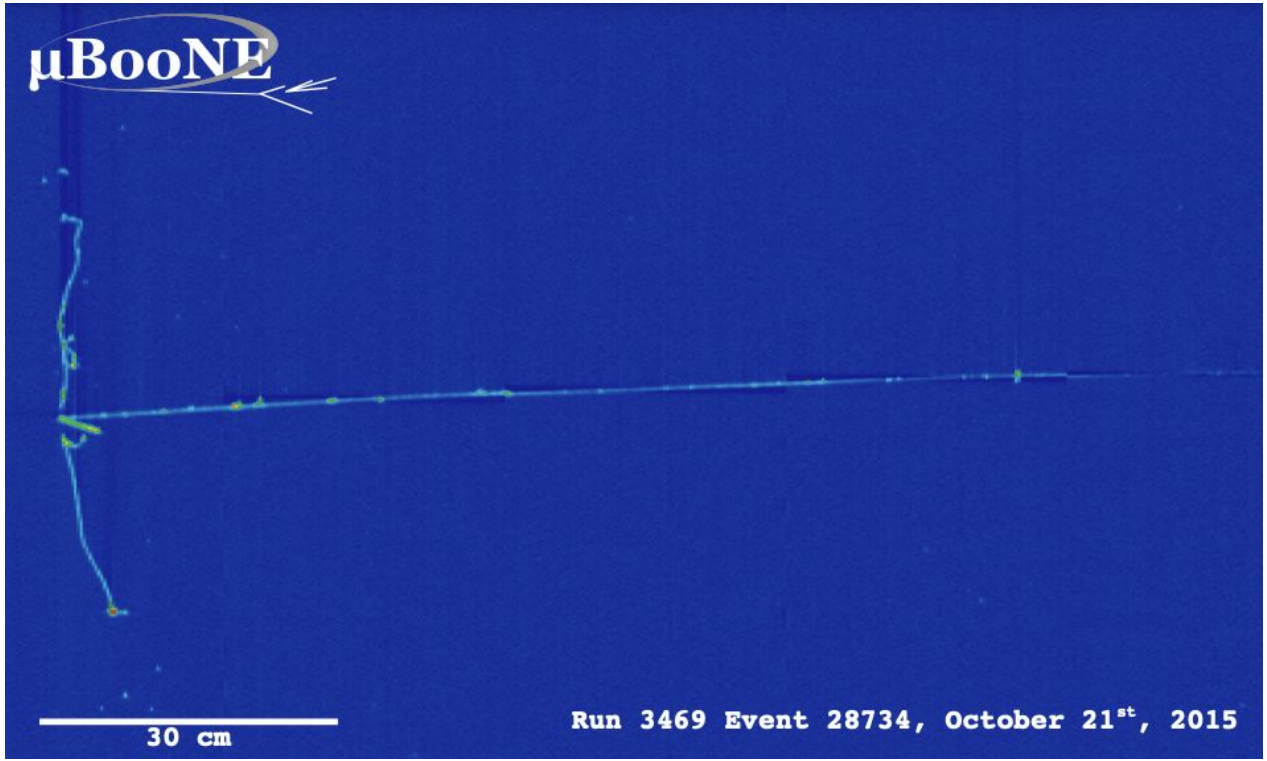
NuMI



Inclusive Muon Neutrino :

Final state → μ + anything else





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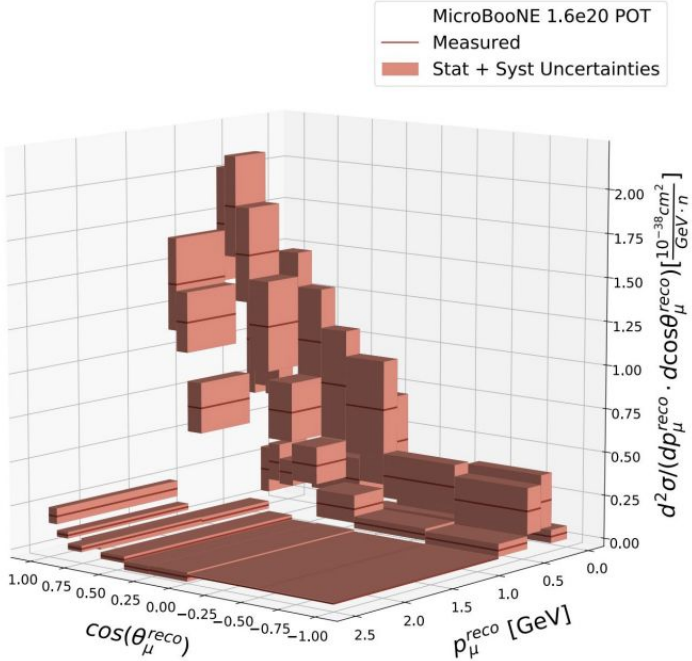
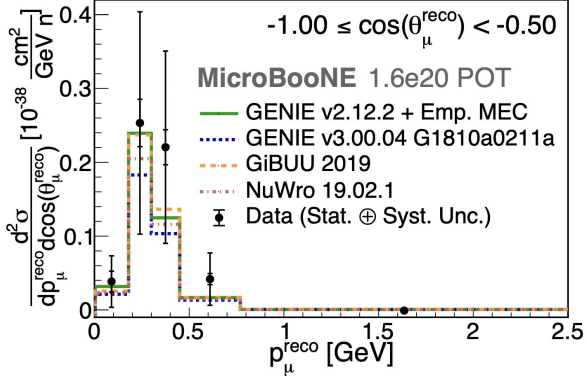
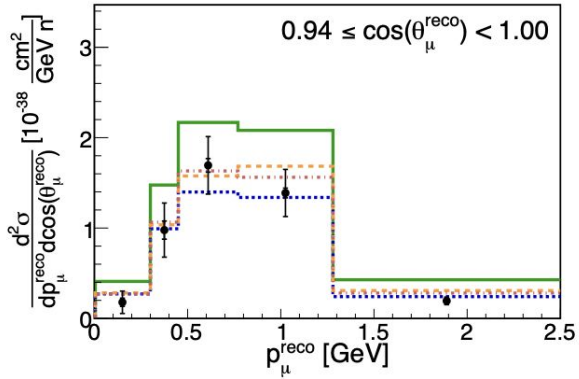
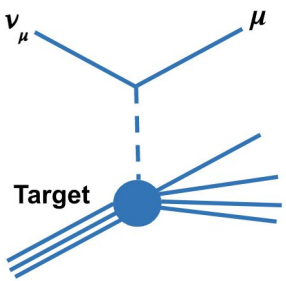
Inclusive Muon Neutrino :







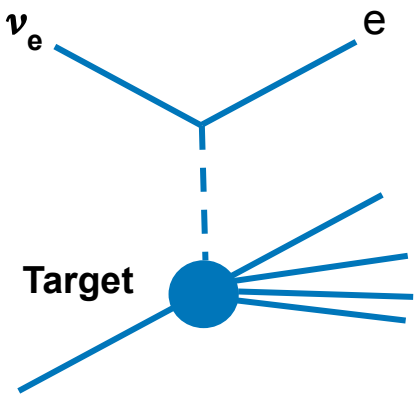


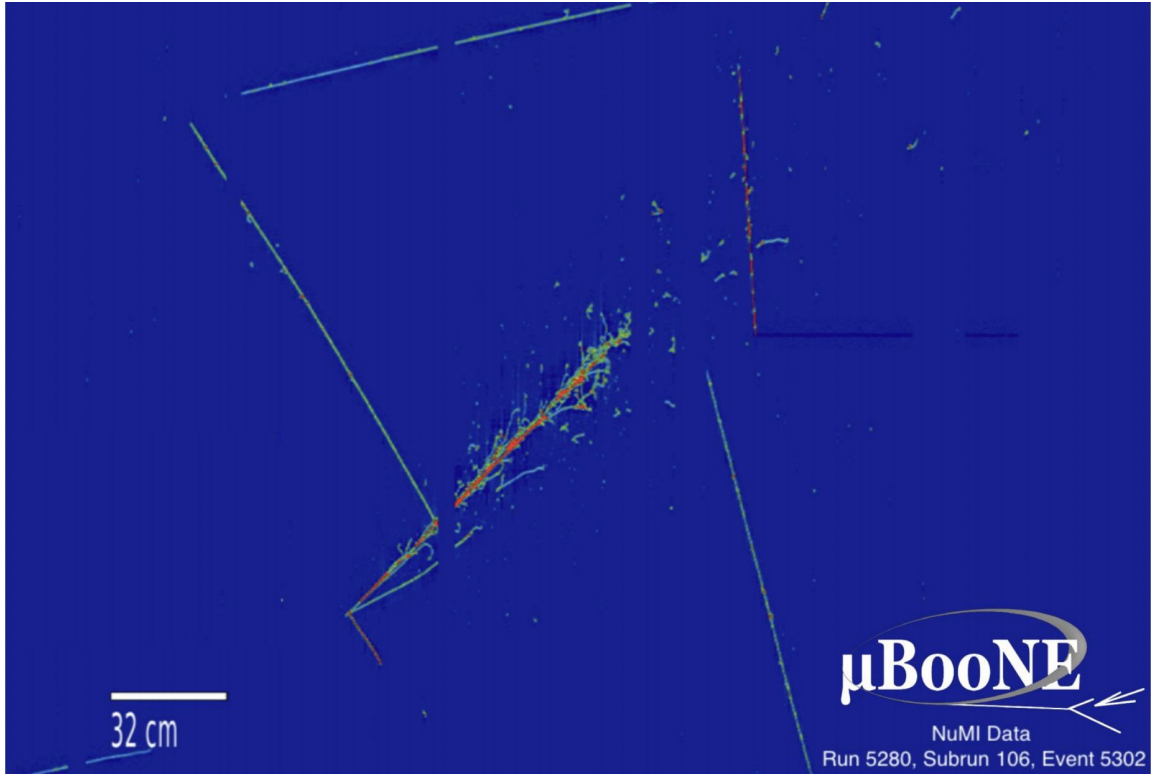
- **First inclusive cross-section measurement: double-differential in muon kinematics**
- **Highest stats measurement on argon to-date**

Upcoming - higher-statistics, higher-dimensionality measurements

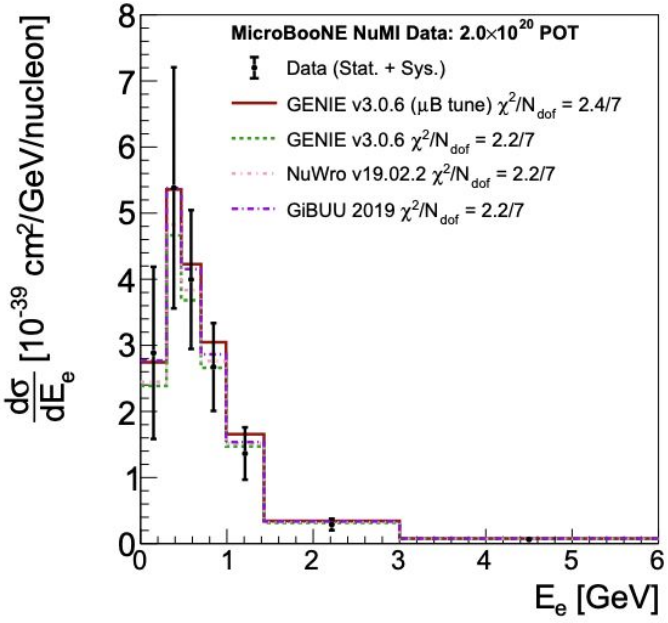
Inclusive Electron Neutrino:

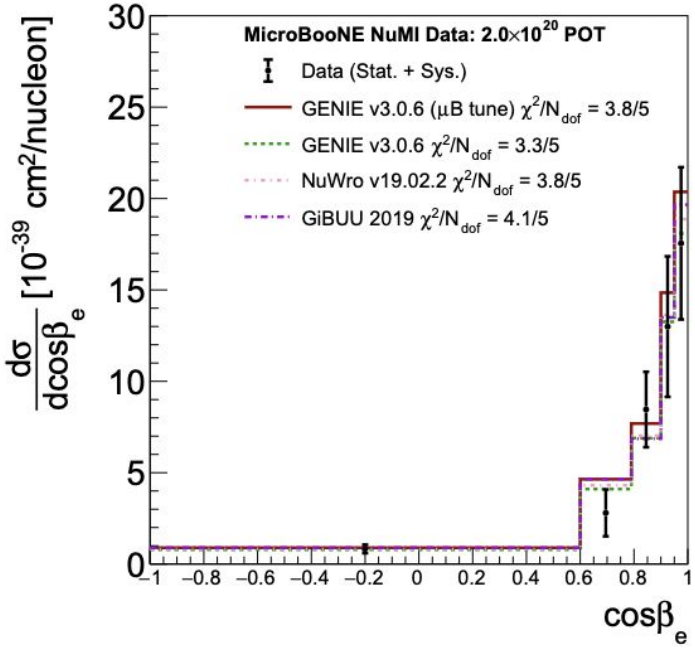
Final state → e + anything else

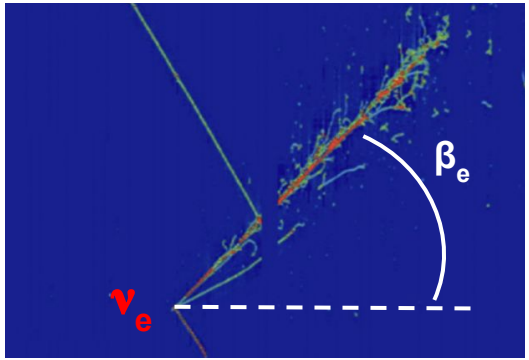




Inclusive Electron Neutrino @ NuMI:







Differential cross section in lepton angle and energy

Signal definition :

Electron + anything else in the final state

- **~243 selected events - Largest sample of ve -Ar interactions**
- **Good agreement with various generators**
- **In future -**
  - **More exclusive channels**
  - **Analyses with full dataset**

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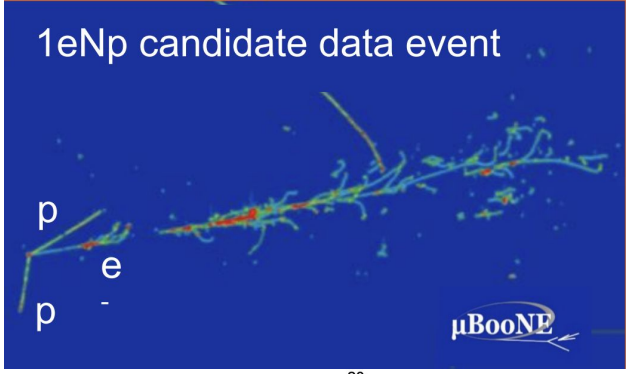
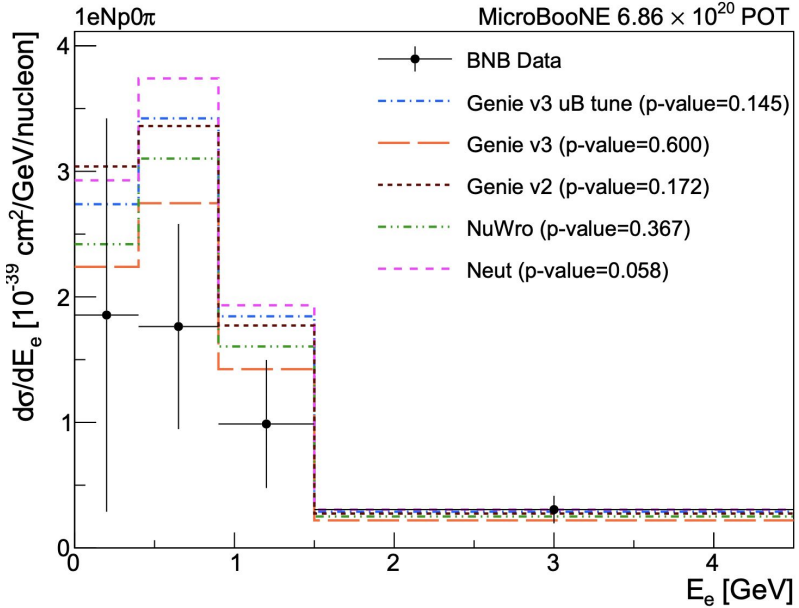
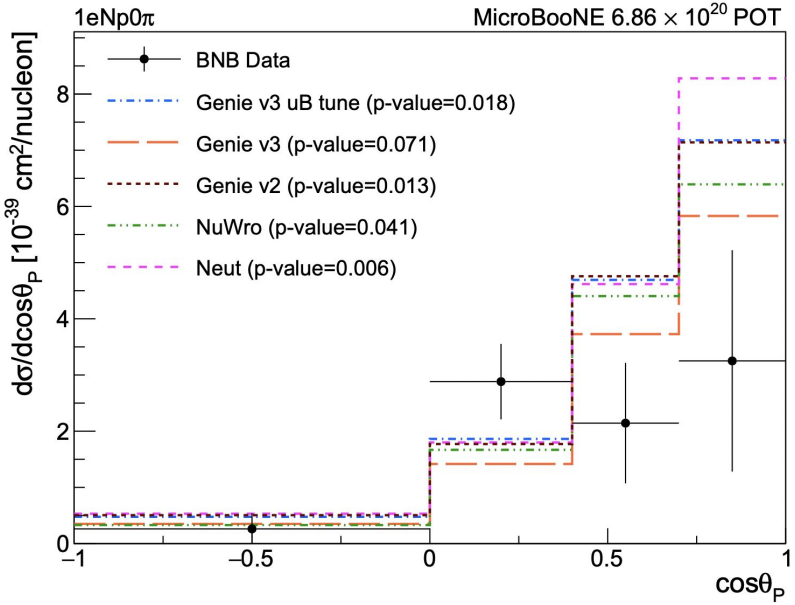
Exclusive Electron Neutrino @ BNB :

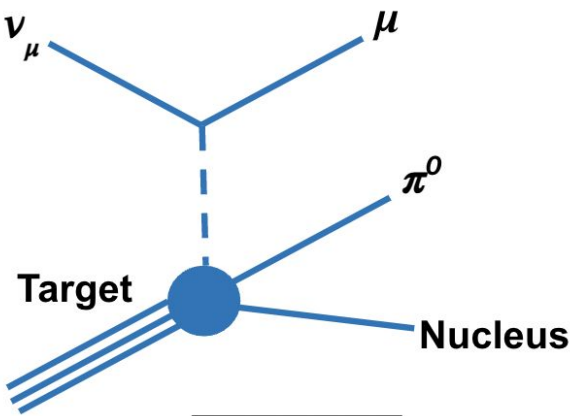
- **Differential cross section in electron and proton kinematic variables (MICROBOONE-NOTE-1109-PUB)**
- **Shed light on further tuning of generators**
  - **Improve ν_e prediction for future new physics searches**

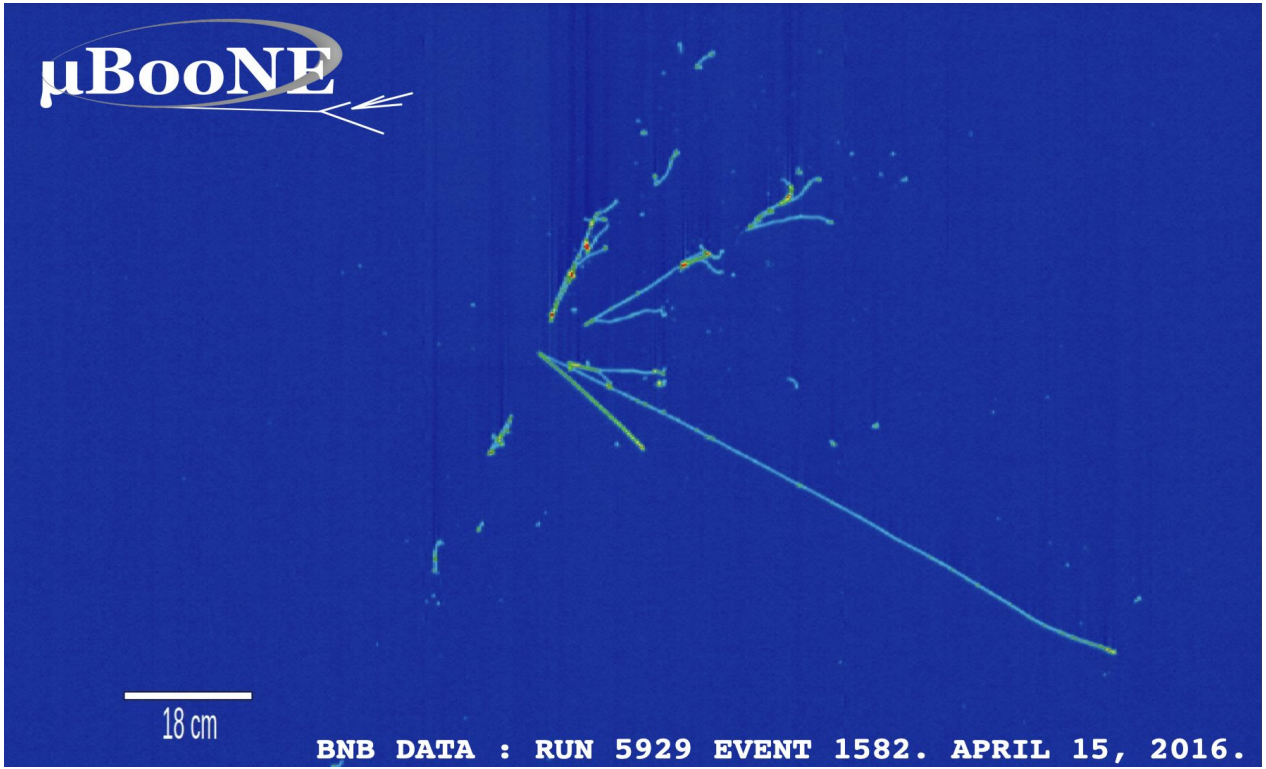






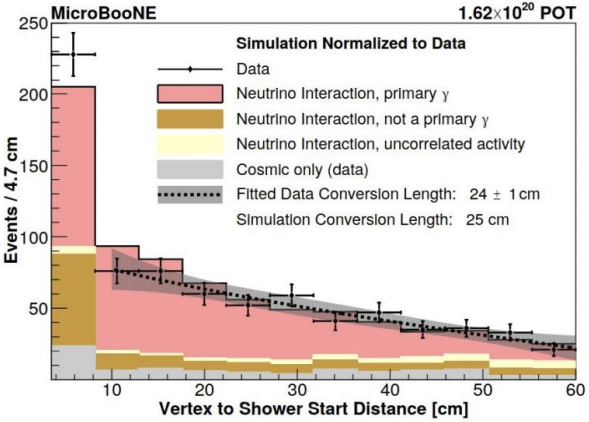
Exclusive Muon Neutrino Interactions : Neutral Pion

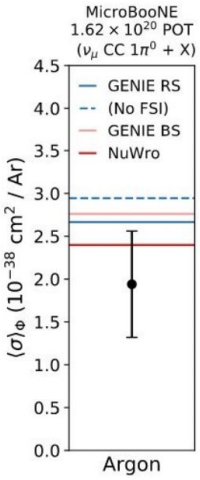


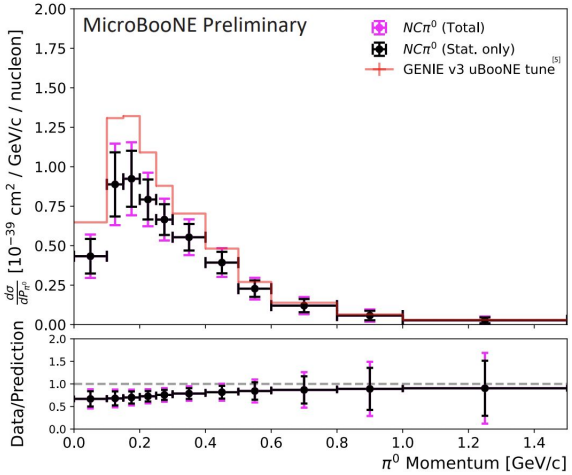


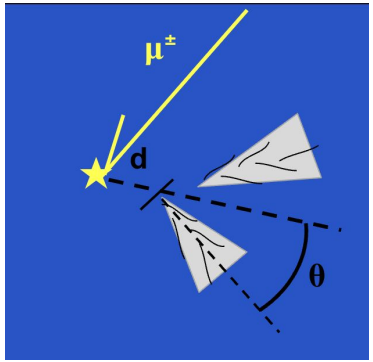
Exclusive Muon Neutrino Interactions : Neutral Pion

- **First measurement of flux averaged νμ-Ar CCπ0 cross section**



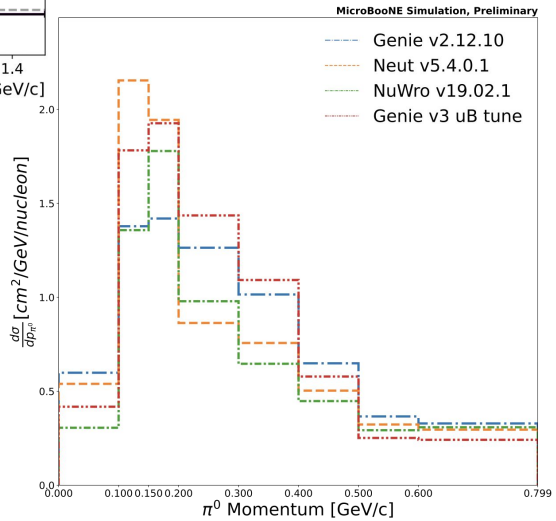




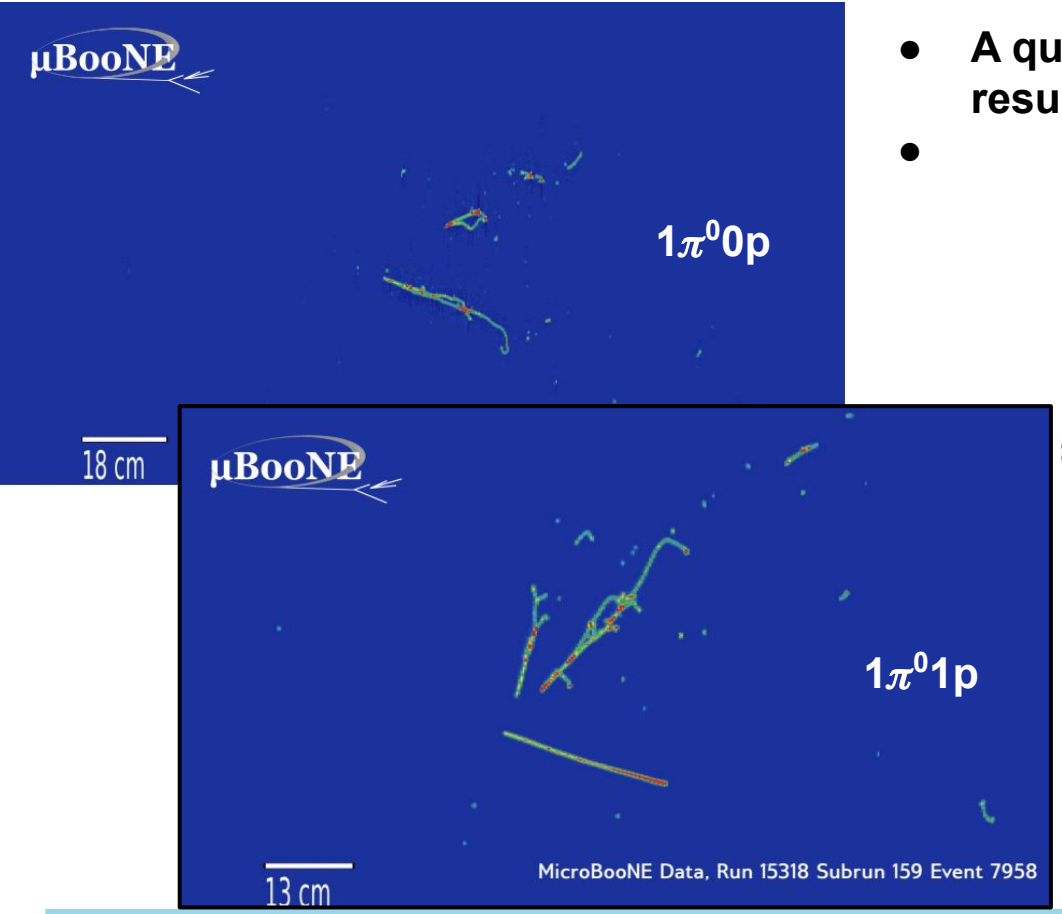


What's next -

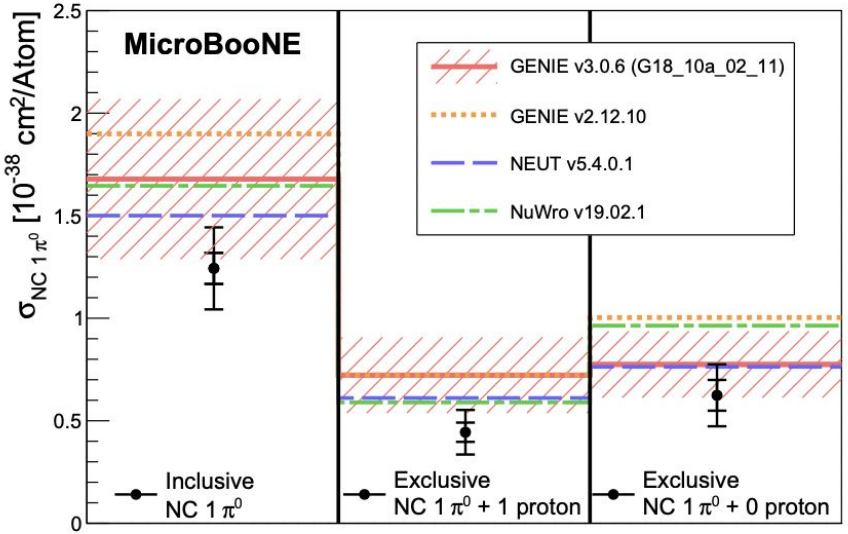
- **νμ CCπ0 differential**
- **νμ NCπ0 differential**
- **νμ CC/NC π0**



Exclusive Muon Neutrino Interactions : Neutral Pion



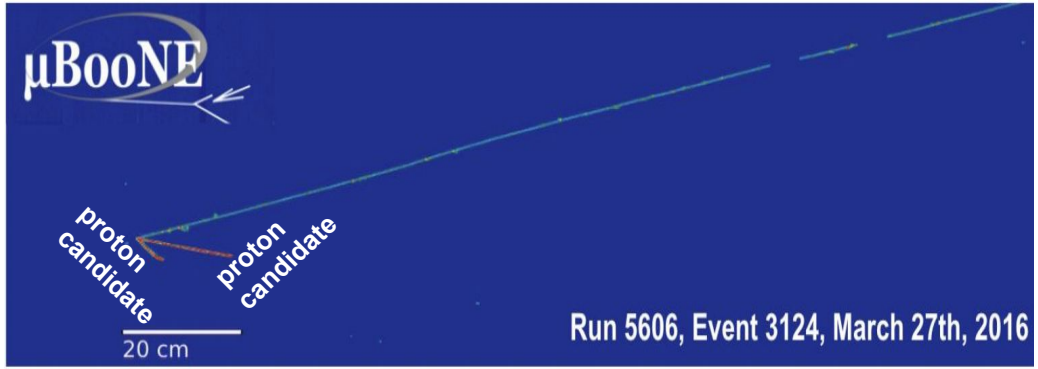
- A quick detour - νμ NCπ0 total cross section results [arXiv:2205.07943]
-



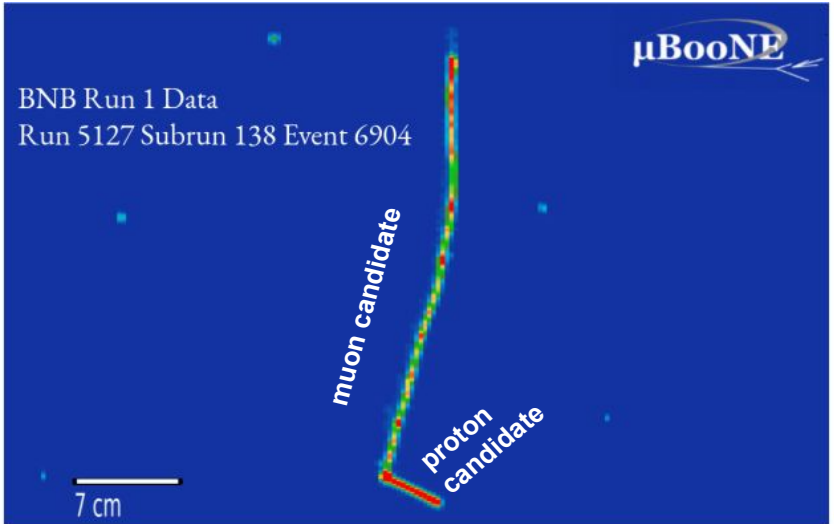
Deficits compared to models studied

Exclusive Final States - Protons:

ν_μ CC 0π 2p



CCQE-like



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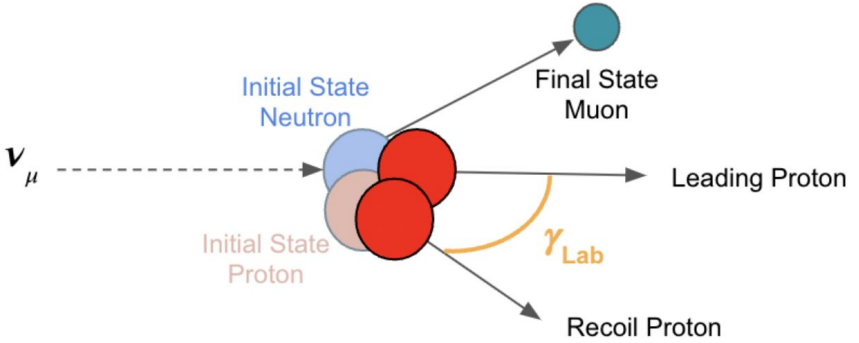
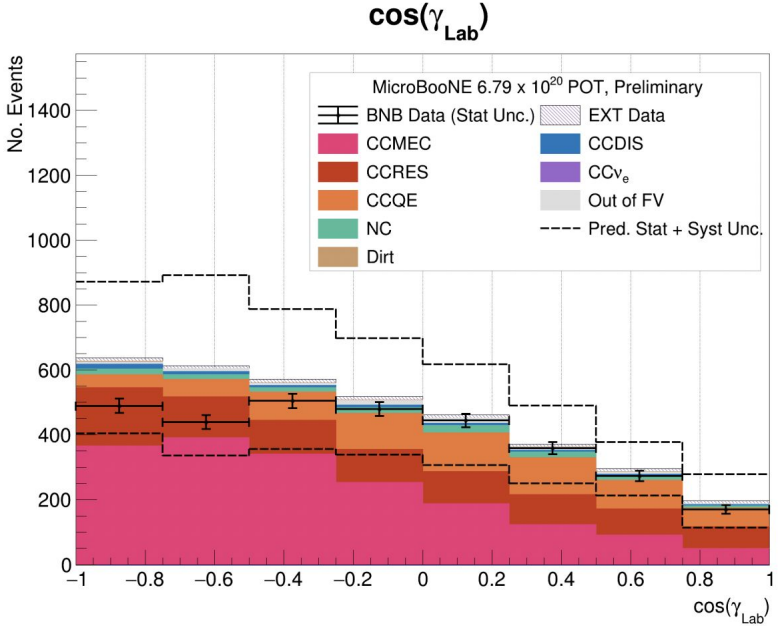
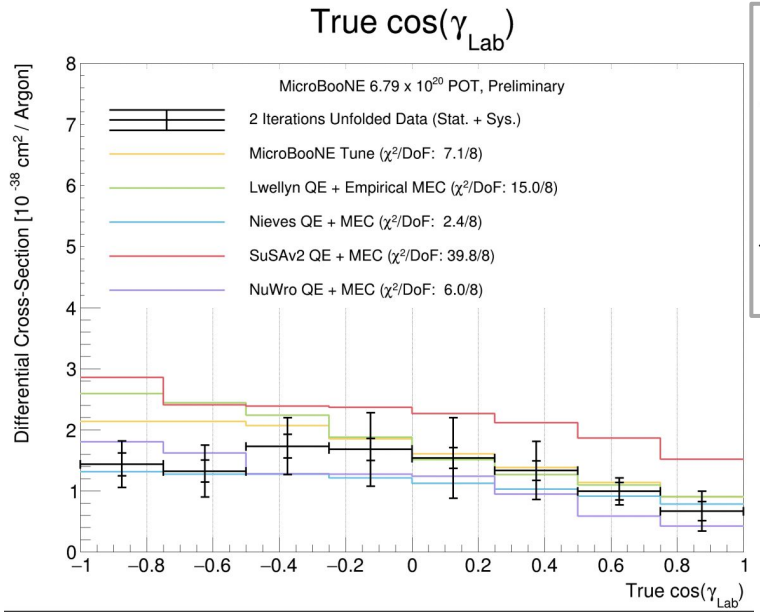
Exclusive Final States - Protons :

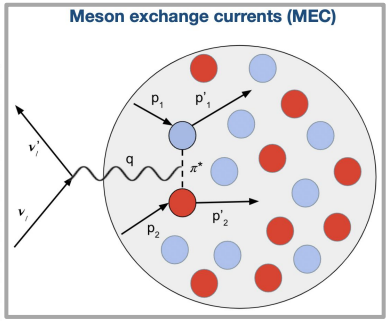
- **First neutrino-argon cross sections for an exclusive 2p final state [MICROBOONE-NOTE-1117-PUB]**

- **angle between protons in lab frame**
  - **Sensitive to modeling choices for MEC and QE**

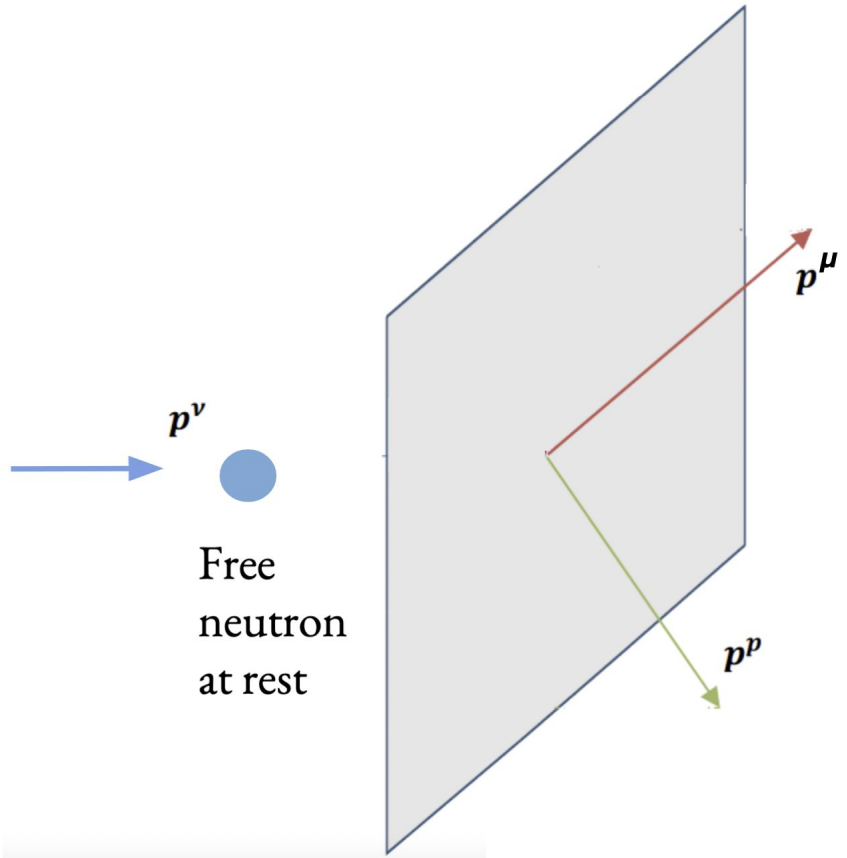








Transverse Kinematic Imbalance (TKI) :

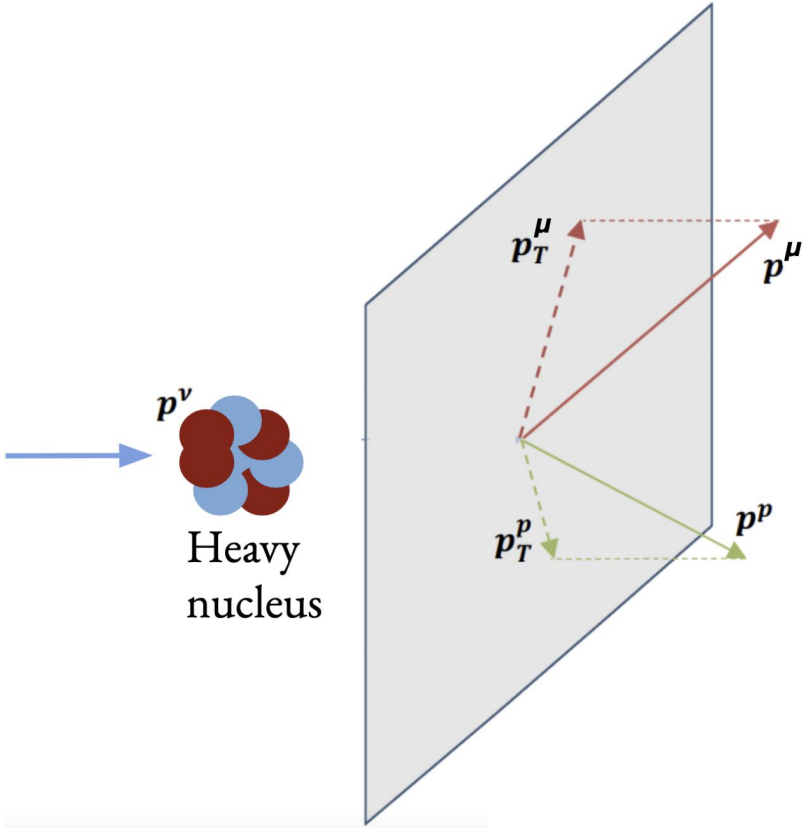


$$\delta p_T = \left| \mathbf{p}_T^\mu + \mathbf{p}_T^p \right| = 0$$

Transverse projections
trivially equal and opposite
(momentum conservation)

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

Transverse Kinematic Imbalance (TKI) :



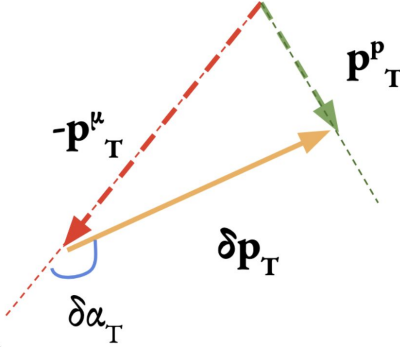
$$\delta p_T = \left| \mathbf{p}_T^\mu + \mathbf{p}_T^p \right| > 0$$

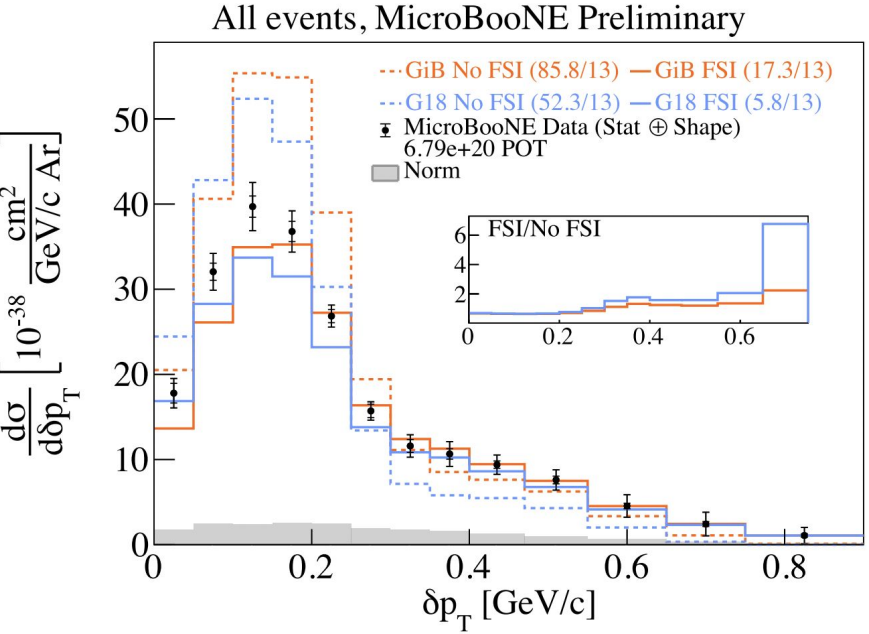
Imbalance due to initial nucleon motion and other nuclear effects

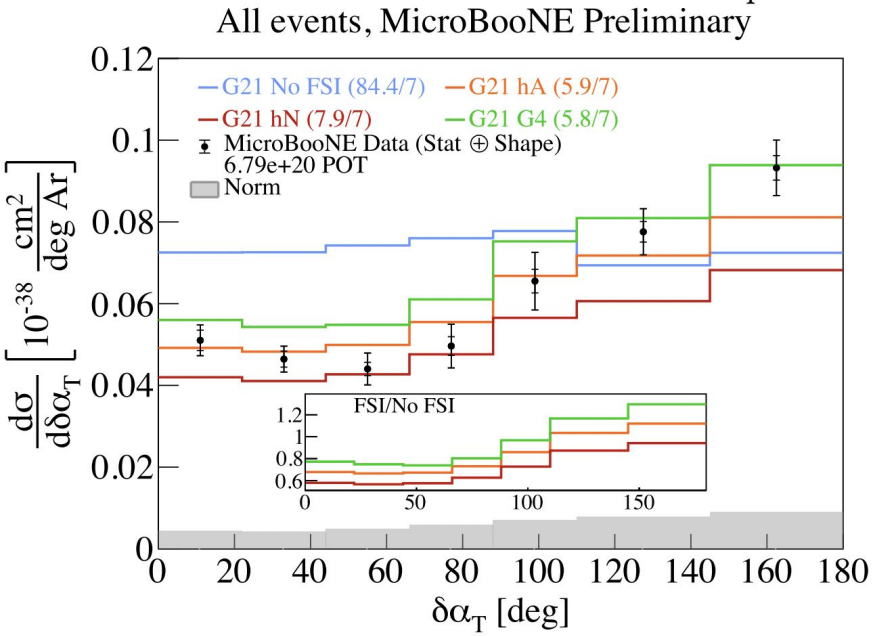
Adapted from S. Dolan, “Exploring nuclear effects with transverse imbalances”

Transverse Kinematic Imbalance (TKI) :

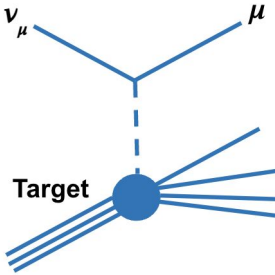
- **First neutrino-argon differential cross sections in TKI variables (MICROBOONE-NOTE-1108-PUB)**
- **Sensitive to details of proton FSI modeling**



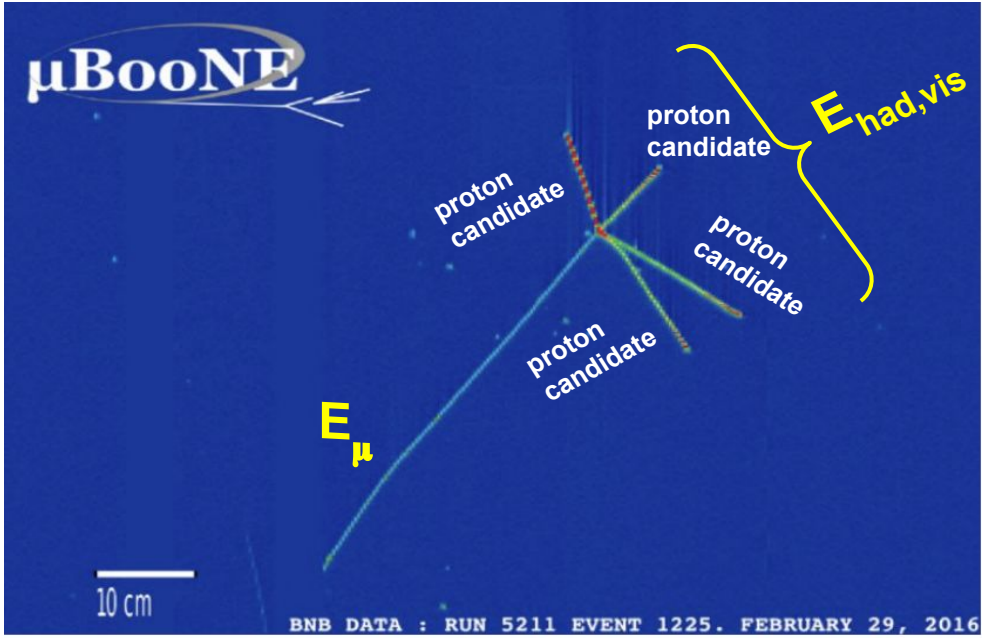




Energy Dependent Inclusive Muon Neutrino Cross Section:

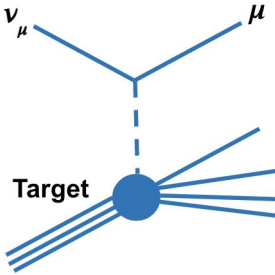


$$E_\nu = E_\ell + E_{had,vis} + E_{had,miss}$$



- Oscillation measurements require understanding of energy-dependent event rates
- Modeling of the undetected missing hadronic energy
- Overcome the challenge by leveraging LArTPC's simultaneous measurements of lepton energy and visible hadronic energy

Energy Dependent Inclusive Muon Neutrino Cross Section:



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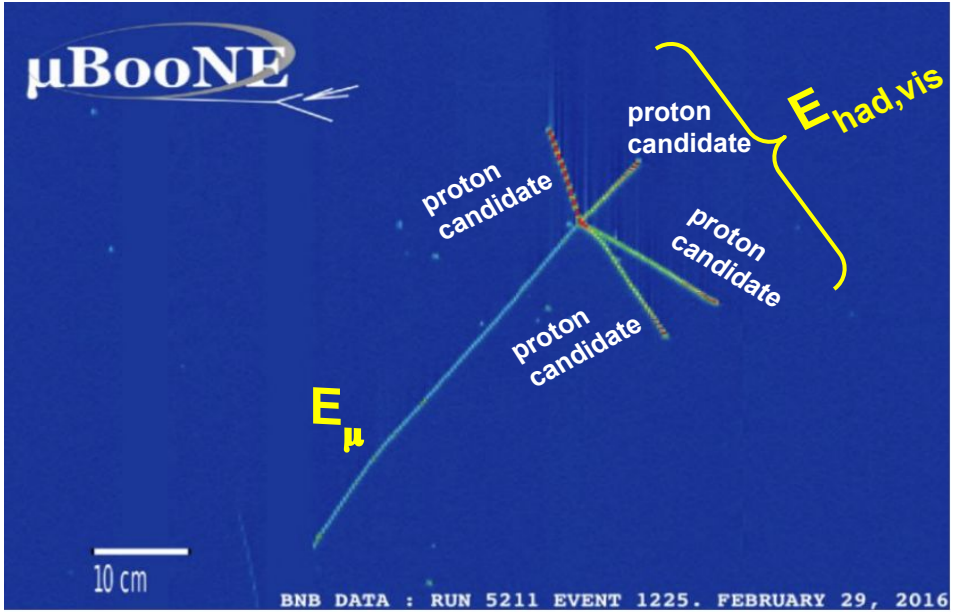

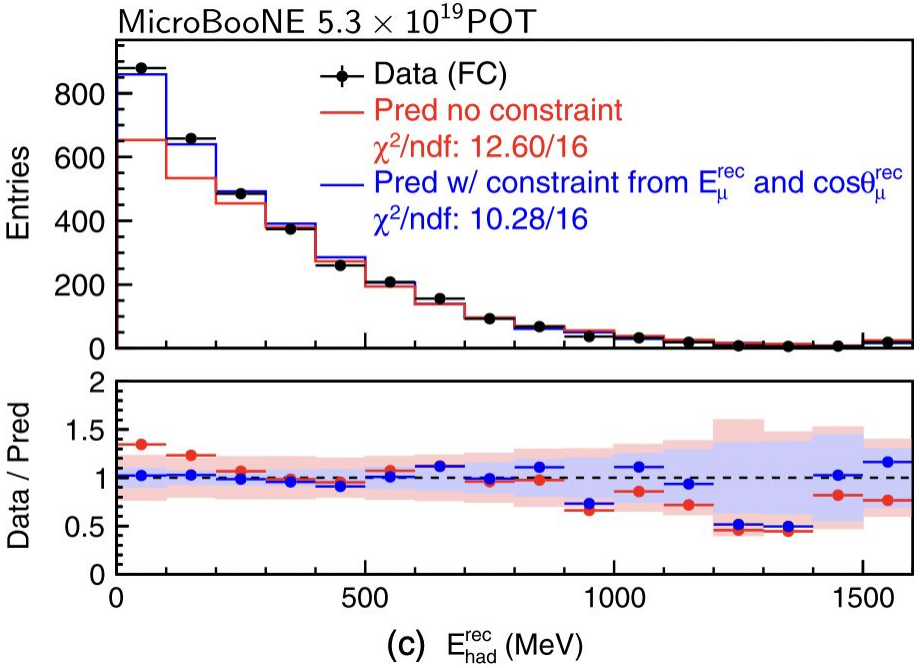

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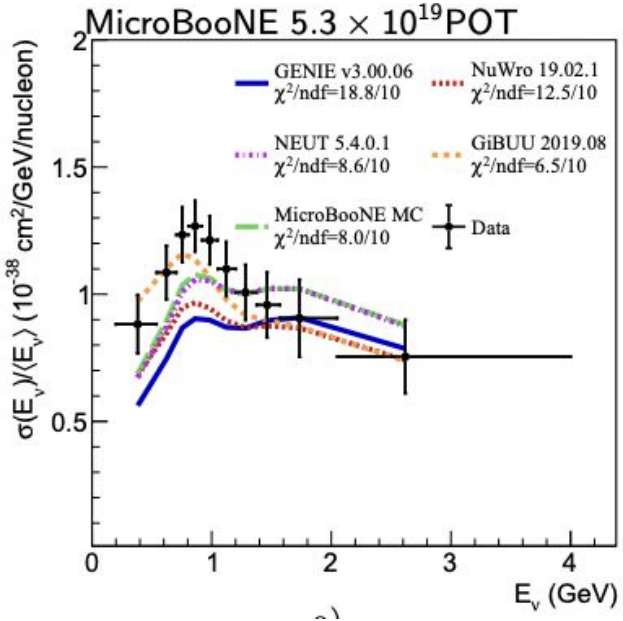

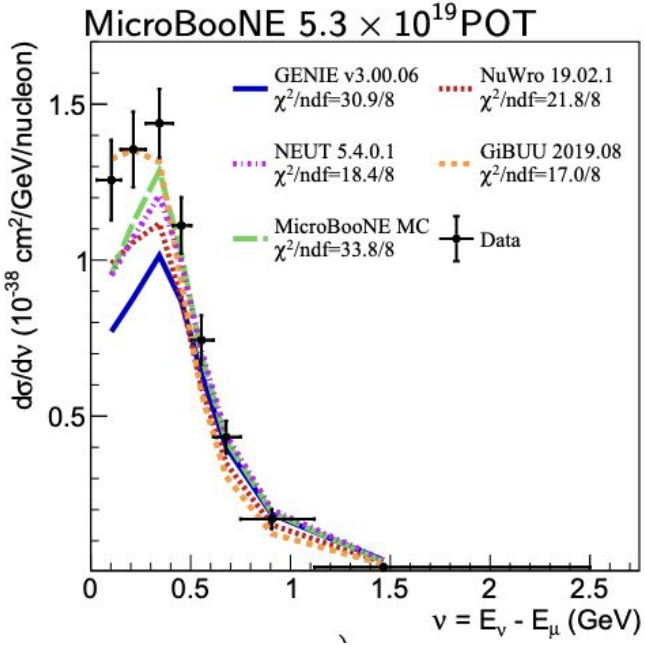

- **Inclusive cross-section looking specifically at hadronic system** [Phys. Rev. Lett. 128, 151801]
- **measured ν_μ CC differential cross section per nucleon as a function of energy transfer dσ/dν**

Next Gen Measurements at MicroBooNE :

ν_μ Inclusive & Exclusive Measurements

- ν_μ CC π^0 differential
- ν_μ CC/NC π^0
- ν_μ CC1π^+
- 2D ν_μ CC 0πNp
- 2D ν_μ CC 0π1p
- ν_μ 2D CC incl.
- ν_μ 3D CC incl.

+ Many more

ν_e Exclusive Measurements

- ν_e CC 0π
- ν_e CC 1eNp
- NuMI ν_e CC Np
- NuMI ν_e / ν_μ
- NuMI ν_e -bar

Other Measurements

- NuMI Λ production
- MeV Scale Physics

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Next Gen Cross Section Measurements at MicroBooNE :

- **Multi differential cross section measurements to explore phase space for better modeling**
- **Directly test and improve GENIE by continuing our tuning effort**
- **Expand new ideas that are more sensitive to mismodelling (TKI, Conditional constraint procedure, etc.)**
- **Reduce uncertainties through ratio/simultaneous measurements, potentially using both beams**

Thank you!

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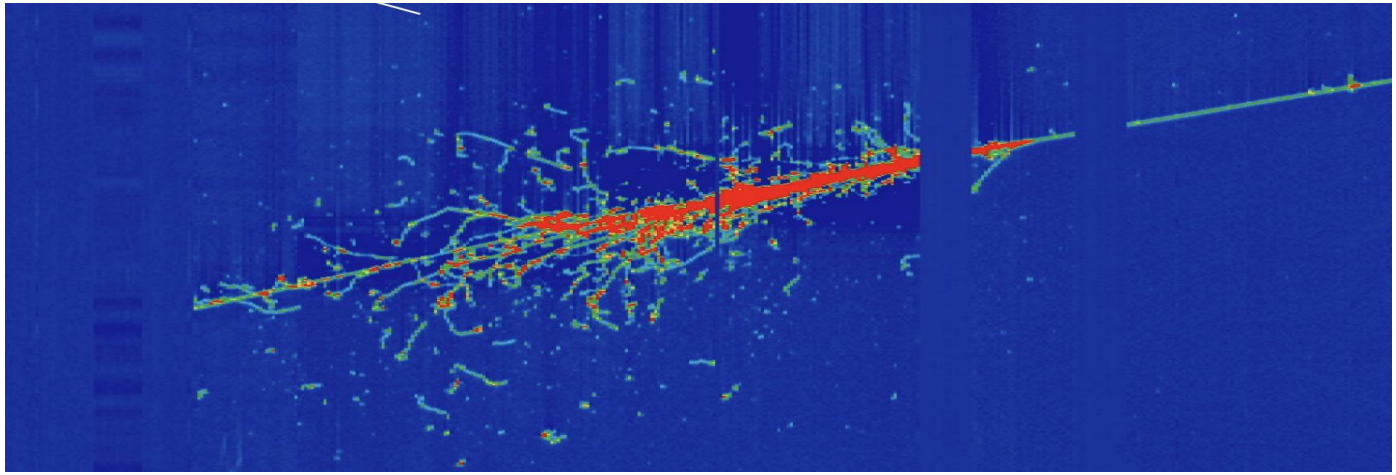
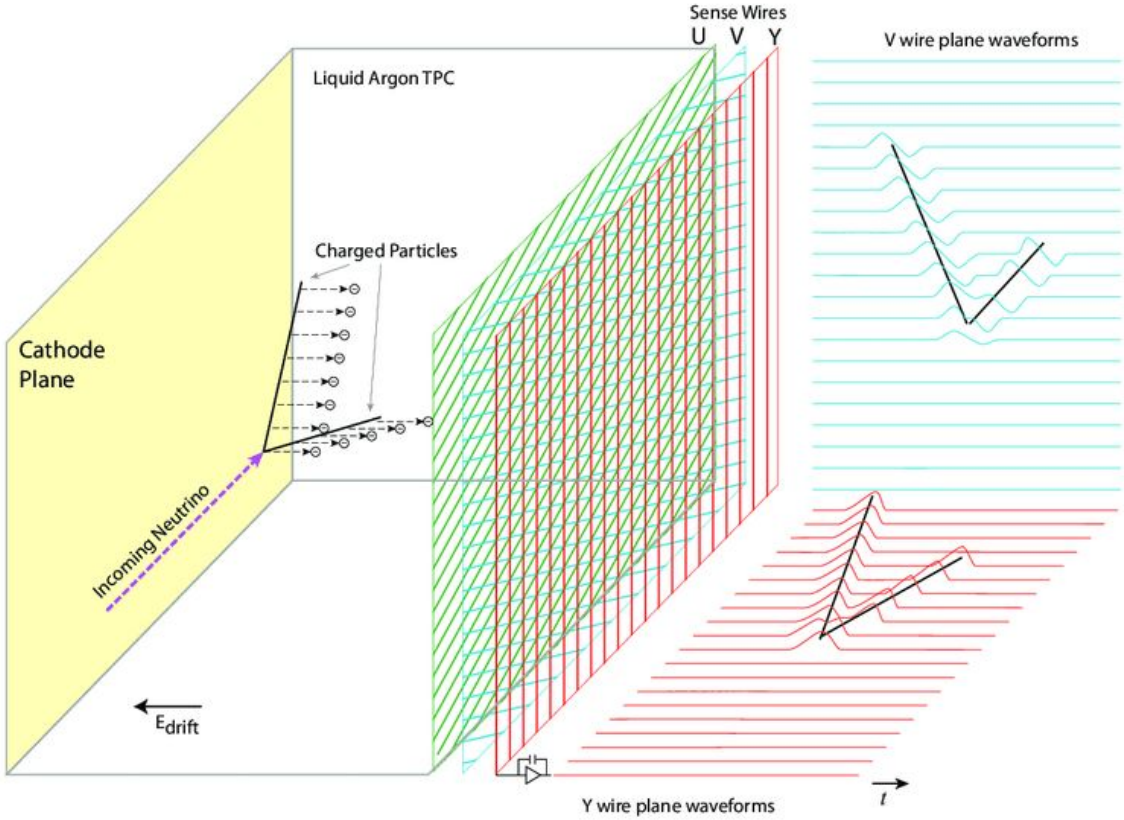
Conclusion

- Largest sample of neutrino-argon interactions available to date
- Rich neutrino interaction physics program at MicroBooNE
  - Crucial for future LArTPC experiments - SBN and DUNE
- Cross section results will help improve v-Ar interactions modelling for the future



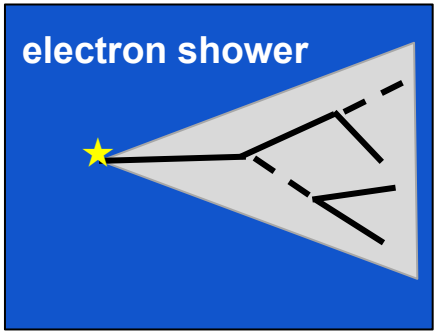
Backup

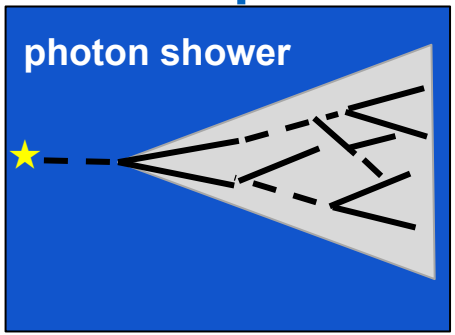
The Crux of LArTPCs

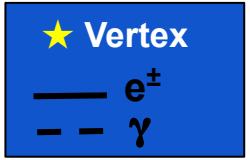


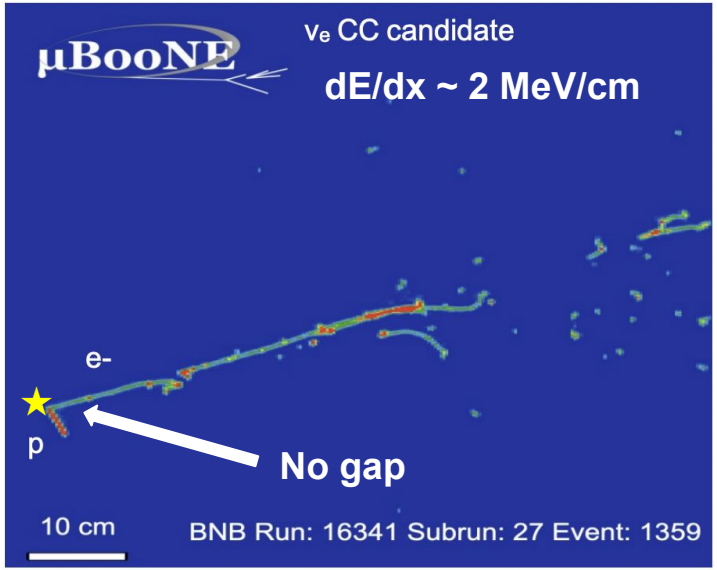
- **Excellent particle imaging detector**
- **mm scale spatial resolution**
- **Light signal by PMTs (PDS)**
  Current (Future) generation LArTPCs

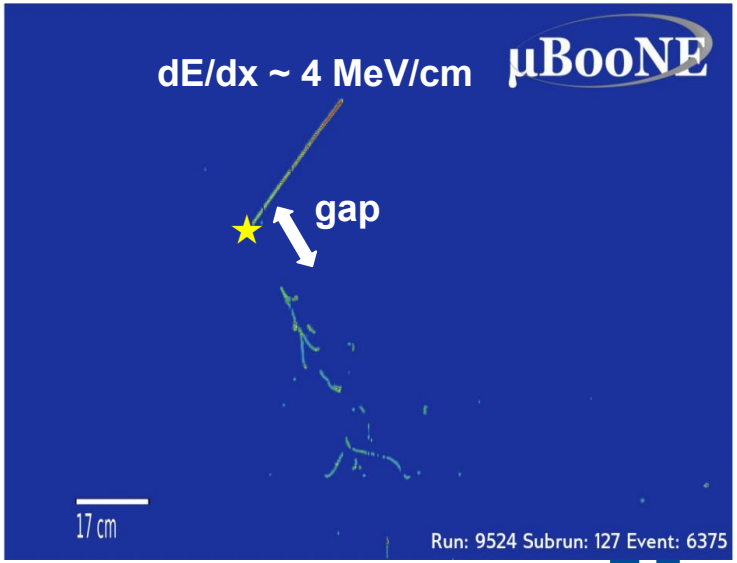
Improvements with LArTPCs - Electron Photon Separation











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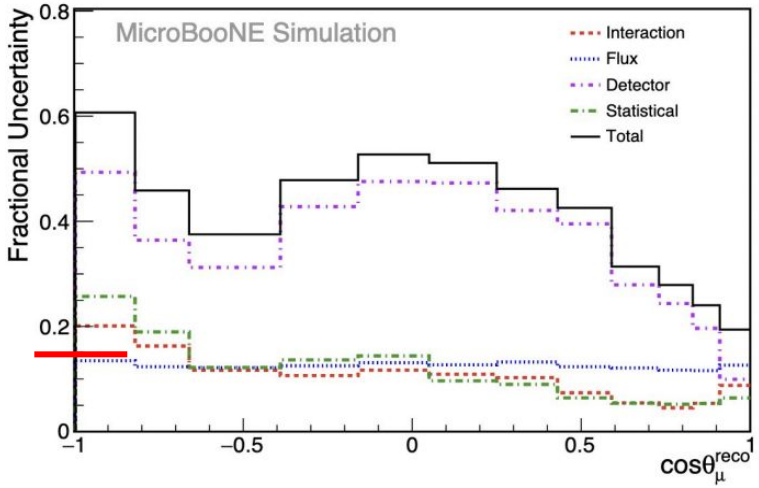
Systematic Uncertainties :

Comparison of systematic uncertainty budget between similar analyses [CC 1μNp0π]

Detector simulation / Reconstruction

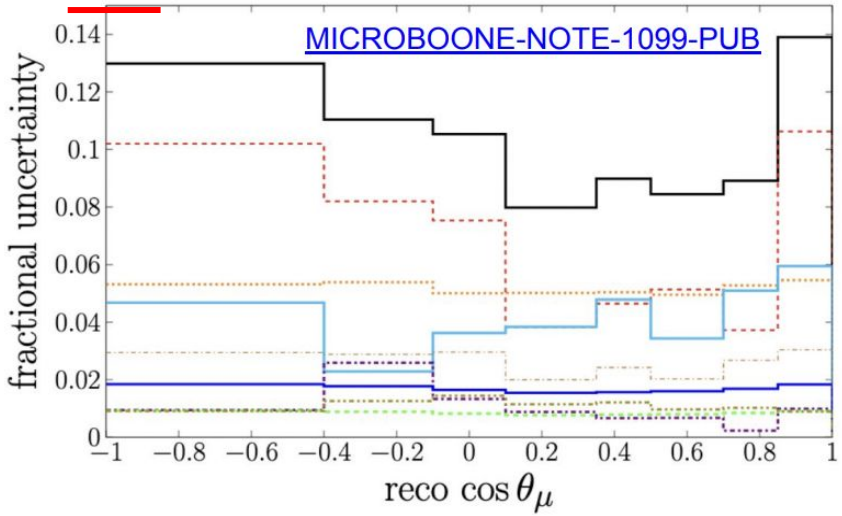
Past

Phys.Rev.D 102 (2020) 11, 112013



Current

$0.30\ \mathrm{GeV}/c \leq \mathrm{reco}\ p_\mu < 0.38\ \mathrm{GeV}/c$



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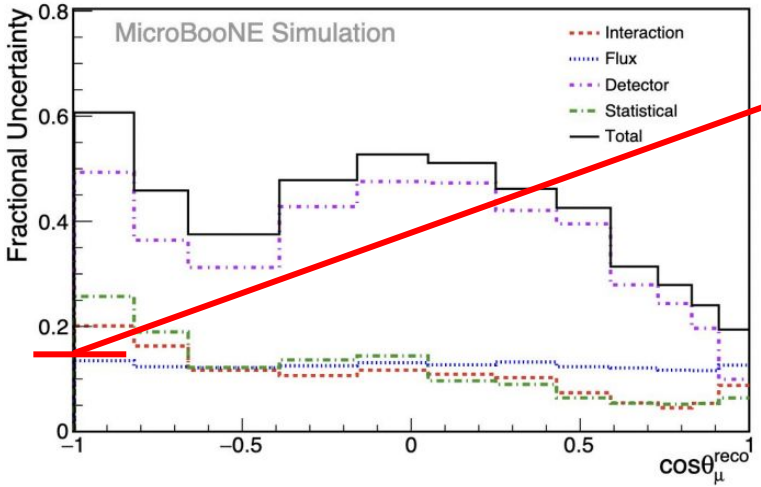
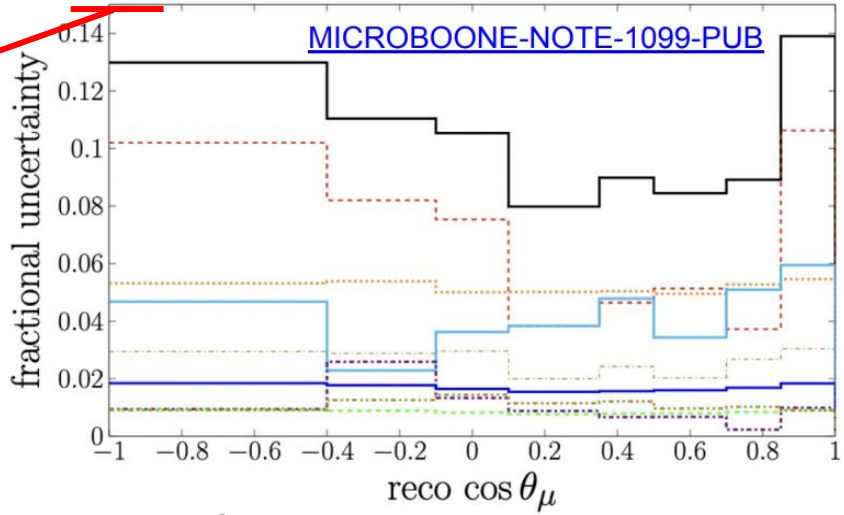


$0.30\ \mathrm{GeV}/c \leq \mathrm{reco}\ p_\mu < 0.38\ \mathrm{GeV}/c$



- **Big effort to improve detector modeling to reduce impact of systematic uncertainties (arXiv:2111.03556)**
- **As statistics rapidly increase - xsec are still systematic dominated**

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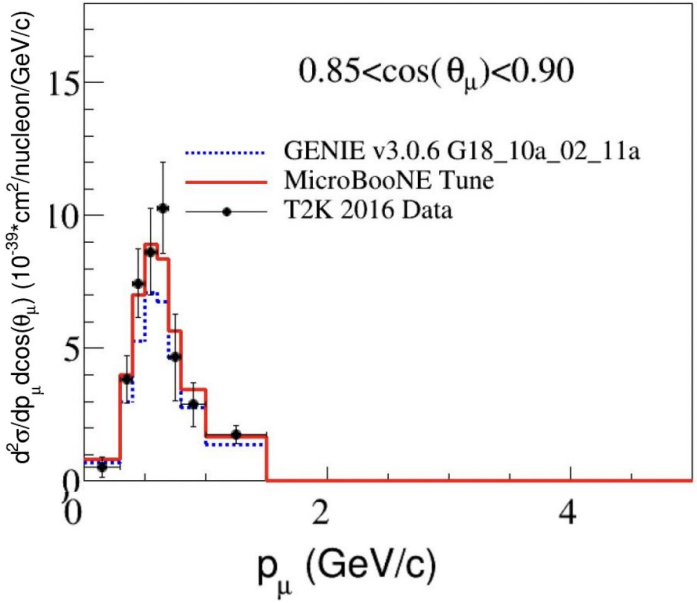
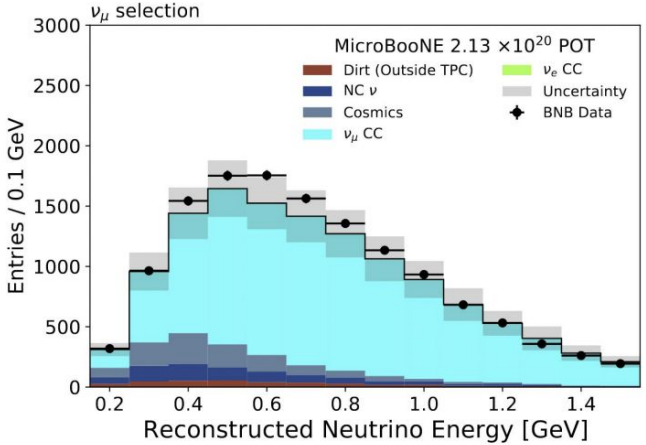
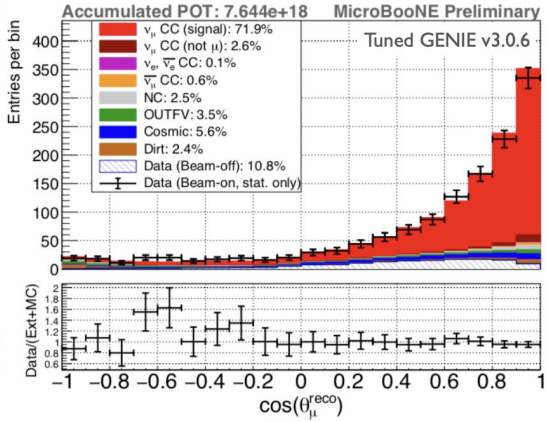
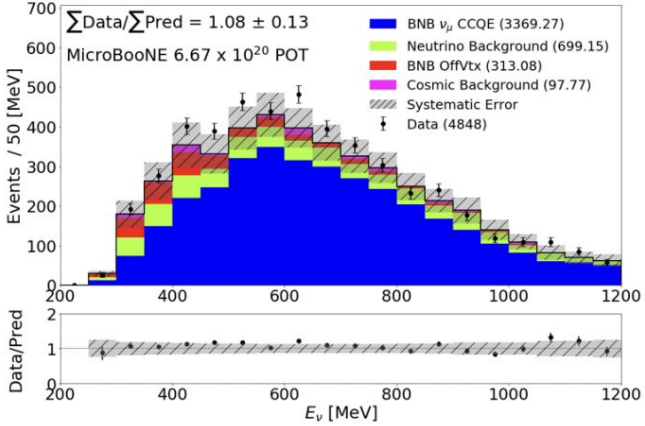
Genie Tune :

- Tuned to T2K CC0π cross-section data
- J-PARC beam used by T2K similar to BNB flux
- 4-parameter fit for CCQE and MEC processes

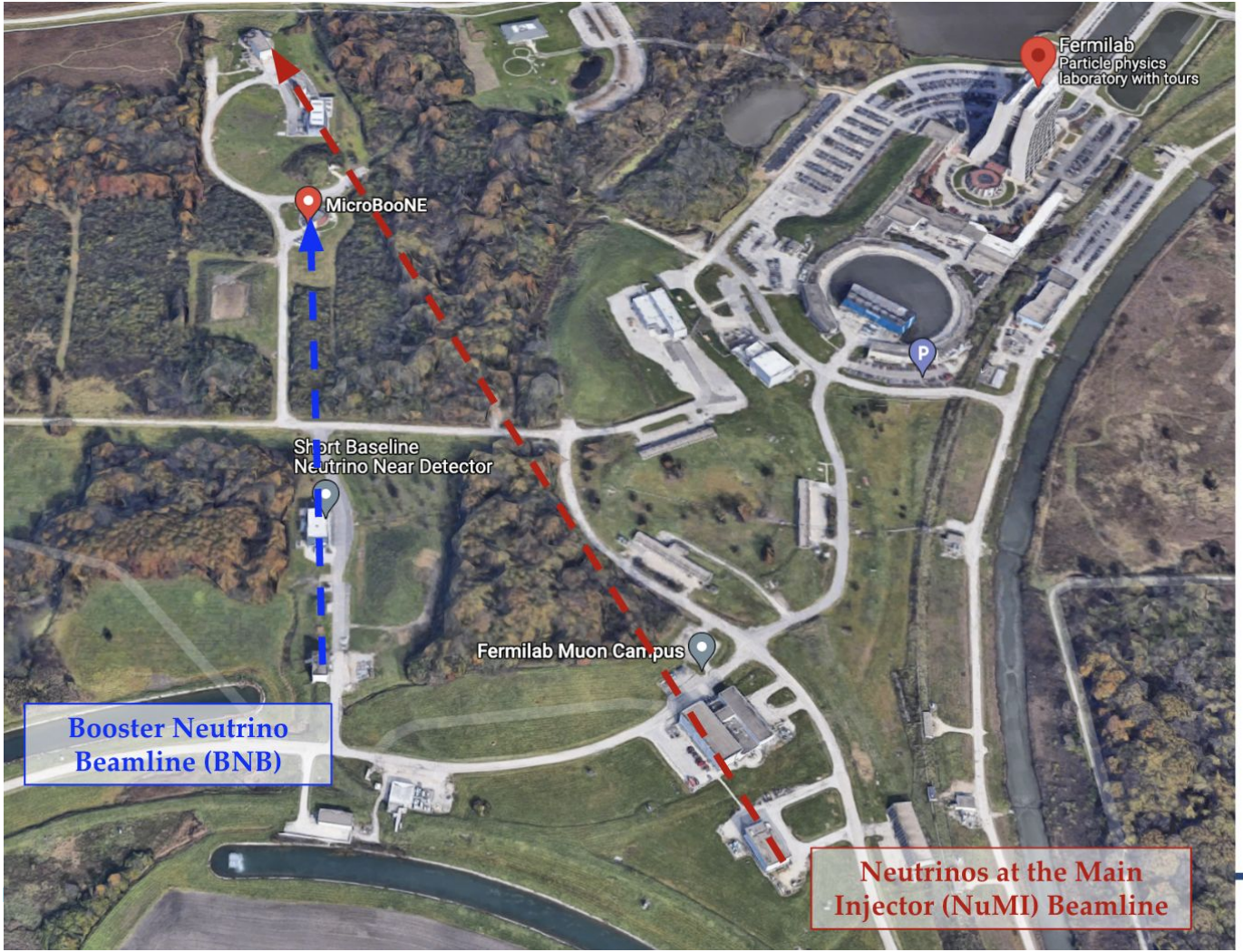








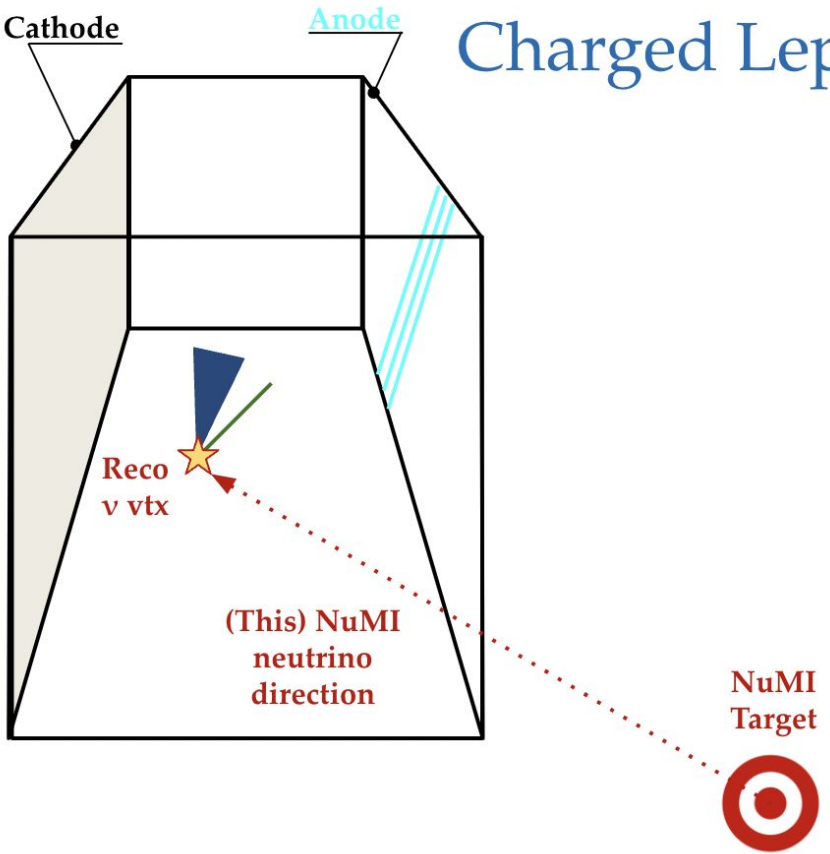
Examples highlight achieved level of data/MC agreement for νμ CC inclusive, CCQE-like events



Where are the ν_e & $\bar{\nu}_e$ coming from in NuMI ?

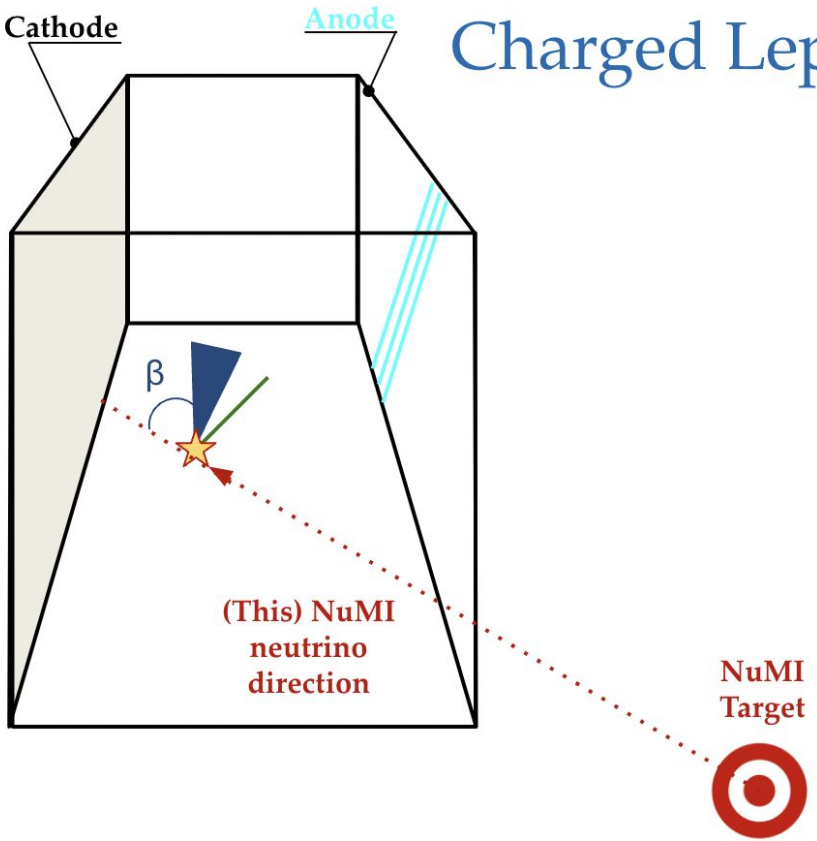
The ν_e and $\bar{\nu}_e$ flux > 60 MeV is dominated by decays from unfocused kaons at the target.

Charged Lepton Angle Reconstruction



1. Assume all electron neutrinos come from the NuMI target.
2. Reconstruct position of interaction vertex.
3. Reconstruct (this) neutrino direction
   → within 3 degrees from true direction for 95% of selected ν_e

Charged Lepton Angle Reconstruction



1. Assume all electron neutrinos come from the NuMI target.
2. Reconstruct position of interaction vertex.
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   → within 3 degrees from true direction for 95% of selected ν_e

4. Calculate lepton angle **β**

0.01 < **cosβ** resolution < 0.05
Only 0.2% of showers are mis-reco in the opposite direction.