MicroBooNE cross-sections from an oscillations perspective

NUFACT 2017

Xiao Luo, Yale University

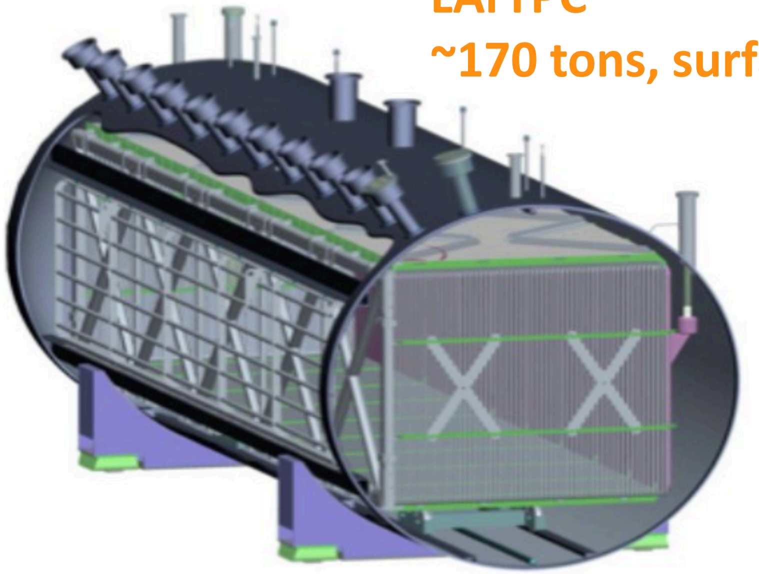
On behalf of MicroBooNE collaboration

MicroBooNE and FNAL neutrino beam

Fermilab

Booster Neutrino Beam

(BNB)

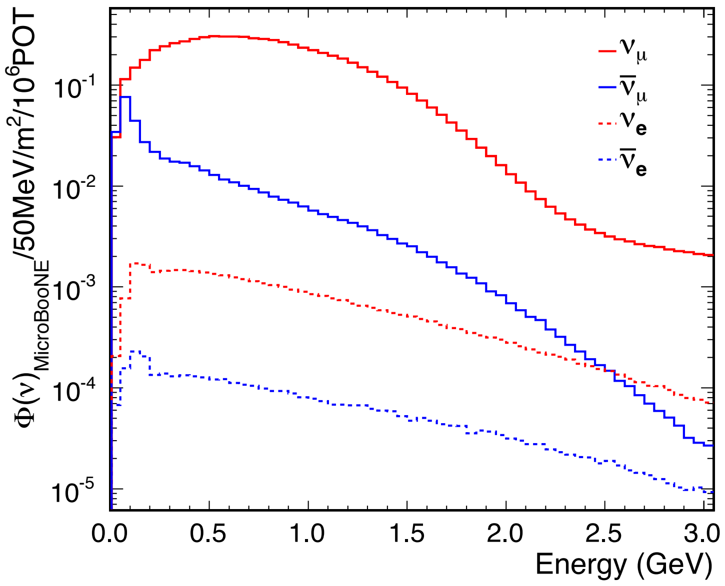


LArTPC

~170 tons, surface detector

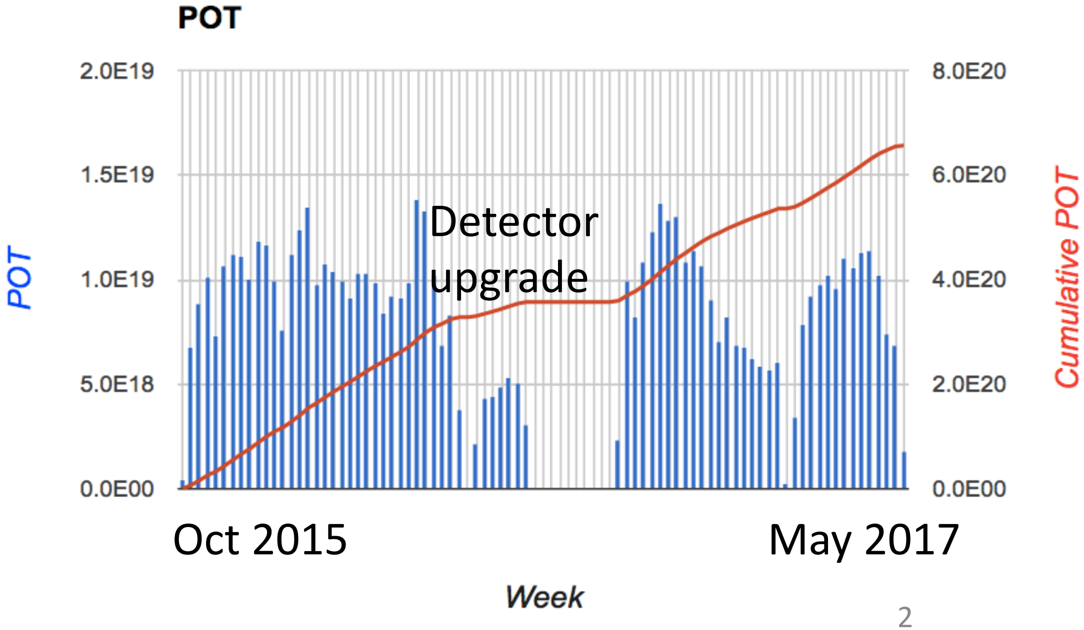
Collecting BNB Neutrino Data for 17 months, ~ 6.5e20 POT collected.

~ 170 k ν_μ CC interactions

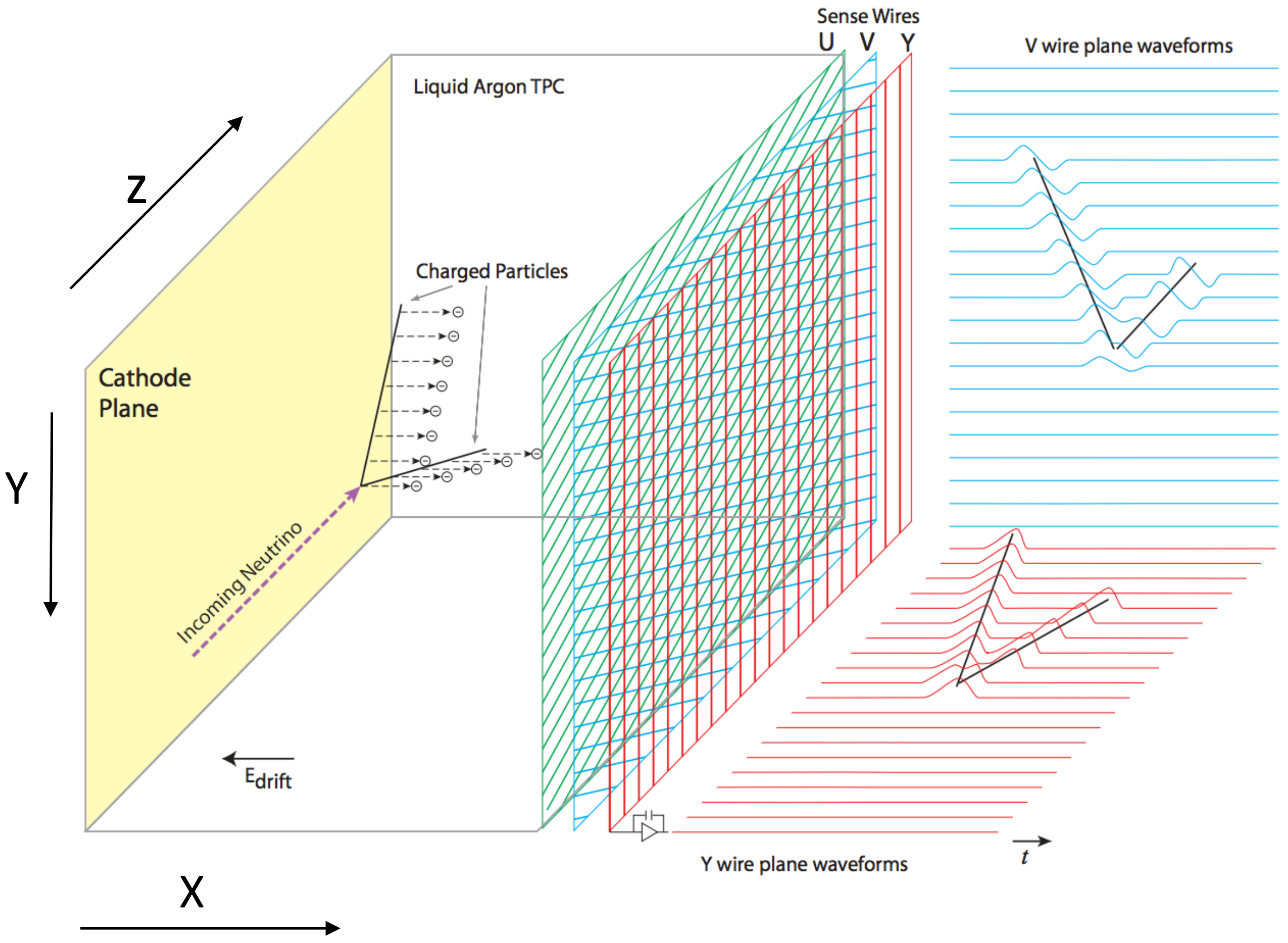


BNB Neutrinos:

- Mainly ν_μ
- ν_μ energy (~700MeV)
- <1% ν_e contamination.

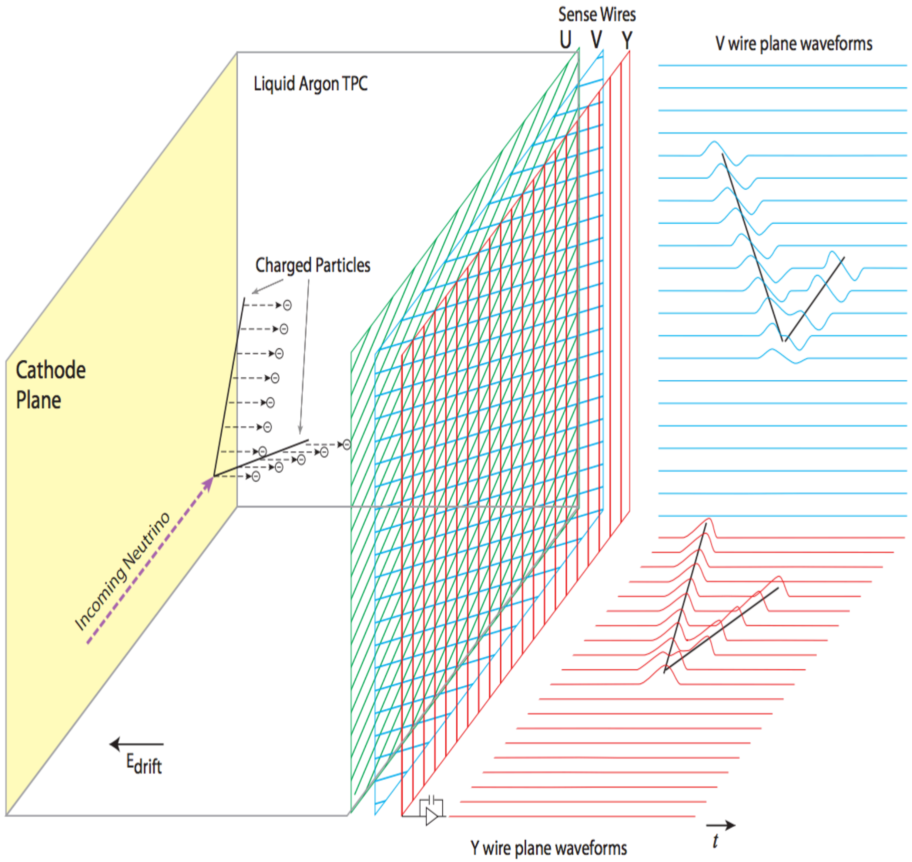


LArTPC Working principle – signals



- Charged particles lose energy through Ar excitation (**scintillation light**) and ionization (**drift electrons**)
- Electrons drift towards anode wire planes under E field.
- MicroBooNE LArTPC has two induction planes and one collection plane.
- 3D reconstruction from drift-time (X) and wire-plane matching (Y,Z).
- Number of electrons collected indicates the amount of energy loss from ionization.

LArTPC Working principle



Advantages:

High Z target: large active volume -> lots of nu interactions.

Finely segmented detector:

- High spatial resolution: 3mm wire spacing -> mm vertex accuracy.
- High calorimetric resolution: trace the charged particle ionization

Strong **particle identification** power to tag

- Tracks: muon, proton, charged pions, kaons, etc.
- Showers: electron, gamma, pi0.
- Cold electronics: Low noise -> low threshold.

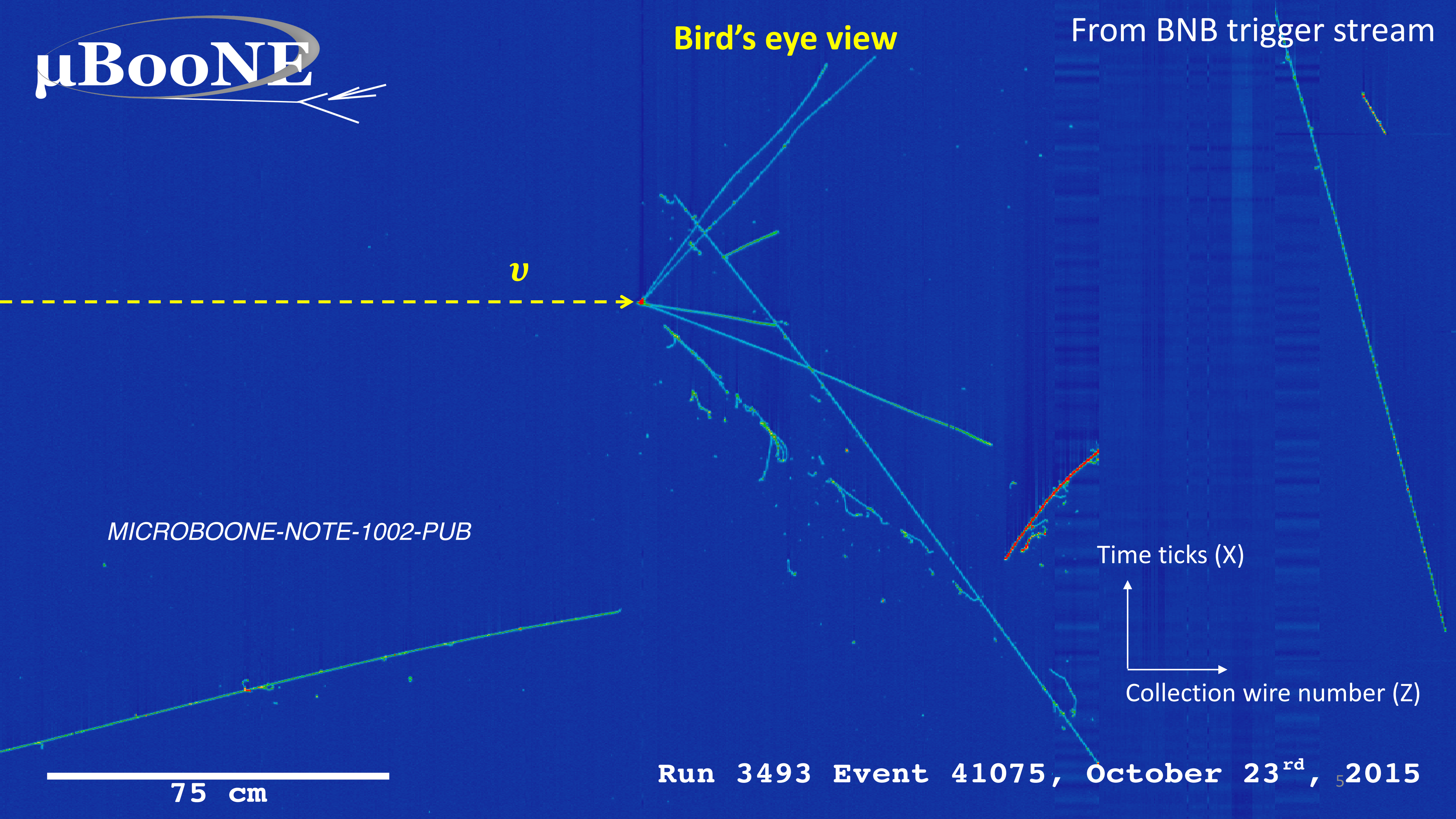
Challenges:

- Cosmic background rejection: ionization chamber is slow (~2ms drift). Surface detector -> ~20 cosmic tracks in 4.8 ms readout window
- High Z target: Nuclear effects affect nu cross-sections.
- Non-uniform detector response: unresponsive channels, shorted wire region.

μBooNE

Bird's eye view

From BNB trigger stream



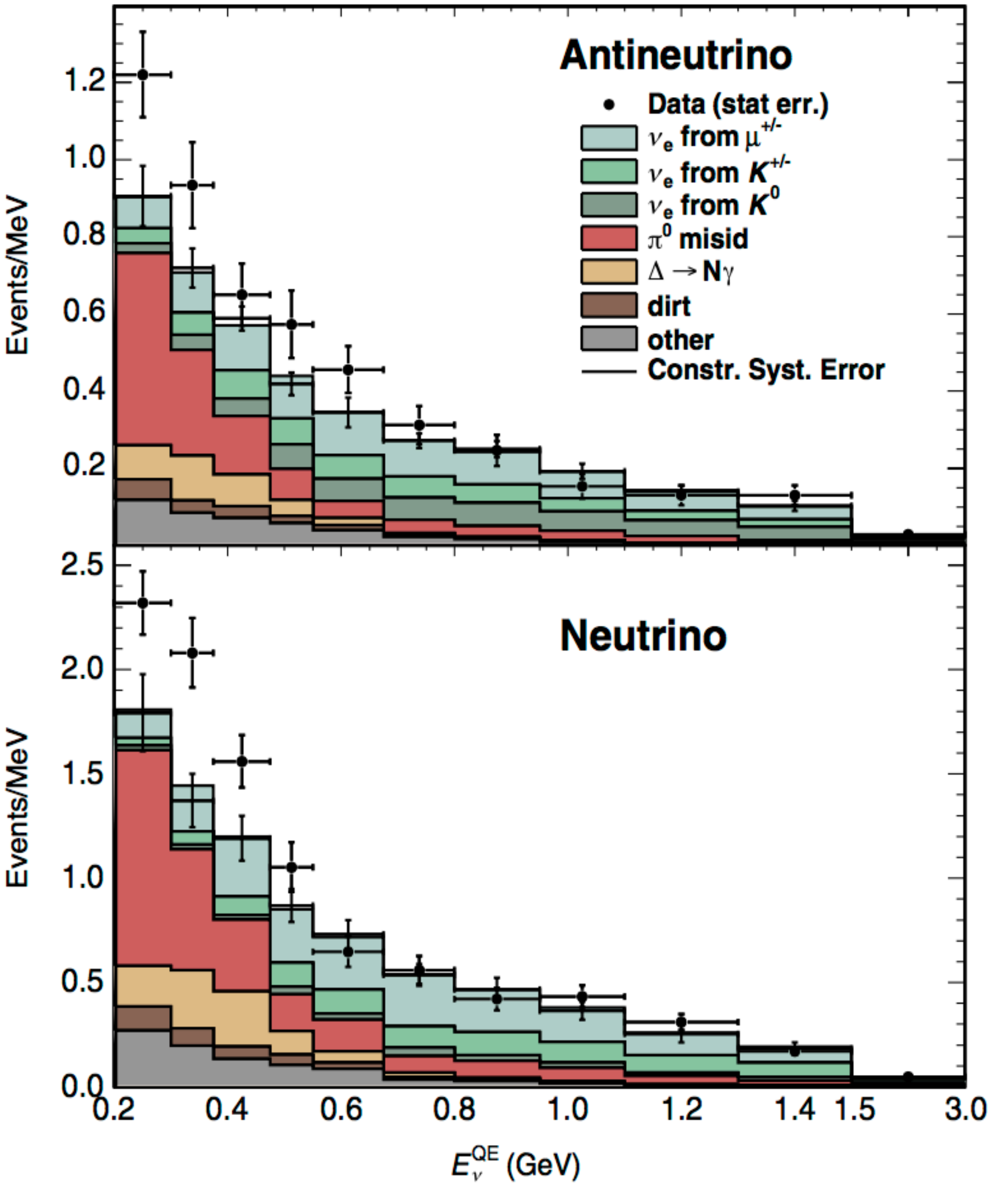
MICROBOONE-NOTE-1002-PUB

Run 3493 Event 41075, October 23rd, 2015

MicroBooNE uses these beautiful images to study neutrino oscillation

- **Goal I**: Understand the nature of the MiniBooNE **low energy excess** of EM events
- **Goal II**: SBN (together with SBND and ICARUS) search for **sterile neutrinos** ($\Delta m^2 \sim 1\ eV^2$) with **5σ sensitivity**.
- **Goal III**: Provide **ν-Ar cross-section measurements** for DUNE.

Goal I: go after MiniBooNE Low Energy Excess



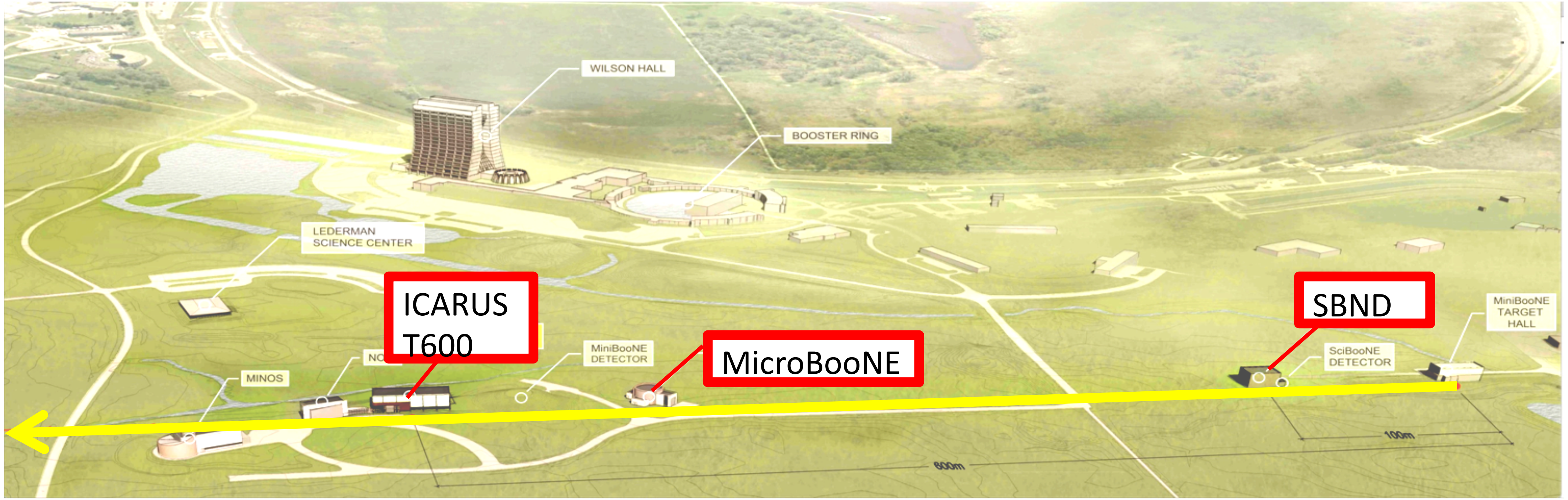
Phys. Rev. Lett. 110, 161801 (2013)

- MiniBooNE sees 2.8 σ and 3.4 σ event excess in $\overline{\nu_\mu} \longrightarrow \overline{\nu_e}$ and $\nu_\mu \longrightarrow \nu_e$
- Significant background is from π^0 misid and γ from delta radiative decay.
- Detector can not distinguish e from γ.

		MiniBooNE	MicroBooNE
Common features		Neutrino source: BNB Detector location: ~540 from the source Flux, L/E	
Differences	Detector	Cherenkov detector e/γ separation **NO**	LAr TPC e/γ separation **Yes**
	Target	Mineral oil (CH2) (806 tons)	Liquid Argon (Ar) (180 tons)

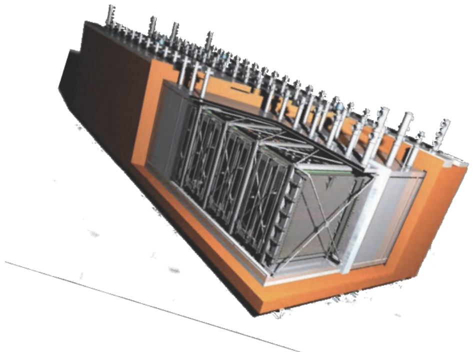
MicroBooNE primary goal: determine if the nature of the excess events are γ like or e like.

Goal II: go after Sterile Neutrino search - SBN program



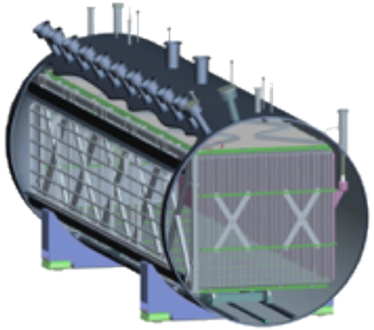
ICARUS

LArTPC: 600m, 476t



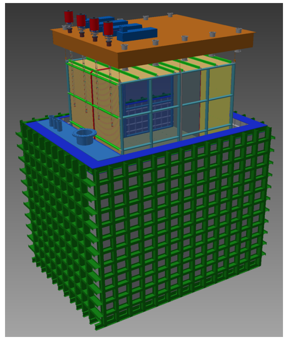
MicroBooNE

LArTPC: 470m, 87t



SBND

LArTPC:110m, 112t



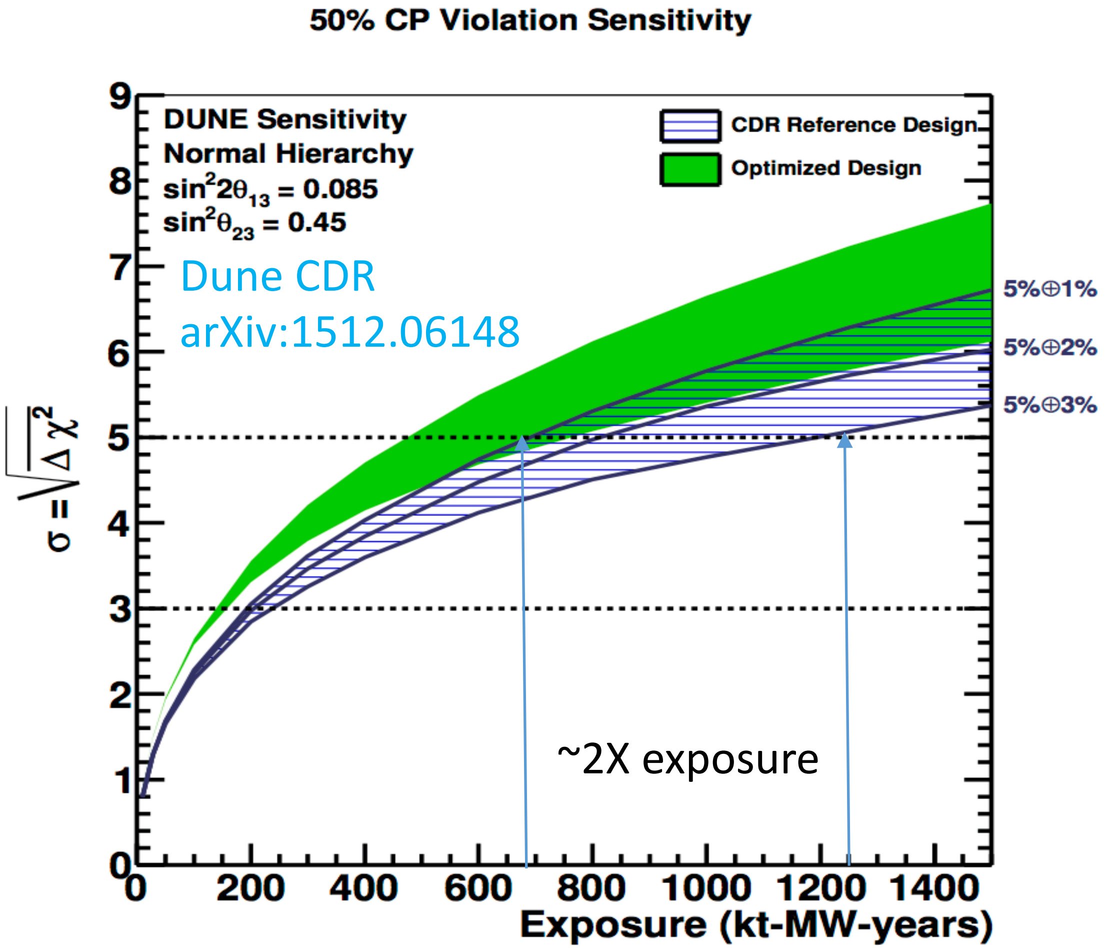
Fermilab Short Baseline Neutrino program:

- Shared neutrino beam (BNB) reduce flux uncertainty.
- All LArTPC detectors: reduce cross-section uncertainty

Goal: 5σ sensitivity for sterile neutrino search at Δm^2 ~ 1eV²

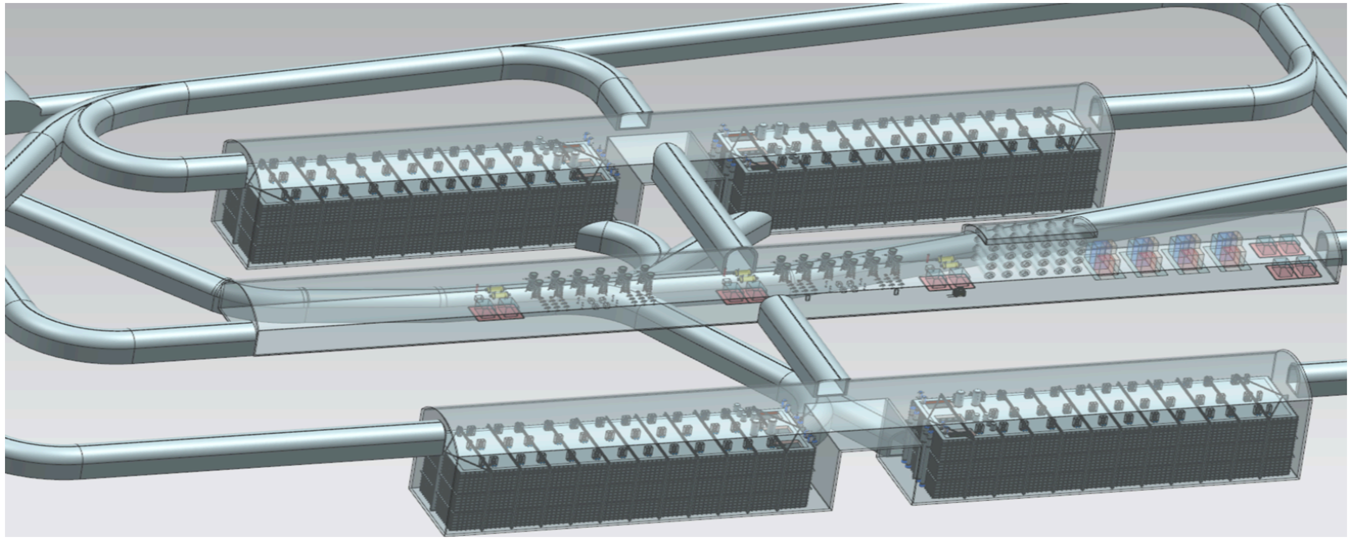
Goal III: go after cross-section uncertainty in Dune

- **Precision measurements** of neutrino oscillation parameters.
- **Neutrino Mass Hierarchy**
- **CP violation: δ_{CP}**



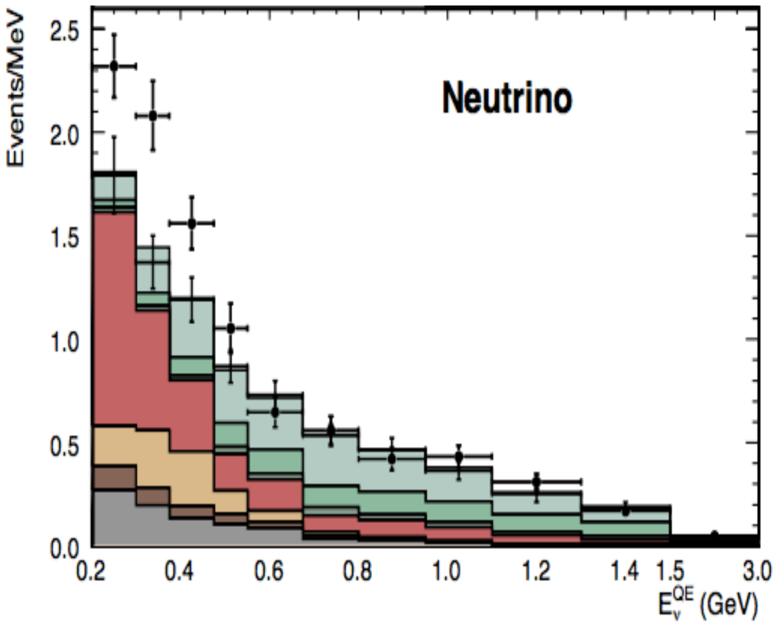
Dune CDR
arXiv:1512.06148

~2X exposure



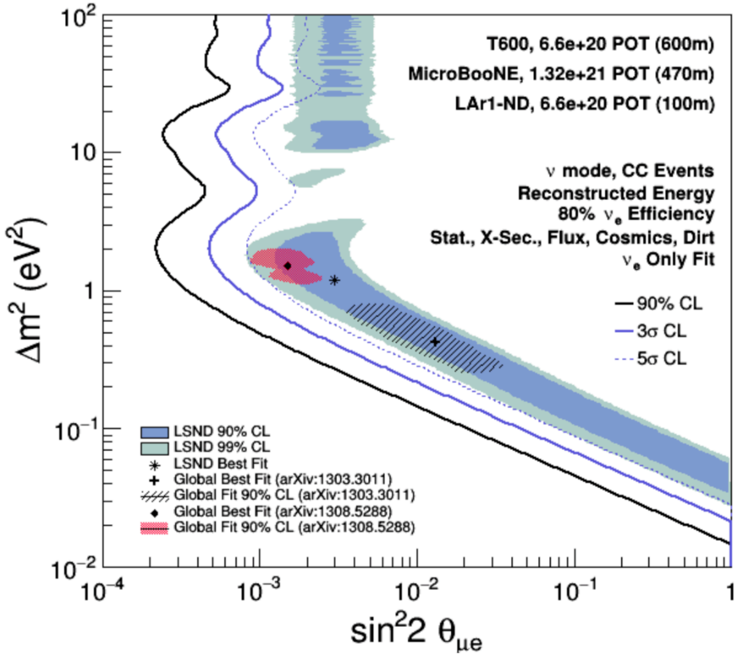
Dune Far detector is LArTPC. MicroBooNE can give **direct cross-section constrain** (particularly in low energy region) for Dune oscillation precision measurements.

Oscillation signals $\nu_\mu \rightarrow \nu_\mu,\ \nu_\mu \rightarrow \nu_e$



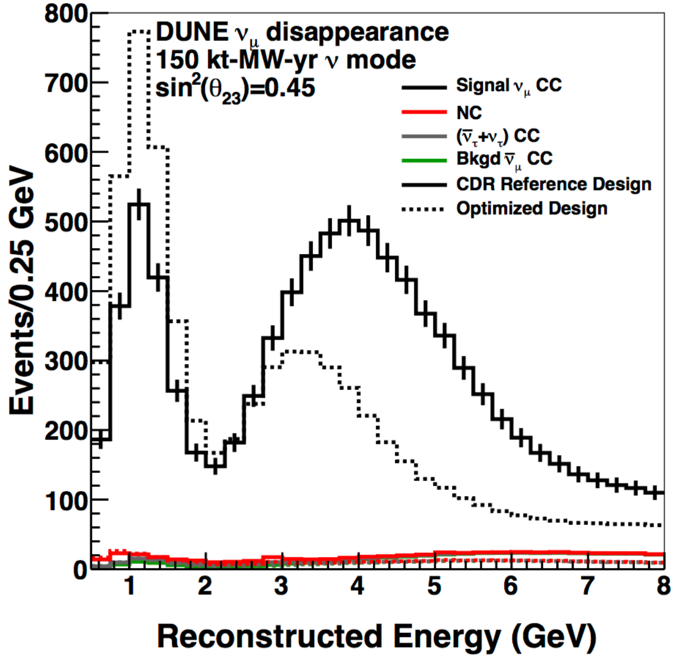
Signal selection

- ν_μCC inclusive
- CCπ^0



ν energy reco.

- ν_μCC inclusive
- Charged particle multiplicity, CC0π
- NC proton identification



Syst. Uncertainty

- CC0π
- CCπ^0

Cross-section impact on Oscillation

ν_μCC inclusive -> ν signal selection, Systematic uncertainty

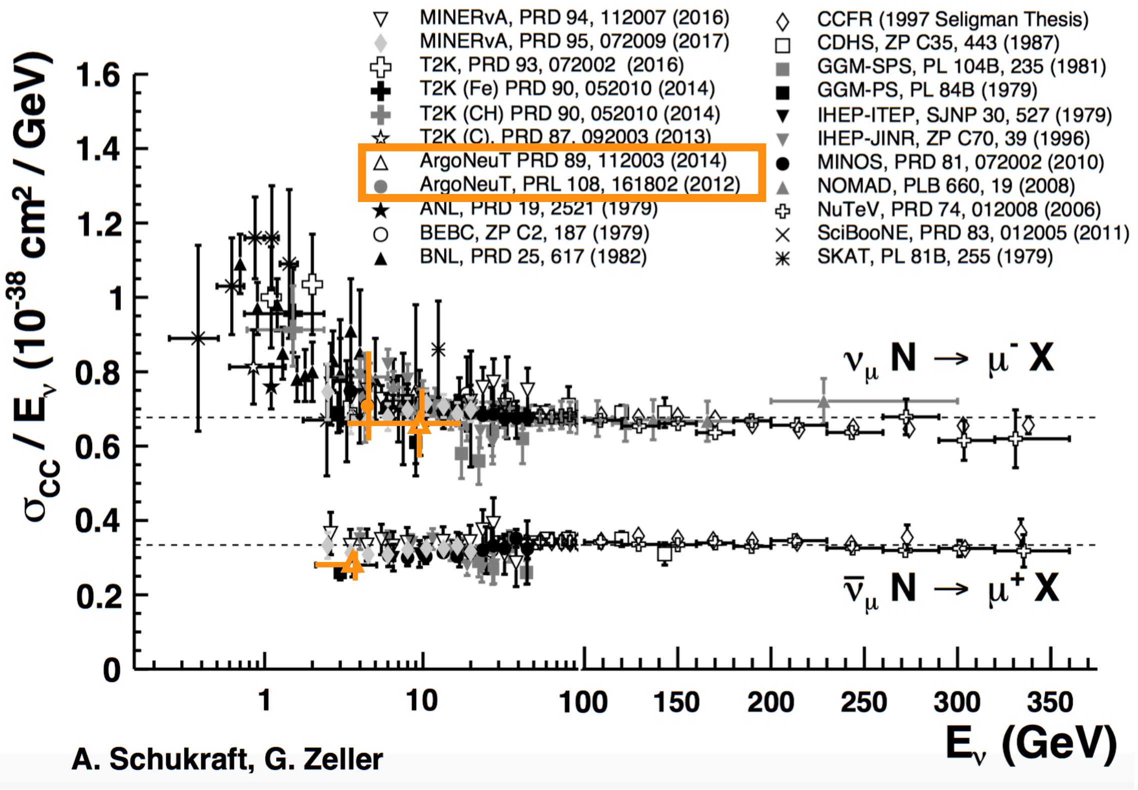
ν_μCC inclusive cross-section

First channel in MicroBooNE cross-section program: ν_μ CC inclusive:

- Relatively simple event signature – tag **long muon track** as the product of the neutrino interaction.
- Muon kinematics is insensitive to FSI.
- A standard channel to compare with other neutrino experiments.

Impact on oscillation:

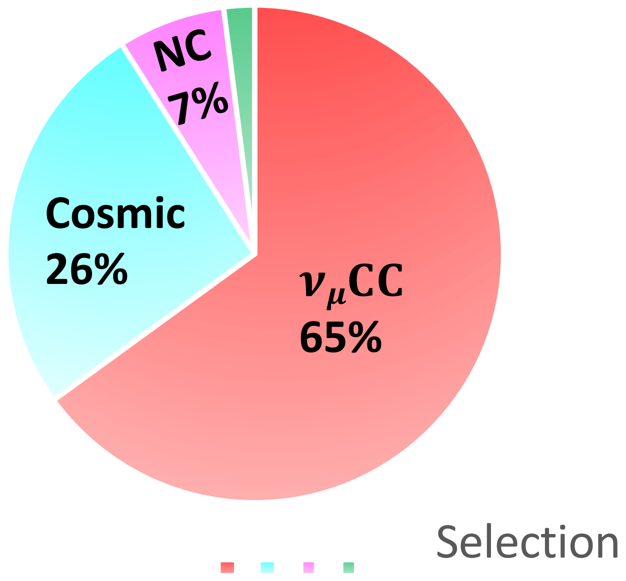
- Signal selection of ν_μ disappearance channel.
- ν_μ CC help to constrain the ν_e rate.

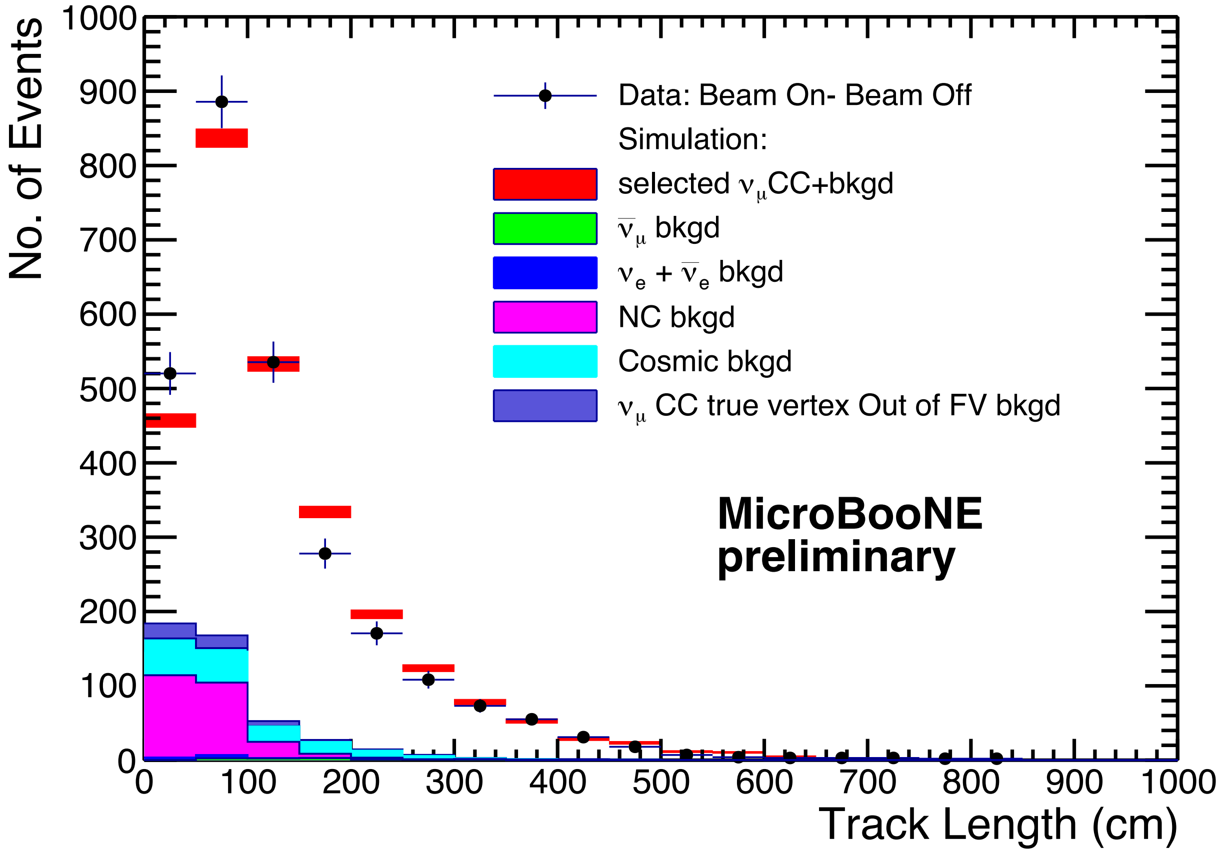


A. Schukraft, G. Zeller

ArgoNeuT is the only existing ν-Ar cross-section

ν_μCC inclusive





- **Purity: 65%, Efficiency: 30%**
- **Improved analysis:**
  - **Scintillation light to improve the selection efficiency**
  - **Muon PID to reduce background**

See Marco Del Tutto's talk Tue. WG2 talk
Check out MicroBooNE public note
MICROBOONE-NOTE-1010-PUB for details.

Differential cross-section is on the way, stay tuned!

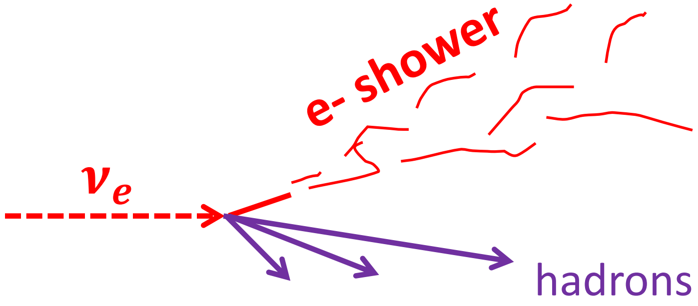
Note: efficiency = # of ν_μCC events after selection / All ν_μCC events inside of FV

Neutrino oscillation Vs Cross-section

CCπ^0 -> ν signal selection, Systematic uncertainty, ν Energy reconstruction

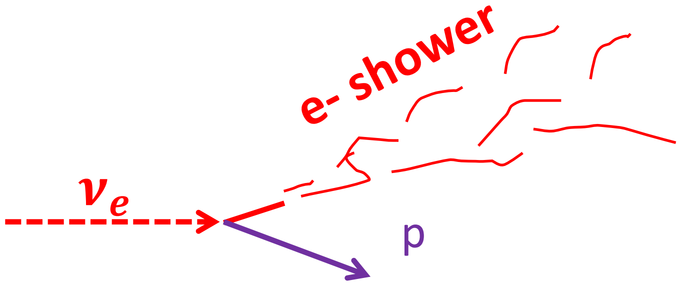
$CC\nu_e$ selection

"Inclusive" search
(1 e + 0π)



- Higher statistics
- **Directly compatible to MiniBooNE**
- Less model dependency

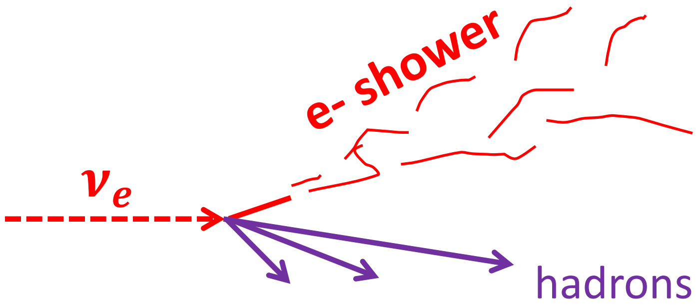
Exclusive QE like
(1e + 1 p)



- Simpler topology
- Lower backgrounds
- Easier E_ν determination

$CC\nu_e$ selection

"Inclusive" search
($1\ e + 0\pi$)



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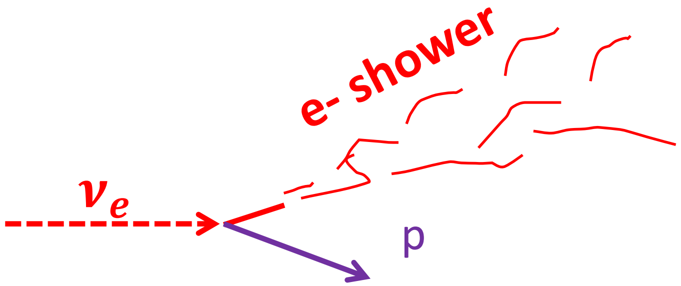

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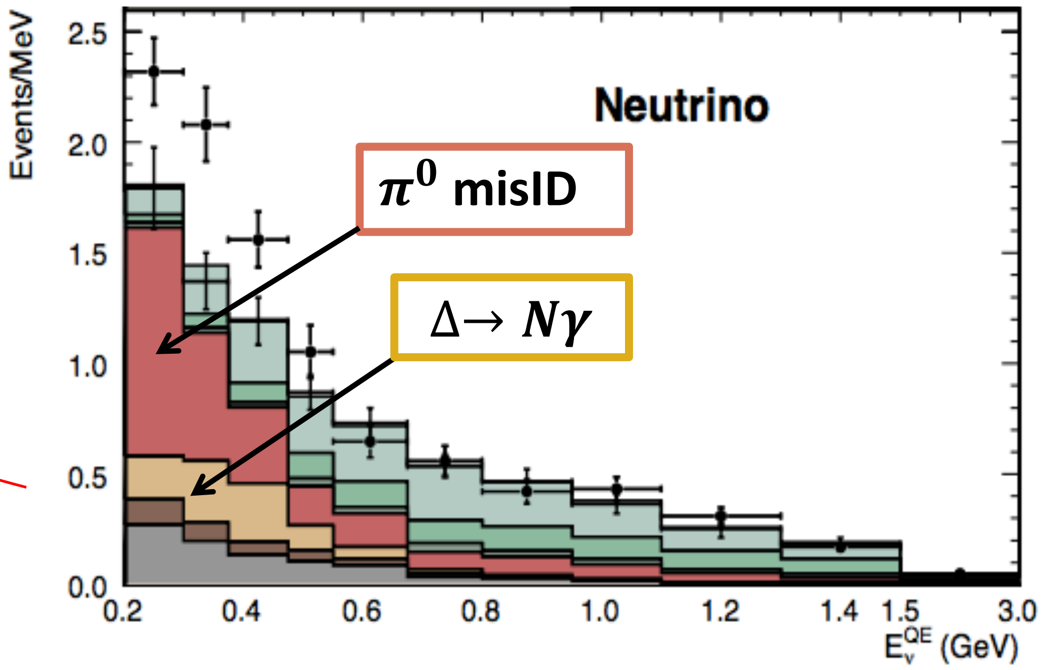
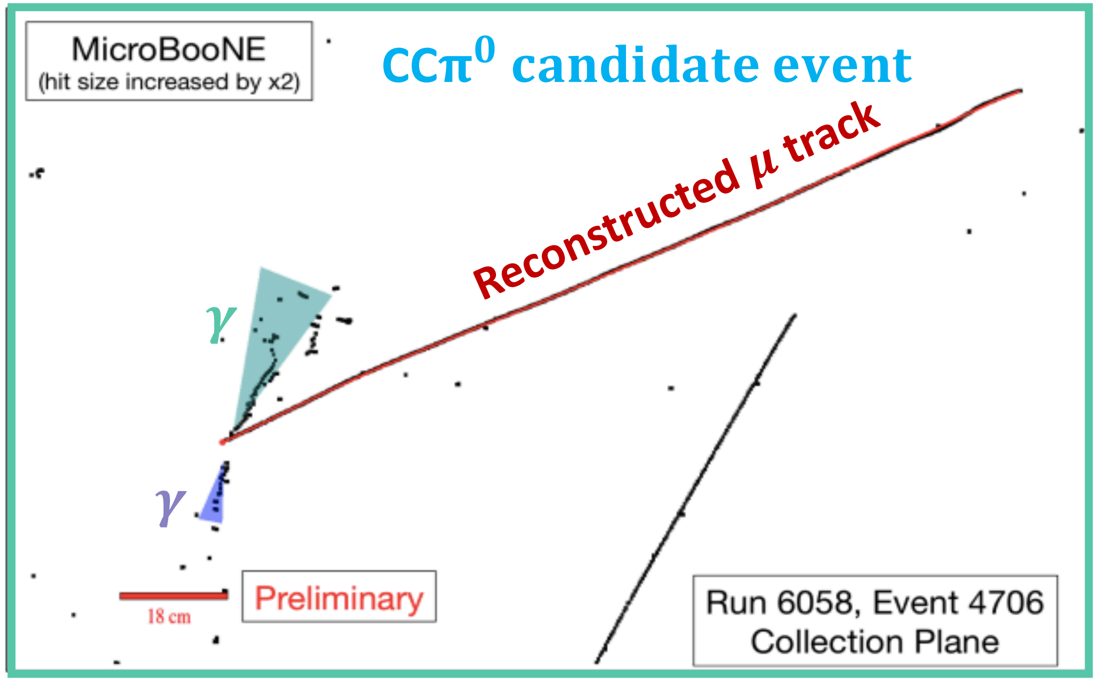


Challenges:

- Suppress photon backgrounds: NCπ^0, CCπ^0, resonant ν interactions in dirt-> γ
- **e/γ separation**

CCπ^0 cross-section measurement



Challenging channel:

- “Shower” reconstruction is difficult especially in the low energy range.
- Strategy: tagging muon and look for two showers

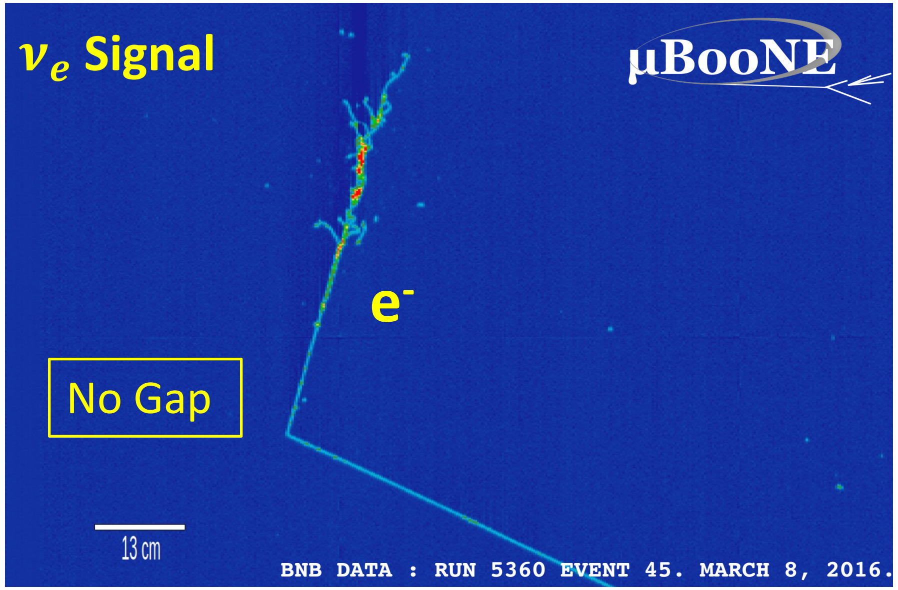
The first CC π^0 cross-section result is on the way, stay tuned!

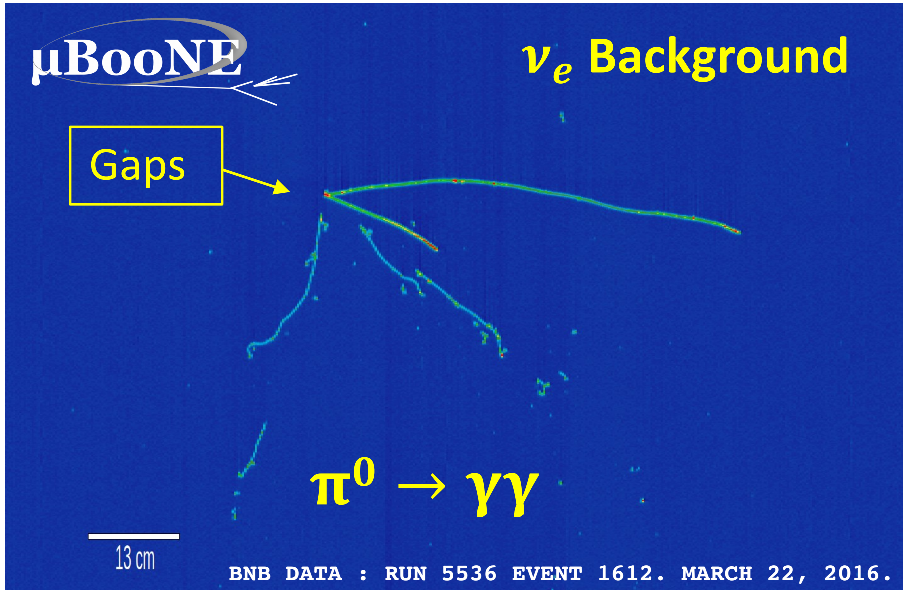
Impact on oscillation physics:

- Easiest channel to provide large pi0 sample
- Utilize the pi0 for shower automated reconstruction development.
- Enable us to study photon background for the ν_e appearance channel.

PID – showers (e/γ)

Electron Vs Gamma



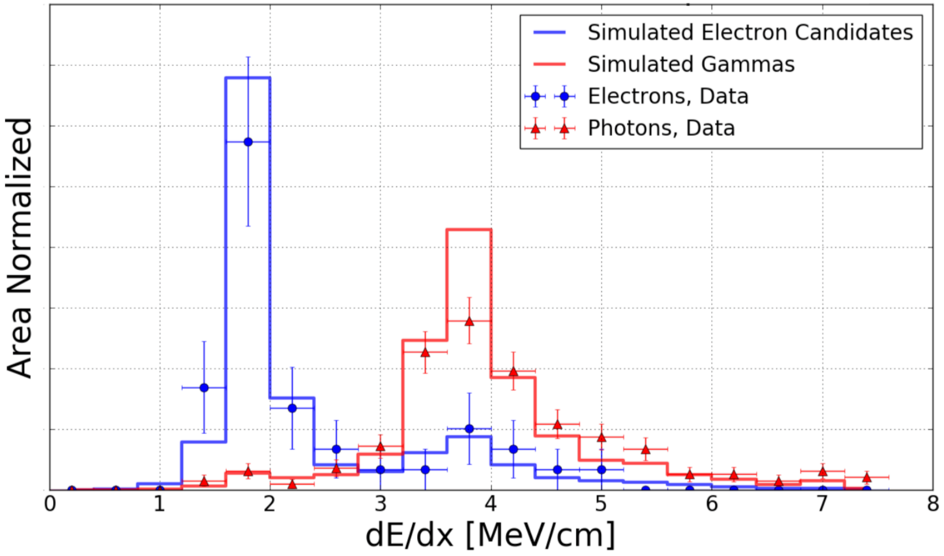


dE/dx at start of the shower?

- e-: 1MIP
- γ: 1MIP if Compton scattering, 2MIP if converting to e^+e^-

Gaps from vertex?

- γ: yes
- e^-: no



ArgoNeuT PhysRevD.95.072005

What Impact PID?

- Require good vertexing.
- Use both **dE/dx** and **gap** handles -> better e^- tagging.
- Study the energy dependence of γ contamination.

Note: ArgoNeuT electron like sample has 20% photon contamination with higher energy NuMI beam.

Neutrino oscillation Vs Cross-section

NC elastic -> ν Energy reconstruction

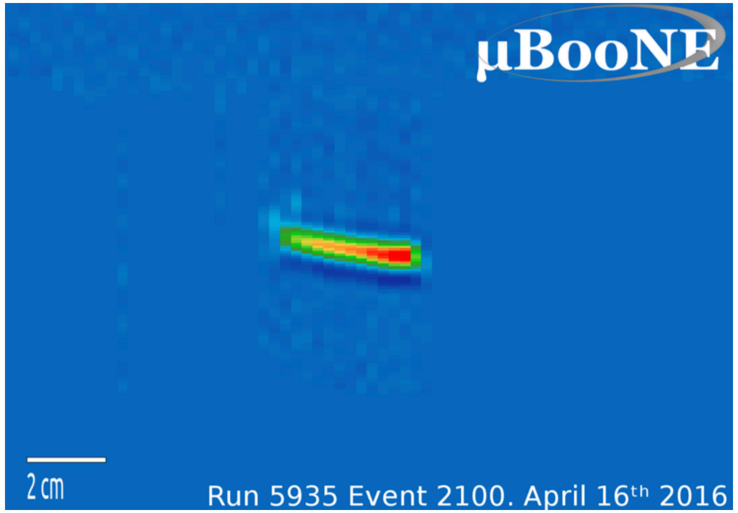
NC elastic – proton identification

- Take advantage of LArTPC PID strength, include **hadron calorimetry** of the final states in **energy reconstruction**.
- $\nu - Ar$ NC elastic cross-section help identify protons and their energy reconstruction

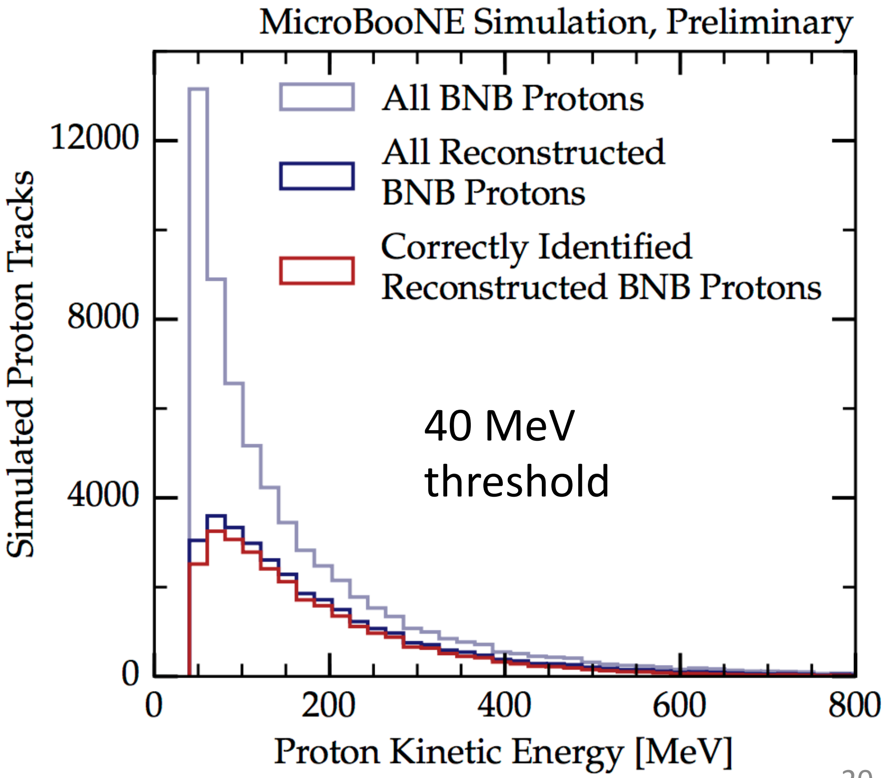
NC elastic cross-section

- ultimate goal: Δs.
- Signature: single short proton track (challenging to select)
- Employed BDT to identify protons
- Continue push to lower proton energy threshold.

Check out our public note for more details: [link]



Example of selected NC proton from BNB data. ~60MeV proton



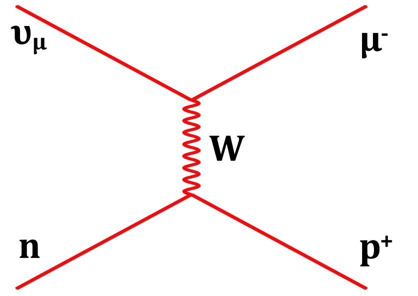
Neutrino oscillation Vs Cross-section

Charged particle multiplicity -> Systematic Uncertainty from nuclear effects

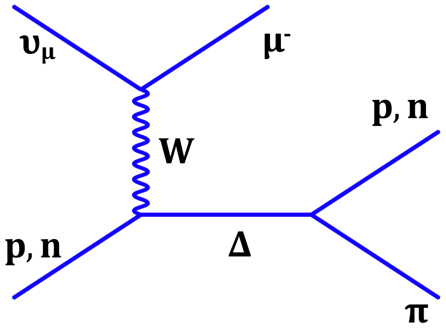
CC0π -> ν Energy reconstruction, Systematic Uncertainty from nuclear effects

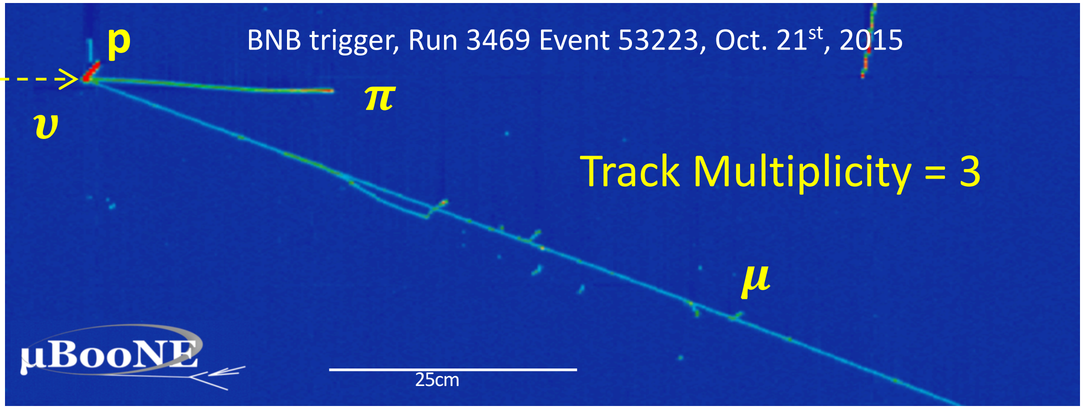
Charged particle multiplicity analysis– Motivation

CCQE



Resonant





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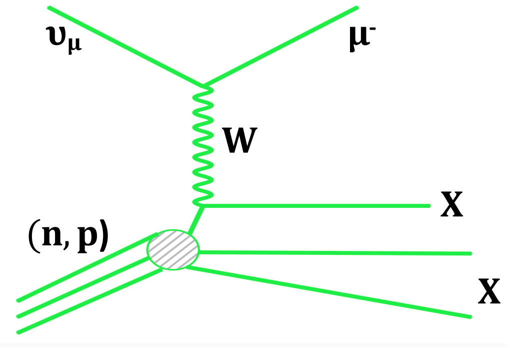
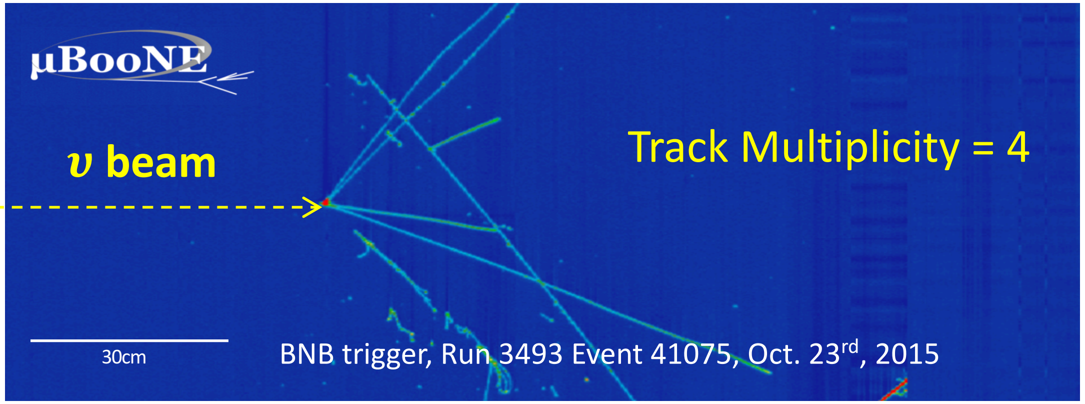




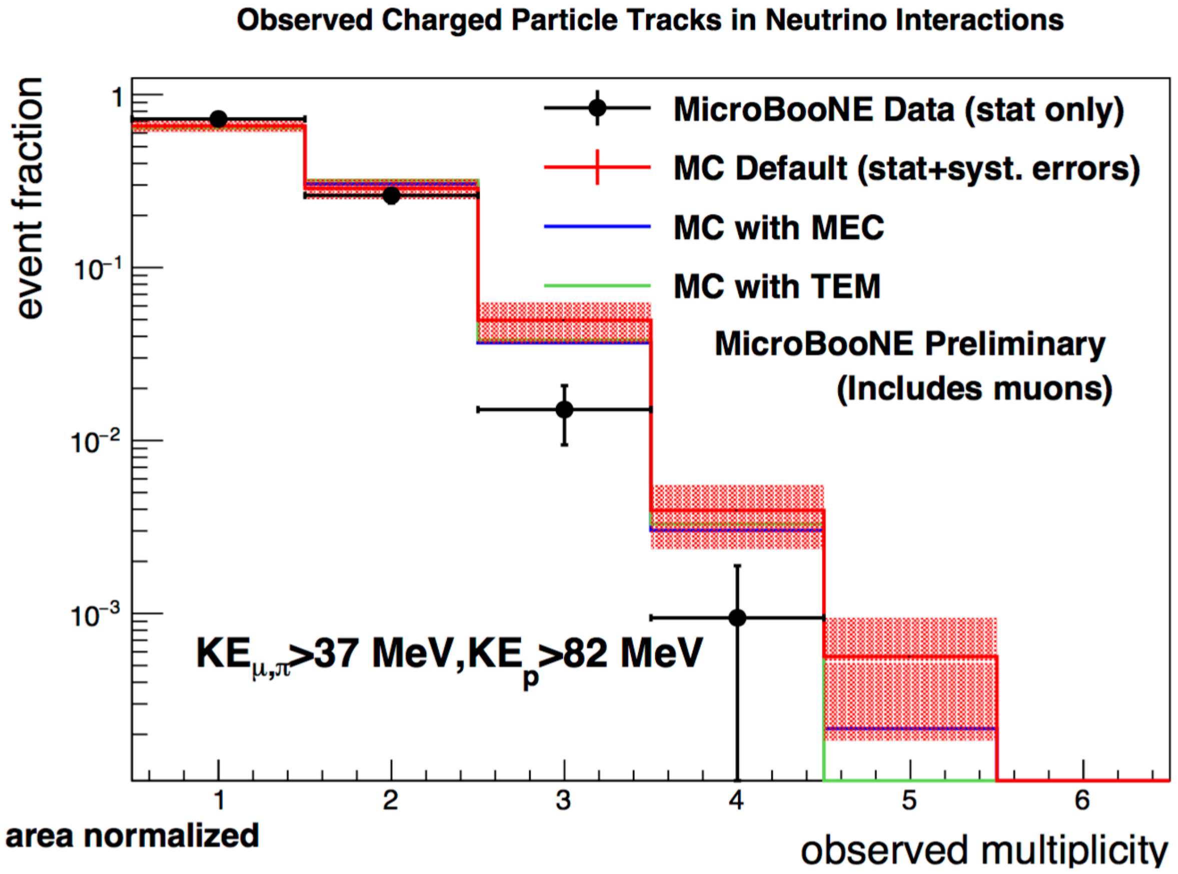
Nuclear Effects:

- Fermi motion
- Nucleon correlation
- Final state interaction

Observables are instead **final state particles**.

Direct count of the number of tracks from ν_μCC events serves as experimental contribution to tuning models for generators, can be a standard measurement on different targets.

Charged particle multiplicity analysis – preliminary result



- Good agreement between MC and data.
- High energy threshold (82MeV for p, 37MeV for μ, π)
- Subset of the data sample, stat. limited for high multiplicity.
- Will reduce the energy threshold and increase statistics.

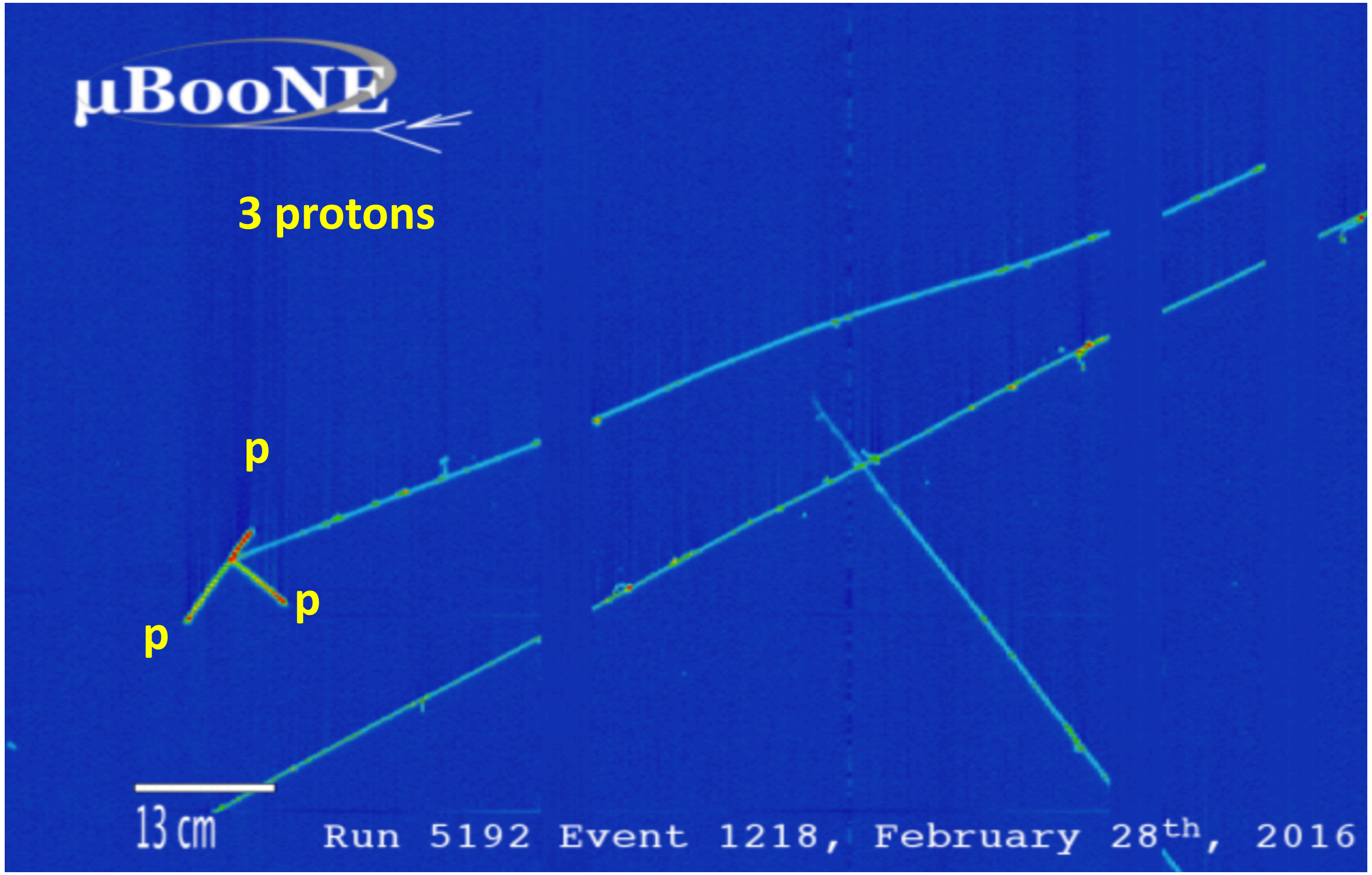
More details about the analysis method and preliminary results can be found in the MicroBooNE public note: MICROBOONE-NOTE-1024-PUB

CC 0π / proton multiplicity

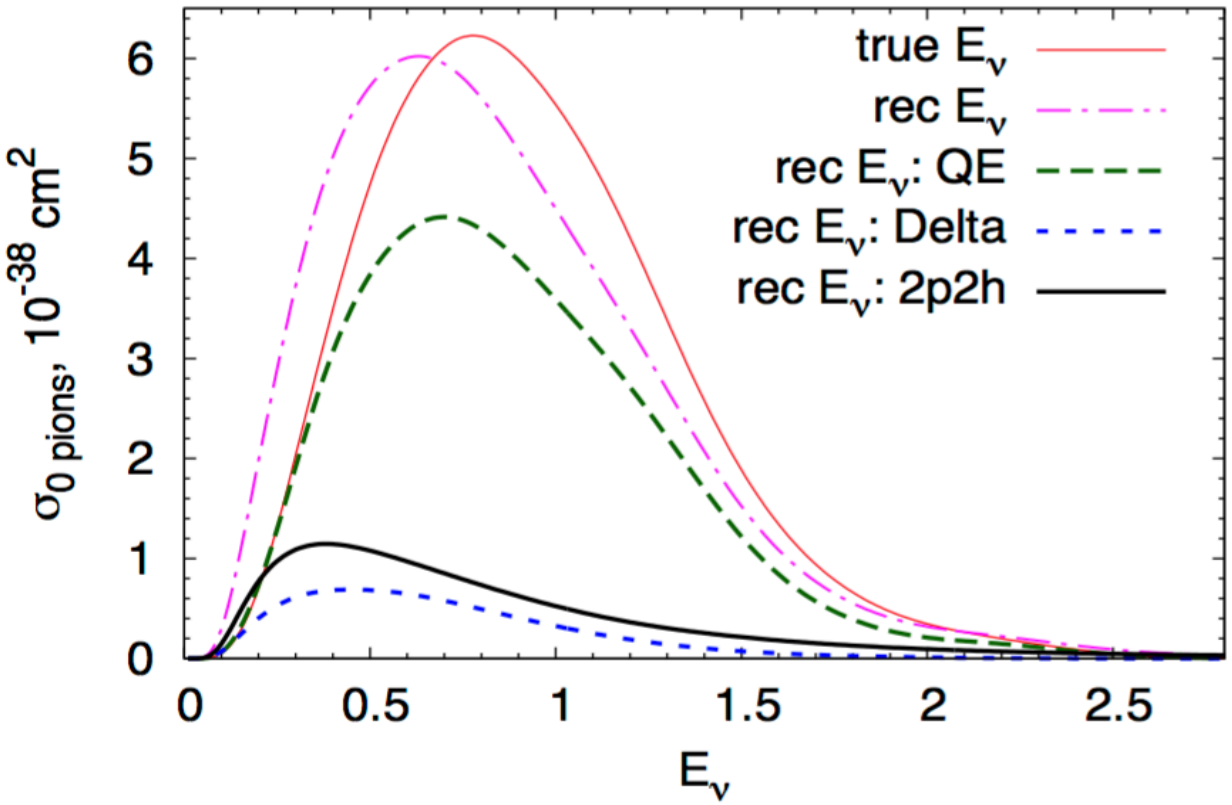
Several active exclusive cross-section analyses with final state topologies:

- **1muon + 1 proton**
- **1 muon + 2 proton**
- **1 muon + n protons, n>2**

Direct cross-section measurements, provide handle to constrain nuclear effects (MEC, 2p2h, FSI) in Ar.



Nuclear Effects affect Oscillation - E_ν unfolding

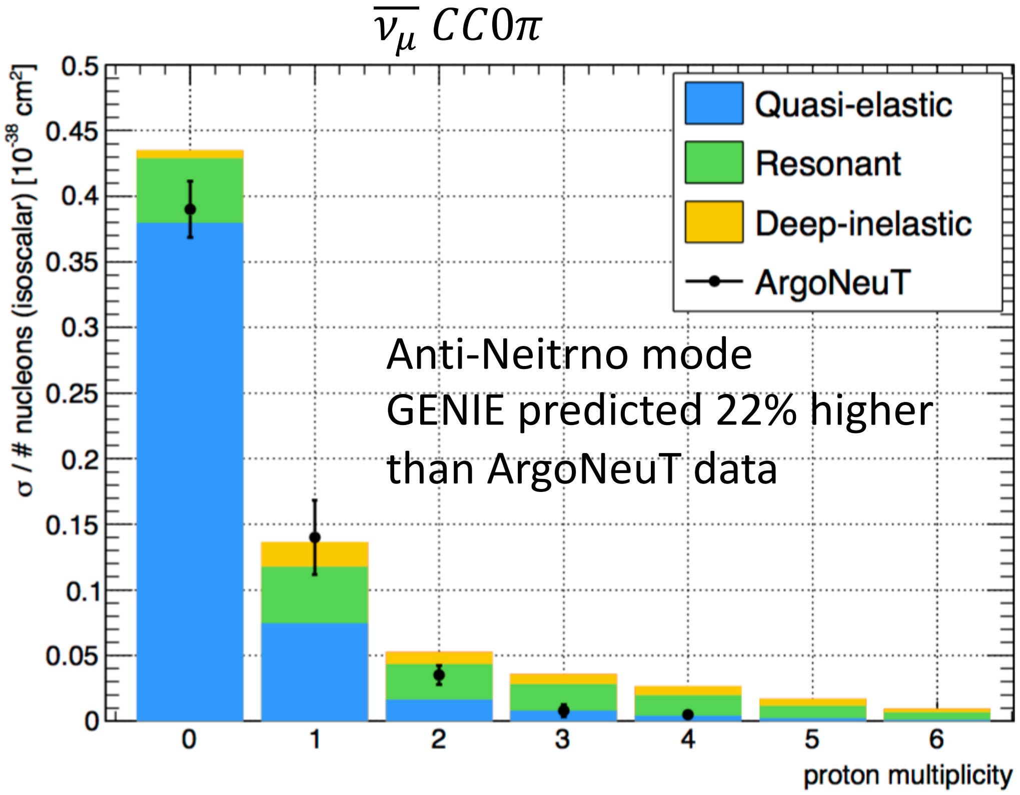


O. Lalakulich K. Gallmeister U. Mosel
arxiv 1203.2935

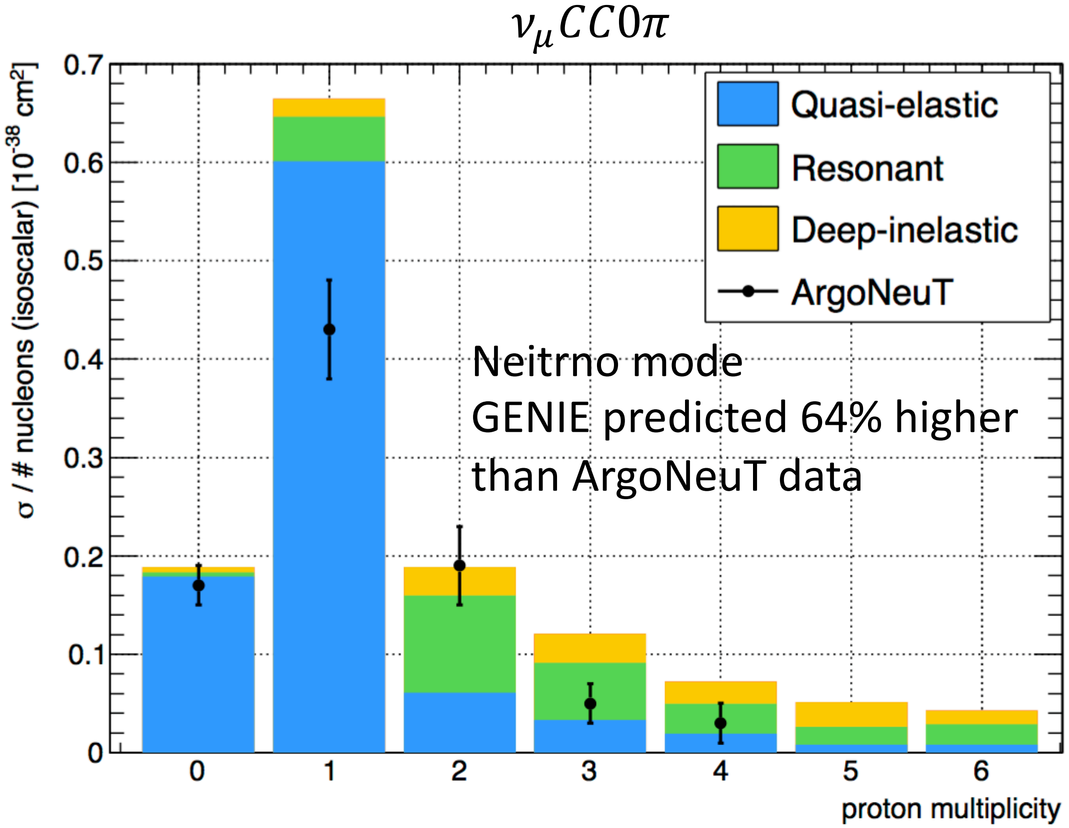
Nuclear effects impact on Oscillation phys.

- ○ Oscillation is measured as function of $\boldsymbol{E_\nu}^{\mathbf{true}}$
- ○ $\boldsymbol{E_\nu}^{\mathbf{reco}}$ **->** $\boldsymbol{E_\nu}^{\mathbf{true}}$ unfolding using MC
- ○ Different models -> different $E_\nu{}^{\text{true}}$ shape -> different oscillation param.
- ○ MicroBooNE proton multiplicity measurements will provide constrains of nucleon correlation/FSI in Ar.

Proton multiplicity -> CP violation


$\overline{\nu_\mu}\ CC0\pi$

Anti-Neitrno mode
GENIE predicted 22% higher
than ArgoNeuT data


$\nu_\mu CC0\pi$

Neitrno mode
GENIE predicted 64% higher
than ArgoNeuT data

From Ornella Palamara NUINT 15 talk

- Effects are different for neutrino and anti-neutrino
- Enter systematic uncertainty of δ_{CP} measurement in DUNE
- MicroBooNE measures proton multiplicity in Ar with more stat.

Conclusion

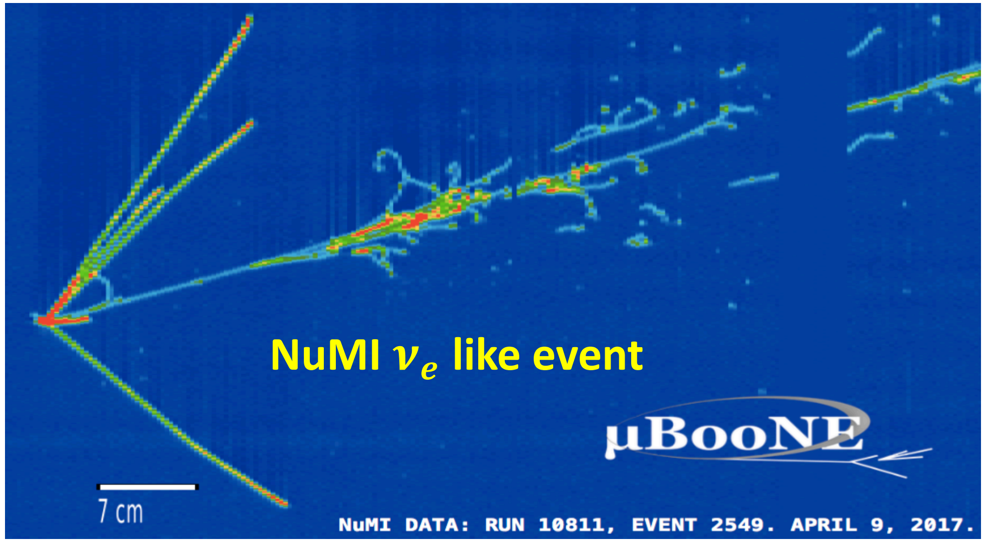
- MicroBooNE targets to understand the **MiniBooNE Low energy excess**, search for ~1eV^2 **sterile neutrino** in Femilab's SBN program and set **cross-section constrains** for DUNE.
- MicroBooNE has an active ν-Ar cross-section program which will significantly contribute to achieving oscillation goals
  - **CC inclusive**
  - **Track multiplicity**
  - **CC 0pi, proton multiplicity**
  - **CCpi0**
  - **NC proton**
- Stay tuned for results in the near future!

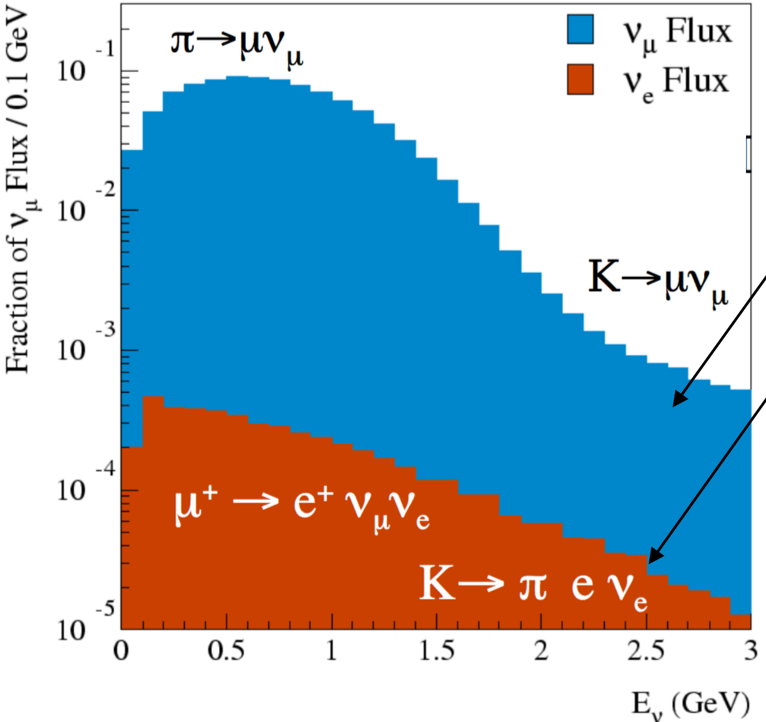
Back up slides

Other cross-section effort useful for osc. phys.

$\nu_e CC$ cross-section from NuMI beam

- MicroBooNE detector sits on 8° off-axis NuMI beam.
- Larger ν_e fraction in NuMI (~5%) than BNB (~0.6%).
- Potential cross check for the BNB low energy excess analysis.
- Currently no ν_eCC results on Lar, will be valuable to DUNE.

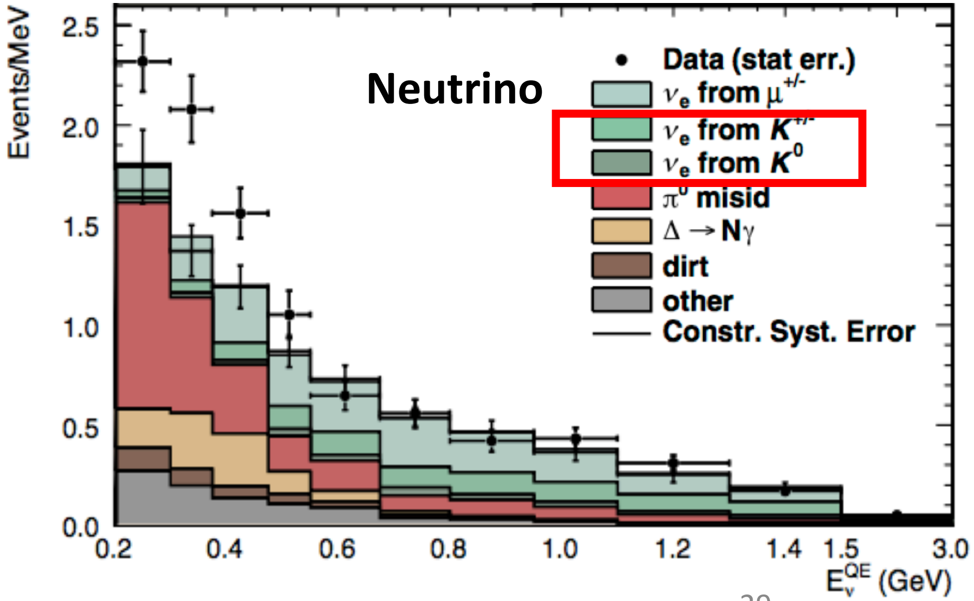




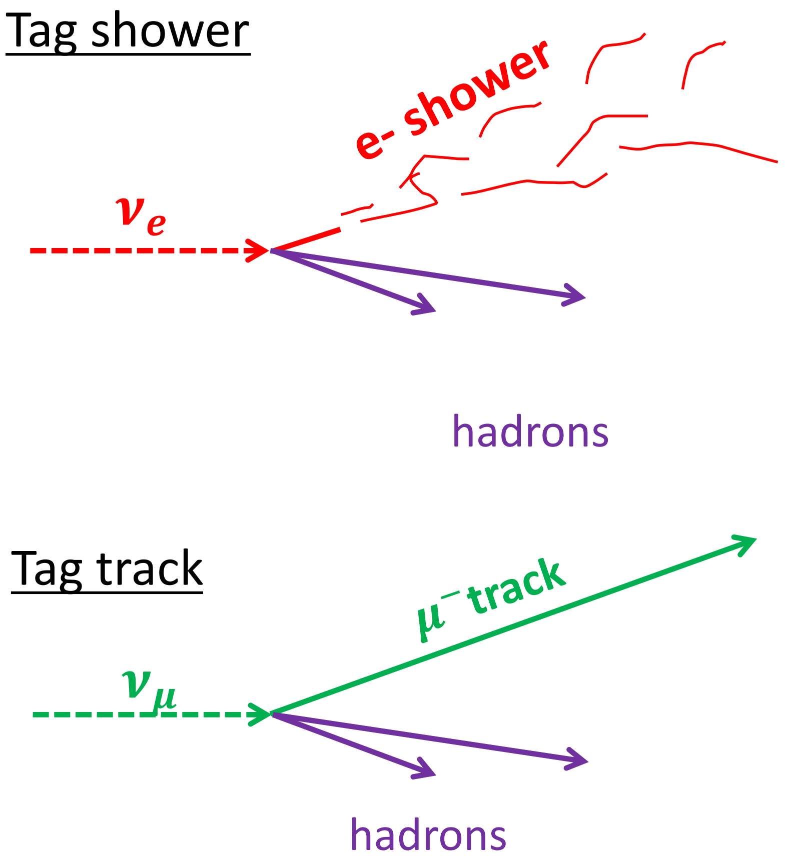
Measure High energy ν_μ rate

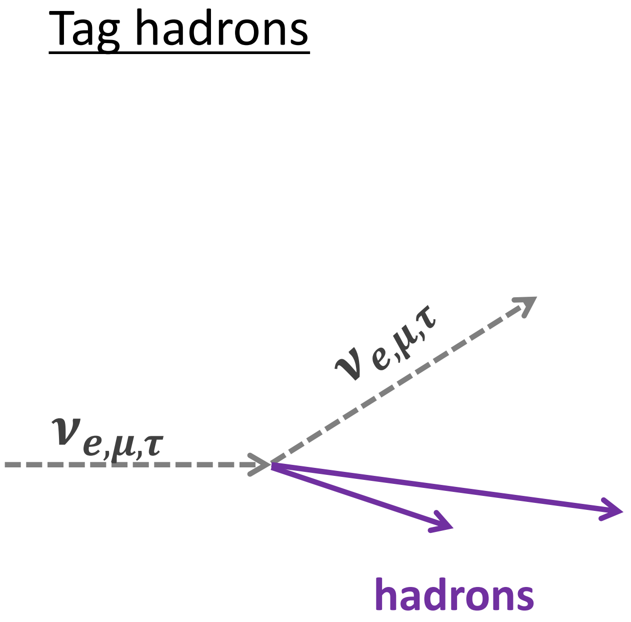
-> constrain the kaon flux

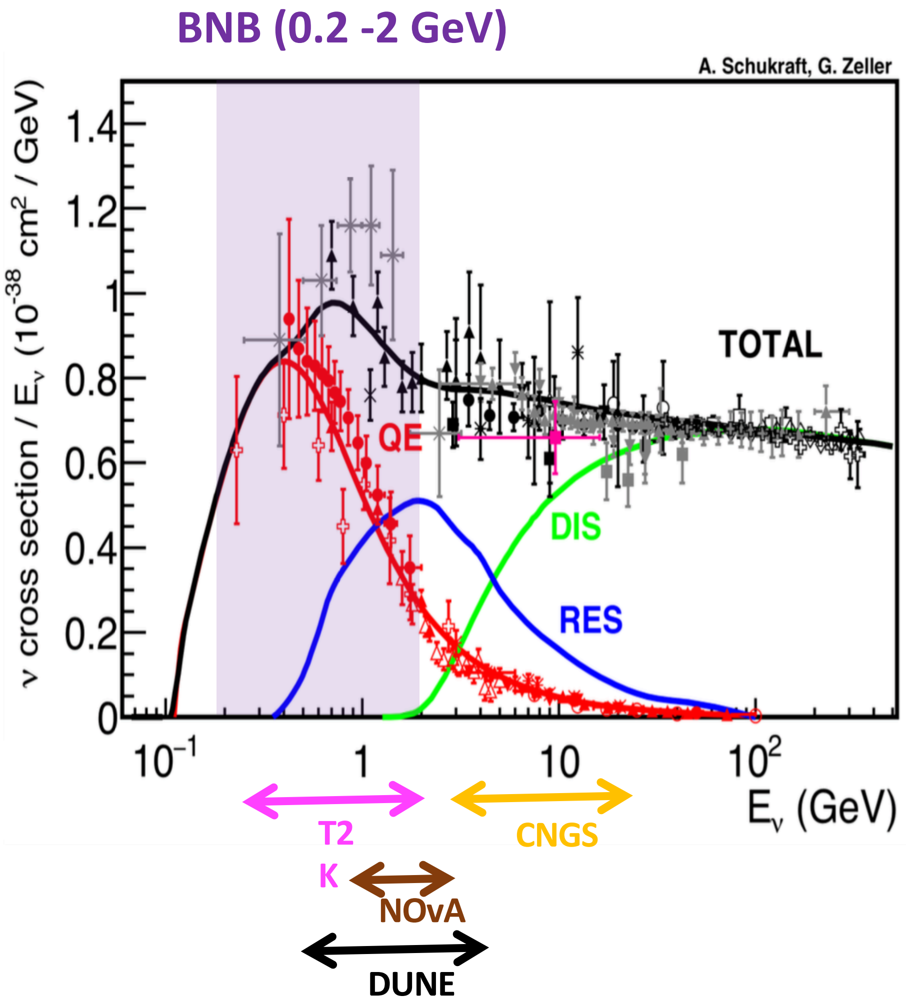
-> constrain the intrinsic ν_e from kaon decay



Neutrino interactions







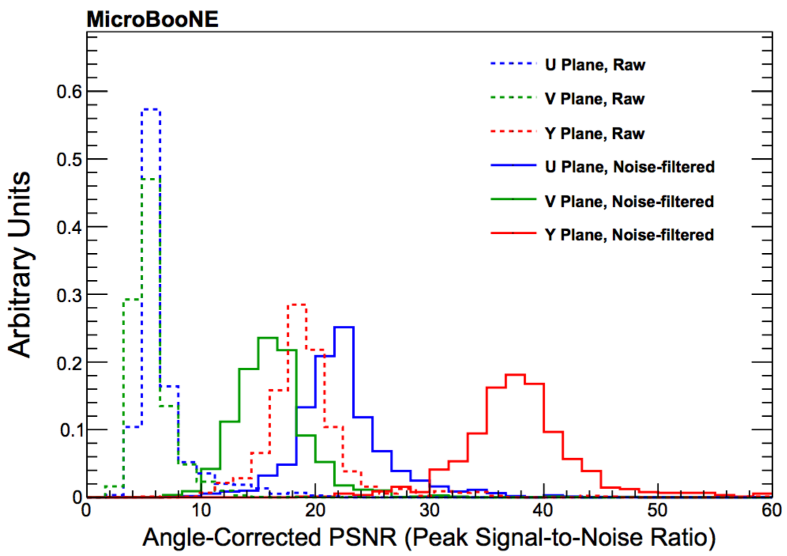
Charged Current

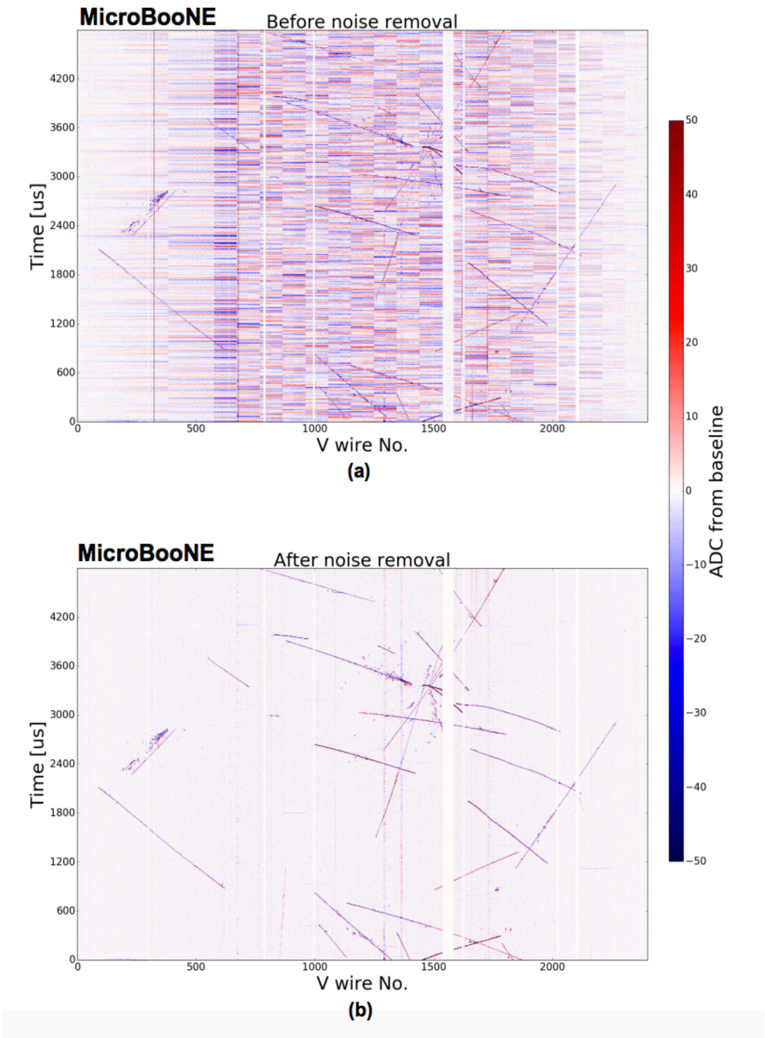
Signal channel, tag lepton gives the flavor of the neutrino

Neutral Current

Background, can provide total neutrino flux

LArTPC Working principle – Noise



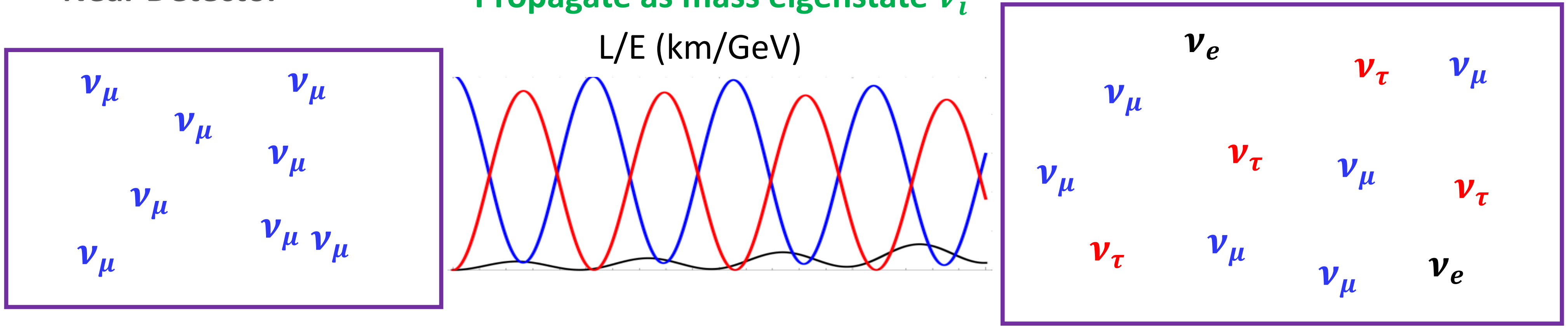


- In MicroBooNE, <400 electron equivalent noise charge (ENC)
- Great Signal/Noise ratio, ~20 (raw data) and ~38 (noise filtered). (https://arxiv.org/abs/1705.07341)
- Misconfigured channels (~8%) and dead (~4%) channels are problematic in MicroBooNE.
- Robust channel recovery is needed for future large scale LArTPC for all cold electronics.

Requirements on the detector:

- Large detector active volume:
  - Increase # of interactions.
  - Capture complete info. of the interactions. (containment)
- **High signal/background ratio:**
  - **Low noise, cold electronics**
  - Underground to prevent cosmic rays.
- Strong particle identification power:
  - Event topology – spacial resolution
  - Calorimetry – energy resolution
  - Segmented detector is highly preferred.
- Low threshold:
  - High efficiency for detect and reconstruct low energy particles.

Accelerator neutrino oscillation



Near Detector

Propagate as mass eigenstate ν_i

L/E (km/GeV)

Far Detector

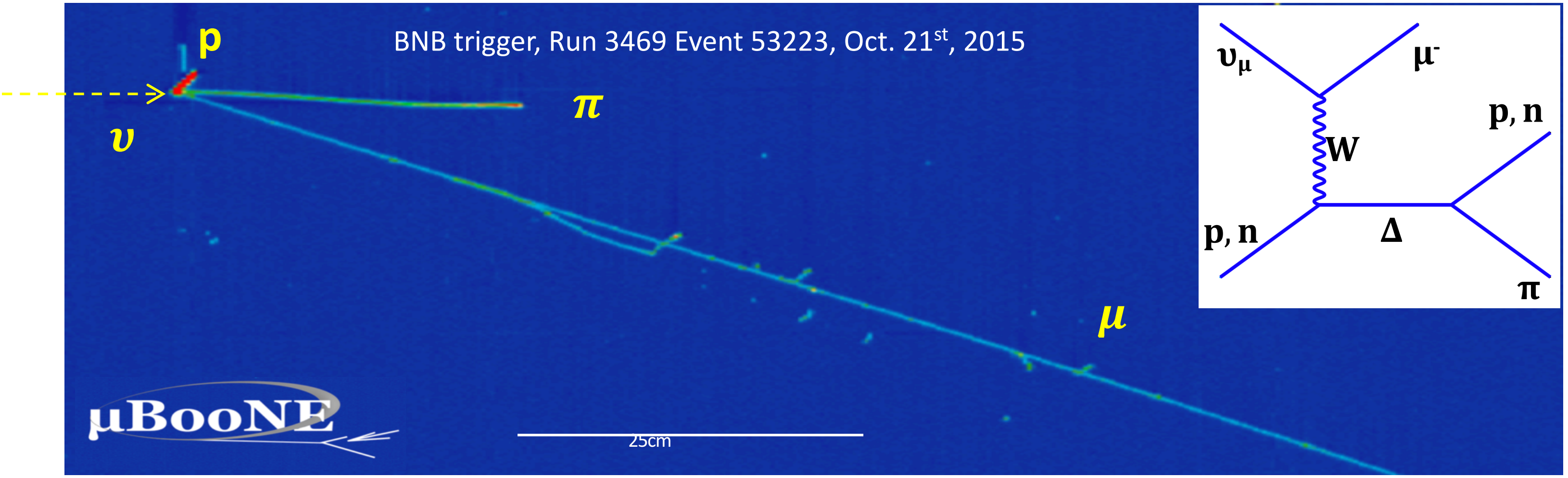
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\text{eV}^2]\frac{L\ [\text{km}]}{\boxed{E}\ [\text{GeV}]}\right)$$

- **Precision measurements** of neutrino oscillation **mixing angles**: $\boldsymbol{\nu_\mu}$ disappearance (θ_{23}), $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}$ (θ_{13}), etc. Amplitude of the oscillation probability.
- **Neutrino Mass Hierarchy**: determine the sign of Δm^2_{23}($\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_\mu}$ or $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_\tau}$) or Δm^2_{13} ($\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_e}$ or $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}$). Frequency of oscillation probability.
- **CP violation:** non-zero phase δ_{CP} generates asymmetry between neutrino oscillation and anti neutrino oscillation. $P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e]$?

Requires to **correctly** detect the **flavor** and **energy** of neutrinos in the detectors with **high Efficiency**.

PID – tracks (muon, pion, proton)

$CC\nu_\mu$ resonant

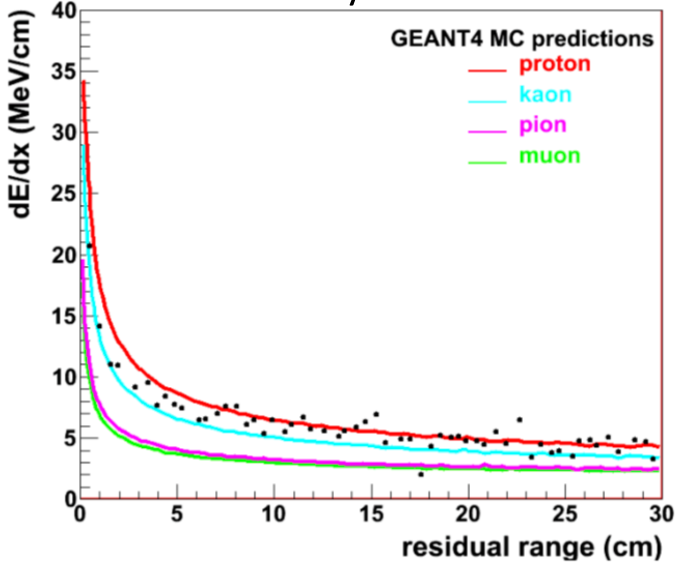


Goal: Identify particle type and reconstruct the energy.

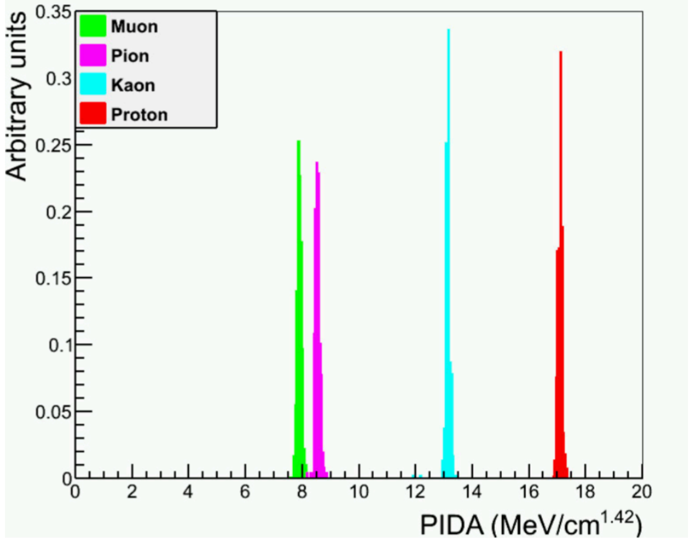
Tool Box:

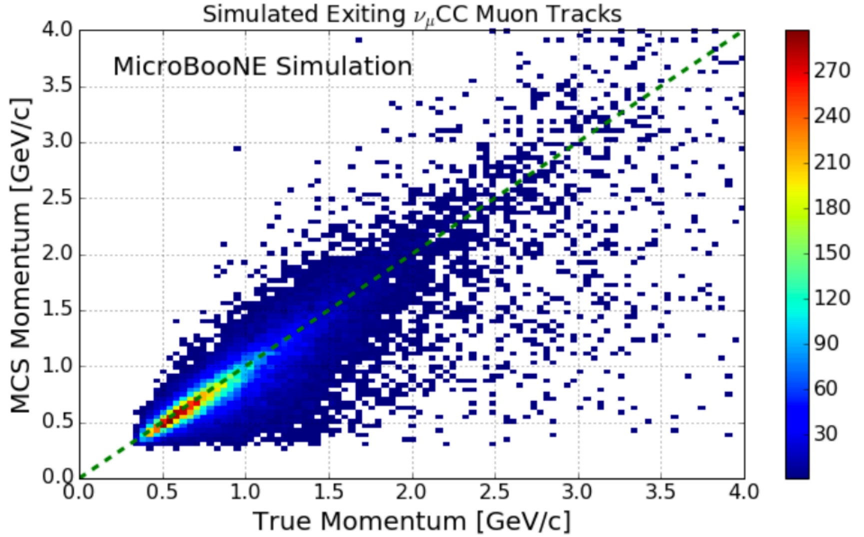
- Bethe Bloch laws (dEdx Vs Residual range) -> PID
- Straggling effect: heavier incoming particle has narrower dE/dx distribution.
- Track range, Multiple Column Scattering -> Kinetic energy
- Delta rays, Bragg peak -> track direction. (Cosmic rejection)

By Ornella Palamara



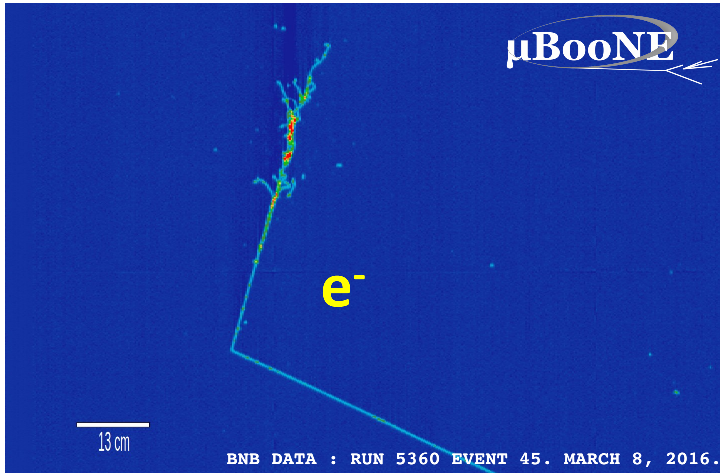
(JINST), 2013 JINST Vol. 8 P08005.

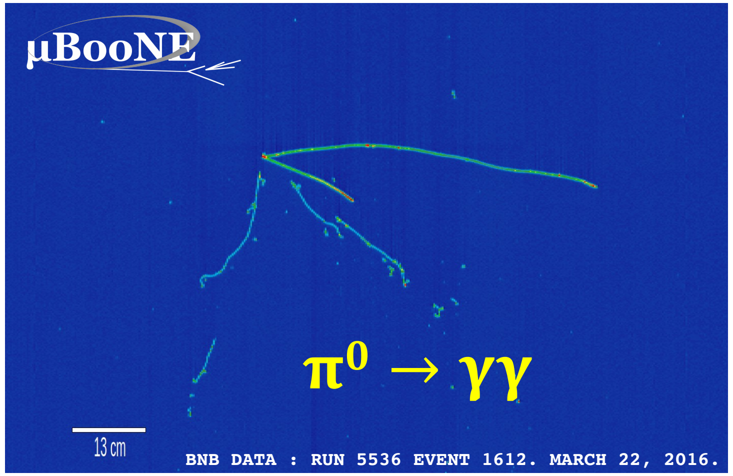




https://arxiv.org/abs/1703.06187

PID – showers(e/gamma)





Goal:

Tag e- from CC ν_e events. NCpi0 events are background.

Tool Box:

- dE/dx of the start of the shower.
- Gap or no Gap from the vertex.
- Warning: each handle alone is not sufficient to tag electrons, especially in low energy range.

W.-M. Yao et al., Journal of Physics G 33, 1 (2006) available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

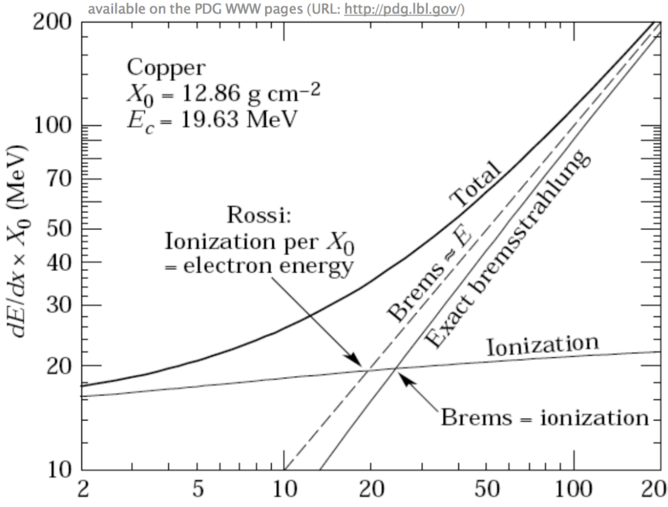
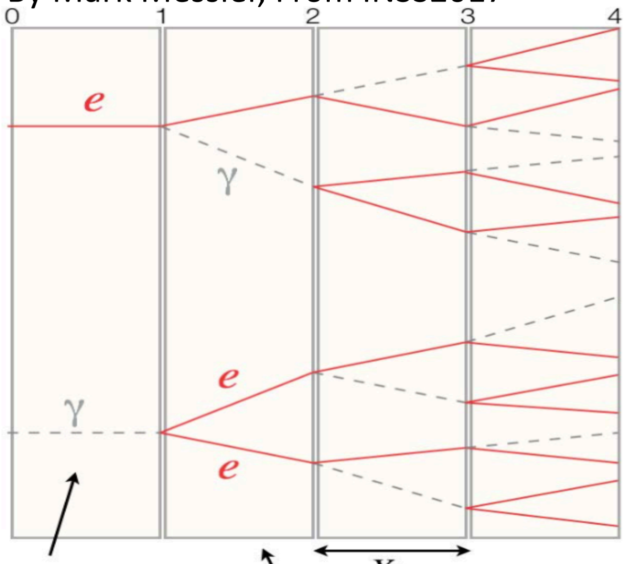


Figure 27.12: Two definitions of the critical energy E_c.

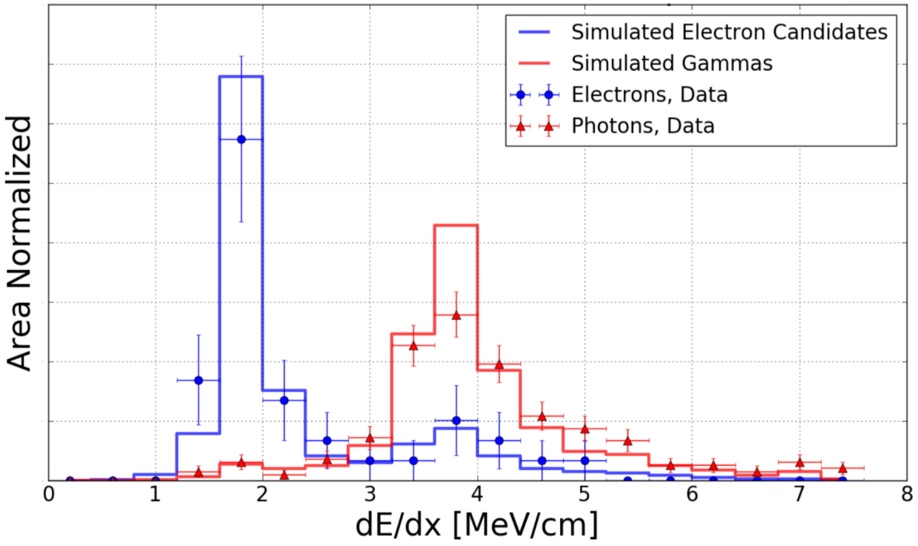
By Mark Messier, From INSS2017



No visible energy in photon shower inside first conversion distance

Visible start of photon shower has twice as much energy as the visible start of the electron shower

Electron Vs Gamma

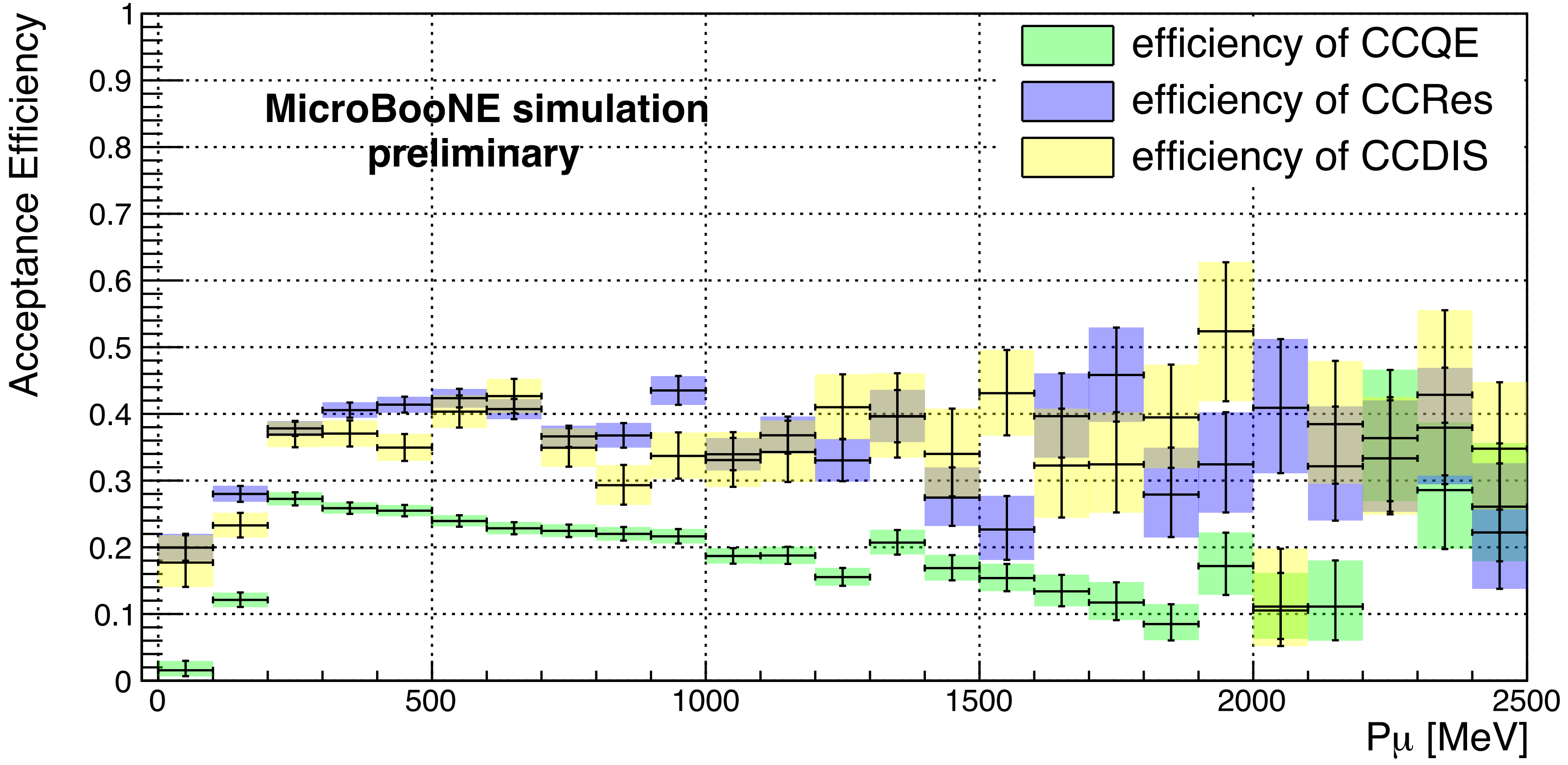


PhysRevD.95.072005

PID – summary at ~GeV neutrino interactions

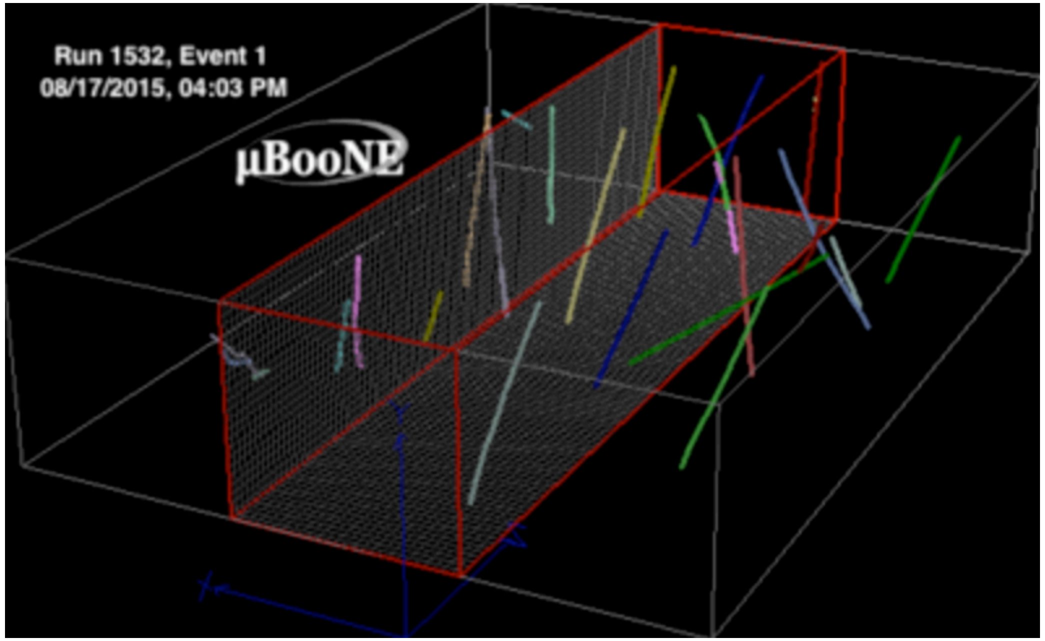
e/γ	$\mu^{\pm}/\pi^{\pm}$	Hadrons p, K, d	neutrons
EM shower (GeV) Track like at the shower start.	**Long tracks**	**Short tracks**	Invisible except scattering caused dot-like nucleus recoil
Electron: 1 MIP <dE/dx> Gamma: 1 or 2 MIP <dEdx>	MIP <dE/dx> for through going tracks Bragg peak for stopping tracks	Highly ionized particle Higher dE/dx Less straggling (narrower dE/dx distribution)	Mostly under energy threshold
Shower Cone gives the direction	KE is basically proportional to range. MCS, bragg peak, delta rays for directionality.	Should have good separation from the MIP tracks in PIDA	
Difficult to reconstruct the full energy: Stochastic nature, low threshold, incompleteness	Easy to reconstruct individual tracks, hard to separate muon and charged pions	Challenging to reconstruct short tracks. Missing track multiplicity	Missing energy for the neutrino energy reconstruction

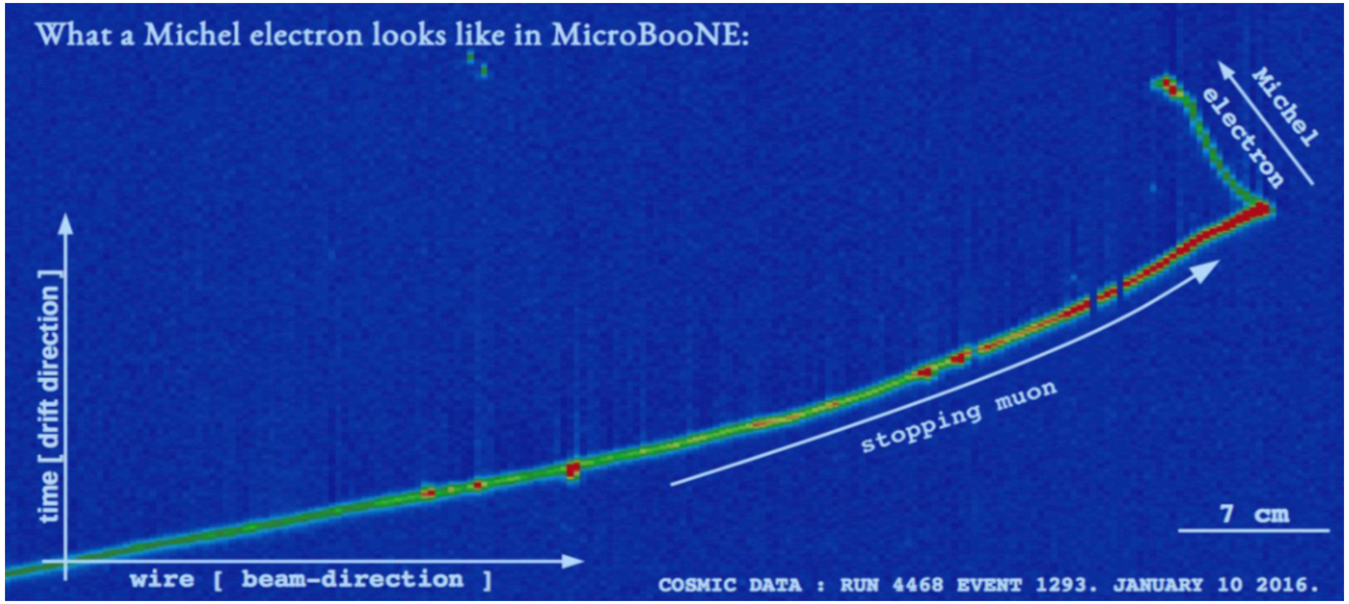
CC inclusive: selection efficiency



LArTPC Working principle – cosmic ray background

- Surface LArTPCs are exposed with cosmic rays constantly, e.g. comic rate in MicroBooNE LArTPC(~70m^3) with rate of 5kHz!
- Pros: Good energy calibration source (MIP muons, Michel e$^-$) for low energy electron reconstruction development.(arXiv 1704.02927)
- Cons: difficult to find neutrino interactions. Strict cosmic rejection significantly lower the neutrino selection efficiency.





- LArTPCs in the SBN program are using Cosmic ray tagger to tag and remove cosmic background.
- DUNE far detector will be underground with 1.5 km rock shielding, the rate of cosmic ray in the detector will be reduced by more than factor of 500,000.

Reconstruction

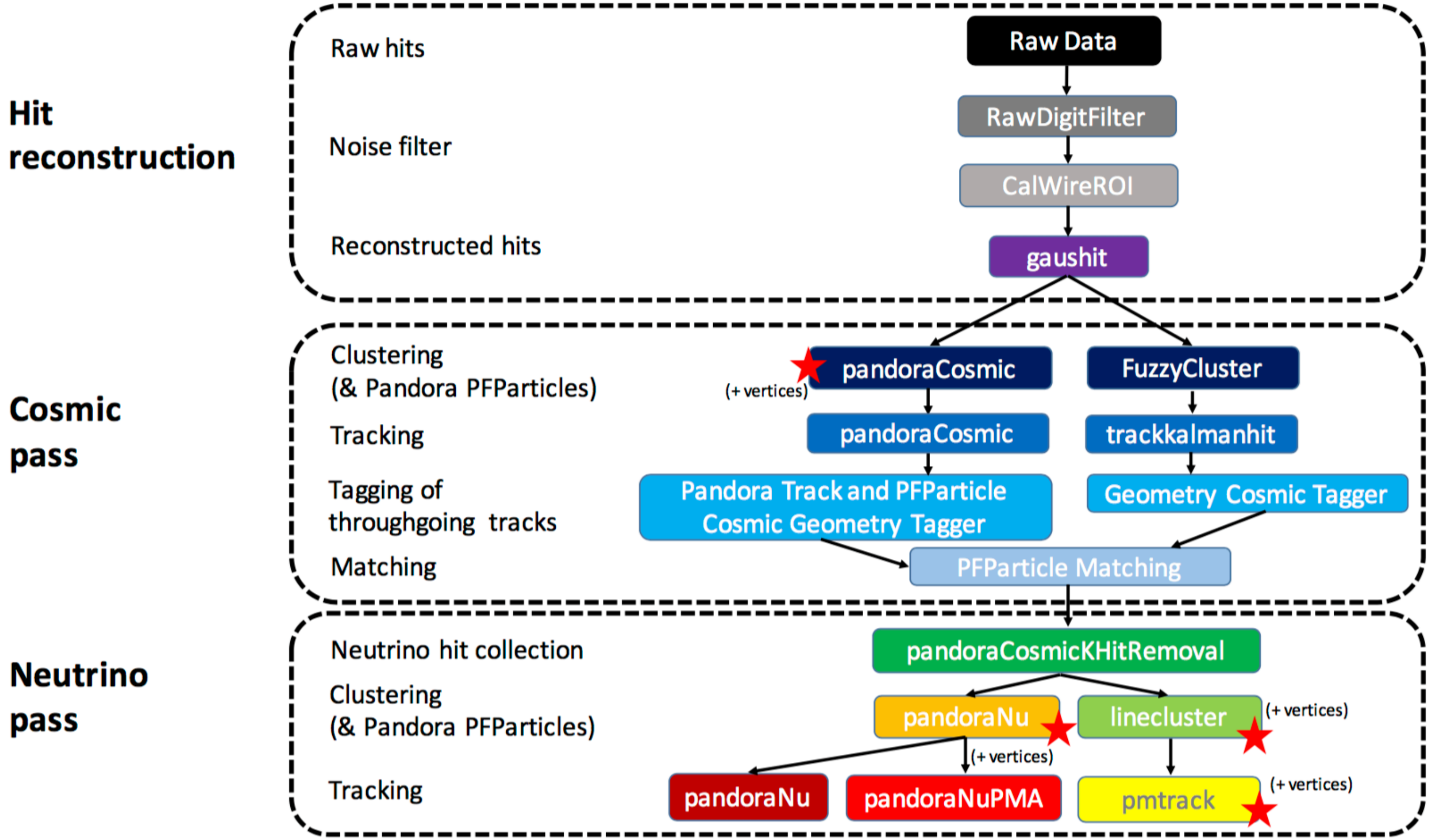


Figure 2: Reconstruction chain for data and MC processing. The red stars on some of the boxes indicate that the algorithms return reconstructed 3D vertices.

Roadmap to ν_μ CC cross-section measurement

- **Systematics Uncertainties in N_{BG} and acceptance efficiency ϵ :**
  - Flux uncertainty (dominant uncertainty)
  - Detector uncertainty: space charge, purity, recombination.
  - Model uncertainty.
  - Reconstruction efficiency: Reco vs true unsmearing matrix
- **P_μ reconstruction for differential cross-section.**
  - Contained track: from range
  - Uncontained track: from multiple scattering

1. Flux integrated cross-section

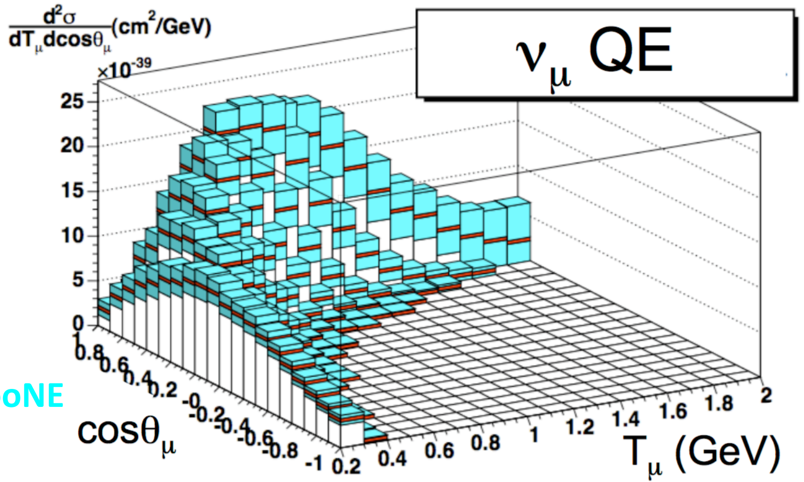
$$\sigma = \frac{N_{\text{measured}} - N_{\text{BG}}}{\epsilon \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu}}$$

Efficiency x acceptance

Number of argon target nucleons

Integrated flux

3. Double differential cross-section



From MiniBooNE

2. Single differential cross-section

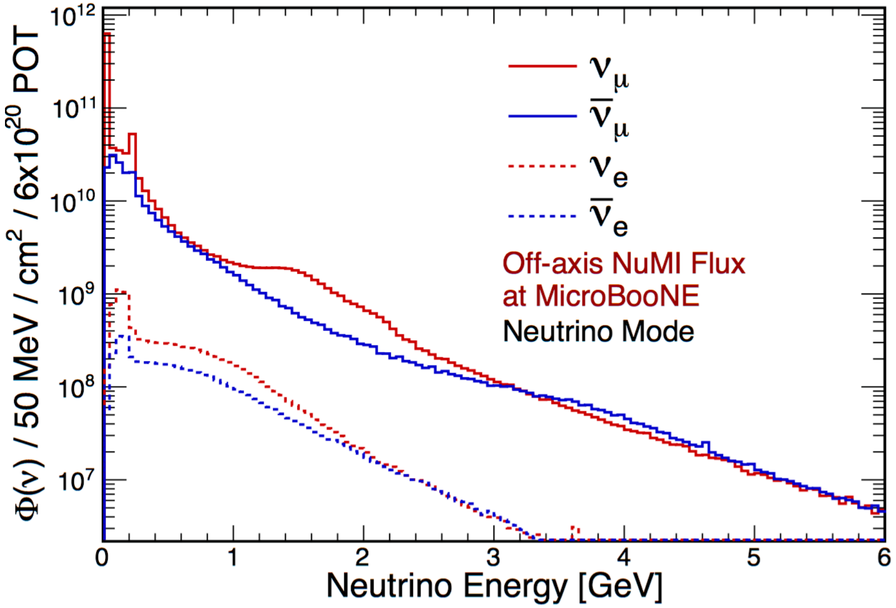
Unsmearing matrix

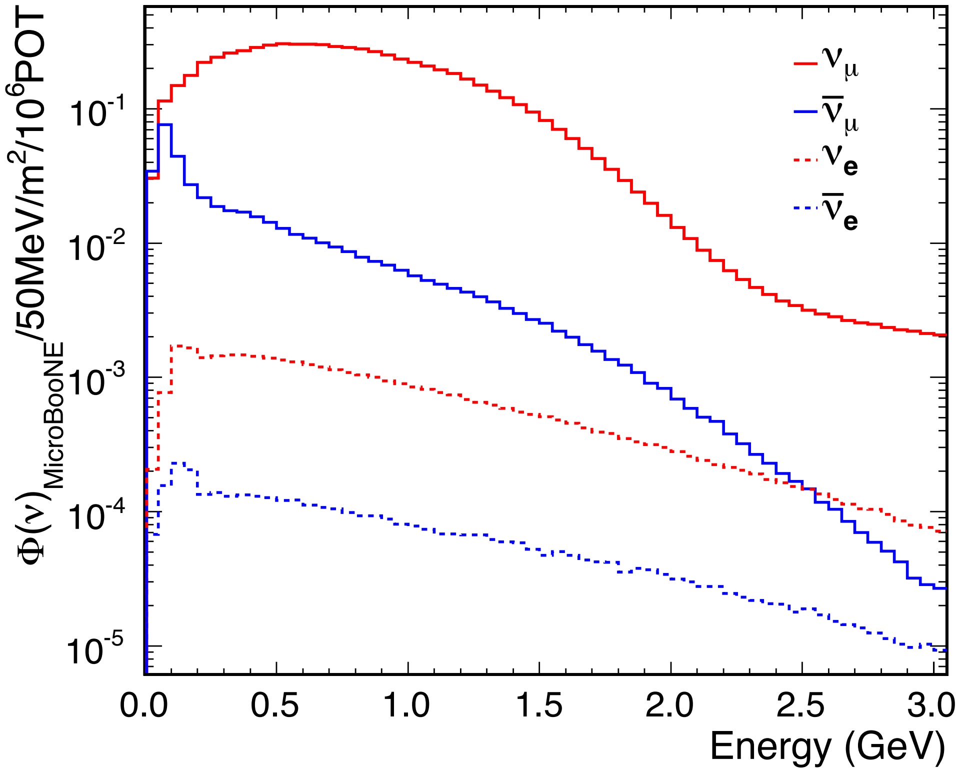
$$\frac{d\sigma}{dp_{\mu,i}} = \frac{\sum_j U_{ij} \cdot (N_{\text{measured},j} - N_{\text{BG},j})}{\epsilon_i \cdot \Delta p_{\mu,i} \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu}}$$

True muon momentum

Bin width

NuMI and BNB


$\Phi(\nu)$ / 50 MeV / cm^2 / 6x10^{20} POT
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
0
1
2
3
4
5
6
Neutrino Energy [GeV]
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
Off-axis NuMI Flux
at MicroBooNE
Neutrino Mode


$\Phi(\nu)_{\mathrm{MicroBooNE}}$/50MeV/m^2/10^{6}POT
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$