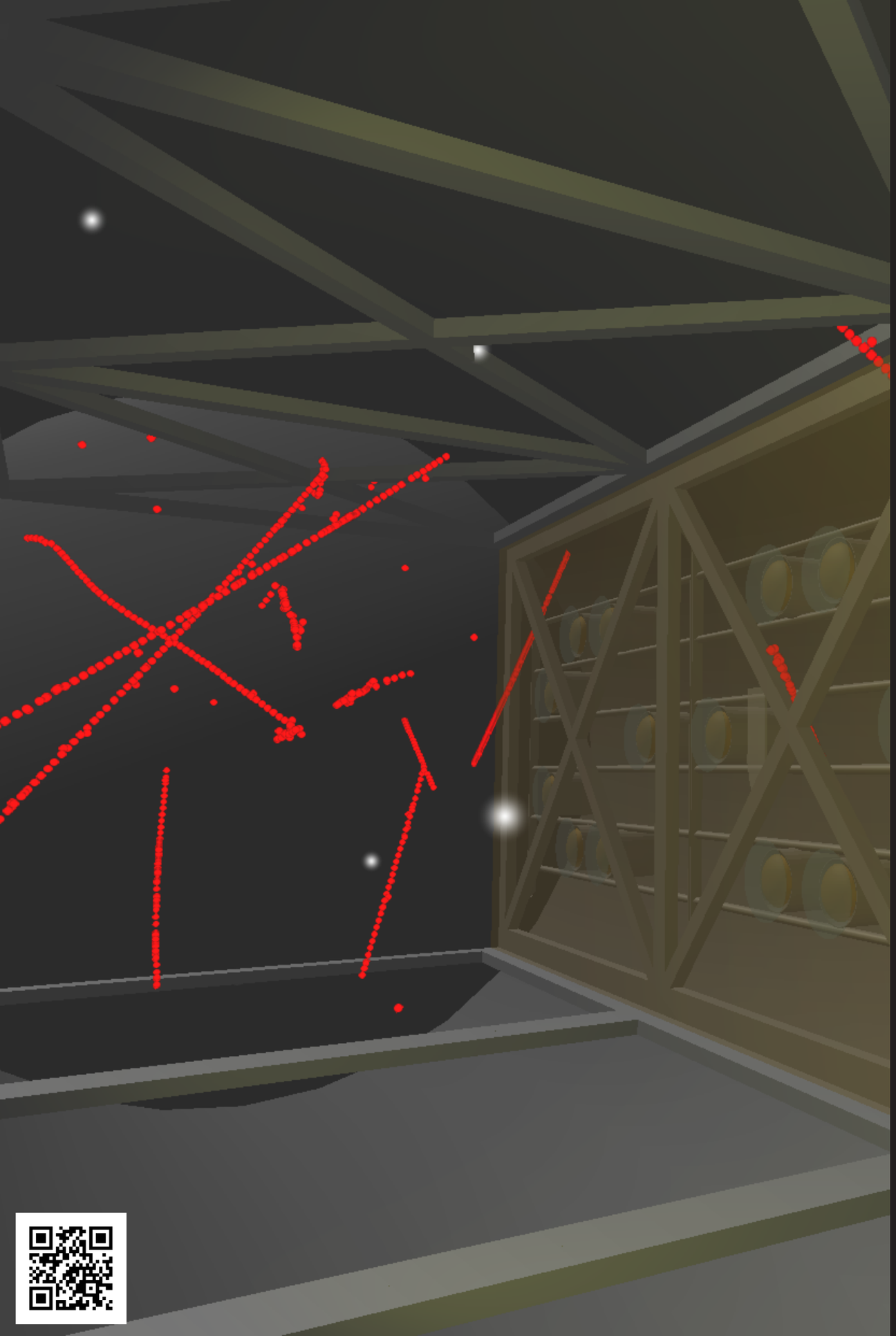


HARVARD UNIVERSITY

μBooNE

# First $\nu_\mu$ Charged-Current Inclusive Cross-Section Measurement from MicroBooNE

**Marco Del Tutto**

Joint Experimental-Theoretical Physics Seminar

**Fermilab**

24th May 2019

# Outline

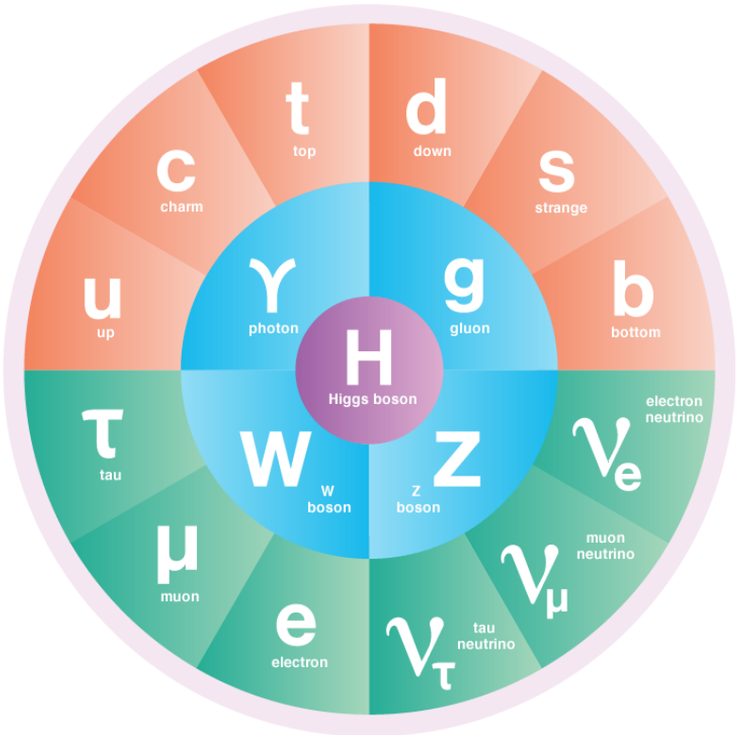
We are entering a new era in neutrino physics:
an **era of precision neutrino oscillation measurements**.

This in turn requires a **deep understanding of neutrino interactions**.
**Liquid Argon Time Projection Chambers** (LArTPCs)
are state-of-the-art detectors in neutrino physics.

I will describe how LArTPCs work, focusing on the
**MicroBooNE experiment** at Fermilab.

I will then present one of the very first neutrino interaction
measurements from the experiment,
the **muon-neutrino charged-current cross section**,
and its important role in MicroBooNE
and in the study of neutrino interactions.

# Neutrinos



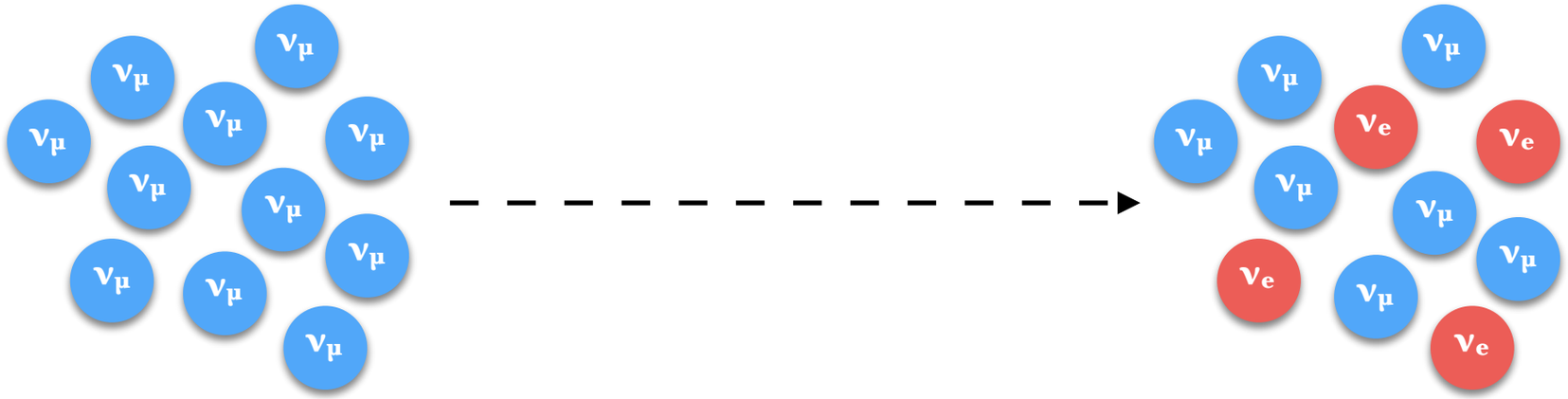

Credit: https://www.symmetrymagazine.org/standard-model/

**In the Standard Model:**

- 3 neutrinos of 3 different flavours (and 3 anti-neutrinos)
- massless neutrinos
- neutrinos only interact weakly (W or Z bosons mediate the interactions)

**Beyond the Standard Model:**

neutrino oscillations: new physics → neutrinos have mass




**However, neutrinos are still the least understood particles…**

# Neutrinos - Open Questions

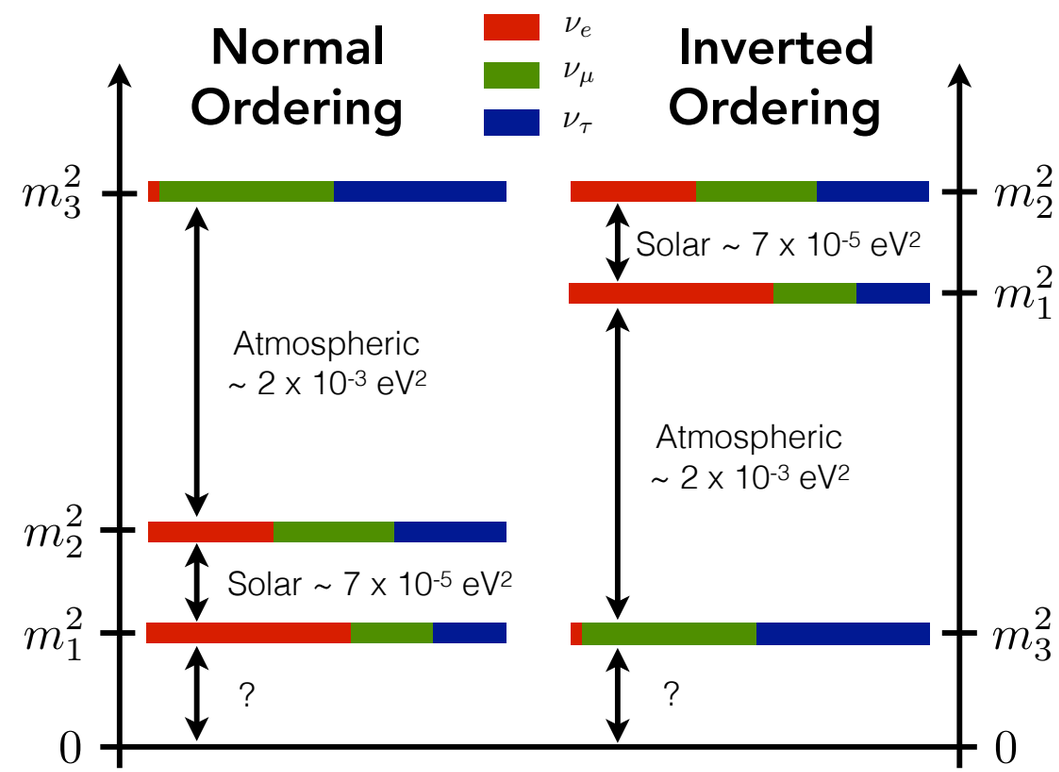
**What is the neutrino absolute mass?**

**What is the mass ordering?**
Valuable information for neutrinoless double beta decay experiments

**Is there CP Violation in the lepton sector?**
**(Is $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ ?)**
Could explain matter/anti-matter asymmetry

**What is the nature of neutrinos?**
Are they Dirac or Majorana?

**Additional (sterile) neutrinos exist?**



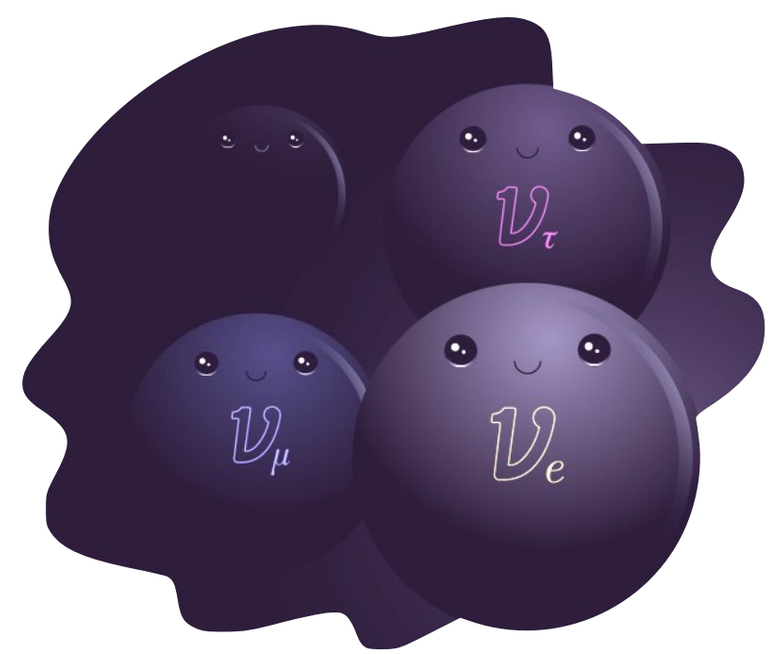




Illustration by Sandbox Studio, Chicago with Ana Kova

# Neutrinos - Open Questions

**What is the neutrino absolute mass?**

Can't be measured by long baseline experiments

**What is the mass ordering?**

Valuable information for neutrinoless double beta decay experiments

Strategy: **long** baseline experiment

**Is there CP Violation in the lepton sector?**

**(Is $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ ?)**

Could explain matter/anti-matter asymmetry

Strategy: **long** baseline experiment

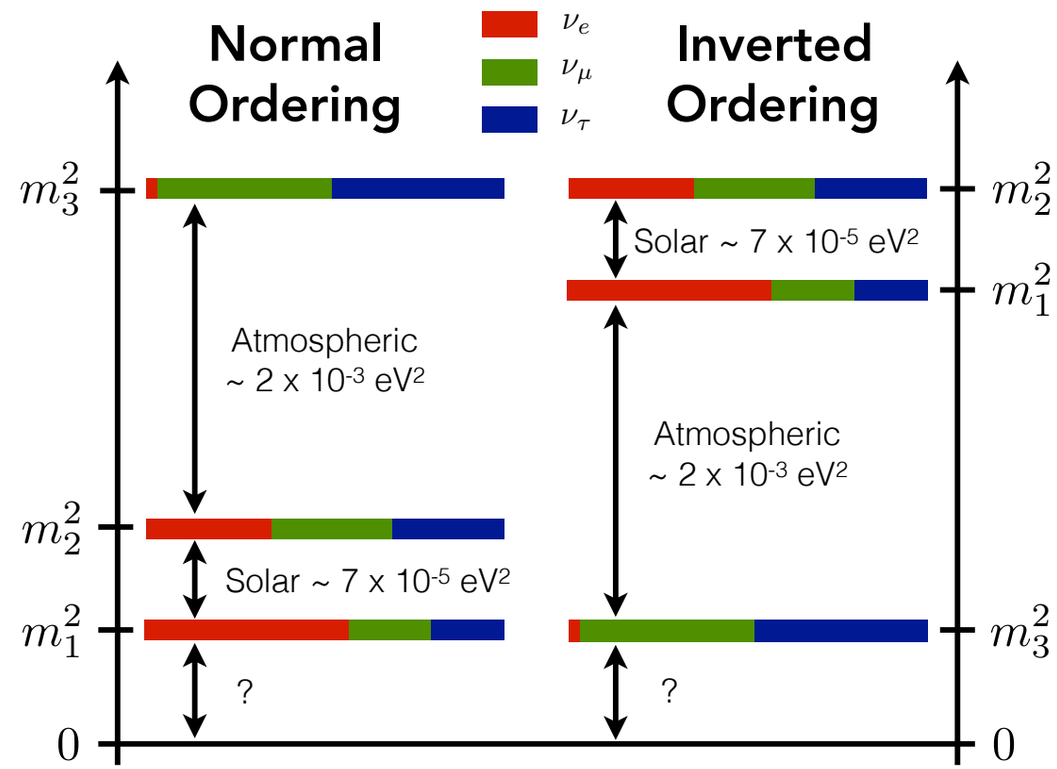
**What is the nature of neutrinos?**

Are they Dirac or Majorana?

Can't be measured by oscillation experiments

**Additional (sterile) neutrinos exist?**

Strategy: **short/long** baseline experiment



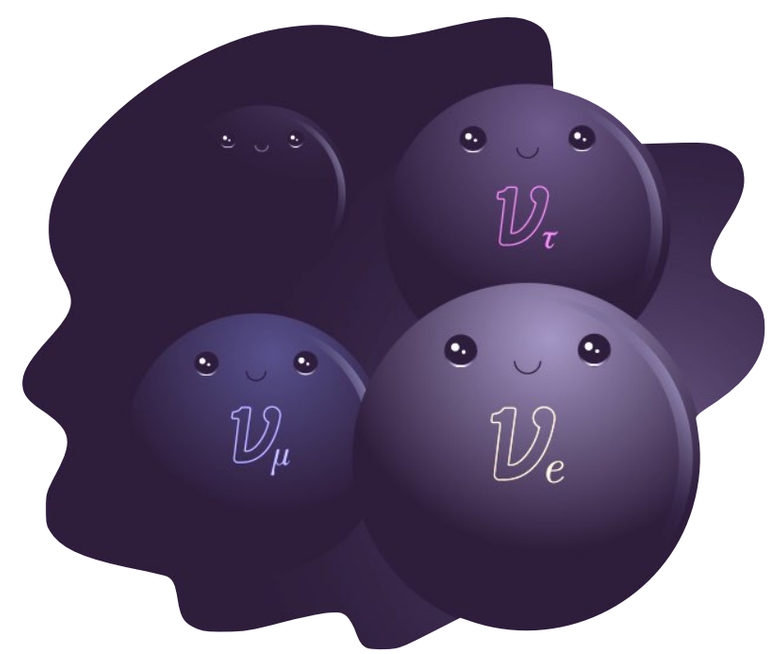




Illustration by Sandbox Studio, Chicago with Ana Kova

# Neutrino Oscillation Experiments

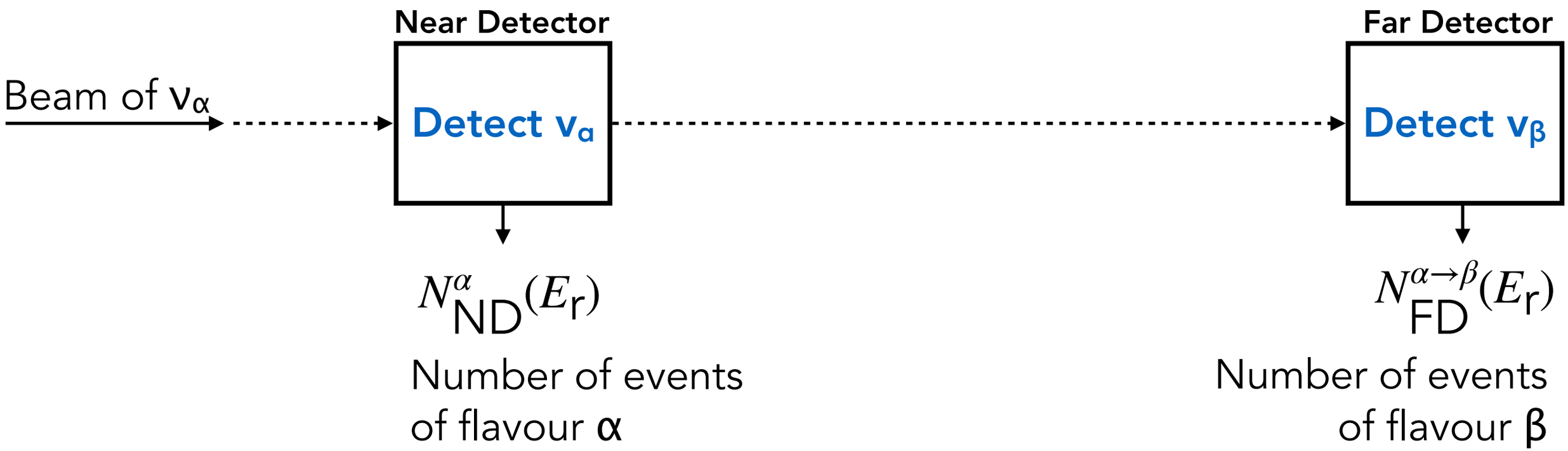
**We want to perform precision neutrino oscillation experiments**

Sketch of a neutrino oscillation experiment:

# Neutrino Oscillation Experiments

**We want to perform precision neutrino oscillation experiments**

Sketch of a neutrino oscillation experiment:

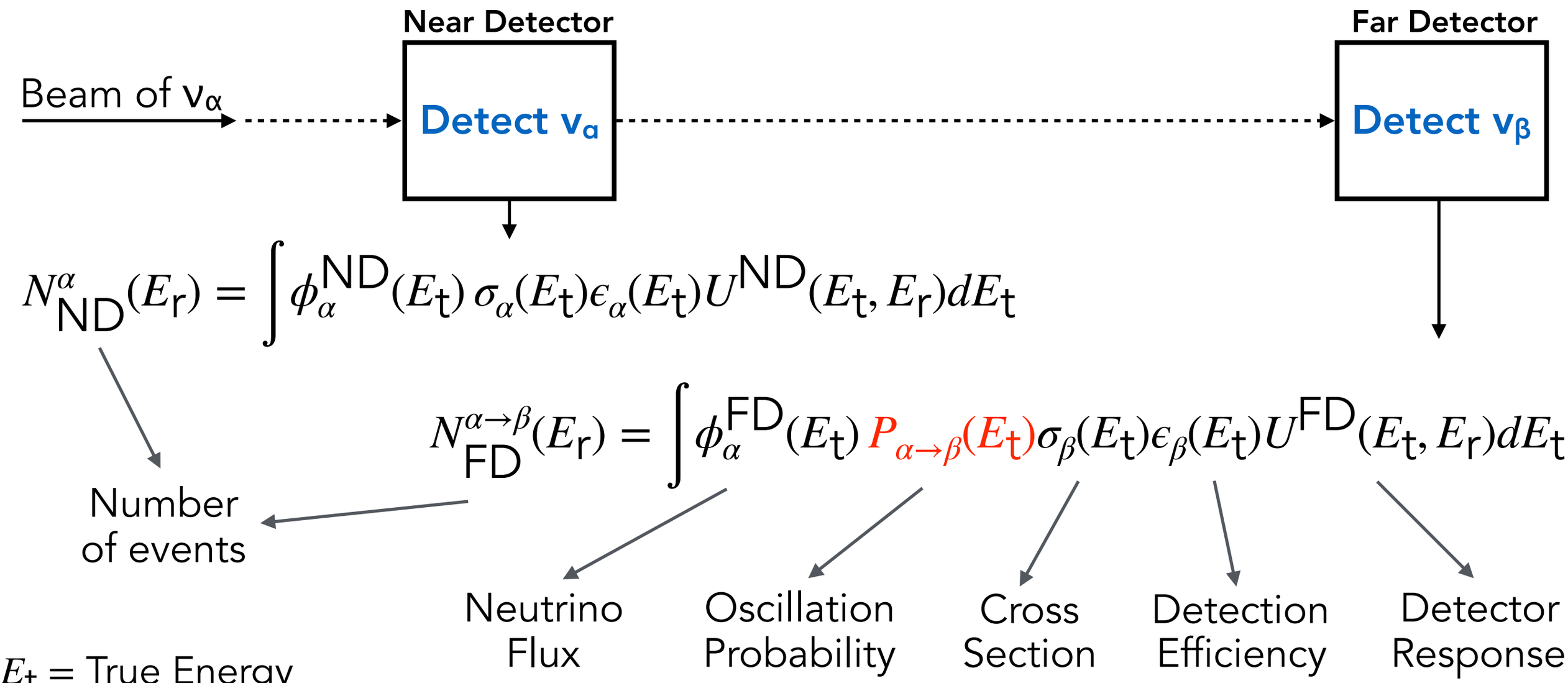



$E_{\mathrm{r}}$ = Reconstructed Energy

# Neutrino Oscillation Experiments

**We want to perform precision neutrino oscillation experiments**

Sketch of a neutrino oscillation experiment:



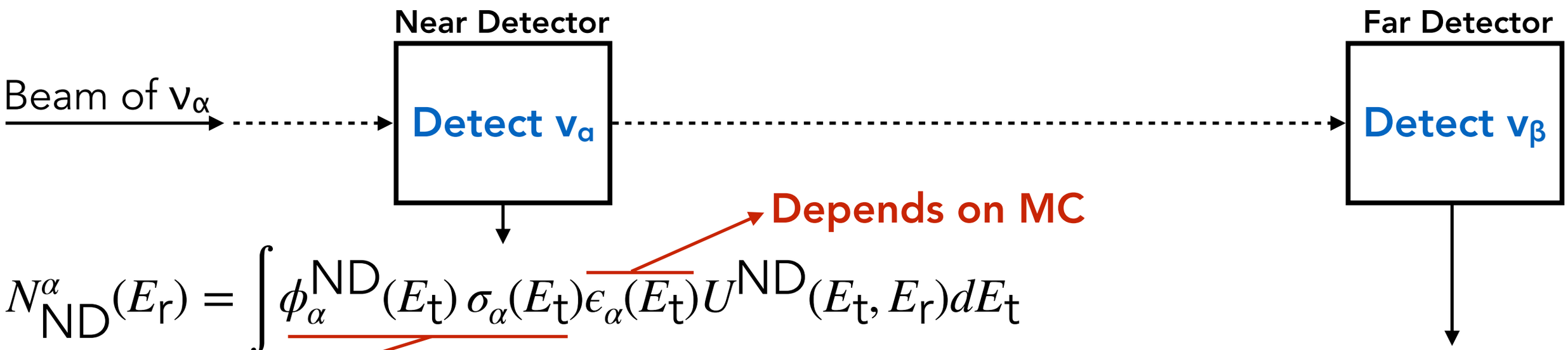

$E_t$ = True Energy
$E_r$ = Reconstructed Energy

*σ also depends on observables like muon momentum

# Neutrino Oscillation Experiments

**We want to perform precision neutrino oscillation experiments**

Sketch of a neutrino oscillation experiment:




**Depends on MC**

$$N^{\alpha}_{\mathrm{ND}}(E_{\mathrm{r}}) = \int \phi^{\mathrm{ND}}_{\alpha}(E_{\mathrm{t}})\, \sigma_{\alpha}(E_{\mathrm{t}}) \epsilon_{\alpha}(E_{\mathrm{t}}) U^{\mathrm{ND}}(E_{\mathrm{t}}, E_{\mathrm{r}}) dE_{\mathrm{t}}$$

**Convolution of cross section and flux**

$$N^{\alpha\to\beta}_{\mathrm{FD}}(E_{\mathrm{r}}) = \int \phi^{\mathrm{FD}}_{\alpha}(E_{\mathrm{t}})\, P_{\alpha\to\beta}(E_{\mathrm{t}}) \sigma_{\beta}(E_{\mathrm{t}}) \epsilon_{\beta}(E_{\mathrm{t}}) U^{\mathrm{FD}}(E_{\mathrm{t}}, E_{\mathrm{r}}) dE_{\mathrm{t}}$$

**We need precise cross section measurements!**

# Neutrino Interactions

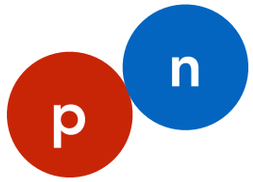
## PAST

**1970-1990's**

Using hydrogen/deuterium-filled bubble chambers:

- to test the V-A nature of the weak interactions
- to measure the axial vector form factor of the nucleon

**Hydrogen**

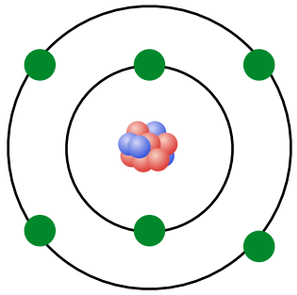



**Deuterium**

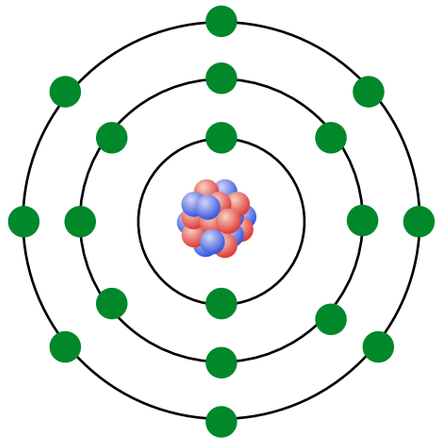
## TODAY

Modern experiments no longer include deuterium but use complex nuclei as their neutrino targets.

For heavy elements **nuclear effects** are not understood: **more data is needed!**



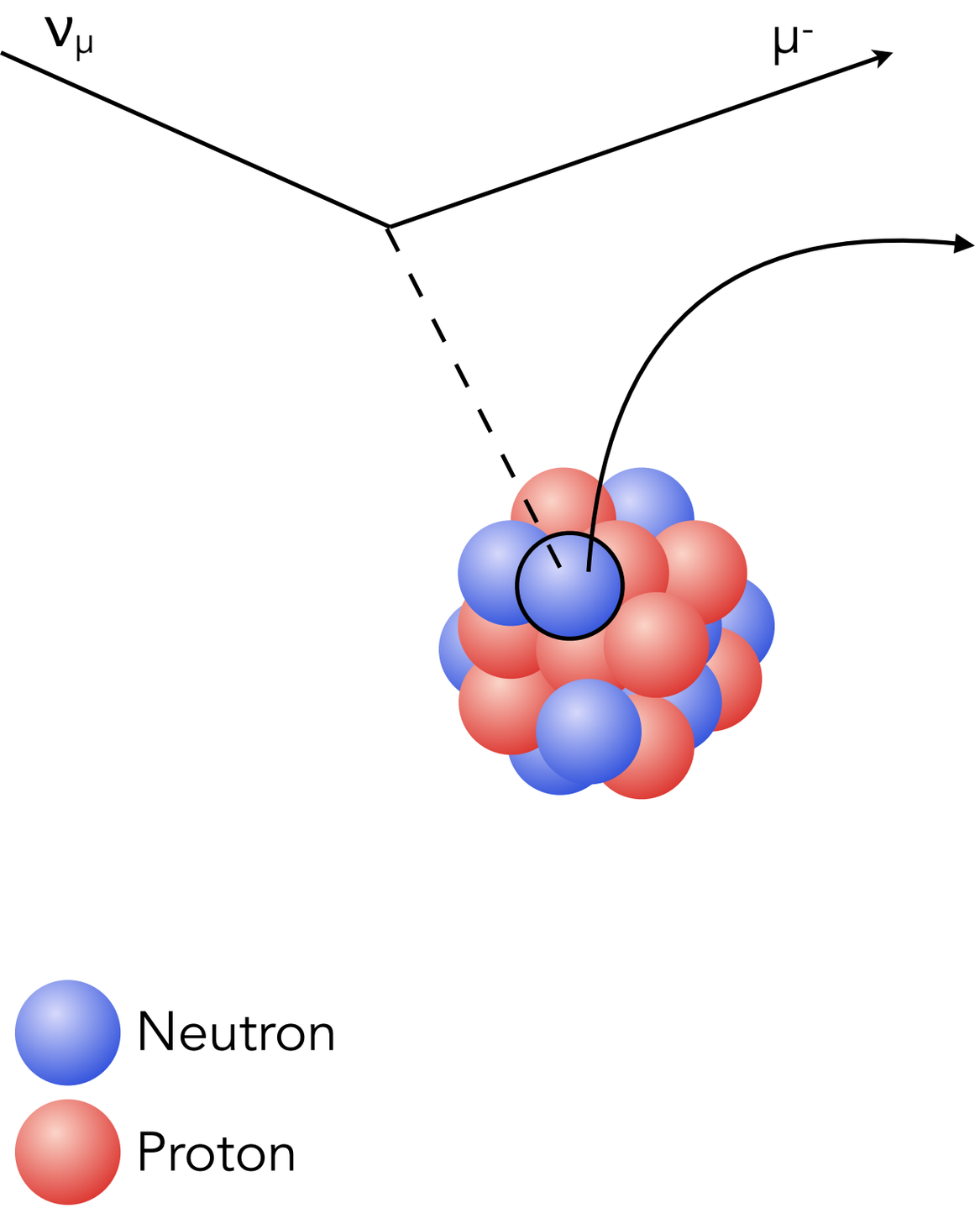
**Carbon**



**Argon**

**MicroBooNE!**

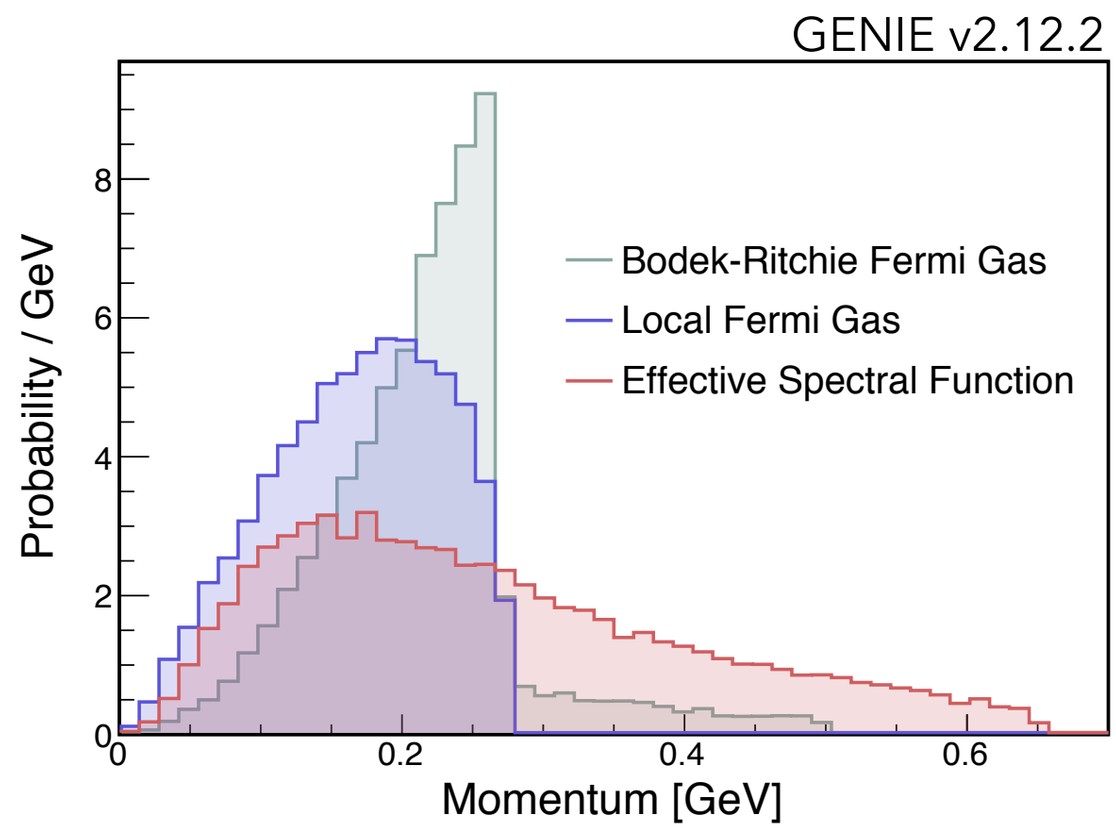
# Nuclear Effects



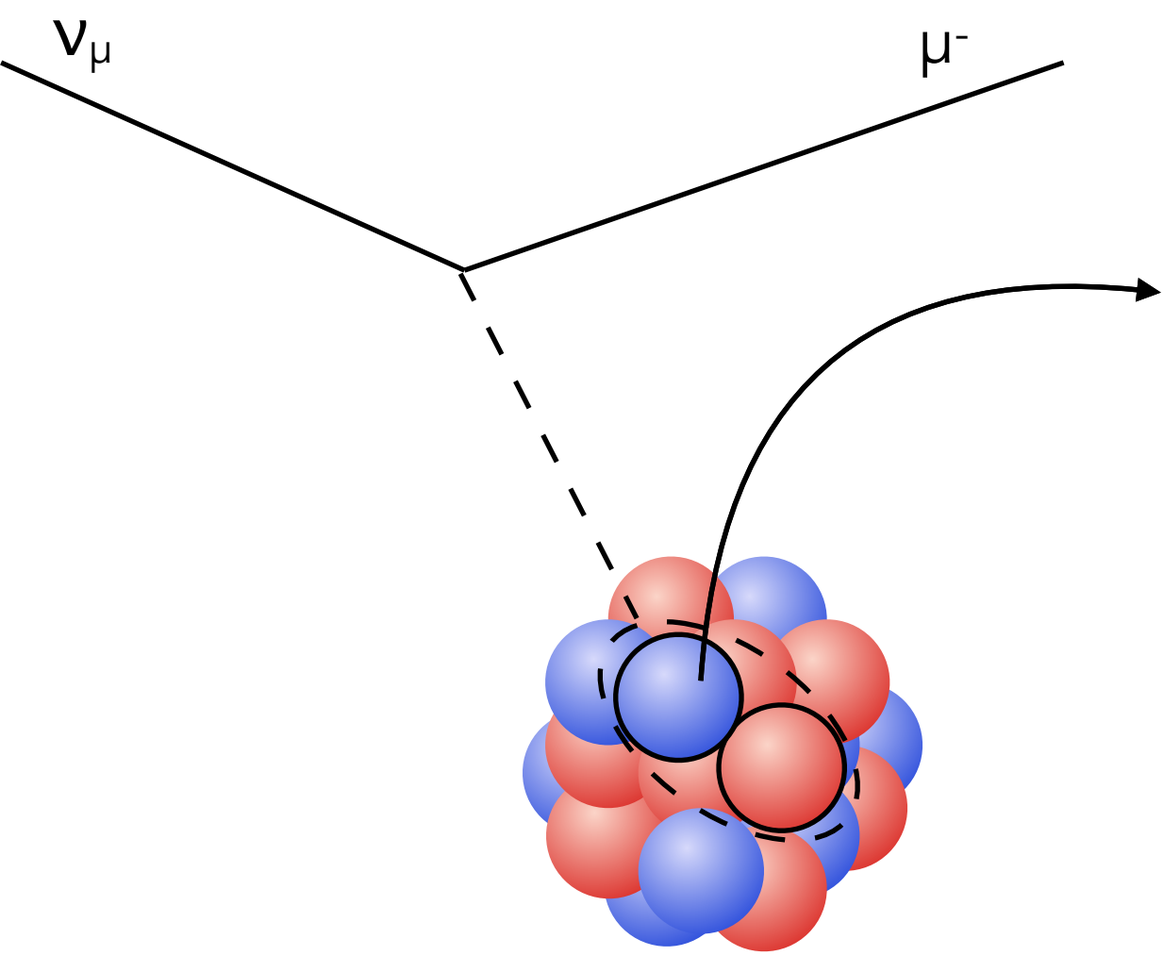

Nucleon embedded in nucleus:

**Fermi Motion** must be taken into account

(Fermi Gas, Spectral Functions, …)



# Nuclear Effects




The neutrino can interact with a **correlated pair of nucleons**:

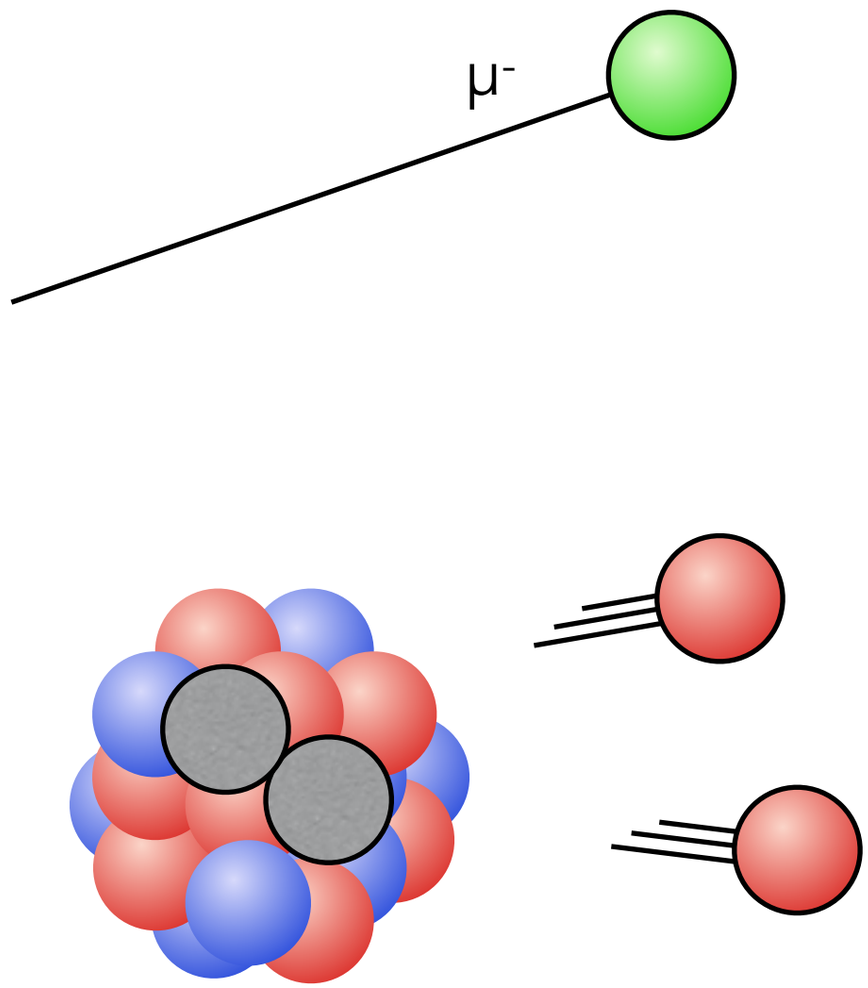
- Meson Exchange Current (**MEC**)
- Short Range Nucleon-Nucleon Correlations

**This leads to…**

Neutron

Proton

# Nuclear Effects




**...two proton emission**

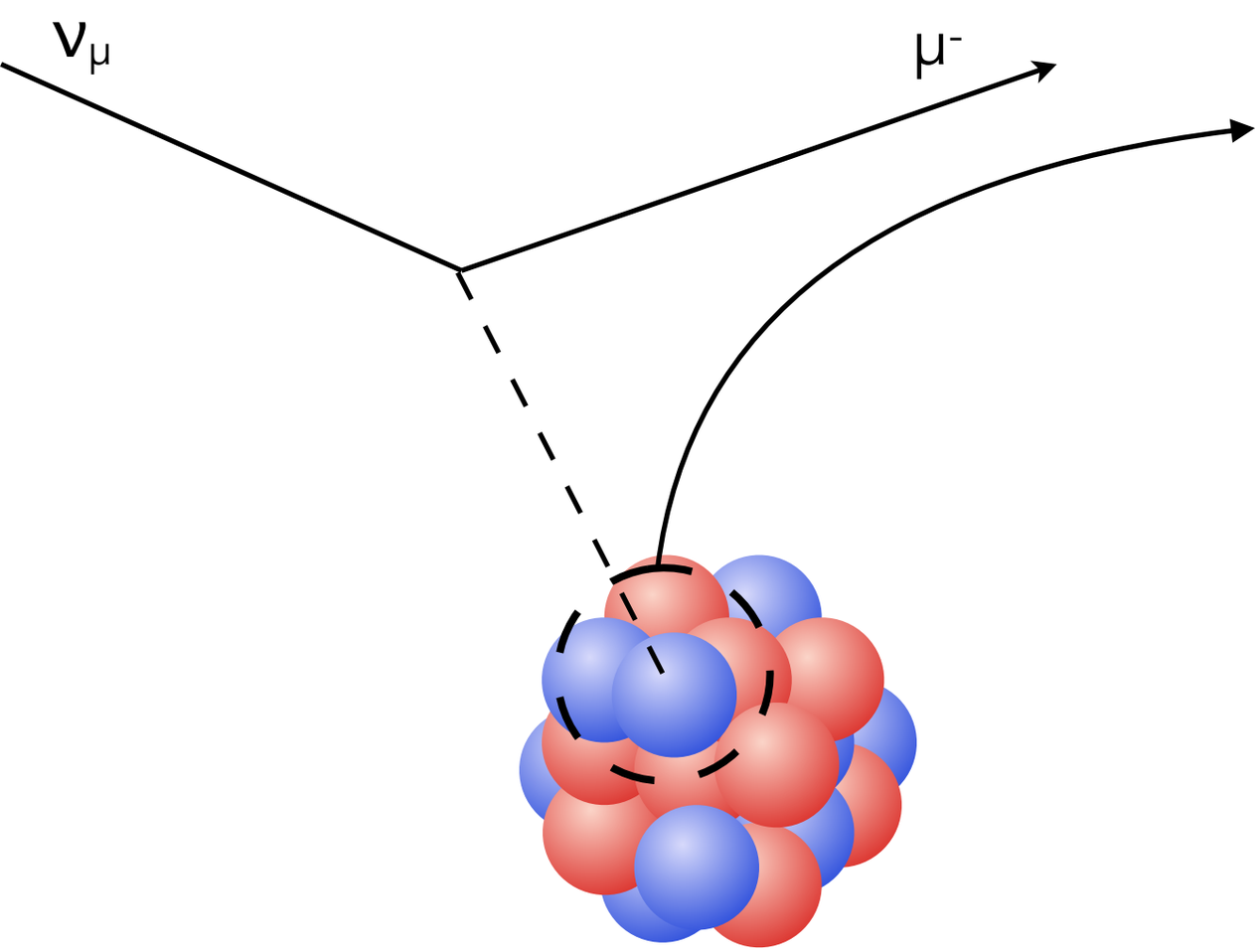
(or even more)

- Final state is different from the "traditional quasi-elastic final state" with 1μ1p
- Need a detector that can resolve hadrons: can be done in LAr!

Neutron

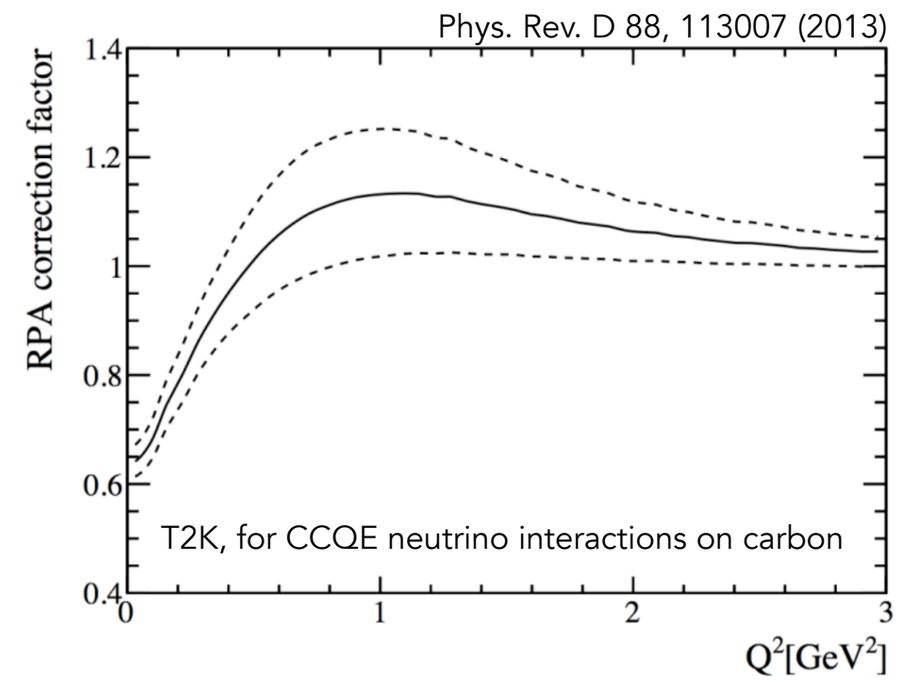
Proton

# Nuclear Effects




## Random Phase Approximation (RPA)

The strengths of electroweak couplings may change from their free nucleon values due to the presence of strongly interacting nucleons.



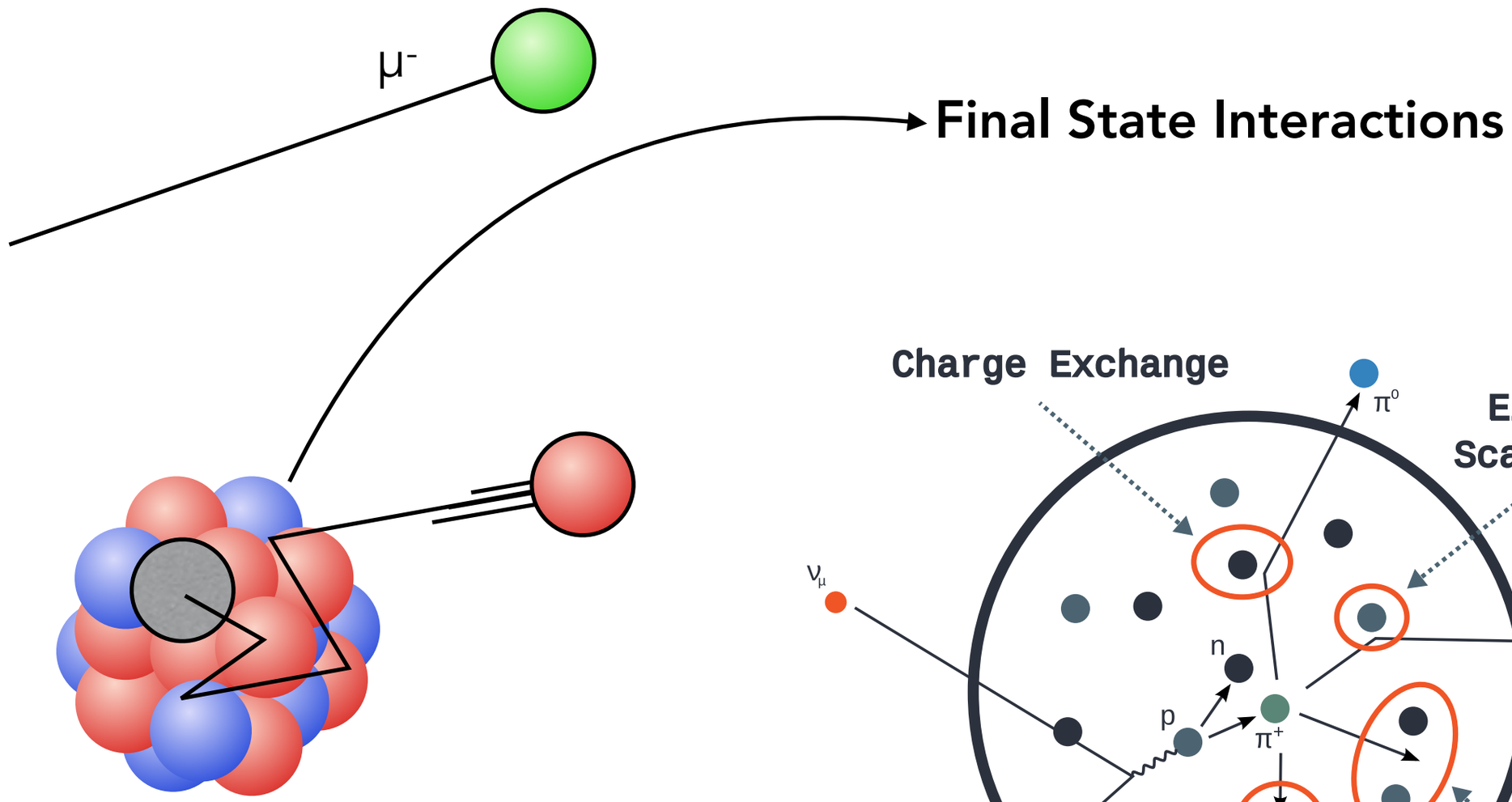

Neutron

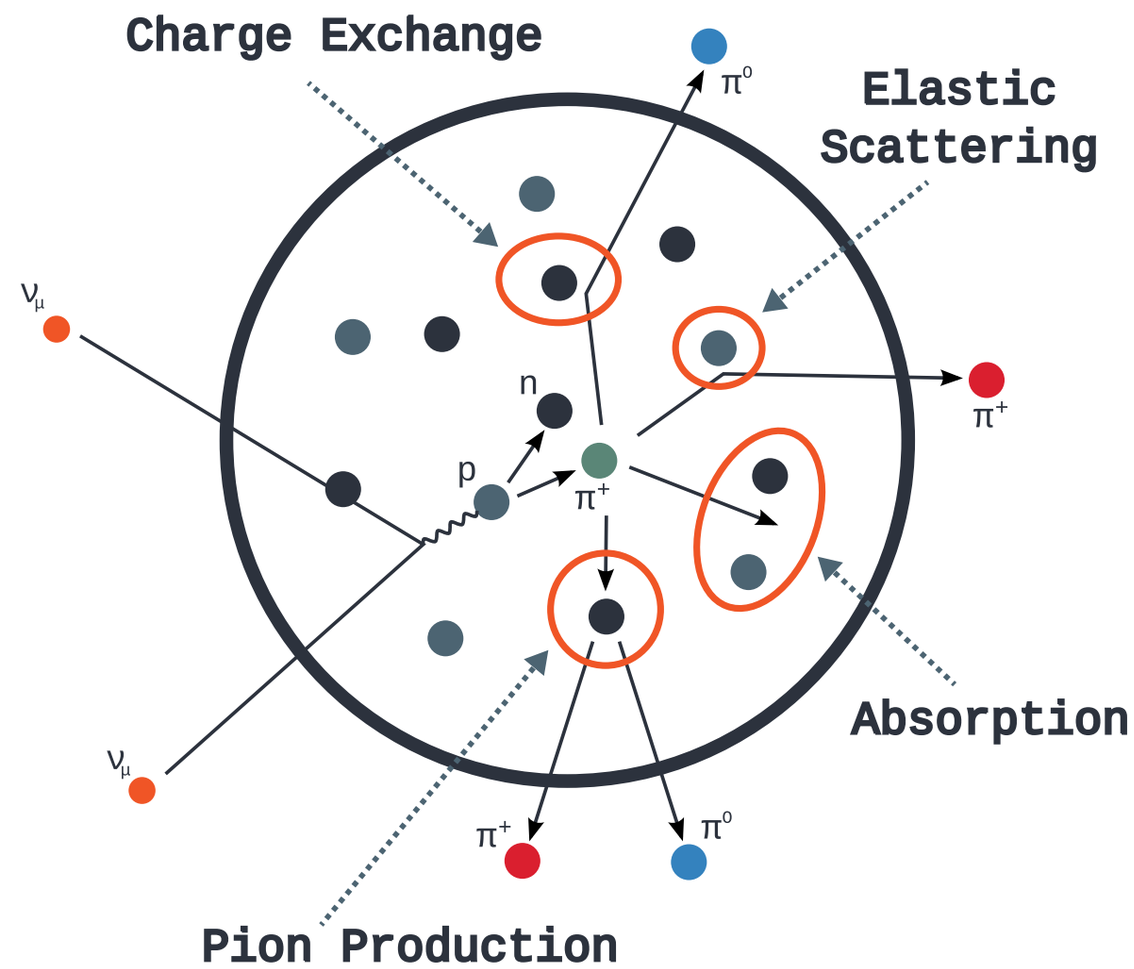
Proton

Continuum Random-Phase Approximation (CRPA) predicts rich physics effects for forward going events (see e.g. Phys. Rev. C 92 024606).

Calculations are done on carbon targets. **Extrapolation** of cross sections from **carbon to argon** is non-trivial (see e.g. Phys. Rev. C 97 044616).

# Nuclear Effects



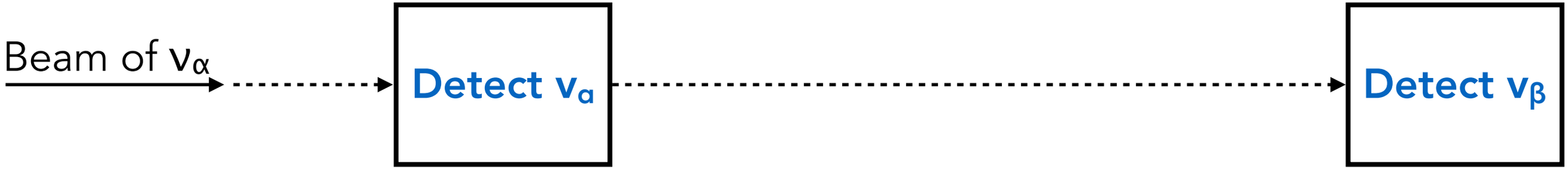




Neutron

Proton

Credit: T. Golan

# Is It Important to Understand Cross Sections?




Example, uncertainties on the predicted number of $\nu_e$ events at the FD:

**T2K**

| Source of uncertainty | $\nu_e$ CC [%] |
|---|---|
| Flux and common cross sections | |
| (w/o ND280 constraint) | 26.0 |
| (w ND280 constraint) | 3.2 |
| Independent cross sections | 4.7 |
| SK | 2.7 |
| FSI + SI (+PN) | 2.5 |
| Total | |
| (w/o ND280 constraint) | 26.8 |
| (w ND280 constraint) | 6.8 |

https://doi.org/10.1103/PhysRevD.91.072010

**NOvA**

| Source of uncertainty | $\nu_e$ CC [%] |
|---|---|
| Cross sections and FSI | 7.7 |
| Normalisation | 3.5 |
| Calibration | 3.2 |
| Detector response | 0.67 |
| Neutrino flux | 0.63 |
| $\nu_e$ extrapolation | 0.36 |
| Total systematic uncertainty | 9.2 |

https://doi.org/10.1103/PhysRevD.98.032012

**DUNE** wants to do better than this.

DUNE will have a **near detector** to achieve this, but in the meantime

we are getting a head start on this with new data on **argon** from **MicroBooNE**.

**CC inclusive** cross sections are fundamental as currently used for MC oscillation studies in DUNE.

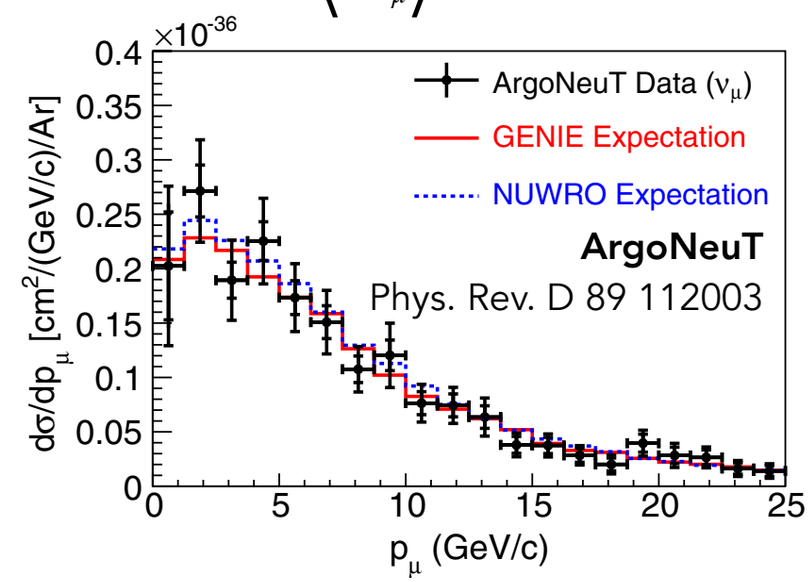
# $\nu_\mu$ CC Inclusive Measurements

From modern accelerator-based neutrino experiments:

| Experiment | Target | References |
|---|---|---|
| ArgoNeuT | Ar | Phys. Rev. Lett. 108 161802<br>Phys. Rev. D 89 112003 |
| MINERvA | CH, C/CH, Fe/CH, Pb/CH | Phys. Rev. Lett. 112, 231801<br>Phys. Rev. D94, 112007<br>Phys. Rev. Lett. 116 |
| MINOS | Fe | Phys. Rev. D81, 072002 |
| NOMAD | C | Phys. Lett. B660, 19 |
| SciBooNE | CH | Phys. Rev. D83, 12005 |
| T2K | CH, $H_2O$, Fe | Phys. Rev. D87, 092003<br>Phys. Rev. D90, 052010<br>Phys. Rev. D93, 072002 |

→ Only ν-Ar measurement!

$\langle E_{\nu_\mu} \rangle = 9.6\,\text{GeV}$



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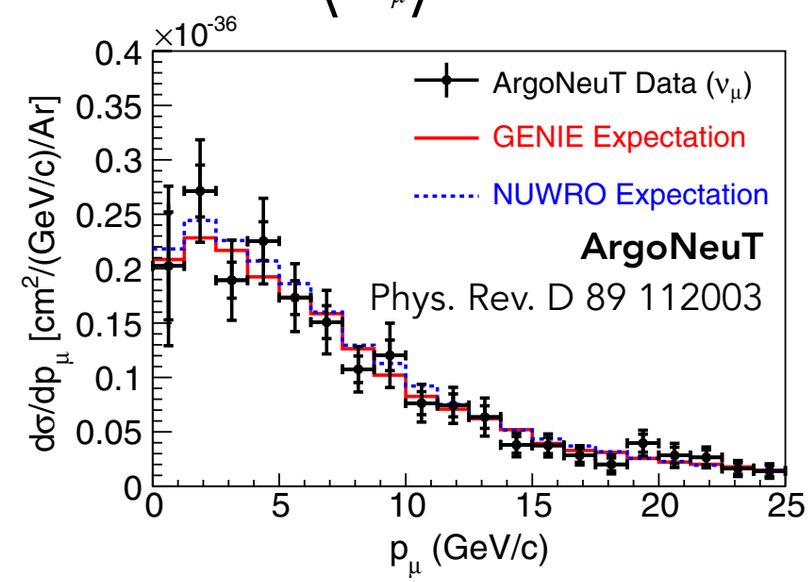



This talk:

| | | |
|---|---|---|
| MicroBooNE | Ar | https://arxiv.org/abs/1905.09694 |

$\langle E_{\nu_\mu} \rangle = 0.8\,\text{GeV}$

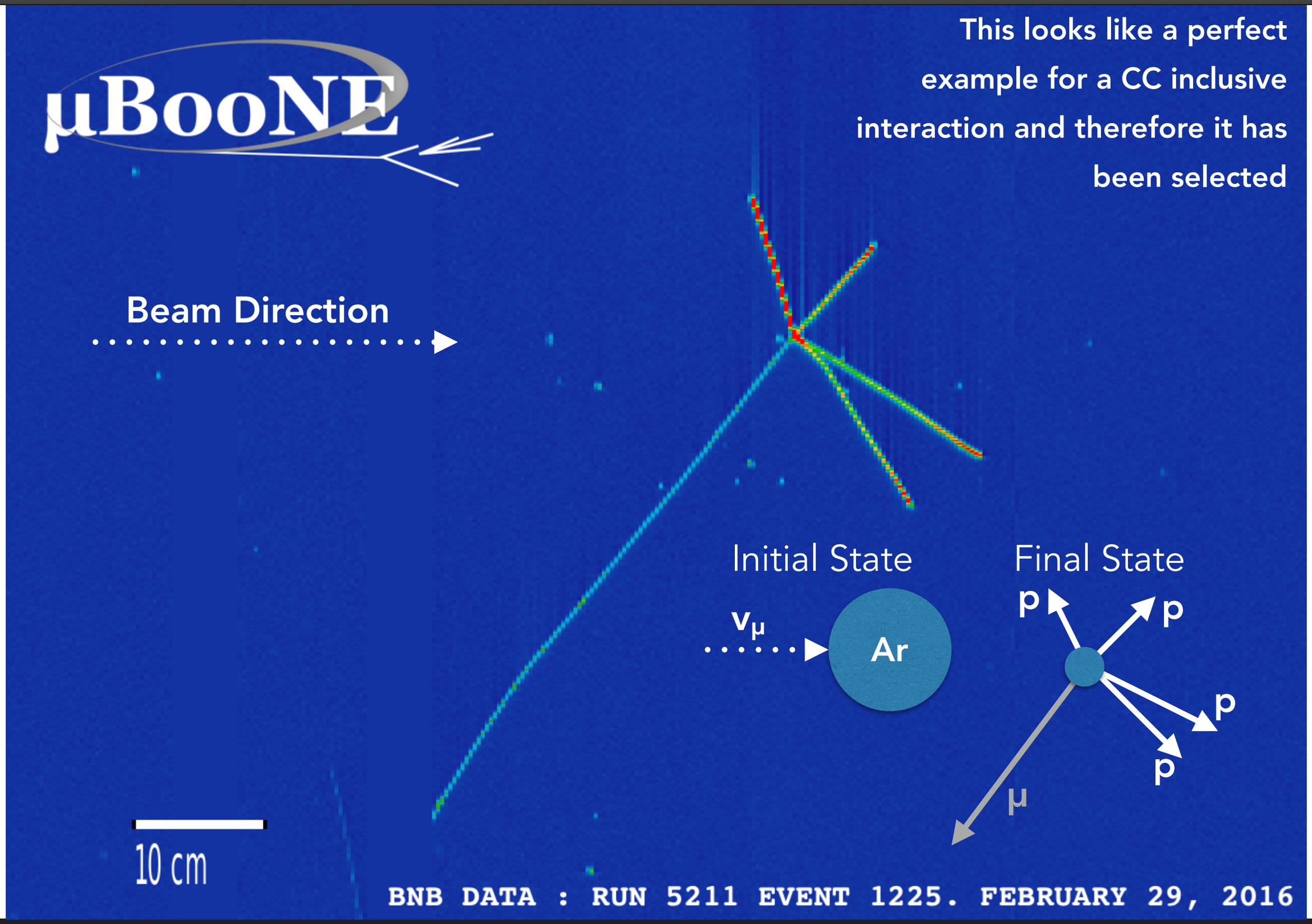
Double-differential

Full angular coverage

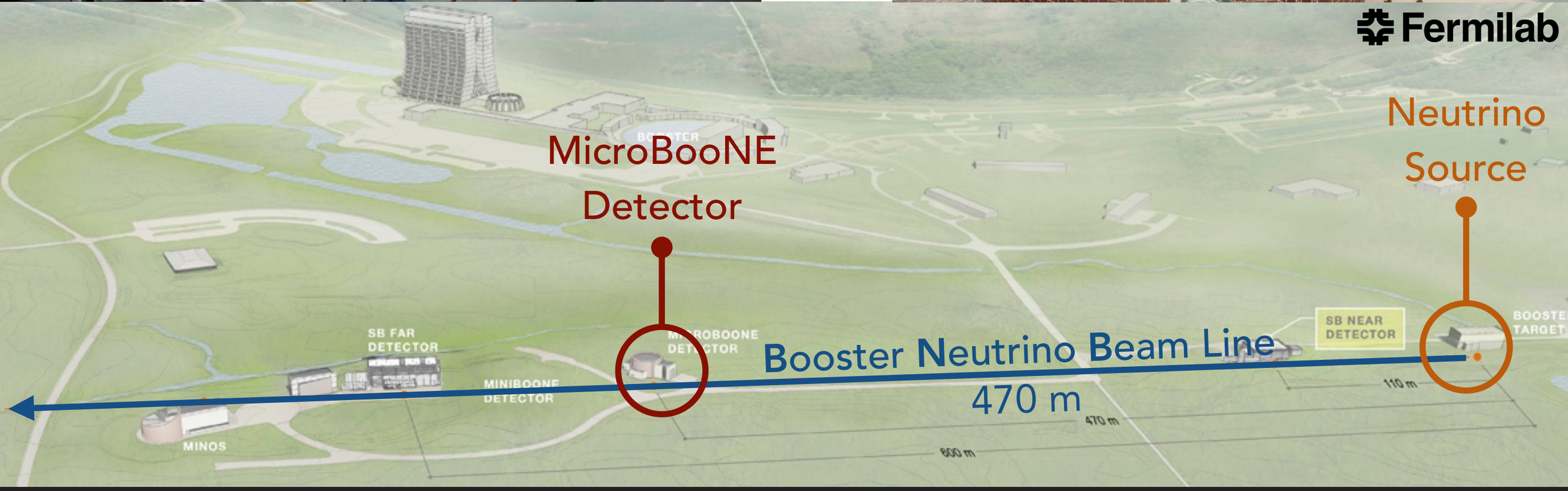
# What Next?

- How can we develop theory models that describe the present data?
- What is the situation going to look like for argon?
- Can MicroBooNE tell us more about final states and nuclear effects?

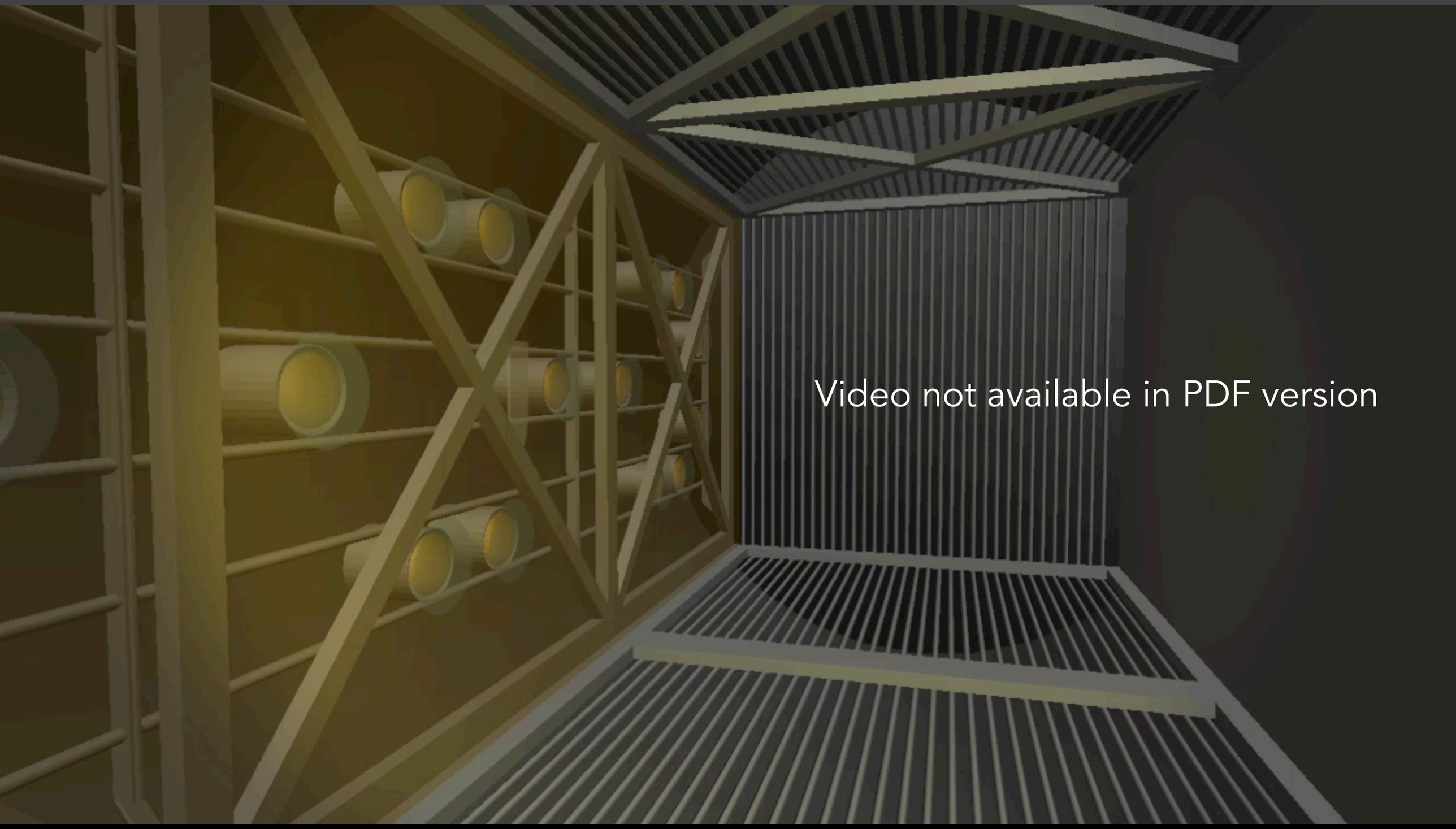
# Liquid Argon Time Projection Chambers



# MicroBooNE


Fermilab
MicroBooNE
Detector
Neutrino
Source
Booster Neutrino Beam Line
470 m
SB FAR
DETECTOR
MINIBOONE
DETECTOR
MINOS
SB NEAR
DETECTOR
110 m
470 m
600 m

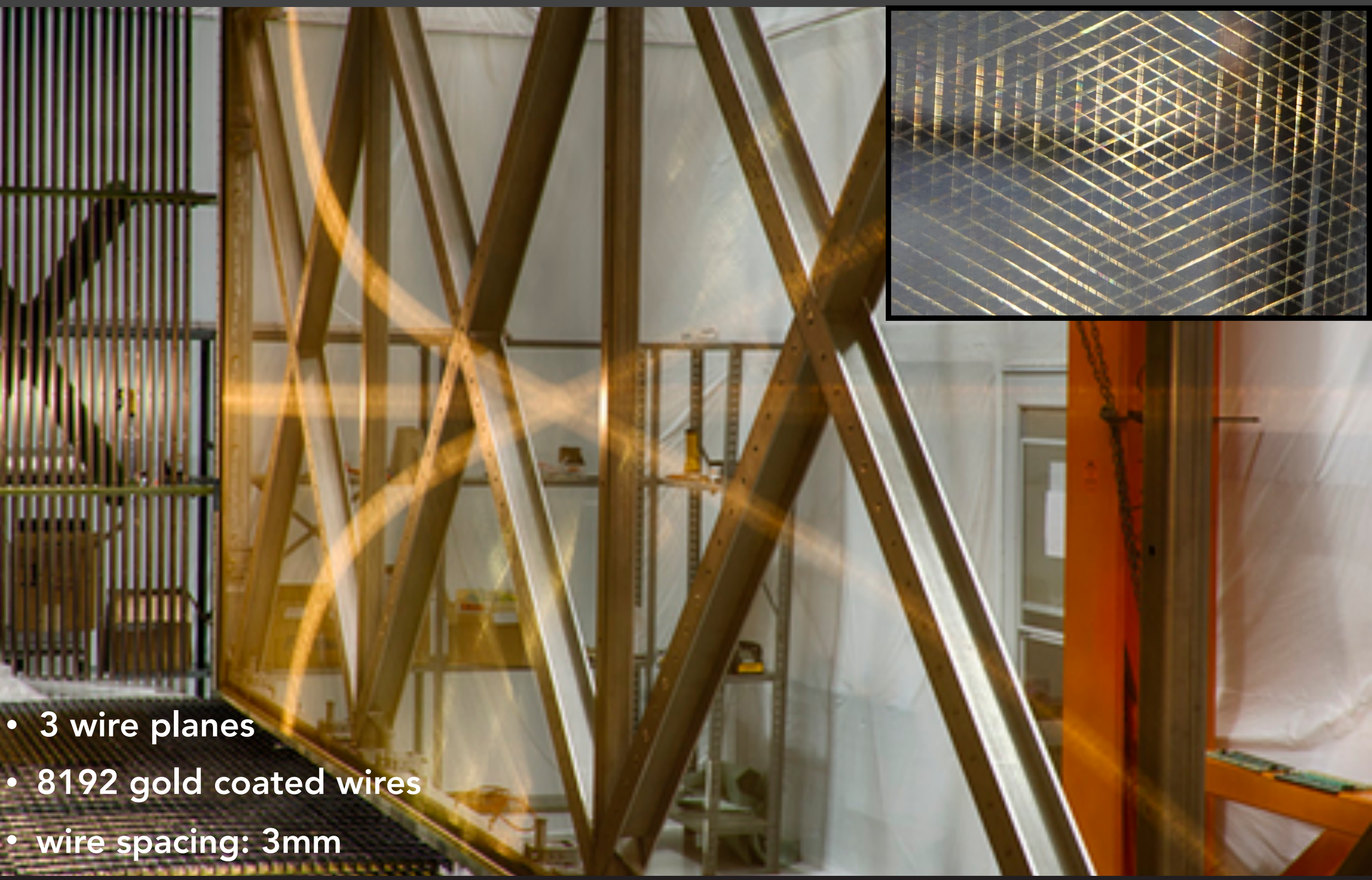
# The Time Projection Chamber




http://venu.physics.ox.ac.uk

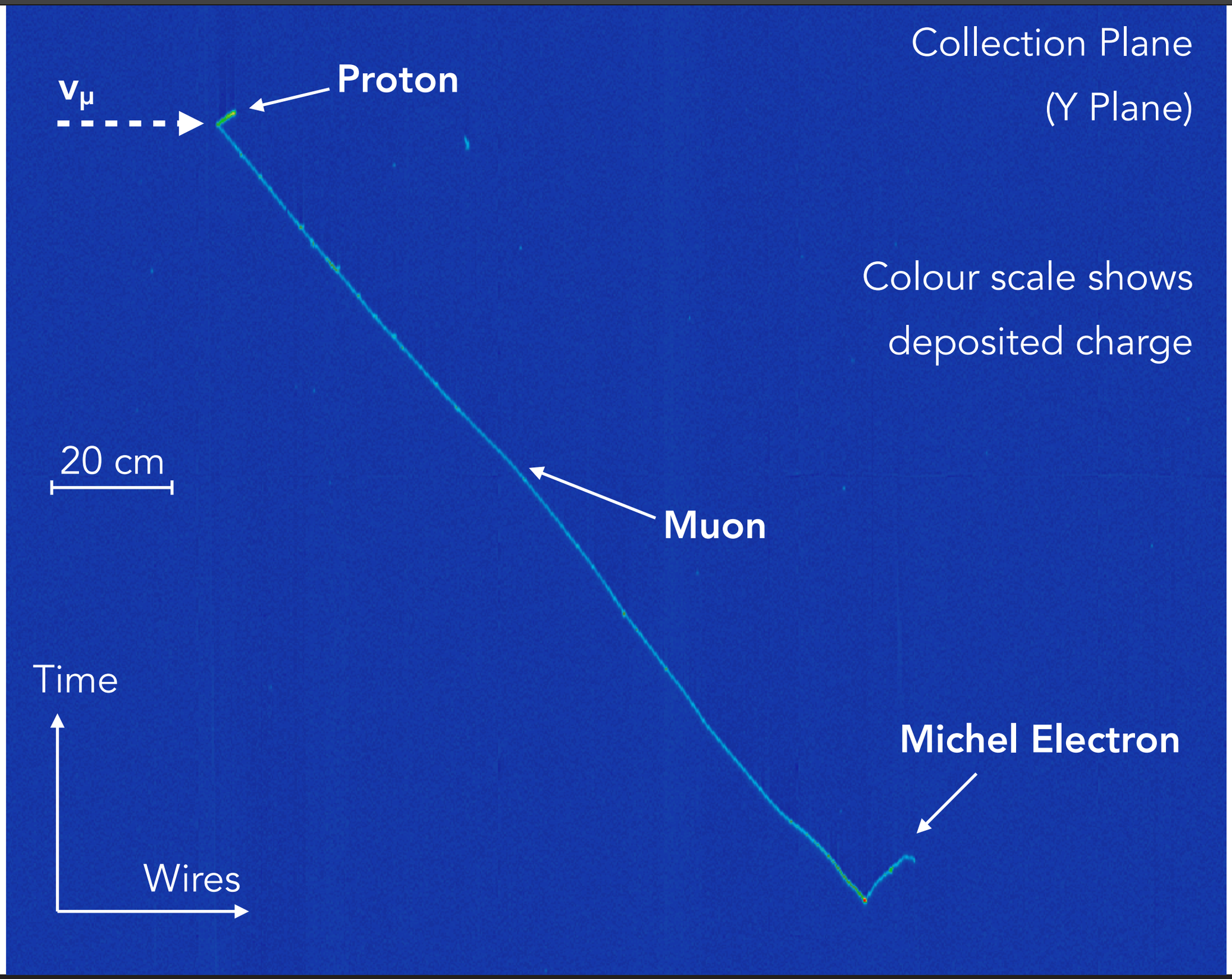
VENu

# MicroBooNE

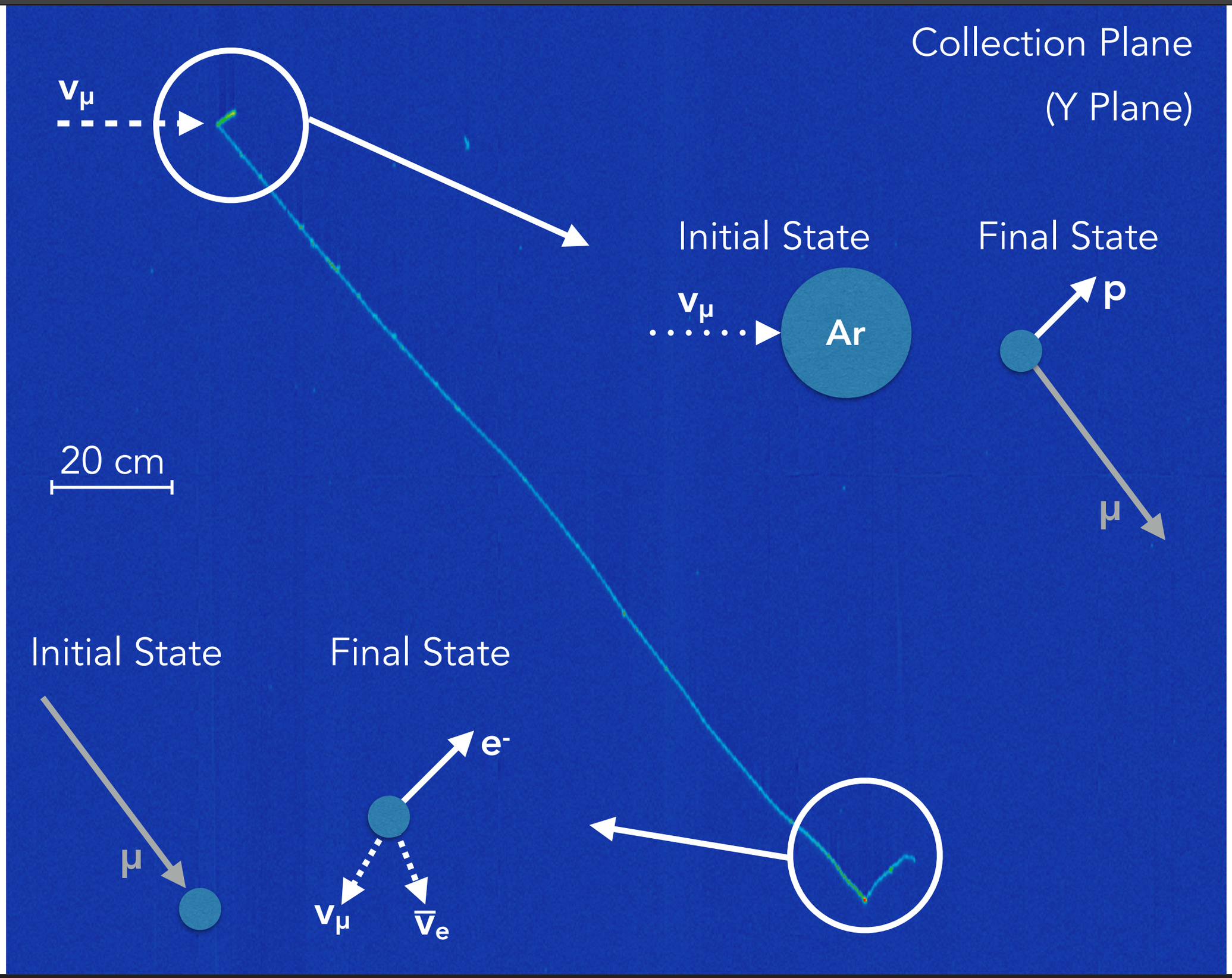


- 3 wire planes
- 8192 gold coated wires
- wire spacing: 3mm

# MicroBooNE

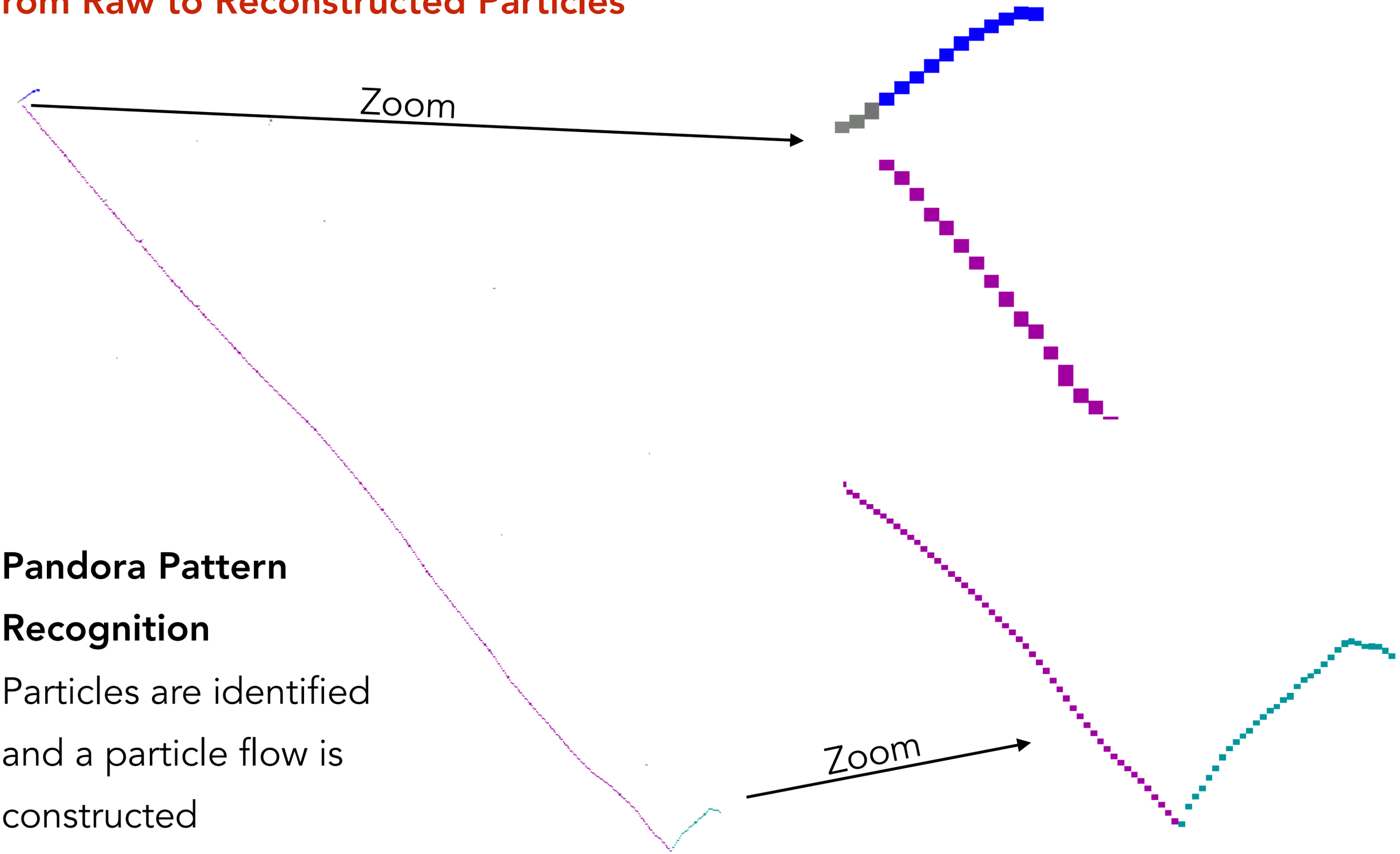

Collection Plane
(Y Plane)
$\nu_\mu$
Proton
Colour scale shows
deposited charge
20 cm
Muon
Time
Michel Electron
Wires

# MicroBooNE


Collection Plane
(Y Plane)
$\nu_\mu$
Initial State
Final State
$\nu_\mu$
Ar
p
μ
20 cm
Initial State
Final State
μ
$e^-$
$\nu_\mu$
$\bar{\nu}_e$

# Event Reconstruction

## From Raw to Reconstructed Particles

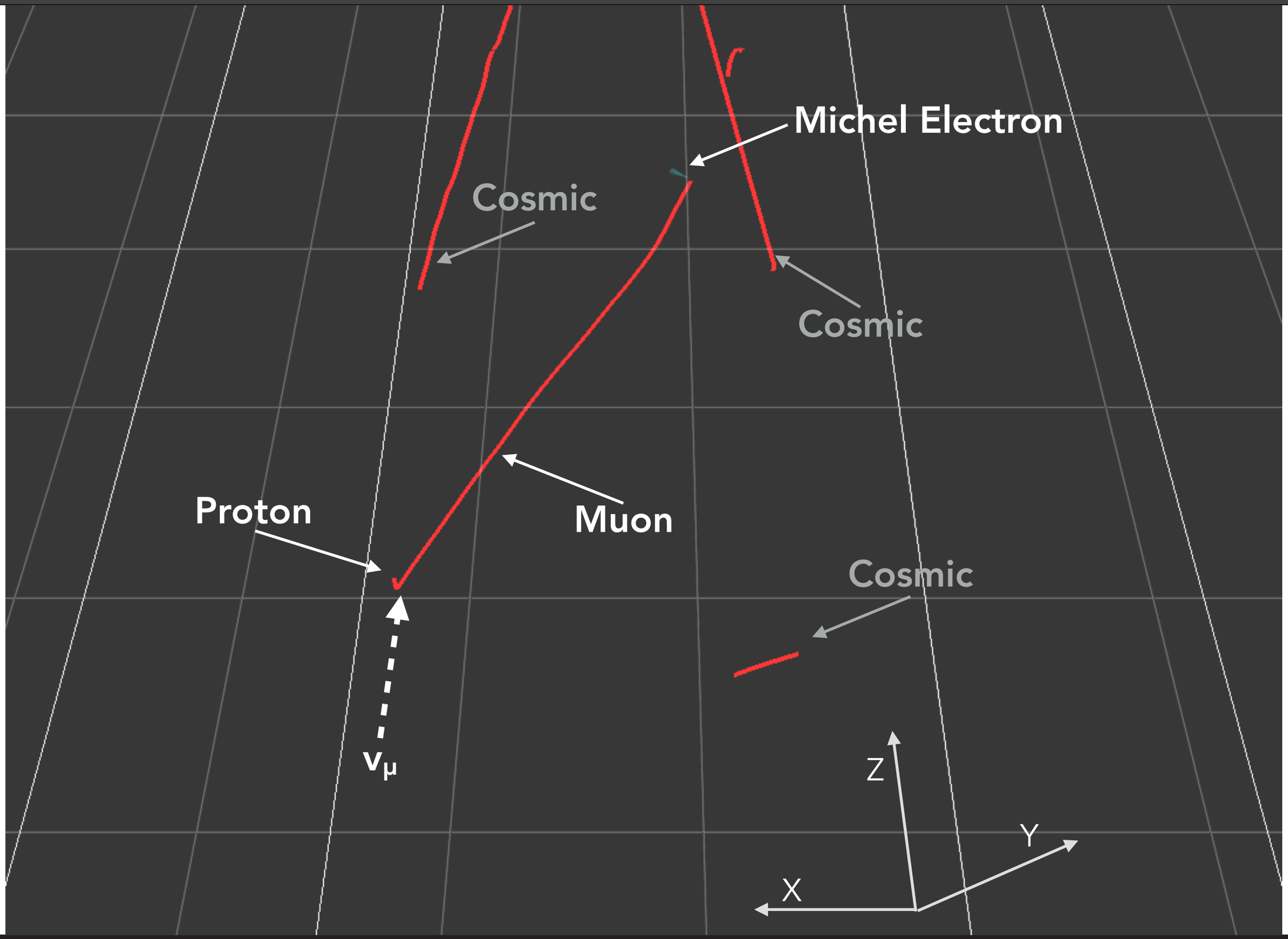



**Pandora Pattern Recognition**

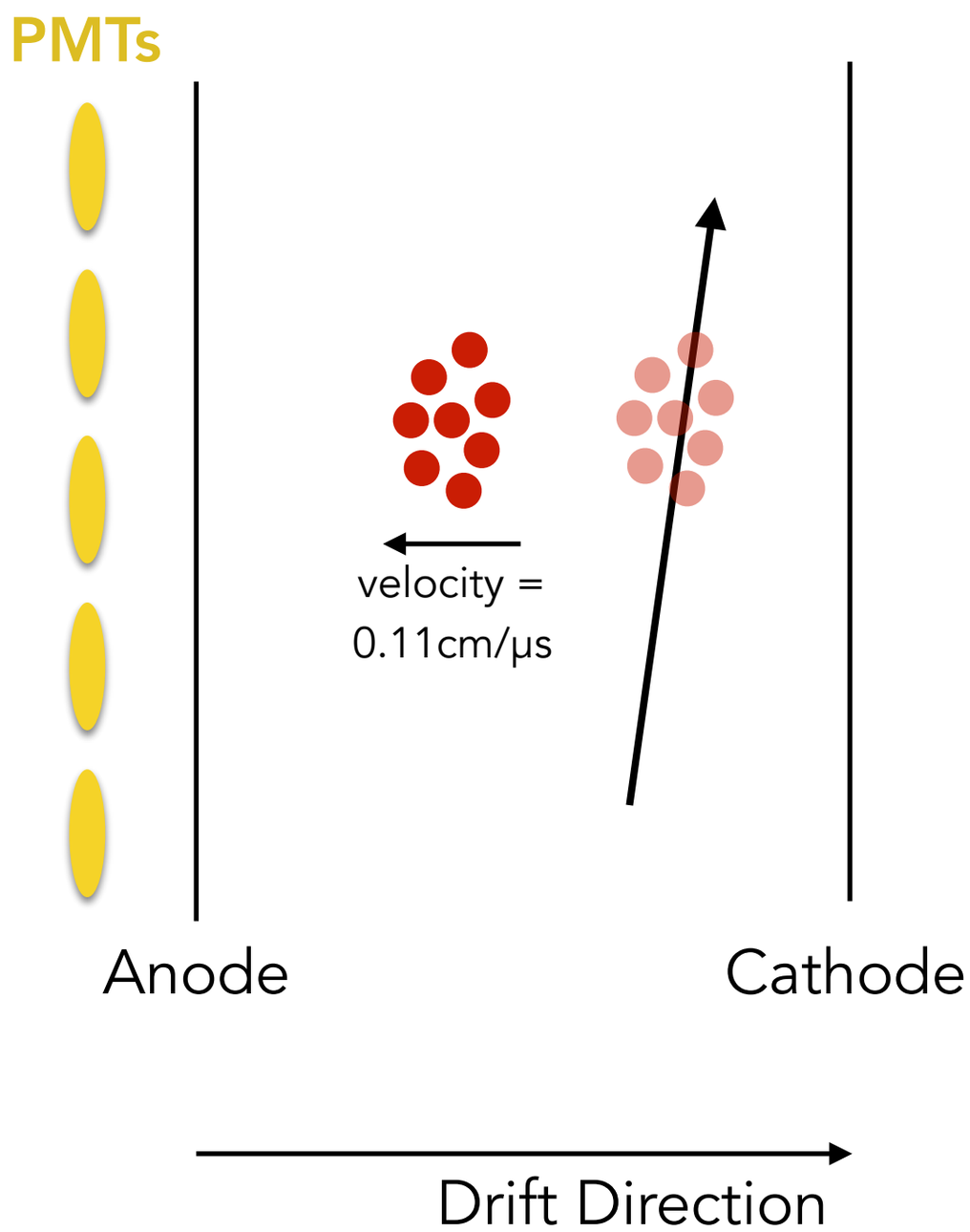
Particles are identified and a particle flow is constructed

Eur. Phys. J. C78, 1, 82 (2018)

# 3D Reconstruction



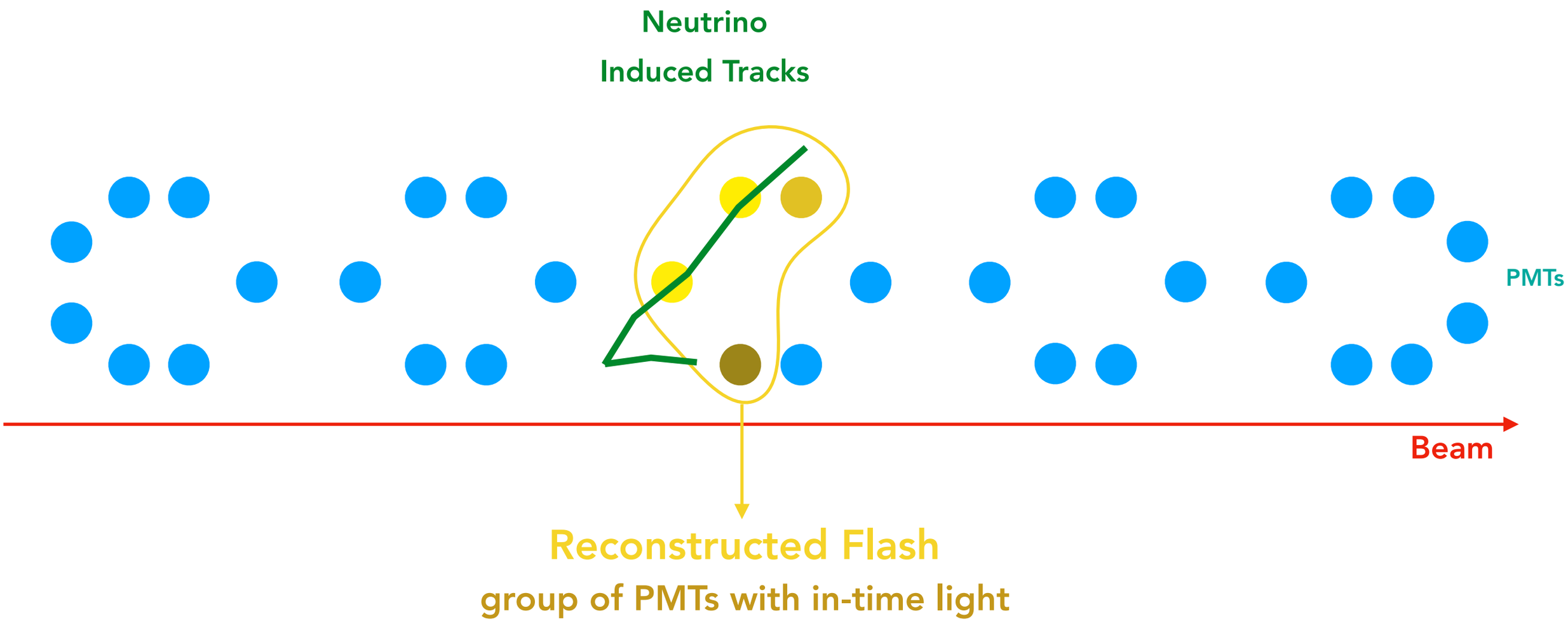
# Drift Time and Interaction Time $t_0$



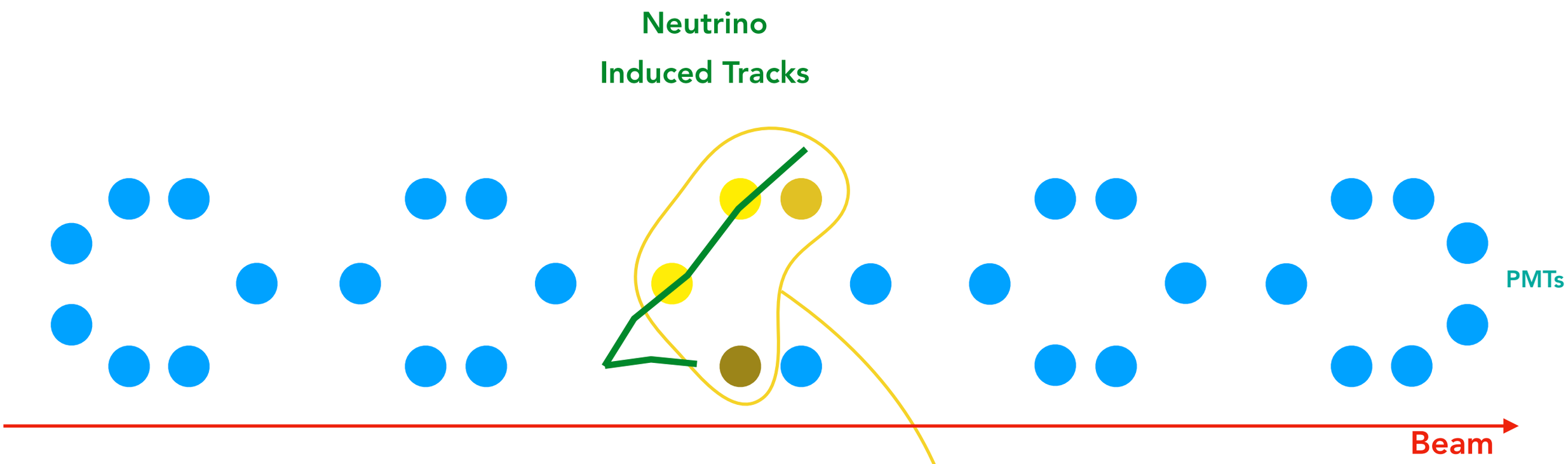

- Ionisation electrons drift toward the anode at a velocity of 0.11cm/μs.
- From cathode to anode it takes **2.3 ms**.
- The interaction time ($t_0$) is needed to reconstruct the position of tracks along the drift coordinate in the detector.
- The $t_0$ is given by the light detectors, as the scintillation is **prompt** (O(ns)).

Optical information needs to be reconstructed to form high level objects like flashes.

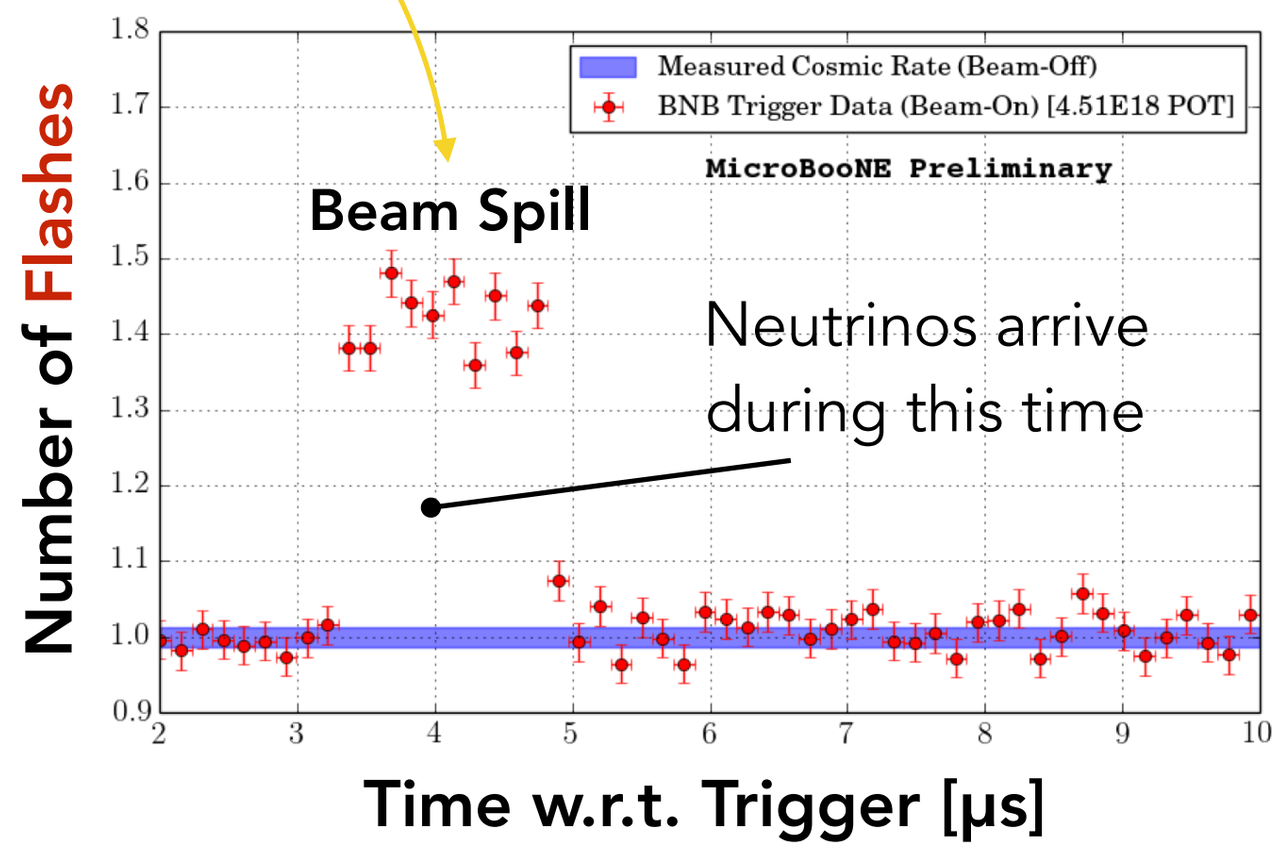
# Optical Reconstruction



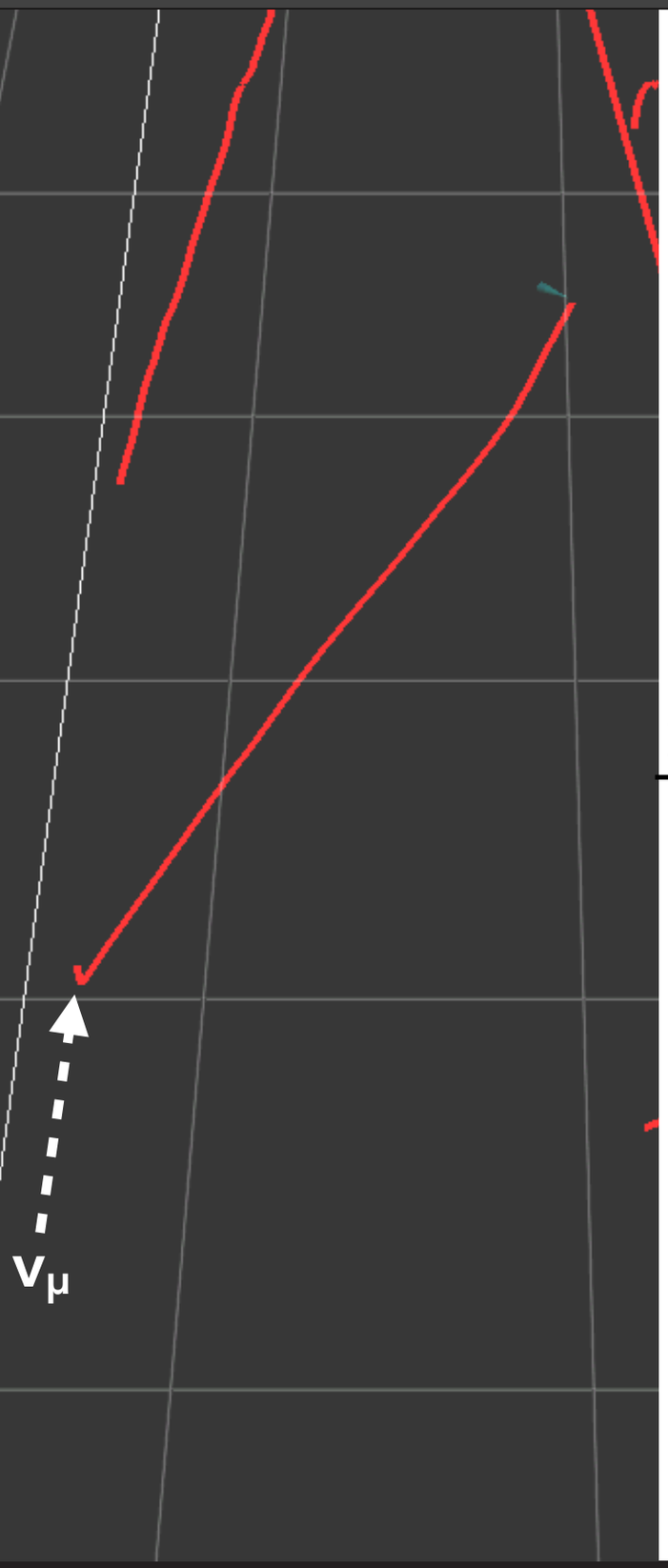
# Drift Time and Beam Spill Time



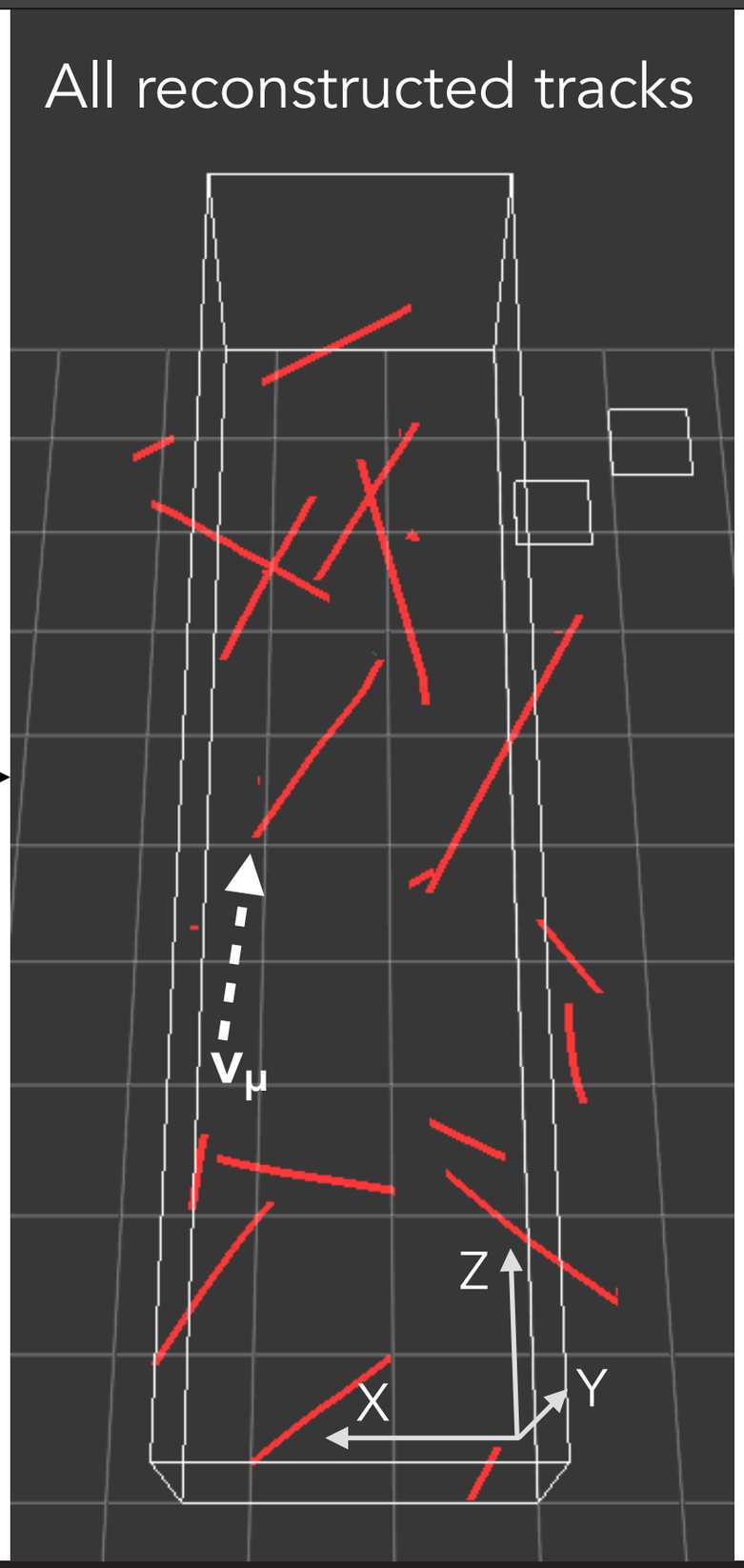

Neutrinos are delivered in spills that last for only **1.6 μs**. The light information (prompt) can be used to identify neutrino interactions during this spill.



# Cosmic Rays




Zooming out



Neutrino induced flash

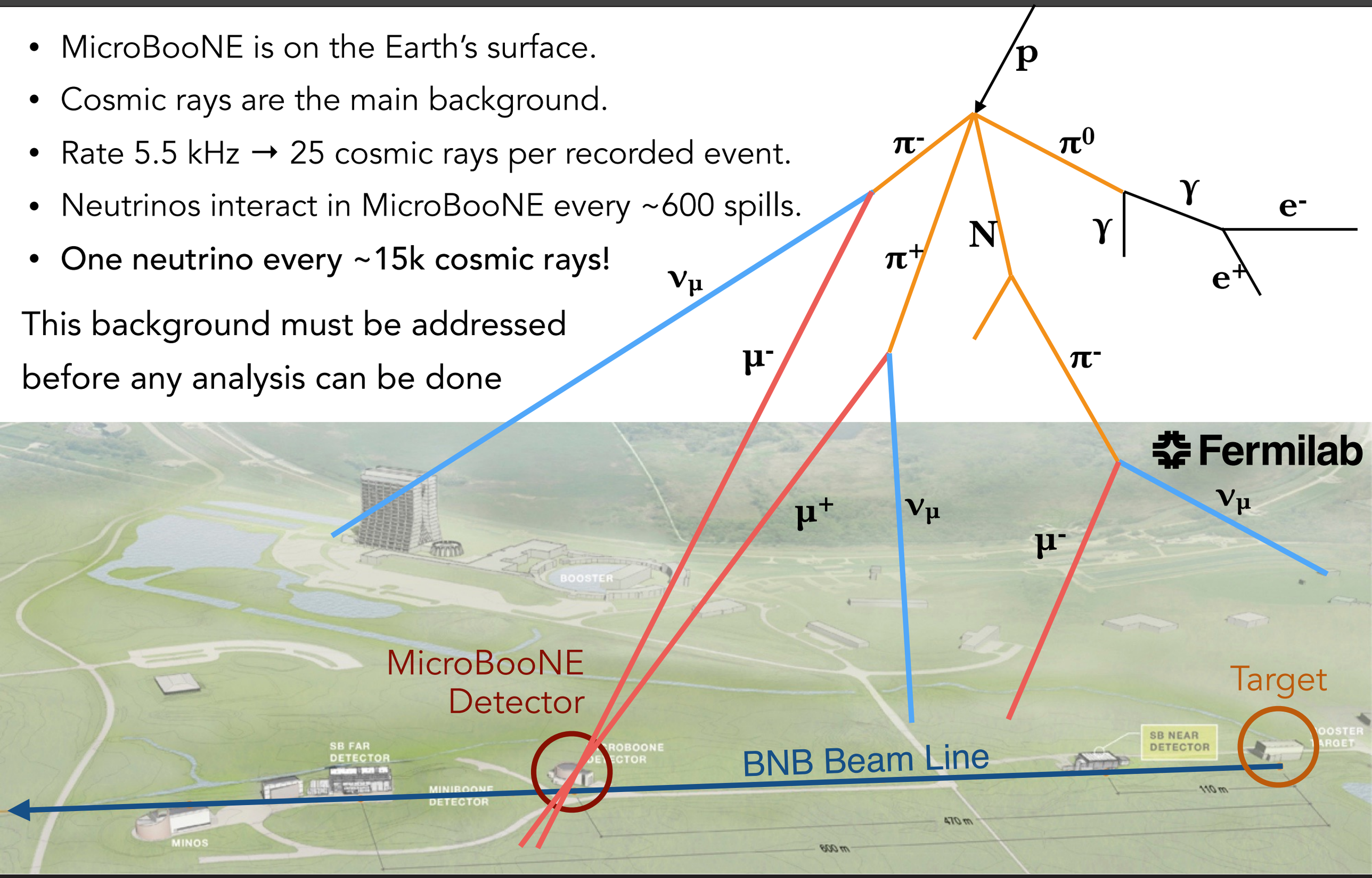
Cosmic induced flash

The event is dominated by cosmics, and is not easy to identify the neutrino induced tracks

# Cosmic Rays

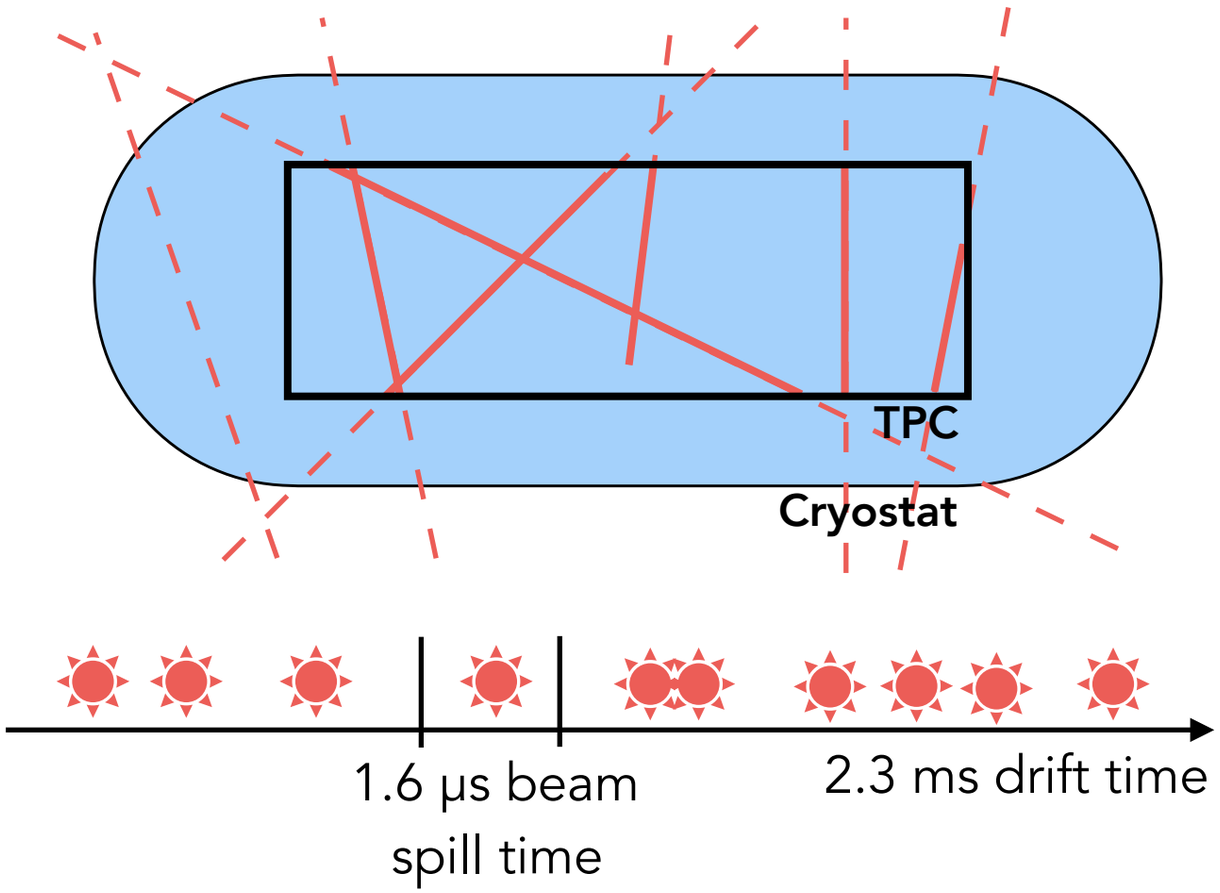
- MicroBooNE is on the Earth's surface.
- Cosmic rays are the main background.
- Rate 5.5 kHz → 25 cosmic rays per recorded event.
- Neutrinos interact in MicroBooNE every ~600 spills.
- **One neutrino every ~15k cosmic rays!**

This background must be addressed before any analysis can be done



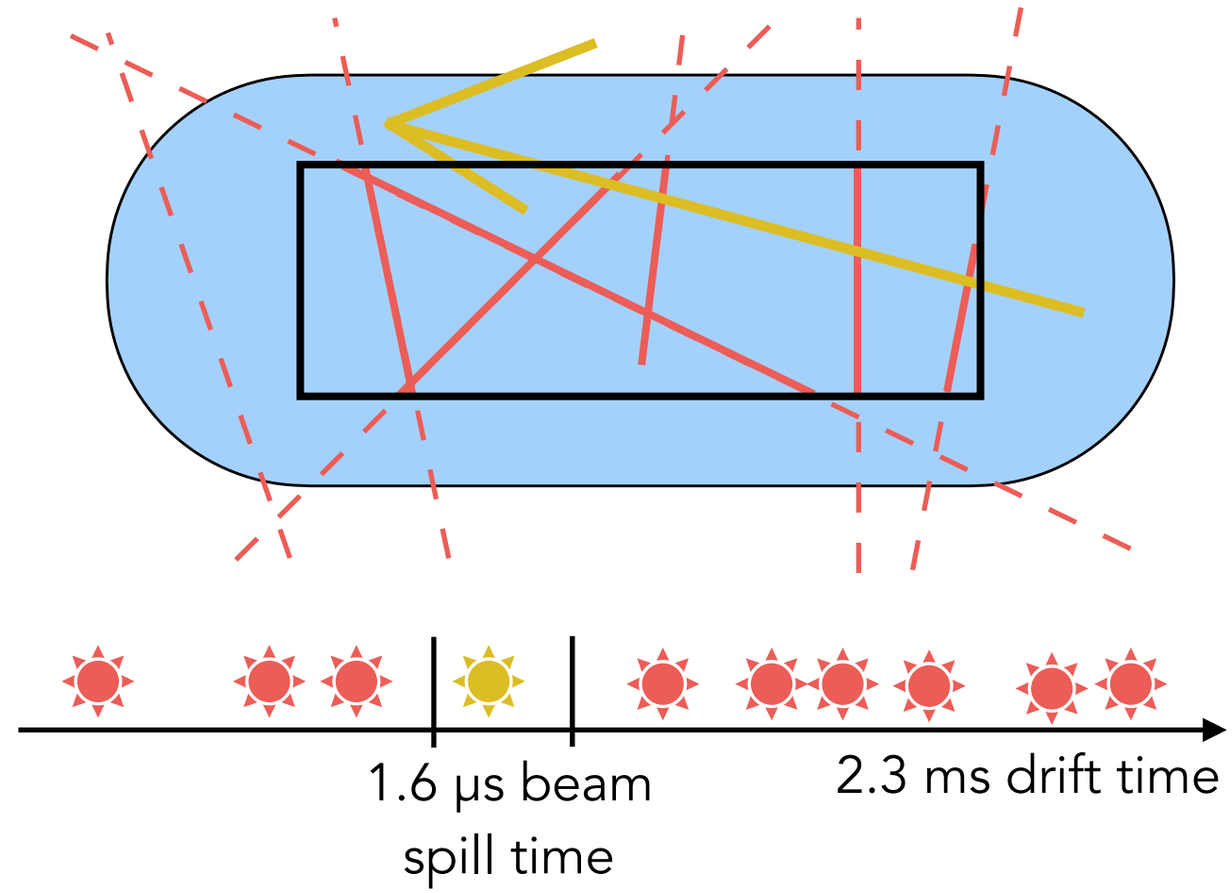
# Cosmogenic Backgrounds

## "Cosmics Only"



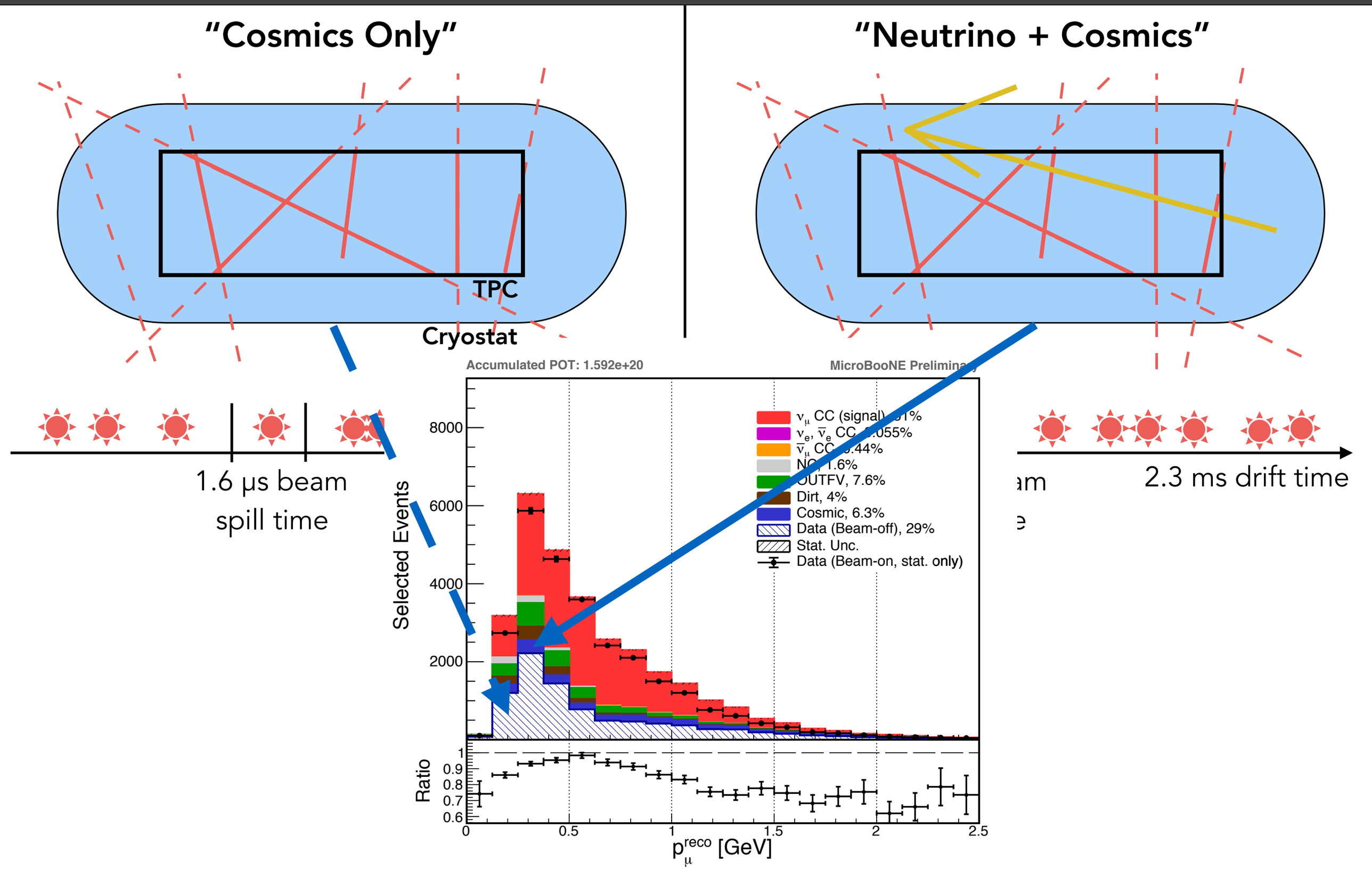

- No neutrino event
- Perfect measurement during beam-off time

## "Neutrino + Cosmics"




- Optical signal from neutrino interaction trigger
- Cosmic induced TPC track picked up by selection
- Cosmic simulated with CORSIKA

# Cosmogenic Backgrounds

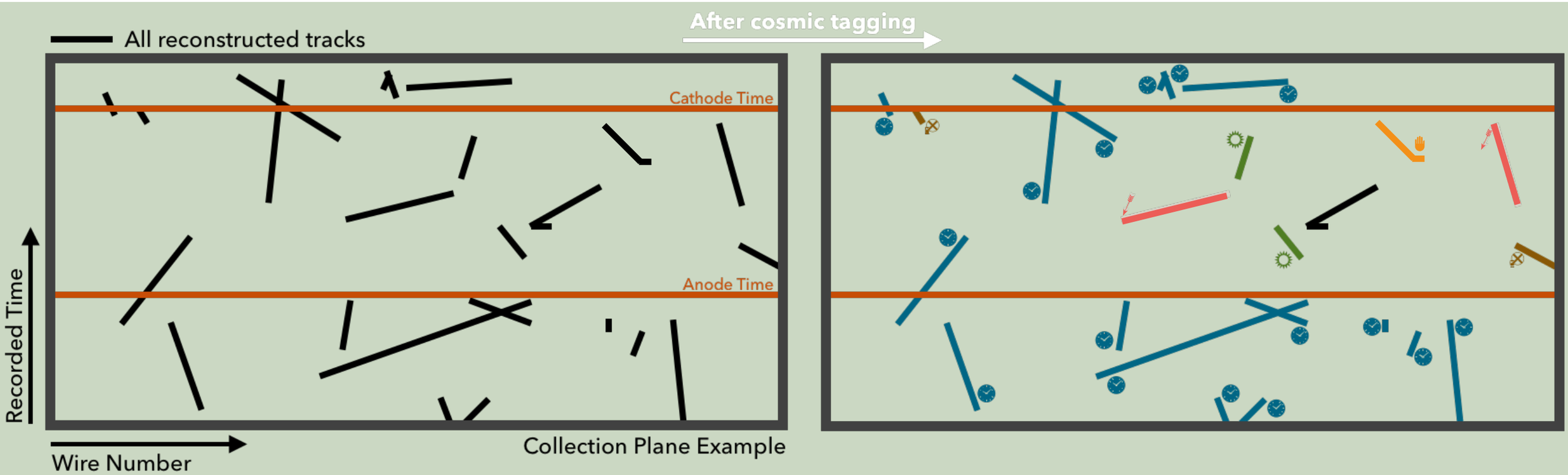


# Tagging of Cosmic Rays

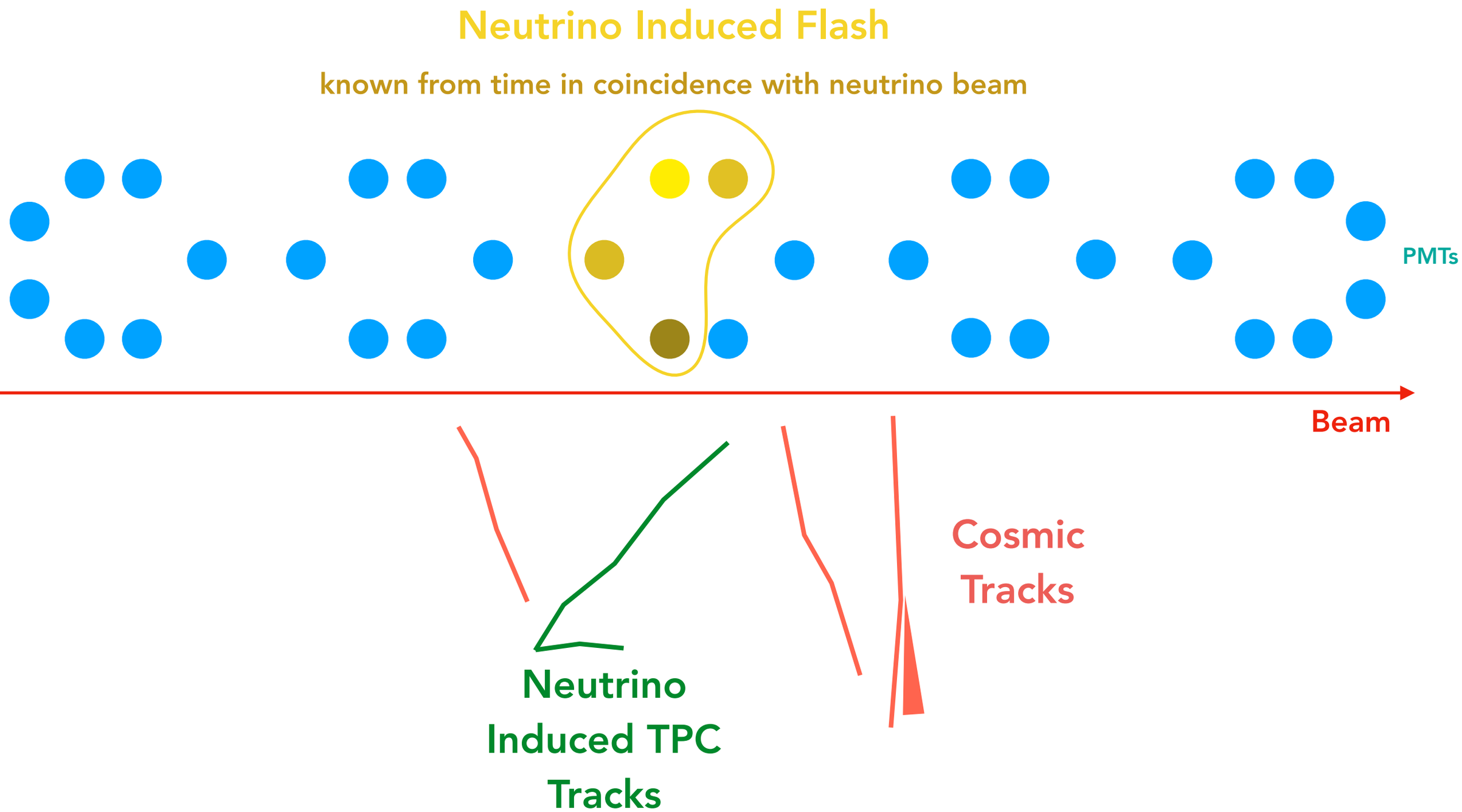
**A track is tagged as cosmic ray if:**

- 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)

99.9% cosmic rejection

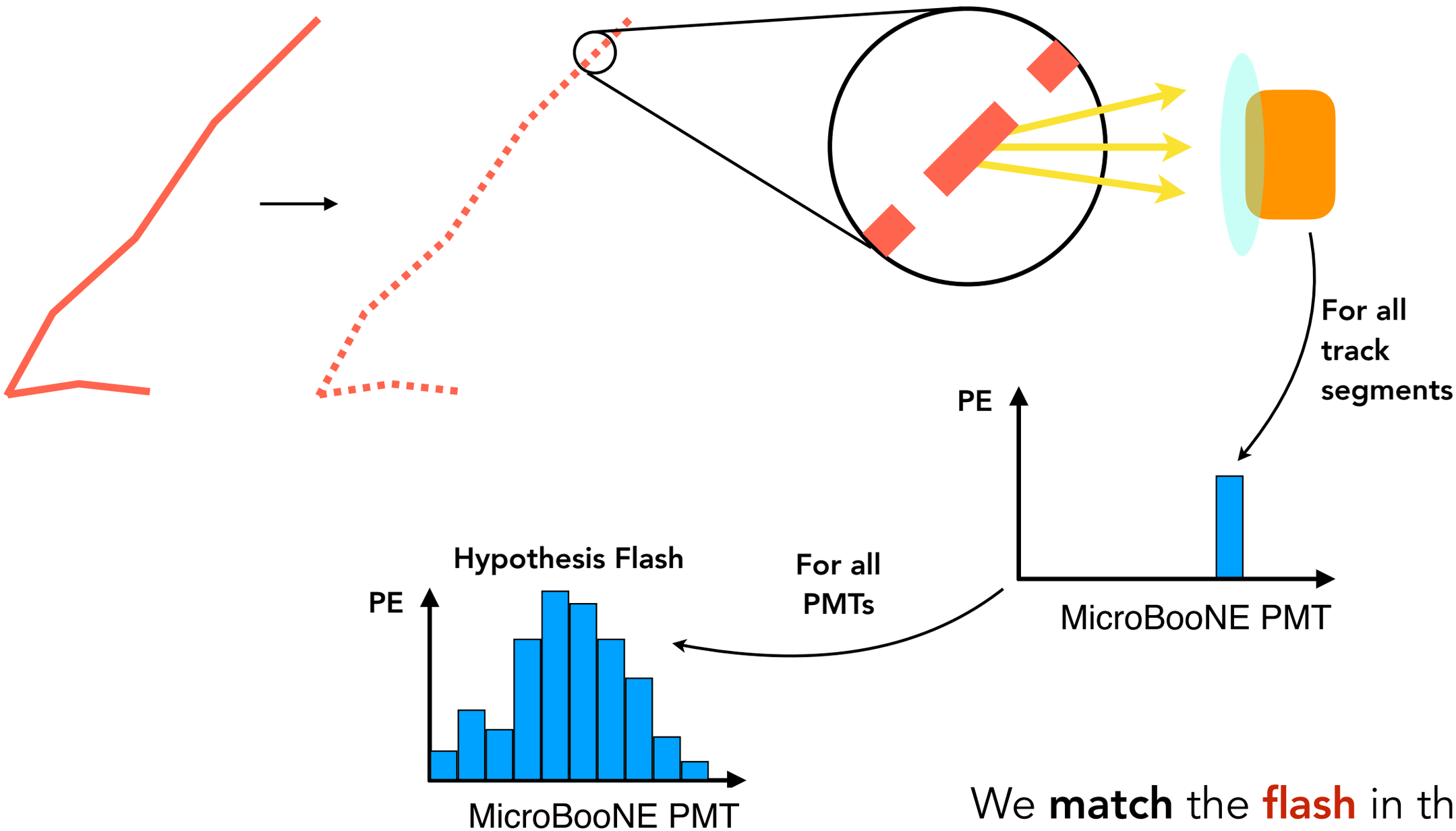


# PMT to TPC Matching




**Need to match the Optical Flash with the TPC tracks to identify the neutrino!**

# PMT to TPC Matching



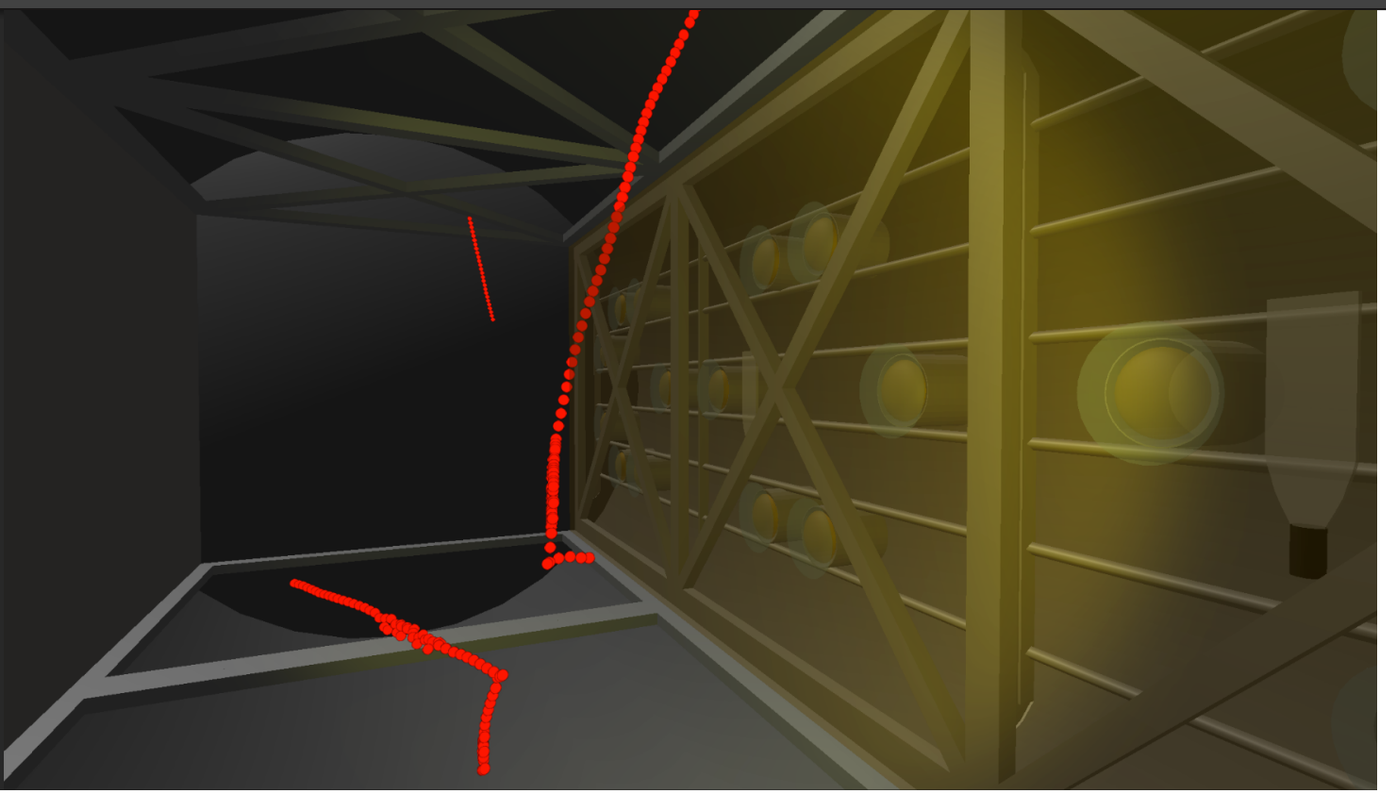

We **match** the **flash** in the beam spill with every reconstructed **TPC interaction**.

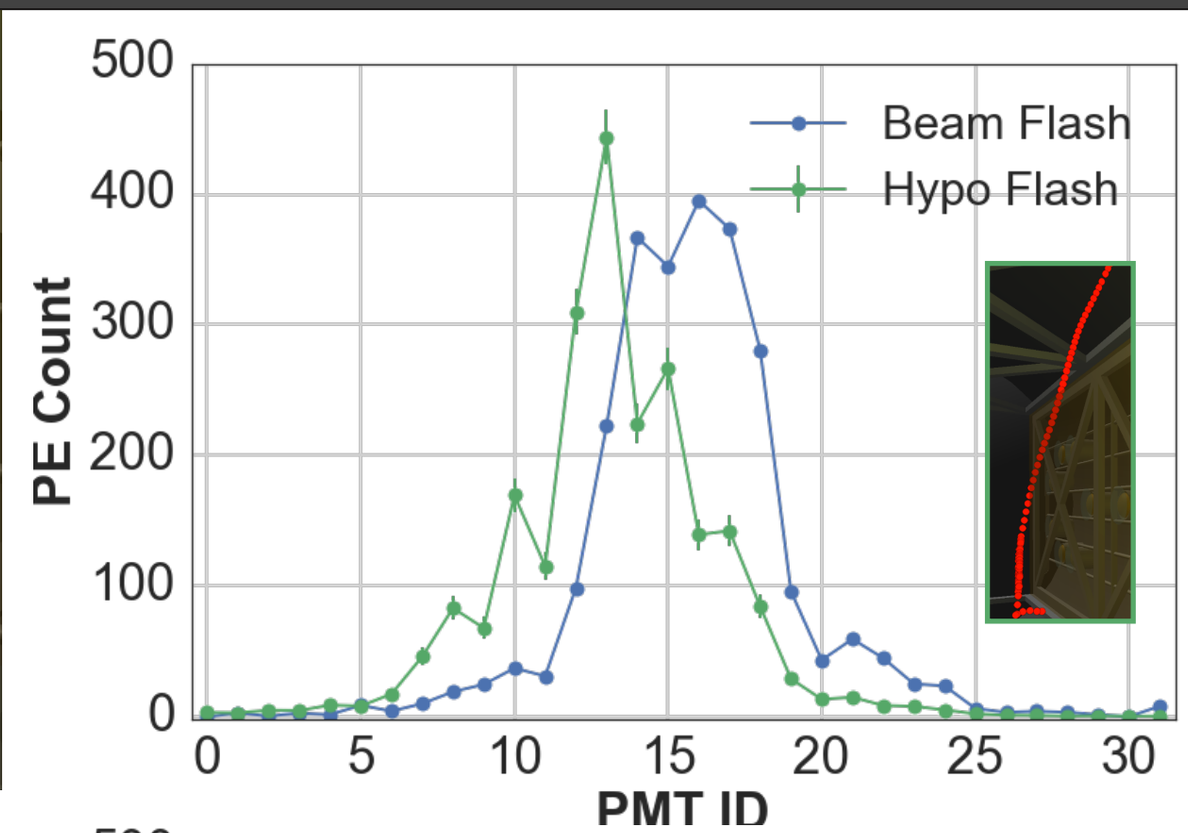
The interaction that best matches with the flash is kept as **neutrino candidate**.

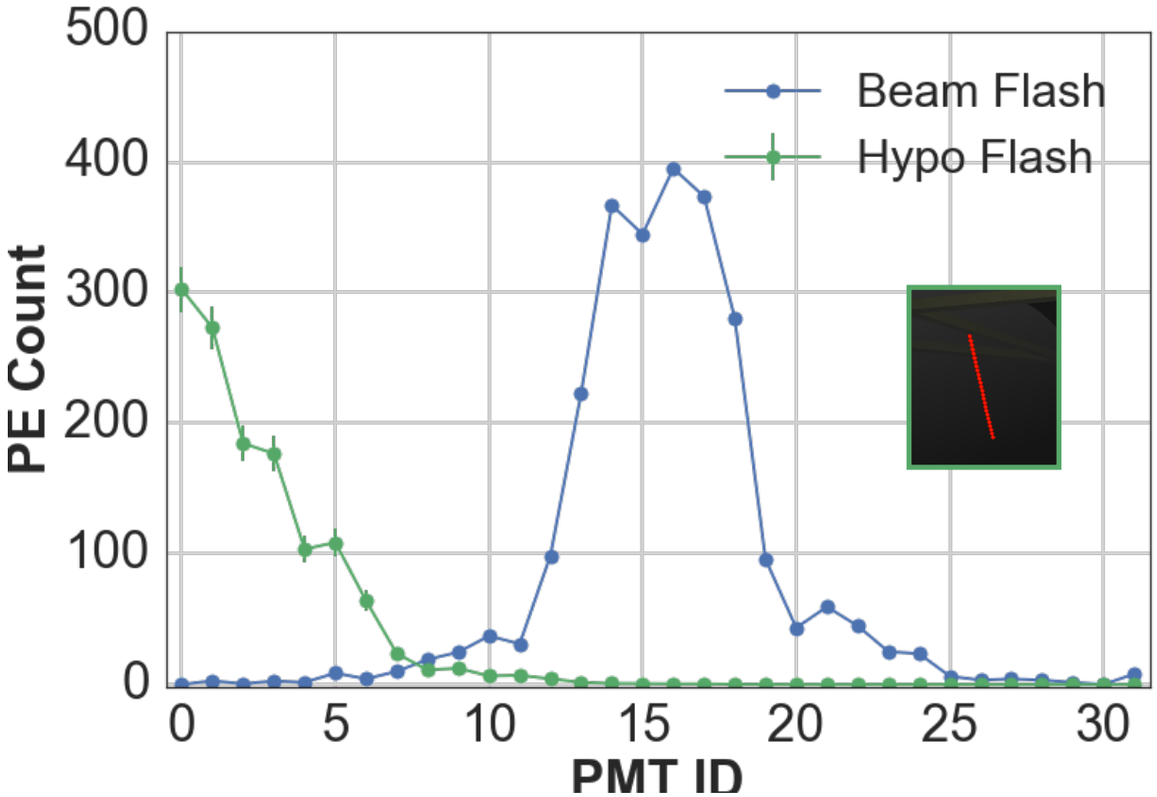
PE = Photo Electrons

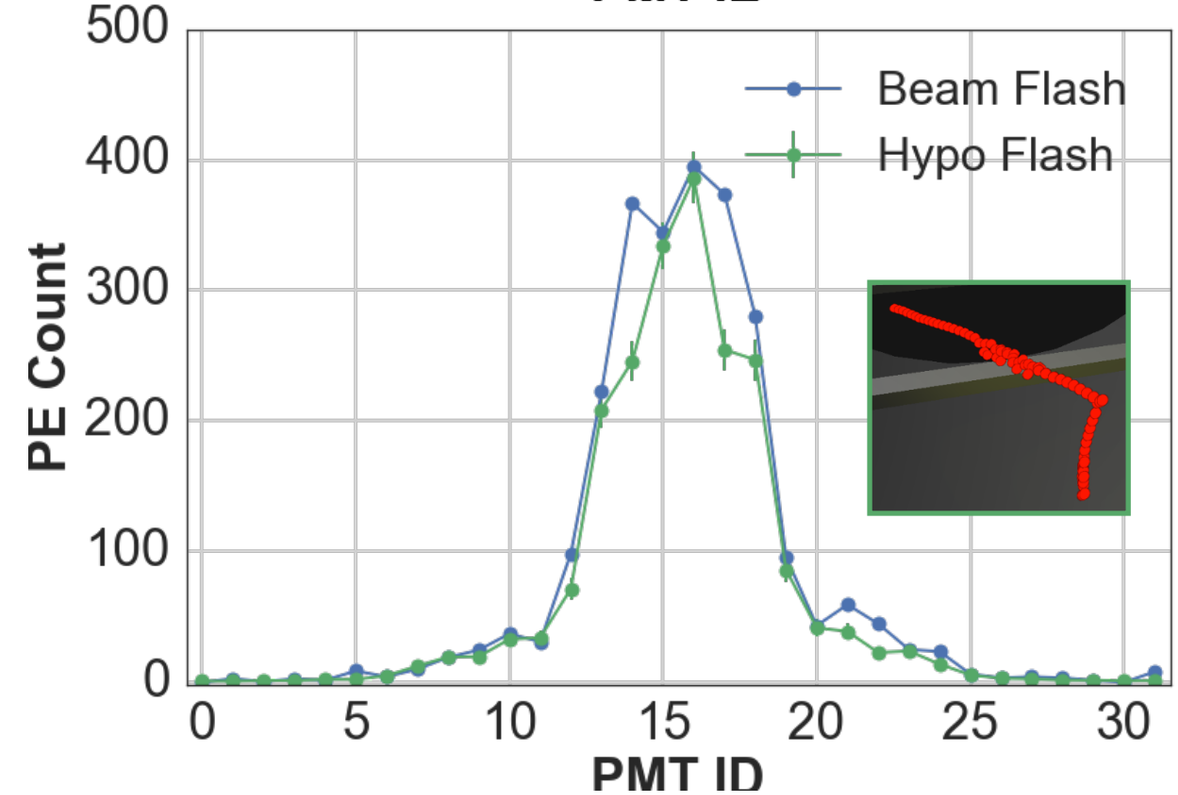
PMT = Photomultiplier

# PMT to TPC Matching

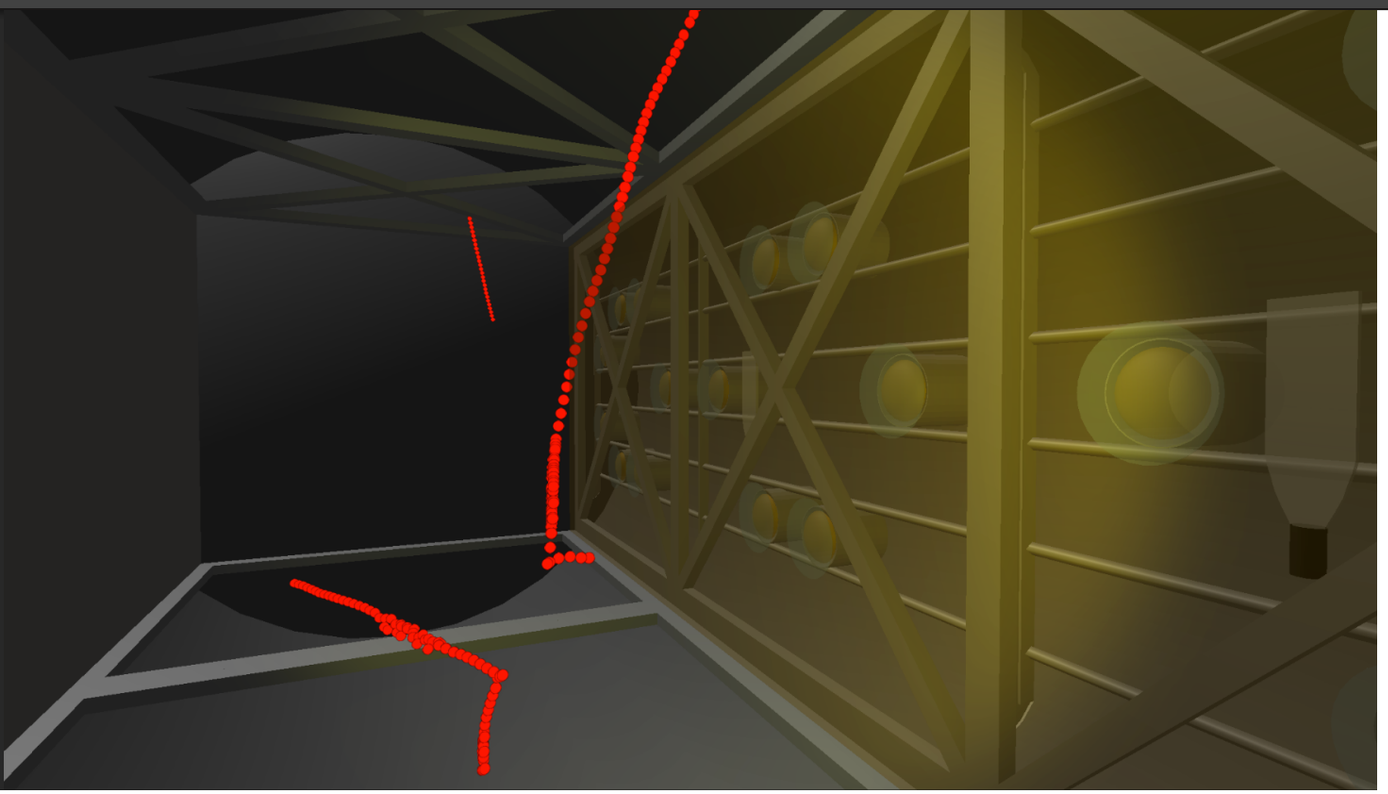




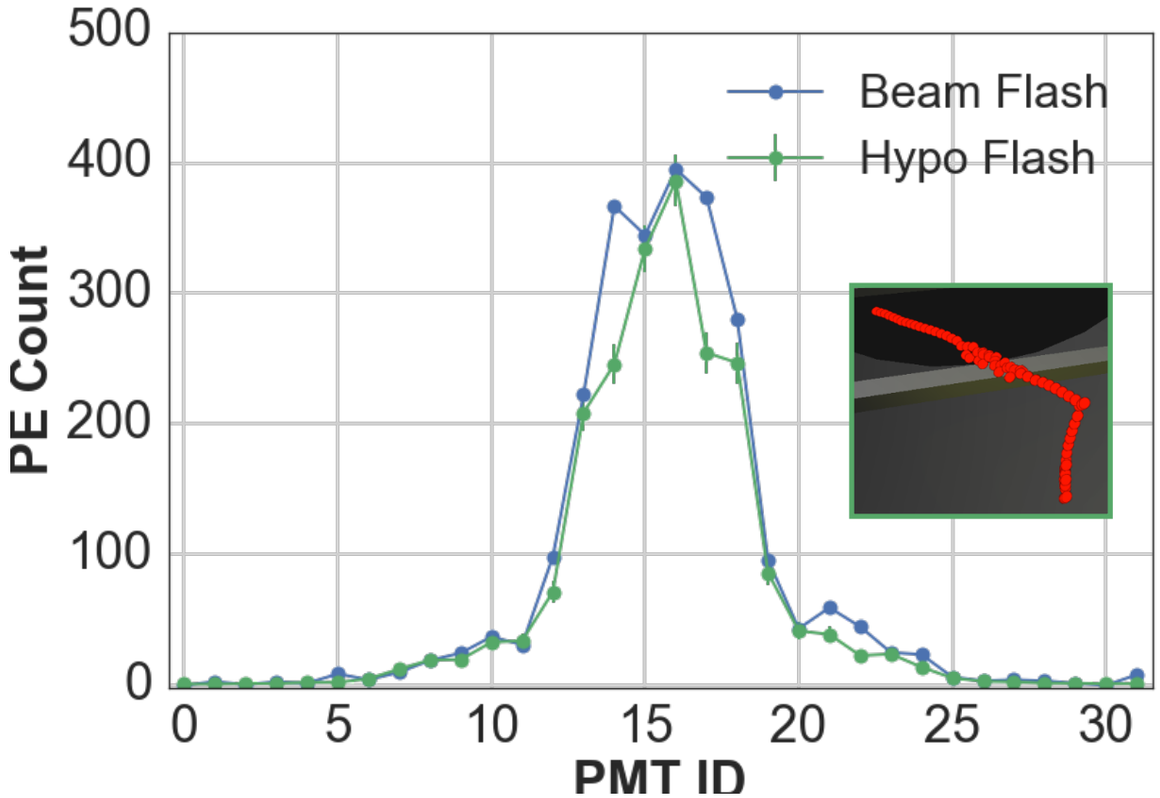



# PMT to TPC Matching



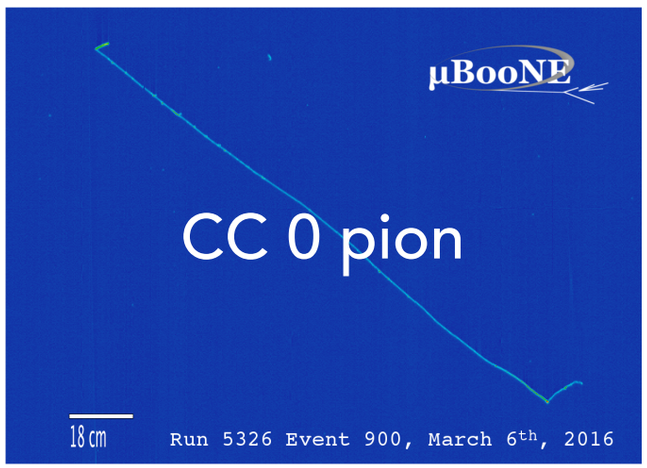
The neutrino interaction is selected!

MicroBooNE is the first to do such flash matching for event selection. This is will be of interest to SBN and protoDUNE.

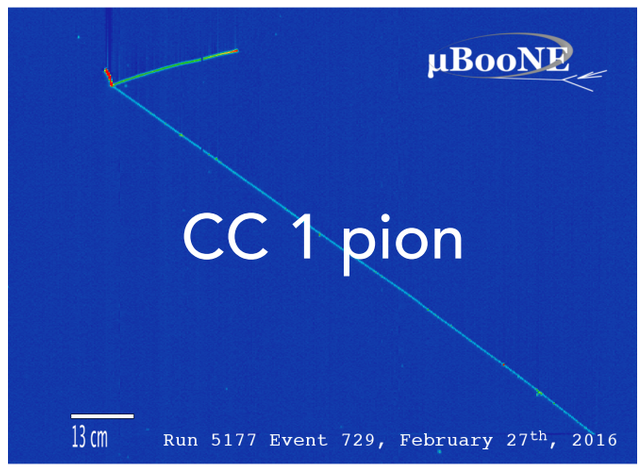


# $\nu_\mu$ Charged Current Inclusive Analysis

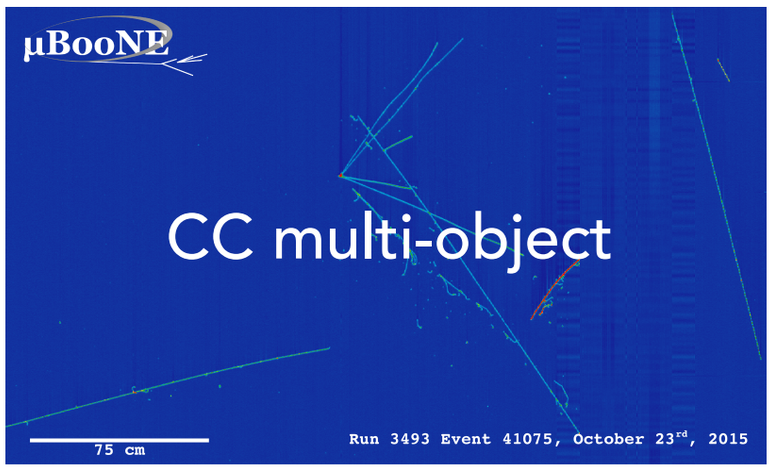
**Inclusive** sample, all **$\nu_\mu$ CC** topologies:




+




+



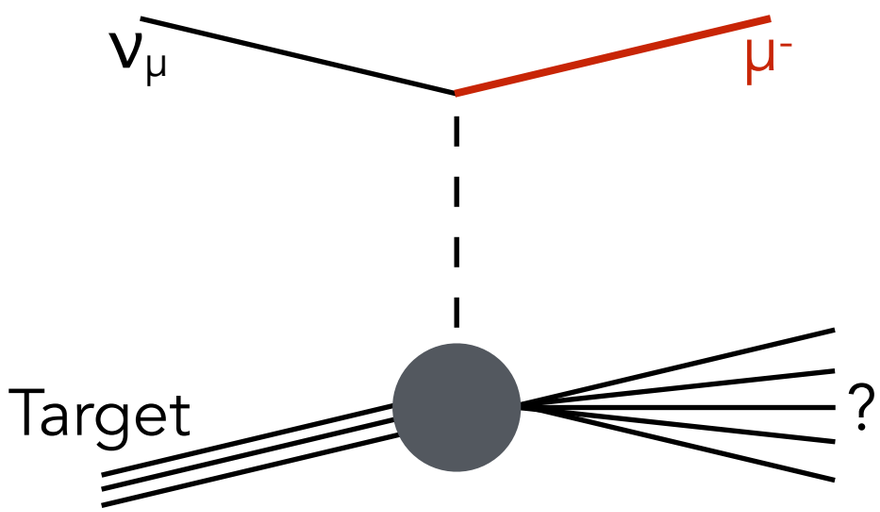

+ …

**Main analysis characteristics:**

- First **double differential** cross sections on **argon**, first inclusive measurement on argon at low **O(1 GeV) neutrino energies**, first differential cross section measurement from **MicroBooNE**
- **Full angular coverage**
- **Full momentum coverage** by using multiple Coulomb scattering (MCS) for momentum reconstruction (includes both **contained** and **exiting** tracks)
- This measurement: first rigorous **test of event generators on argon**

# $\nu_\mu$ Charged Current Inclusive Analysis

**Inclusive** sample, all **$\nu_\mu$ CC** topologies:




- One of the first channels we addressed in the MicroBooNE cross-section program
- Well defined signature: exercising track reconstruction; not affected by shower reconstruction
- We have an automated reconstruction and event selection

**Inclusive measurements are important:**

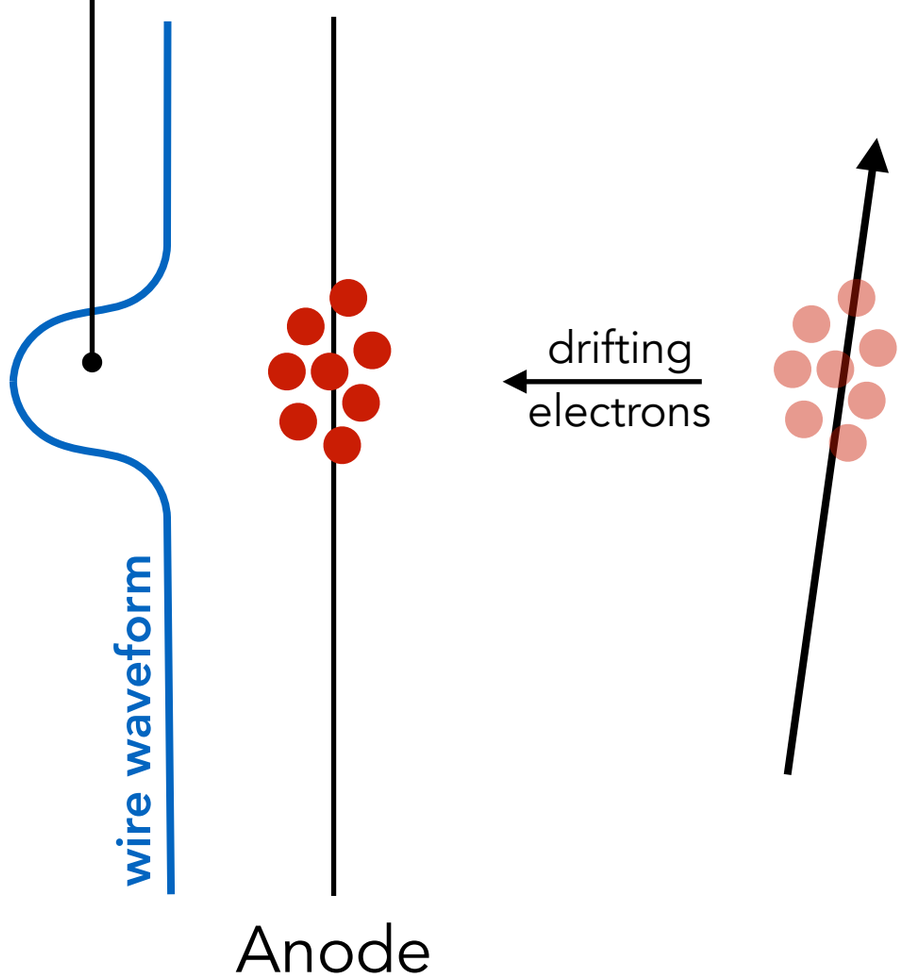
- High purity and efficiency.
- Not sensitive to hadron uncertainties.
- Tests many things at once (multiple contributing processes).
- New cross section measurement on argon, provide input for theory.
- $\nu_e$ rate constraint in MicroBooNE through correlation with neutrino parents.
- Provide a pre-selection to study other exclusive channels (proton kinematics, …).

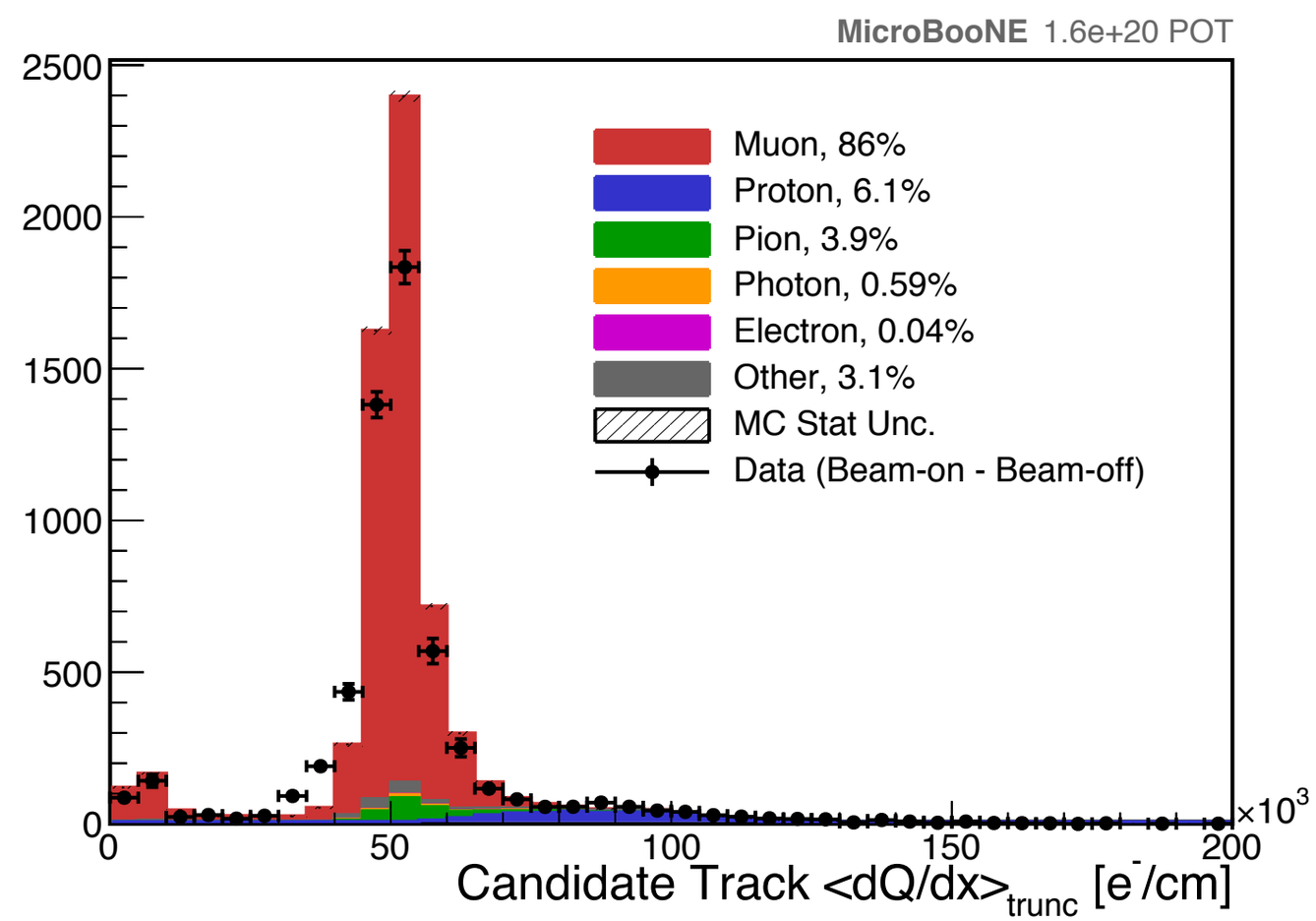
# Muon Identification

**Track dQ/dx v.s. track length is used for a MIP consistency check**

The area below the waveform is proportional to the deposited charge

This can be used to ensure the selected track is a Minimum Ionising Particle (MIP) as the muon should be.



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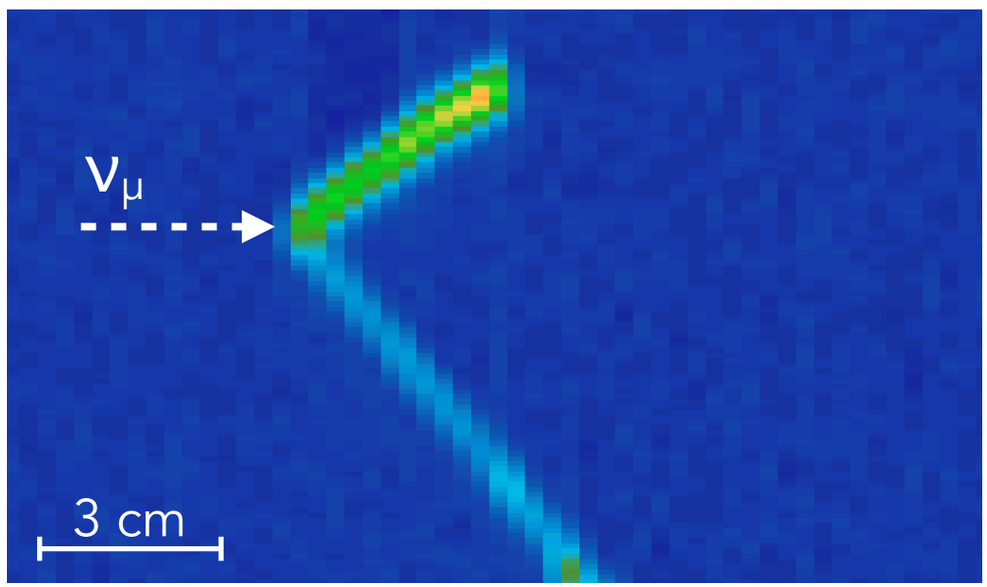
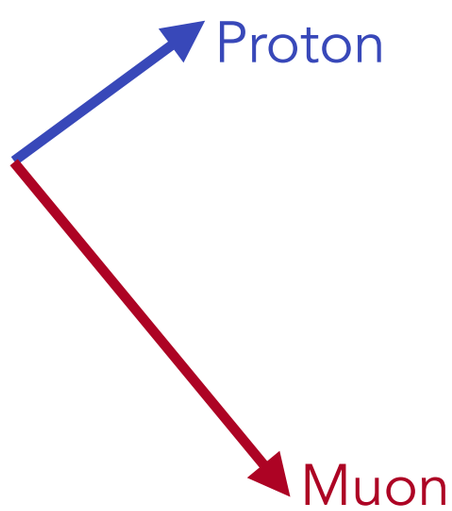
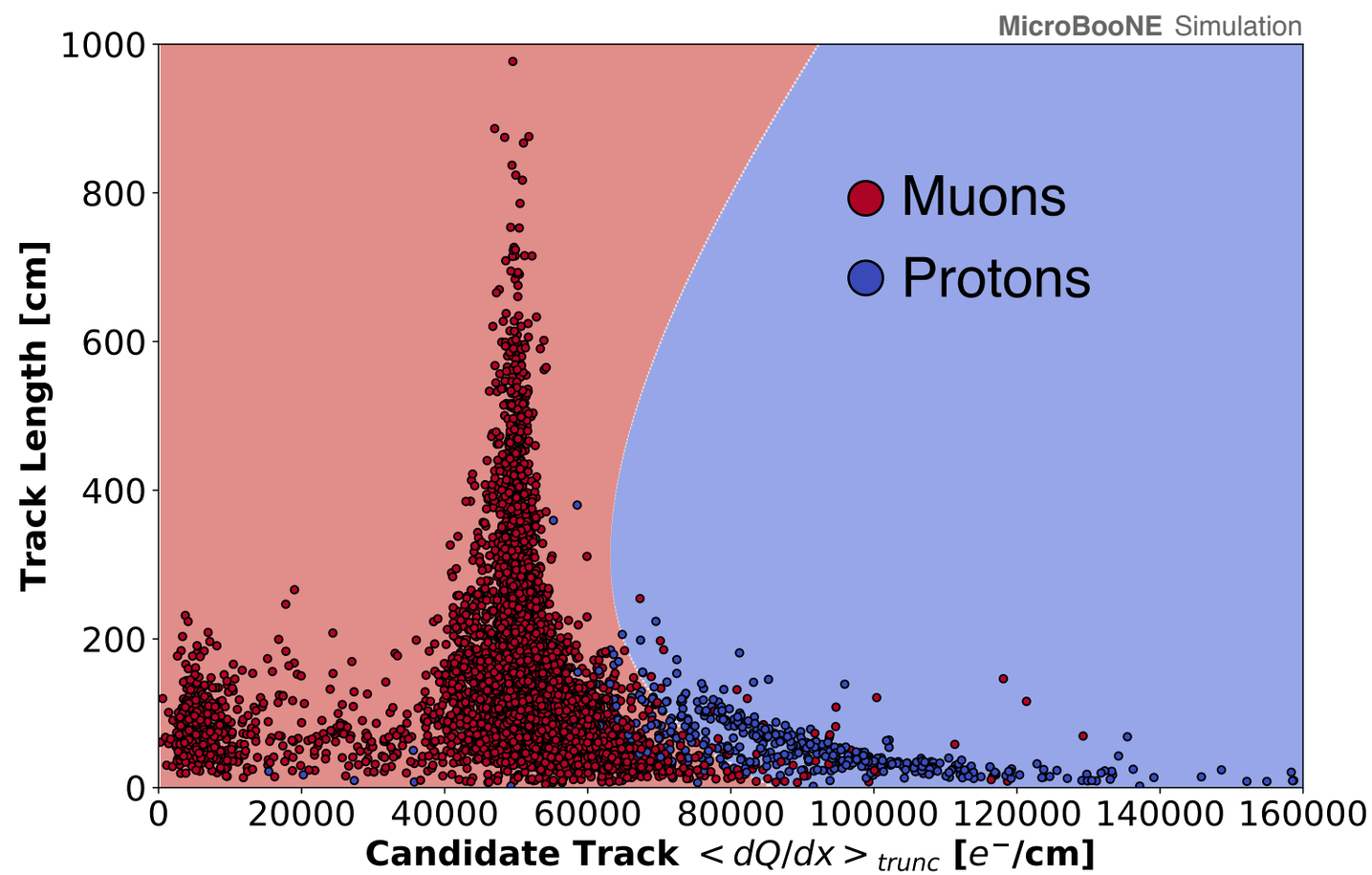
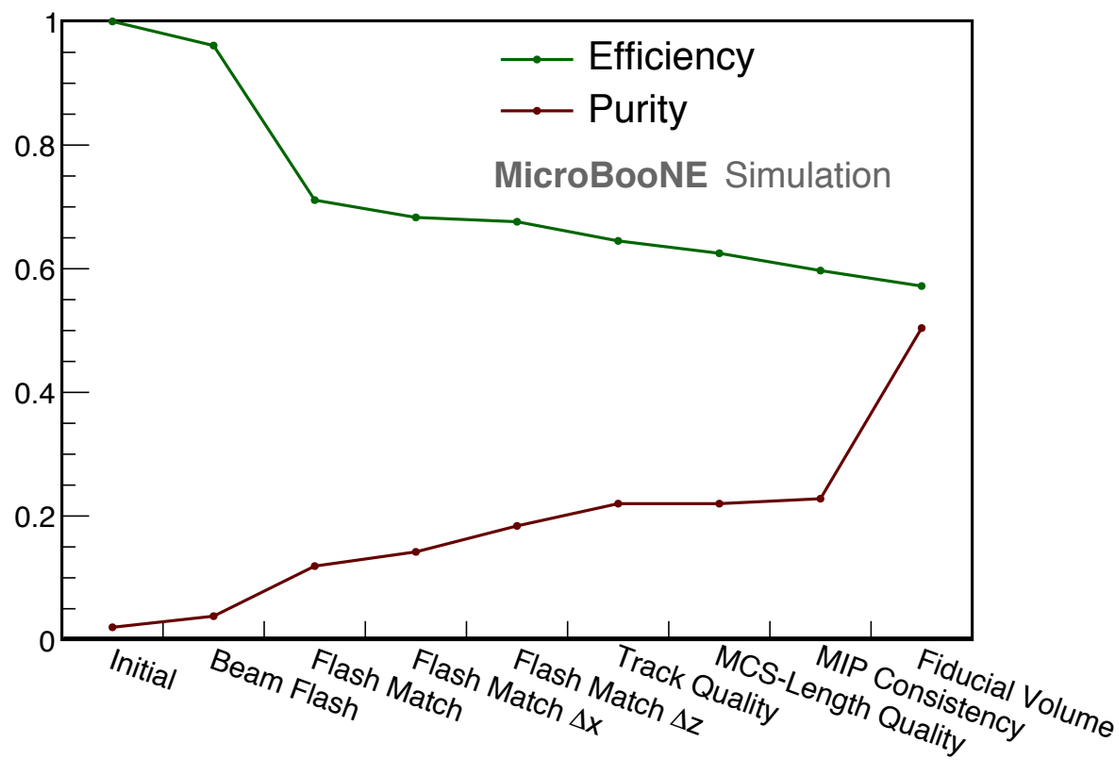


# Event Selection - Performance

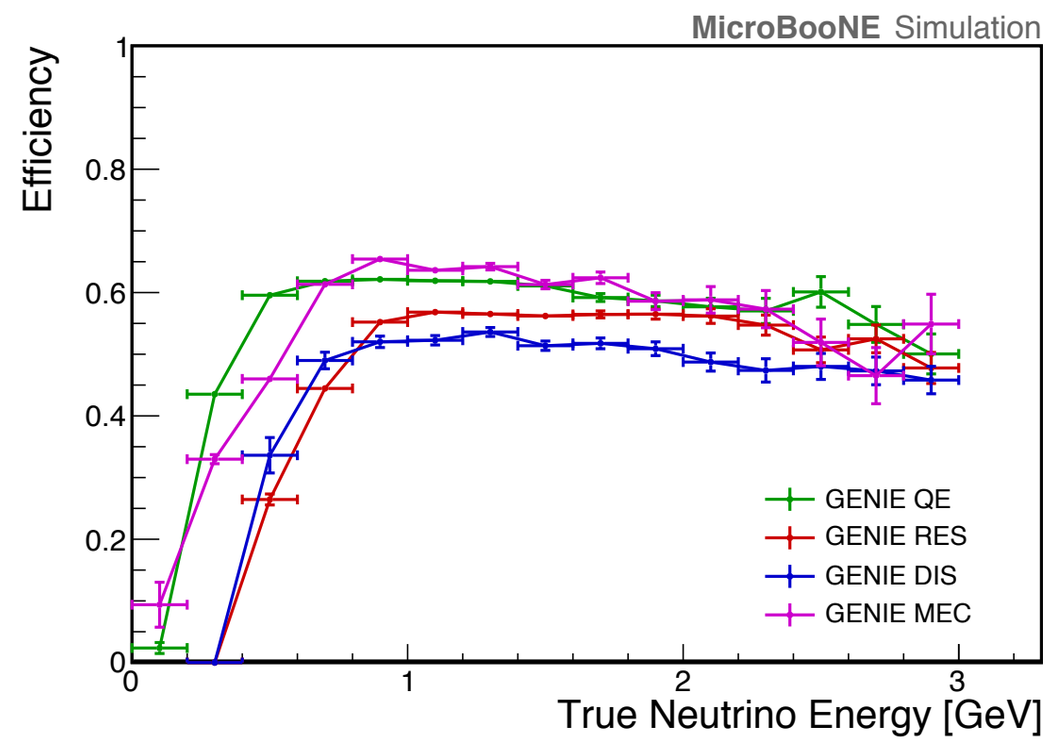
**Purity and efficiency for every selection cut**




Overall efficiency x acceptance: 57.2%

Overall purity: 50.4%

**Efficiency for different GENIE interaction modes**

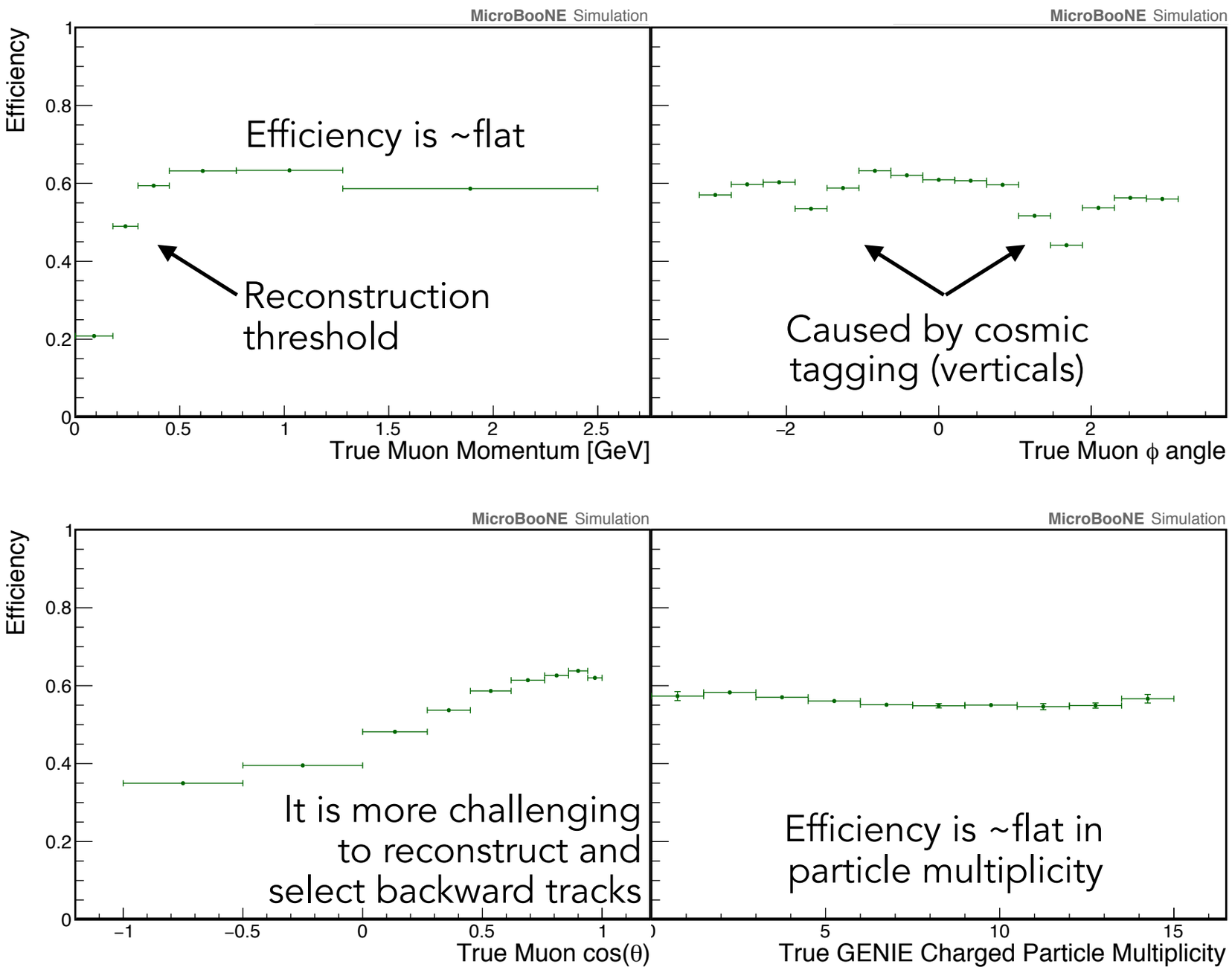


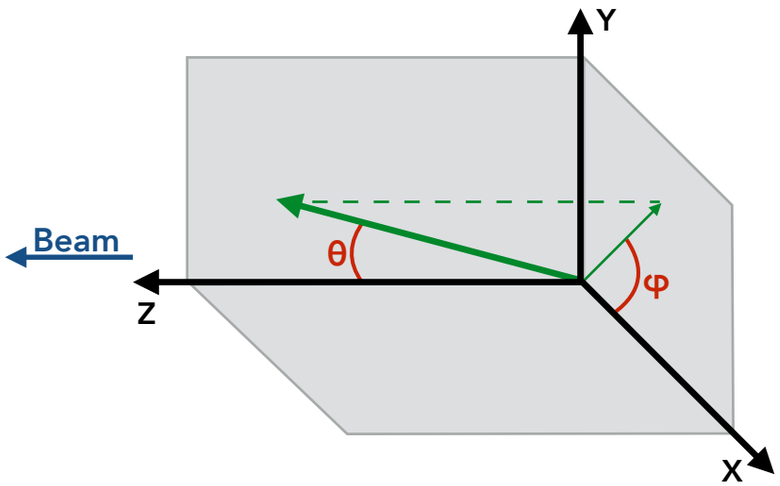

All interaction modes are selected with roughly the same efficiency, making this analysis really inclusive

There is a negligible contribution from CC coherent pion production events not plotted.

# Event Selection - Performance

Statistical uncertainties only (not visible with this scale)




θ: angle w.r.t. the beam line

φ: angle around the beam line

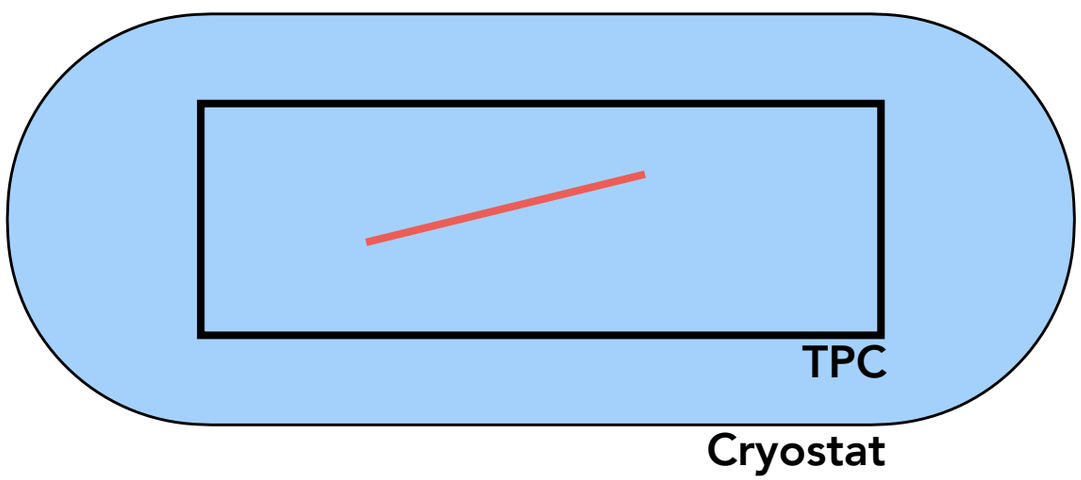
# Momentum Reconstruction

Methods of momentum reconstruction in a LArTPC:

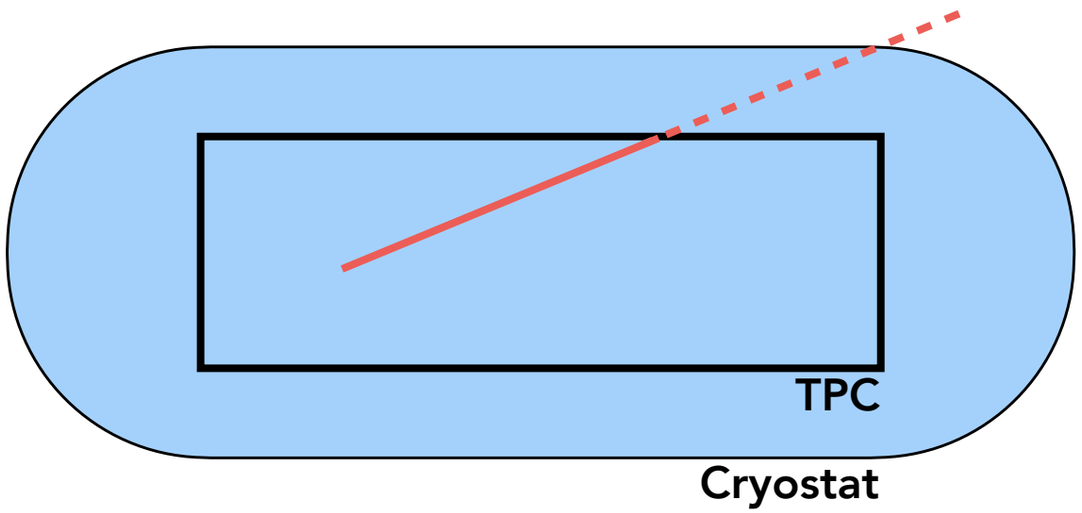
- Range-based (only for contained muons)
- Calorimetric (only for contained muons)
- **Multiple Coulomb Scattering (for contained and exiting muons)** → USED IN THIS ANALYSIS

**The majority of BNB muons in MicroBooNE are exiting!**

Contained Track




Exiting Track




MicroBooNE MCS Paper: JINST 12 P10010 (2017)

# Momentum Reconstruction

Methods of momentum reconstruction in a LArTPC:

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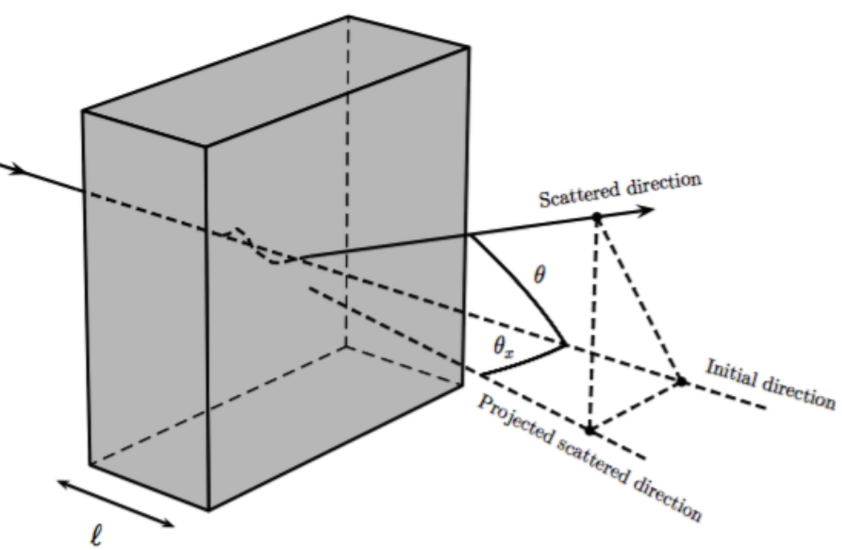
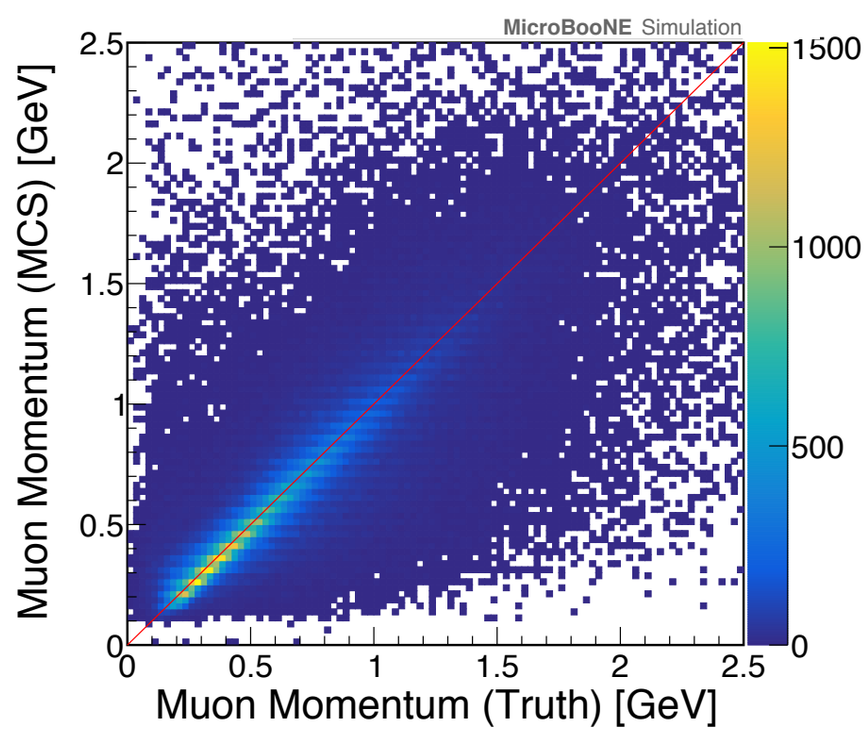
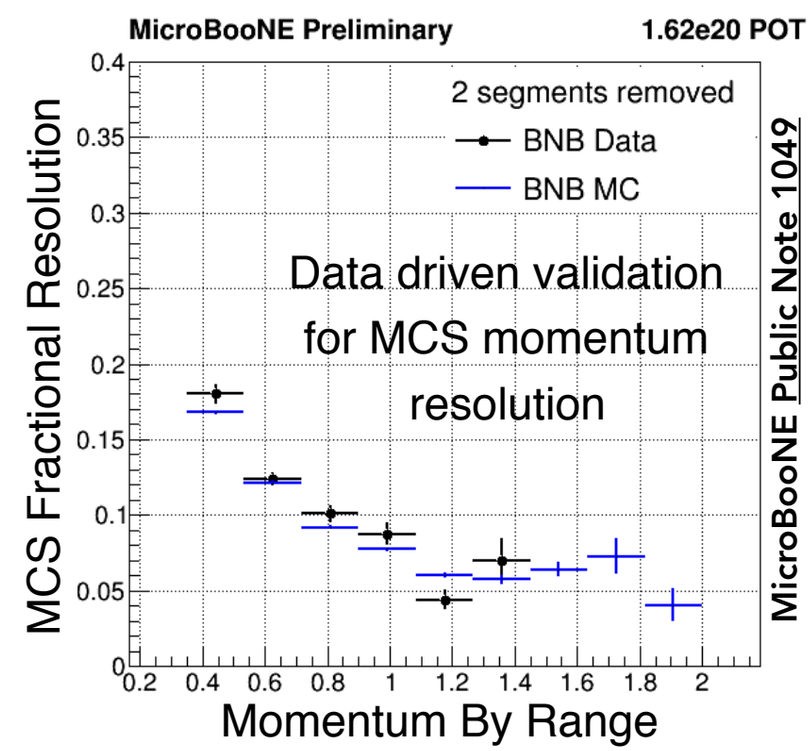
**The majority of BNB muons in MicroBooNE are exiting!**

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

The RMS of the scattering angle $\sigma$ is fit along the particle trajectory to estimate the momentum $p$



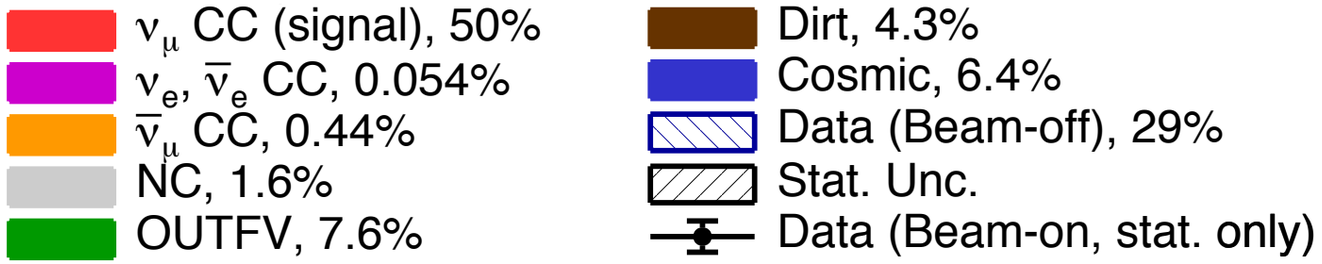



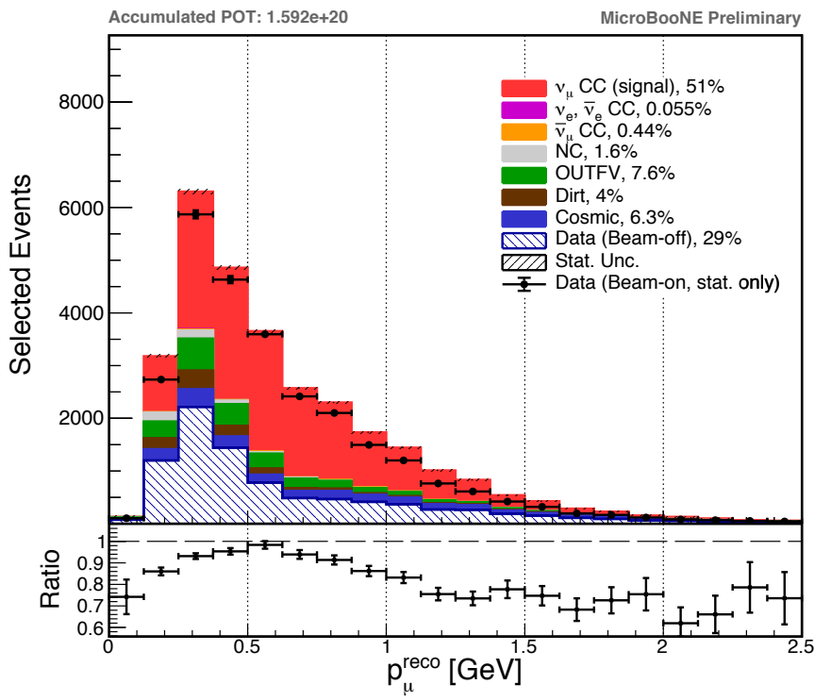



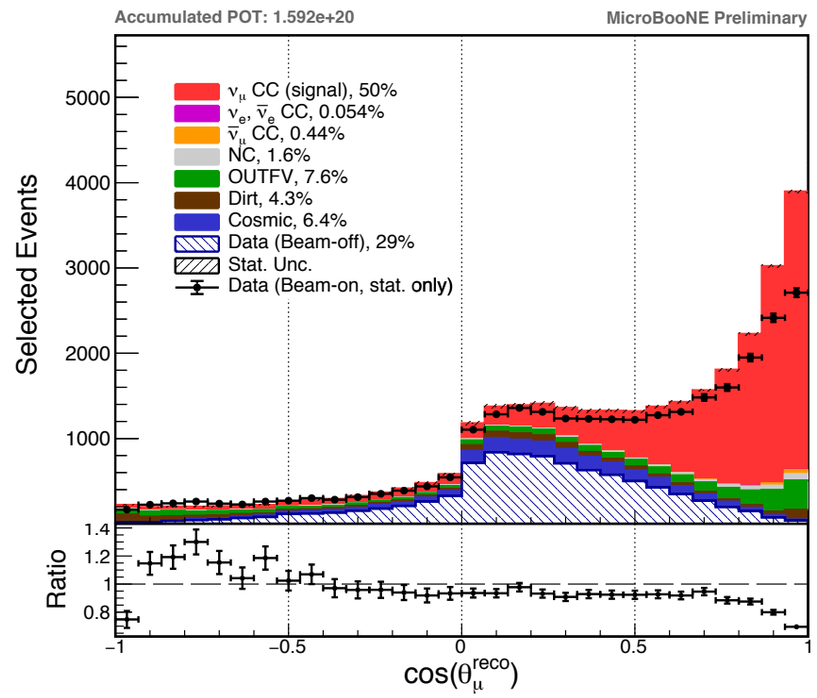

MicroBooNE MCS Paper: JINST 12 P10010 (2017)

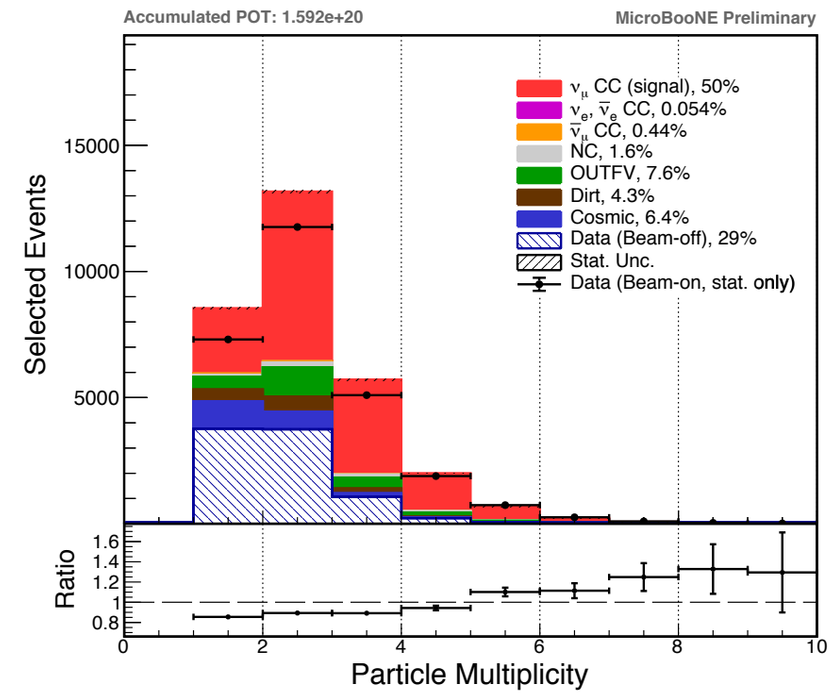
# Event Selection - Selected Events

## Distributions of selected events




*Reconstructed muon momentum.*

Full momentum coverage thanks to MCS used for momentum reconstruction: allows to include exiting tracks.

*Cosine of the muon θ angle.*

θ is the angle w.r.t. the neutrino beam line.

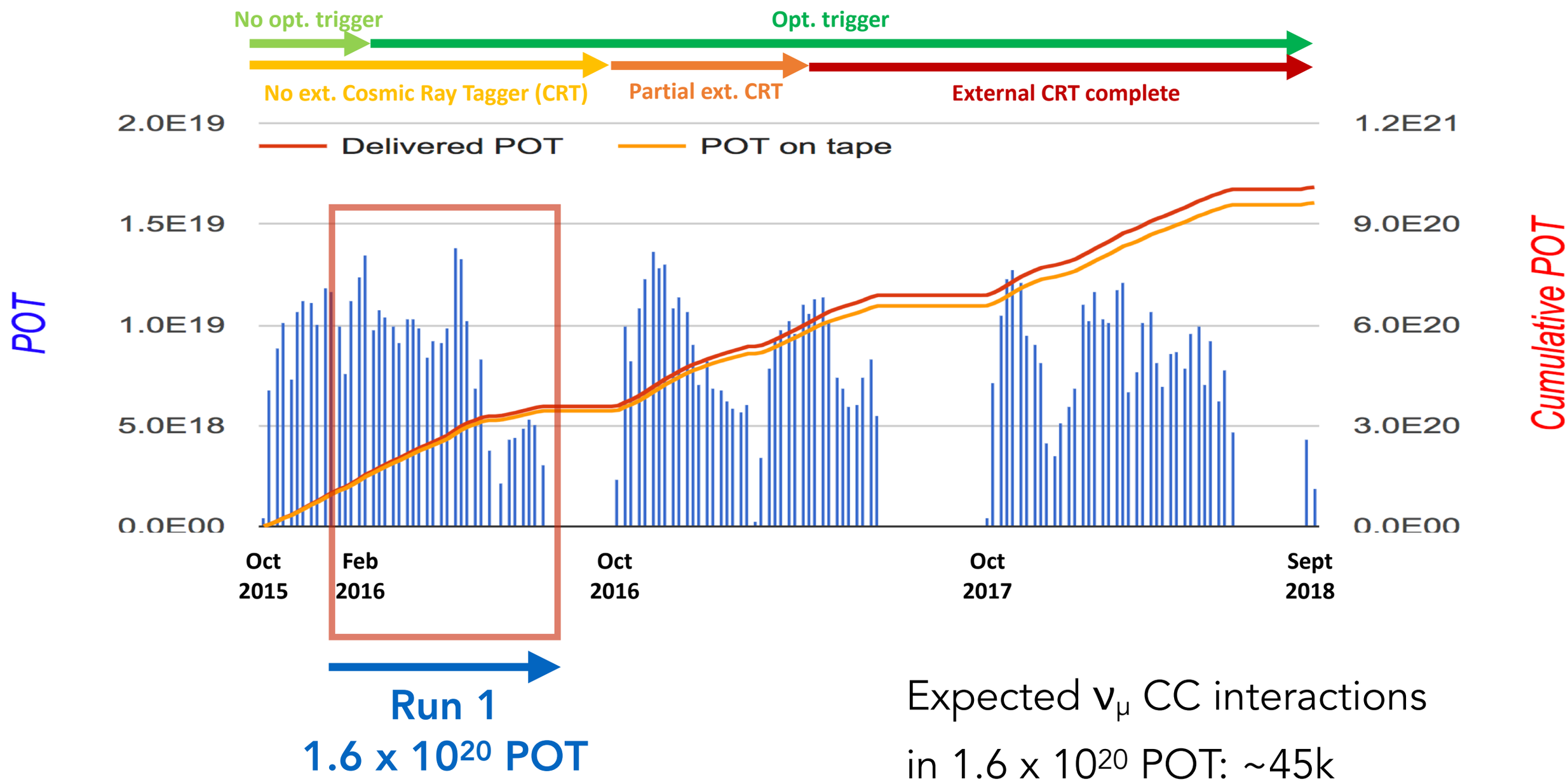
Full angular acceptance.

*Number of reconstructed particles from the neutrino vertex (including muon).*

This selection can be used for more exclusive channels.

Model prediction from GENIE v2.12.2 + Emp. MEC

# Booster Neutrino Beam (BNB) Data Taking




Expected $\nu_\mu$ CC interactions in $1.6 \times 10^{20}$ POT: ~45k

Thank you to Fermilab for providing beam, computing and support!

POT: Protons on Target

# Cross-Section Measurement

**Single-differential cross sections**:

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

**Double-differential cross section**:

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

*i* identifies a bin in the $p_\mu$ $\cos\theta_\mu$ space

| | |
|---|---|
| $N_i$ | number of selected events in reconstructed bin i (data) |
| $B_i$ | number of background events in reconstructed bin i (MC and cosmic data) |
| $\tilde{\varepsilon}_i$ | overall efficiency (selection eff. x acceptance) in reconstructed bin i (MC) |
| $N_{target}$ | number of target nucleons |
| $\Phi$ | muon neutrino flux (integrated over all energies) |

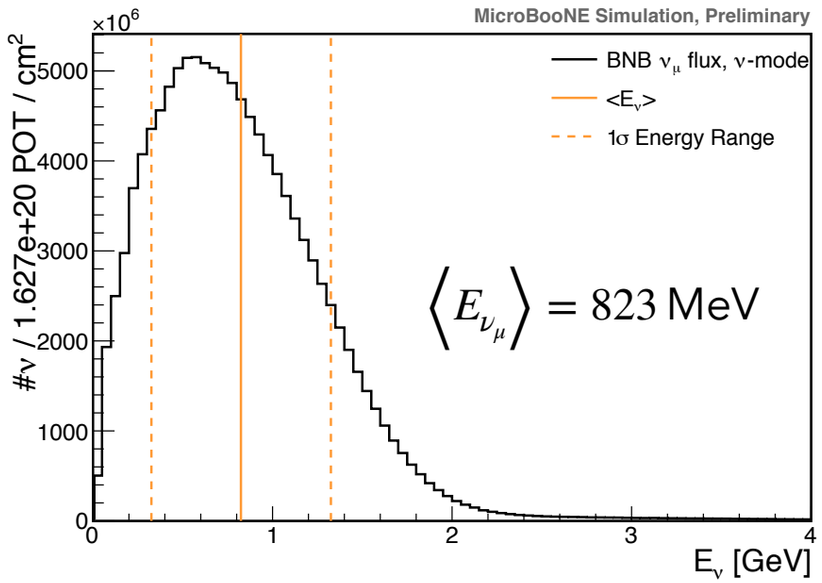
# Cross-Section Measurement

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

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

**Flux integrated cross section:**

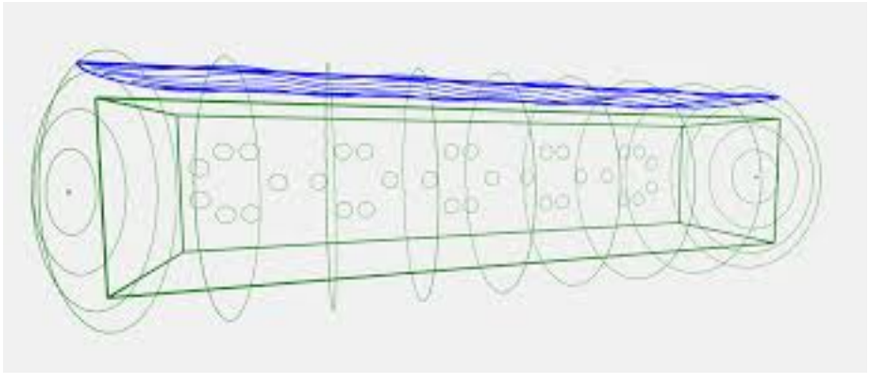
- detector dependent
- less model bias




98% of the flux is below 2 GeV

**Number of targets:**

- temperature and pressure are constantly monitored to measure the number of targets
- we have measured contaminants < 1ppm*
- we treat the full volume as pure argon



*MICROBOONE PUBLIC NOTE 1026
https://microboone.fnal.gov/public-notes/

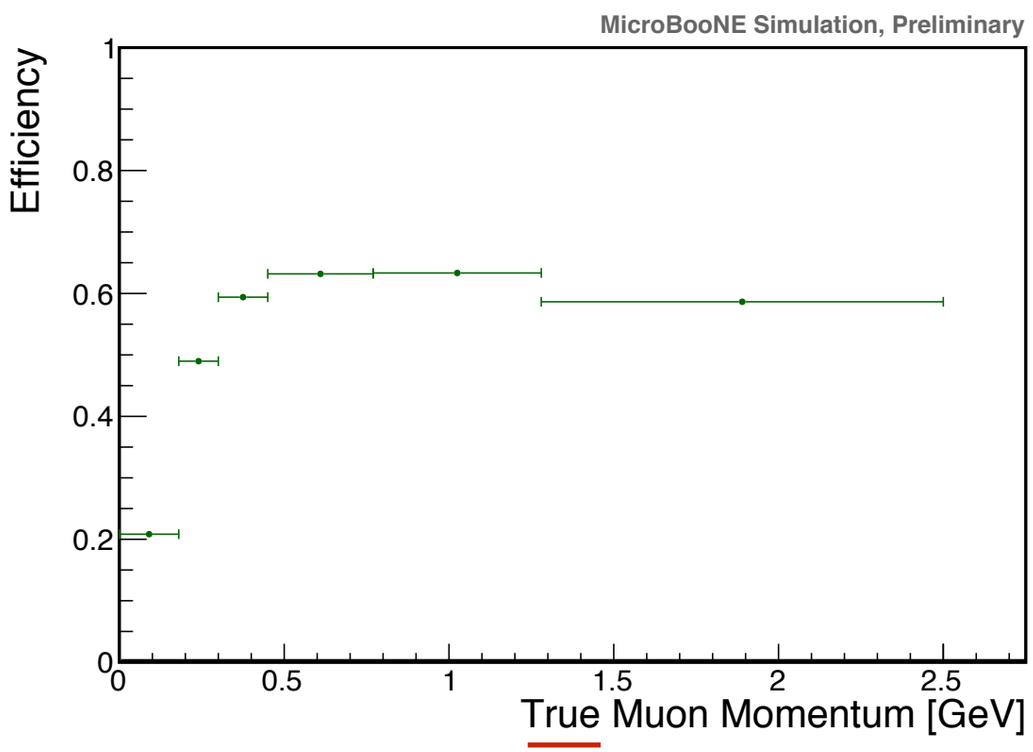
# Cross-Section Measurement

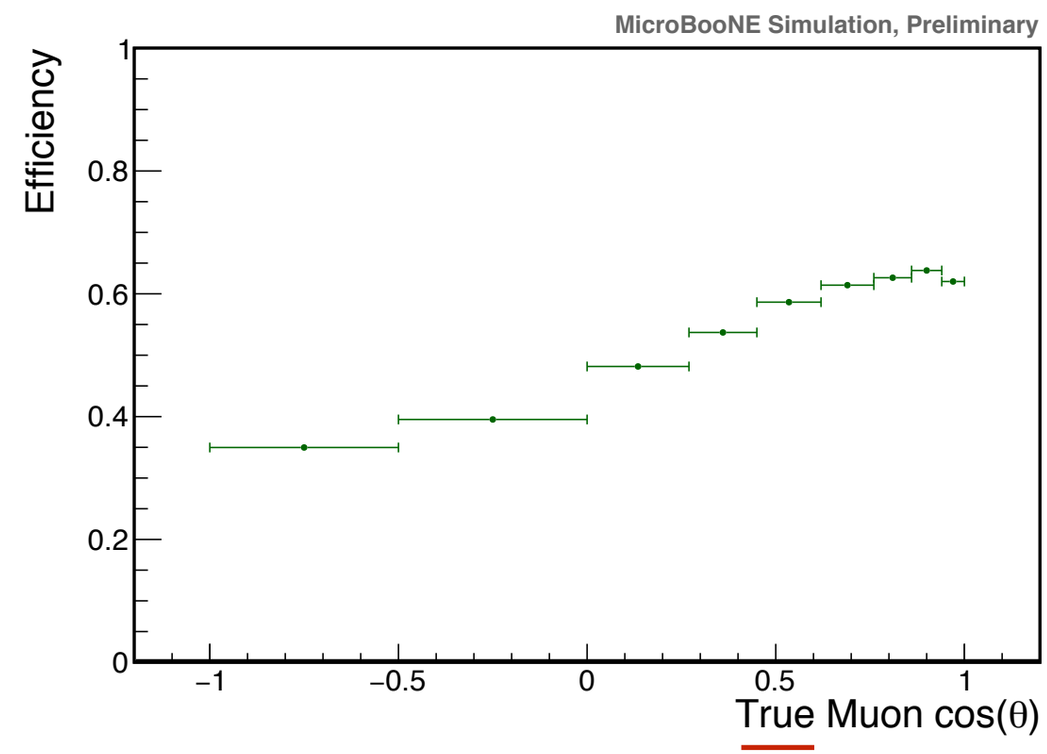
$$\left\langle \frac{d\sigma}{dp_\mu^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i} \qquad \left\langle \frac{d\sigma}{d\cos\theta_\mu^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target}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

**Efficiency**

only statistical uncertainties shown here

systematic effects shown in following slides




Efficiency depends on **true** muon kinematics

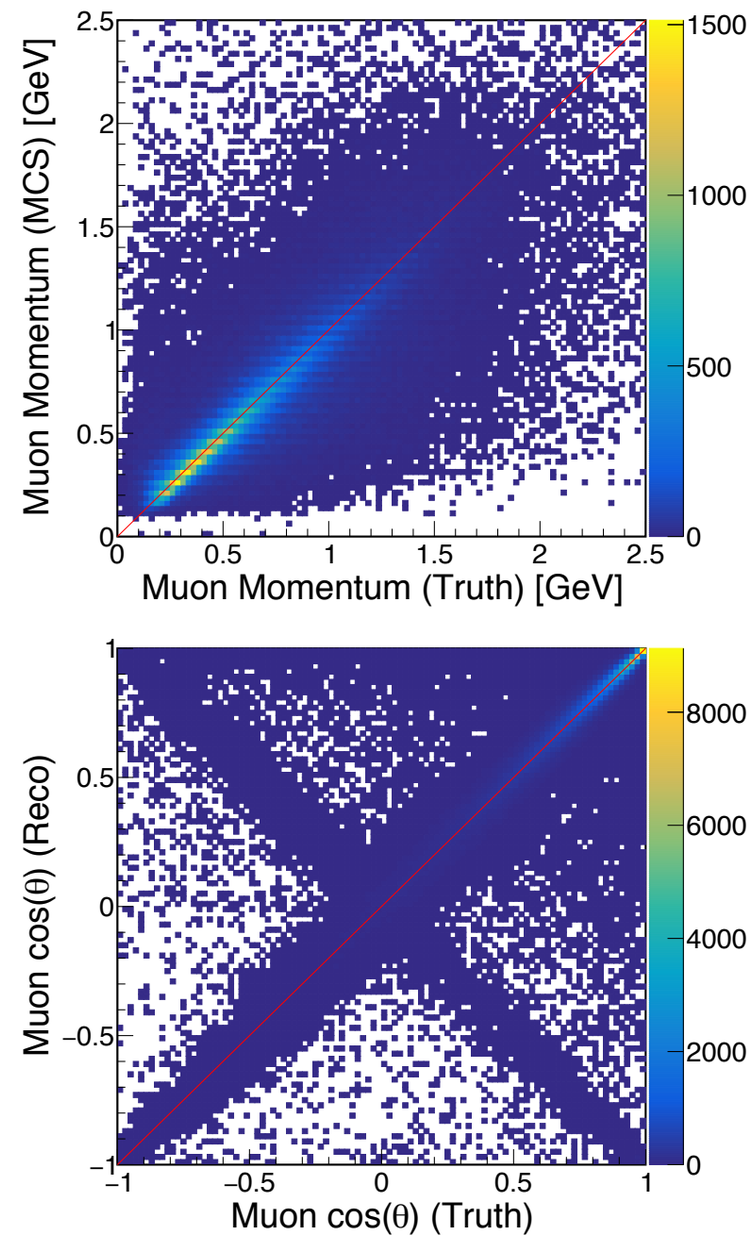
# Cross-Section Measurement

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

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

## Forward Folding

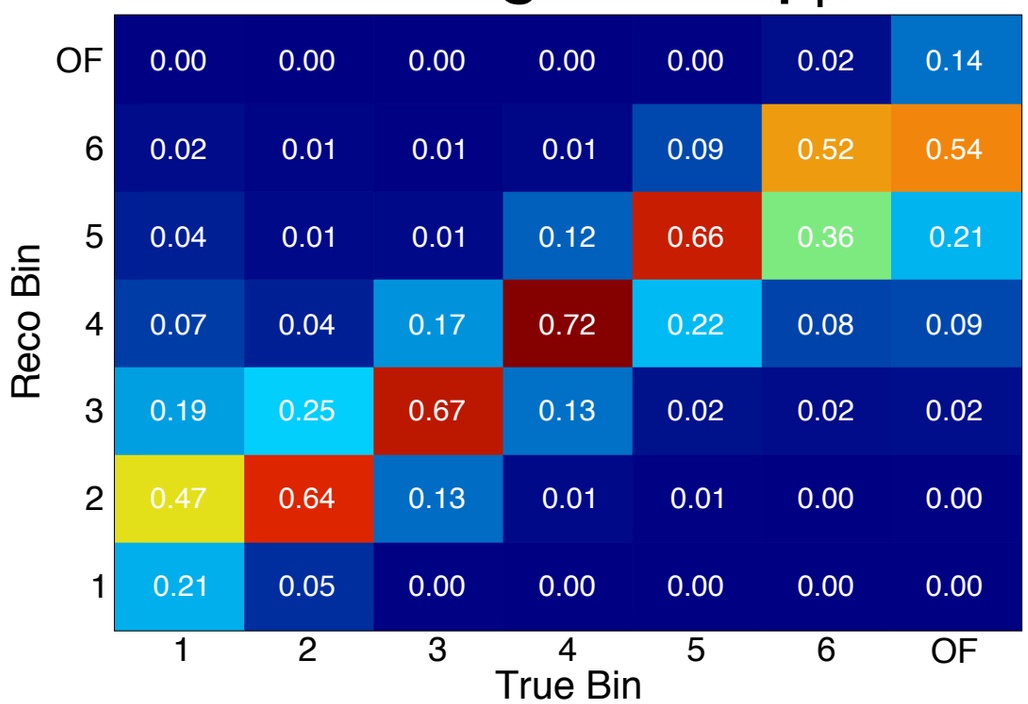
- We have **not** unfolded the measurement to true muon momentum and true muon angle
- Final result will be in **reconstructed** muon momentum and angle
- Unfolding introduces biases that inflate uncertainties
- The efficiency is **forward folded** to be as a function of reconstructed variables



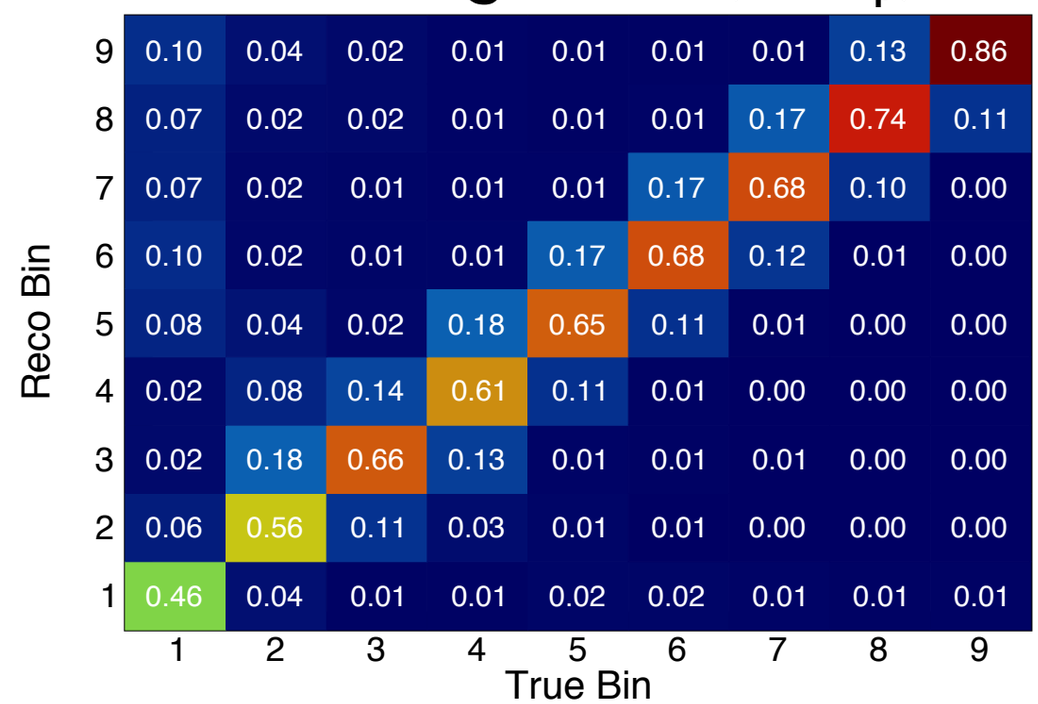
# Forward Folding

$$N_i^{\text{reco}} = \sum_j S_{ij} N_j^{\text{true}} \qquad S_{ij} = P(\text{observed in bin i | true value in bin j})$$

**Smearing Matrix ($p_\mu$)**




**Smearing Matrix ($\cos\theta_\mu$)**

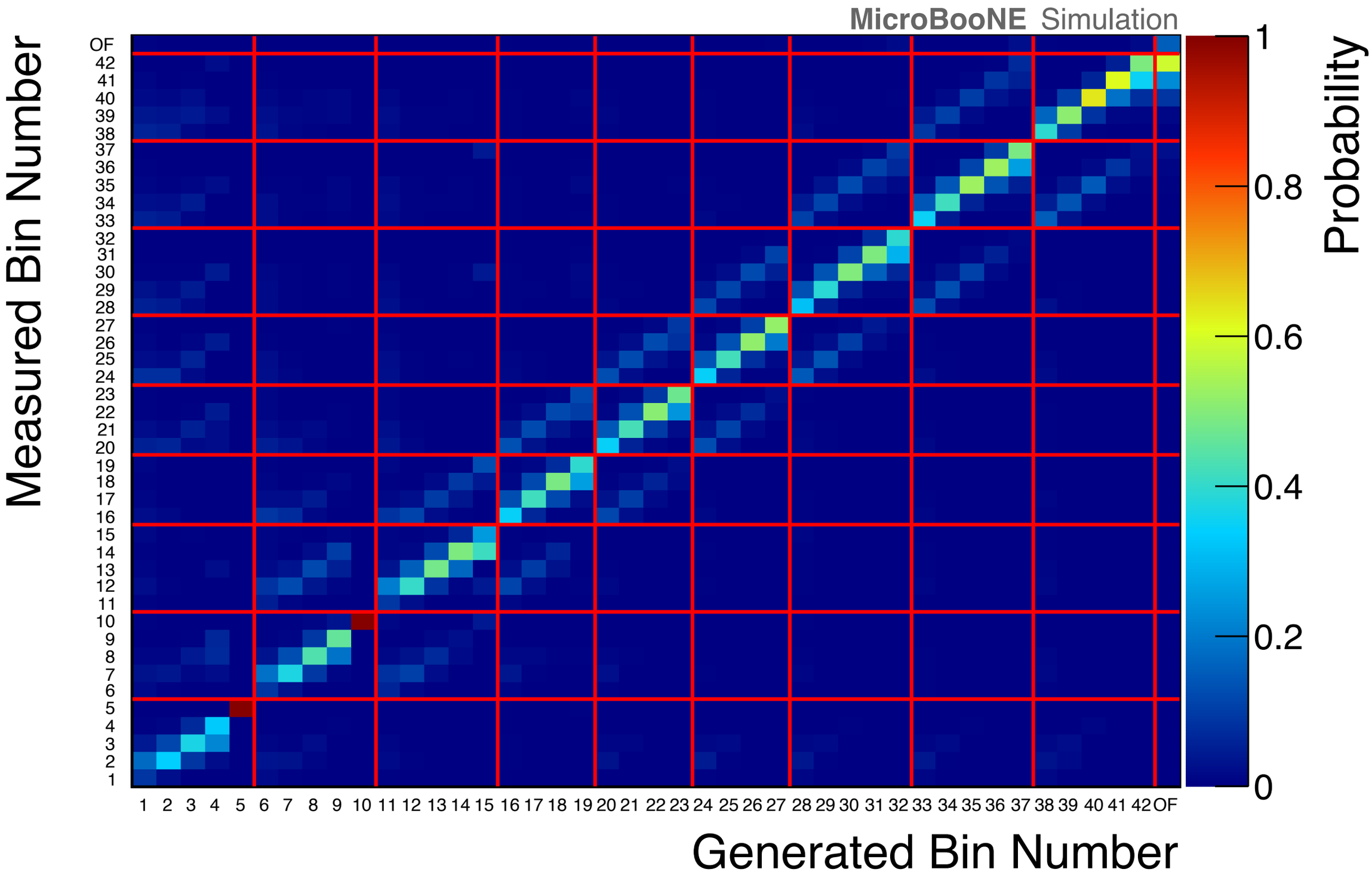



The efficiency in reconstructed bin *i* is given by: $\tilde{\epsilon}_i = \dfrac{\sum_j S_{ij} N_j^{\text{sel}}}{\sum_j S_{ij} N_j^{\text{gen}}}$

The smearing matrix S will be published with the cross section measurement to allow testing other generators/predictions.

# Forward Folding

For the double-differential cross section



# How are the Systematics Estimated?

The goal is to evaluate three systematic covariance matrices in order to get to the full systematic covariance matrix:

$$E^{\text{syst}} = E^{\text{flux}} + E^{\text{xsec}} + E^{\text{detector}} + \ldots$$

**multisim**

- Generating several MC replicas, each one called a "universe".
- Parameters in the models are varied within their uncertainties.
- Done through event reweighting. Requires only one MC run.

**unisim**

- Changing one detector parameter at a time according to its uncertainty.
- Each parameter variation corresponds to a MC run.
- The difference between the central value cross section and the cross section calculated with the new MC runs gives an indication of the systematic uncertainty on the cross section.

# How are the Systematics Estimated?

**Multisim**

### Central Value

$$\left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta x_\mu)_i}$$

Reminder:

$N_i$: from data (doesn't change)

$B_i$: from MC (changes in every universe)

### Universe *s*

$$\left\langle \frac{d\sigma^{s}}{dx_\mu} \right\rangle_i = \frac{N_i - B_i^s}{\tilde{\epsilon}_i^s \cdot N_{target} \cdot \Phi_{\nu_\mu}^s \cdot (\Delta x_\mu)_i}$$

$$\tilde{\epsilon}_i^s = \frac{\sum_{j=1}^{M} S_{ij}^s N_j^{s,\text{sel}}}{\sum_{j=1}^{M} S_{ij}^s N_j^{s,\text{gen}}}$$

Background events, efficiency and smearing matrix change in every universe

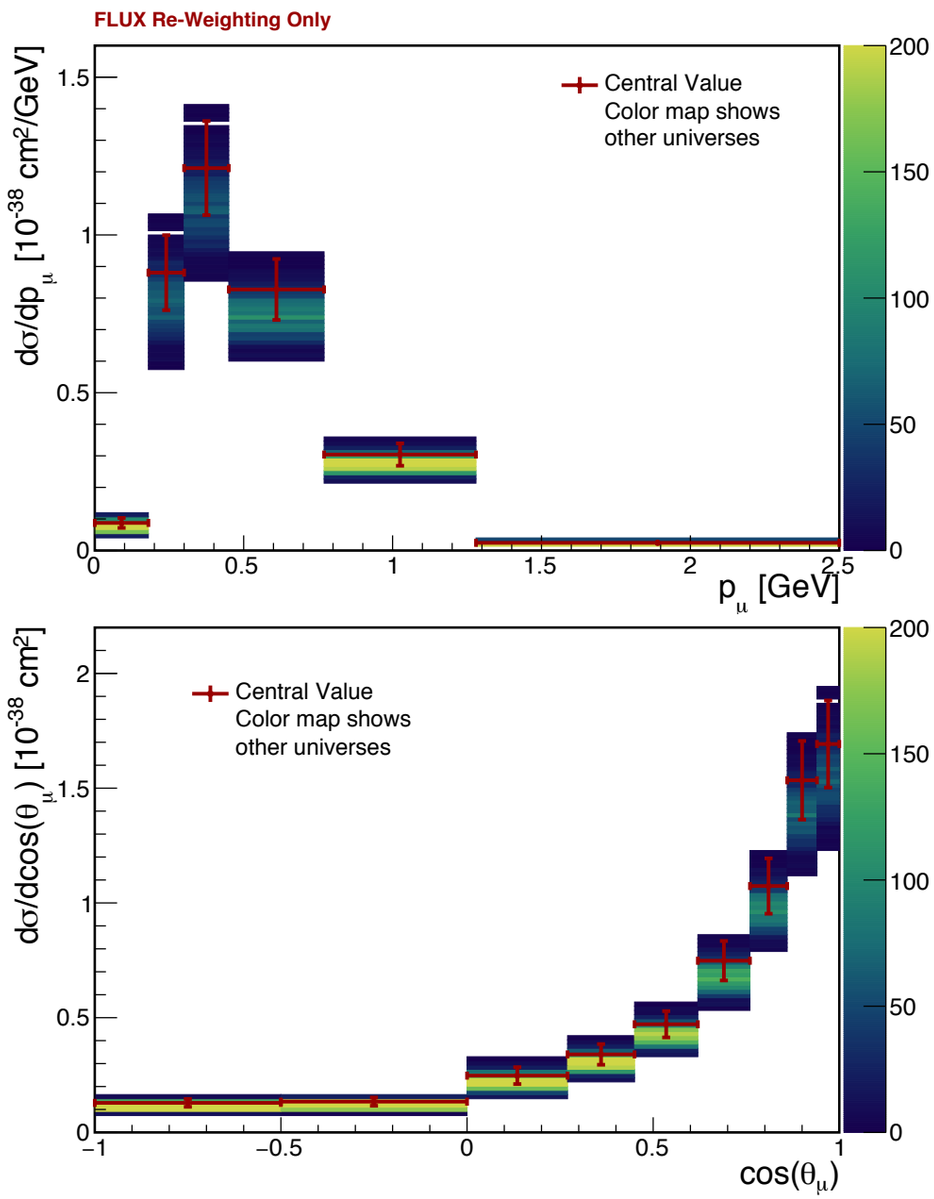
The covariance matrix is calculated as:

$$E_{ij} = \frac{1}{N_s} \sum_{s=0}^{N_s} \left( \left\langle \frac{d\sigma^s}{dx_\mu} \right\rangle_i - \left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_i \right) \left( \left\langle \frac{d\sigma^s}{dx_\mu} \right\rangle_j - \left\langle \frac{d\sigma^{cv}}{dx_\mu} \right\rangle_j \right)$$

# Neutrino Flux and Cross Section Uncertainties

## Neutrino Beam Flux

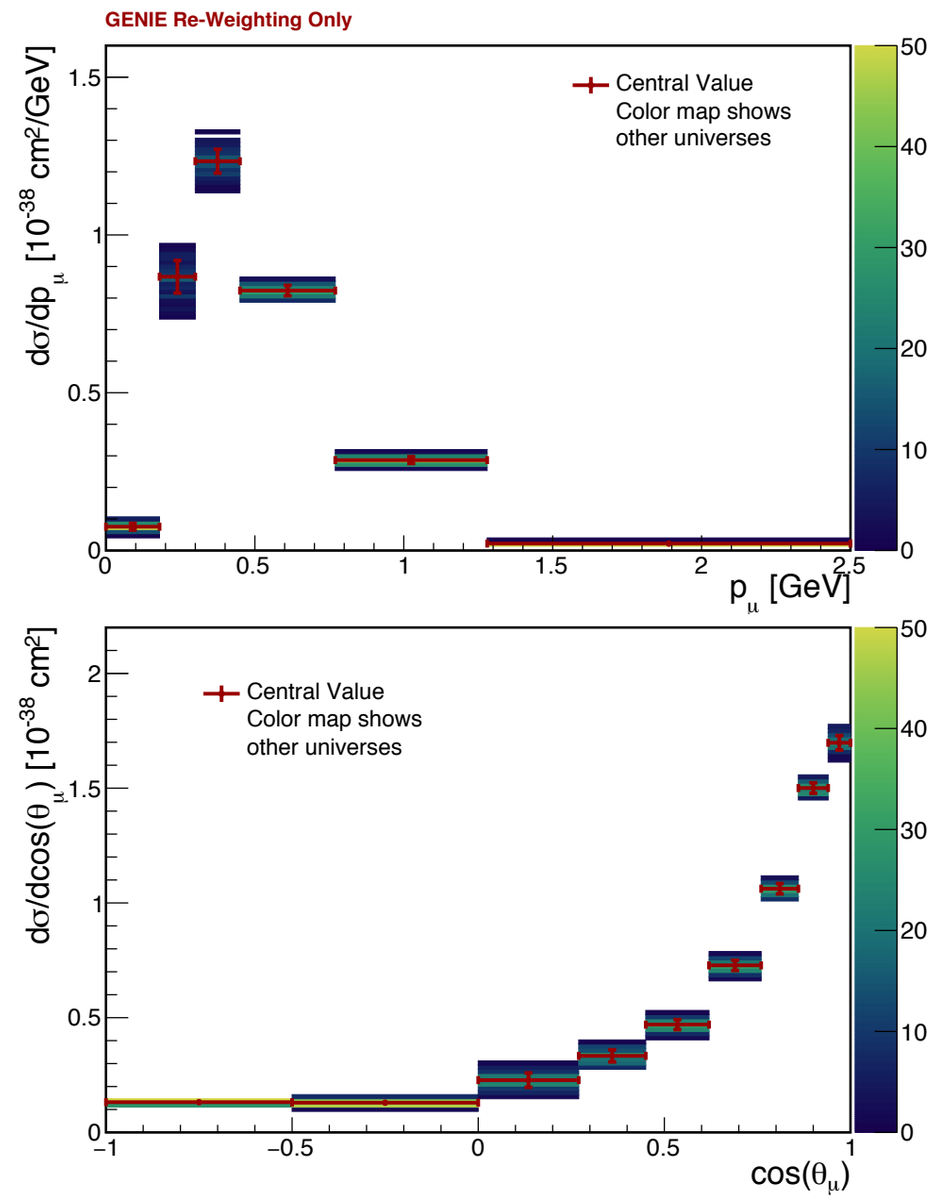
Using framework adapted from the MiniBooNE collaboration **(PRD 79, 072002, 2009)**




**Relative Uncertainty on Total Cross Section: 12%**

## Cross Section Modelling

GENIE provides over 35 parameters to be reweighed




**Relative Uncertainty on Total Cross Section: 4%**

# Detector Systematics

We generated MC samples for each one of these detector parameters and recalculated the cross section for each: $\sigma^m$.

The uncertainty has then been evaluated as:

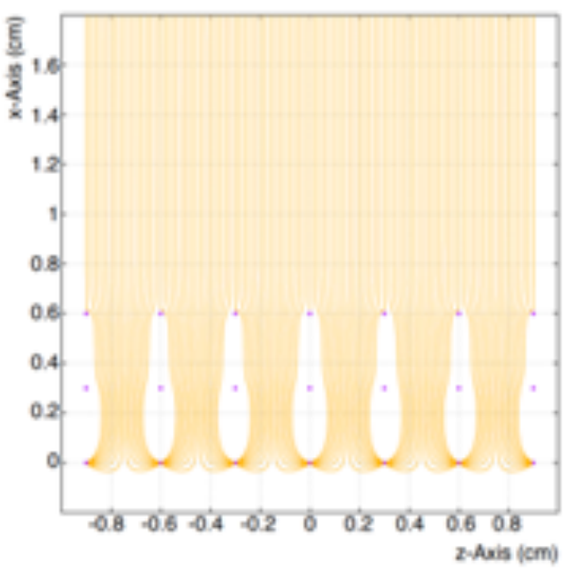
$$E_{ij}^{\text{det}} = \sum_m \left(\sigma_i^{\text{cv}} - \sigma_j^m\right)\left(\sigma_j^{\text{cv}} - \sigma_j^m\right)$$

| Systematic Sample | Relative Uncertainty [%] |
|---|---|
| **Induced Charge Effect** | 13.0 |
| **Light Yield Model** | 4.7 |
| **Channel Saturation** | 4.3 |
| **Space Charge Effect** | 3.7 |
| **TPC Visibility** | 3.7 |
| **Electron Lifetime** | 2.9 |
| **Misconfigured Channels** | 1.8 |
| **Longitudinal Diffusion** | 1.7 |
| **Transverse Diffusion** | 1.6 |
| **PE Noise** | 0.4 |
| **Wire Response** | 0.2 |
| **Wire Noise** | 0.1 |
| **Electron Recombination** | 0.1 |

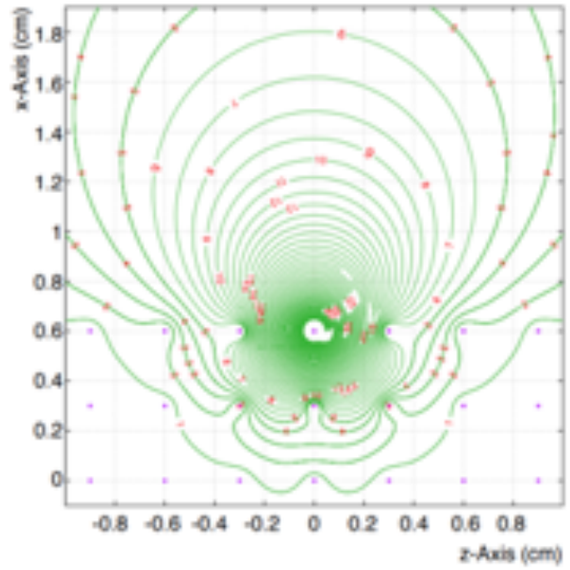
**Detector Response Relative Uncertainty on Total Cross Section: 16%**

# Detector Systematics - Induced Charge

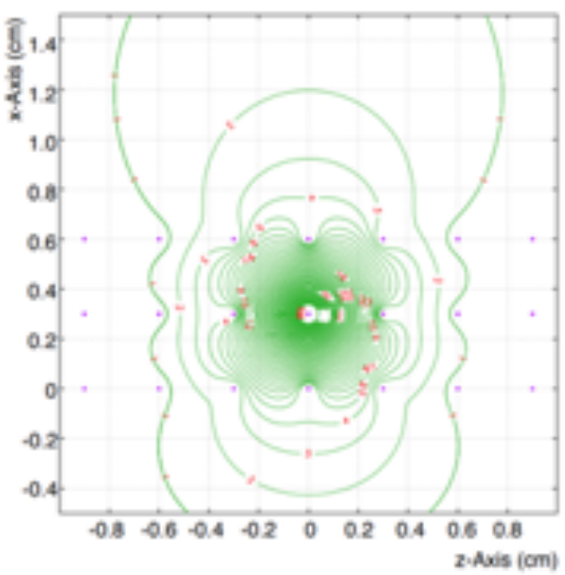
MicroBooNE Signal Processing Papers:
JINST 13 (2018) no.07, P07006 & P07006



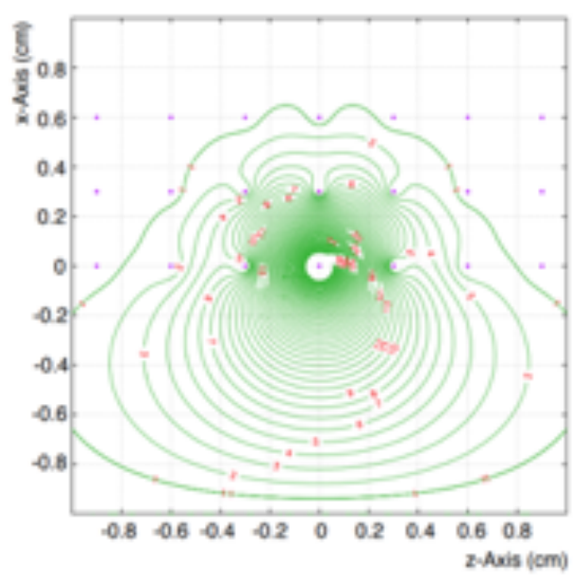

(a) Electron drift paths.




(b) Weighting potential on a U wire.




(c) Weighting potential on a V wire.




(d) Weighting potential on a Y wire.

- The impact on our reconstruction and analyses is strongest for tracks traveling towards the wire plane.
- We have verified that we can see this in several analyses. Simulation of dynamic induced charge improves our data/MC agreement.
- Future simulation will include simulation of dynamic induced charge as default.

MicroBooNE is the first LAr TPC experiment to take this into account

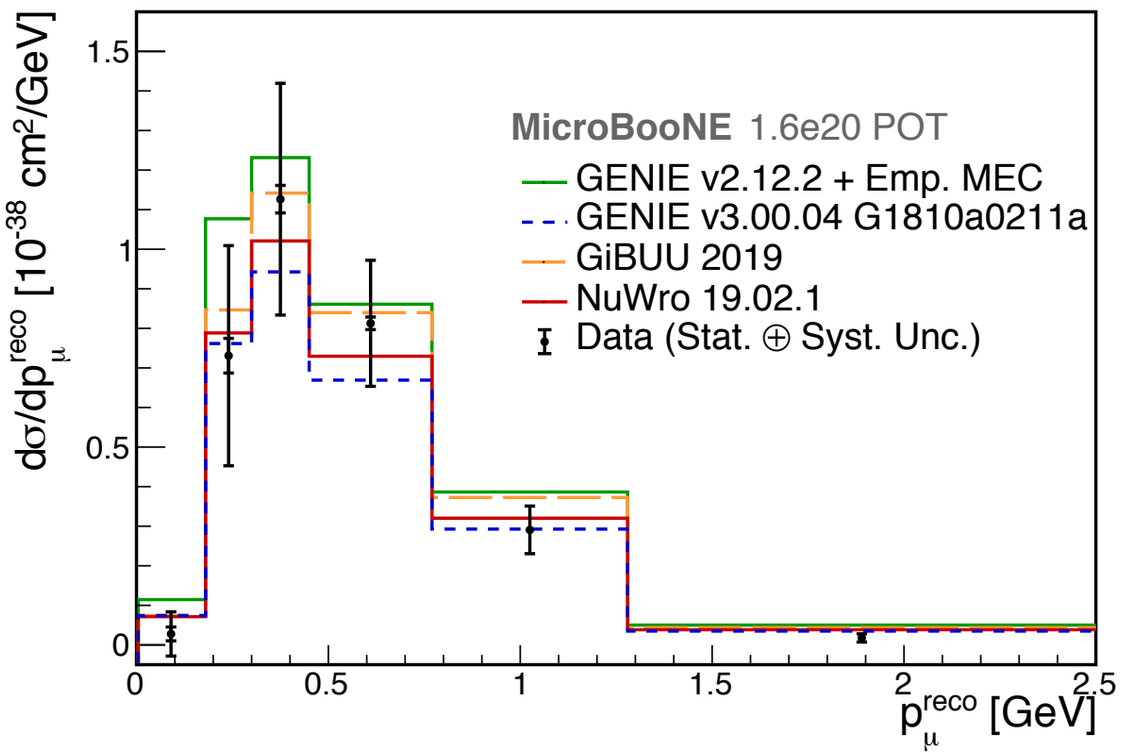
# Summary of Systematics

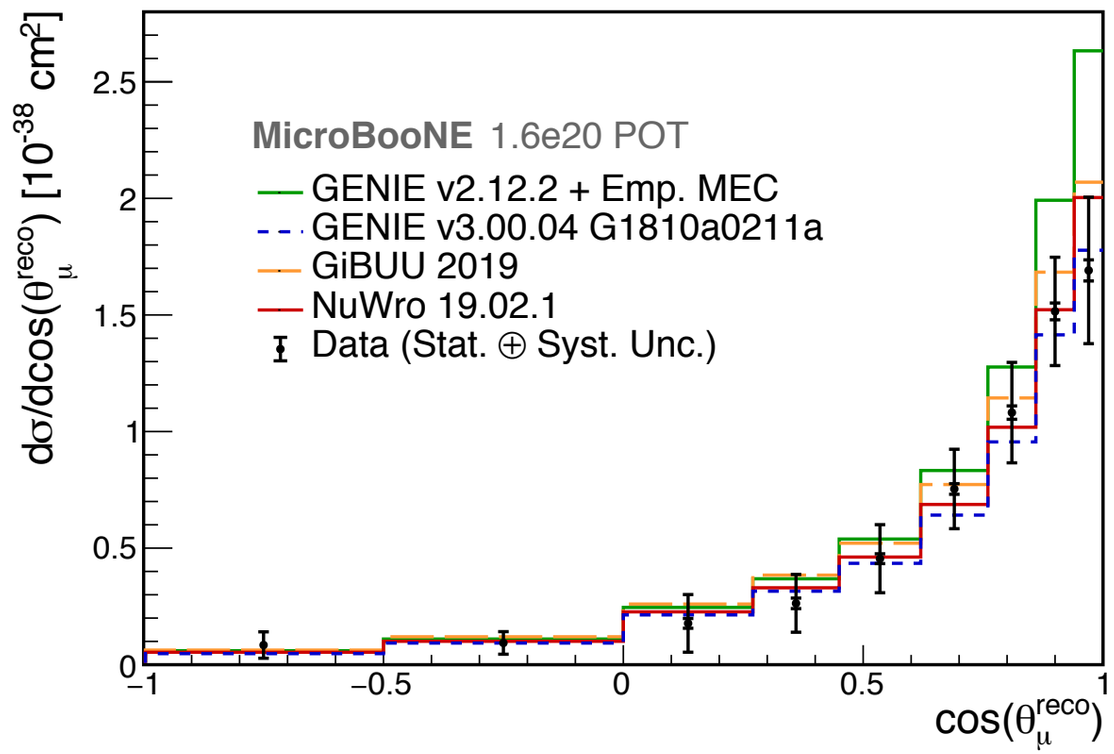
- Described previously
- Improved reconstruction and cosmic ray tagger will mitigate this background
- It will be reduced when we switch to a neutrino simulation with cosmic data overlaid

| Source of Uncertainty | Relative Uncertainty | |
|---|---|---|
| **Beam Flux** | 12.2 | ◆ |
| **Cross Section Modelling(*)** | 3.9 | ◆ |
| **Detector Response** | 16.2 | ◆ |
| **POT Counting** | 2.0 | |
| **Dirt Background** | 10.9 | ◆ |
| **Cosmics (Corsika)** | 4.1 | ◆ |
| **Cosmic (data)** | 0.7 | |
| **MC Statistics** | 0.2 | |
| **Stat** | 1.4 | |
| **Total** | 23.8 | |

(*) Includes an additional uncertainty on MEC interactions (1.5%)

# Cross Section Measurement

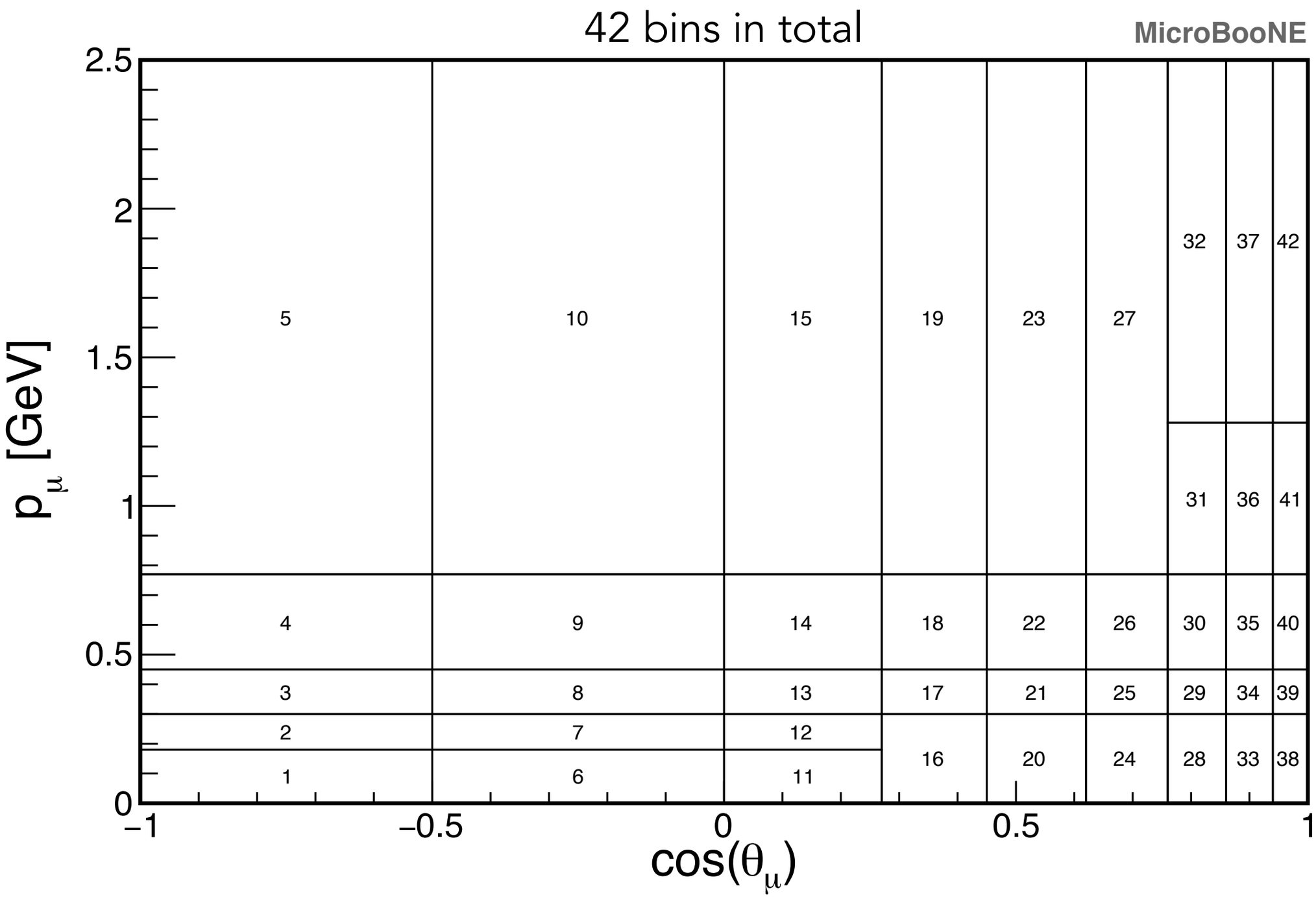


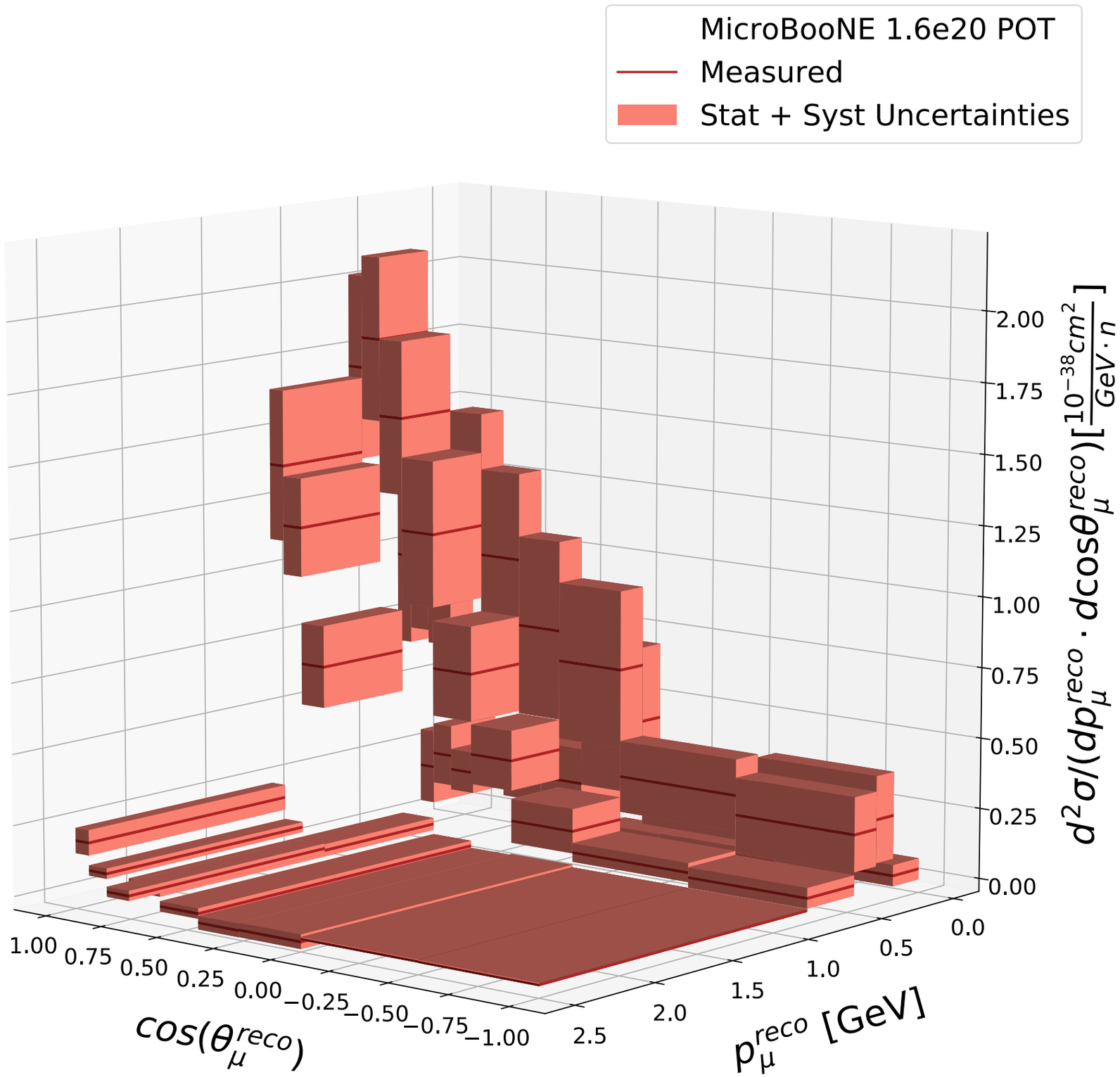

| Model Element | GENIE v2 + MEC (v2.12.2) | GENIE v3 (v3.00.04 G1810a0211a) | NuWro (19.02.1) | GiBUU (2019) |
|---|---|---|---|---|
| **Nuclear Model** | Bodek-Ritchie Fermi Gas **[1]** | Local Fermi Gas **[2, 3]** | Local Fermi Gas **[2, 3]** | Consistent nuclear medium corrections throughout. Also uses a LFG model for nucleon momenta, a separate MEC model **[11]**, and propagates final state particles according to the Boltzmann-Uehling-Uhlenbeck equations **[11]** |
| **Quasi-elastic** | Llewellyn-Smith **[4]** | Nieves **[2, 3]** | Nieves **[2, 3]** | |
| **MEC** | Empirical **[5]** | Nieves **[2, 3]** | Nieves **[2, 3]** | |
| **Resonant** | Rein-Seghal **[6]** | Berger-Seghal **[7]** | Berger-Seghal **[7]** (pion production from **[9]**) | |
| **Coherent** | Rein-Seghal **[6]** | Berger-Seghal **[7]** | Berger-Seghal **[7]** | |
| **FSI** | hA **[8]** | hA2018 **[8]** | Oset **[10]** | |

# Now moving to the double-differential cross section!

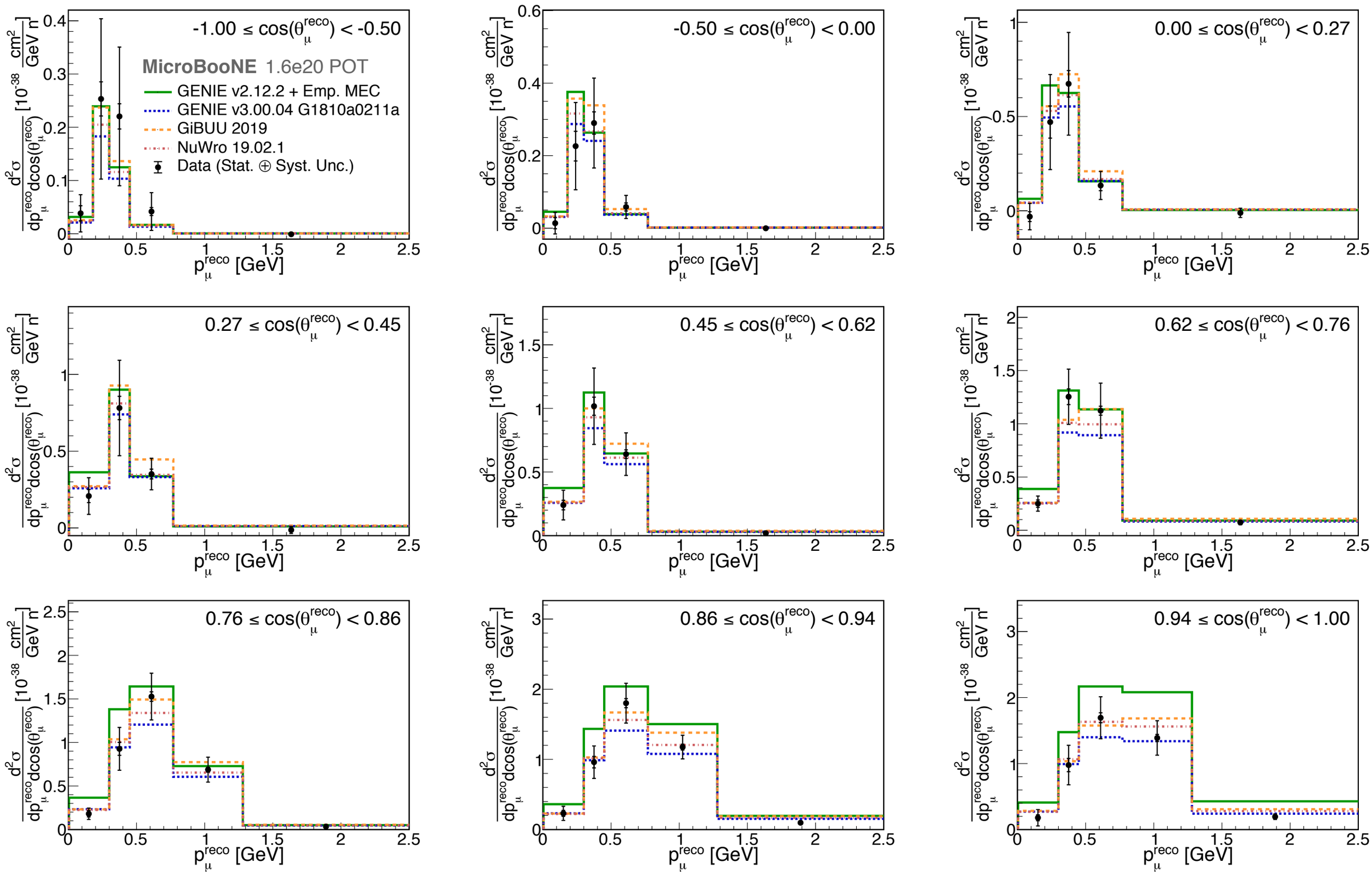
**Binning for the double-differential cross section measurement:**



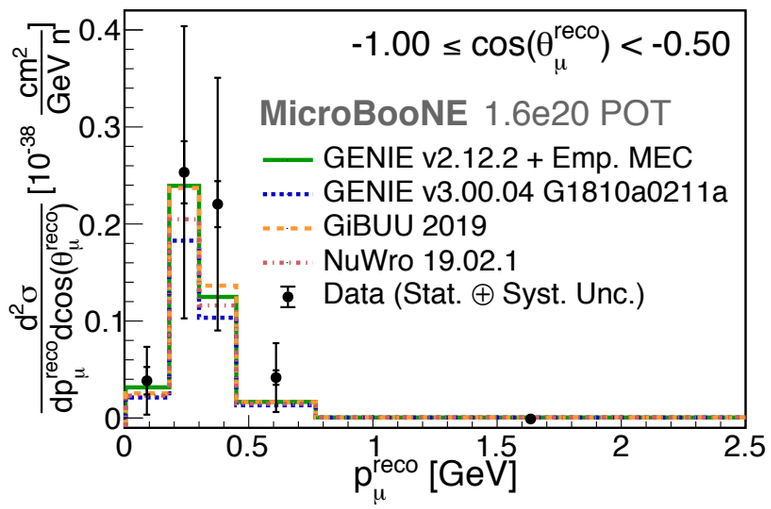
# First Double-Differential Measurement on Argon

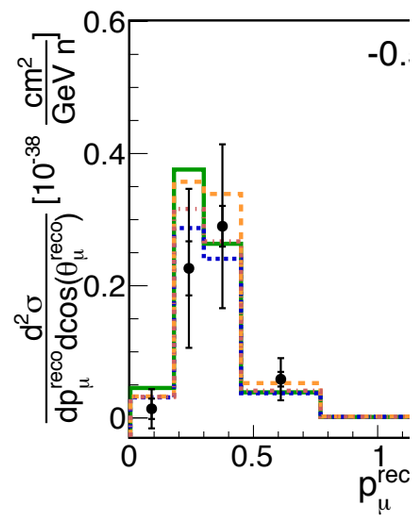


# Cross Section Measurement

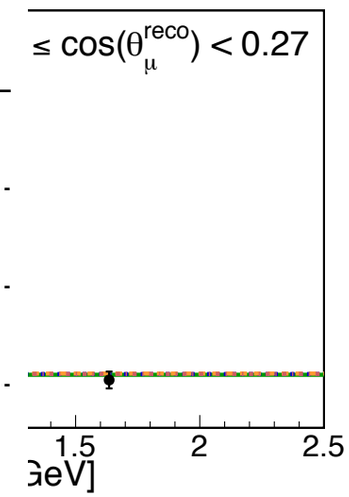


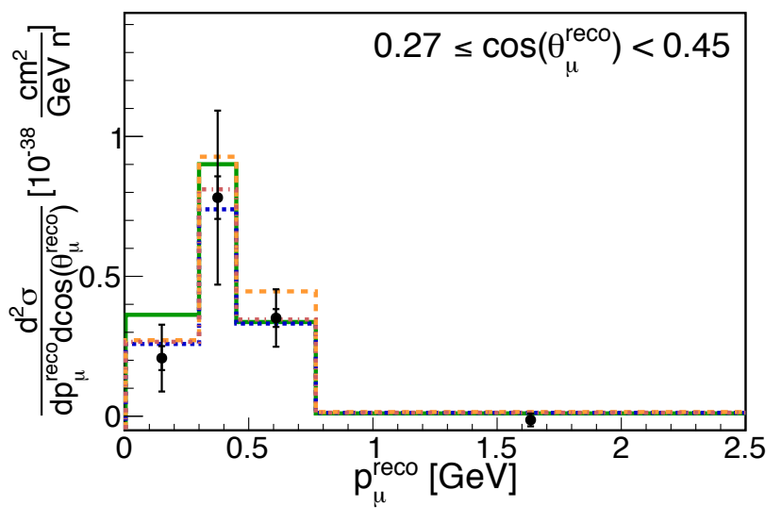
# Cross Section Measurement

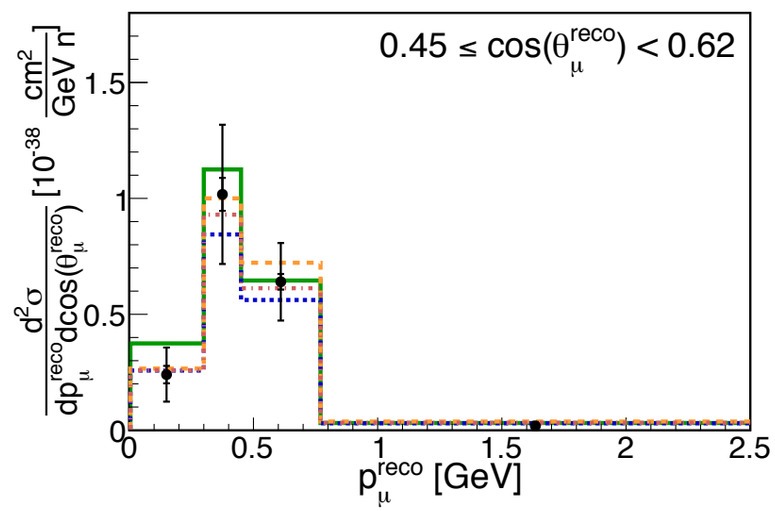


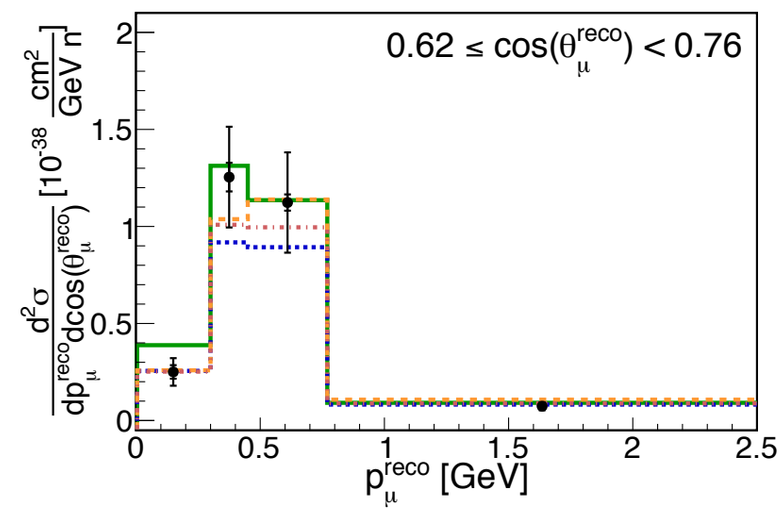



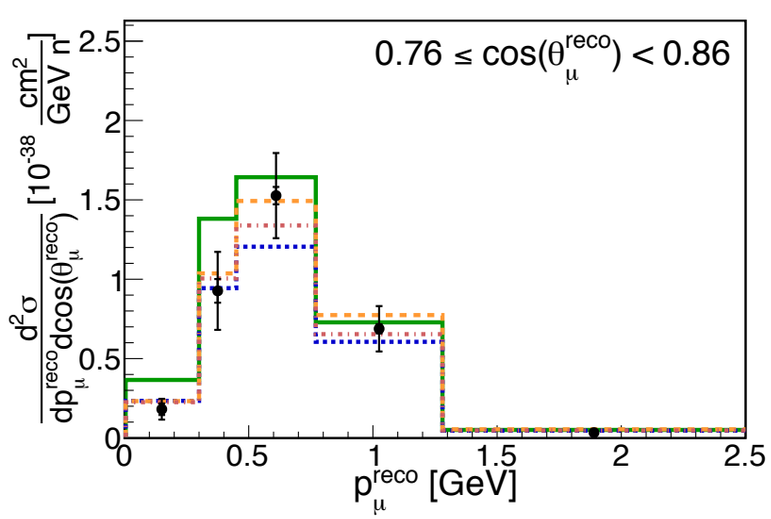

| Model | $\chi^2$ |
|---|---|
| GENIE v2 + MEC | 245.9 |
| GENIE v3 | 108.8 |
| GiBUU | 172.9 |
| NuWro | 126.5 |

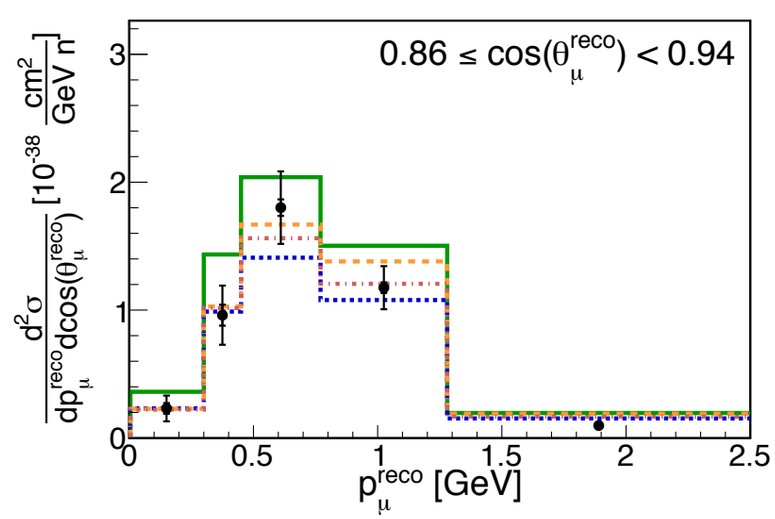


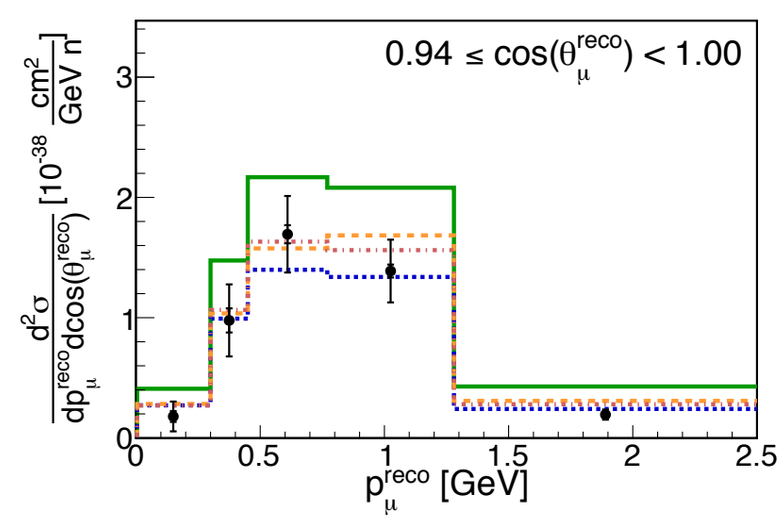



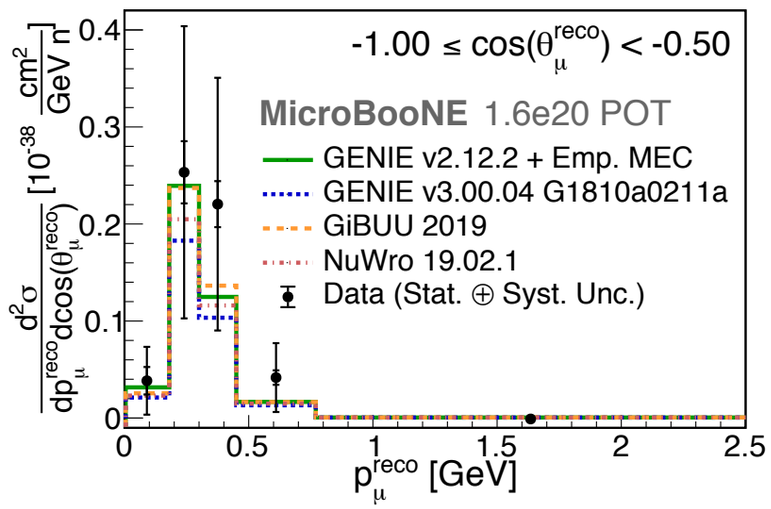



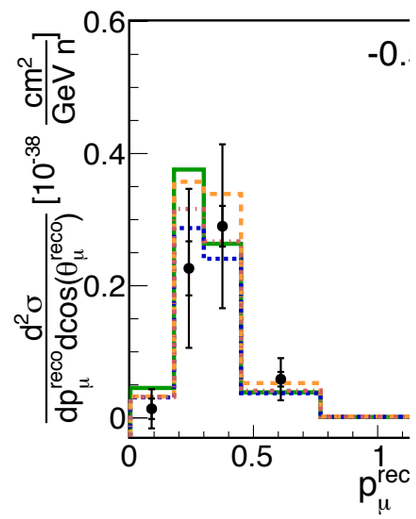



# Cross Section Measurement



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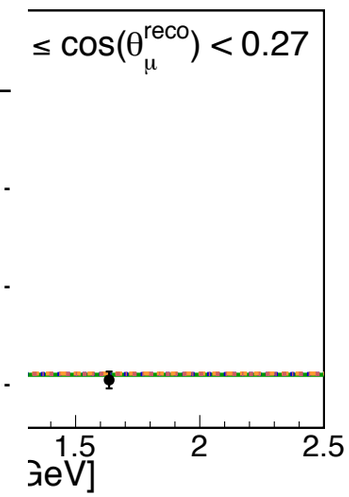
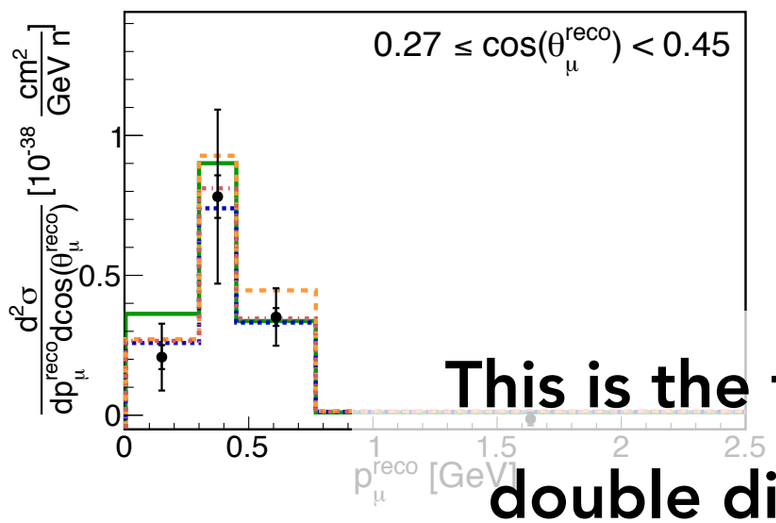
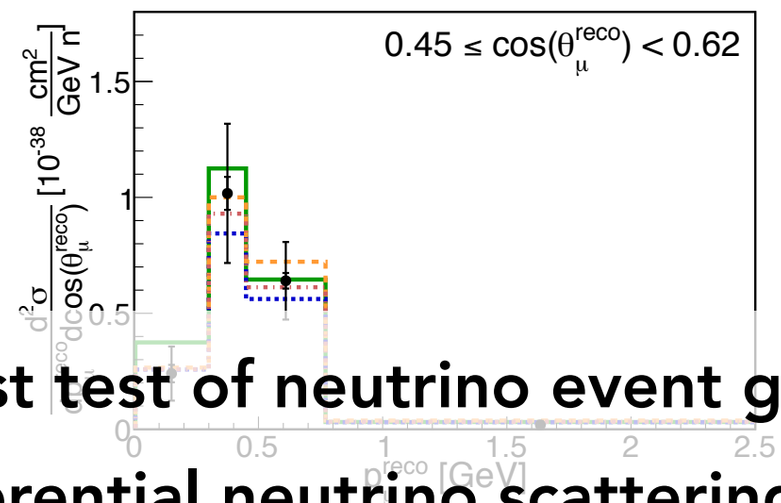
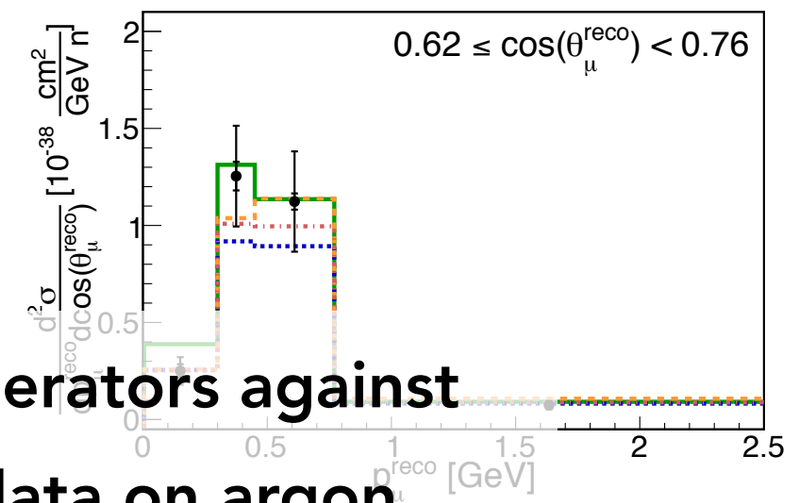
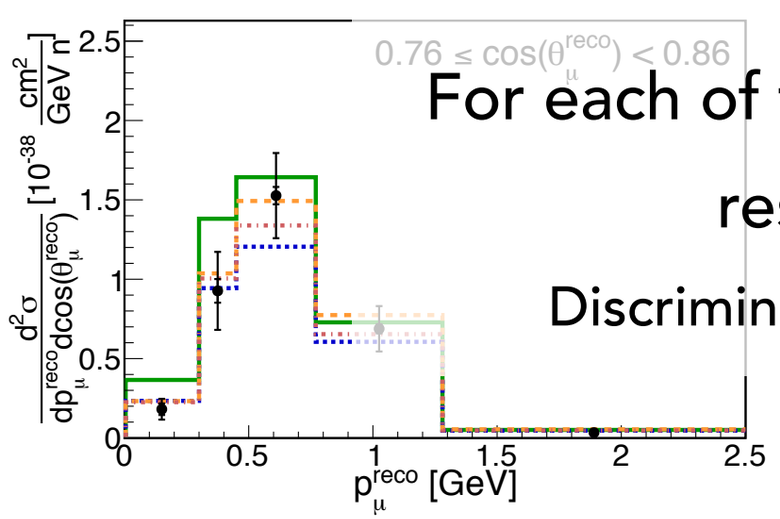
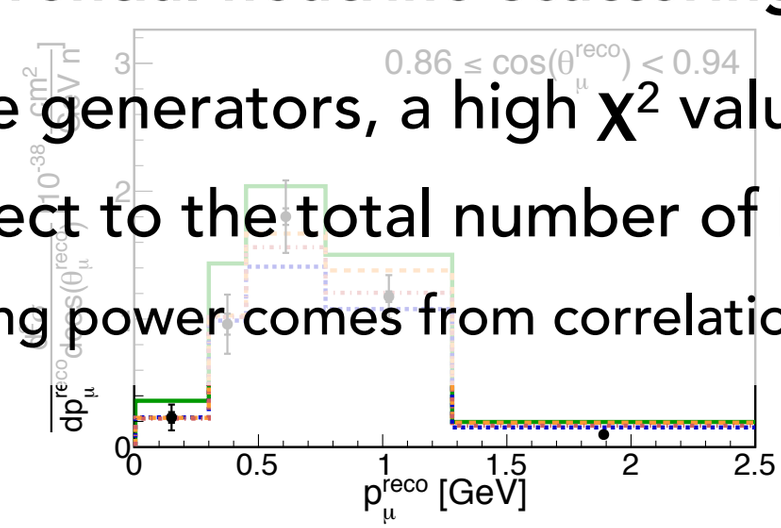


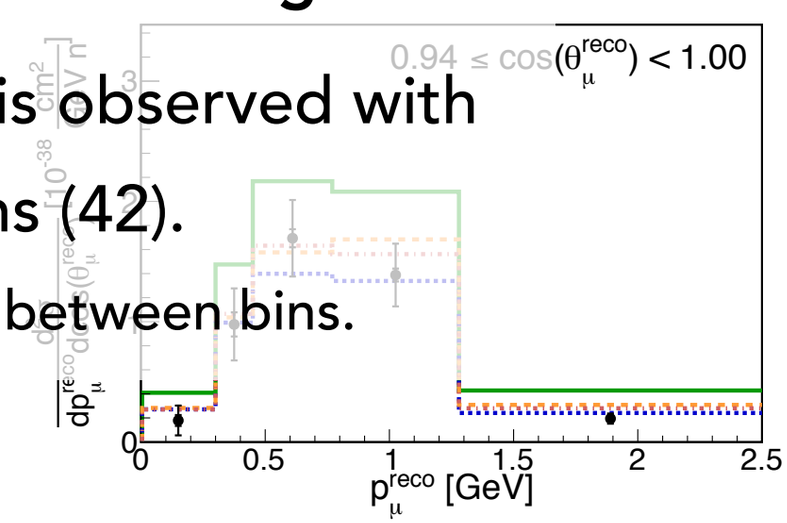


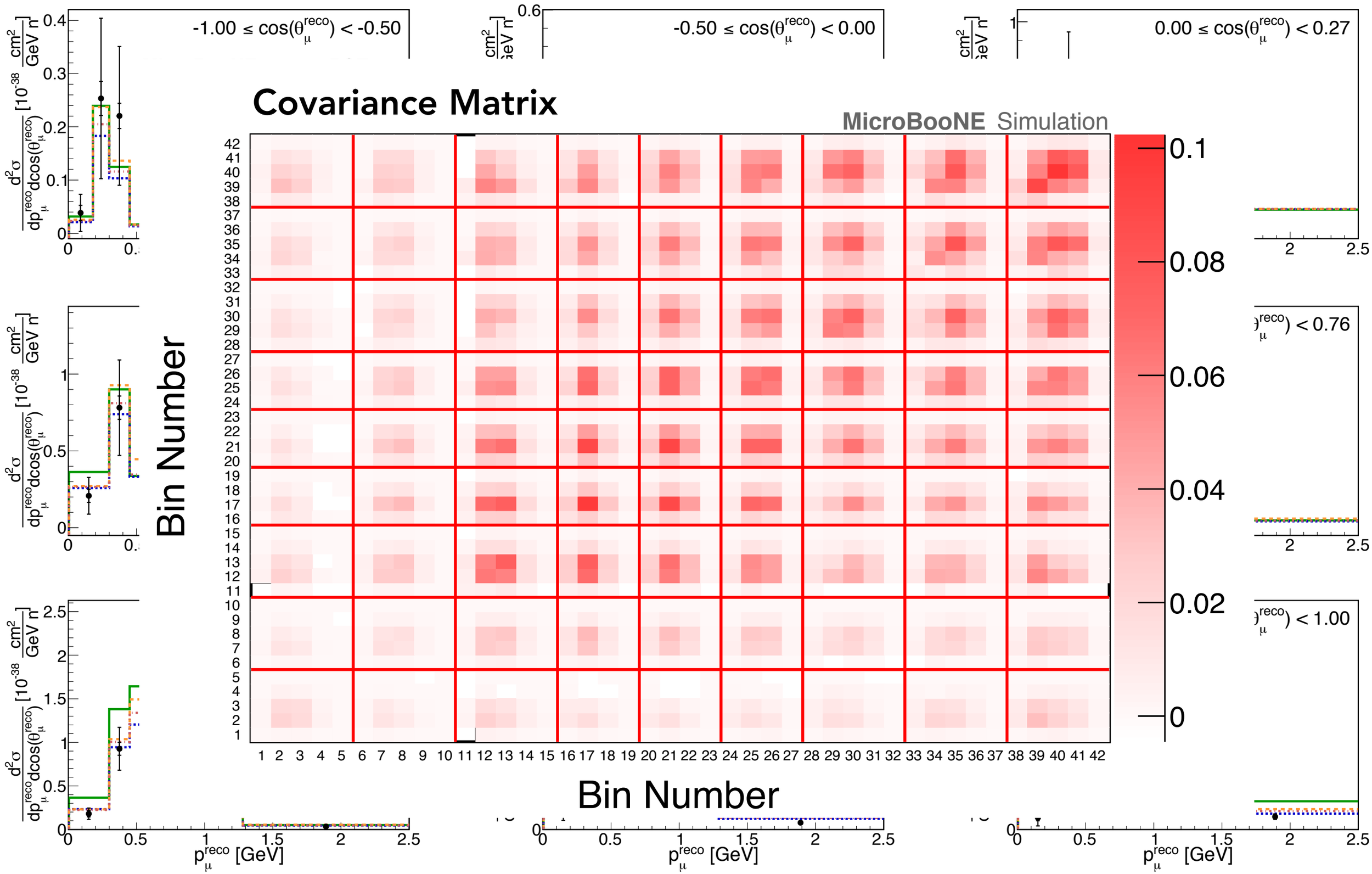




**This is the first test of neutrino event generators against double differential neutrino scattering data on argon.**

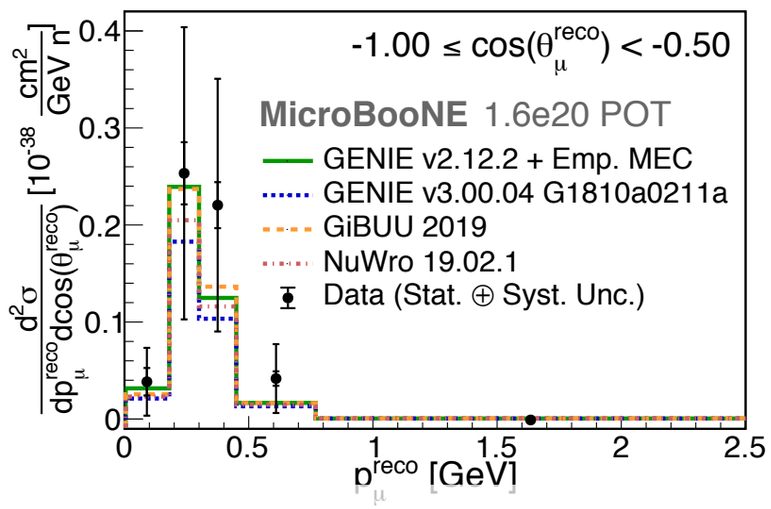
For each of the generators, a high $\chi^2$ value is observed with respect to the total number of bins (42).

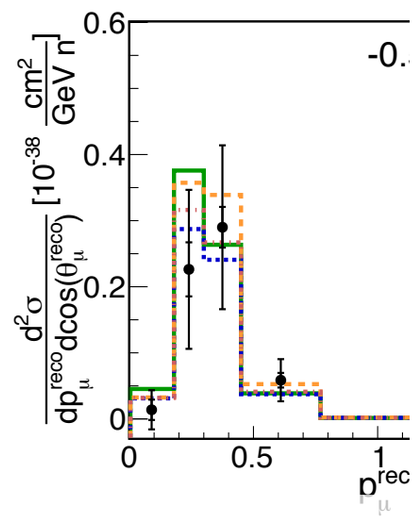
Discriminating power comes from correlations between bins.

# Cross Section Measurement



# Cross Section Measurement



| Model | $\chi^2$ |
|---|---|
| GENIE v2 + MEC | 245.9 |
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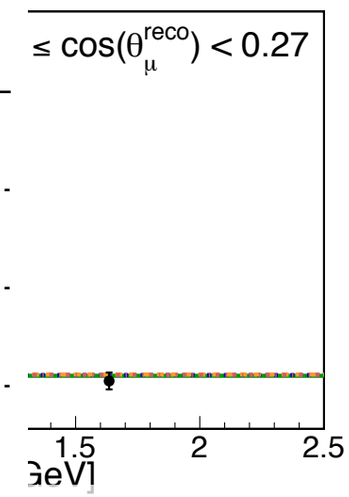
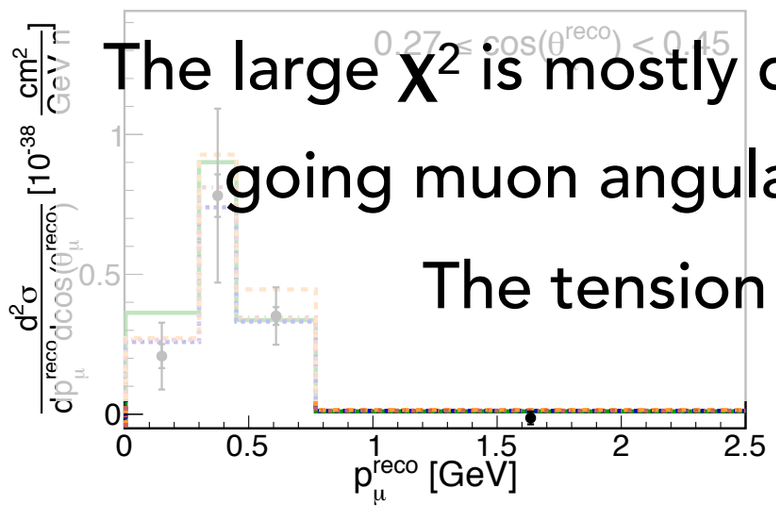
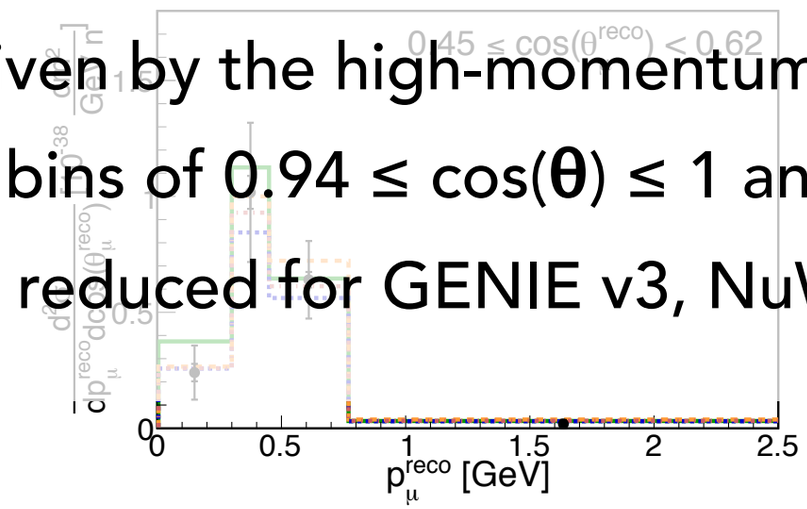
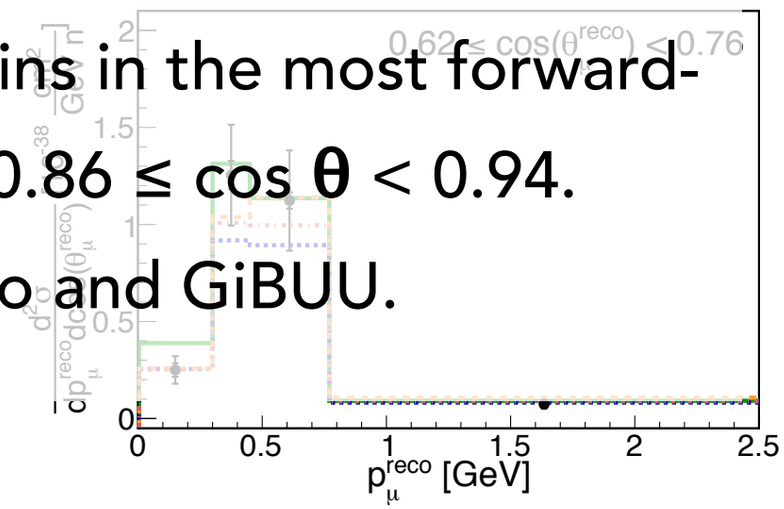


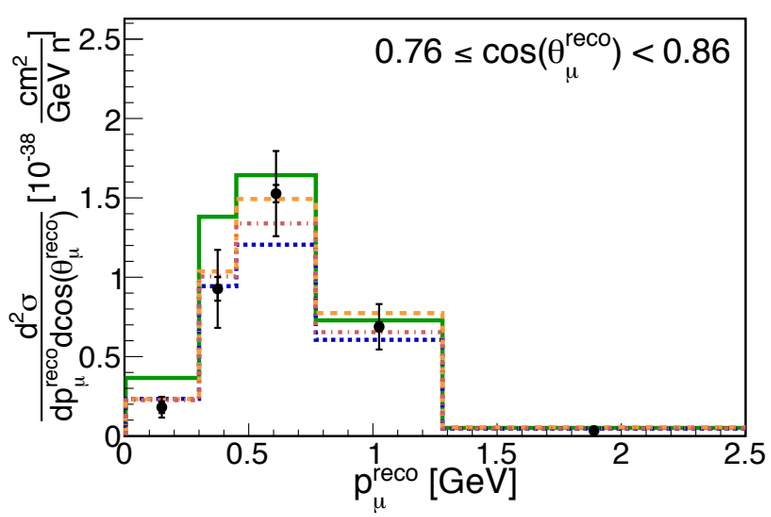
The large $\chi^2$ is mostly driven by the high-momentum bins in the most forward-going muon angular bins of $0.94 \leq \cos(\theta) \leq 1$ and $0.86 \leq \cos\theta < 0.94$.

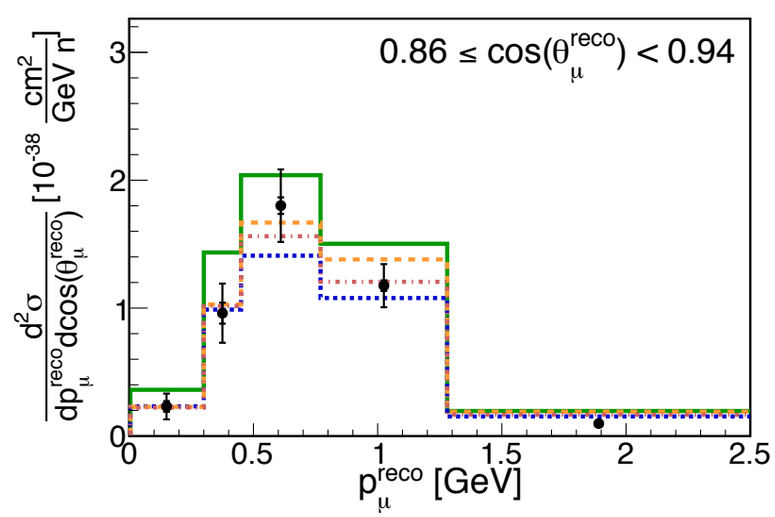
The tension is reduced for GENIE v3, NuWro and GiBUU.

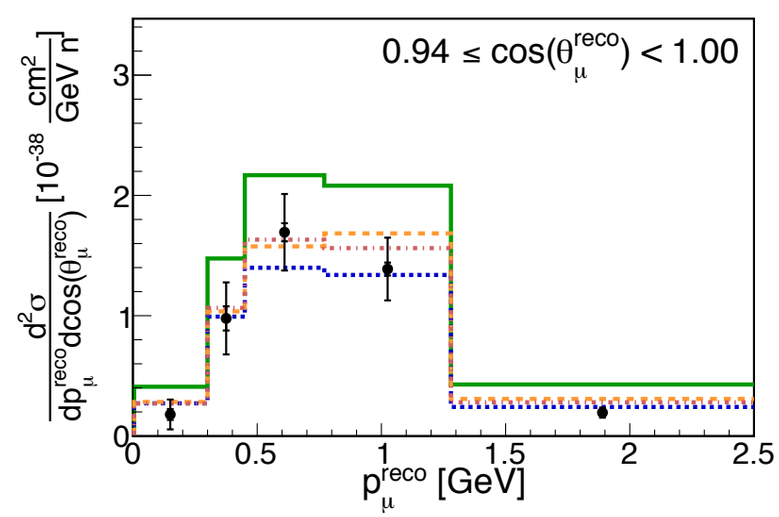


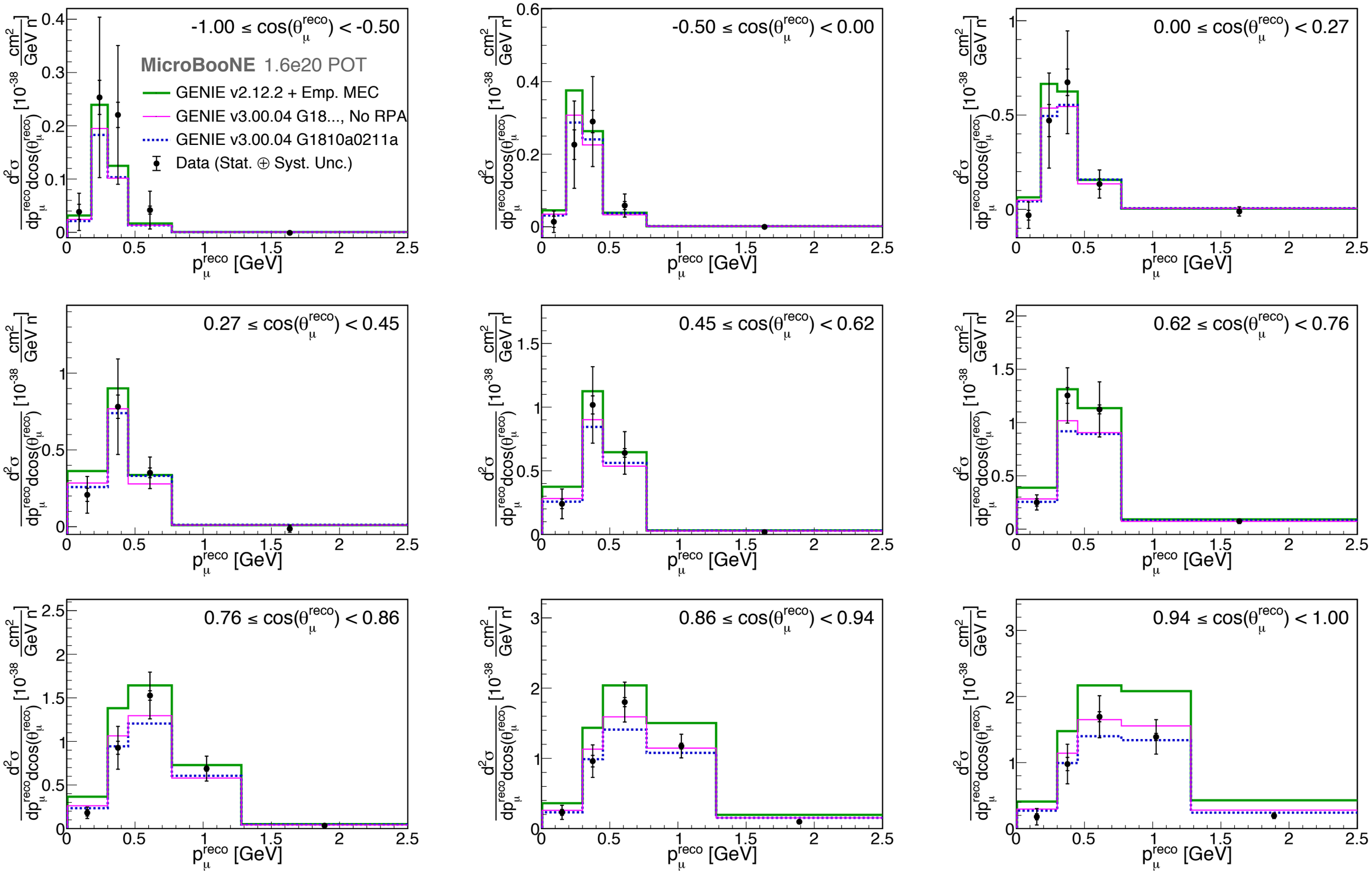



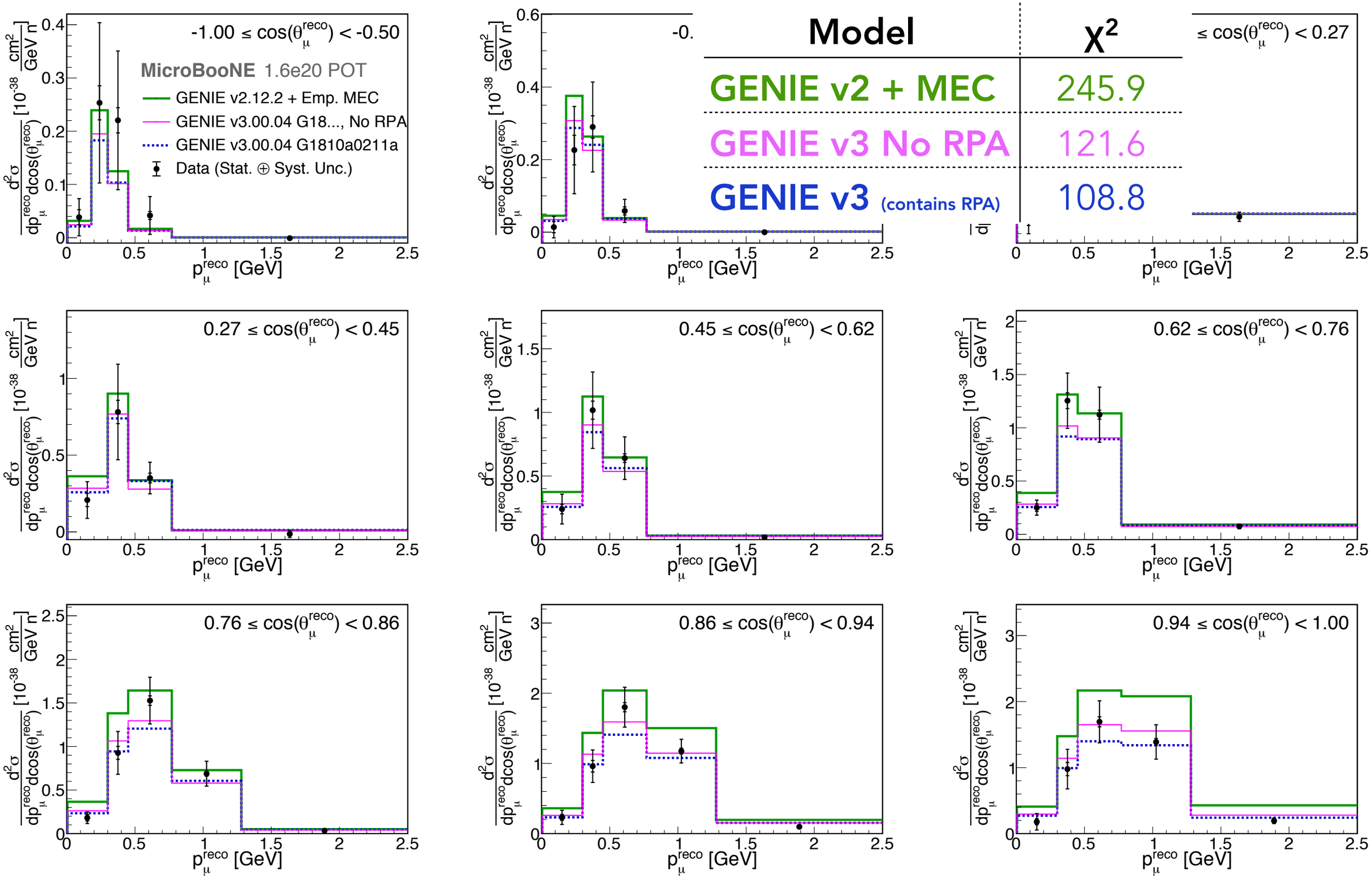



# Cross Section Measurement

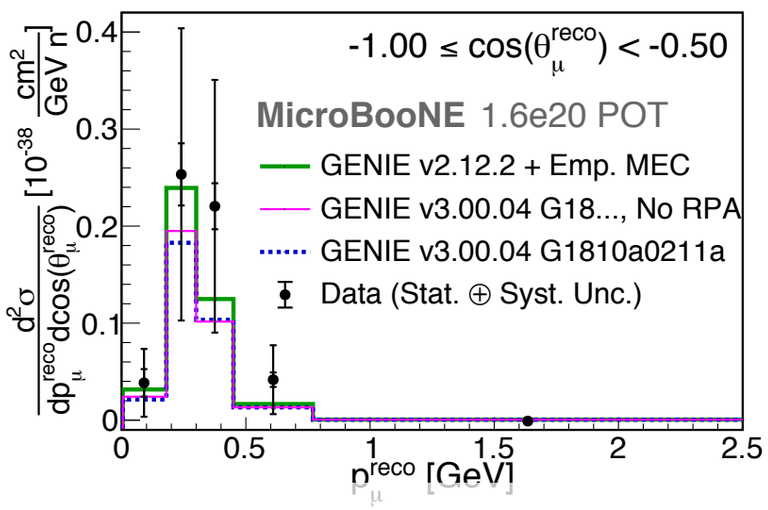


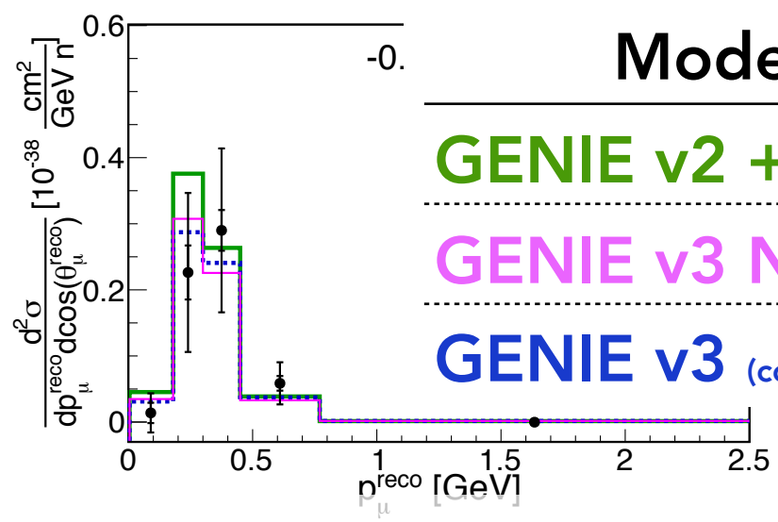
# Cross Section Measurement



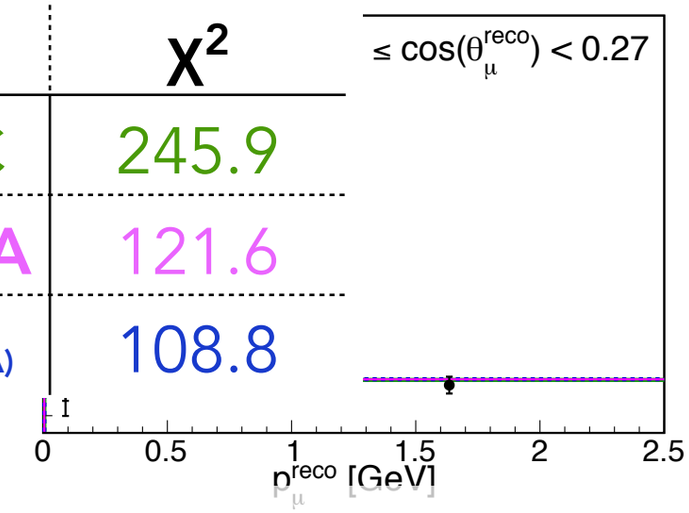

| Model | $\chi^2$ |
|---|---|
| GENIE v2 + MEC | 245.9 |
| GENIE v3 No RPA | 121.6 |
| GENIE v3 (contains RPA) | 108.8 |

# Cross Section Measurement



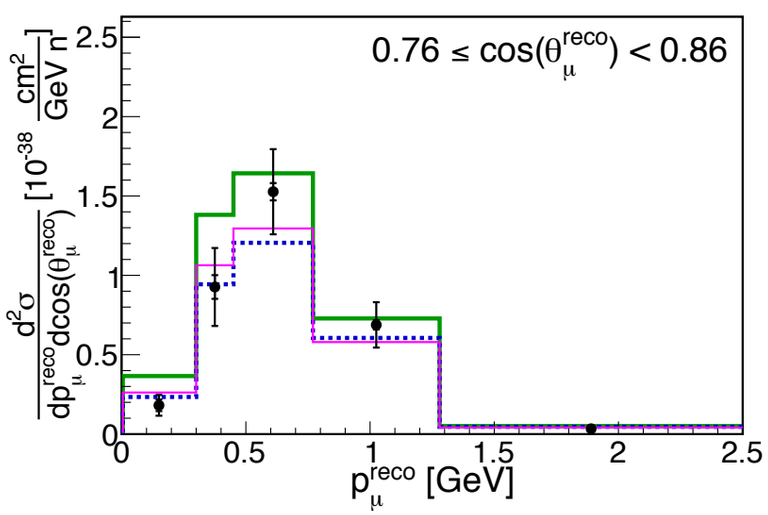



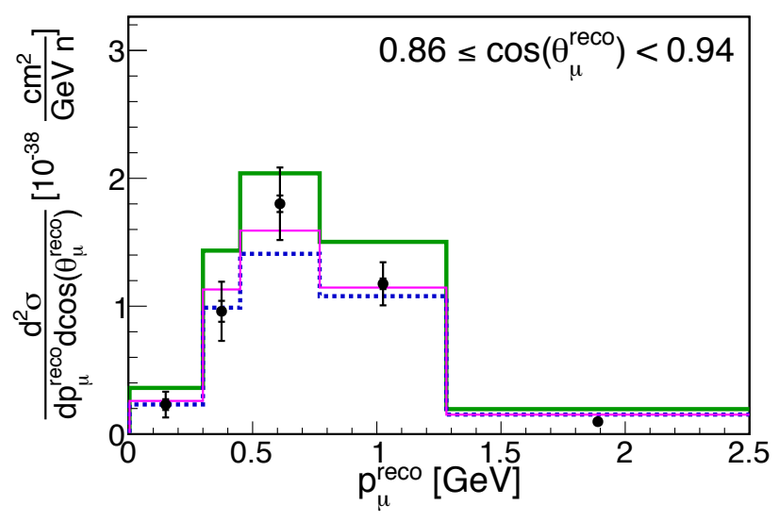

| Model | $\chi^2$ |
|---|---|
| GENIE v2 + MEC | 245.9 |
| GENIE v3 No RPA | 121.6 |
| GENIE v3 (contains RPA) | 108.8 |

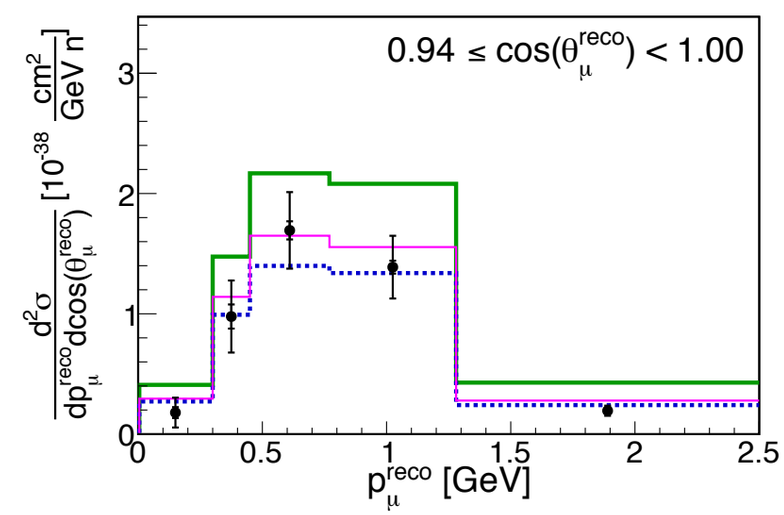



The reduced tension originates from the overall reduced cross section in the forward region when adopting the Local Fermi Gas nuclear initial state.

To a lesser extent also from the RPA correction as included in the Genie v3 and NuWro predictions.



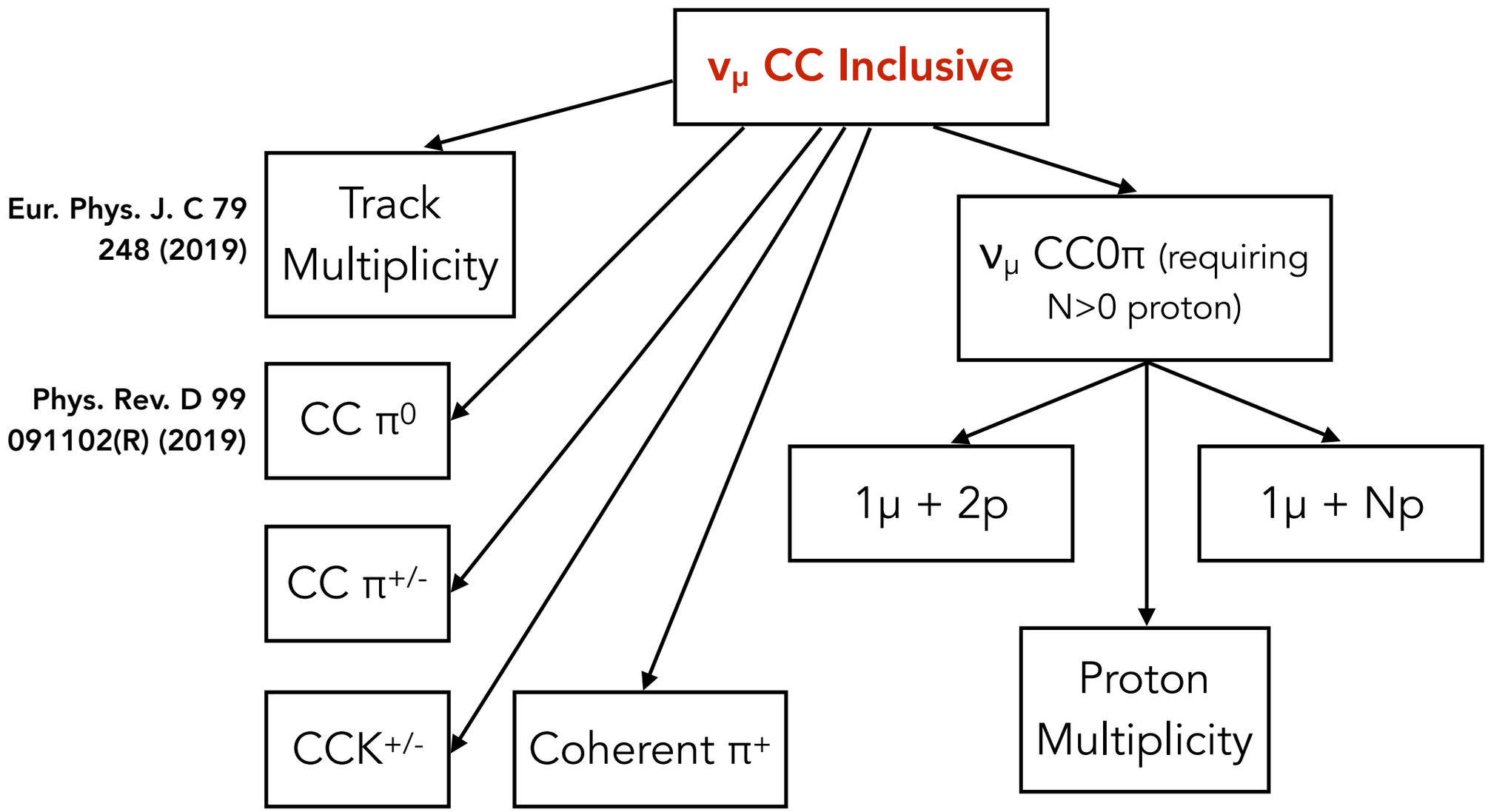



# Many More Analyses to Come!

**Important for the MicroBooNE electron-neutrino "low energy excess" analysis: this analysis is used as a base for a muon-neutrino constraint.**

**This analysis can be used as a preselection for many other $\nu_\mu$ exclusive cross-section measurements :**



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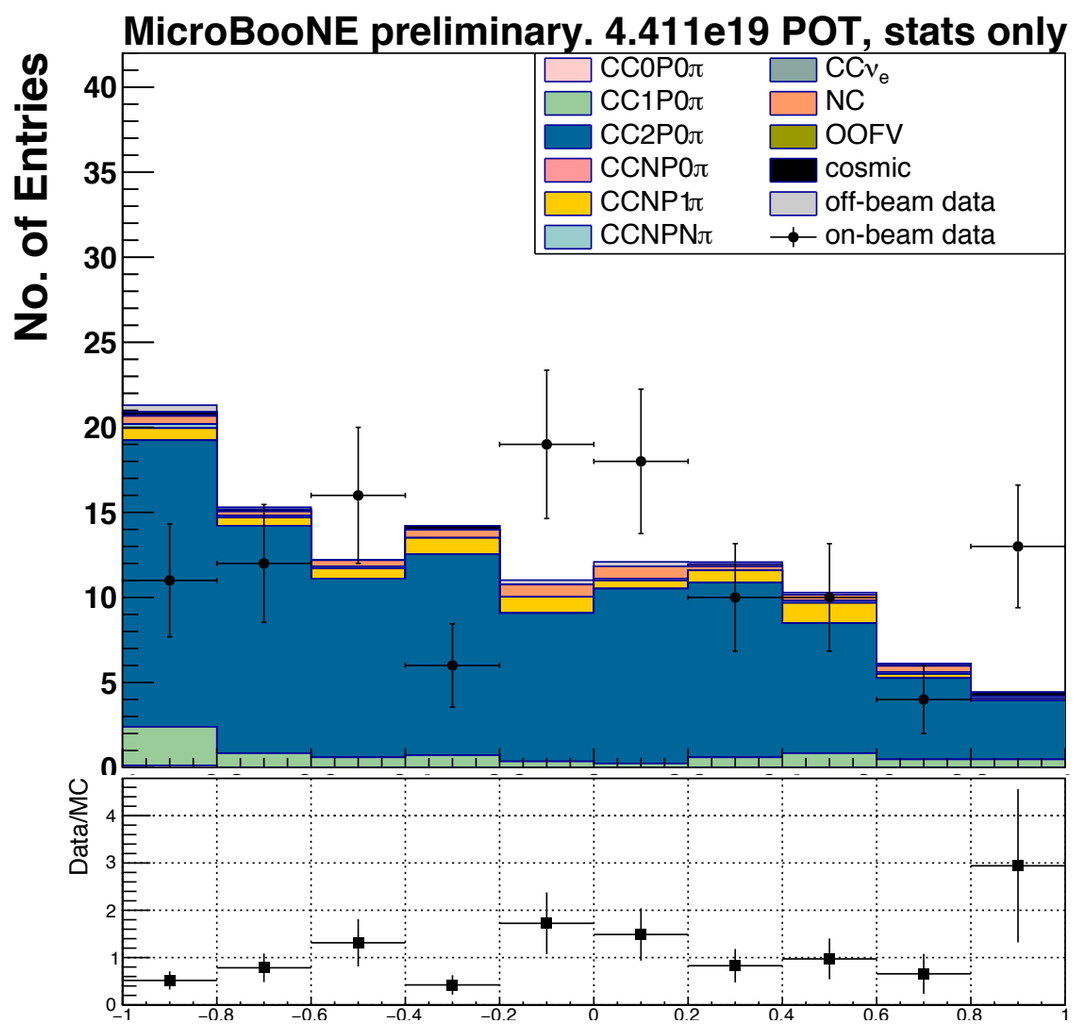
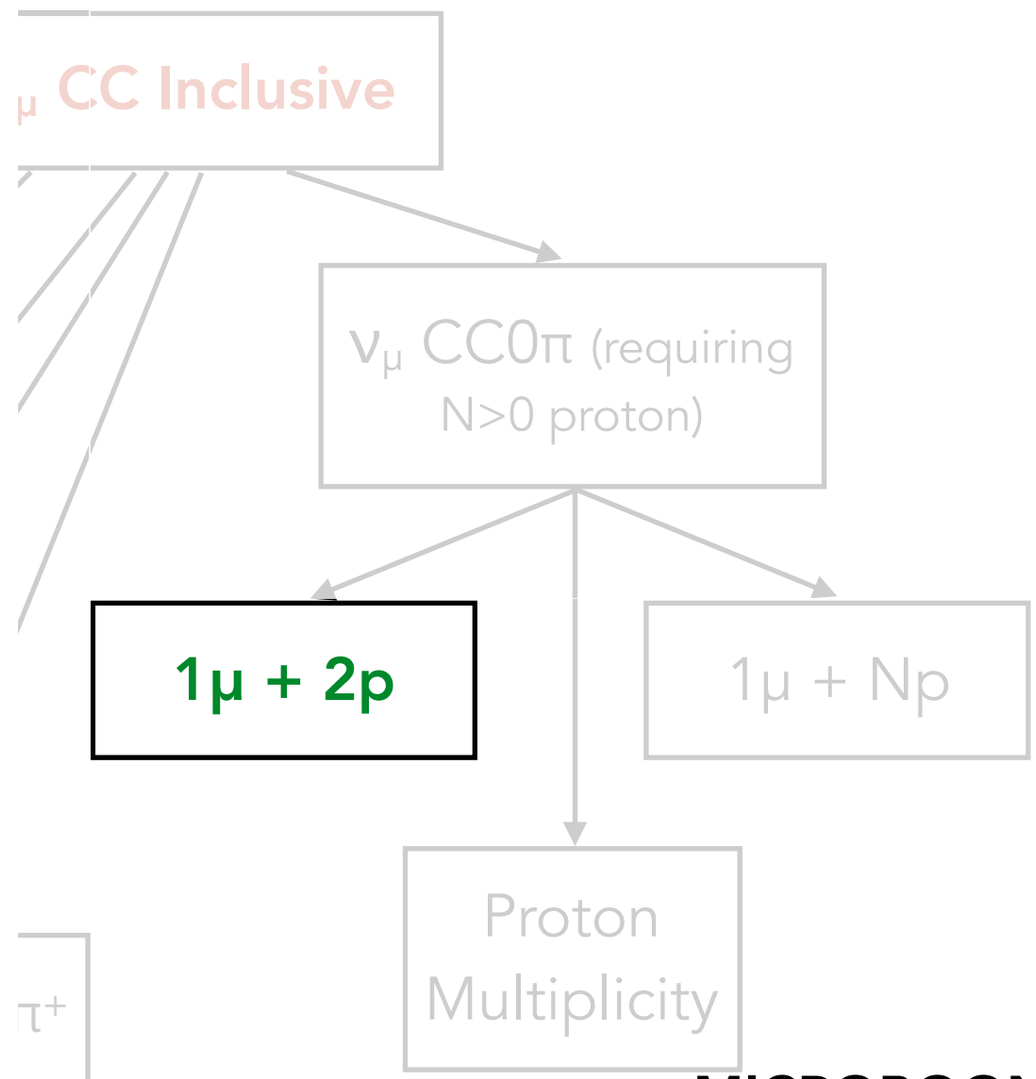



Opening angle between the two protons




**MICROBOONE NOTE 1056**

**https://microboone.fnal.gov/public-notes/**

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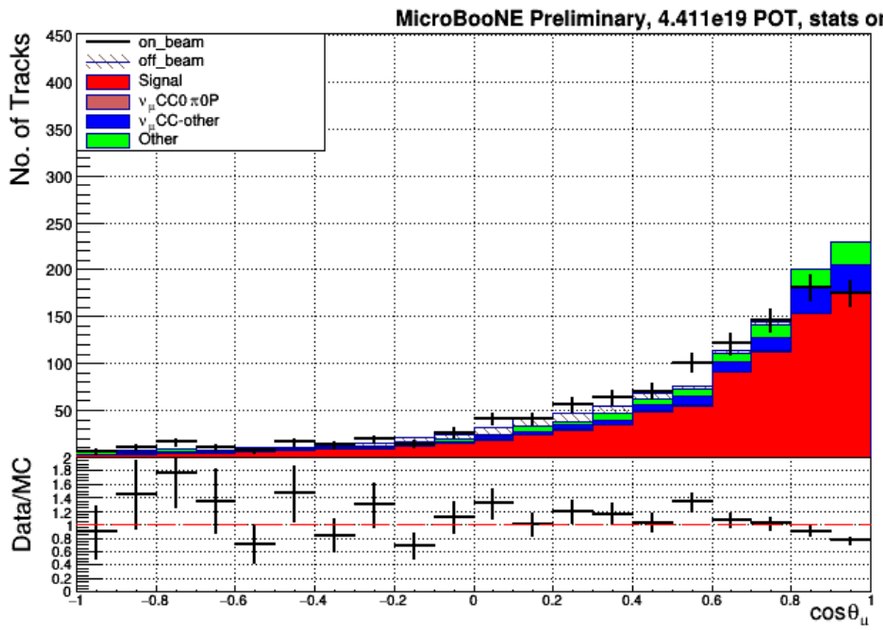


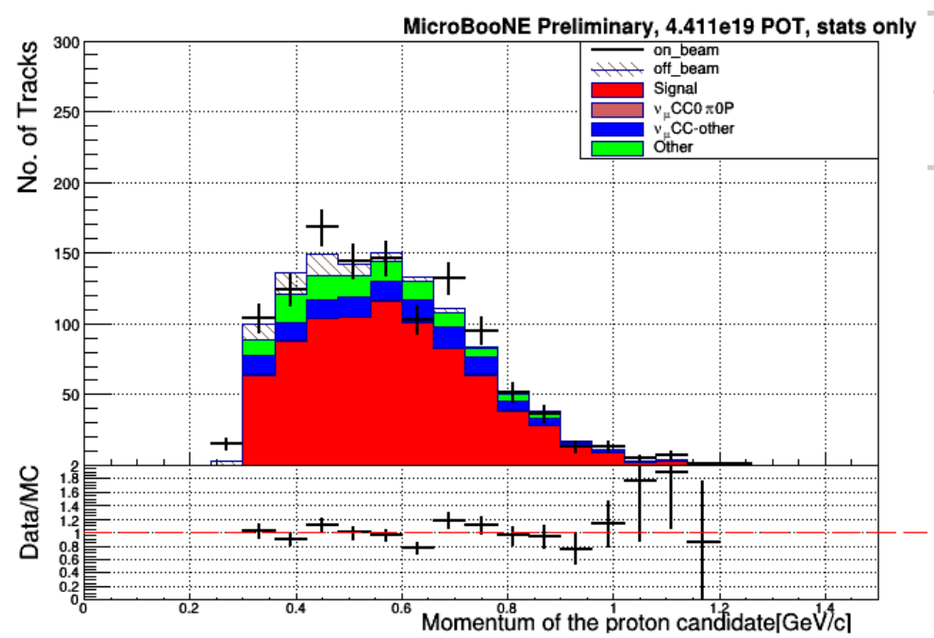


usive

$\nu_\mu$ CC0$\pi$ (requiring N>0 proton)

+ 2p

**1μ + Np**

Proton Multiplicity

**MICROBOONE NOTE 1056**

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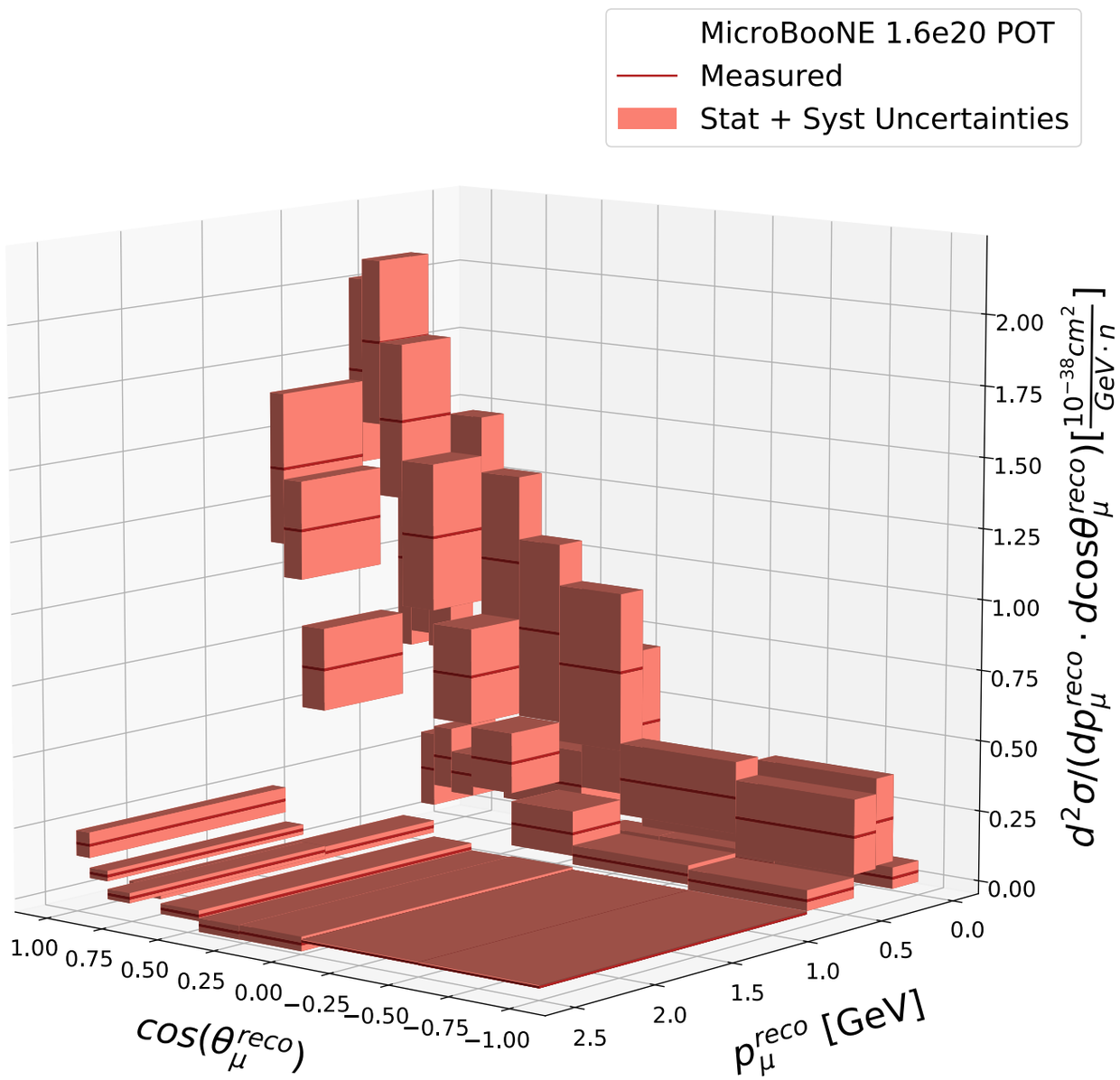
# Conclusions

**This is the first differential cross section on argon!**




$\sigma = 0.693 \pm 0.010\,(\text{stat.}) \pm 0.165\,(\text{syst.}) \times 10^{-38}\ \text{cm}^2$

- First **$\nu_\mu$ CC inclusive** cross section on **argon** at $E_\nu \sim 0.8$ GeV
- **Full angular coverage**
- **MCS for momentum reconstruction**, which allows the **selection of exiting tracks** and so there is no high momentum cut-off
- The analysis has helped **understanding the detector**, and implement improvements to the detector simulation and event reconstruction.
- **Paper** preprint: https://arxiv.org/abs/1905.09694

*Thank you!*

# References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**[10]** Nuclear Physics A 484, 557 (1988)
**[11]** Physics Reports 512, 1 (2012)