NuMI ν_μ CC Inclusive Analysis Status

Guadalupe Moreno, **Promita Roy**

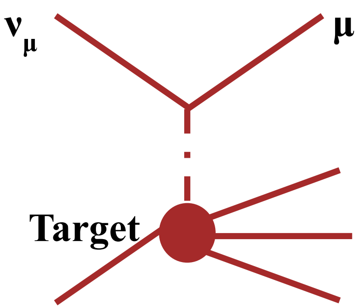
ICARUS Collaboration Meeting

October 14, 2024

Overview ν_μ CC Inclusive Selection

As part of the efforts to study the NuMI ν-Ar cross-section at ICARUS, ***we are analyzing the ν_μ inclusive charged current channel, which consists of studying the kinematics of the μ at the final state, without imposing constraints on the hadronic system.***

ν_μ CC Inclusive



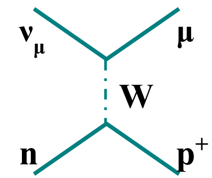
Final state:

μ

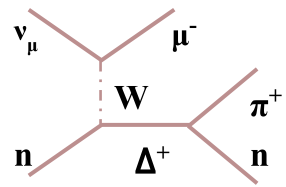
+

anything else

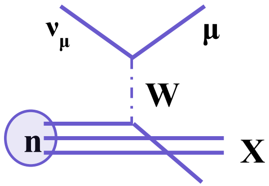
Quasi-elastic scattering (QE)



Resonance production (RES)



Deep Inelastic scattering (DIS)



Considering that we are studying the ν_μ CC inclusive channel, we must consider all interactions at the final state, i.e.

- ***Quasi-elastic scattering (QE)***
- ***Resonance production (RES)***
- ***Deep Inelastic scattering (DIS)***
- ***2p-2h (MEC)***

❖ ***In this channel the dominant background is due to cosmic ray interactions.*** This background will be constrained with cosmic data i.e OFF-Beam NuMI data.

Revisiting ν_μCC inclusive selection criteria

Pre-selection (for cosmic background rejection)

- Remove everything that is a **Pandora clear cosmic**
- **Fiducial Volume cut**: the vertex should be contained in the Fiducial Volume:
  - x = (-358.49+25 , -61.94-25) cm ∪ (61.94+25 , 358.49-25) cm
  - y = (-181.86+25 , 134.96-25) cm
  - z = (-894.951+30, 894.951-50) cm
- **CRLongestTrackDirY** > - 0.7 : Longest track's Y-direction (under Cosmic Ray hypothesis)
- **Barycenter Flash Matching** < 1m

μ- selection (for muon signals)

- Muon track
  - **Distance from Vertex** < 10 cm
  - **Contained**
    - Length > 50 cm
    - $\chi^2_\mu < 30$ & $\chi^2_p > 60$ [which tells us basically that the track is consistent with muon and inconsistent with proton]
  - **Exiting**
    - Length>100cm

Review ν_μCC Inclusive Selection using BFM

- *The Barycenter flash matching tool developed by **J. Smedley** matches the **optical flashes (PMT OpFlashes) to the TPC slices** by minimizing the distance between the **weighted charge center of the slice and the weighted center of the flash**, thus rejecting out-of-time slices based on the time of the flash.*

- This slide and the following slides show
  a. *Current status of the inclusive selection,*
  b. *Initial results of application of 3-fold matching (CRT-TPC-PMT) to improve background rejection,*
  c. *Data-MC comparisons*
  d. *Glance at the muon momentum*
  e. *Preliminary study of systematic errors in this ν_μ **CC** Inclusive channel.*

- ***Efficiency = selected signal / all signal***
- ***Purity = selected signal / (selected signal + background)***
- ***Selected signal is ν_μCC***

Considering all events	Purity ν_μ CC	Purity (ν_e CC + NC)	Purity (out-of-time Cosmics)	Purity (In-time cosmics)	Efficiency ν_μ CC
Fiducial	0.016	0.005	0.502	0.478	0.56
+ clear cosmic	0.071	0.022	0.448	0.458	0.54
+ Track cut	0.094	0.011	0.447	0.448	0.50
+ Longest track in Y direction	0.229	0.038	0.327	0.406	0.46
+ Barycentre flash matching	0.674	0.077	0.055	0.20	0.40

3-fold Matching

CRT-PMT-TPC matching

- Previous studies made by **Andrea S. (doc-27838), Francesco P. (doc-28827) and Anna H.(doc 32538, 32375)** had shown the possibility of using the time-matched CRT-hit for each OpFlash to identify entering/exiting tracks.

- This CRT-PMT(flash) matching is performed by matching an optical flash with one or more CRT hits and could be useful in rejecting in cosmics which is the principal background in our **ν_μCC inclusive analysis.**

- So, we wanted to explore CRT-PMT matching tool along with all the other ν_μCC inclusive selection criteria and investigate if we can do a better background rejection.

- ***For this purpose a CRT-PMT matched spill-cut is used on top of Barycentre flash matched slices which investigates if there is any match between CRT system and PMT flash within the NuMI beam gate and accordingly rejects or selects the slices (more info on sbn docdb 38233-v1).***

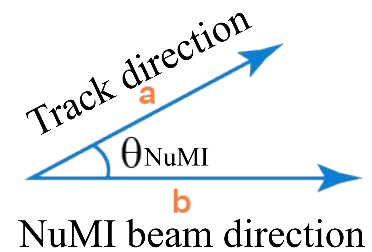
- ***We are using Run2 reprocessed onbeam and offbeam NuMI data and latest NuMI MC sample.***

CRT-PMT-TPC matching

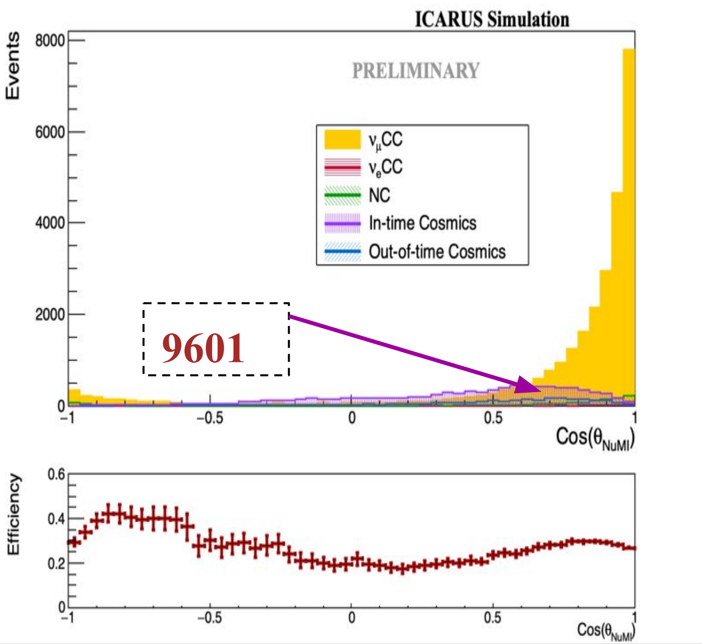
Cos θ_{NUMI}

Pre-BFM selection: Fiducial volume cut, Not a Pandora Clear Cosmic, Longest track Y-direction cut, Track cut, Split muons cut

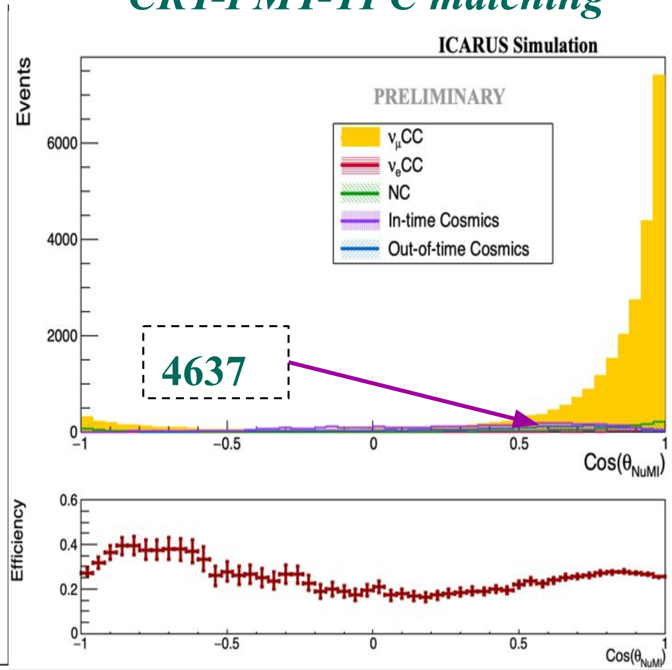
$$\cos(\theta_{NuMI}) = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}$$

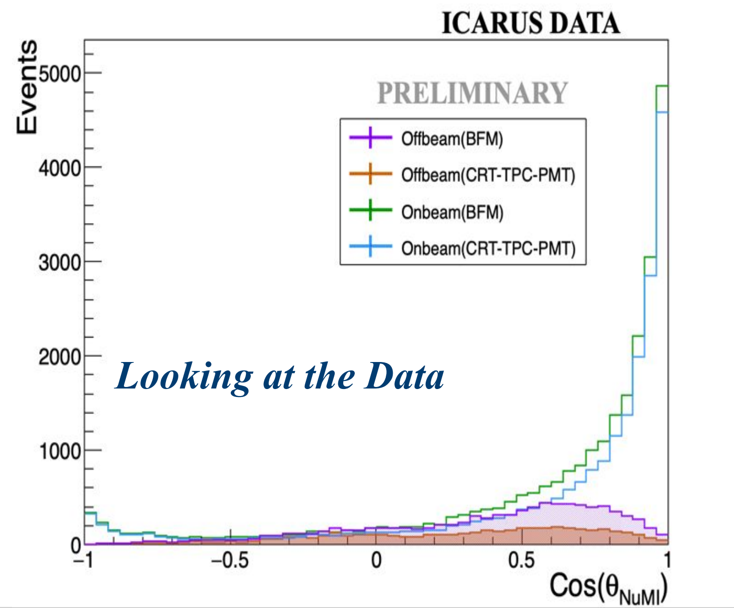


Barycentre flash matching



CRT-PMT-TPC matching



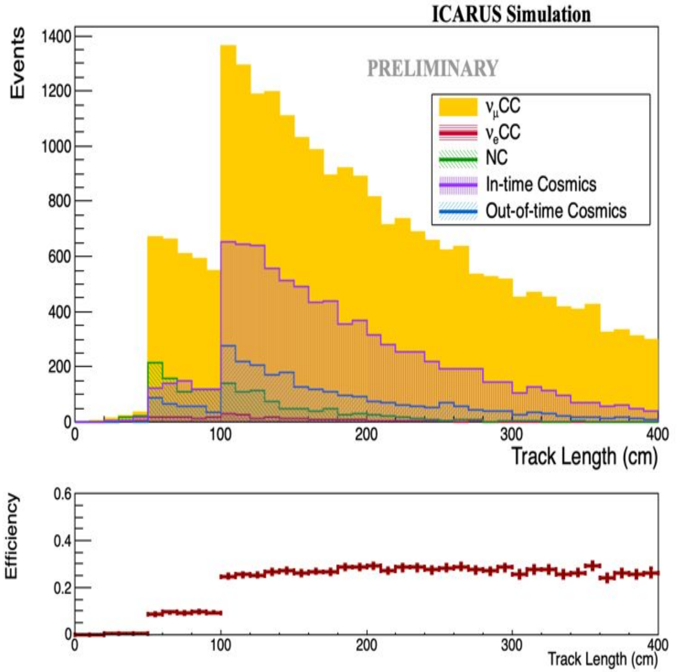


*On using triple matching (CRT-PMT-TPC), **in-time cosmics (offbeam data)** is reduced considerably.*

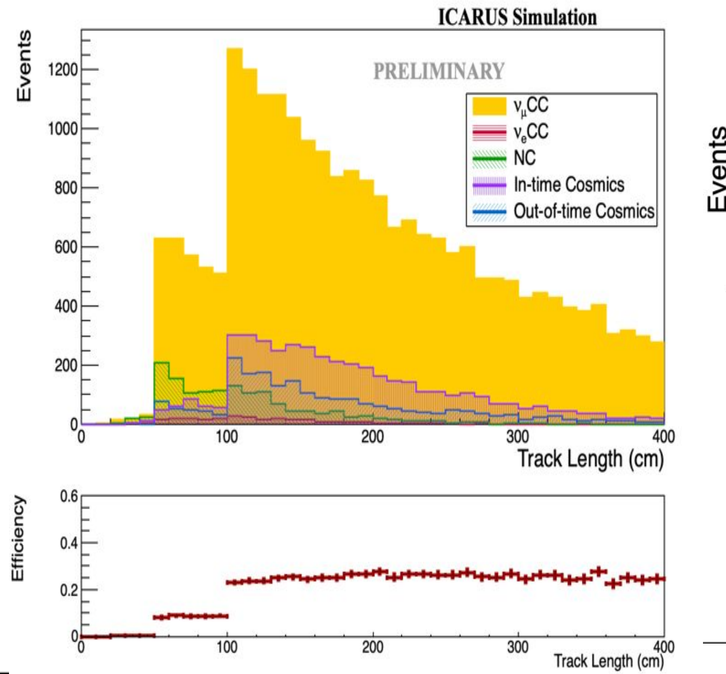
CRT-PMT-TPC matching *Track length*

Pre-BFM selection: Fiducial volume cut, Not a Pandora Clear Cosmic, Longest track Y-direction cut, Track cut, Split muons cut

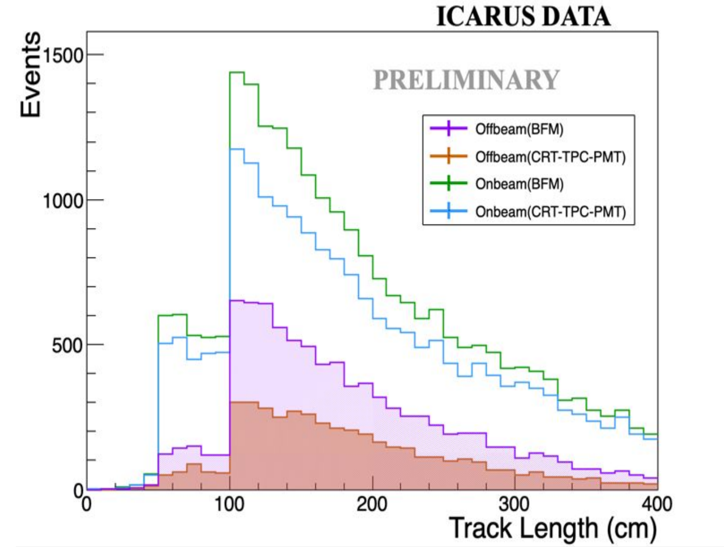
Barycentre flash matching



CRT-PMT-TPC matching



Looking at the Data



- *On using triple matching (CRT-PMT-TPC), **in-time cosmics** is reduced considerably.*
- *For **out-of-time cosmics**, performance of triple matching is similar as barycentre flash matching*

Efficiency and Purity *BFM and CRT-PMT-TPC matching*

- *Efficiency = selected signal / all signal*
- *Purity = selected signal / (selected signal + background)*
- *Selected signal is ν_μ CC*

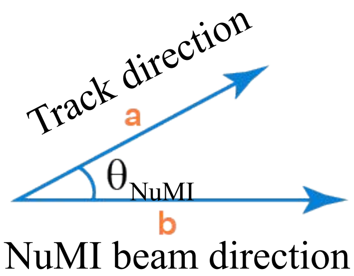
Efficiency
CRT-PMT-TPC match w splittrk cut: ***26%***
BFM w splittrk cut: ***27.5%***

Considering all events	Purity ν_μ CC	Purity (ν_e CC + NC)	Purity (out-of-time Cosmics)	Purity (In-time cosmics)	Efficiency ν_μ CC
Fiducial	0.016	0.005	0.502	0.478	0.56
+ clear cosmic	0.071	0.022	0.448	0.458	0.54
+ Track cut	0.094	0.011	0.447	0.448	0.50
+ Longest track in Y direction	0.229	0.038	0.327	0.406	0.46
+ Barycentre flash matching	**0.674**	0.077	0.055	**0.20**	0.40
+ CRT-PMT spillcut (CRT-PMT-TPC matching)	**0.761**	0.087	0.052	**0.11**	0.371

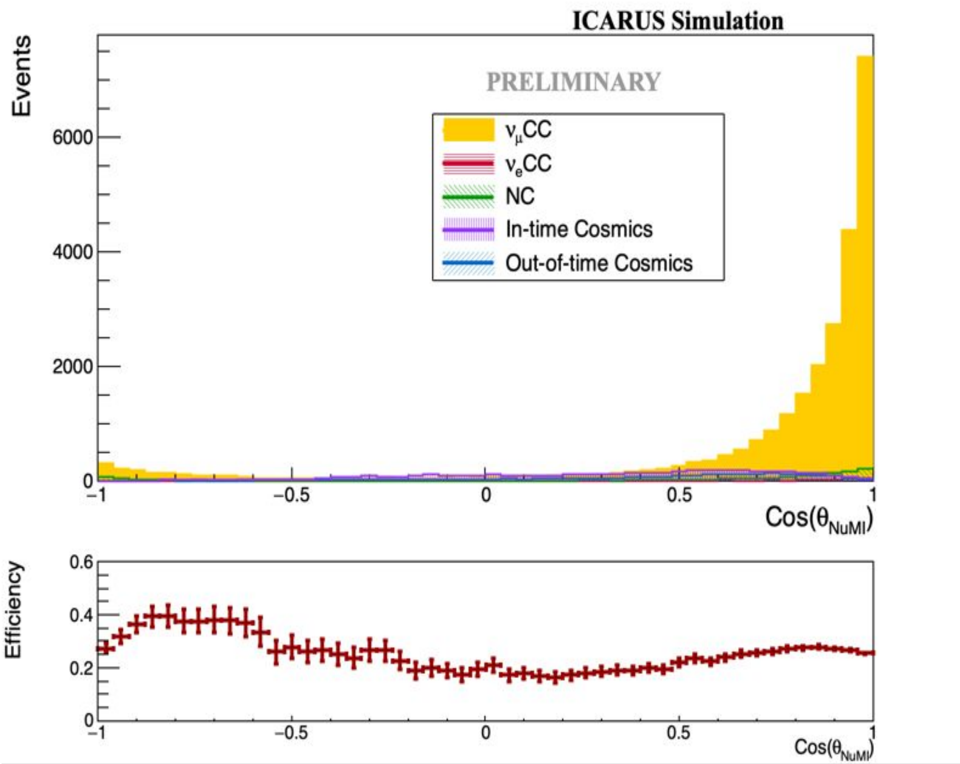
Inclusive Selection *Data vs MC*

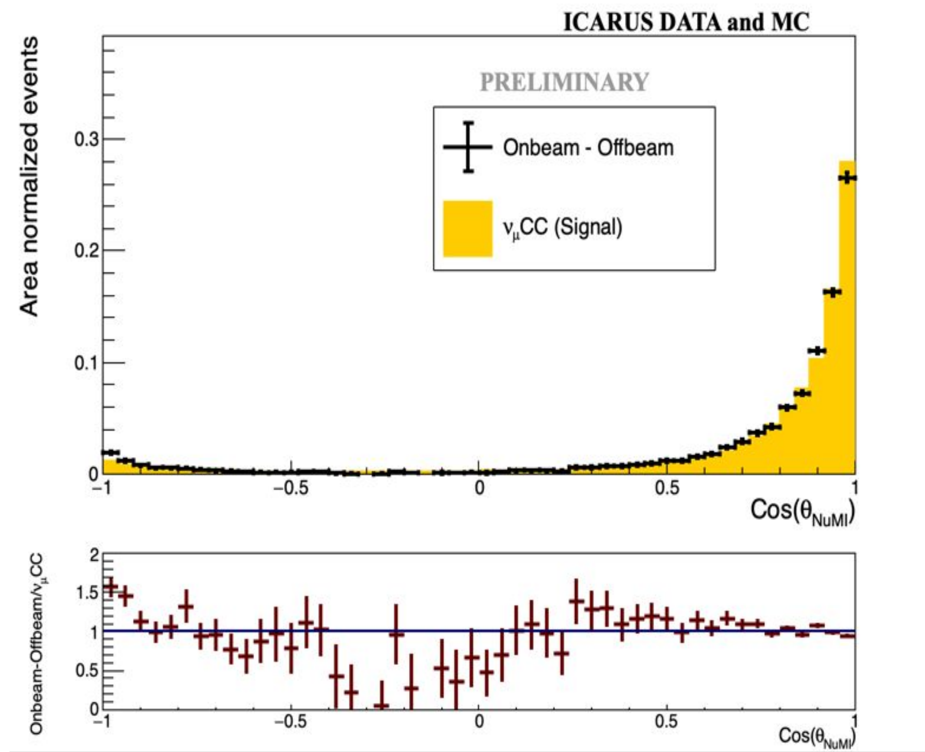
- Inclusive selection criteria with triple matching is used
- ***"OnBeam - OffBeam"*** is matched with the signal **(ν_μ CC) MC**
- The Data-MC plot is area normalized

$$cos(\theta_{NuMI}) = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}$$



Cosine θ_{NUMI}

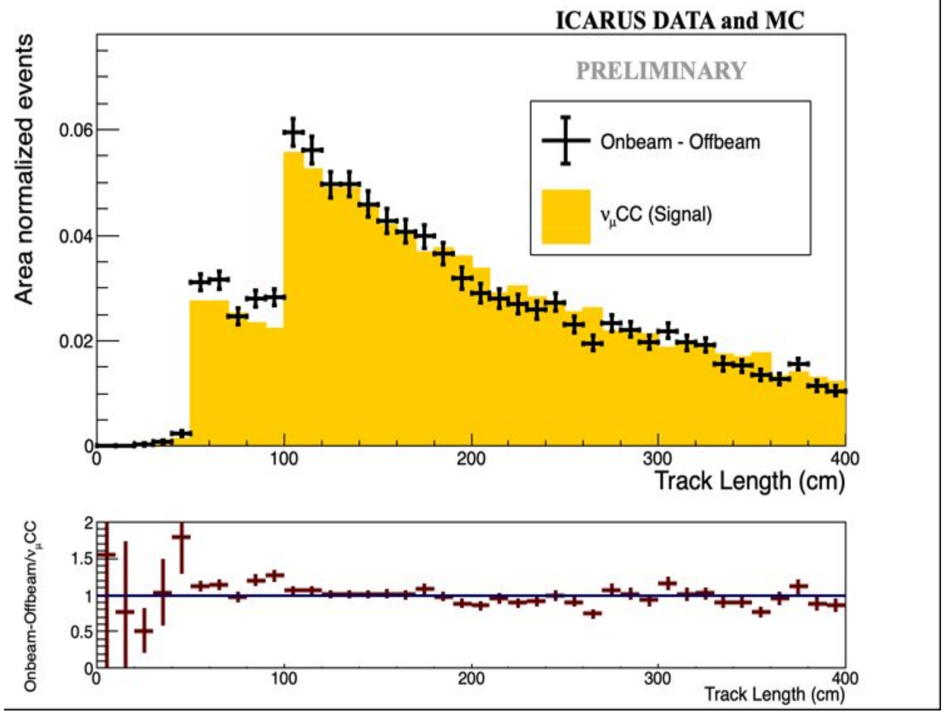




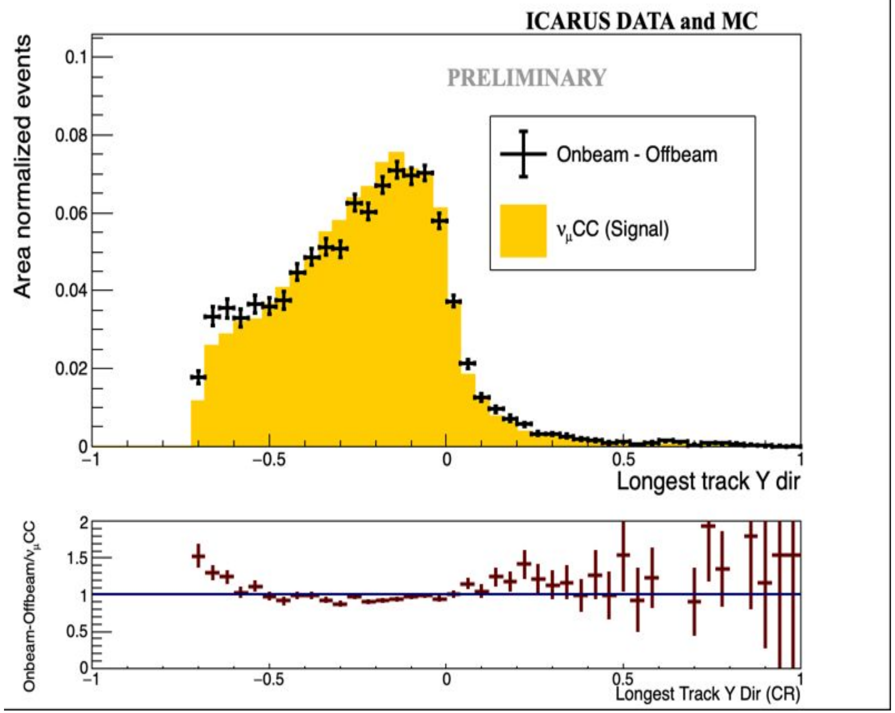
Inclusive Selection *Data vs MC*

- Inclusive selection criteria with triple matching is used
- ***"OnBeam - OffBeam"*** is matched with the signal **(ν_μ CC)** **MC**
- The Data-MC plots are area normalized

Track length



Longest track in Y- direction

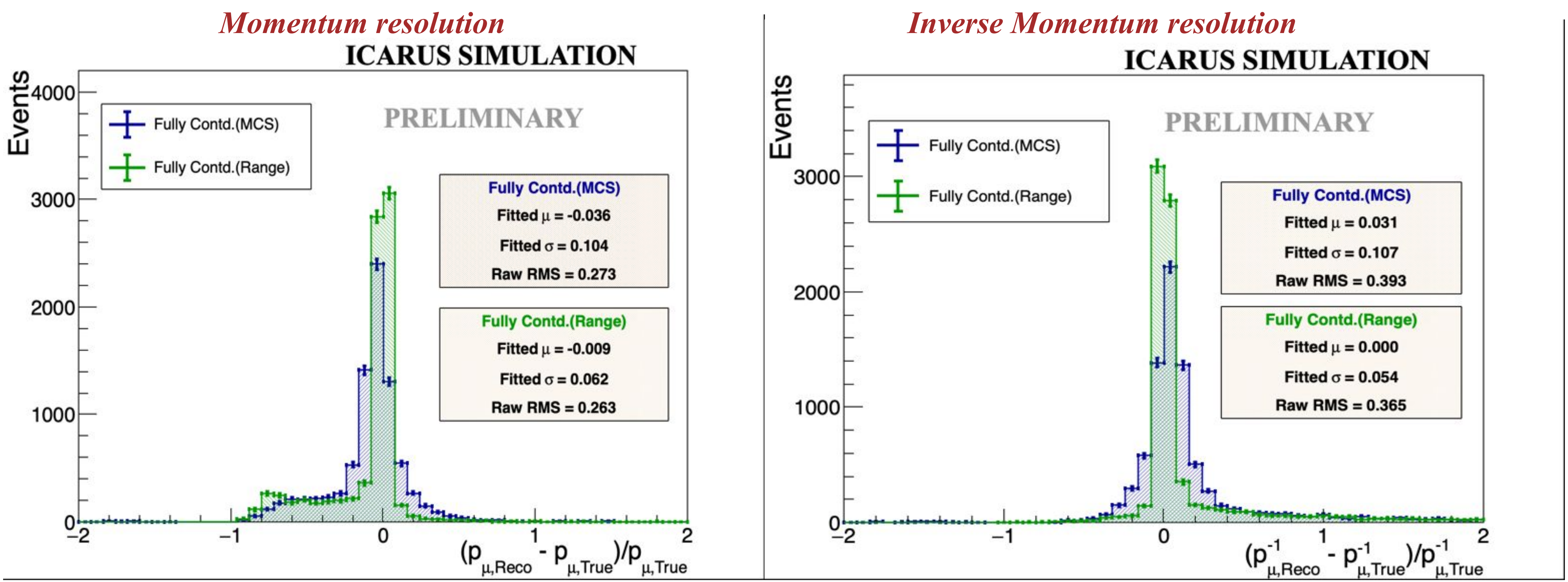


Muon Momentum *MC (Inclusive selection)*

Sbn-docdb 31487-v2 by **Moon**

- ***Range based momentum***
- ***MCS:*** *Occurs when a charged particle enters a medium and undergoes electromagnetic scattering with the atoms. This scattering deviates the original trajectory of the particle within the material. The deflection of muons from the original trajectory within the material form a Gaussian distribution with mean at 0 and standard deviation varying with the track momentum.*

Split track cut is applied for both **(Thanks to Bruce & Harry)**



Muon Momentum *MC (Inclusive selection)*

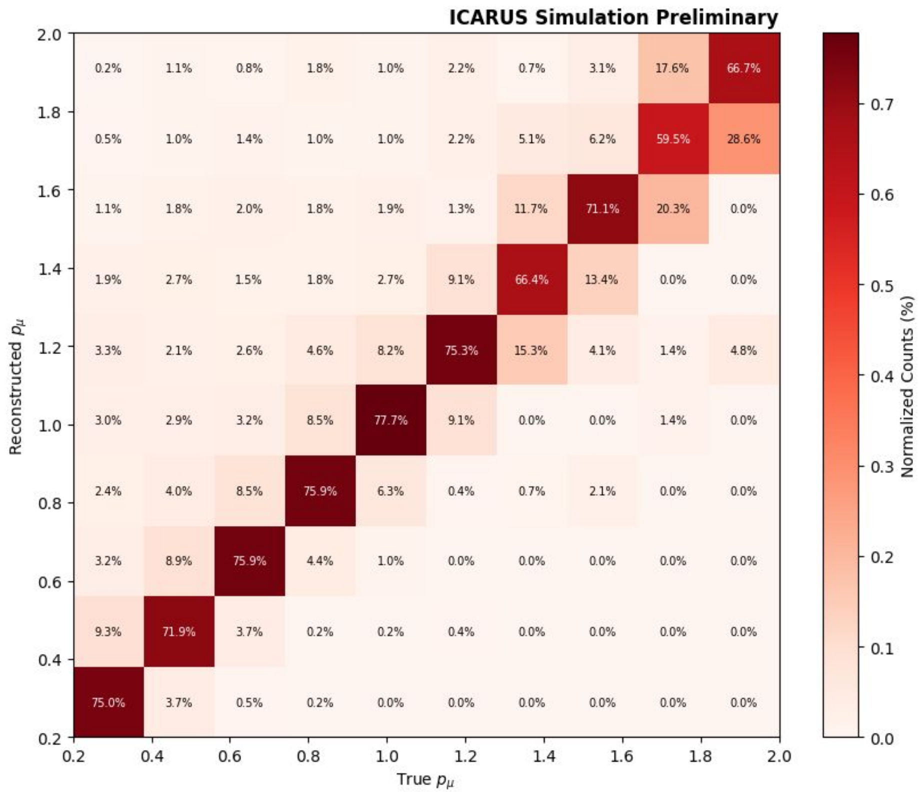
Fully Contd.(Range)

- ***Fractional bias(μ)*** < 1%
- ***Fractional resolution(σ)*** ~ 5-6%

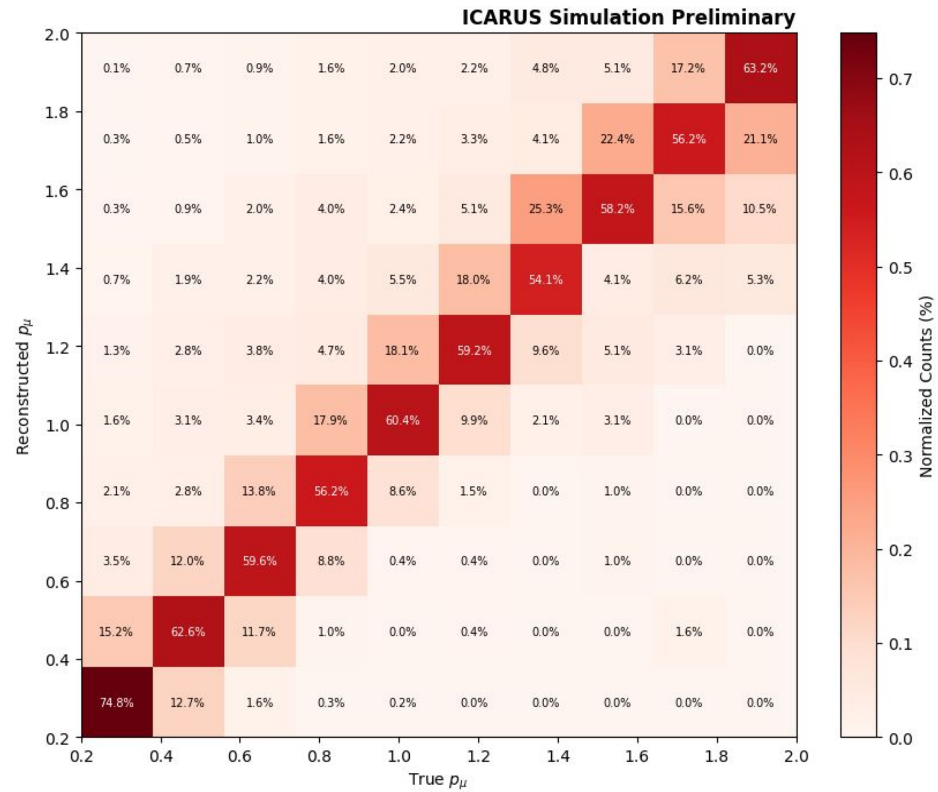
Fully Contd.(MCS)

- ***Fractional bias(μ)*** < 4%
- ***Fractional resolution(σ)*** ~ 10%

Fully contained tracks (range)



Fully contained tracks (MCS)



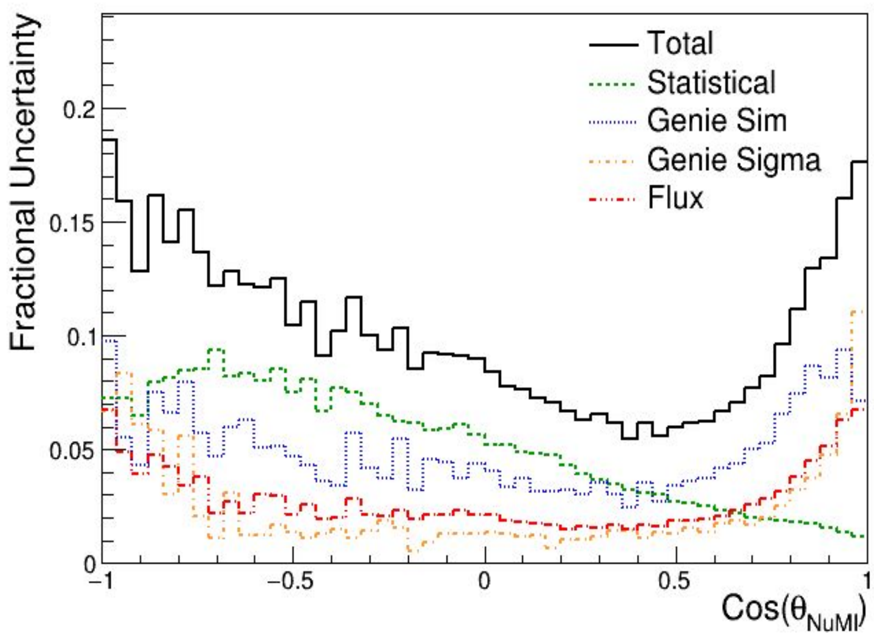
Systematics (to do)

Inclusive selection

In this study we only consider the systematics due to the **Flux and the ν interactions**.

The systematic errors can be categorized as

- Detector
- **Flux:** we use a combination of all beamline systematics and the Npc (number of principal components) hadron production components.
- **Neutrino interaction (GENIE):** we utilize two kind of GENIE weights
  - Genie Sigma (Multisigma) weights are assigned to parameters that we assume operate independently from others. This means we can adjust these parameters individually without affecting the rest.
  - Genie Sim (Multisim) is employed for parameters that are interdependent. To see the impact of these variations, we generate event weights for numerous "universes," each representing different settings of these parameters.

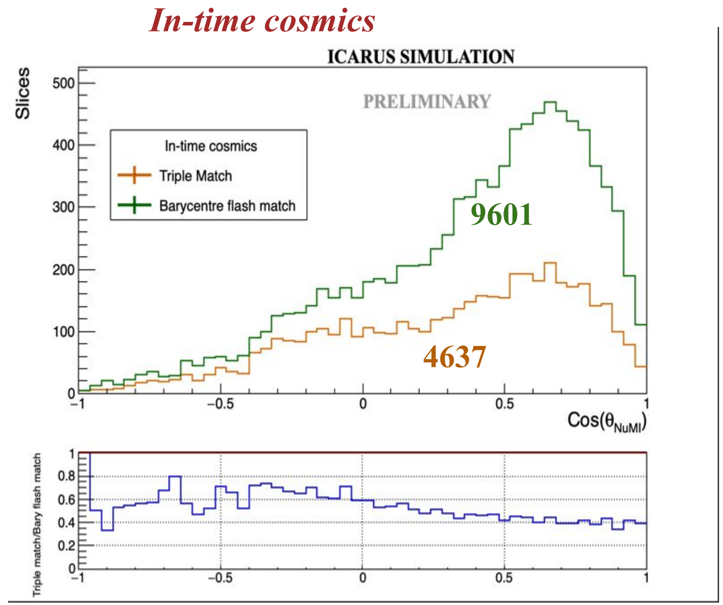


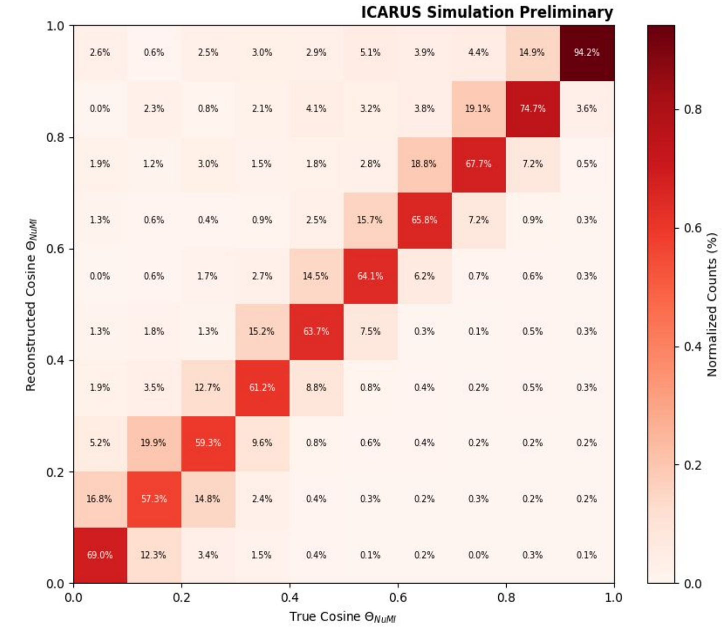
Detector systematics:

We have started producing small samples for detector systematics and started looking at them following the way **Jacob Z.** is doing (**sbn-docdb 35850-v1, 36027-v2, 36350-v1** and many others)

Summary *and Next To Do's*

- CRT-PMT-TPC matching comes out to be an effective tool rejecting for in-time cosmics.
  - Final purity of the signal increases by ~ **9-10 %** and final efficiency reduces by **~1.5%.**
  - More investigations at a deeper level is going on, so further improvements are anticipated.
- The initial area normalized Data and MC comparison plots look decent with the newly produced MC and Run2 reprocessed datasets.
  - Need to add POT to these plots and look at them closely.
- Muon momentum studies show that applying Split track cut clears out a lot of mis-reconstructed tracks which otherwise affects the momentum estimation. For fully contained sample MCS performs almost as good as range based reconstruction. The reco vs true matrix looks almost identical for both.
- Recently we have started looking at Flux, GENIE and Detector systematics. We will continue the systematics study and have a breakdown of each of them.
- Next step is to extract cross-section using unfolding matrix (reco-true cosineΘ_{NuMI})

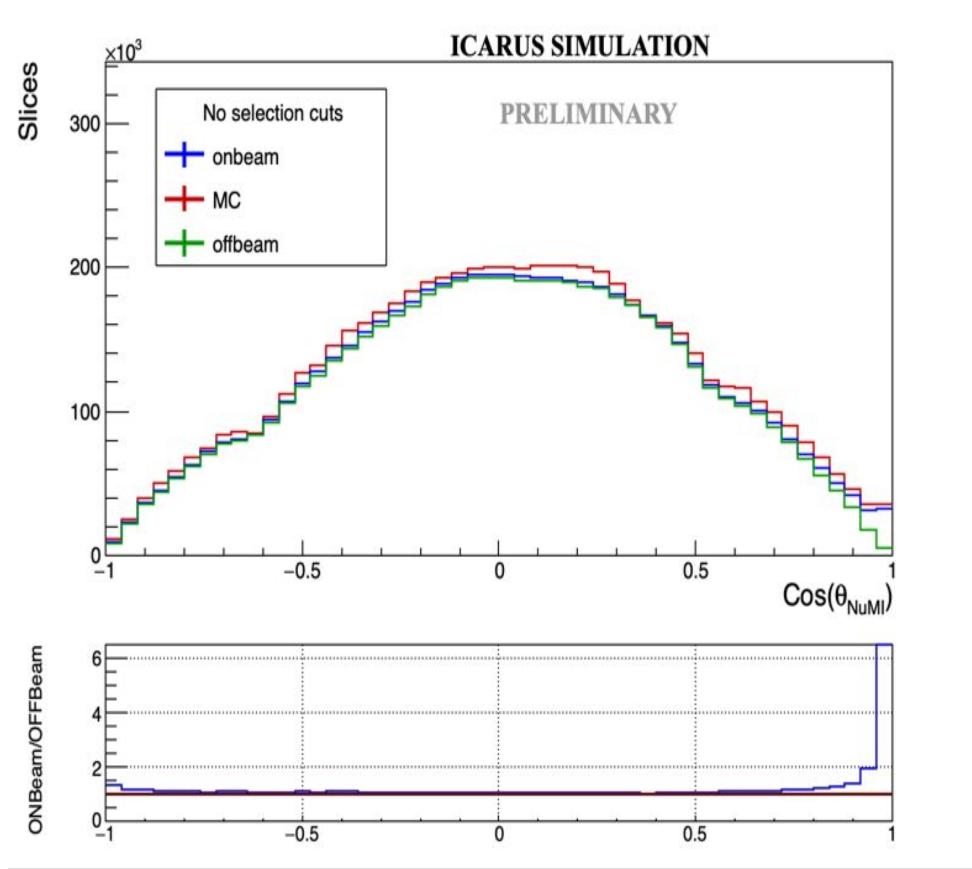




Back up

Using data (onbeam and offbeam)

Considering all events	Purity ν_μ CC
Pre-bary selection cuts + Barycentre flash matching	0.65
+ CRT-PMT spillcut (CRT-PMT-TPC matching)	0.8



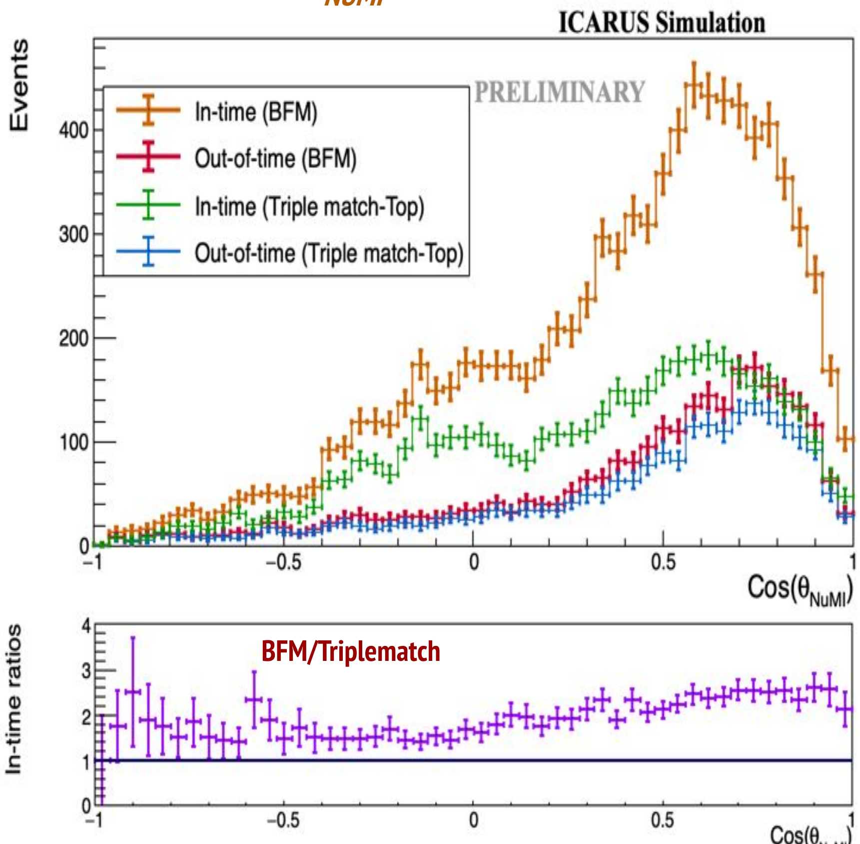
sbndocdb: **32106-v1(Jacob Larkin, Joseph Z.)**

Looking closely at the cosmics *In-time & Out-of-tim*

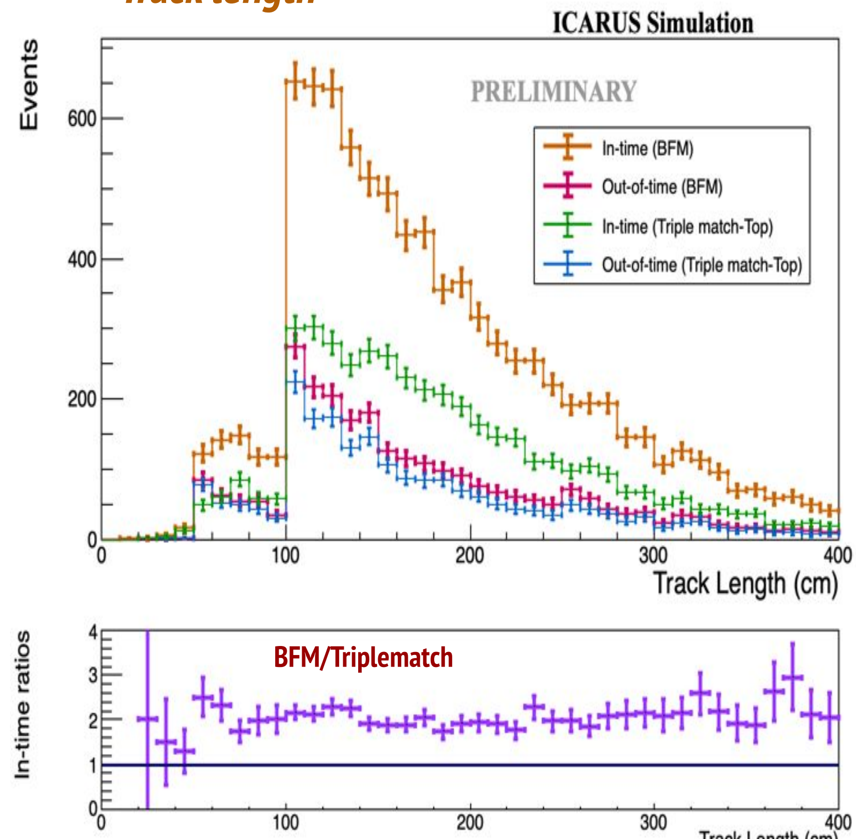
Only Top CRT

- In-time cosmics is reduced considerably after using triple matching
- In-time ratios (BFM/Triple match) shows the extent of reduction

Cosine θ_{NUMI}



Track length



MCS momentum estimation

Original highland formula:

$$\sigma_o^{\mathrm{HL}} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0}\right)\right],$$

MicroBOONE used:

$$\sigma_o = \sqrt{(\sigma_o^{\mathrm{HL}})^2 + (\sigma_o^{\mathrm{res}})^2}.$$

where the second term is inherent detector angular resolution ~3mrad

MicroBOONE tuned the highland formula and replaced *S2* with *k(p)*

$$\kappa(p) = \frac{0.105\ \mathrm{MeV}}{(p(\mathrm{GeV}))^2} + 11.004\ \mathrm{MeV}.$$

Thus, the tuned standard deviation (of the gaussian distribution) used by MicroBOONE (at $l = X_0$) becomes the following:

$$\sigma_o^{\mathrm{RMS}} = \sqrt{(\sigma_o)^2 + (\sigma_o^{\mathrm{res}})^2} = \sqrt{\left(\frac{\kappa(p)}{p\beta c}\right)^2 + (\sigma_o^{\mathrm{res}})^2}.$$

Muon Momentum MC (Inclusive selection)

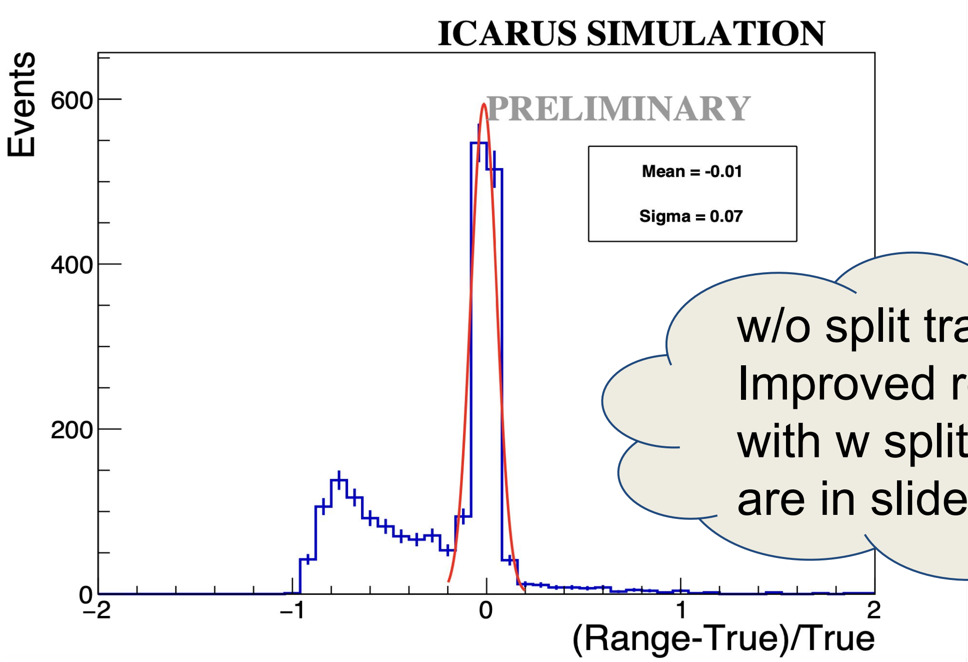
Muon momentum resolution (p_μ)

The collection of the deflection of muons from the original trajectory within the material form a Gaussian distribution with mean at 0 and standard deviation given by the Highland formula:

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{p\beta c} z \sqrt{\frac{\ell}{X_0}}\left[1 + 0.0038 \ln\left(\frac{\ell}{X_0}\right)\right]$$

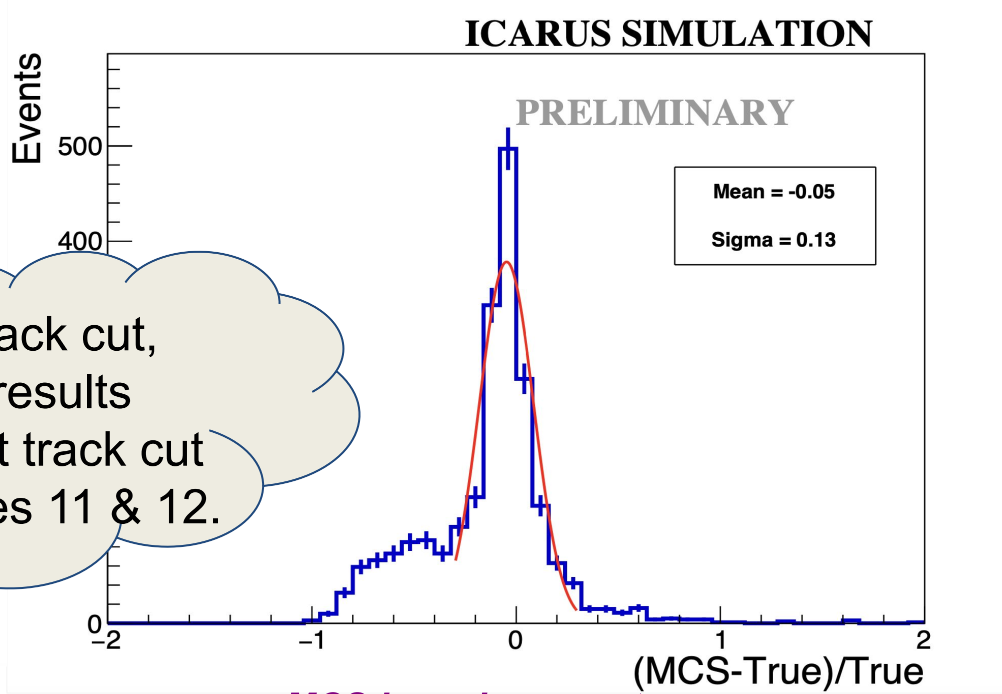
- β: v/c
- ℓ: is the distance traveled inside the material
- X_0: Radiation length

Fully contained



Range based momentum

w/o split track cut,
Improved results
with w split track cut
are in slides 11 & 12.



MCS based momentum

Muon Momentum *MC (Inclusive selection)*

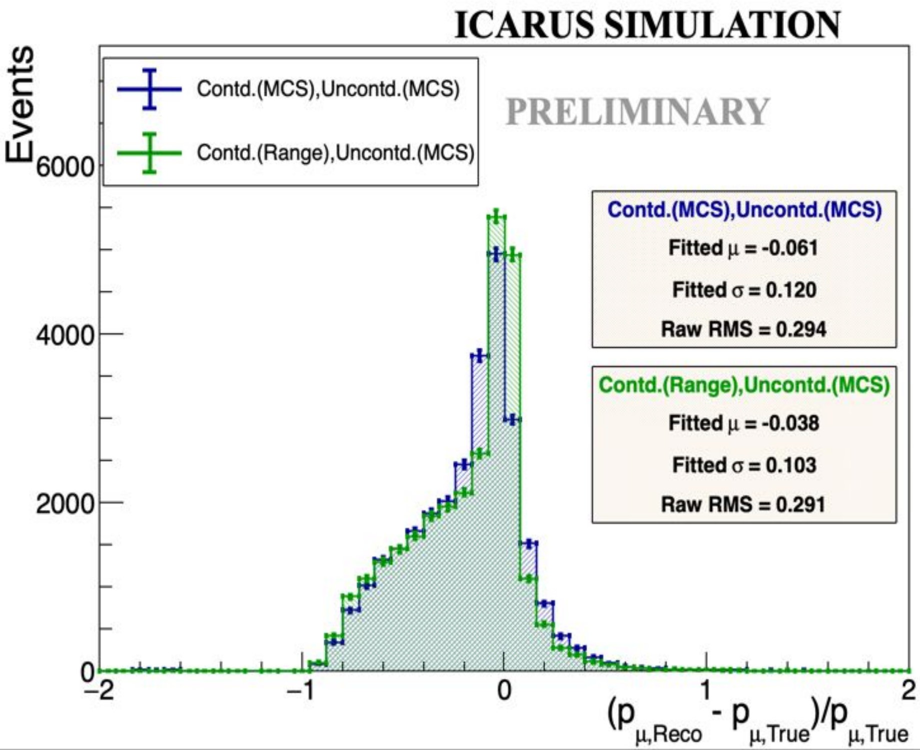
Contained + exiting sample

Contd.(Range), Uncontd.(MCS)
- *Fractional bias(μ)* < 4%
- *Fractional resolution(σ)* ~ 8-10%

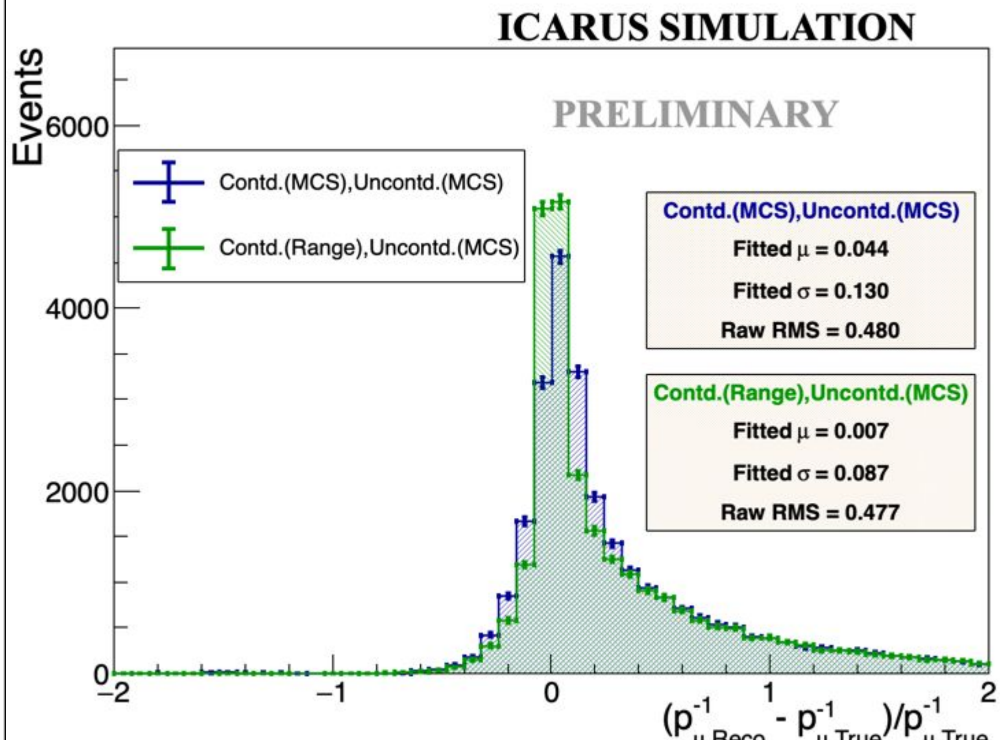
Contd.(MCS), Uncontd.(MCS)
- *Fractional bias(μ)* ~ 4-6%
- *Fractional resolution(σ)* ~ 12-13%

Split track cut is applied for both

Momentum resolution



Inverse Momentum resolution

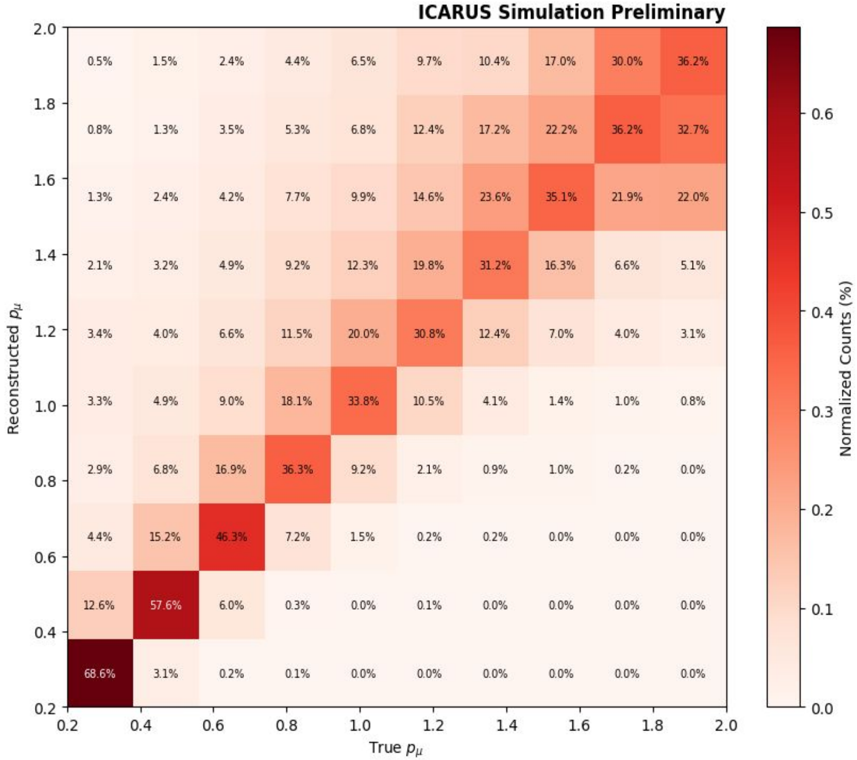


Muon Momentum *MC (Inclusive selection)*

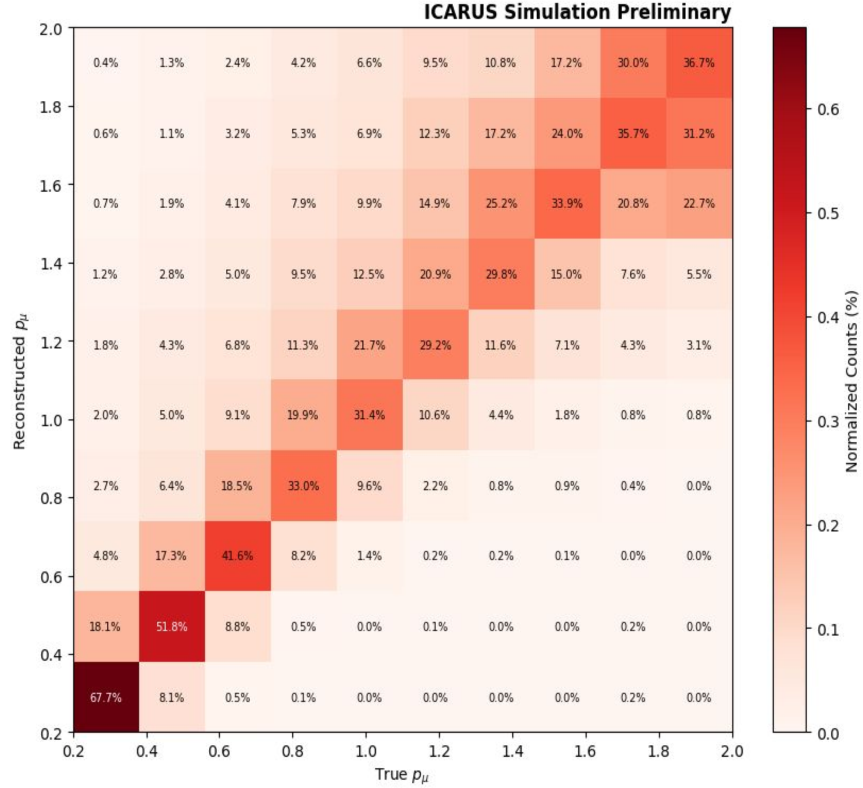
Contained + exiting sample

- Underestimation of the MCS momentum due to track mis-reconstruction
- These mis-reconstruction distort the MCS angle distribution for the track and push the MCS momentum to lower values, especially for higher momentum tracks (that should have small scattering angles)
- Applying **split-track cut**, we could clear out a chunk of mis-reconstructed tracks and that improved the resolution.

Contained(Range), Uncontained (MCS)



Contained(MCS), Uncontained (MCS)



New MC and data samples

- **icaruspro_production_v09_89_01_01p01_2024A_ICARUS_NuMI_MC_NuMI_MC_flatcaf (official production in July, 2024)**
- **Run2 reprocessed NUMIMajority (v09_89_01) (official production in September, 2024)**
- **Run2 reprocessed OFFBEAMNUMIMajority (v09_89_01) (official production in September, 2024)**

Flash classification IDs: Type of match between a TPC object (e.g. PMT flash) and CRT system

A. With CRT hit

noMatch = 0 < No CRT hit/match>

This will actually cut both entering and exiting tracks so it would not work if we want to keep neutrinos with exiting muons.

Events in the last bin of Cosine θ_{NUMI}

Cosmic veto	**4500**
Cosmic tagger	**7000**

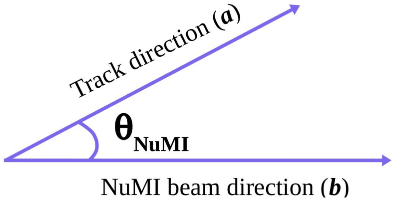
B. With CRT-PMT matching

- ★ A spill is considered as "***Cosmic***" when all intime flashes are entering
- ★ If a spill has anything not entering, that should not be considered as a cosmic

- **enTop = 1, ///< Matched with Top CRT hit before optical flash>**
- **enSide = 2, ///< Matched with Side CRT hit before optical flash>**
- **enTop_exSide = 3, ///< Matched with one Top CRT hit before the optical flash and matched with one Side CRT hit after the optical flash>**
- **enTop_mult = 6, ///< Matched with multiple Top CRT hits before the optical flash>**
- **enTop_exSide_mult = 7, ///< Matched with multiple Top CRT hits before the optical flash and more than 1 side CRT hits after the optical flash>**

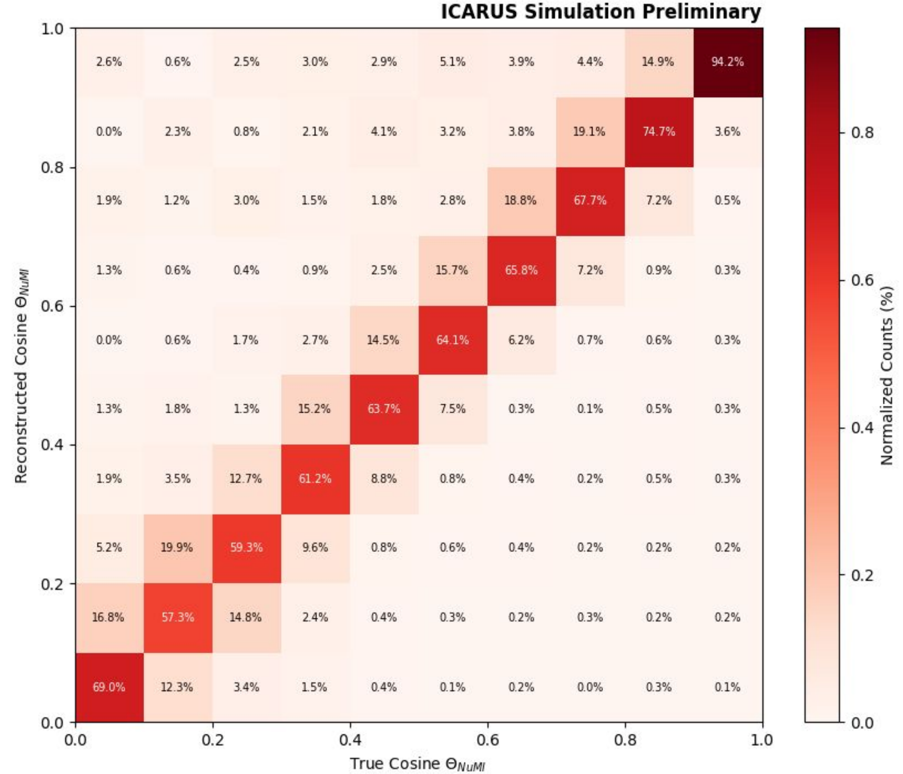
Inclusive Selection *MC Unfolding matrix*

$$\cos(\theta_{NuMI}) = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}$$



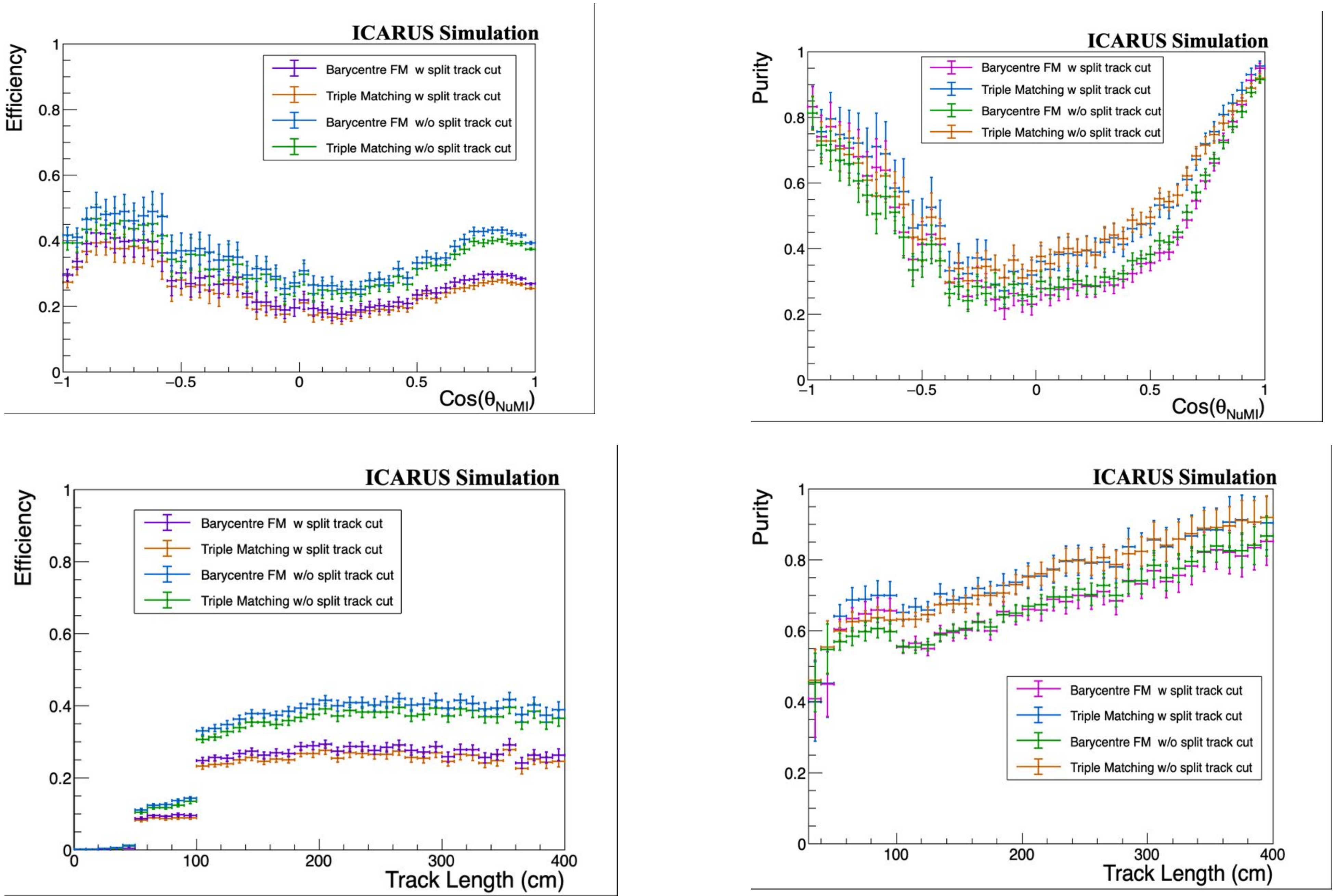
The $U_{\mu a}$ is the ***unfolding matrix*** that basically takes us from the measured variable to the true variable. The purpose of this matrix is to tell us the probability that an event observed in bin *a* (measured) actually occurred in bin μ (true). We can use our MC simulation to perform a migration matrix indicating what fraction of events generated in each true bin μ were observed in each reconstructed bin *a*.

Cosine Θ_{NuMI} : Reconstructed vs True



Unfolding

$$\left\langle \frac{d^n\sigma}{d\mathbf{x}} \right\rangle_{\mu} = \frac{\sum_a U_{\mu a}\,(D_a - B_a)}{\Phi\, T\, \Delta \mathbf{x}_{\mu}}$$



ICARUS Simulation
Efficiency
Barycentre FM w split track cut
Triple Matching w split track cut
Barycentre FM w/o split track cut
Triple Matching w/o split track cut
Cos(θ_NuMI)
ICARUS Simulation
Purity
Barycentre FM w split track cut
Triple Matching w split track cut
Barycentre FM w/o split track cut
Triple Matching w/o split track cut
Cos(θ_NuMI)
ICARUS Simulation
Efficiency
Barycentre FM w split track cut
Triple Matching w split track cut
Barycentre FM w/o split track cut
Triple Matching w/o split track cut
Track Length (cm)
ICARUS Simulation
Purity
Barycentre FM w split track cut
Triple Matching w split track cut
Barycentre FM w/o split track cut
Triple Matching w/o split track cut
Track Length (cm)