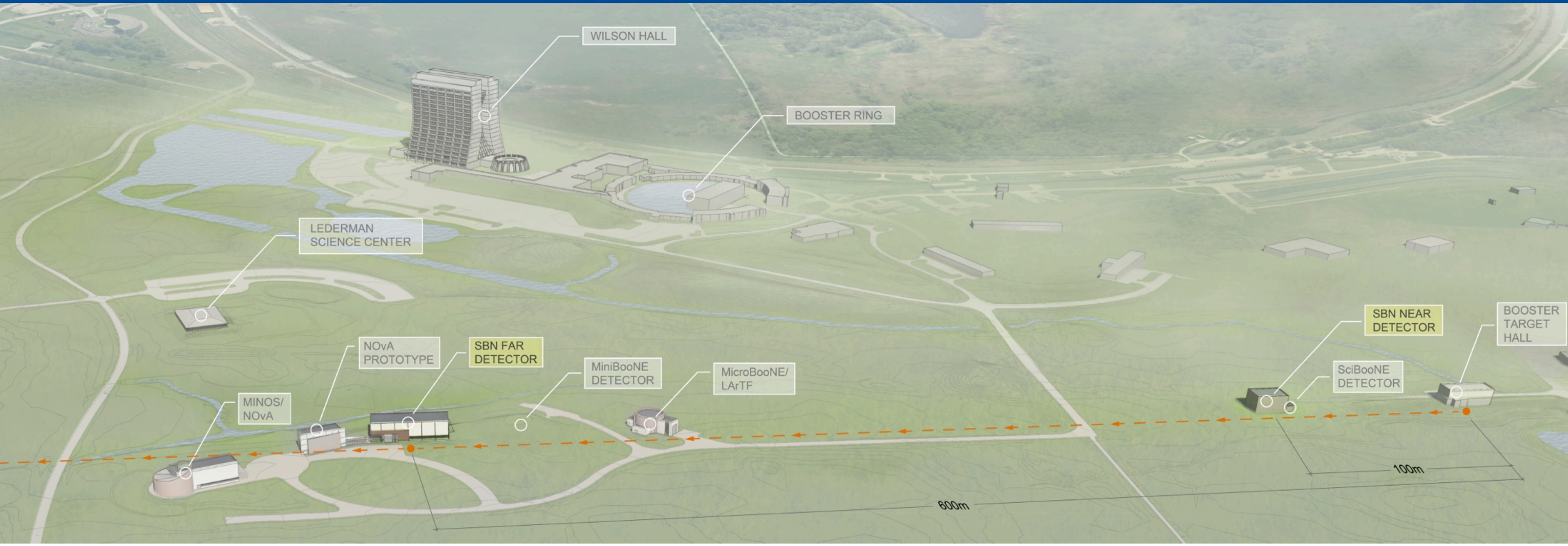


Status of the SBN Analysis Working Group

PAC Meeting

December 8th, 2020

Ornella Palamara, Daniele Gibin

SBN Analysis Group – Recent activities

The group takes care of all the aspects of the
multi-detector physics analysis for
SBN sterile neutrino oscillation searches

- Since our last presentation in January 2020, it has been a challenging period, but we
  - Maintained **regular meetings**
  - Organized **two** (online) **Workshops**
    - V SBN Analysis Workshop (Monday, March 23rd – Friday, March 27th, 2020)
    - "SBN Calorimetry" mini-workshop on July 6th-7th, 2020
  - Organized **tutorials** on SBN software tools
  - Made a **large Monte Carlo production** for SBND and ICARUS and analyzed the data
  - Begun comparing **ICARUS data with our Monte Carlo simulation**

A new **SBN Working Group** (**SBN Analysis Infrastructure**) has been created

[SBN Analysis Working Group Organizational Chart in overflow slides]

Outline

The SBN Analysis Infrastructure Group

SBN Event Simulation, Selection and Reconstruction

SBN Oscillation Sensitivity Studies

SBN Detector Systematics

First ICARUS data/Monte Carlo comparison

SBN Analysis Infrastructure Working Group

SBN Working Group, Co-conveners: Wes Ketchum, Joseph Zennamo

Goal to coordinate and address **data and software infrastructure** and **computing resource** needs **across the SBN** to enable SBN Program's science goals

Working alongside the current other SBN working groups, focusing on **basic infrastructure and software organization**

Recent activities

- Restructure software infrastructure to enable **seamless sharing of code across the SBN**
  - Further developing **common analysis framework** for SBN analysis
- Preparing for first **large scale SBN-wide Production**
  - Successful first test production, producing 500,000 SBND and ICARUS simulated events
  - Using lessons learned to inform 2021 production planning, with plans for >15 million simulation events and all available ICARUS data events (~5 million anticipated)
- Preparing a new **software release** to allow for the consistent processing of **data and simulation** across ICARUS and SBND

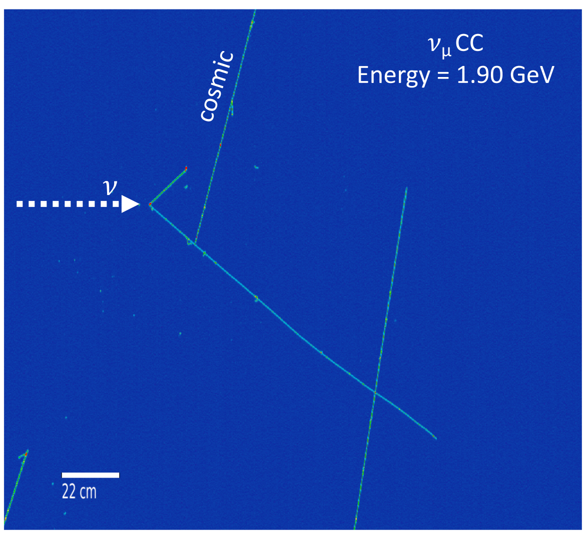
[more in overflow slides]

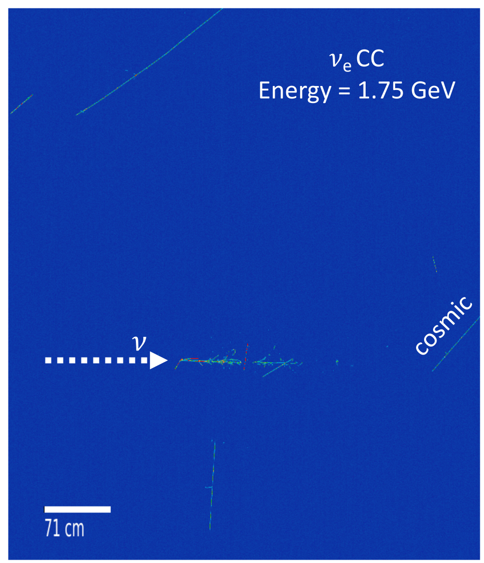
SBN Event Simulation, Selection and Reconstruction

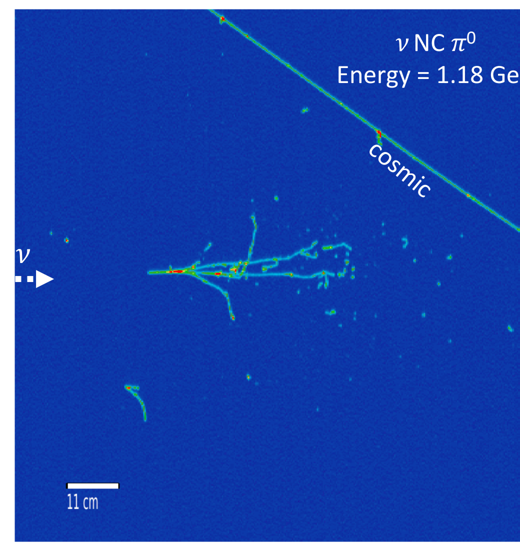
Event Simulation

Recent MC production: High Statistics samples of Booster Neutrino Beam (**BNB**) **ν_μ and ν_e neutrino events** including **cosmics,** in the **ICARUS** and **SBND** detectors

- **BNB Neutrinos**
  - "Modern" neutrino event Monte Carlo (**recent physics tune - GENIE 3**)
    - Model and systematic assignments informed by recent data (T2K, MINERVA etc.), in agreement with MicroBooNE data. [more in overflow slides]
- **Cosmic background** simulated with COsmic Ray SImulations for KAscade (CORSIKA)

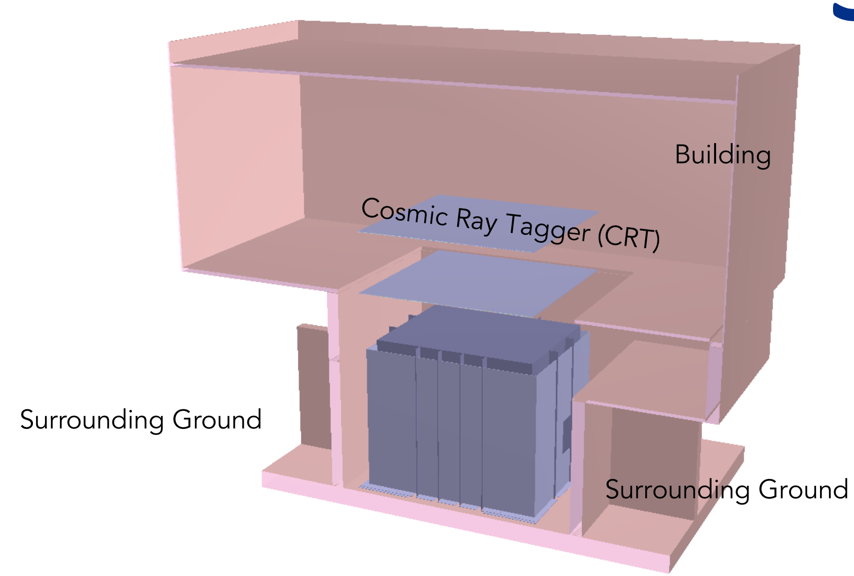


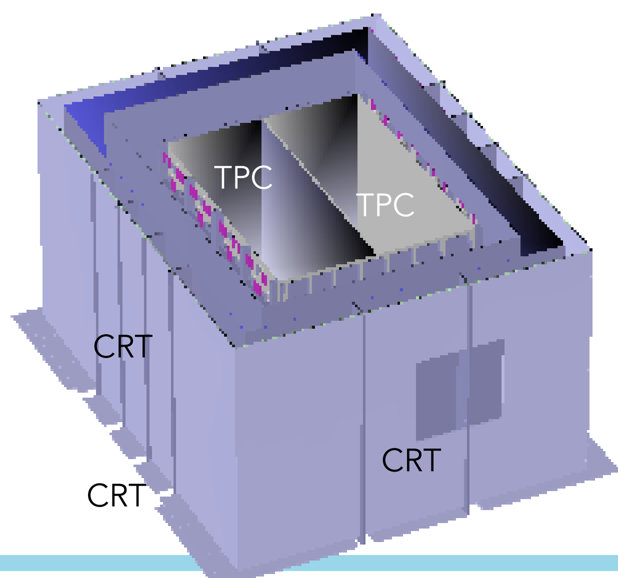


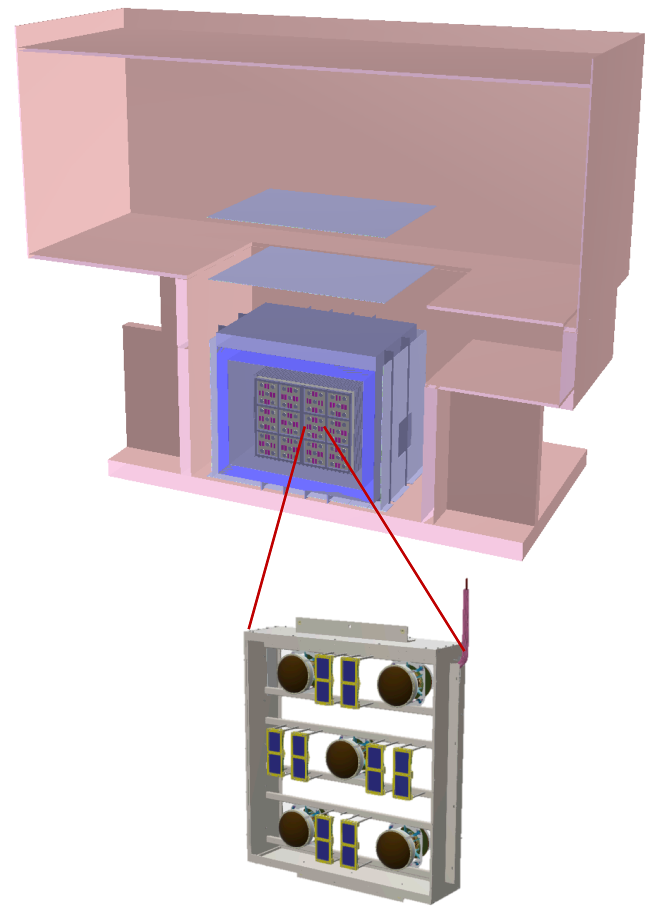


Detector Simulation

SBND



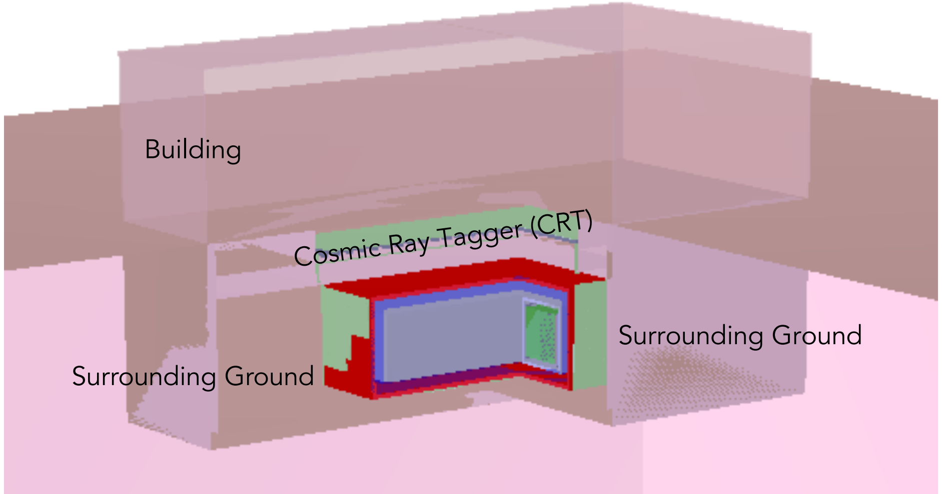


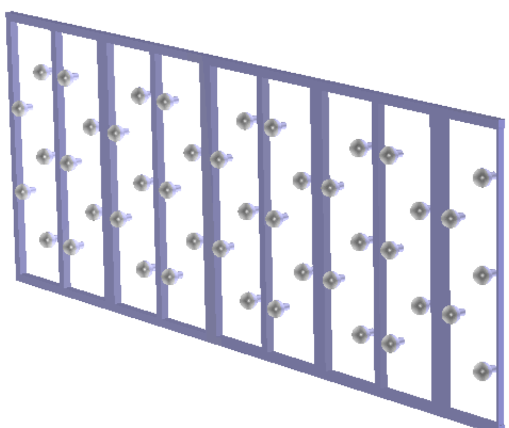


Photon Detection System module (x24)
PMTs (PTB coated and uncoated) and
ARAPUCAS

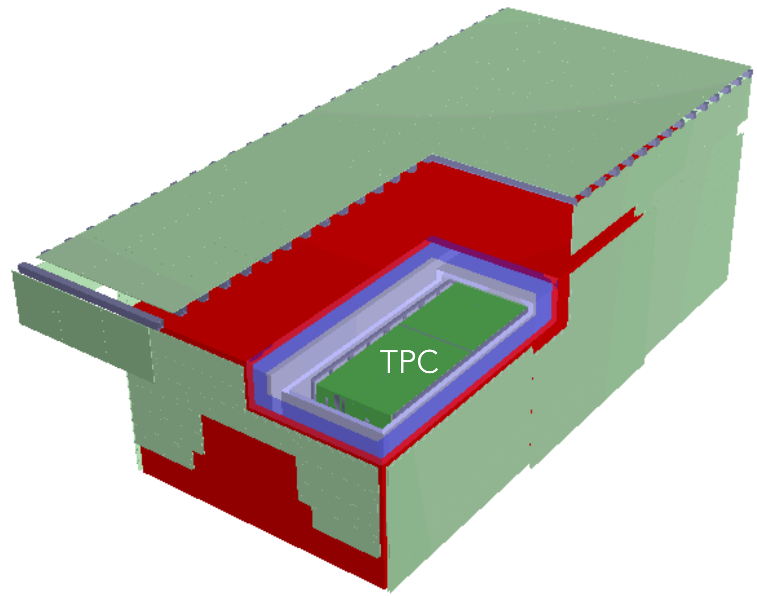
Detector Simulation

ICARUS





Photon Detection System
(PMTs)



SBN Data Composition

Trigger of the TPC readout is based on **PMT signal multiplicity above threshold**, in coincidence with the BNB spill (**1.6 μs spill duration**).
Can be due to a **neutrino interaction** or to **cosmic rays** that enter the TPC in the beam spill time.

From the simulation , **without an overburden** [3m of concrete above the detector]

SBND — 1 "in time" cosmic every 8 neutrinos

- A trigger due to neutrino interaction every 20 BNB spills
- A trigger due to "in-time" cosmic muon every 160 BNB spills

[and 5 "out-of-time" cosmic muons per TPC drift]

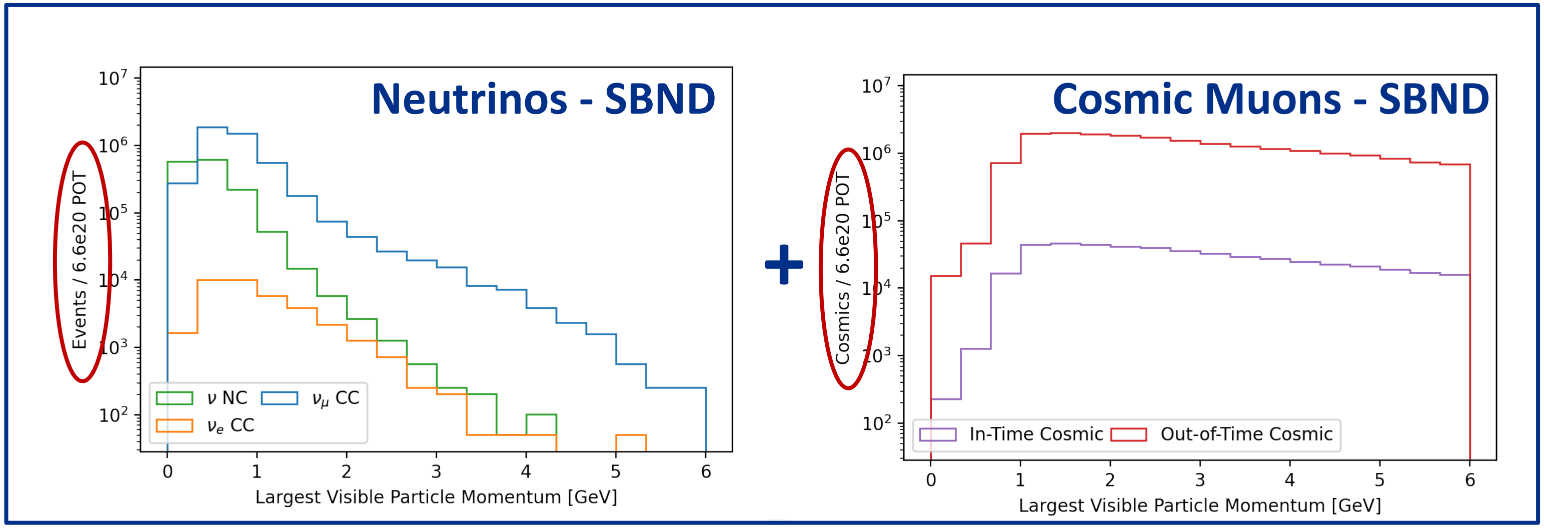
ICARUS — 5 "in time" cosmic for every neutrino

- A trigger due to neutrino interaction every 180 BNB spills
- A trigger due to "in-time" cosmic muon every 35 BNB spills

[and 17 "out-of-time" cosmic muons per TPC drift]

$(\text{SBND/ICARUS})_{\nu} \sim 10$

$(\text{SBND/ICARUS})_{\text{cosmic "in-time"}} \sim 1/4.6$



Exploiting three detector systems

Current analysis combines TPC, PDS, CRT info

- **TPC**:
  - Hit finding & Reconstruction (position, charge)
  - ***Pandora**** pattern recognition
    - "**Slices**" of reconstructed "objects", classified as **tracks and showers**

- **Photon Detection System**
  - Reconstructed **Optical Flashes**
- **Cosmic Ray Tagger (CRT)**
  - Reconstructed **Hits**
  - Reconstructed **Tracks**

*Pandora pattern-recognition algorithms, Eur. Phys. J. C75(9), 439 (2015), Eur. Phys. J. C 78, 82 (2018)

Also adopted by MicroBooNE, (Proto)DUNE

Recent Progress in the Simulation

- Significant progress in the simulation of **physical effects**
  - Updated **electron diffusion constants** (from ProtoDUNE measurement, private communication)
  - **Space Charge Effect** (SCE) [due to accumulation of slow-moving ions from cosmics] included in the simulation
  - Updated **optical model** (updated refraction index, Rayleigh scattering length from recent measurements)
- Significant progress in **detector's description and reconstruction**
  - **TPC**:
    - Detector response and noise level from real data
    - Signal processing (different for SBND and ICARUS - different S/N)
    - SCE effect corrections included
    - Improved track/shower discrimination and reconstruction
    - Updated calorimetry calibration
  - **CRT**:
    - Detector response from real data
  - **Photo Detection System**:
    - Description of optical devices
    - Optical flash reconstruction
- Progress from combining different detectors (ex. charge - light matching, CRT-TPC track matching)

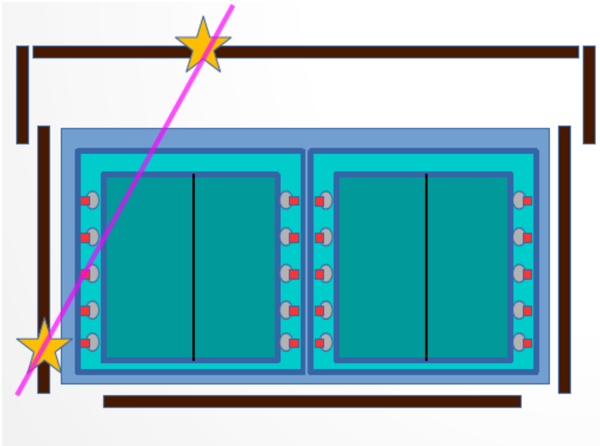
[in overflow slides]

In-time Cosmic removal by using the CRT

- The signals provided by the **CRT** system can be used to identify the presence of a cosmic muon crossing the detector in-time with the beam-spill.
  - CRT Hit-veto: Reject events with a **CRT hit above a threshold** and **in-time with the beam spill window** (-0.1μs : 1.7 μs) provides a strong reduction of the events triggered by cosmic muons **(75% reduction for SBND)** and it is an effective pre-selection for the ν_e CC candidate in the fiducial volume (**few % reduction for the ν_e CC event**)

CRT Hit veto	SBND AV(FV)	ICARUS AV(FV)
ν_μ CC	21(18)%	11(9)%
ν_e CC	8(5)%	4(2)%

- CRT Track-veto: Filter events with **in-time CRT tracks** (at least **two planes with CRT hits coincident within 100 ns**). It is an effective selection, preserves the neutrino signals (**only a few % reduction for the ν_μ CC event in SBND**) and provides a good (**~40%**) reduction of the cosmic events (CRT configuration to be optimized).

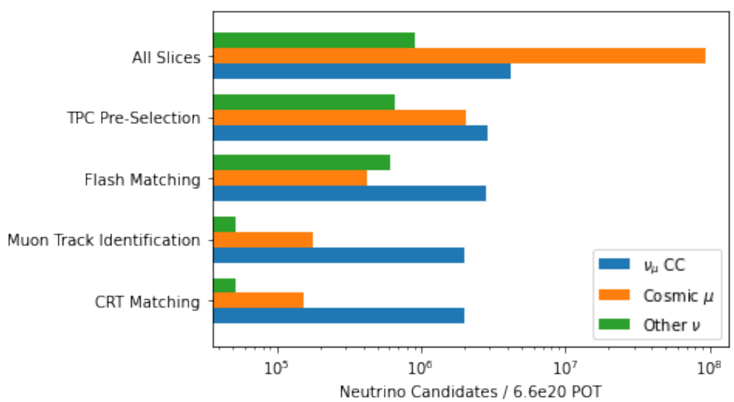


Current Neutrino Event Selection and Background Rejection

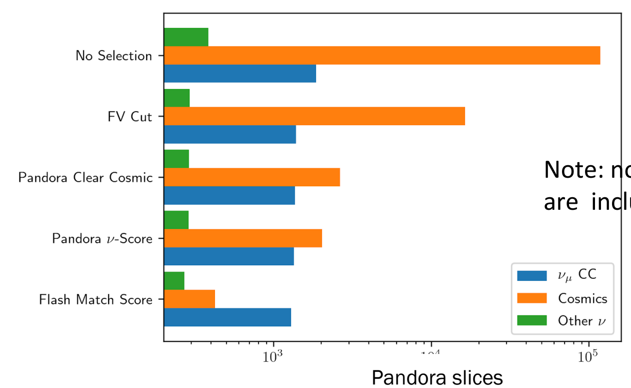
- The analysis includes:
  - A Fiducial Volume cut
  - ***Pandora*** unambiguous cosmic removal and high ν-score "slice" selection
  - Selection from "flash matching": charge-light matching in each Pandora slice
  - **ν_μ CC event selection**:
    - Muon track ID (topological selection and calorimetric PId for contained muons)
    - Filter in-time CRT tracks to remove cosmic events
  - **ν_e CC event selection**:
    - Selection of events with at least one reconstructed shower with E>200 MeV
    - Removal of in-time cosmic muons using CRT hits
    - Exploitation of "e-gamma discrimination": gap at the reconstructed neutrino vertex and/or dE/dx cut to identify background photons

[details and examples of performances in overflow slides]

SBND



ICARUS



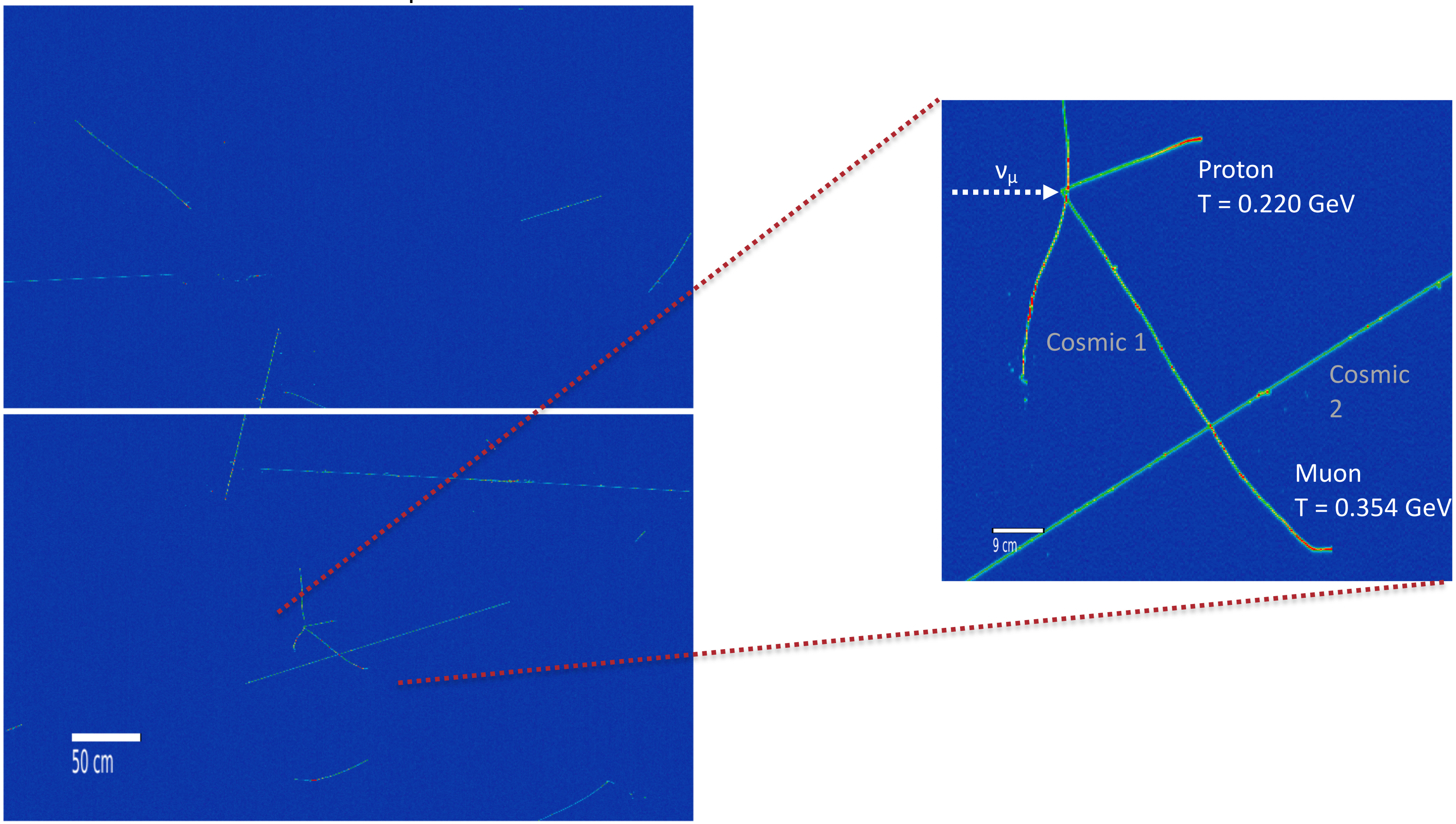
Note: not all the steps are included yet

Illustration of the **ν_μ CC selection steps**. The two graphs are not intended for direct comparison

BNB Neutrino Event

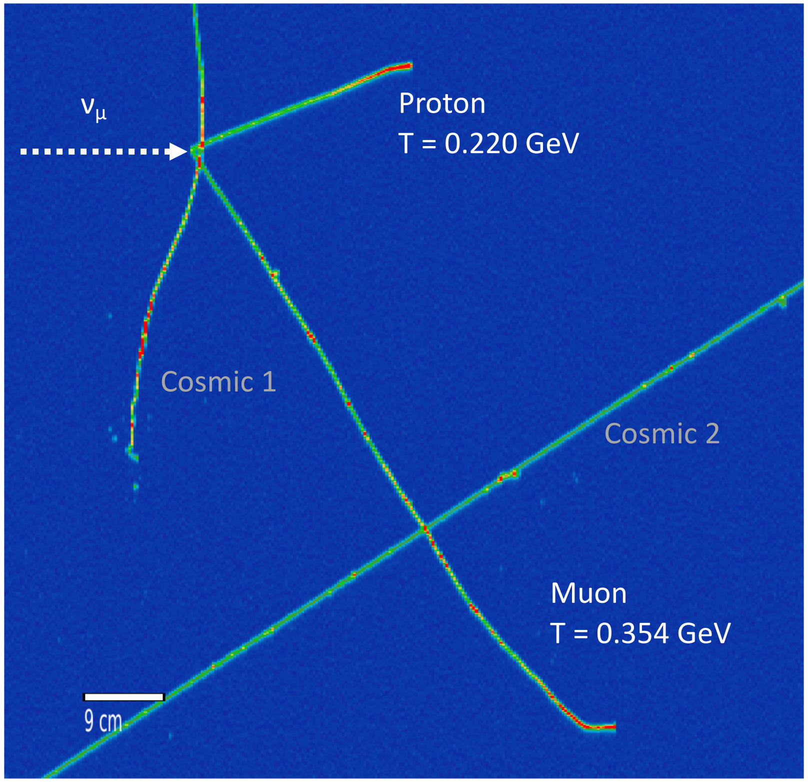
ν_μ CC
Energy = 0.697 GeV

Bottom: TPC 0; Top: TPC 1



BNB Neutrino Event

ν_μ CC
Energy = 0.697 GeV

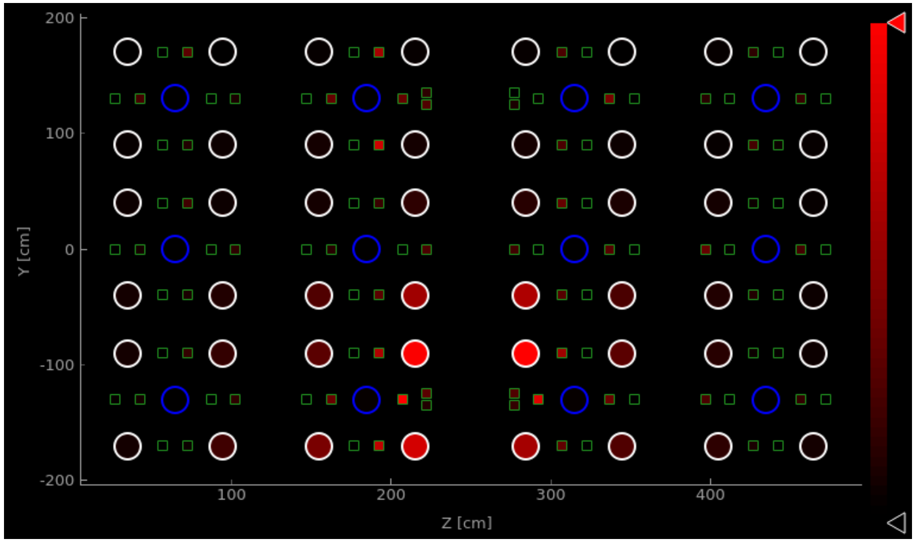


TPC

SBND PDS
White: Coated PMTs
Blue: Uncoated PMTs
Green: Arapucas

spill=1.6 μs

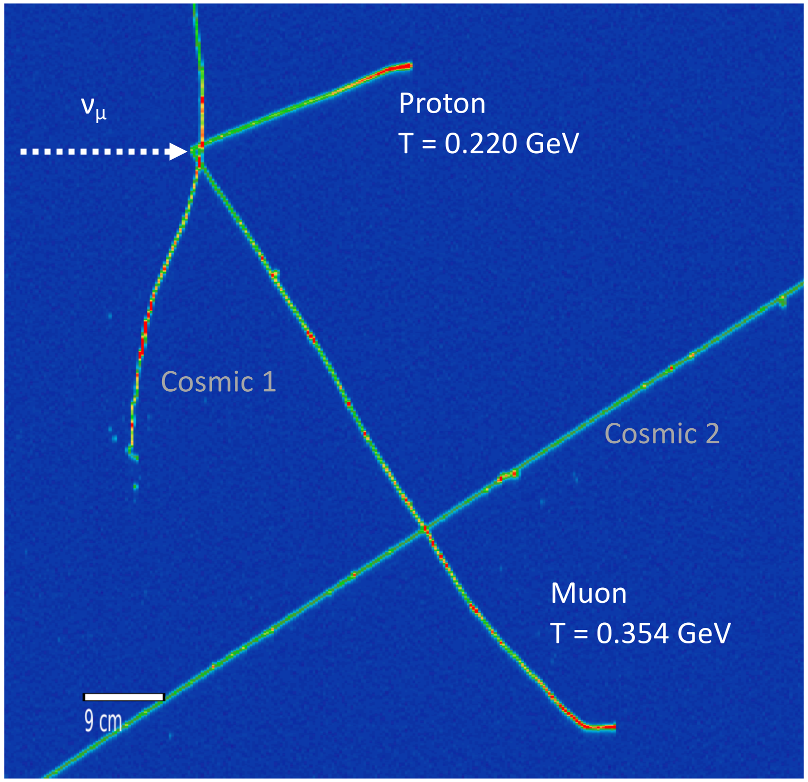
Neutrino-Induced Flash, time = 0.9 μs



Photon Detection System

BNB Neutrino Event

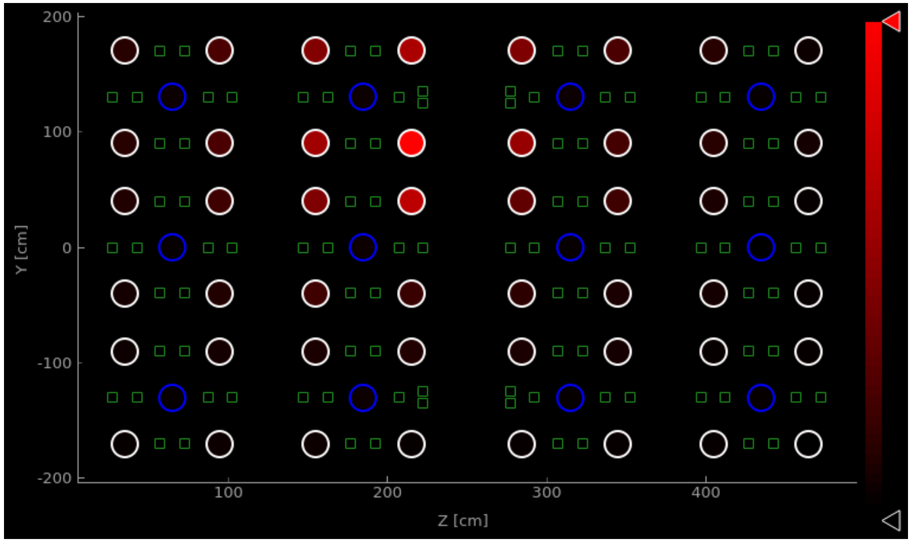
ν_μ CC
Energy = 0.697 GeV



SBND PDS
White: Coated PMTs
Blue: Uncoated PMTs
Green: Arapucas

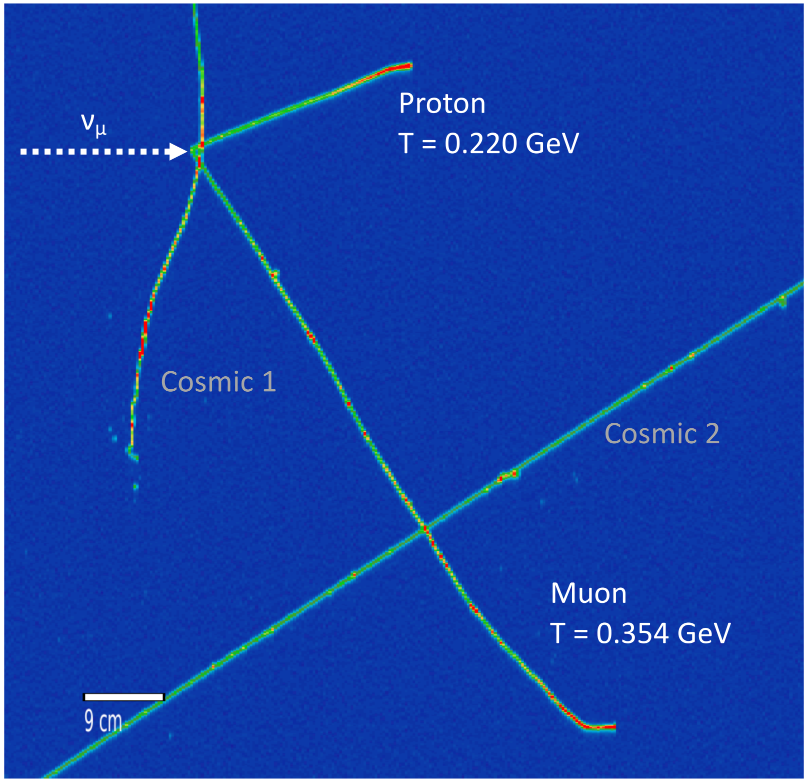
out-of-time
(spill=1.6 μs)

Cosmic 1 Induced Flash, time = 89 μs



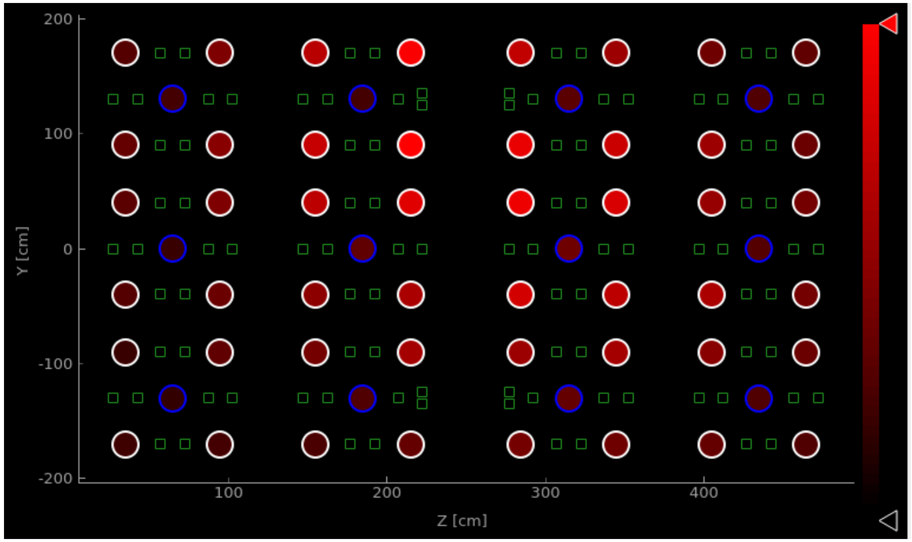
BNB Neutrino Event

ν_μ CC
Energy = 0.697 GeV



SBND PDS
White: Coated PMTs
Blue: Uncoated PMTs
Green: Arapucas

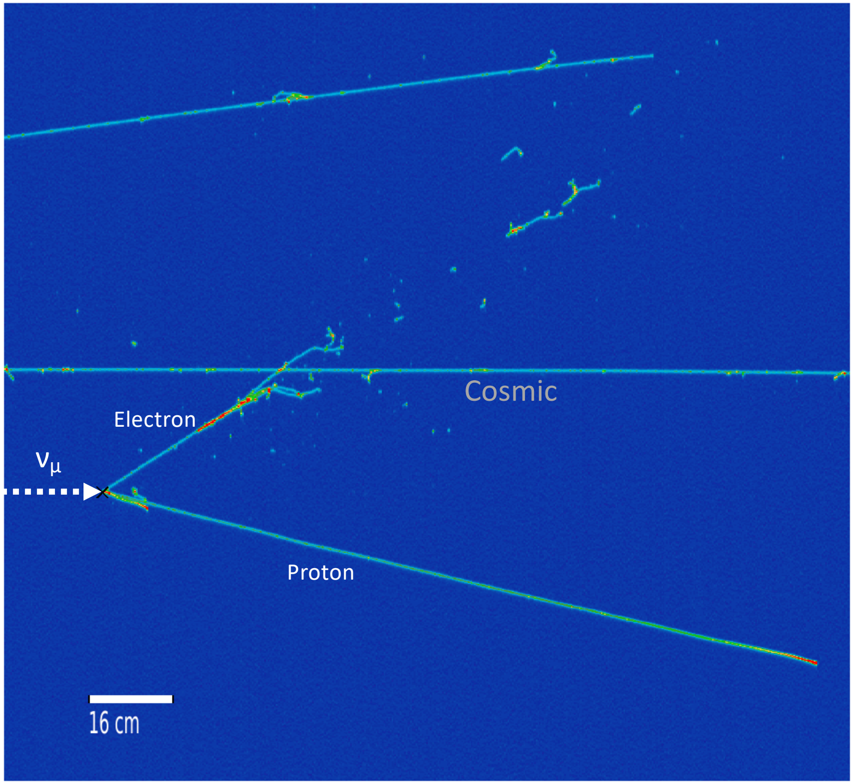
Cosmic 2 Induced Flash, time = -492 μs



This is a long cosmic muon that lights up all PMTs. It crossed the TPC close to the cathode plane, so the reflected light is large (see the flashes in the uncoated PMTs)

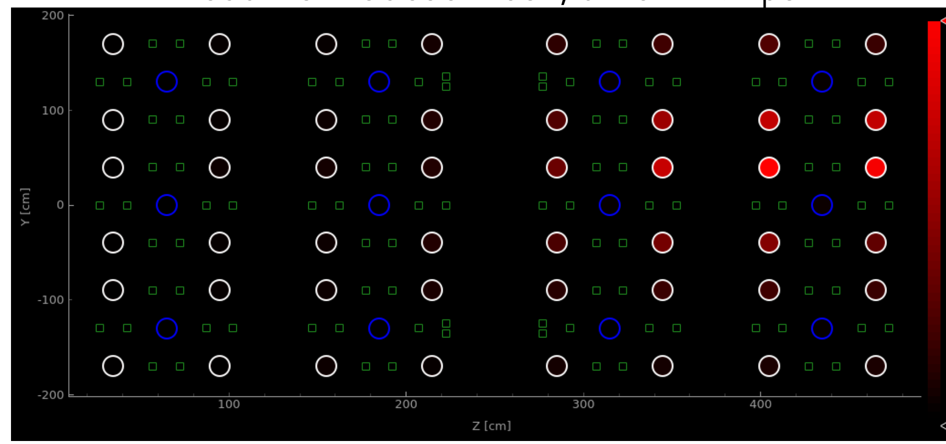
BNB Neutrino Event

ν_e CC
Energy = 1.58 GeV

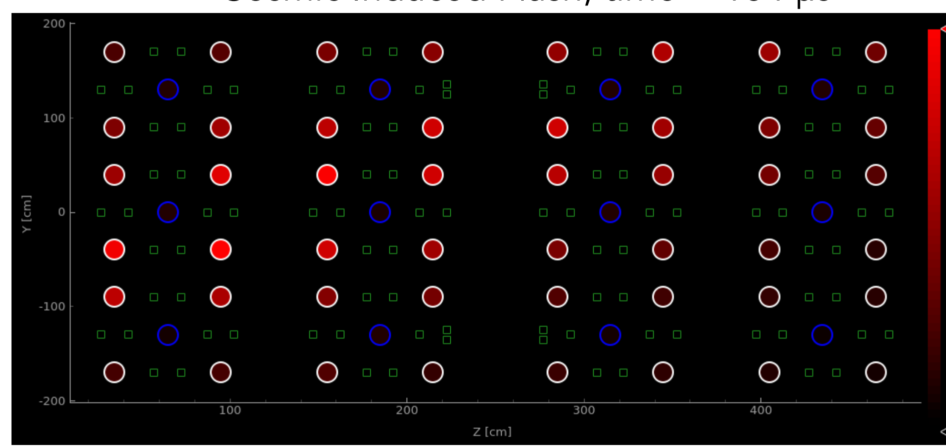


SBND PDS
White: Coated PMTs
Blue: Uncoated PMTs
Green: Arapucas

Neutrino Induced Flash, time = 1.4 μs

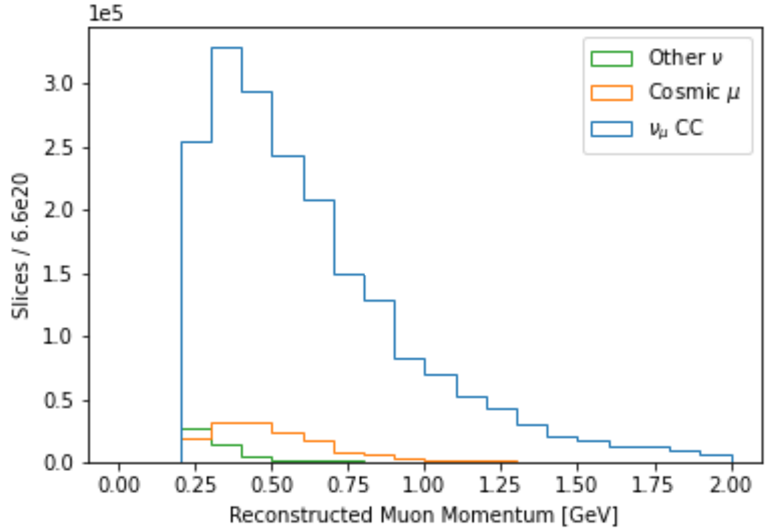


Cosmic Induced Flash, time = 184 μs



ν_μ CC Event Selection – Current status

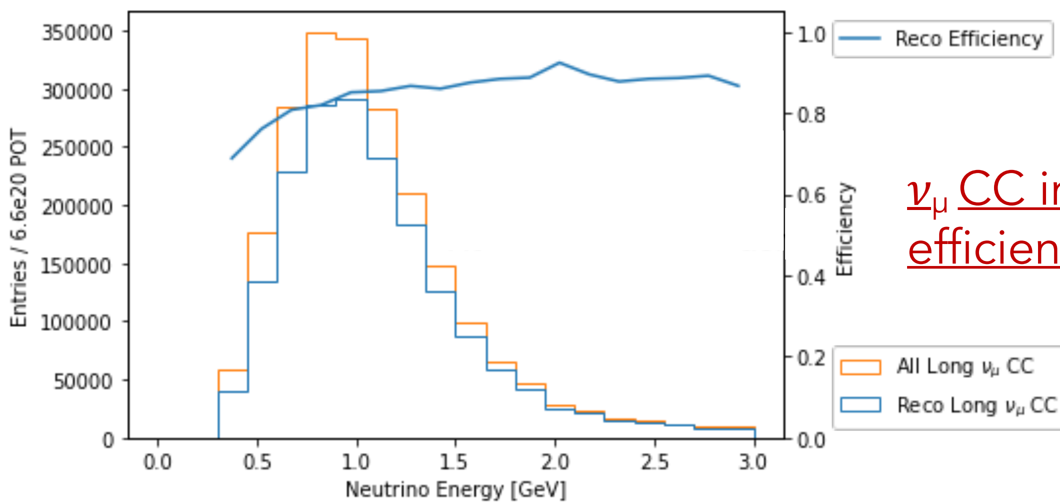
After all the selections



ν_μ CC: 90.1%
cosmic background: 7.6%
ν NC background: 2.3%

SBND

ν_μ CC interactions in the Fiducial Volume, with a >50 cm long contained muon track or a >100 cm long exiting muon track

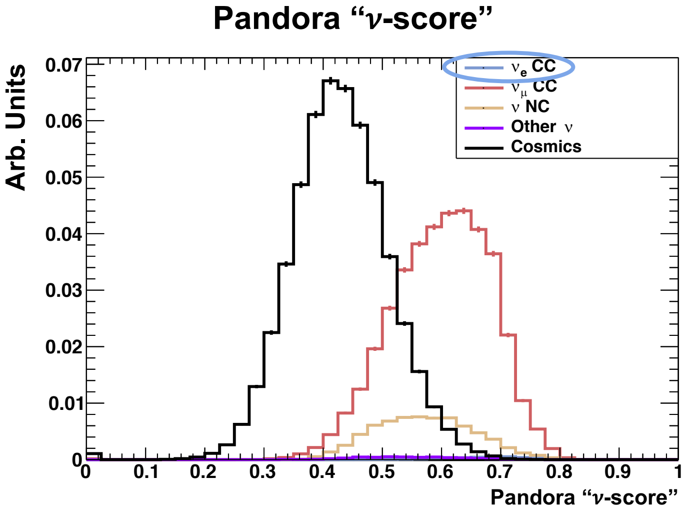


ν_μ CC integrated efficiency: 83.4%

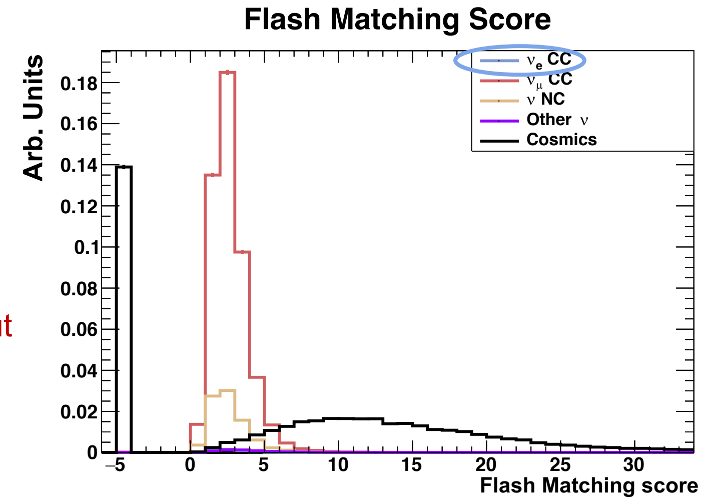
For reference, ν_μ CC efficiency assumed in the SBN proposal: 80%

ν_e CC Event Selection – Current Status

Different analysis stages (after applying FV cut and the CRT hit-veto)



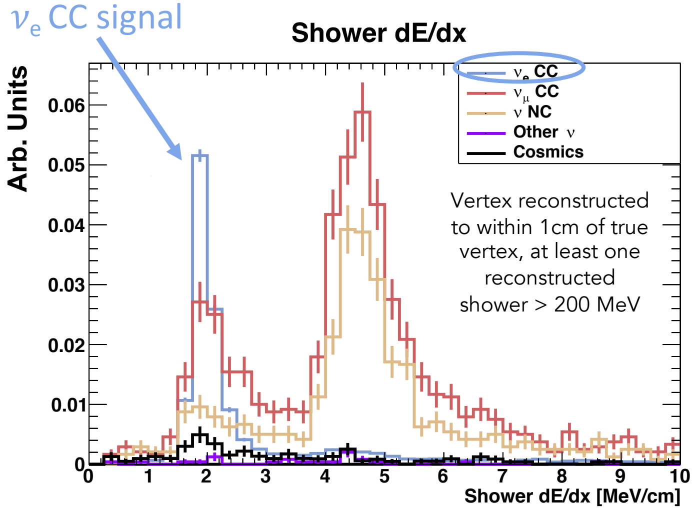
"ν-score" cut



Flash-matching cut

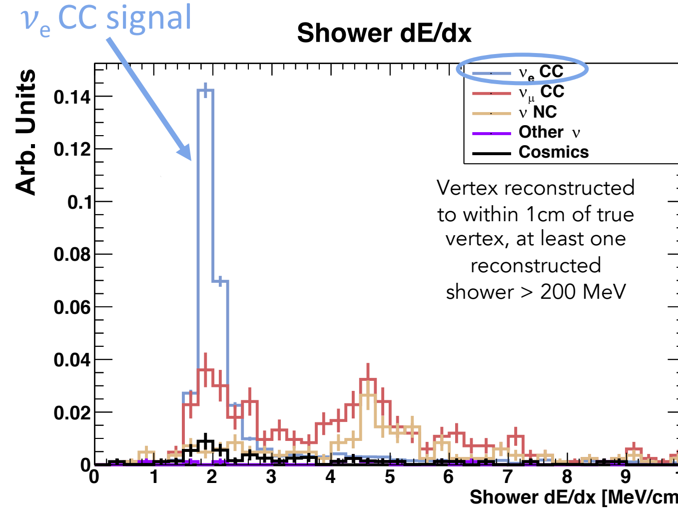
SBND

ν_e CC signal



Gap from the vertex cut

ν_e CC signal



dE/dx cut still to be exploited…

ν_e CC Event Selection – Current Status

- **Current** status of ν_e event selection and reconstruction in SBN(D)
  - An **effective reduction of the cosmic and ν NC background** can be achieved for SBND (after dE/dx cut) , but still significant contribution from $\boldsymbol{\nu_\mu}$ **CC background** remains
  - Signal efficiency is not yet at the level assumed in the SBN proposal, but
  - **Improvements** to the analysis are **in progress**. Still to be exploited:
    - Cylindrical cut to remove electromagnetic activity around cosmic muons
    - Improved flash-matching
    - Calorimetric PiD for tracks

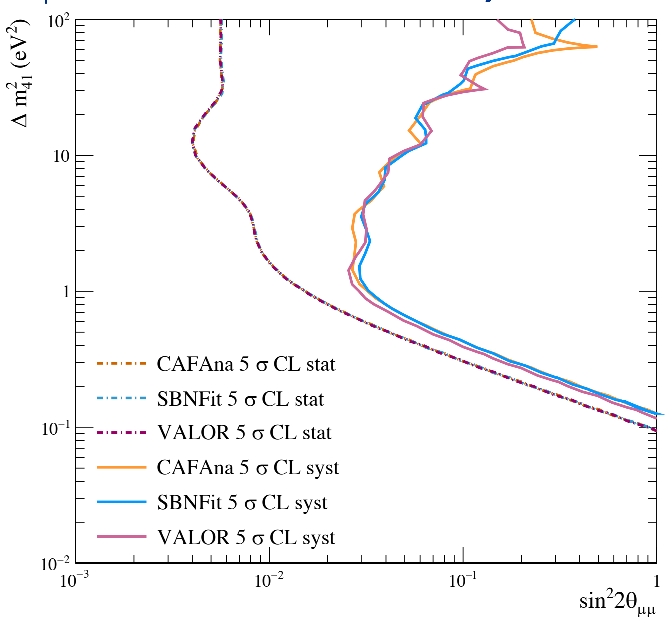
Some problems at reconstruction level are not SBN-specific.
Work in progress within the Liquid Argon community!

SBN Oscillation Sensitivities

SBN Oscillation Sensitivity – Current Status

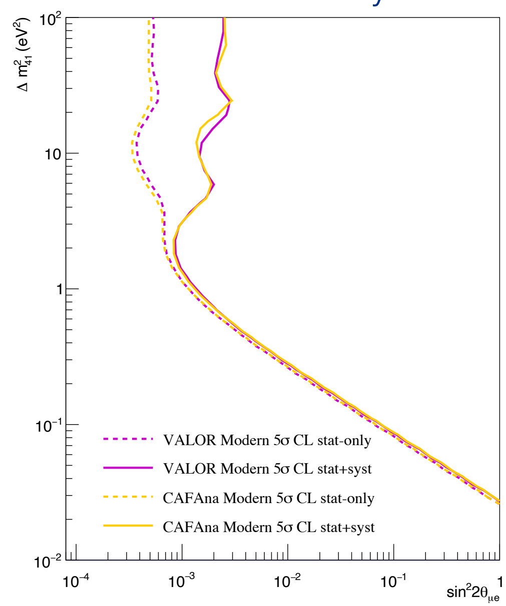
- Three **independently-developed fitting frameworks** with common inputs
  - **CAFAna**: *Analysis framework used by NOvA and DUNE*
  - **SBNfit**: *Analysis framework used by MicroBooNE*
  - **VALOR**: *Analysis framework used by T2K*
- Redundancy allows for detailed validation/cross-checks and evaluation of effects coming from fitter approximations and alternative statistical methodologies
- **Substantial validation effort** (and detailed cross-fitter comparisons) **improved agreement/enhanced confidence** in the calculations

3+1 ν_μ disappearance sensitivity
(proposal-era event selection and systematic assignments)



Note these are 5σ sensitivities

3+1 ν_e appearance sensitivity
(proposal-era event selection and systematic assignments)



Mock data analysis/Robustness tests

The SBN oscillation physics potential has stringent systematic error constraints → Model dependencies <u>might play a role</u>

An **analysis workflows to evaluate and mitigate impacts** is under development

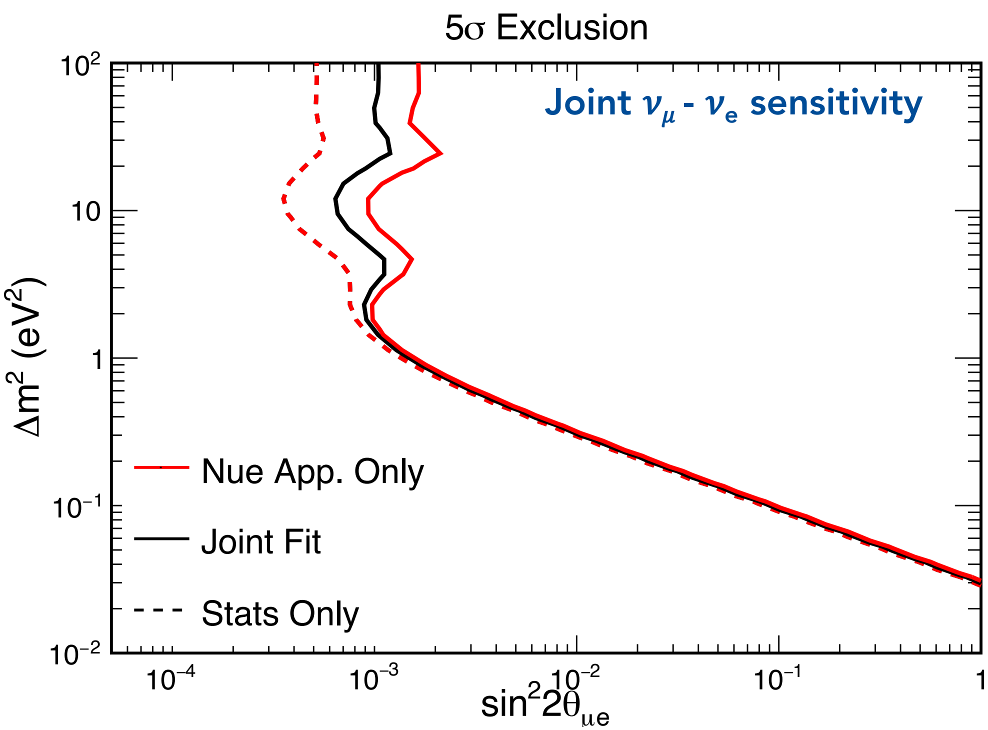
<u>Current Analysis procedure</u>

- **Use the baseline physics MC in the fitters** *(to create MC templates and construct SBN predictions)*
- **Use alternative physics MC to construct fake data** *(**Mock data**)*
- **Fit SBND fake data and study systematic pulls**
- Use systematic pulls to try and diagnose the (unknown) physics content of the alternative MC
- **Use the SBND fake data fit to produce a spectrum prediction for the far detector** and compare to the ICARUS fake data spectrum.
  - Characterize extrapolation biases, relative to the error of constrained systematic parameters.
- **Develop/test strategies to mitigate biases.**

Toward a Joint Analysis of ν_μ and ν_e Samples

SBN is in a **unique position** to exploit the complementarities between ν_μ and ν_e oscillation signatures

This necessitates a **joint analysis of all oscillation channels**

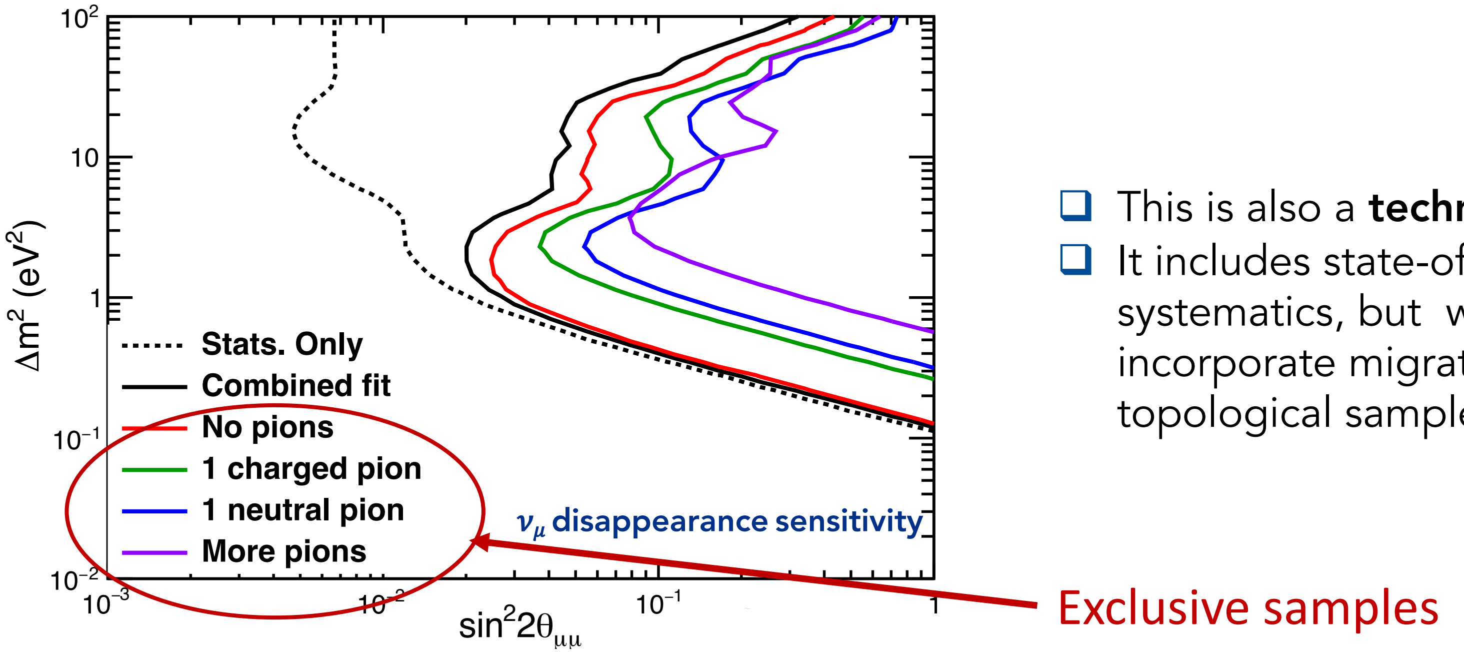


The joint analysis brings in the additional ν_μ CC sample and it allows $\sin^2\theta_{\mu\mu}$ and $\sin^2\theta_{ee}$ to float (fixed in the standalone ν_e appearance analysis)

- This is a **technical milestone.**
- A joint analysis places emphasis on uncorrelated ν_μ/ν_e systematics and on detector effects and migration between different topological samples.
- We have a **suitable joint analysis framework** to address these questions.

Toward a Joint Analysis of Exclusive Samples

Enlarge the analysis further by
separating the inclusive samples based on their hadronic topology and
fit them all jointly



- This is also a **technical milestone**.
- It includes state-of-the-art systematics, but work remains to incorporate migrations between topological samples.

Collaboration with SciDAC: “Accelerating Discovery”

SBN collaborators have been working with SciDAC (Scientific Discovery through Advanced Computing) program to port **3+N fitting software** (SBNfit) onto **high-performance-computing** (HPC) infrastructure at National Energy Research Scientific Computer (NERSC) Center.

[more in overflow slides]

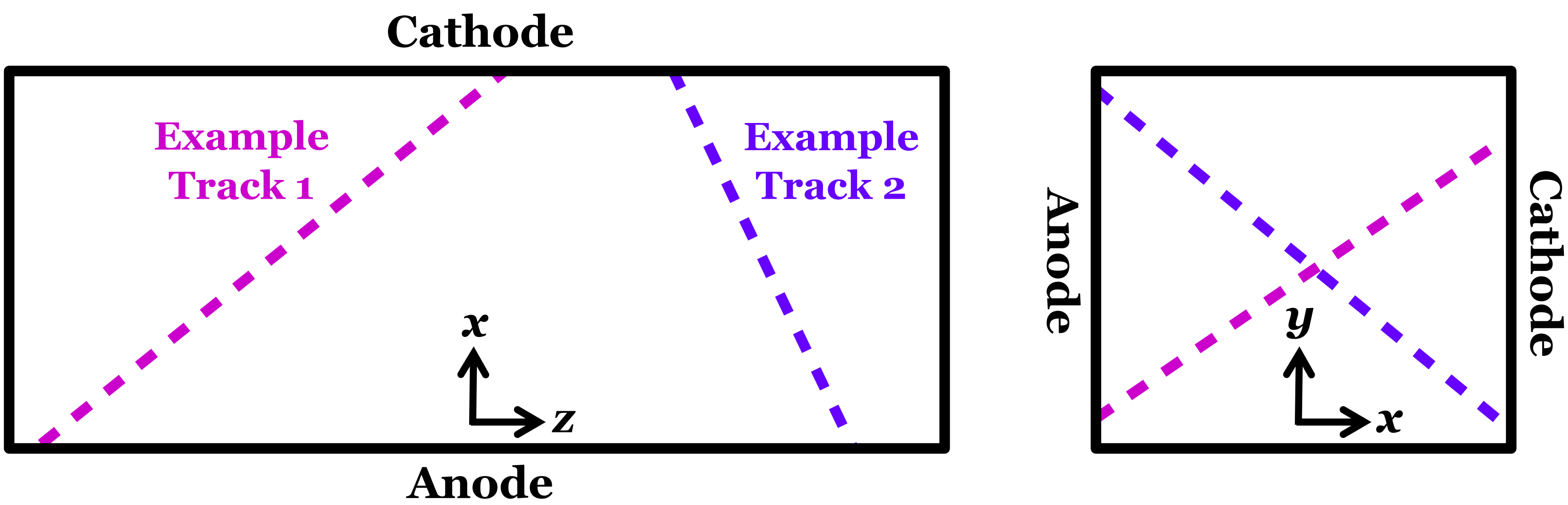
FERMILAB-PUB-20-069-SCD

Detector Systematics

First ICARUS data/Monte Carlo comparisons

ICARUS Track Selection

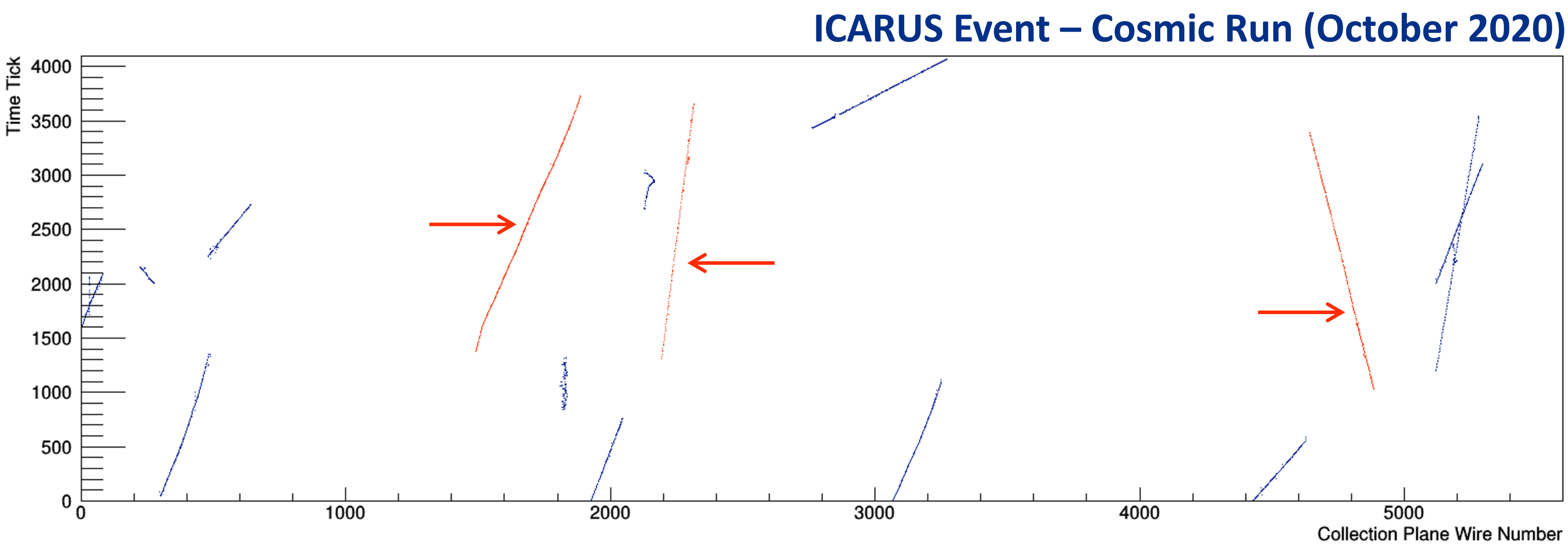
Select "anode-cathode-crossing" cosmic muons in first ICARUS data to study detector effects → use to tune detector simulation



- Simple **2D track reconstruction** using **collection** plane only
  - Simple hit-finding (> 10 ADCs) to find signals on collection plane
  - 2D clustering → reconstructed track objects
  - Select **tracks with maximum drift time consistent with charge traveling from cathode to anode**

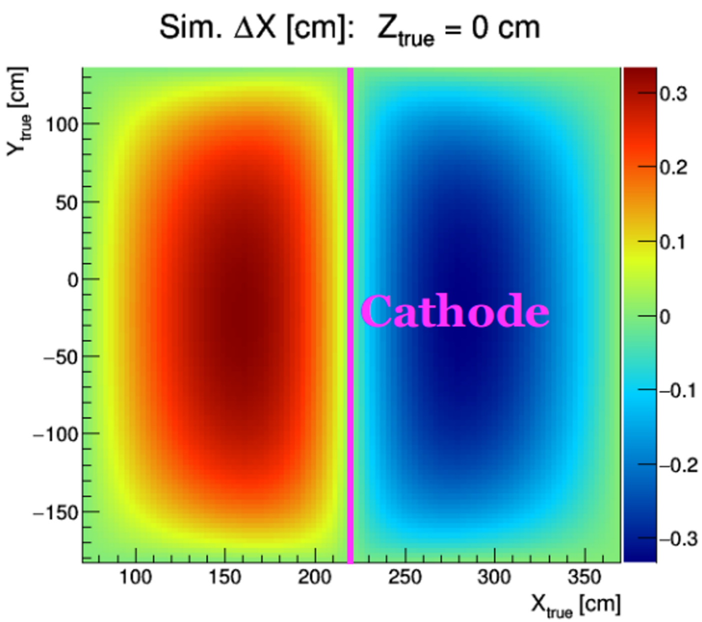
ICARUS Track Selection

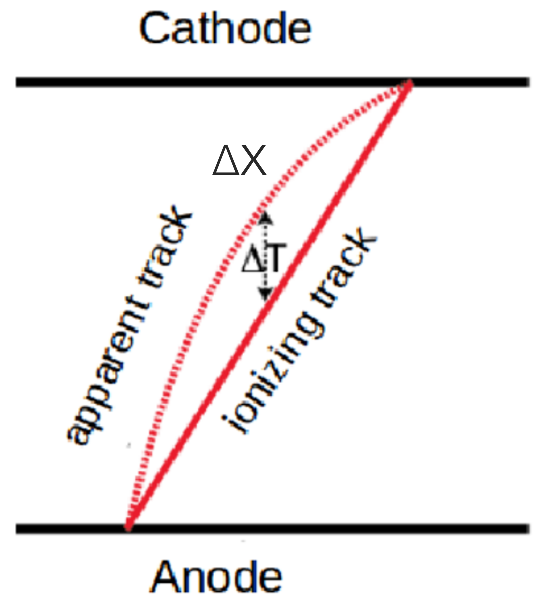
Select "anode-cathode-crossing" cosmic muons in first ICARUS data to study detector effects → use to tune detector simulation



- Simple **2D track reconstruction** using **collection** plane only
  - Simple hit-finding (> 10 ADCs) to find signals on collection plane
  - 2D clustering using DBSCAN → reconstructed track objects
  - Select **tracks with maximum drift time consistent with charge traveling from cathode to anode**

Studies of Space Charge Effects

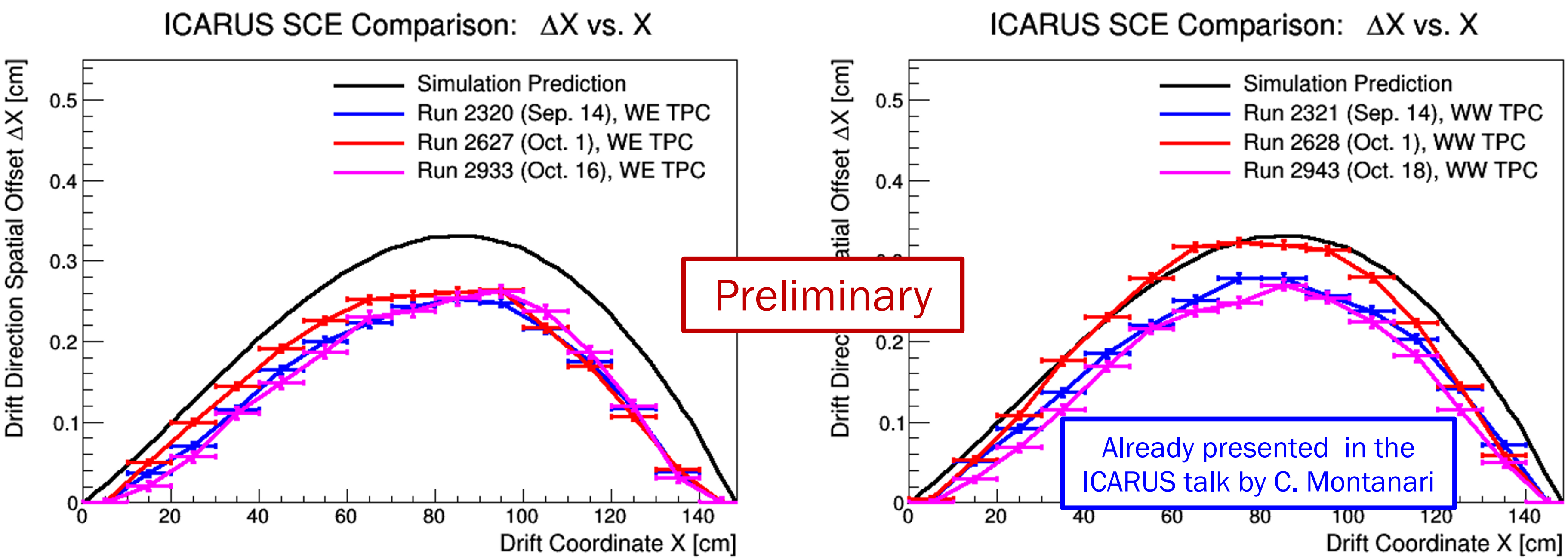




- Study **space charge effects** (SCE) using 2D info (hit times from collection plane) from anode-cathode-crossing cosmic muons
  - Effect smaller in **drift direction (ΔX ~ 0.3 cm)**, but measurable
  - Methodology previously explored at ICARUS (arXiv:2001.08934)
- Later: full offline calibration in 3D will make use of pairs of near-crossing cosmic muon tracks (arXiv:2008.09765)

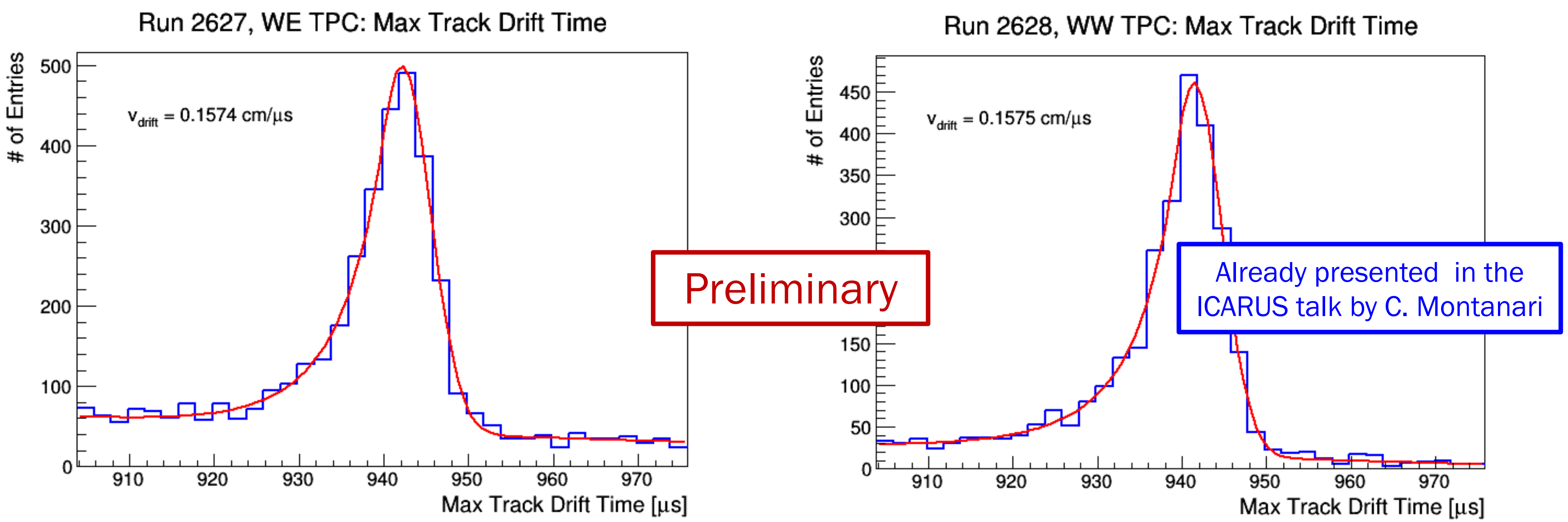
[SCE Simulations for ICARUS and SBND in overflow slides]

SCE Measurements @ ICARUS



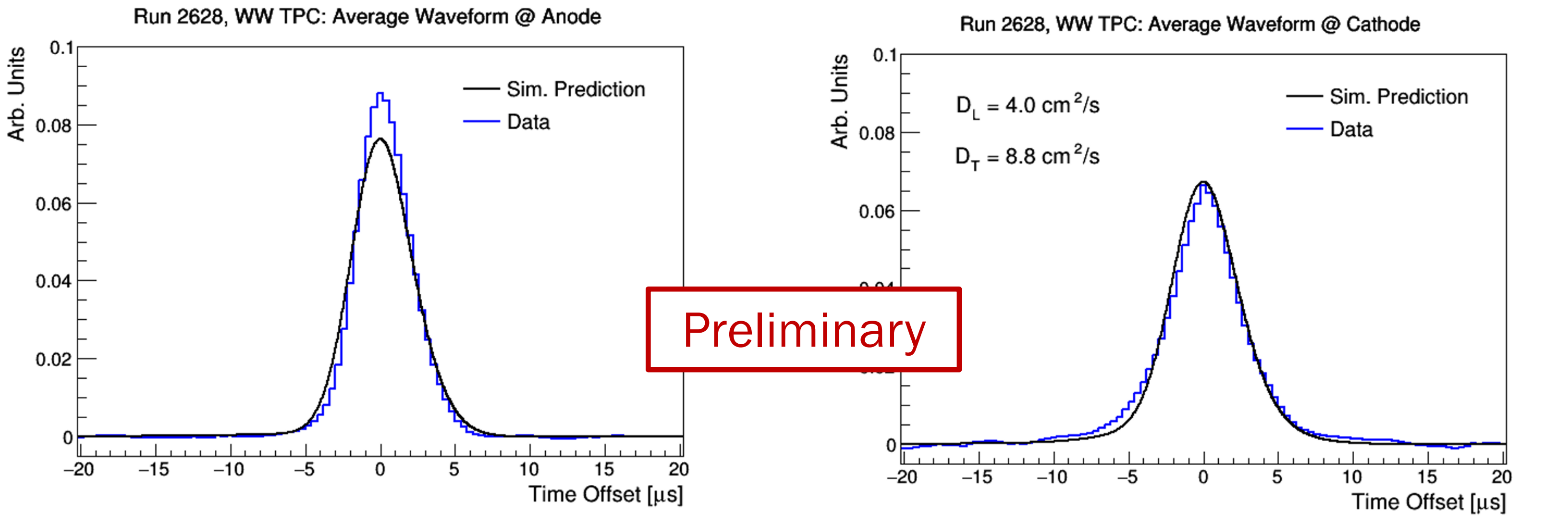
- ❑ Compare data measurements to prediction from simulation
  - ❑ First results show rough agreement with simulation, aside from small time dependence (under investigation)
- ❑ Use results to <u>tune SCE simulation</u> for ICARUS and use the developed method also for SBND

Drift Velocity @ ICARUS



- Same track sample used to **measure the electron drift velocity** by measuring maximum drift time of charge associated with tracks
  - Preliminary results in line with previous ICARUS measurements
- Allows data-driven study of electric field in the detector, that can be used to tune the simulation and estimate systematic uncertainties (in progress)

Electron Diffusion from ICARUS data



- Take average waveform at anode and cathode for all selected tracks
  - Anode: use to <u>tune electronics and wire field response simulation</u>
  - Average cathode waveform as **probe of diffusion**
    - Simulation folds in both longitudinal (D_L)and transverse diffusion (D_T)
    - Reasonable agreement between data and simulation
  - Must first correct for field response bias before making precise measurement (in progress)
  - Use extracted diffusion constants to <u>tune SBND/ICARUS simulation</u>

Improving Detector Simulation with data availability

Detector Effect	Current Status	Planned Updates
TPC Noise	noise spectra from data in use	ICARUS: currently tuning w/ data
TPC Elec. Response	full simulation in place	ICARUS: tune gain/shape w/ data
Electric Field Response	2D simulation, 1D deconvolution	2D deconvolution (early next year)
✓ Diffusion	full simulation in place	currently tuning w/ ICARUS data
✓ Space Charge Effects	full simulation in place	ICARUS: currently tuning w/ data
Electron Lifetime	full simulation in place	ICARUS: tune after purity improves
✓ e-Drift Velocity	full simulation in place	currently tuning w/ ICARUS data
e-Recombination	data-driven models in use	new model available soon (ArNEST)
Light Production	full simulation in place	charge/light anti-correlation to be included (ArNEST)
Light Propagation	full simulation in place	ICARUS: currently tuning w/ data

✓ **First results shown**

Emphasis on tuning simulation w/ **first ICARUS data**

Detector Effects in Sensitivity Analysis

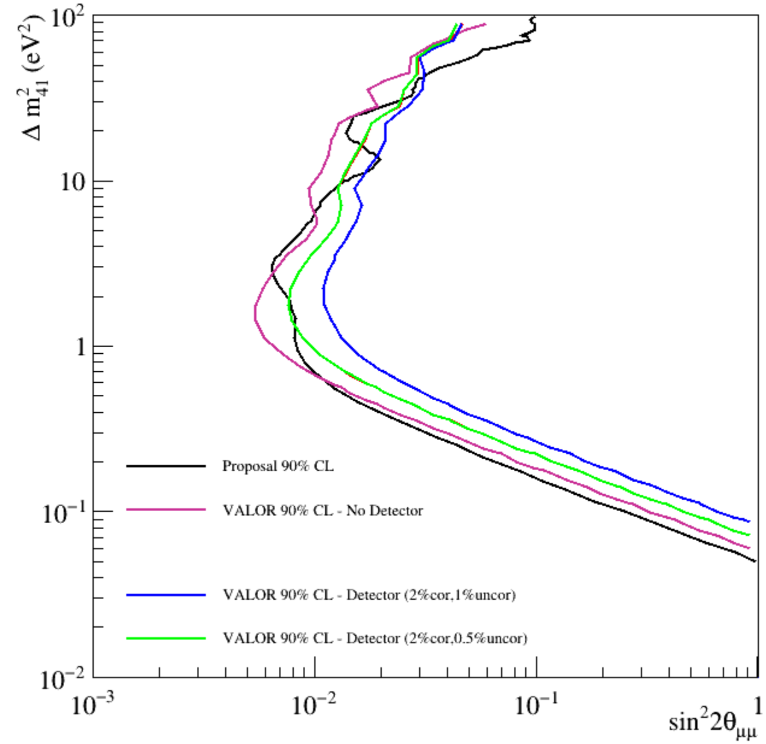
- Currently, detector effects are not included in standard SBN sensitivity calculations
- **Evaluation of detector effects will be based on data**. Strategy:
  - Tuning of detector MCs (first data are available!)
  - Correction of biases between detectors (need SBND data!)
  - Evaluation of residual uncertainties

- In parallel, a discussion between several SBN Analysis groups, informs the **development of an early scheme for incorporating residual uncertainties into oscillation fits**

Current method, under test:

Efficiency/normalization effects for several kinematic bins for all distinct event types (background and signal) contributing to oscillation analysis samples

Muon-neutrino disappearance sensitivity for different detector error assignments
(just for illustration purpose)



Summary

Making progress toward
SBN oscillation physics sensitivity results
based on the full event simulation and reconstruction.

Measurements from SBN data
begin to be used to refine and tune the simulations
and address detector systematics.

SBN tools for neutrino event selection and reconstruction
and for background rejection
will be soon validated with real data!

Overflow

SBN Analysis Working Group Organizational Chart

SBN Analysis Working Group

Convener: Daniele Gibin
Convener: Ornella Palamara

Neutrino Event Generators

(Simulation and tuning on SBN data)
Convener: Jarek Nowak
Convener: Marco Roda

TPC reconstruction

(Clustering, vertexing, track and shower reconstruction)
Convener: Yun-Tse Tsai, Tracy Usher
Convener: Dom Brailsford

TPC Simulation and Calibration

(Consistent hit/charge reconstruction, dQ/dx->dE/dx, lifetime and space charge measurements and cross-validation)
Convener: Filippo Varanini
Convener: Mike Mooney

Light Detection Systems Simulation & Reconstruction

(LDS signals, timing, LDS-TPC matching)
Convener: Alessandro Menegolli
Convener: Diego Garcia Gamez

CRT Simulation & Reconstruction

(CRT signals, timing, CRT-TPC matching)
Convener: Umut Kose
Convener: Ivan Lepetic

Event Selection, Cosmic ID and Rejection

(Triggers, PID, consistent combination of TPC, CRT and LDS, cross-validation on exclusive channels)
Convener: Christian Farnese
Convener: Michelle Stancari

Systematics and Oscillation Sensitivities

(Consistent evaluation of flux, cross-sections and detector systematics, tools to evaluate oscillation sensitivities)
Convener: Daniele Gibin
Convener: Costas Andreopoulos

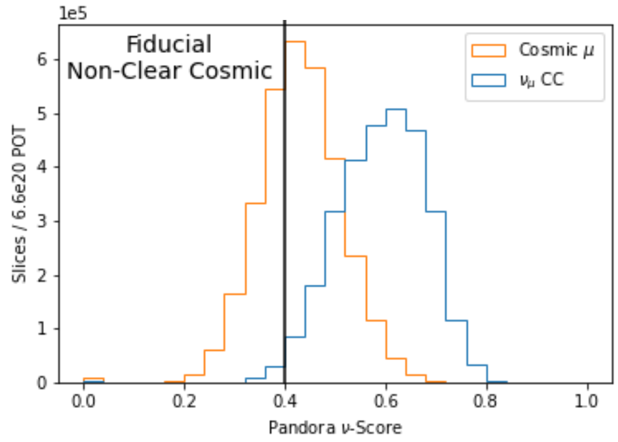
SBN Analysis Infrastructure Working Group

Main focus topics

- **Release Management**
  - Maintain high-quality releases of SBN-specific software packages
- **Production and Resource Management**
  - Work with Fermilab Scientific Computing Division and SBN collaboration to maintain production workflows, and manage access to data
- **Simulation Software Management**
  - Develop infrastructure to support data-driven detector simulations and maintain consistent configuration
- **Analysis Software Management**
  - Develop infrastructure to process & analyze data & simulation in a consistent way
- **Beam and "Dirt" Simulation**
  - Develop and improve beamline simulations and uncertainties

Slicing in pandora

- Pandora removes **'obvious' cosmic rays** during reconstruction, but 'less obvious' cosmic rays remain, which must be handled
- After running **2D** and **3D** hit reconstruction, Pandora divides 3D hits into groups, using proximity and direction-based assessments. These groups are called **"slices"**
- A slice should contain a **single neutrino interaction** (and all child particles) or a **cosmic ray** (and any associated EM activity)
- The 2D hits in each slice are then reconstructed via two separate algorithm pathways (cosmic and neutrino), creating **two reconstruction outcomes**
- Information from the two reconstruction outcomes are used to score how cosmic-like/neutrino-like the slice is. The **slice ID score** is calculated from a Booster Decision Tree, which assesses:
  - Neutrino vertex position
  - Vertex activity
  - Geometry of the overall reconstruction in the slice
  - Geometry of the longest track in the slice



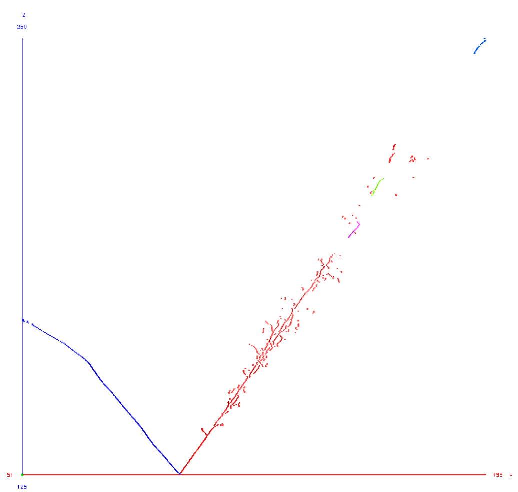
TPC Performance – Recent improvements

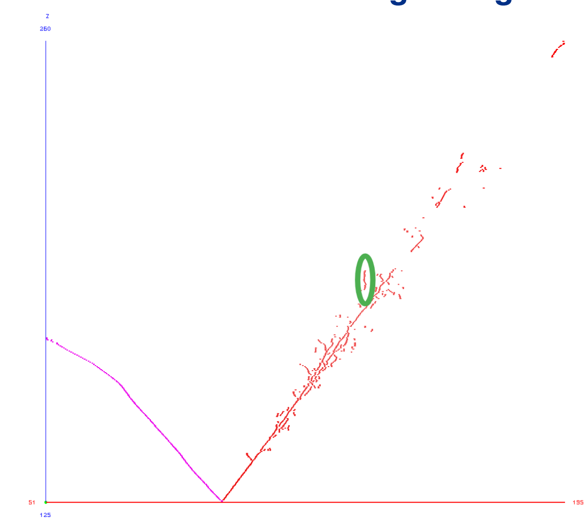
Shower 'mop up'

After Pandora shower classification

Iterative grownING of showers by merging secondary reconstructed showers into a parent shower, using 2D and 3D information

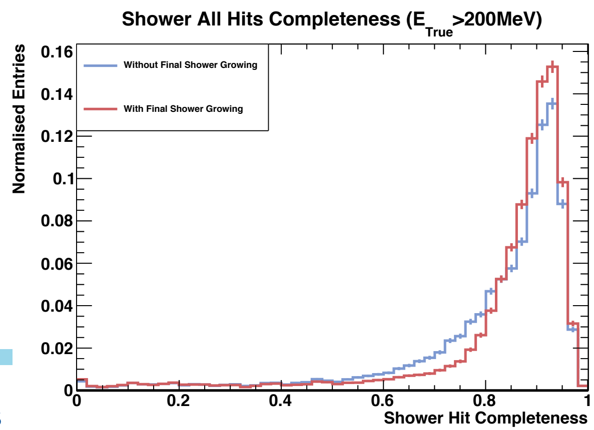
With shower growing

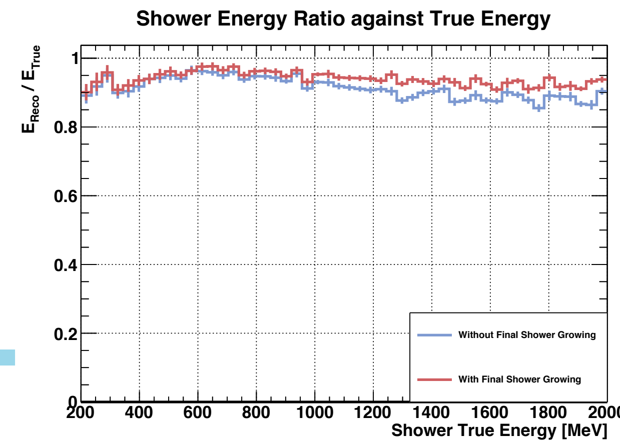




Colors correspond to individual reconstructed object

The highlighted cluster was previously absent from —any— reconstructed object



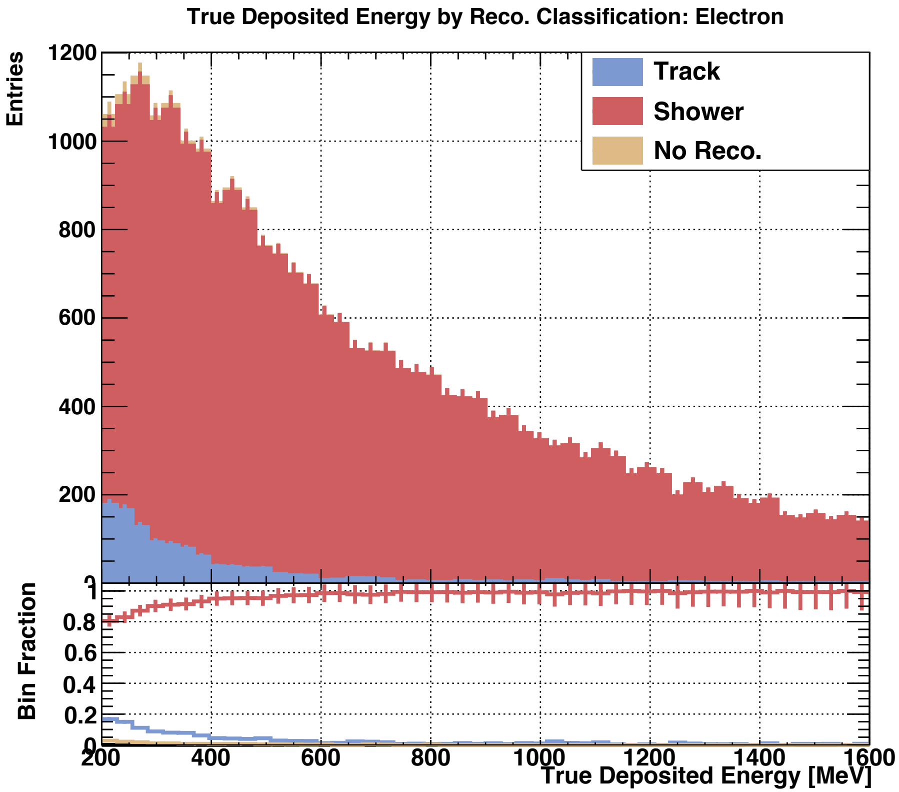


TPC Performances

Track-Shower discrimination

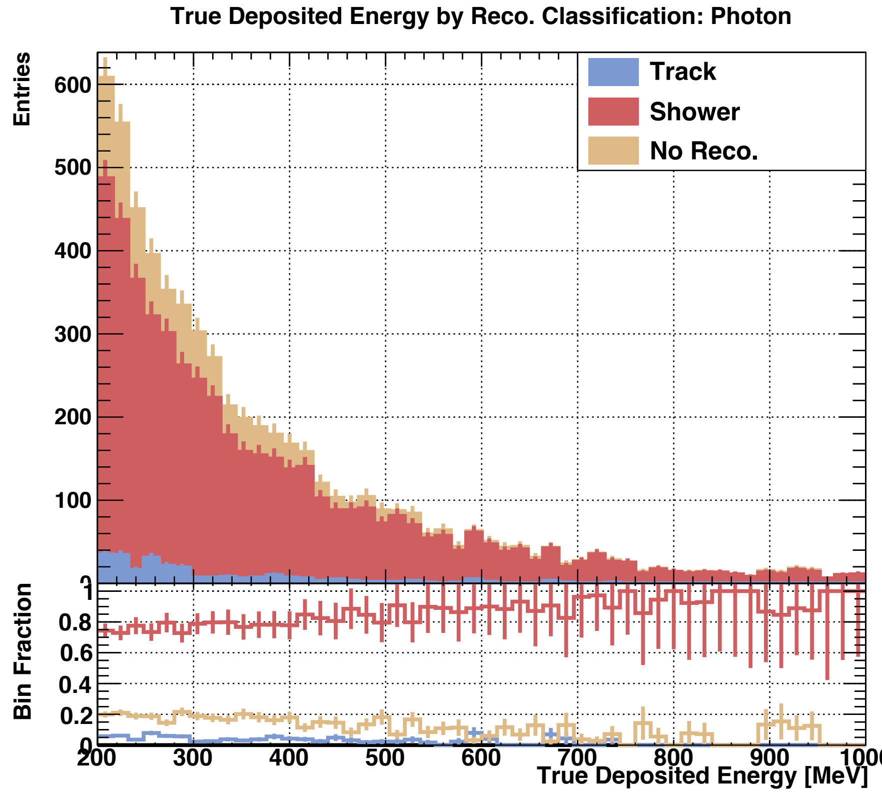
Current performances of Pandora's track/shower classification algorithm
(after optimization of the BDT classifier algorithm)

SBND, ν_e BNB



Electrons

> 200 MeV deposited energy



Photons

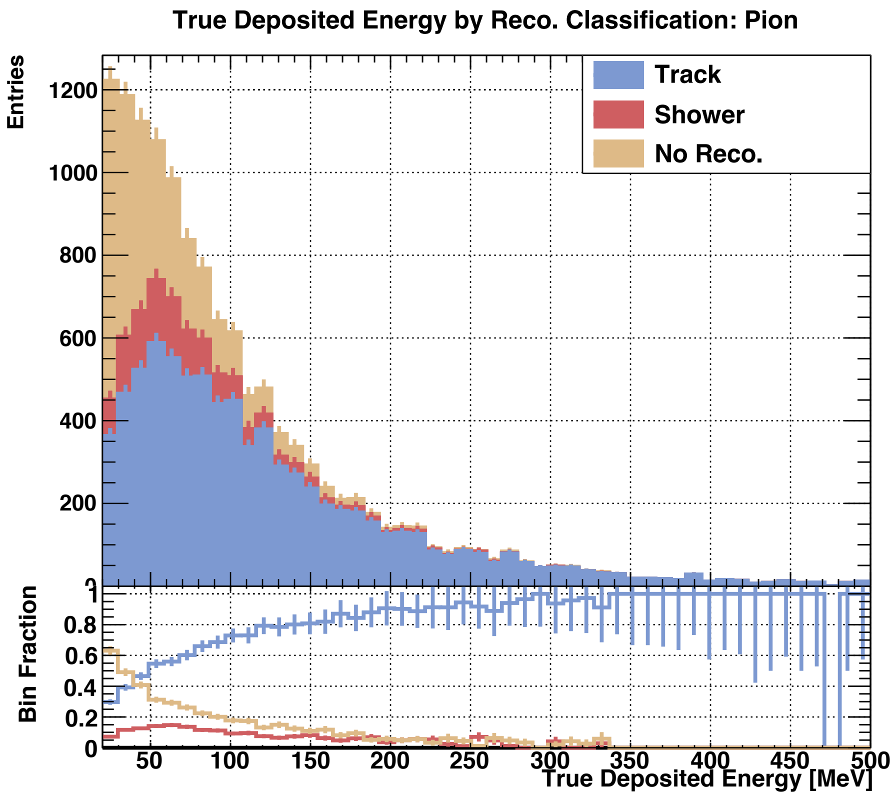
> 200 MeV deposited energy

TPC Performances

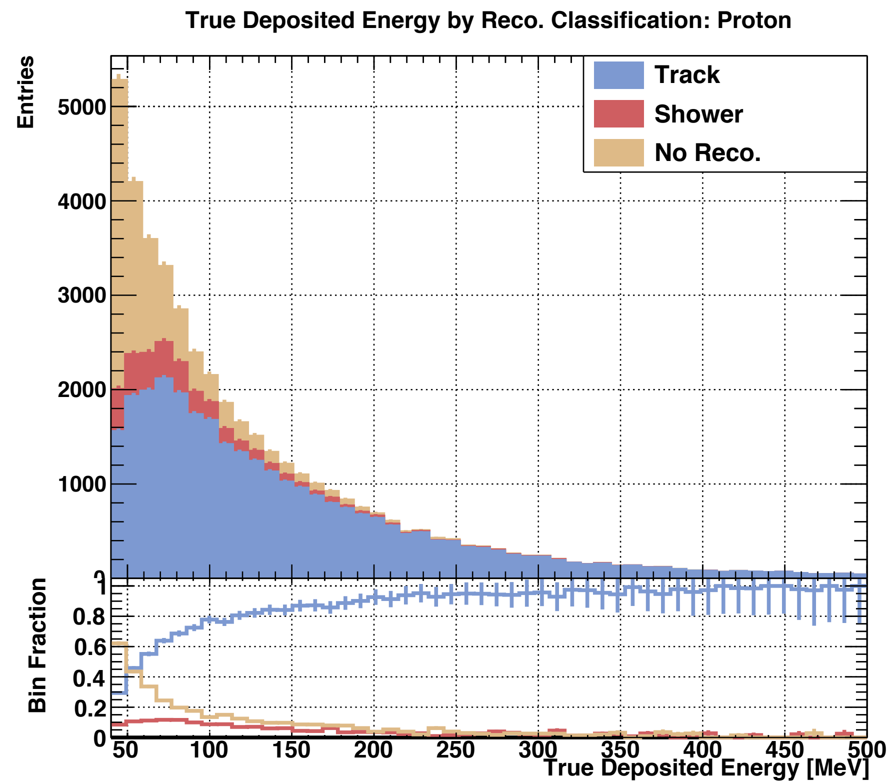
Track-Shower discrimination

Current performances of Pandora's track/shower classification algorithm
(after optimization of the BDT classifier algorithm)

SBND, ν_e BNB

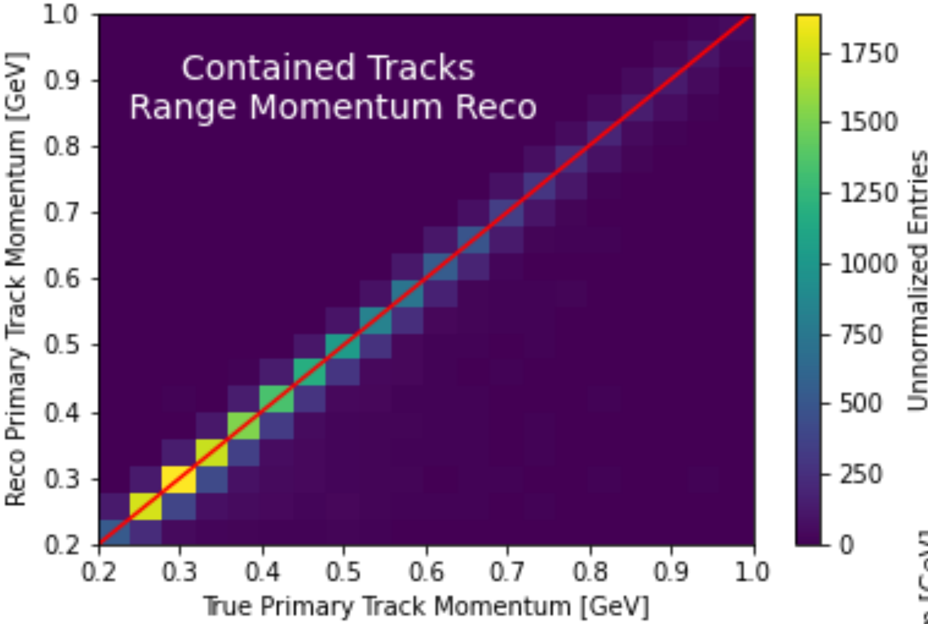


Charged Pions
> 20 MeV deposited energy



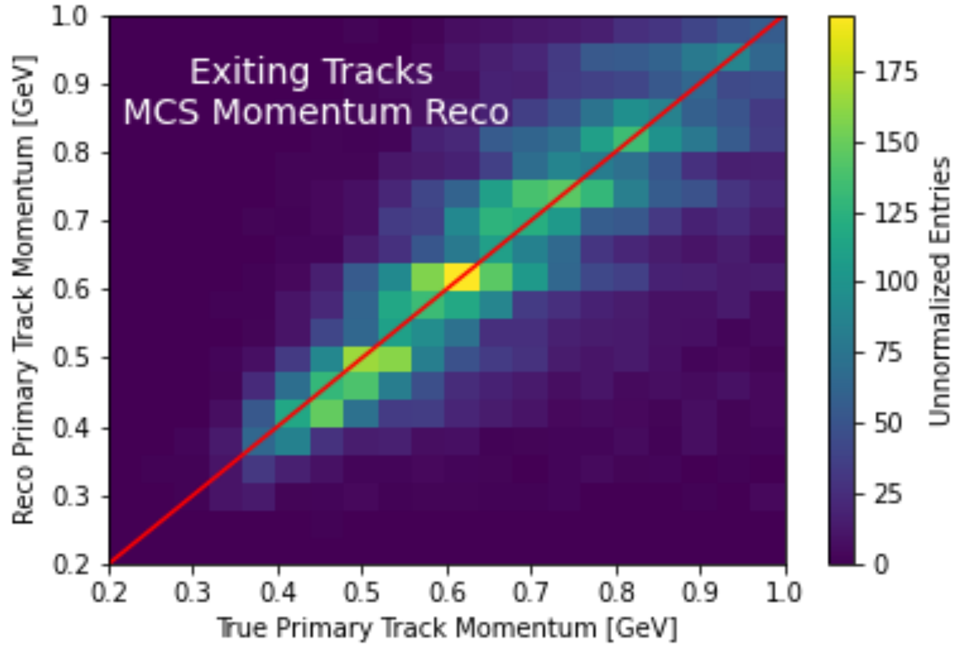
Charged Protons
> 40 MeV deposited energy

ν_μ Events – muon reconstruction



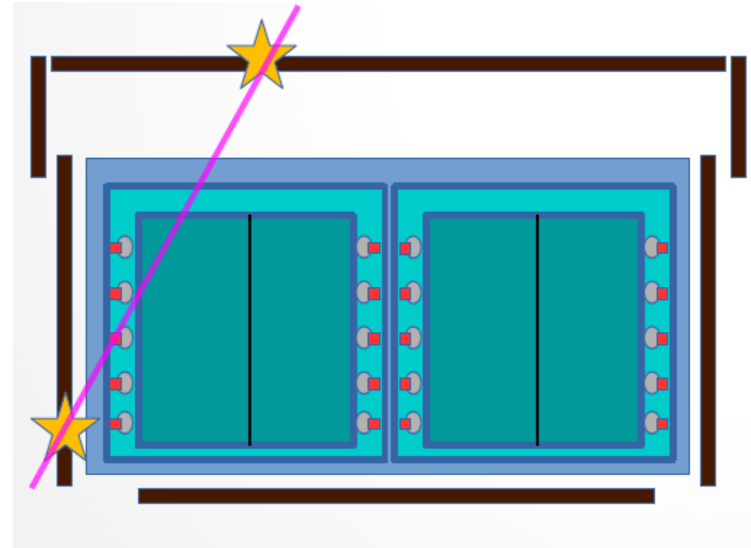
Momentum from range for contained muon, track >50 cm

Momentum from Multiple Coulomb Scattering for exiting muon, track >100 cm



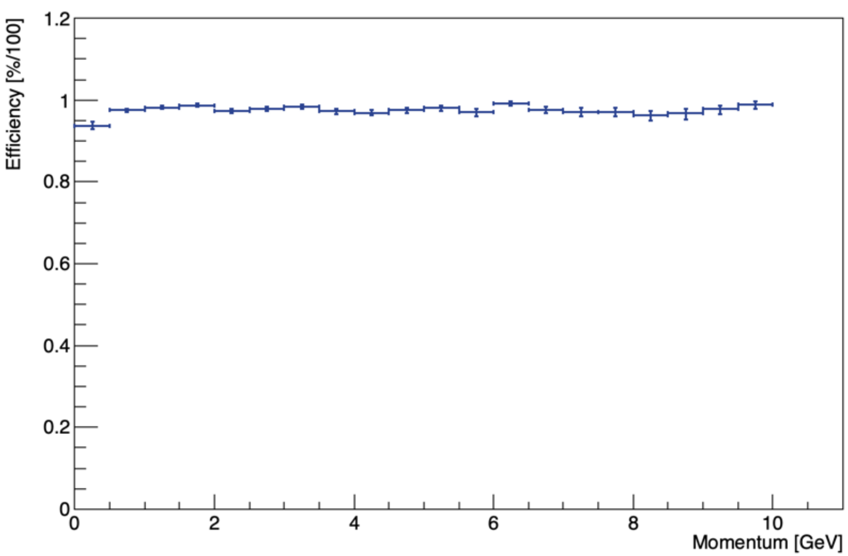
CRT performance

- Hit: activity above threshold on two adjacent, perpendicular modules
- Track: hits on two planes (on different sides of the TPC)
- Both are working efficiently

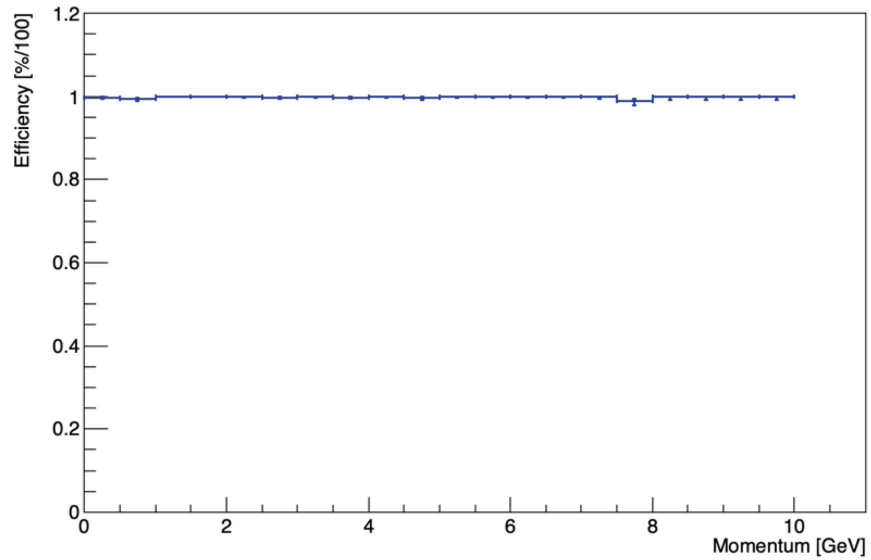


Cosmic muons

SBND



Hit Reconstruction Efficiency

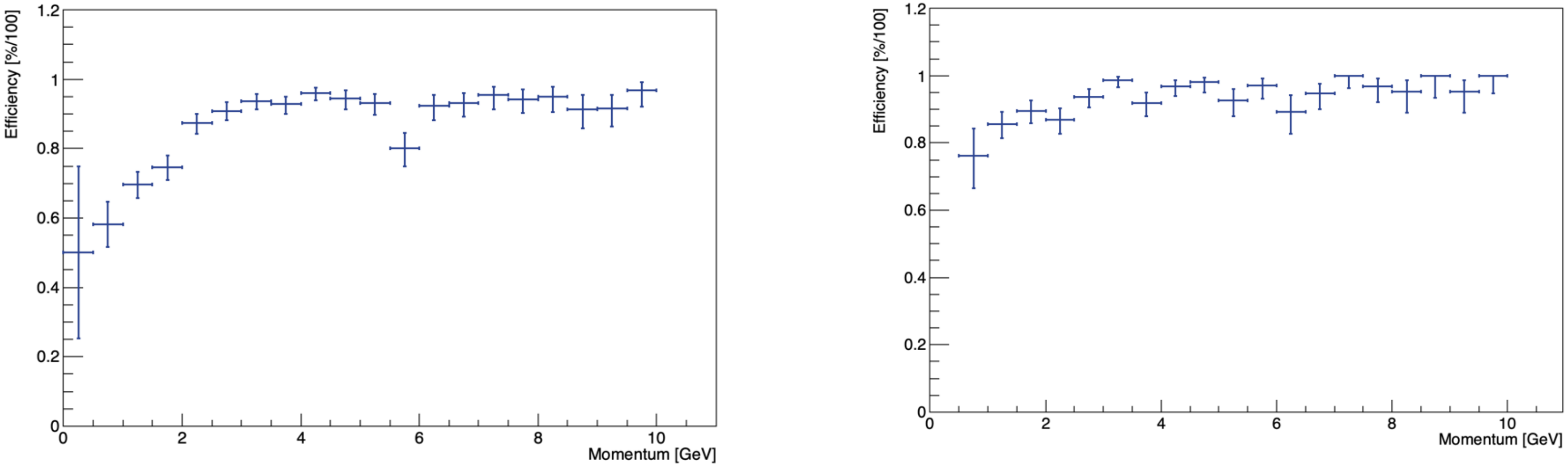


Track Reconstruction Efficiency

CRT-TPC Hit and Track Matching

- Hit matching: Is there a hit in the CRT that corresponds to a TPC track?
- Track matching: Is there a CRT track that matches a TPC track?
- Both are working efficiently

Cosmic muons
SBND



Hit Matching Efficiency

Track Matching Efficiency

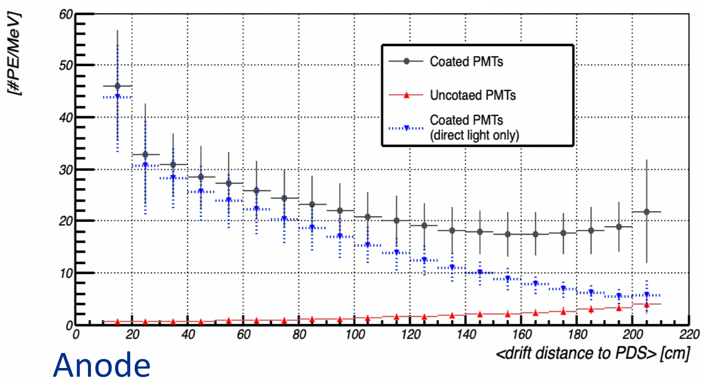
Photo Detection Systems Performance

SBND

ν_e events (no cosmics)

Reconstructed Flashes

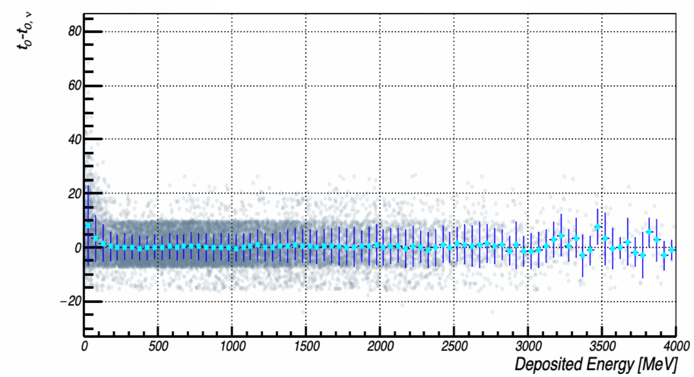
Light Yield



Anode (PDS)

Cathode

Time resolution



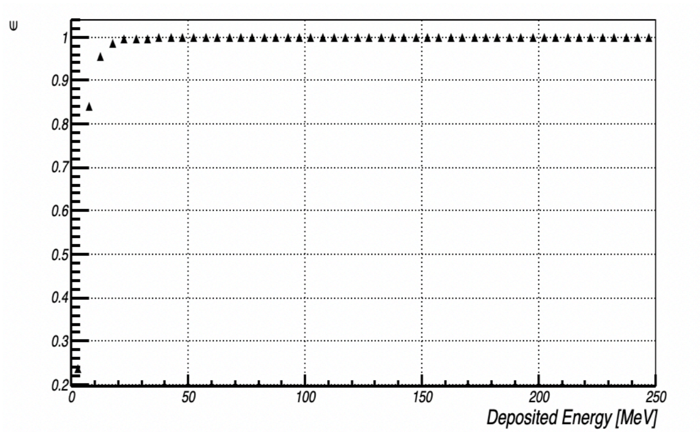
For all drift distances and deposited energies

Bias: 0.65 ns

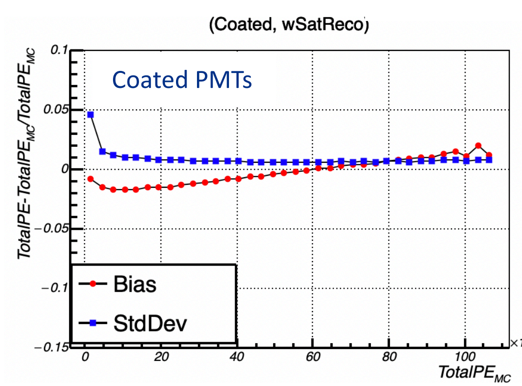
σ: 5.42 ns

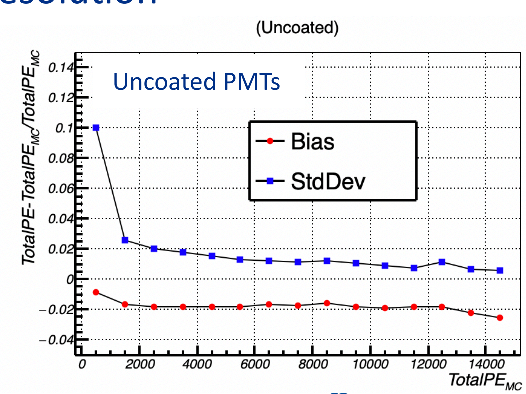
Drift distance can be estimate using exclusively the light signals with a resolution ~8cm

Flash reconstruction efficiency



Total PE resolution



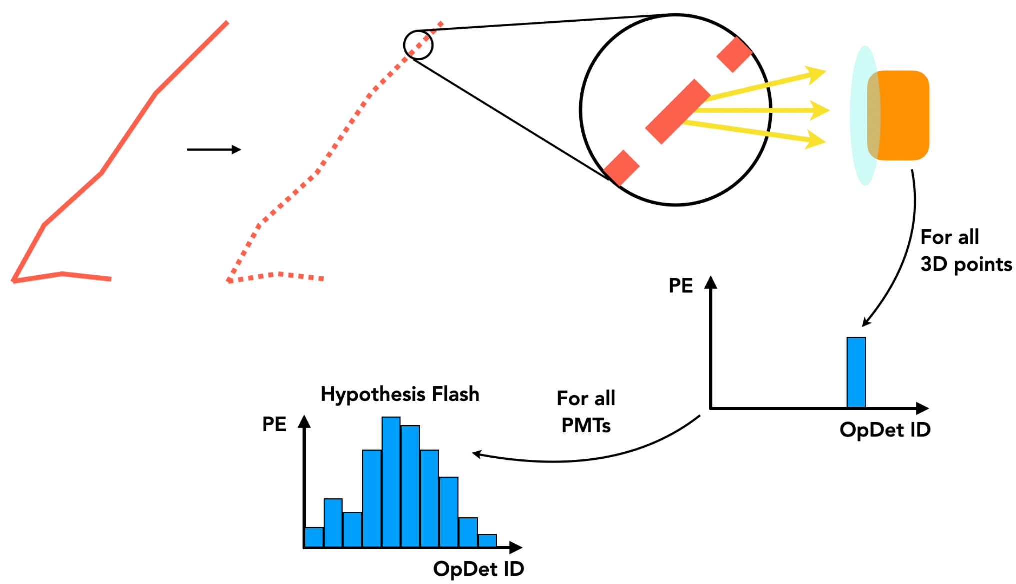


Charge-Light matching

currently being integrated/developed

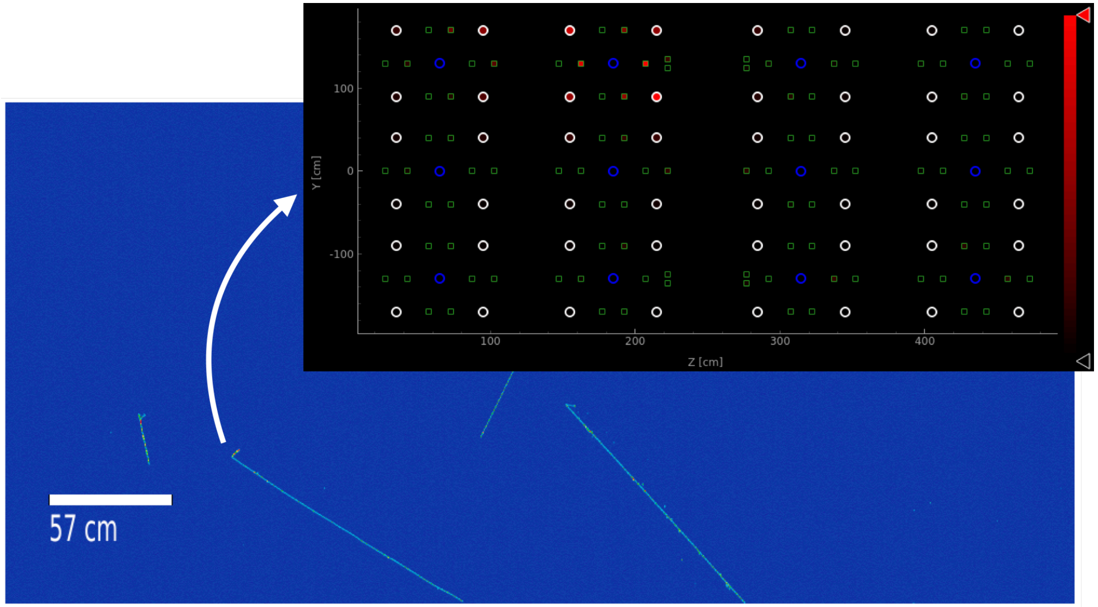
- Flash Matching goals
  - Identify a **neutrino interaction** from cosmic backgrounds
  - Provide $\mathbf{T_0}$ for each TPC interaction
- Originally developed for MicroBooNE
- Ingredients for flash matching:
  - Reconstructed Flashes
  - TPC Pandora Reconstructed Objects (cosmic muon, final state particles from ν interaction…)

Step 1
From a TPC object, construct a "**flash hypothesis**": the flash the we would expect to see from such TPC object.
Step 2
Compare the flash hypothesis with all the reconstructed flashes to find the best match.

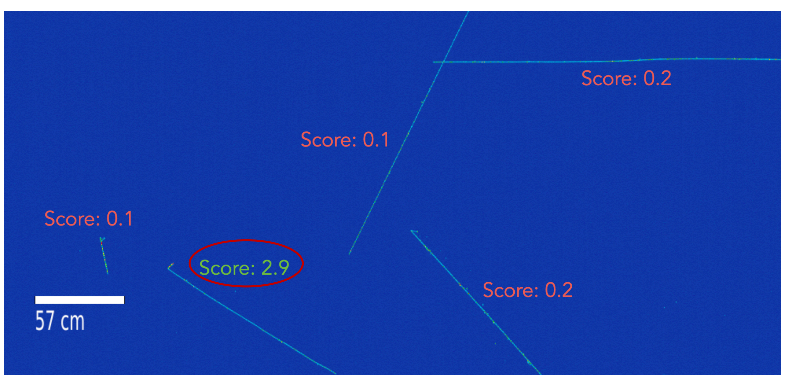


Charge-Light matching

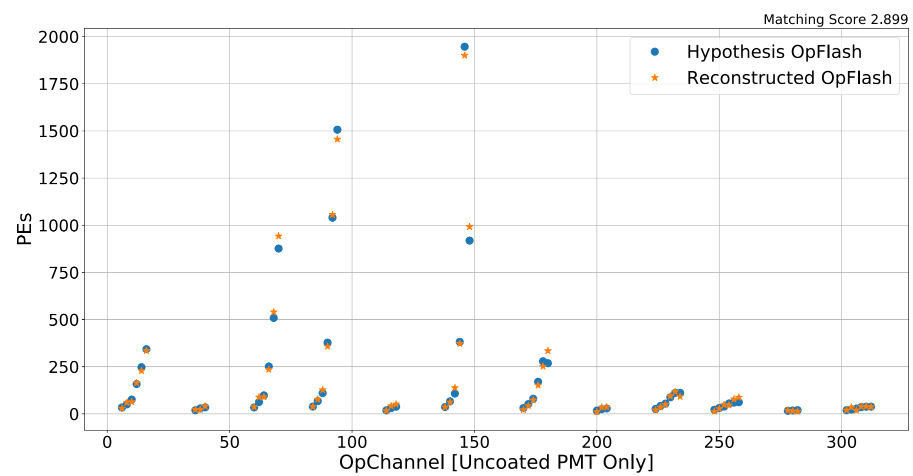
currently being integrated/developed



Showing the reconstructed flash from the neutrino interaction



Showing the flash matching scores for every Slice

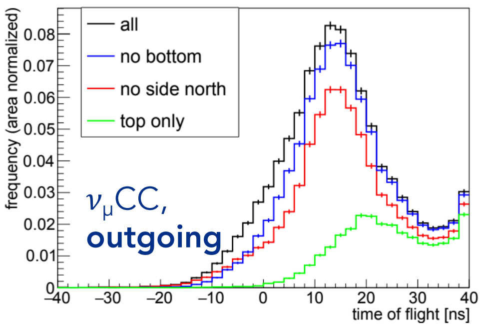


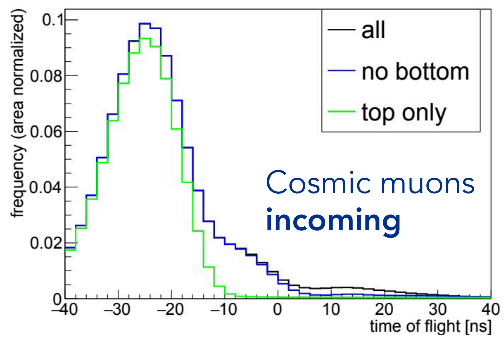
Alternative Rejection of in-time Cosmic Muon by Time-of-Flight*

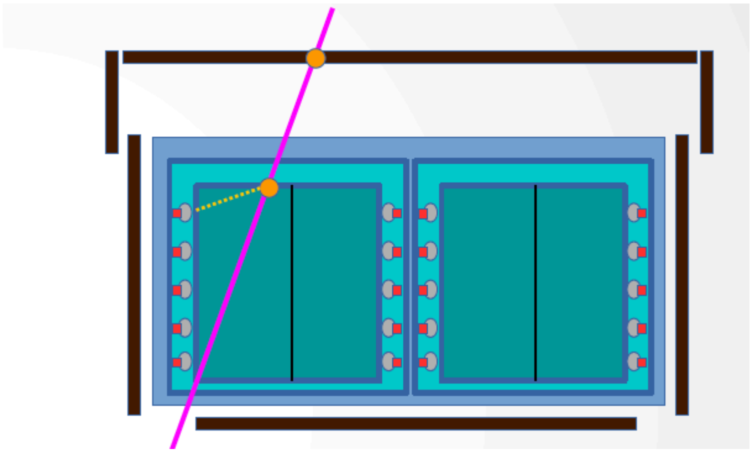
- Use the difference between CRT and PMT hit times to reject cosmic muons by distinguishing incoming/outgoing tracks with

  $TOF=t_{CRT}-t_{PMT}$ >0 outgoing <0 incoming

ICARUS, simulation. Events with > one CRT hit



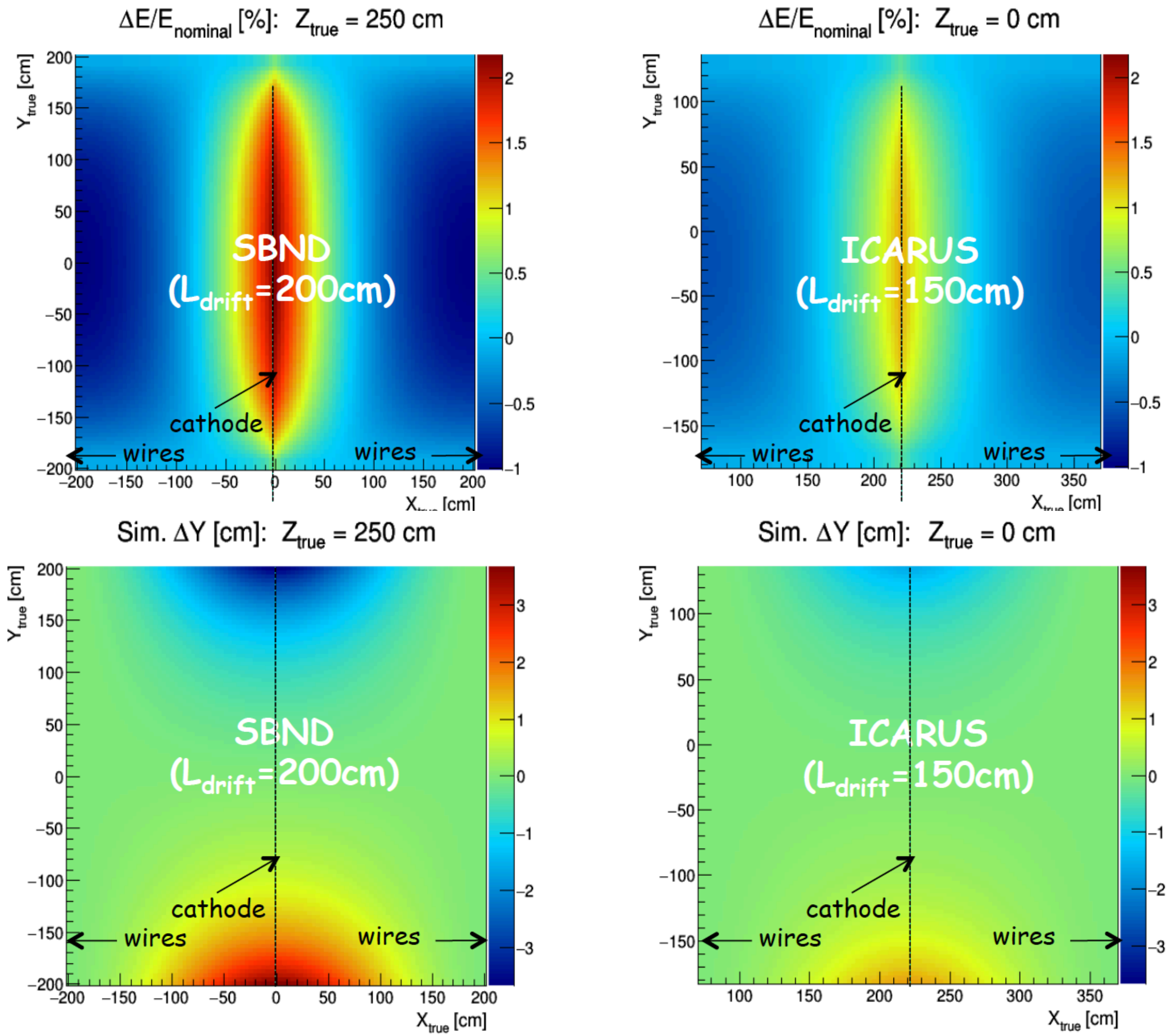




- **More than 95% of the incoming cosmic muons** can be rejected, reducing the inefficiency for neutrinos to a few percent level also for ν_μ CC events
- The method (currently under study) requires an **adequate CRT/PMT time resolution and synchronization.**

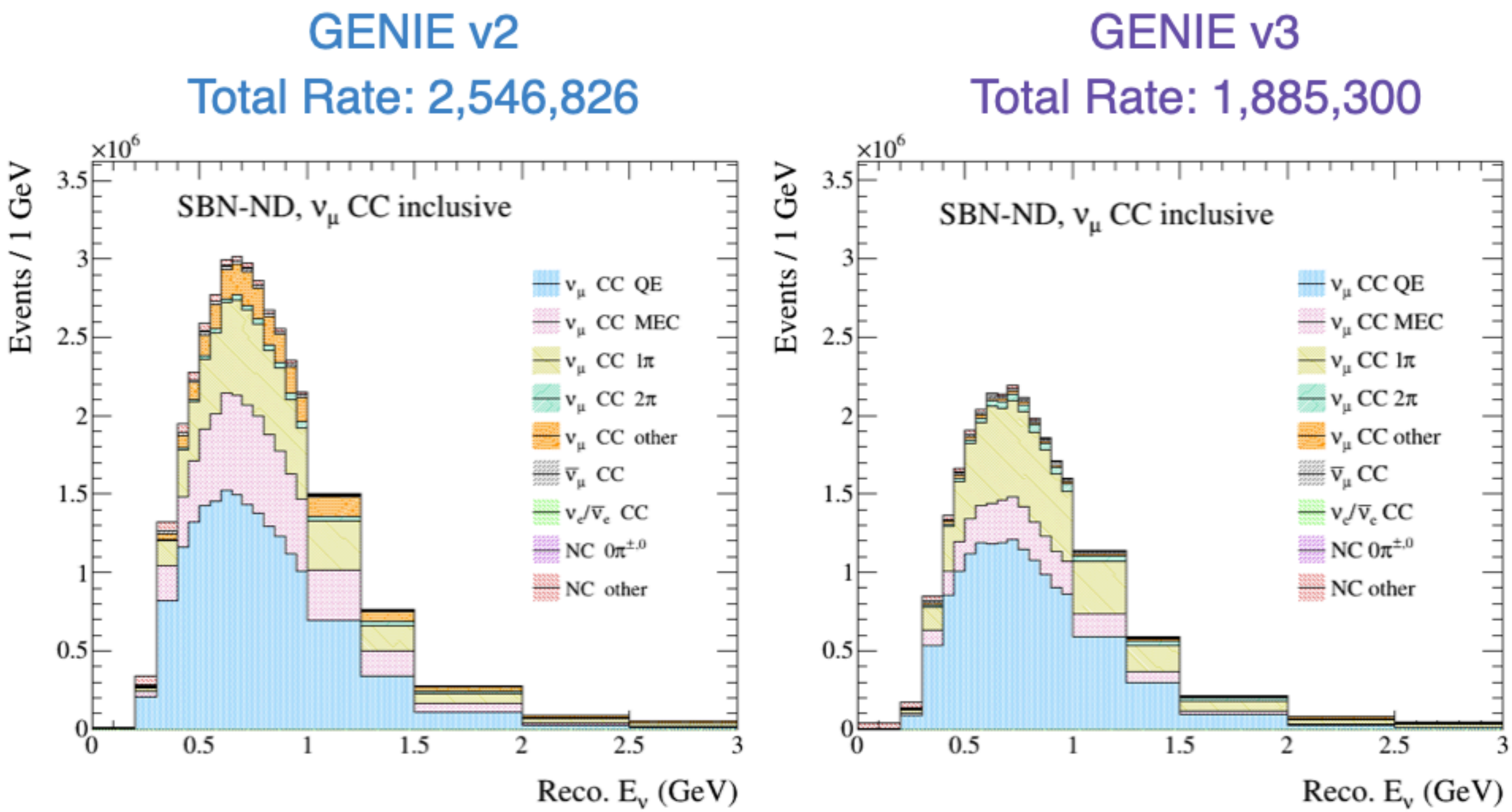
*Not yet exploited in the current analysis

Space Charge Effects simulation



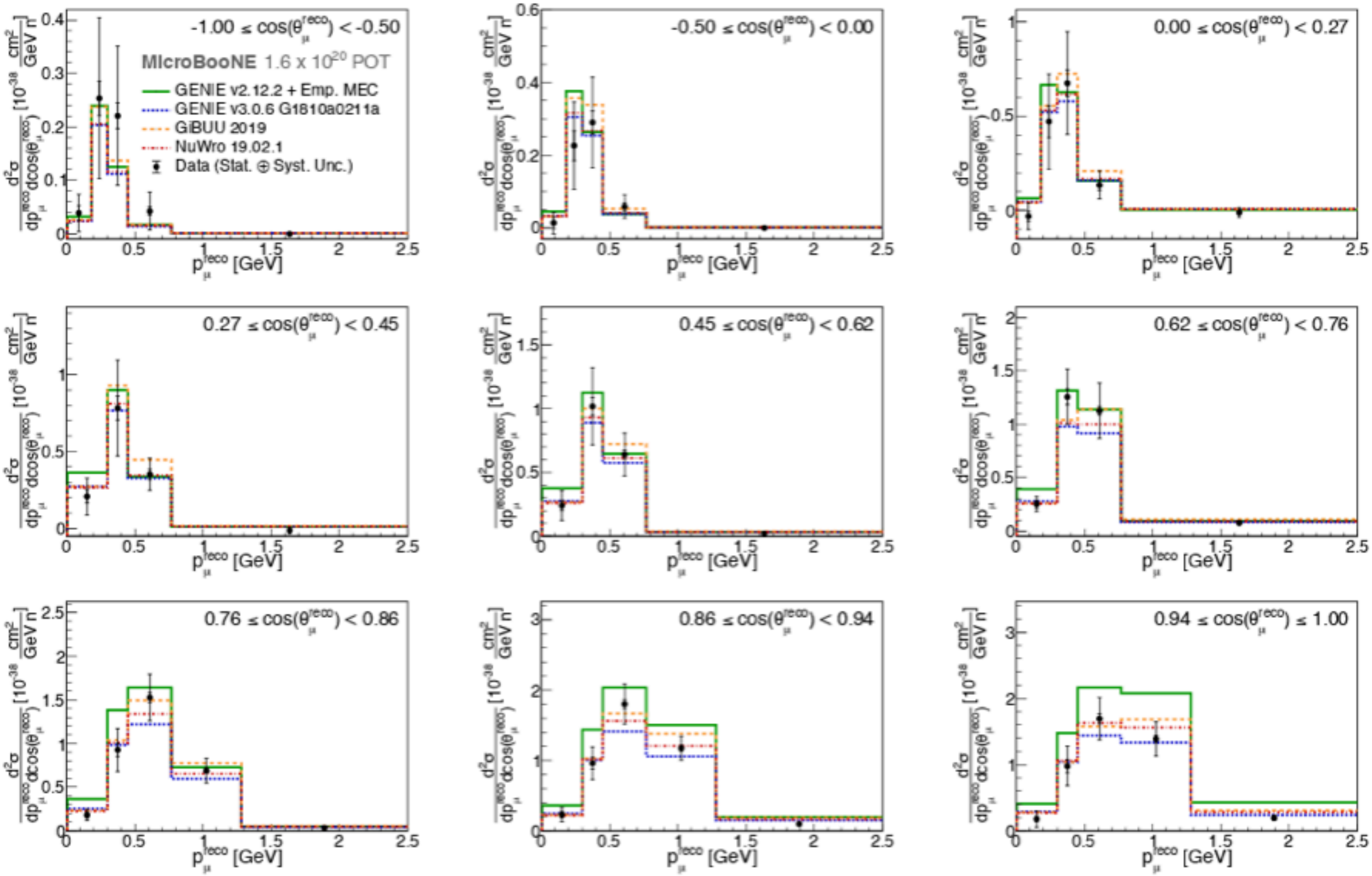
ν_μ CC Inclusive Event Rate Breakdown

GENIE v2.12 “Default+MEC” tune vs GENIE v3.0.6 G18_10a_02_11a tune



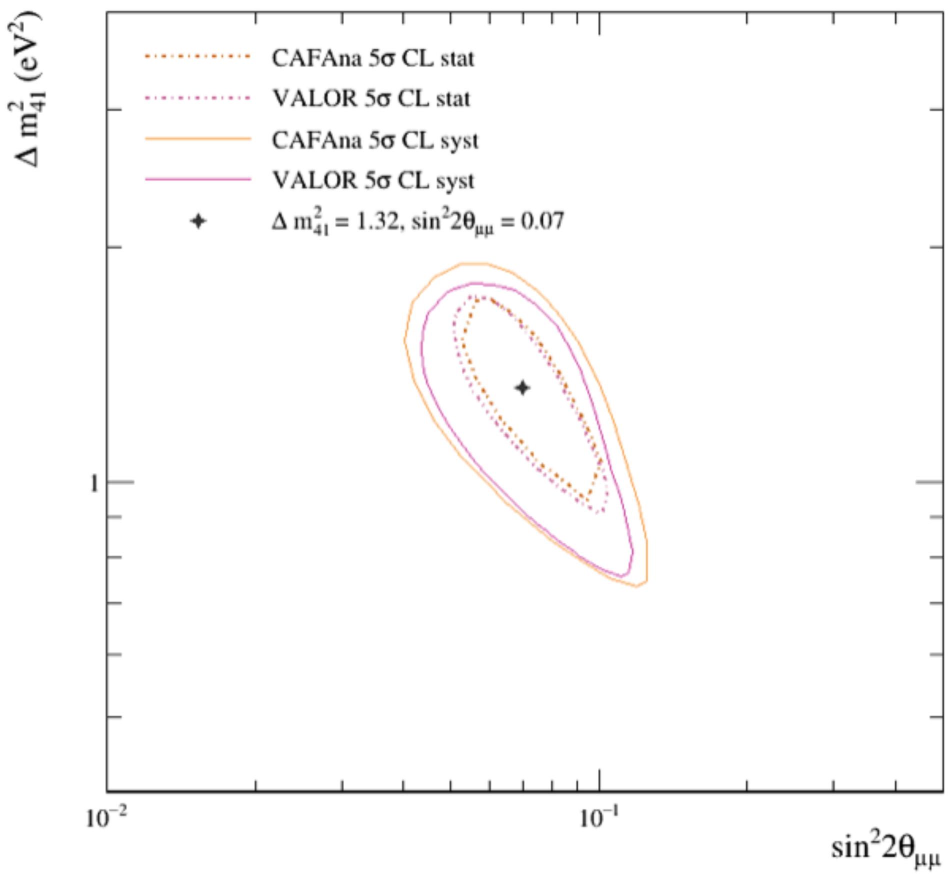
Most-notable difference is the 25% total rate reduction going from v2 to v3

GENIE v2.12 “Default+MEC” tune vs GENIE v3.0.6 G18_10a_02_11a tune



GENIE v3.0.6 G18_10a_02_11a tune shows much better agreement with uB ν_μ CC Inclusive data

Fitter comparisons with injected muon-neutrino disappearance signal



Collaboration with SciDAC: "Accelerating Discovery"

SBN collaborators have been **working with SciDAC** (Scientific Discovery through Advanced Computing) program **to port 3+N fitting software** (SBNfit) onto **high-performance-computing** (HPC) infrastructure at NERSC.

- Significant speedup on a single core has been achieved
- Plus access to HPC cluster (Cori)

FERMILAB-PUB-20-069-SCD

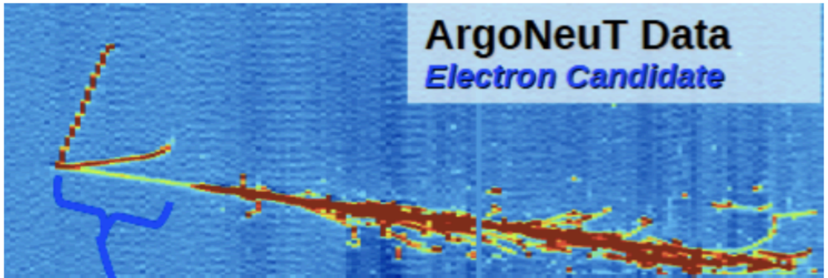
	$N_{\text{univ}} = 10^4\ (3\sigma)$	$N_{\text{univ}} = 10^8\ (5\sigma)$
Cori phase 1 (Haswell)	7.2×10^5	7.2×10^3
Cori phase 2 (KNL)	1.2×10^6	1.2×10^4

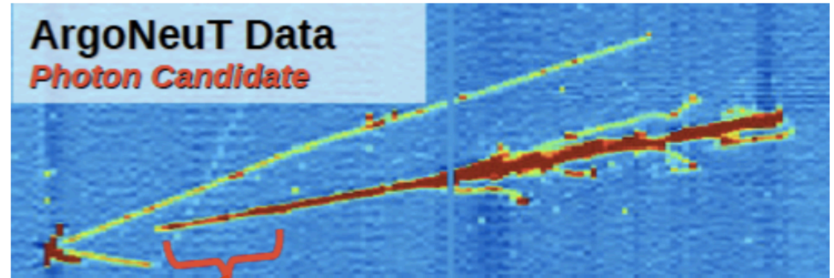
Table 4: Upper boundaries on grid sizes that can be processed when running *a full day* on all of Cori phase 1/2.

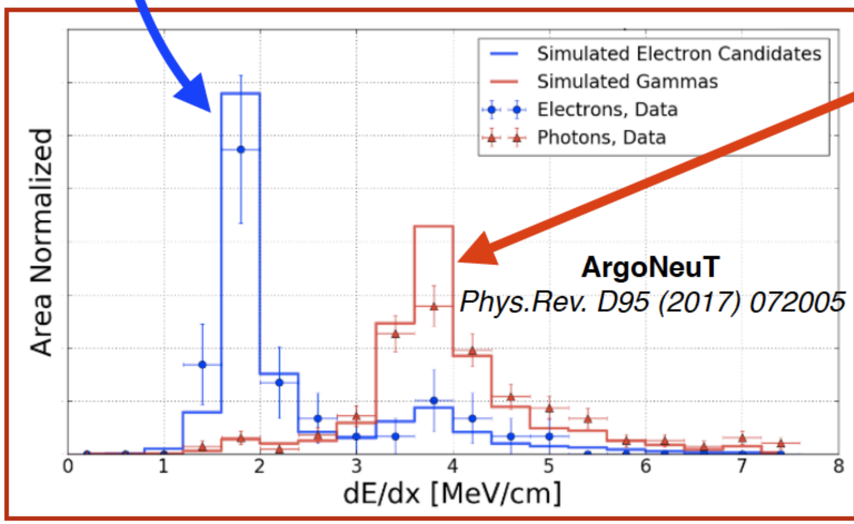
In ~1 day, grid sizes of 10^6 and 10^4 can be probed at 3σ and 5σ, respectively.

This enables **time-efficient** and **quantitatively robust scanning of multi-dimensional parameter space** of new physics models to high significance!

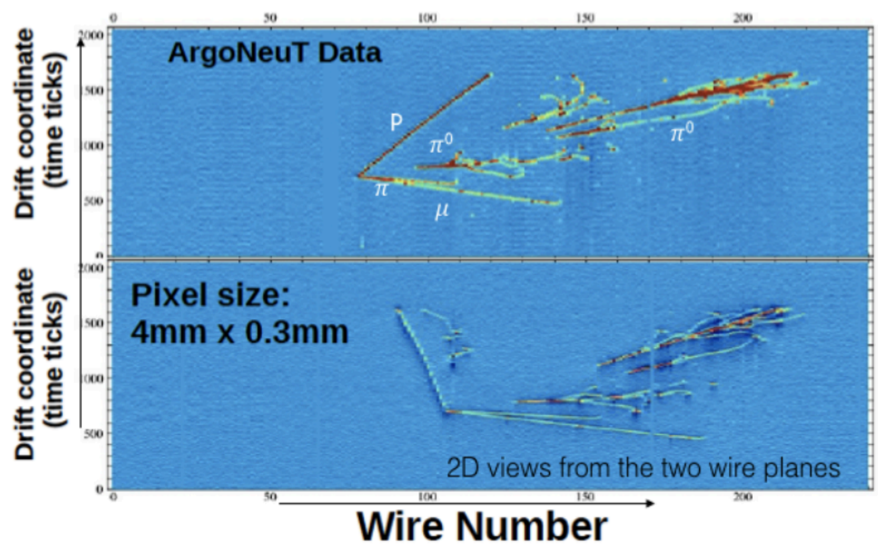
Electron-γ discrimination in LAr





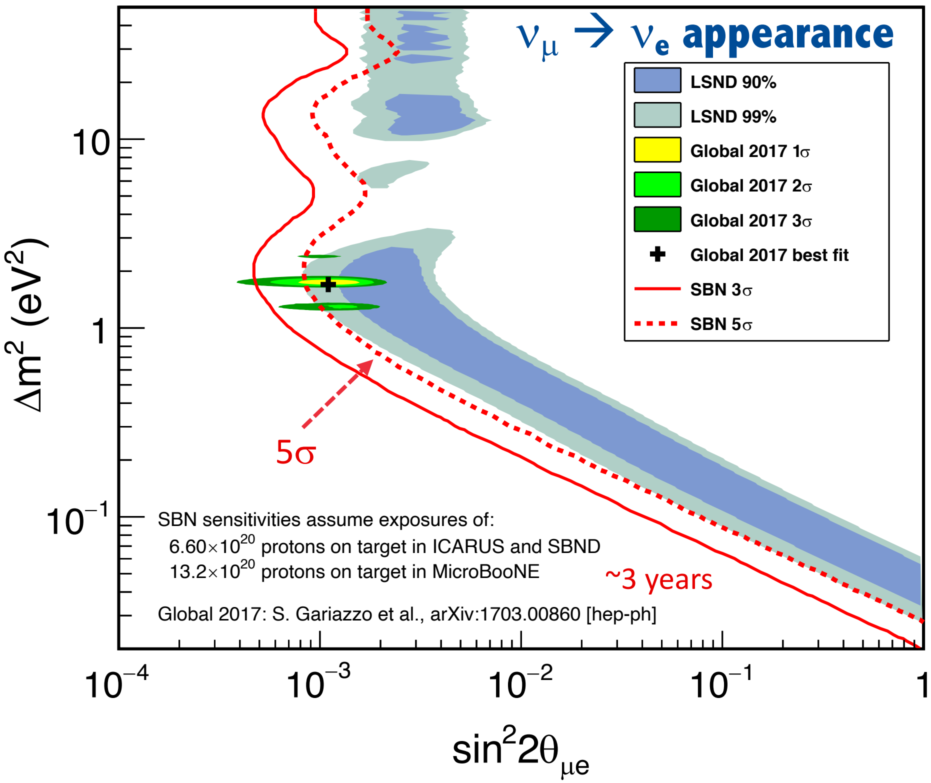


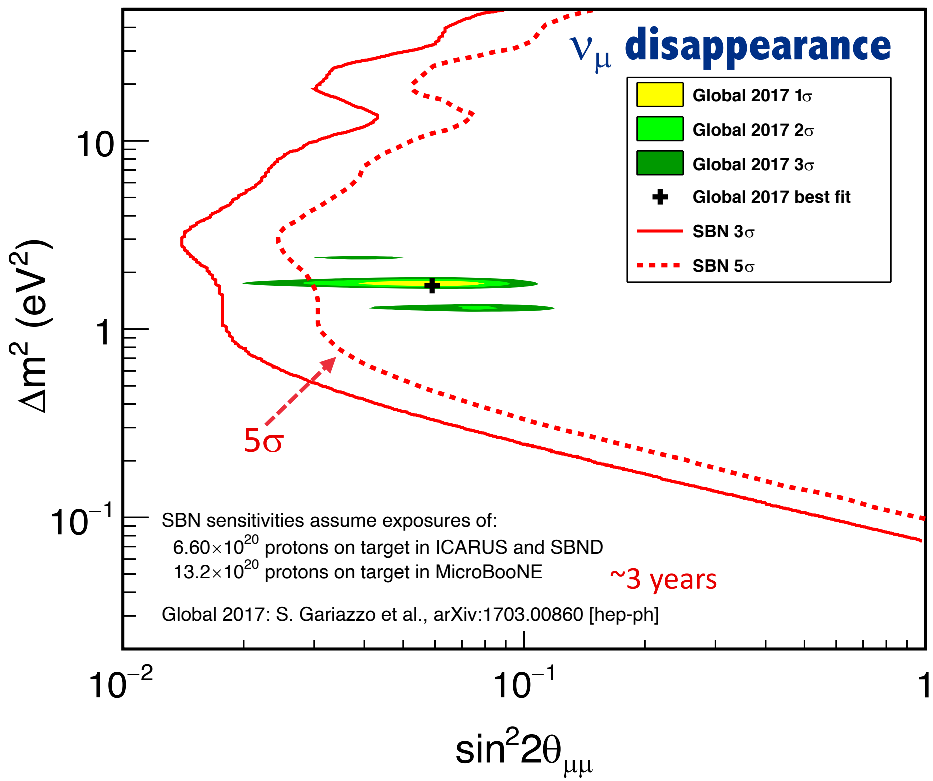
Analyzing topology and dE/dx



The SBN Oscillation Program

Sensitivities to oscillations ONLY enabled with near and far detectors





Combination of the SBN detectors enables 5σ coverage of the 99% C.L. allowed region of the original LSND signal and the global best fit values.

ν_e appearance cannot occur without ν_μ disappearance.

This is a critical aspect of verifying an oscillation hypothesis.