Status of Oscillations at SBN

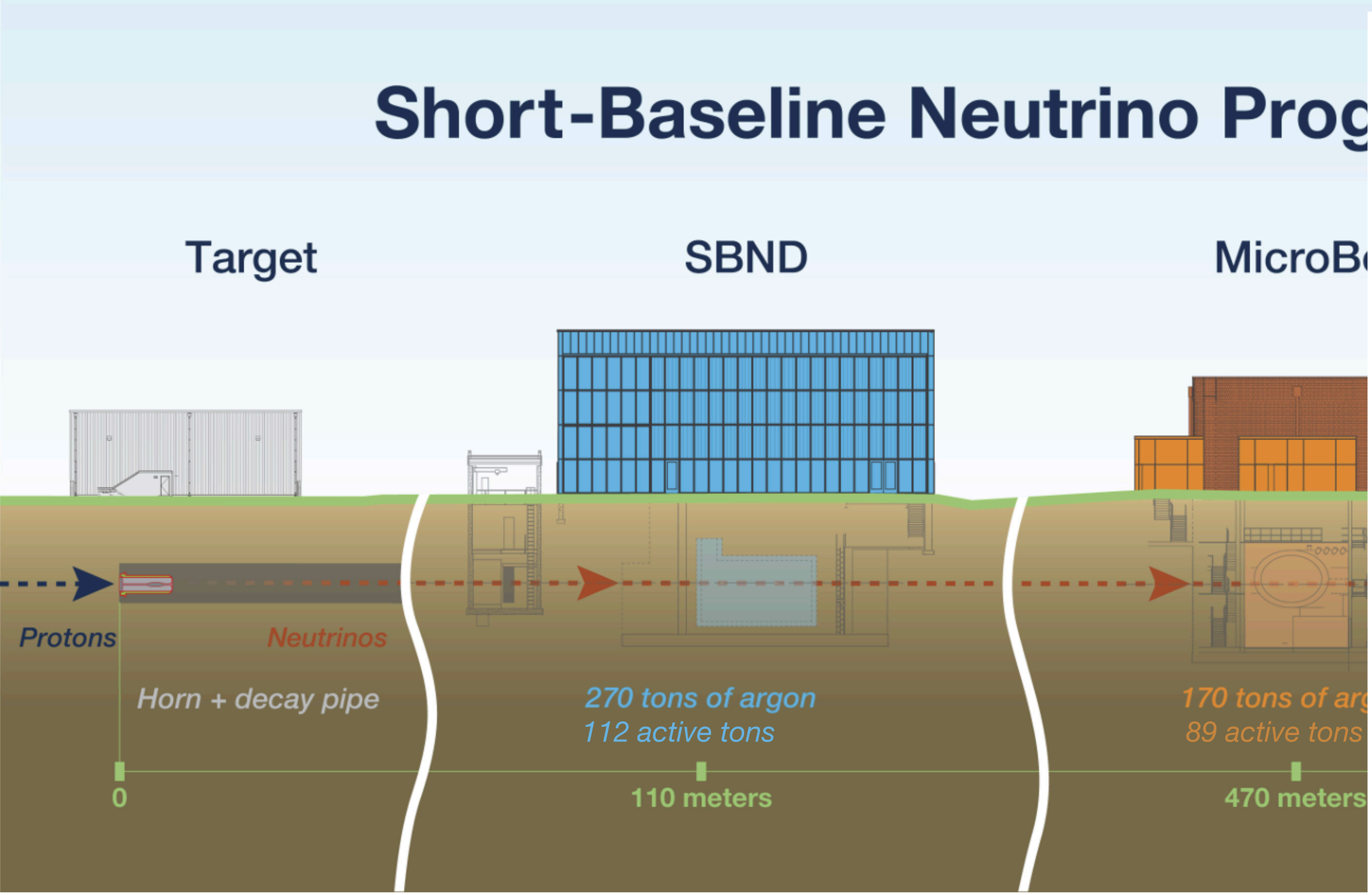
Ibrahim Safa for the SBND and ICARUS collaborations

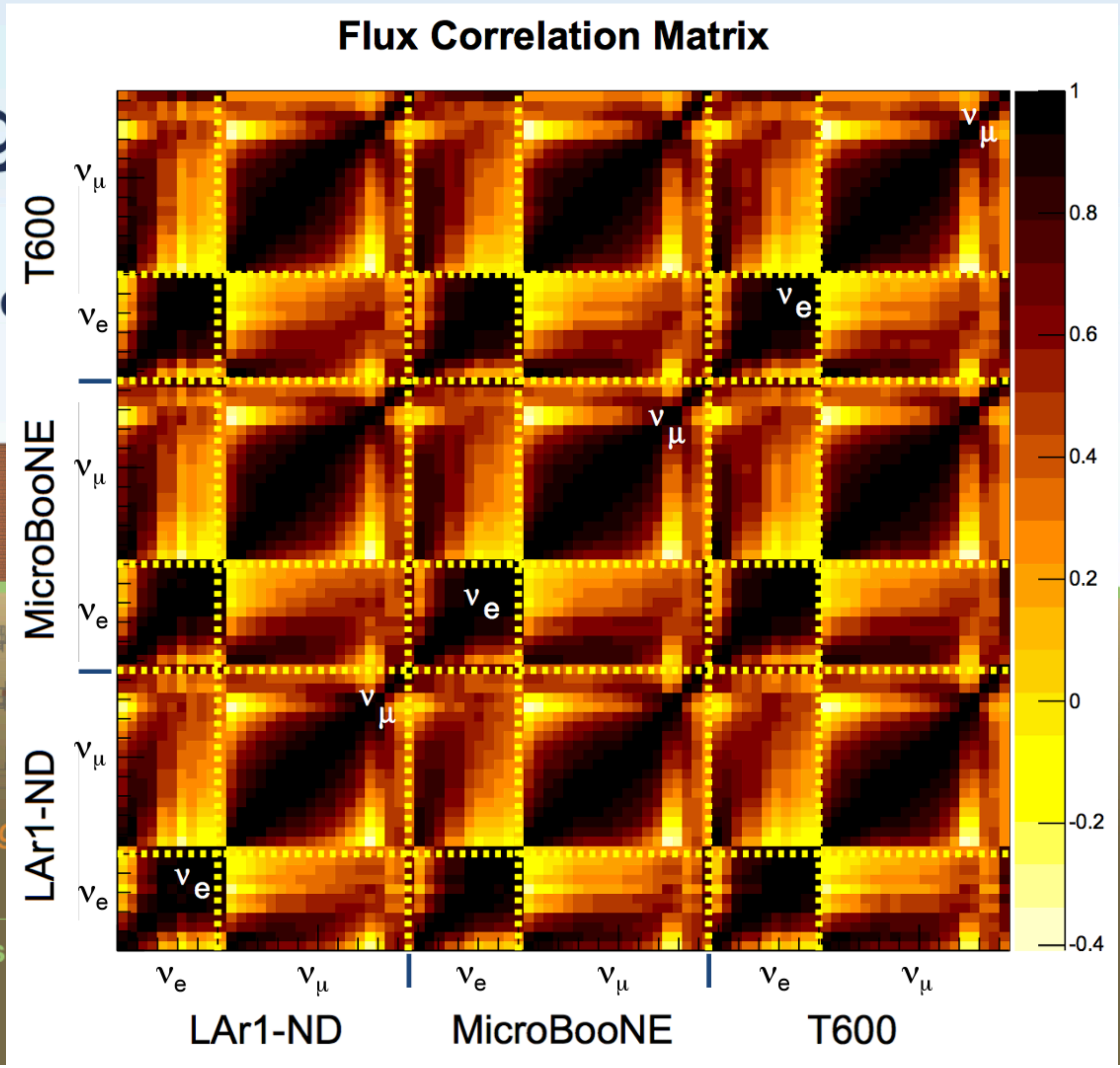
Short-Baseline Experiment-Theory Workshop

Santa Fe, NM — April 3rd 2024

Short-Baseline Neutrino Program at Fermilab

- Three Liquid Argon TPCs at different baselines.
- Each detector, on its own, contains a rich physics program. Combined, these detectors aim to definitively probe eV-scale sterile neutrinos in the 3+1 paradigm, and provide strong tests of other short baseline oscillation models.
- Shared detector technology, nuclear target, and beam. Goal is to reduce flux and cross-section uncertainties to % level. *Crucial for oscillation searches*. Detector systematics need to be similarly constrained.





R. Acciarri et al arXiv:1503.01520v1

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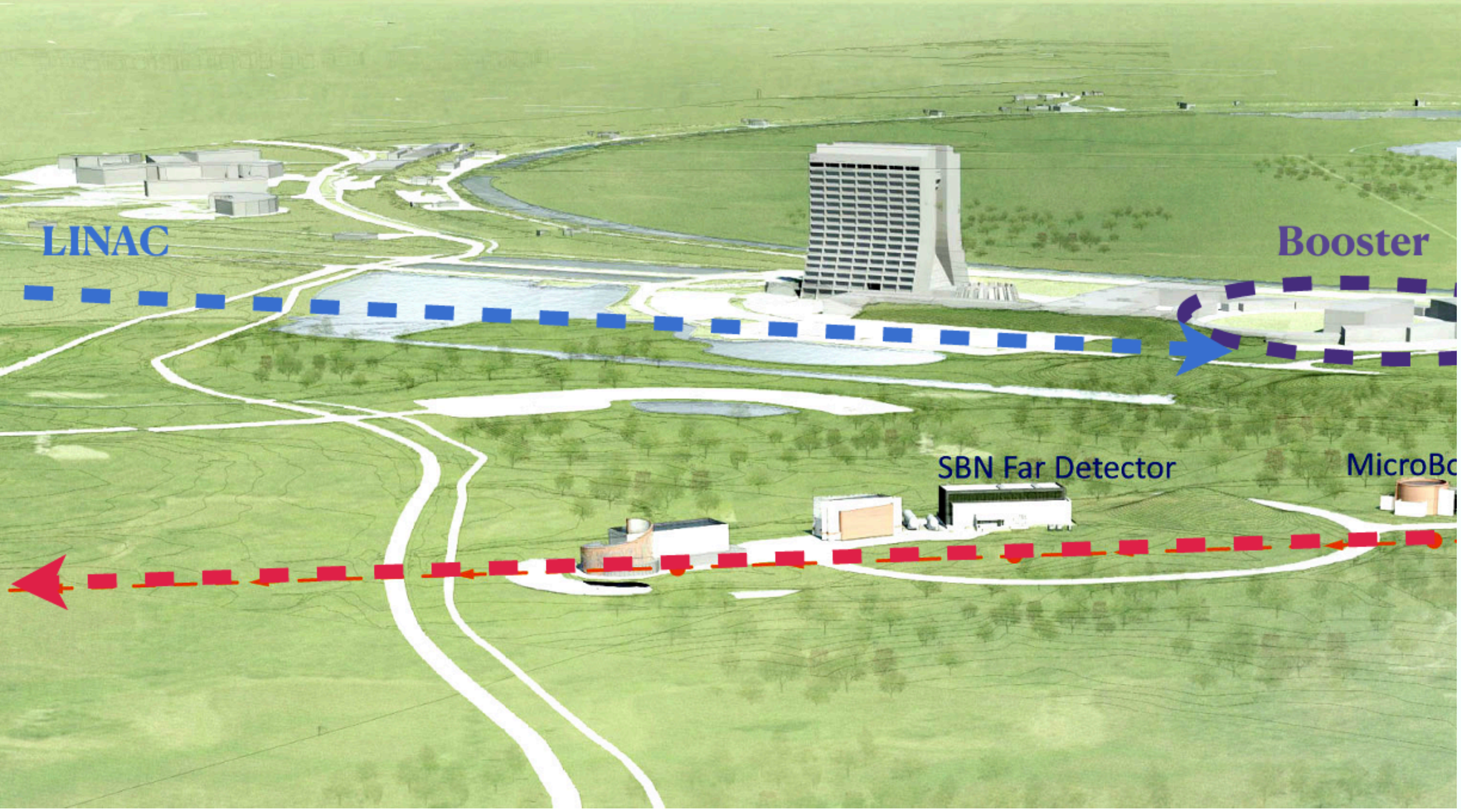
Booster Neutrino Beam

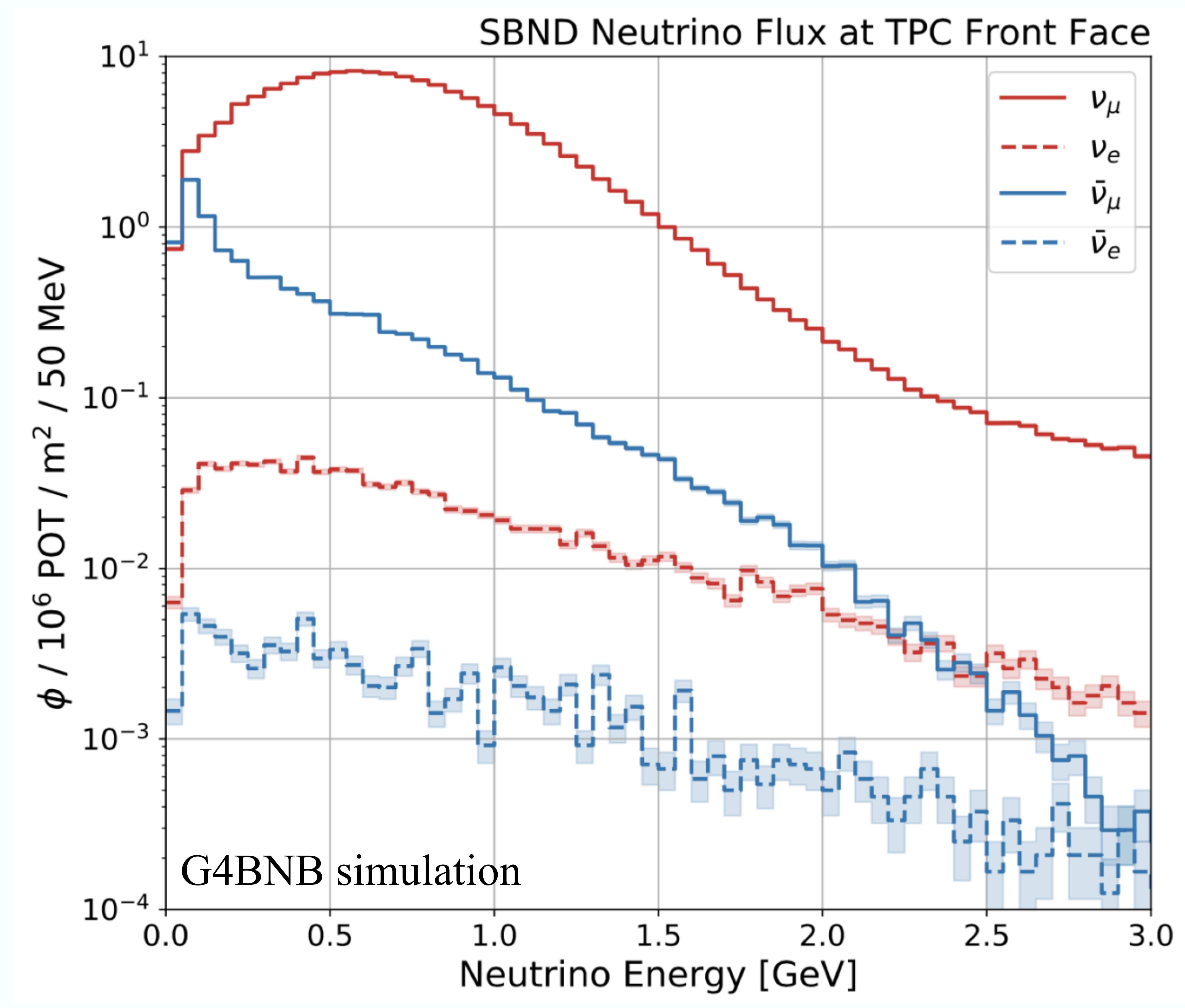
— 8 GeV proton beam on Be target. Mean numu energy of 0.8 GeV

ν_μ (93.6%) — $\bar{\nu}_\mu$ (5.9%) — $\nu_e + \bar{\nu}_e$ (0.5%)

~3M events/yr in SBND! 400k in ICARUS!

Booster Neutrino Beam





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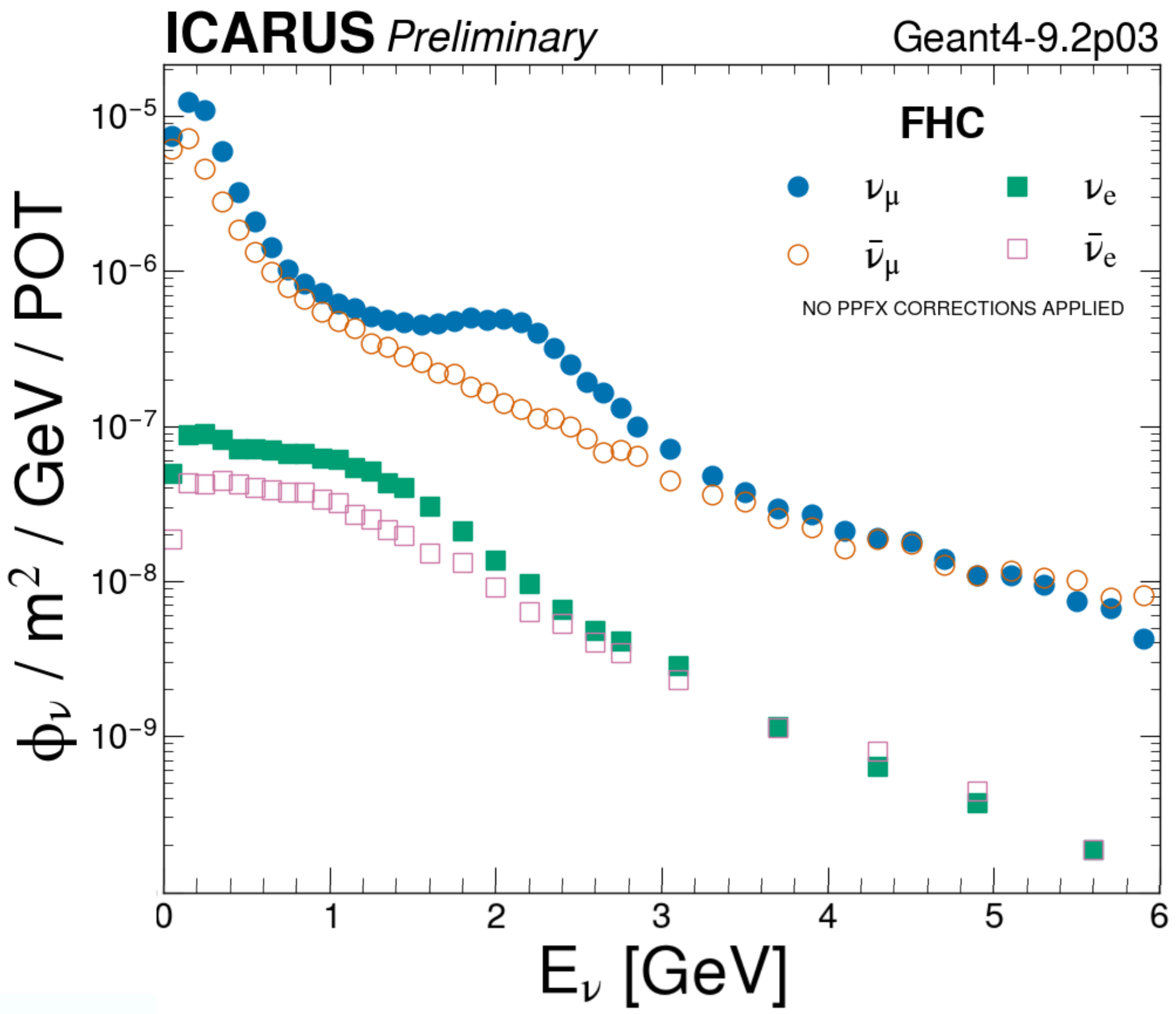
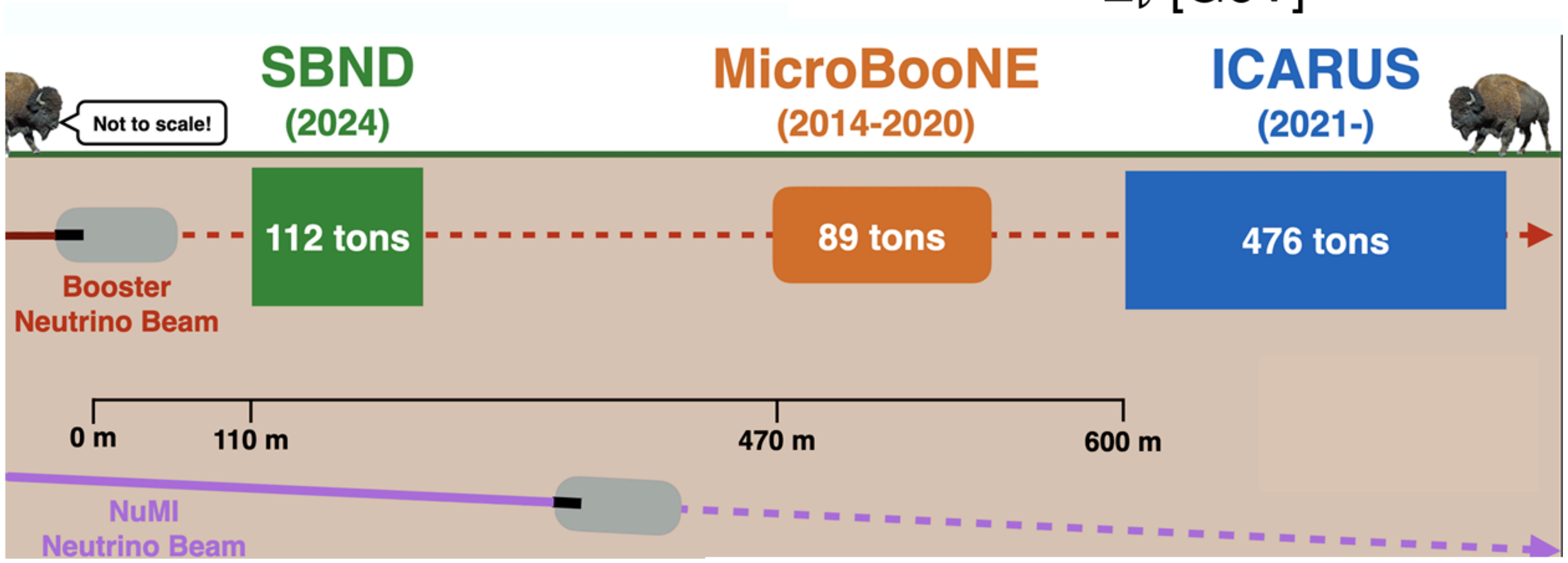
Neutrinos at the Main Injector (NuMI)

- ICARUS and MicroBooNE also see the NuMI beam!
- Expected ~10^5 events/yr in ICARUS from NuMI (>1GeV)
- In context of 3+1, provides additional information to break degeneracy between ν_e appearance ($\nu_\mu \rightarrow \nu_e$) and disappearance ($\nu_e \rightarrow \nu_s$)
- Location (far off-axis) introduces lots of intricacies in flux modeling, needs to be done carefully.

ν_e contributes >5% of the flux between 0.5 and 1.5GeV

$\nu_e : \nu_\mu$ ratio is ~10x higher than BNB

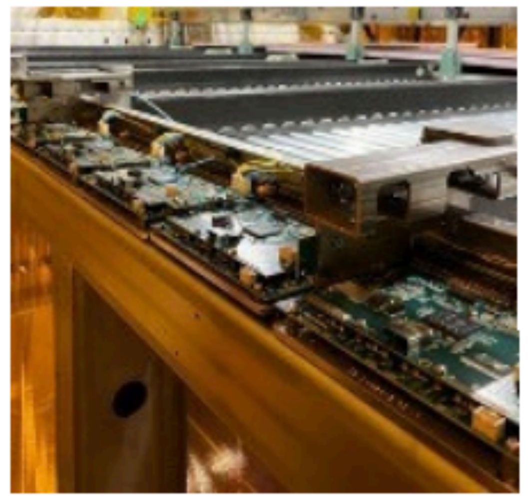




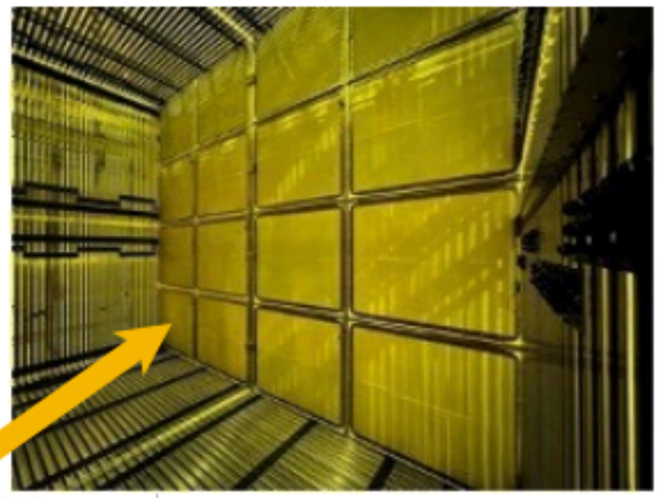
Short Baseline Near Detector (SBND)

LArTPC

Active mass is 112 t
Active volume is 4×4×5 m³

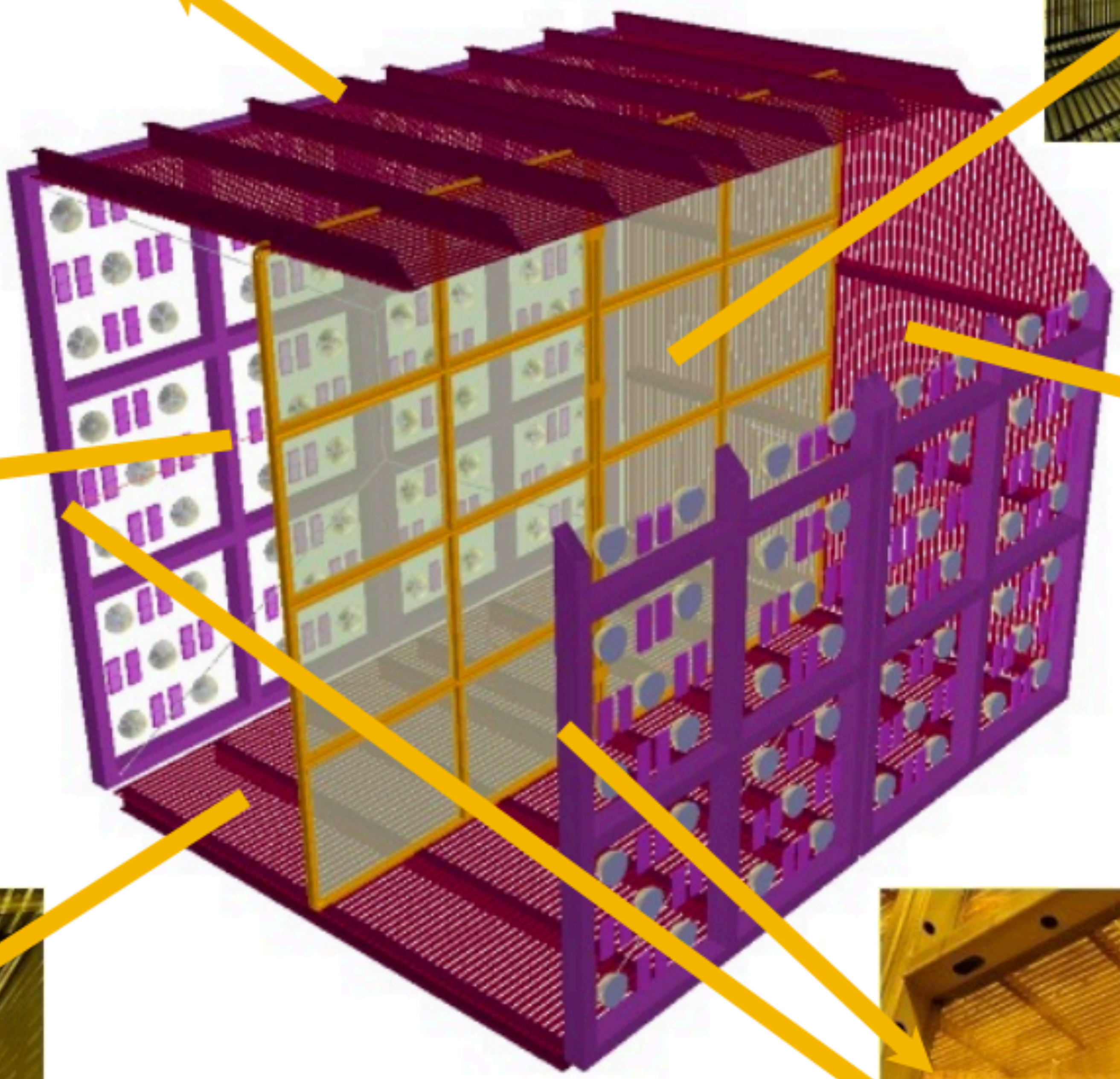


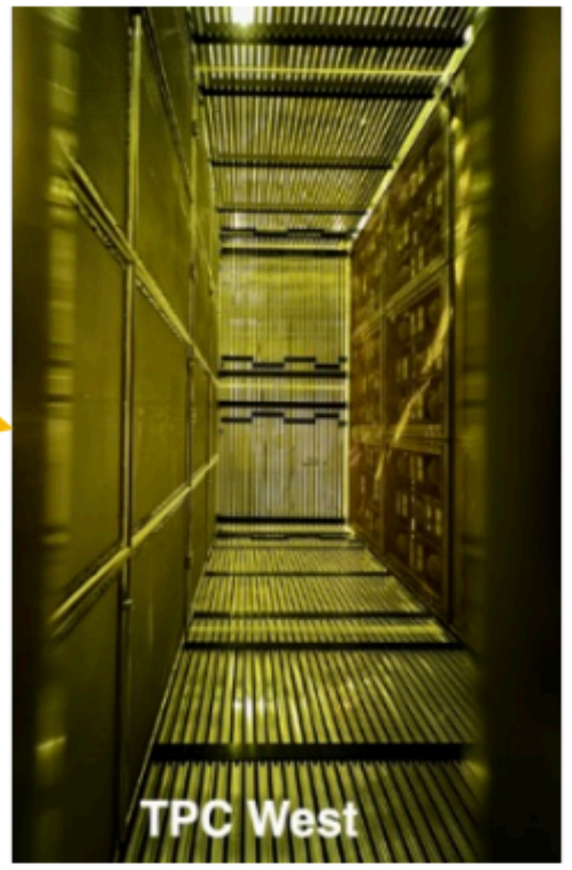
Cold Electronics (in LAr)
pre-amplify and digitize
TPC wire signals



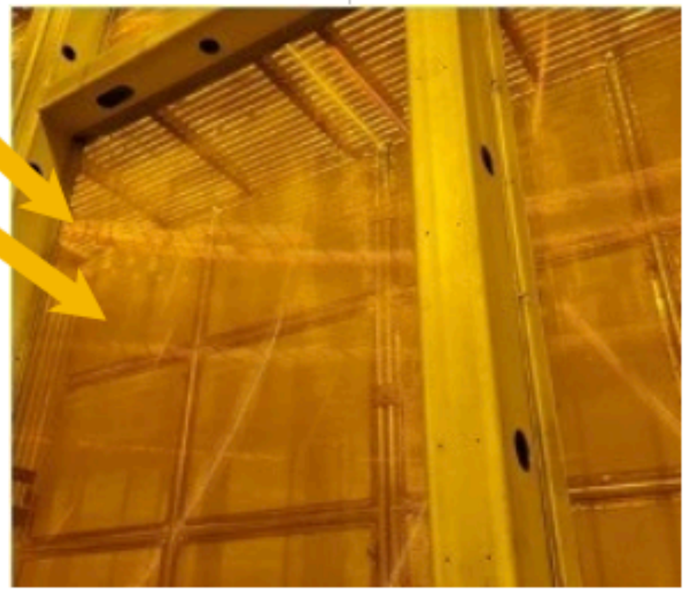
Cathode Plane at –100 kV
divides the detector into two
drift volumes

Drift distance is 2 m,
max. drift time is ~1.28 ms





Field Cage wraps around
the two TPCs to step down
the voltage and ensure a uniform
electric field of 500 V/cm



Anode Plane on either side,
each with three wire planes
with 3 mm wire spacing and
different orientation per plane

Total of 11,260 wires

Short Baseline Near Detector (SBND)

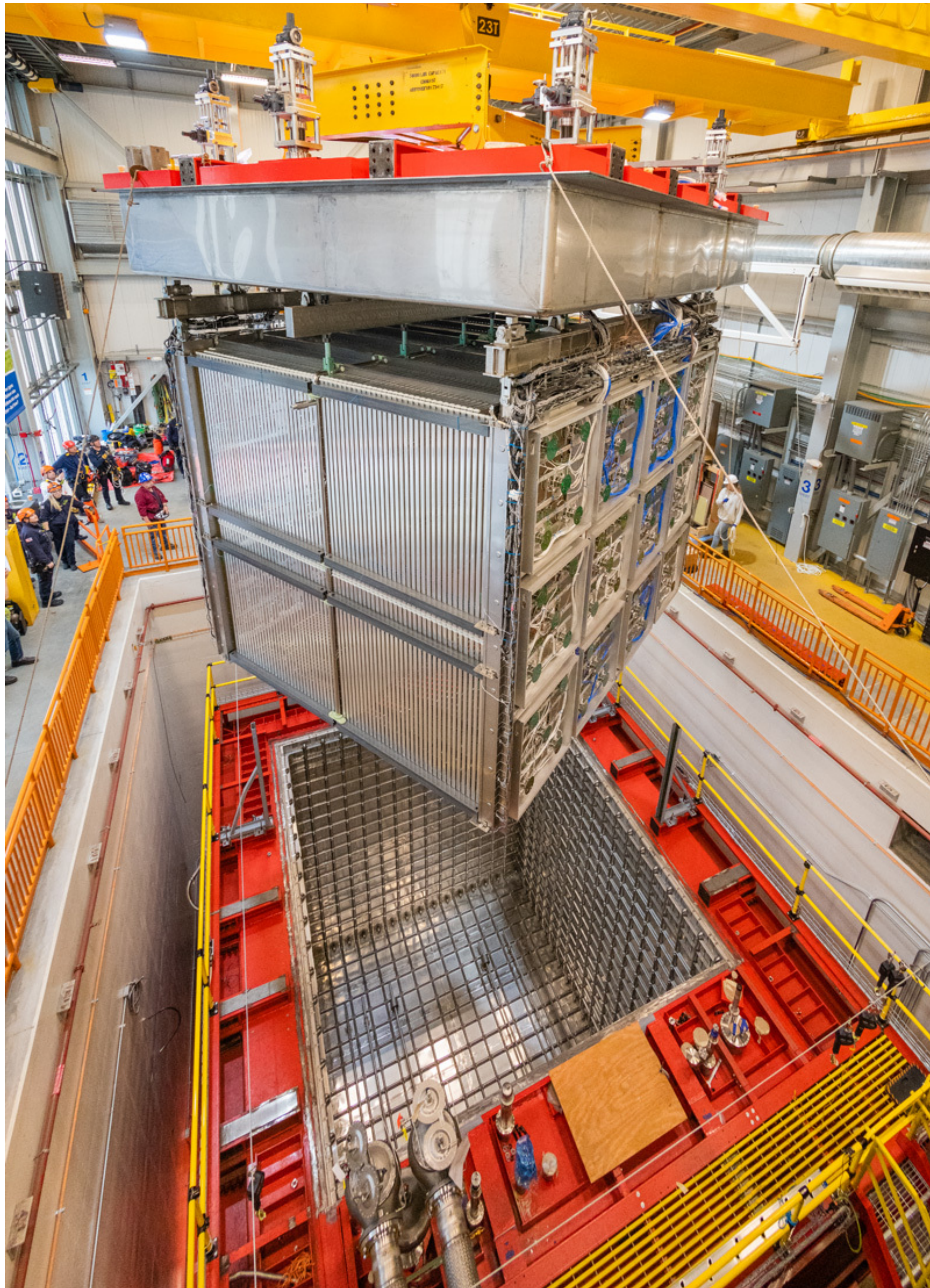
— Detector assembly and installation complete!

— Detector was cooled and filled with Liquid Argon in early 2024. Commissioning began in February. We started taking shifts!

— The BNB has resumed operations this year.

— Calibration stage imminent!

— First SBND Physics Run to follow.



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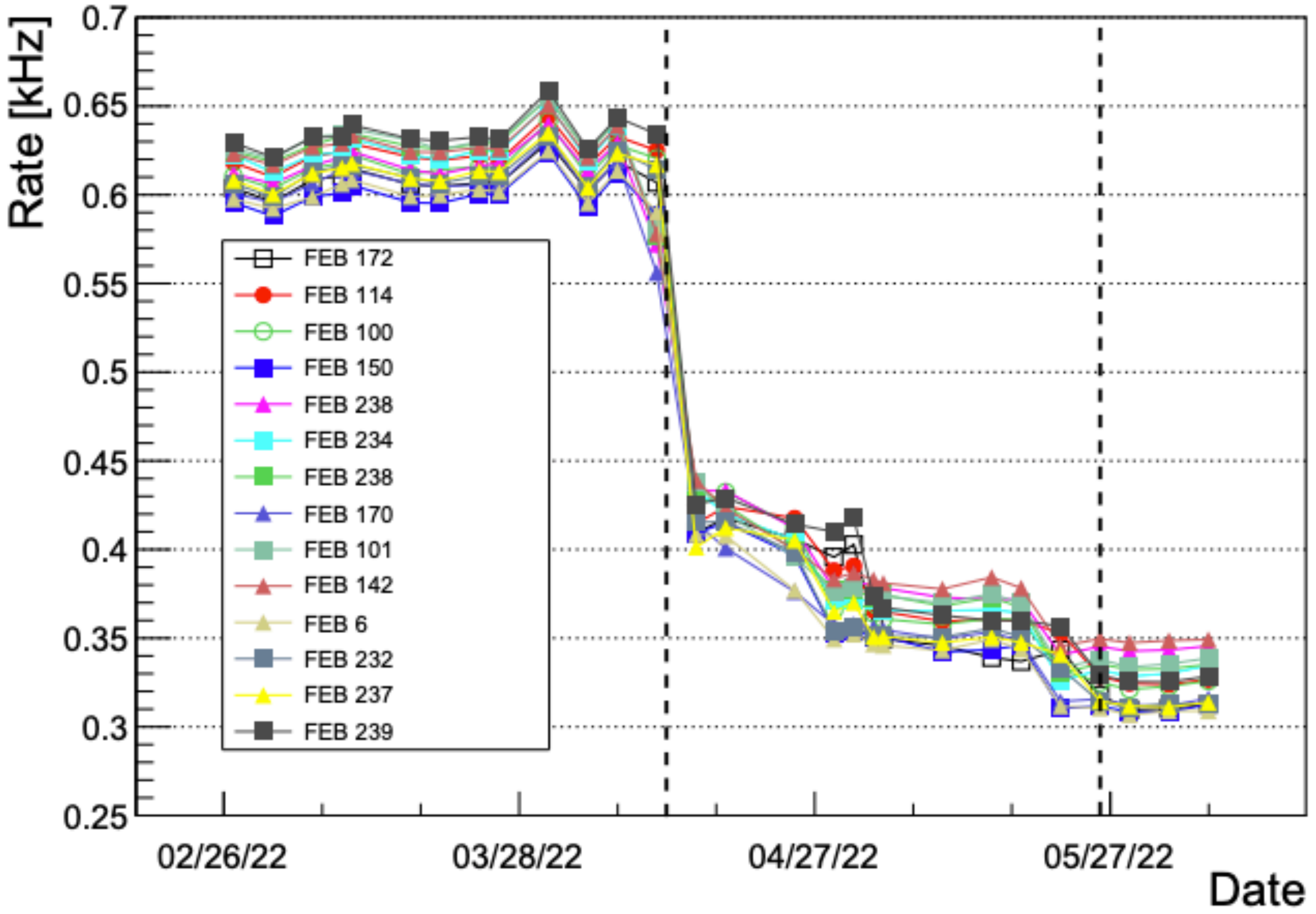
ICARUS

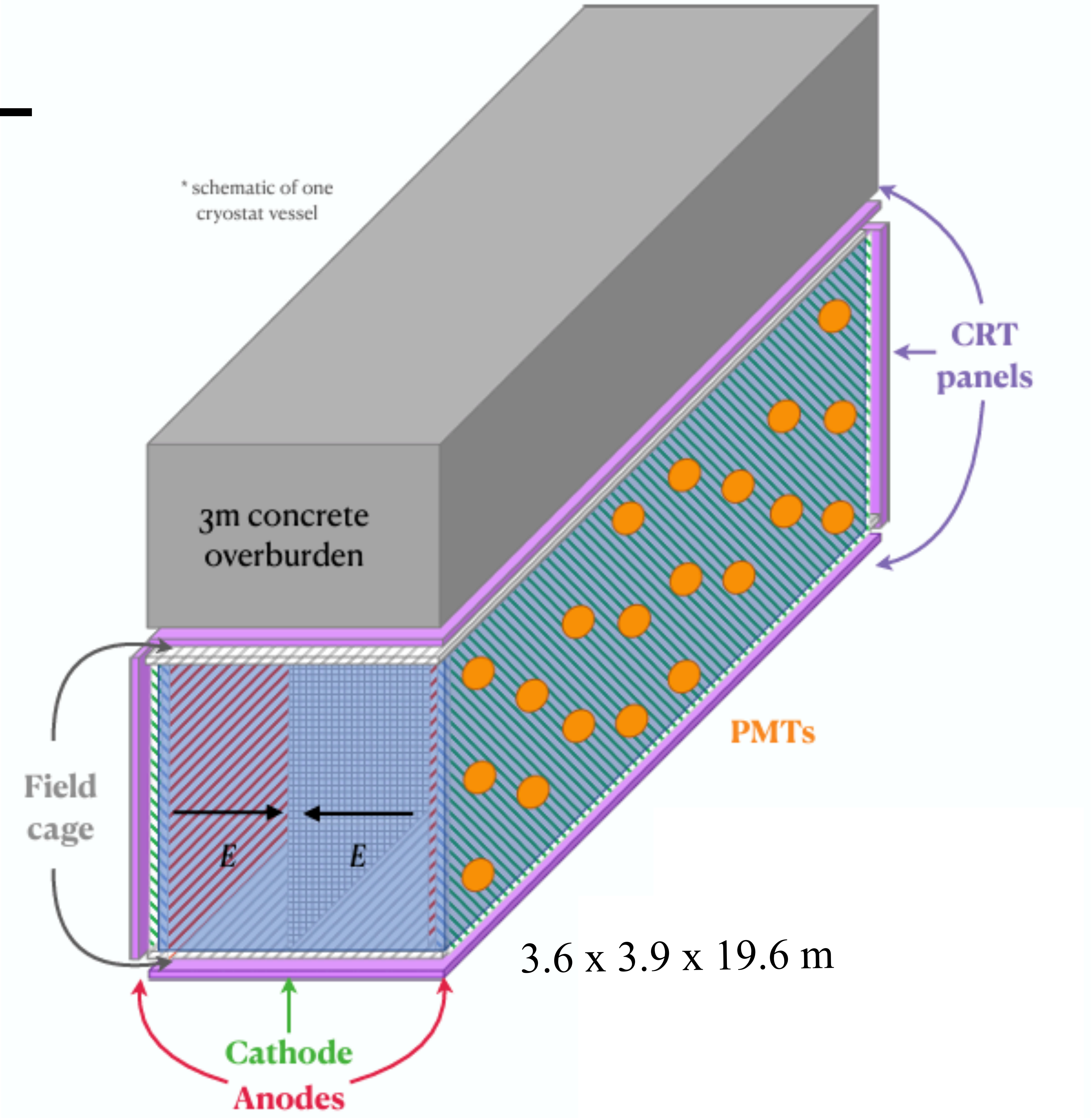
— Two cryostat vessels. Each vessel contains a single cathode in the center and two drift volumes (4 TPCs total).

— PMTs to detect scintillation light and CRT to tag entering/exiting events.

— 3m concrete overburden reduces cosmic rates by a factor of ~2.

arXiv:2301.08634v1





ICARUS

— Operated at the Gran Sasso underground Laboratory (Italy), collecting data from the LNGS beam for 3 years (2010-2013).

— Upgraded for on-surface operations and moved to Fermilab (USA) in 2018.

— Operating since 2021. Taking physics quality data since June 2022!

ICARUS Operations

— Data collected so far over two run periods:

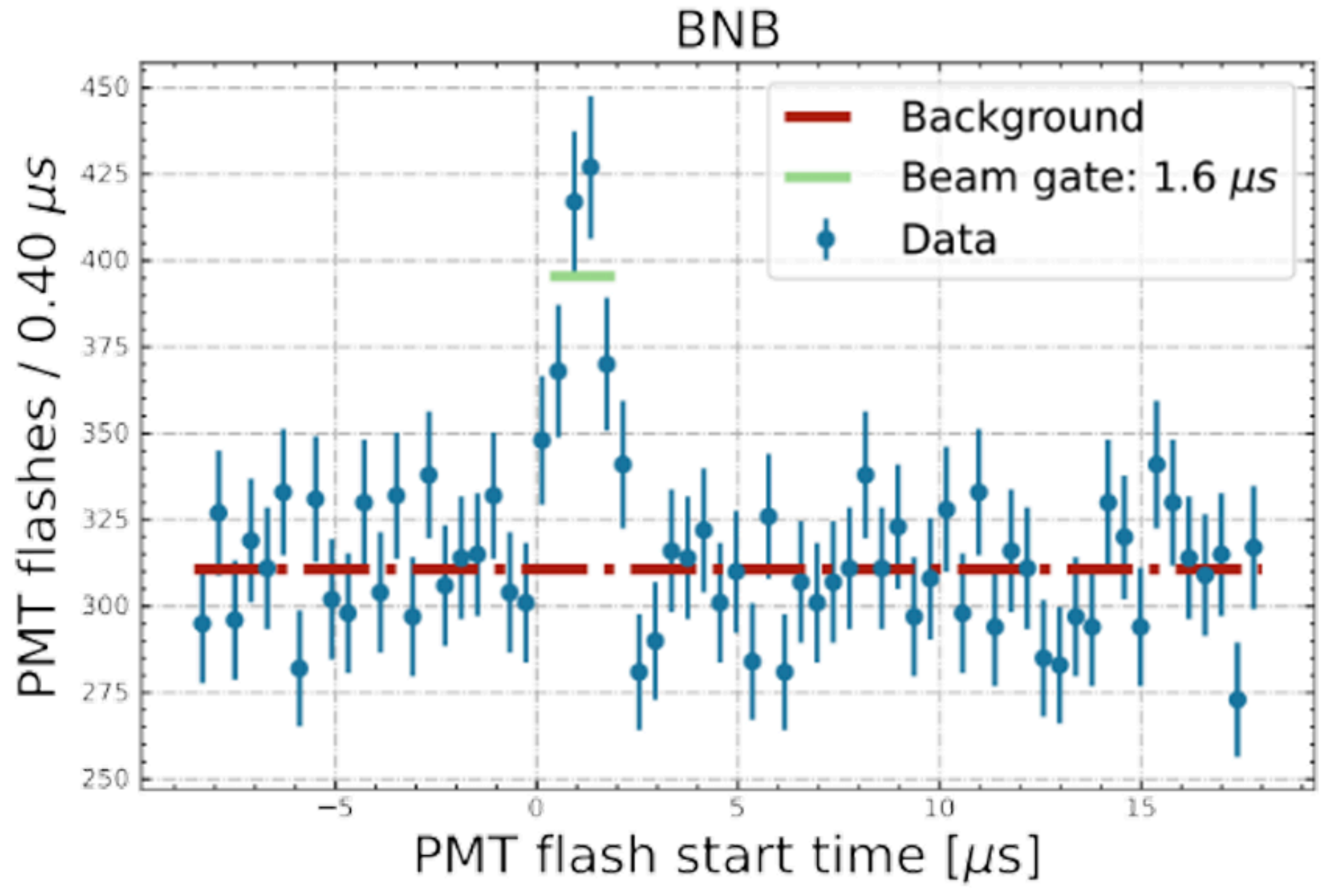
— BNB ~ 2×10^{20} POT

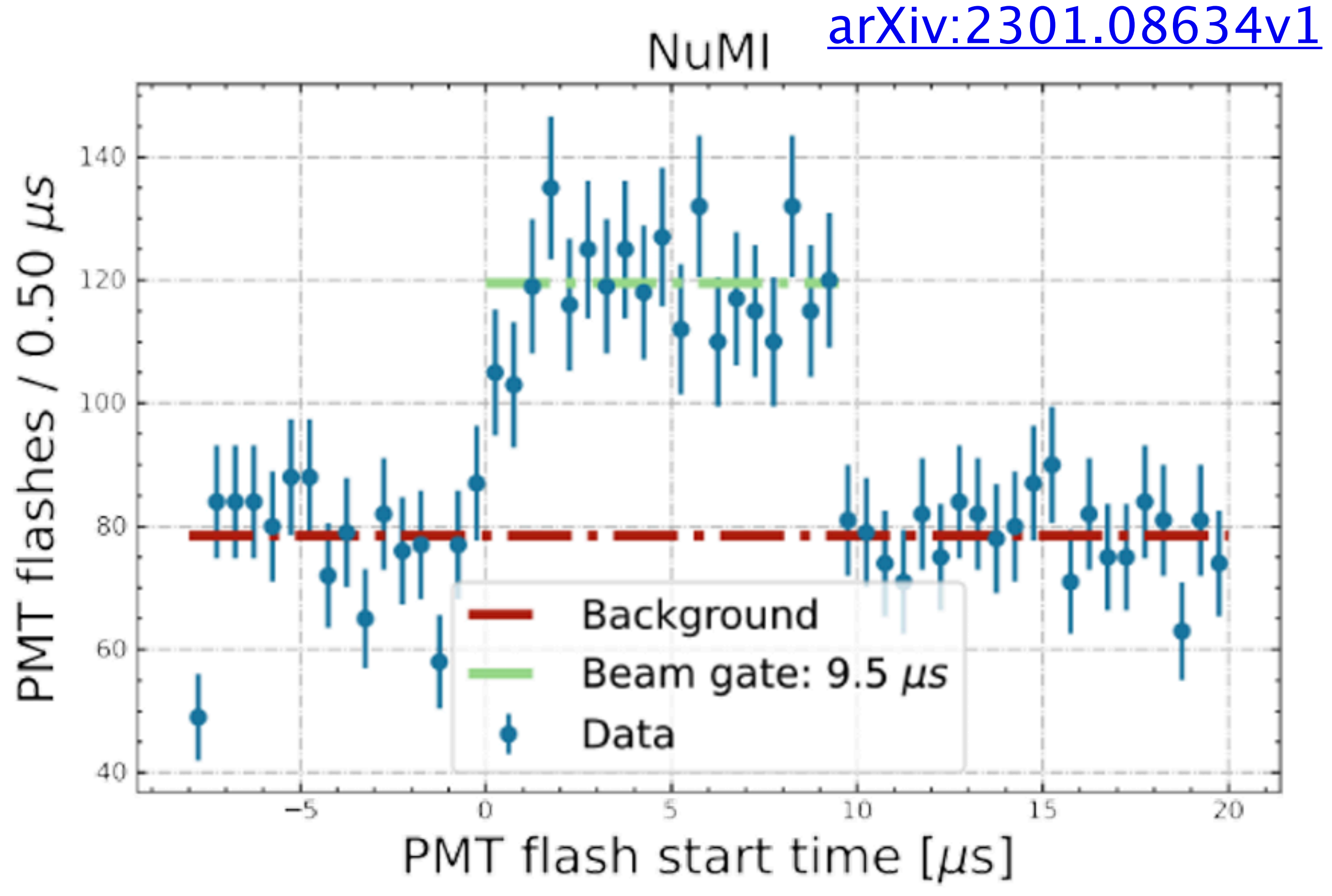
— NuMI ~ 2.7×10^{20} POT

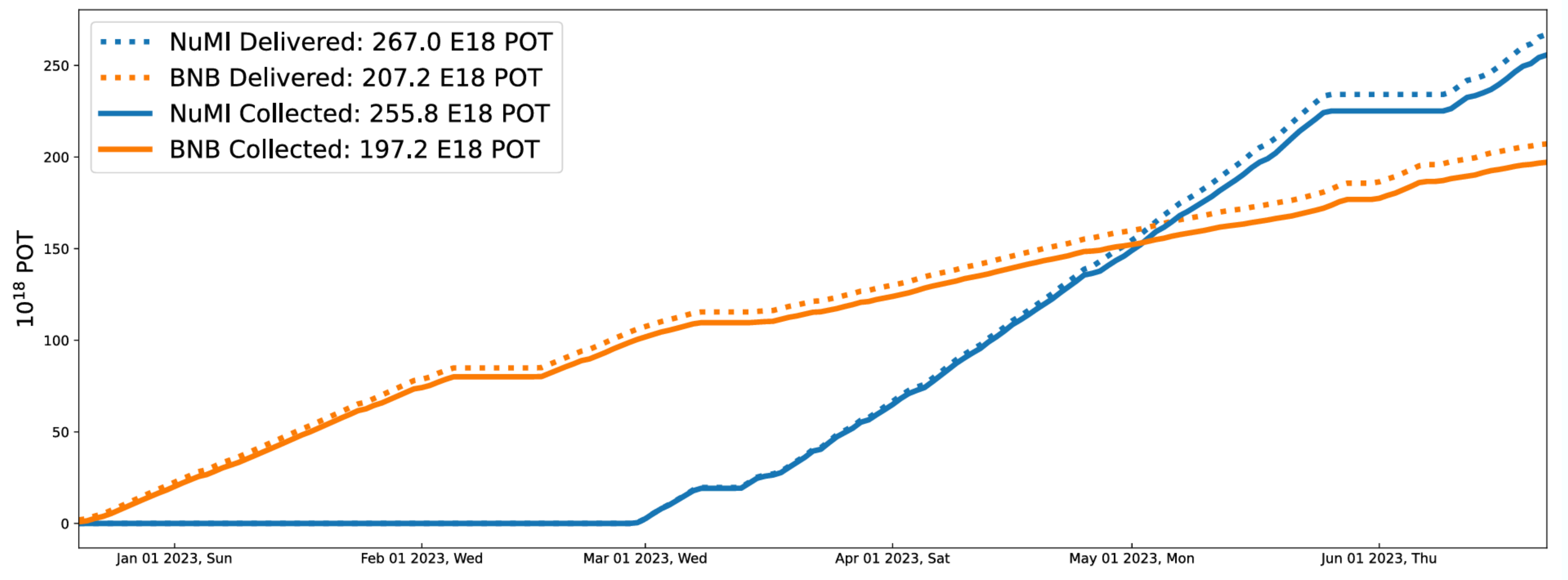
— ICARUS livetime >95%.

— BNB recently resumed operations!

arXiv:2301.08634v1





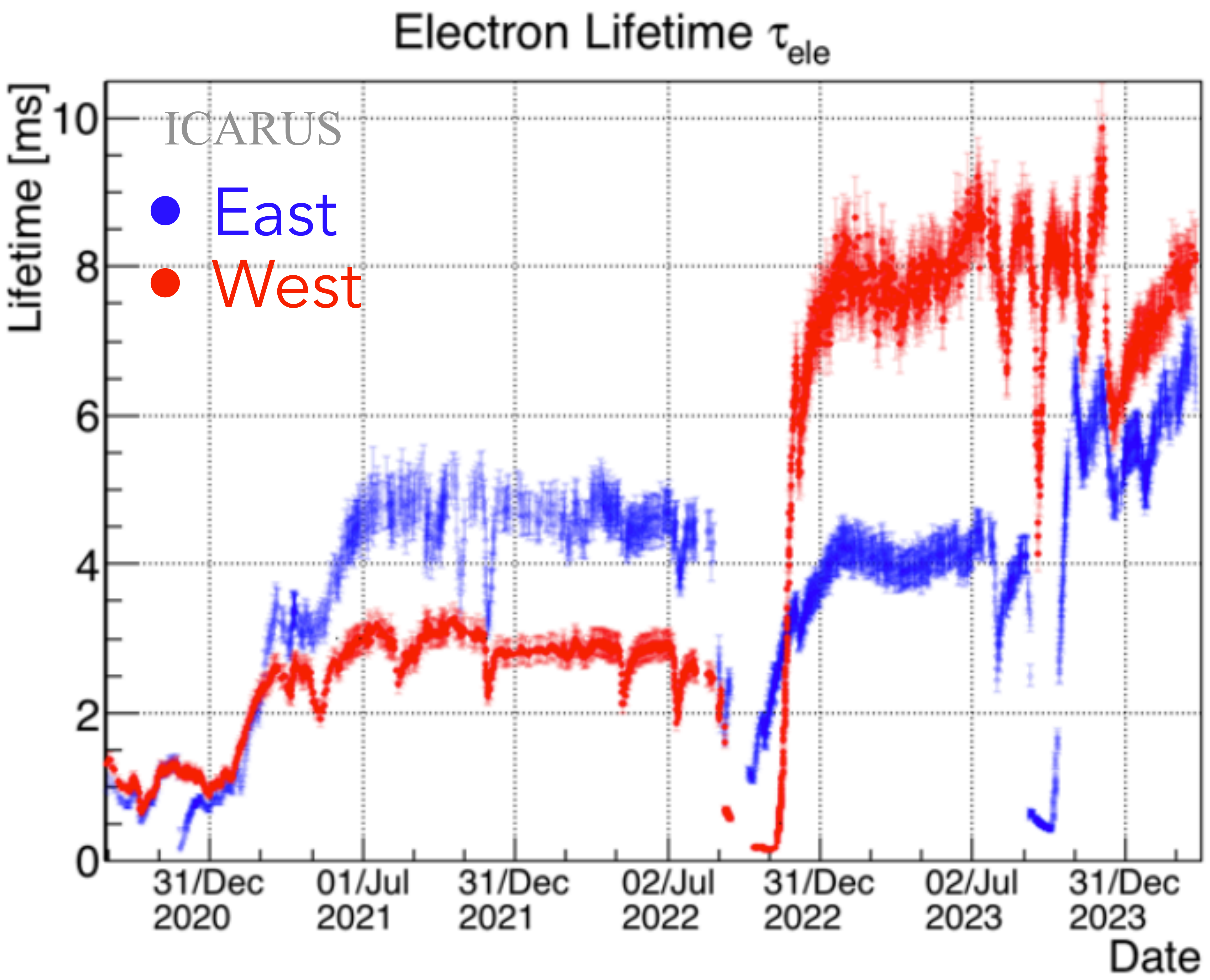


ICARUS Commissioning

— Huge undertaking to model detector response and perform calibration measurements in preparation for analysis. Recent publication documents progress [ref]

— Electron lifetime inversely proportional to impurities in argon.

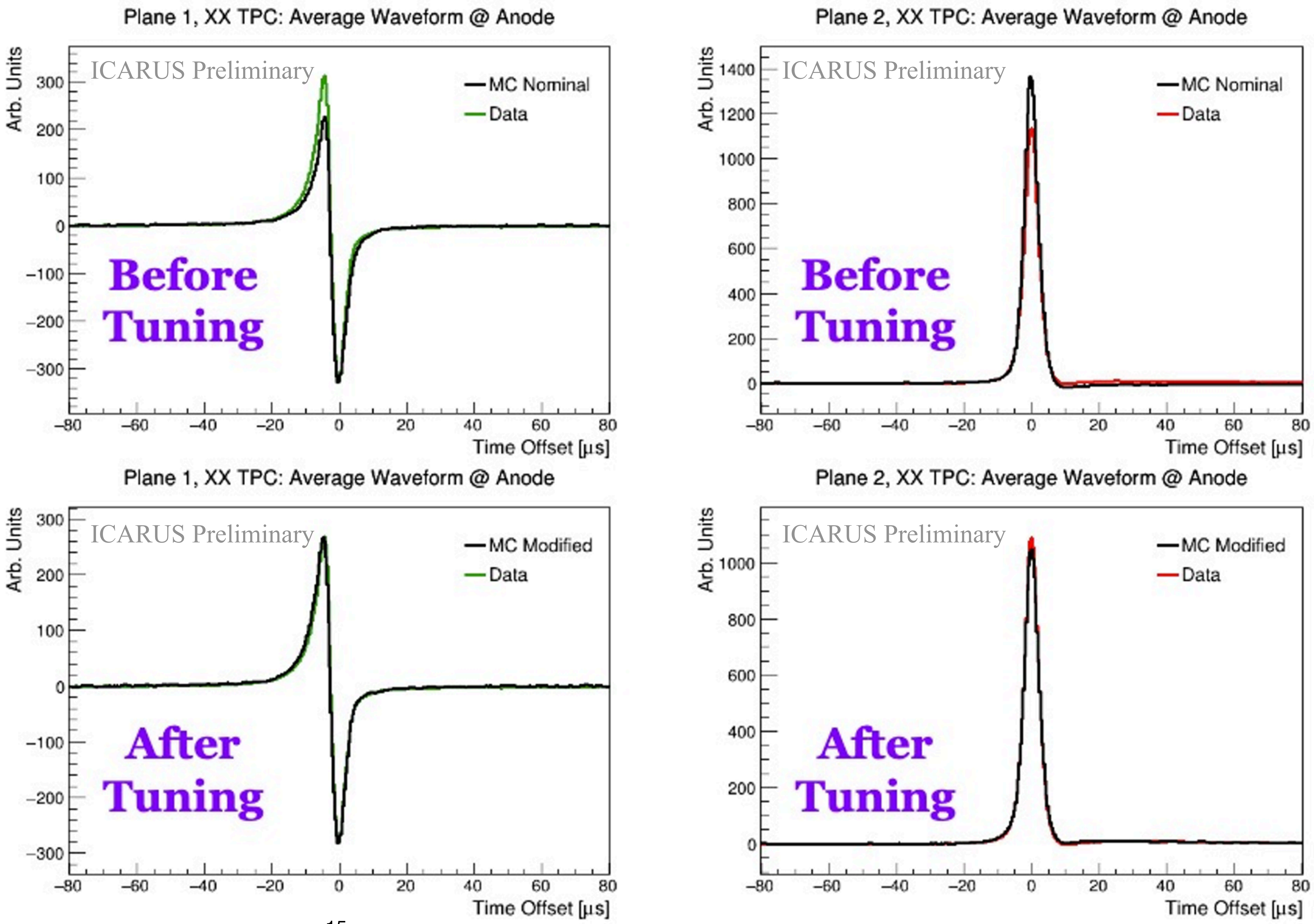
— Drift time is ~1ms. ~3ms lifetime is enough to collect good quality data. Recently reached ~7-8ms after improvements in argon purity.



ICARUS Calibration

— Calibrating detector response leads to improved modeling of detector

— Great agreement with data after tuning of MC charge readout.



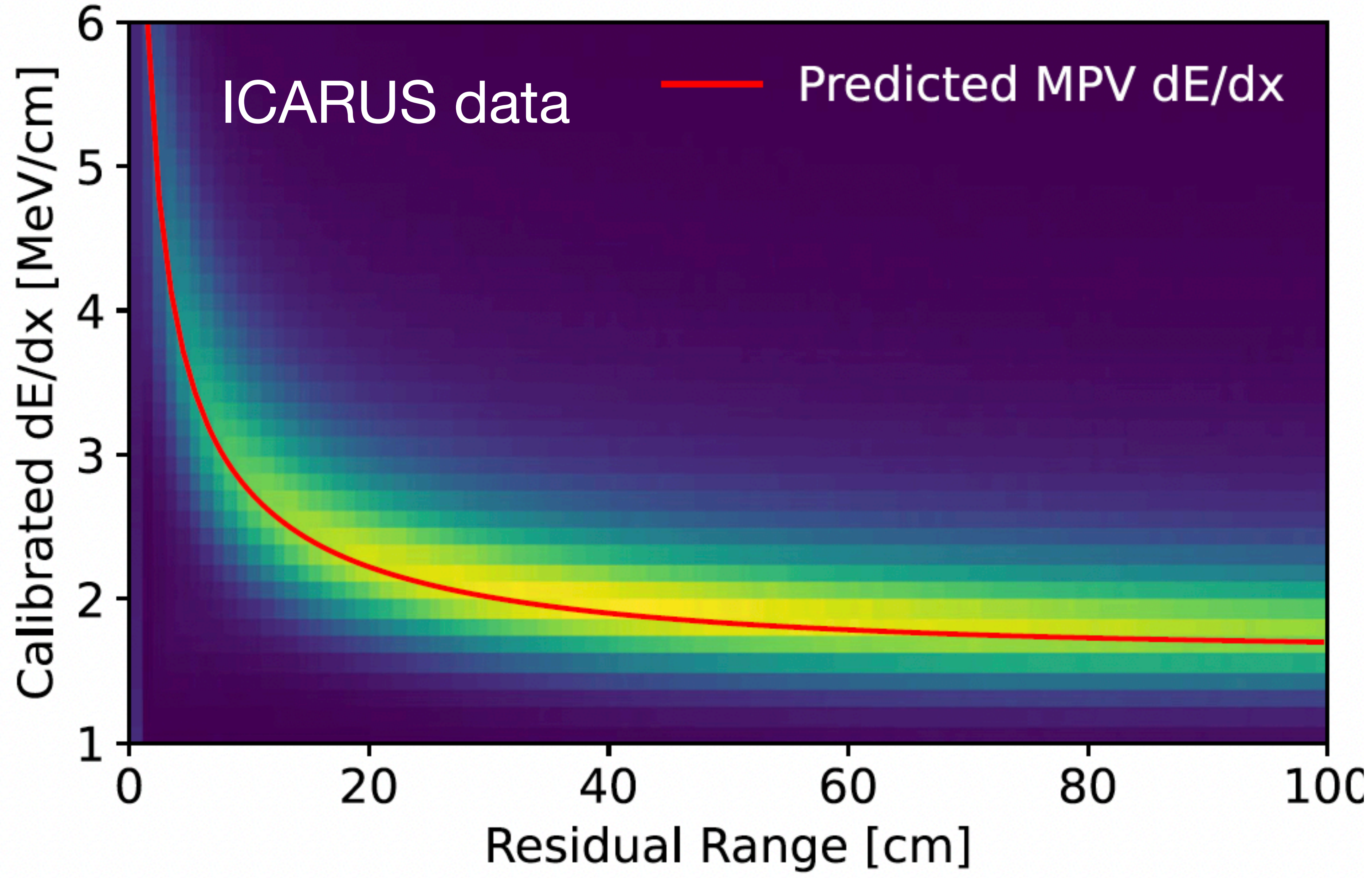
ICARUS Calibration

— Sample of stopping muons (cosmic) used to calibrate gain.

— Gain calibration is verified by comparing to theoretical muon dE/dX

— Comparison of calorimetric energy prediction and range prediction shows good agreement between two independent methods

— Further improvements in the pipeline (planned data reprocessing with improved detector response) and large MC sets with new detector model.



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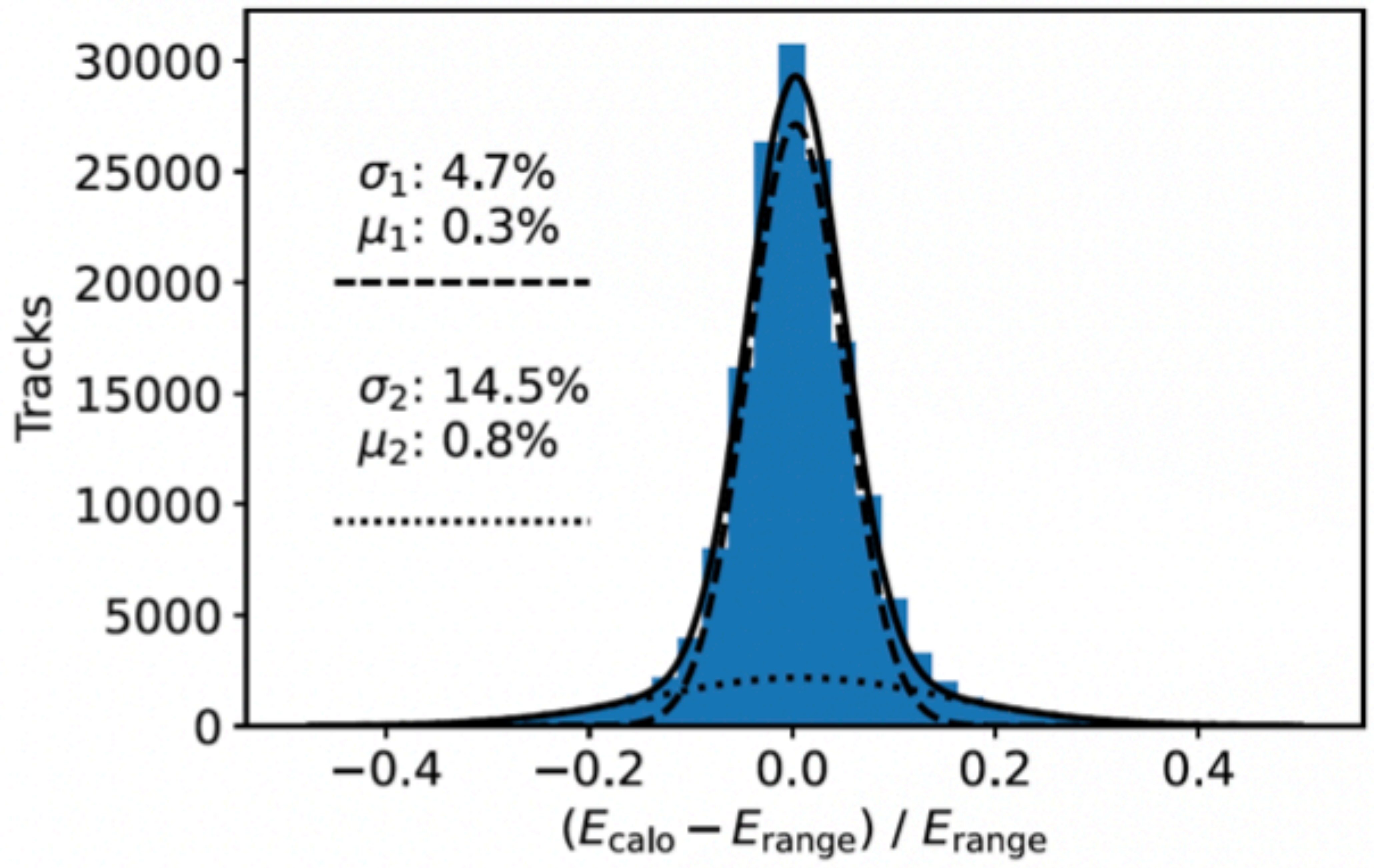
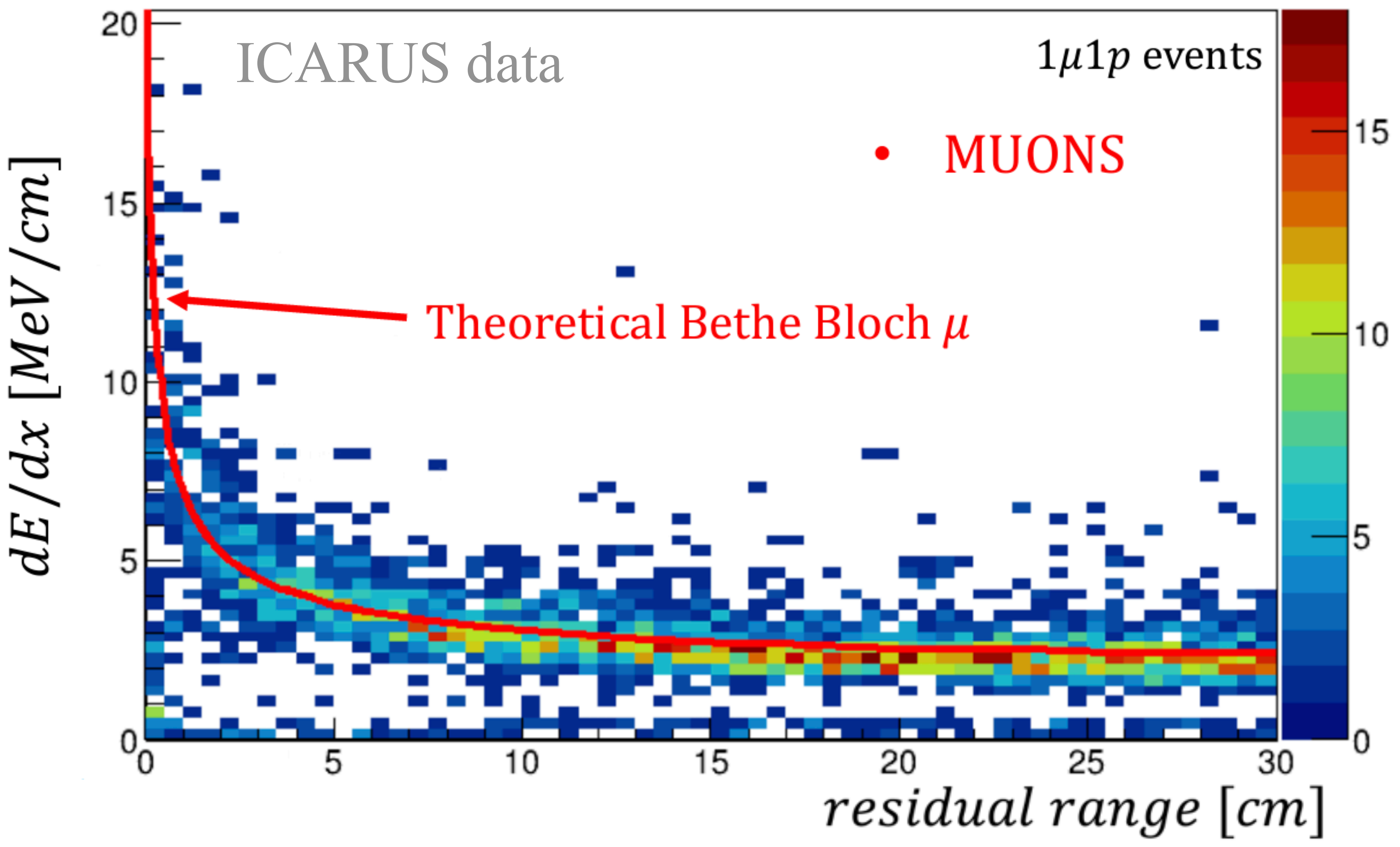
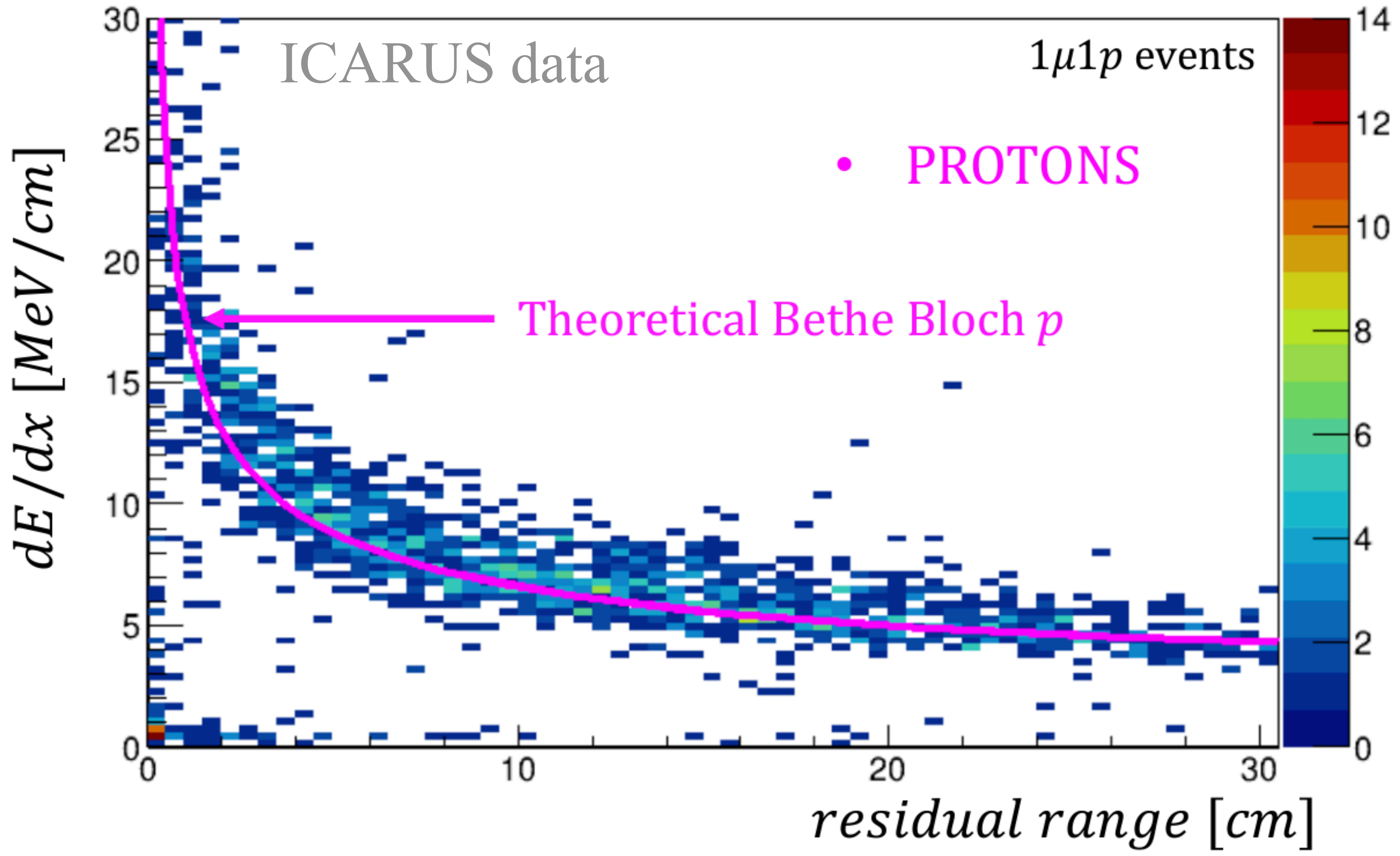


ICARUS reconstruction

- Reliable calorimetric reconstruction and separation of muons and protons in ICARUS with pandora!

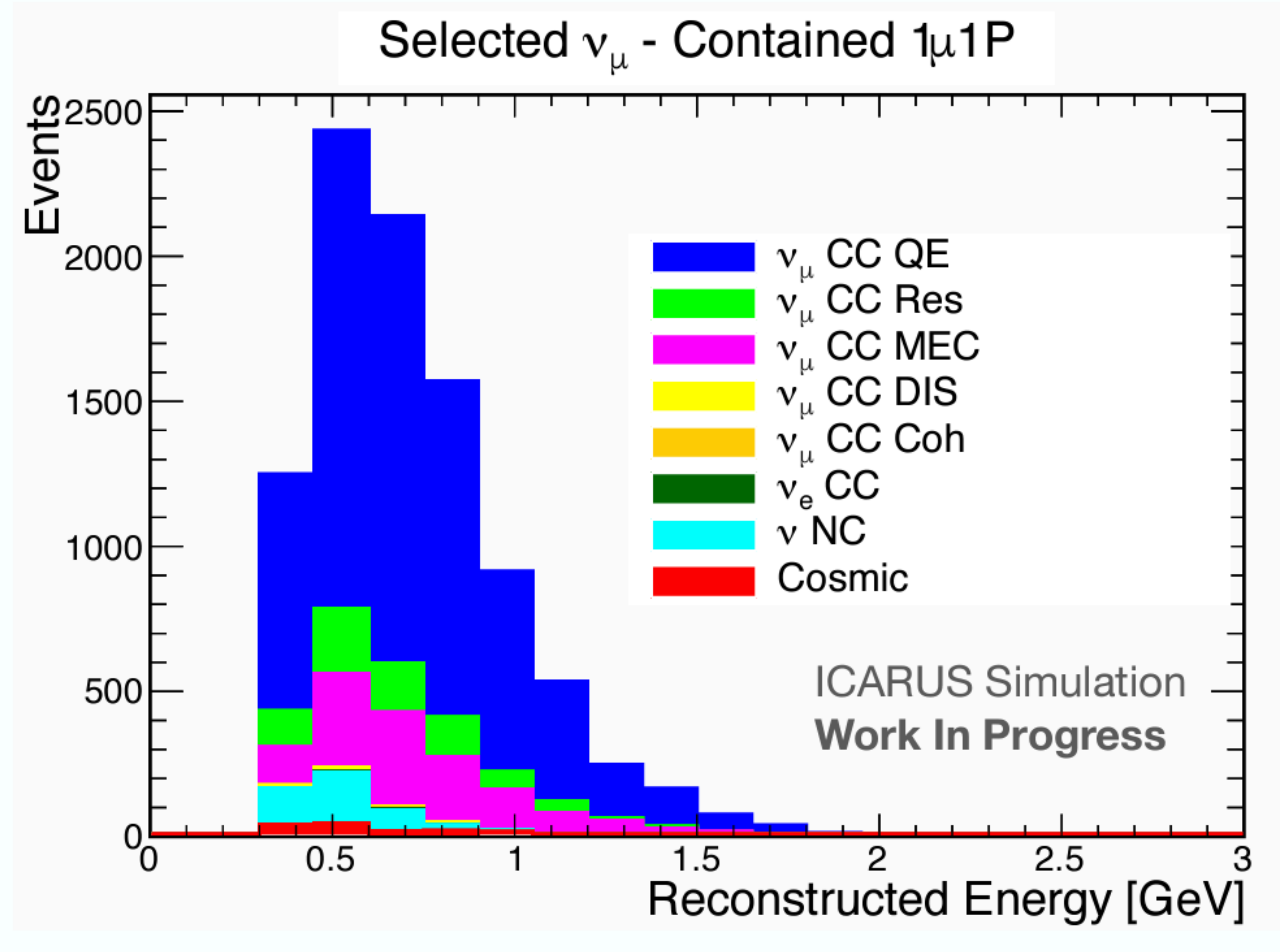




Event selections

— Focused efforts with current tools (pandora) on fully contained 1μ1p sample for ν_μ disappearance search using BNB beam (mostly quasi-elastic numu CC interactions).

— ICARUS selection normalized to collected POT

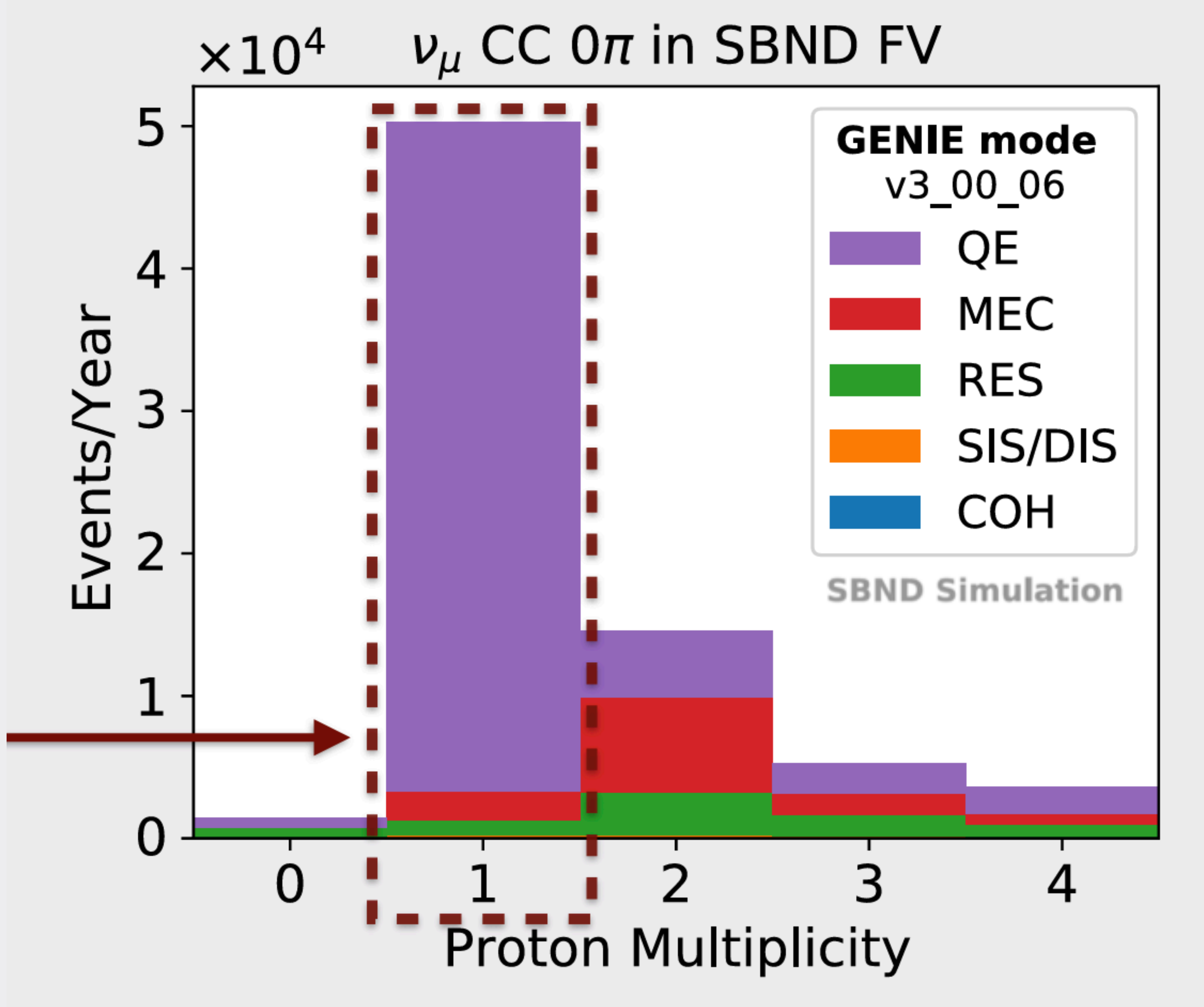


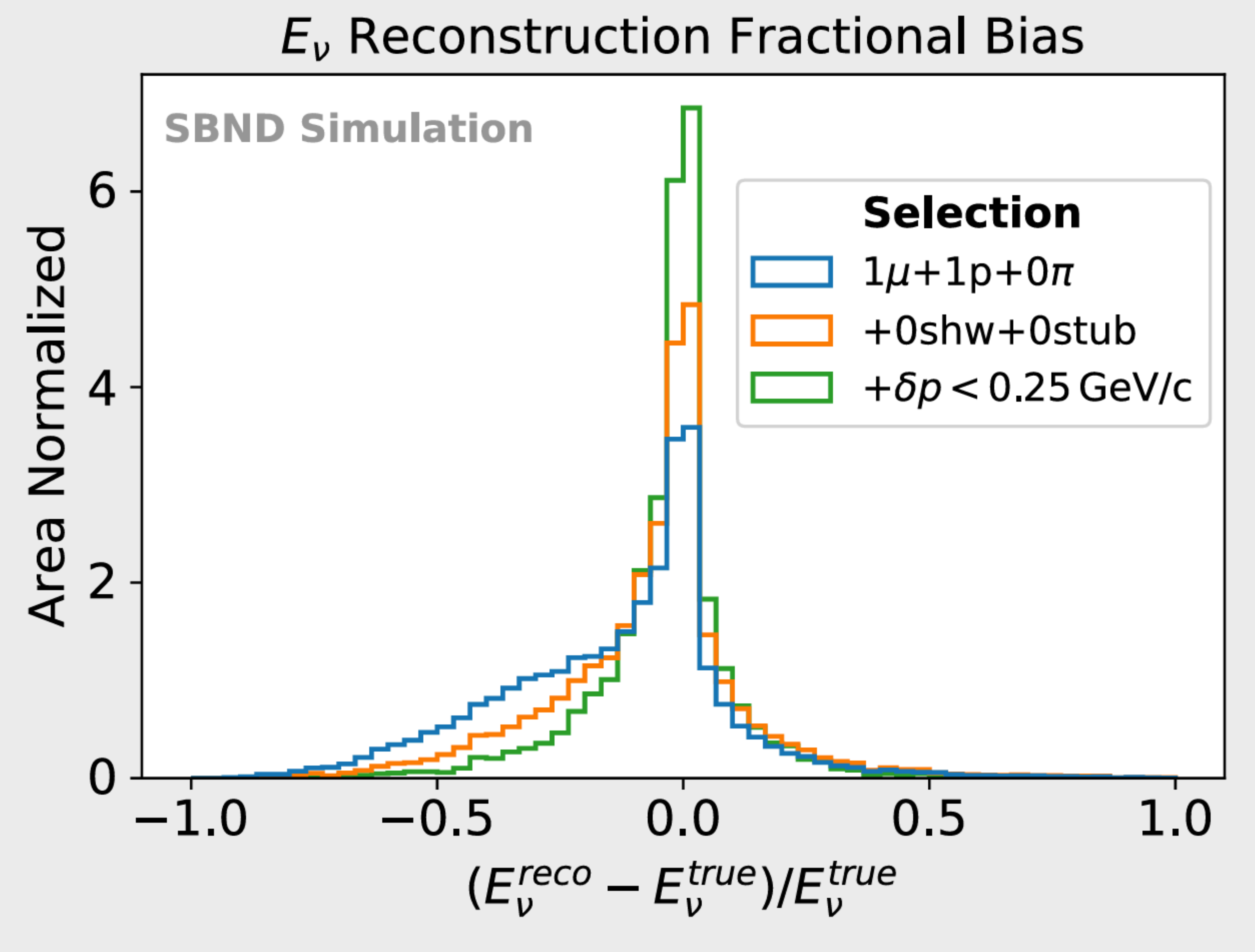
$$E_\nu = E_\mu + KE_P$$

Event selections

— Complementary work on SBND. Fully contained 1μ1p sample for ν_μ disappearance search using BNB beam with Pandora (mostly quasi-elastic numu CC interactions).

— Achieve good energy resolution in SBND with pandora.





$$E_\nu^{reco} = E_\mu + T_p + E_B + E_T$$

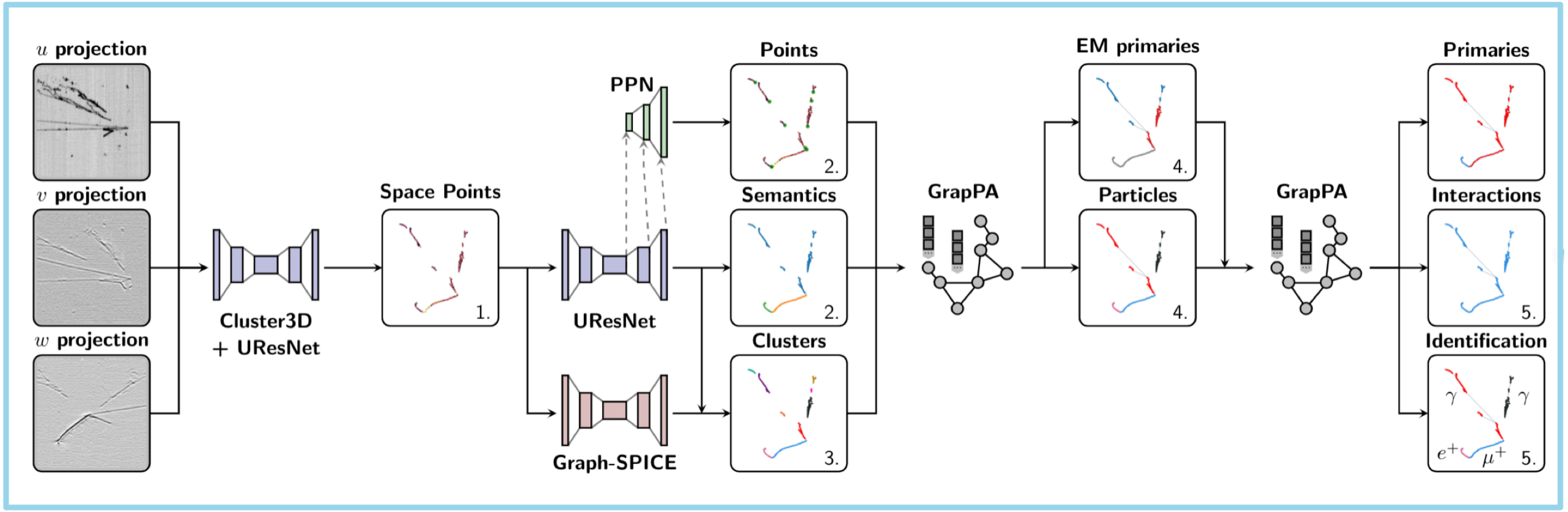
E_B : binding energy

$E_T = \sqrt{p_T^2 + M_A'^2} - M_A'$

E_μ : reconstructed muon energy

T_p : proton kinetic energy

ML Reconstruction



- Large coordinated team effort on both SBND and ICARUS.
- end-to-end ML reconstruction has been developed and implemented in both SBND and ICARUS simulation.
- Expect updates from active developers and analyzers this summer!

Fitting frameworks

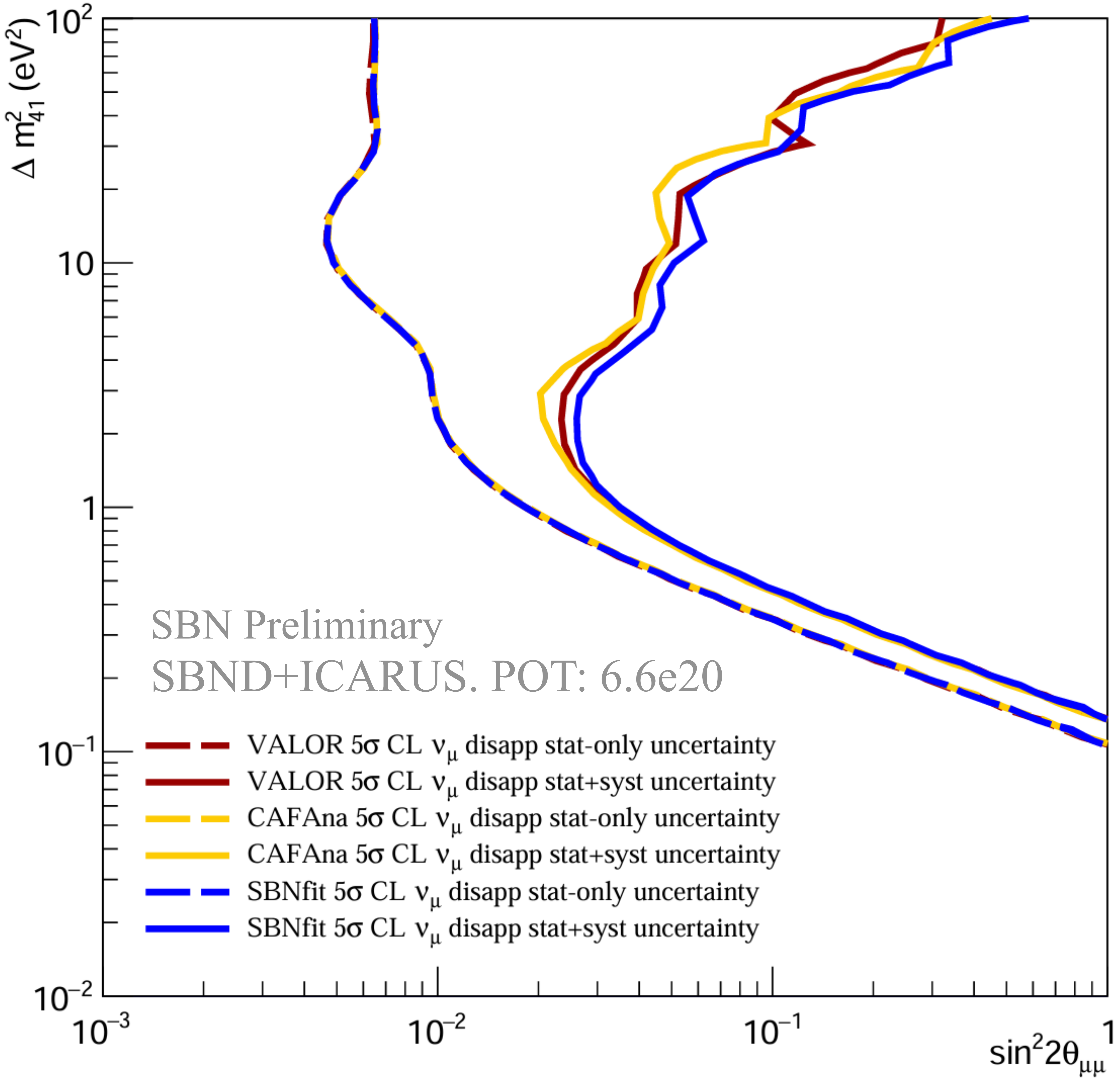
— High neutrino rates (and correspondingly large MC stats), multiple detectors, oscillation channels, beams, dozens of systematic parameters, increases dimensionality of the problem.

— Need analysis and fitting frameworks that can handle unprecedented amount of neutrinos we will collect.

— Fits can have hundreds and up to a thousand knobs.

— Sensitivities robust across three independent fitters. Each with slightly different treatment of systematic uncertainties.

— Syst. Uncertainties considered in these comparisons refer to cross section and flux uncertainties only. No detector systematics.

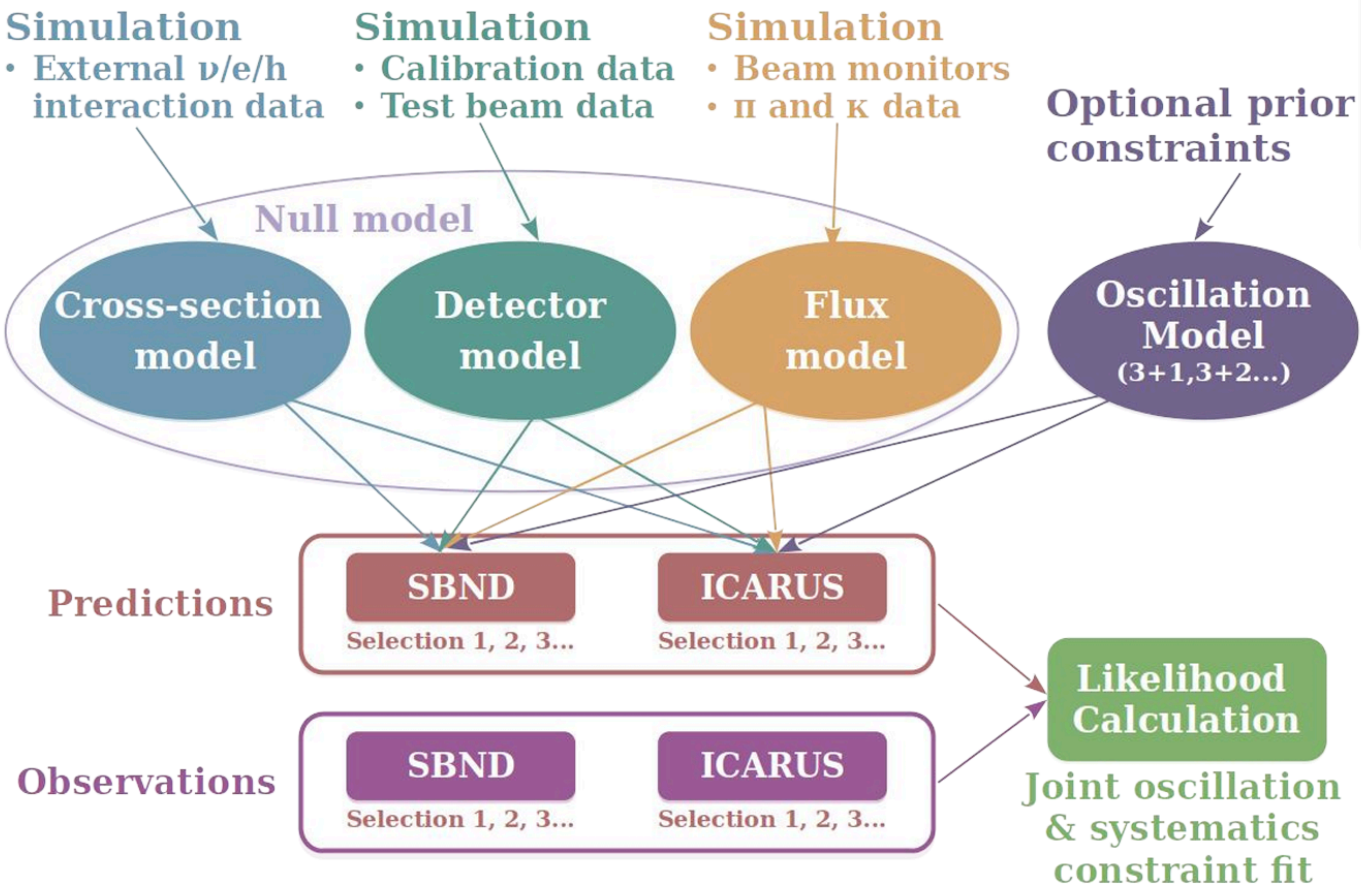


— Software framework established within the T2K experiment in 2010 (Phys.Rev. D85 (2012) 031103).

— Binned likelihood approach that simultaneously fits physics and nuisance parameters.

— In principle can handle an arbitrary number of beam configurations, detectors, and final state topologies.

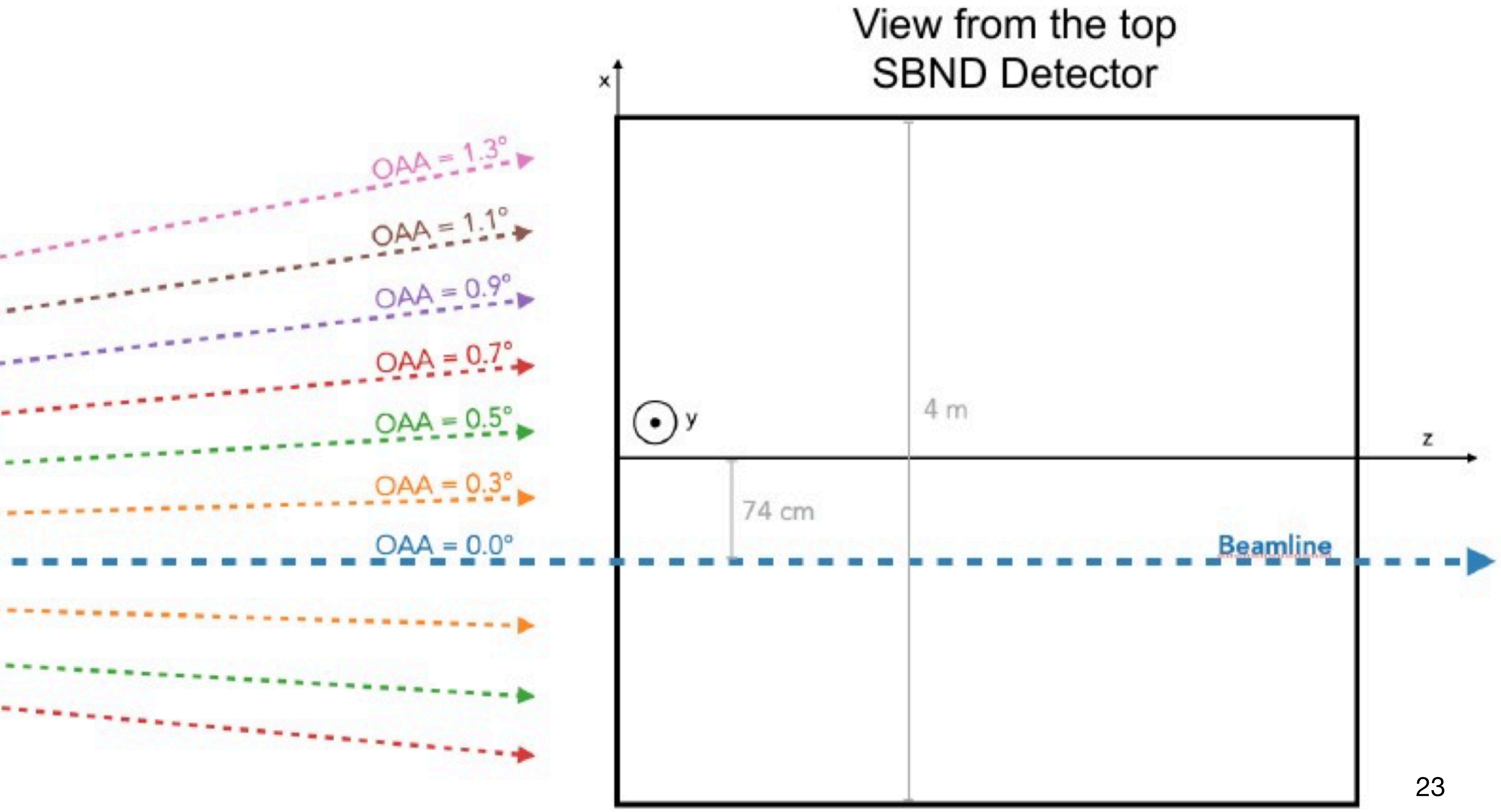
— Recent work to include PRISM and study effect on systematic constraints and sensitivities.

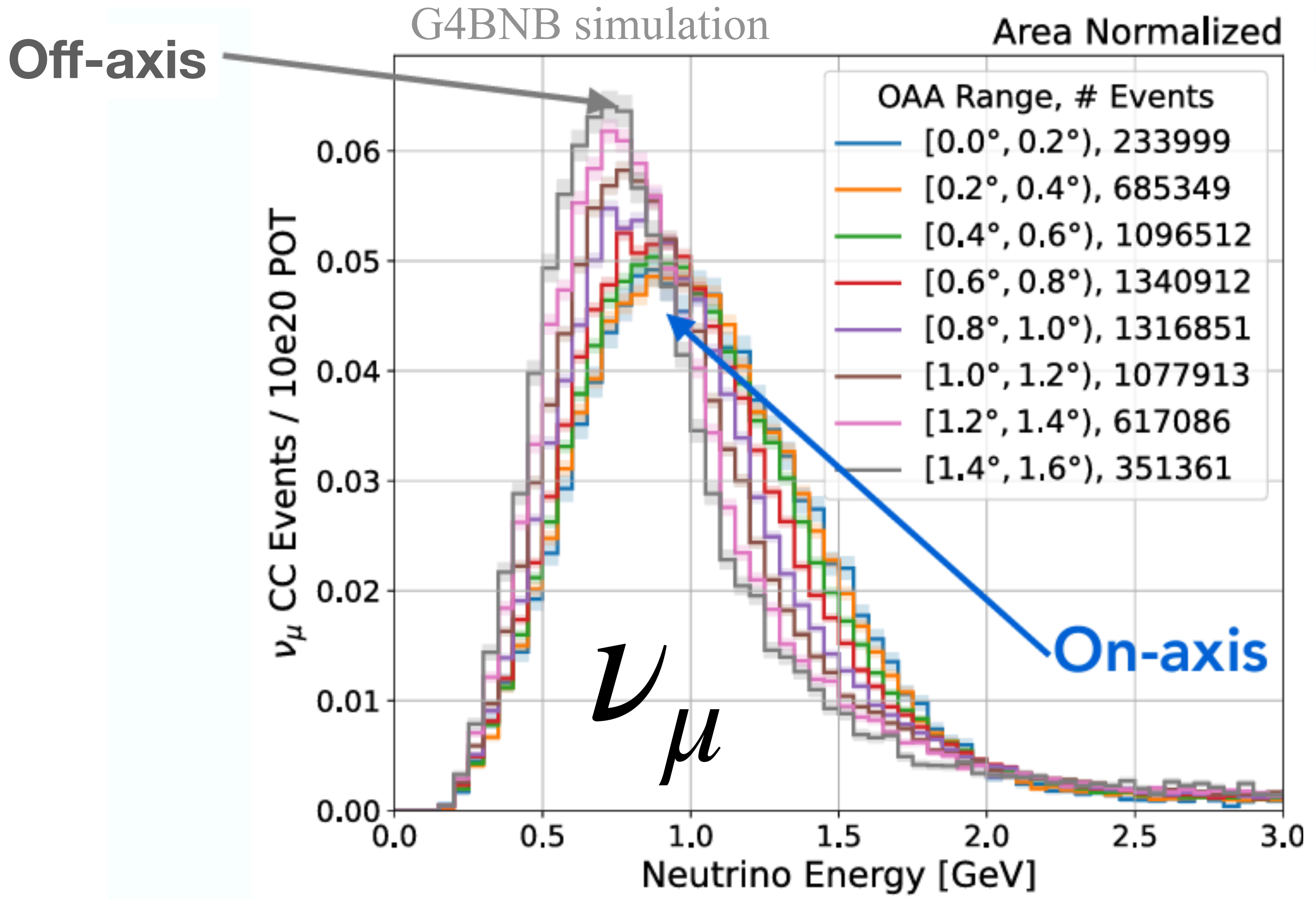


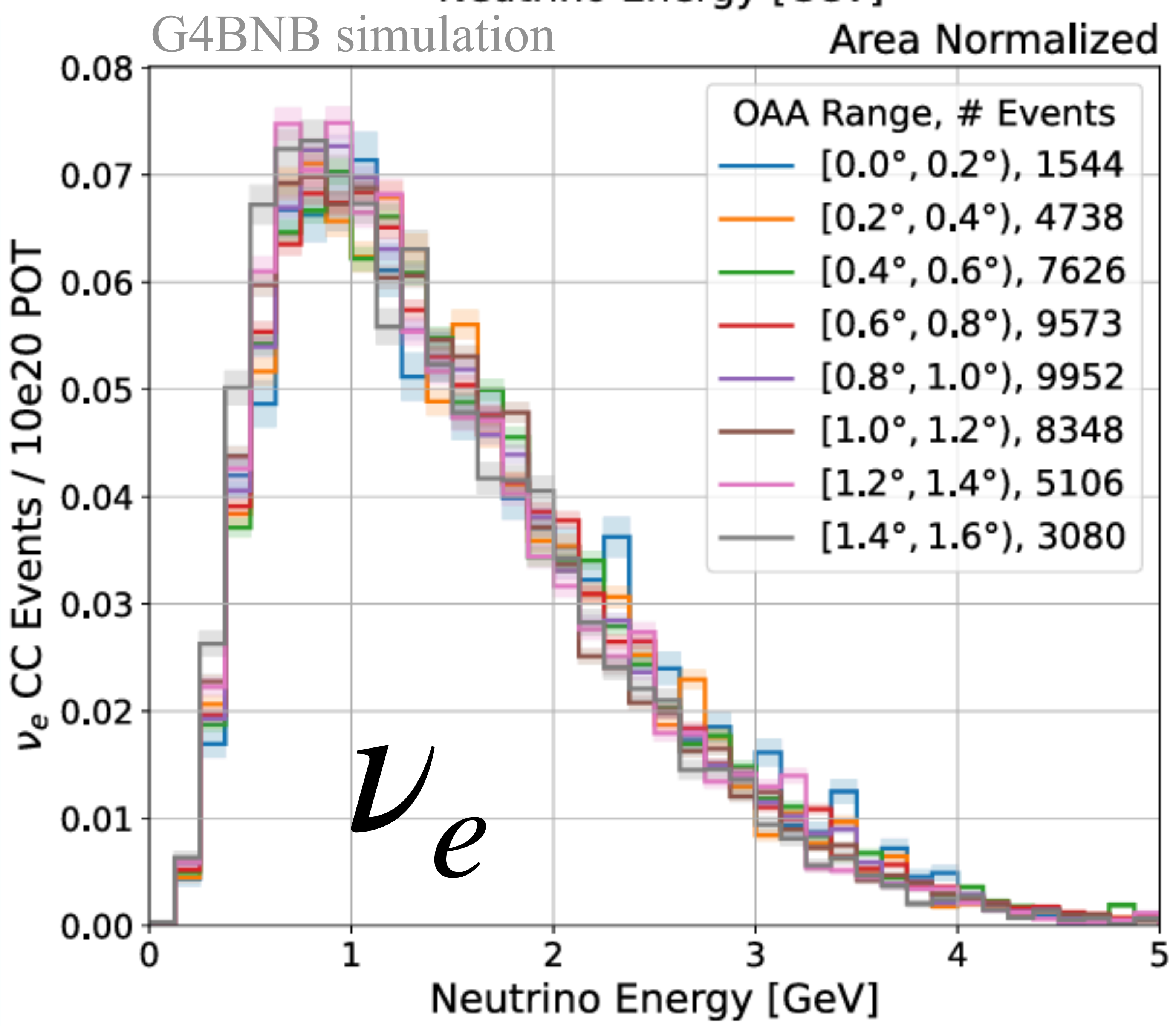
SBND-PRISM

— SBND's proximity to the beam allows exposure to BNB of up to ~1.6° off-axis!

— Enormous dataset also enables this (one can split the dataset into several angular bins while preserving statistical strength)



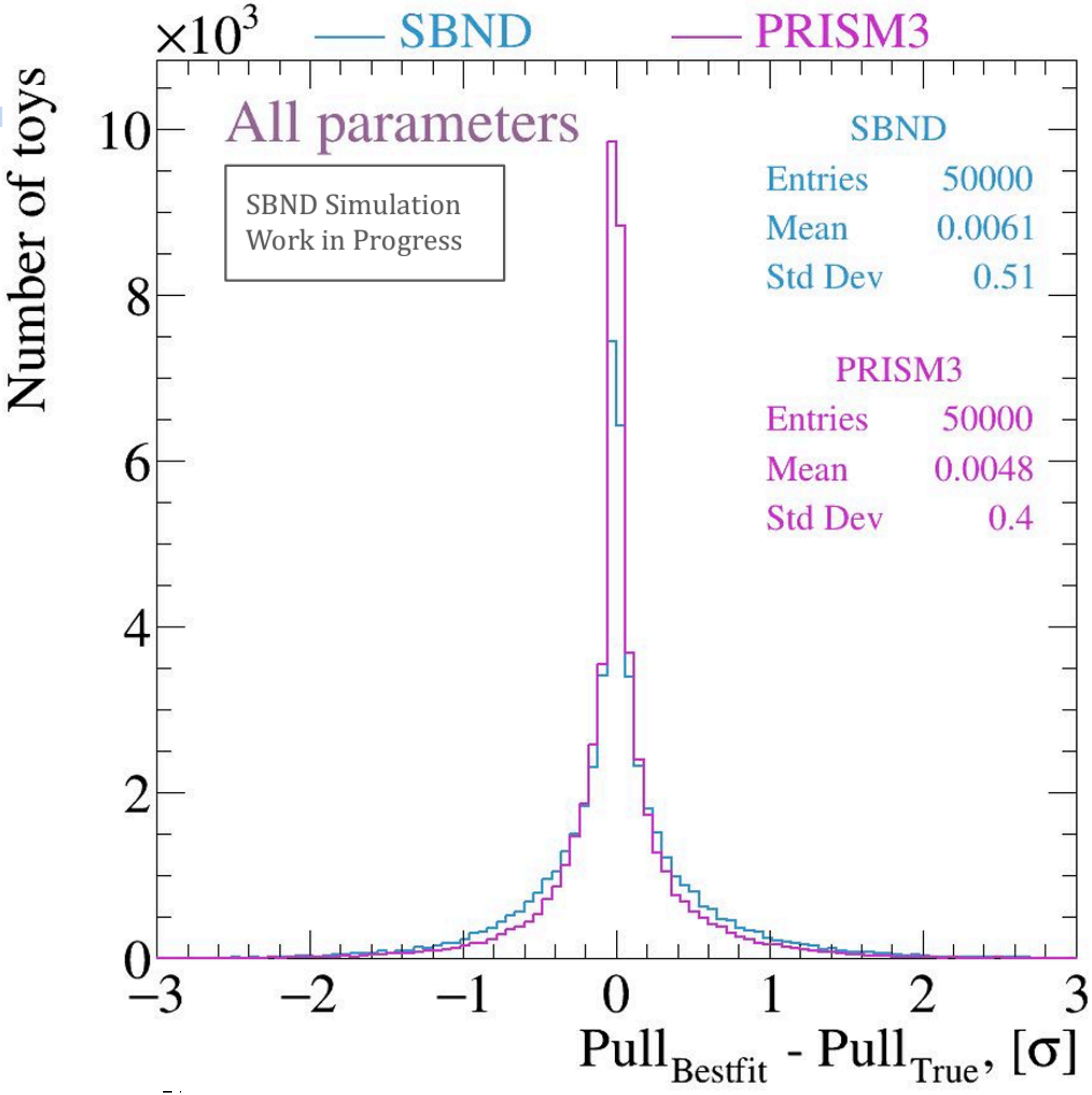




— First studies of PRISM with VALOR ongoing!

— PRISM3 is dividing the detector into three regions.

— Pull distributions visibly narrower, indicating a reduction of uncertainty (standard deviation is also smaller 0.5->0.4).



$PROfit

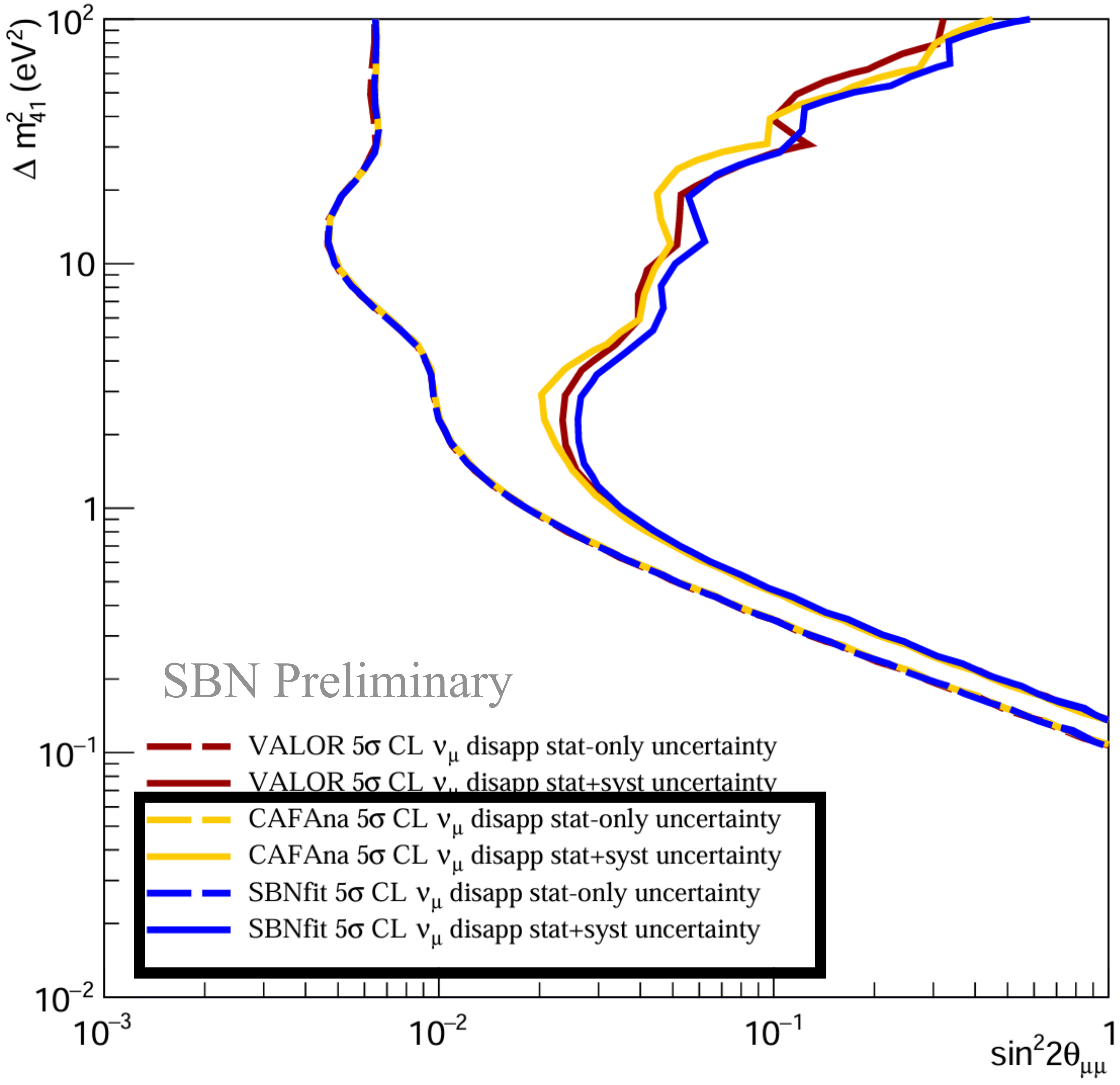
— Fitting framework combining features and expertise from predecessors (**SBNfit** *Phys.Rev.D 96, 055001 (2017)* & **CAFana** *J.Phys.Conf.Ser.664 (2015)*).

— Event-by-event oscillation and systematic evaluation enabling both binned and unbinned likelihood fits.

— Ability to treat systematics either as covariance matrix, pull terms, or combination of both. Multi-dimensional nuisance handling.

— Built-in capabilities to run on distributed high-performance computing grids

— Flexibility to add arbitrary number of beams, detectors, channels.

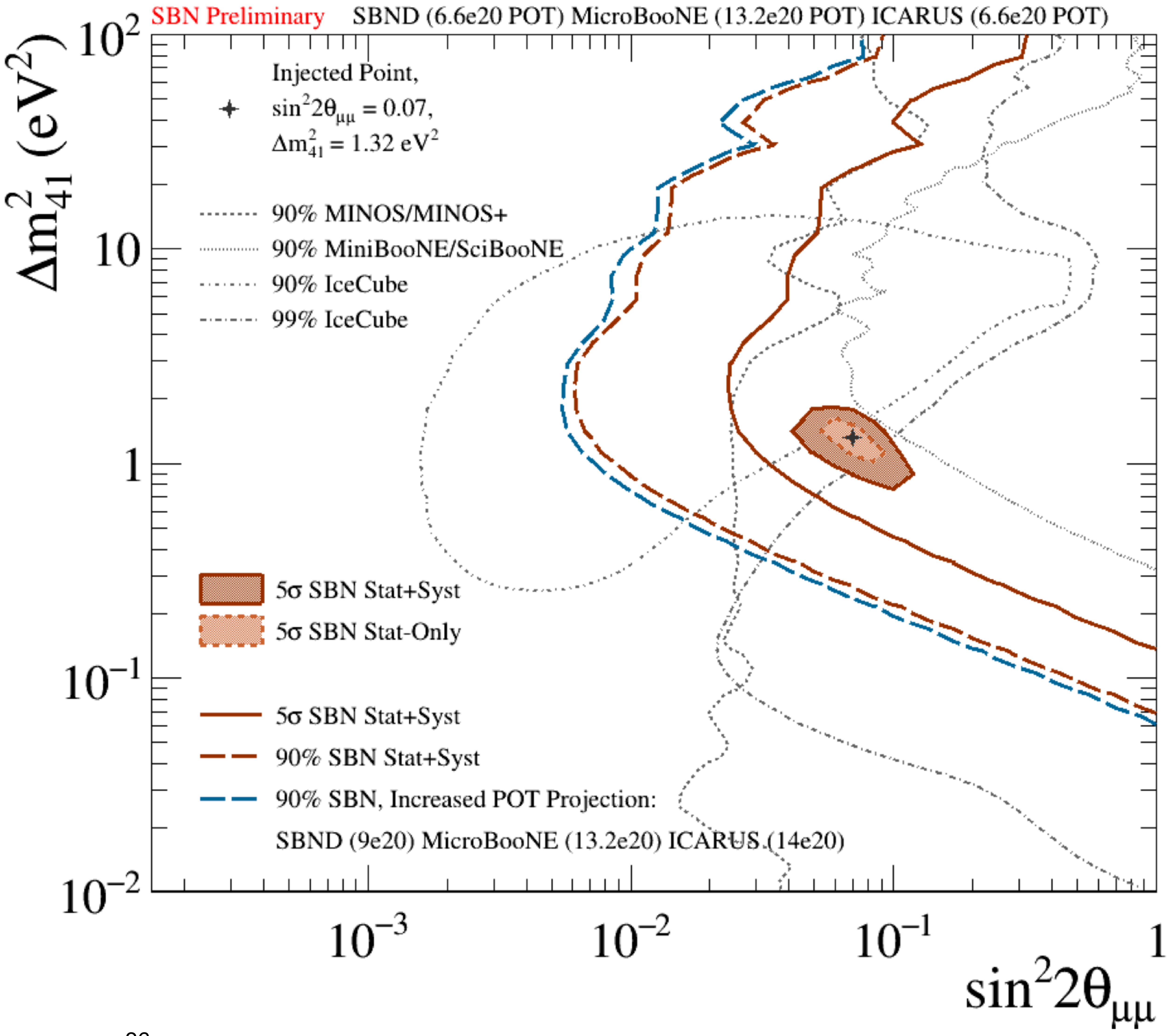


analysis plan

— A first SBN analysis using BNB to probe $\nu_\mu$disappearance is possible with current tools, and achievable with O(months) of SBND data.

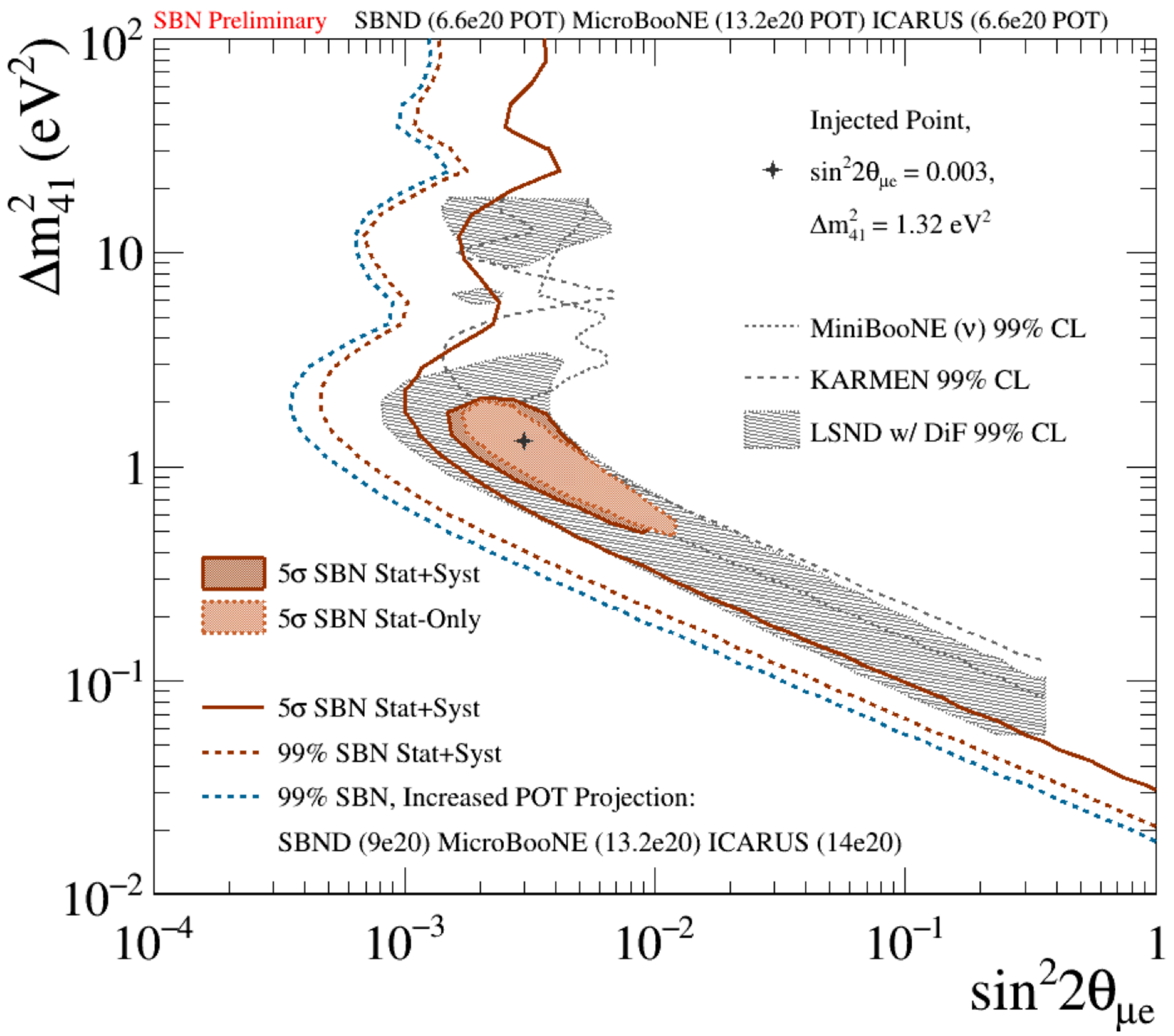
— Plan is dynamic. More oscillation channels are being explored actively and will be included as reconstructions and selections are validated.

— Result that comes out depends on status of ML reco, event selection optimization, detector modeling and uncertainty estimation, fitting frameworks.

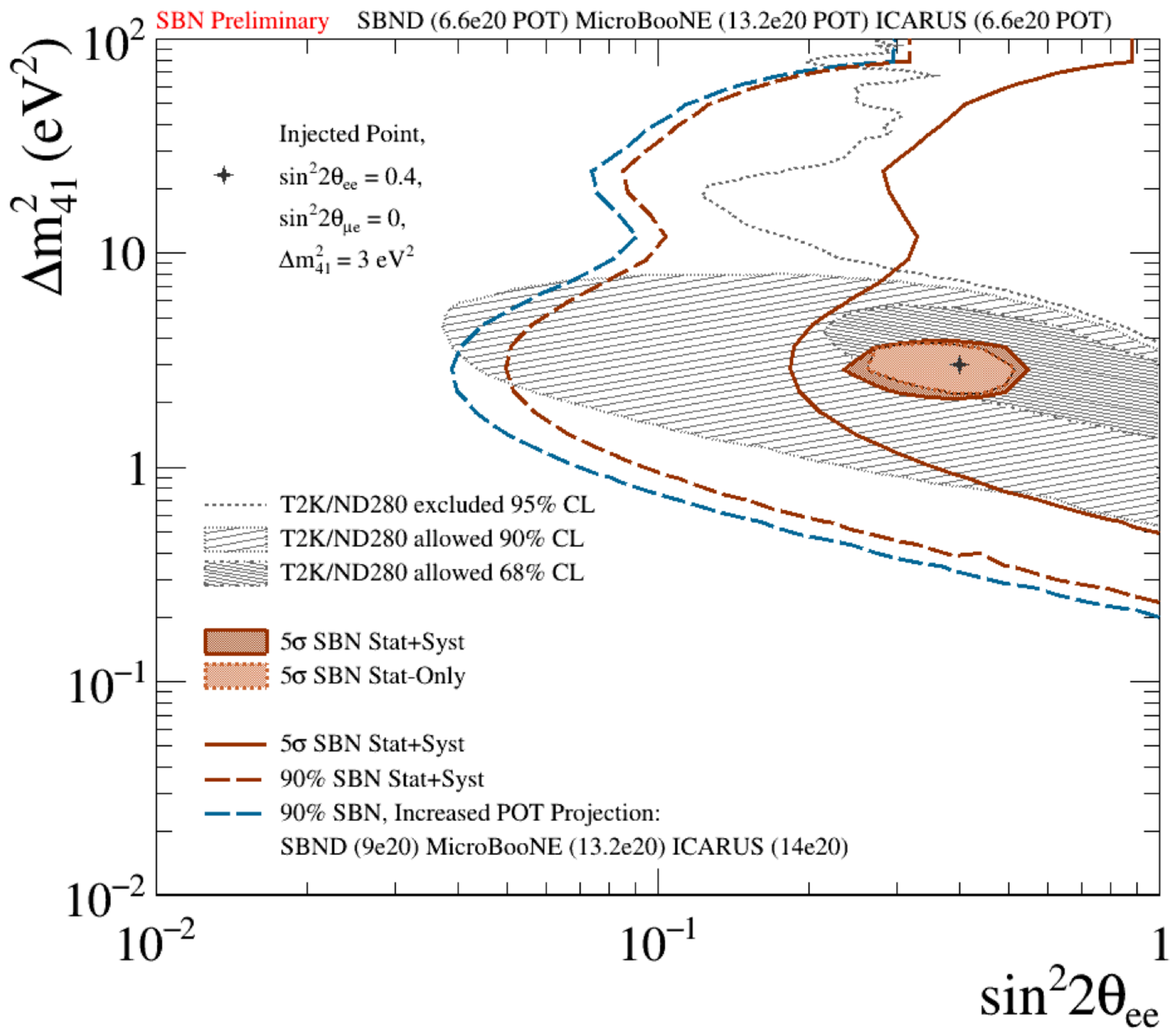


ν_e sensitivities

ν_e appearance



ν_e disappearance



— Current ν_e sensitivities, assuming ν_e appearance or disappearance ***only.*** Under 3+1 hypothesis, appearance and disappearance interfere.

— SBN will have sensitivity for many models and extensions beyond 3+1. Exploring best ways to report our results so that they are of use to the theory community. Ideas welcome!

Summary

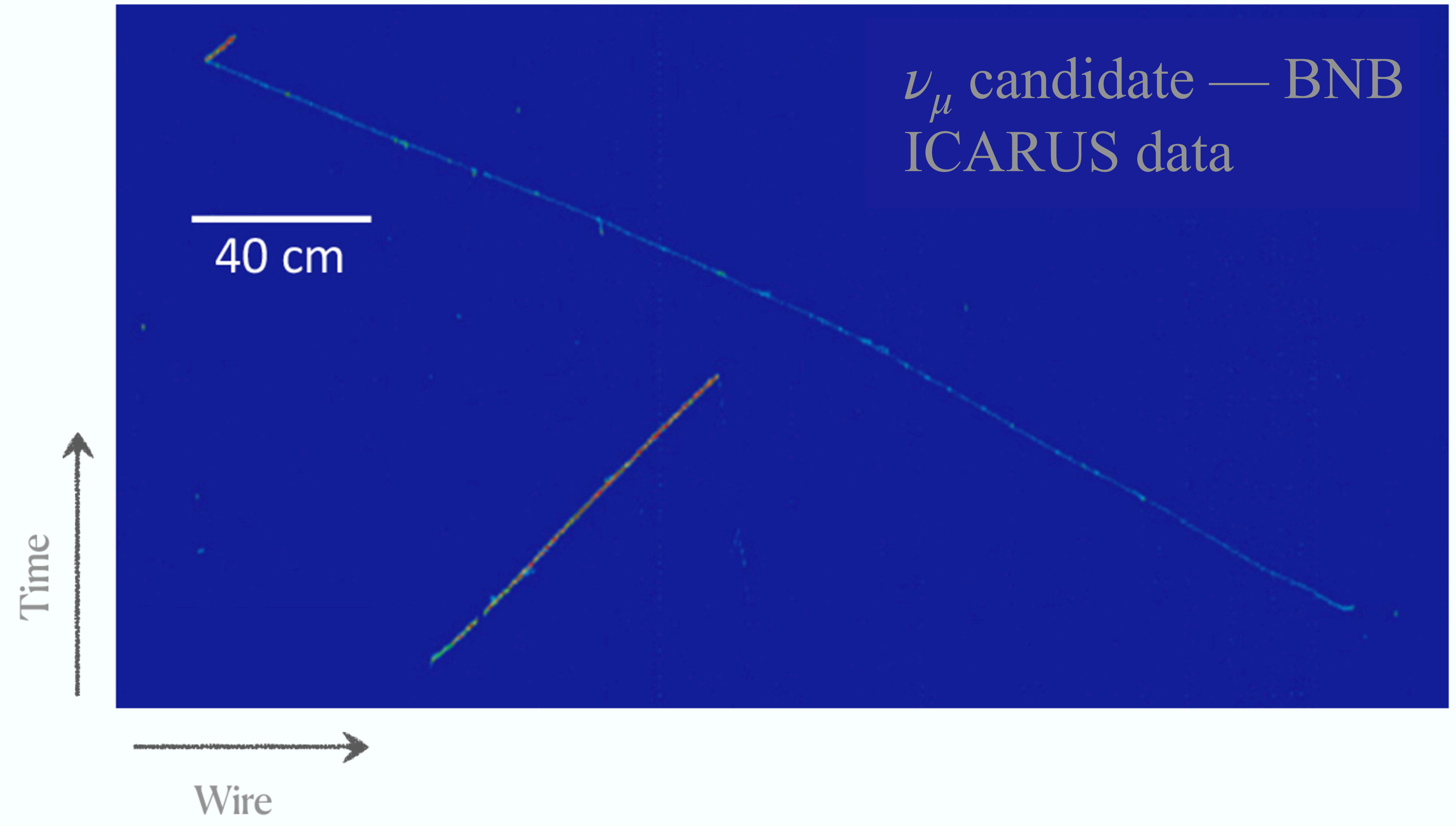
— SBN program is being fully realized with the commissioning of the near detector having officially started.

— ICARUS is operational and taking physics quality data since 2022. Immense effort to nail down detector modeling and uncertainty estimation.

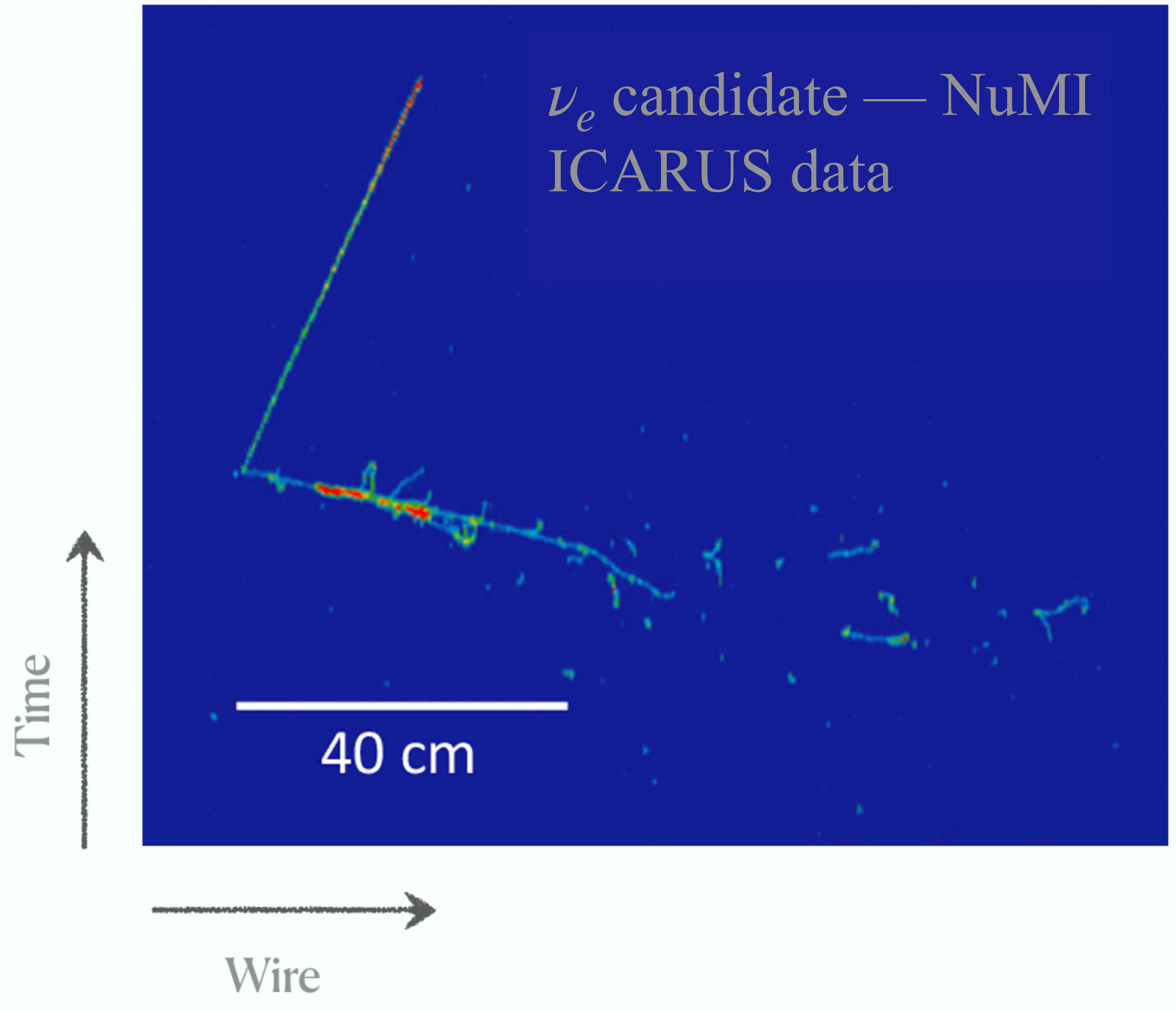
— SBN collaborators are coordinating development efforts among experiments including signal processing, reconstruction, fitting frameworks, and event selections, to ensure readiness for oscillation analysis once SBND data is available.

— A first SBN analysis of ν_μ disappearance with BNB is possible with current tools. Further channels are being pursued actively.

Muon neutrino candidate from BNB in one ICARUS TPC



Electron neutrino candidate from NuMI beam



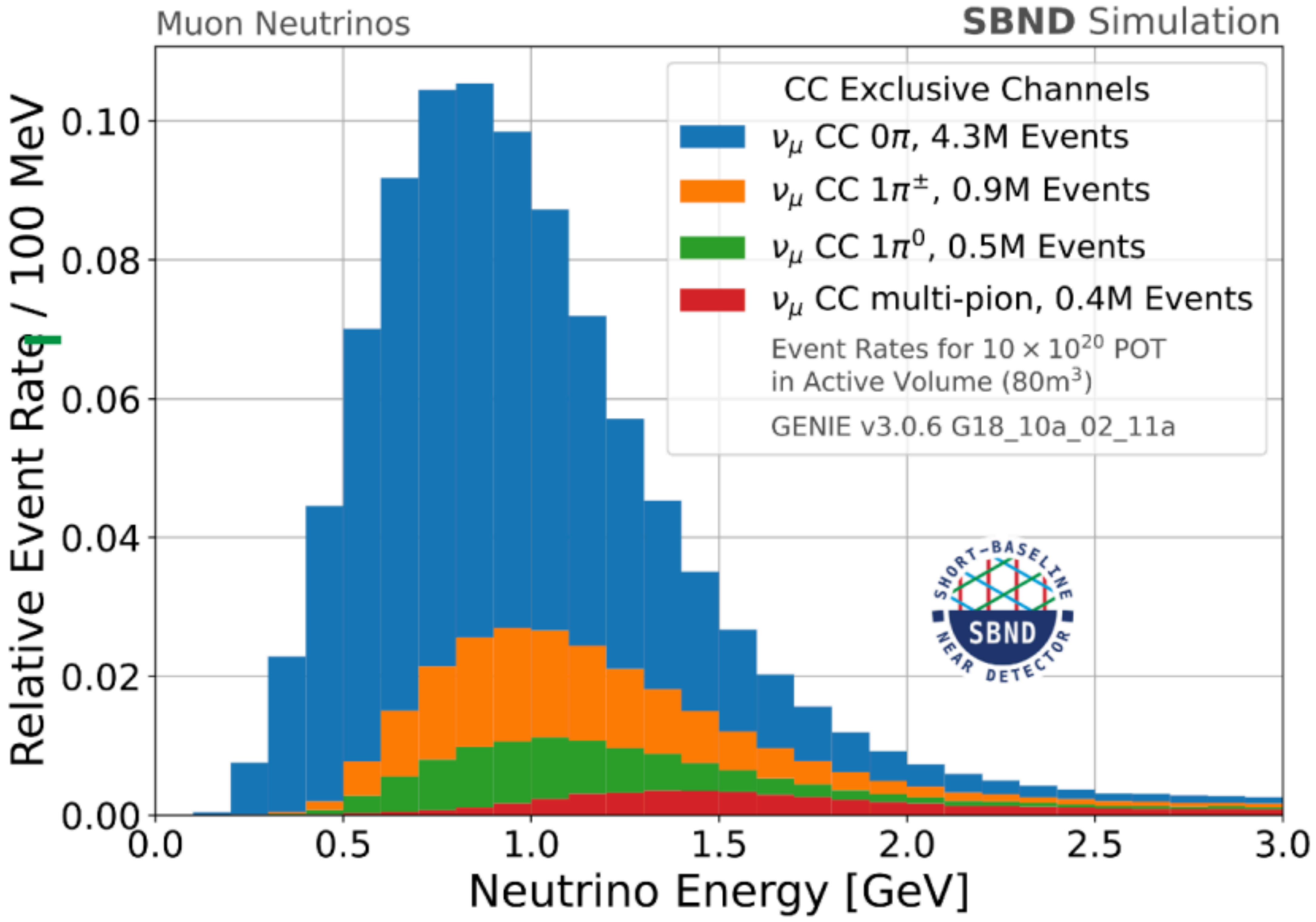
Thank you!

Imaging Cosmic And Rare Underground Signals

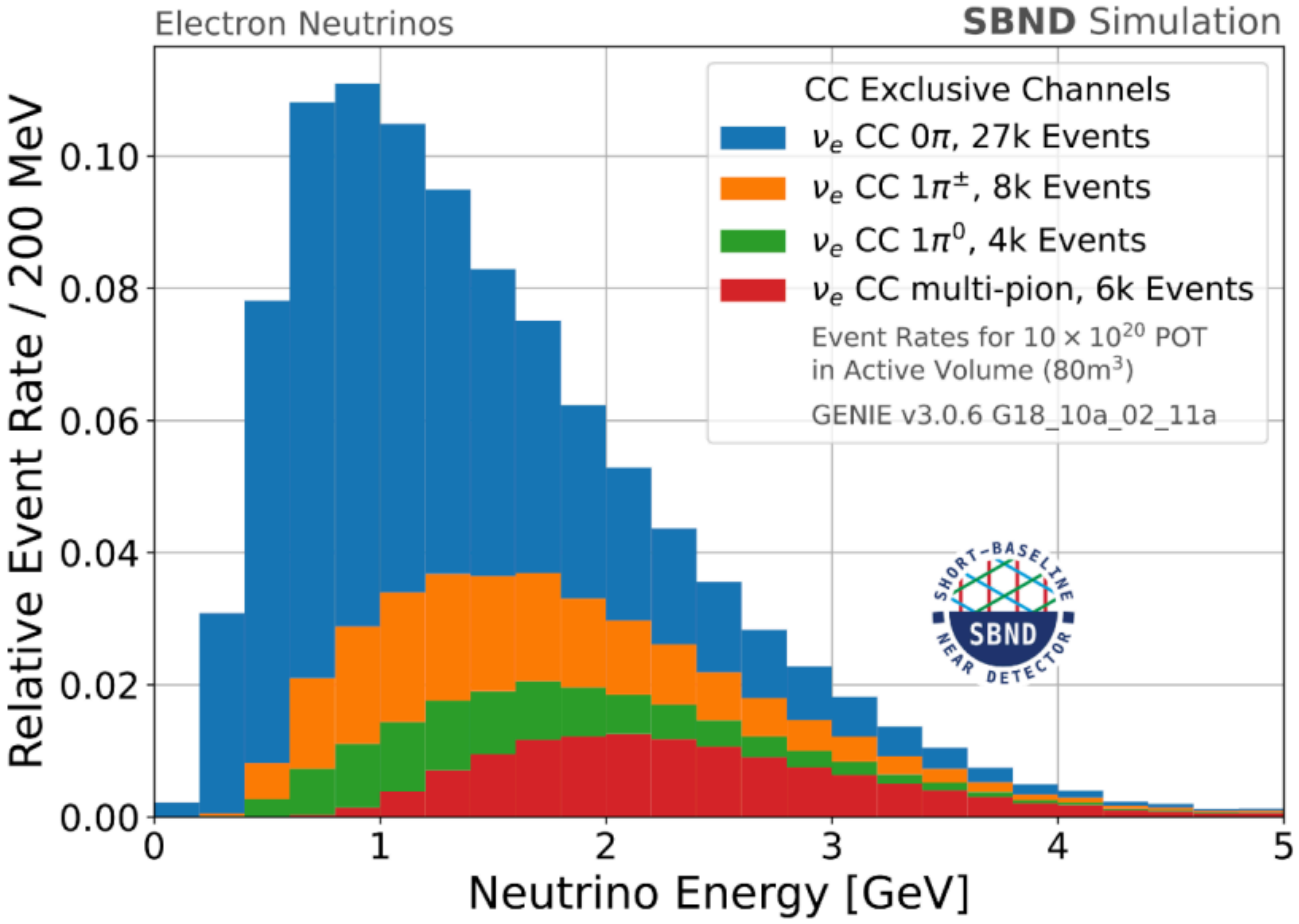
SHORT-BASELINE NEAR DETECTOR

SBND

SBND rates



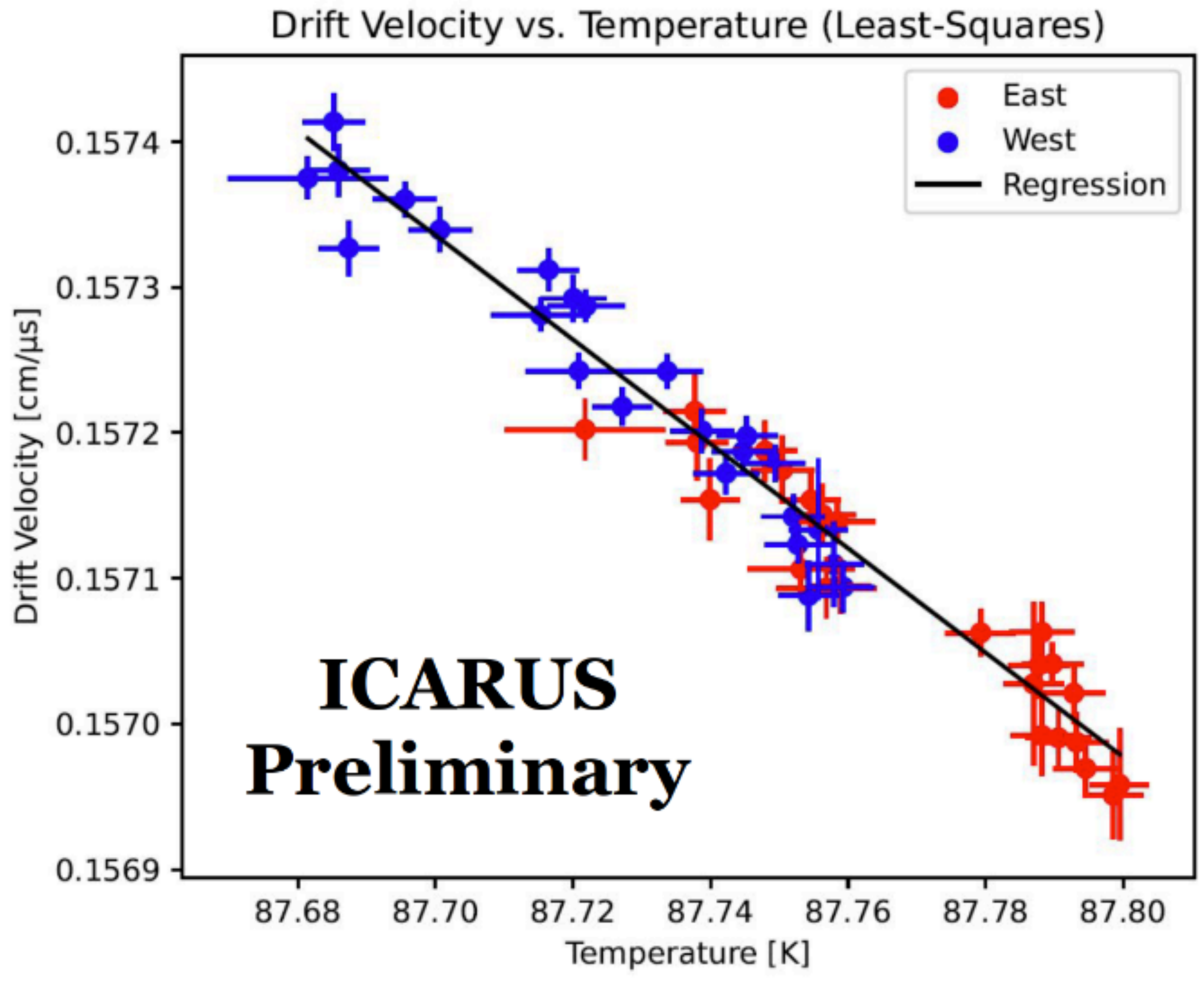
Muon Neutrinos
SBND Simulation
CC Exclusive Channels
ν_μ CC 0π, 4.3M Events
ν_μ CC 1$\pi^\pm$, 0.9M Events
ν_μ CC 1π^0, 0.5M Events
ν_μ CC multi-pion, 0.4M Events
Event Rates for 10×10^{20} POT
in Active Volume (80m^3)
GENIE v3.0.6 G18_10a_02_11a
Relative Event Rate / 100 MeV
Neutrino Energy [GeV]
0.00
0.02
0.04
0.06
0.08
0.10
0.0
0.5
1.0
1.5
2.0
2.5
3.0



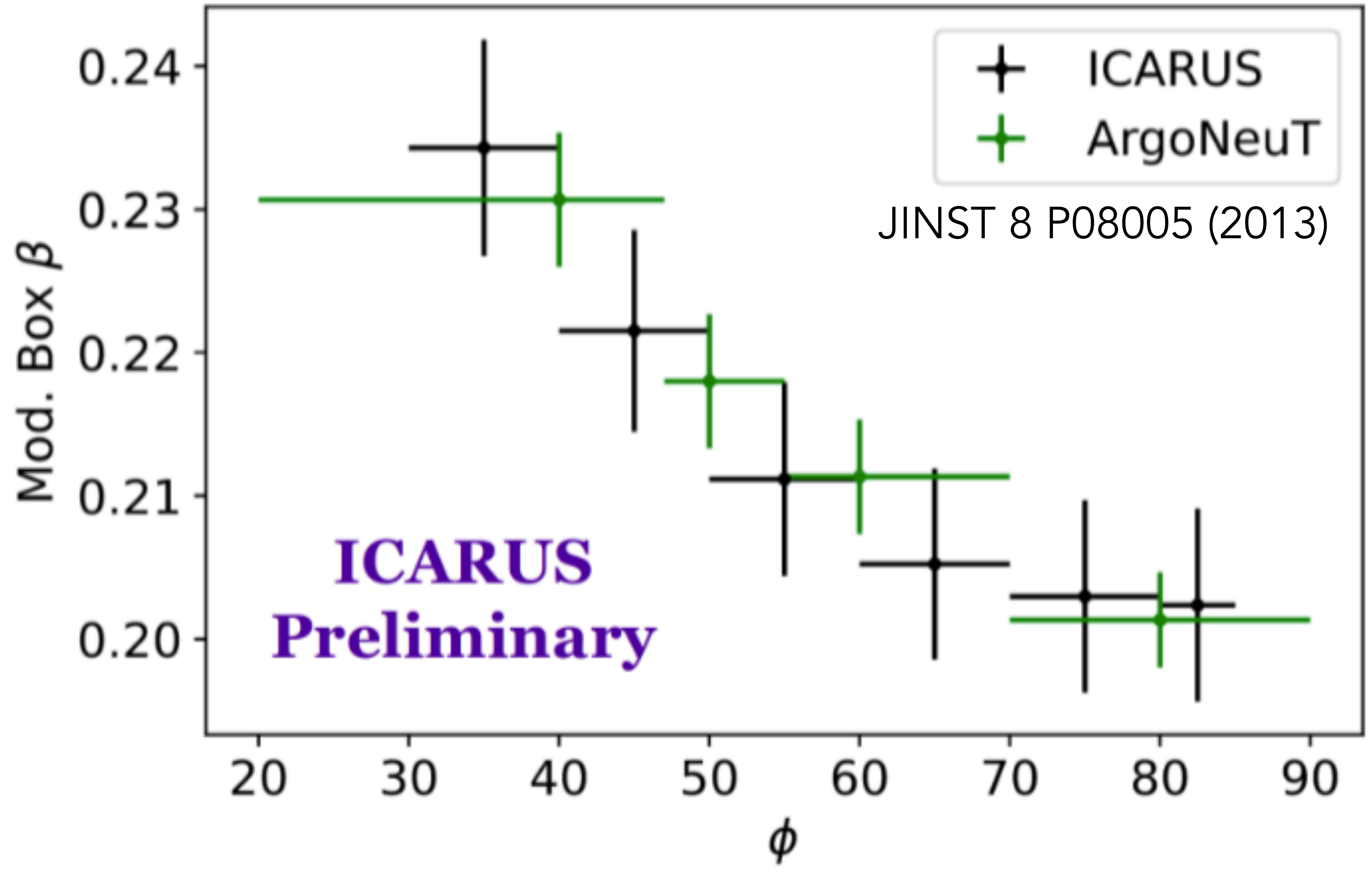
Electron Neutrinos
SBND Simulation
CC Exclusive Channels
ν_e CC 0π, 27k Events
ν_e CC 1$\pi^\pm$, 8k Events
ν_e CC 1π^0, 4k Events
ν_e CC multi-pion, 6k Events
Event Rates for 10×10^{20} POT
in Active Volume (80m^3)
GENIE v3.0.6 G18_10a_02_11a
Relative Event Rate / 200 MeV
Neutrino Energy [GeV]
0.00
0.02
0.04
0.06
0.08
0.10
0
1
2
3
4
5

LAr measurements

$$dE/dx = (exp(\beta W_{ion} \cdot (dQ/dx)) - \alpha)/\beta.$$



Measurement of the electron drift velocity as a function

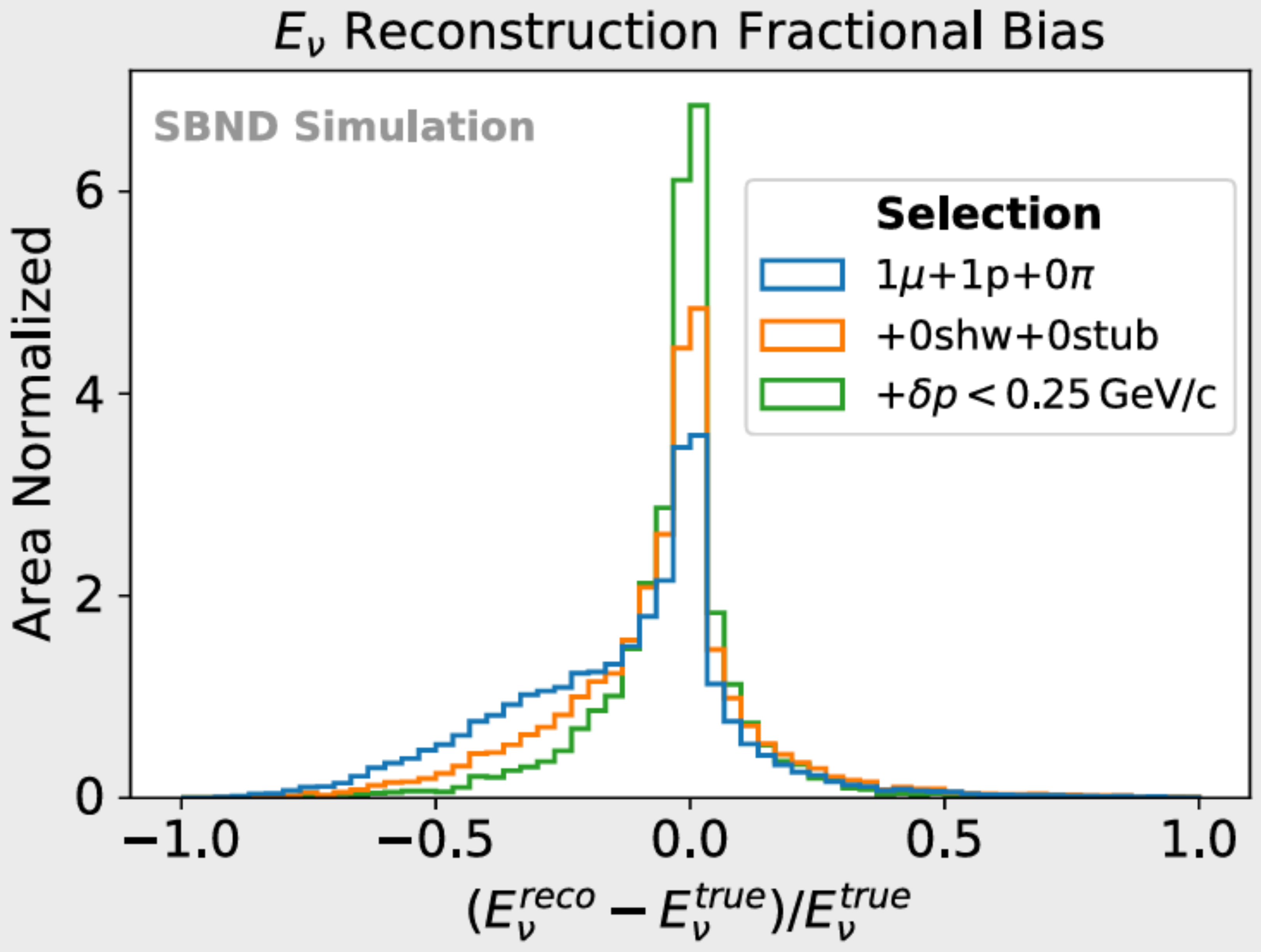


JINST 8 P08005 (2013)

Measurement of the angular dependence of electron absorption (recombination) relative to electric field direction

SBND Ereco

Neutrino Energy Reconstruction



- Neutrino energy reconstruction is important for oscillation searches
- LArTPCs allow calorimetric energy calculation

$$E_\nu^{reco} = E_\mu + T_p + E_B + E_T$$

E_B : binding energy

$E_T = \sqrt{p_T^2 + M_A'^2} - M_A'$

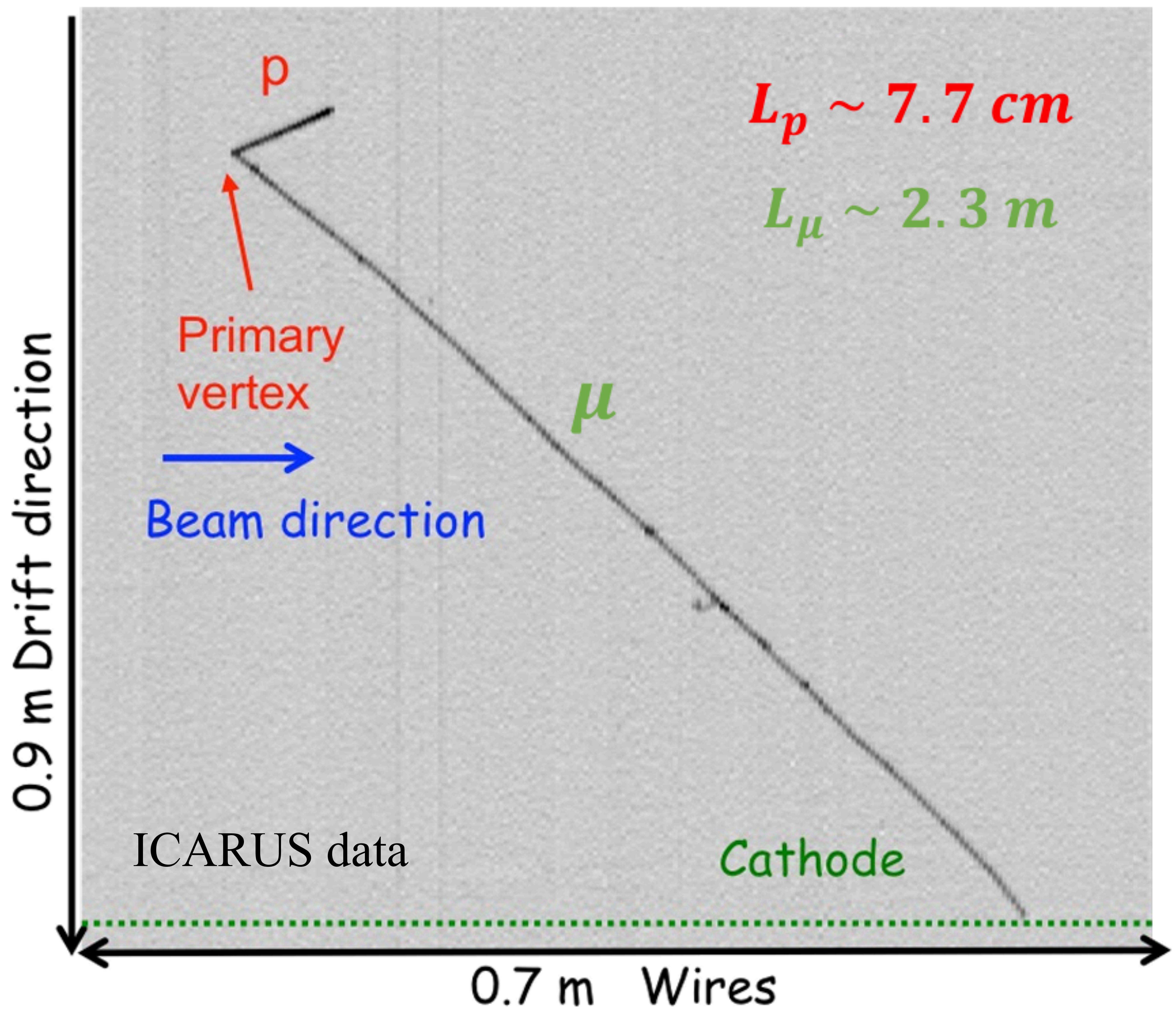
E_μ : reconstructed muon energy

T_p : proton kinetic energy

  - Selected high-purity 1p0π events have good energy reconstruction

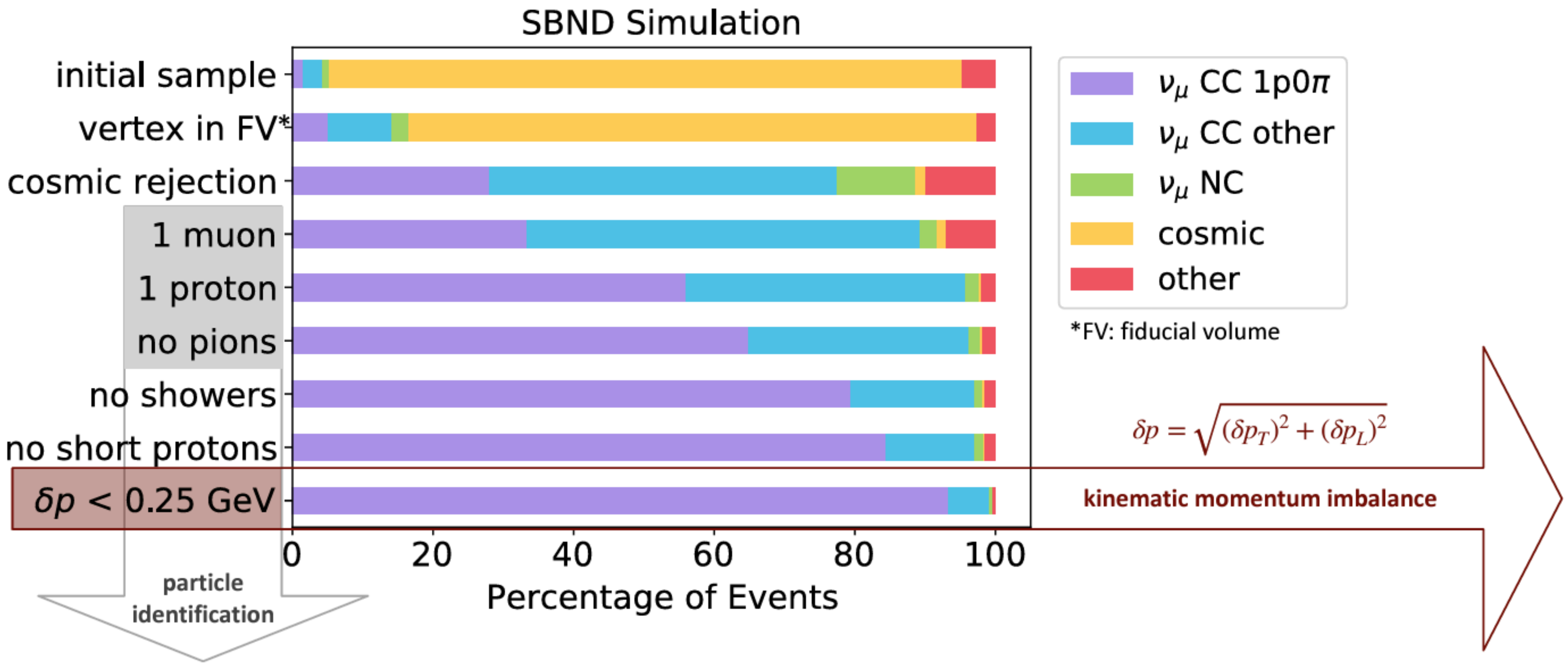
Reconstruction

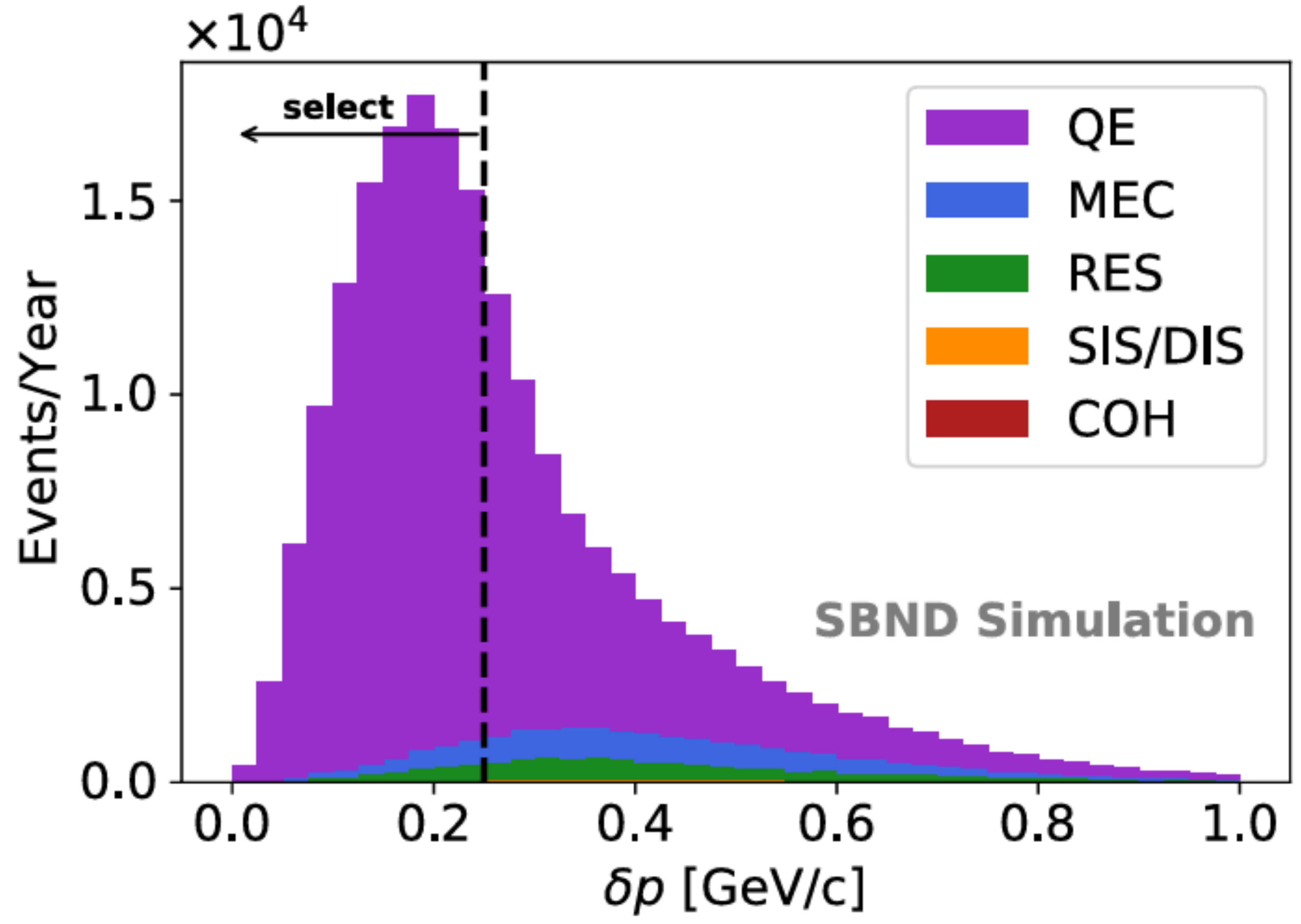
- Hand-scanned neutrino event.

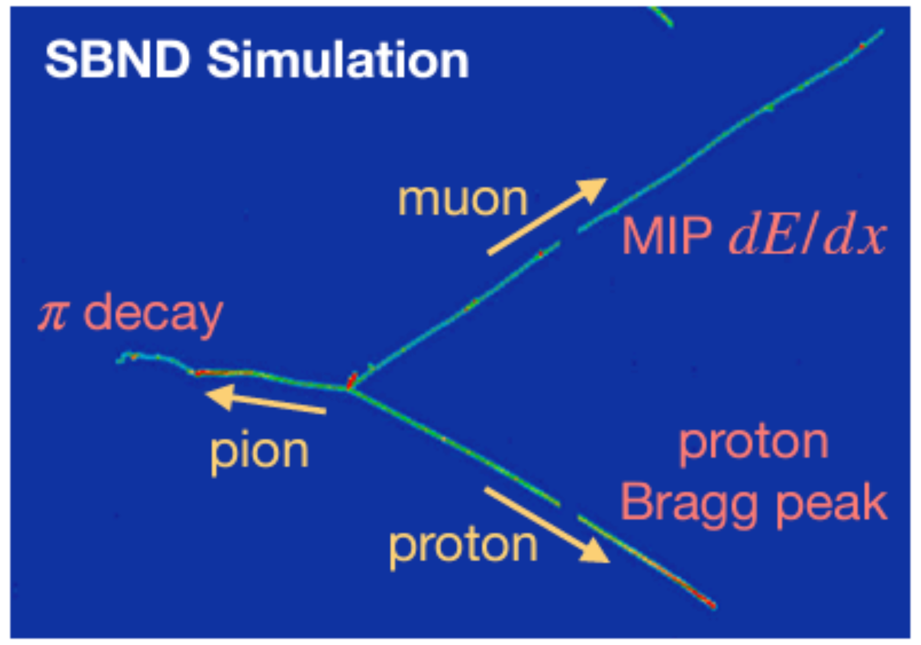


SBND Event selections

Event Selection







- SBND has multiple tools for high-efficiency and high-purity event selection
- High-resolution LArTPC images and calorimetry enables identification of particles species

- Selecting events with low momentum imbalance rejects non-QE interaction events
- We obtain a final sample with signal purity 93%, QE purity 95%, at efficiency 23%

NuMI off-axis

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta_{\text{Lab}}^2}$$