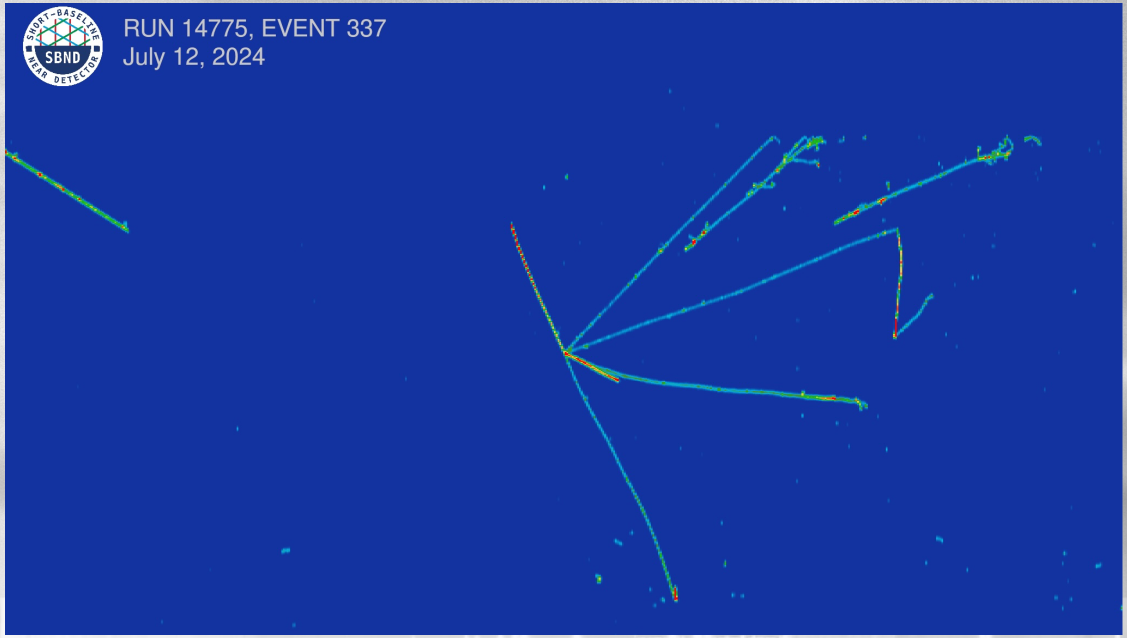
FERMILAB-SLIDES-25-0316-PPD

Fermilab

SHORT-BASELINE NEAR DETECTOR SBND

2025-12-04

Toward SBND's First Cross Section Measurements



Sungbin Oh on behalf of the SBND collaboration
Fermilab

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Contents

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01

Why Do We Study Neutrino Interactions?

Essential Input for All Neutrino Experiments

We can study neutrinos only in the case that there are

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- Neutrino source
- Neutrino detector

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    - Neutrino interaction model for interaction **rate** and **outcomes**

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Phys.Rev. 92 (1953) 830-831

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.

Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

An experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_{-}+p\rightarrow n+\beta^{+}, \qquad (1)$$

has been calculated[2,3] from beta-decay theory to be given by the expression,

$$\sigma=\left(\frac{G^2}{2\pi}\right)\left(\frac{\hbar}{mc}\right)^2\left(\frac{p}{mc}\right)^2\left(\frac{1}{v/c}\right), \qquad (2)$$

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Essential Input for All Neutrino Experiments

We can study neutrinos only in the case that there are

- Neutrino source
- Neutrino detector
  - Neutrino interaction model for interaction **rate** and **outcomes**
- Measured a fundamental property of neutrinos: their existence!

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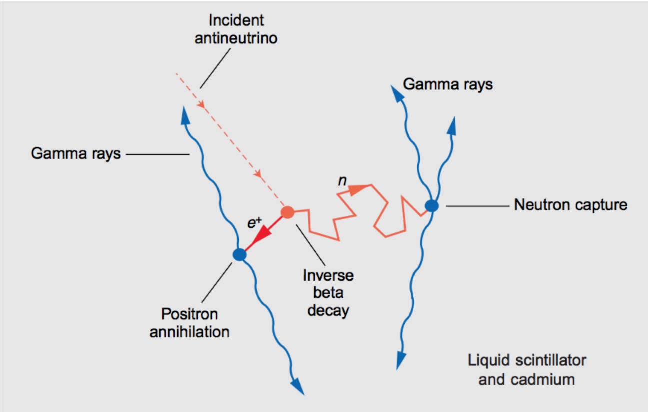

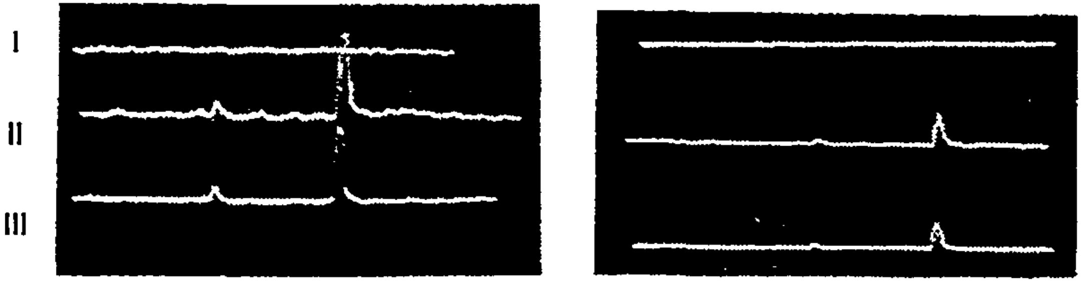

(b) Positron scope   Neutron scope

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Essential Input for All Neutrino Experiments

Neutrino Oscillation

Essential Input for All Neutrino Experiments

Neutrino Oscillation: Tool for neutrino studies

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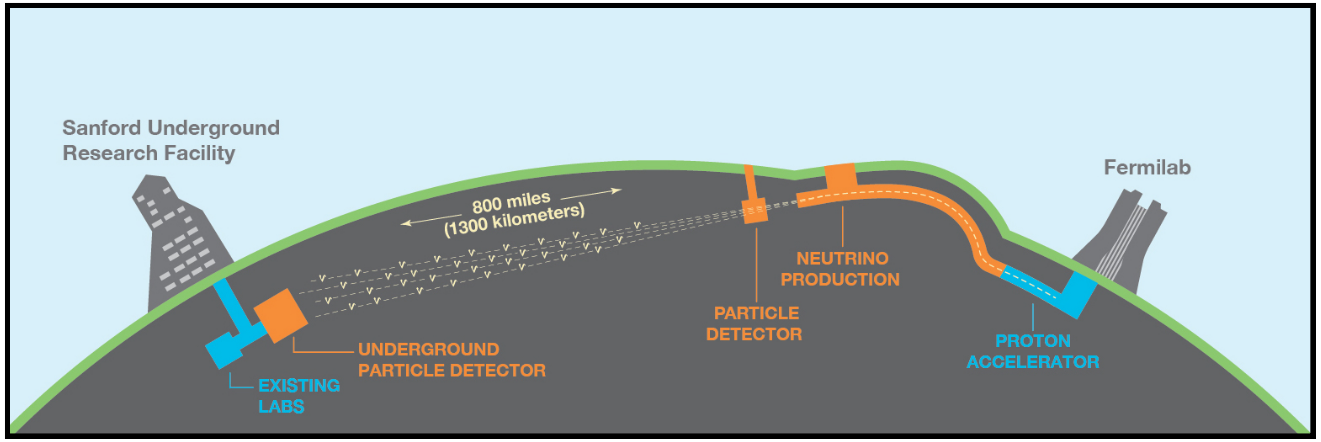
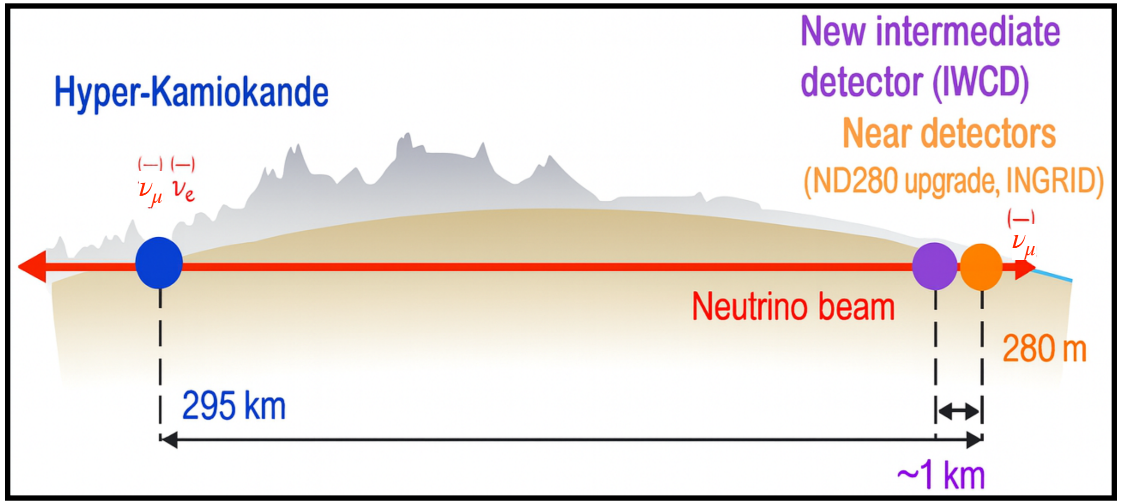
Neutrino Oscillation: Tool for neutrino studies

- DUNE and T2HK: essential for deeper understanding to lepton mixings and validating charge-parity (CP) symmetry violation in them

	E_ν	Proton Beam	Active Target
DUNE	Peak ~ 3 GeV	30 GeV 1.3 MW	Liquid argon 17 kton x 4
T2HK	Peak ~ 600 MeV	120 GeV 1.2 - 2 MW	Water 187 kton





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Neutrino cross section plays a **critical** role

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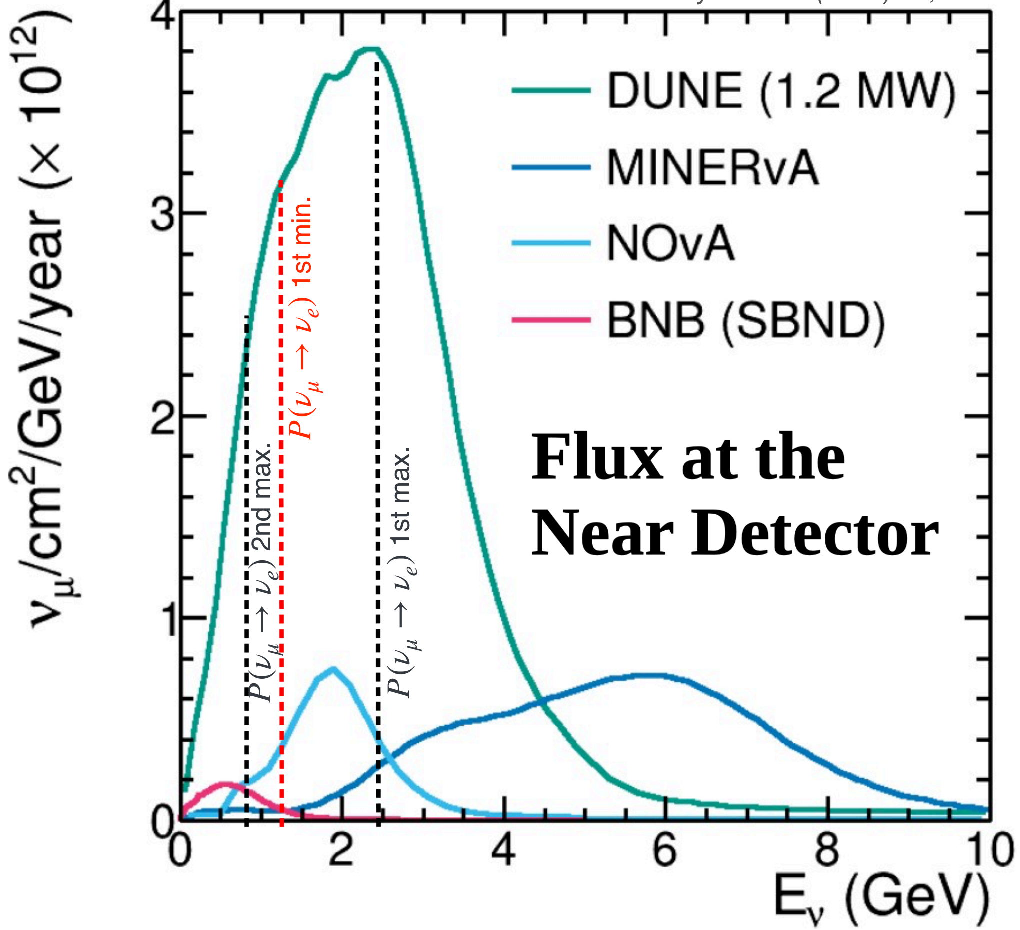
Neutrino cross section plays a **critical** role

- Event rate at near detector
  - $N(E_\nu^{reco.}) = \int \Phi_\nu(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$

DUNE Collab. *Eur.Phys.J.C 80 (2020) 10, 978*



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Flux | Cross section | Detector effect

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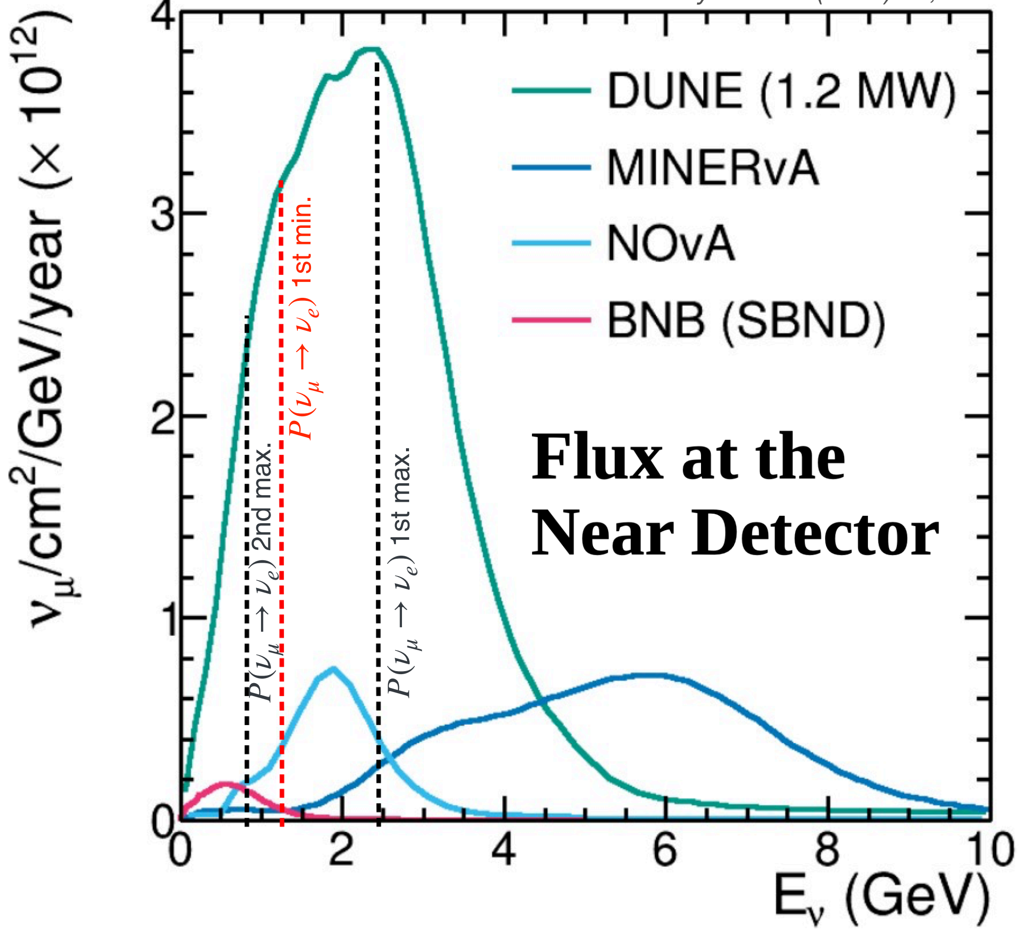

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- In fact, it is more complicated than this!

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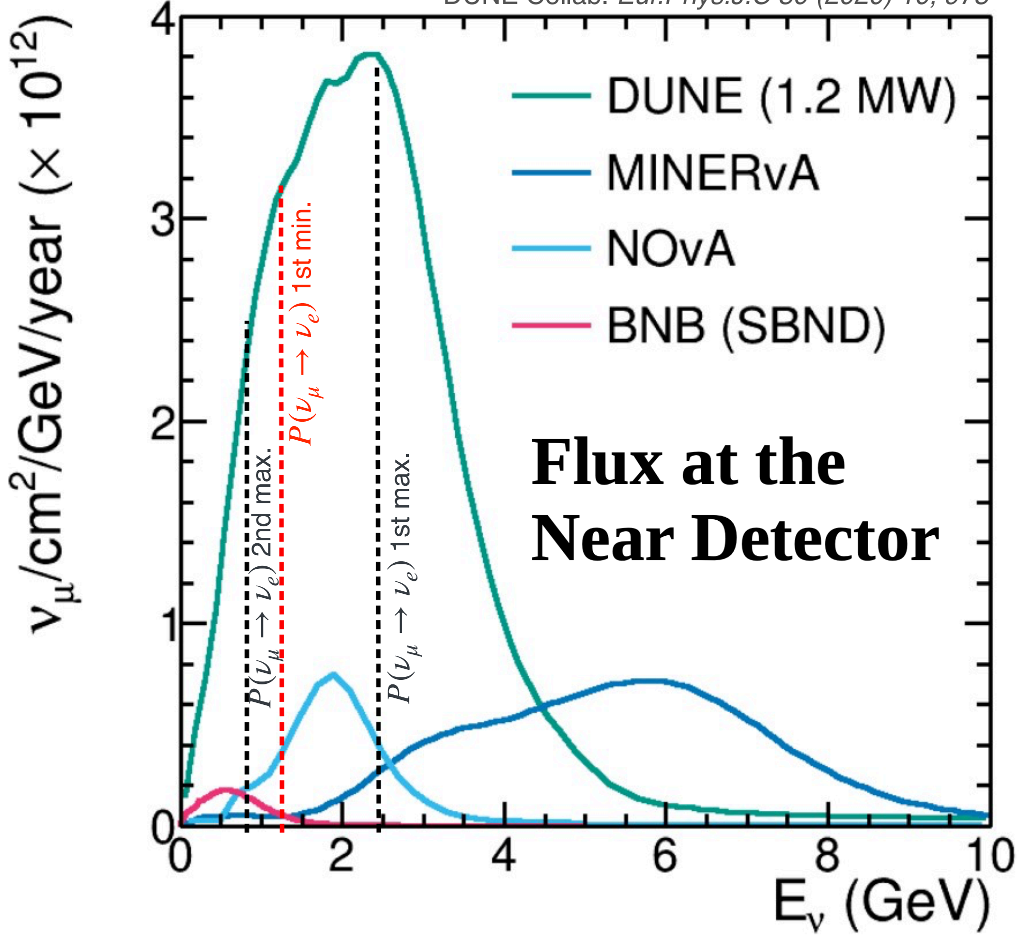

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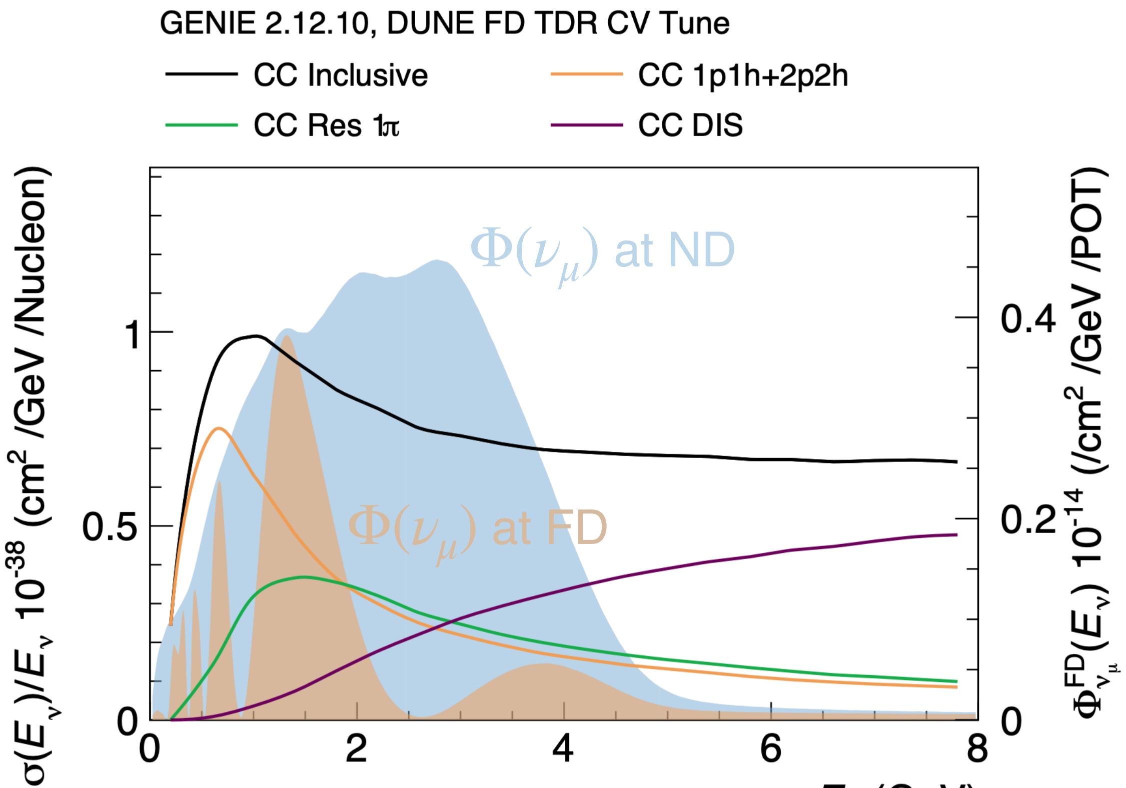
$$\sigma(E_\nu)\epsilon(E_\nu) = \int \frac{d\sigma(E_\nu)}{dO}\epsilon(O\,|\,E_\nu)dO,$$

where O is final state particles kinematics



DUNE Collab. *arXiv:2103.04797*

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- Event rate at near detector
  - $$N(E_\nu^{reco.}) = \int \underbrace{\Phi_\nu(E_\nu)}_{\text{Flux}}\underbrace{\sigma(E_\nu)}_{\text{Cross section}}\underbrace{\epsilon(E_\nu)}_{\text{Detector effect}}dE_\nu$$
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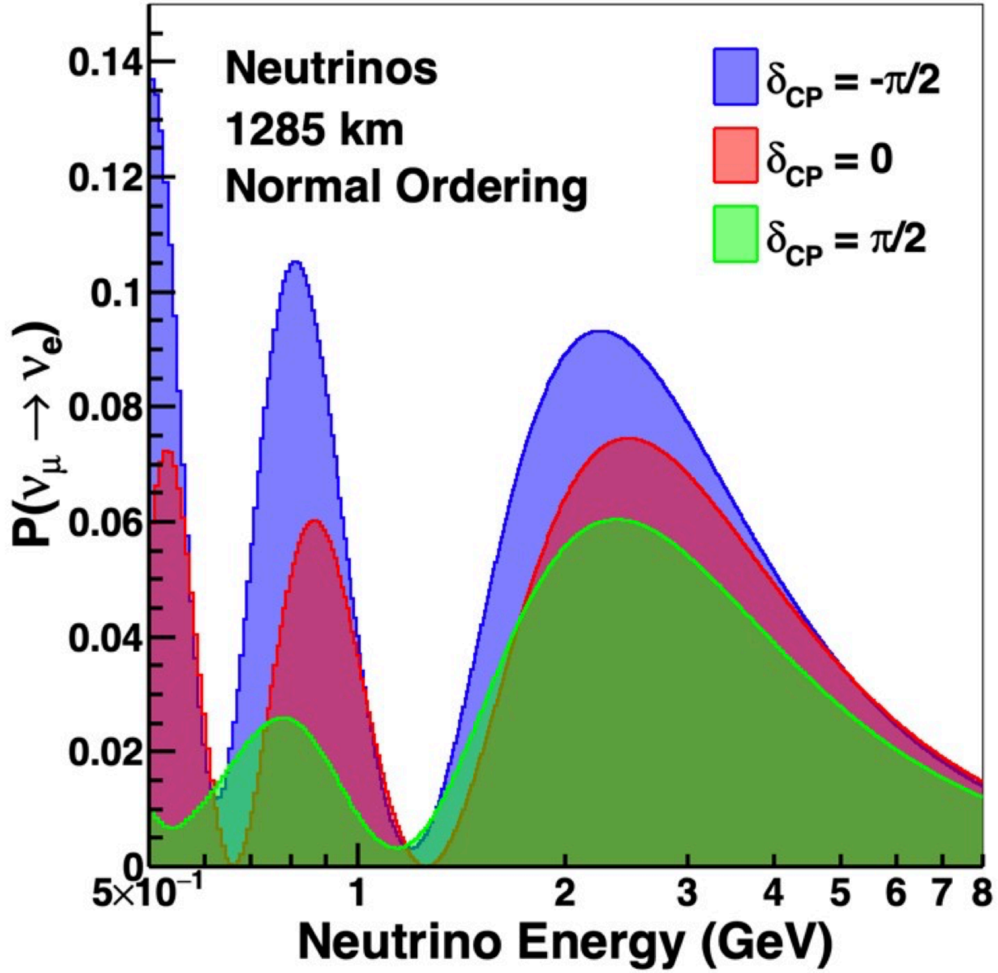
  where O is final state particles kinematics
- Far detector: oscillation probabilities play too!

DUNE Collab. *Eur.Phys.J.C 80 (2020) 10, 978*



Essential Input for All Neutrino Experiments

Neutrino Oscillation: Tool for neutrino studies

- DUNE and T2HK: essential for deeper understanding to lepton mixings and validating CP phase in them

Neutrino cross section plays a **critical** role

- One of the leading systematic uncertainty source of modern long baseline experiment

NOνA 2024 Result's Uncertainty Budget

Source	$\lvert\Delta m^2_{32}\rvert$	$\sin^2\theta_{23}$	δ_{CP}
Beam flux	+0.02/-0.05	+0.07/-0.14	+0.18/-1.15
Calibration	+0.57/-0.74	+0.58/-2.91	+1.95/-19.5
Detector model	+0.07/-0.11	+0.07/-0.71	+0.43/-3.79
Lepton Reco.	+0.37/-0.57	+0.49/-0.82	+0.70/-3.33
ND – FD Uncor.	+0.10/-0.14	+0.44/-0.45	+0.91/-4.60
Cross Sections	+0.27/-0.45	+0.56/-0.93	+2.30/-11.2
Neutron model	+0.10/-0.16	+0.49/-0.09	+0.49/-1.49
Systematic Unc.	+0.70/-0.94	+1.20/-3.27	+3.33/-24.1
Statistical Unc.	+1.31/-1.80	+4.00/-15.5	+7.59/-85.1

NOvA Collab. *FERMILAB-PUB-25-0619-PPD*

T2K 2023 ν_μ Disappearance Uncertainty Budget

TABLE II. Uncertainties on the number of events in each SK sample broken down by error source after the near-detector analysis. The first two rows show the uncertainties when flux and crosssection systematics (constrained by the near detector) are propagated without correlation, whereas the third (Flux+Xsec) has smaller uncertainties due to the anticorrelations in the near-detector analysis, and corresponds to what is used in the analysis. "SK det." includes uncertainties from the SK detector response.

Error source (units: %)	1Rμ ν-mode	1Rμ $\bar{\nu}$-mode
Flux	2.9	2.8
Xsec (ND constrained)	3.1	3.0
Flux+Xsec (ND constr.)	2.1	2.3
SK-only Xsec	0.6	2.5
SK det.	2.1	1.9
Total	3.0	4.0

T2K Collab. *Phys.Rev.D 108 (2023) 7, 072011*

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One of the leading systematic uncertainty sources

↓

Important and NOT well understood

↓

If there is a physical phenomenon
that we do not have a model to predict the observation well,
that is an excellent sole motivation to study deeper!

So			
Be			
Ca			
De			
Le			
NI			
Cr			
Ne			
Systematic Unc.	+0.70/-0.94	+1.20/-3.27	+3.33/-24.1
Statistical Unc.	+1.31/-1.80	+4.00/-15.5	+7.59/-85.1

NOvA collab. *FERMILAB-PUB-25-0619-PPD*

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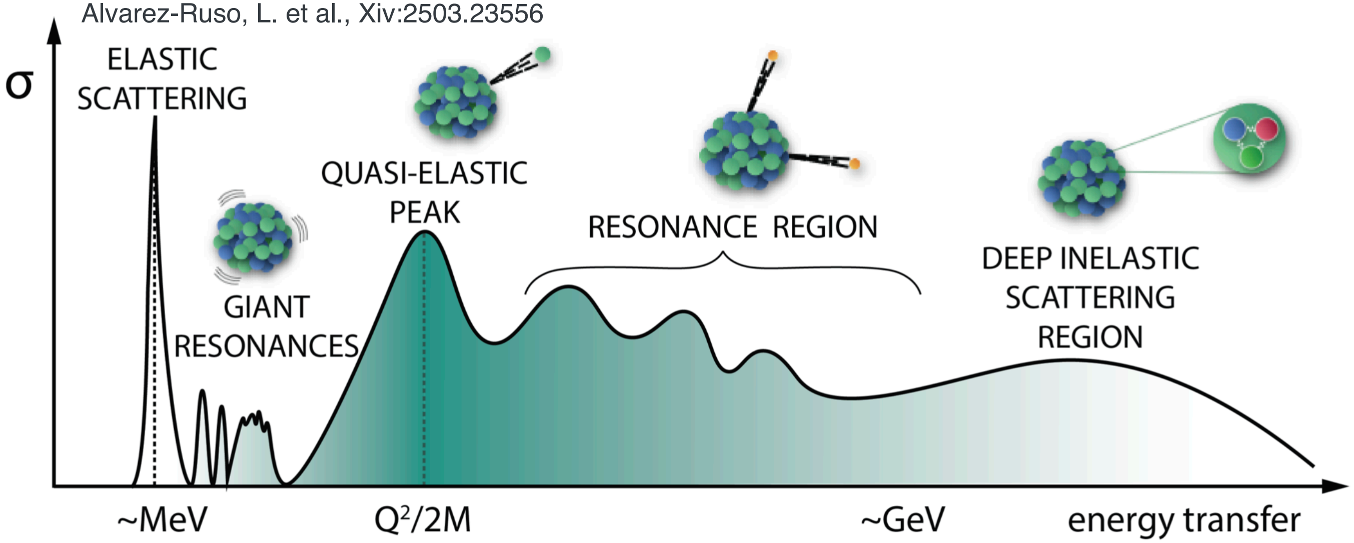
Current Landscape

- ν-nucleus interaction mechanisms

Alvarez-Ruso, L. et al., Xiv:2503.23556



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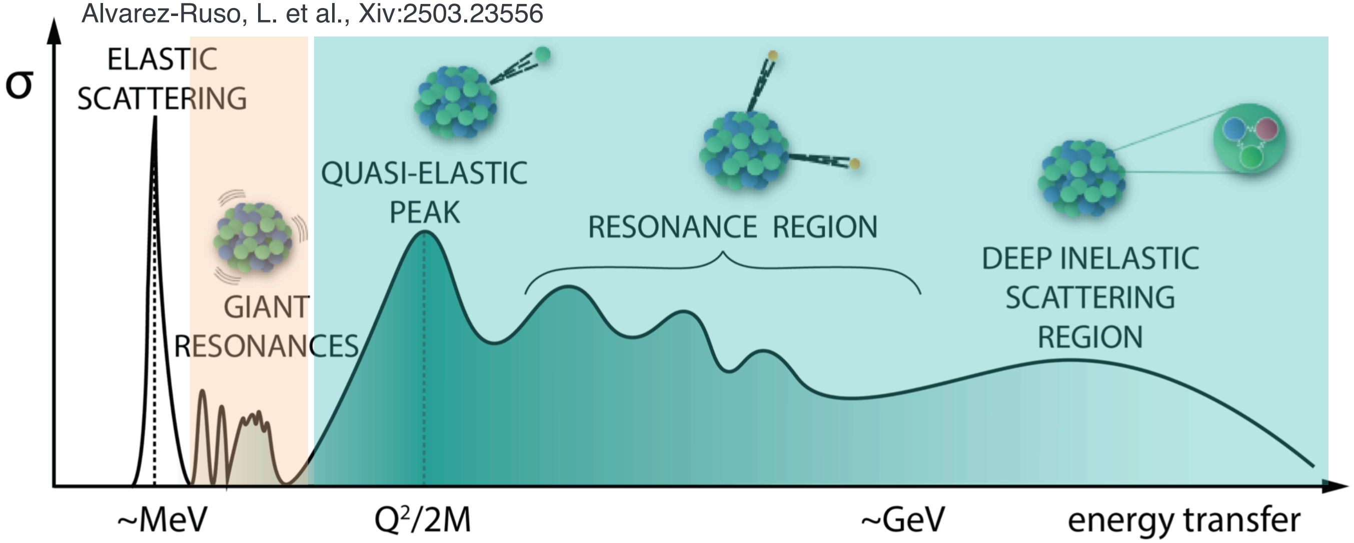

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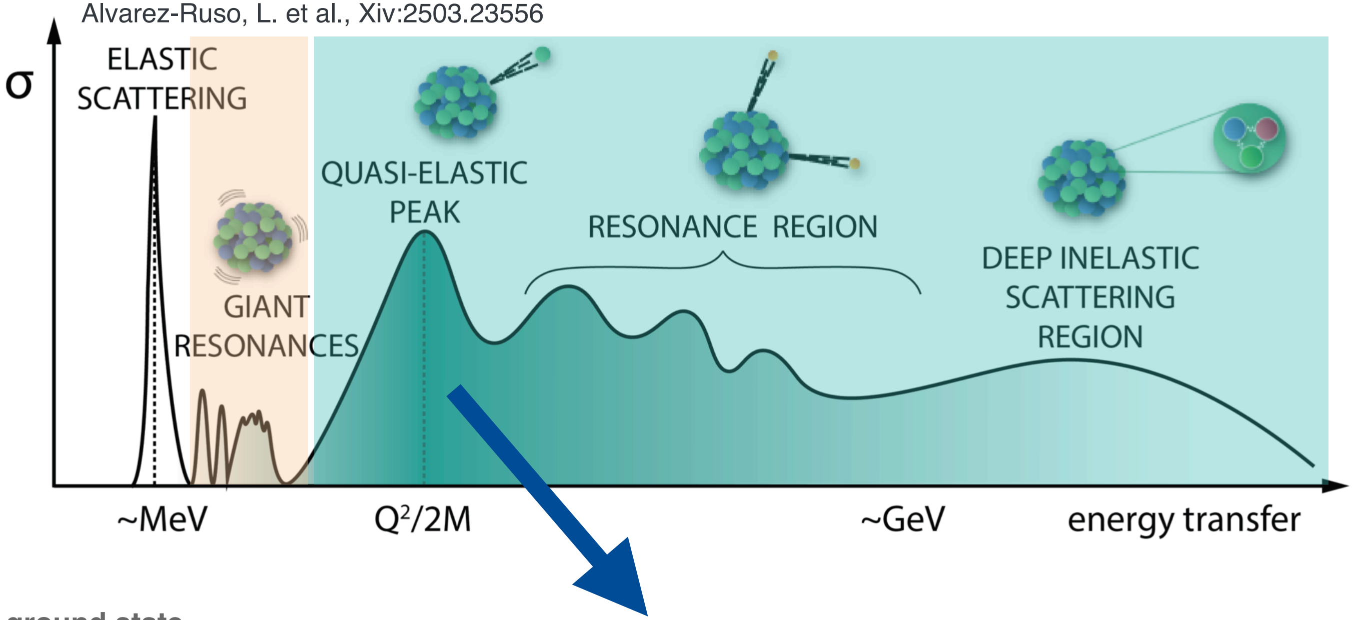
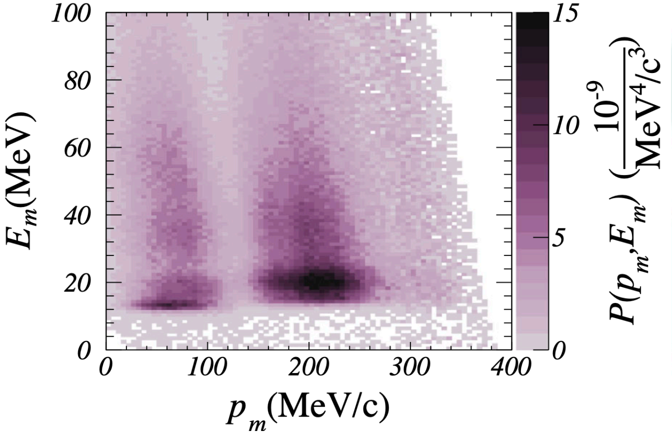
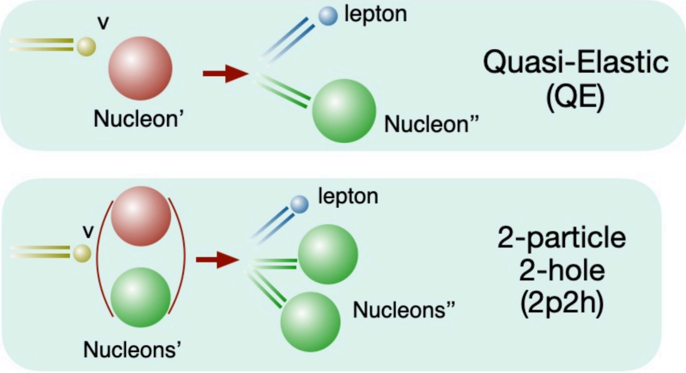


Nuclear ground state





J. Lab. Hall A Collab. *Phys.Rev.D* 105 (2022) 11, 112002

Figure credit to Jeff Hartnell

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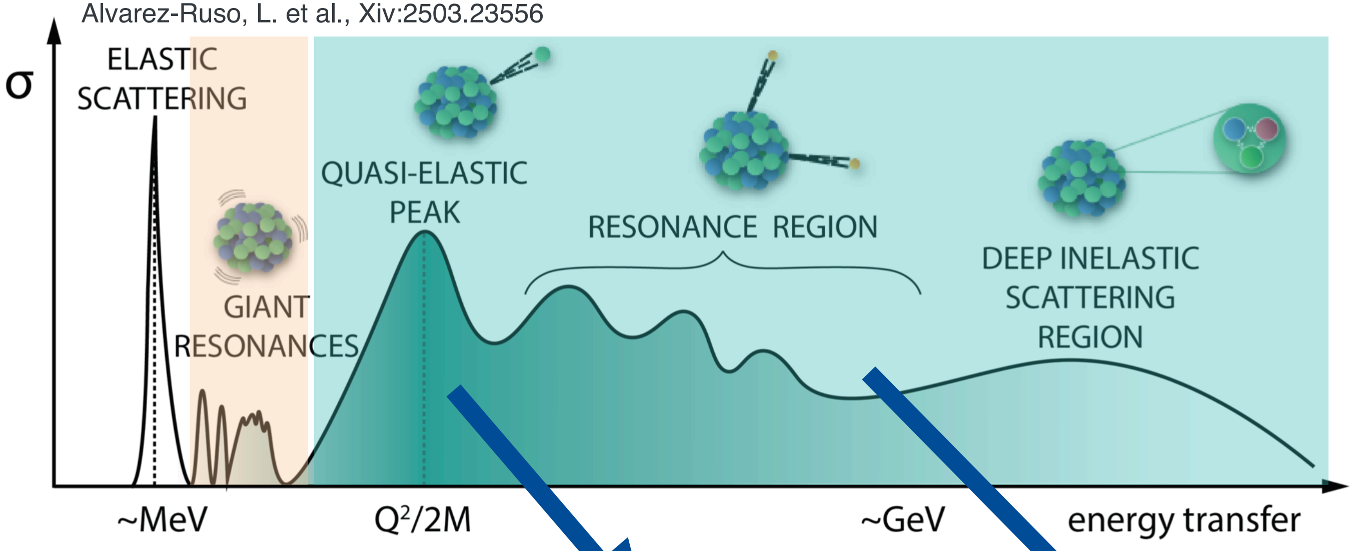

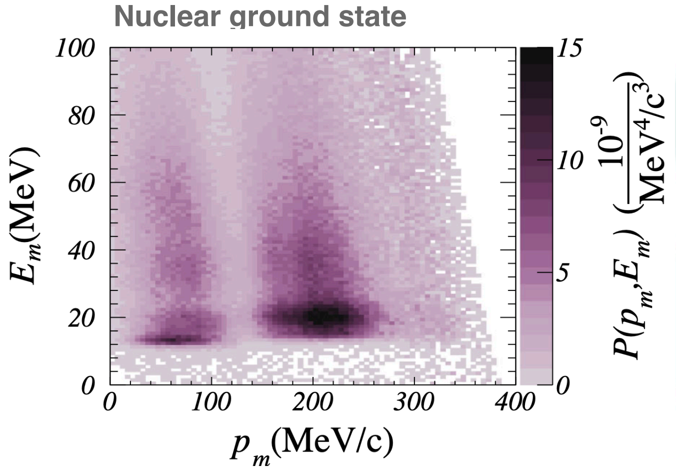

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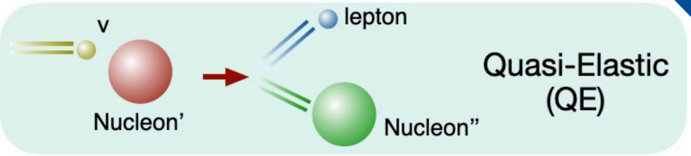

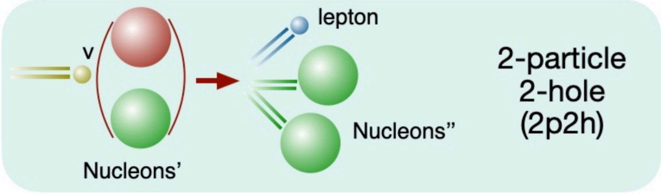

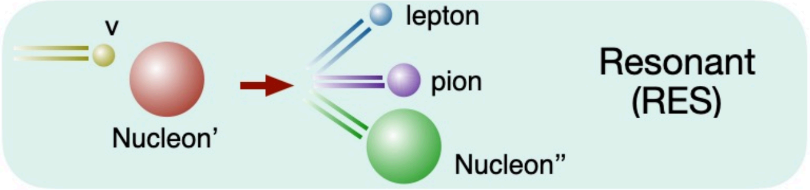

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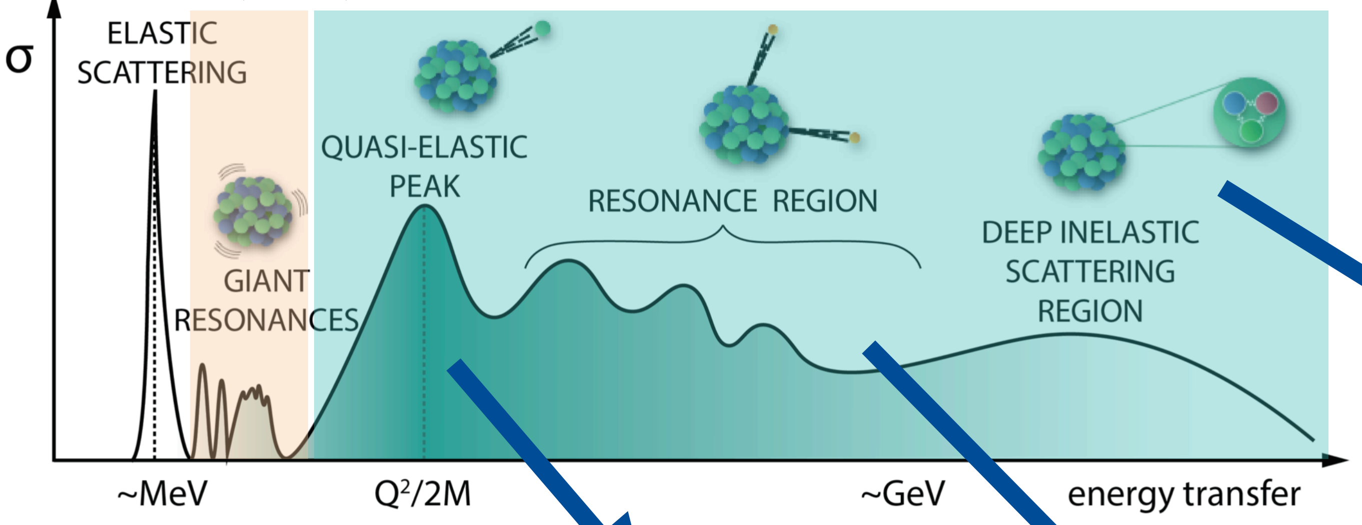
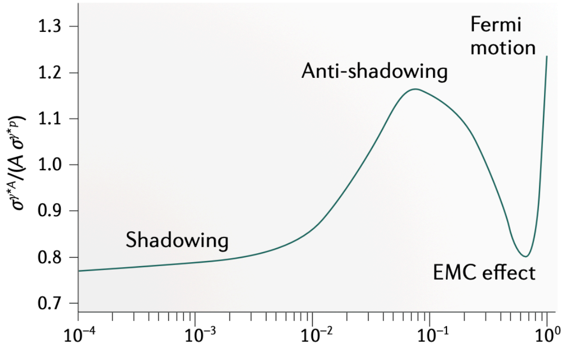
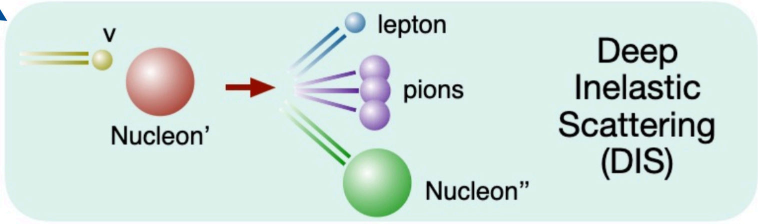


Nuclear effects to partons



S.R. Klein, H. Mäntysaari, *Nature Rev.Phys. 1 (2019) 11, 662-674*



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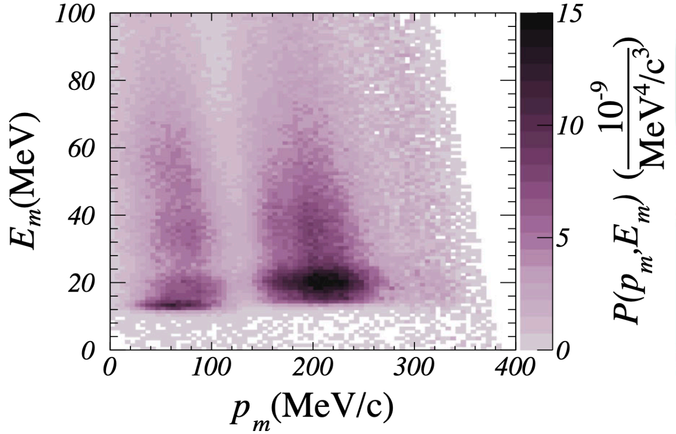

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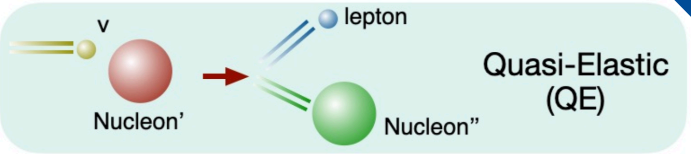

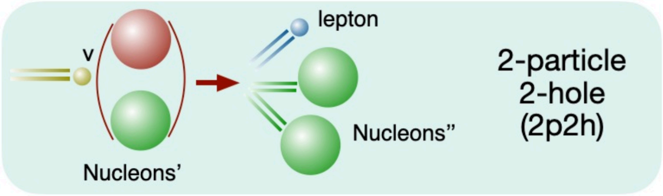

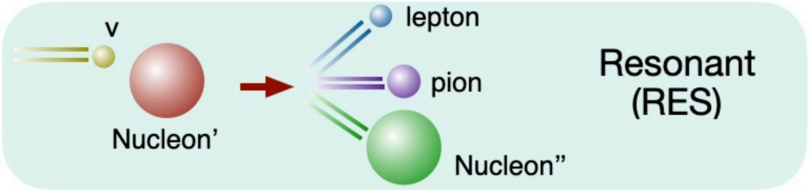

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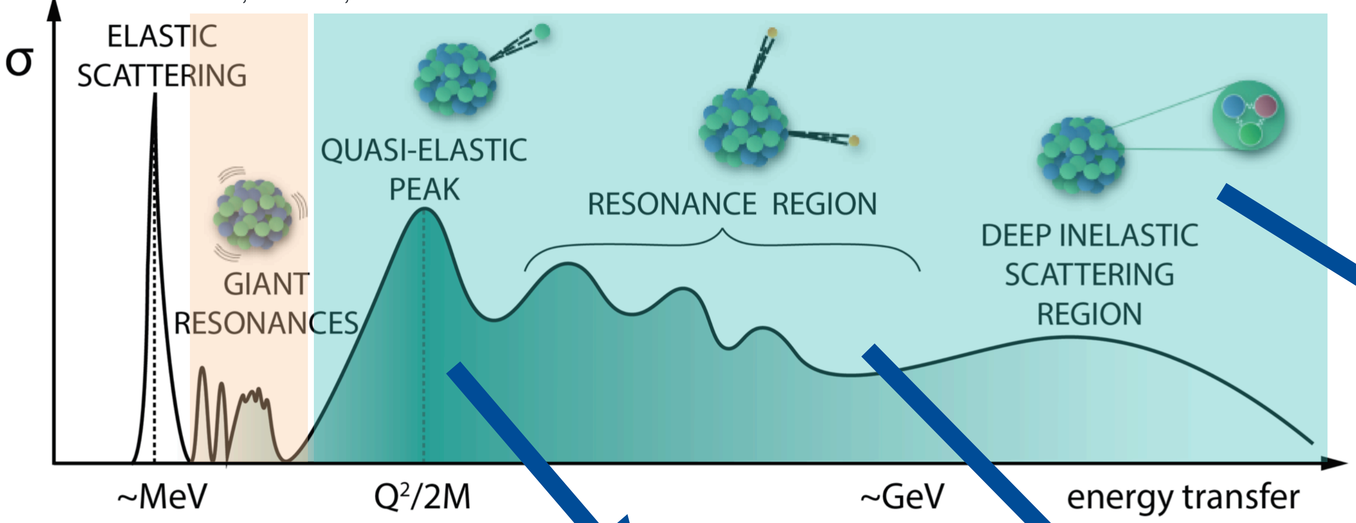

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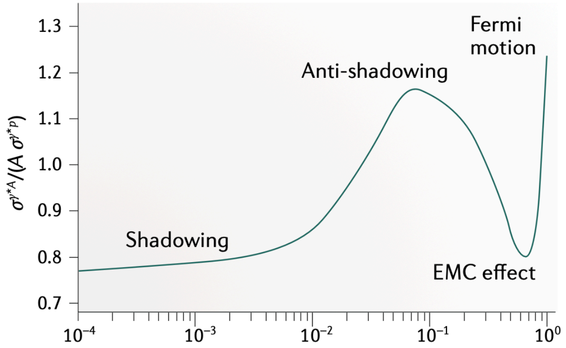

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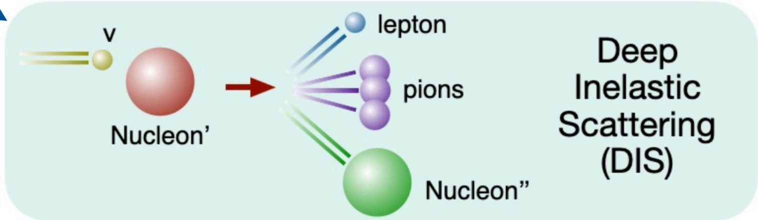

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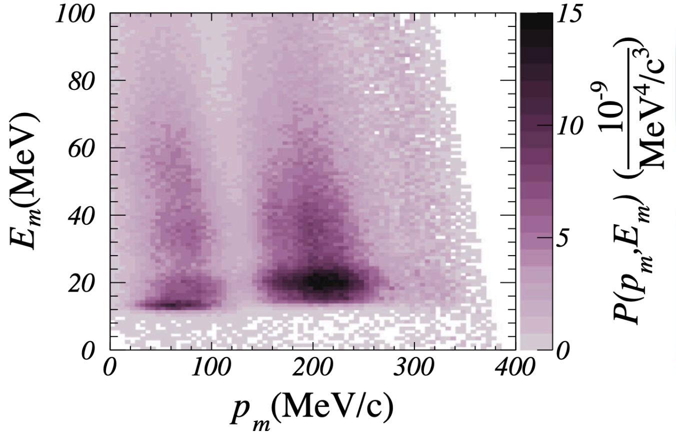

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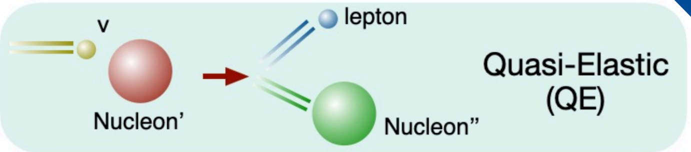


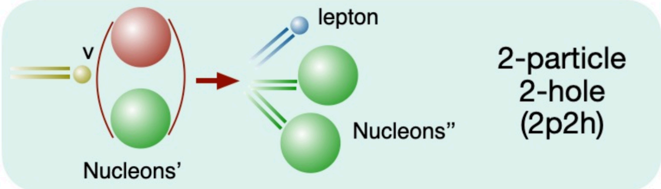
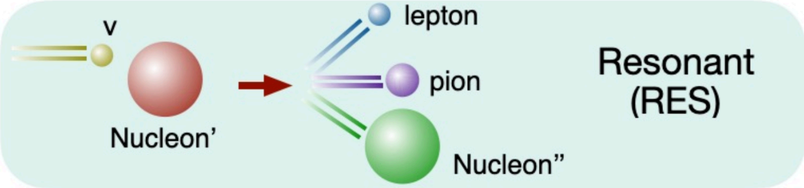


Figure credit to Jeff Hartnell

Overlapping region



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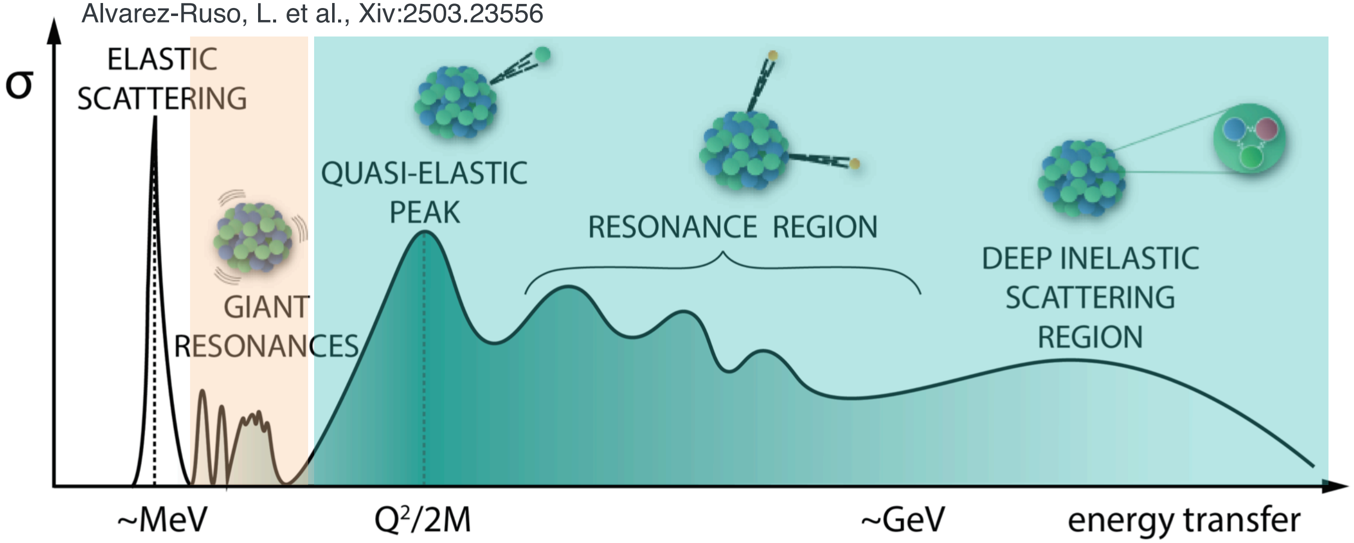
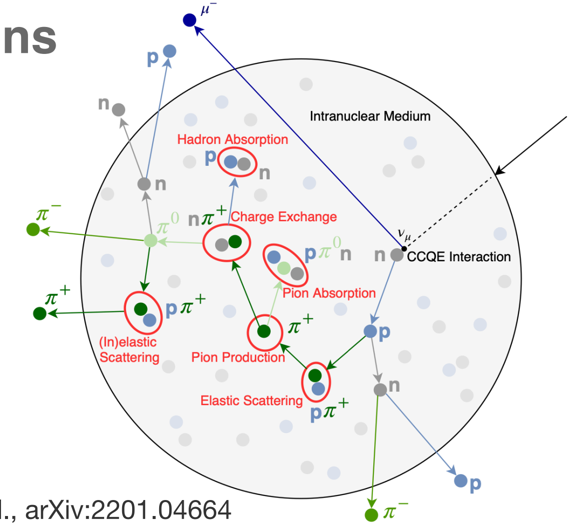


Final state interactions

LArTPC

Low hadron energy thresholds

- p, $\pi^{\pm}$ ~ O(10 MeV)
- $\pi^0 \rightarrow \gamma\gamma$



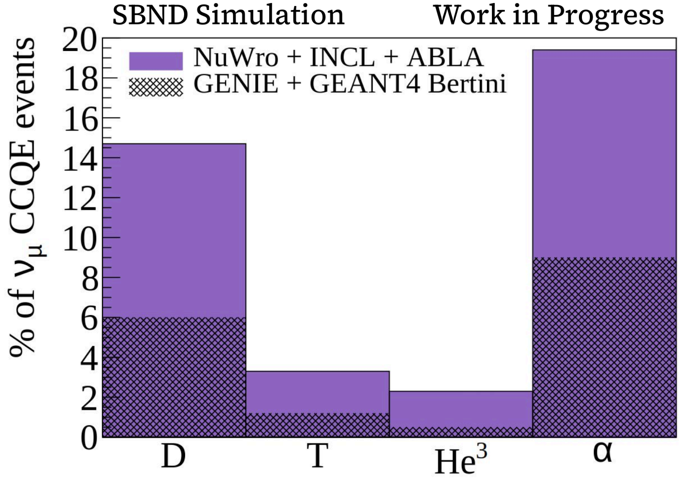
L. Bathe-Peters et al., arXiv:2201.04664

Nuclear fragmentations

LArTPC

Excellent charge calorimetry

- Access to deuterons?



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Effort for Improving Models and Event Generators are very ACTIVE

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

ACHILLES

NuWro

Wrocław Neutrino Event Generator

More data in all topologies are important

- Multi differential cross sections
- More exclusive channels

02

Short Baseline Near Detector (SBND): Setup for Neutrino Interaction Studies

Short Baseline Neutrino (SBN) Program

Use the same neutrino source with MiniBooNE: Booster Neutrino Beam (BNB) @ Fermilab

- Liquid argon time projection chamber (LArTPC) detector technology: R&D for future LArTPCs!
- Three LArTPCs at different baselines

	Active Mass (ton)	Baseline (m)	Operation
SBND	112	110	2024 -
MicroBooNE	89	470	2015 - 2021
ICARUS	476	600	2021 -

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- Three LArTPCs at different baselines
  - Combined analyses to maximize sensitivity for eV-scale sterile neutrino: also ν_μ disappearance
- A wide physics program includes precise ν-Ar interaction studies and BSM searches
  - i.e. Dark matters, heavy neutral leptons

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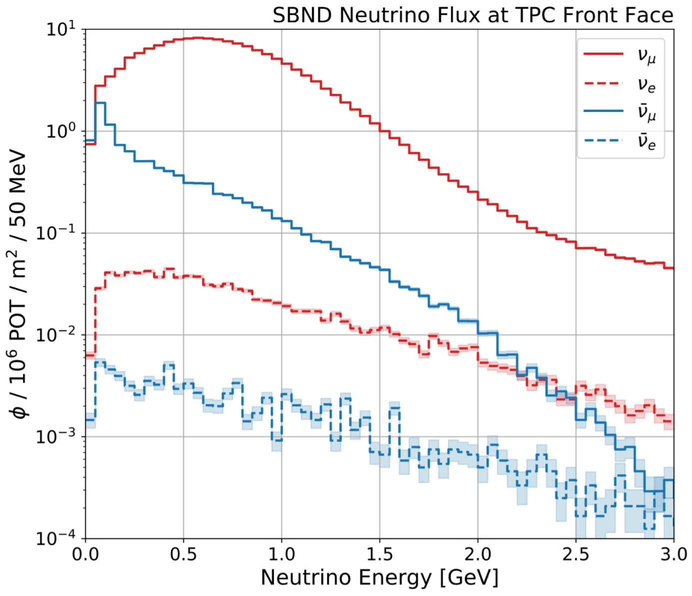
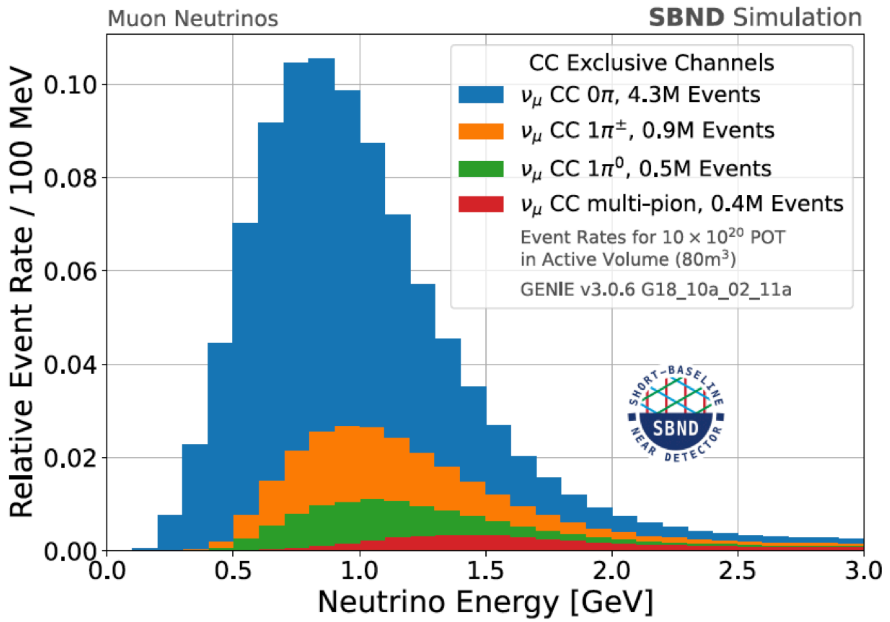
Uniqueness of SBND

Proximity: 110 m from the BNB target

- High neutrino flux → high neutrino event rate → the world's largest ν-Ar scattering data set to-date
  - ~3 years of operation → ~6 million neutrino events



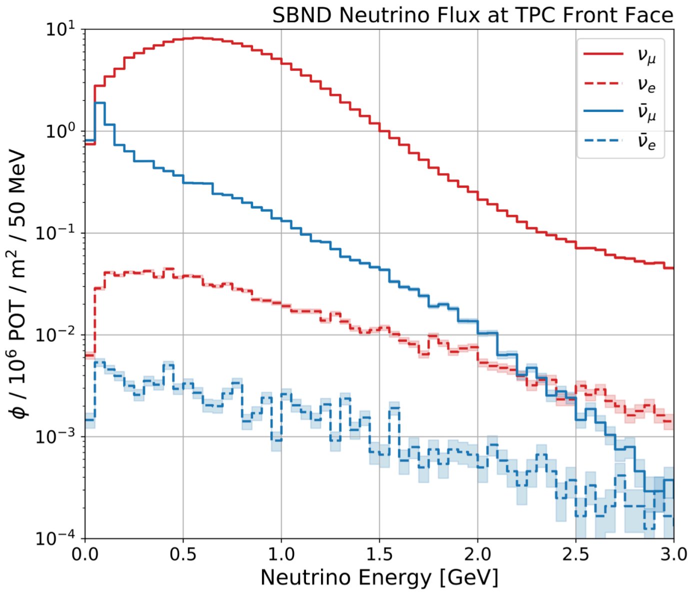


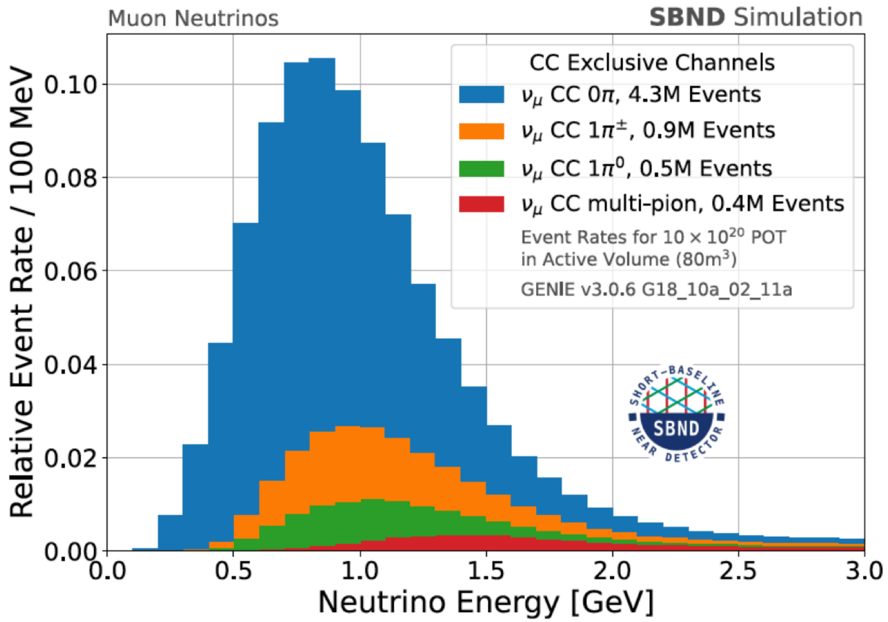
Uniqueness of SBND

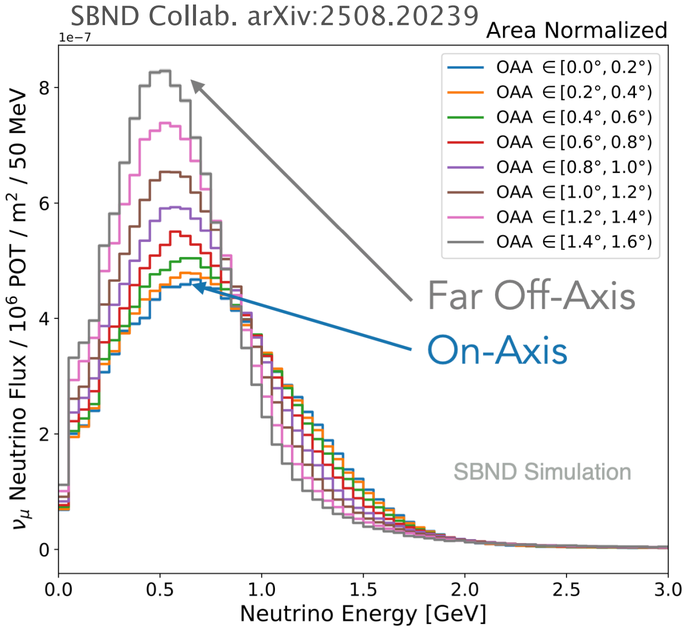
Proximity: 110 m from the BNB target

- High neutrino flux → high neutrino event rate → the world's largest ν-Ar scattering data set to-date
  - ~3 years of operation → ~6 million neutrino events
- Off-axis neutrino flux inside the active volume
  - Opportunity to further constrain neutrino interactions models
- Constrain ν flux and ν-argon interaction models as a near detector for the SBN oscillation studies

NOνA: *Phys.Rev.D* 106 (2022) 3, 032004
T2K: Phys.Rev.D 108 (2023) 7, 072011







High Statistics!

For 3.5×10^{20} POT data, neutrino interactions in SBND TPC active volume

- Based on GENIE v3.04.02 AR23_20i_00_000 (DOI:10.5281/zenodo.15635784)

3.5×10^{20} POT	Channel	Neutrino Interactions in SBND TPC Active Volume
ν_μCC	Inclusive	~ 2.07 M
	1 proton ($E_K > 50$ MeV), No $\pi^\pm$ (EK > 30 MeV) and π^0	~ 0.90 M
	2 protons ($E_K > 50$ MeV), No $\pi^\pm$ (EK > 30 MeV) and π^0	~ 0.32 M
	Exactly 1 $\pi^\pm$ ($E_K > 30$ MeV) and no π^0	~ 0.27 M
	Exactly 1 π^0 and no $\pi^\pm$($E_K > 30$ MeV)	~ 0.16 M
ν_eCC	Inclusive	~ 15 k
	Exactly 1 $\pi^\pm$ ($E_K > 30$ MeV) and no π^0	~ 2.6 k
NC	Inclusive	~ 0.84 M
	At least 1 proton ($E_K > 50$ MeV)	~ 0.42 M
	At least 1 π^0	~ 0.14 M
Coherent	CC	~ 3.7 k
	NC	~ 2.9 k
Scatter to e^-	NC	~ 175
	CC	~ 9

Current GENIE Models and Coming Updates

SBN-wide work toward the publication of the updates is currently in progress

	Current (Ar23)	Coming Updates (Ar25)
Nuclear Ground State	Correlated Fermi Gas *Phys.Lett.B* 785 (2018) 304-308	Argon Spectral Function *Phys.Rev.D* 105 (2022) 11, 112002
Axial Form Factor	Z-expansion fit to Deuterium data *J.Phys.G* 52 (2025) 6, 065003	Minerva data + LQCD results *Nature* 614 (2023) 7946, 48-53 Ann.Rev.Nucl.Part.Sci. 72 (2022) 205-232
QE	Valencia *Phys.Rev.C* 83 (2011) 045501	Reweights from Ar23/LFG to CRPA *Phys.Rev.D* 106 (2022) 7, 073001
	Charm: Kovalenko *Sov.J.Nucl.Phys.* 52 (1990) 934-936	
	Strange: Pais *Annals Phys.* 63 (1971) 361-392	
	Meson exchange current SuSAv2	Improving 2p2h uncertainty to model spreads SuSAv2(default), Valencia and Martini
		1p1h – 2p2h interference Reweight to *Phys.Rev.C* 112 (2025) 4, 045501
Resonant	Berger-Sehgal *Phys.Rev.D* 76 (2007) 113004	
Coherent Pion Production	Berger-Sehgal *Phys.Rev.D* 76 (2007) 113004	
DIS/SIS	Bodek-Yang Nucl.Phys.B Proc.Suppl. 112 (2002) 70-76	
Hadronization	AGKY *Eur.Phys.J.C* 63 (2009) 1-10	
Final State Interction	GENIE hA2018 *Phys.Rev.D* 104 (2021) 5, 053006	Improving uncertainties to model spreads INCL, Geant4 Bertini, and GENIE hA

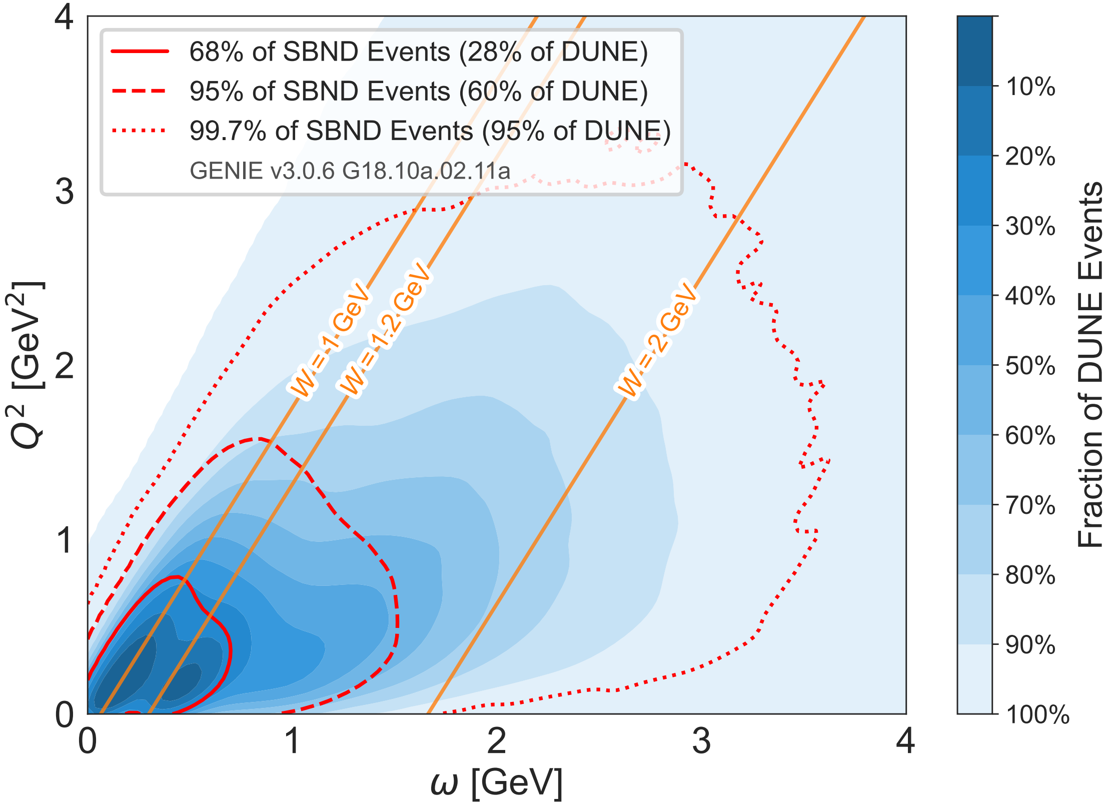
Overlap with DUNE?

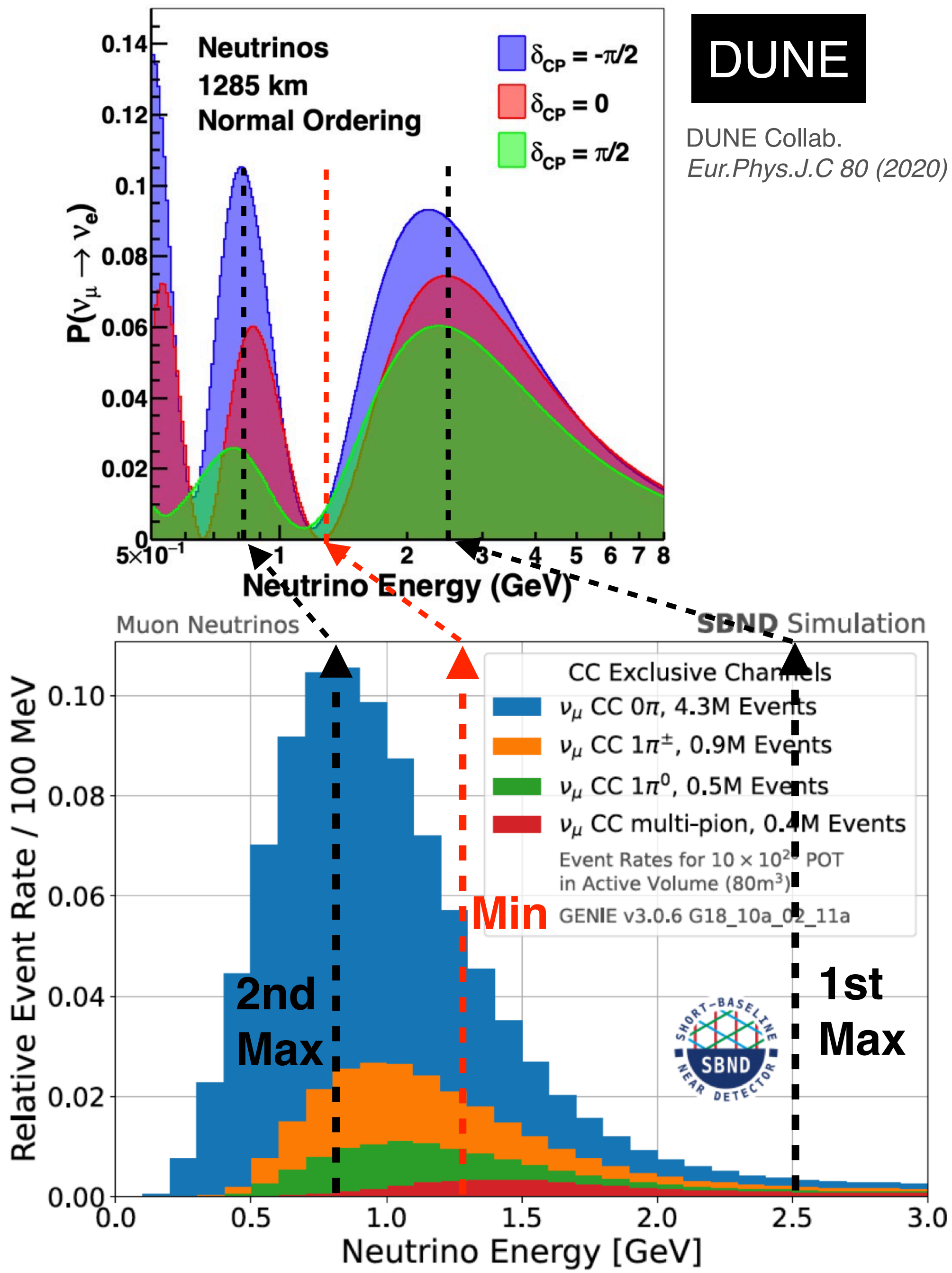
Neutrino energy

- Good coverage to the 2nd $P(\nu_\mu \to \nu_e)$ maximum

Interaction phase space

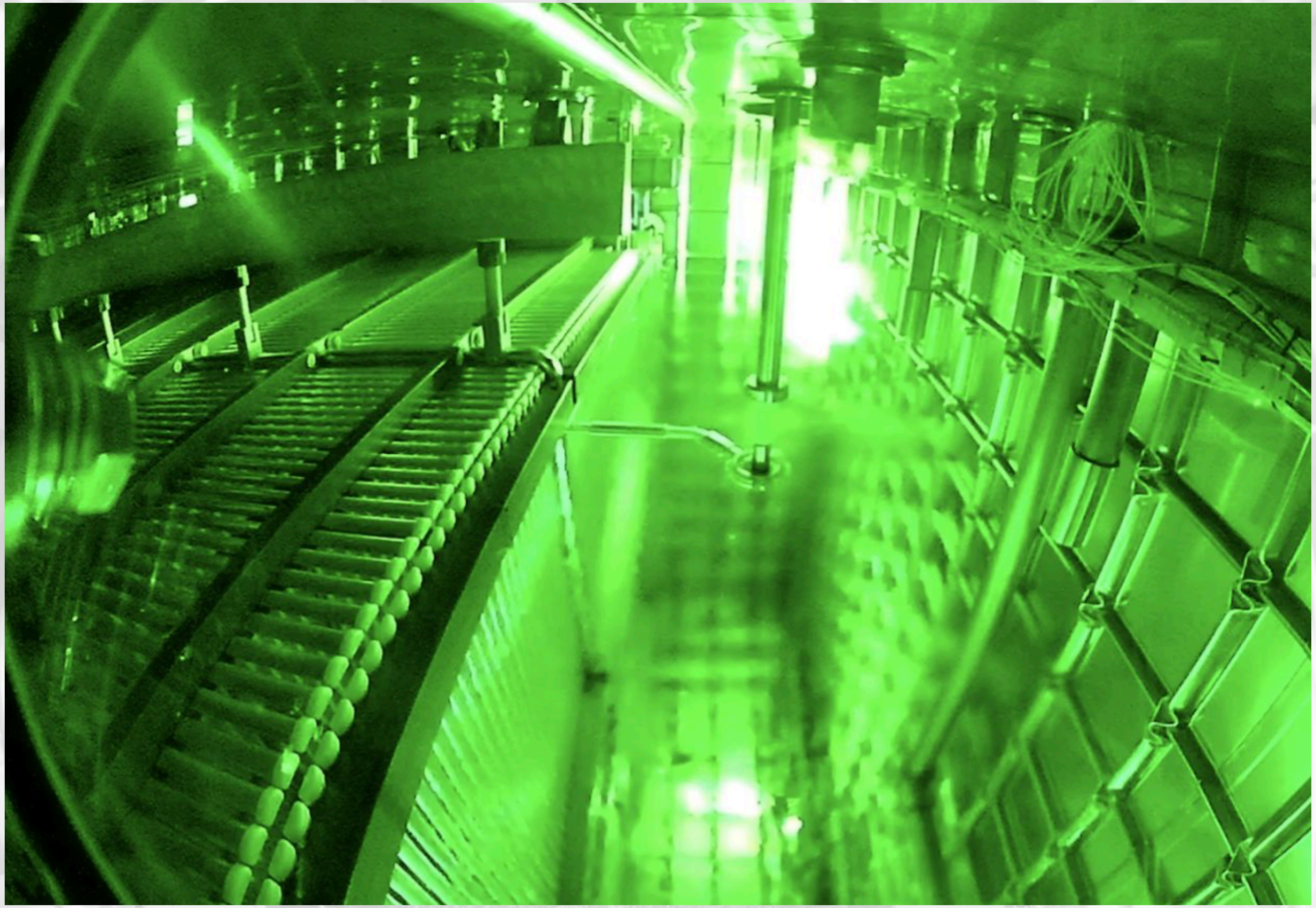
- SBND 3σ covers 95% of DUNE's events





DUNE

DUNE Collab.
Eur.Phys.J.C 80 (2020) 10, 978

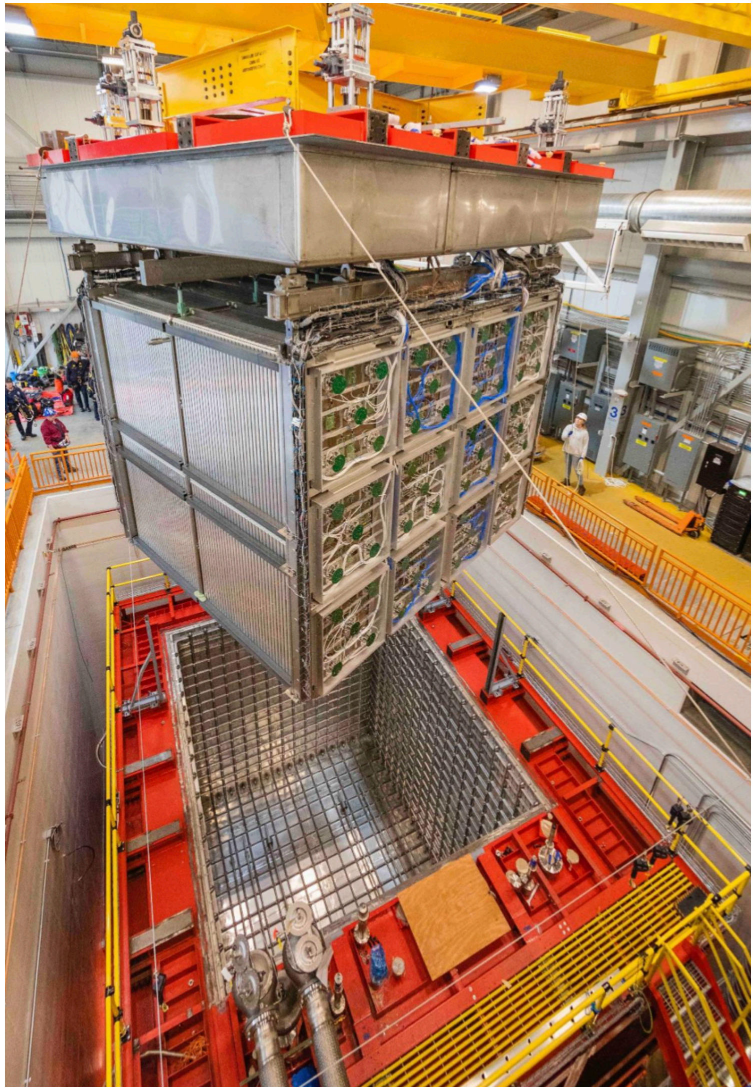


03

SBND:
Detector Status and the First Physics Run

SBND in a Nutshell

Liquid argon time projection chamber



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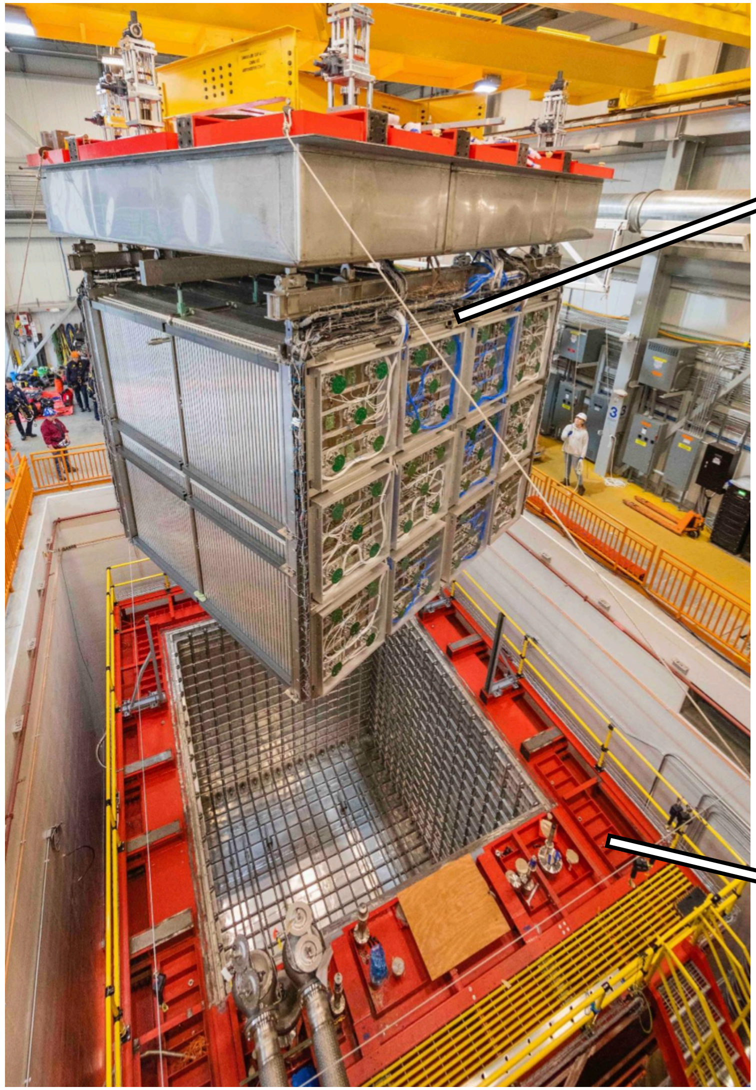
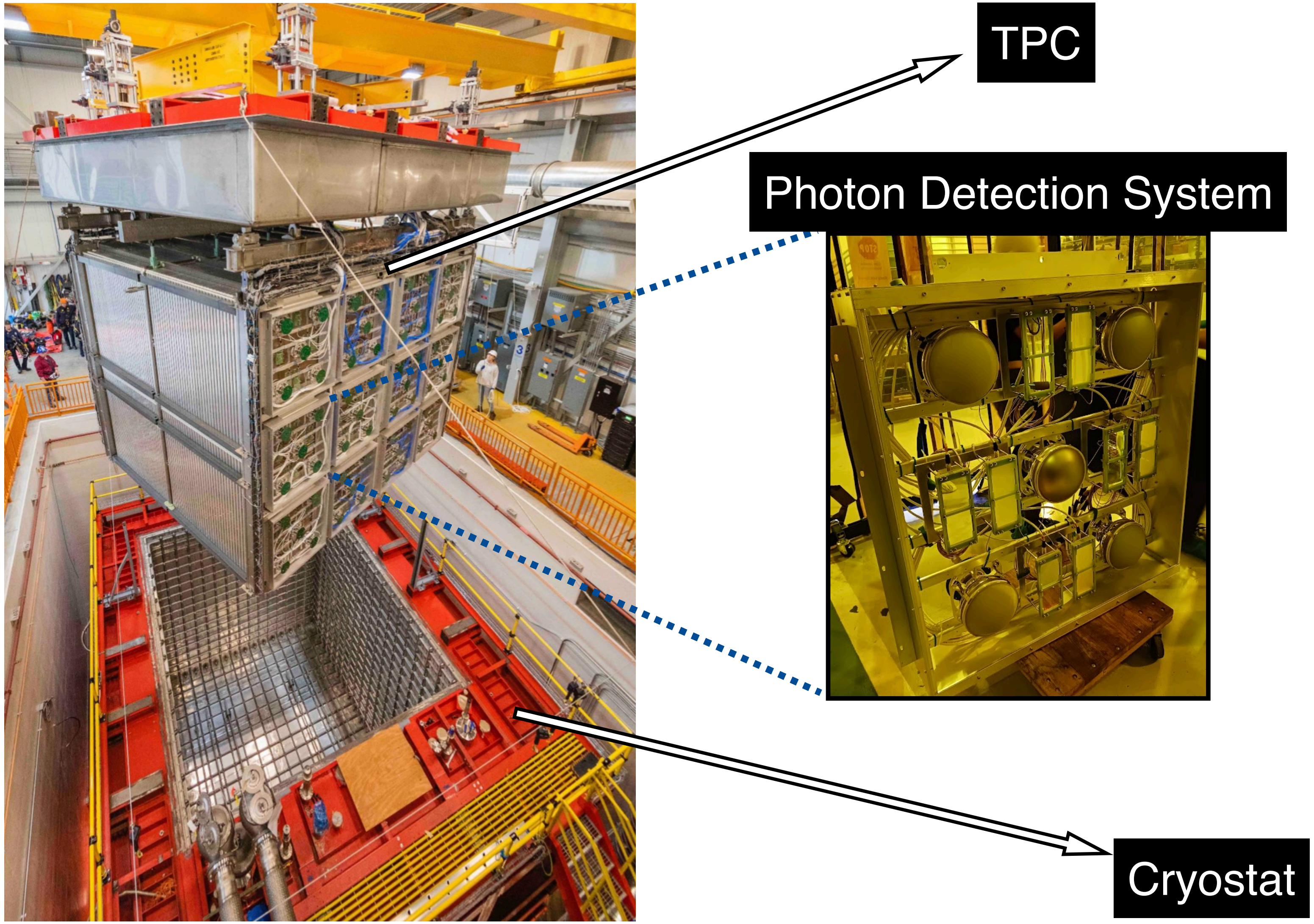


TPC

Cryostat

SBND in a Nutshell

Liquid argon time projection chamber



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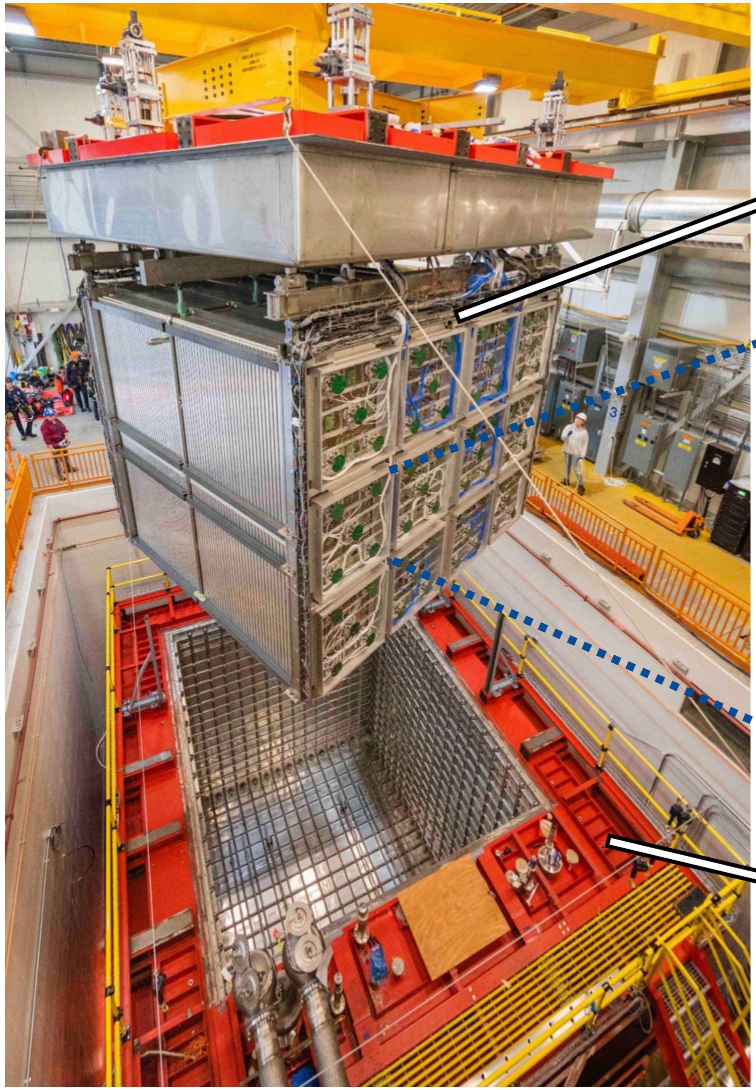
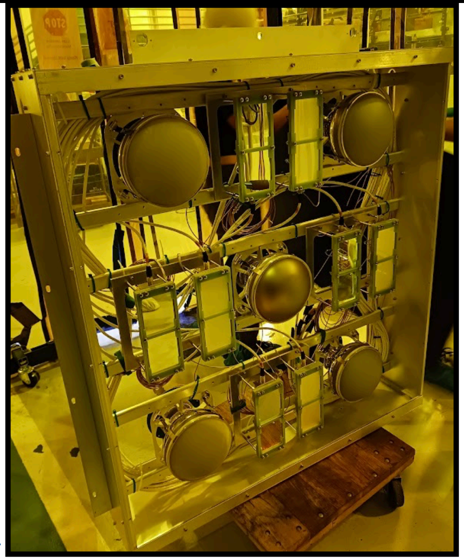
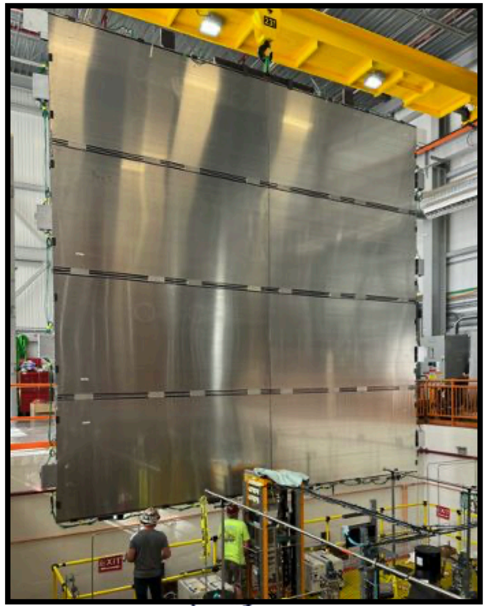


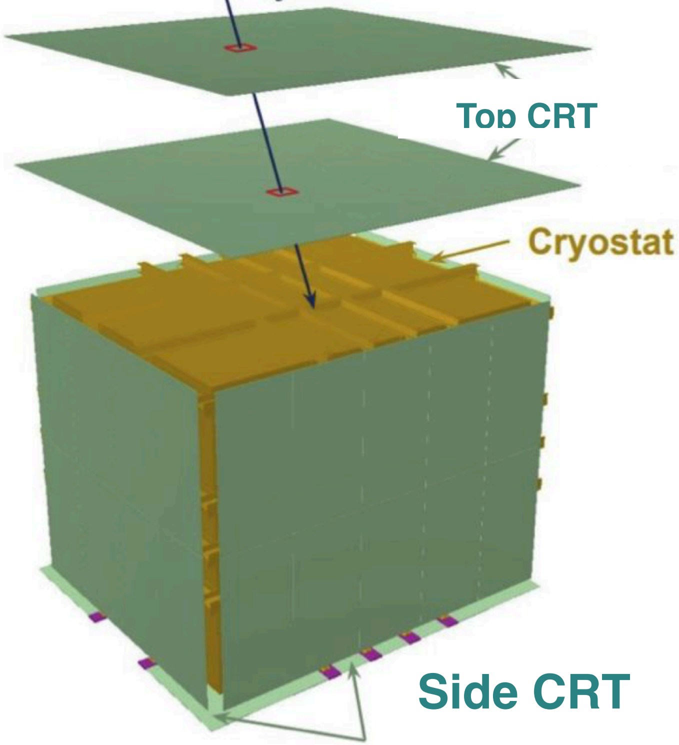
TPC

Photon Detection System



Cryostat

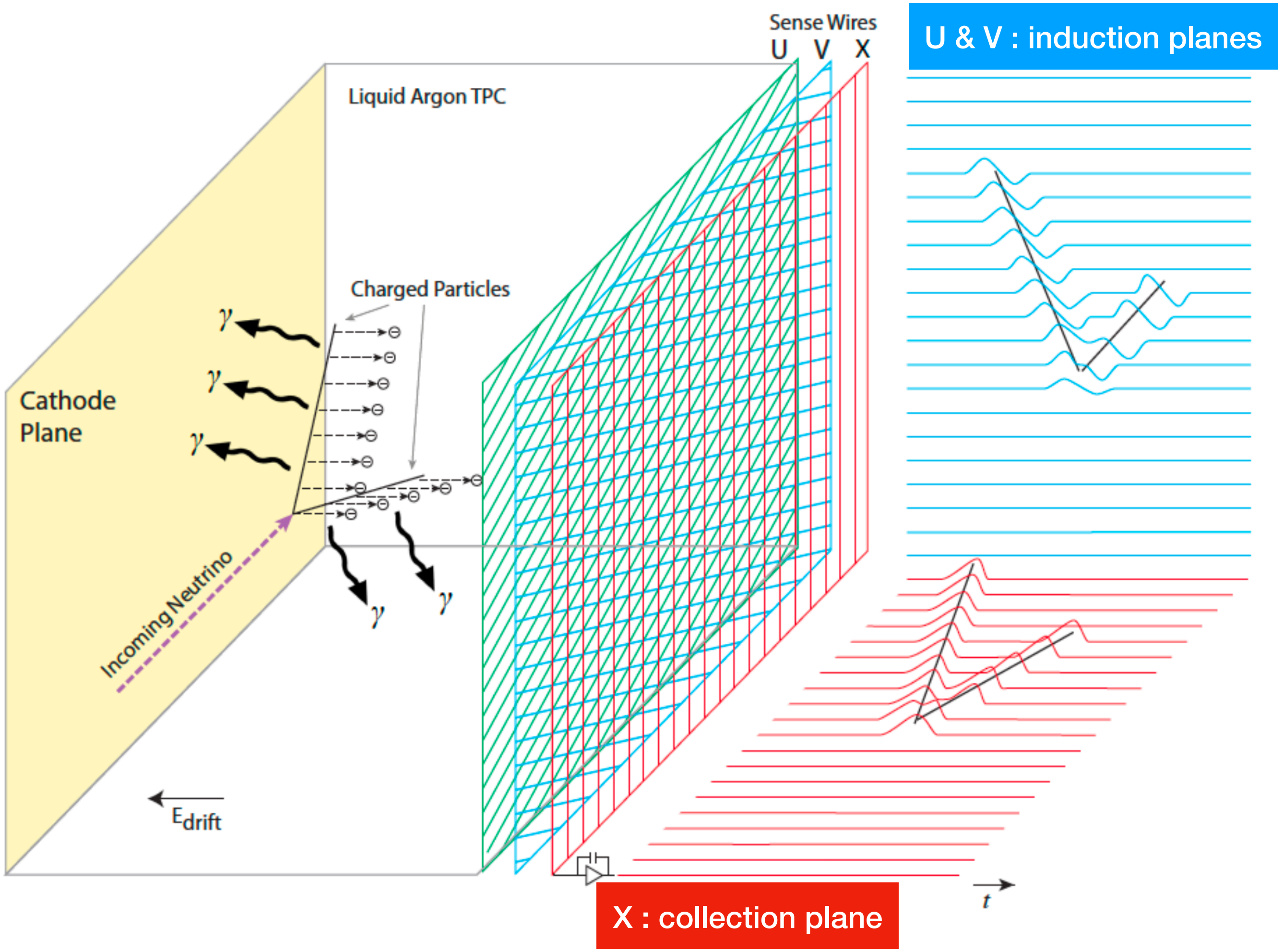


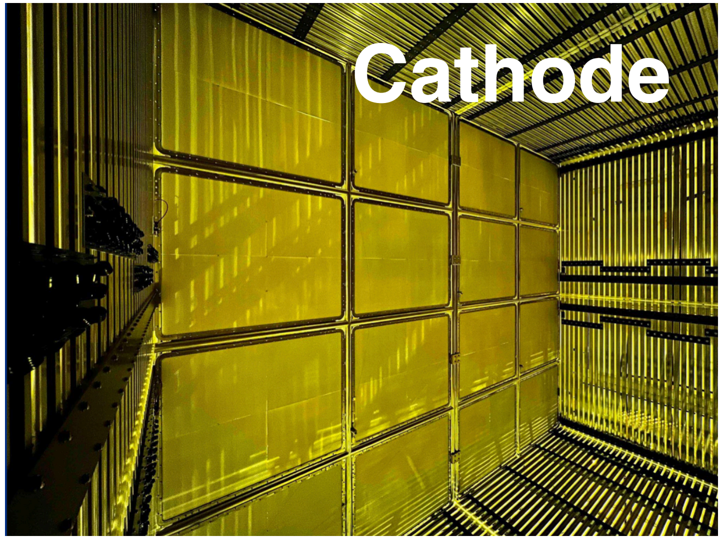


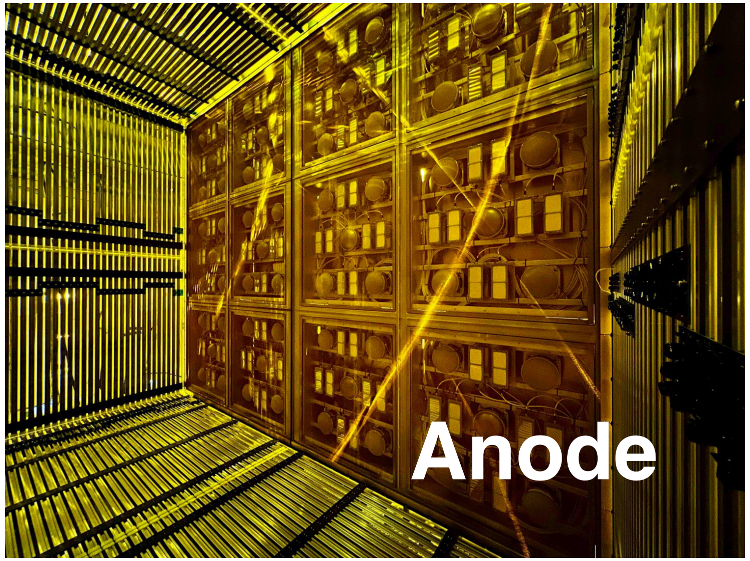
SBND: TPC

Two electron drifting volumes share a central HV cathode plane

- A field cage for uniform 500 V/cm E-field







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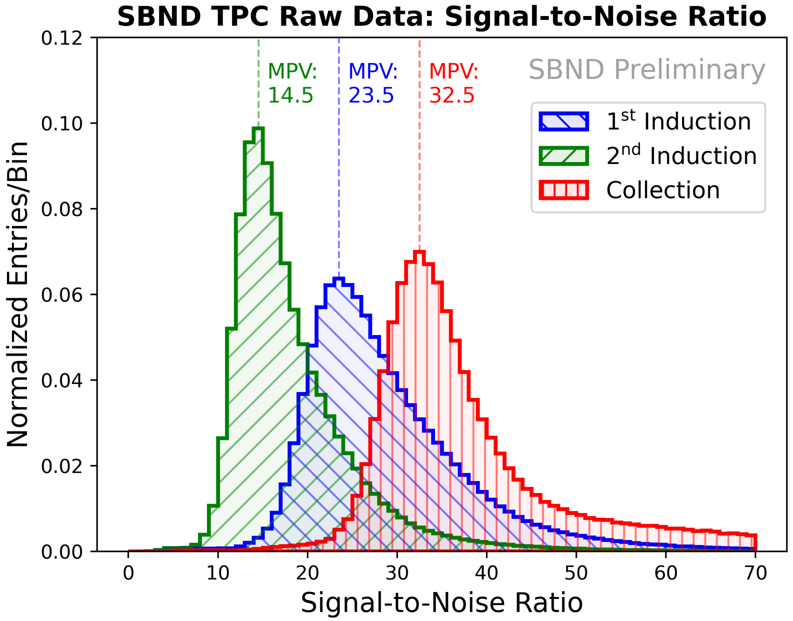
Imaging with low noise 3-layer charge readout wires with 3 mm pitch



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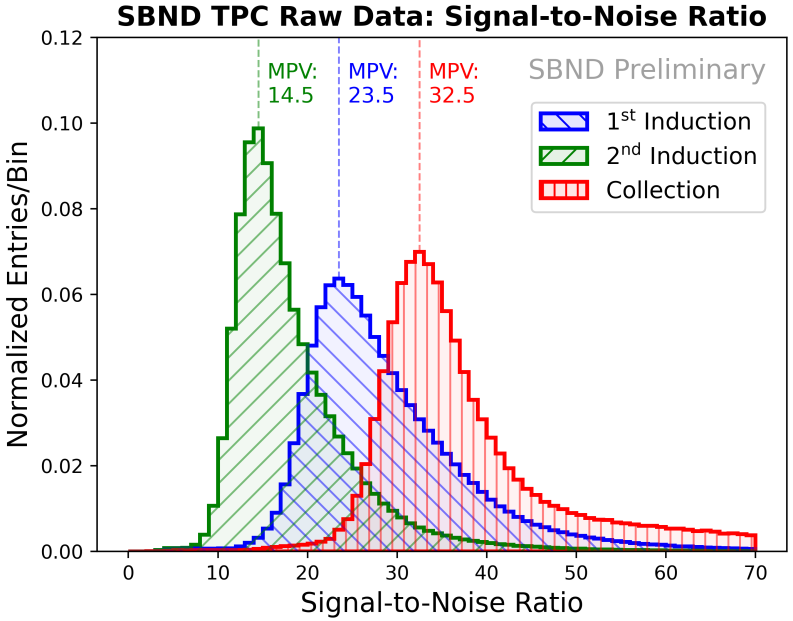

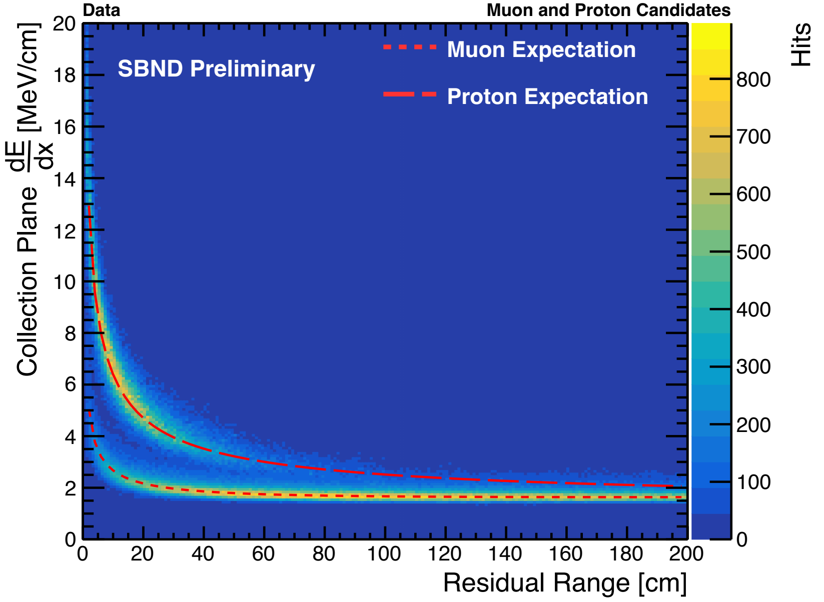

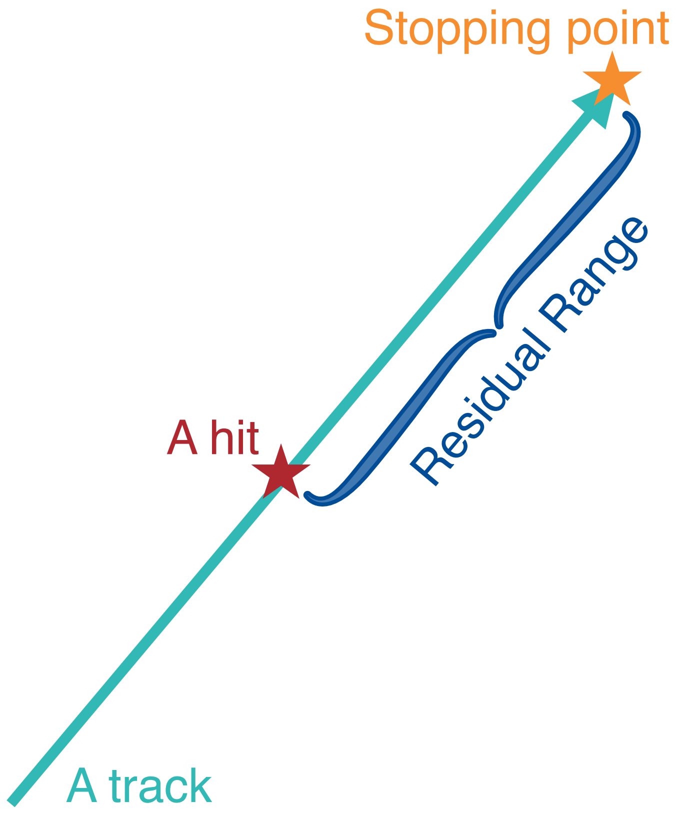

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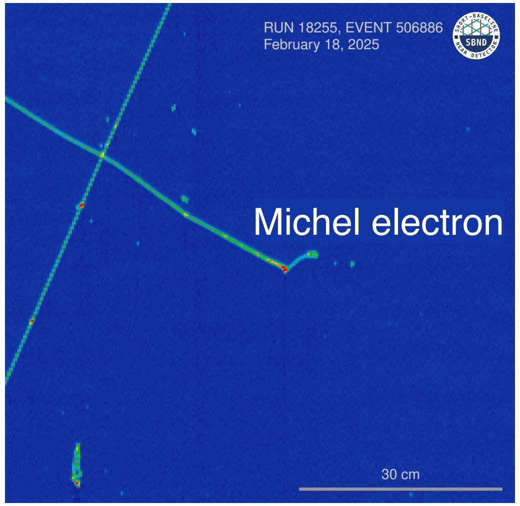
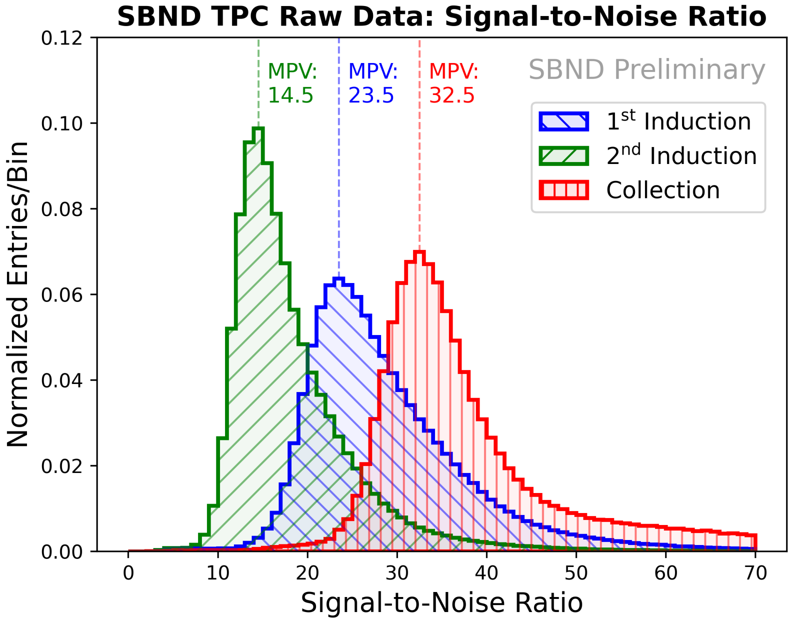
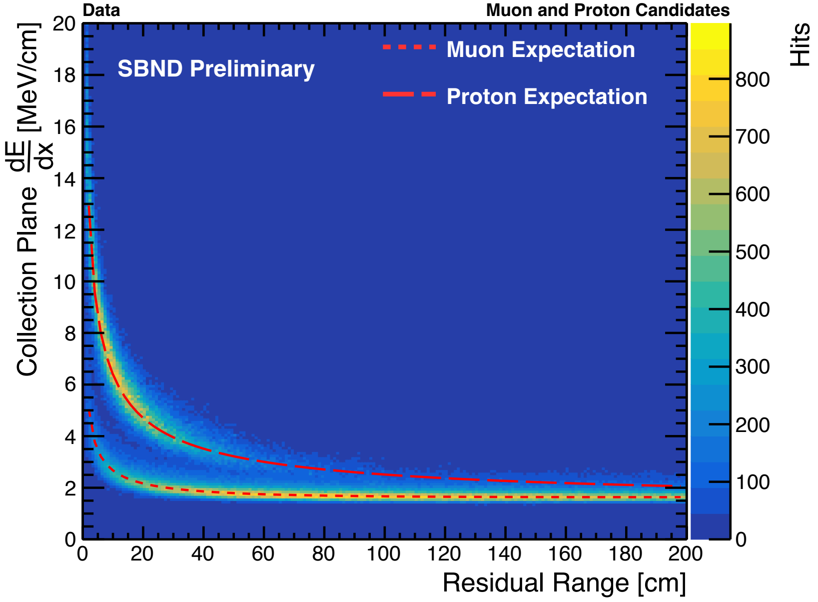
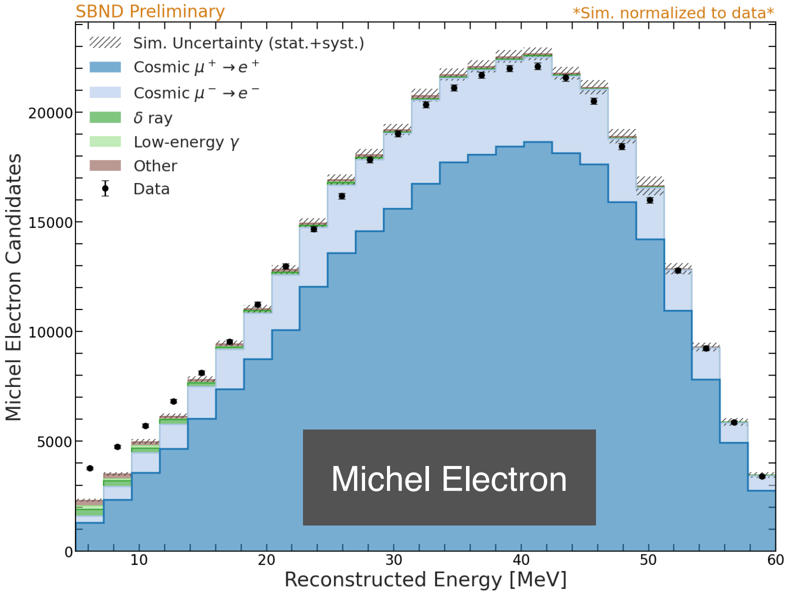
- Excellent charge calorimetry
- Sensitivity to low energy activities









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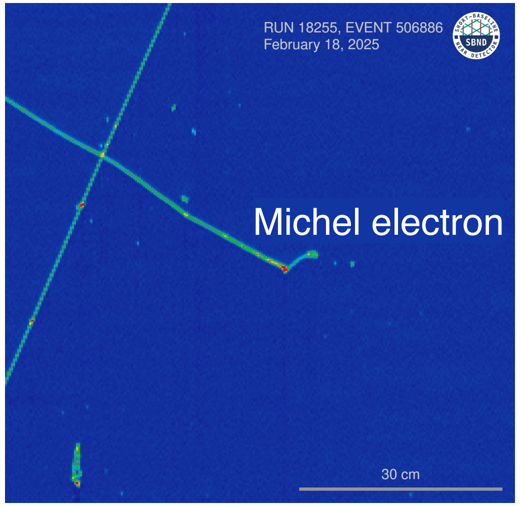
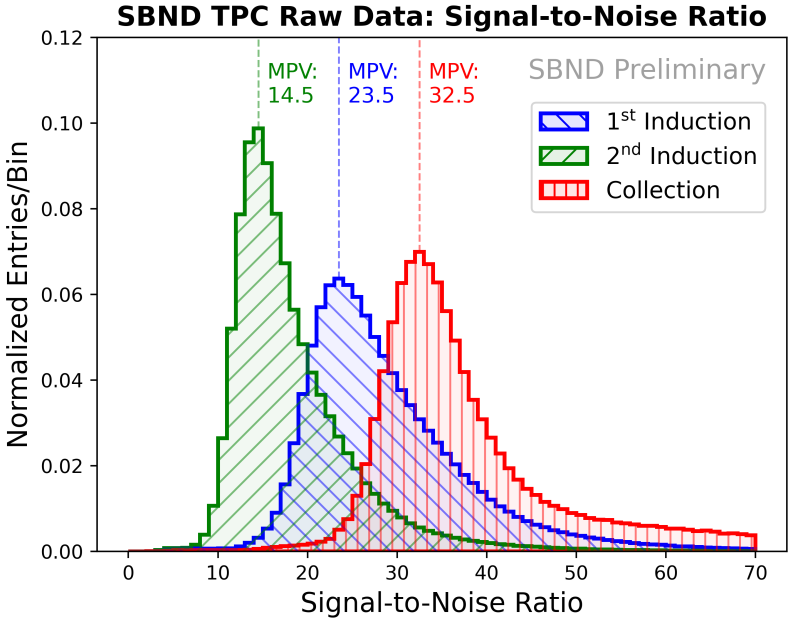
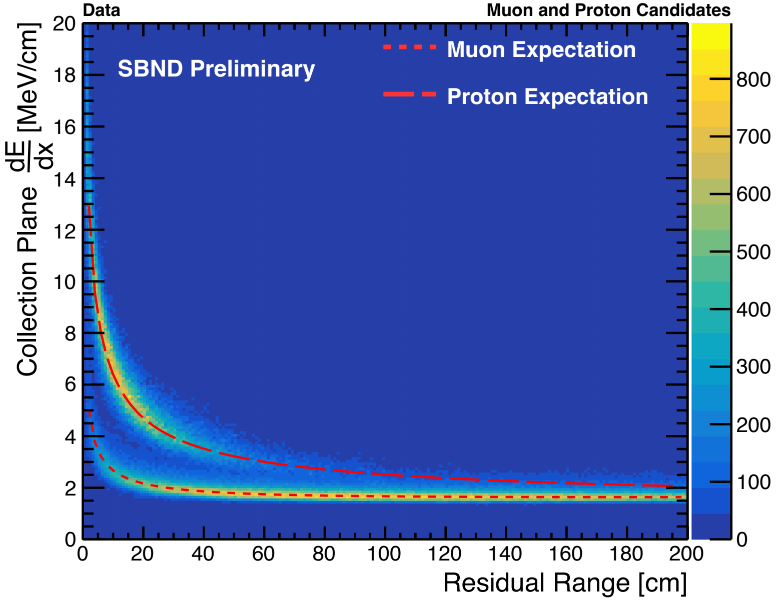


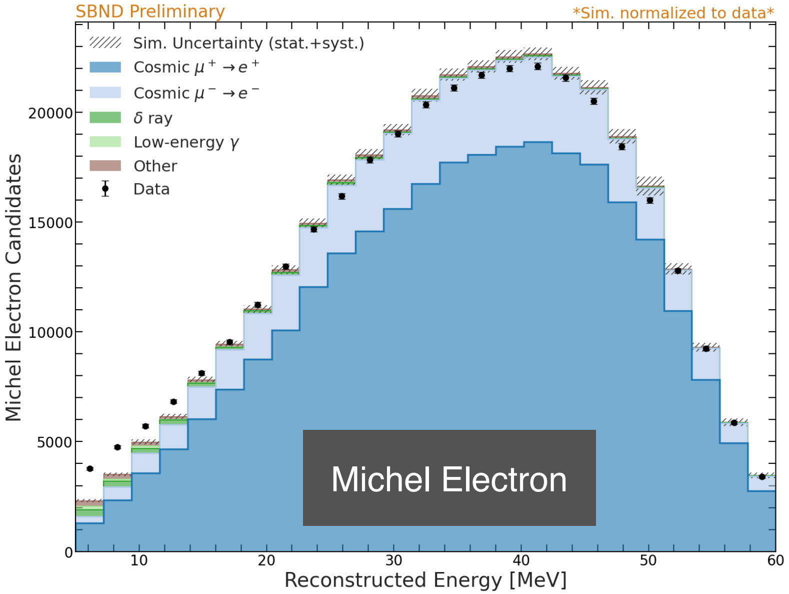
Imaging with low noise 3-layer charge readout wires with 3 mm pitch

- Excellent charge calorimetry
- Sensitivity to low energy activities

} **Essential for precise cross section studies**







SBND: Photon Detection System (PDS)

Light detection is critical to the event trigger system and cosmic rejection

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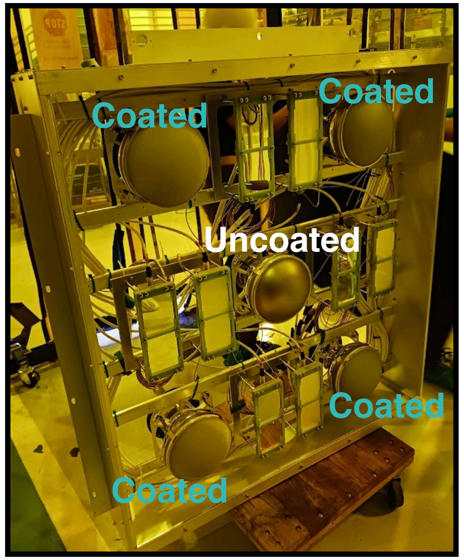
Sensitive both to VUV from scintillations and lights from wavelength shifting coatings

- Reflective foil panels coated with wavelength shifter embedded into the cathode plane
- Better light detection uniformity across the detector coordinates

***Coated: for wavelength shifting of scintillating photons ($\lambda \sim 127$ nm) to photocathode sensible regions ($\lambda \sim 440$ nm)**



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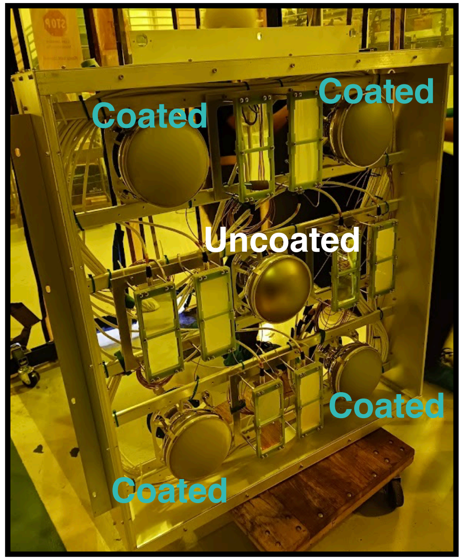

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O(ns) timing resolution

- $\sigma \sim 1.7$ ns: excellent tool for cosmic rejection + extending physics scope

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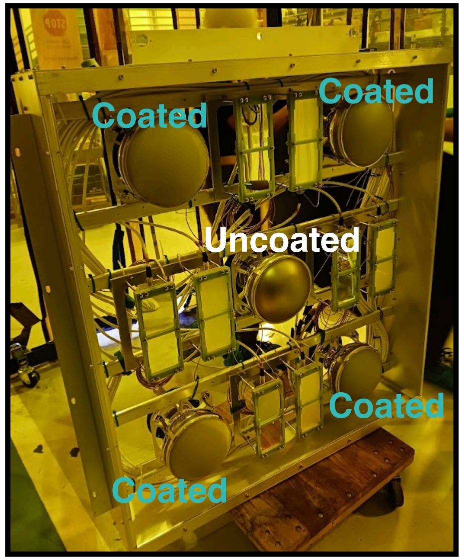
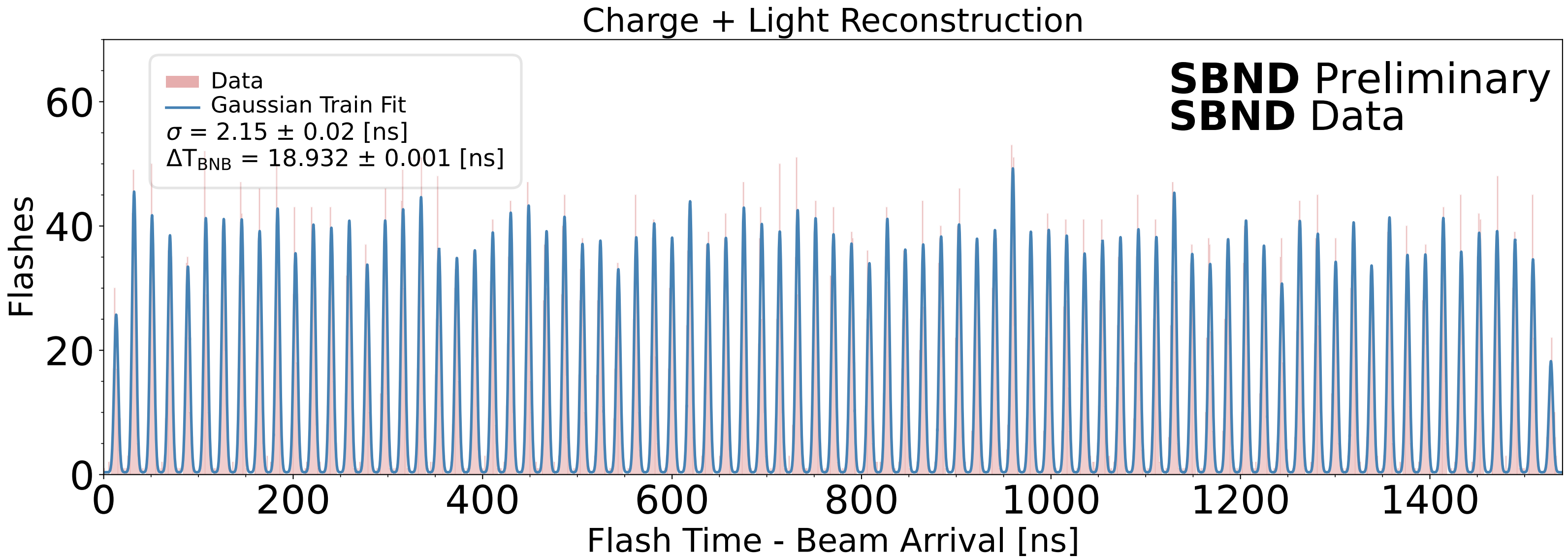
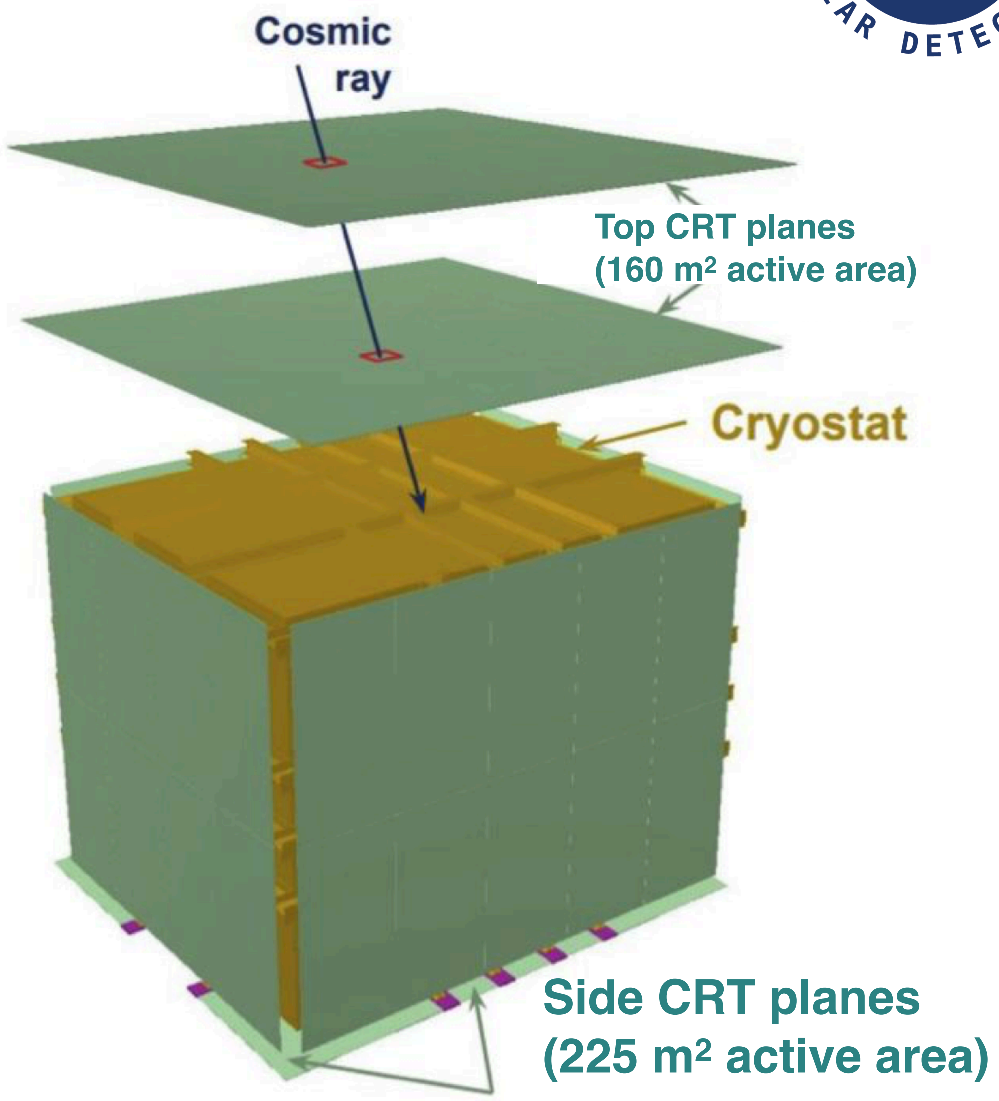




SBND: Cosmic Ray Tagger

Cosmic ray tagger (CRT)

- Surrounds the SBND cryostat on all 6 sides



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- Built from 11.2 cm wide scintillator strips
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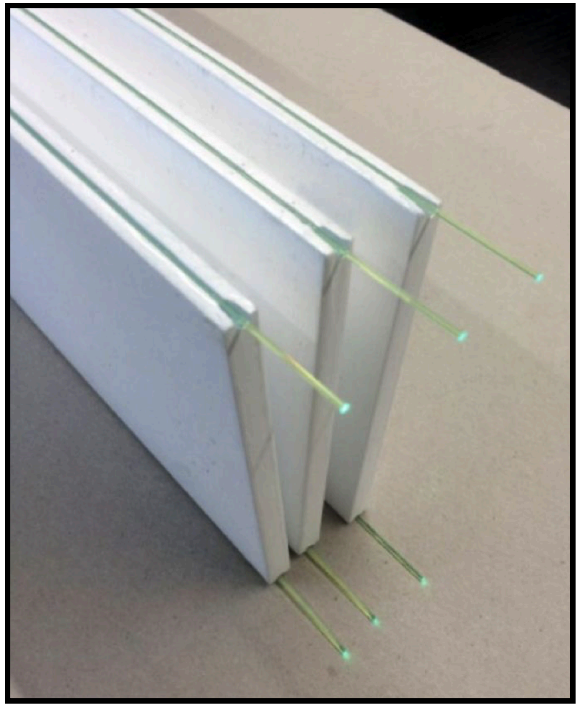
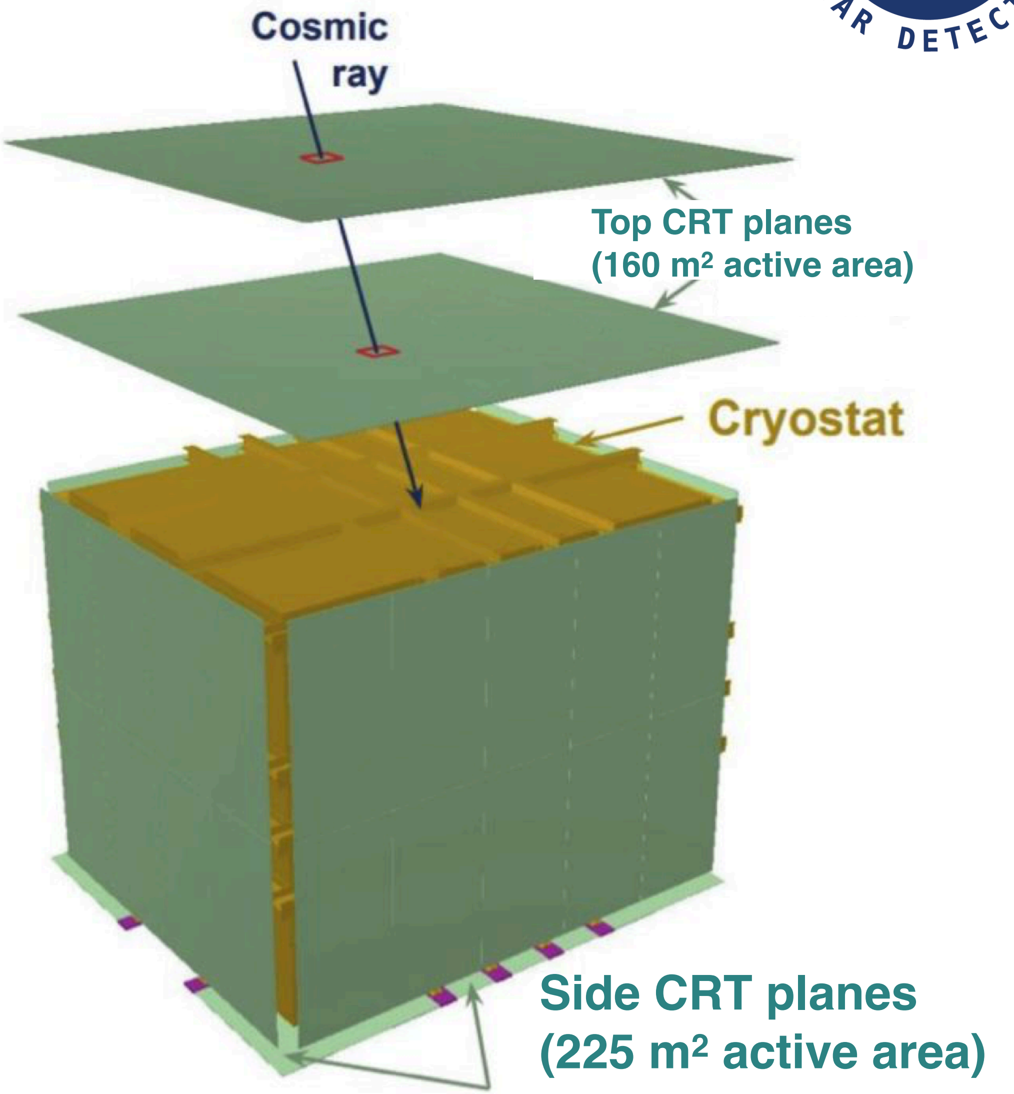
    - Silicon photomultipliers (SiPMs) for light collection





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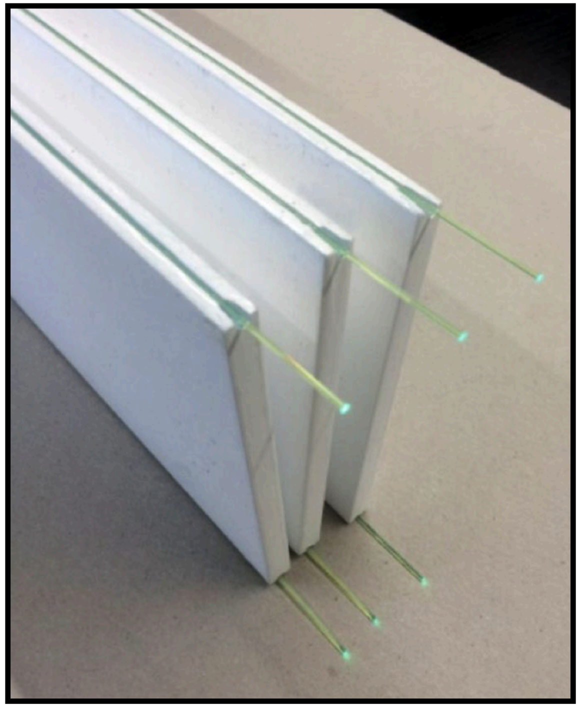

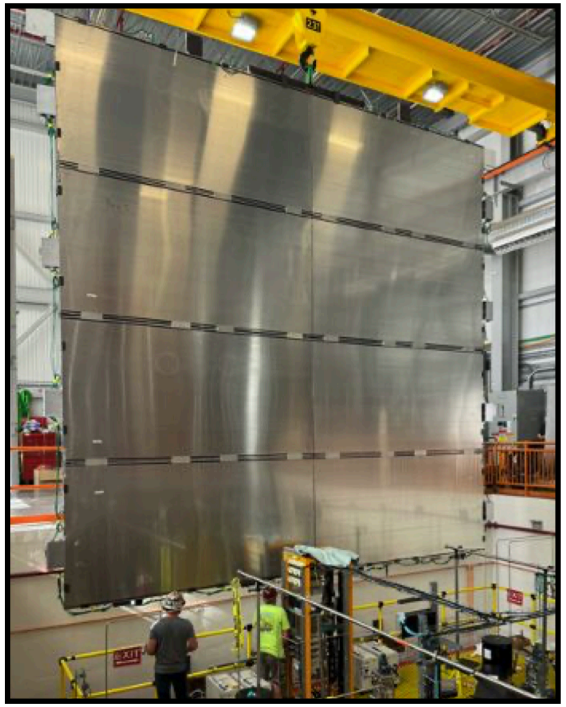

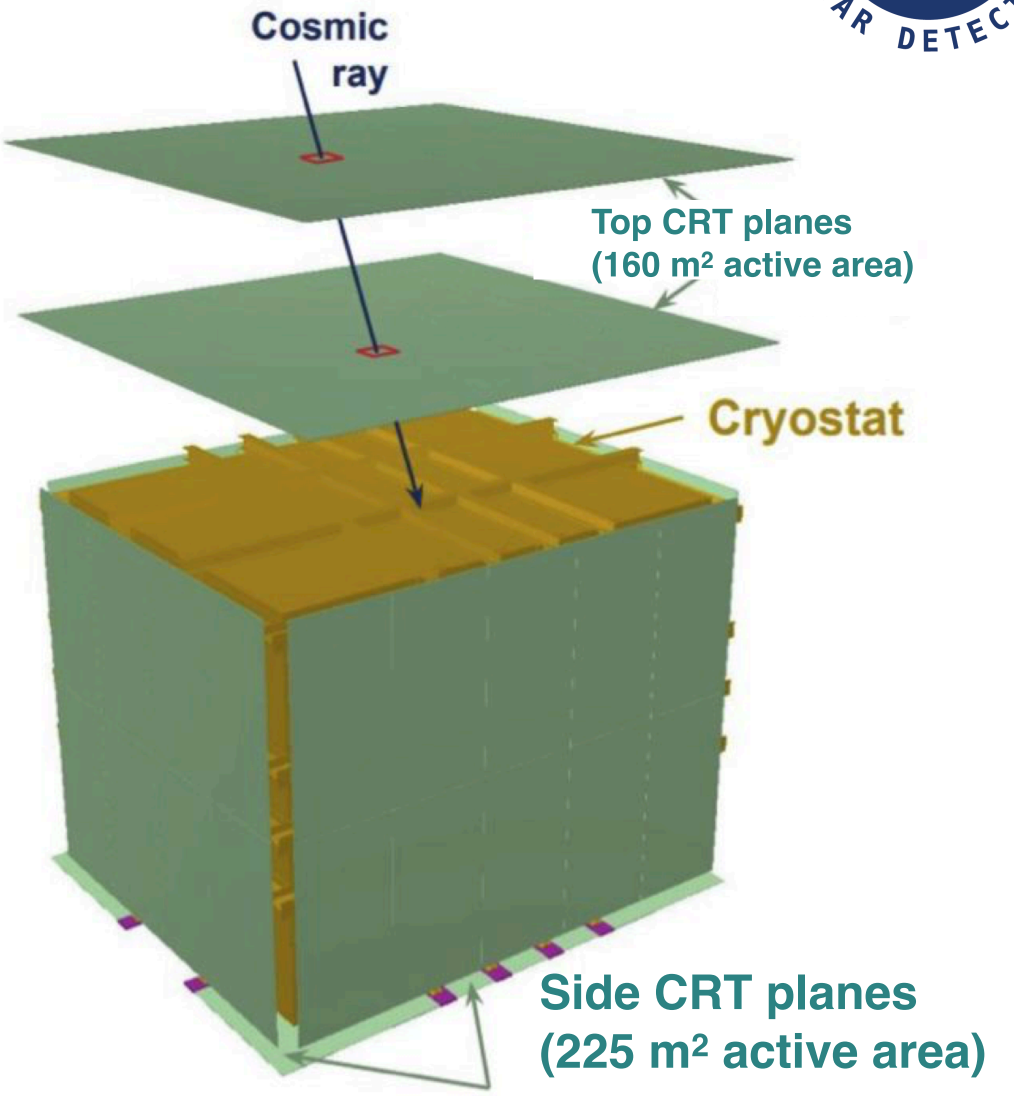

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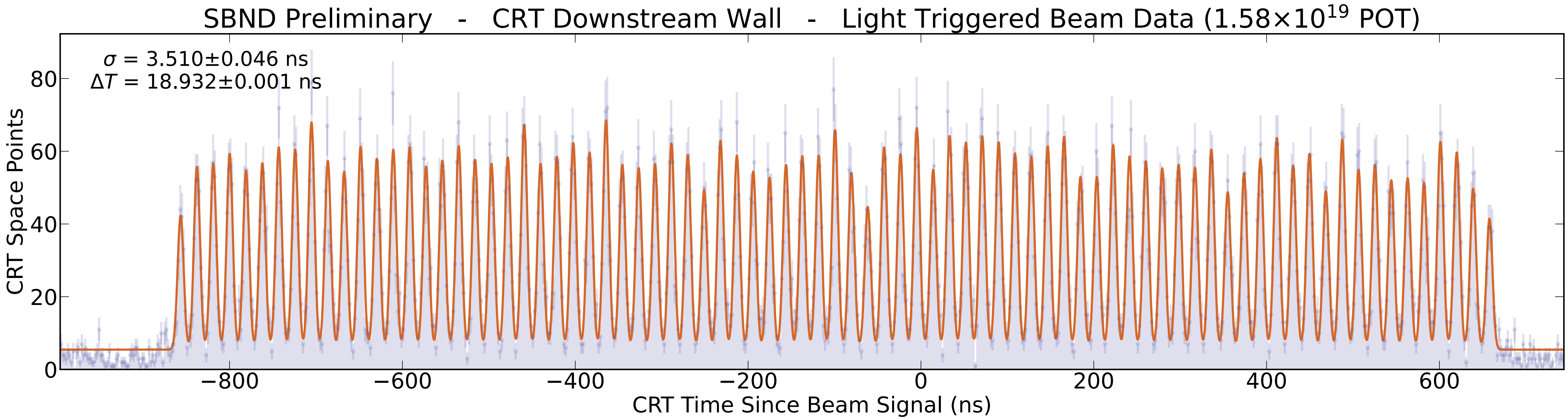

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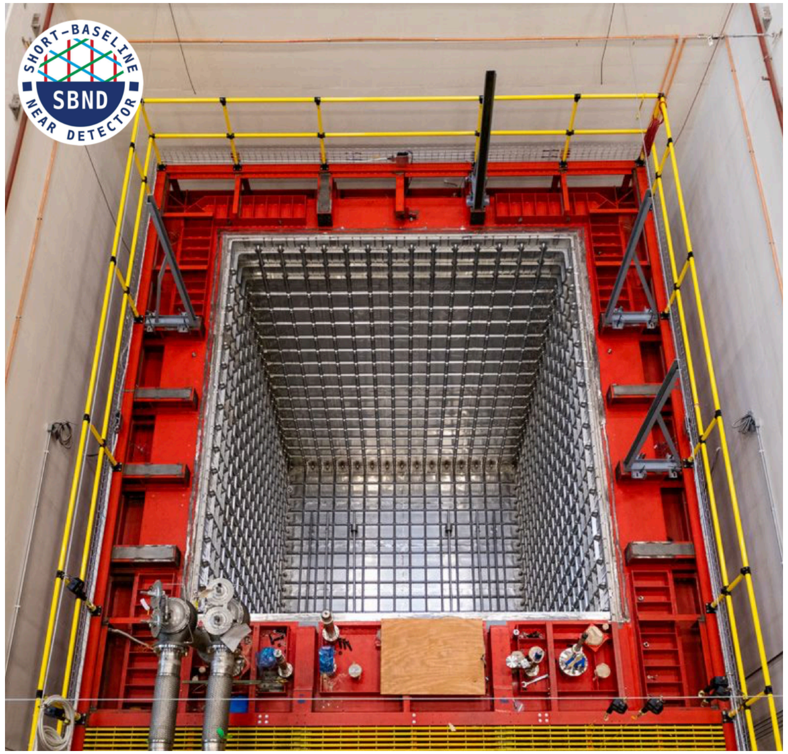
SBND: Cryostat and Cryogenics

Heart of the LArTPC experiments: literally pumps the experiment

- Under 1 atm, argon boiling point is 87.3 K and freezing point is 83.8 K



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- Liquid argon purity is critical
  - i.e. H_2O, O_2: charge yield reduction, N_2: light yield reduction

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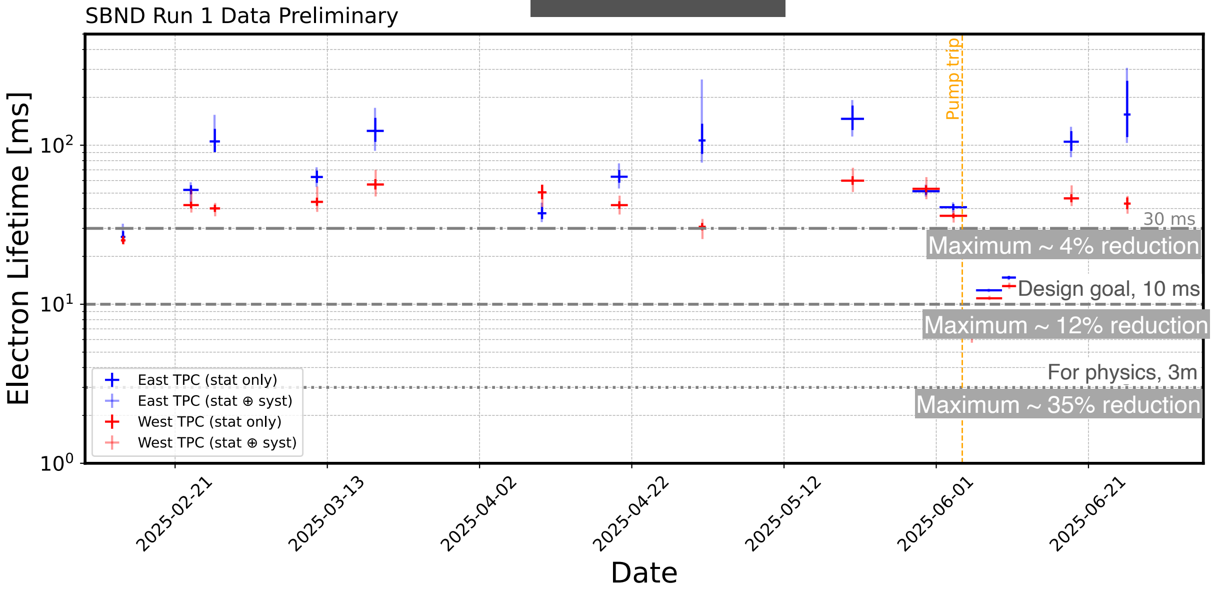
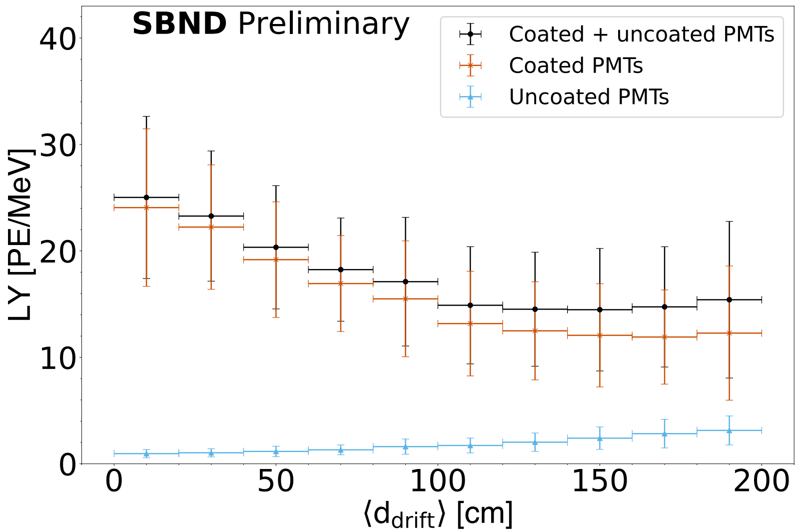
Heart of the LArTPC experiments: literally pumps the experiment

- Under 1 atm, argon boiling point is 87.3 K and freezing point is 83.8 K
- Liquid argon purity is critical
  - i.e. H_2O, O_2: charge yield reduction, N_2: light yield reduction
- Exceeding the design goals
- A very successful collaboration between CERN and Fermilab engineers and physicists

Charge Yield



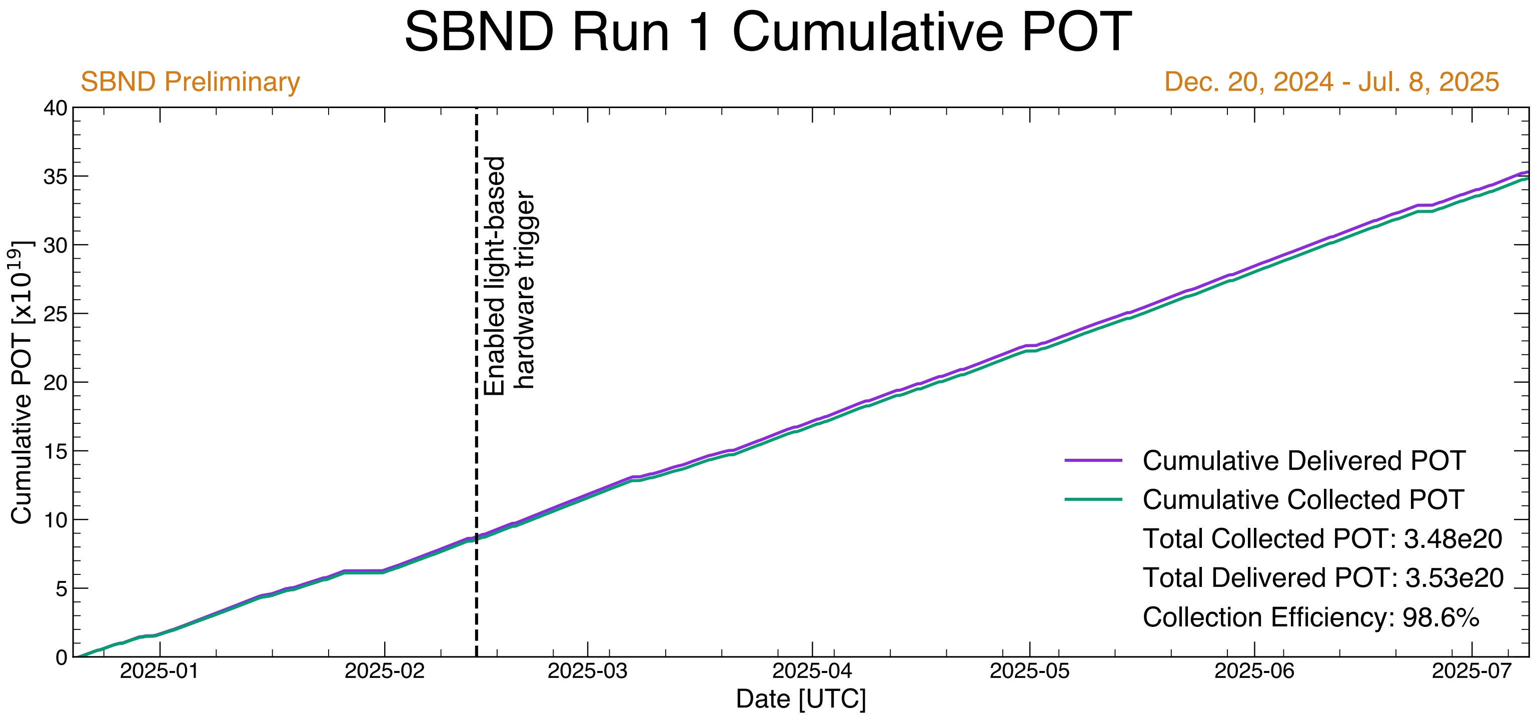
Light Yield



First Physics Run

SBND's first physics data taking period was very successful

- Amazing amount of delivered POT: 3.53×10^{20}
  - Huge thanks to our colleagues in the accelerator division for enabling us the world's largest ν-Ar data set
- Very high collection efficiency: 98.6%
  - Excellent operation team and highly reliable shifters - current run will deliver even bigger data set



Concluded ~ 4 months ago

04

Ongoing SBND Cross Section Efforts and Plans

ν_μCC 1p0π

An ideal channel for studying nuclear effects with high quasi-elastic scattering purity

ν_μCC 1p0π

An ideal channel for studying nuclear effects with high quasi-elastic scattering purity

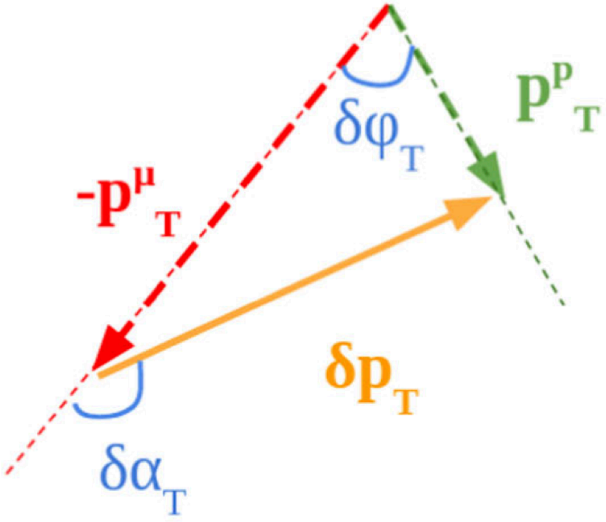
ν_μCC 1p0π

An ideal channel for studying nuclear effects with high quasi-elastic scattering purity

- Kinematic imbalance in the plane perpendicular to the incident neutrino's momentum

X. -G. Lu et al. *Phys.Rev.C* 94 (2016) 1, 015503

In plane perpendicular to incident neutrino's momentum



MicroBooNE Collab. *Phys.Rev.D* 108 (2023) 5, 053002

ν_μCC 1p0π

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- Sensitive to
  - Nuclear ground state modeling

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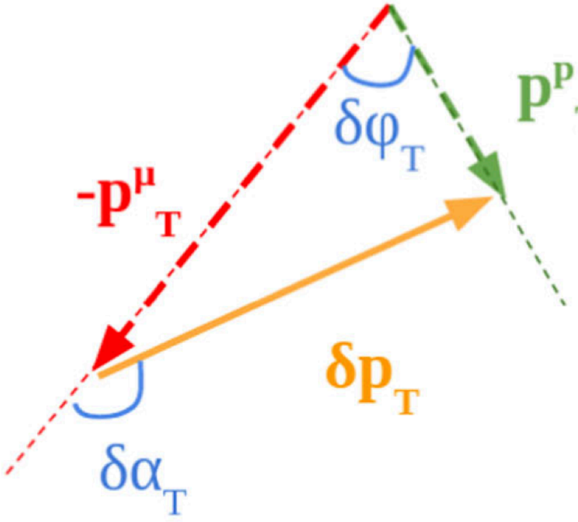
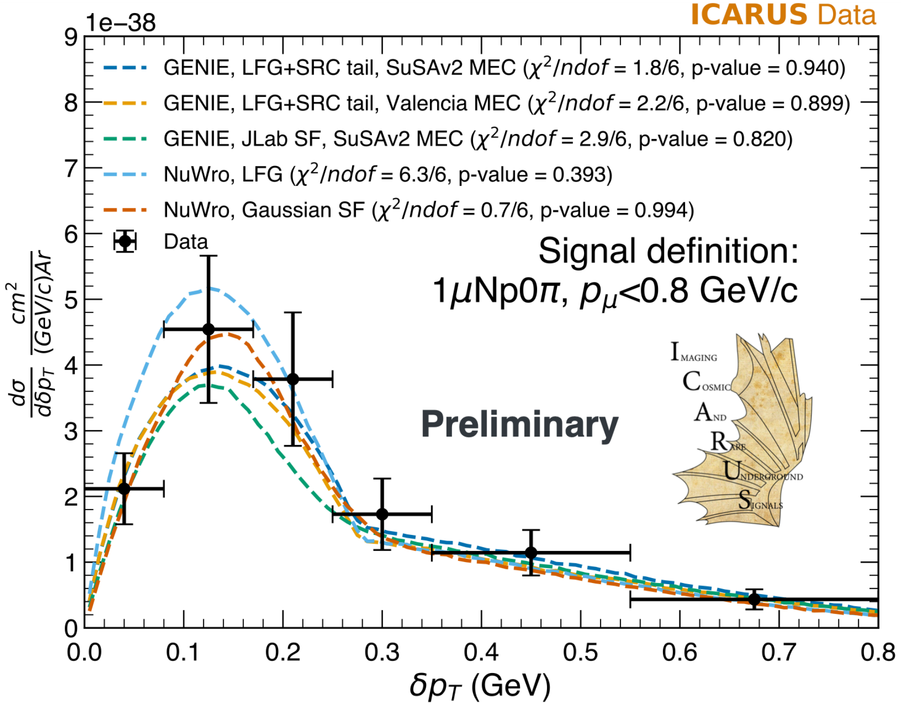


MicroBooNE Collab. *Phys.Rev.D* 108 (2023) 5, 053002



* B. Howard, & J. Kim(2025). *ICARUS cross-sections using the NuMI beam off-axis at Fermilab: program and first results*. Fermilab Seminar, Wilson Hall One West, Oct. 15.

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ν_μCC 1p0π

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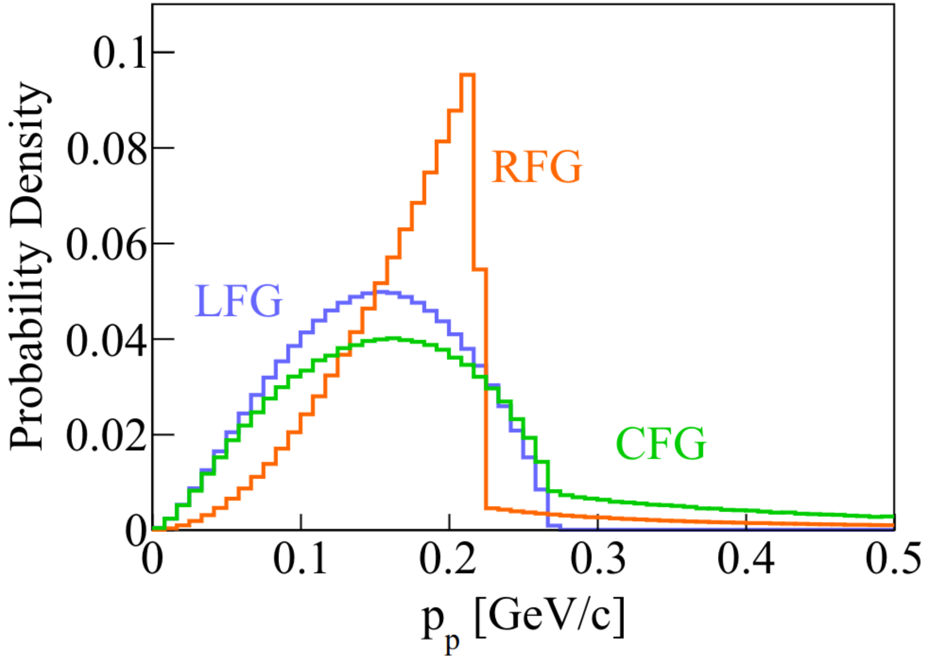
Nuclear ground state models

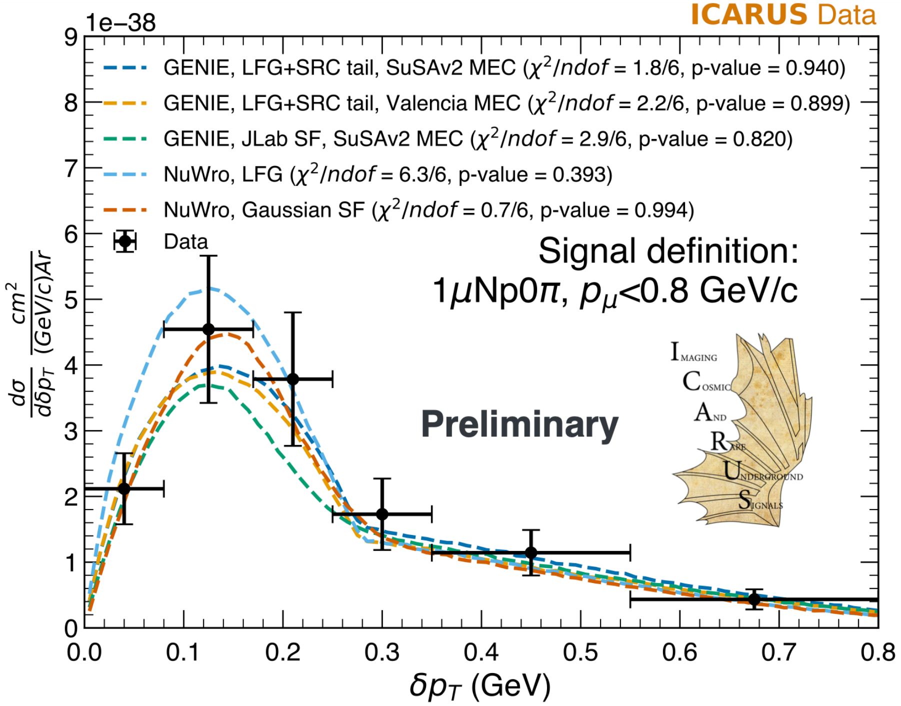
Local Fermi Gas

Relative Fermi Gas

Correlated Fermi Gas (~ spectral function)

e4v Collab. *Phys.Rev.D* 103 (2021) 113003





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ν_μCC 1p0π

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X. -G. Lu et al. *Phys.Rev.C* 94 (2016) 1, 015503

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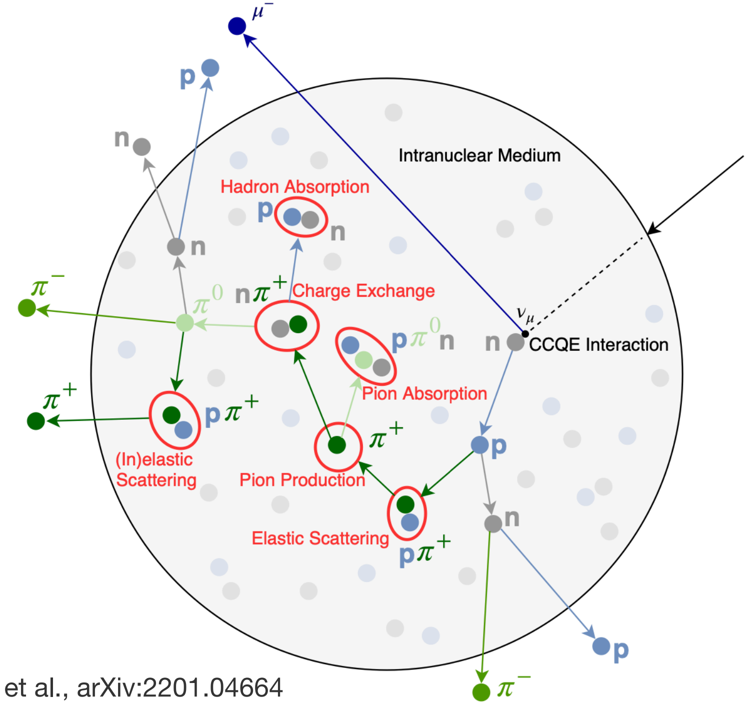
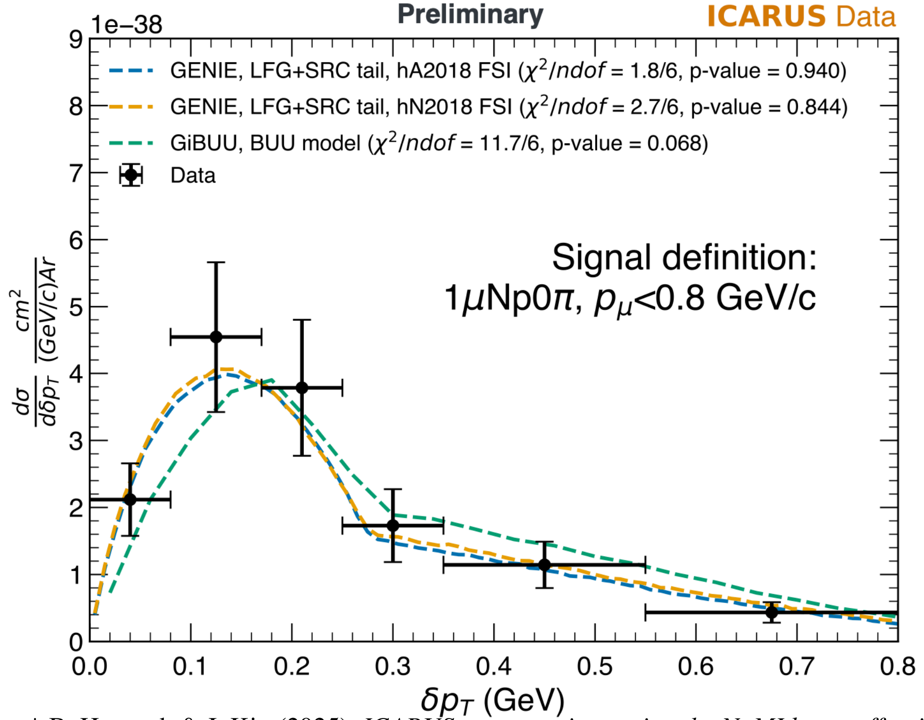
    - Final state interactions



L. Bathe-Peters et al., arXiv:2201.04664



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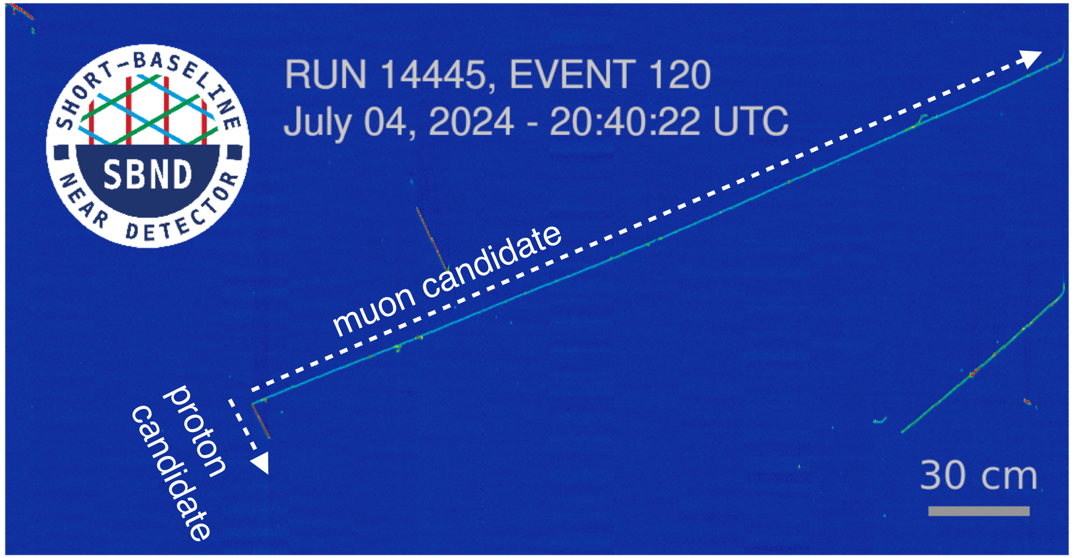
ν_μCC 1p0π

Signal event definition

- Final state kinematics
  - Exactly one muon with P_μ in [220, 1000] MeV/c
  - Exactly one proton with P_p in [300, 1000] MeV/c
  - No charged pions with $P_{\pi^\pm} > 70$ MeV/c
  - No neutral pion
  - Other particles not listed are allowed
- Events are fully contained within the detector volume



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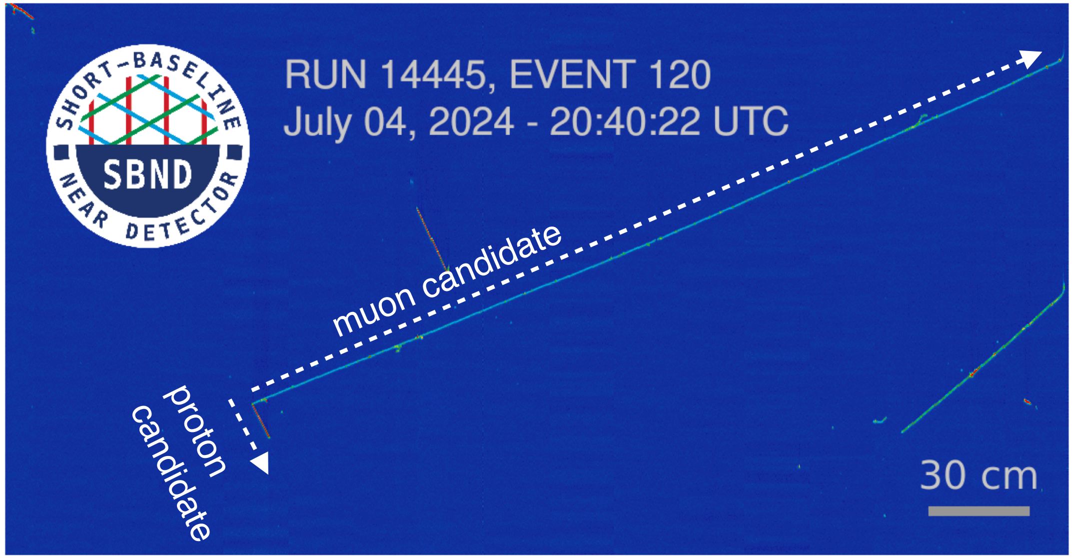
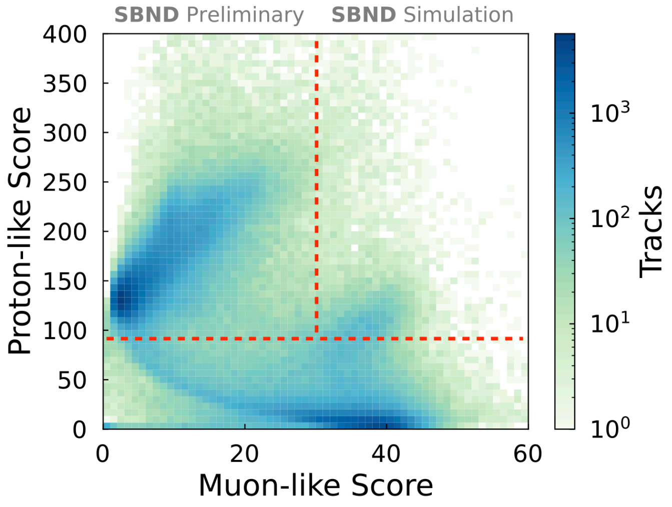


Event selection in data

- Cosmic rejection: neutrino-like events (eff.: 79%, purity: 21%, CCQE purity: 33%)
- Two-track topology: with only two trajectories emerging from a common vertex (eff.: 50%, purity: 59%, CCQE purity: 63%)
- Particle identification: 1μ + 1p (eff.: 39%, purity: 92%, CCQE purity: 82%)

ν_μCC 1p0π



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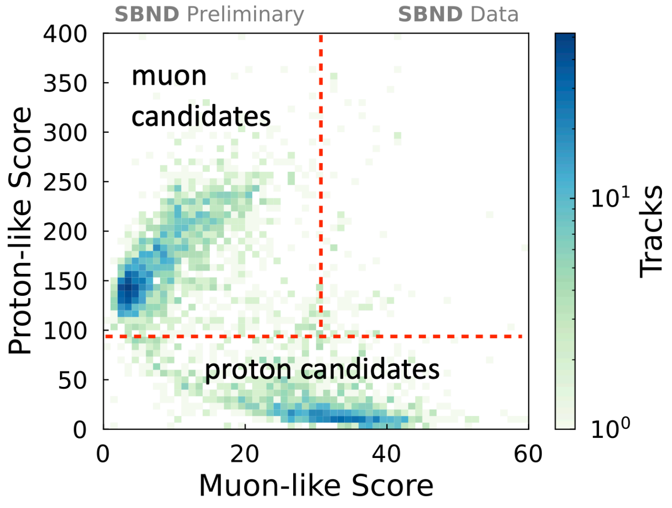

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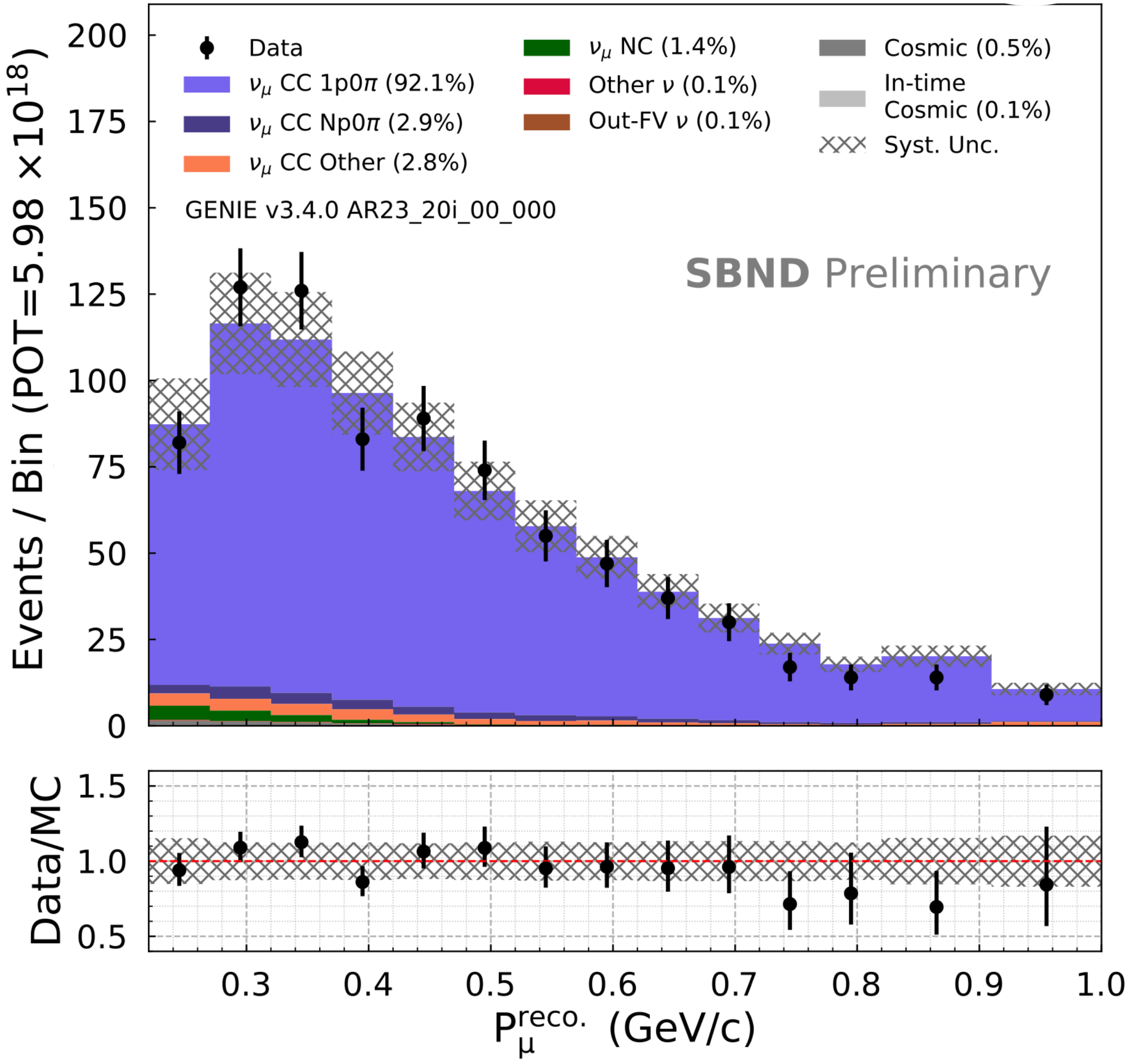
	Muon	Proton
Efficiency	94.7%	84.0%
Purity	97.0%	99.1%

ν_μCC 1p0π

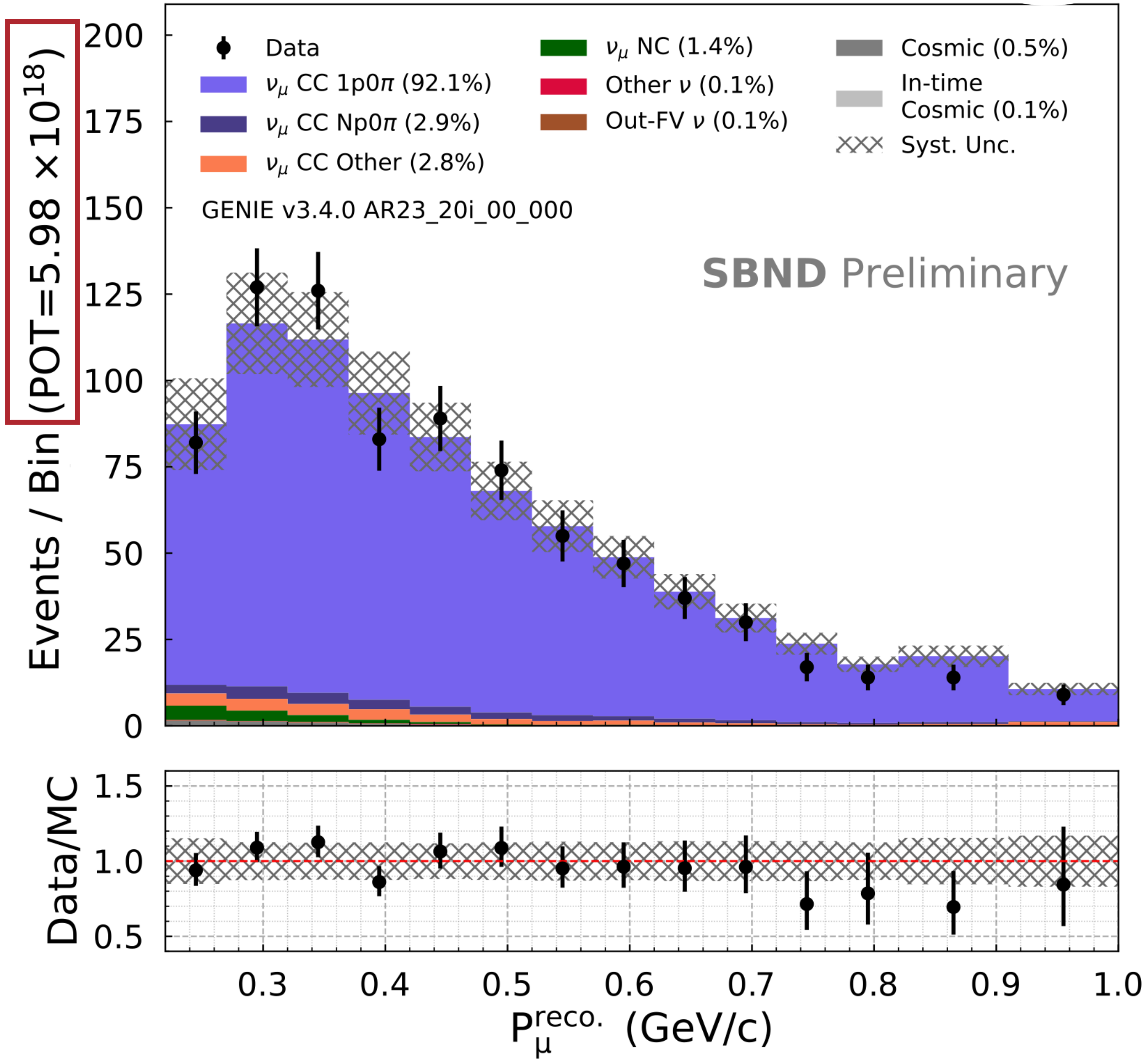
First data and MC comparison!!!



ν_μCC 1p0π

First data and MC comparison!!!

- POT = $5.98 \times 10^{18} \rightarrow \sim$3 days



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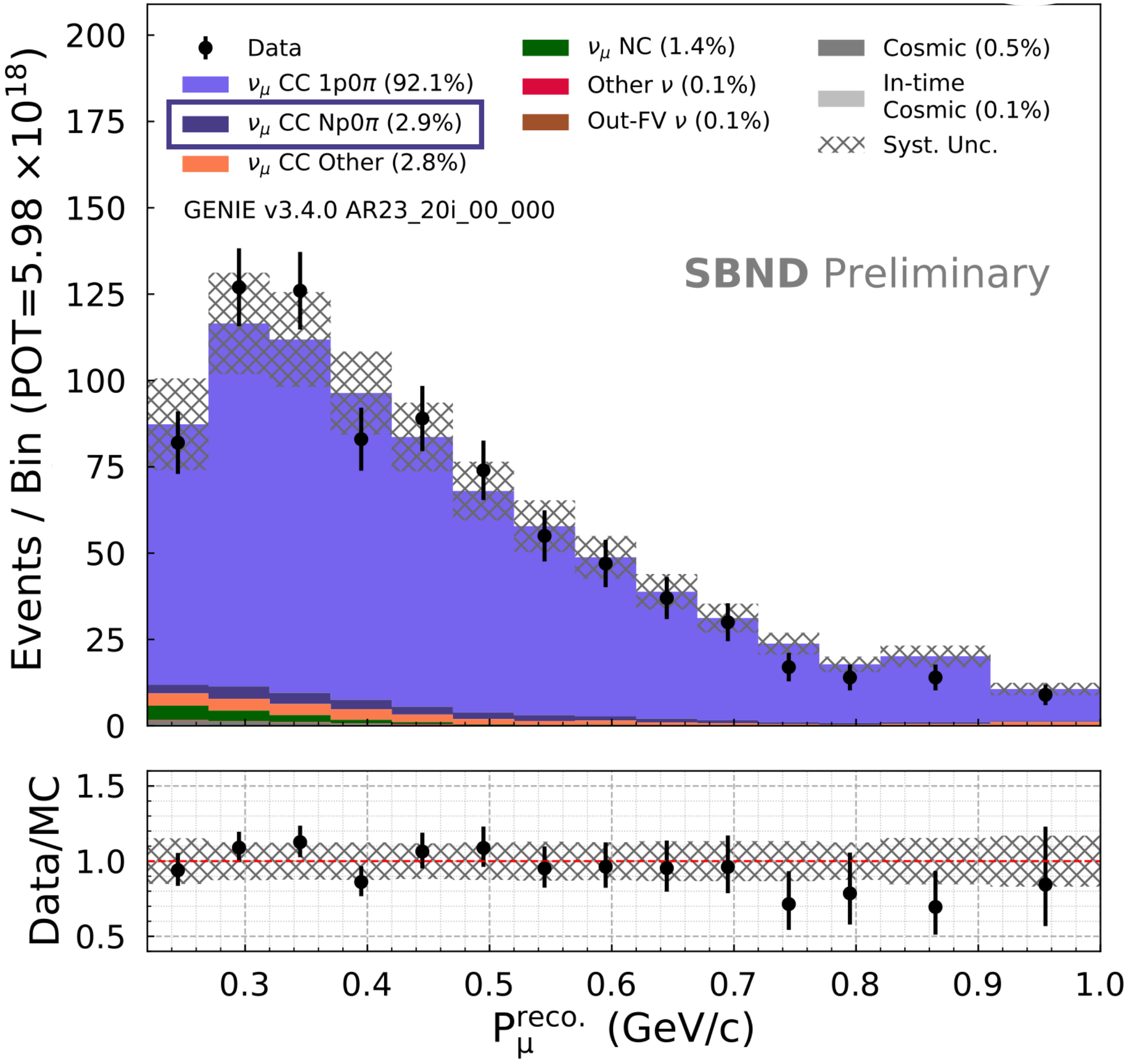

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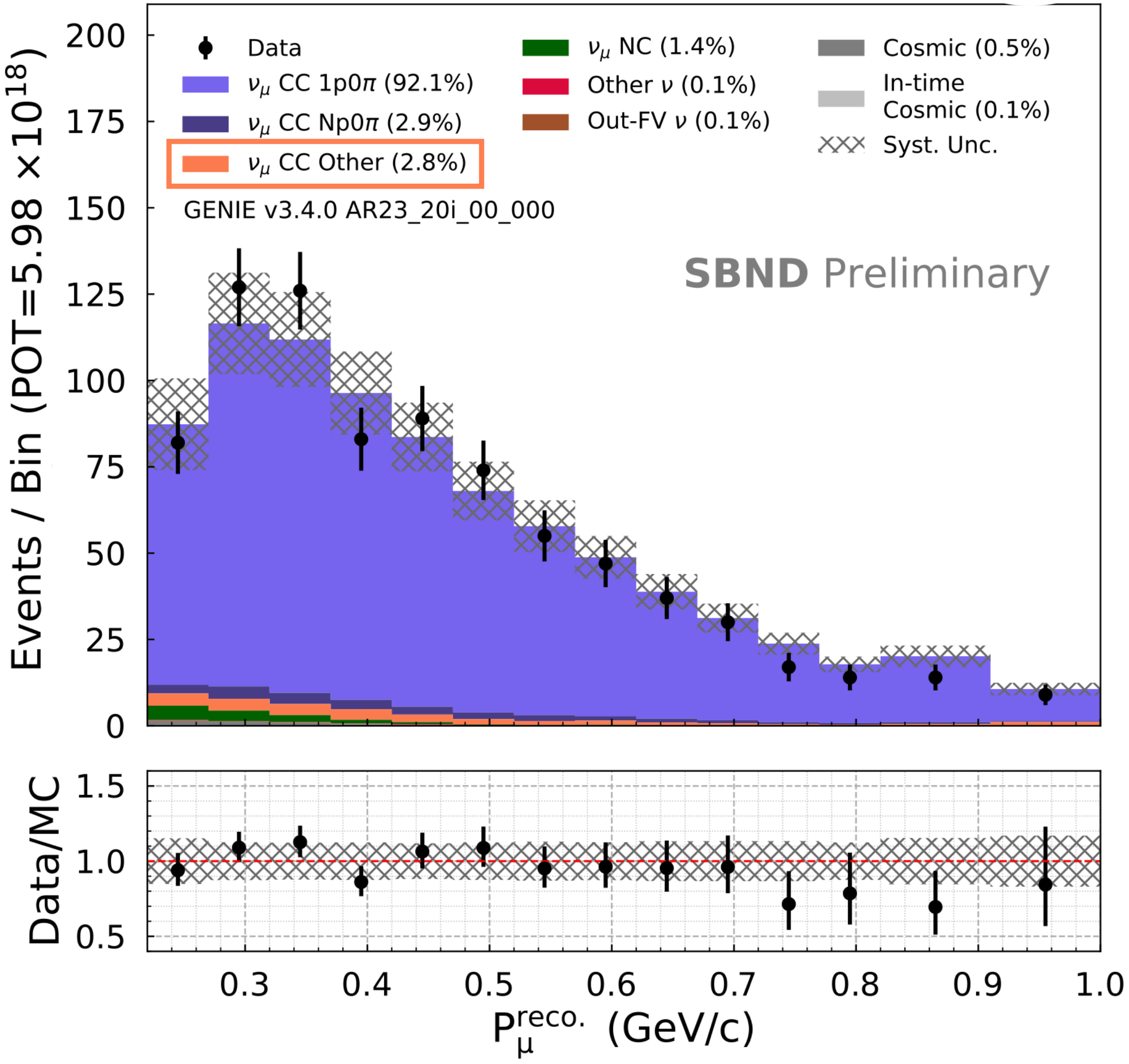

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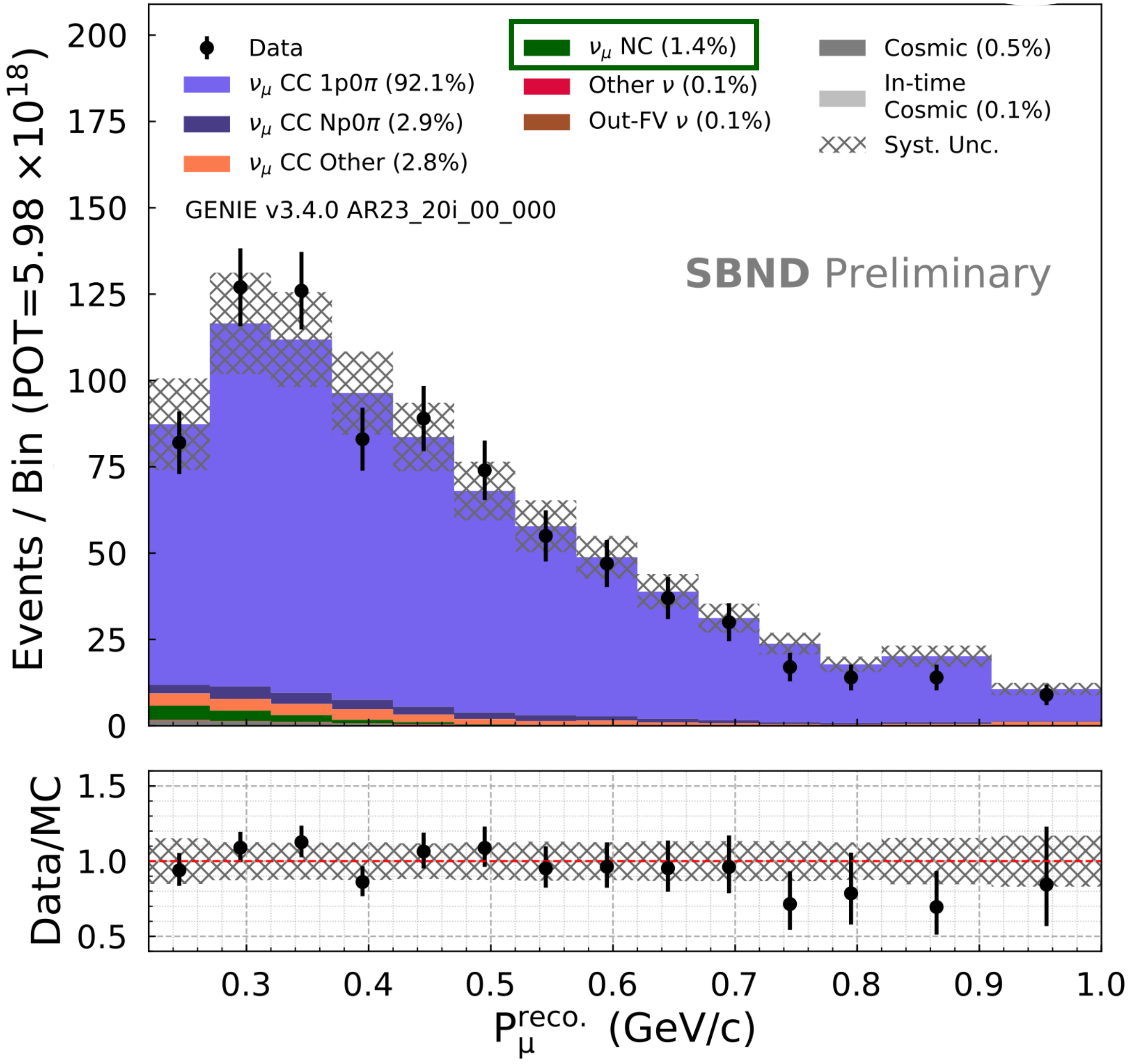

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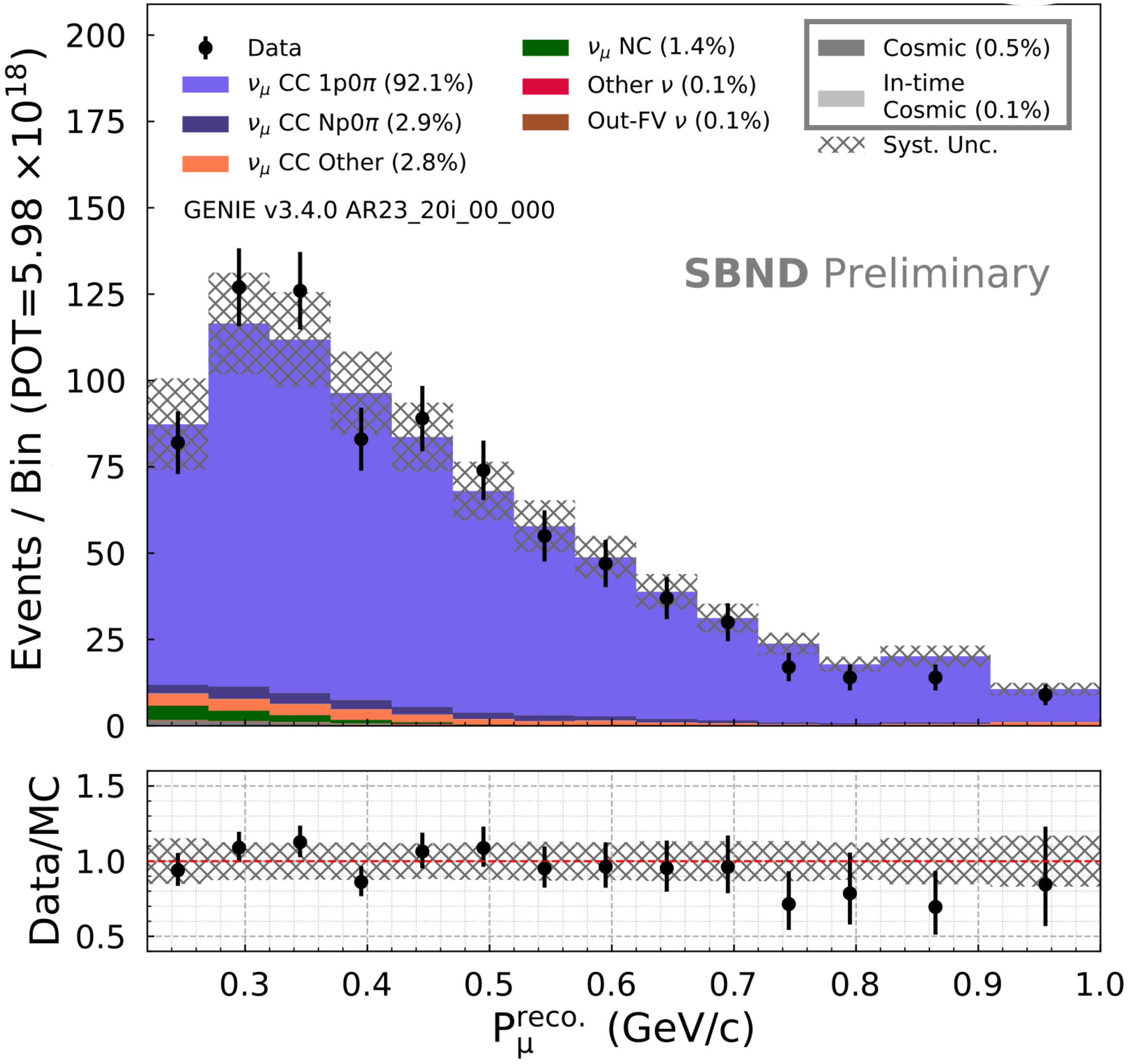

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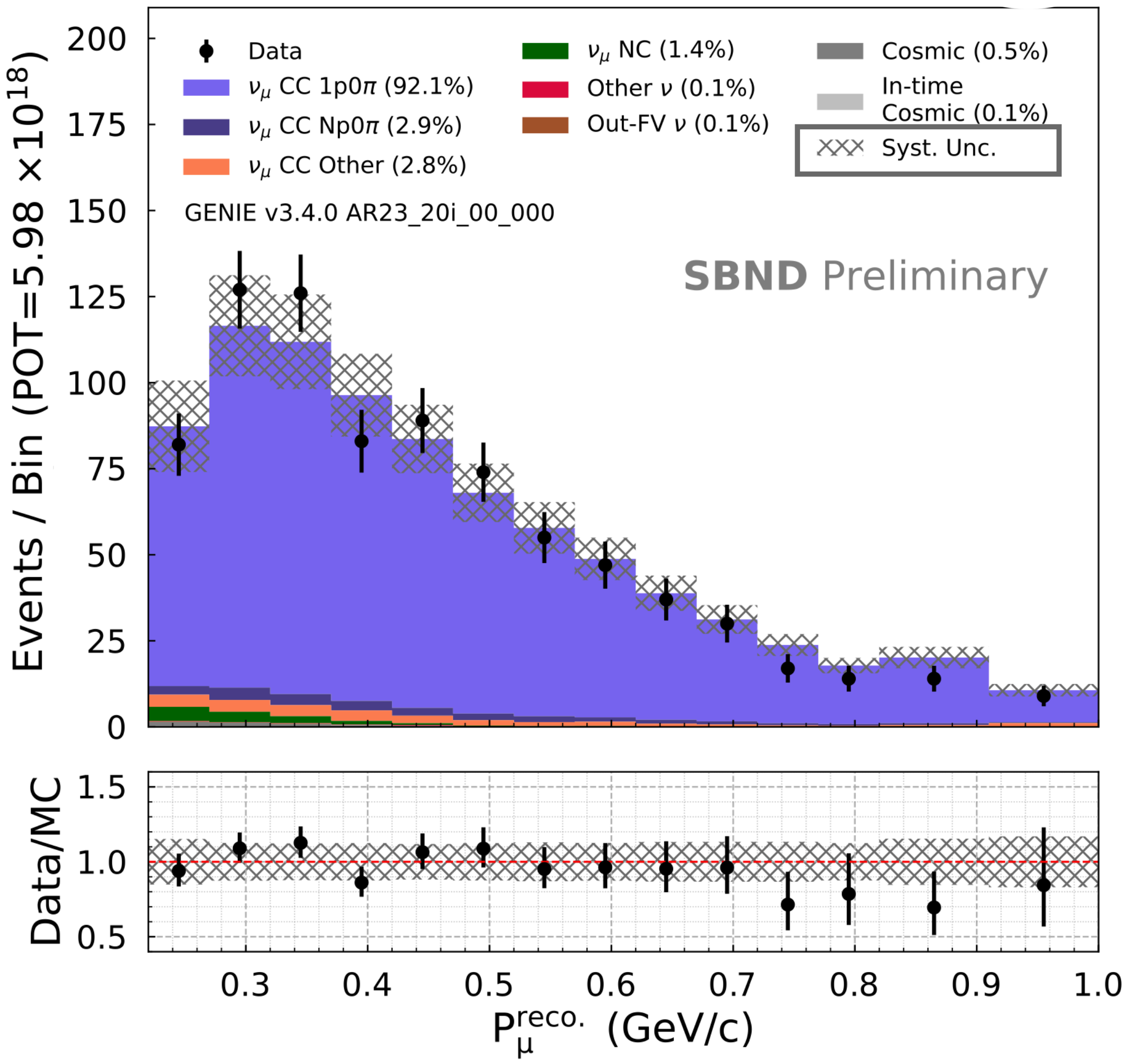
- MC uncertainty on event rate with
  - Neutrino flux
  - Cross section model
  - Detector effects (SCE + recombination)



ν_μCC 1p0π

W. Tang et al. *JINST* 12 (2017) 10, P10002

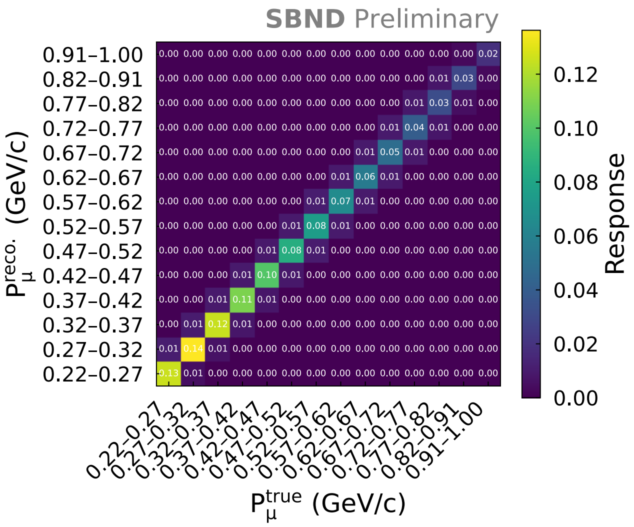
Cross section extraction strategy: Wiener-SVD unfolding used in the first analysis round

ν_μCC 1p0π

W. Tang et al. *JINST* 12 (2017) 10, P10002

Cross section extraction strategy: Wiener-SVD unfolding used in the first analysis round

- Two types of matrices for the unfolding
  - Response matrix
    - Event selection efficiency × truth-reco. response matrix



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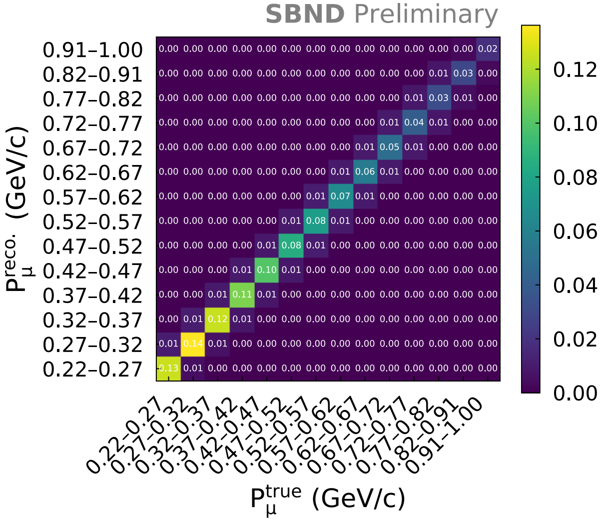
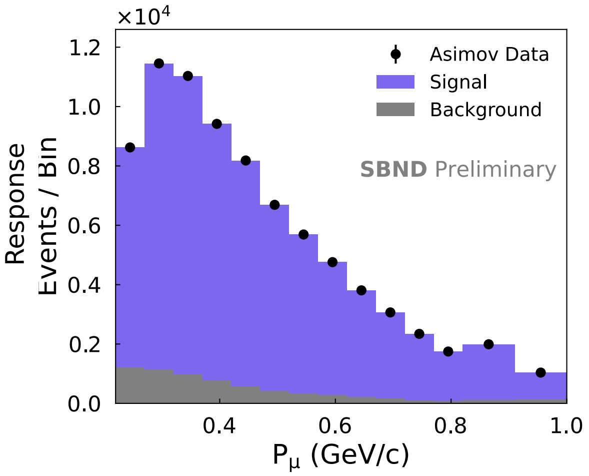
- Unfolding with regularization





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W. Tang et al. *JINST* 12 (2017) 10, P10002

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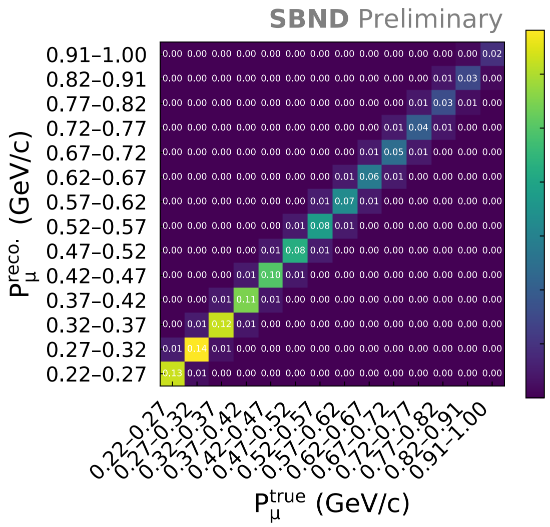
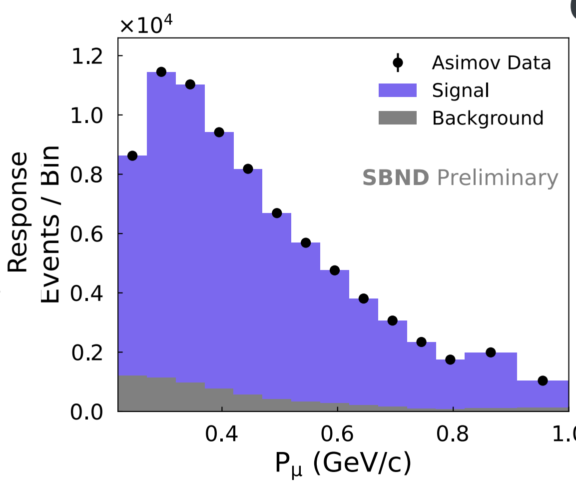
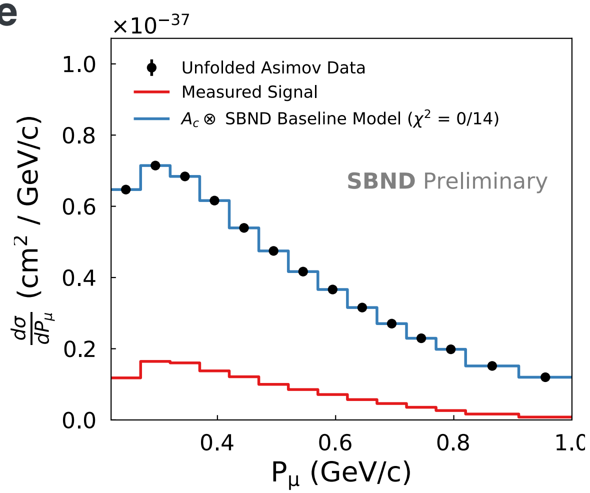
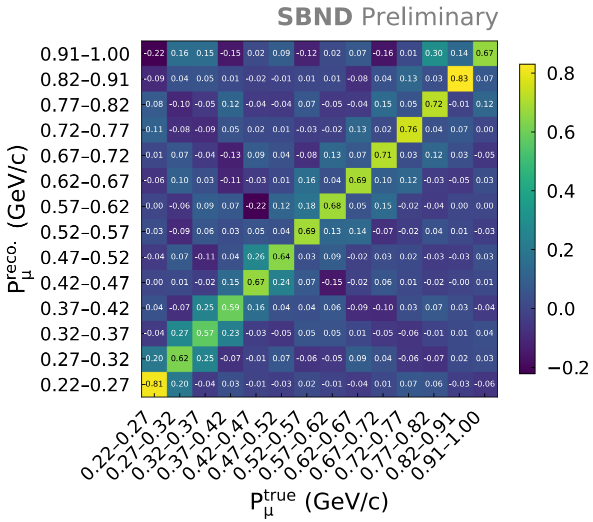
  - Covariance matrices for uncertainties
- Unfolding with regularization
- Cross section results in regularized space: together with the smearing matrix for model comparisons





Closure Test

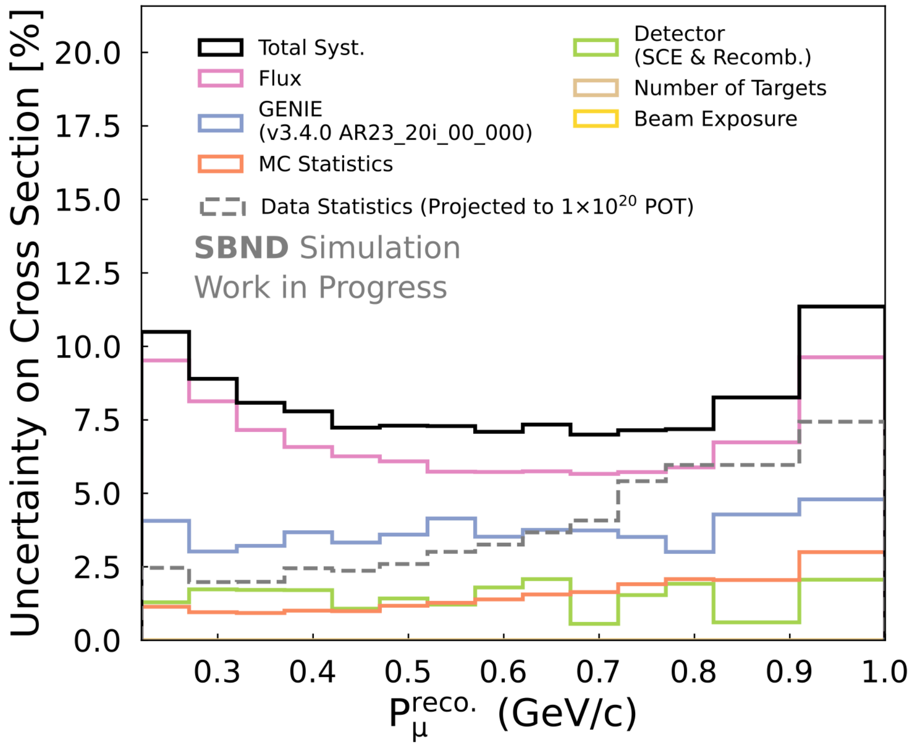




ν_μCC 1p0π

Systematic uncertainty in cross section

- Using Asimov data



	Flux	Cross section	SCE & Recomb.	# of Targets	Beam exposure	MC statistics	Total
Uncert.	6.4%	3.1%	1.7%	1%	2%	0.9%	7.7%

ν_μCC 1p0π

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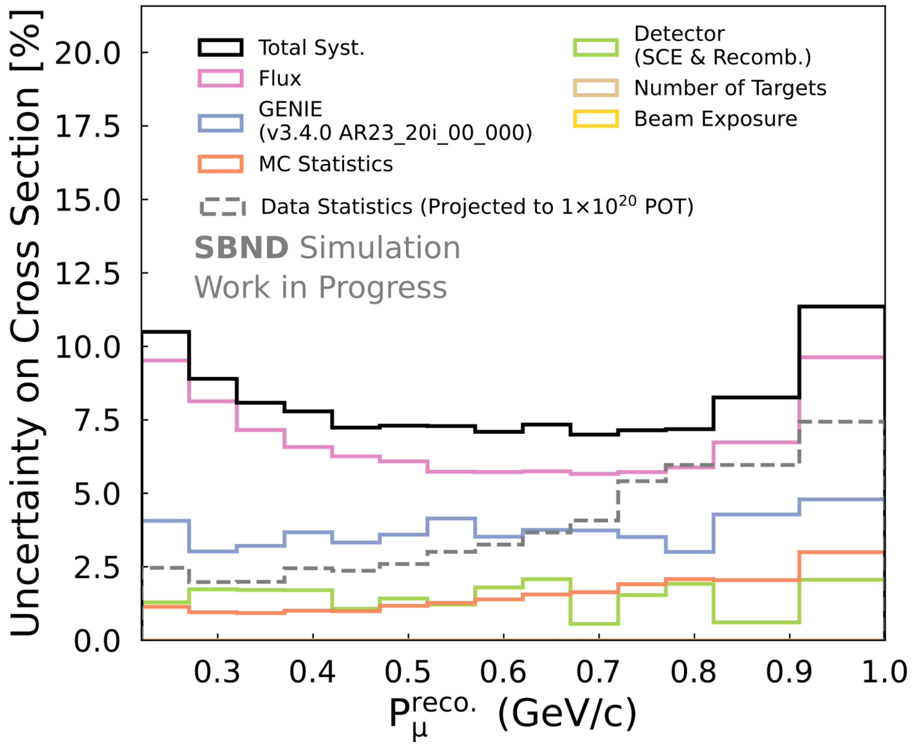
- Using Asimov data

Neutrino flux

- Leading source of uncertainty
- Improvements in simulation and uncertainties are coming soon with more efforts in p-Be scattering data!



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ν_μCC 1p0π

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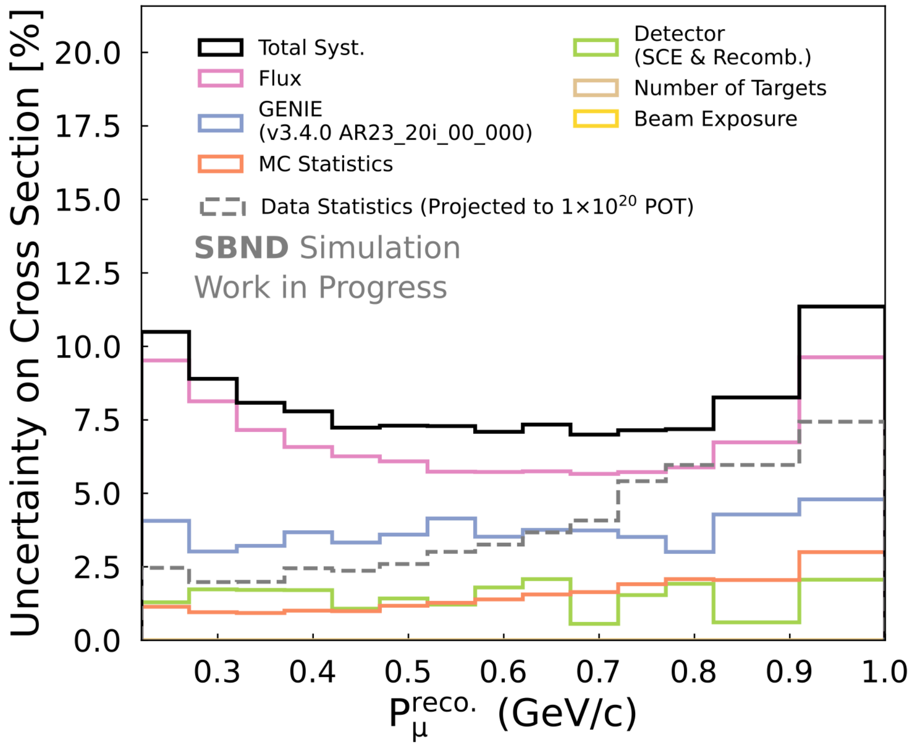
Neutrino interaction model

- From the GENIE event generator
- Updating baseline models that would reduce this budget
- GiBUU sample is ready for further studies



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Neutrino interaction model

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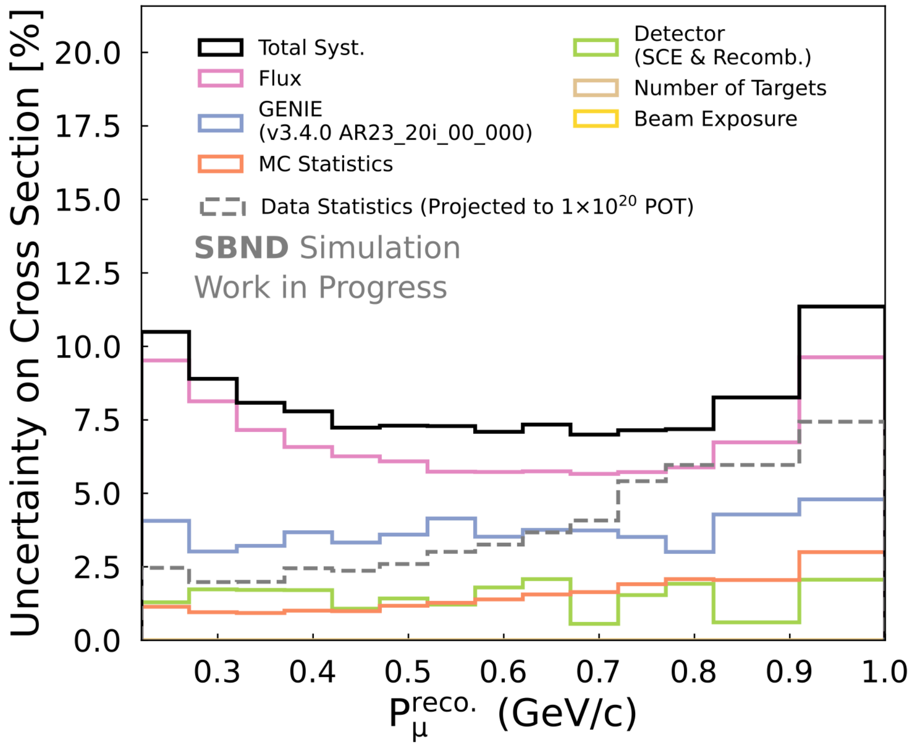
- GiBUU sample is ready for further studies

Detector simulation

- For now, considering lEl distortion and electron-argon recombination (largest effect in MicroBooNE)



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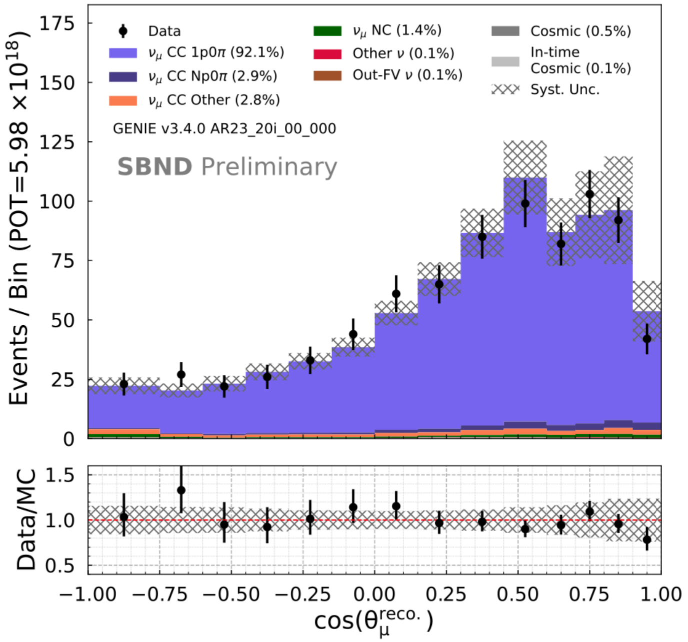
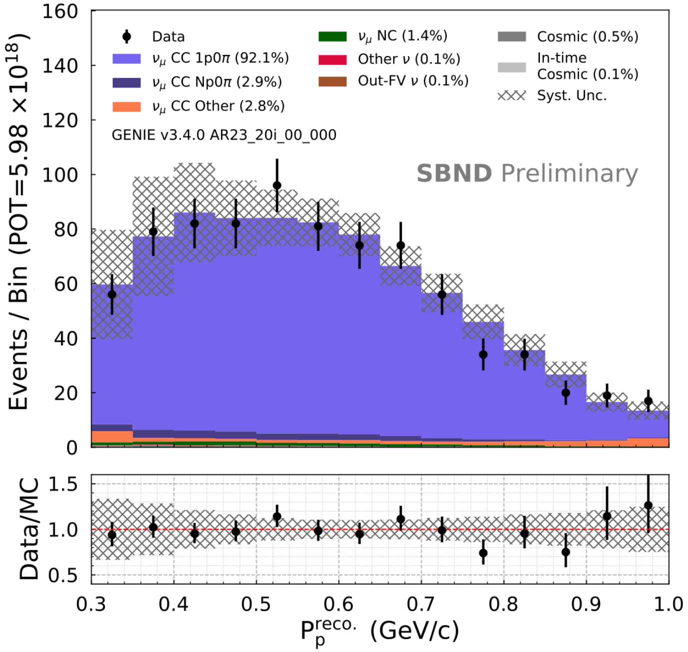
ν_μCC 1p0π

For the first result, we aim to produce 1D differential cross section measurements in

- Particle kinematics
  - P_μ, $\cos\theta_\mu$, P_p and $\cos\theta_p$

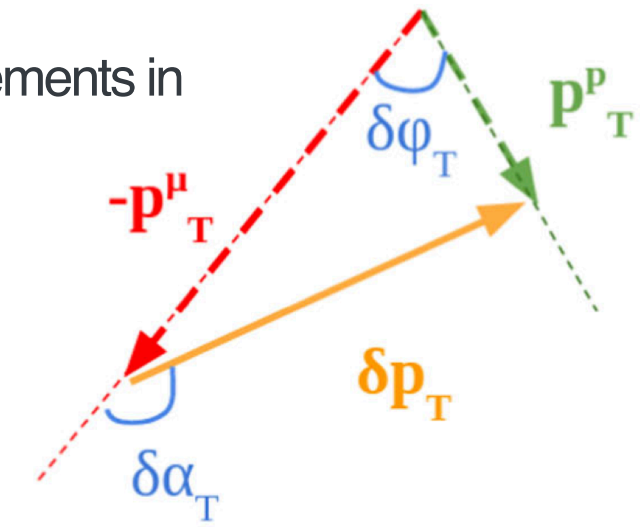




ν_μCC 1p0π

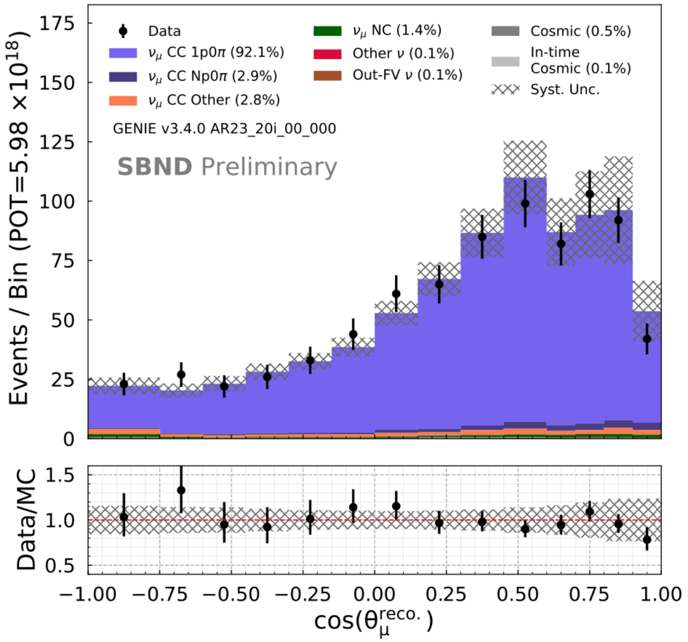
In plane perpendicular to incident neutrino's momentum

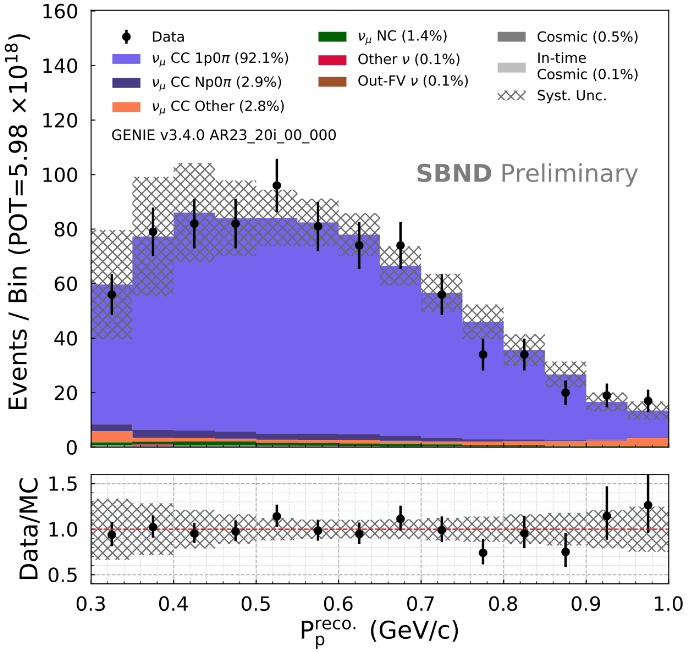
X. -G. Lu et al. *Phys.Rev.C* 94 (2016) 1, 015503
MicroBooNE Collab. *Phys.Rev.D* 108 (2023) 5, 053002

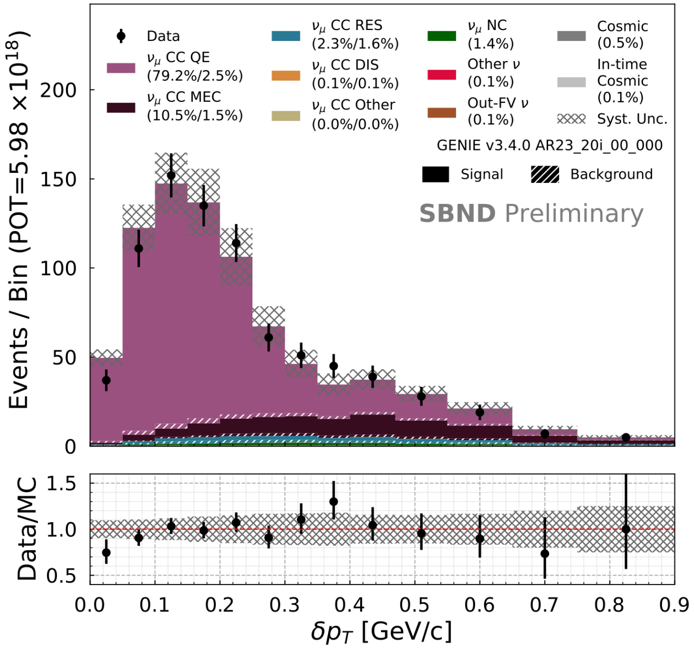


For the first result, we aim to produce 1D differential cross section measurements in

- Particle kinematics
  - P_μ, $\cos\theta_\mu$, P_p and $\cos\theta_p$
- Variables for transverse kinematic imbalance
  - δp_T, $\delta\alpha_T$ and $\delta\phi_T$
- Will use larger data with about 1×10^{20} POT



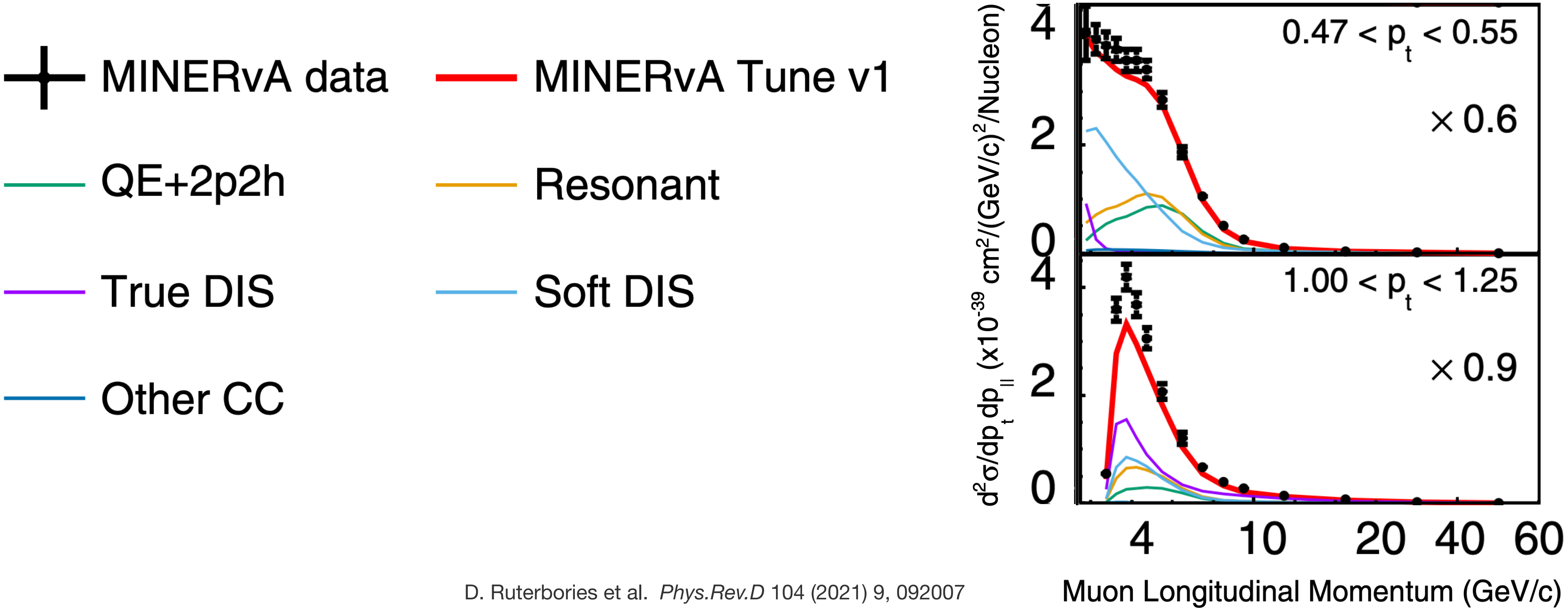




Inclusive ν_μCC

The channel with the largest statistics

- Lepton kinematics is less affected by final state interactions: good for studying multiple topologies at once
- Multi-differential cross section measurements for precision studies
- For the first result, we aim 2D differential cross section measurements in $(P_\mu, \cos\theta_\mu)$



D. Ruterbories et al. *Phys.Rev.D* 104 (2021) 9, 092007

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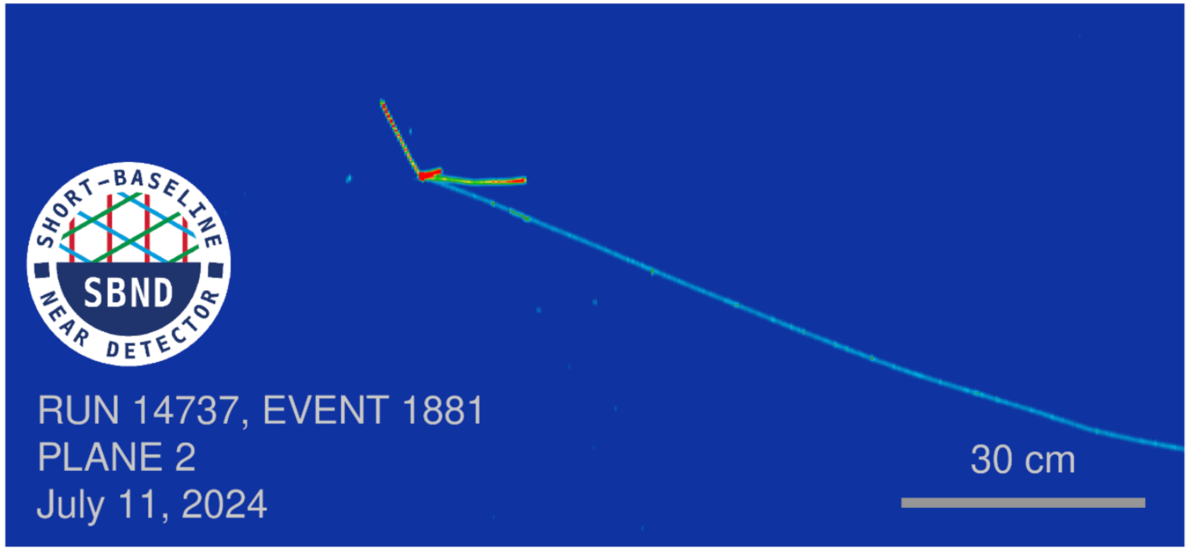
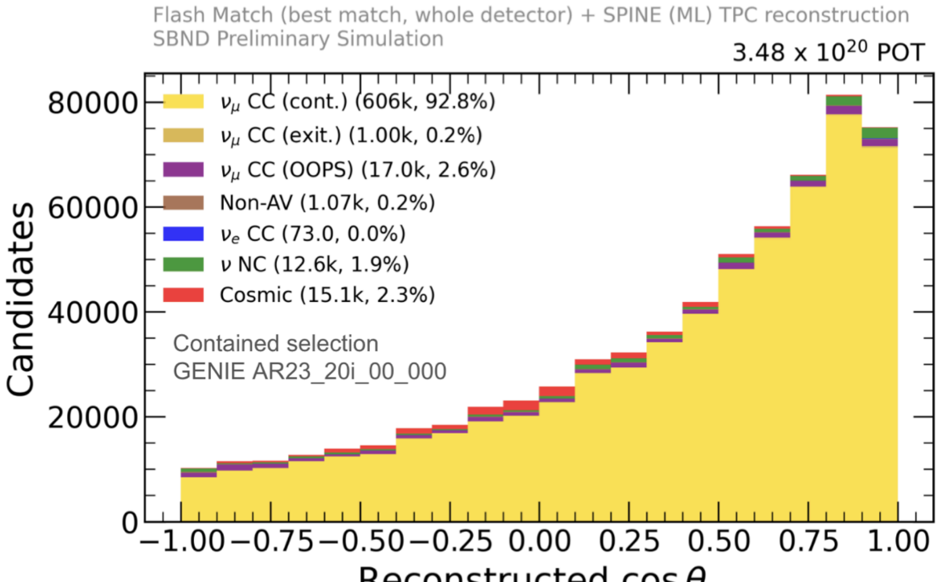
Event selection is mature

- Entering systematic uncertainty study stage





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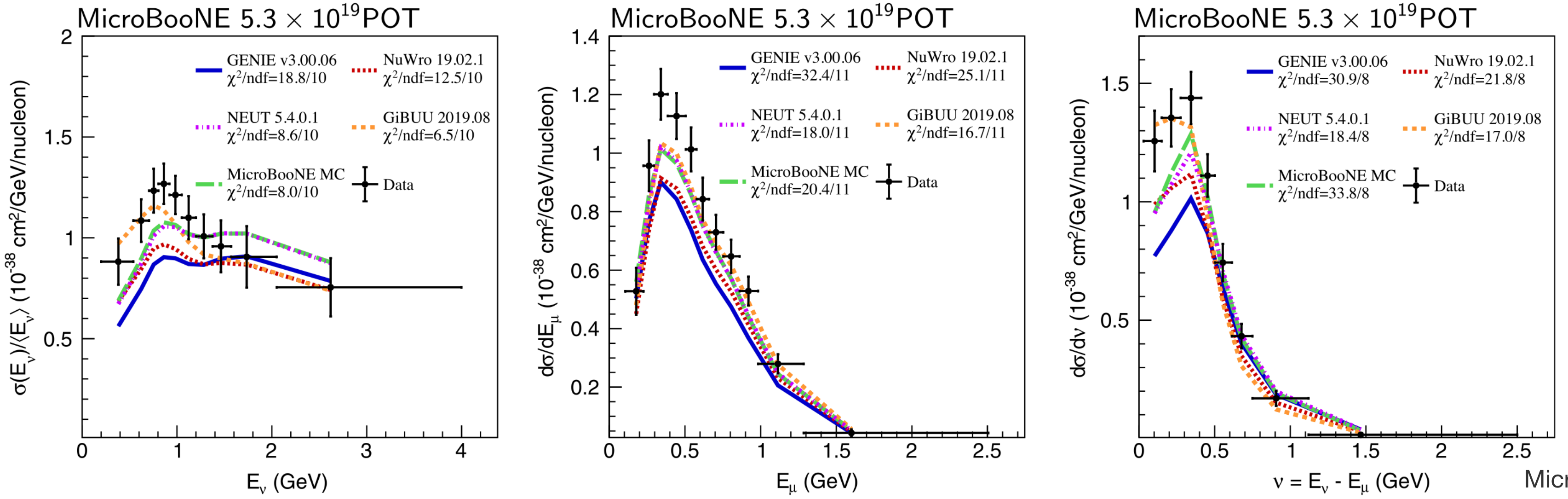
Event selection is mature

- Entering systematic uncertainty study stage

Including E_ν in cross sections provides further sensitivity to model differences



MicroBooNE Collab. *Phys.Rev.Lett.* 128 (2022) 15, 151801

Inclusive ν_eCC

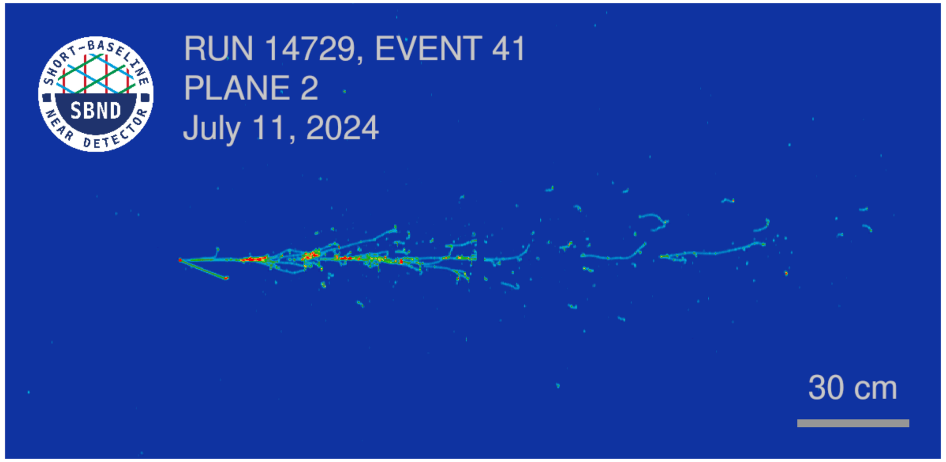
Important for DUNE for its ν_e-appearance studies!

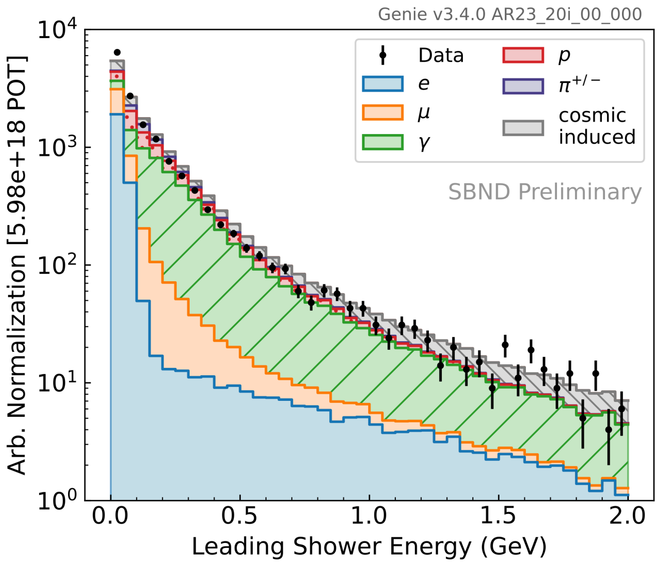
For the first result, we aim 1D differential cross section measurements in

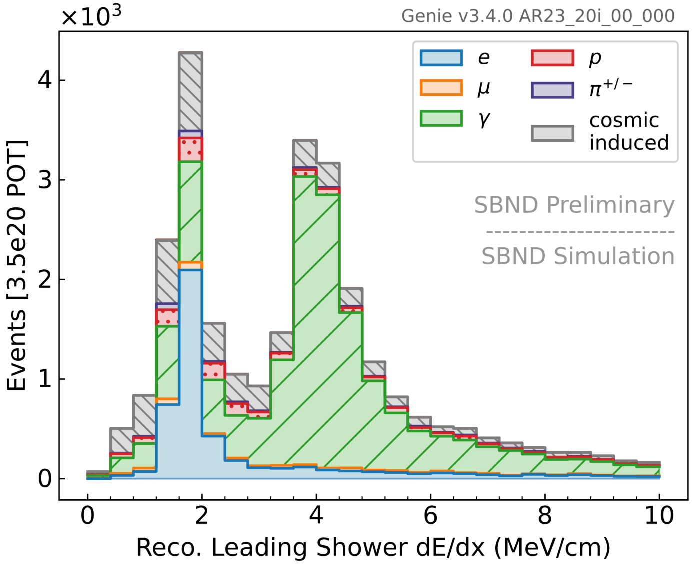
- E_e and $\cos\theta_e$
- Photon and electron separation is being developed: critical for the SBN oscillation physics!

Event selection is mature

- Performing studies for systematic uncertainties







Inclusive ν_eCC

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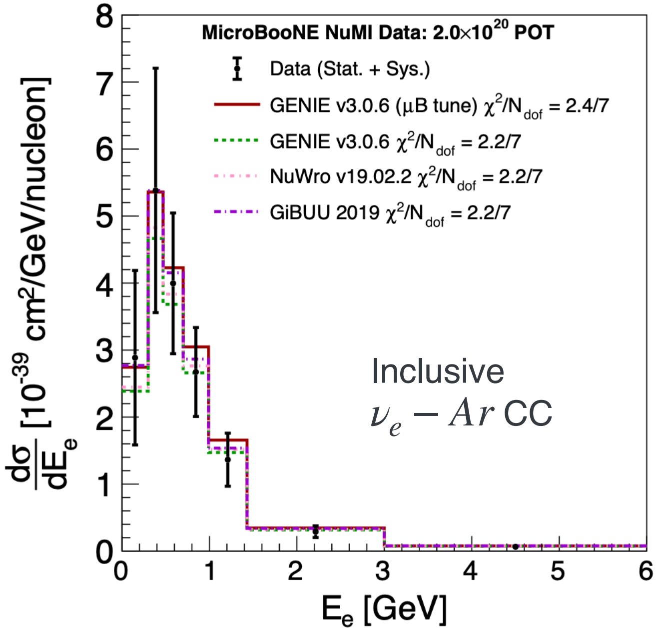
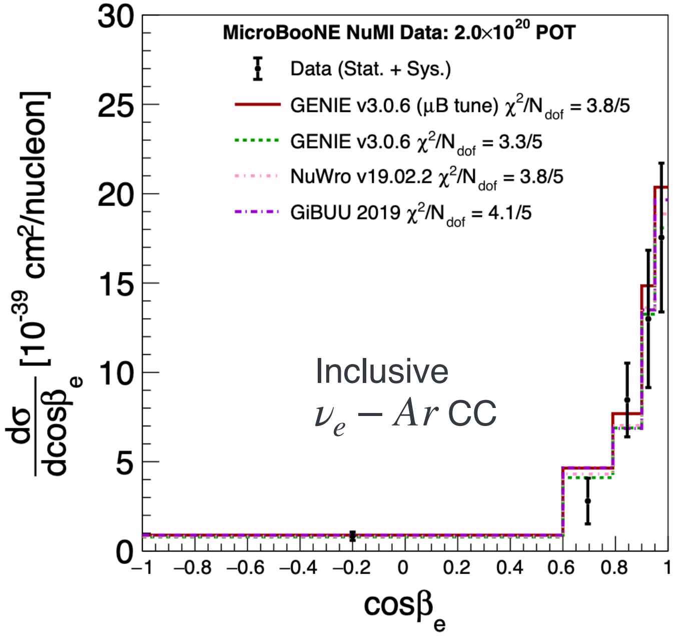
Both larger statistics and improved neutrino flux uncertainties are important





Source of uncertainty	Relative uncertainty [%]
Beam flux	17.4
Detector	6.8
Cross section	5.8
POT counting	2.0
Out-of-cryostat	1.8
Proton/pion reinteractions	1.2
Beam-off normalization	0.1
Total systematic uncertainty	19.8
Monte Carlo statistics	0.8
Data statistics	10.0
Total uncertainty	22.2

MicroBooNE Collab. *Phys.Rev.D* 105 (2022) 5, L051102

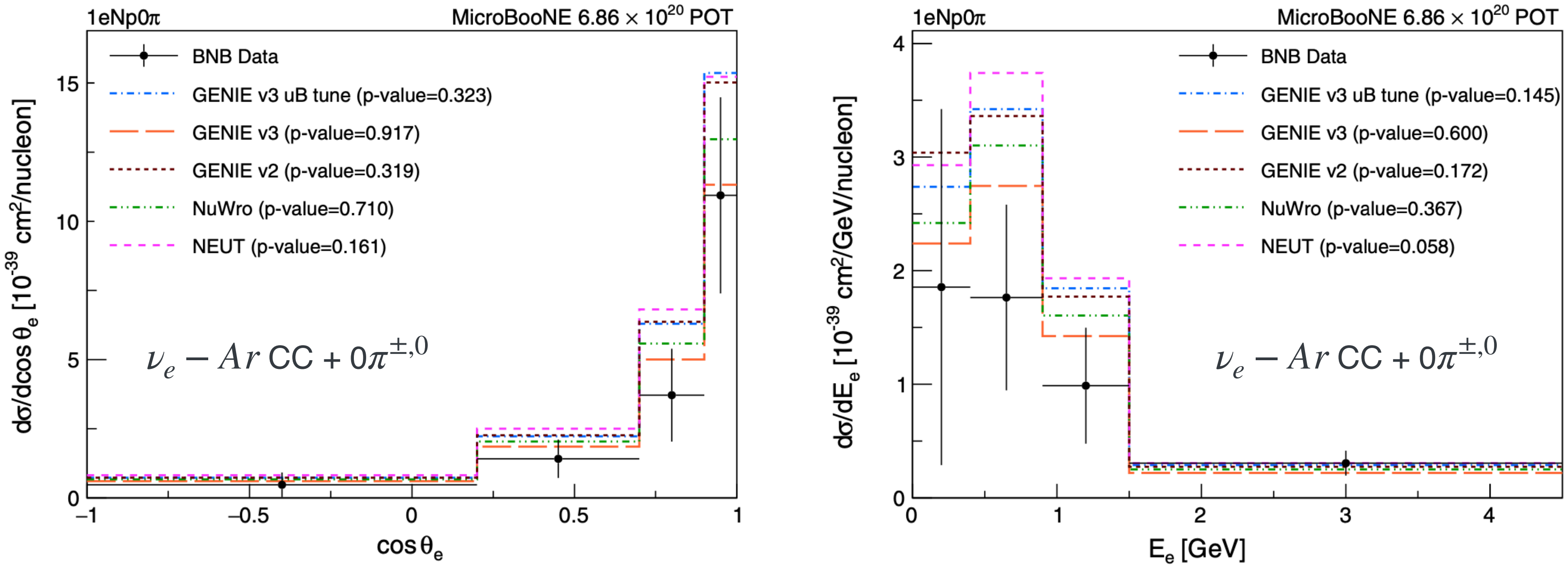
Inclusive ν_eCC

Important for DUNE for its ν_e-appearance studies!

For the first result, we aim 1D differential cross section measurements in

- E_e and $\cos\theta_e$
- Photon and electron separation is being developed: critical for the SBN oscillation physics!

SBND's will provide more opportunities to study in exclusive channels

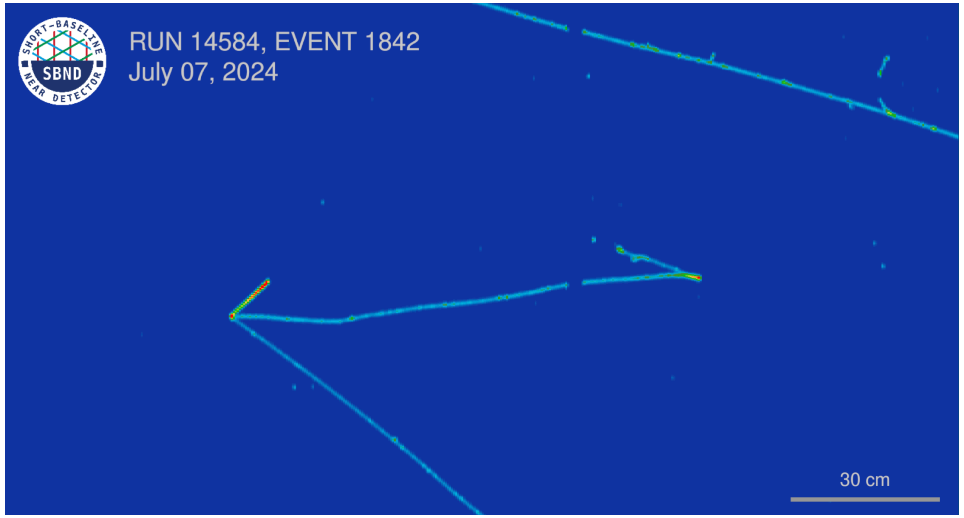


MicroBooNE Collab. *Phys.Rev.D* 106 (2022) 5, L051102

More Exclusive Channels in ν_μCC

$1\mu 1\pi^{\pm} Np$

- Contribution is mostly from resonant production
  - Important channel for 0π RES and DUNE



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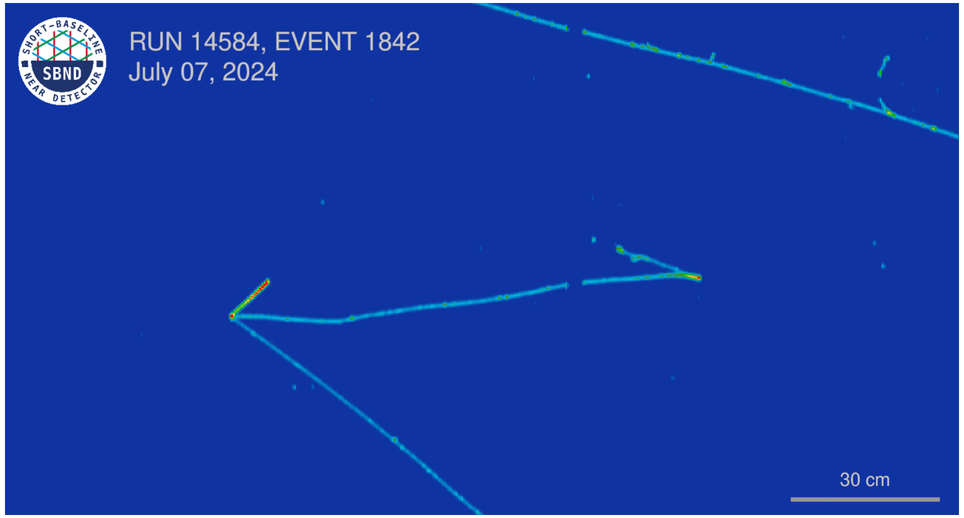

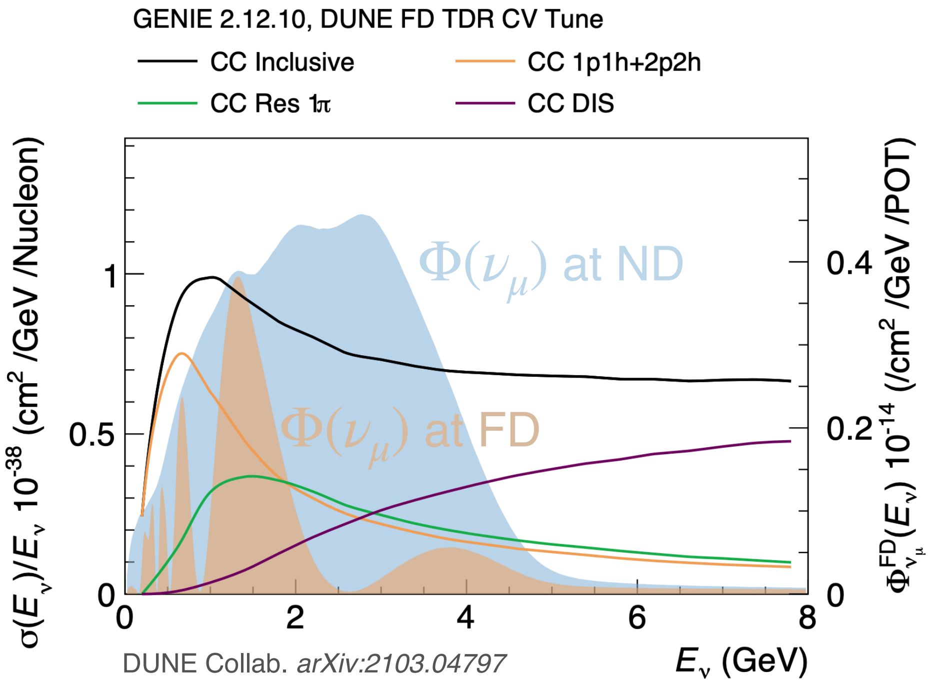

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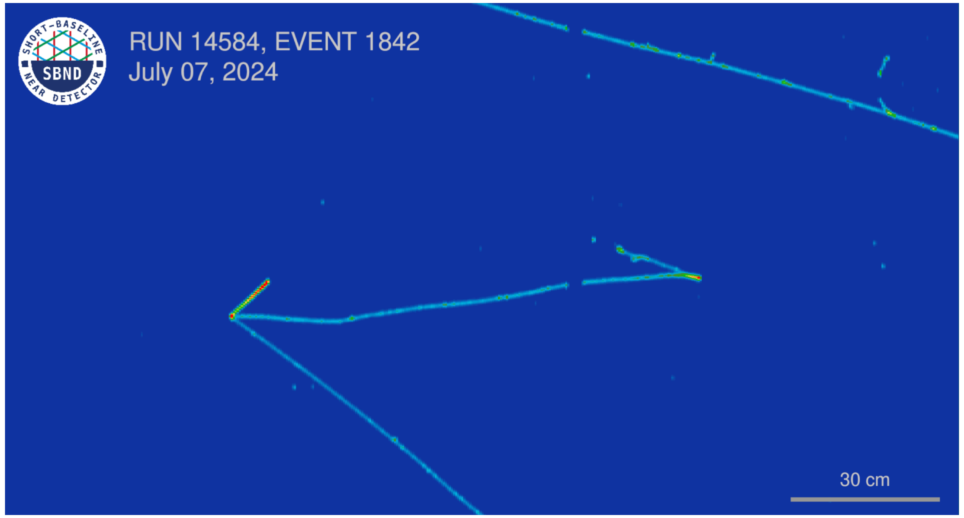
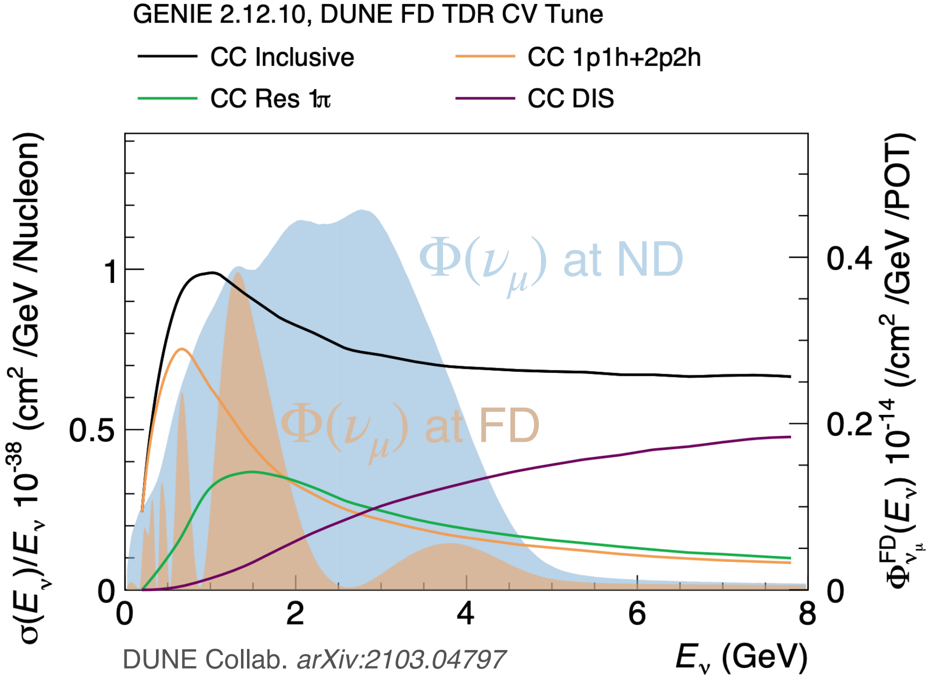
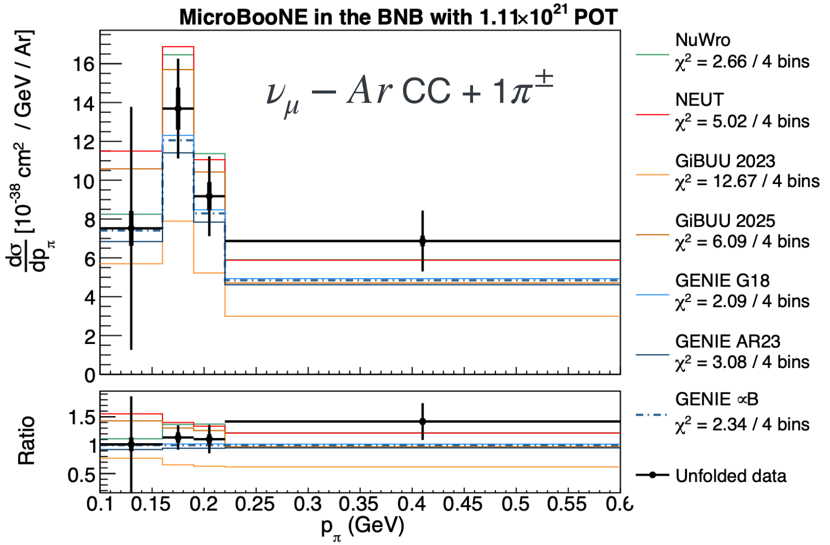
    - Extending phase space for $\pi^{\pm}$ to higher energy region





DUNE Collab. *arXiv:2103.04797*



MicroBooNE Collab. arXiv:2509.03628

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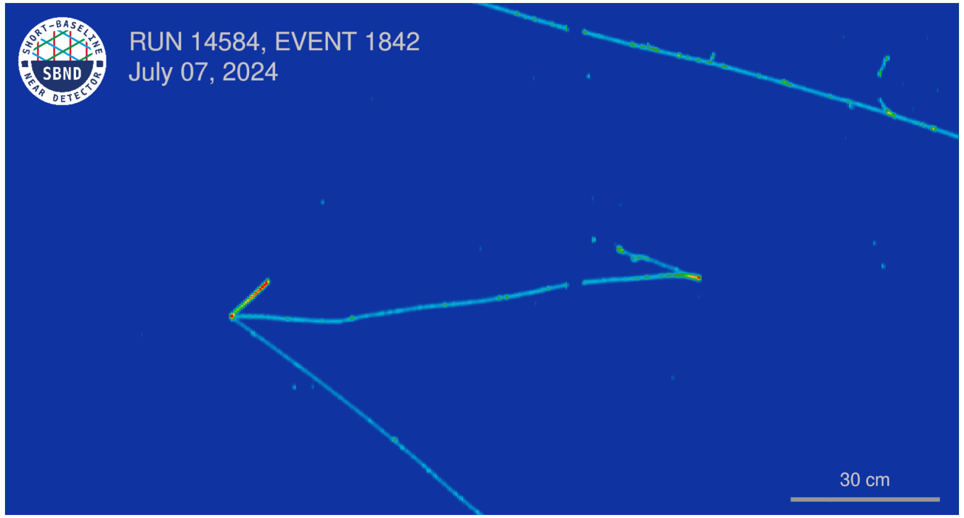

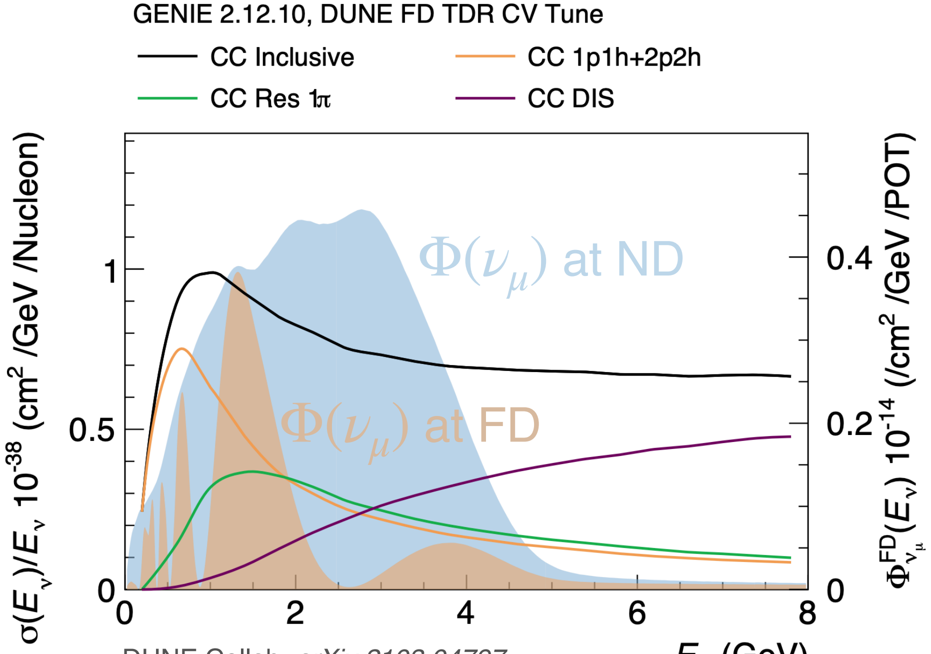

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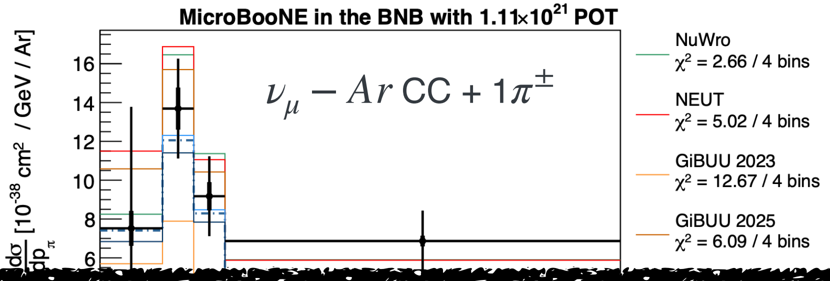


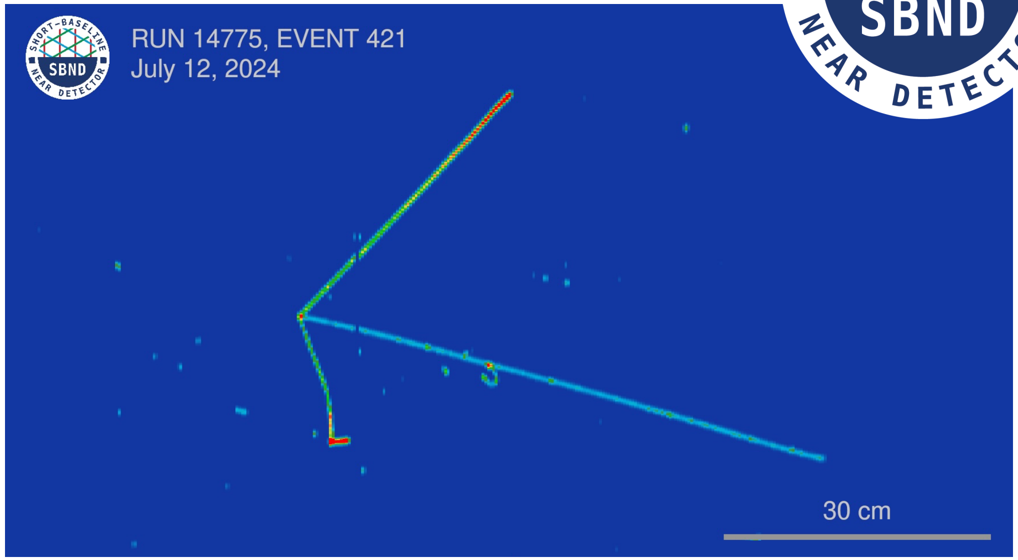
tion in empirical models. Additionally, new methods for pion momentum estimation, such as Ref. [81], are essential for extending differential cross sections to the full range of pion energies.

MicroBooNE Collab. arXiv:2509.03628

More Exclusive Channels in ν_μCC

$1\mu 2p 0\pi$

- Sensitive to various nuclear effects
  - The 4-momentum transfer is shared between two nucleons by a meson exchange current (MEC)
  - Short range correlations between nucleons
  - Final state interactions



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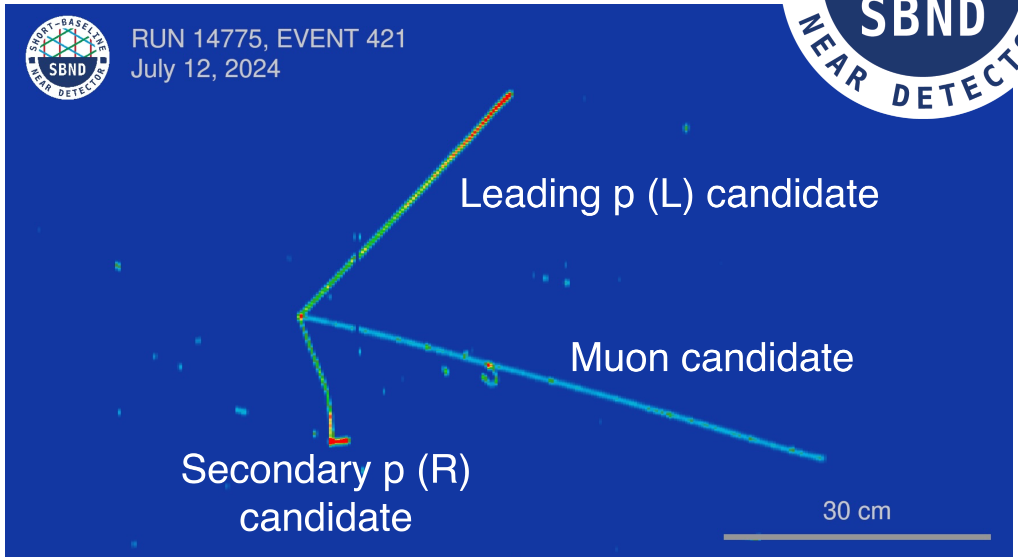
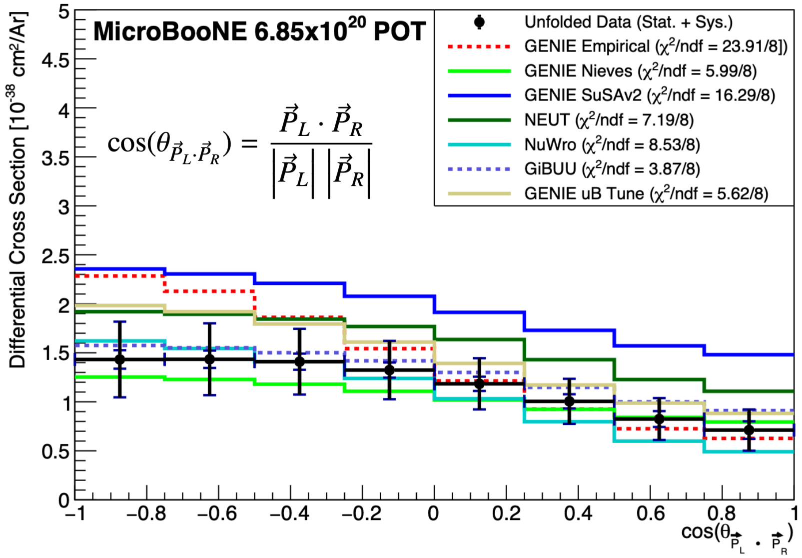
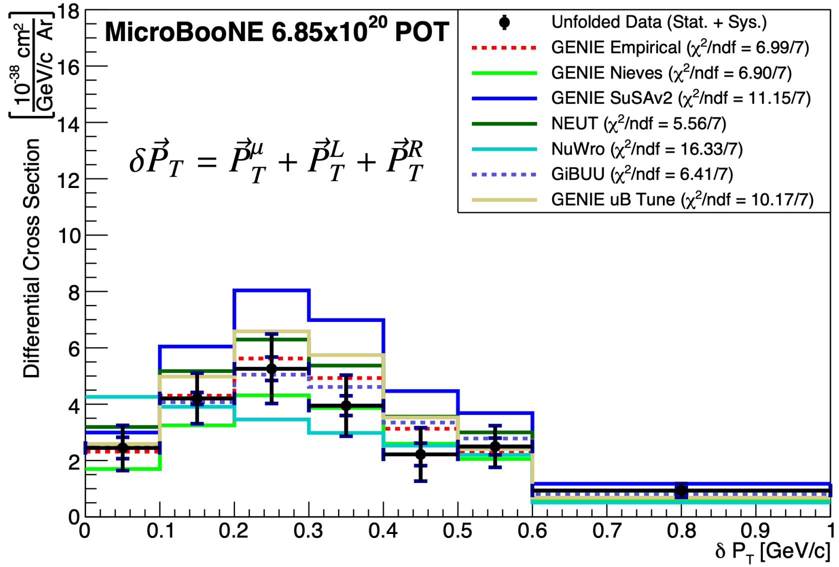
  - Final state interactions
- Could constrain models for them







MicroBooNE Collab. arXiv:2211.03734

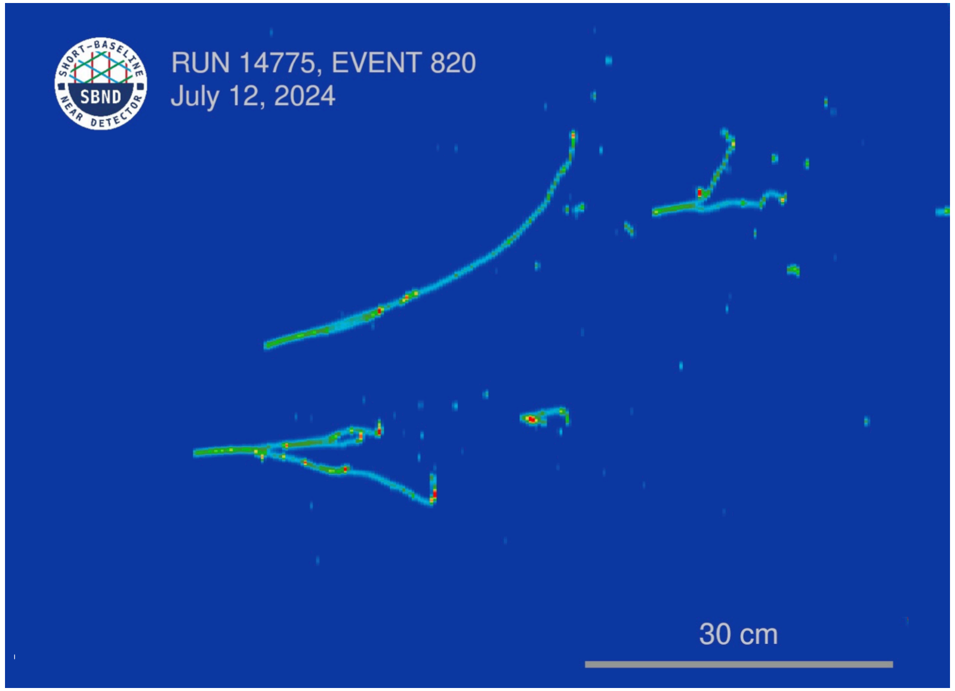
Neutral Pion Production

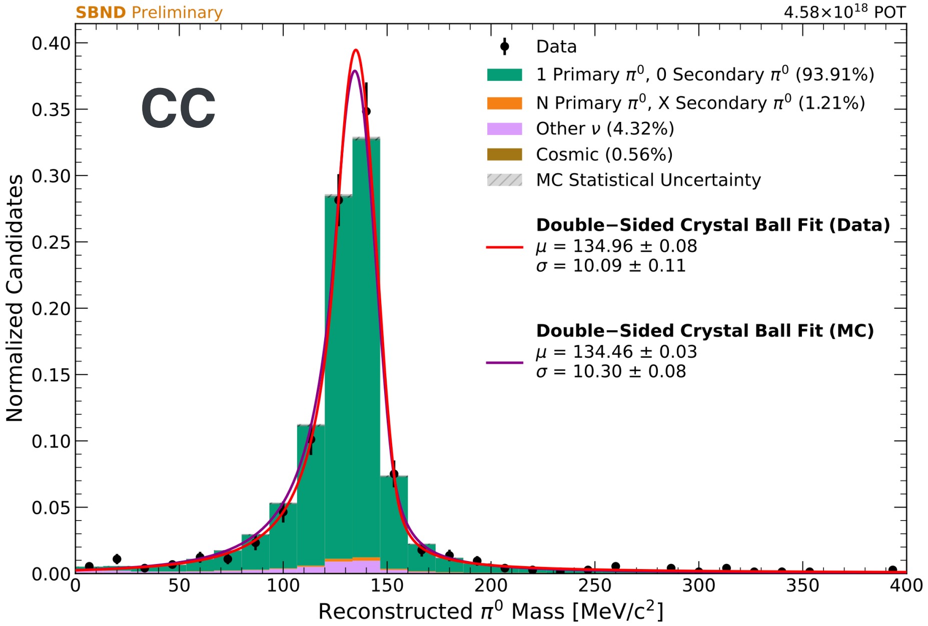
Studies are going on for both NC and CC interactions

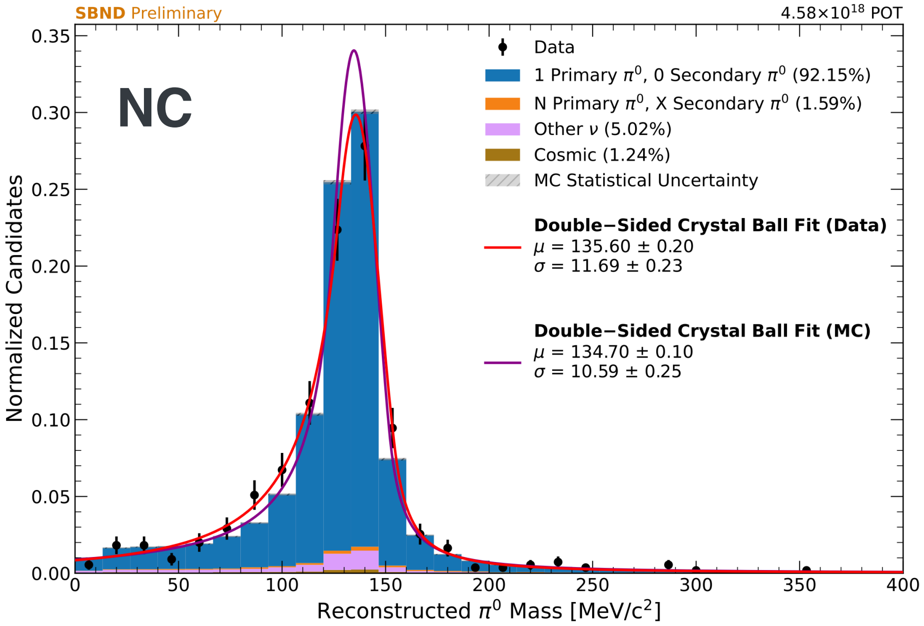
- Dominant background for BSM searches with showers

Excellent π^0 mass reconstruction

- Double-sided Crystal Ball fits to reconstructed π^0 show better than 10% resolution in both CC and NC channels
- Thanks to good shower energy and angle resolution







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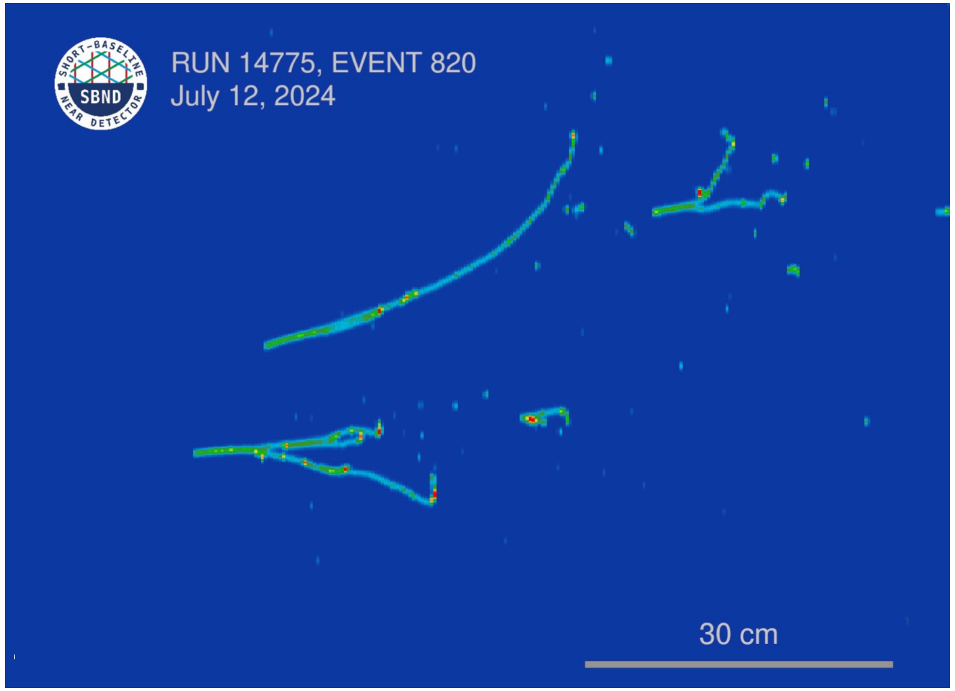
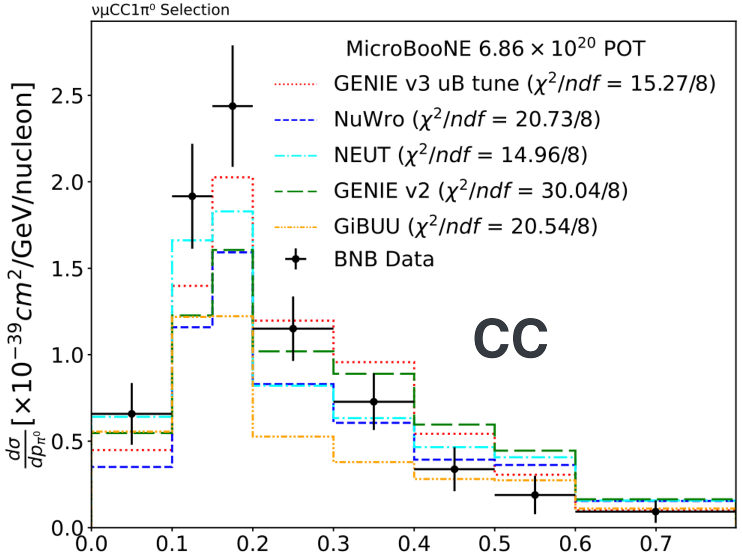
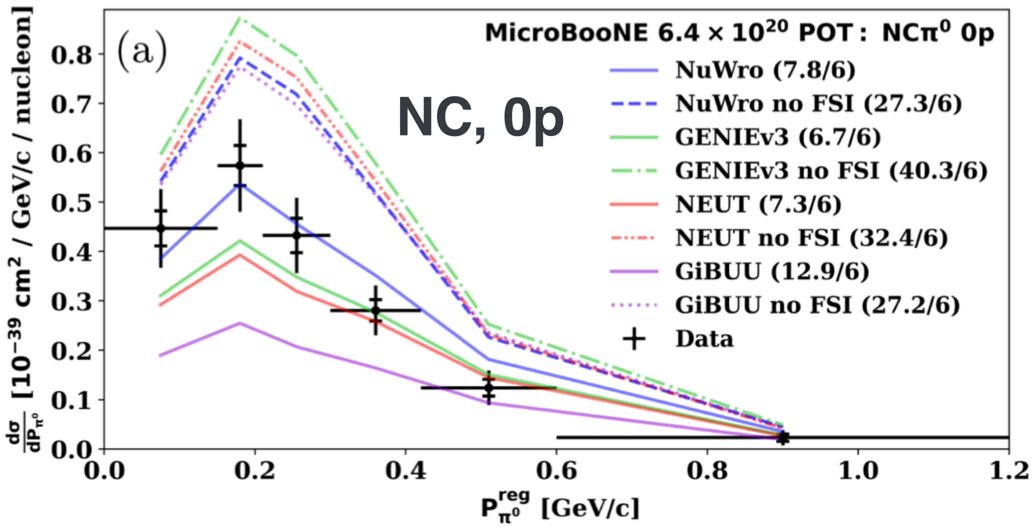


Could provide constraints to final state interaction (FSI) and resonance (especially π^0) modeling



MicroBooNE Collab. *Phys.Rev.D* 110 (2024) 9, 092014



MicroBooNE Collab. *Phys.Rev.Lett.* 134 (2025) 16, 161802

NC 1p

Isolated proton track

- Could provide NC elastic-enriched event selection
- Cross section at low Q^2 is sensitive to s-quark spin fraction

MICROBOONE-NOTE-1053-PUB

$$G_A^{NC}(Q^2) = \frac{1}{2}G_A^{CC}(Q^2) + \frac{1}{2}G_A^s(Q^2)\,,$$

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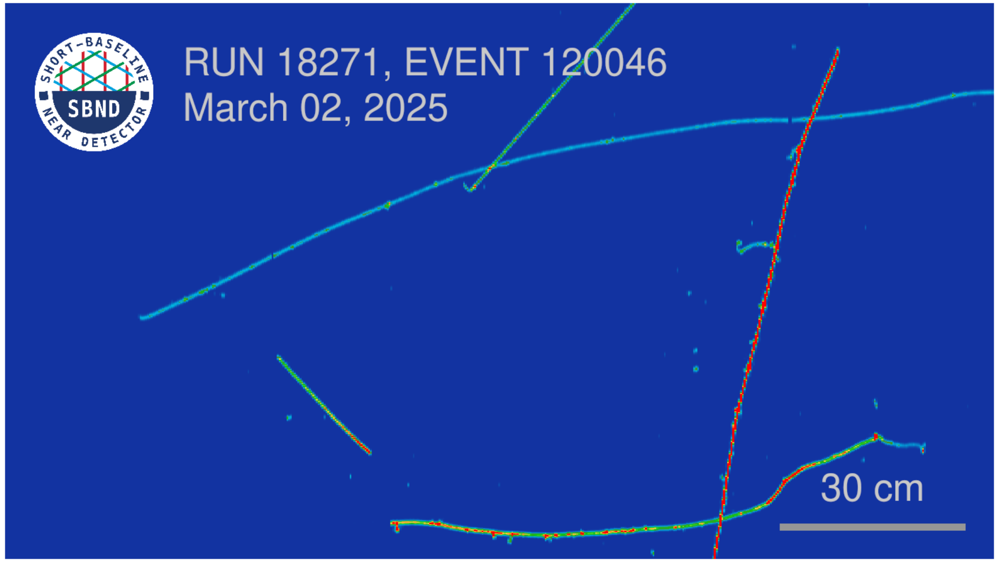

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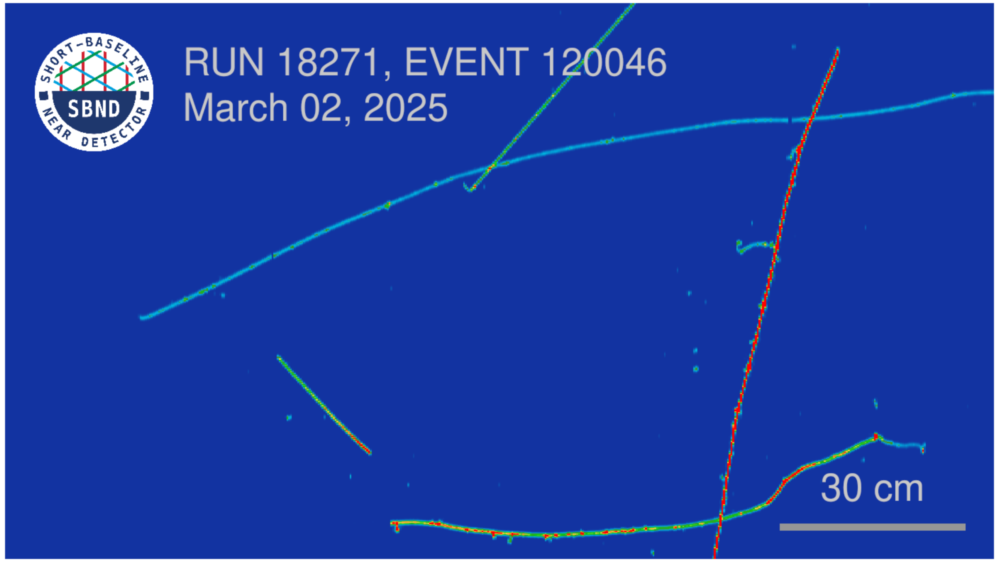

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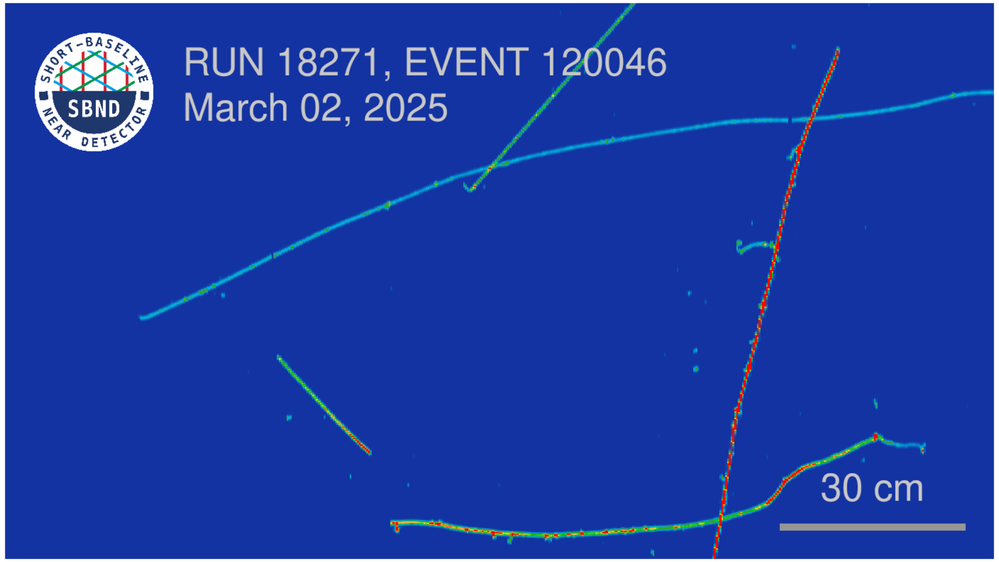

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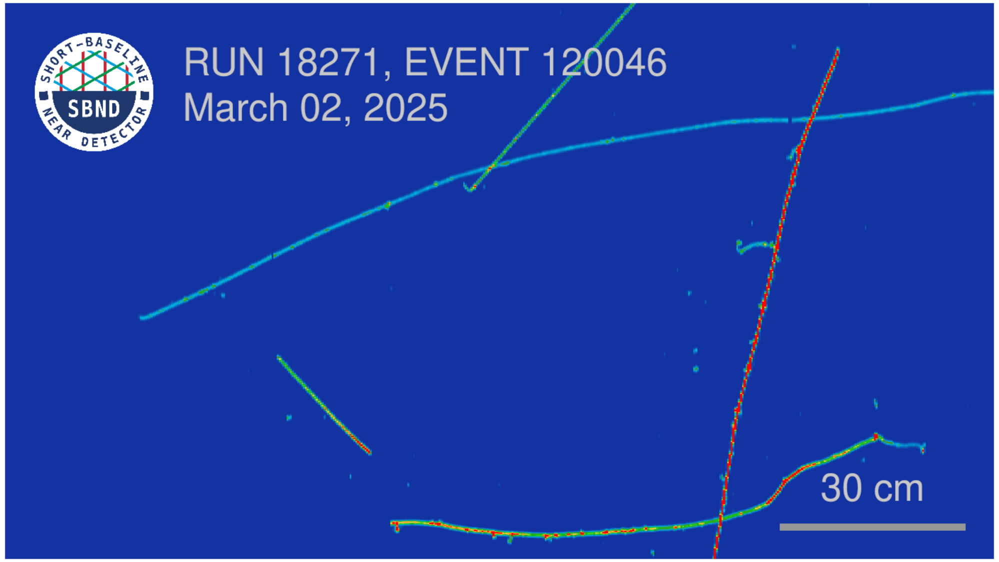

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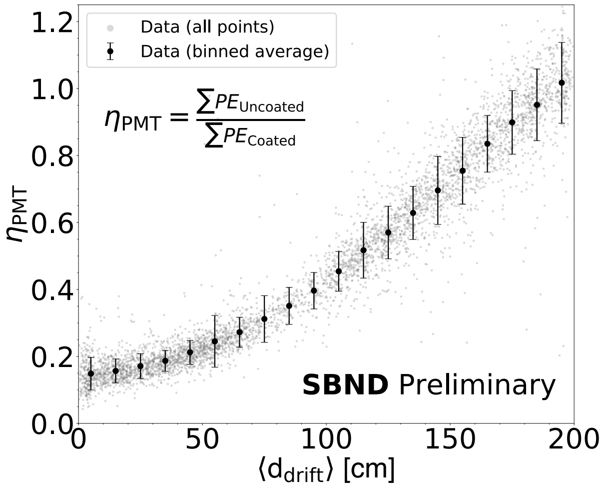
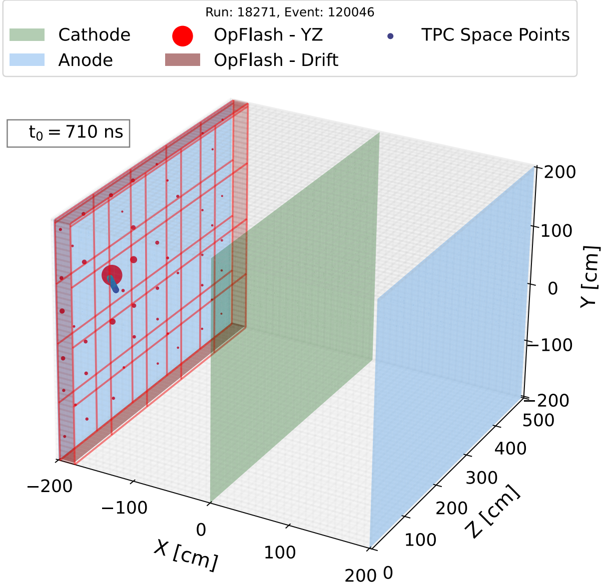
- Reconstruction for low energy proton is essential: E_K^p = 50 MeV → $Q^2 = 0.1\ \mathrm{GeV}^2$
- Matching between TPC and PMT reconstructions
  - Combine information from TPB coated and uncoated PMTs

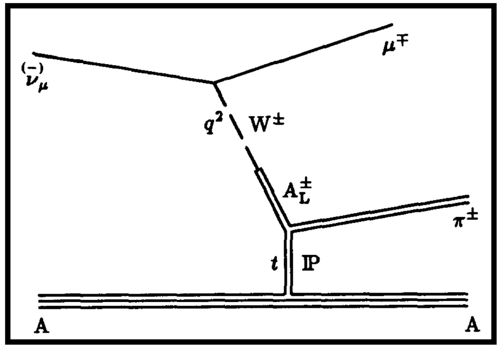
$$\eta_{\mathrm{PMT}} = \frac{1}{\mathrm{N_{Box}}}\sum_{\mathrm{Box}} \frac{\mathrm{N^{co}_{PMT}}}{\mathrm{N^{unco}_{PMT}}}\frac{\mathrm{PE^{unco}_{Box}}}{\mathrm{PE^{co}_{Box}}}\frac{\mathrm{PE_{Box}}}{\mathrm{PE_{Total}}}$$





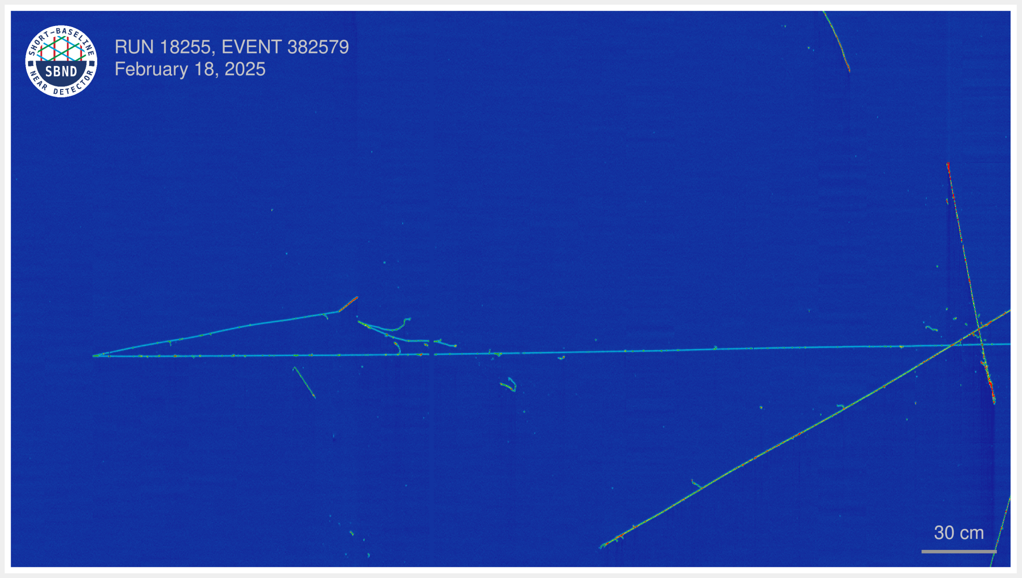
Rare Interactions

Physics Letters B 313 (1993) 267-275



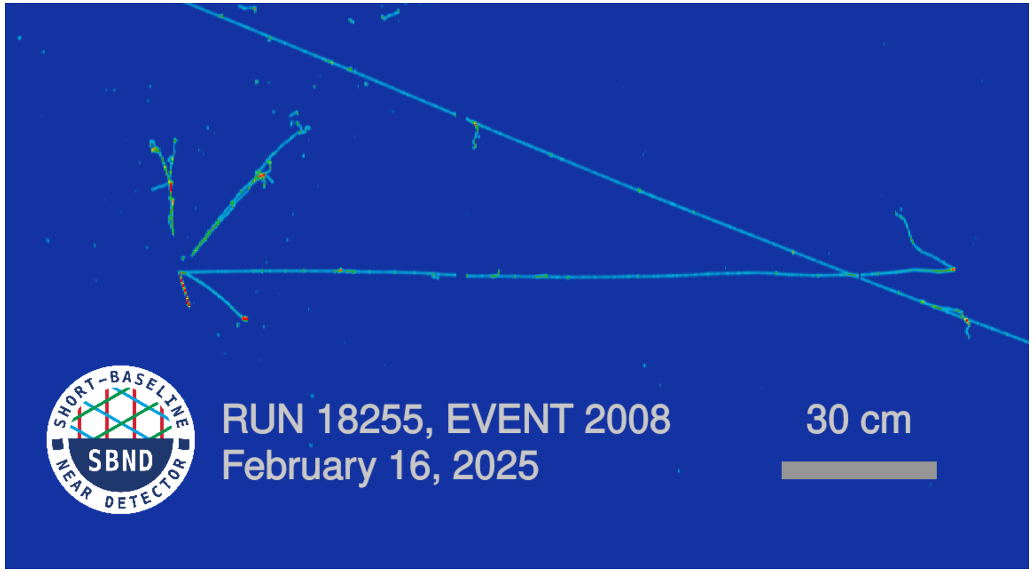
Coherent ν_μCC

- $1\mu^\pm + 1\pi^\mp$
- First goal is 1D differential cross section measurement in $|t|$ and muon kinematics
- Only one published result for argon is from ArgoNeuT*
  - With NuMI beam, flux averaged cross section for each of neutrino and anti-neutrino mode



η meson production from ν_μCC interactions

- Focusing on $\eta \to \gamma\gamma$ decay channel (BF ~ 40%)
  - M($\gamma\gamma$) ~ 548 MeV
- Could provide an access to high order resonances (i.e. N1535 and N1650)



* ArgoNeuT Collab. *Phys.Rev.Lett.* 113 (2014) 26, 261801

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Quick Summary for the Ongoing Efforts

3.5 x 10^{20} POT	Channel	Neutrino Interactions in SBND TPC Active Volume
ν_μCC	Inclusive	~ 2.07 M
	1 proton (E_K > 50 MeV), No $\pi^\pm$ (EK > 30 MeV) and π^0	~ 0.90 M
	2 protons (E_K > 50 MeV), No $\pi^\pm$ (EK > 30 MeV) and π^0	~ 0.32 M
	Exactly 1 $\pi^\pm$ (E_K > 30 MeV) and no π^0	~ 0.27 M
	Exactly 1 π^0 and no $\pi^\pm$(E_K > 30 MeV)	~ 0.16 M
ν_eCC	Inclusive	~ 15 k
	Exactly 1 $\pi^\pm$ (E_K > 30 MeV) and no π^0	~ 2.6 k
NC	Inclusive	~ 0.84 M
	At least 1 proton (E_K > 50 MeV)	~ 0.42 M
	At least 1 π^0	~ 0.14 M
Coherent	CC	~ 3.7 k
	NC	~ 2.9 k
Scatter to e^-	NC	~ 175
	CC	~ 9

Quick Summary for the Ongoing Efforts

Cells in **color** are ongoing analyses: and many more!!

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Scatter to e^-	NC	~ 175
	CC	~ 9

05

Summary

Summary

Neutrino interaction model is essential for all neutrino experiments

- For modern long baseline neutrino oscillation experiments, it is one of the leading sources of systematic uncertainties
- Constraining the uncertainty is critical for the future experiments such as DUNE

Summary

SBND offers unique opportunities for neutrino-argon interaction studies

- Its proximity to BNB target provides unprecedented statistics and access to off-axis flux effect
- All subsystems' performances are excellent
- First physics run from December 2024 to July 2025 is successful
  - With 98.6% collection efficiency, total data of 3.48×10^{20} POT is collected
  - World's largest neutino-argon dataset to-date is of excellent quality and is currently being analyzed

Summary

SBND has a very active neutrino-argon cross section program

- ~10 analyses are at mature stages, many more to follow soon!
  - Some of them are in the systematic uncertainty evaluation stage
  - Most of them have well-defined event selections
- We plan to publish cross section results in regularized space together with the smearing matrix for model comparisons
- Please contact us if you have more ideas for interesting cross section measurements!!!

Thank you!

SBND Collaboration Meeting June 2025 at University of Sheffield, UK

Fermilab

FermiFORWARD

U.S. DEPARTMENT of ENERGY

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NOvA and T2K X-sec Uncertainties to δ_{CP}

- NOvA: dominant contribution is from uncertainties for difference between ν_e and ν_μ cross-sections
  - $\sim 2\%$ correlated and $\sim 2\%$ anti-correlated
  - Studying ν_e interactions in ND is important
    - Improving models for flux and ν_μ help for reducing uncertainty for this study

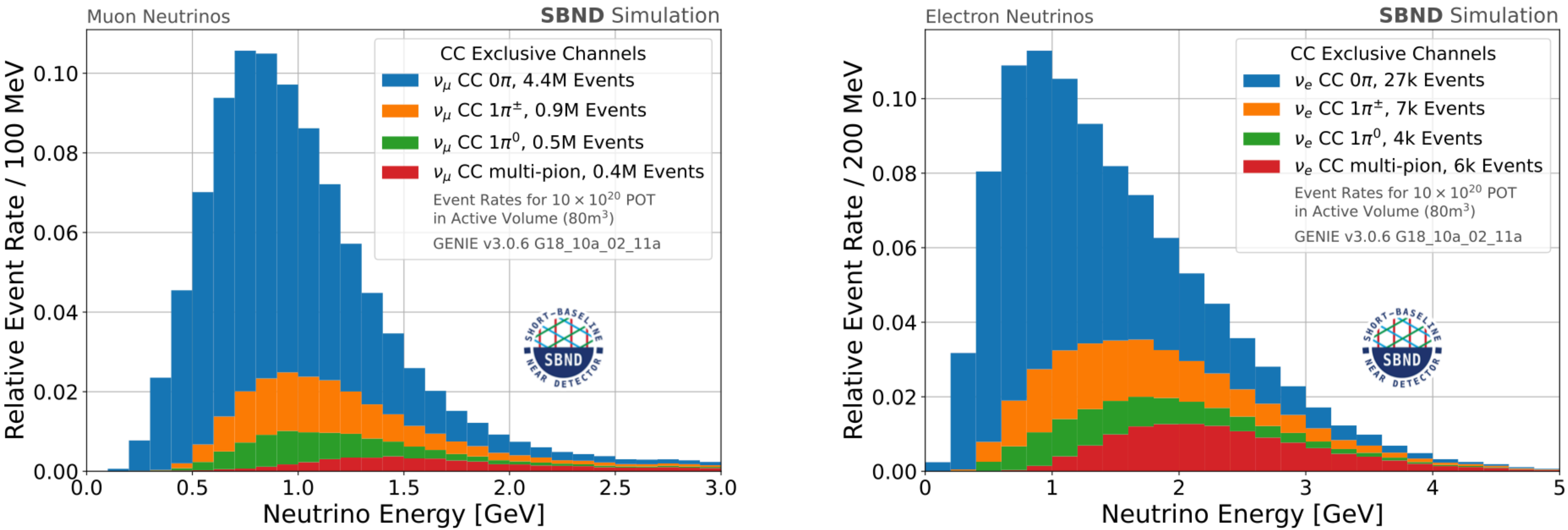
- T2K
  - Non-CCQE
    - Ad-hoc reweight to Non-CCQE contribution in NEUT CCQE model for discrepancy between ND data and simulation
  - Data-driven pion
    - ND data-driven pion momentum modification

Table 19 Shifts of the 90% confidence interval boundaries of δ_{CP}, in radians, as a result of the simulated data studies. The values in the top row correspond to the results of the data fit, assuming normal ordering. The values for each simulated data set are added to (subtracted from) the right (left) δ_{CP} interval edge from the data fit. Only the absolute size of the shift is taken into account

Simulated data set	Change to 90% CL of δ_{CP}	
	−3.01	−0.52
CCQE 3-comp nom.	0.04	0.02
CCQE 3-comp high	0.05	0.03
CCQE 3-comp low	0.04	0.03
CCQE z-exp nom.	0.01	0.01
CCQE z-exp high	0.05	0.04
CCQE z-exp low	0.00	0.00
CCQE removal energy	0.00	0.02
Non-CCQE	0.06	**0.09**
2p2h Martini	0.04	0.04
MINERvA pion tune	0.05	0.04
Data-driven pion	**0.07**	0.04
Pion SI	0.00	0.01

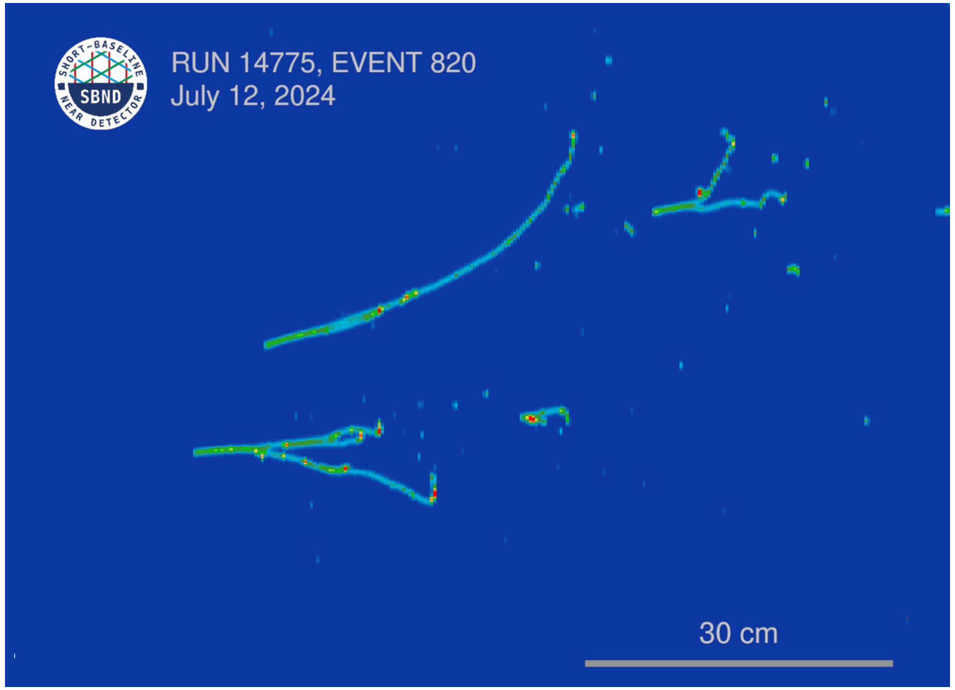
The simulated data sets with the largest impact are typed in bold

For Discussion about the Table



- For 10 x 10^{20} POT
- numuCC: ~ 6.2M → 2.17 M for 3.5x10^{20} POT which is ~ 5% more than my table
  - Probably due to rounding
- nueCC: ~ 44k → 15.4k for 3.5x10^{20} POT, which is similar with my table

Neutral Pion Production



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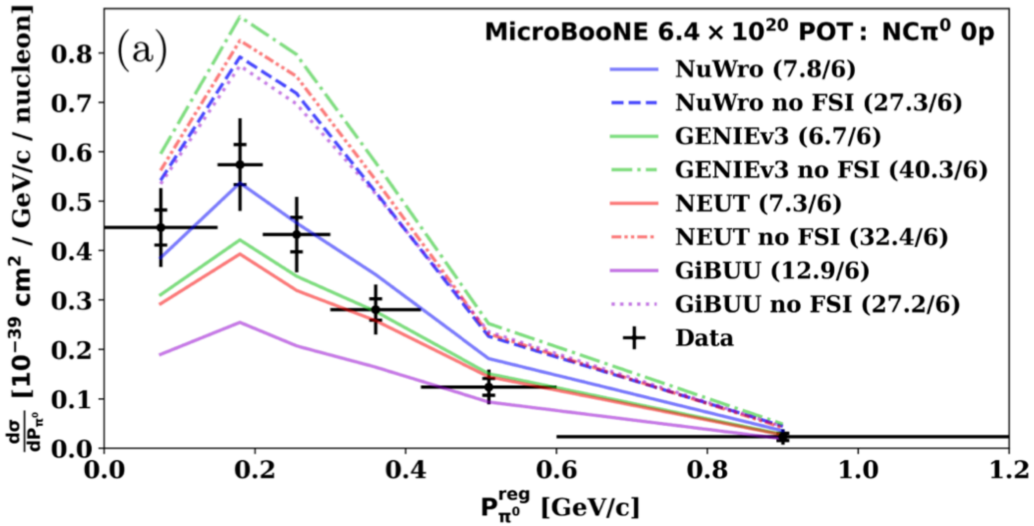
Could provide constraints to final state interaction (FSI) modelings

NC, 0p



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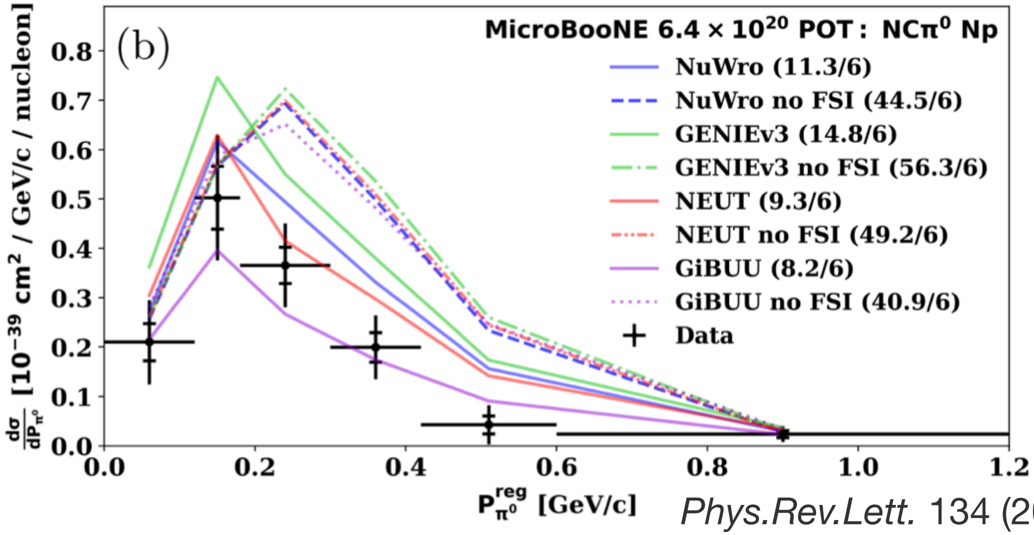
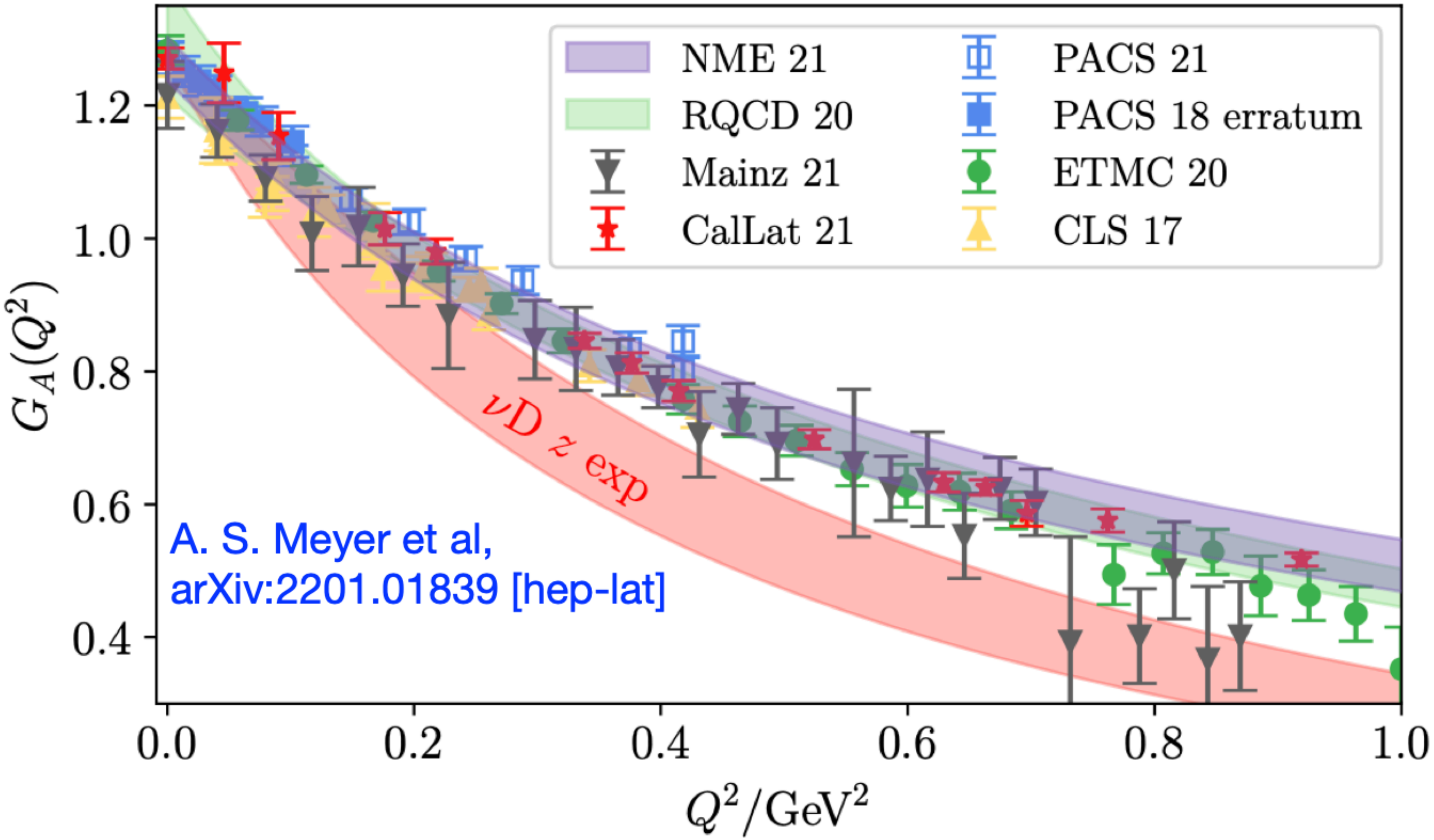


Phys.Rev.Lett. 134 (2025) 16, 161802

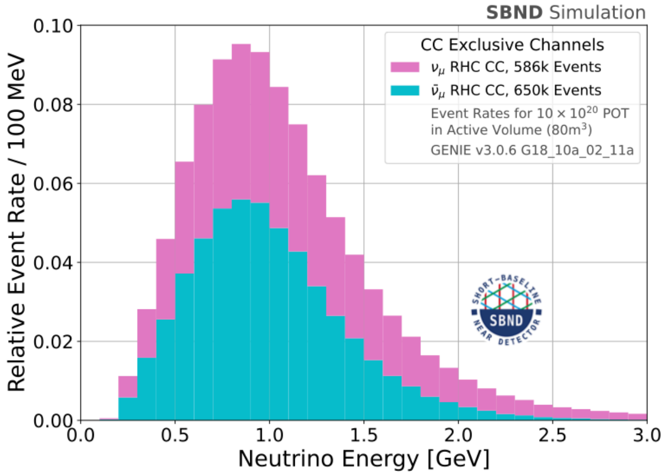
Z-exp

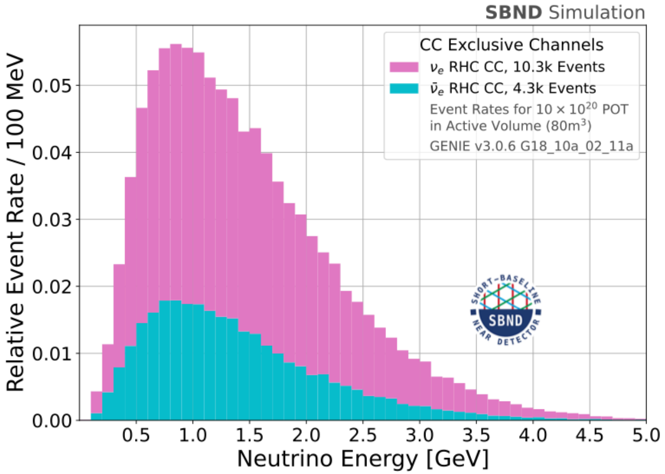


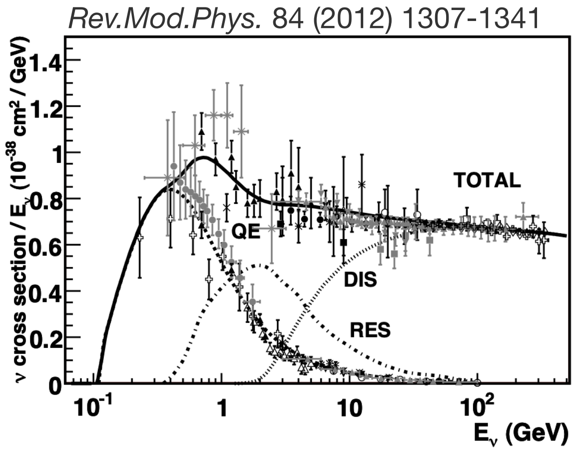
A. S. Meyer et al,
arXiv:2201.01839 [hep-lat]

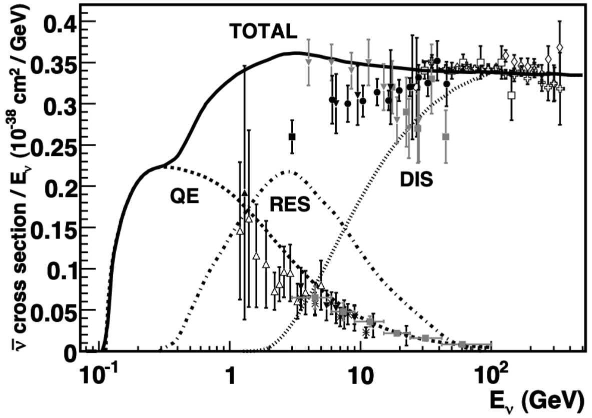
Anti Neutrino Mode

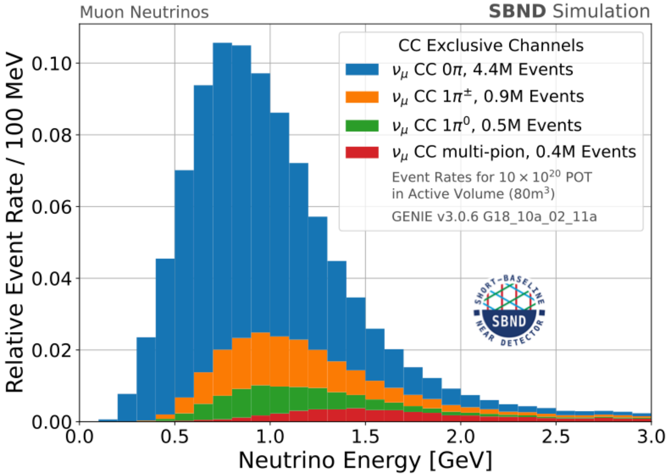
- $\bar{\nu}_\mu$ fraction from 6.9% to 83.9%

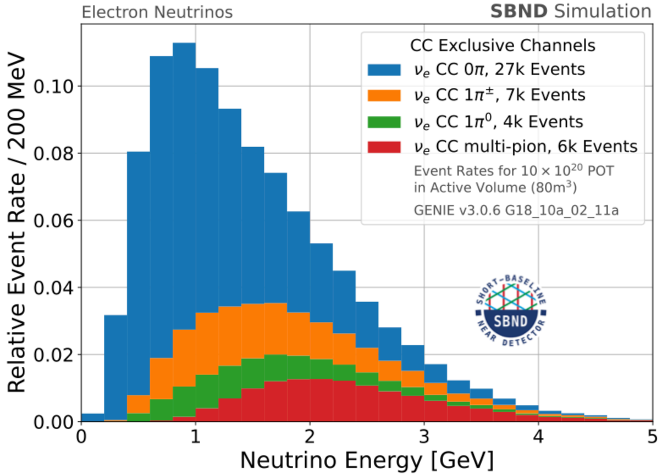


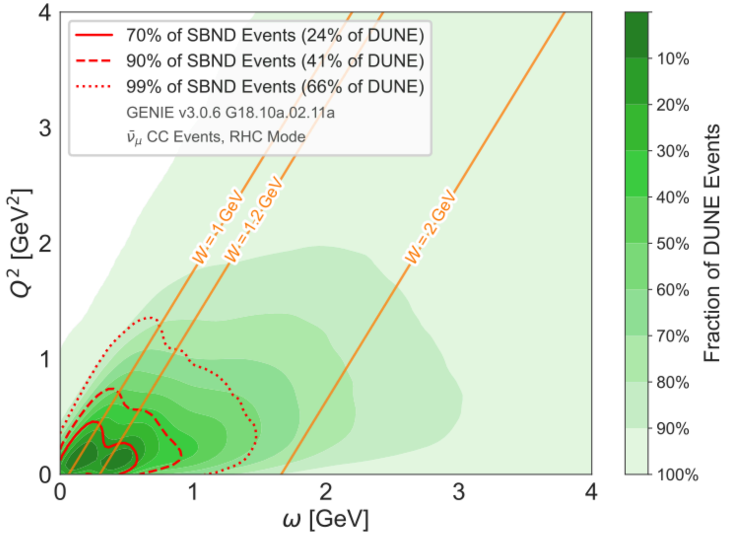












Comments

- https://docs.google.com/document/d/1EygOwMo1u70ND_xgcOu4EbKq7IMhlt3nOohTtmimshI/edit?tab=t.0

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