Welcome to CERN!

NuXTract

NUSTEC WORKSHOP · NEUTRINO CROSS SECTION

The LOC:
Laura Munteanu
Stephen Dolan
Pablo Barham Alzás

CERN

Contents

1. Workshop overview
2. Getting around CERN
3. Moving around the area
4. Party! 🎉

Your devoted LOC

WORKSHOP OVERVIEW

All details at: https://indico.cern.ch/event/1302529/

Mon: 222/R-001

	Welcome Coffee Break		*222/R-001, CERN*	13:30 - 14:00
14:00	Welcome and introduction	*Dr Stephen Dolan*	*222/R-001, CERN*	14:00 - 15:30
15:00	Coffee break		*222/R-001, CERN*	15:30 - 16:00
16:00	General overview	*Dr Vishvas Pandey*	*222/R-001, CERN*	16:00 - 18:00
17:00				
18:00				

09:00	General overview	*Dr Clarence Wret, Clarence Wret*	*500/1-001 - Main Auditorium, CERN*	09:00 - 10:00
10:00	Experiment Overview	*Dr Clarence Wret, Clarence Wret*	*500/1-001 - Main Auditorium, CERN*	10:00 - 10:30
	Coffee break		*500/1-001 - Main Auditorium, CERN*	10:30 - 11:00
11:00	Experiment Overview	*Laura Munteanu, Laura-Iuliana Munteanu*	*500/1-001 - Main Auditorium, CERN*	11:00 - 12:30
12:00	Lunch break		*222/R-001, CERN*	12:30 - 14:00
13:00				
14:00	Methods	*Adi Ashkenazi, Adi Ashkenazi, adi ashkenazi*	*31/3-004 - IT Amphitheatre, CERN*	14:00 - 15:30
15:00	Coffee break		*31/3-004 - IT Amphitheatre, CERN*	15:30 - 16:00
16:00	Methods	*Adi Ashkenazi, Adi Ashkenazi, adi ashkenazi*	*31/3-004 - IT Amphitheatre, CERN*	16:00 - 17:00

Tue: Main auditorium (500/1-001) and 31/3-004

WORKSHOP OVERVIEW

Wed: 513/1-024

- 09:00 – **Experiment Overview** — *513/1-024, CERN* — 09:00 - 10:30
- **Coffee break** — *513/1-024, CERN* — 10:30 - 11:00
- 11:00 – **Data release** — *Dr Stephen Dolan* — *513/1-024, CERN* — 11:00 - 12:30
- **Lunch break** — *513/1-024, CERN* — 12:30 - 14:00
- 14:00 – **Data release** — *Dr Vishvas Pandey* — *513/1-024, CERN* — 14:00 - 15:30
- **Coffee break** — *513/1-024, CERN* — 15:30 - 16:00
- 16:00 – **Data release** — *Adi Ashkenazi, Adi Ashkenazi, adi ashkenazi* — *513/1-024, CERN* — 16:00 - 17:30

Thu: 222/R-001

- 09:00 – **Experiment Overview** — *222/R-001, CERN* — 09:00 - 10:30
- **Coffee break** — *222/R-001, CERN* — 10:30 - 11:00
- 11:00 – **Experiment Overview** — *Pablo Samuel Barham Alzas* — *222/R-001, CERN* — 11:00 - 12:45
- **Lunch** — *222/R-001, CERN* — 12:50 - 14:00
- 14:00 – **Fitting and tuning to data** — *Dr Clarence Wret, Clarence Wret* — *222/R-001, CERN* — 14:00 - 15:30
- **Coffee break** — *500/1-001 - Main Auditorium, CERN* — 15:30 - 16:00
- 16:00 – **Breakout sessions**
- 17:00
- 18:00

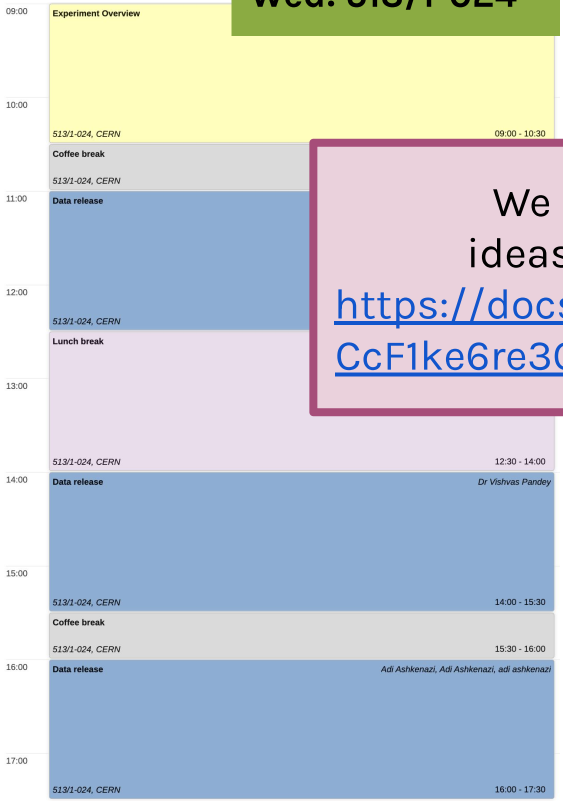
Party later!

Fri: 222/R-001

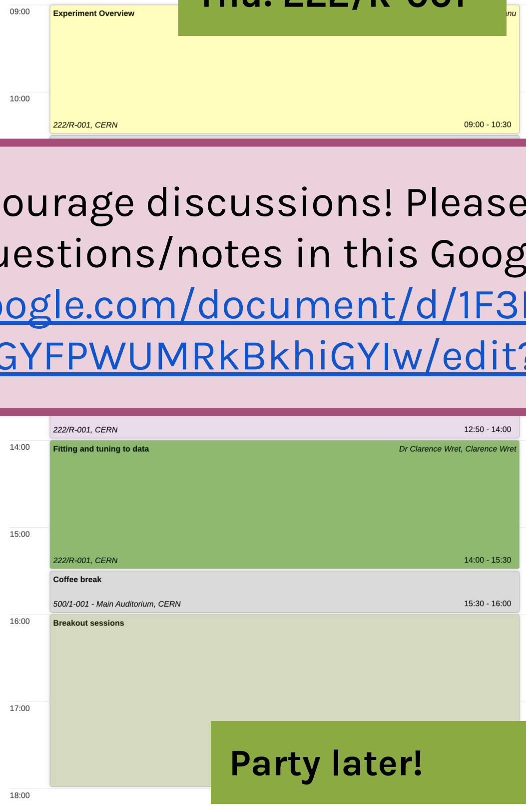
- 09:00
- **Summary and closing discussions** — *Adi Ashkenazi, Adi Ashkenazi, adi ashkenazi* — *222/R-001, CERN* — 09:30 - 10:30
- **Coffee break** — *222/R-001, CERN* — 10:30 - 11:00
- 11:00 – **Summary and closing discussions** — *Dr Stephen Dolan* — *222/R-001, CERN* — 11:00 - 12:30
- **Lunch** — *222/R-001, CERN* — 12:30 - 14:00
- 14:00

WORKSHOP OVERVIEW

Wed: 513/1-024

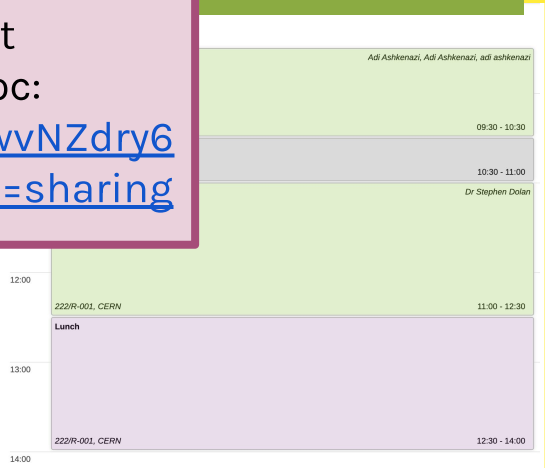


Thu: 222/R-001



Party later!

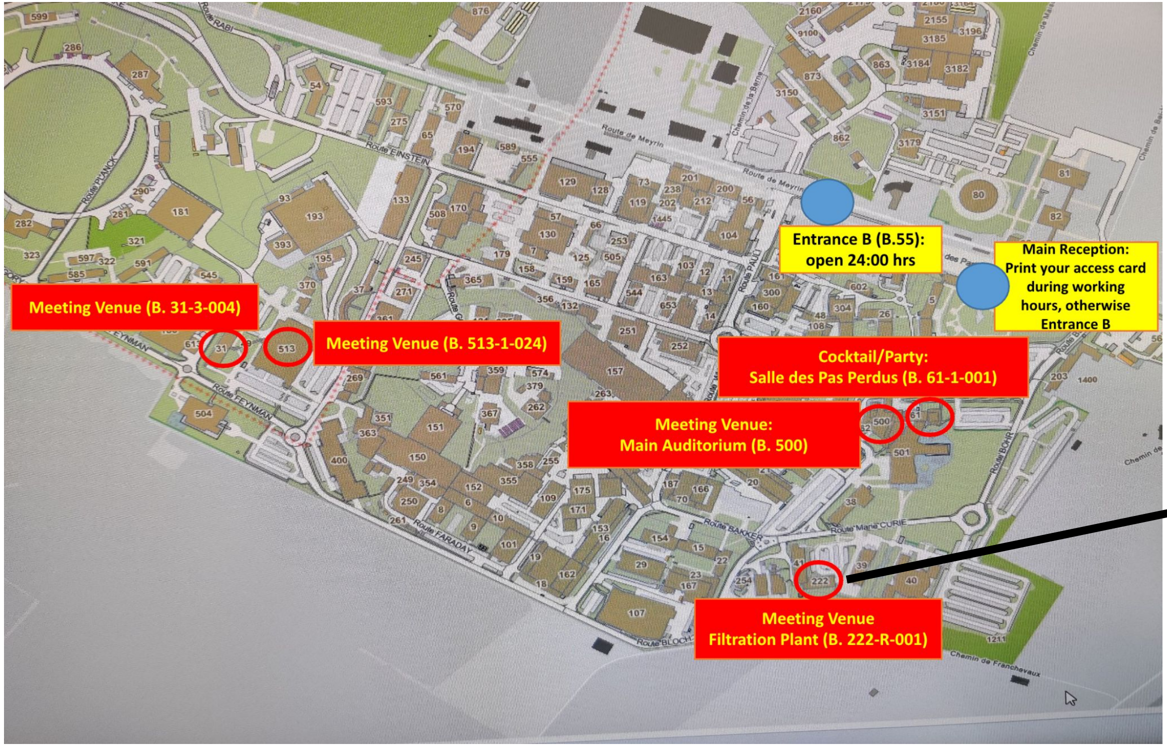
Fri: 222/R-001



We encourage discussions! Please post ideas/questions/notes in this Google doc: https://docs.google.com/document/d/1F3P22wvNZdry6CcF1ke6re3QDiGYFPWUMRkBkhiGYIw/edit?usp=sharing

GETTING AROUND CERN

You can use CERN Maps (https://maps.cern.ch, or download the MapCERN iOS/Android app) to find your way around campus.



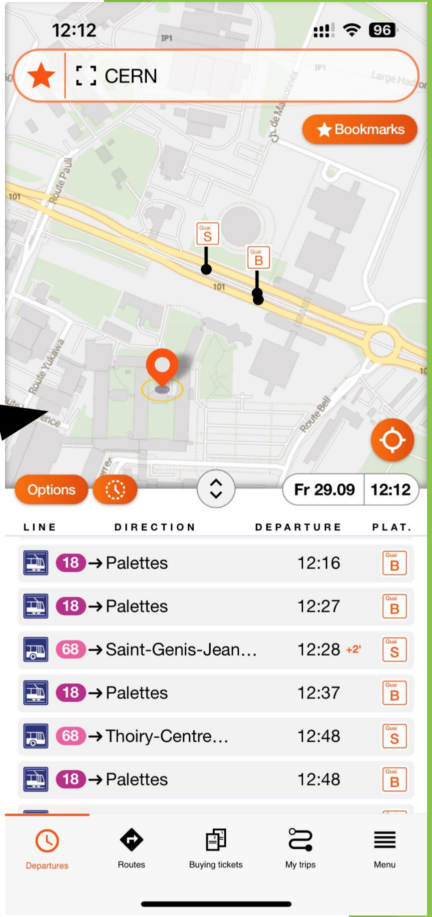
You are here

MOVING AROUND THE AREA

- Main way into Geneva is **Tram 18 -> Palettes** (Cornavin station, Plainpalais…).
- Main way into St Genis/France is **Bus 68 -> Saint-Genis/Thoiry Centre Commercial**.
- Both leaving from the Esplanade des Particules (in front of the CERN Globe).

Use the **TPGPreview** iOS/Android app to see timetables and buy tickets from your phone.

Tickets can also be bought at machines in the tram stations or onboard of the buses.

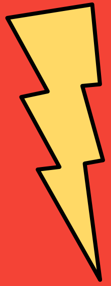


[Restaurant recommendations from the LOC]()

PARTY! 🎉

- Workshop dinner/party will take place on **Thursday at 19h** on the **1st floor of building 61 (above R1)**.
- Will consist of a standing cocktail dinner + drinks.
- Followed by some fine wines and local cheese carefully selected by the LOC subject to your kind contributions!

- Vegetarian and vegan options will be available.
- Please let us know if you have any other dietary requirements you didn't write on the form!



We wish you have a great time at CERN and a productive workshop!

The LOC:
Laura Munteanu
Stephen Dolan
Pablo Barham Alzás

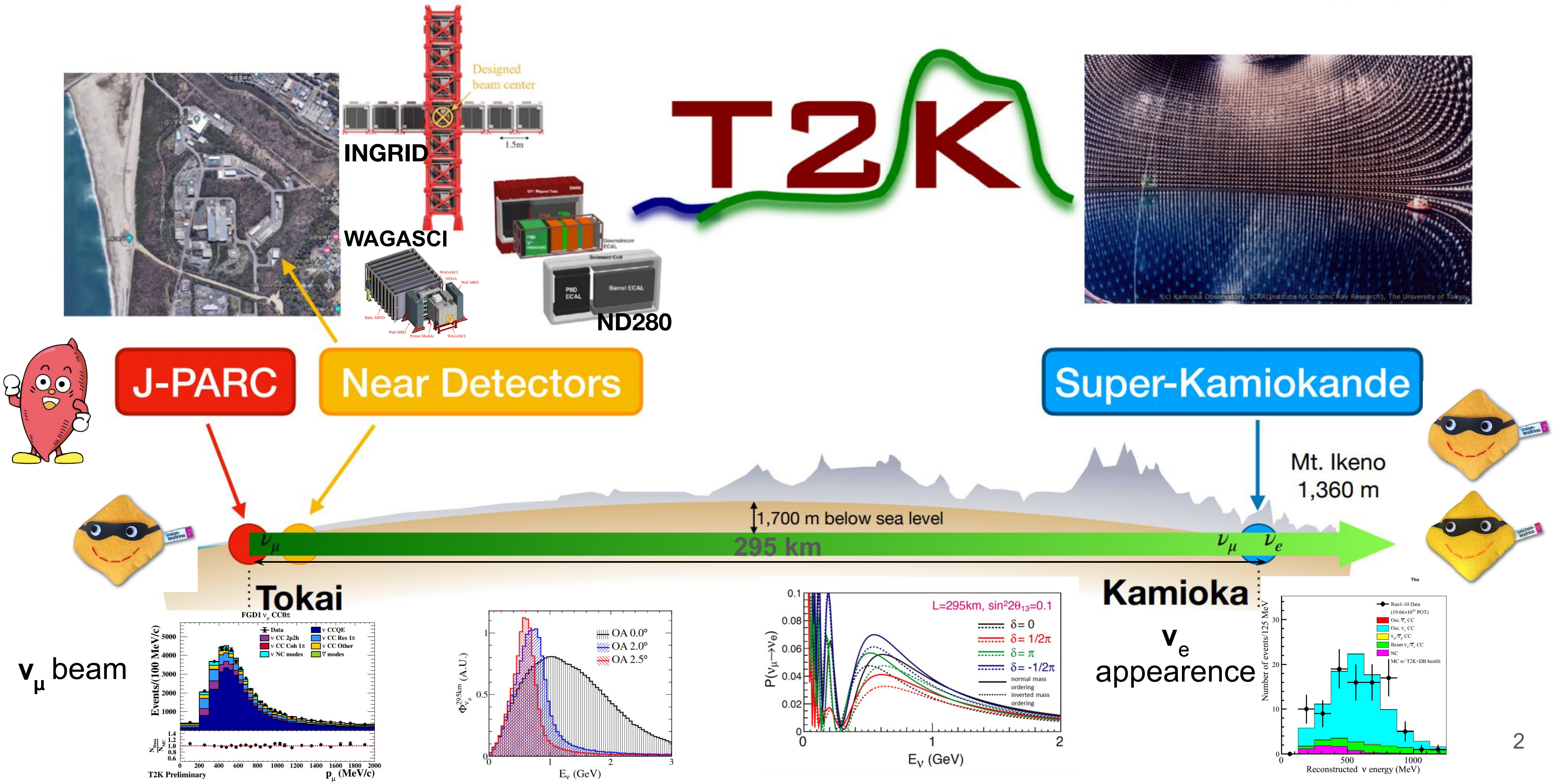
With special thanks to Antonella and Elena, the Neutrino Secretariat

Introduction: T2K

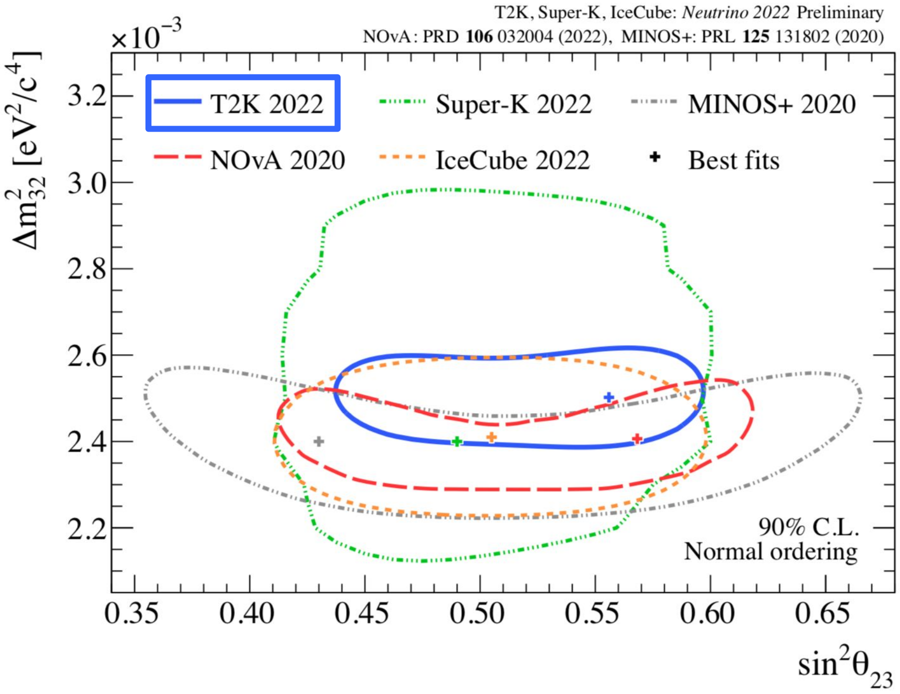
Sam Jenkins
Margherita Buizza Avanzini

on behalf of the T2K experiment

The T2K experiment

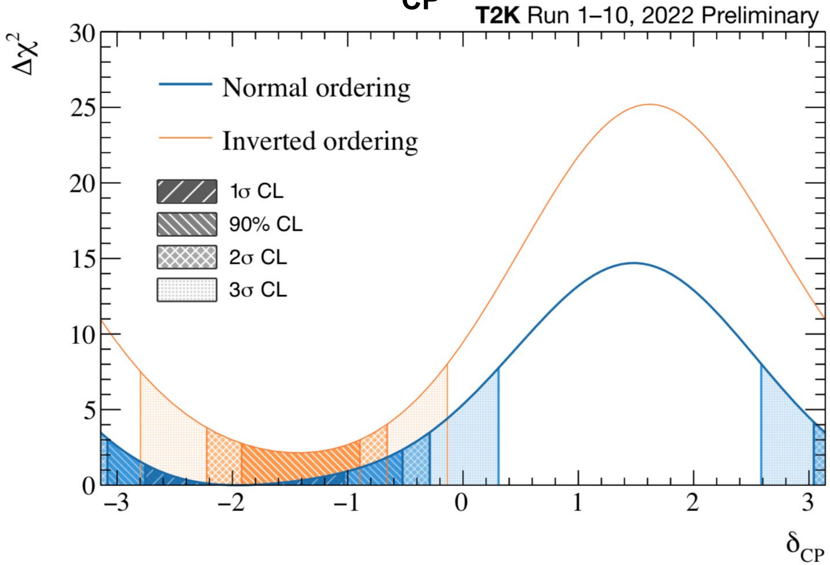


T2K oscillation measurements



World leading measurement of the atmospheric parameters!

and of δ_{CP}!



Large region of δ_{CP} values excluded at 3σ

CP conservation excluded at 90%

Preference for Normal Ordering

Why neutrino cross sections matter for the oscillation analysis?

To extract the **oscillation probability**, we compare the **number of detected neutrino interactions** in the **near detector** to the **far detector**:

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi^{far}(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi^{near}(E_\nu) \otimes D^{near}(\vec{x})}$$

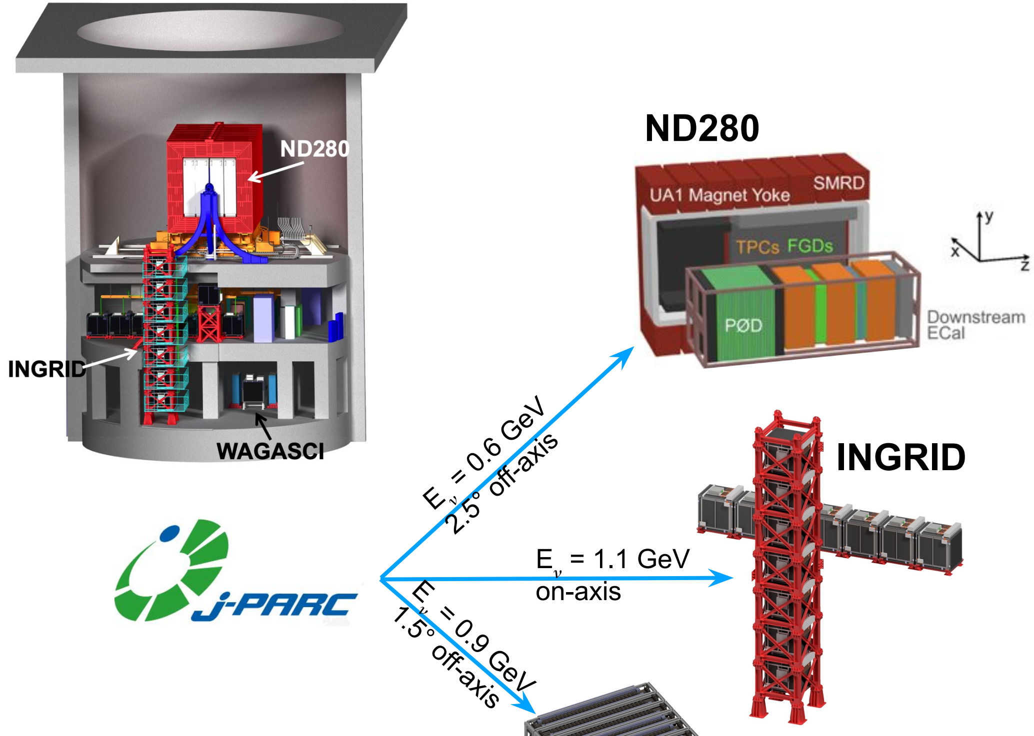
Event rates determined by the **neutrino interaction probability** (cross section), the **neutrino flux** and the **detector effects**. Any uncertainties on these quantities will affect the predictions of N^{far} and N^{near} and thus the precision of the oscillation probability measurements

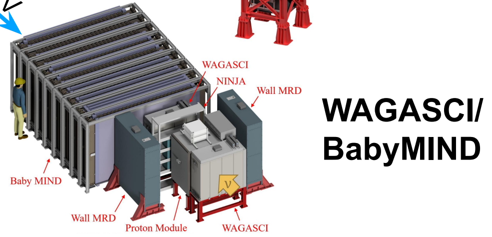
In the 2022 T2K oscillation analysis: total systematic uncertainty of 5.2% (ν_e appearance in neutrino mode), ~4% comes from the uncertainty on neutrino interaction processes

Currently in T2K the dominant systematics come from uncertainty on neutrino cross sections
⇒ let's measure neutrino cross sections @T2K near detectors!

NOTE: today not the major problem, we have ~100 ν_e appearance events... but this will become a problem for HK (where we expect more than 2000 ν_e appearance events)

T2K cross-section measurements





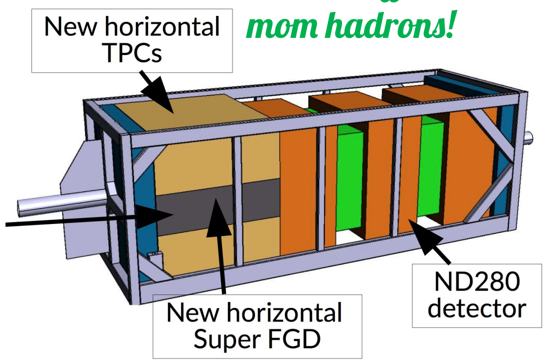
T2K world-leading experiment also in the ν xsec field!

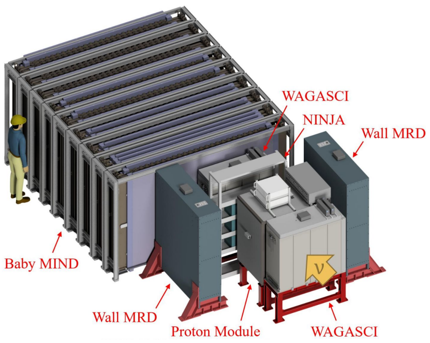
T2K near detector complex allows to measure neutrino cross sections:

- at **different off-axis**, i.e. different energies
- on **different targets**: Carbon, Oxygen, Iron,...
- with **different samples**: $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$
- spanning **different final state topology** (CC0pi, CC0pi1p, CC1pi, CC1pi1p,...)
- **limiting model dependence ⇒** this provide stable and **long-lived results** supported by **sophisticated data release**
- So far **>20 publications**: 6 CC-Inclusive, 3 ν_e, 12 CC0pi, 4 CC1pi

What T2K xsec measurements can teach to HK and DUNE?

++ on understanding nuclear effects and on low mom hadrons!



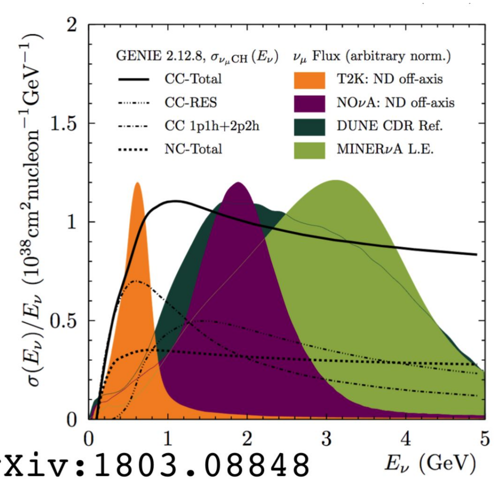


++ on understanding the water target (same as SK) and the energy dependence of xsec

Previous **focus on dedicated CC0pi measurements,** the most abundant channel in T2K (12 publications + 5 ongoing). **Sophisticated systematics model** developed for the oscillation analysis (based on spectral function)

Now moving to **characterise the CC1pi channel**, the 2nd most abundant in T2K (4 publications + 5 ongoing) - known to be mismodeled

Expecting even more exciting measurements thanks to the ND280-Upgrade and WAGASCI/BabyMIND!



arXiv:1803.08848

HK - same neutrino beam, same near detectors (to begin with), same far detector technology ⇔ obvious synergy!

DUNE - different spectra and target, but **T2K characterisation and parameterisation of CC0pi and CC1pi** interactions can be beneficial. We expect increased sensitivity to the **hadronic system** with the ND280 upgrade (also neutrons!). Also, xsec **extraction techniques and tools** could help.

What T2K is going to discuss during this workshop?

Tuesday morning: cross section extraction method (unfolding)

Cross-section extraction using template fitting in T2K cross-section measurements	*Margherita Buizza Avanzini et al.*
500/1-001 - Main Auditorium, CERN	11:30 - 11:50

Binned log-likelihood template fitting with T2K	*Nick Latham*
500/1-001 - Main Auditorium, CERN	12:00 - 12:15

Tuesday afternoon: looking forward ND280 Upgrade (forward folding?)

Unbiased reconstruction of calorimetric variables in cross-section analyses	*Katharina Lachner*
31/3-004 - IT Amphitheatre, CERN	14:25 - 14:40

Thursday morning: dealing with the efficiency correction

Dealing with high dimensional efficiency corrections in T2K's cross-section measurements	*Sam Jenkins et al.*
222/R-001, CERN	09:00 - 09:20

+ a series of other T2K collaborators giving more general or theory-related talks

Intro to MINERvA

Noah Harvey Vaughan *(they/them)*

PhD Candidate, Oregon State University

NuXTract 2023

Monday October 2nd, 2023

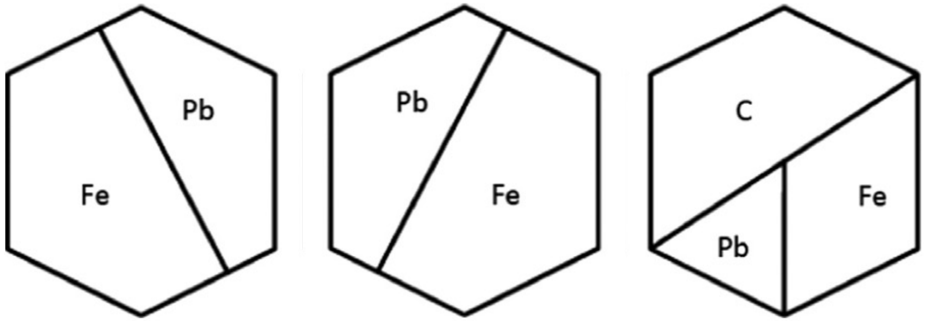
Oregon State University

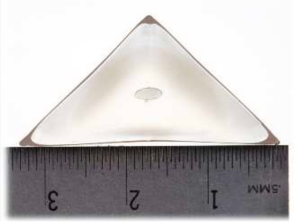
MINERvA Experiment

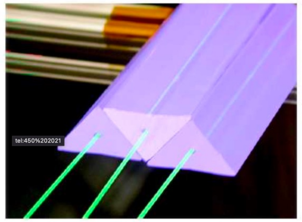
MINERvA = Main INjector ExpeRiment on v (nu) A (atom)

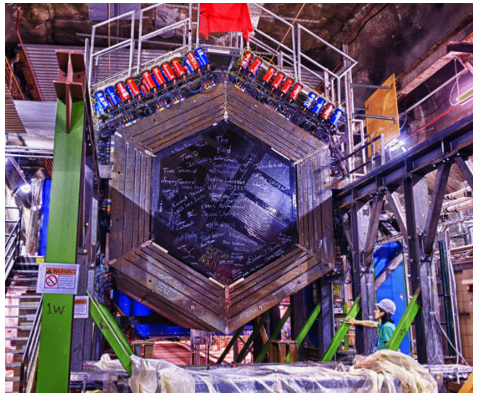
- Dedicated x-section experiment at FNAL
- Data runs from 2009 – 2019:
  - NuMI LE POT: $4.0 \times 10^{20}\ \nu$, $1.7 \times 10^{20}\ \bar{\nu}$
  - NuMI ME POT: $\sim 3 \times$ LE ν, $\sim 7 \times$ LE $\bar{\nu}$

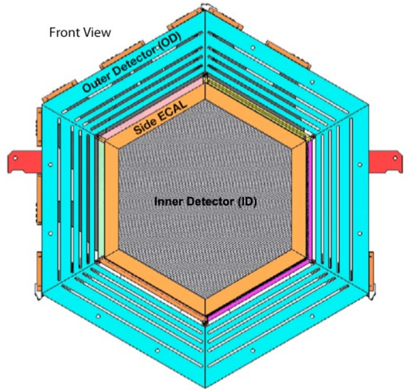
Geometry of nuclear target planes

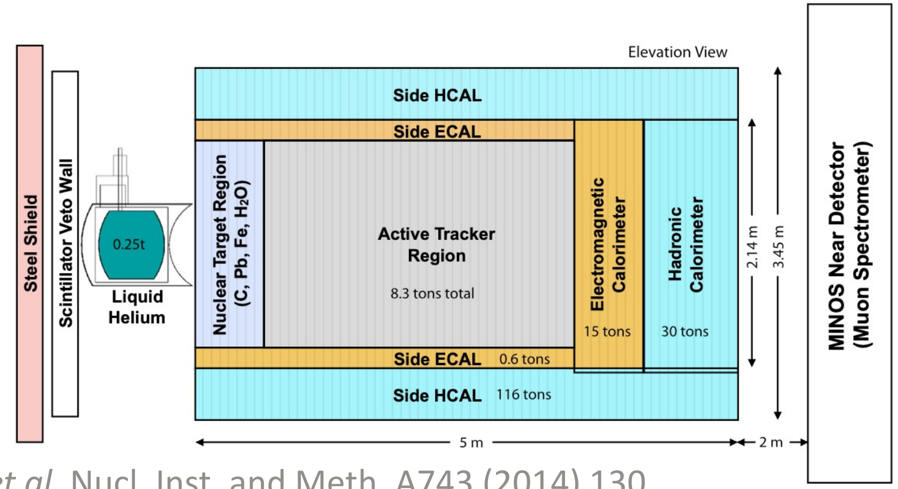












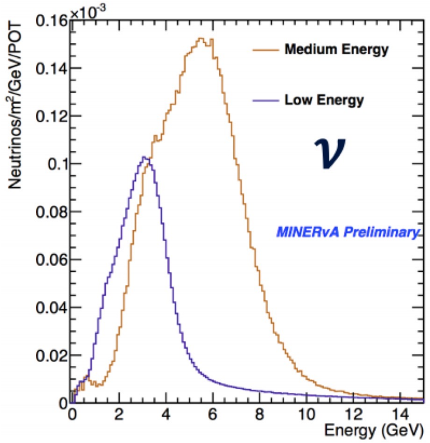
Aliaga, et al. Nucl. Inst. and Meth. A743 (2014) 130

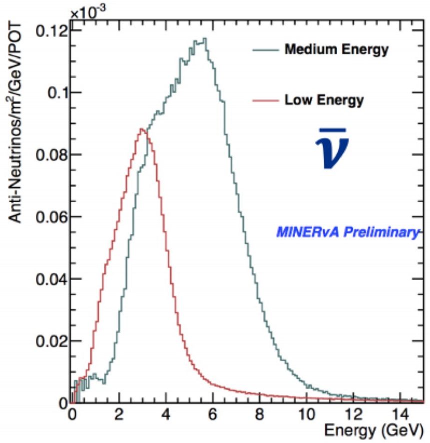
Why measure cross sections?

- Exactly what MINERvA was built for!
- Containing both passive nuclear targets & active tracker allows for wide breadth of cross section analyses
- Low- & medium-energy NuMI flux is well constrained
- Very high statistics dataset
  - Uncertainty is systematics dominated in most analyses
  - Allows study of difficult to detect processes e.g., CCE $\bar{\nu}$ on hydrogen

MINERvA for DUNE/HyperK

- $\nu, \bar{\nu}$ spectra overlapping DUNE
- Probes similar processes as HyperK
- Tunes on existing generator informs new versions
- Preservation efforts allow for reanalysis
- Detector planes repurposed for DUNE ND prototypes





Collaboration in front of MINERvA planes repurposed for DUNE-ND 2x2 prototype

MINERvA at NuXTract

Publishing Cross Sections at MINERvA

- Summary of publication history
- Overview of steps analyzers take to extract a cross section
- More detailed look at unfolding, testing analyzers perform

Tuesday, 3 October, 11:00

Data Preservation at MINERvA

- Efforts to preserve analysis tools, how they're used
- Examples of in-progress "Data Preservation Era" analyses
- Preserving the MINERvA dataset

Wednesday, 4 October, 16:00

Acknowledgements

Introduction: NOvA

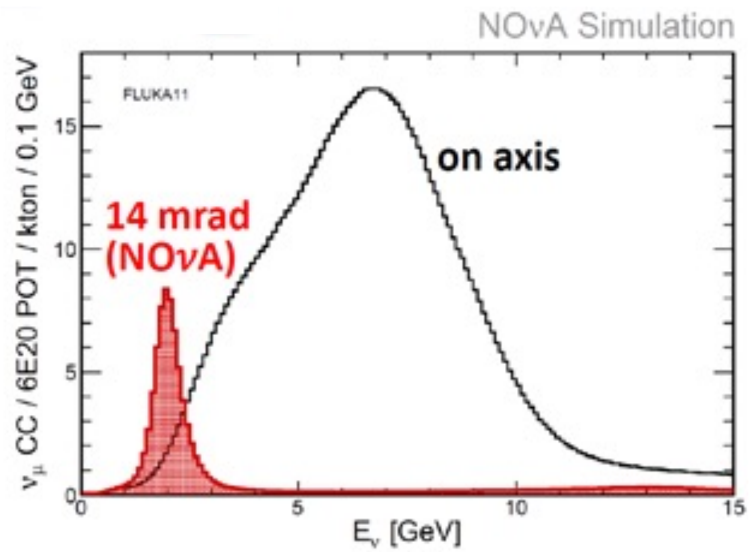
NuXTract 2023 – CERN

Gregory Pawloski
University of Minnesota

What is NOvA (w.r.t. Cross Sections)

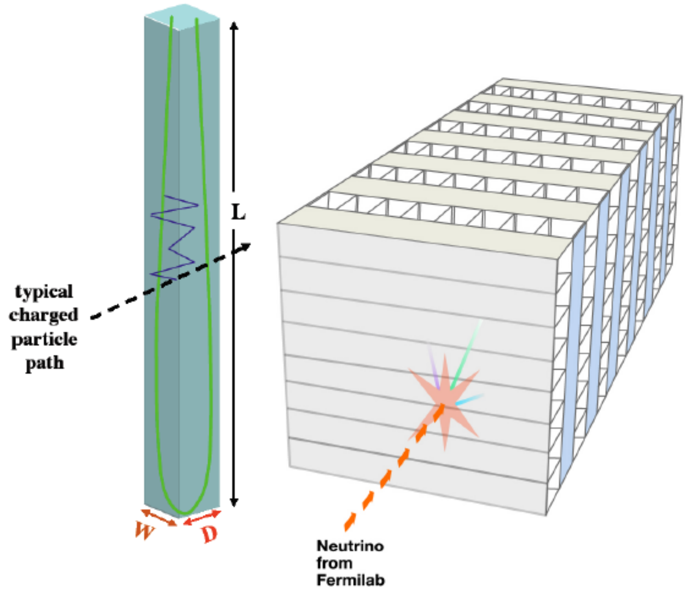
Accelerator neutrino experiment

- NuMI beam at Fermilab
- E ≈ 1.9 GeV (off-axis narrow band beam)
- ν_μ and $\bar{\nu}_\mu$ beam modes



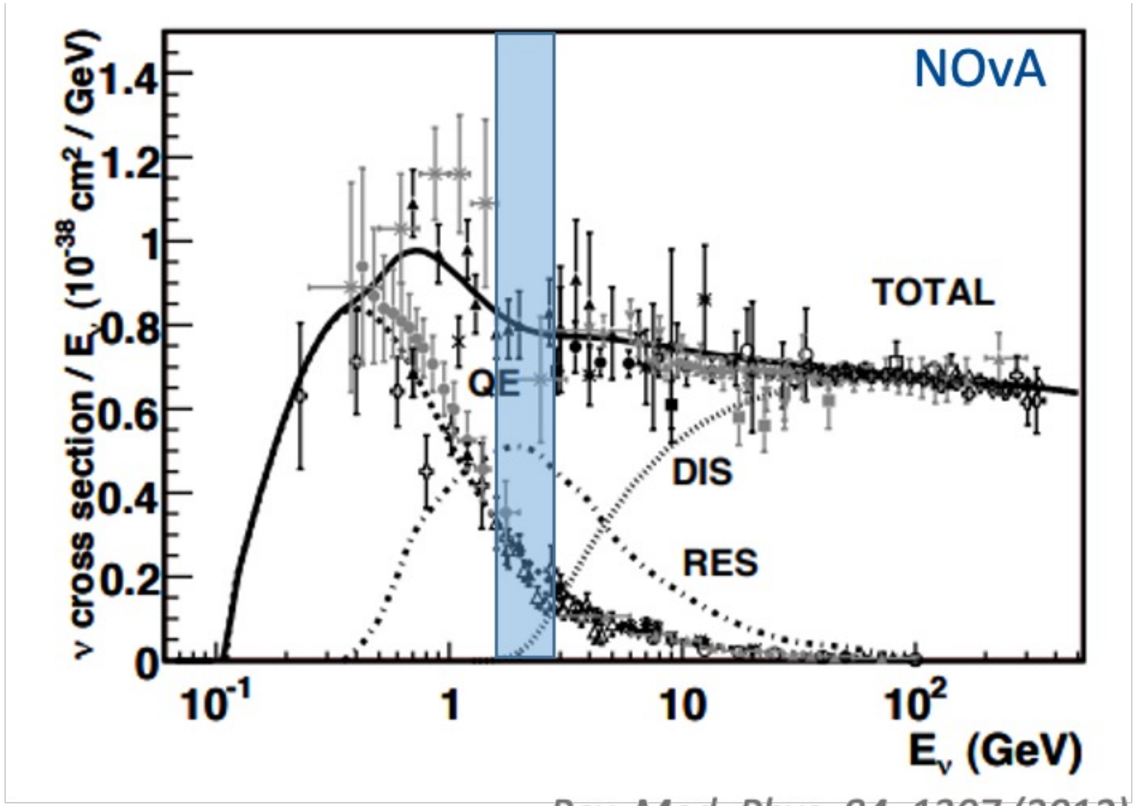
Near Detector

- ~1km from production target at Fermilab
- Active liquid scintillator hydrocarbon target
  - 67% C, 11% H with 16% Cl, 3% Ti, 3% O
- Tracking calorimeter



Why NOvA Measures Cross Sections

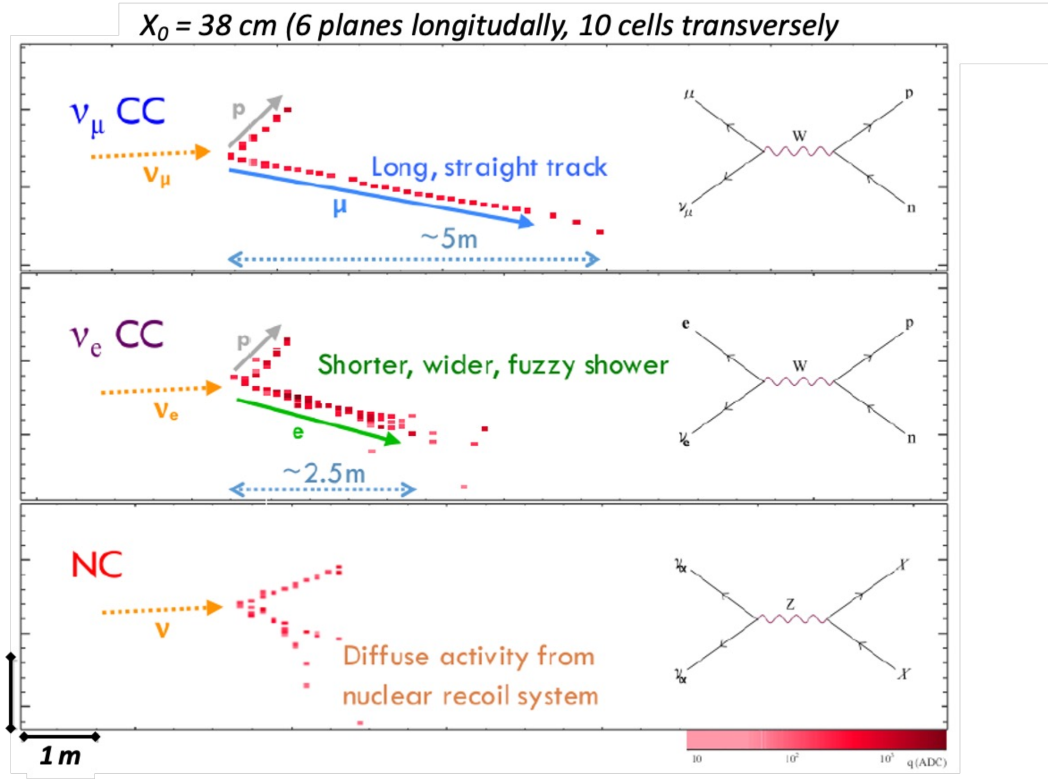
NOvA interactions probe an interesting energy regime



Rev. Mod. Phys. 84, 1307 (2012)

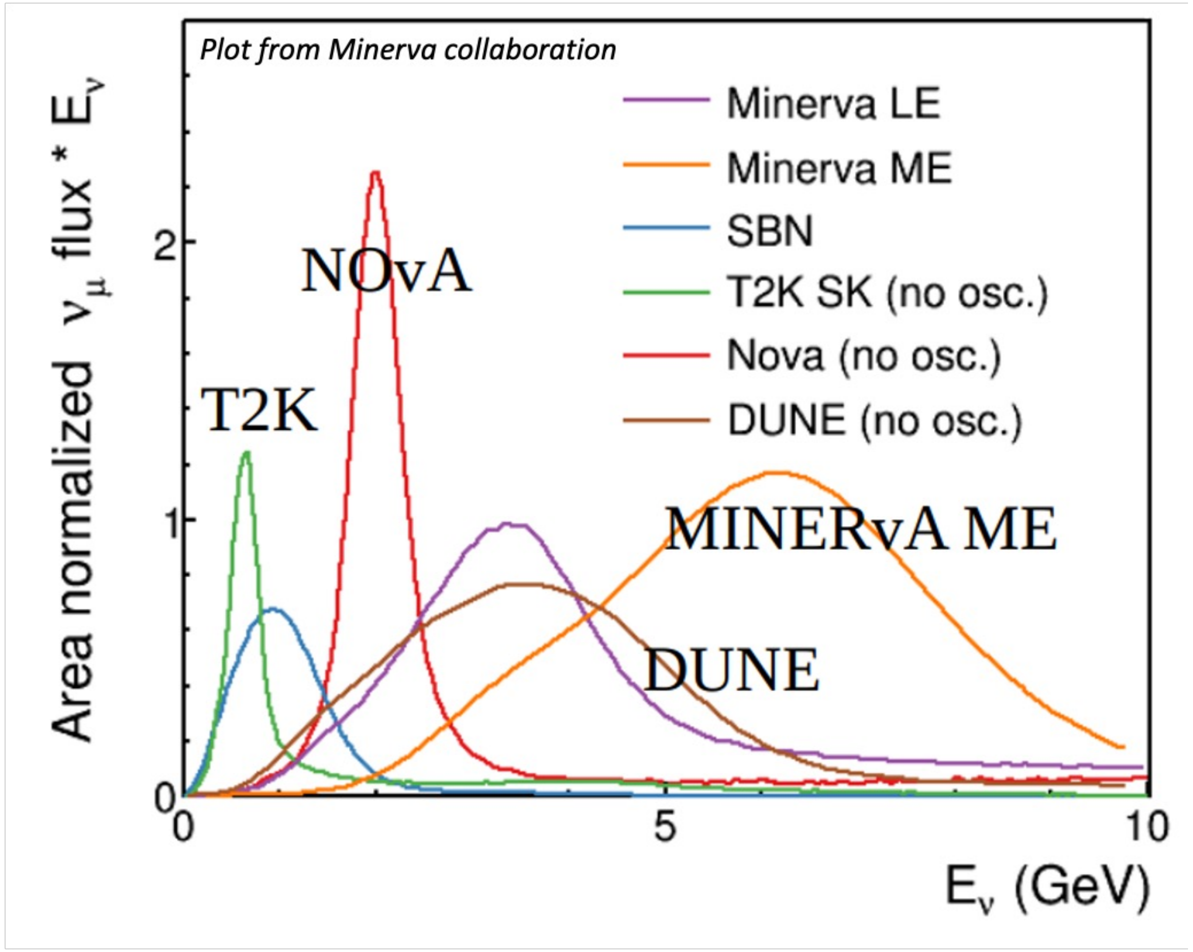
Energy is where resonant production is dominant and mix of QE, 2p2h, RES, and DIS is important

Tracking calorimeter detects individual particles



Can probe individual particle kinematics (lepton and hadronic particles)

How is NOvA relevant for DUNE?



NOvA completes the experimental coverage of neutrino energies that are relevant for DUNE

Resonant enhanced region

What you will hear about

How NOvA presents its results

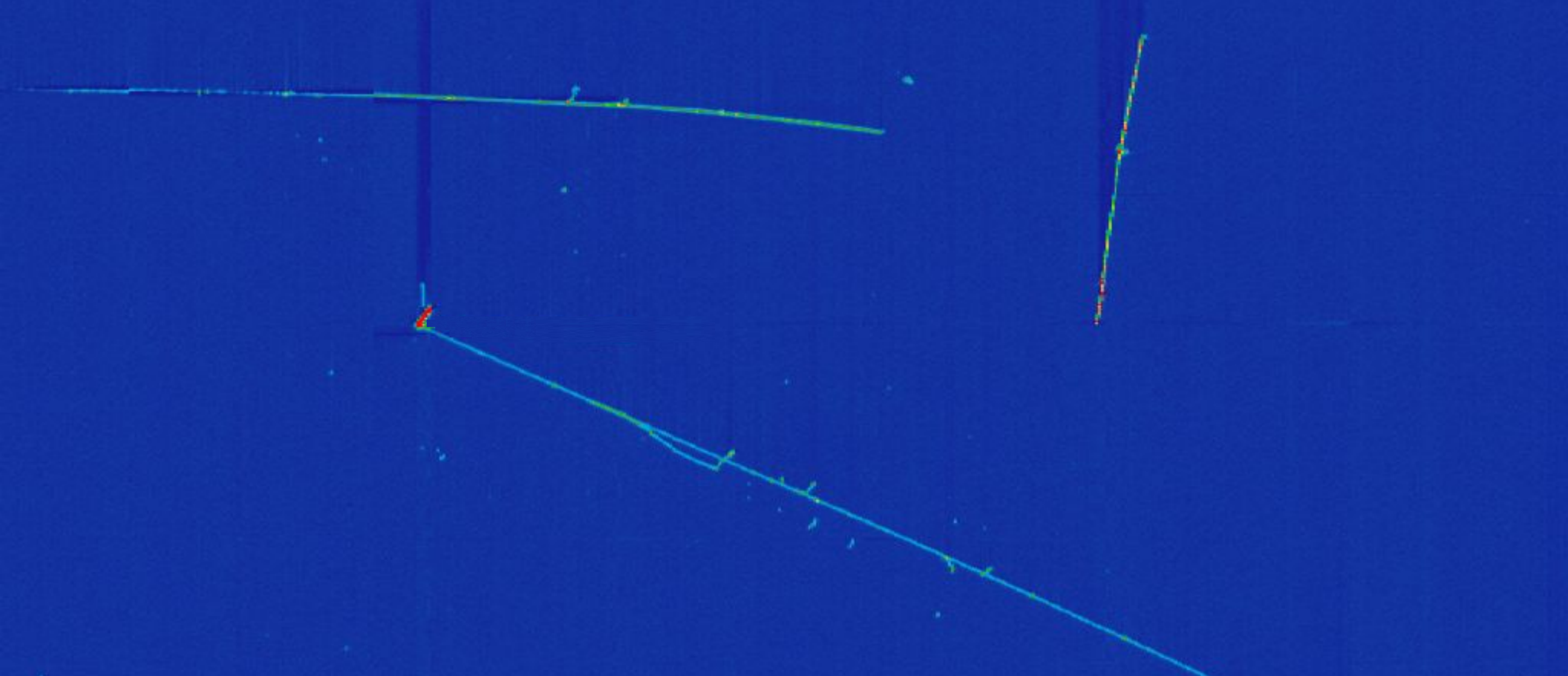
What type of observables we look at

How do we handle uncertainties

How do we present in true values

How do we make comparisons with models

Introduction to MicroBooNE



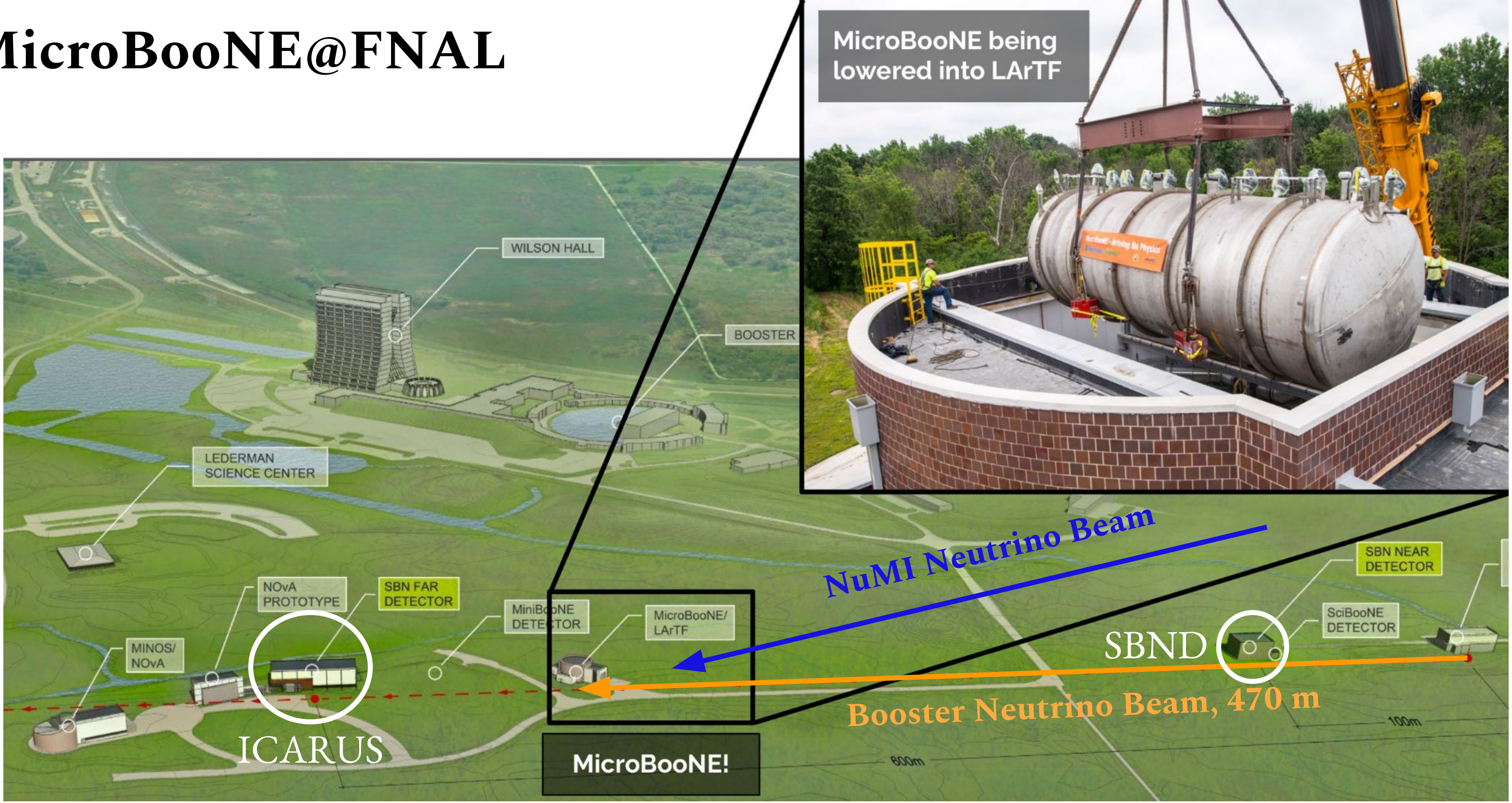
Afroditi Papadopoulou apapadopoulou@anl.gov
on behalf of the MicroBooNE Collaboration

10/2/2023, NuXTract, CERN

Argonne NATIONAL LABORATORY

μBooNE

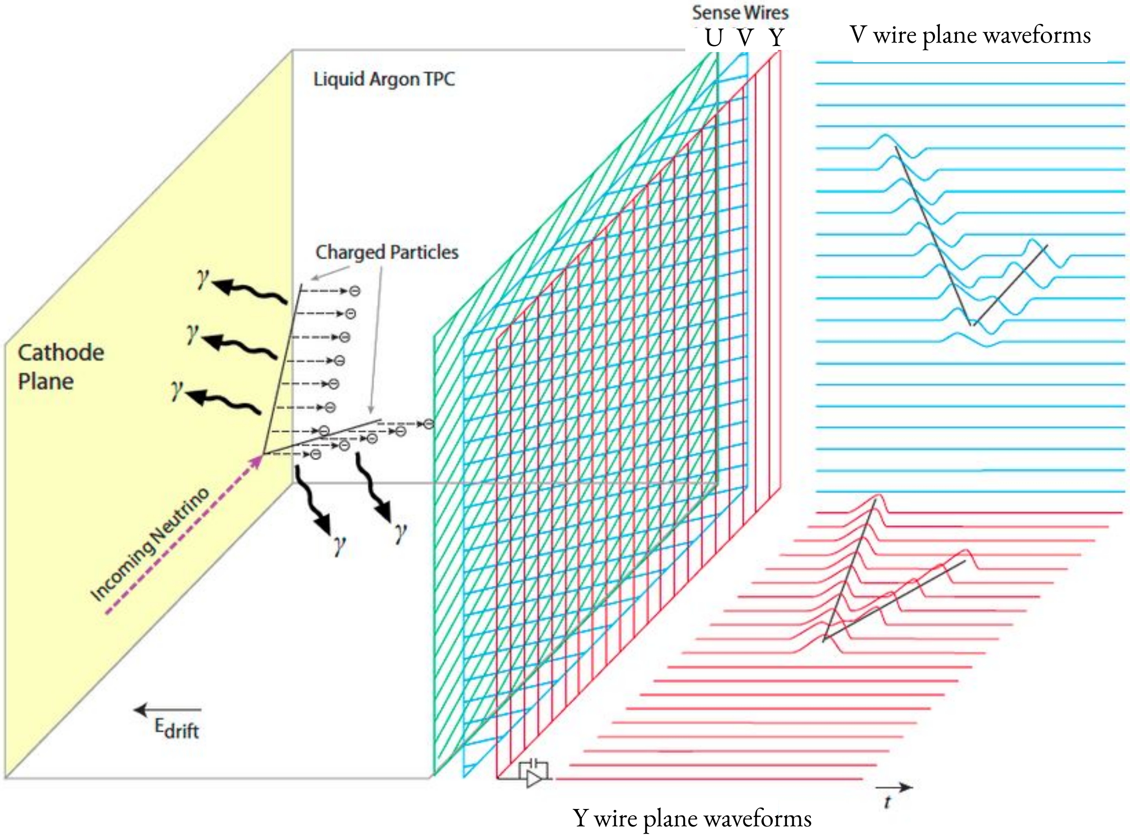
MicroBooNE@FNAL



85 tonne Liquid Argon Time Projection Chamber (LArTPC)

JINST 12, P02017 (2017)

LArTPC Operation Principle

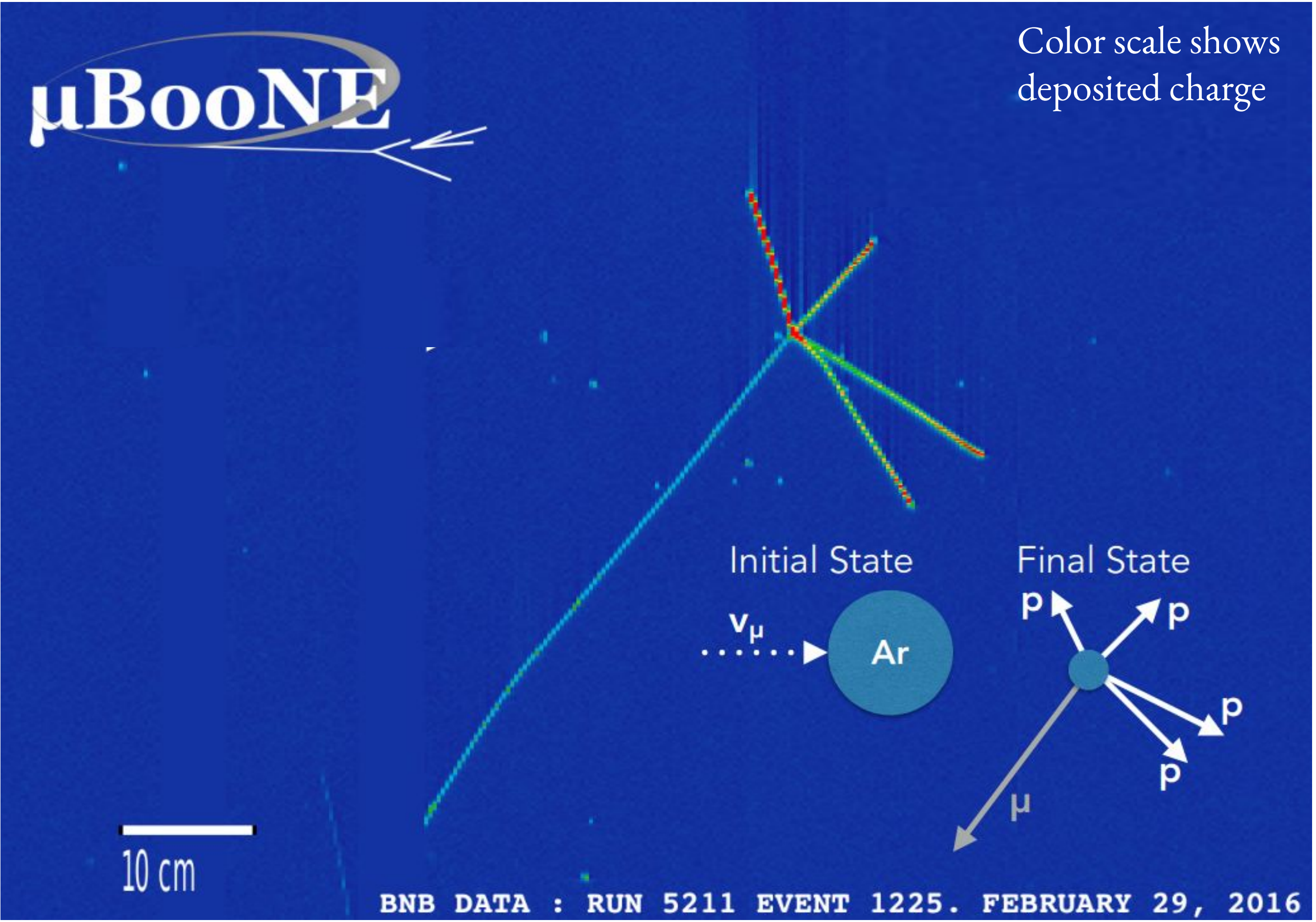


MicroBooNE

- 3 wire planes
- 8192 gold coated wires
- 3 mm wire spacing
- 32 PMTs

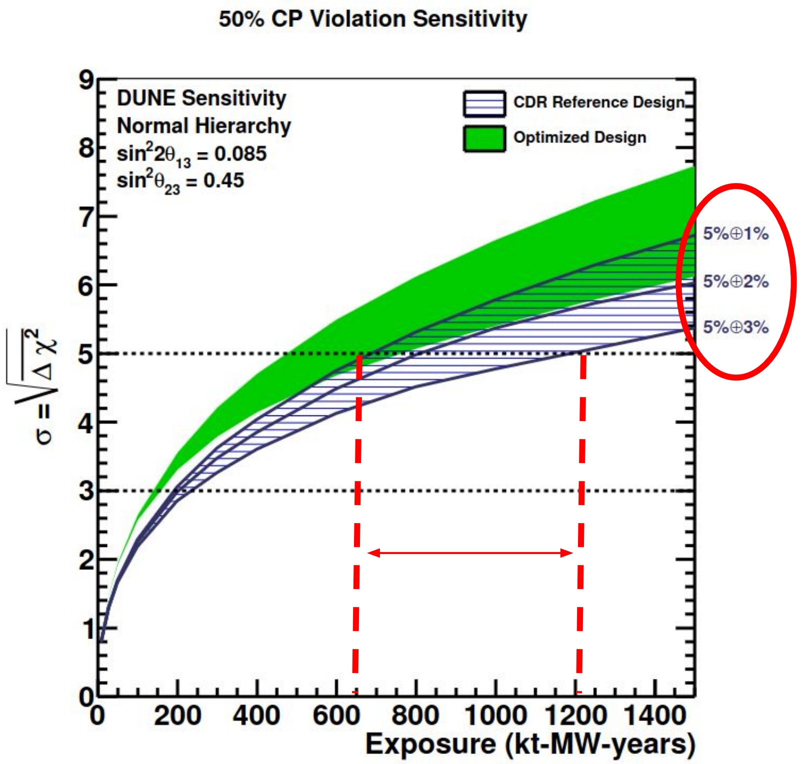
JINST 12, P02017 (2017)

MicroBooNE Data Events



- Largest available neutrino-argon data set with ~500k recorded neutrino interactions
- Over 10 released and more than 30 active MicroBooNE cross section analyses
- Multiple cross sections reported

High Precision Cross Section Measurements Needed



DUNE CDR, arXiv:1512.06148

- Mismodeling can impact required run time of forthcoming flagship experiments

- But … head start with MicroBooNE to provide cross sections & uncertainties to be used by DUNE & HK

Already Public Results

CC inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 1D ν_e CC inclusive @ NuMI
  Phys. Rev. D105, L051102 (2022)
  Phys. Rev. D104, 052002 (2021)

Pion production

- ν_μ NCπ^0 @ BNB
  Phys. Rev. D 107, 012004 (2023)

CC0π

- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Kinematic Imbalance @ BNB
  arXiv:2301.03700, arXiv:2301.03706
  submitted to PRL & PRD
- 1D ν_μ CC1p0π @ BNB
  Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CC2p @ BNB
  arXiv:2211.03734, submitted to PRL
- 1D ν_μ CCNp0π @ BNB
  Phys. Rev. D102, 112013 (2020)

Rare channels

- η production @ BNB, submitted to PRL
  arXiv:2305.16249
- Λ production @ NuMI
  arXiv:2212.07888, accepted by PRL

Already Public Results

CC inclusive

- 1D ν_μ CC inclusive @ BNB
  Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB
  Phys. Rev. Lett. 128, 151801 (2022)
- 1D ν_e CC inclusive @
  Phys. Rev. D105, L05
  Phys. Rev. D104, 052

Pion production

- ν_μ NCπ^0 @ BNB
  Phys. Rev. D 107, 012004 (2023)

CC0π

- 1D ν_e CCNp0π @ BNB
  Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π Kinematic Imbalance @ BNB
  arXiv:2301.03700, arXiv:2301.03706

3 (2020)

ed to PRL

2020)

Rare channels

- η production @ BNB
  arXiv:2305.16249
- Hyperon (Λ,Σ) production @ NuMI
  arXiv:2212.07888, accepted to PRL

MicroBooNE (& adjacent) talks

- Model validation (Nitish)
- Cross section extraction techniques (Afro)
- Block-wise unfolding (S. Gardiner)
- Tuning (M. Kirby)
- Wiener SVD unfolding (Xin)

Thank you!

Backup Slides

An Introduction to ProtoDUNE-SP

Richie Diurba (Bern) for the DUNE Collaboration
NuXTract 2023

Overview of ProtoDUNE-SP

- ProtoDUNE Single Phase (SP) is the first "full-scale" engineering test of DUNE Far Detector Module 1.
- Liquid argon time projection chamber with 700 tons of argon.
- Took two months of beam data-taking from September to November 2018.
    - Beam used to measure hadron-Ar cross sections.
    - See status of all work in the CERN report.
- ProtoDUNE-SP has published five papers on its performance:
    - Detector performance (*JINST* **15** P12004)
    - Design and operation (*JINST* **17** P01005)
    - Track/shower separation using a CNN (*EPJC* **82** 903)
    - Michel electron reconstruction (*Phys. Rev. D* **107**, 092012)
    - Reconstruction of cosmic/beam using Pandora (*EPJC* **83** 618)

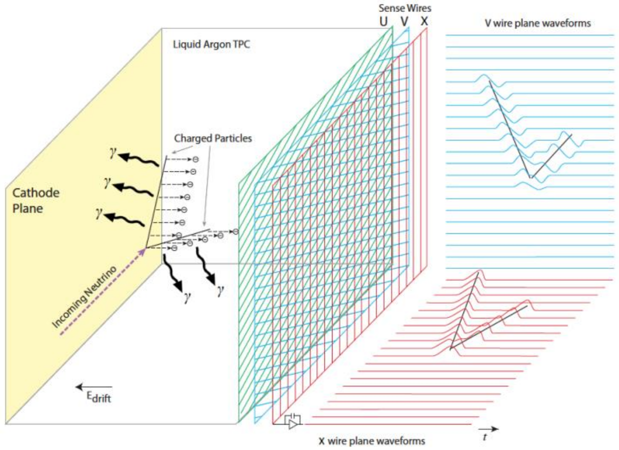


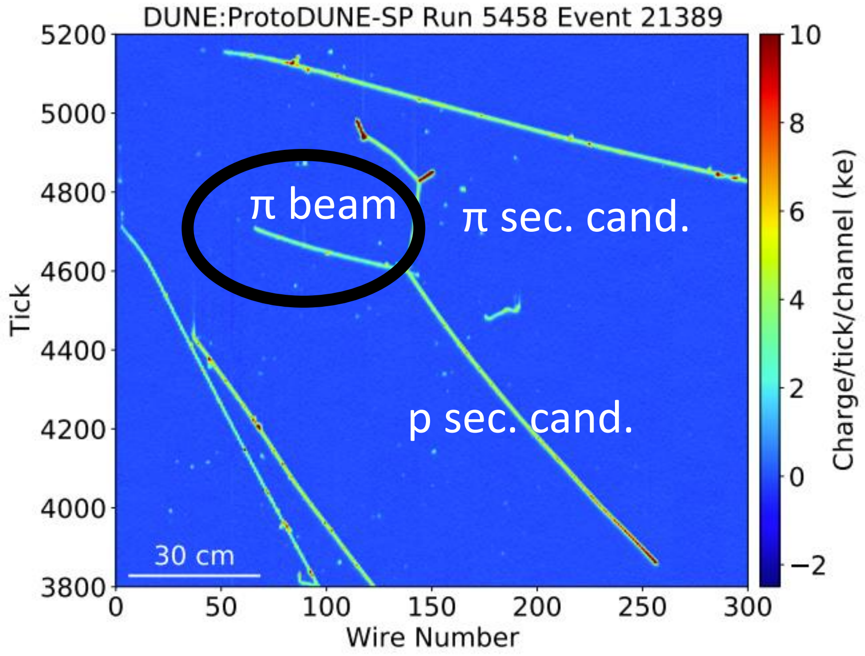
Diagram of the operating principle for liquid argon time projection chambers (TPCs). (arXiv:2002.03005)

ProtoDUNE-SP has surpassed technical specifications of DUNE FD Design Requirements (*JINST* **15** P12004):

Detector parameter	*ProtoDUNE-SP performance*	*DUNE specification*
Average drift electric field	500 V/cm	250 V/cm (min) 500 V/cm (nominal)
LAr e-lifetime	> 20 ms	> 3 ms
TPC+CE Noise Signal-to-noise ⟨SNR⟩	 (C) 550 e, (I) 650 e ENC (raw) (C) 48.7, (I) 21.2 (w/CNR)	 < 1000 e ENC
CE dead channels	0.2%	< 1%
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance — 3.6 m)
PDS time resolution	14 ns	< 100 ns

ProtoDUNE-SP Cross Sections

- CERN NP provided a hadron beam originating from SPS (*Phys. Rev. Accel. Beams* **22**, 061003).
- Operate as a traditional test beam experiment to measure how hadrons travel through argon using.



1 GeV/c positive pion candidate inelastic interaction

ProtoDUNE-SP in the Future

- Final state interactions (FSI) and secondary interactions (SI) systematic uncertainties present challenges for meas. like T2K's oscillation analyses.
  - Can tune and constrain these uncertainties with real data.
- Identifying secondary interactions and "vetoing" events to clean sample of events where $E_{vis.}$!=$E_{had.}$ due to secondary interactions.

Common reweight software for FSI and SI: GENIERW and Geant4RW.

FSI and SI Examples:

- Tuning to world pion data (used by T2K)
- Exploring cascades with alternative models and data.

Final-state interactions

MFP_pi	hA2018	+20%	-20%
MFP_N	hA2018	+20%	-20%
FrCEx_pi	hA2018	+50%	-50%
FrInel_pi	hA2018	+40%	-40%
FrAbs_pi	hA2018	+30%	-30%
FrPiProd_pi	hA2018	+20%	-20%
FrCEx_N	hA2018	+50%	-50%
FrInel_N	hA2018	+40%	-40%
FrAbs_N	hA2018	+20%	-20%
FrPiProd_N	hA2018	+20%	-20%

Final state interaction modeling uncertainties suggested for GENIE using GENIERW.

MFP="Mean Free Path"

What is Being Presented at NuSTEC

- Work-in-progress analyses for ProtoDUNE-SP with focuses on the methods used to extract the cross sections.
    - Richie Diurba: Unfolding two histograms to measure a K^+-Ar total inelastic cross section
    - Jake Calcutt: Abs+CeX+Other π+-Ar total inelastic cross section using a likelihood fitter.
    - Yinrui Liu: Multi-dimensional unfolding to be used for π+-Ar total inelastic cross section.
- All talks emphasize how the measurements are made and what tools and pitfalls exist.

NINJA

Quick Fire Talk : the NINJA experiment

Hitoshi Oshima for the NINJA Collaboration
ICRR, the University of Tokyo
oshima@icrr.u-tokyo.ac.jp

NuXTract 2023, CERN, Oct. 2 – 6, 2023

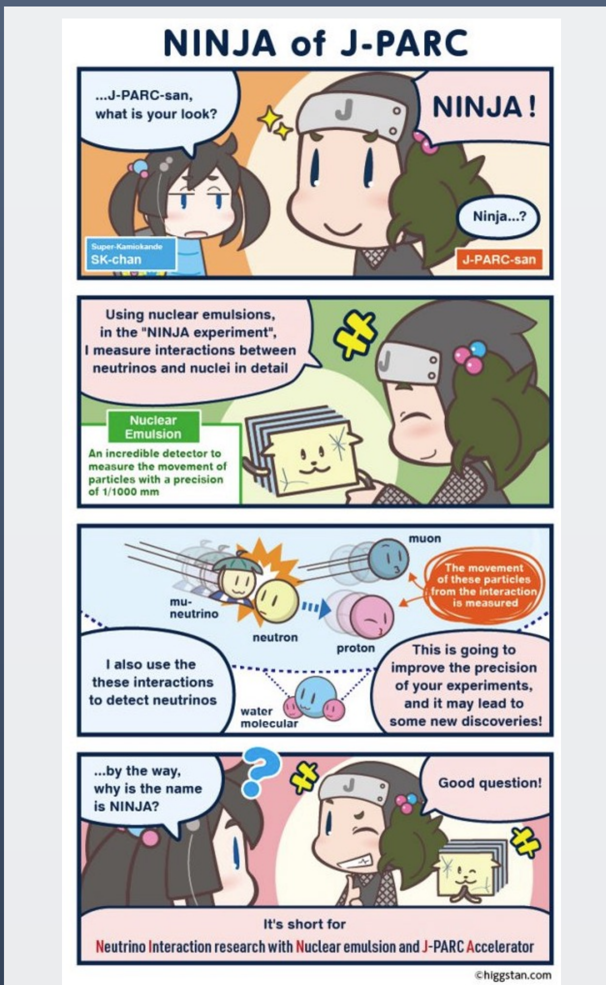
NINJA Experiment

Country: Japan · Croatia · the UK (13 Institutes, ~50 researchers)

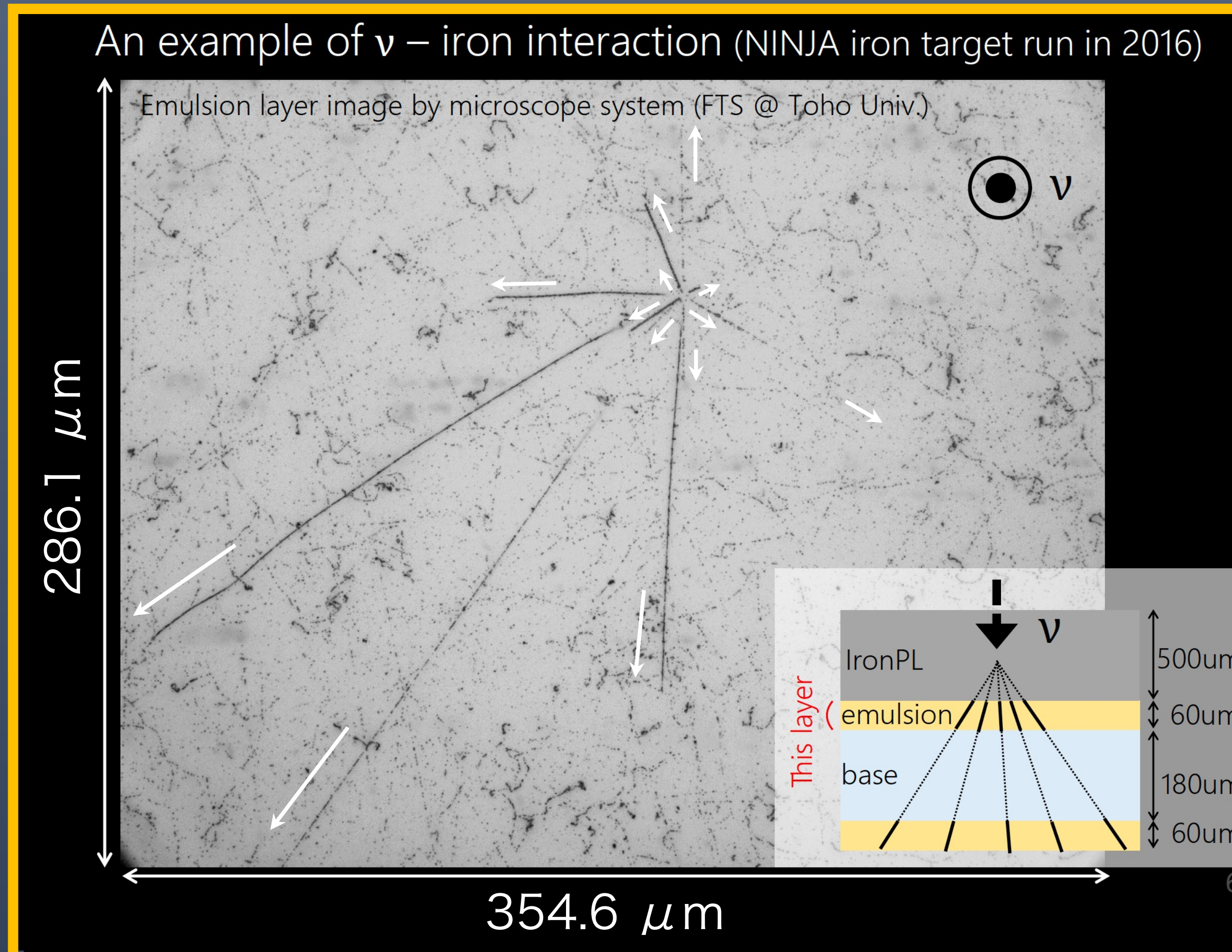
We aim to study neutrino-nucleus interactions using the emulsion detector @ J-PARC.

→ Various targets (H_2O, D_2O , Fe, C, etc.)

→ Low momentum thresholds ~ 200 (50) MeV/c for protons (pions)



An example of ν – iron interaction (NINJA iron target run in 2016)



Why are we measuring cross sections?

We want to

- Understand neutrino – nucleus interactions in the sub-GeV to multi-GeV energy region.
- Understand neutrino - water interactions and reduce the systematic uncertainties of neutrino interactions in the T2K/HK experiment.
- Conduct a sterile neutrino search after understanding neutrino-nucleus interactions in near future.

➡ For these motivation, we are measuring cross sections for protons and pions with low-momentum thresholds.

Our contribution to Hyper-K & DUNE

Our measurements and results will lead to a better understanding of neutrino-nucleus interactions:

- ν - nucleus interactions including nuclear effects
  - low momentum protons & pions
  - 2p2h interactions
- ν - nucleon interactions using Heavy-water & Water

➡ Our results are expected to serve as the foundation for building reliable neutrino interaction models.

What we would like to discuss at this workshop

Towards precise understanding neutrino-nucleus interactions and reducing the uncertainties, we would like to discuss

- What measurements and analyses in which NINJA's emulsion detectors are maximally useful.

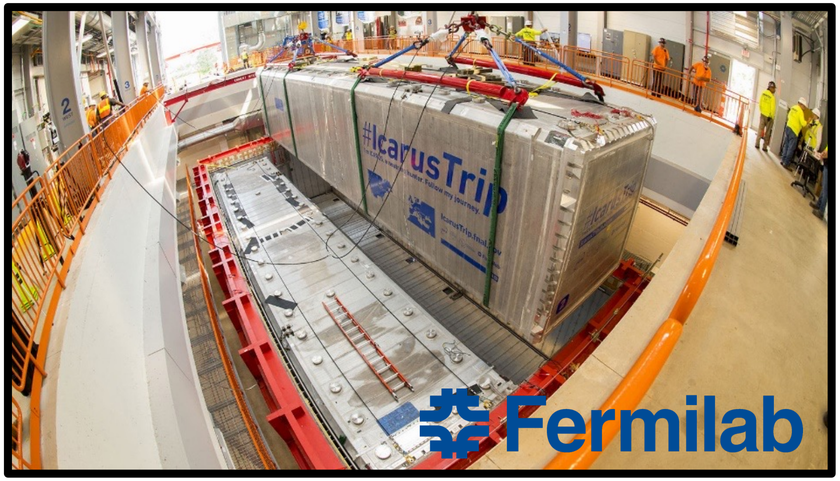
- What measurements of physical quantities would contribute to reducing the systematic uncertainties of the neutrino interaction models.

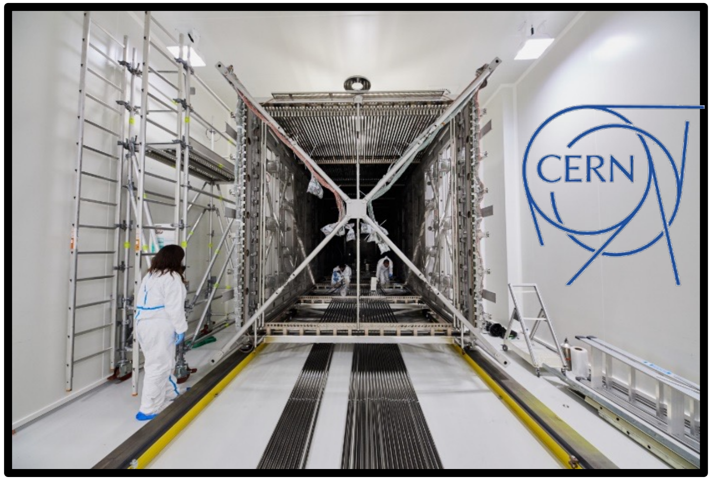
Neutrino-Argon interaction measurements using the NuMI beam at ICARUS

Stephen Dolan
For the ICARUS collaboration

stephen.joseph.dolan@cern.ch

The ICARUS experiment



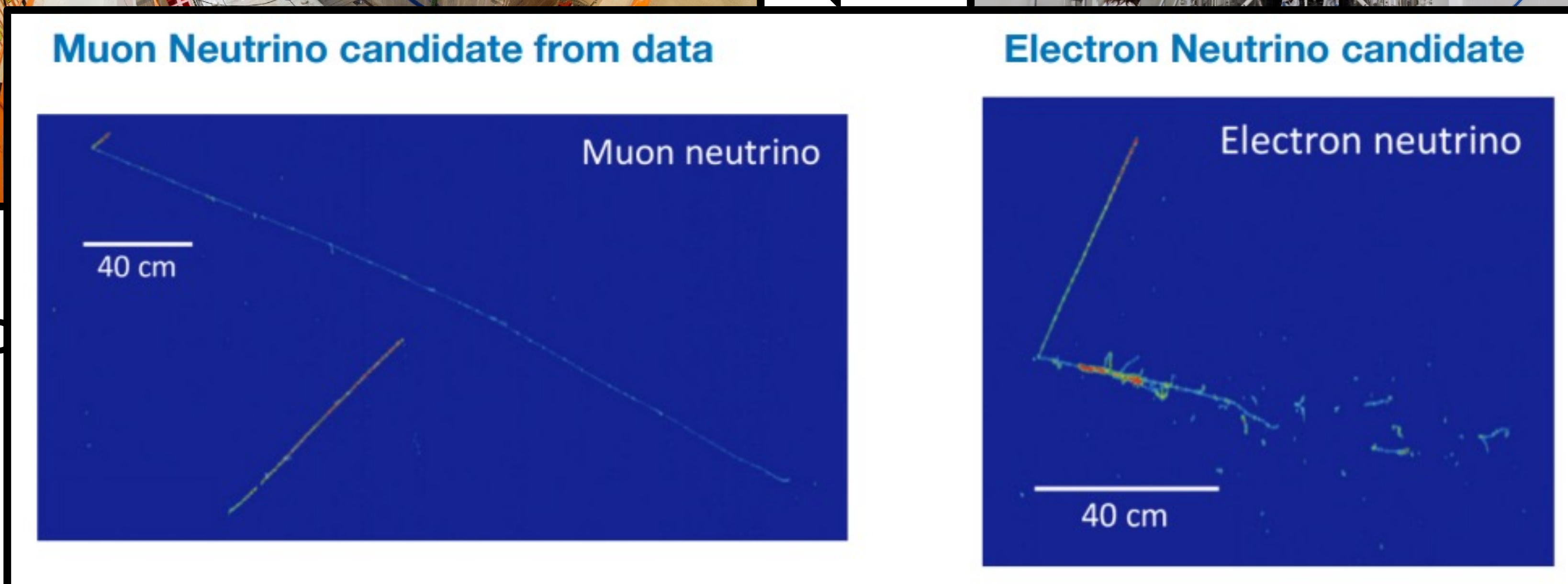


ICARUS

- The first large LArTPC: 476 ton active mass
- 2 modules; 4 TPCs; 360 PMTs, surrounding CRTs

2010-14 Data taking, Gran Sasso	2014-17 Refurbishment, CERN	July 2017 Transport to Fermilab	2021- Data taking as part of SBN

The ICARUS experiment



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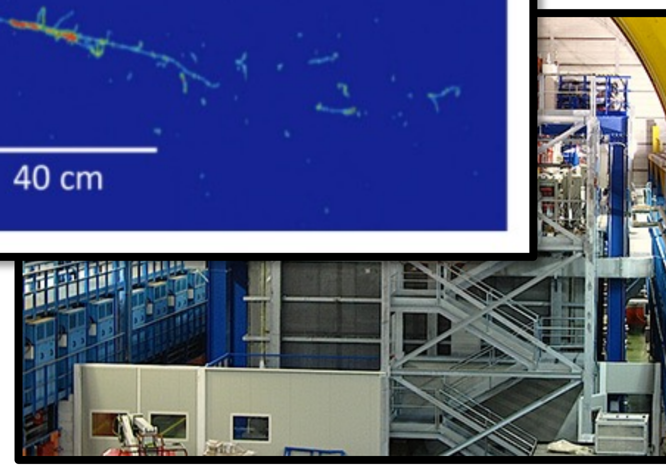

2010-14 Data taking, Gran Sasso

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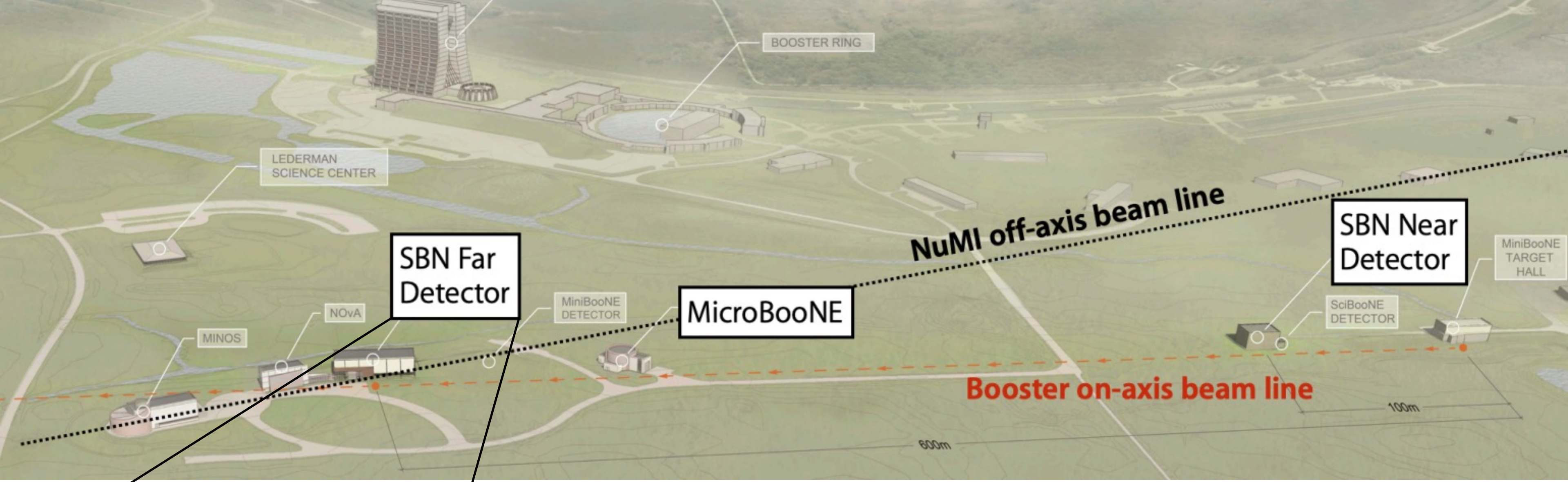
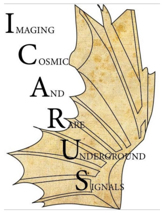
2021- Data taking as part of SBN

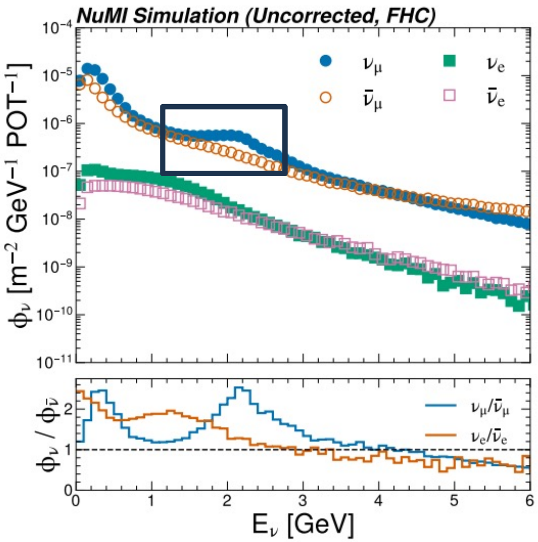
The NuMI flux at ICARUS

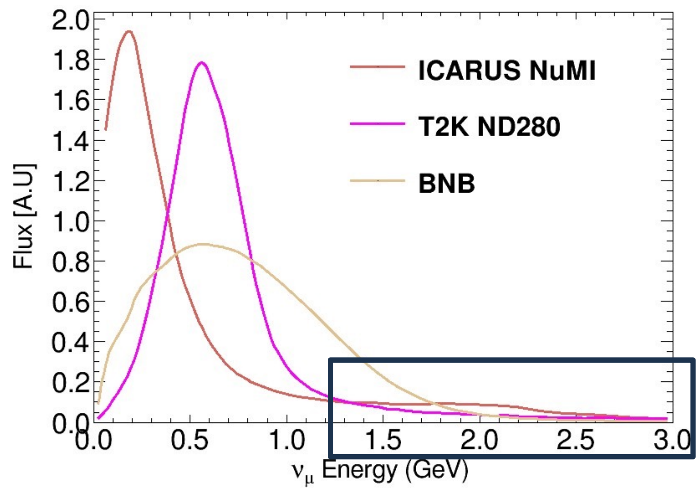


ICARUS-T600



BNB baseline: 600 m
Total LAr: 760 ton
Active LAr: **476 ton**
NuMI off-axis angle*: 5.9°



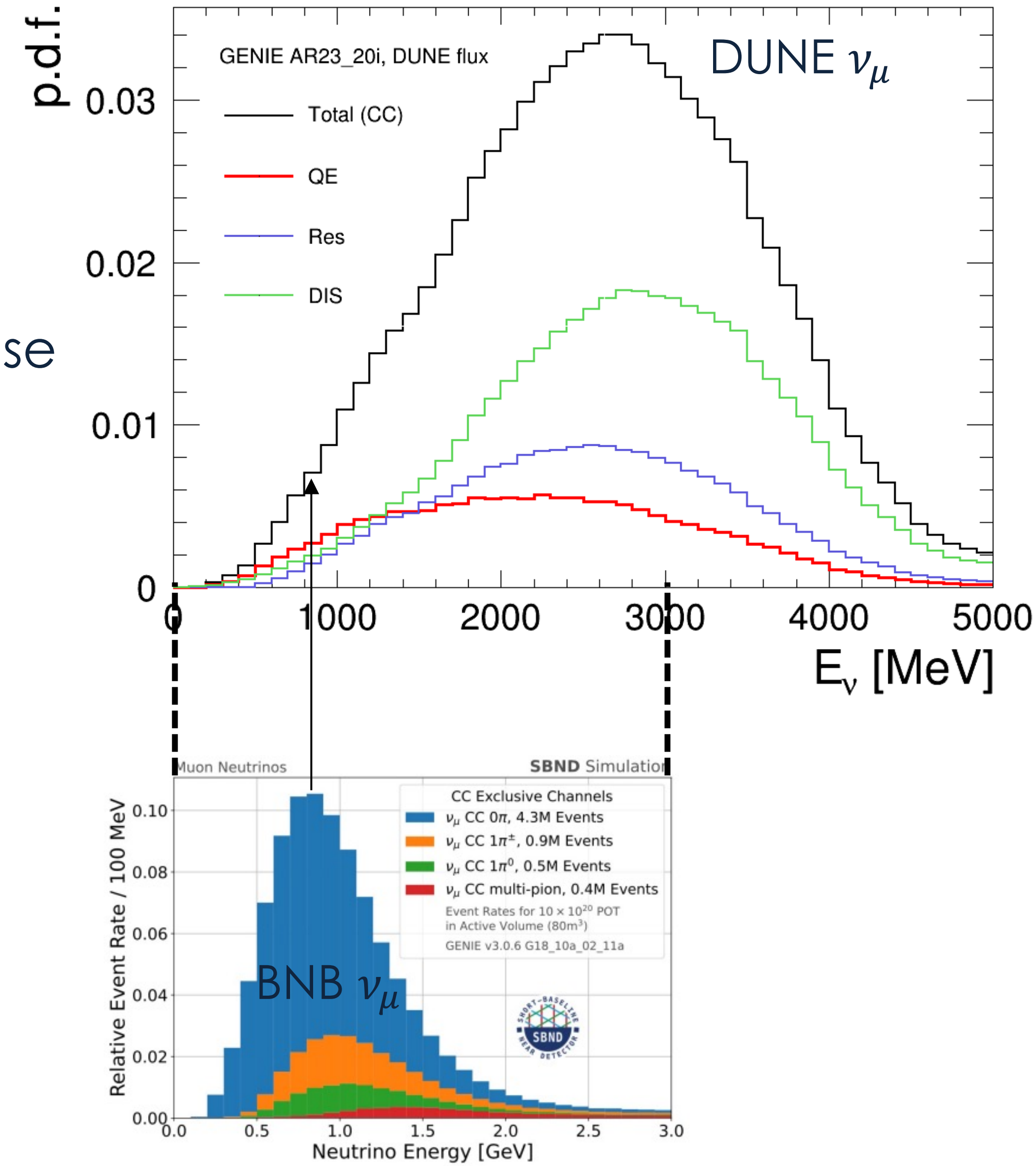


* As measured from close to the target, observed neutrinos come from a wide range of angles

Why NuMI?

(Why are you measuring cross sections?)

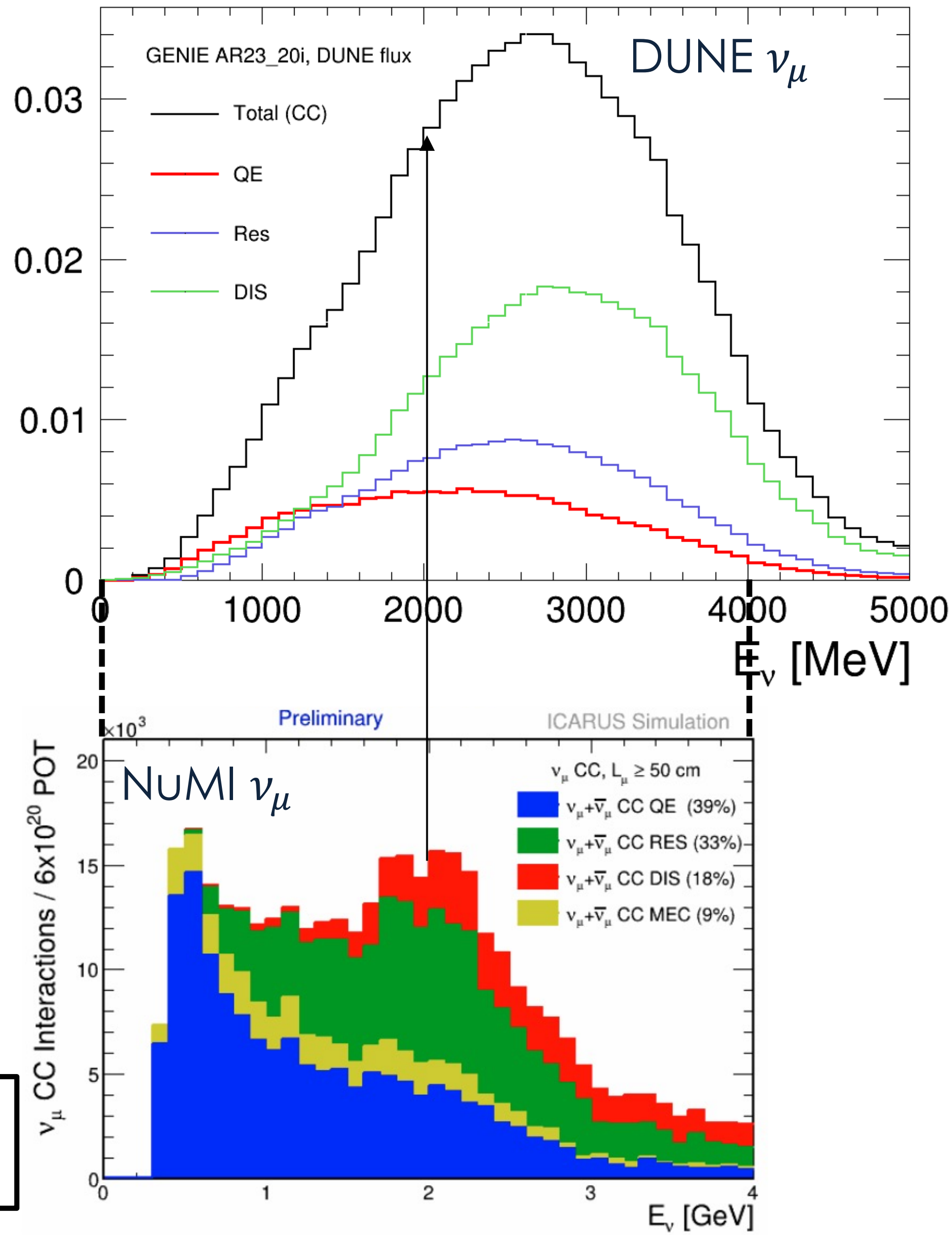
- Interactions in the Booster beam are limited in their phase space coverage for DUNE



Why NuMI?

(Why are you measuring cross sections?)

- Interactions in the Booster beam are limited in their phase space coverage for DUNE
- NuMI at ICARUS offers additional complementary phase space coverage
- Expect to make leading contributions for ν_μ-Ar interactions at E_ν greater than ~2 GeV!



~500k CC events / 6×10^{20} PoT

Approach to result longevity

(How do you expect your measurements to be used when DUNE and Hyper-K are running?)

- ICARUS results ***must*** be quantitatively useful when DUNE is building and tuning its interaction model for real data analysis
  - Sufficiently robust results for model benchmarking and parameter tuning in a decade or more time
- To achieve this, avoidance of model bias will be crucial. We are building a framework to allow:
  - Data driven background constraints
  - Provision of unregularised results
  - Multi-dimensional efficiency corrections
  - Tailored control samples to characterise detector response
- Plan for comprehensive data releases including:
  - Covariance matrices as well as the Universes/toys used to build them
  - Correlations between flux shape and measured cross section
- Possibility of joint/correlated measurements
  - Joint NuMI+BNB, joint ICARUS+SBND
  - Allows easier use of multiple data sets in future DUNE model tuning

Short-Baseline Near Detector (SBND): Neutrino Interactions Program

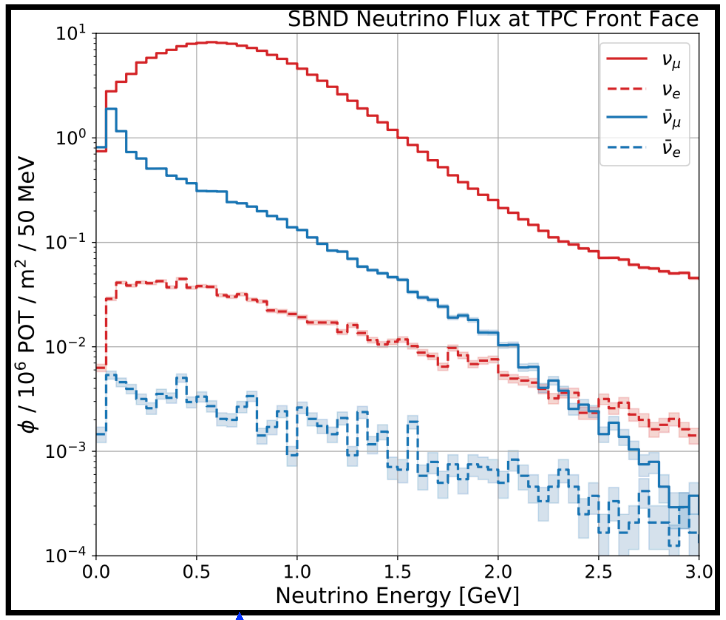
Vishvas Pandey
for the SBND Collaboration

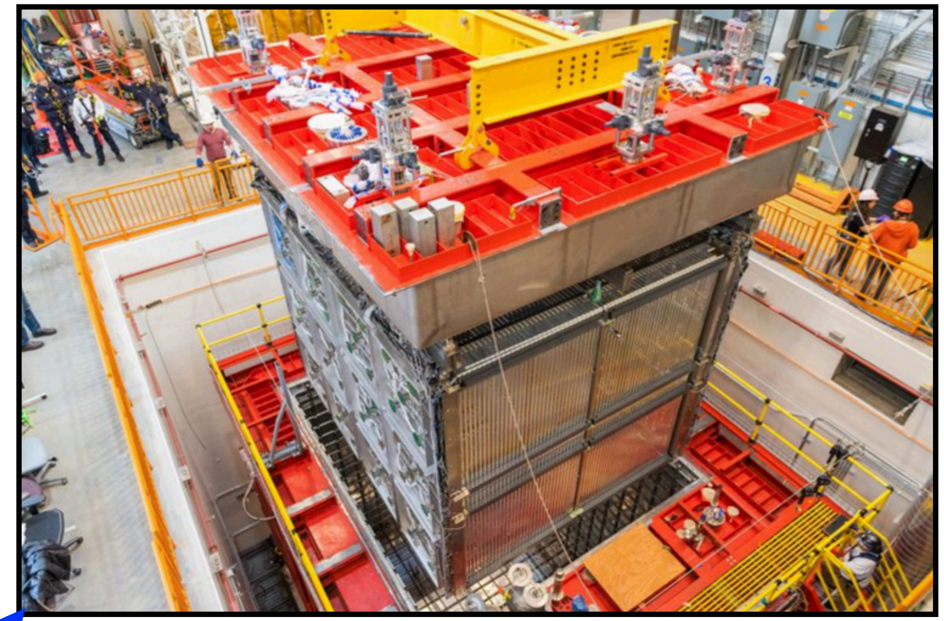
Fermilab

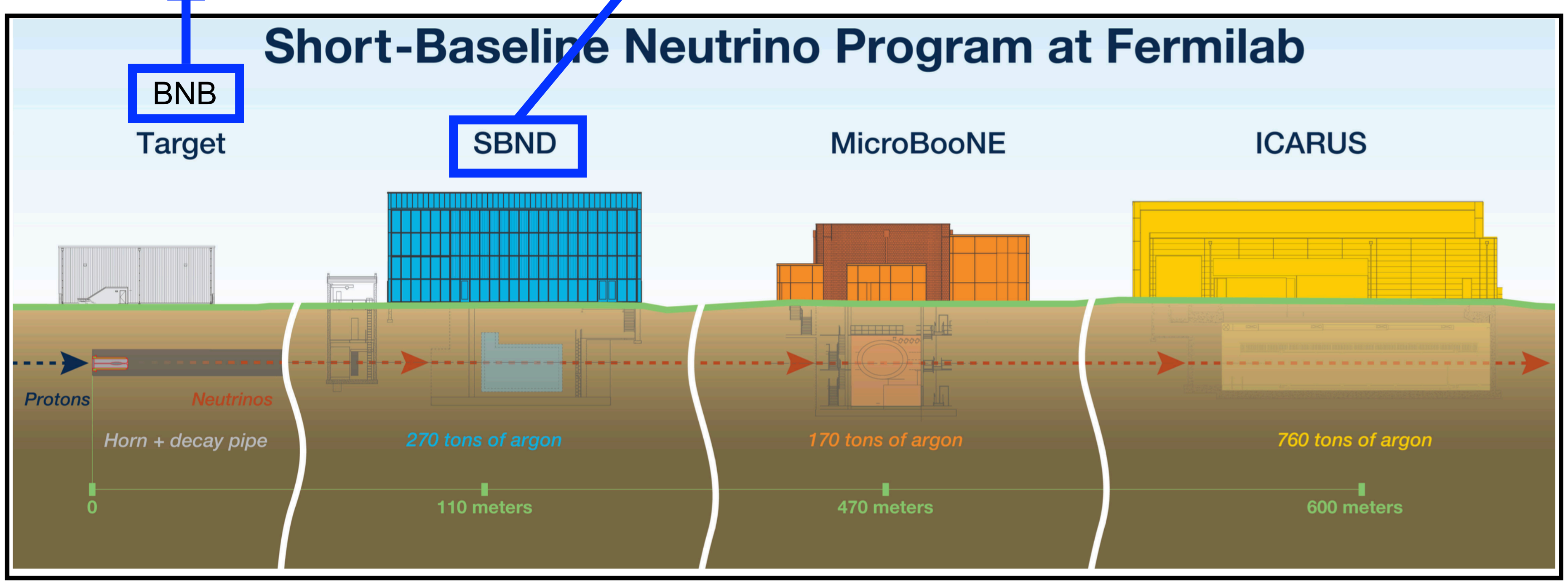
SHORT-BASELINE SBND NEAR DETECTOR

Short-Baseline Near Detector (SBND)

- The Short-Baseline Near Detector (SBND) is the near detector of the Short-Baseline Neutrino (SBN) program located along the Booster Neutrino Beamline (BNB) at Fermilab.
- SBND has broad science goals as part of SBN program and on its own, addressing alternative explanations of the short-baseline anomaly, BSM searches and **precision studies of neutrino-argon interactions**.







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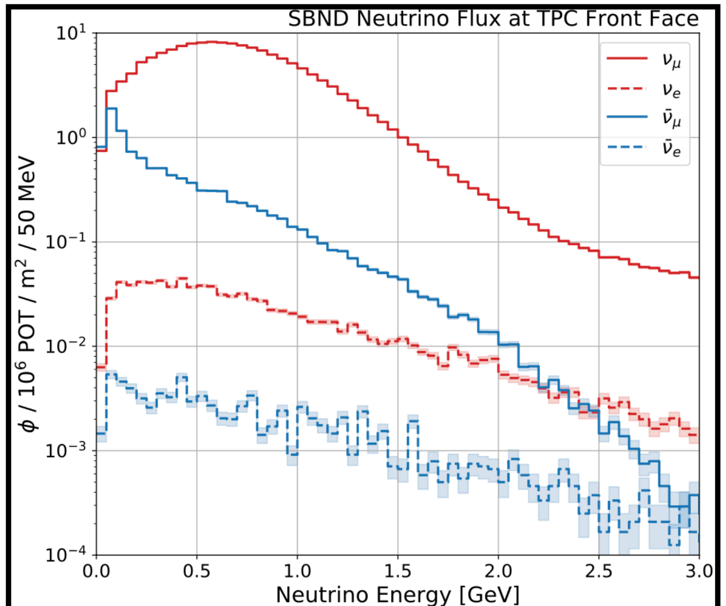
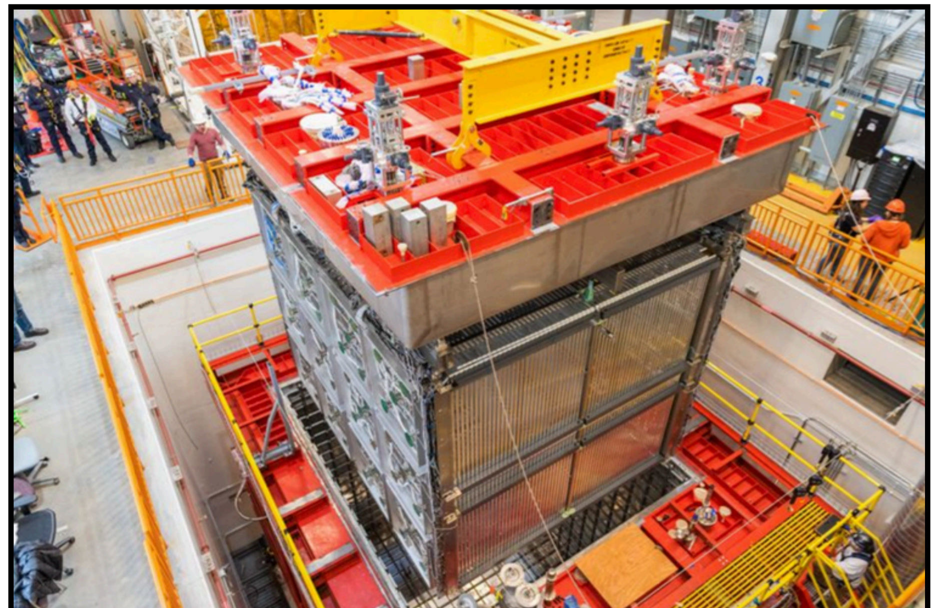
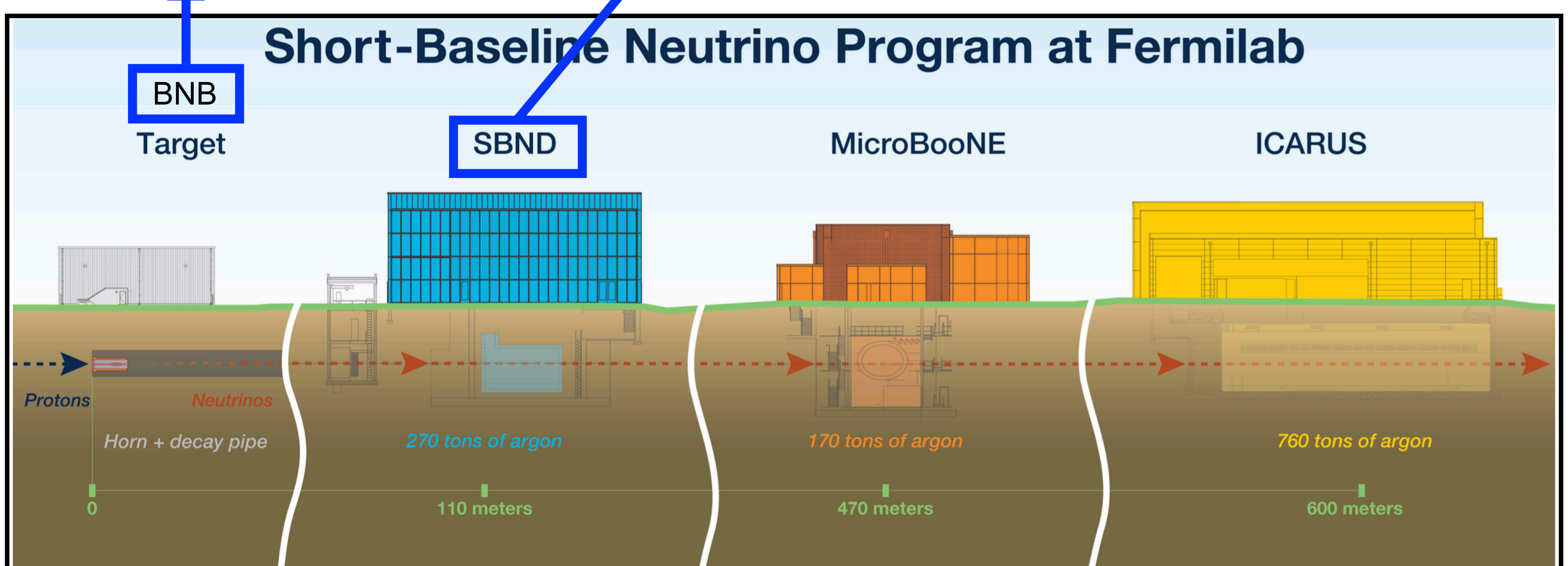
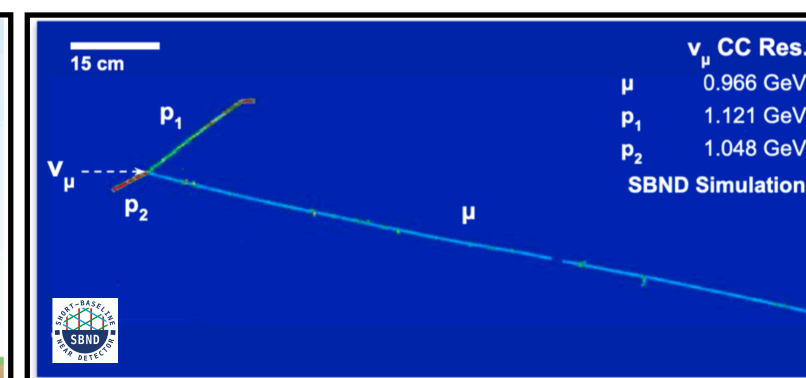




- SBND is a **LArTPC** detector combined with a **unique photon detection system**

  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold





Neutrino Interactions in SBND

- Due to its proximity to neutrino source, SBND expects approximately **2 million ν_μ CC and 15 thousand ν_e CC** interactions per year, with around
  7,000 total neutrino interactions observed per day

  - Every ~3 months, SBND will collect a dataset equivalent to the full MicroBooNE BNB five-year run

- SBND will record ~20–30x more neutrino–argon interactions than is currently available

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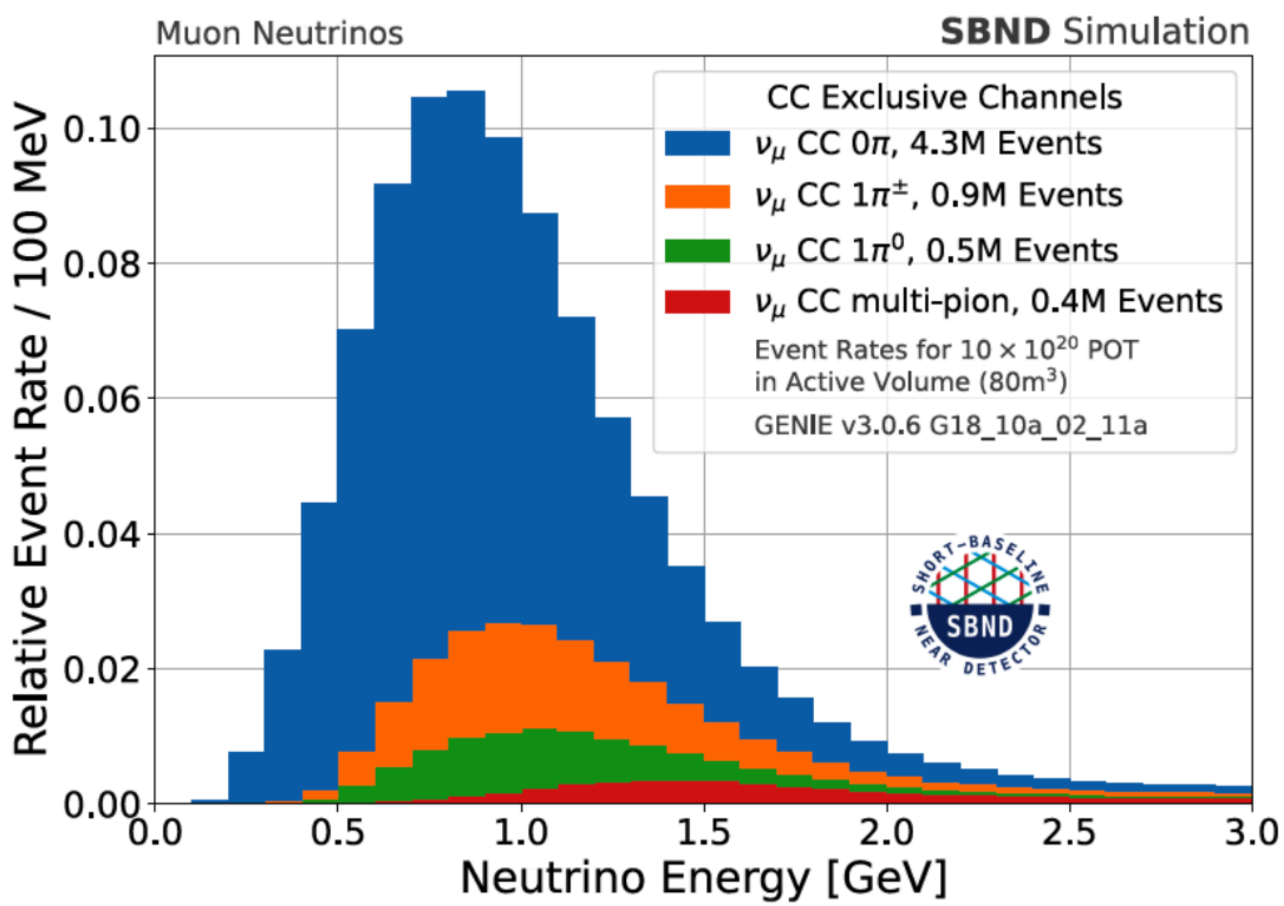
  - Every ~3 months, SBND will collect a dataset equivalent to the full MicroBooNE BNB five-year run
- SBND will record ~20–30x more neutrino–argon interactions than is currently available
- Large statistics, combined with LArTPC capabilities, will allow us to study different variables, exclusive and rare channels

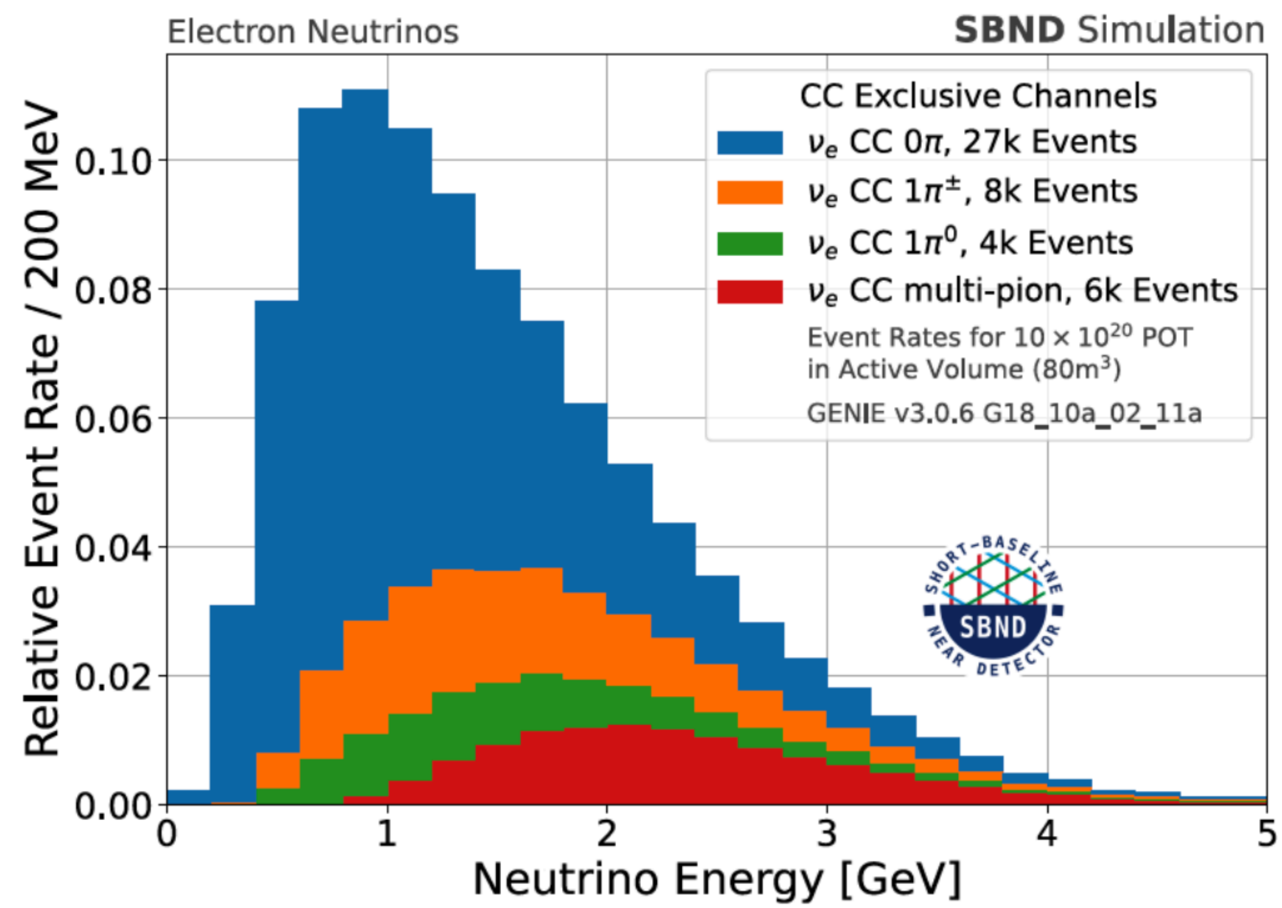
$\nu_\mu - ^{40}Ar$

2M ν_μ CC events in 1 year



$\nu_e - ^{40}Ar$

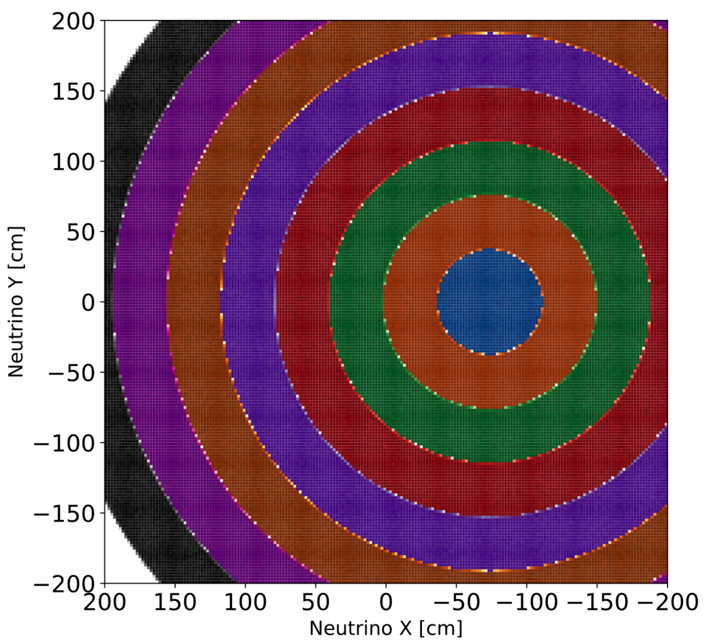
15k ν_e CC events in 1 year



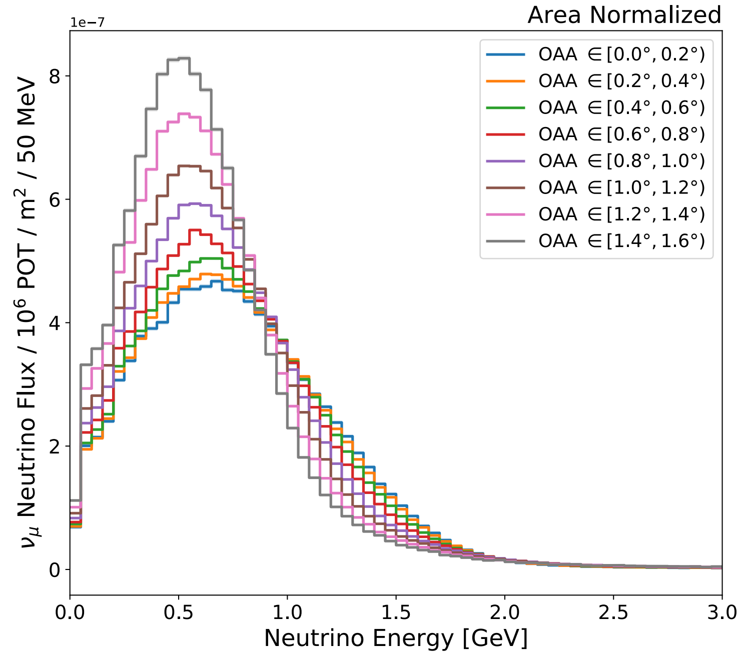
Neutrino Interactions in SBND

- **SBND-PRISM:**
  - Being close (110 m) to the neutrino source
  - Positioned offset relative to the beam center
  - SBND sees neutrinos from a range of off-axis angles (OAAs)
  - SBND-PRISM will allows studying energy dependent neutrino cross section measurement

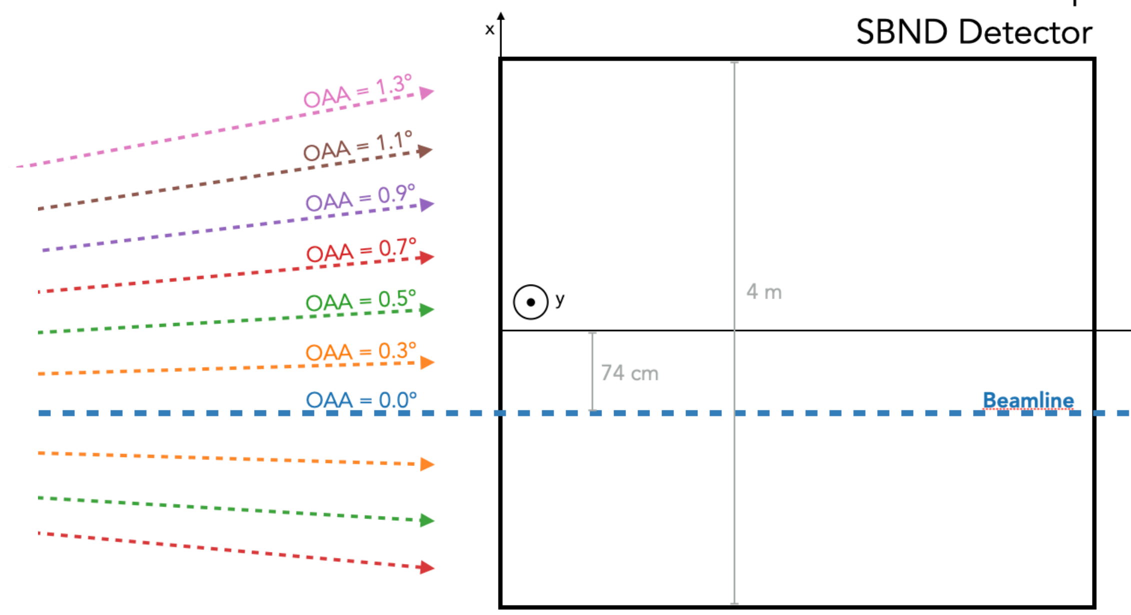
View from the beam direction
SBND Detector



ν_μ flux in each of the OAA regions



View from the top
SBND Detector



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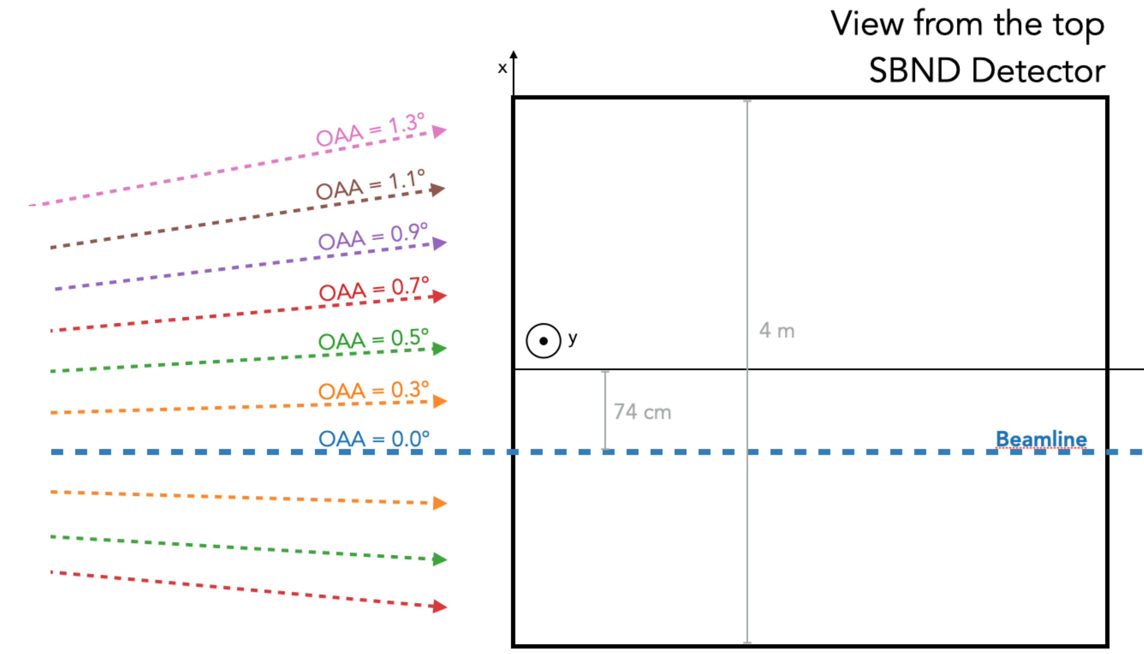

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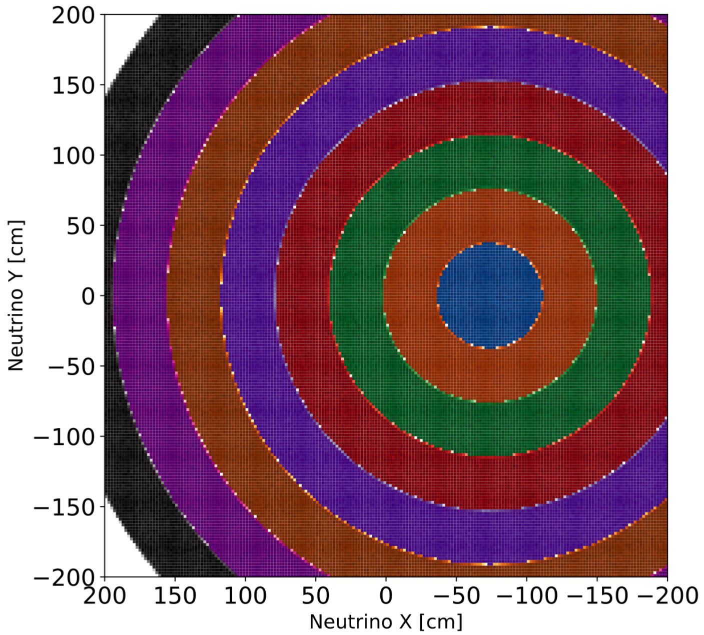

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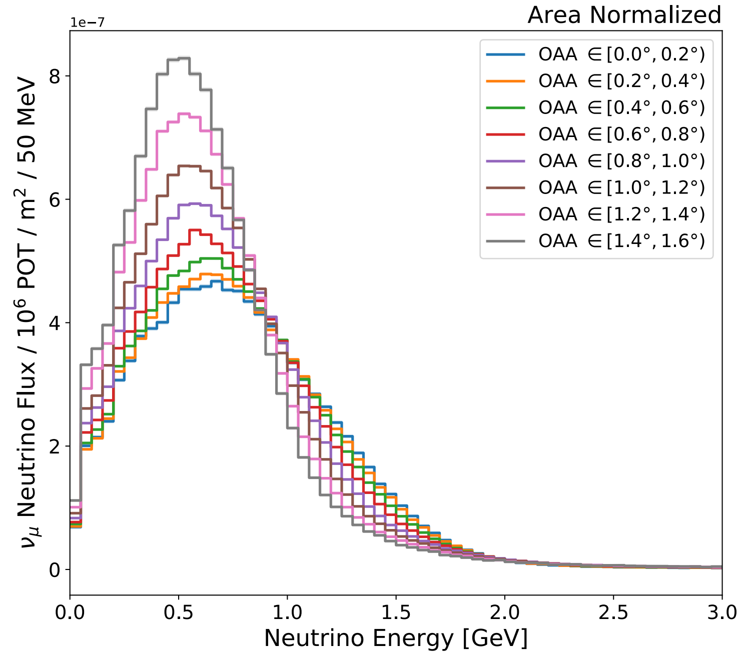
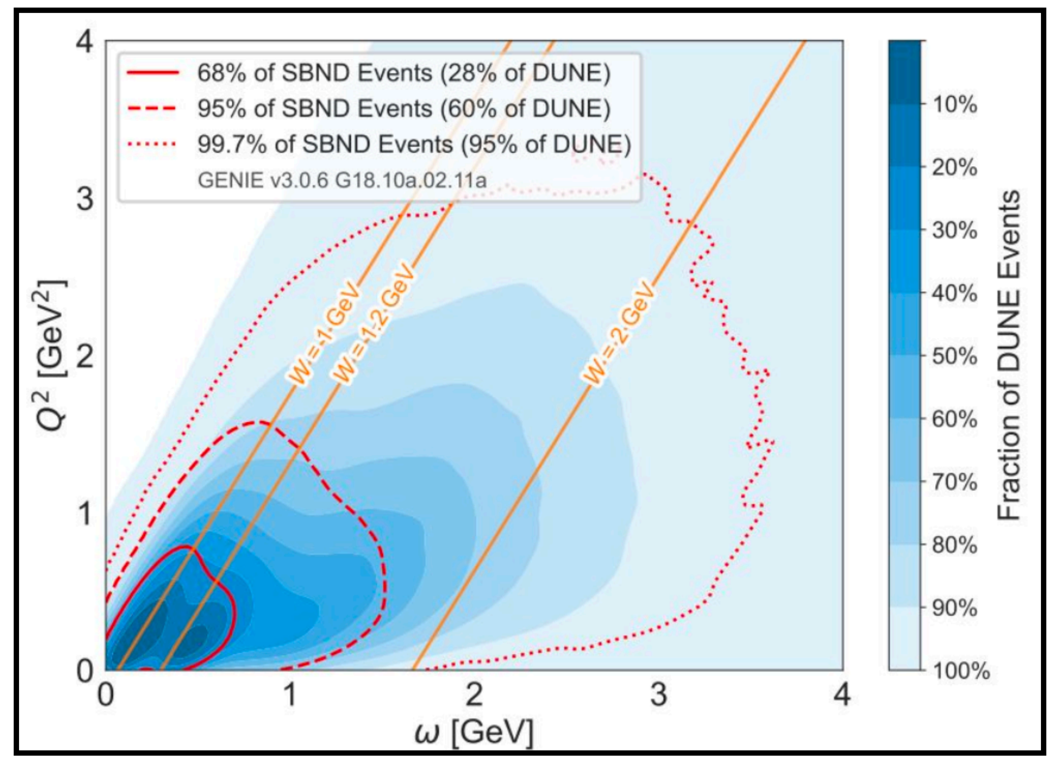


■ **SBND and DUNE:**

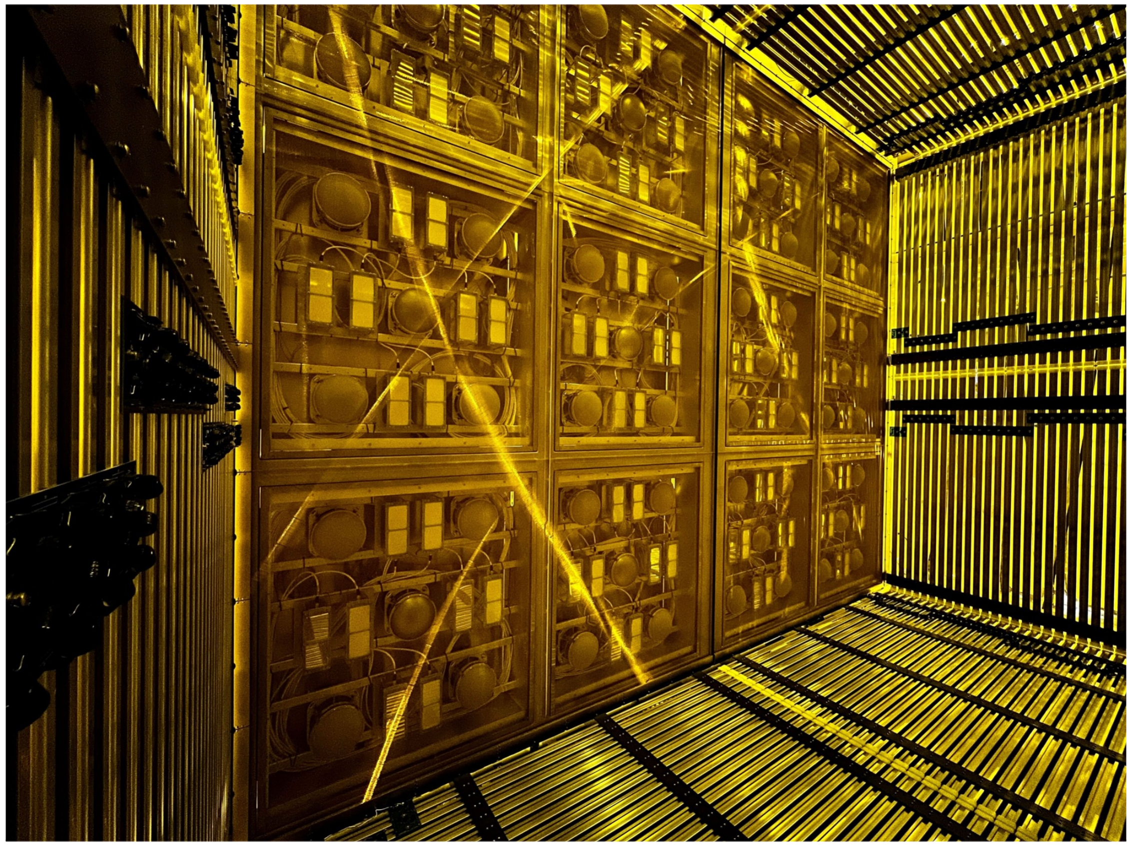
- SBND interactions will cover significant parts of kinematic phase space relevant for DUNE.
- SBND measurements can be used to constrain the same physics DUNE needs to know.



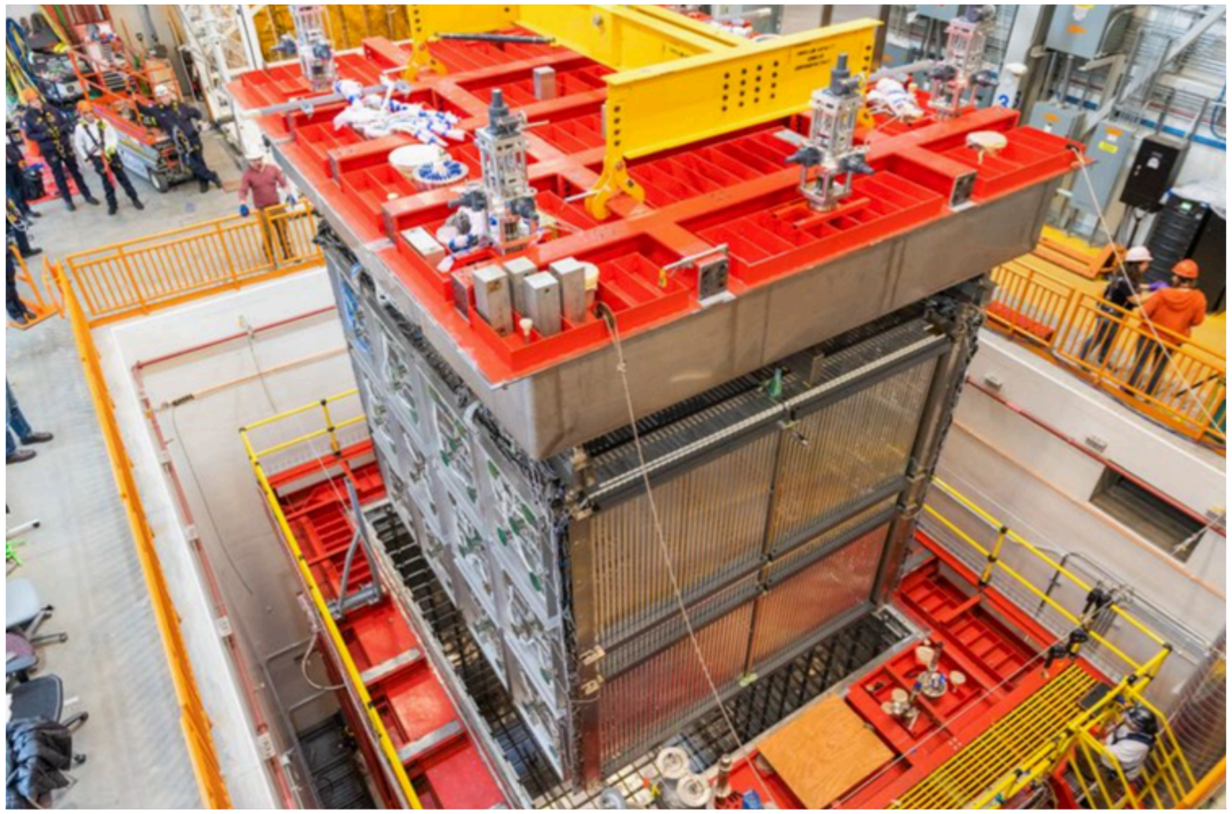
DUNE kinematic coverage is represented with the blue 2D histogram

SBND kinematic coverage is shown with 3 contours, representing 68%, 95%, and 99.7% of all SBND data.

SBND Status



- The SBND detector installation is completed. The operation is expected to start early in 2024.
- SBND will enable a generational advance in the study of neutrino-argon interactions in the GeV energy range
  - unprecedented statistics
  - unique detector capabilities (large photon detector coverage, low thresholds, ns timing, …)
  - multiple correlated fluxes (PRISM)
- Stay Tuned!



Thank you!

262 Total Collaborators

210 Scientific Collaborators
(faculty/scientists, postdocs, PhD students)

40 Institutions

5 Brazilian Universities

CERN

1 Spanish University, 1 National Laboratory

1 Swiss University

8 UK Universities, 1 National Laboratory

18 US Universities, 4 National Laboratories