Fermilab

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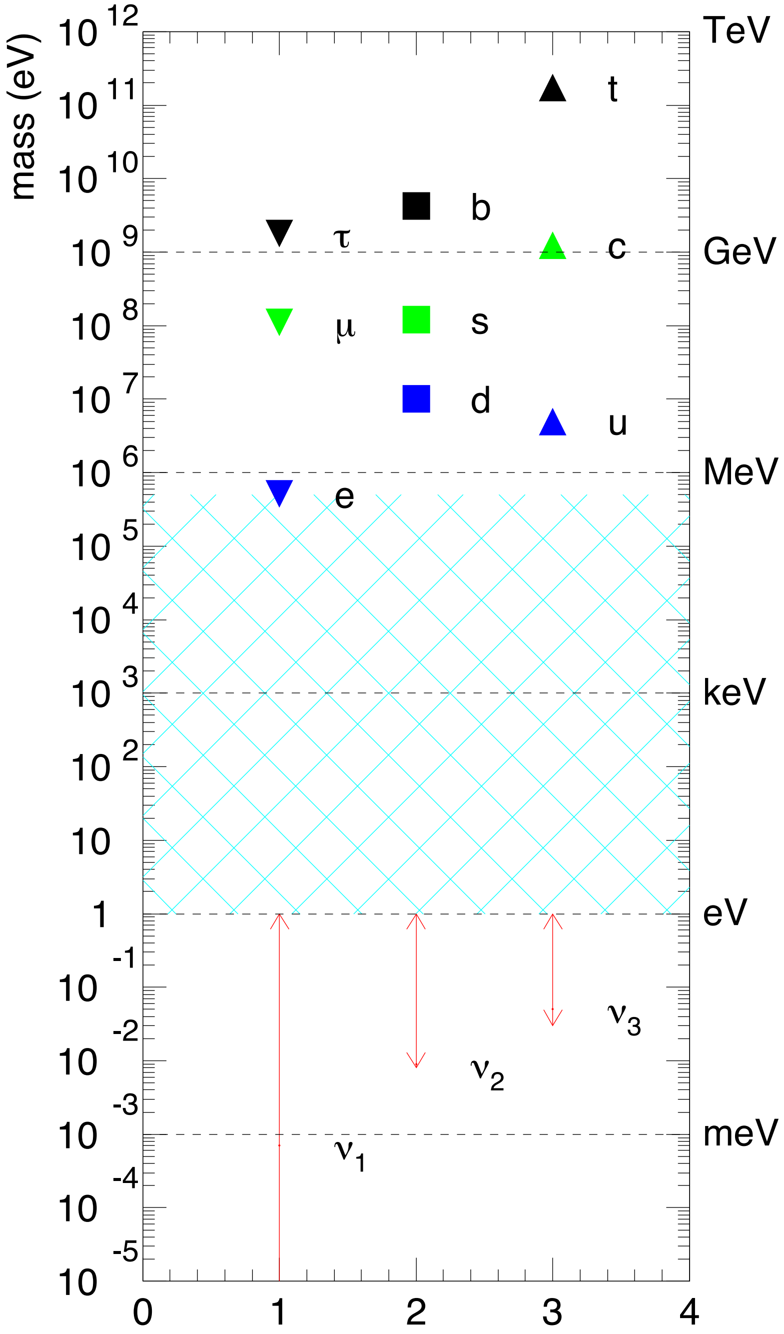
Neutrino Physics

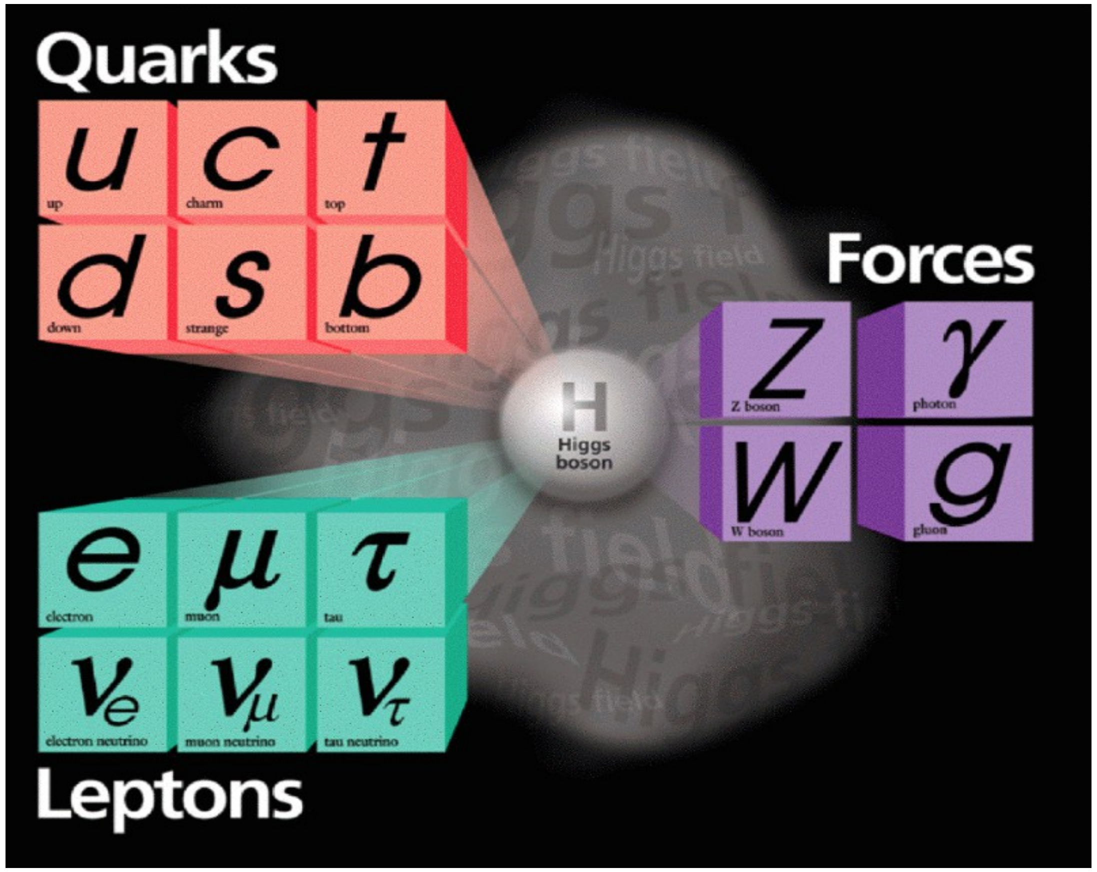
Minerba Betancourt, Fermilab

01 August 2024

Is the standard model complete?



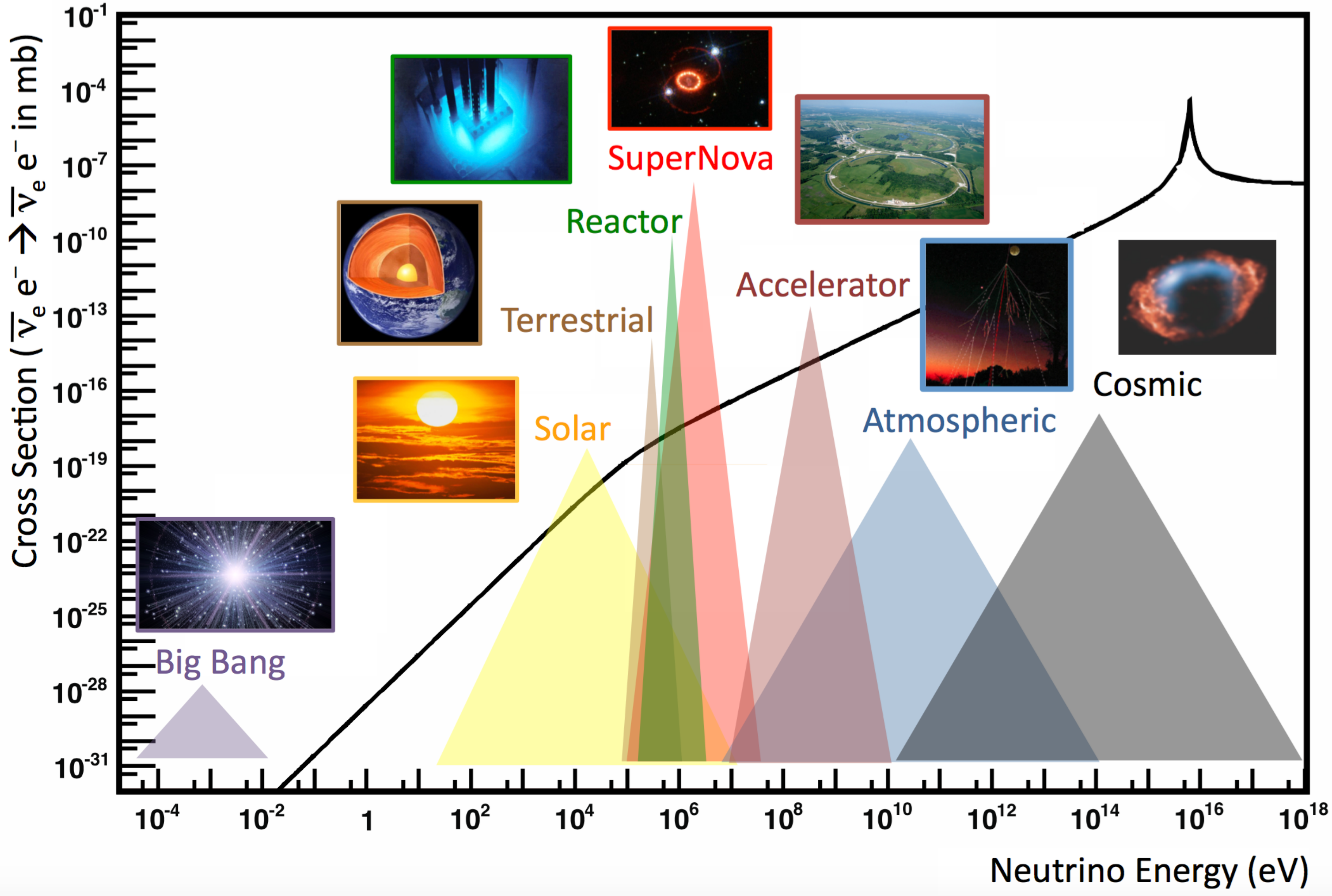
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U^* \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$



- Why is there such large gap between neutrino masses and quark masses?
- Why do quarks and leptons exhibit different behavior?
- What is the absolute mass of neutrino?

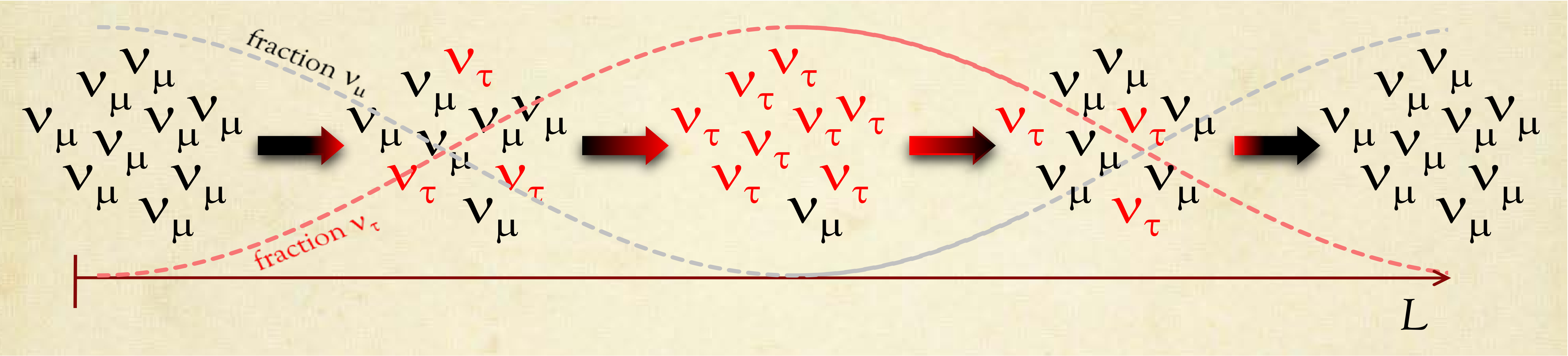
Where do neutrinos come from?

- Neutrinos are the most common matter particles in the universe



- Reviewing the neutrino interactions relevant to neutrino oscillation at the few GeV region

Neutrinos Oscillate!



- Neutrinos have mass and weak flavor states

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

- There is a non-zero probability of detecting a different neutrino flavor than that produced at the source

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m_{23}{}^2 L}{E_\nu}\right)$$

- The physics parameters are: the mixing angle and one mass squared difference

What do we know?

- The probability of a neutrino ν_μ transforming into a ν_e

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U^* \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\sum_j U_{\beta j} e^{-i\frac{\Delta m_j^2 L}{2E}} U_{\alpha j}|^2$$

- where the mixing matrix has 3 mixing angles and one phase

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & cos\theta_{23} & sin\theta_{23}\\ 0 & -sin\theta_{23} & cos\theta_{23}\end{pmatrix}\begin{pmatrix}cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13}\end{pmatrix}\begin{pmatrix}cos\theta_{12} & sin\theta_{12} & 0\\ -sin\theta_{12} & cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

What do we know?

- The probability of a neutrino ν_μ transforming into a ν_e

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^* \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = |\sum_j U_{\beta j} e^{-i\frac{\Delta m_j^2 L}{2E}} U_{\alpha j}|^2$$

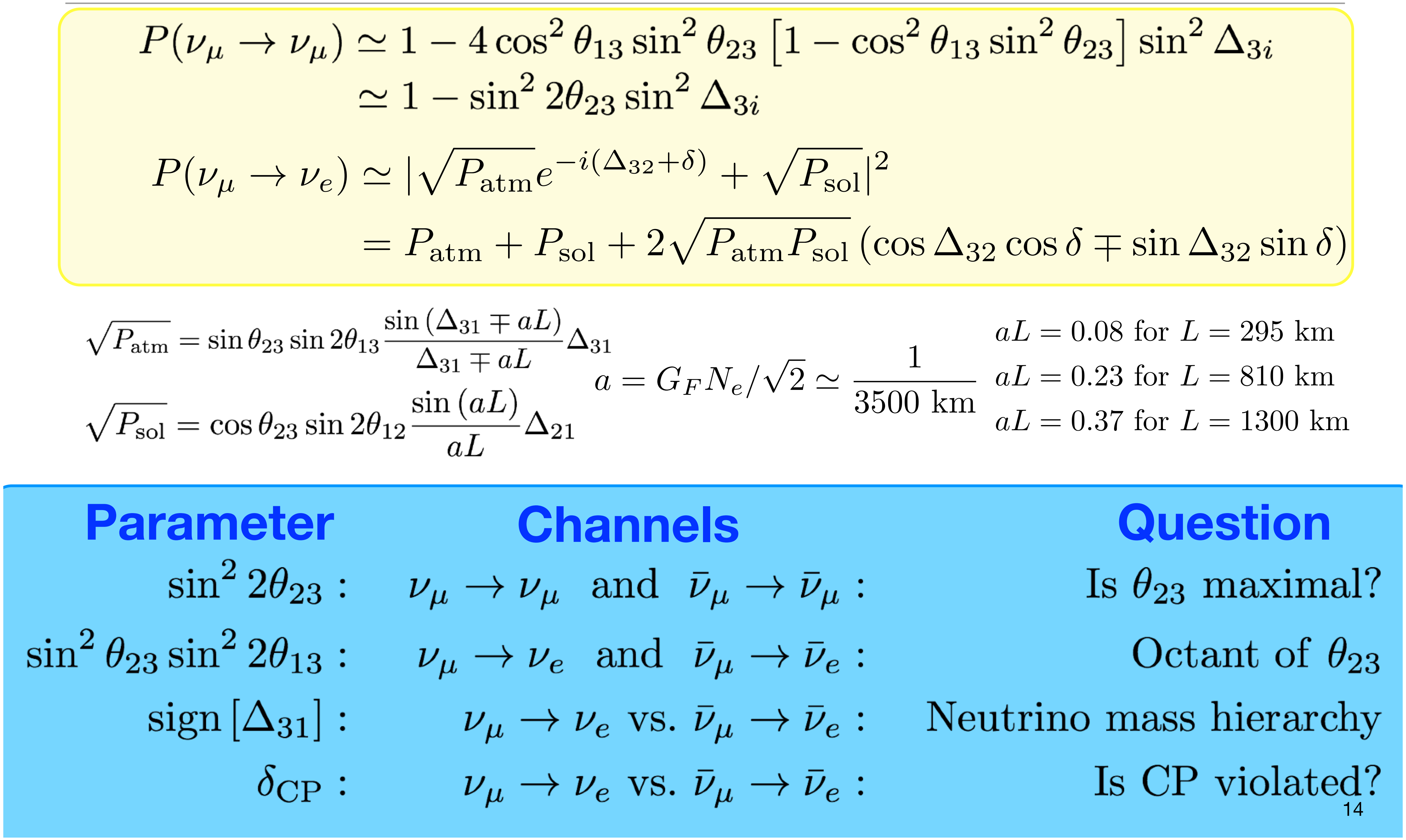
- where the mixing matrix has 3 mixing angles and one phase

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$\lvert\Delta m_{32}^2\rvert \equiv \lvert m_3^2 - m_2^2\rvert$ $\simeq 2 \times 10^{-3}\ \mathrm{eV}^2$	$\Delta m_{31}^2 \simeq \Delta m_{32}^2$	$\Delta m_{21}^2 \simeq 8 \times 10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \longrightarrow \nu_\mu$ $\nu_\mu \longrightarrow \nu_\tau$	$\nu_e \longrightarrow \nu_e$ $\nu_\mu \longrightarrow \nu_e$	$\nu_e \longrightarrow \nu_e$ $\nu_e \longrightarrow \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor

Neutrino Oscillation at Long Baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]



$$\begin{aligned} P(\nu_\mu \to \nu_\mu) &\simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left[1 - \cos^2\theta_{13}\sin^2\theta_{23}\right]\sin^2\Delta_{3i} \\ &\simeq 1 - \sin^2 2\theta_{23}\sin^2\Delta_{3i} \end{aligned}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq |\sqrt{P_{\rm atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\rm sol}}|^2 \\ &= P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm}P_{\rm sol}}\left(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta\right) \end{aligned}$$

$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL}\Delta_{31}$$

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}$$

$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500\ \text{km}}$$

$aL = 0.08$ for $L = 295$ km

$aL = 0.23$ for $L = 810$ km

$aL = 0.37$ for $L = 1300$ km

Parameter	Channels	Question
$\sin^2 2\theta_{23}$:	$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$:	Is θ_{23} maximal?
$\sin^2\theta_{23}\sin^2 2\theta_{13}$:	$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$:	Octant of θ_{23}
$\text{sign}\left[\Delta_{31}\right]$:	$\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$:	Neutrino mass hierarchy
$\delta_{\rm CP}$:	$\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$:	Is CP violated?

Mark Messier, Neutrino 2023 summer school

The Atmospheric Neutrino Anomaly

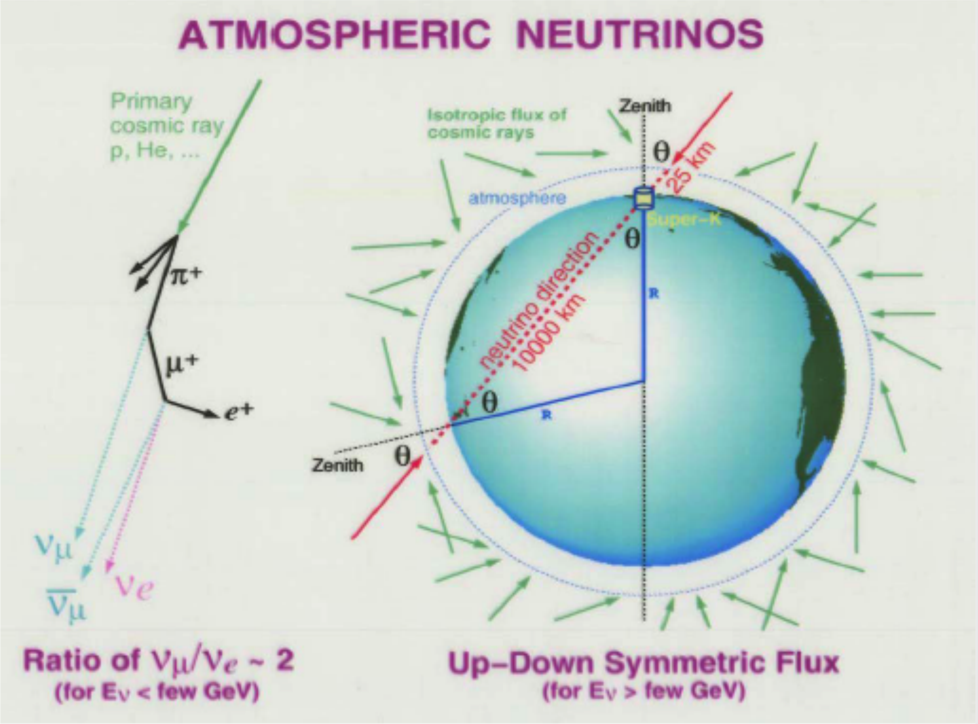
- Cosmic rays hit the earth isotropically
- People expected:

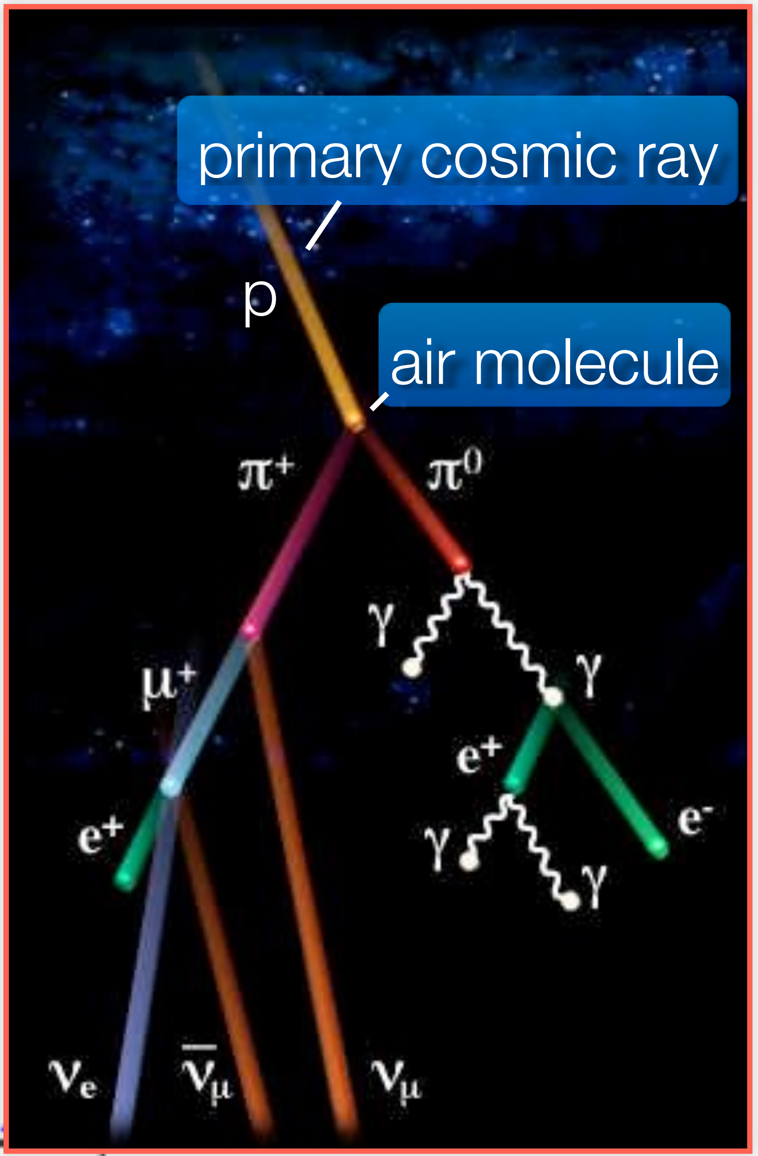
$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 1$$

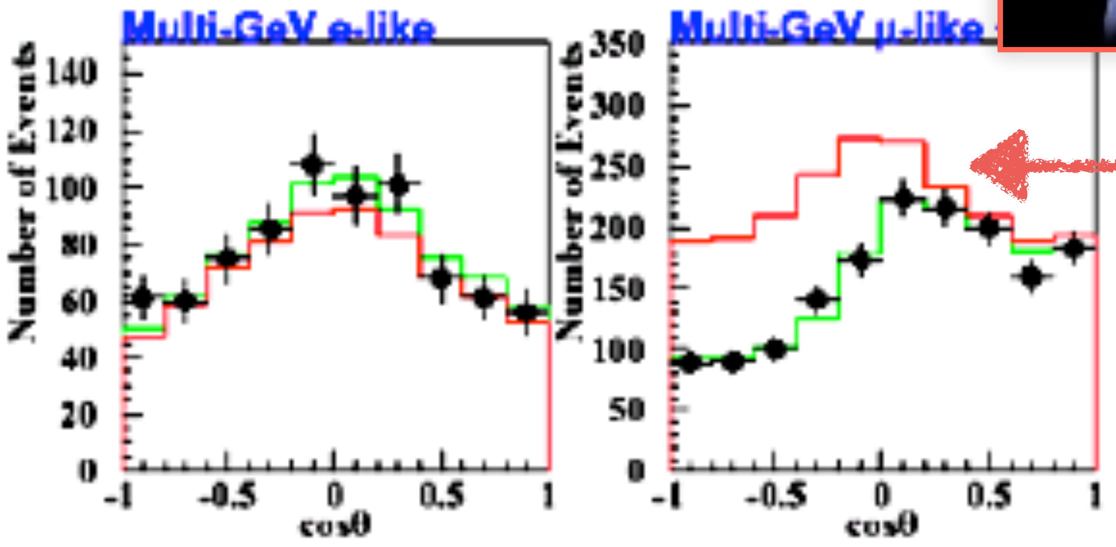
- However, Super-Kamiokande found

$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 0.54 \pm 0.04$$

- In 1998 Super-Kamionkande announces the discovery of neutrino oscillation





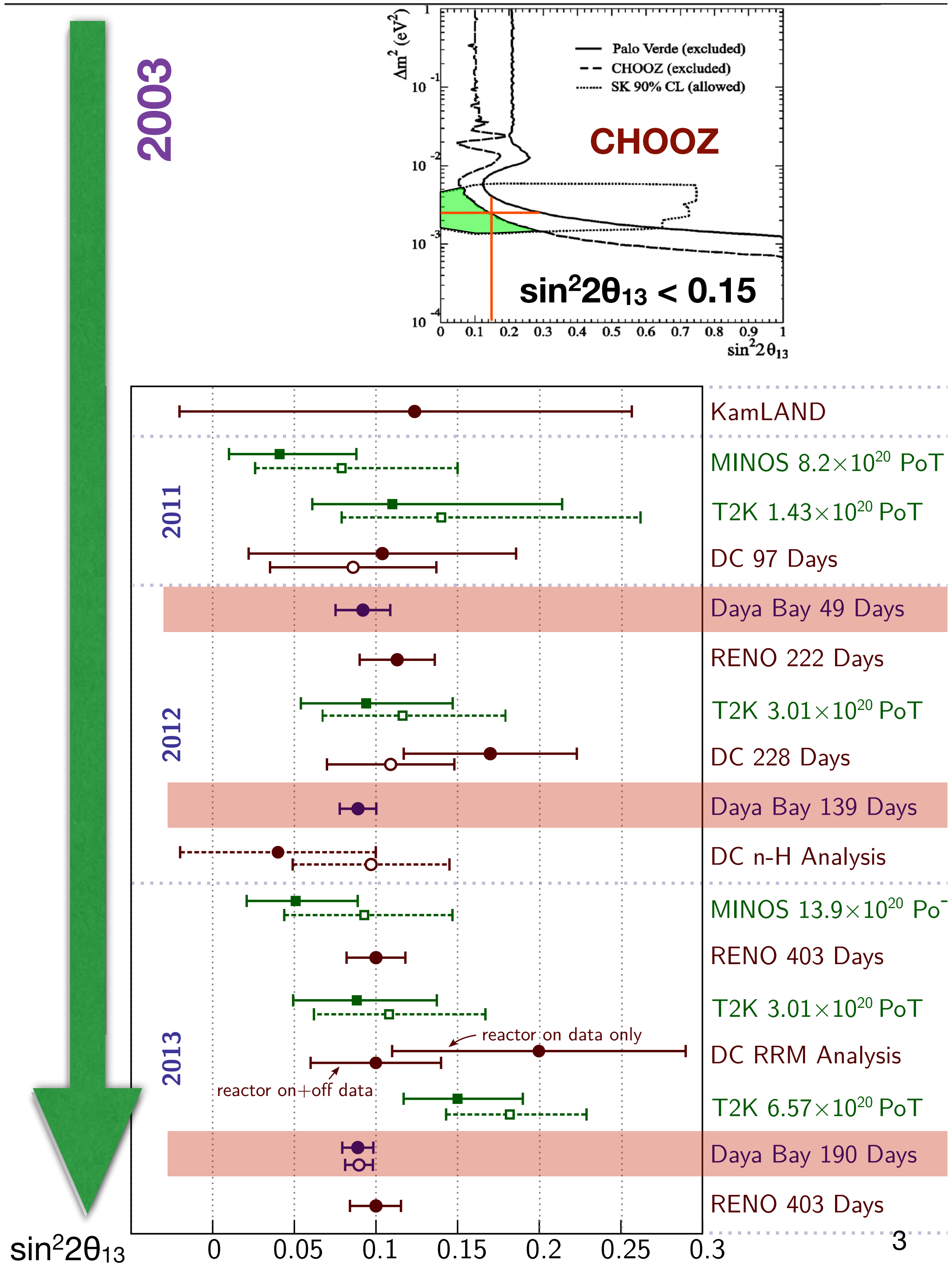


Upward-going muon neutrinos depleted

Field moves quickly

- Around 2003 neutrino physicists searched for the parameter $\sin^2\theta_{13}$
- The parameter $\sin^2\theta_{13}$ has now been measured
- In 2012 Daya Bay measured $\sin^2\theta_{13}$ for the first time
- Today is best known angle!

$$React. \rightarrow \sin^2\theta_{13}(4.7\%)$$



Remaining Questions

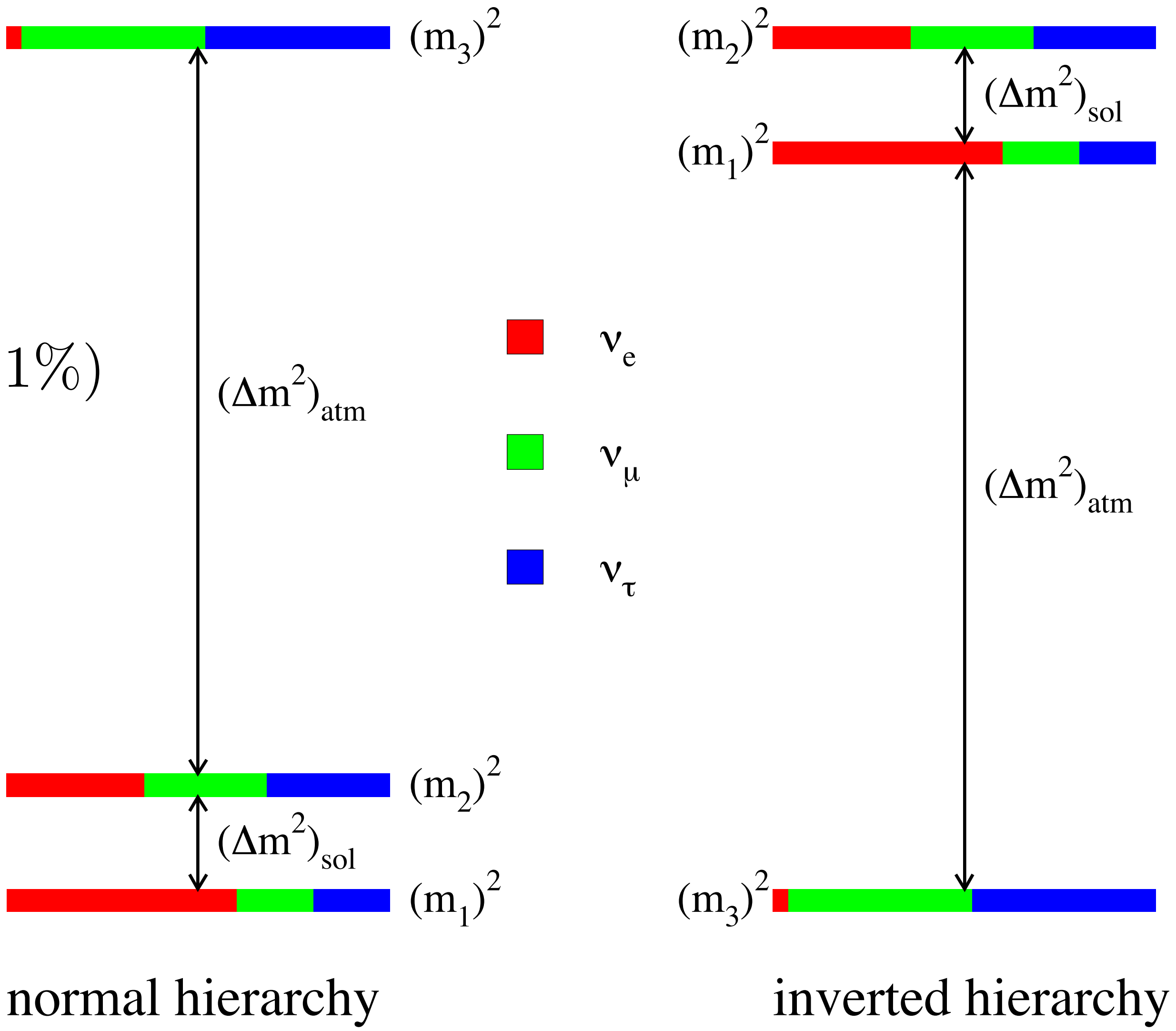
- Is there CP violation in the lepton sector?
  - May explain matter-antimatter asymmetry
- What is the mass hierarchy? (sign of Δm^2_{32})
  - Important to be able to understand the reach of experiments that study whether neutrinos are their own antiparticle or not
- Is θ_{23} maximal?
- Is there a fourth "sterile neutrino"?

$$\Delta m^2_{23} = (2.510 \pm 0.027) \times 10^{-3}\ \mathrm{eV}^2\ (\pm 1.1\%)$$

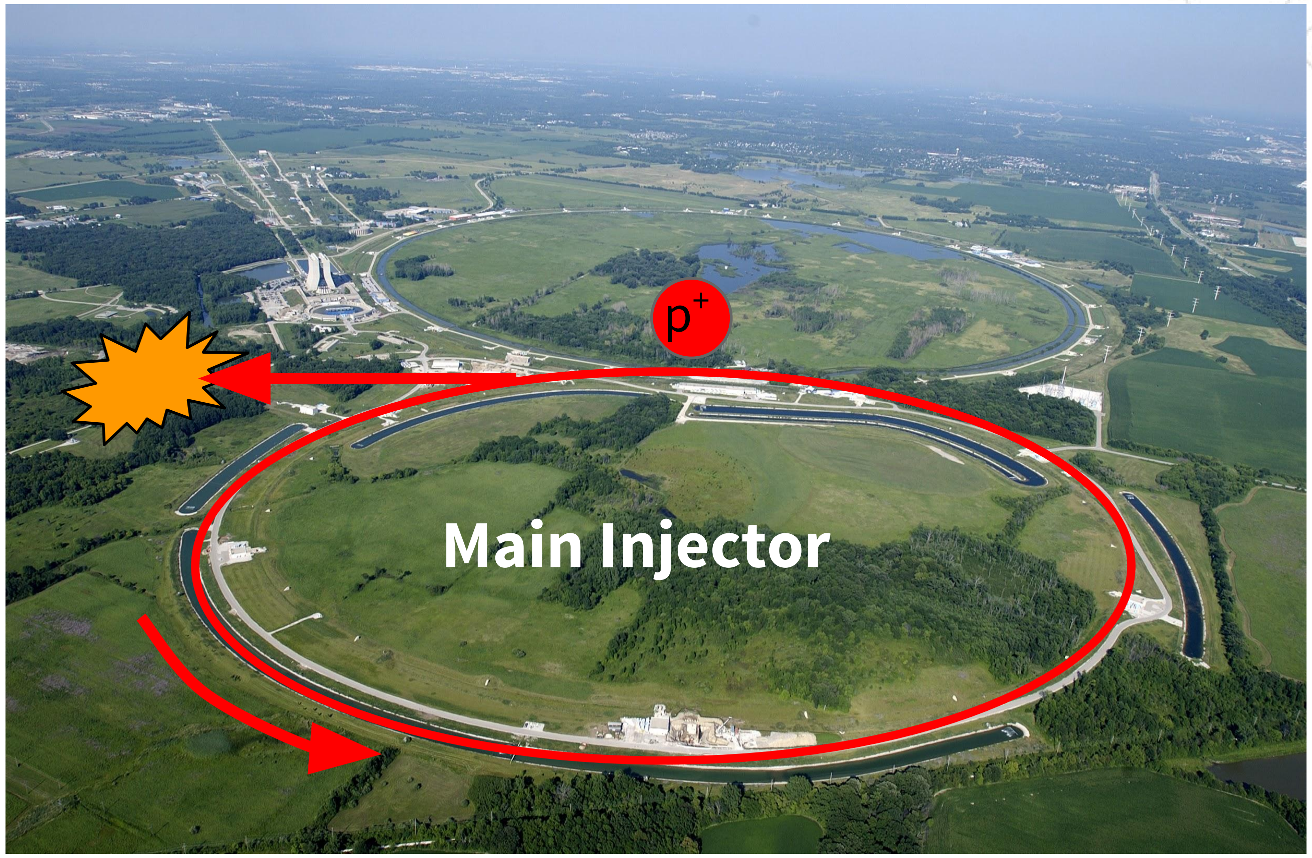
$$40^\circ < \theta_{23} < 52^\circ$$

$$\Delta m^2_{12} = (7.42 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2\ (\pm 2.8\%)$$

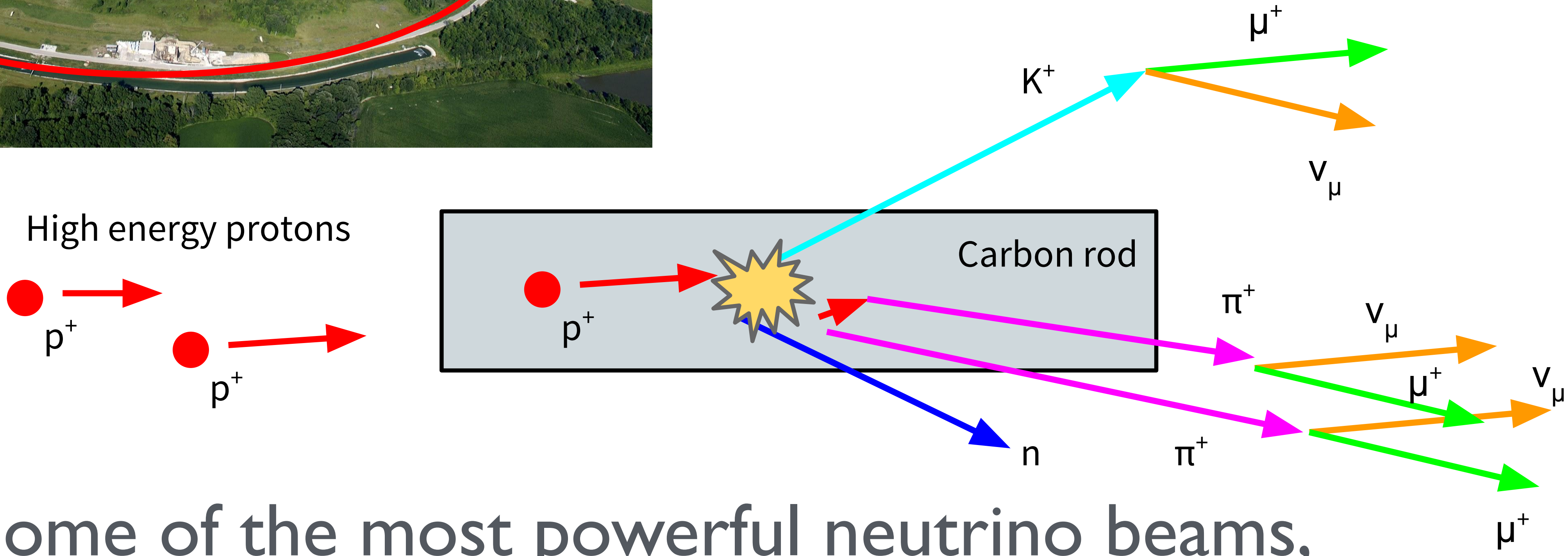
$$31^\circ < \theta_{12} < 36^\circ$$



How to make a neutrino beam



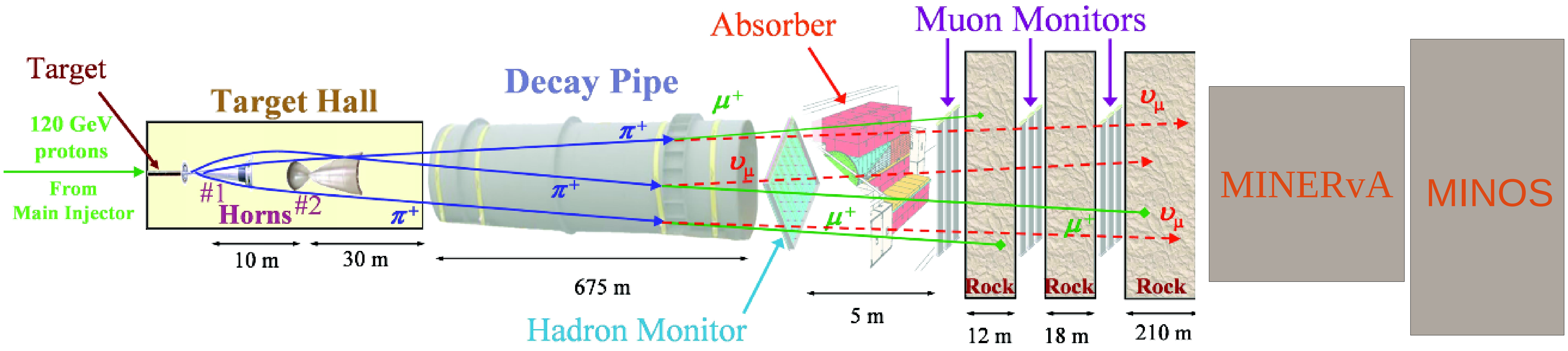
- Protons hit carbon
- Charged pions are produced
- Pions and kaons decay to neutrinos



Fermilab: home of the most powerful neutrino beams, two neutrino beams: NuMI and Booster

Neutrinos From Accelerators

- A beam of protons interact with a target and produce pions and kaons

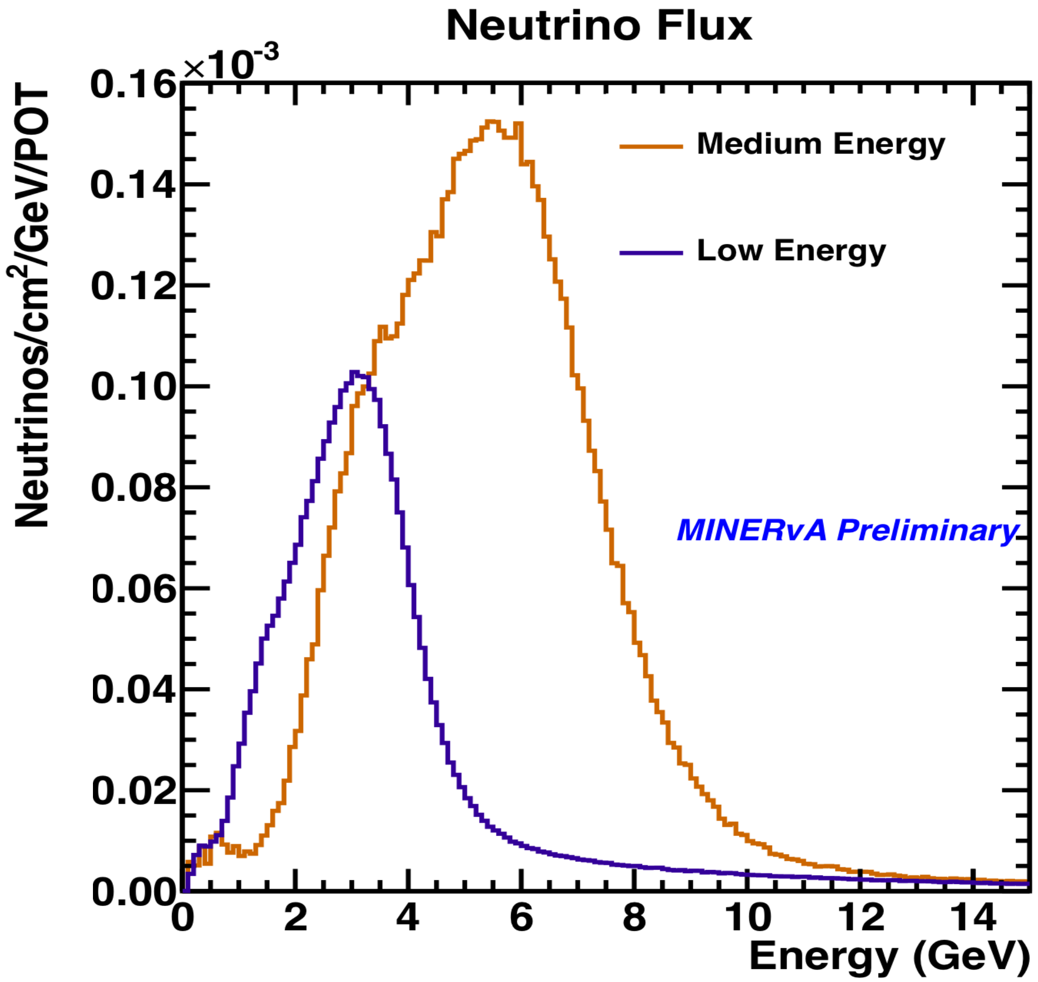


- Focusing system (2 horns, with current, emitting B field)
- Decay region (large pipe, filled with helium)
- Monitors and absorbers
- Neutrino beam produces mainly ν_μ and small component of ν_e

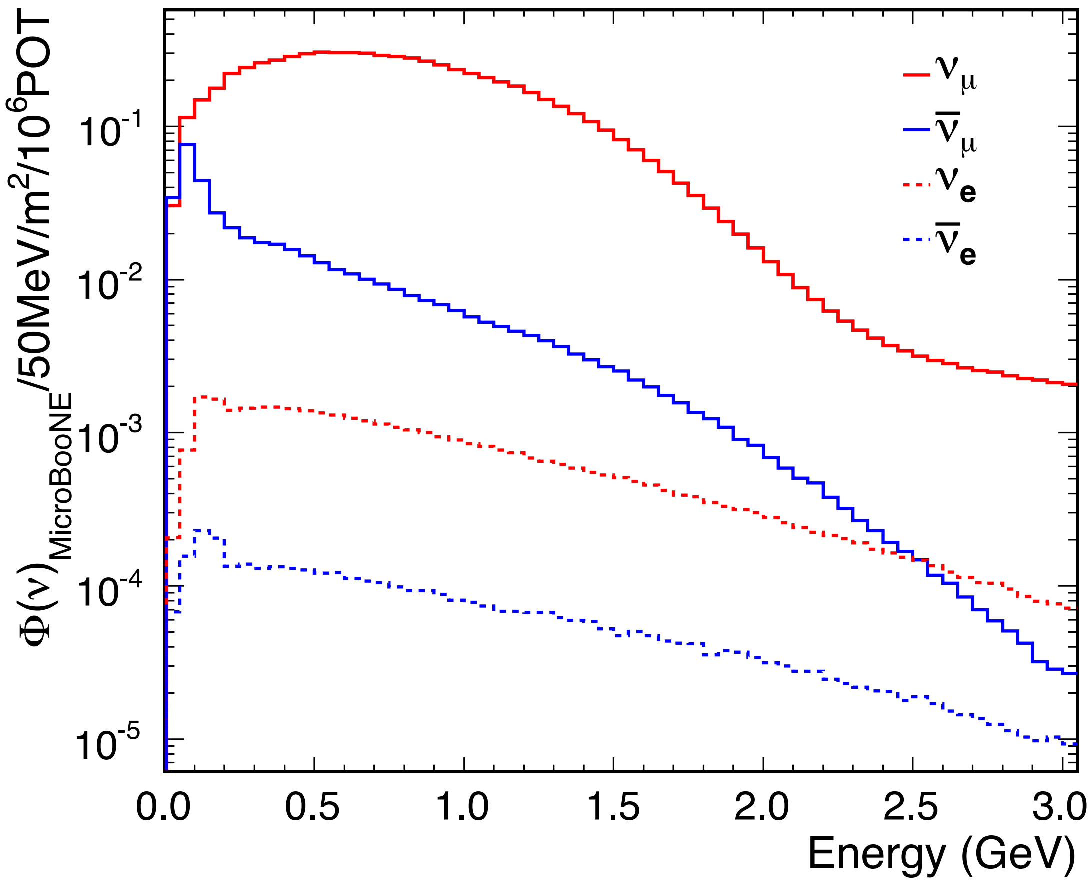
Neutrino Energy Spectrum

- The target and second magnetic horn can be moved relative to the first horn to produce different energy spectra
- This allows a study of neutrino interaction physics across a broad neutrino energy range
- Neutrino oscillation experiments use interactions in the near and far detectors to study oscillation physics

Neutrinos from NuMI



Neutrinos from Booster



Neutrino Oscillation Program at Fermilab

Long-BaseLine Neutrino Oscillation Program

Present

2032

CP violation?
Mass hierarchy?

NOvA

DUNE

Cross Section Experiment

Collected data for several years

MINERvA

Short-BaseLine Neutrino Oscillation Program

Sterile Neutrinos?

Present

2022

2024

MiNiBooNE

MicroBooNE

ICARUS

SBND

Long-baseline Experiments: What can we learn?

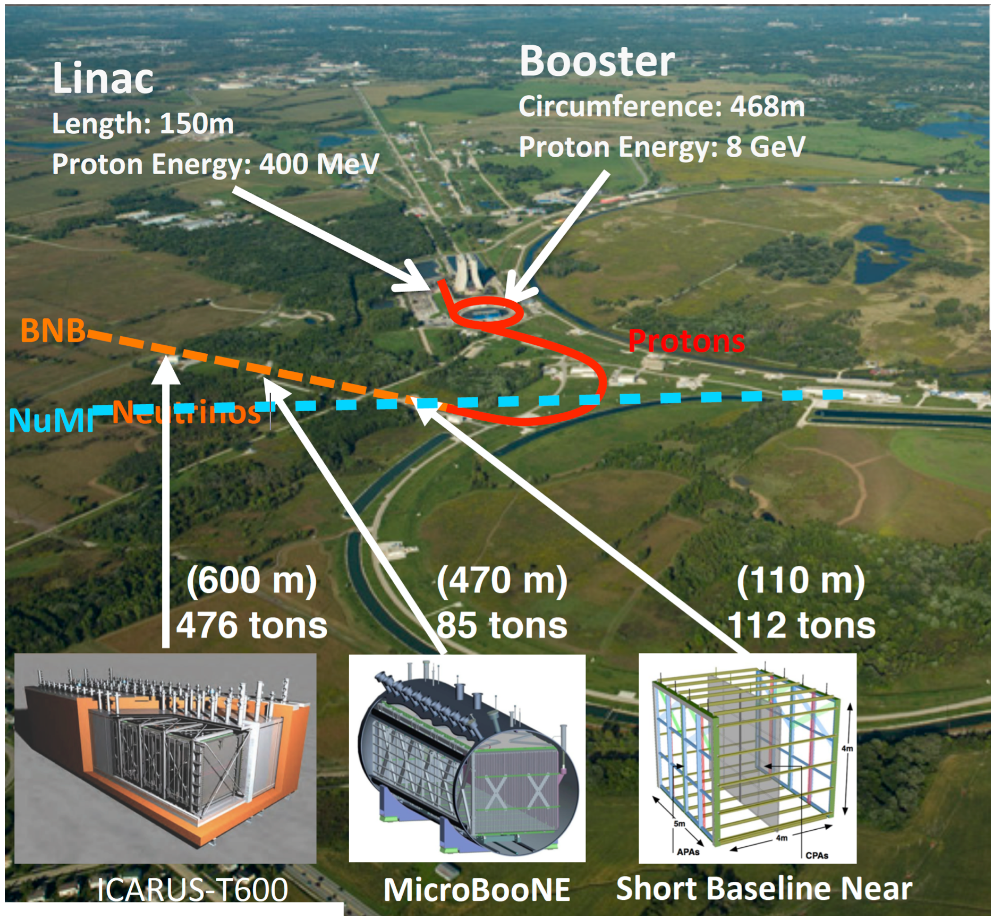
- Use a high intensity beam of neutrinos from Fermilab
- Construct detectors at far locations: MINOS+ at 735 km (ended data-taking), NOvA at 810 km (taking data) and DUNE at 1300 km (in design)

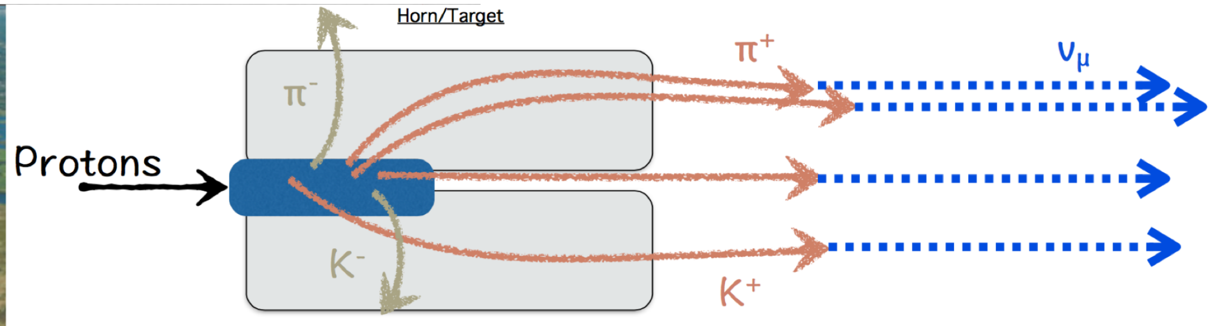
$$P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e] \ ?$$

also, T2K in Asia T2K

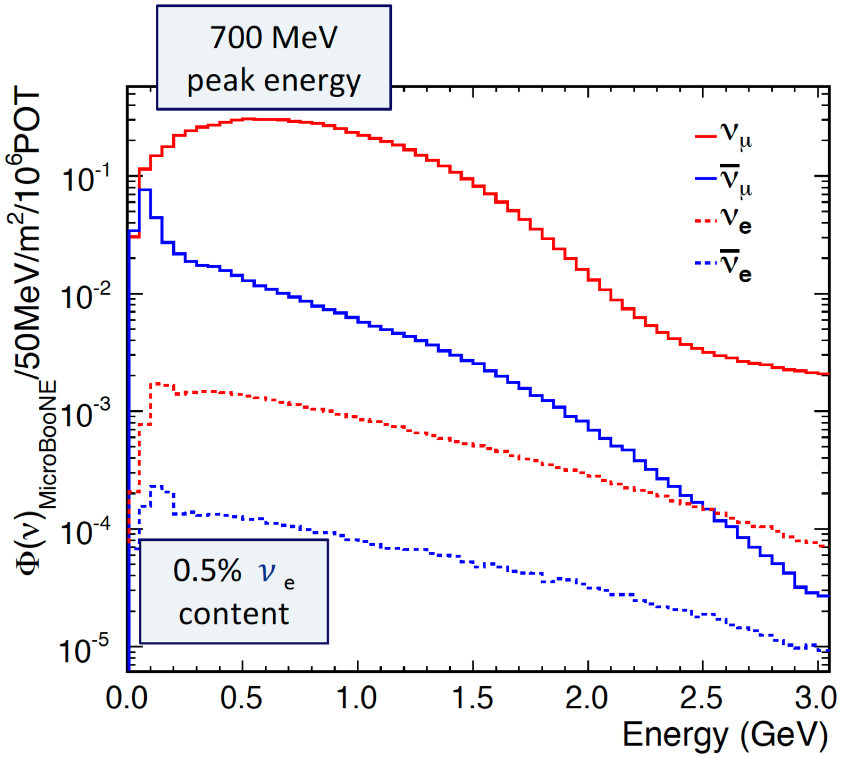
Short-baseline Experiments

- Three argon Time Projection Chambers (TPC) detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations
  - Measuring both appearance and disappearance channels

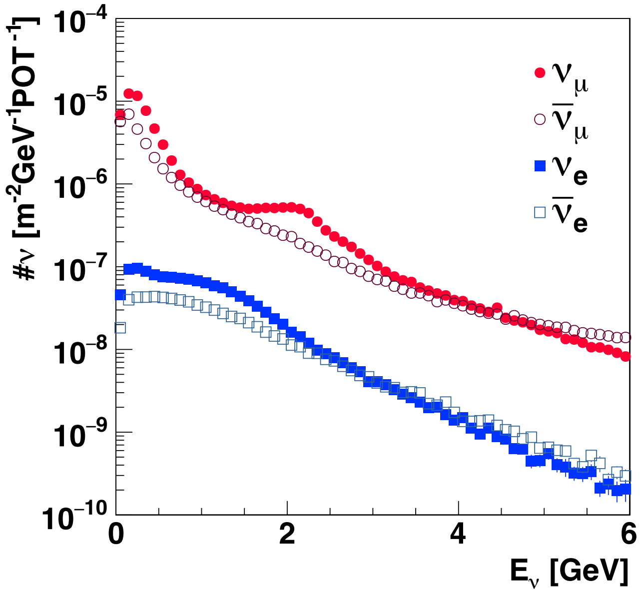




Neutrinos from Booster



Neutrinos from NuMI

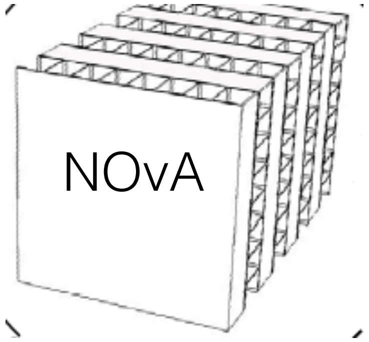


All Accelerator-Based Experiments at Fermilab

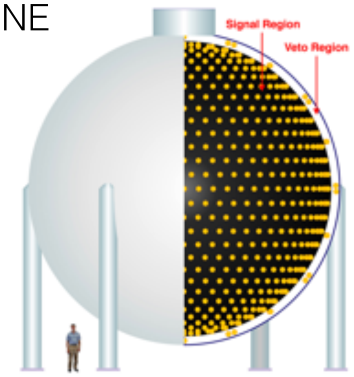
- We are using heavy targets for oscillation experiments, such as carbon and liquid argon
- Using heavy targets involves modeling nuclear effects
- We need to model nuclear effects on a range of nuclei

Carbon

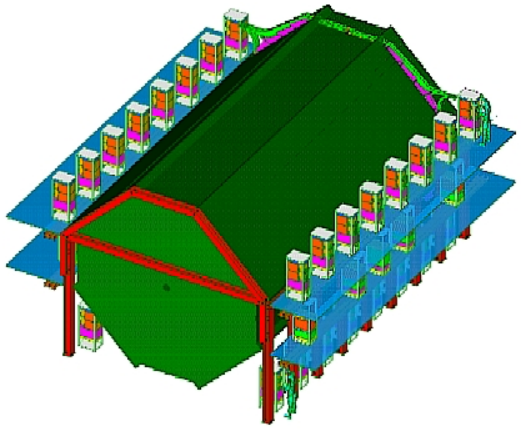
14Kton



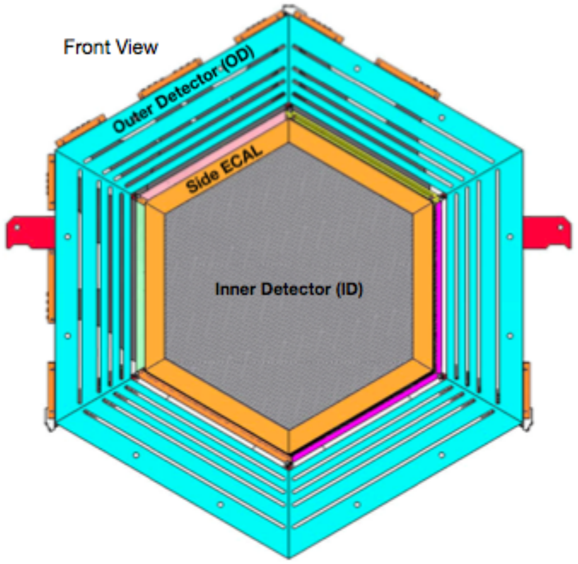
MiniBooNE



MINOS



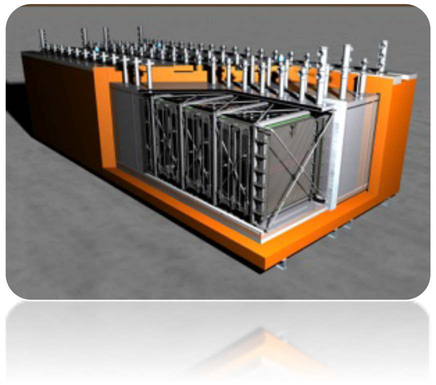
MINERvA



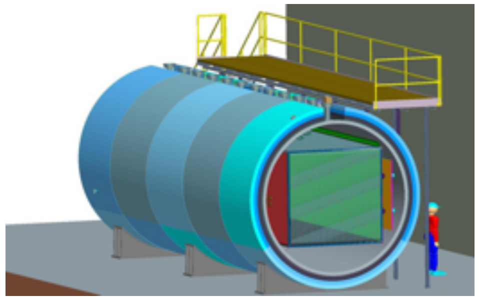
Carbon, iron, lead, helium, water

Liquid Argon

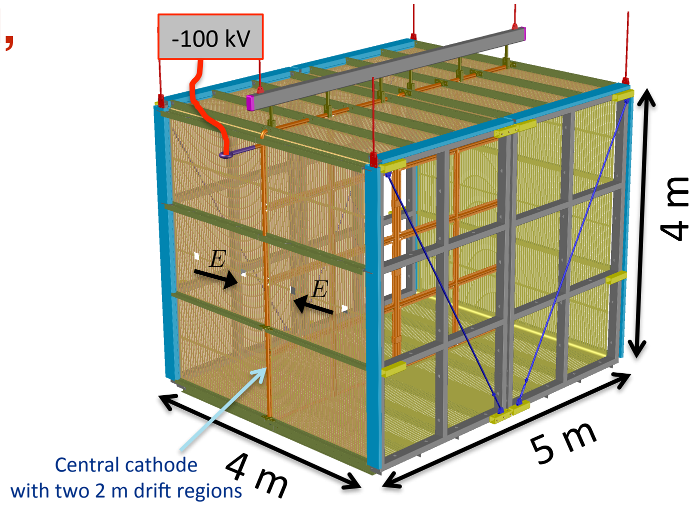
ICARUS



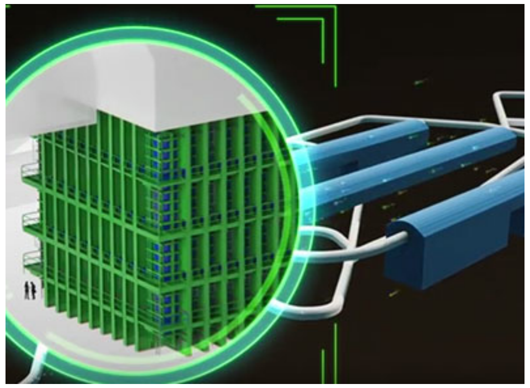
MicroBooNE



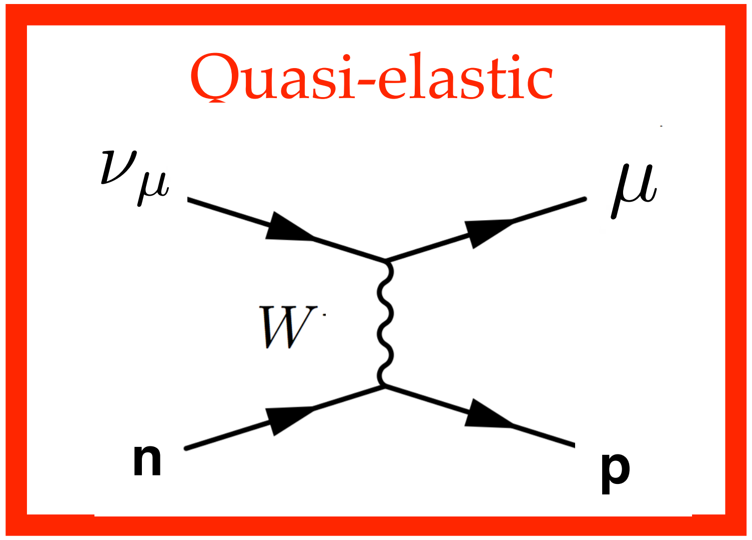
SBND



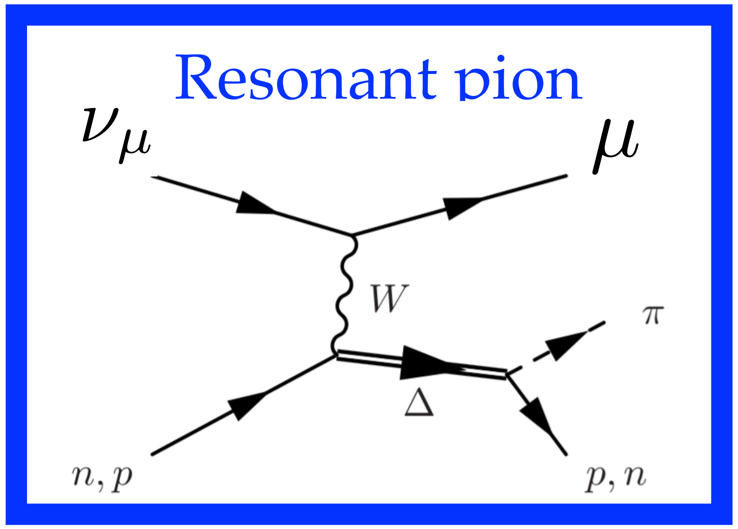
DUNE **40Kton**



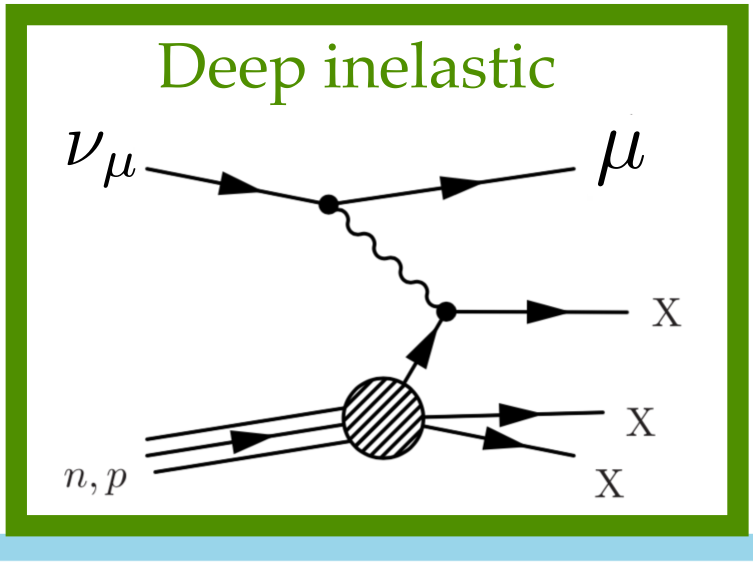
Charged Current Interactions


Quasi-elastic

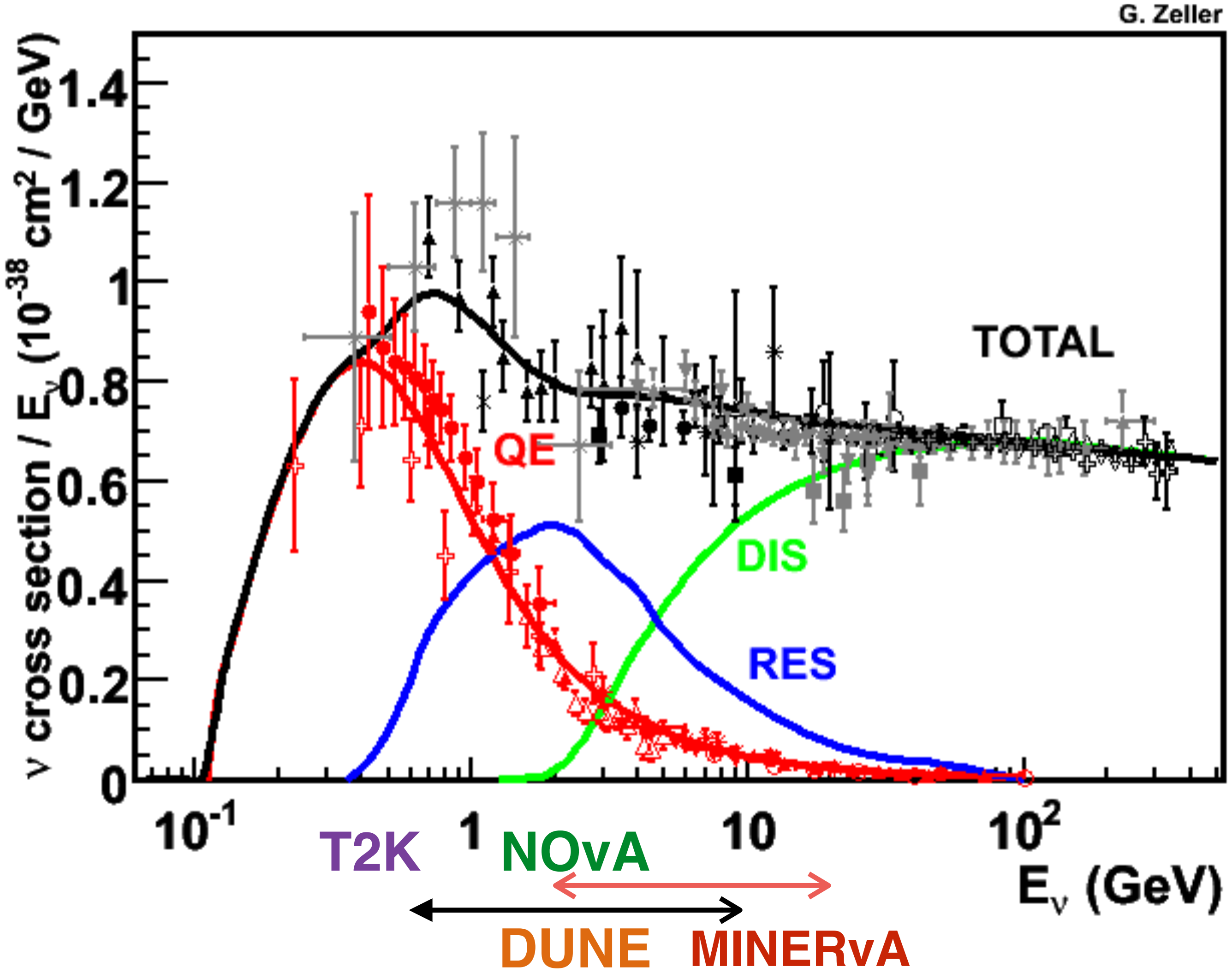
QE


Resonant pion

RES


Deep inelastic

DIS



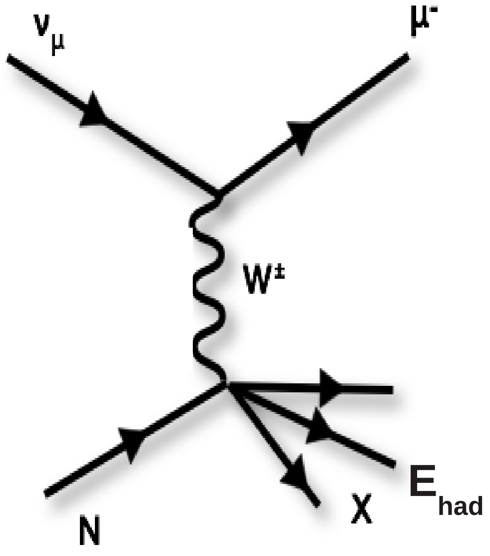
J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

In More Detail

- Oscillation probability depends on neutrino energy E_ν
- We need to reconstruct the neutrino energy precisely

$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{E_\nu})$$

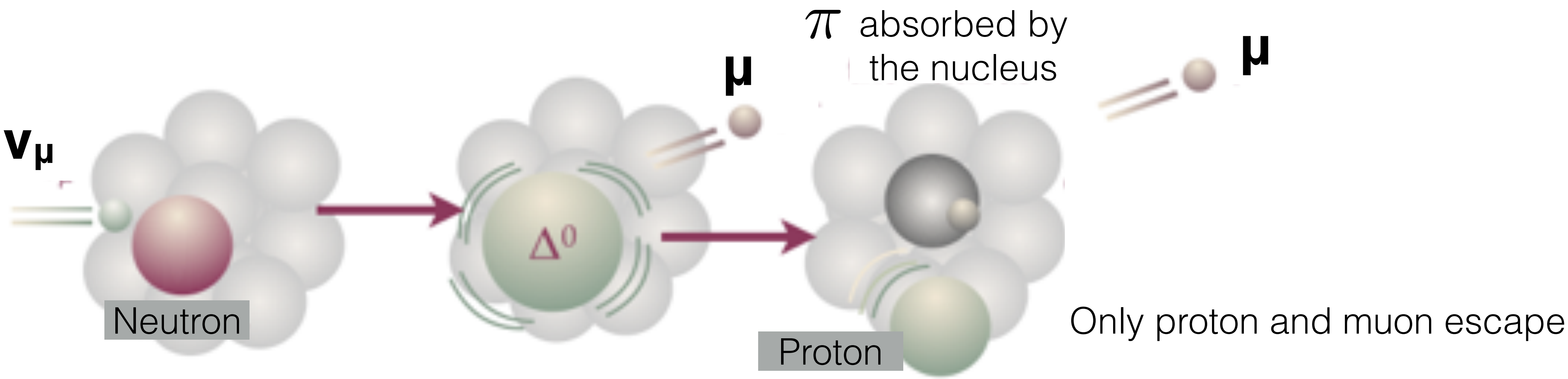
- Neutrino energy reconstruction is obtained using the final state particles of neutrino-nucleus interaction
  - Fully active experiments reconstruct the energy using: $E_\nu = E_{lepton}$+hadron



- Nuclear effects modify the kinematics of the particles and the reconstruction of the neutrino energy

Example of Nuclear Effects (Final State Interaction)

- Final state interaction (FSI):
  - Due to final state interactions, particles can interact with nucleons and pions can be absorbed before exiting the nucleus and other nucleons get knocked out

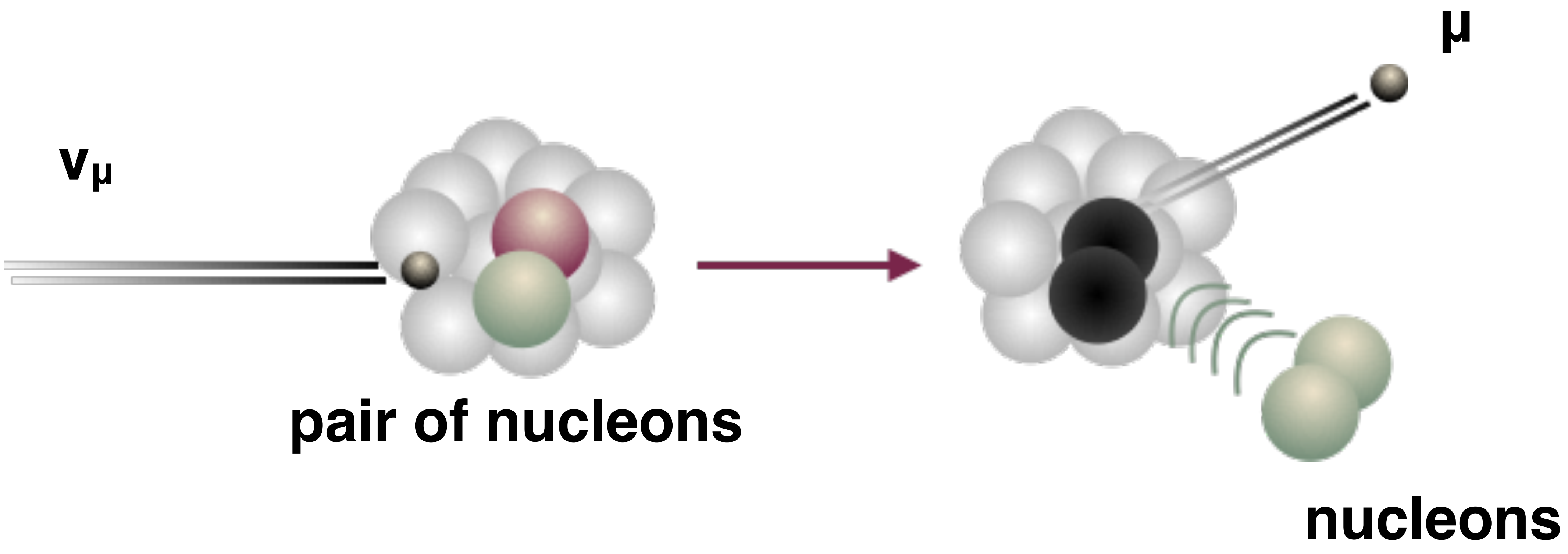


Start as a RES interaction, the pion is absorbed and the interaction looks QE like in our detector

- Nuclear effects modify the true/reco neutrino energy relationship and final-state particle kinematics
- Pion absorption is twice as big in Argon as it is in Carbon!

Example of Nuclear Effects (multi-nucleon interaction)

- Nuclear effects modify the neutrino energy, for example multi-nucleon interactions

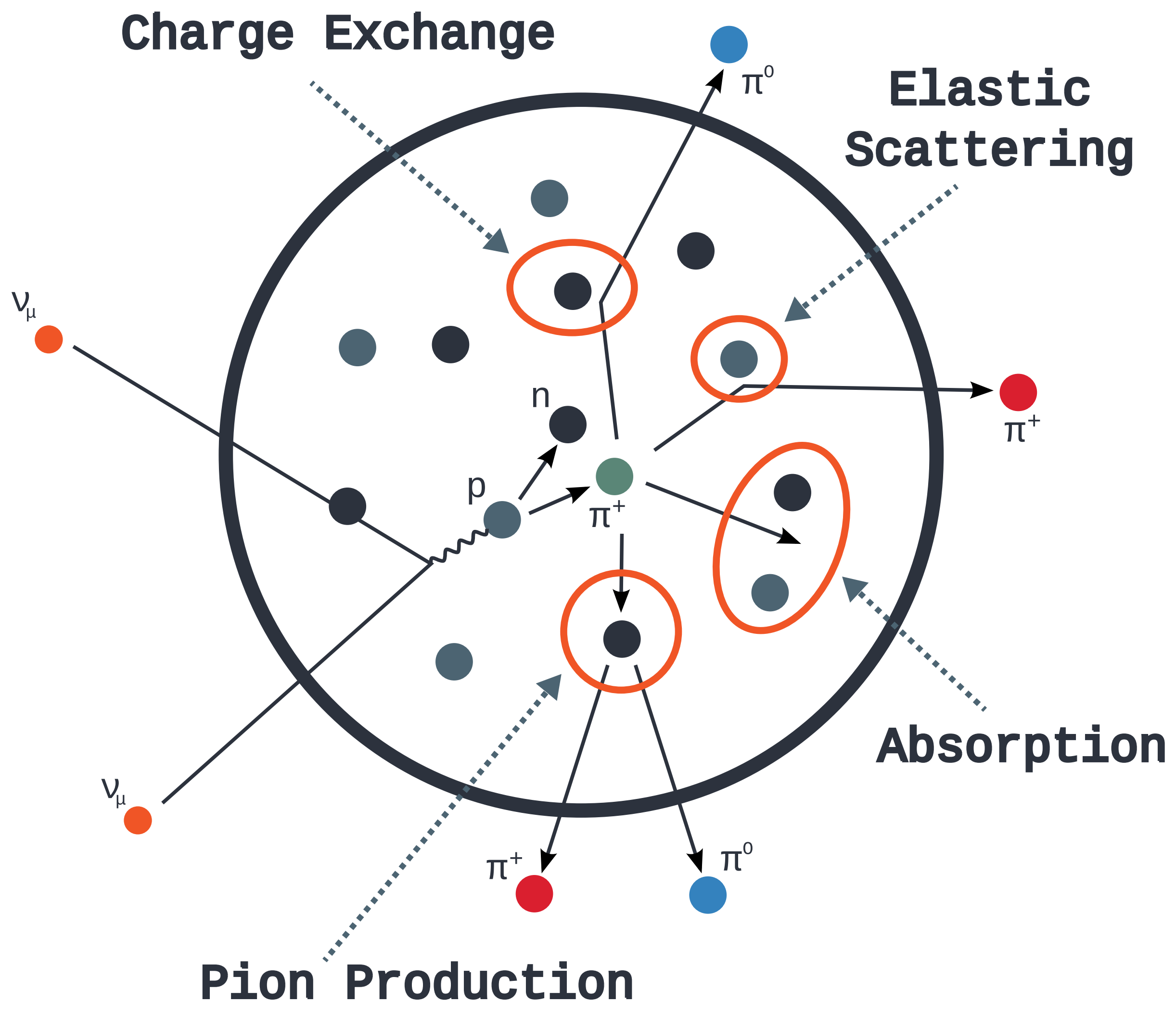


- The resulting di-nucleon pair undergo final state interaction and produce low energy proton and neutrons which we do not detect well

- Multi-nucleon processes smear the reconstructed neutrino energy
- The nuclear effects are big (>20%)

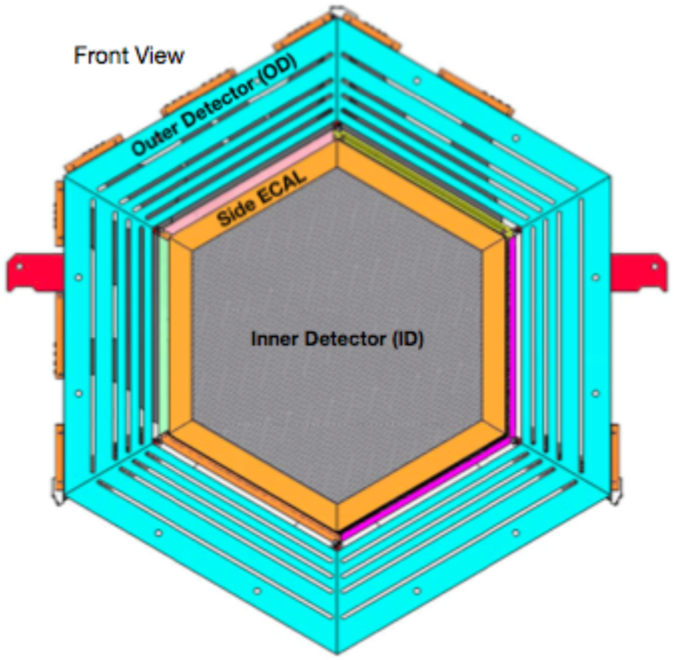
Example of Nuclear Effects (Final State Interactions)

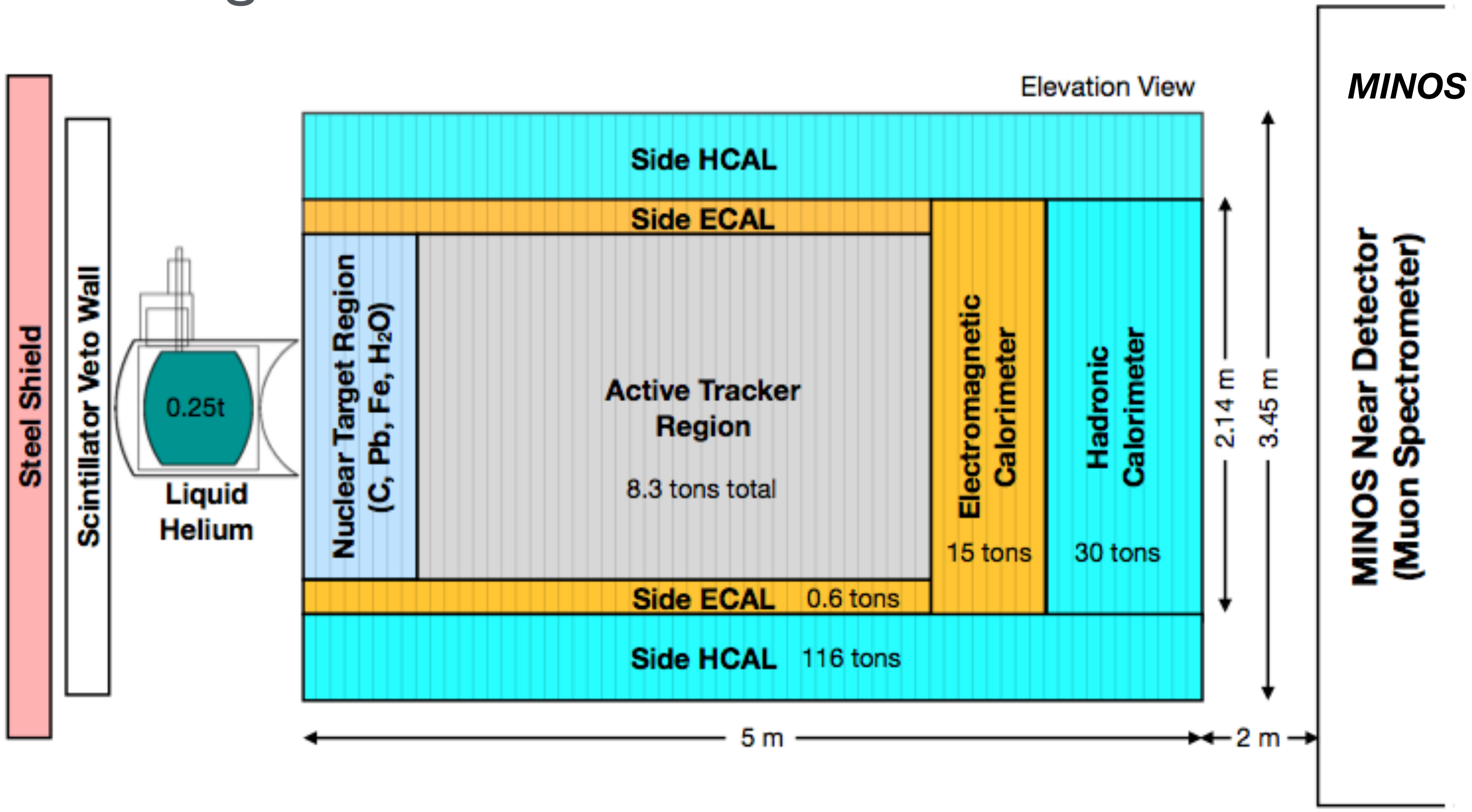
- Other examples of final state interactions:



Studying Nuclear Effects in MINERvA

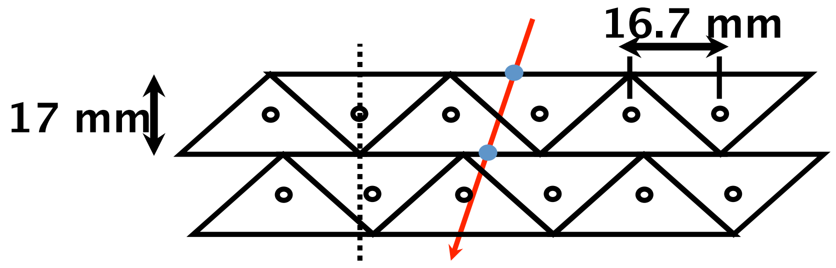
- Fine-grained scintillator tracker surrounded by calorimeters
- MINERvA has different nuclear targets iron, lead, carbon, helium, and water

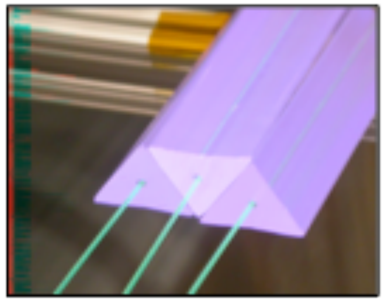




MINOS ND magnetized

Thanks to MINOS





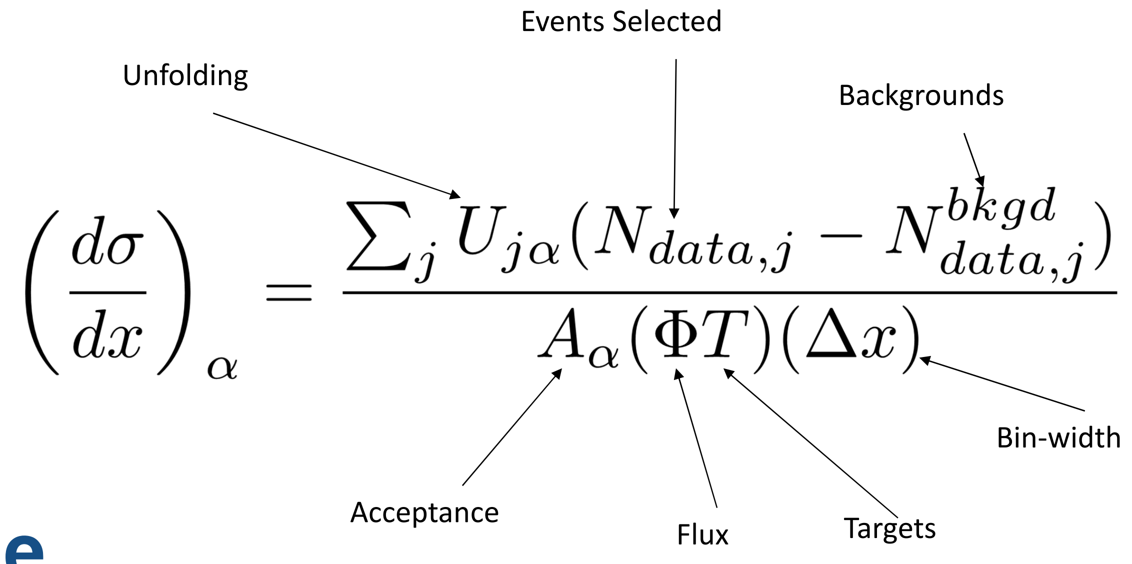
Three views of scintillator bars give unambiguous 3D track reconstruction

Design, calibration, and performance of the MINERvA detector

Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

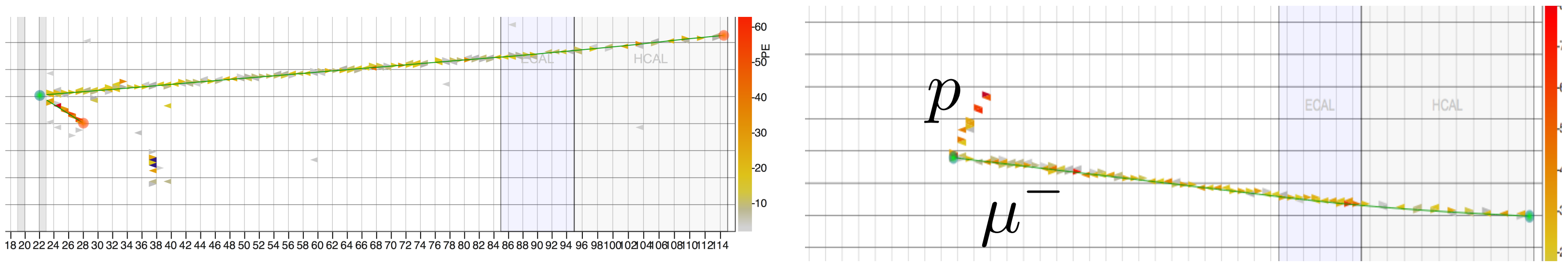
Cross Section Measurements

- Cross section is extracted using:



$$\left(\frac{d\sigma}{dx}\right)_{\alpha} = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_{\alpha}(\Phi T)(\Delta x)}$$

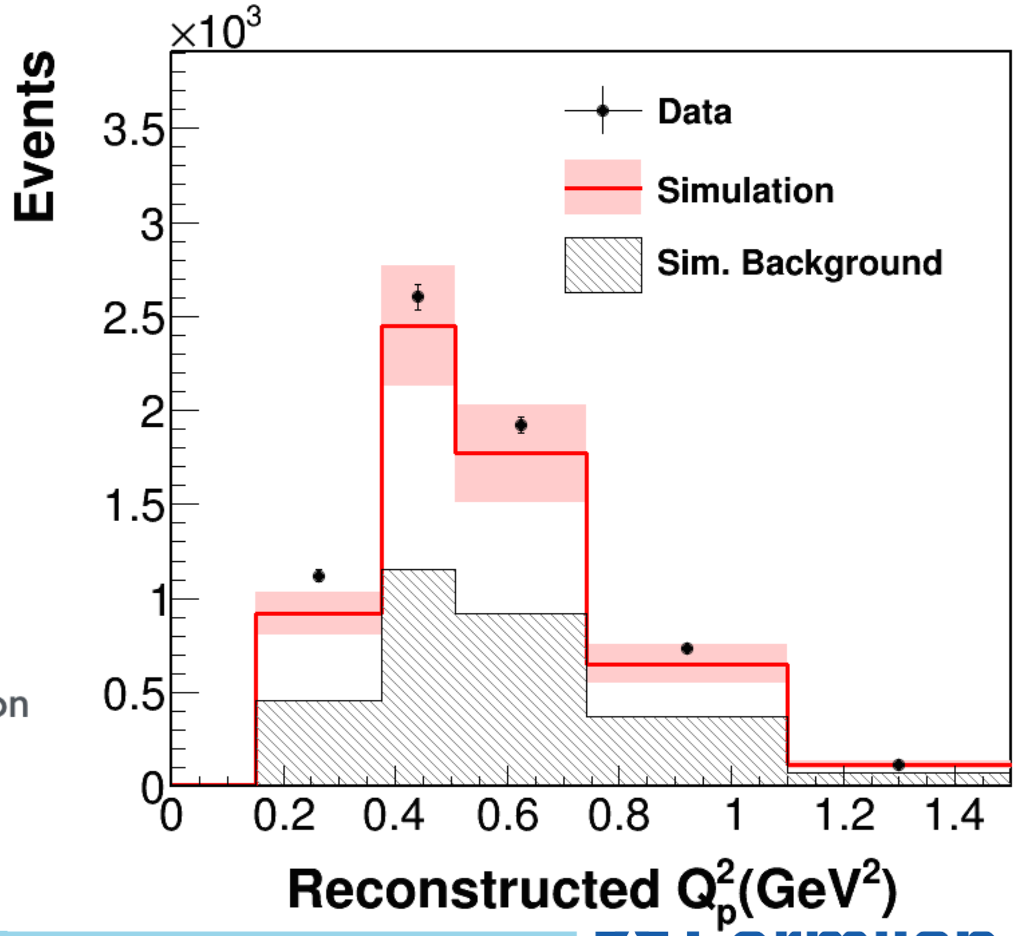
Selected sample



- At least two tracks
- Reconstructed vertex is in the target material
- Proton particle identification score: remove events with pions
- Michel electron cut: remove events with low-energy pions by searching for Michel electron

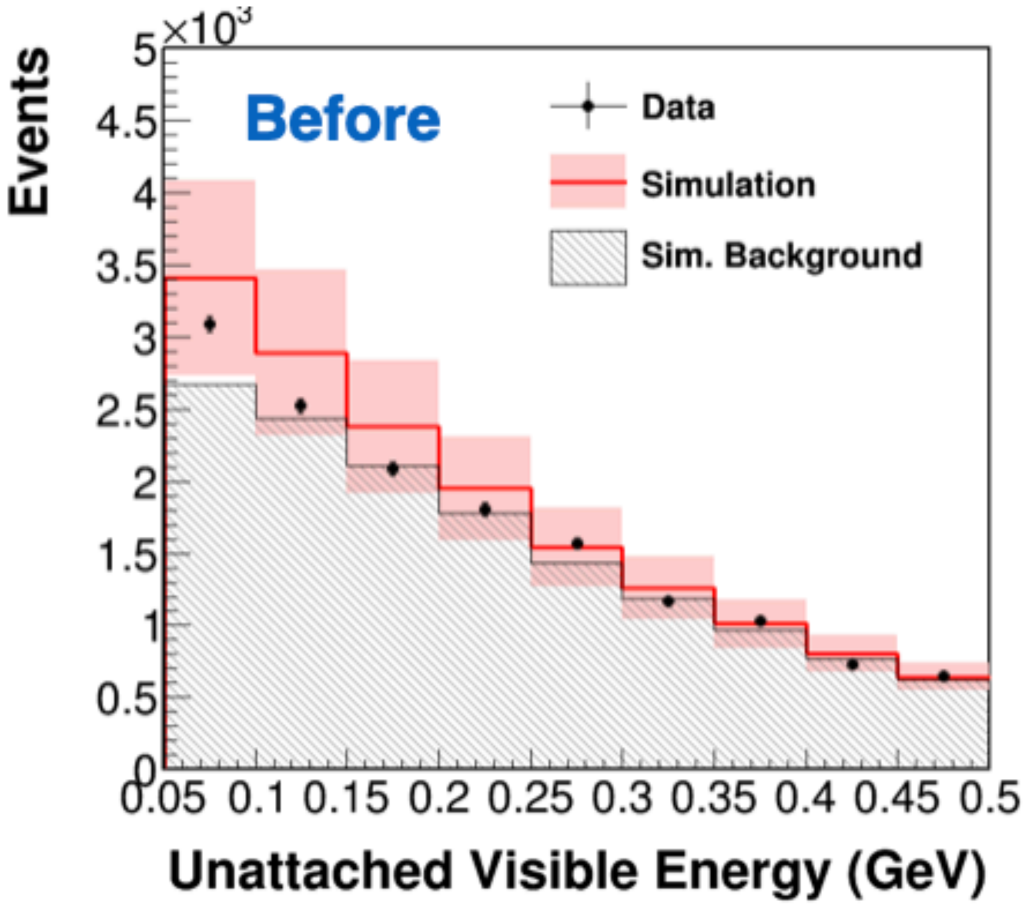
$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\mu_{\nu}}) \longrightarrow \begin{array}{l} \mu^- \to e^- \bar{\nu}_e \nu_{\mu} \\ \mu^+ \to e^+ \nu_e \bar{\nu_{\mu}} \end{array}$$

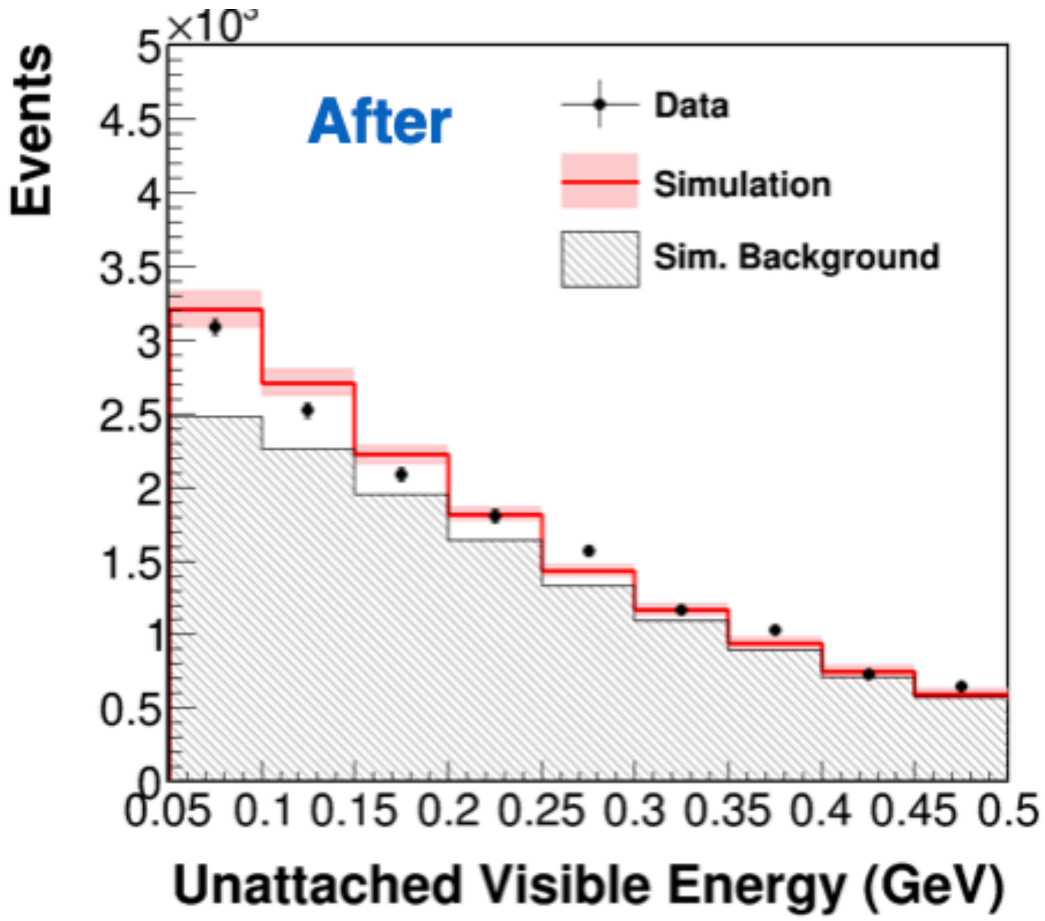
- Cut on energy far from the vertex: remove inelastic events with untracked pion



Background Constraint Procedure for Non-CCQE like

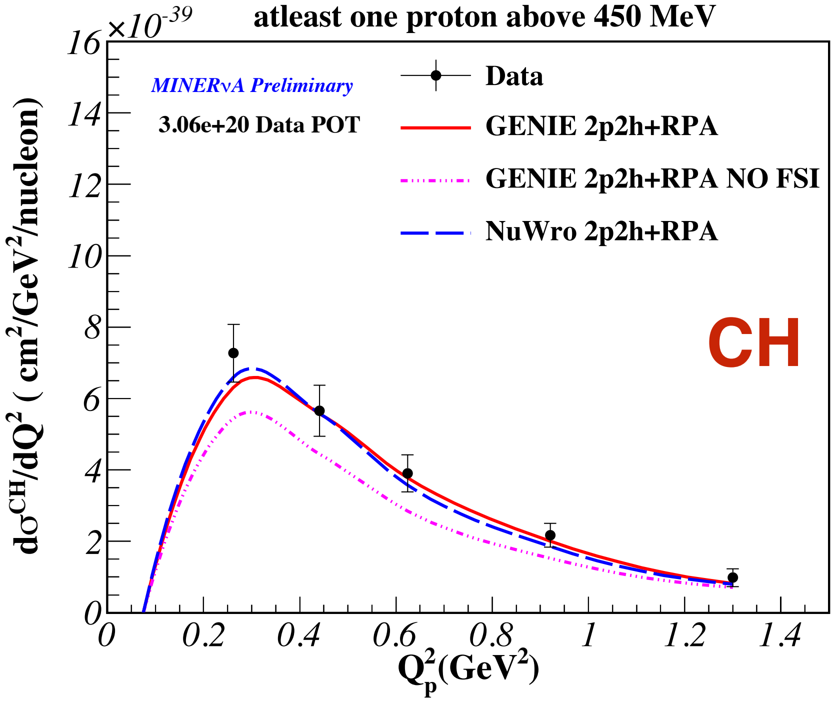
- Using the unattached visible energy for the events passing the proton pID for two different bins of Q^2 in the tracker
- Using the background dominated region in the unattached visible energy distribution
- Let the background float in the fit while keeping the signal constant until the total matches the data distributions

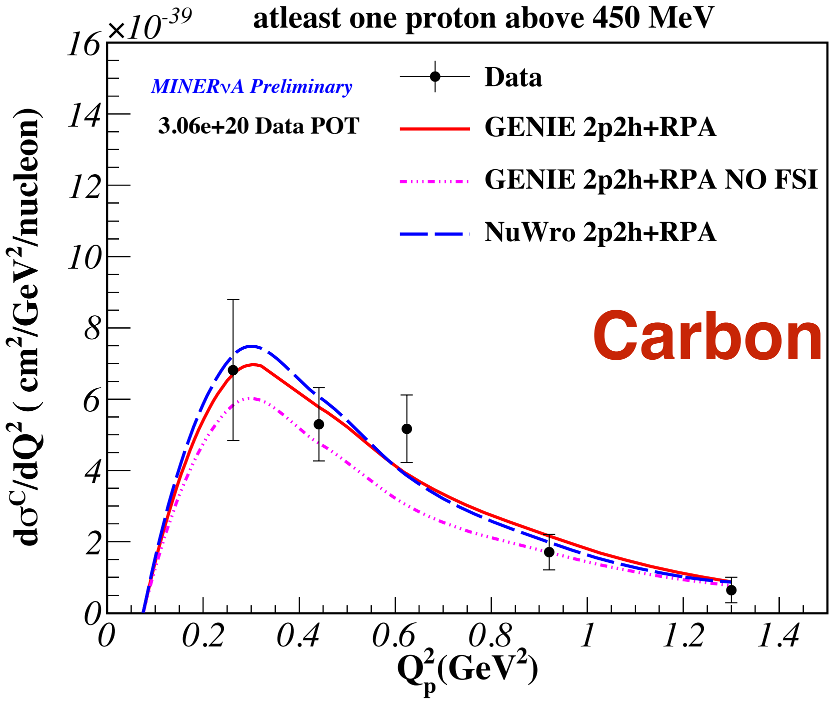




Comparing with Generators (GENIE vs NuWro)

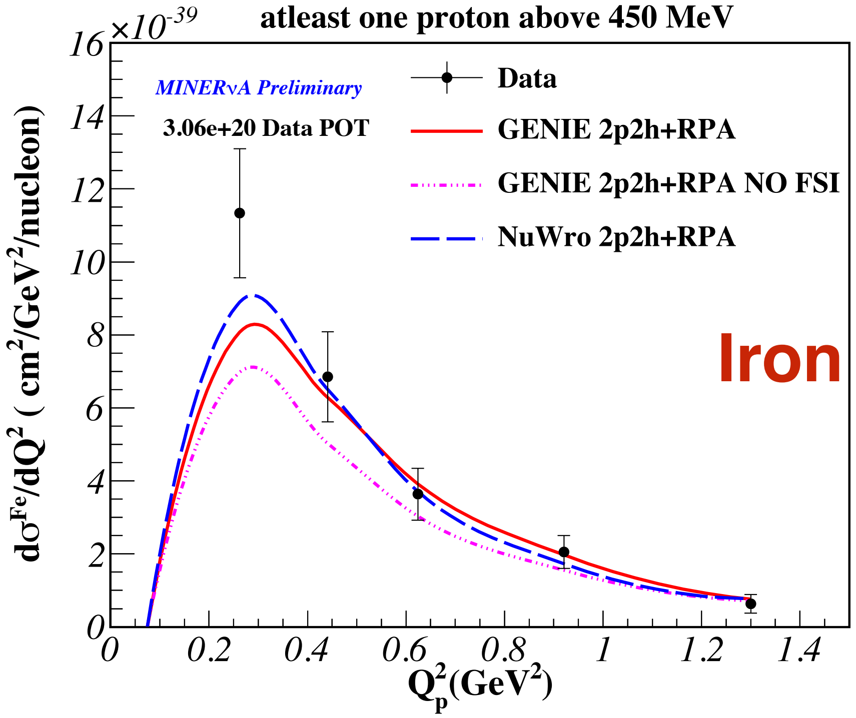
- Data prefers the simulation with final state interactions

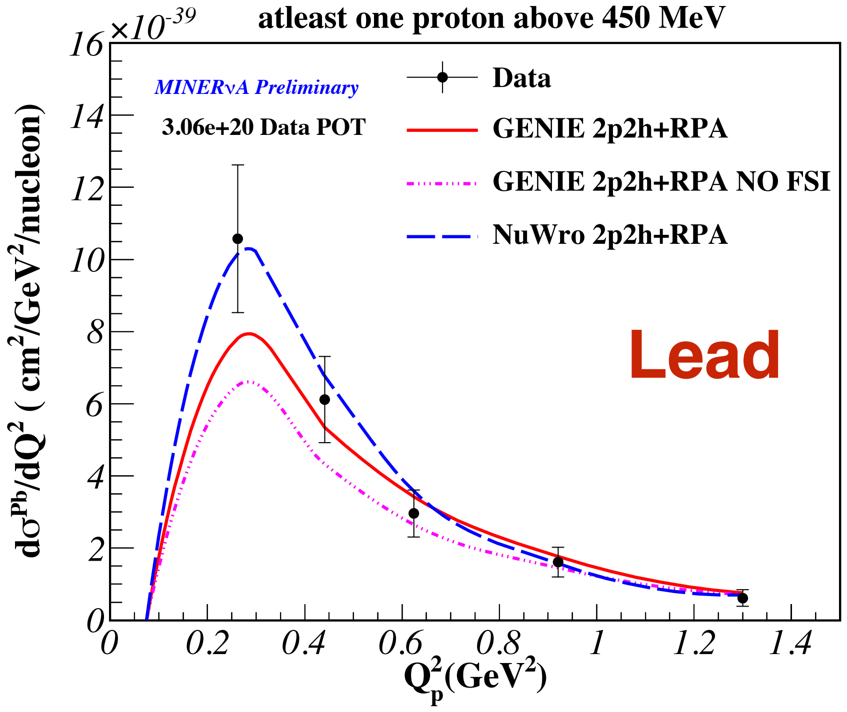




X²/d.o.f

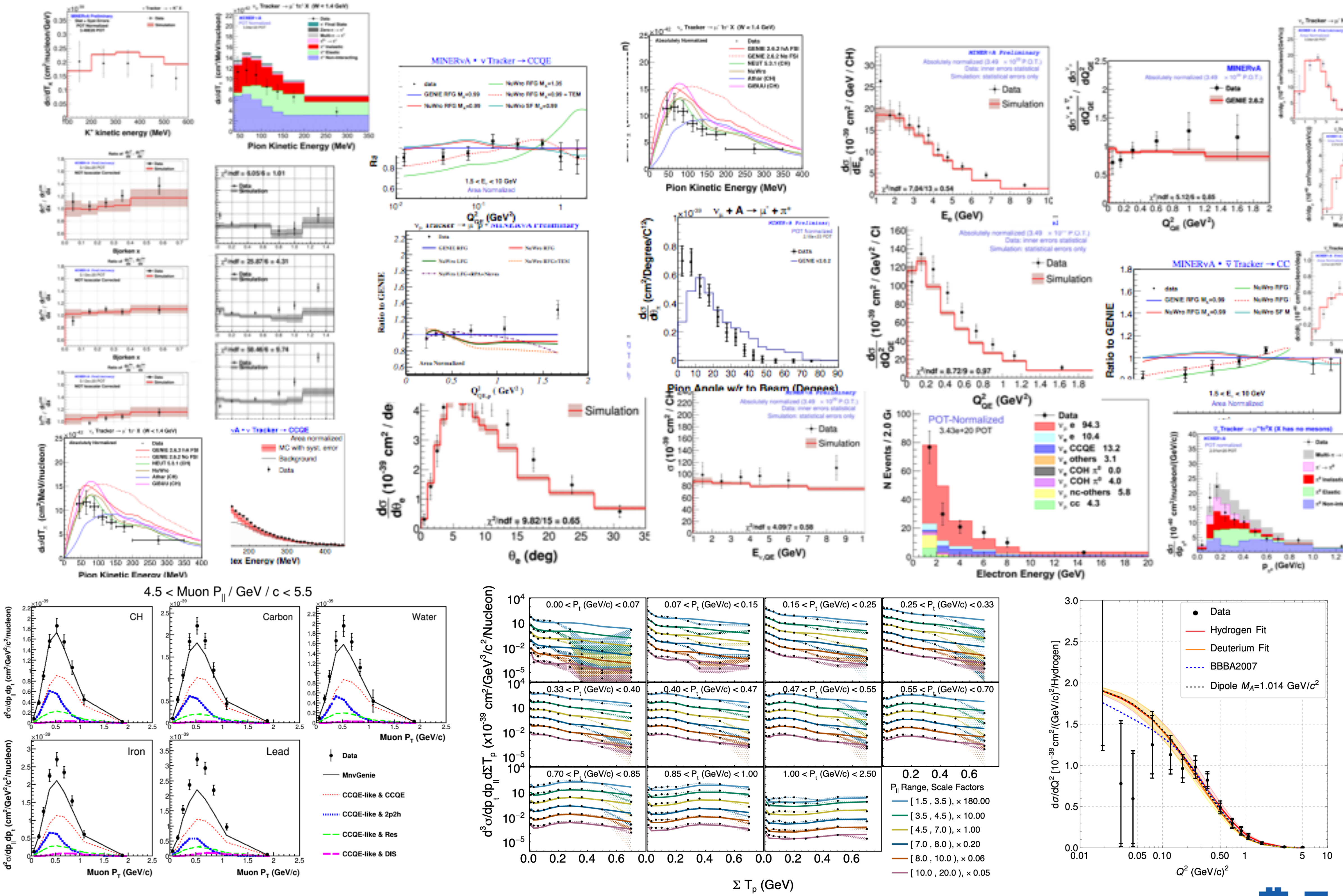
	carbon	iron	lead
GENIE	5.9/5	19.9/5	17.5/5
NuWro	6/5	14.6/5	11.1/5





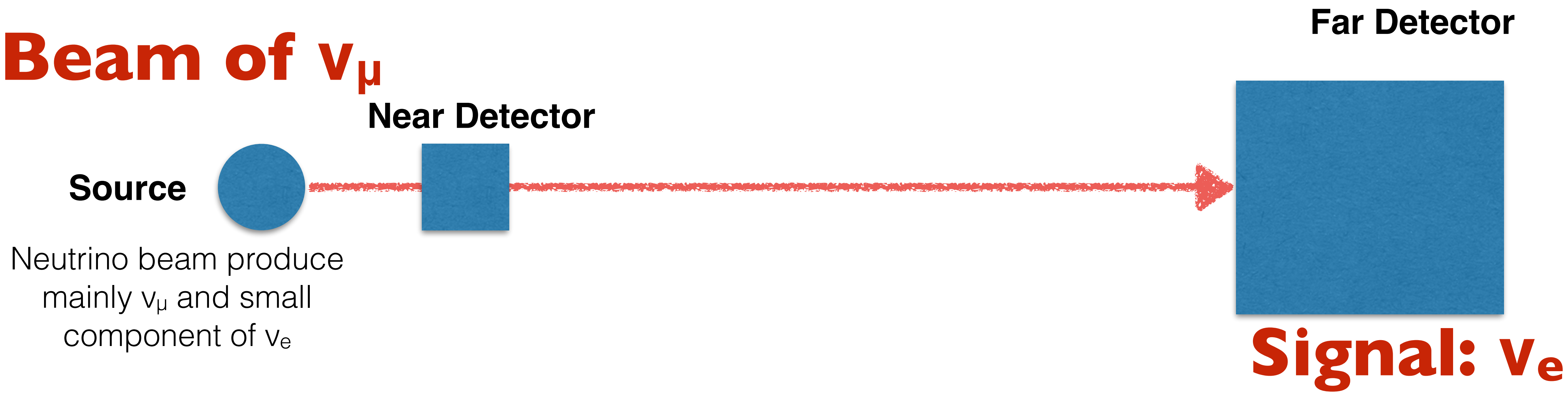
- The A dependence in NuWro seems to be more favored by the data

MINERvA Results



Addressing these Remaining Questions

- Is there CP violation in the lepton sector $P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e]$?
- What is the mass hierarchy? (sign of Δm^2_{32})



Beam of ν_μ

Far Detector

Near Detector

Source

Neutrino beam produce
mainly ν_μ and small
component of ν_e

Signal: ν_e

$\phi \times \sigma \times$ **Nuclear Effects**

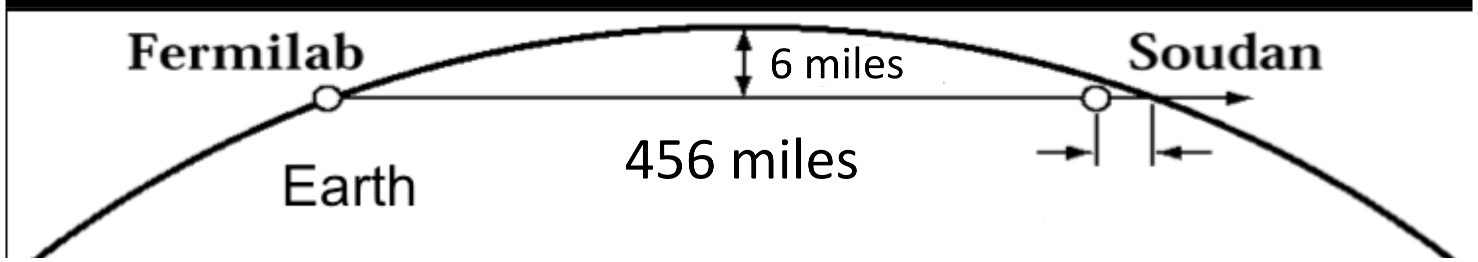
$\phi' \times \sigma \times$ **Nuclear Effects** $\times P_{\nu_\mu \rightarrow \nu_e}$

Nuclear model

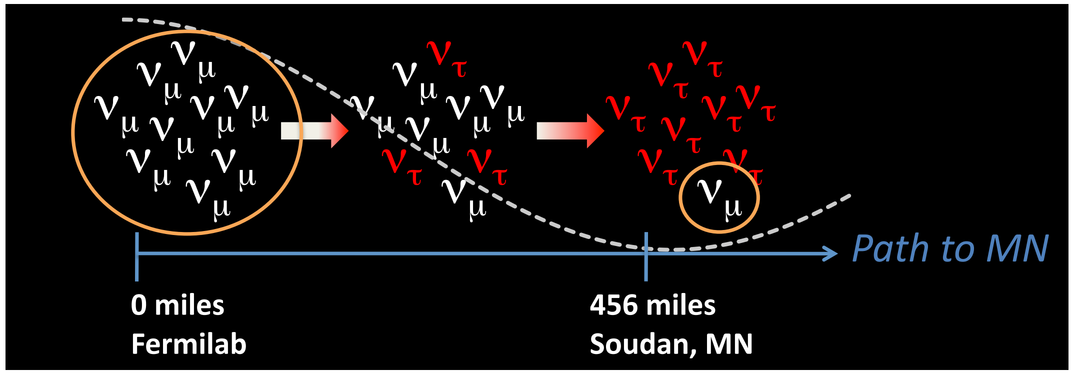
- Use simulations to extrapolate from near detector to far detector $\sigma_{\nu\mu}$—>$\sigma_{\nu e}$
- We definitely need a nuclear model to convert from produced to detected energy spectra and topologies in the near and the far detectors
- This illustrates the significance of precise knowledge of neutrino interactions physics needed for oscillation studies

Where is the Far and Near Detector?

Neutrinos make the journey from Fermilab to northern Minnesota



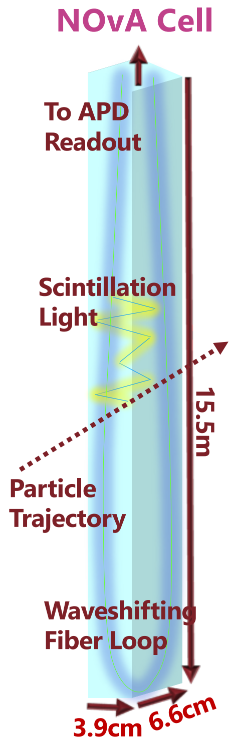
Illinois
Wisconsin
Minnesota

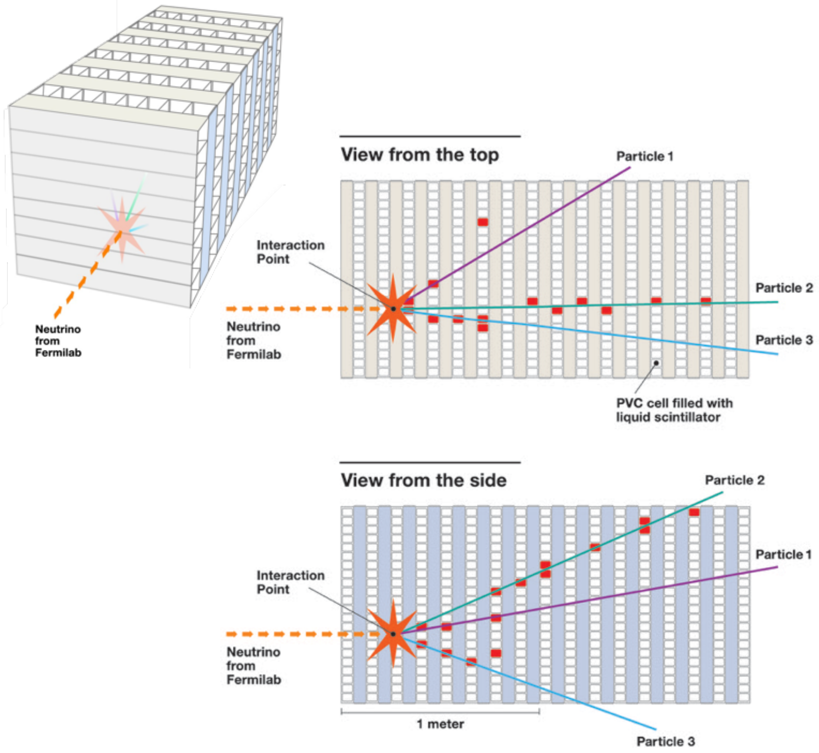


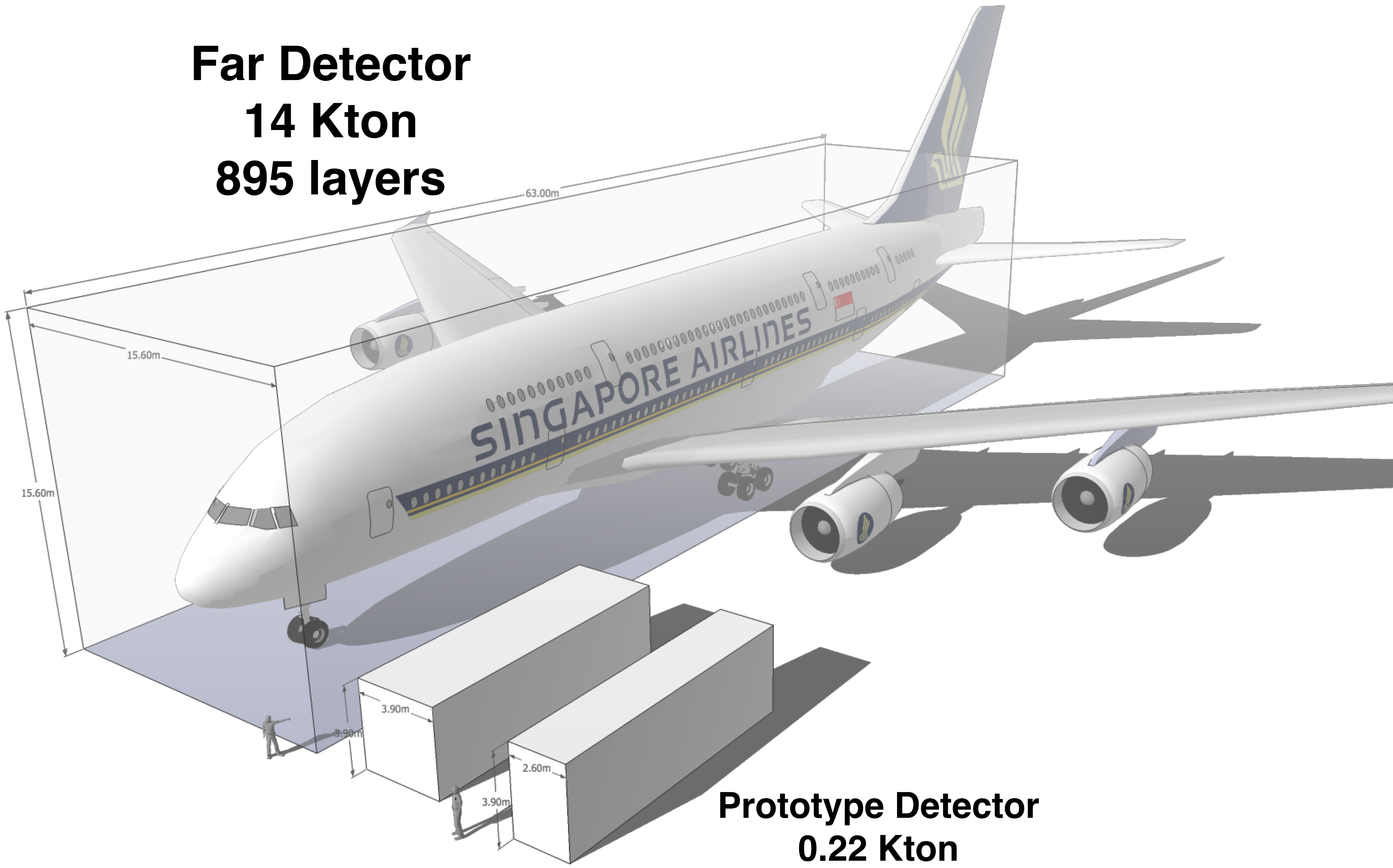
NOvA detectors are segmented liquid scintillator

- Orthogonal layers of cells provide top and side views for each event
- NOvA has been running for 10 years!

NOvA Experiment







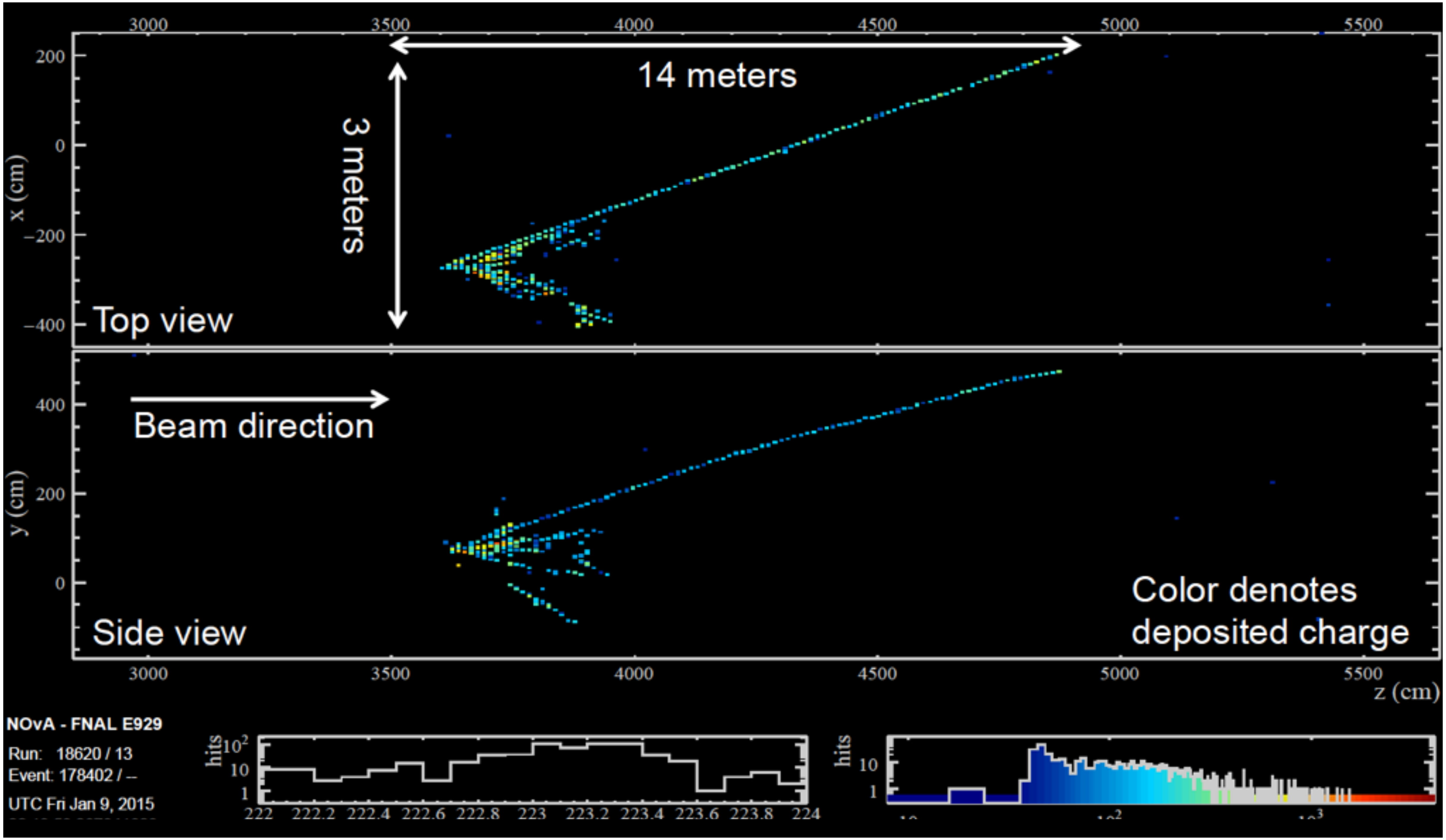
Far Detector
14 Kton
895 layers

Prototype Detector
0.22 Kton
200layers

Near Detector
0.3 Kton
214 layers

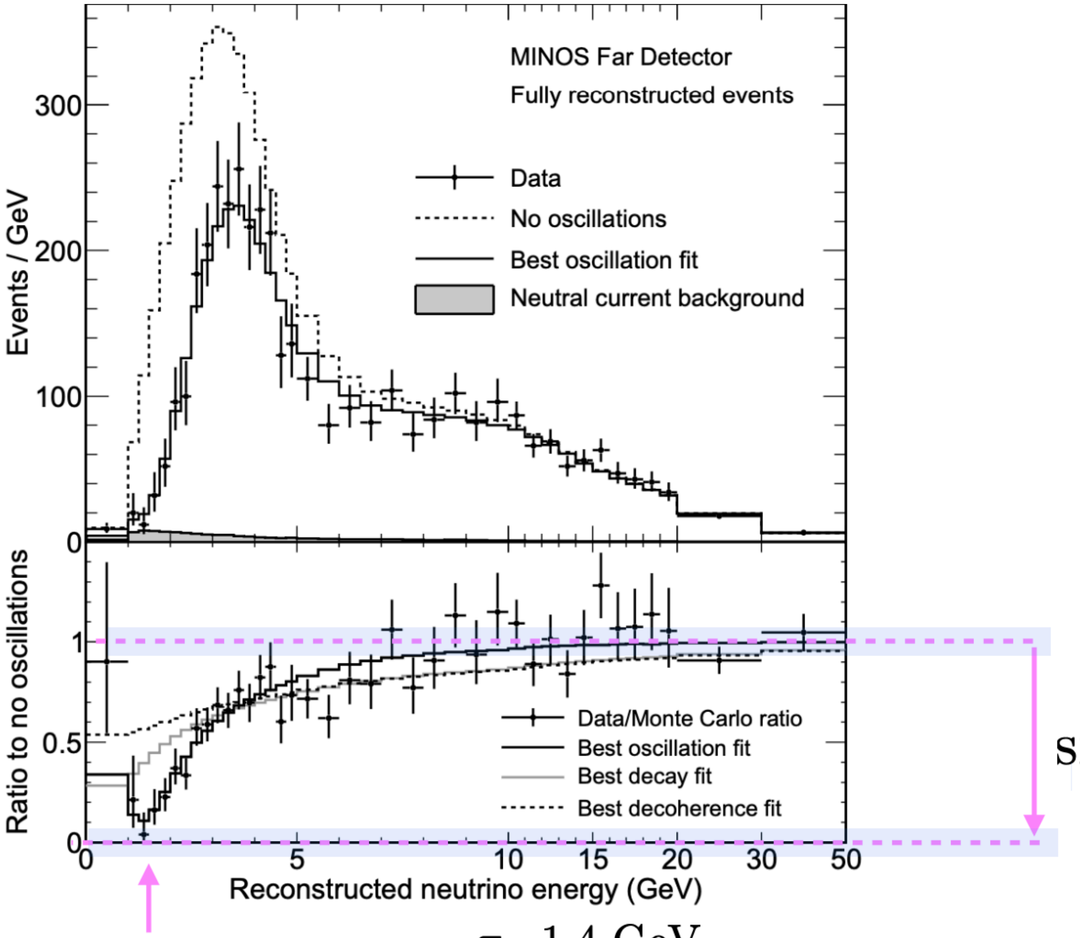
Sample	NOvA
N_μ^{rec} FHC	211
N_μ^{rec} RHC	105
N_e^{rec} FHC	82
N_e^{rec} RHC	33

A Neutrino Interaction from the NOvA Experiment



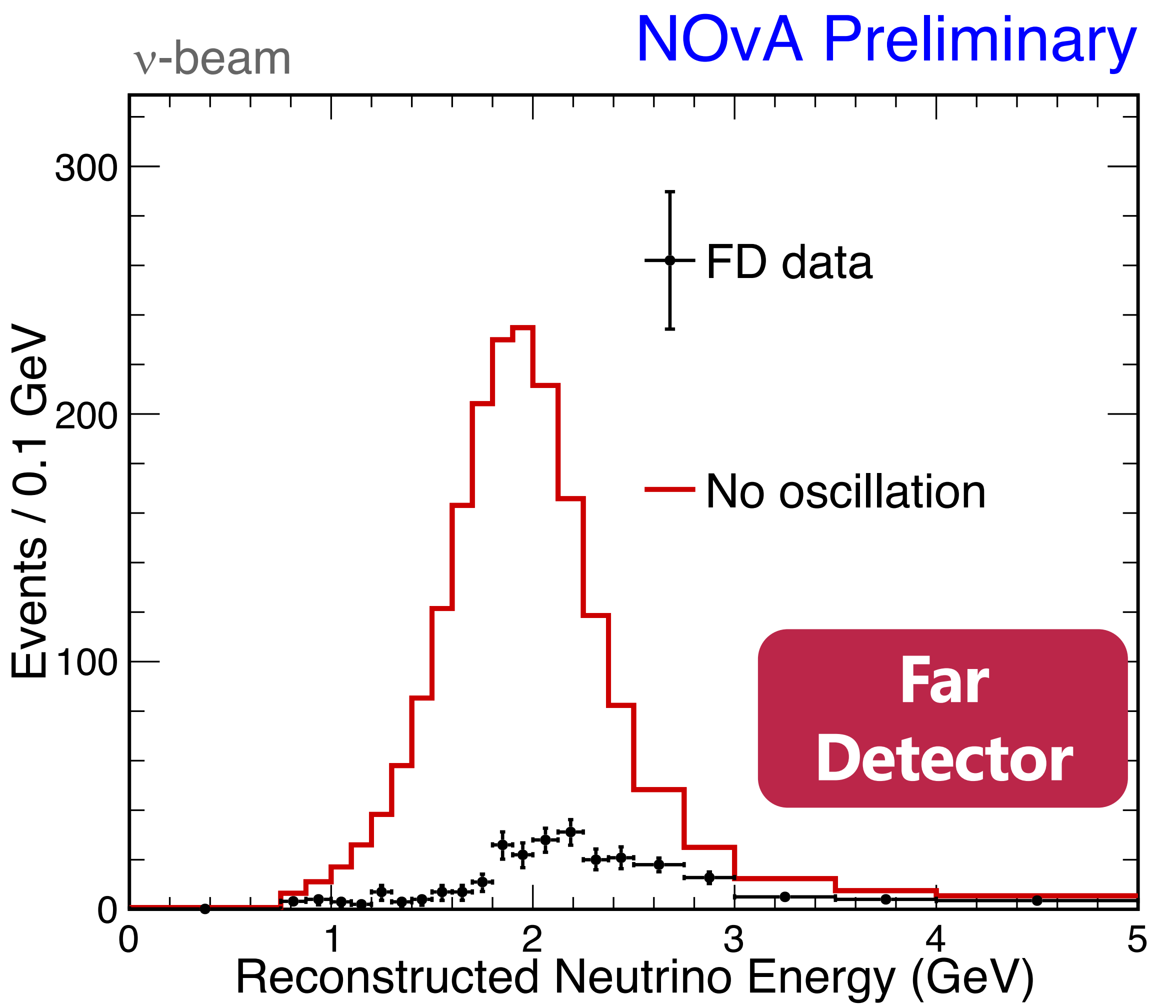
Neutrino Oscillations at Long Baseline

MINOS Experiment



$$\sin^2 2\theta_{23} \simeq 1$$

1.4 GeV $\Delta m^2_{32} \simeq \dfrac{\pi}{2.54}\dfrac{1.4\ \text{GeV}}{735\ \text{km}} = 2.3 \times 10^{-3}\ \text{eV}^2$



Phys.Rev.Lett. 106 (2011) 181801

NOvA Experiment

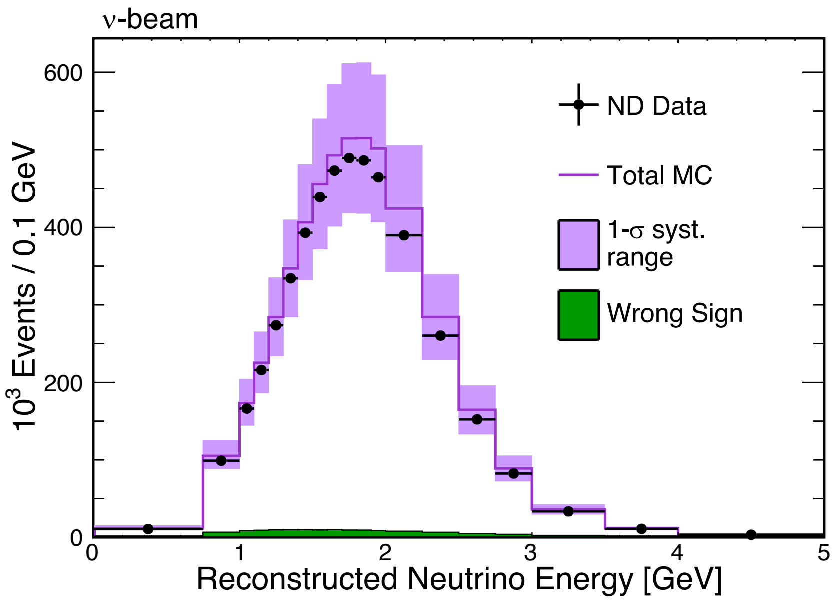
Near Detector

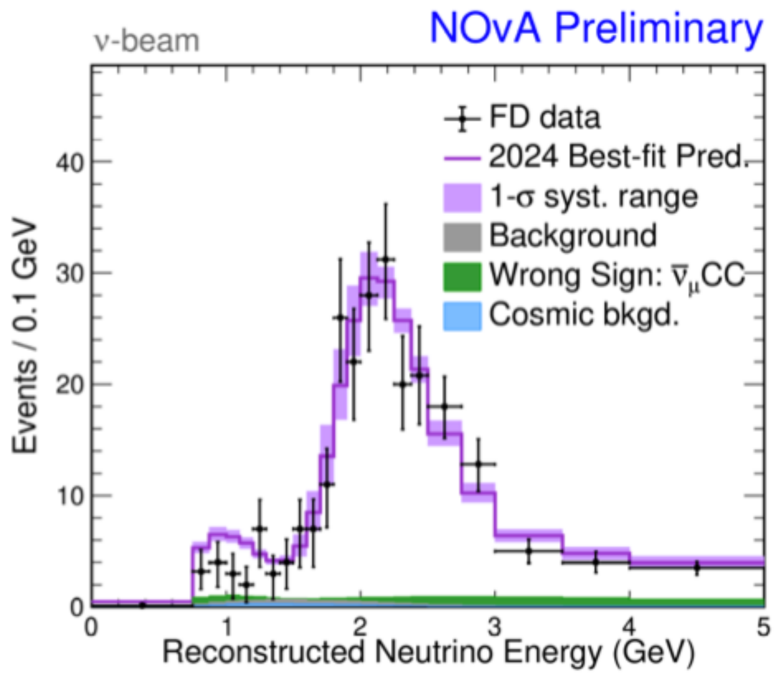
ν_μ

Far Detector

ν

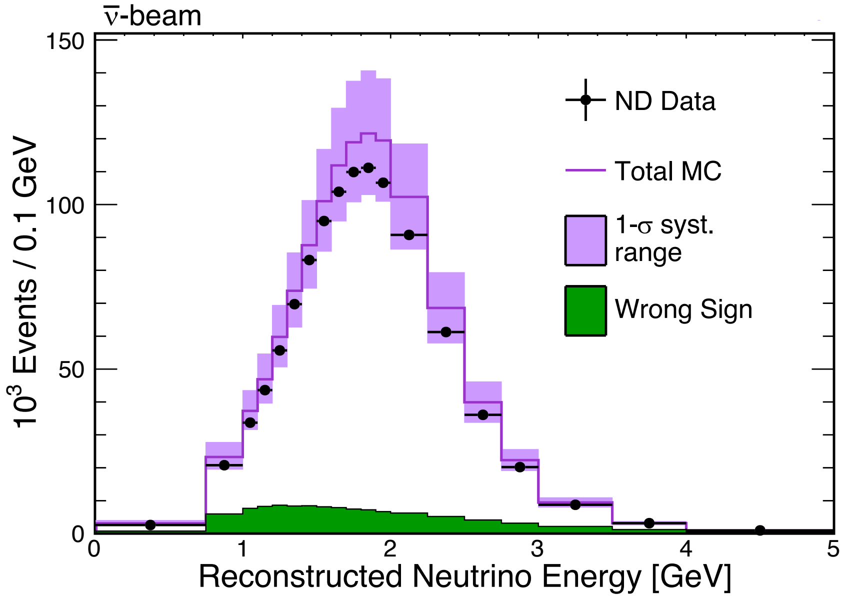
6.5M Events

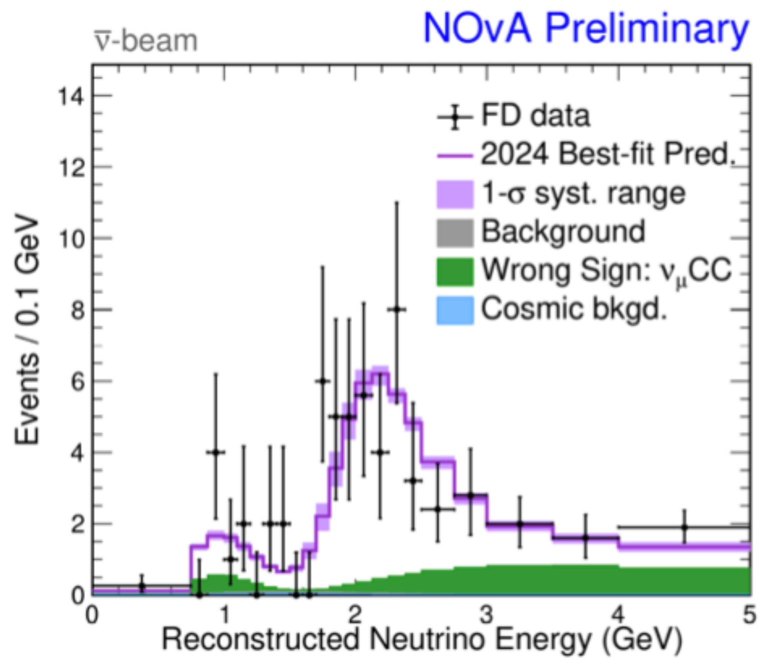




$\bar{\nu}$

1.5M Events

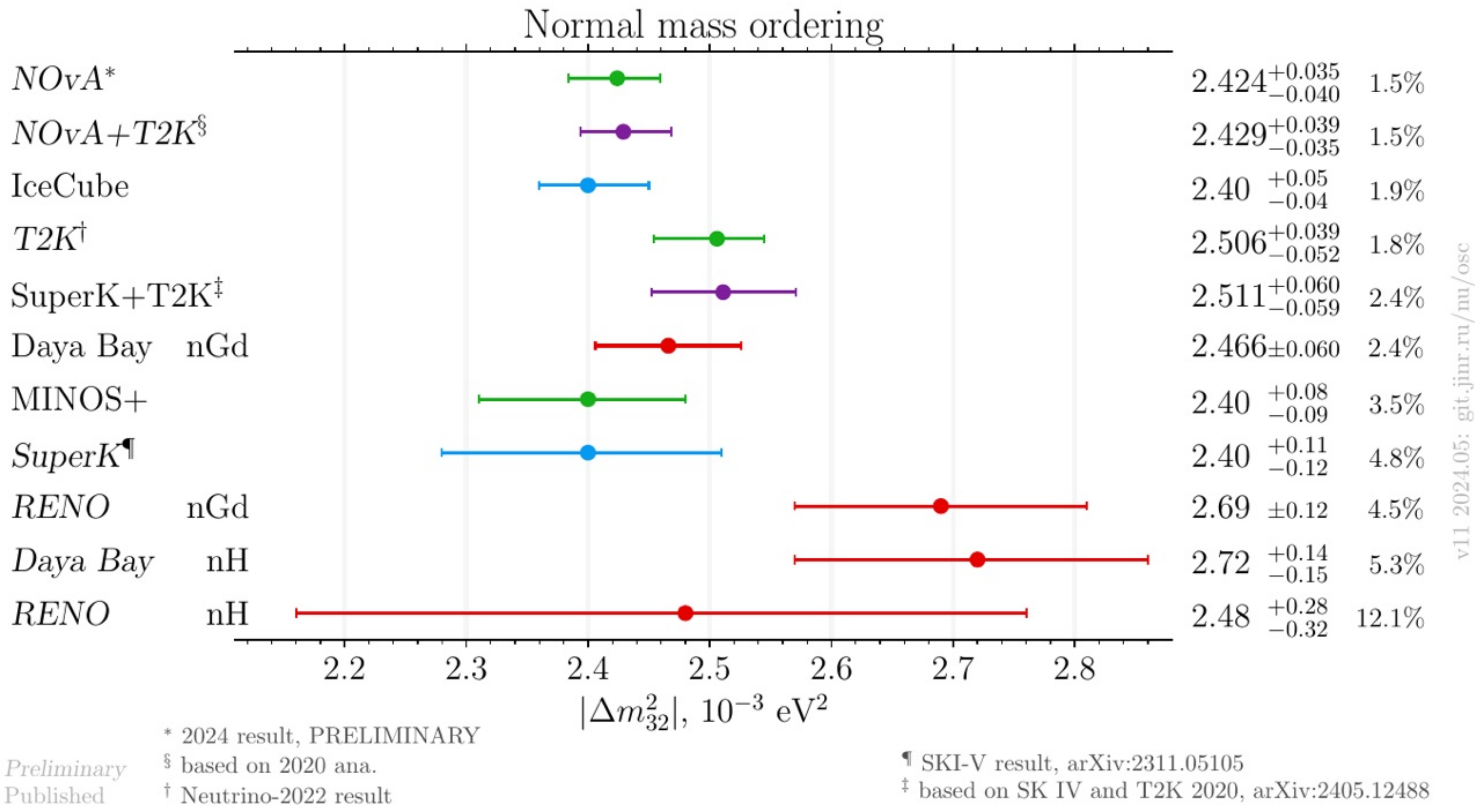




Erika Catano, Fermilab JETP, June 2024

Δm^2_{32} is now the most precisely known PMNS parameter

Δm^2_{32} is now the most precisely known PMNS parameter.
NOvA's new result achieves a precision of 1.5%



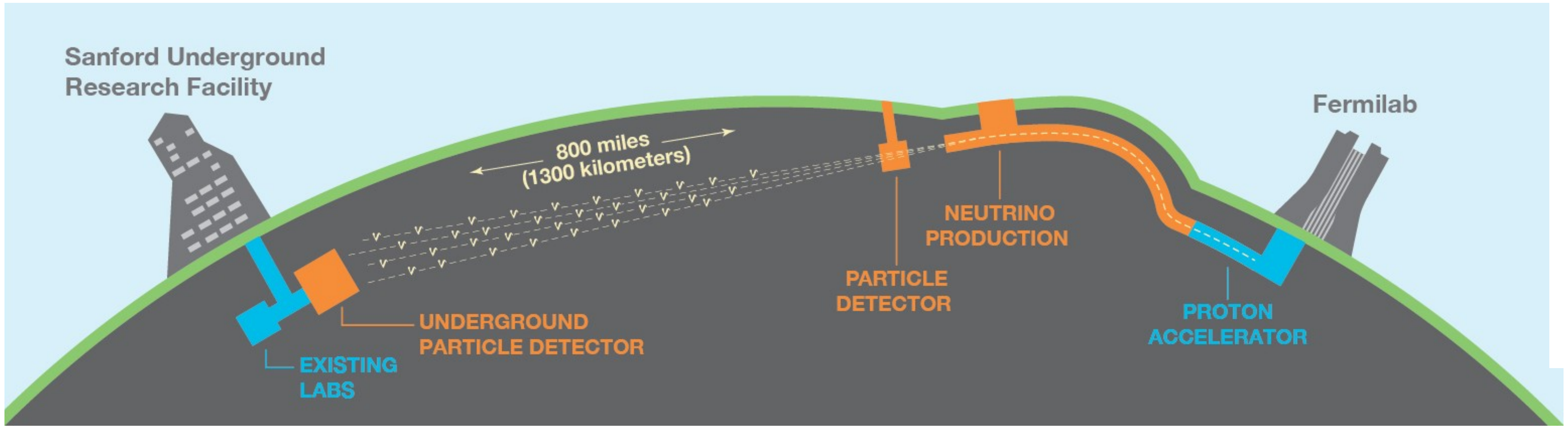
* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488

Erika Catano, Fermilab JETP, June 2024

Next Long-baseline neutrino experiment

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

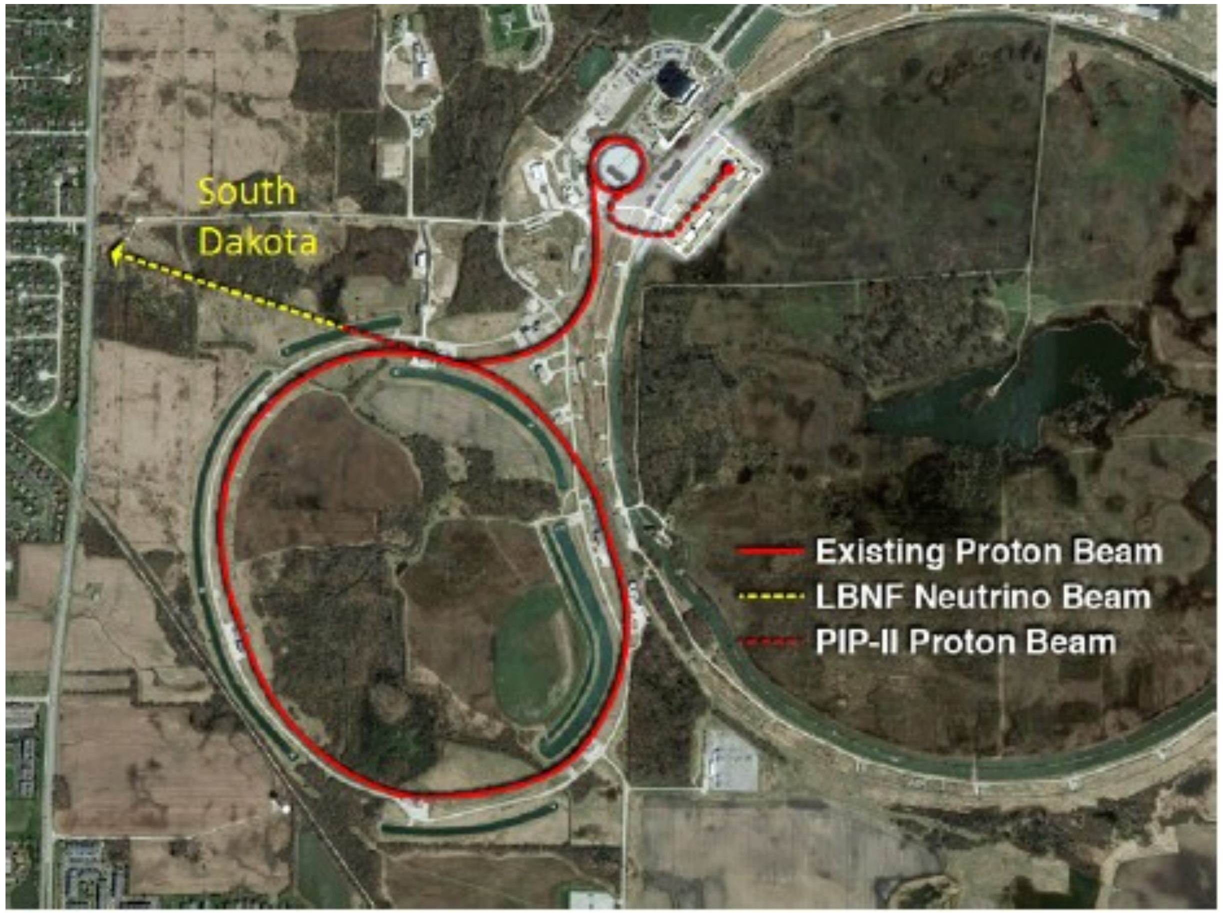


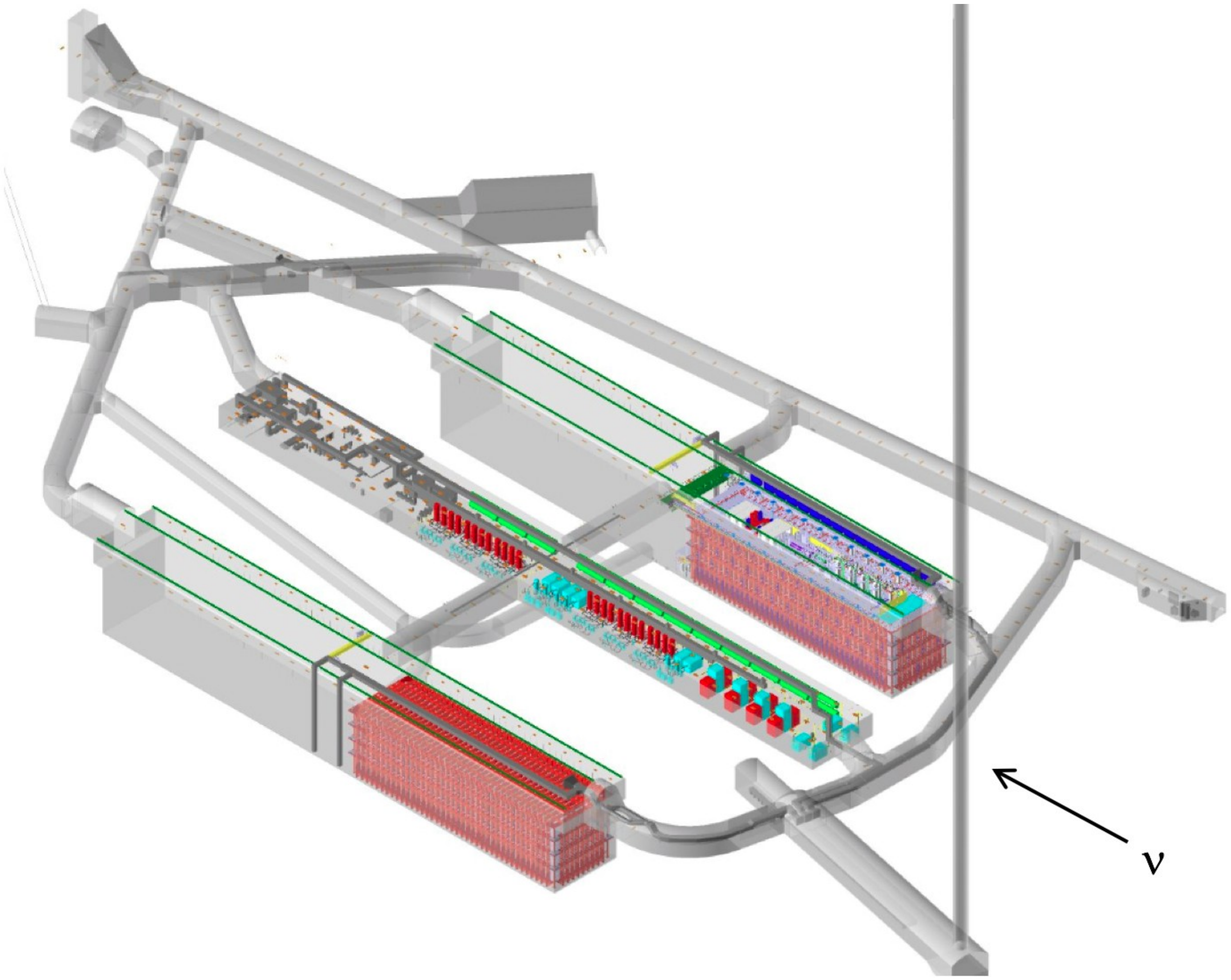
Sample	DUNE
N_{μ}^{rec} FHC	7000
N_{μ}^{rec} RHC	3500
N_{e}^{rec} FHC	1500
N_{e}^{rec} RHC	500

- Long-baseline neutrino oscillations, including discovery sensitivity to CP violation and neutrino mass ordering
- MeV-scale neutrino physics, including supernova burst astrophysics and solar neutrinos
- Broad program of physics searches beyond the Standard Model

Neutrino Beam and Underground Facilities

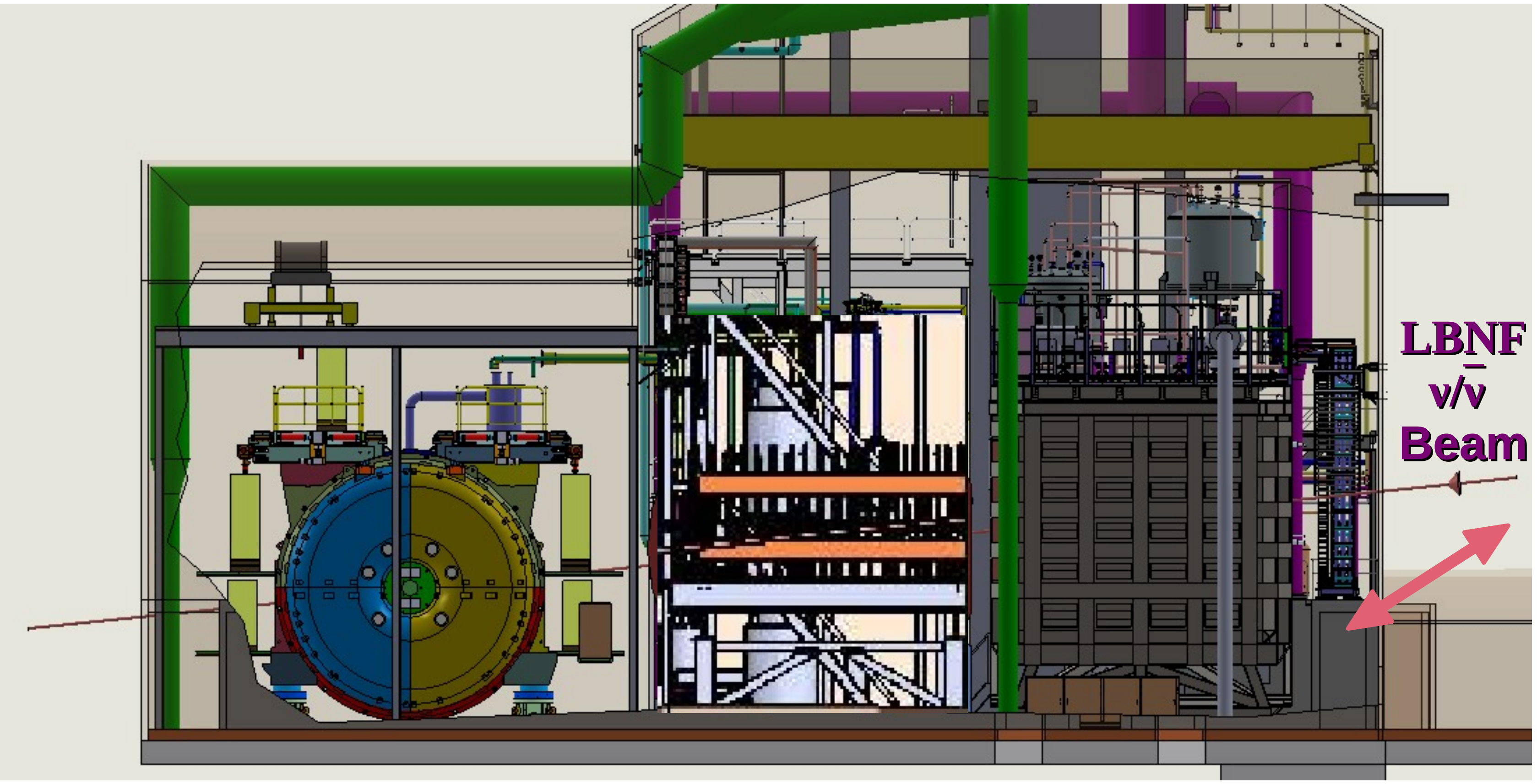
- Most intense neutrino beam in the word will provide up to 1.3 MW intensity, designed to allow for future upgrade to 2.4 MW
- Deep underground cavern at SURF to accommodate four 17-kiloton argon Far Detector modules and underground near site



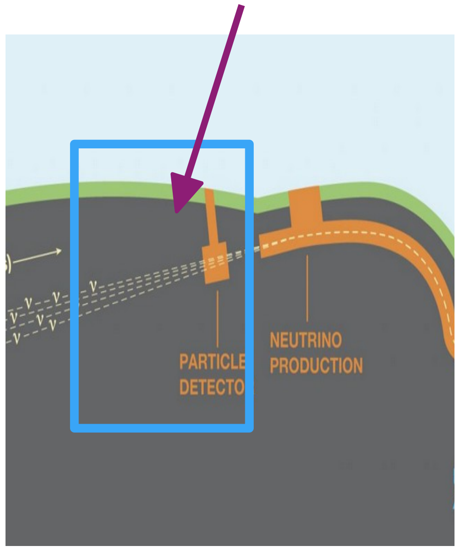


Near Detector at Fermilab

- Near Detector Complex houses a set of detectors to predict the far detector spectrum and monitor the beam stability
- A liquid argon TPC (ND-LAr) plus a Muon Spectrometer (TMS), these can move off -axis (PRISM system)
- An on-axis detector (SAND)



60 meters underground



SAND
System for On-Axis Neutrino Detection

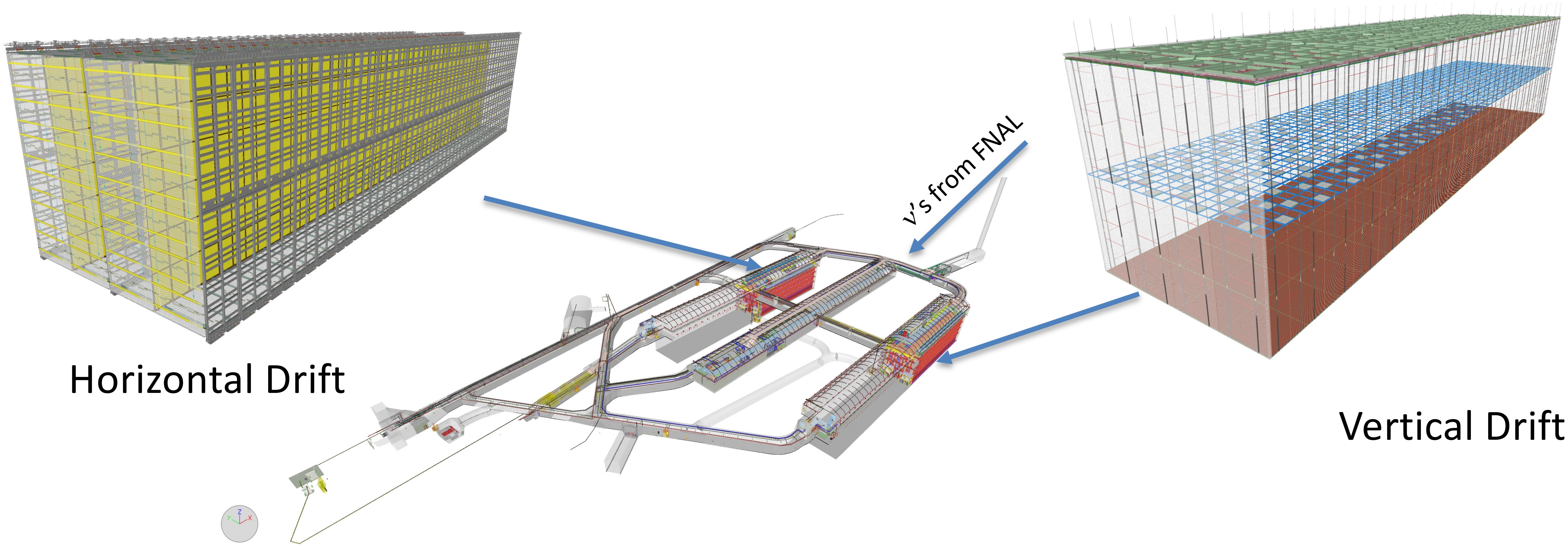
TMS
Magnetized Temporary Muon Spectrometer

ND-LAr
Modular Liquid Argon TPC

PRISM
30m Off-Axis Mobility for LAr + Spectrometer

Two LArTPC designs for Far Detector

- First detector to be installed in NE cavern has horizontal drift technology like ICARUS
- Second detector will go into SE cavern and has vertical drift technology



ν's from FNAL

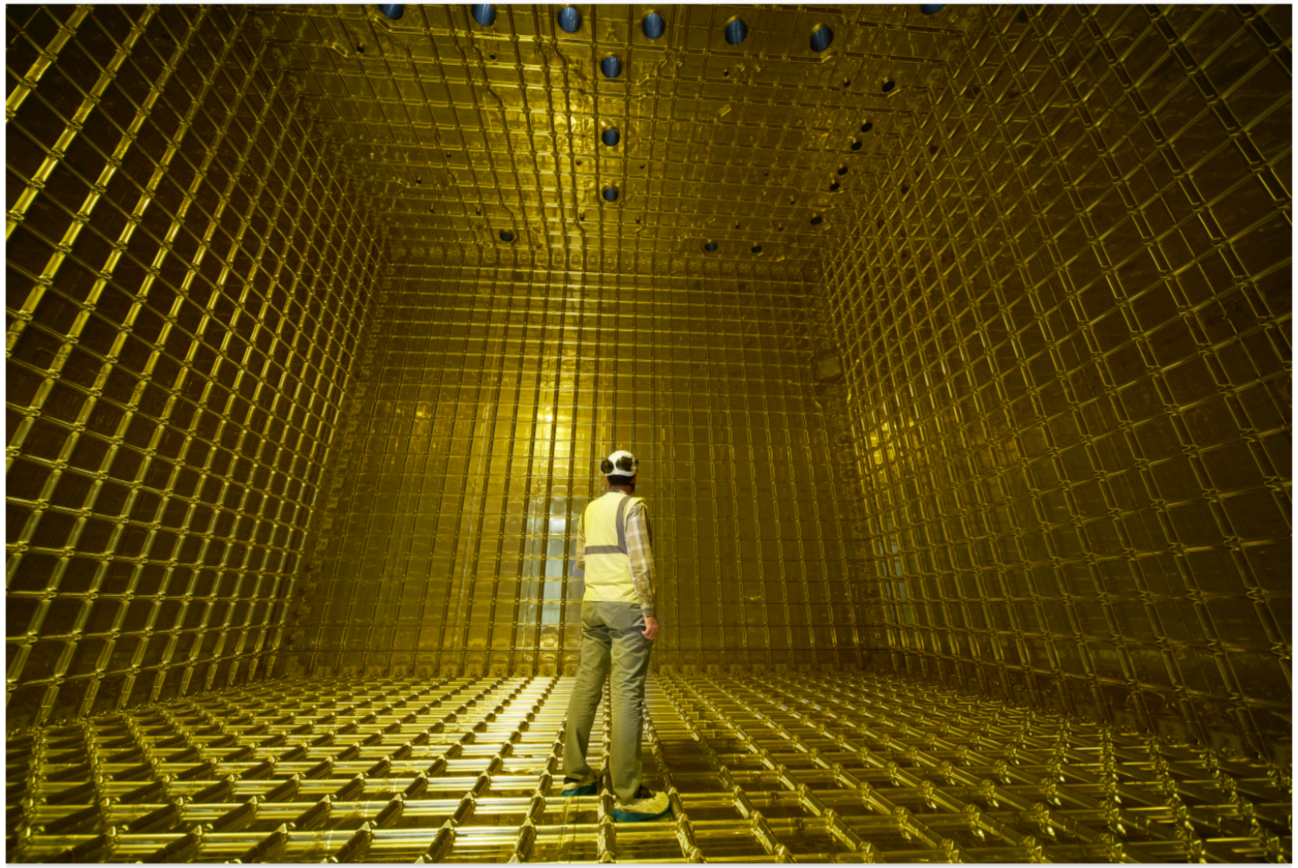
Horizontal Drift

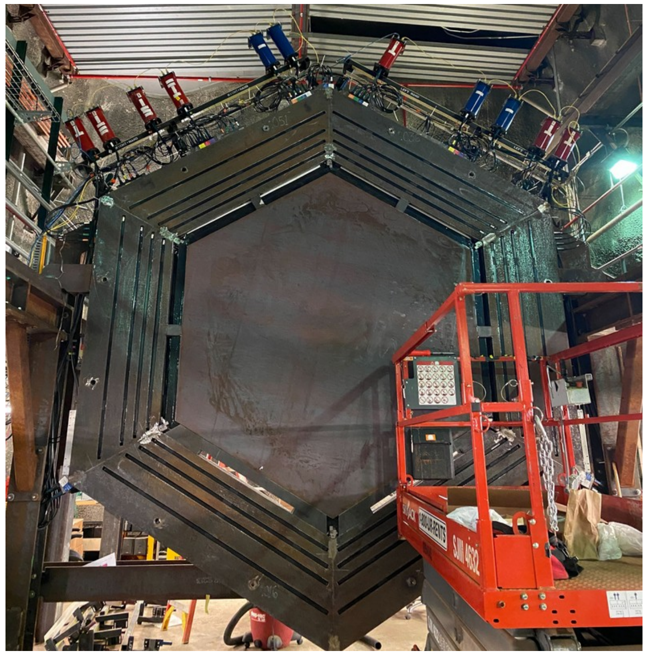
Vertical Drift

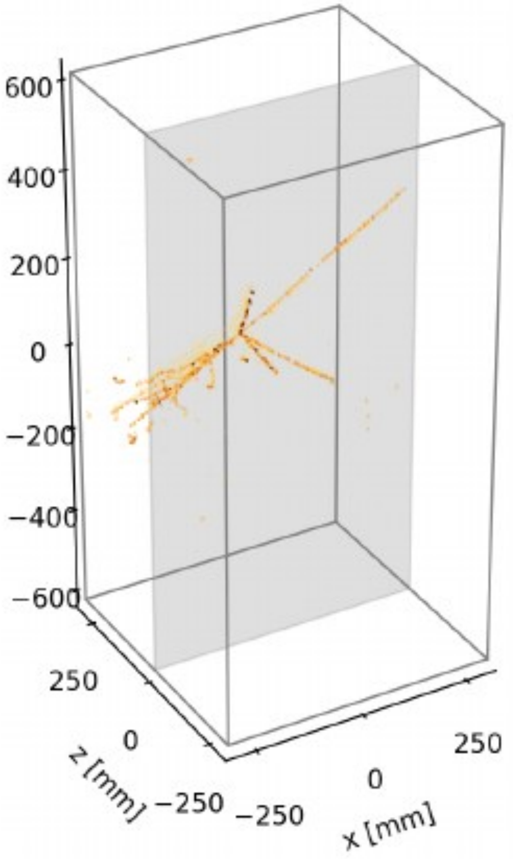
Far and Near Detector Prototyping

- Large-scale DUNE prototypes operated at CERN Neutrino Platform with low noise, stable high voltage and high purity
- Stable operation of ProtoDUNE shows that the technology will work and is scalable to full DUNE
- Several publications from the successful operation between 2018 and 2020

DUNE prototype in CERN







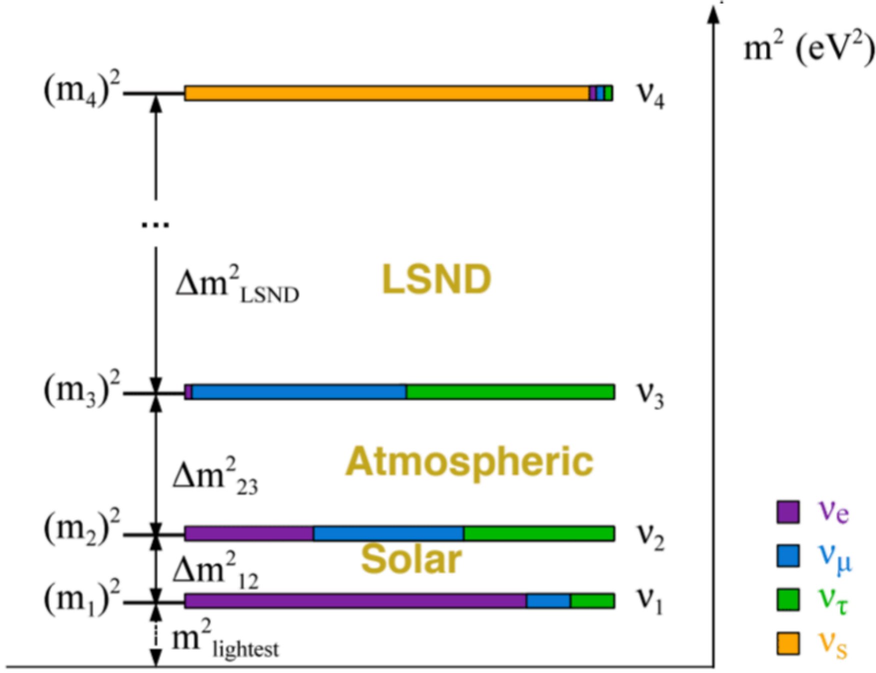
- Near Detector LAr 2x2 prototype Module-1 operated successfully at Bern, preparation for neutrino beam test at Fermilab underway

Is there a fourth neutrino?

- Four anomalies have been observed in neutrino experiments at short baseline in the last 20 years
- These anomalies provided hints to indicate there is a fourth and non-weakly interacting (sterile) type of neutrino

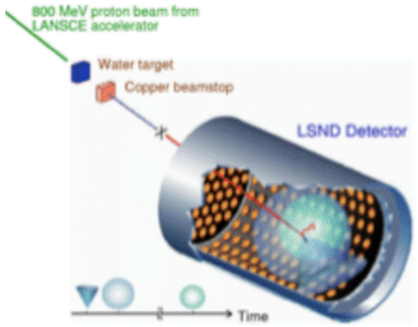
Experiment	Type	Channel	Significance
LSND anomaly	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE anomaly	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e	ν_e disappearance	2.8 σ
Reactors anomaly	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

- Each possibly explained by non standard sterile neutrino states driving oscillations at $\Delta m^2_{new} \approx 1$ eV^2 and small $\sin^2(2\theta_{new})$
- Is there any additional physics beyond the 3- flavor mixing neutrino oscillation?



Sterile Neutrino Physics

Low energy $\overline{\nu}_\mu$ beam from a decay-at-rest pion beam (Los Alamos, 1993-1998)



LSND

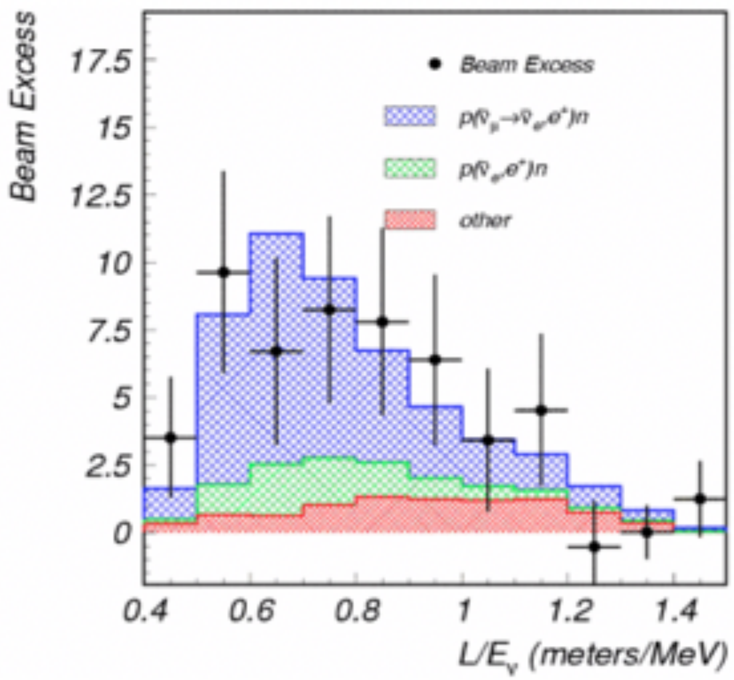
Baseline 30 m

E= [20 – 50] MeV

L/E ≈ 1 m/MeV

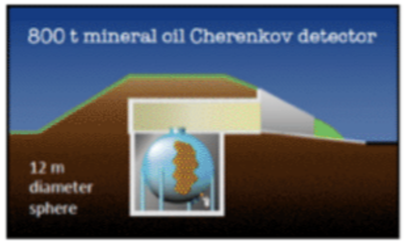
PRD 64 (2001) 112007

167 tons liquid scintillator



Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)

L/E similar to LSND



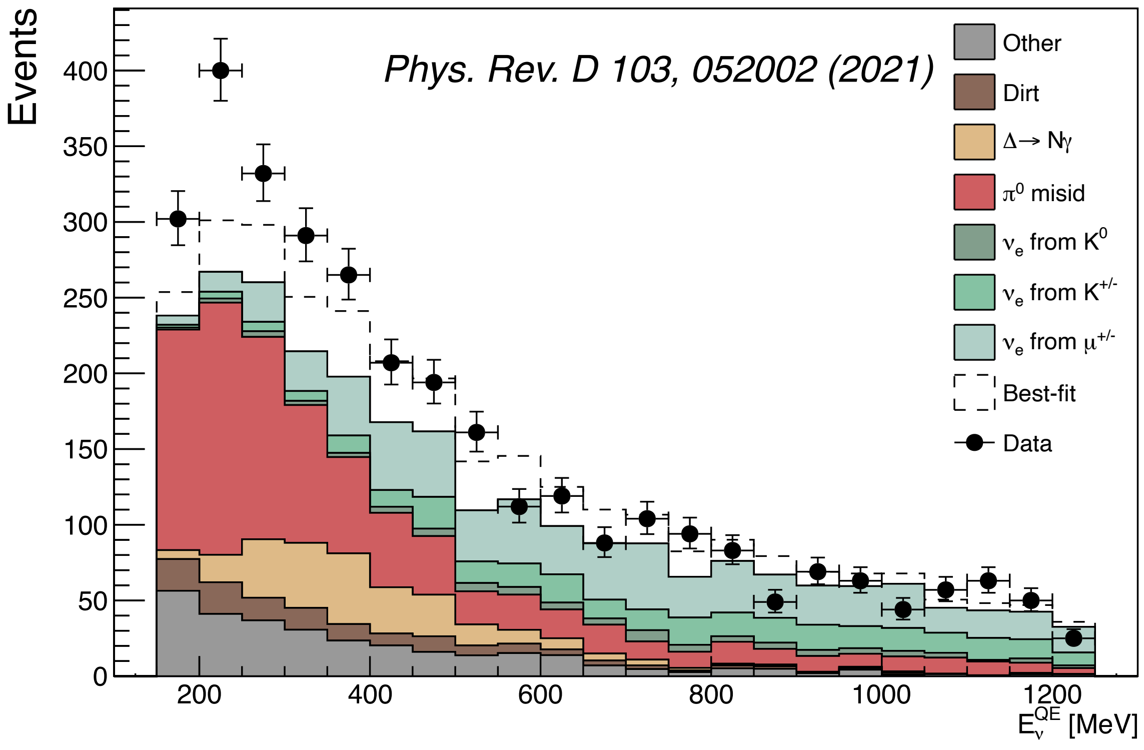
MiniBooNE

Baseline 540 m

E=[0 - 2] GeV

L/E ≈ 1 m/MeV

800 tons mineral oil

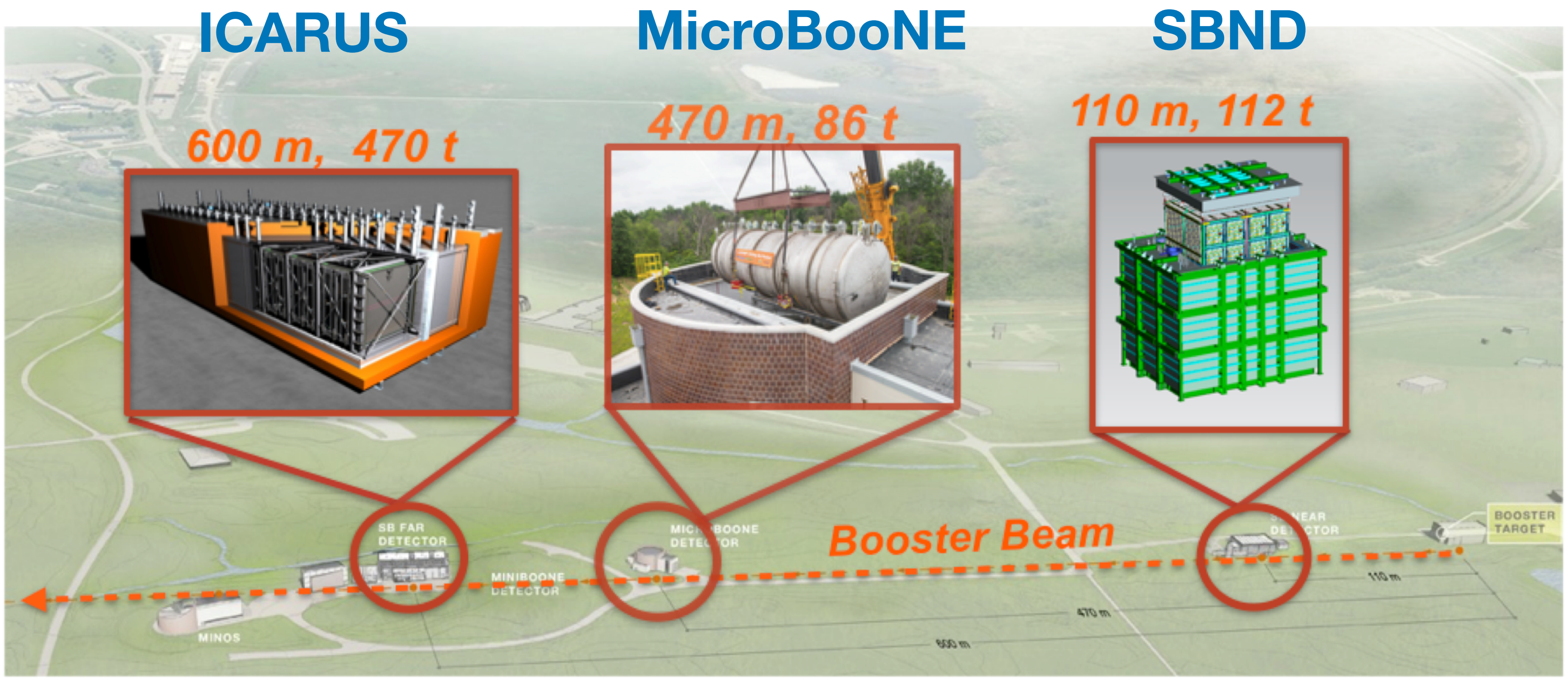


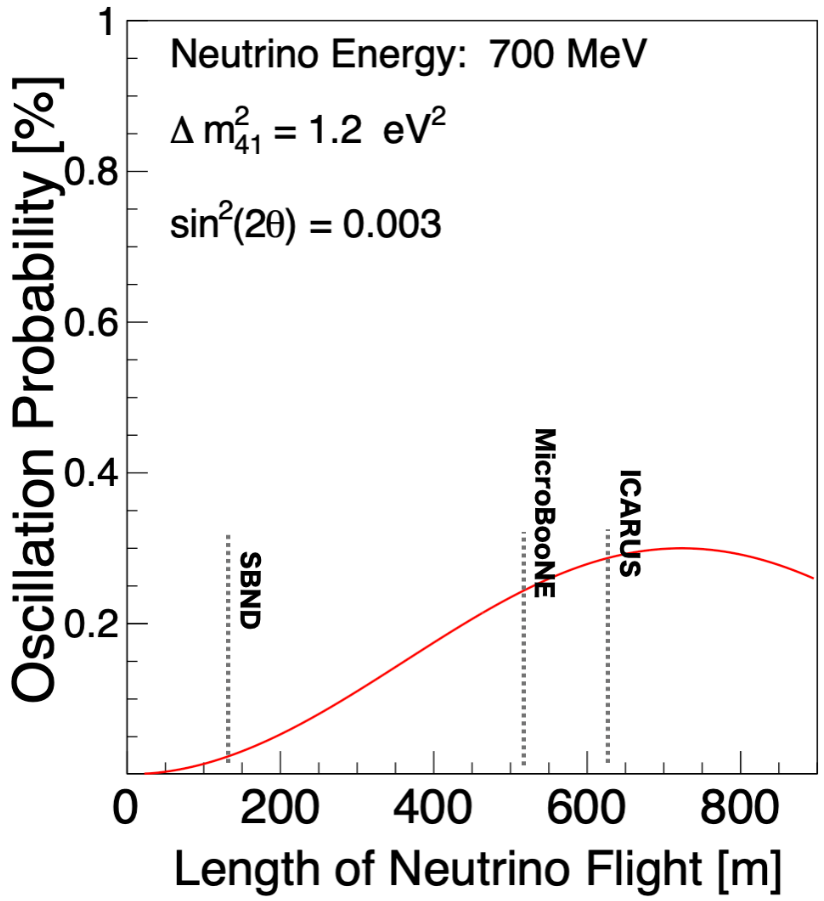
Phys. Rev. D 103, 052002 (2021)

- Sterile neutrino scenario is far from understood:
  - No evidence in ν_μ disappearance experiments (IceCube, NOvA, MINOS/MINOS+)
  - No precise indication from recent $\bar{\nu}$ flux measurement at reactors
  - Planck data/Big Bang cosmology: at most one further flavor with m_{new}<0.24 eV

Short Baseline Program (SBN)

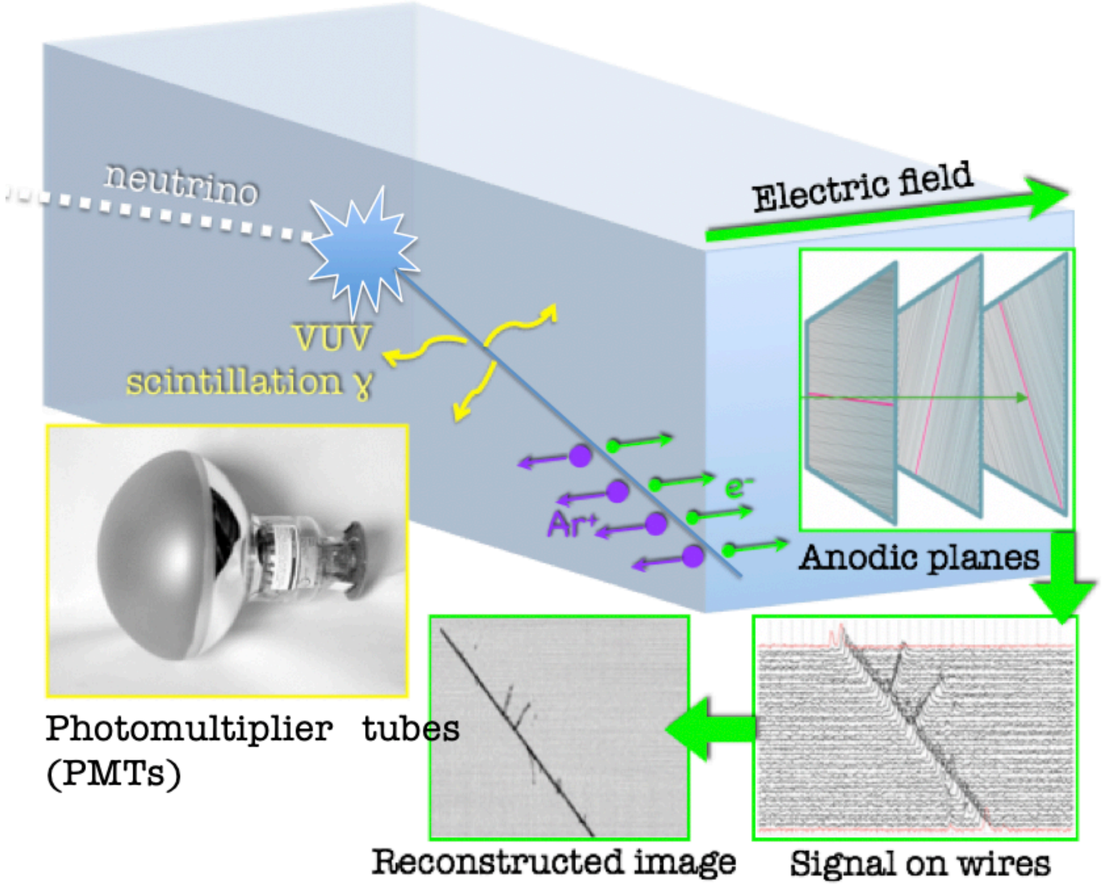
- Three LArTPC detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations
  - Measuring both appearance and disappearance channels
- Measure neutrino cross sections on liquid argon
- Same detector technology and neutrino beamline: reducing systematic uncertainties to the % level
  - A detection technique providing an excellent neutrino identification to reduce the backgrounds



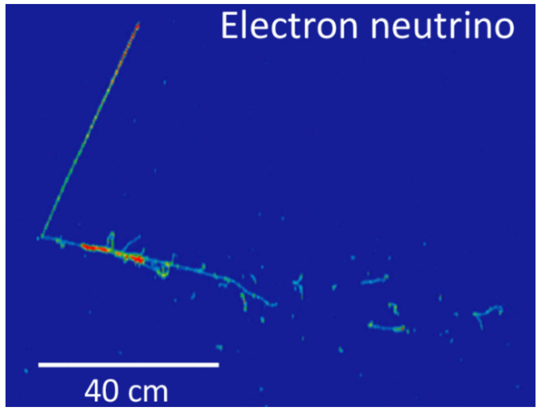


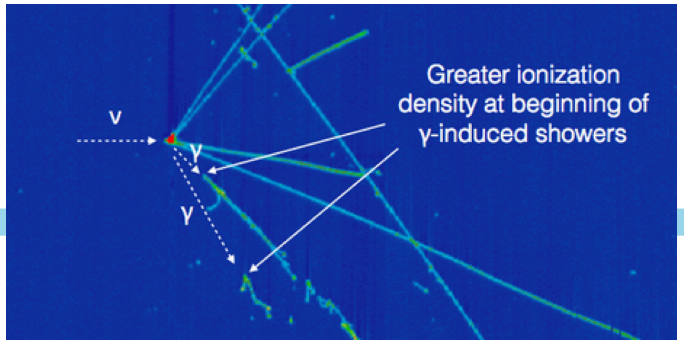
Liquid Argon TPC Detection Technique

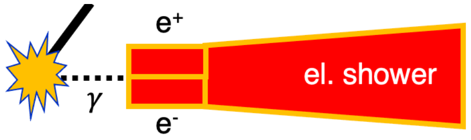
- Tracking device: precise 3D event topology with ~mm^3 resolution for ionizing particle
- Scintillation light detected by PMTs to provide event time and trigger
- Charged particles from neutrino interactions ionize the LAr, production ionization electrons drifting in 1 ms toward readout sense wires



- Powerful particle identification by dE/dx vs range
- Remarkable e/γ separation: calorimetric capabilities can distinguish e from γ at the shower start

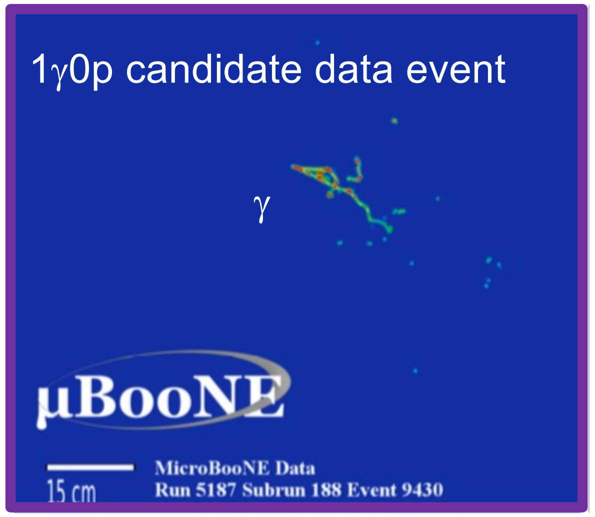


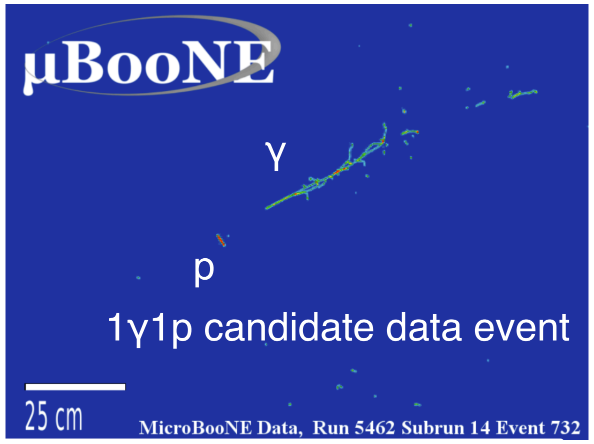


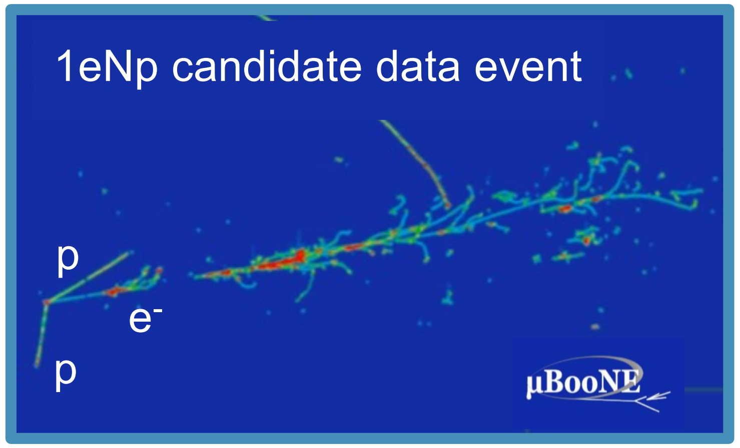


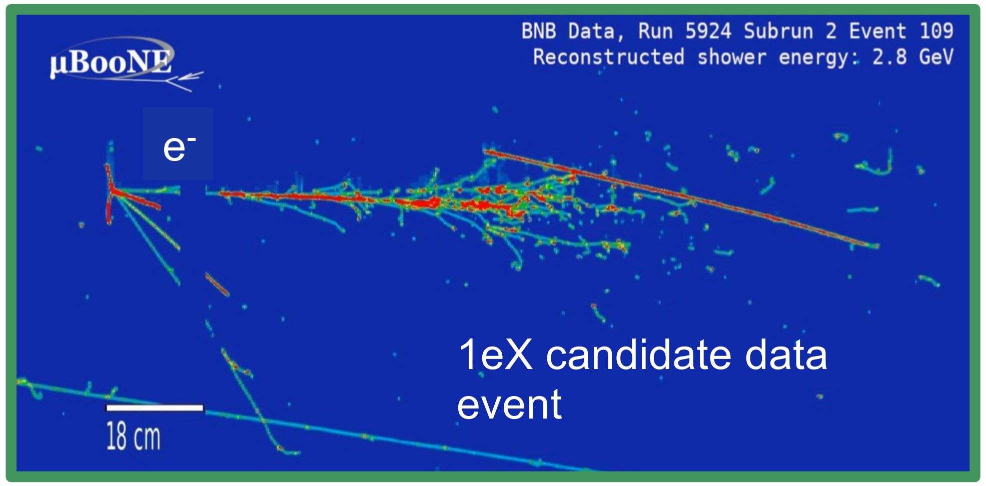
First Low-Energy Excess Search with MicroBooNE

- Four independent analyses
  - Single-photon analysis
    - NC Δ->Nγ hypothesis
      - 1γ0p, 1γ1p
  - Searches for a ν_e excess
    - Quasi-elastic kinematics (1e1p)
    - MiniBooNE-like final states (1eNp, 1e0p)
    - All ν_e final states (1eX)



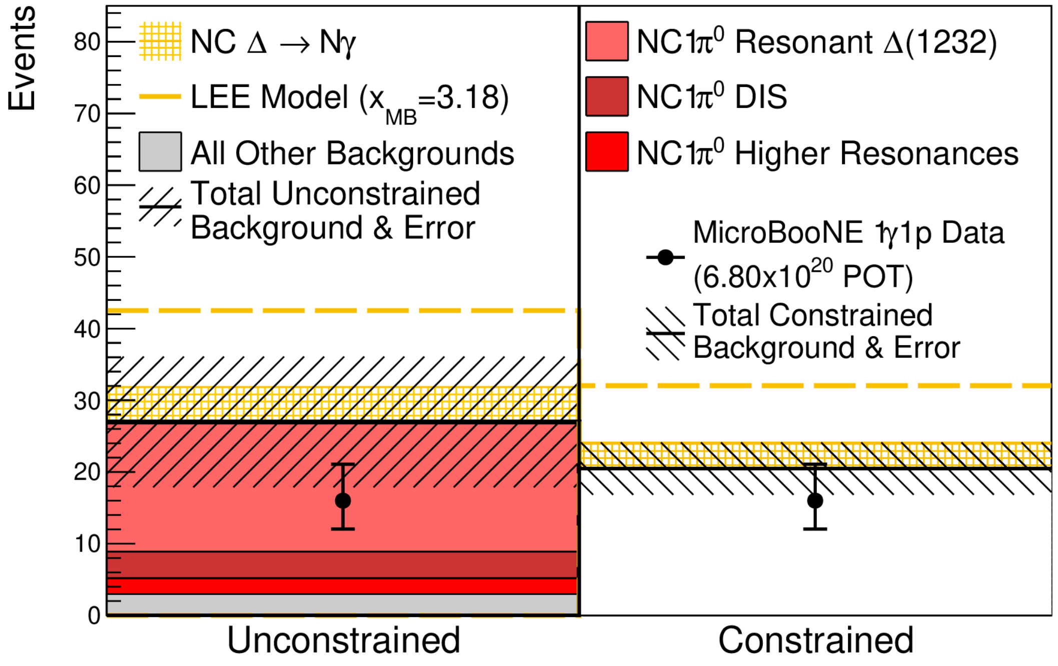






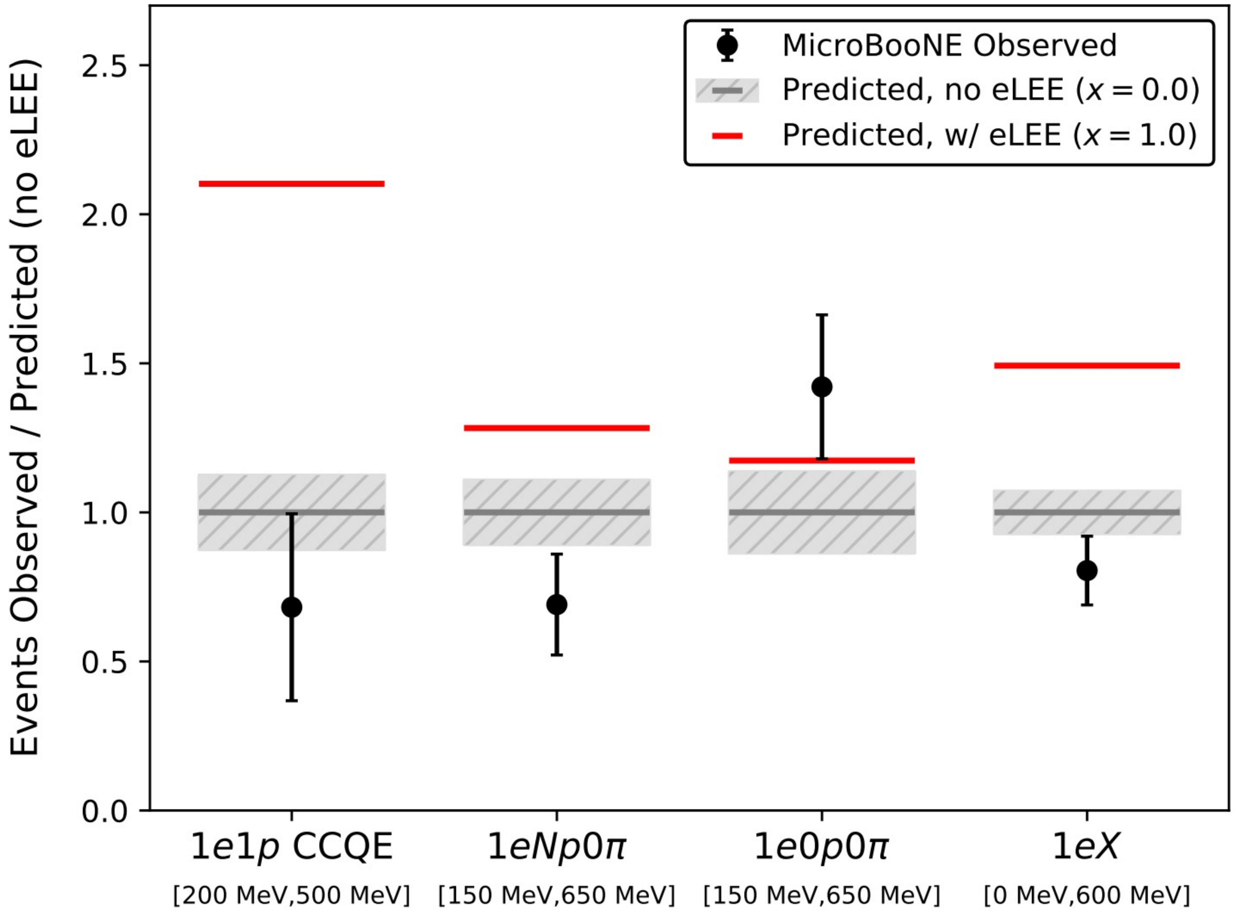
First Low-Energy Excess Search with MicroBooNE

- No evidence for an enhanced rate of single photons from NC Δ->Nγ decay above nominal MC predictions



https://arxiv.org/pdf/2110.14080.pdf, https://arxiv.org/pdf/2110.14065.pdf, https://arxiv.org/pdf/2110.13978.pdf

- Observe ν_e candidate events in agreement, or below, the predicted rates
- Reject the hypothesis that ν_e CC interactions are fully responsible for the MiniBooNE excess at > 97% C. L. in all analyses

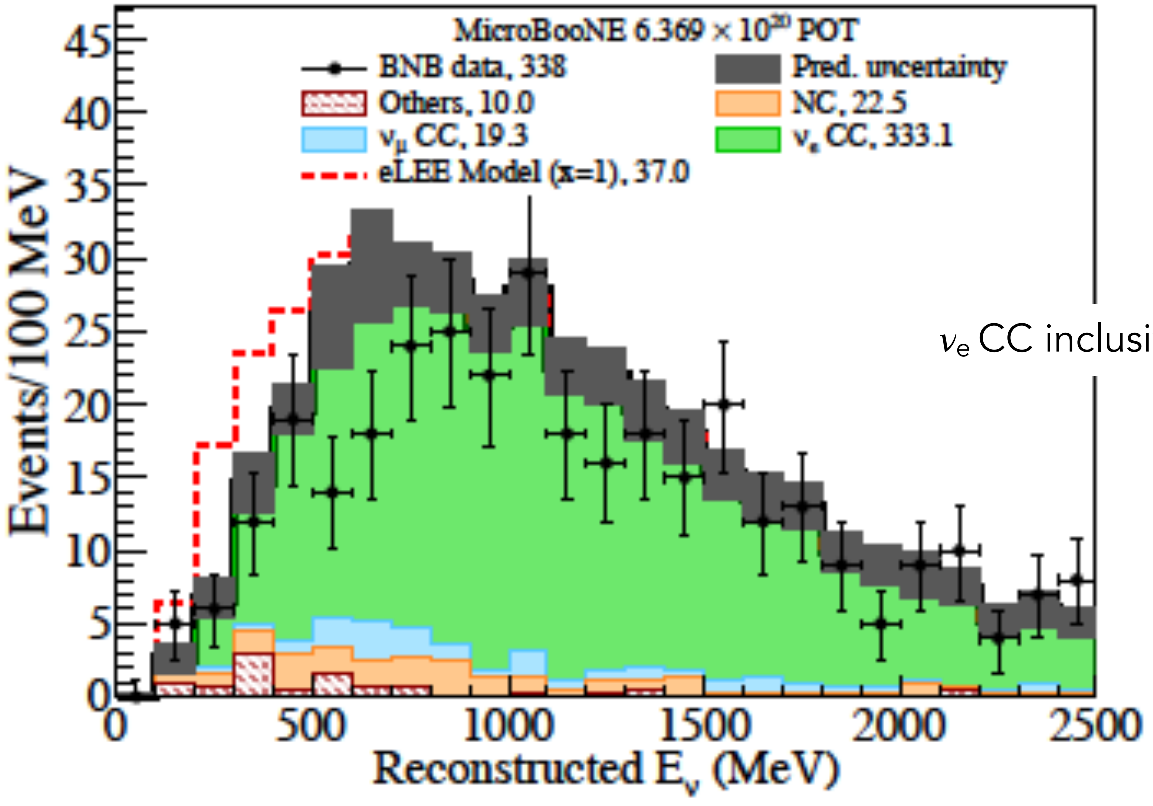


https://arxiv.org/abs/2110.14054

First Low-Energy Excess Search with MicroBooNE

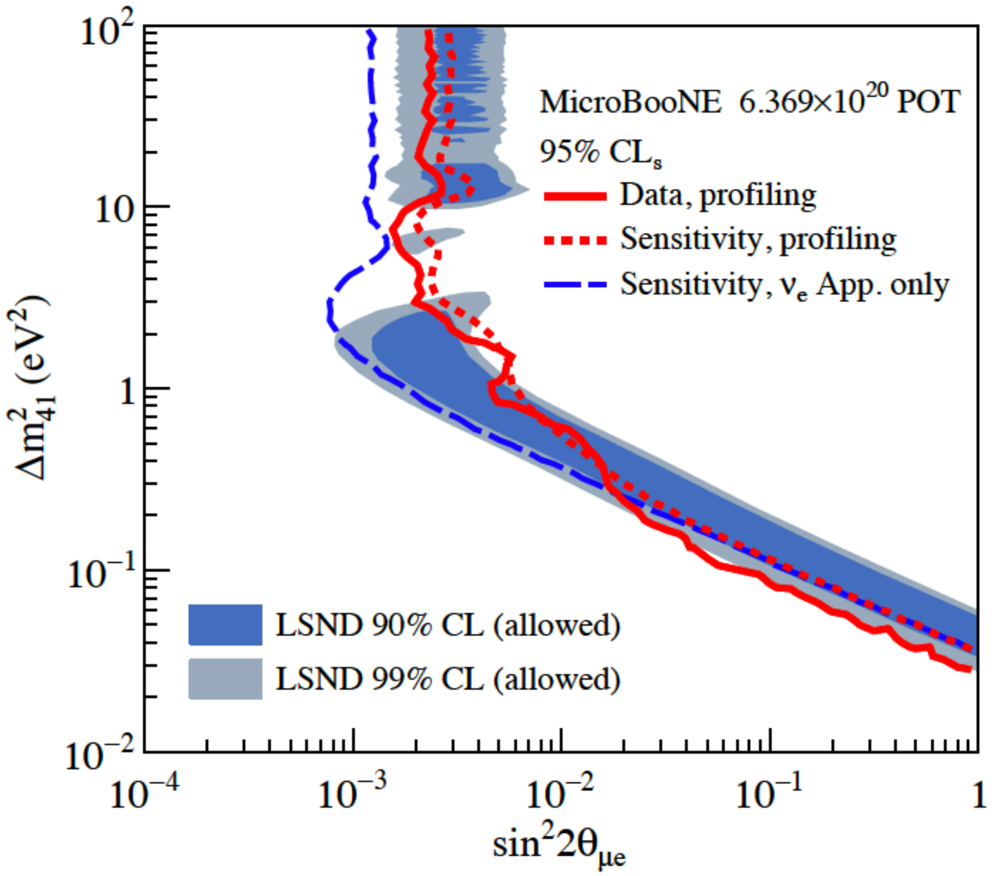
- The MicroBooNE experiment presented the results of the first analyses searching for an excess of low-energy electromagnetic events

P. Abratenco et al., Phys. Rev. Lett. 128, 241801



ν_e CC inclusive

P. Abratenco et al., https://arxiv.org/abs/2210.10216

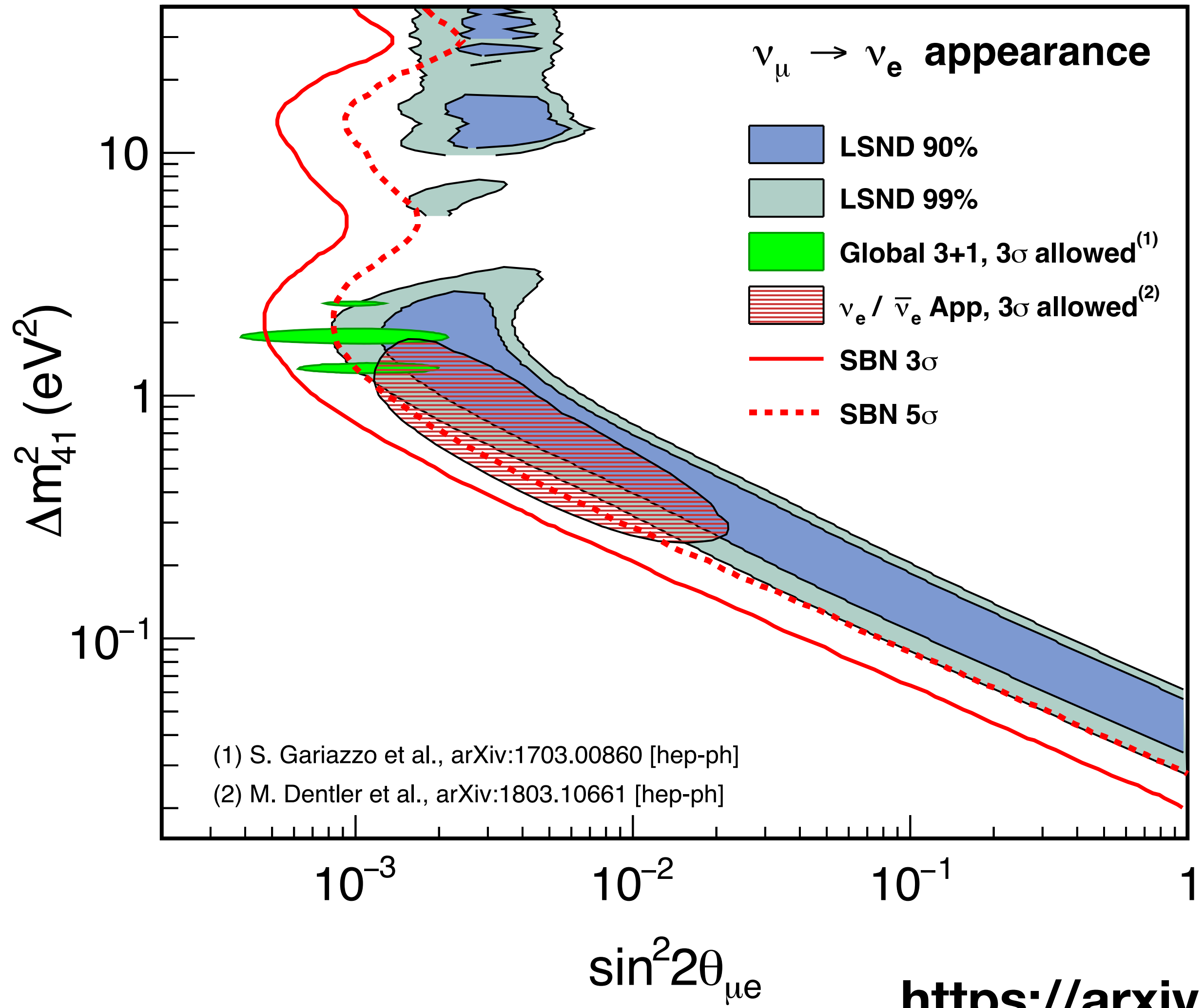


- No hints of an electromagnetic events excess, but results do not rule out existence of sterile neutrinos

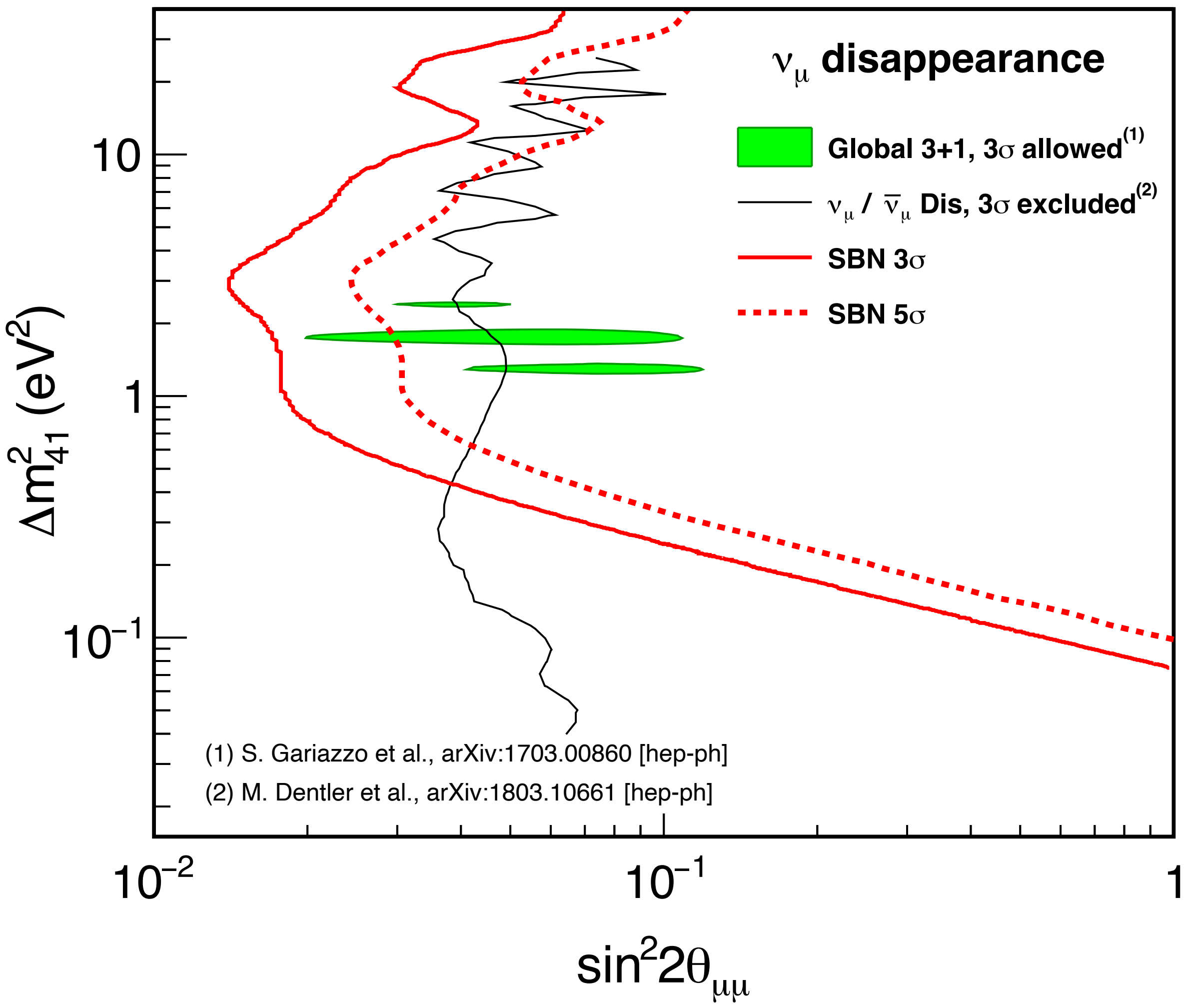
Sensitivity of SBN program

- Searches for both ν_e disappearance and ν_μ appearance

ν_e appearance



ν_μ disappearance

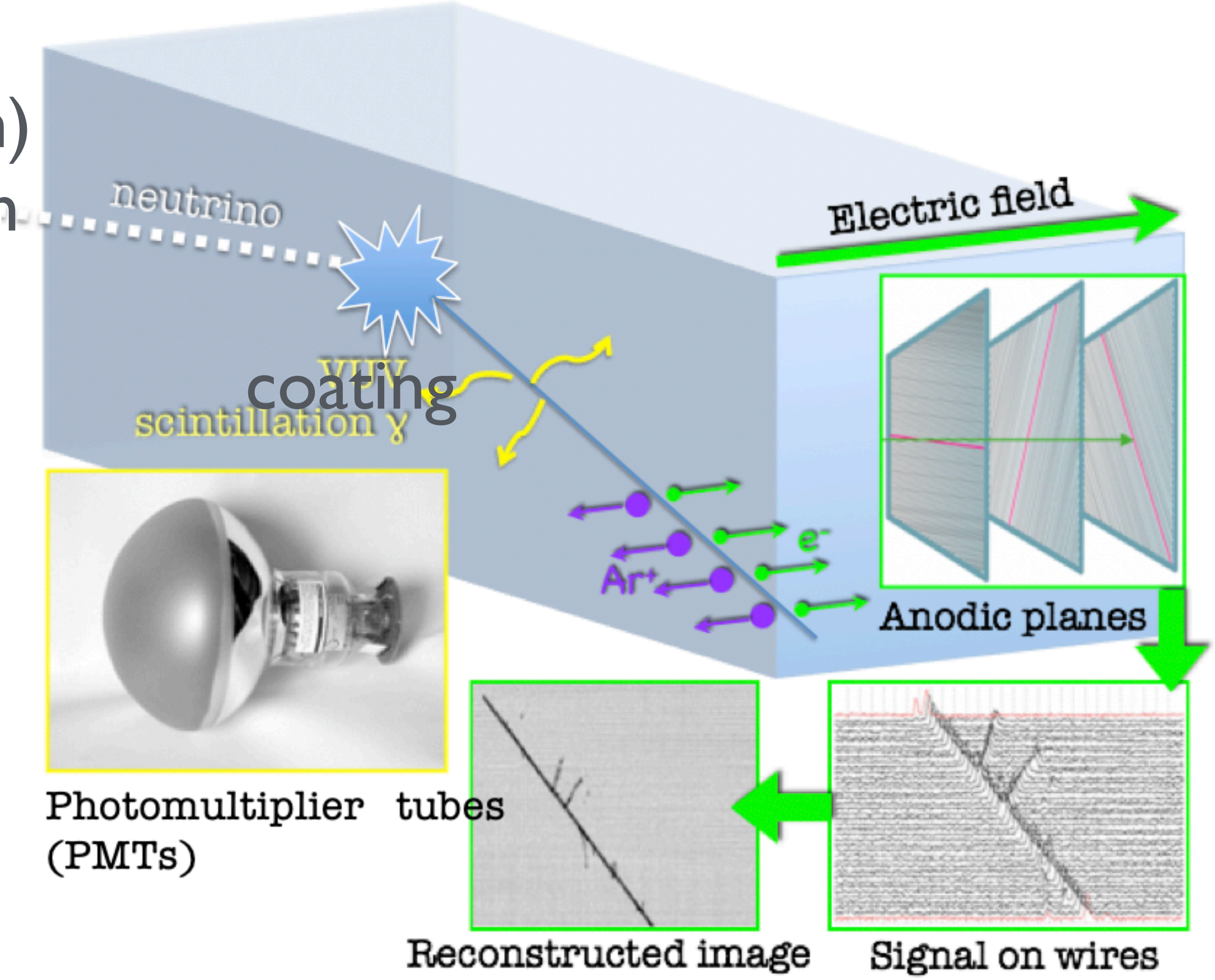


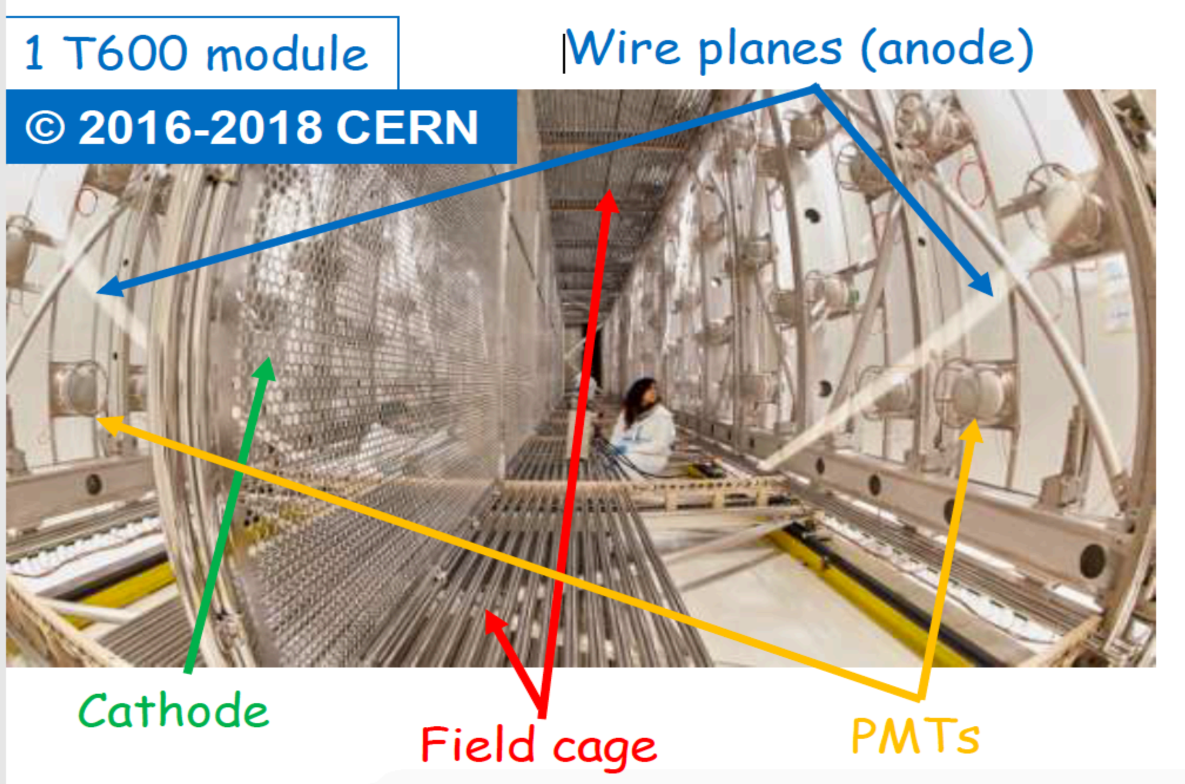
https://arxiv.org/pdf/1903.04608.pdf

- SBN cover much of the parameters allowed by past anomalies at >5σ significance

ICARUS (Imaging Cosmic And Rare Underground Signals)

- Liquid Argon technology for ν physics was proposed in1977 by C. Rubbia
- Many years of R&D at INFN/CERN culminated in first large-scale experiment at LNGS underground labs
- 2 TPCs per module with central cathode, 1.5 m drift, E_D=0.5 kV/cm, Δt~1 ms
- 3 readout wire planes (2 induction+collection) per TPC, ~54000 wires at 0, 60 degrees, 3 mm pitch: a continuous read-out
- 360 (8” PMTs)



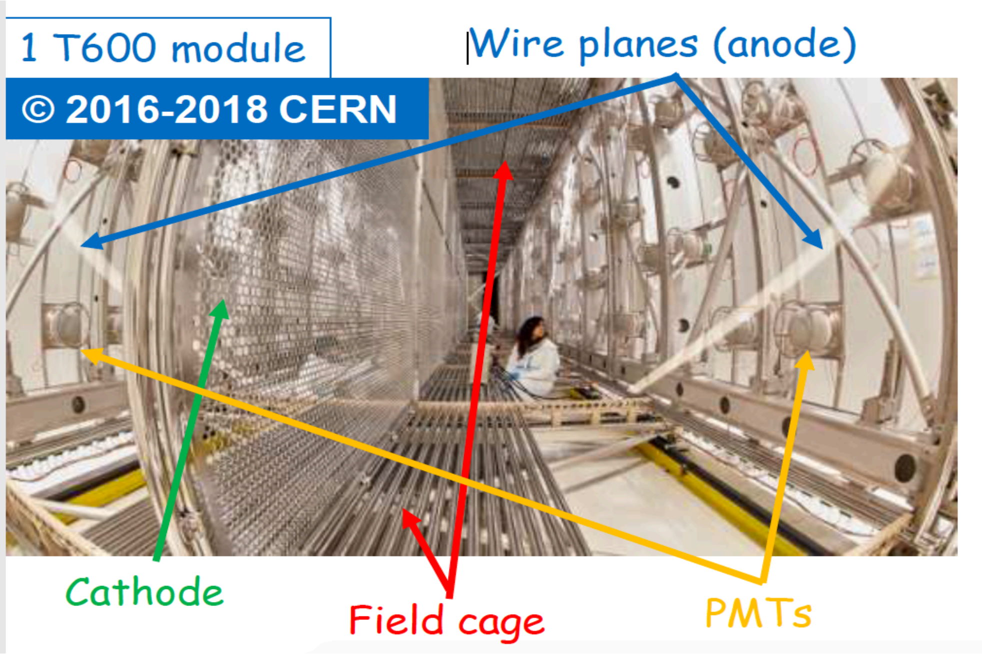


© 2016-2018 CERN

ICARUS at FNAL

- Several technology improvements were introduced, aiming to further improve the achieved performance ICARUS previous runs: new cold vessels, improvement of the cathode planarity, higher performance read-out electronics and upgrade of the PMT system
- ICARUS began commissioning in 2020, collecting first neutrino data in June 2021

TPC



PMT

side CRT

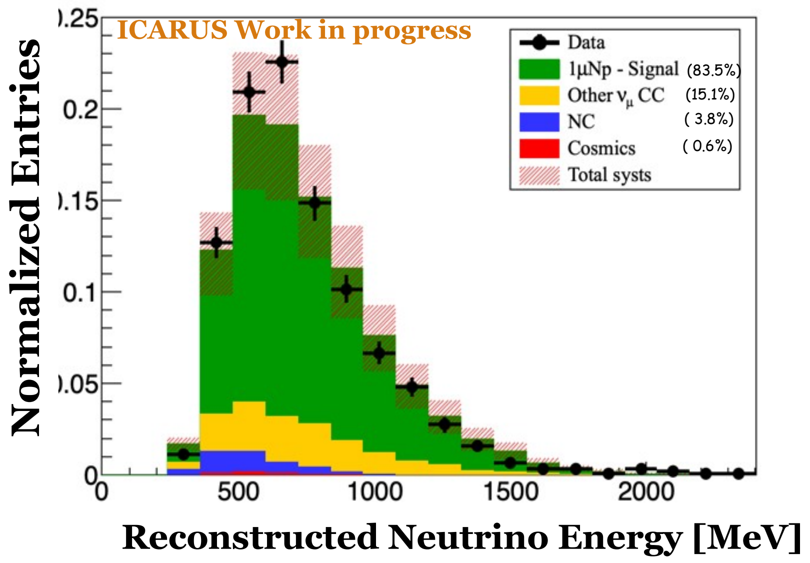
Top CRT

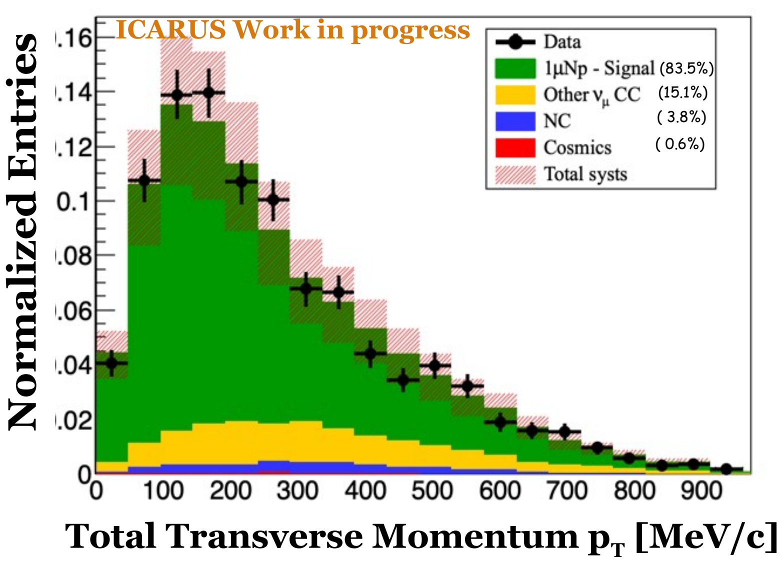
Neutrino Oscillation Analysis

- ICARUS is pursing single-detector neutrino oscillation measurement
- Studying events from BNB with 1μ Nproton and 0π, two approaches traditional reconstruction (Pandora) and machine learning based reconstruction

Pandora
1μNp0π Selection

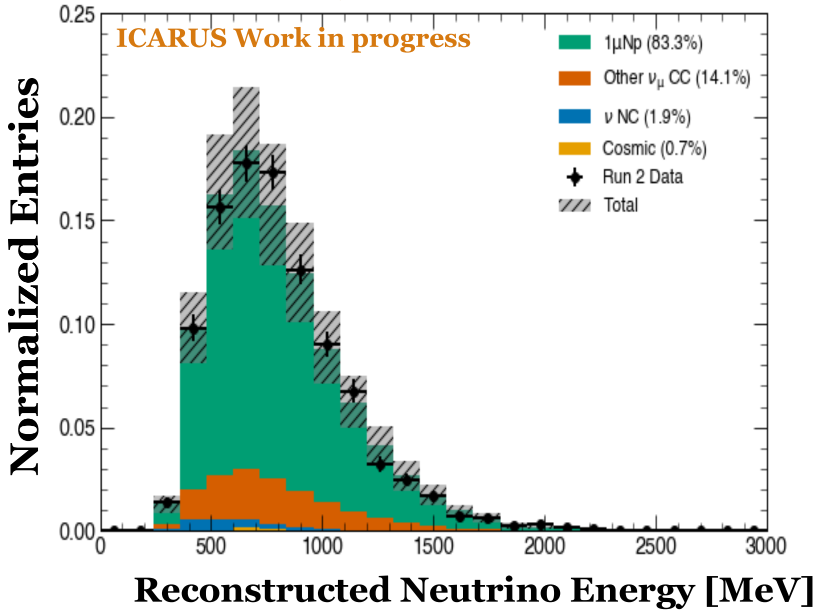
Efficiency ~ 50%
Purity ~ 80%

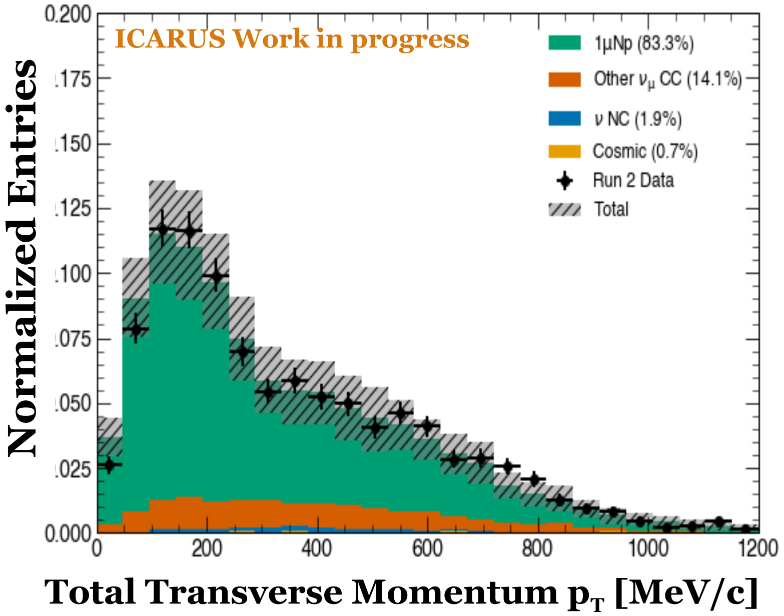




ML (SPINE)
1μNp0π Selection

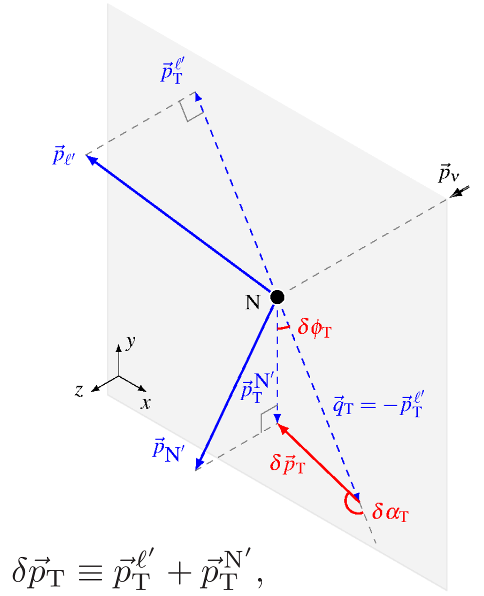
Efficiency ~ 75%
Purity ~ 80%





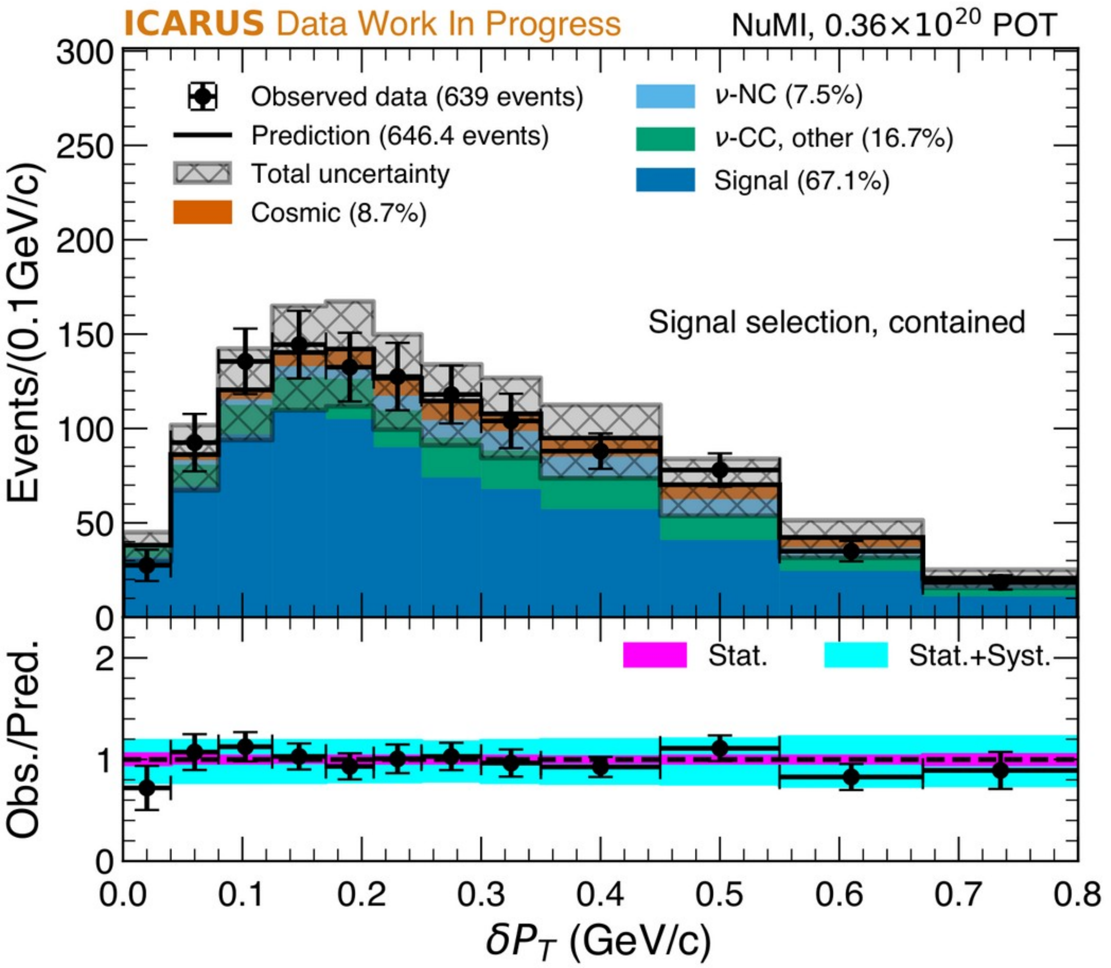
CC 0π Event Selection for fully contained Events

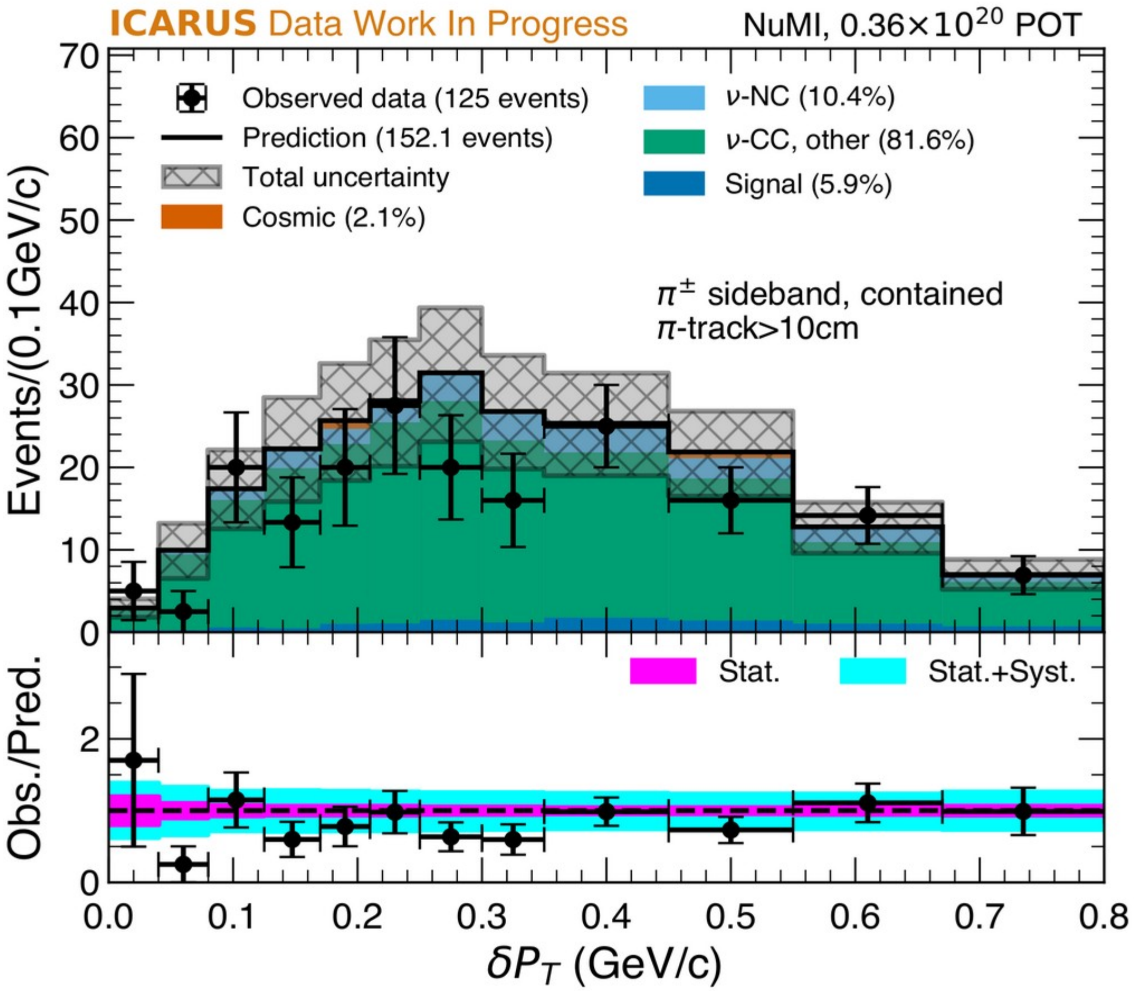
- First cross section measurement: 1μ+Nproton+0π
- Observables δP_T and $\delta\alpha_T$, sensitive to initial and final state effects
- Events with contained muons and protons
- Main background is events with pions



$$\delta\vec{p}_T \equiv \vec{p}_T^{\ell'} + \vec{p}_T^{N'},$$

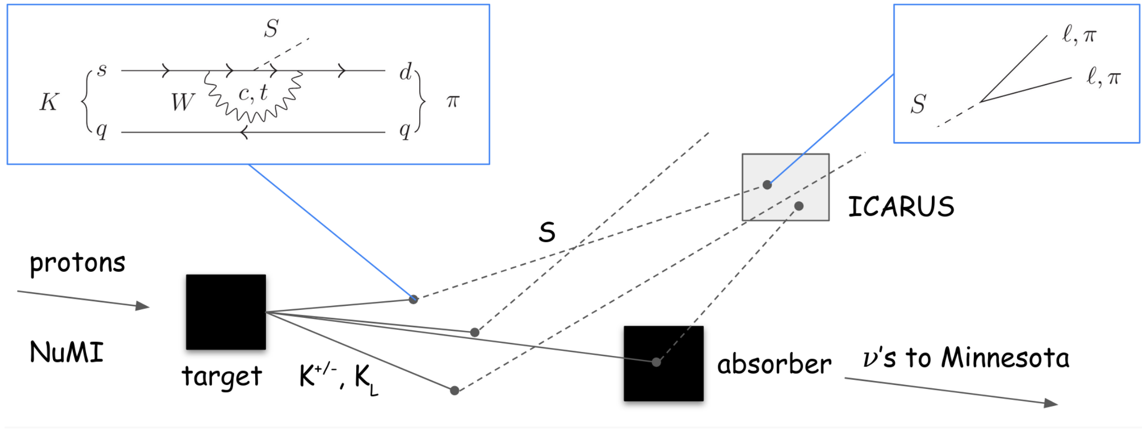
$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\ell'}\cdot\delta\vec{p}_T}{p_T^{\ell'}\delta p_T},$$

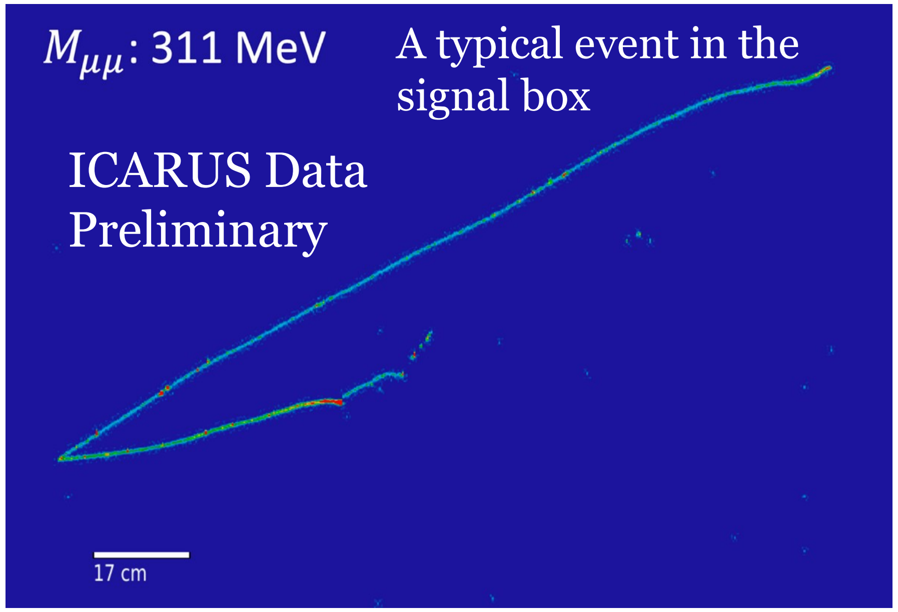




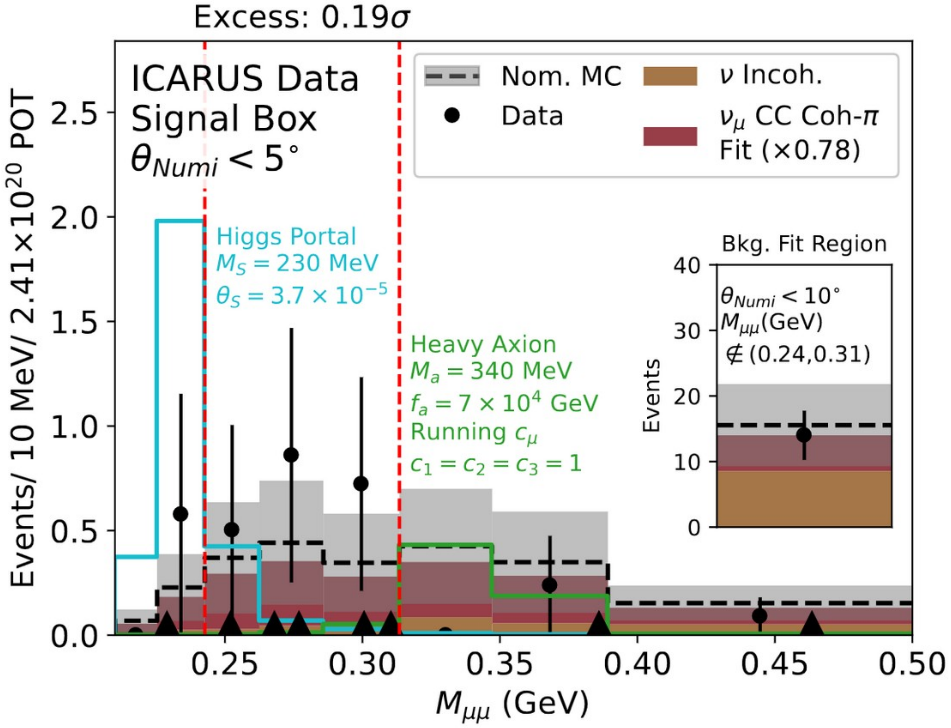
BSM Searches with NuMI

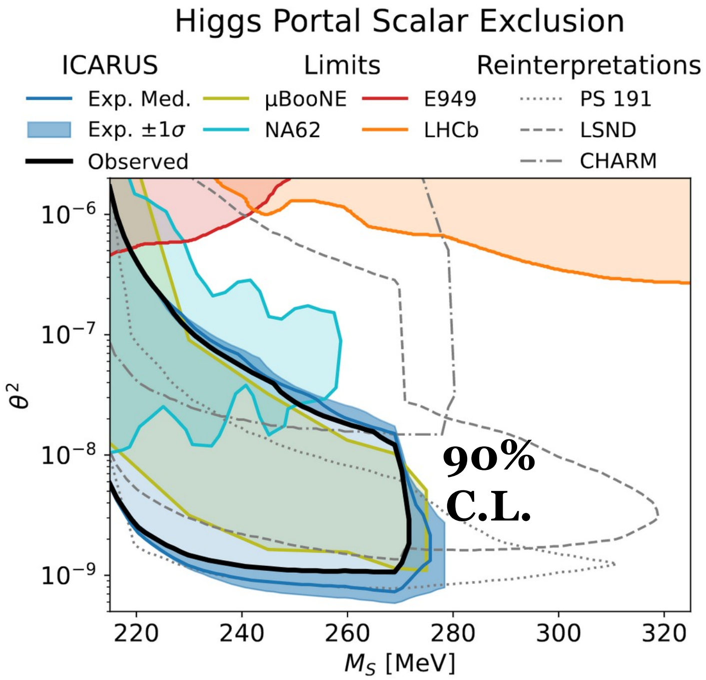
- Certain BSM searches benefit from sitting off-axis such as kaon coupled Higgs portal scalars

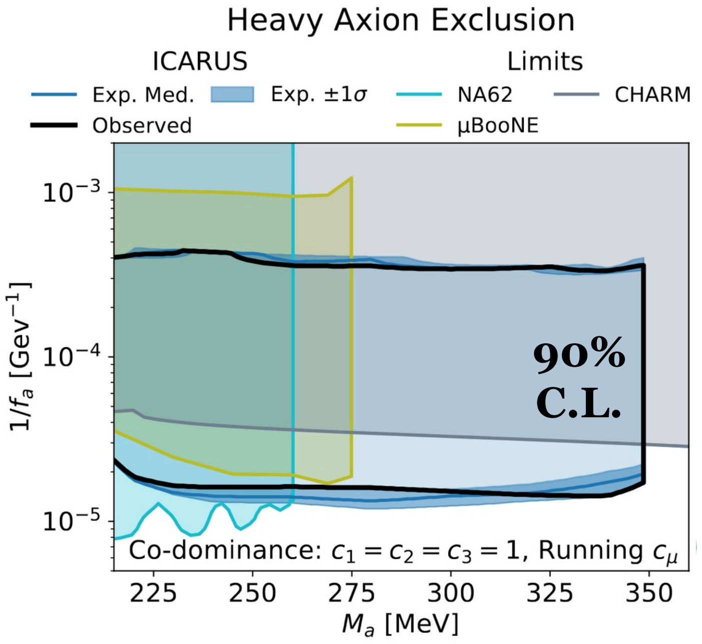




- BSM models considered so far, both involving kaon decay and contained dimuon final states: Higgs Portal Scalar and Heavy QCD Axion
- Topology: events with two muons, search: look for resonance t specific value



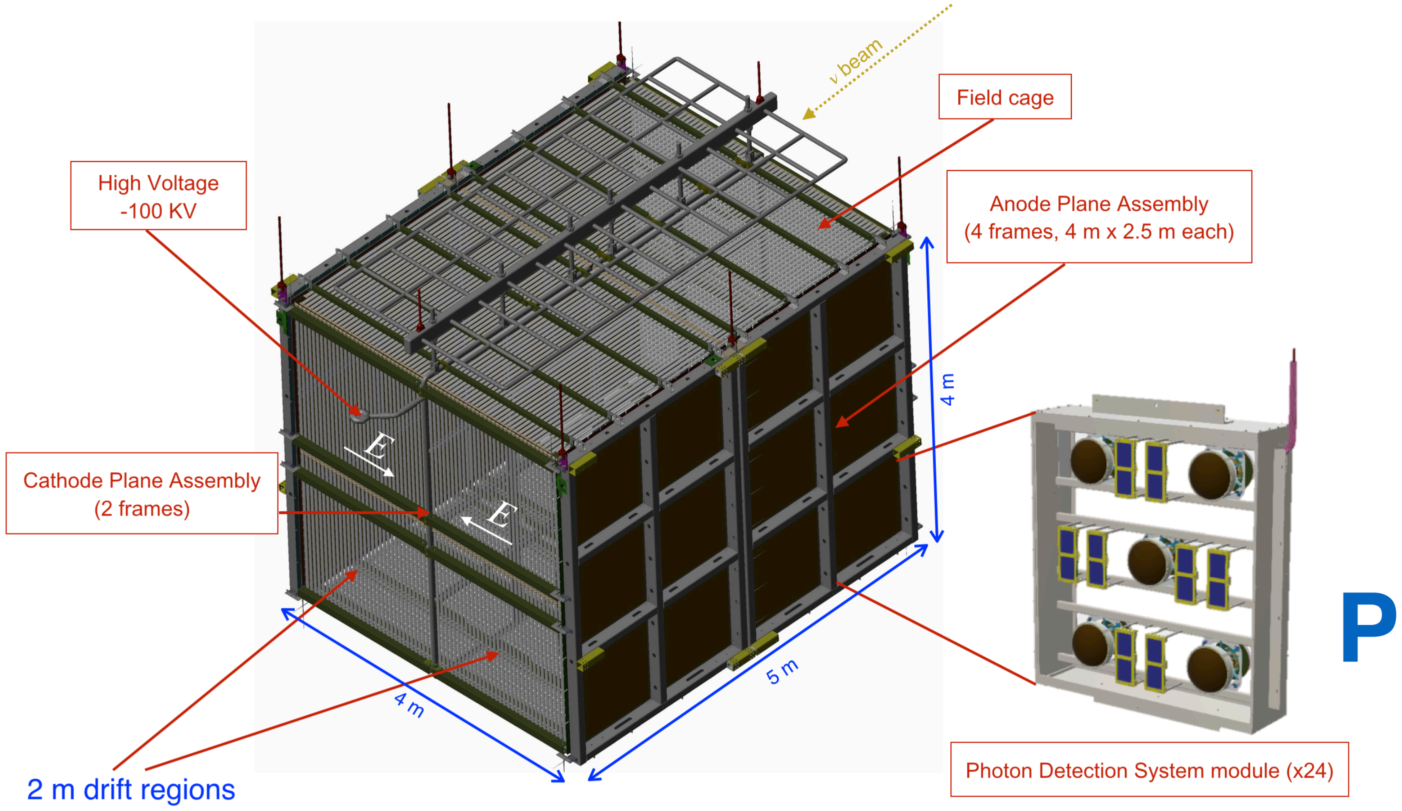




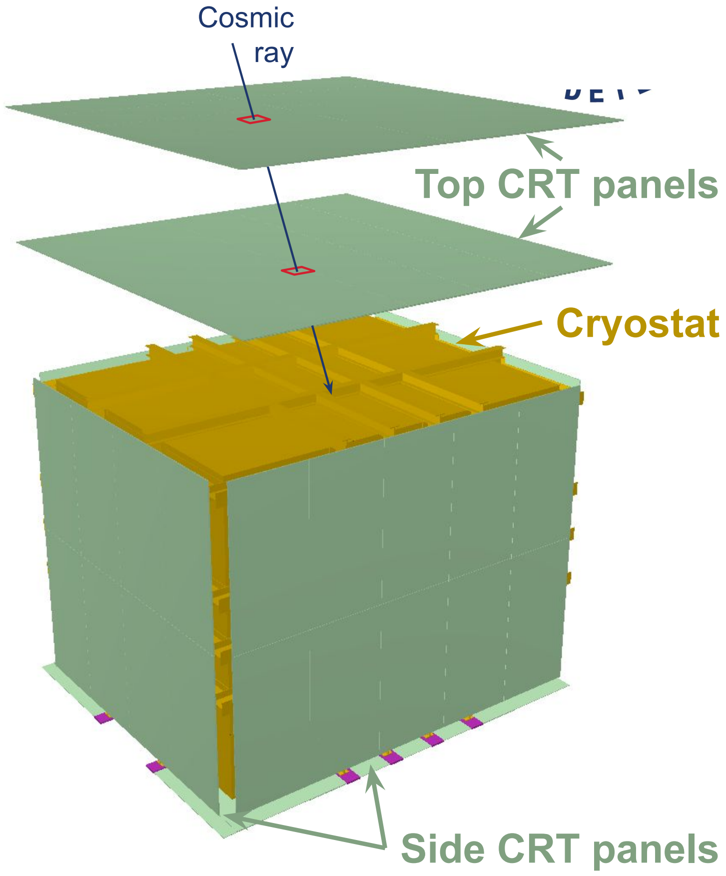
SBND Experiment

- The SBND detector contains three systems, a TPC system, a photon detector system (PDS) with 120 PMTs and 192 X-Arapucas and a Cosmic Ray Tagger (CRT)
- SBND is located on the surface

TPC



PDS

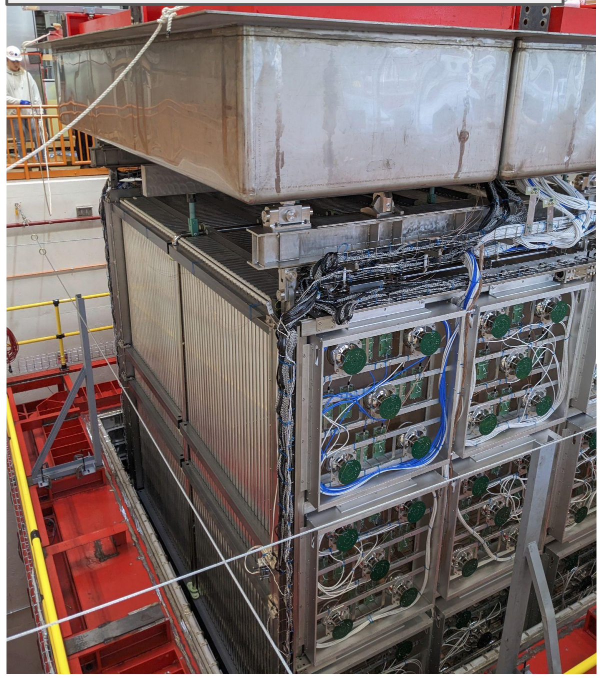


CRT

SBND Detector Installation

APA Assembly, Dec. 2018

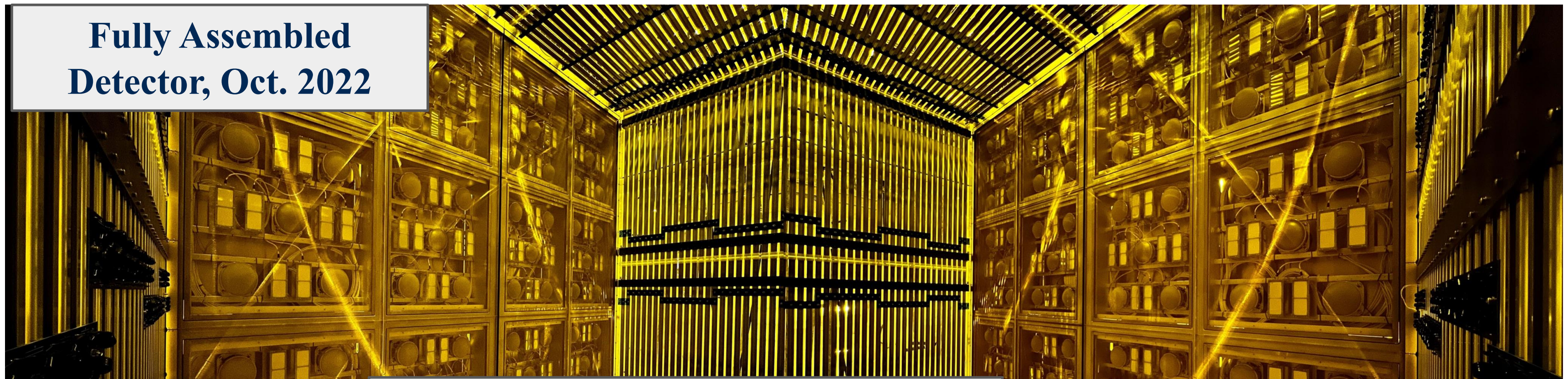
Detector inserted in the cryostat, Apr. 2023



Detector inside the Cryostat, Apr. 2023

Cathode HV Feedthrough Installation, Jul. 2023

Fully Assembled Detector, Oct. 2022

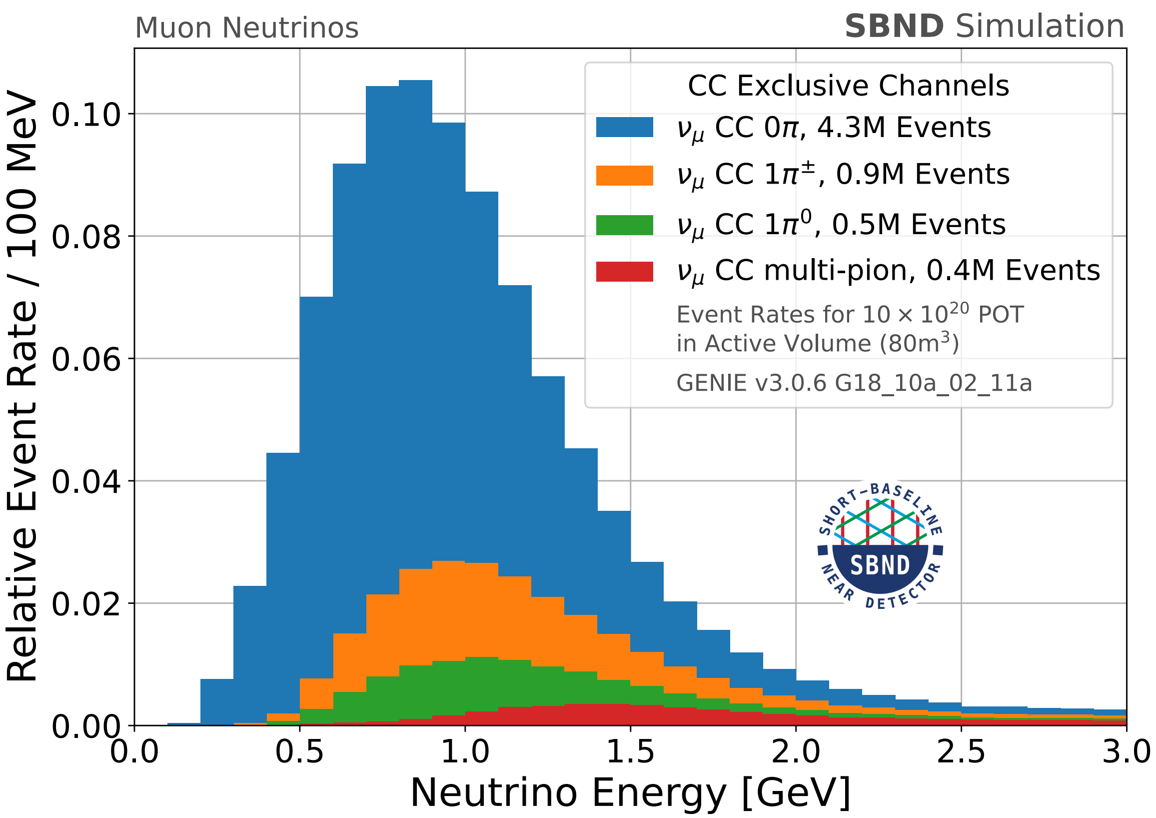


Towards commissioning: Installing cables

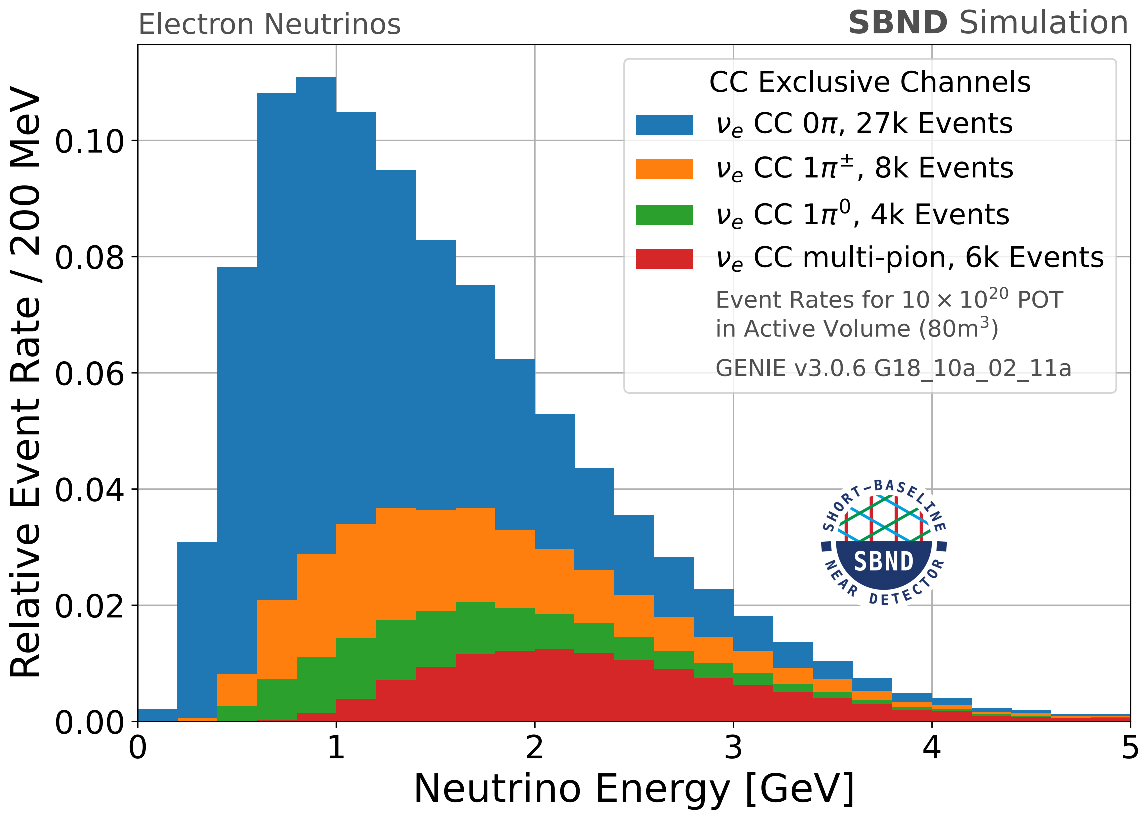
Towards commissioning: Purity monitors

Neutrino Interactions at SBND

- New data sets will reach the order of millions of neutrino interactions for single channels



1.5M ν_μ CC events in 1 year

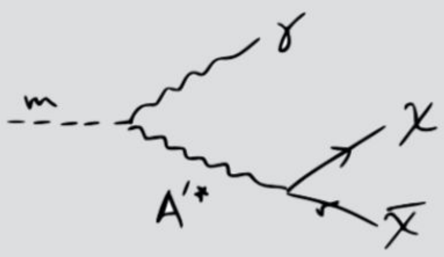


12k ν_e CC events in 1 year

BSM Searches with Booster

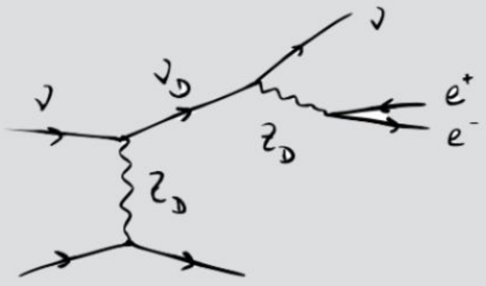
- Rich BSM searches: Neutrino tridents, dark matter, Higgs portal, heavy neutral lepton, millicharged particles…

Light Dark Matter



Romeri Kelley Machado PRD 2019

Dark Neutrinos

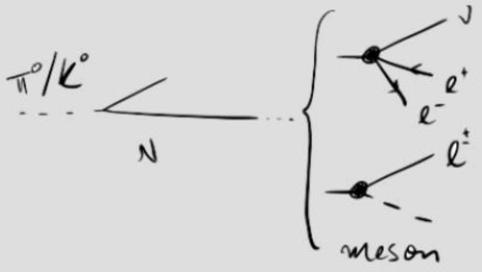


Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Millicharged Particles

Magill, Plestid, Pospelov, Tsai, PRL 2019
Harnik Liu Palamara, JHEP 2019

Heavy Neutral Leptons

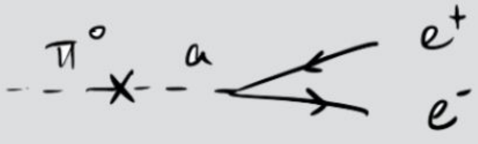


Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

Higgs Portal Scalar

Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Axion-like Particles

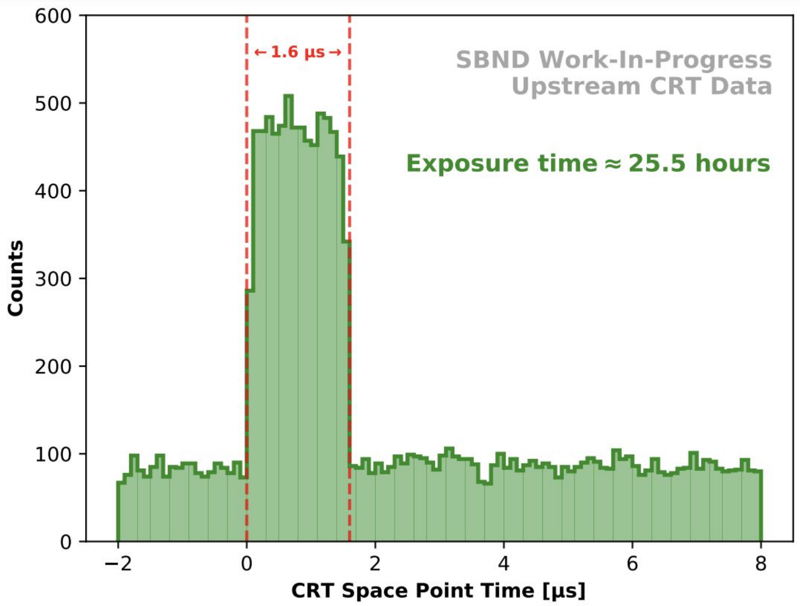


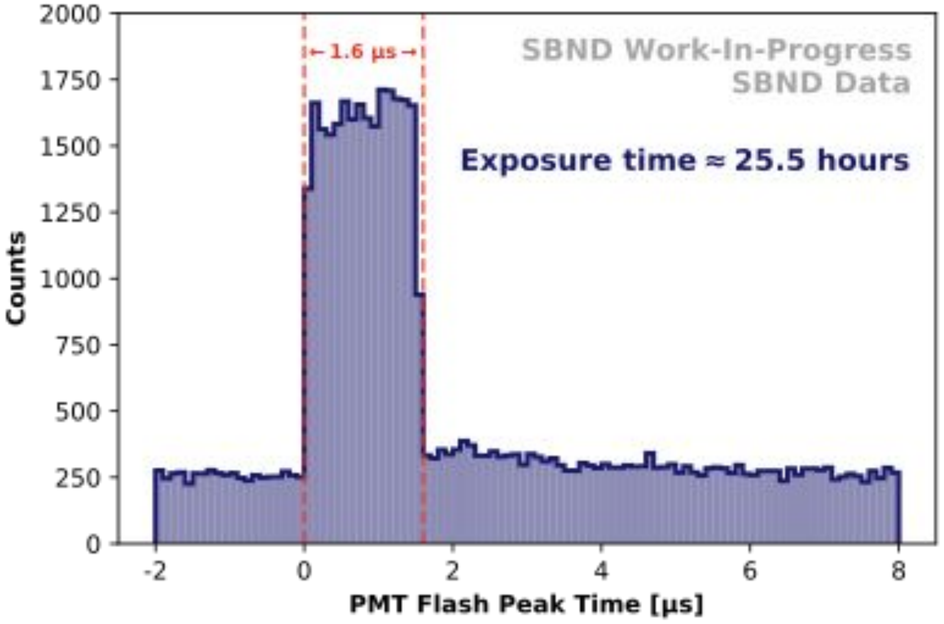
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

Image credits: Pedro Machado, Marco Del Tutto

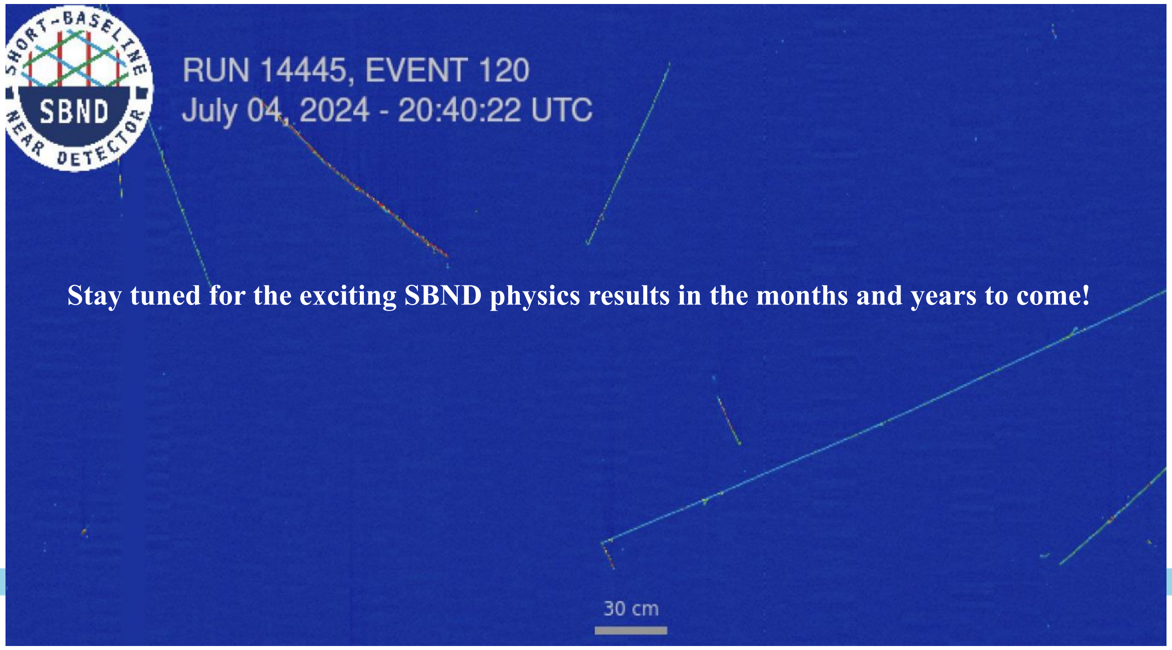
Detector Commissioning

- Starting to commission the different systems TPC, PMT and CRT
  - 1.6 μ wide per reflecting the duration of the BNB spill





First neutrino interactions



Stay tuned for the exciting SBND physics results in the months and years to come!

Summary

- Neutrinos are great probes to answer fundamental questions about the nature of matter and the evolution of the universe

- Several discoveries since the first experimental evidence of neutrinos

- Fermilab has excellent program looking to answer the remaining questions in neutrino oscillations

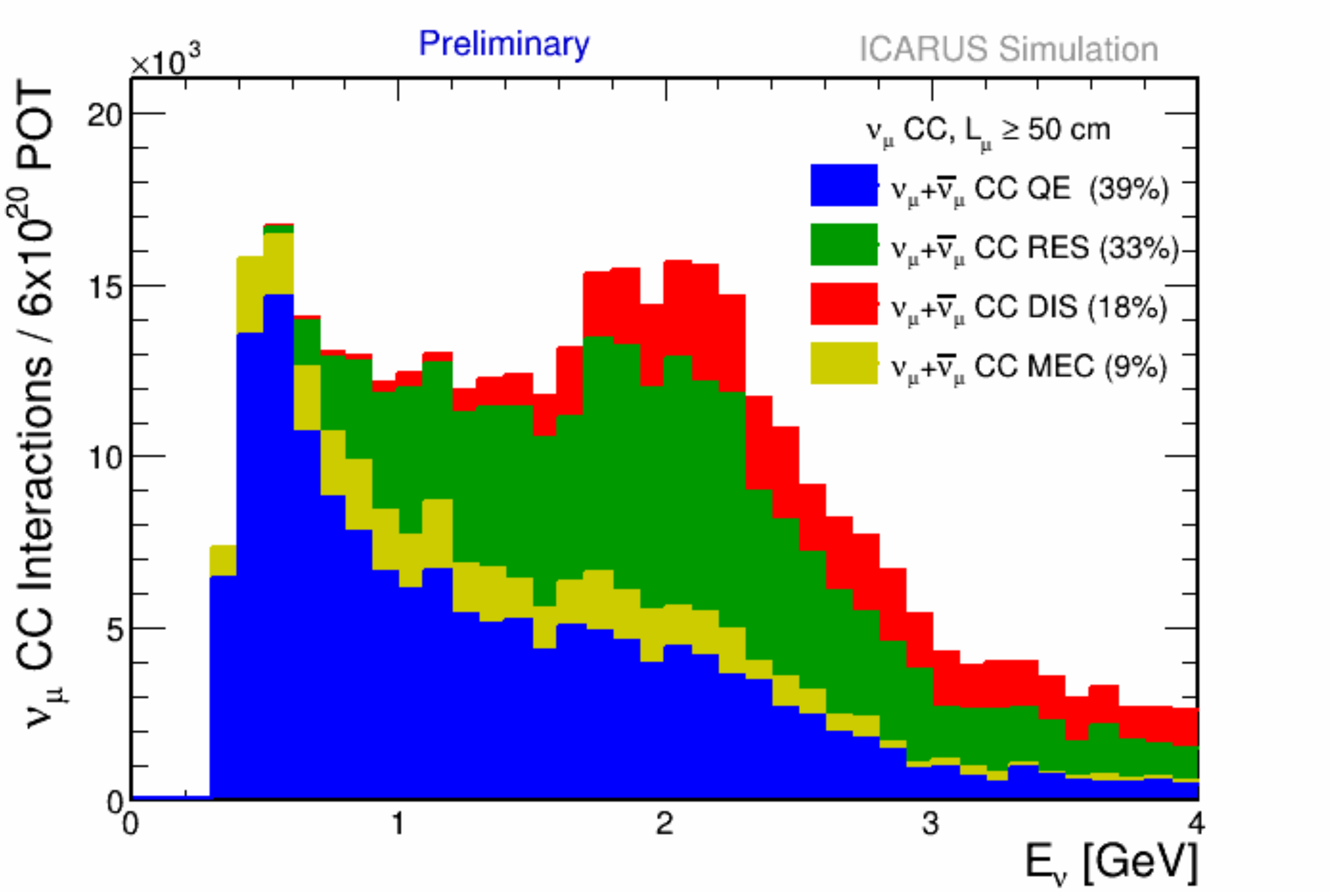
- Long baseline program: measuring the three mixing angles, mass hierarchy and searching for CP violation
  - DUNE is making excellent progress with the detector prototypes and design

- The SBN detectors will perform a world-leading search for eV-scale sterile neutrino by looking at both appearance and disappearance channels
  - Rich physics program of neutrino-argon scattering measurements and BSM physics
  - SBND completed the construction of the detector and starting the commissioning
  - ICARUS is collecting physics quality data with Fermilab neutrino beams and making the first measurements

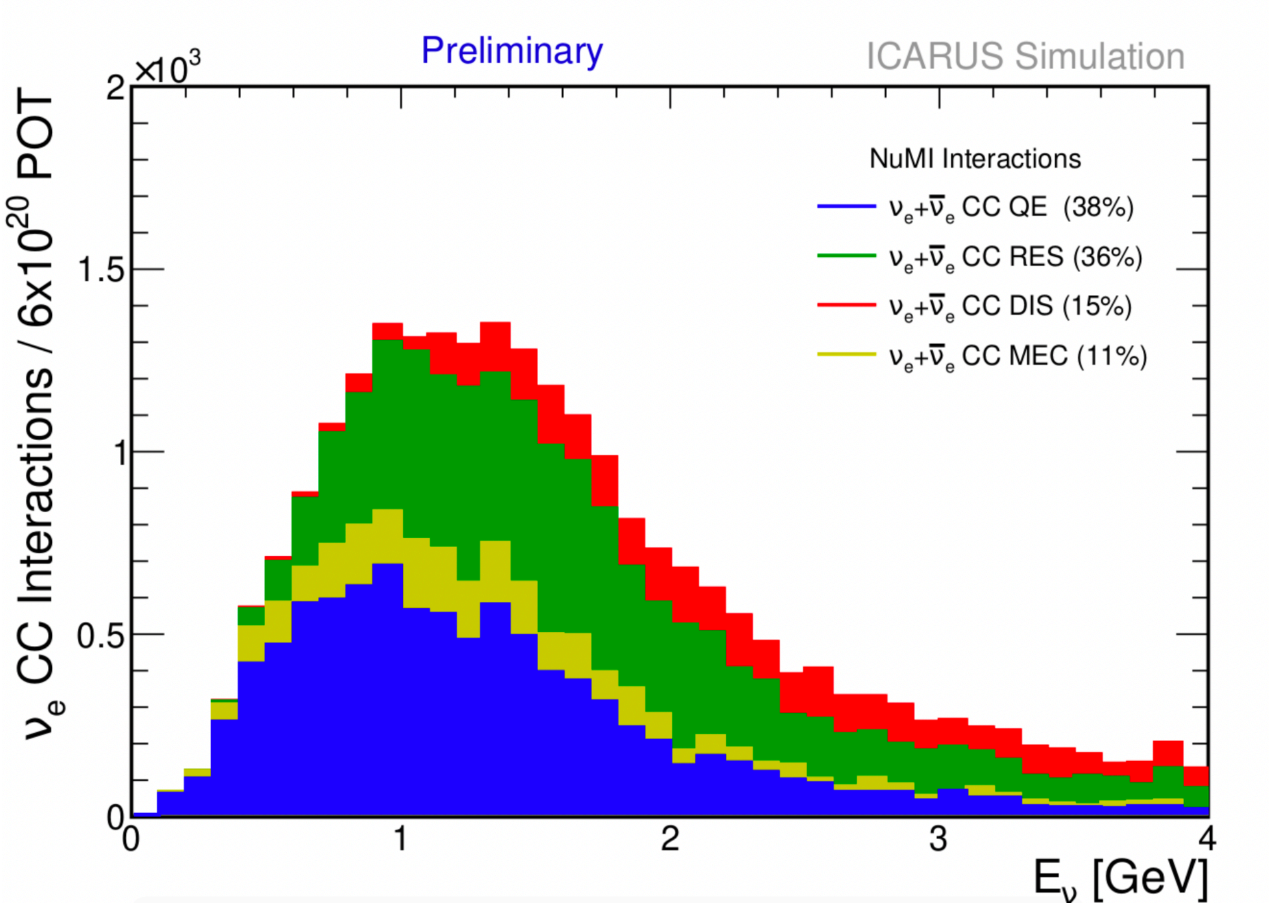
Neutrino Interactions from NuMI off axis at ICARUS

- Excellent statistics to make cross section measurements for quasi-elastic and pion production scattering, for both electron and muon neutrinos

Muon Neutrino



Electron Neutrino

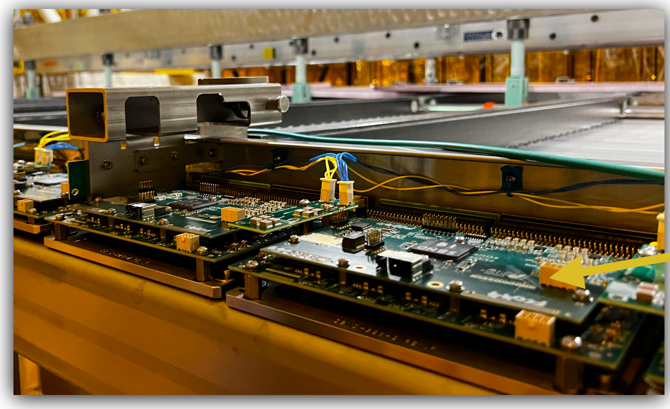


Expected event rates for 1 year

Muon neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	186400	40262	142780	77060
Electron neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	8256	2000	7905	3678

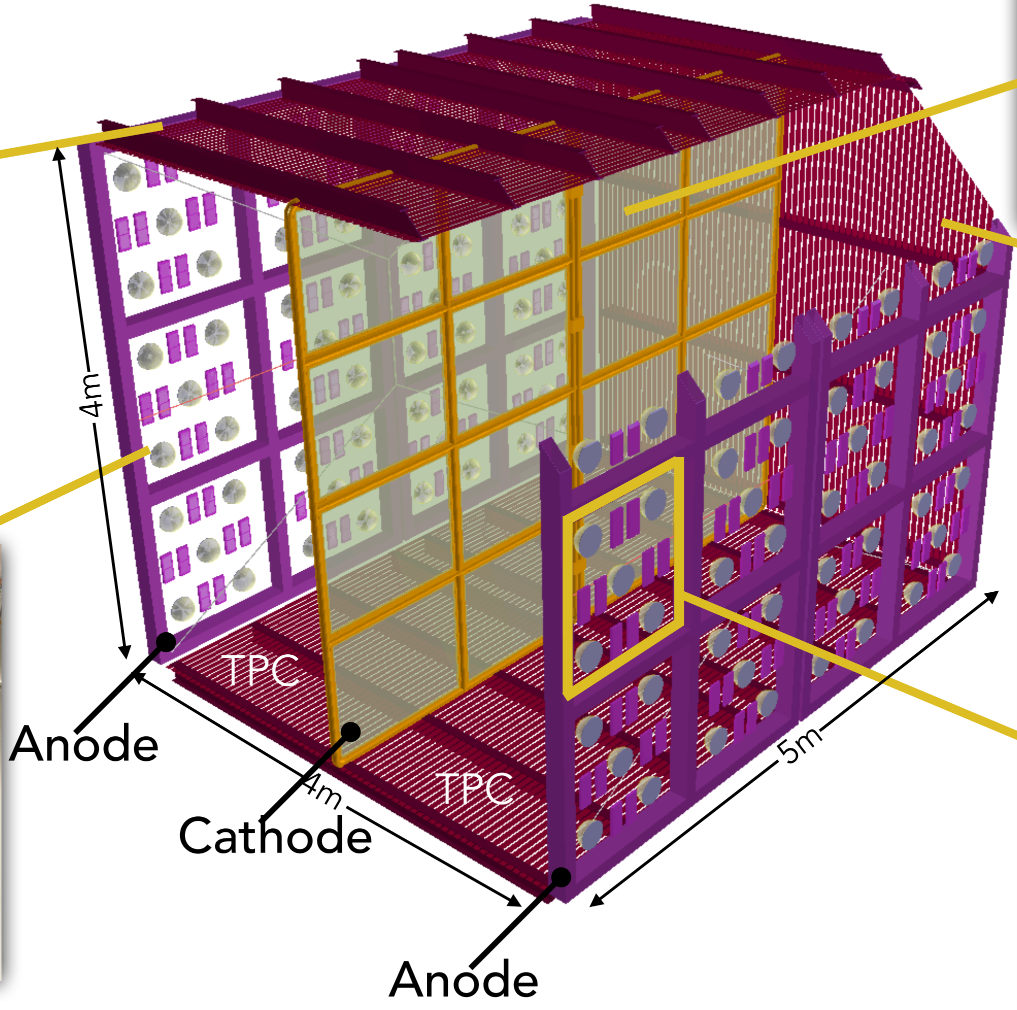
SBND Detector

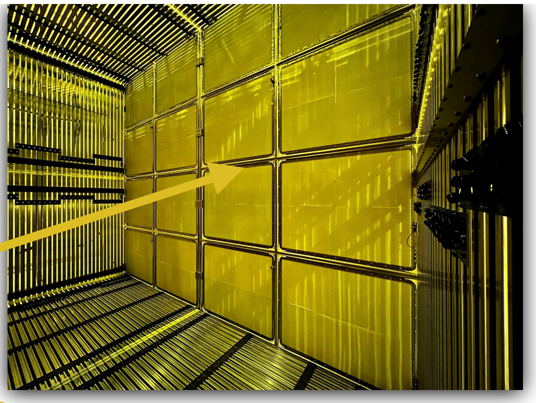
TPC Cold electronics



Two Time Projection Chambers

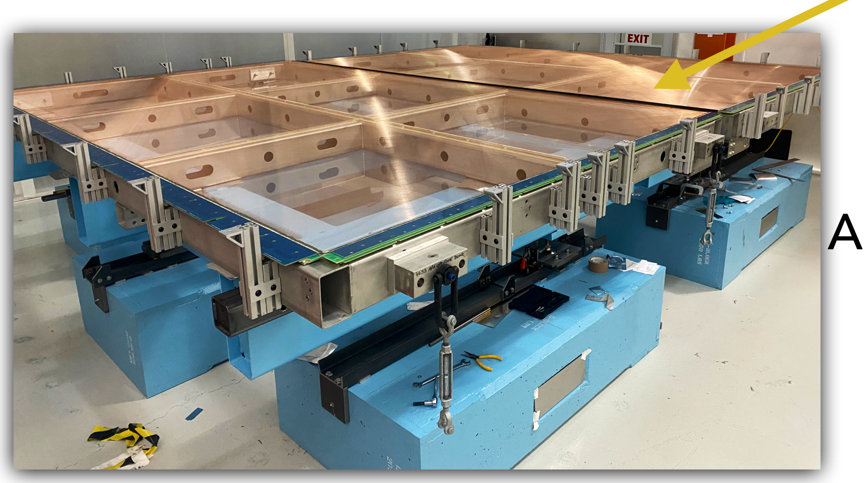
Total dimension: 4m x 4m x 5m





Cathode
covered with TPB
coated reflectors

Field Cage



Wire Plane - 3 readout planes, ~11000 wires

Photo Detection System: 120 PMTs,
192 X-Arapucas