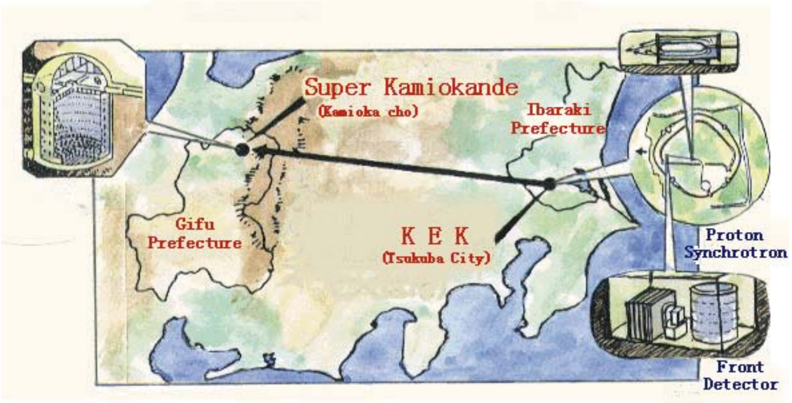
Decade work results from the NOvA experiment

Oleg Samoylov (JINR, Dubna)
on behalf of the NOvA collaboration

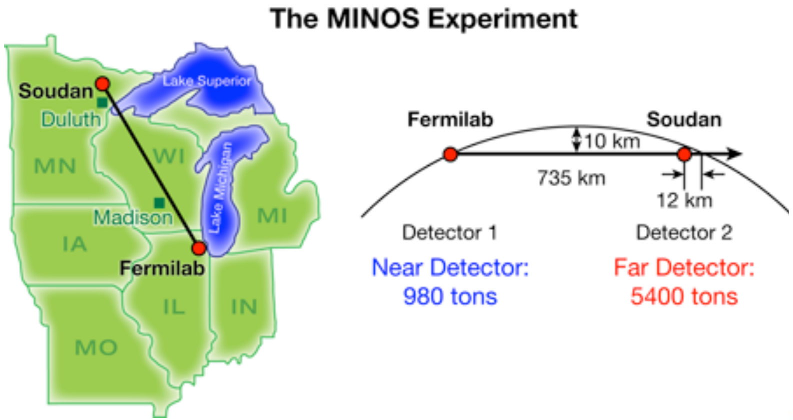
The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment

- **Origin and Concept**: NOvA was conceived as a successor to the MINOS experiment, designed to use the NuMI beamline (Fermilab) for studying electron neutrino appearance.
- **Detector Design**: Two detectors concept: near and far ones. The detectors are highly active tracking calorimeters built with low atomic-number materials to optimize electromagnetic shower identification.
- **Beamline Configuration**: Positioned 14 mrad off-axis, the detectors are exposed to a neutrino flux with energies chosen to the first oscillation maximum, minimizing high-energy neutrino backgrounds from neutral current interactions.
- **Far Detector Placement**: Located 810 km from the neutrino source, the Far Detector maximizes sensitivity to the neutrino mass hierarchy by enhancing the matter effect.
- **Broader Physics Goals**: Beyond oscillation studies, NOvA contributes to neutrino-nucleus cross-section measurements, sterile neutrino searches, astroparticle and exotic physics.

First generation LBNE: K2K & MINOS

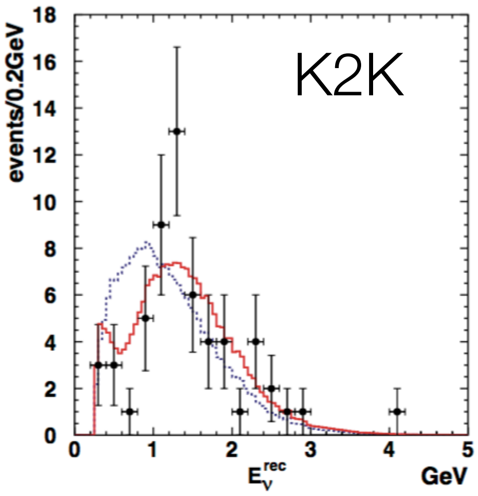


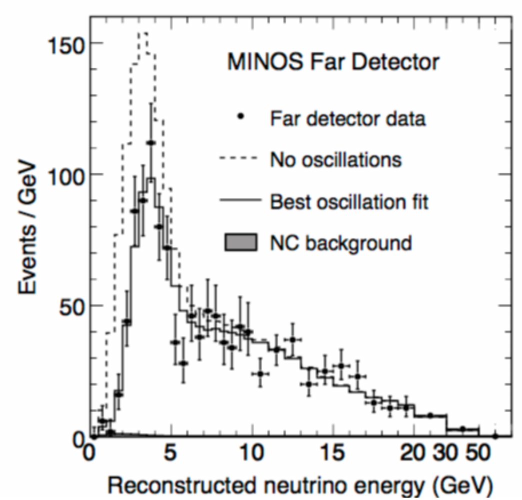
- Beam generated at KEK
- Neutrinos detected at Super-Kamiokande (Water Cherenkov Detector)
- Baseline of 250 km
- Operated 1999-2004

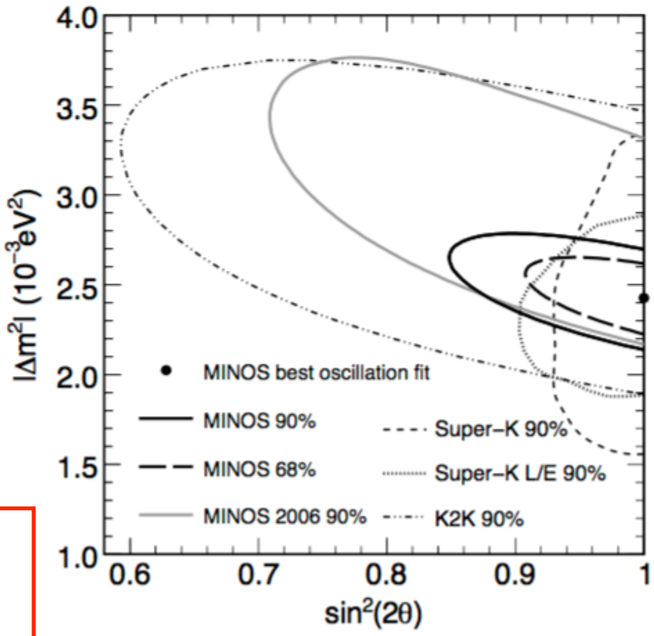


- Beam NuMI generated at Fermilab
- Neutrinos detected at magnetized steel far detector (5.4 kilo-ton) in Soudan mine
- Baseline of 735 km
- Operated 2005-2012(2016)

First generation LBNE: K2K & MINOS



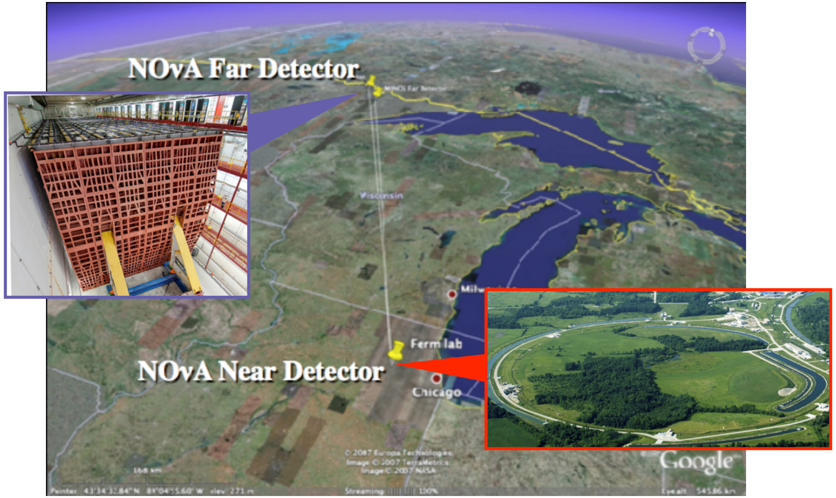




$$P_{\mu\to\mu} = 1 - (\sin^2 2\theta_{23} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right) + \dots$$

- The experiments were able to measure $|\Delta m^2_{32}|$
- Important for building the current generation of neutrino experiments (L/E ≈ 500 km)

Current generation LBNE: T2K & NOvA



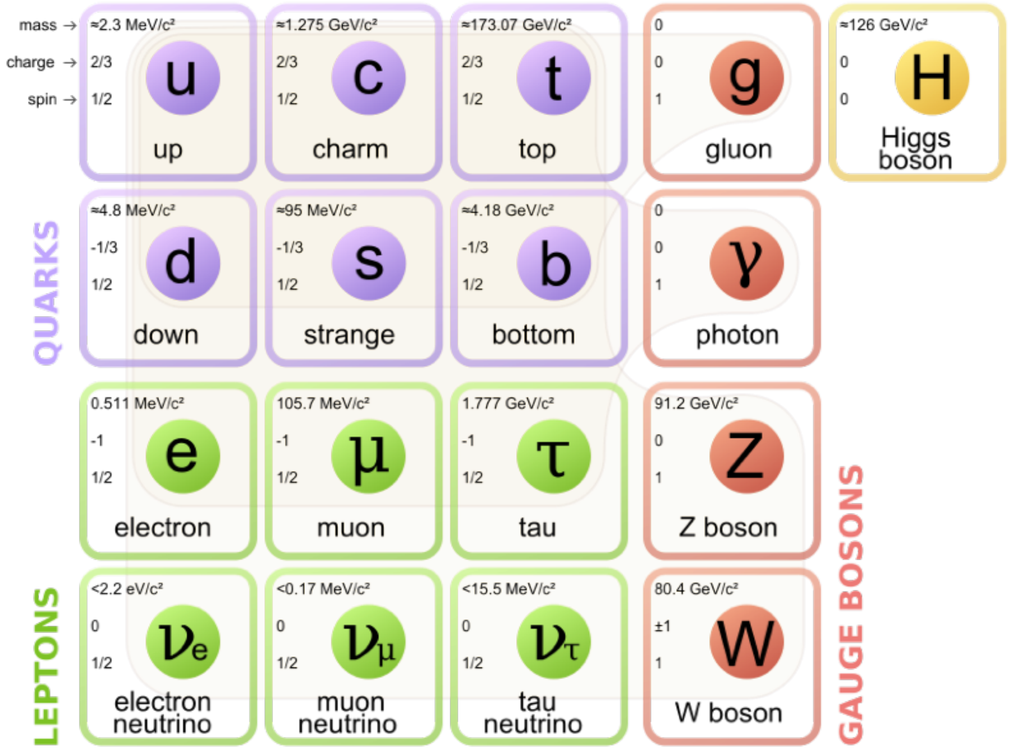
T2K

- Beam from J-PARC (Tokai)
- Neutrinos detected at Super-Kamiokande (Water Cherenkov Detector)
- Baseline of 295 km
- Operating since 2009 (by 2027)

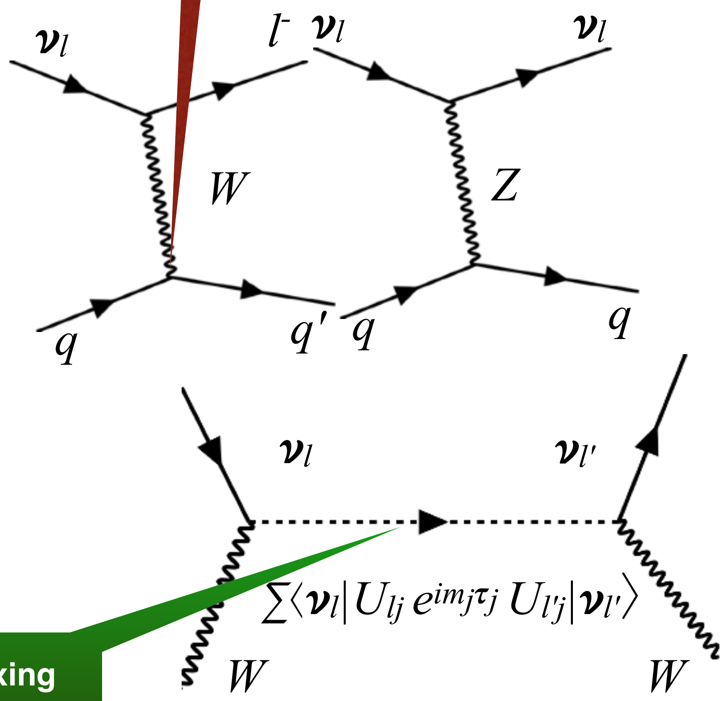
NOvA

- Beam NuMI generated at Fermilab
- Neutrinos detected at segmented liquid scintillator detector in Ash River
- Baseline of 810 km
- Operating since 2014 (by 2027)

Neutrino Oscillation



CKM quark mixing



PMNS neutrino mixing

Neutrino Oscillation

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

$\theta_{23} \sim 48.3°$ | $\theta_{13} \sim 8.5°$ | $\theta_{12} \sim 33.6°$

$|\Delta m^2_{32}| = |m^2_3 - m^2_2| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\nu_\mu \to \nu_\mu$

$\nu_\mu \to \nu_\tau$

atmospheric and long baseline

$\Delta m^2_{31} \simeq \Delta m^2_{32}$

$\nu_e \to \nu_e$

$\nu_\mu \to \nu_e$

reactor and long baseline

$\Delta m^2_{21} = |m^2_2 - m^2_1| \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$

$\nu_e \to \nu_e$

$\nu_e \to \nu_\mu, \nu_\tau$

solar and reactor

Oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, CP phase δ, $|\Delta m^2_{13}|$, Δm^2_{12}

NOvA

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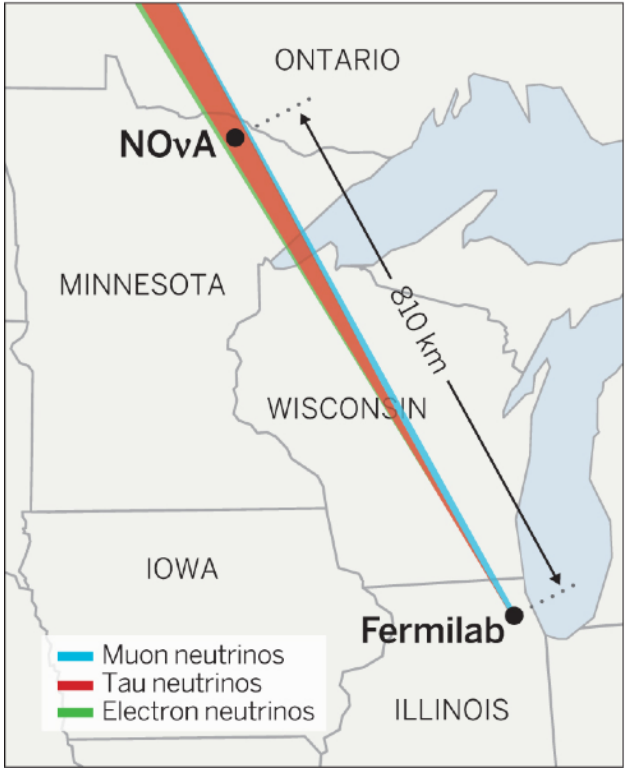
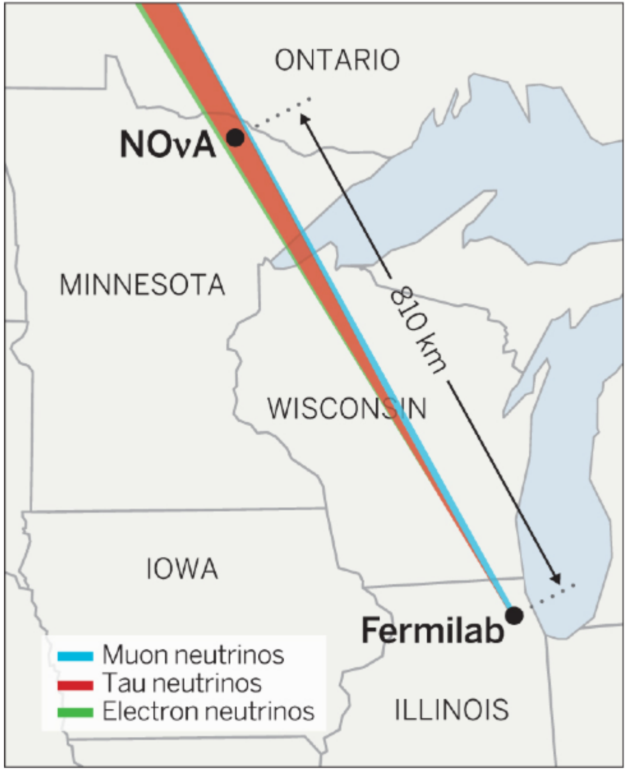
The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



K. ENGMAN / [SCIENCE 345, 6204]

Mass Hierarchy

The NuMI Off-Axis ν_e Appearance Experiment



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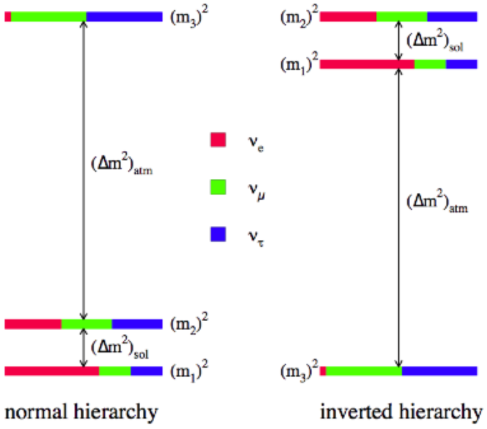
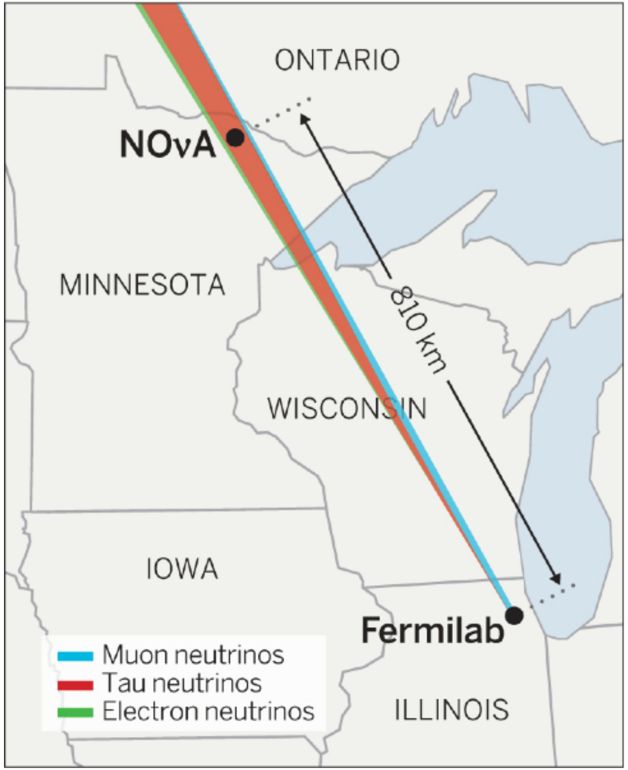
- Is the most electron-like state lightest?
- i.e. Does the pattern of the masses match the charged leptons?



Mass Hierarchy

The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



K. ENGMAN / [SCIENCE 345, 6204]

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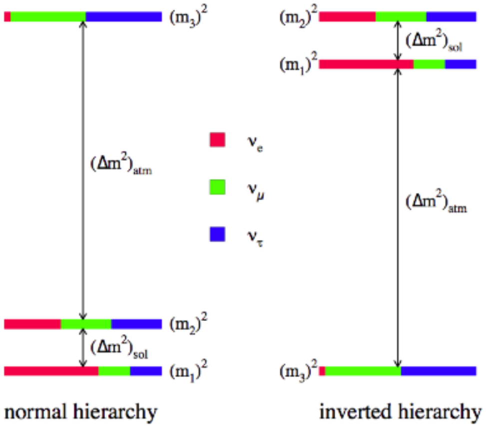
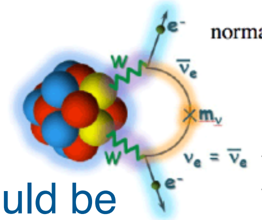
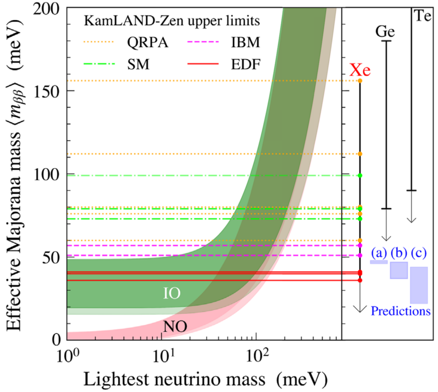


- Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- Observation of $0\nu\beta\beta$ would be proof they are
- Impact of IH determination: lack of $0\nu\beta\beta$ implies Dirac nature

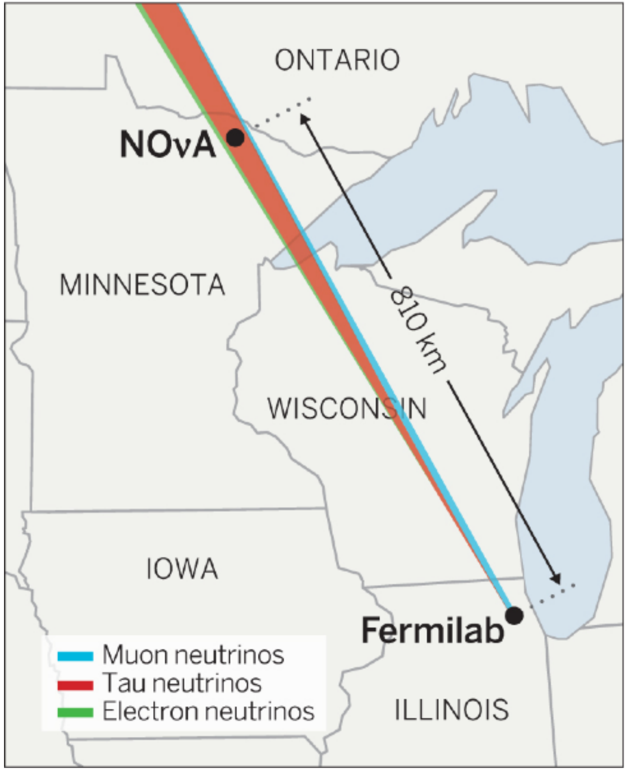




KamLAND-Zen, PRL130 051801(2023)

CP-violation

The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



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- Does e.g. $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$? $\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$
- Insight into fundamental symmetries of the lepton sector
- Why is the universe not equal parts matter and antimatter?
- Sakharov conditions: Baryon number violation • Out of thermal equilibrium • C and CP violation
- CPV in the Standard Model, e.g. for K and B mesons, but too small
- "Leptogenesis": generate asymmetry in neutrinos, transfer to baryons
- Require **neutrino appearance** experiment to discover

Mixing pattern

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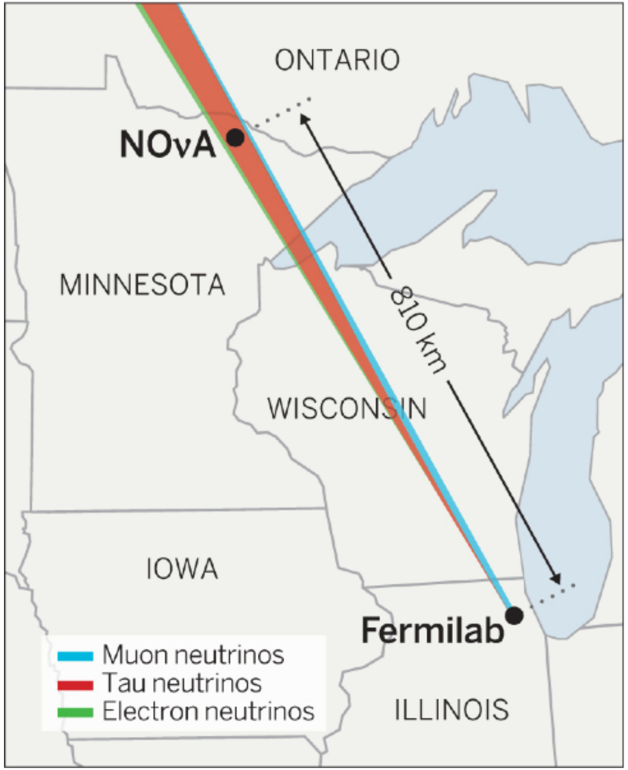
The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



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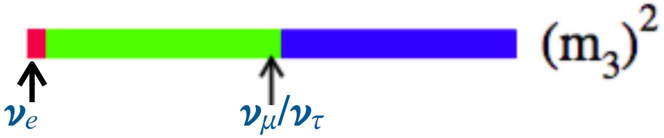
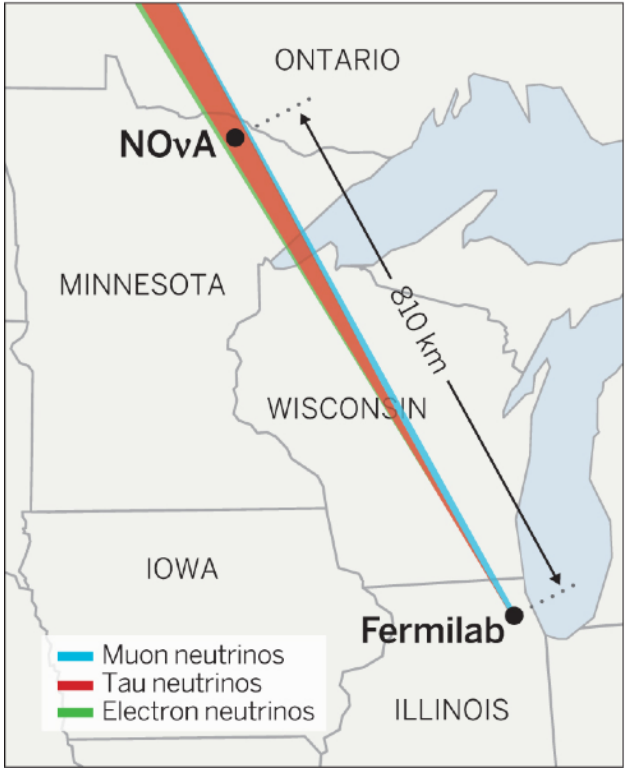
- Only a small fraction of ν_e in $|\nu_3\rangle$ (the famous $\mathrm{Sin}^2 2\theta_{13}$)
- The remainder is split about 50/50 ν_μ/ν_τ ($\mathrm{Sin}^2\theta_{23}$)
- Accident? Or a sign of underlying structure?



- Is θ_{23} exactly 45°?
- If not, what octant?
- $< 45°$ $|\nu_3\rangle$ more ν_τ, like in quarks
- $> 45°$ $|\nu_3\rangle$ more ν_μ, unlike quarks

Mixing pattern

The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



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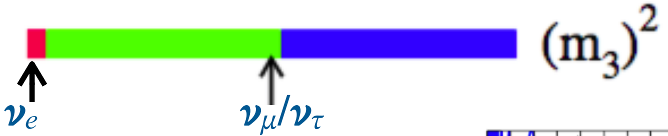

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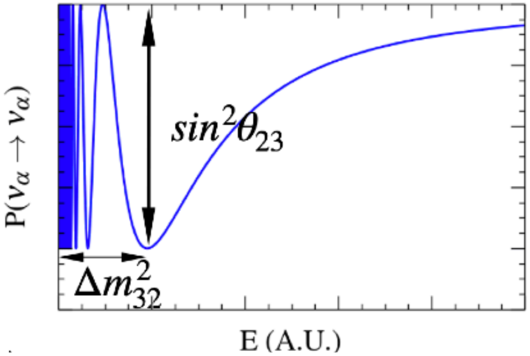

Mixing pattern

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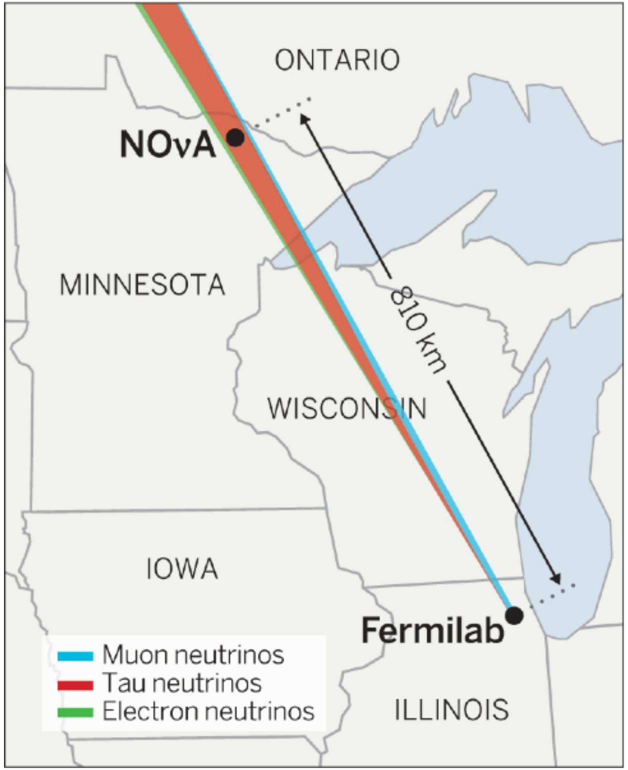

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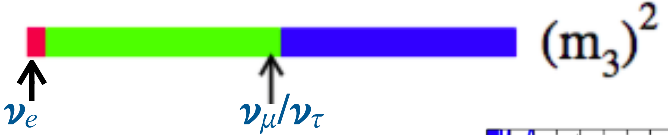

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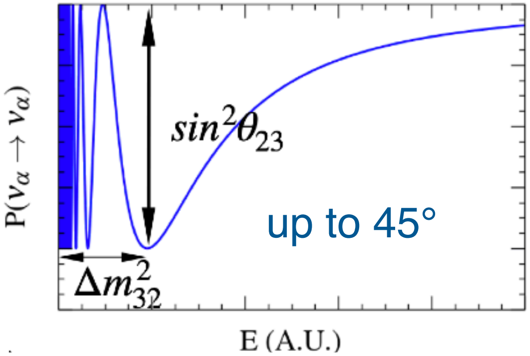
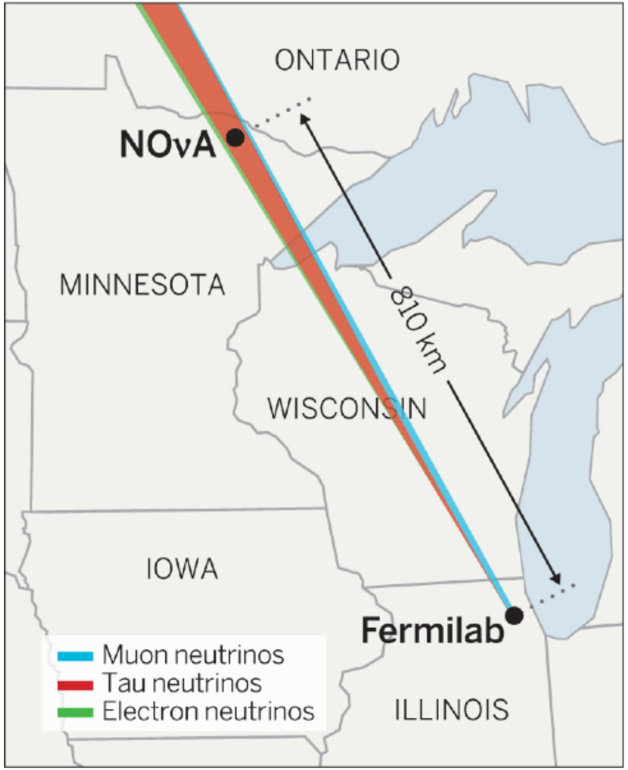


ν_e Appearance measurement

The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



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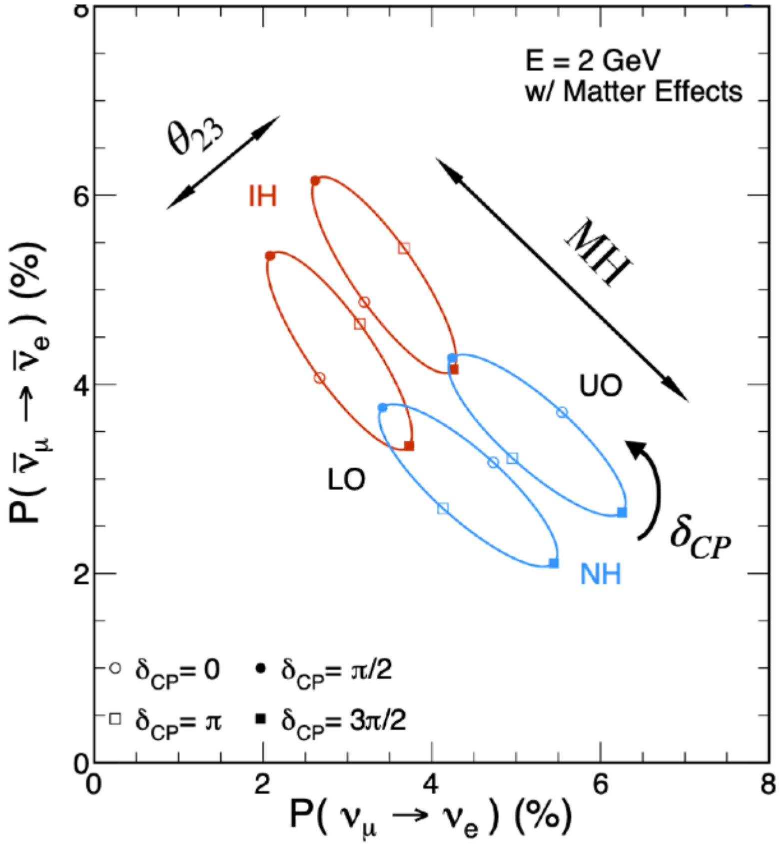
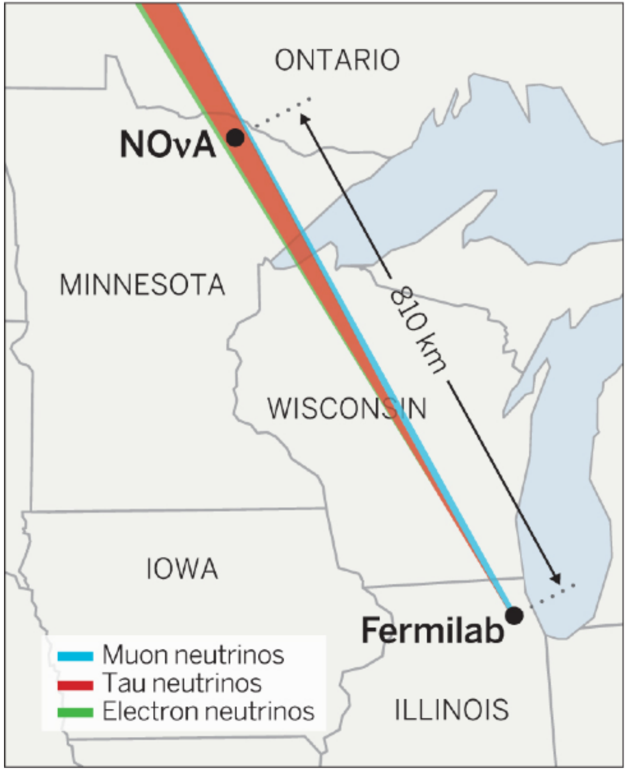
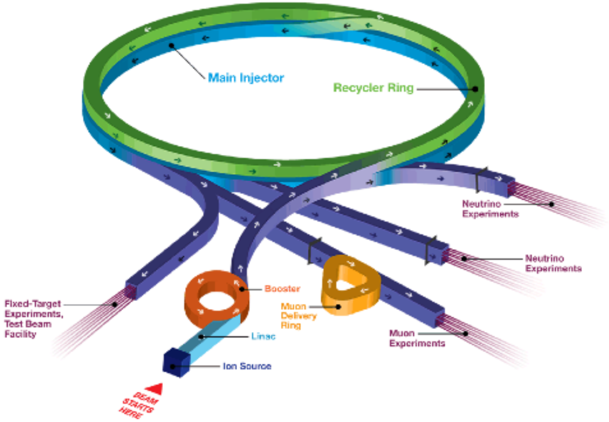


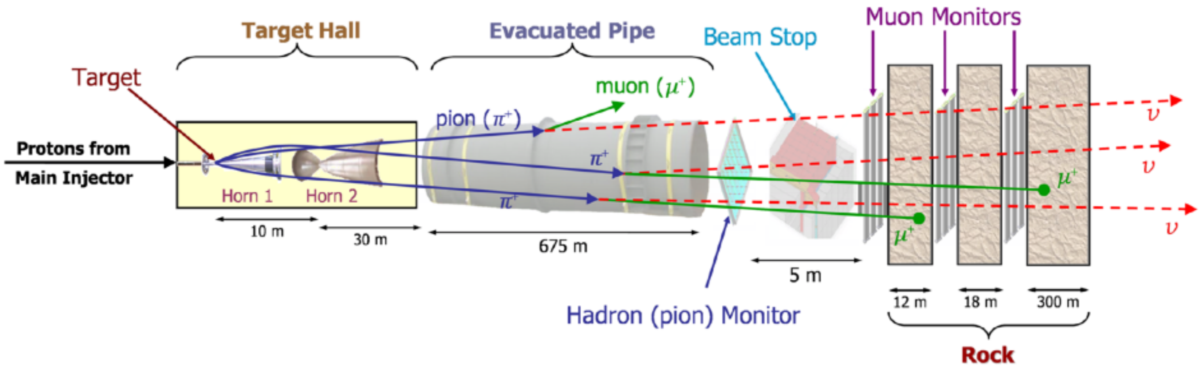
NuMI beam @ Fermilab

The **N**uMI **O**ff-Axis ν_e **A**ppearance Experiment



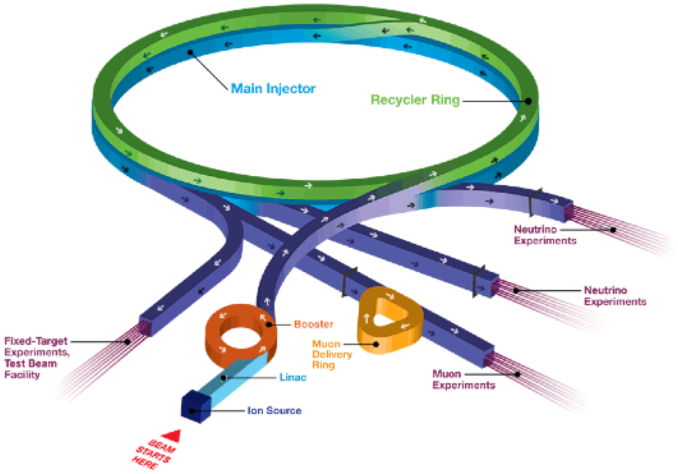
K. ENGMAN / [SCIENCE 345, 6204]

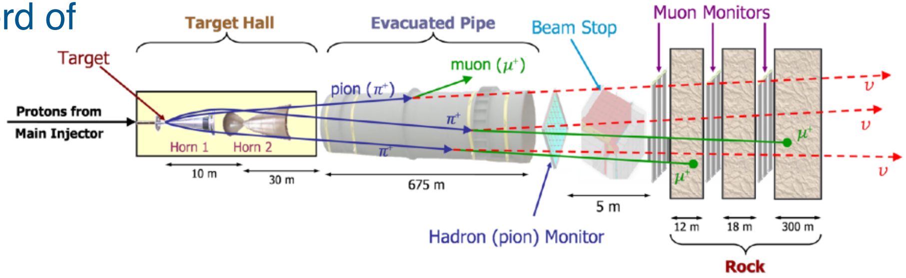




NuMI beam @ Fermilab

- **Neutrino Production**: Neutrinos are produced by directing 120 GeV protons from the NuMI Main Injector onto a graphite target.
- **Magnetic Horns**: Magnetic horns focus positively or negatively charged mesons, depending on the mode (neutrino or antineutrino).
- **Decay Pipe**: These pions and kaons decay, generating (anti)neutrinos as they travel through the decay channel.
- Fermilab Accelerator Upgrades:
  - ➡ The design beam power for NOvA was 700 kW, but recent upgrades have increased it to 900 kW.
  - ➡ The current average beam power is 850 kW, with a record of 1018 kW received in the summer of 2024.
- **Exposure**: The latest NOvA analysis uses exposures of 26.61×10^{20} POT (neutrino mode) and 12.5×10^{20} POT (antineutrino mode).





NuMI beam @ Fermilab

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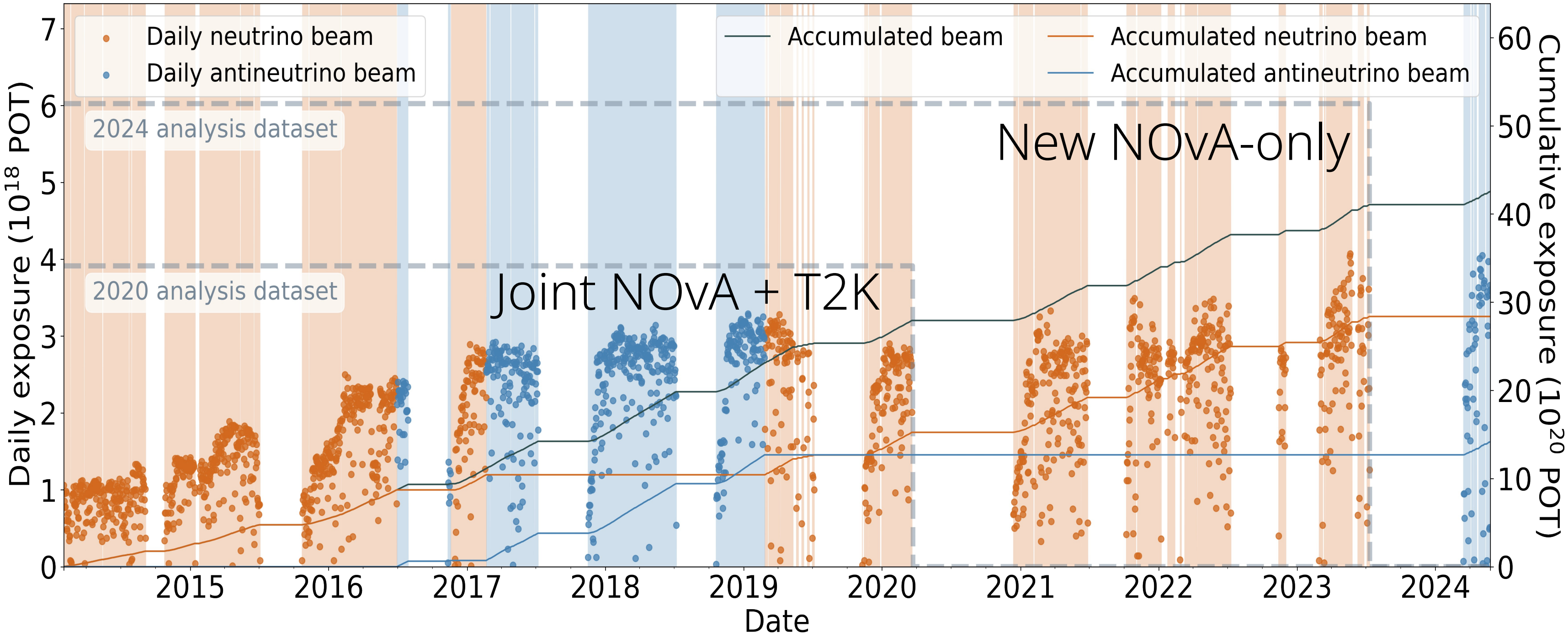
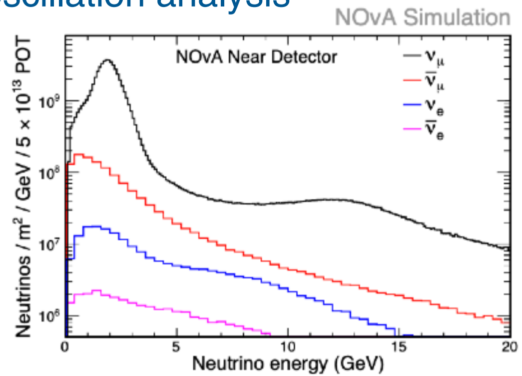


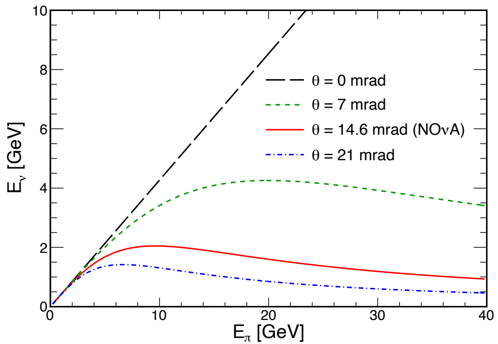
- 10 years of the neutrino beam to NOvA! (2014-2023)
- Neutrinos 26.61×10^{20} POT and antineutrinos 12.5×10^{20} POT.

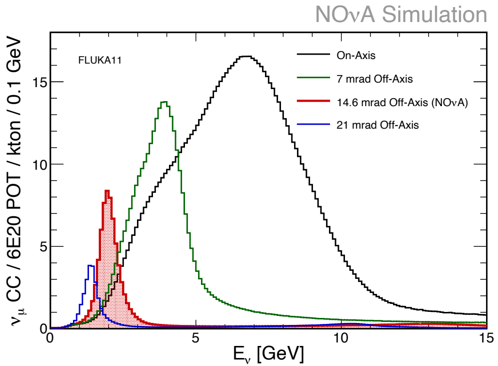
J.Wolcott @ Neutrino-2024

NuMI beam for NOvA

- NOvA detectors are sited 14 mrad off the NuMI beam axis
- With the medium-energy NuMI tune, yields a narrow 2-GeV spectrum at the both NOvA detectors
- Reduces NC and ν_e CC backgrounds in the oscillation analysis while maintaining high ν_μ flux at 2 GeV
- Composition in the Energy Range 1–5 GeV:
  - ➡ 96% νμ in neutrino mode,
  - ➡ 83% ν̄μ in antineutrino mode,
  - ➡ Less than 1% νe and ν̄e.
- Remaining events consist of "wrong-sign" particles: antineutrinos in neutrino mode and neutrinos in antineutrino mode.
- These features make the NuMI beam particularly well-suited for precise measurements in the NOvA experiment.

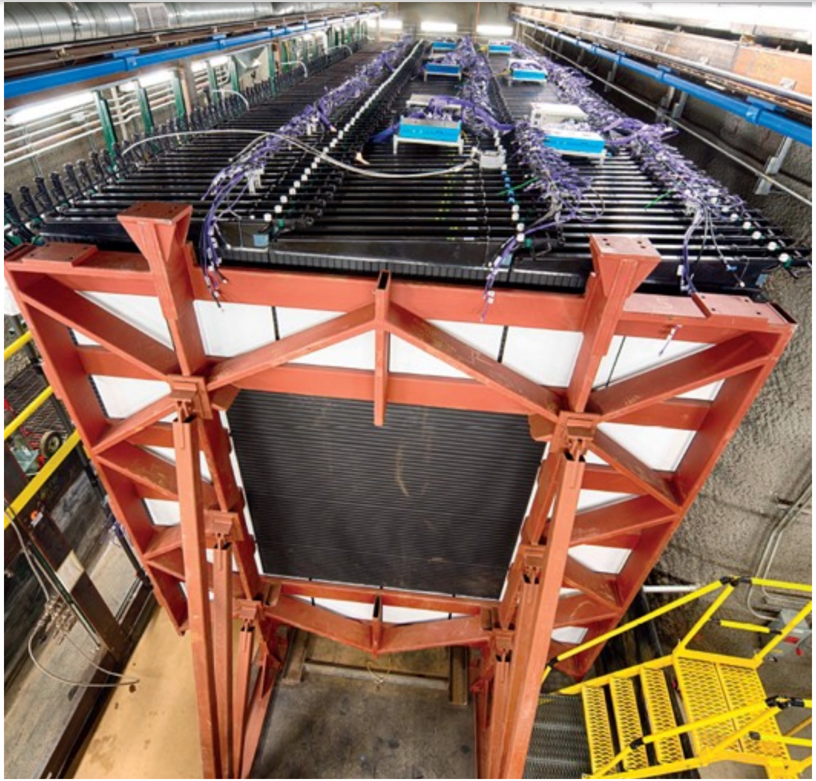




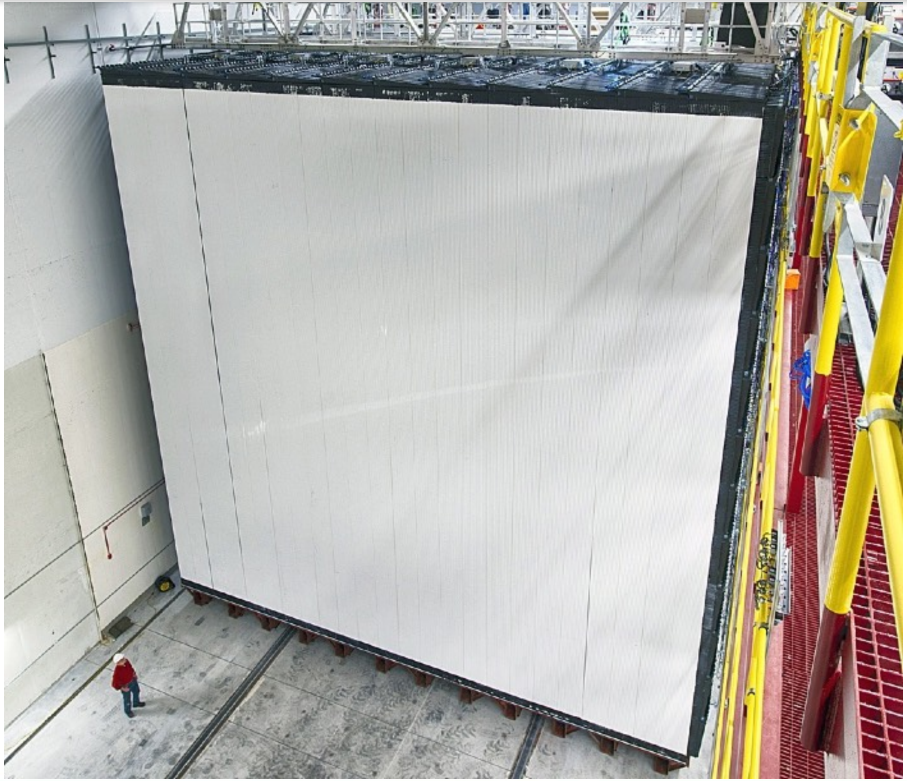


Two detector scheme

Near Detector: 290 tons, ~$4\times4 m^2 \times 16$ m

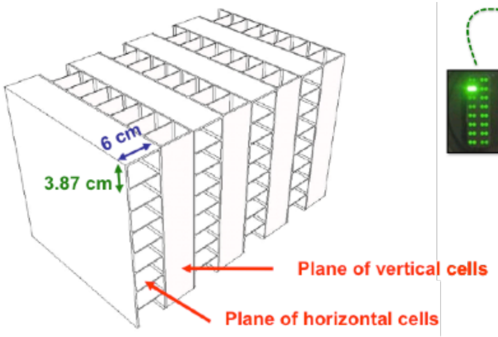


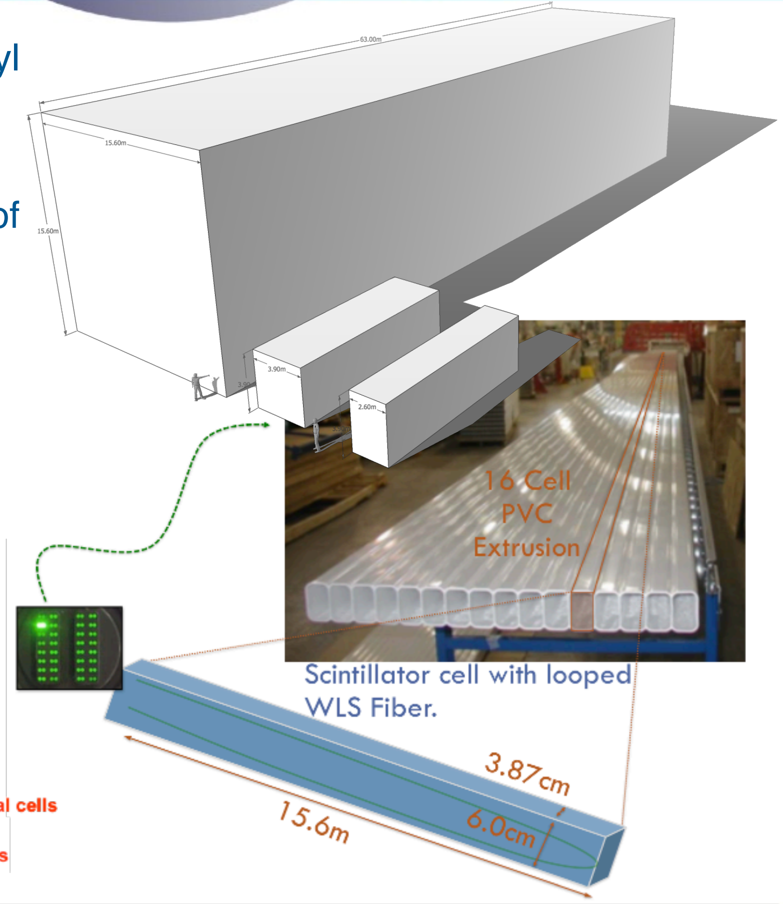
Far Detector: 14 kt, ~$16\times16 m^2 \times 60$ m



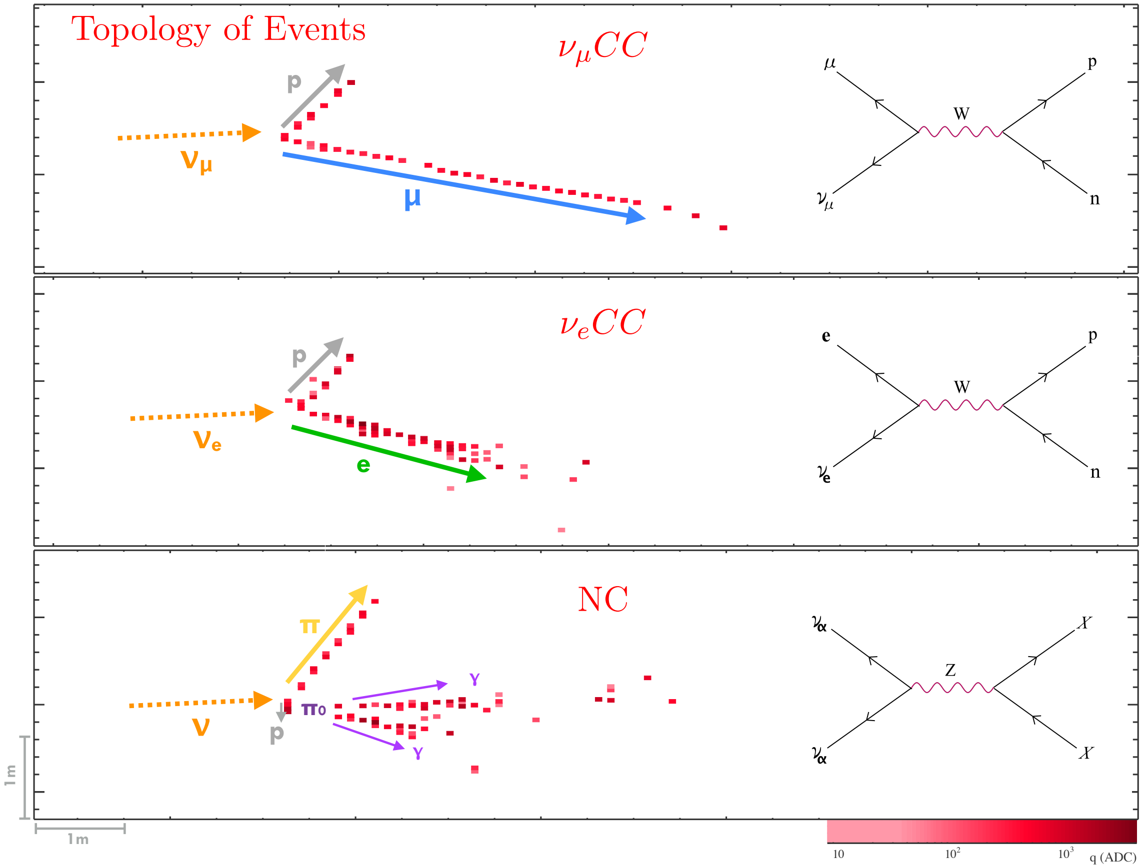
NOvA detectors

- The NOvA detectors are tracking calorimeters made of polyvinyl chloride (PVC) cells (+TiO_2) filled with liquid scintillator.
- The cells are **6.0 cm long (beam direction)** and **3.9 cm wide (transverse)**, with external walls of 4.8 mm and internal walls of 3.3 mm.
- Alternating horizontal and vertical planes improve tracking resolution.
- Scintillator: ~95% mineral oil, ~5% pseudocumene, plus trace chemicals.
- Light is captured by **wavelength-shifting fibers** running through each cell in a loop, terminating at avalanche photodiode (APD) pixels (~344,000 in the FD).
- Elemental composition (by mass): 66.7% carbon, 16.1% chlorine, 10.8% hydrogen.

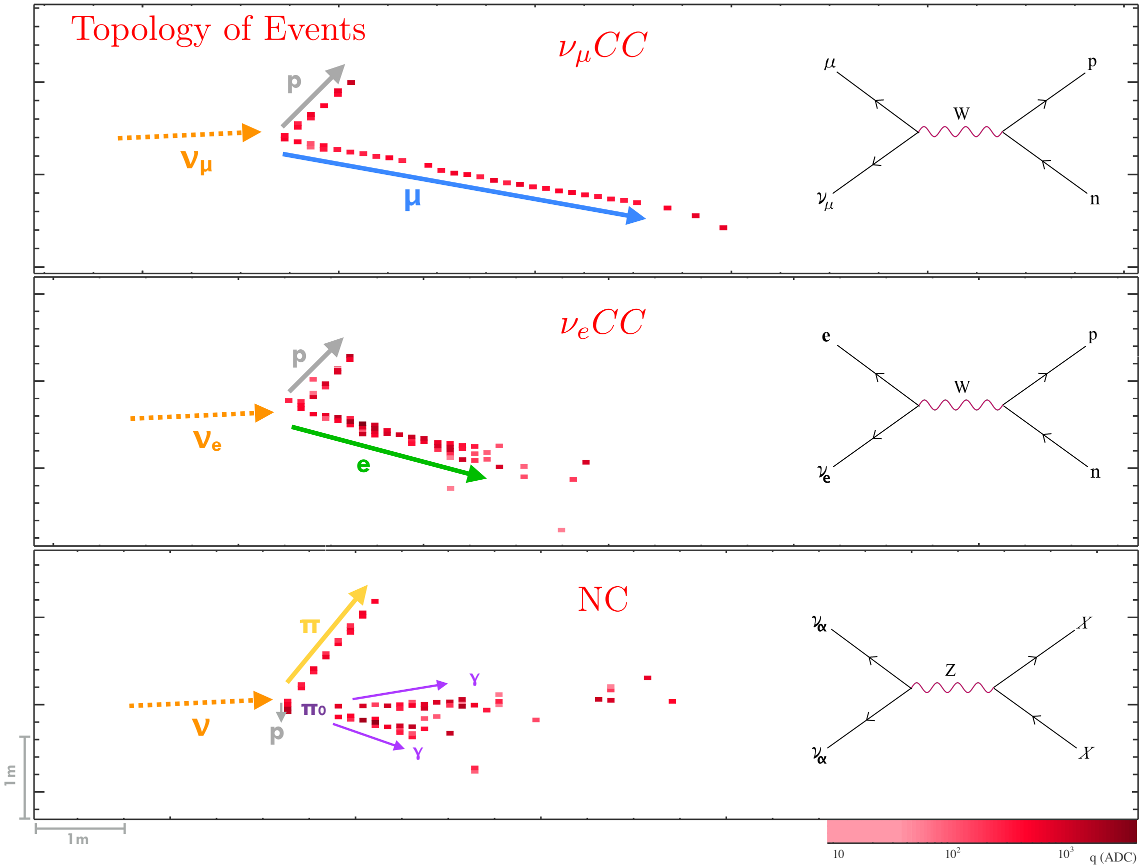




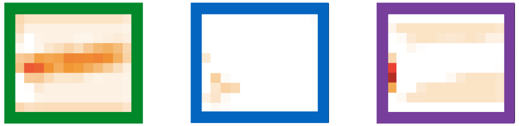
Event topologies

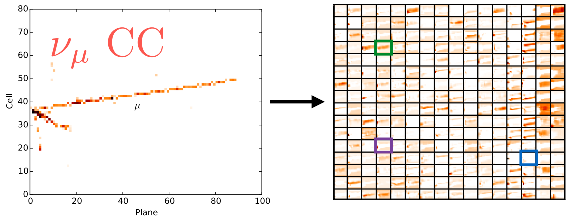


Event topologies. Id with NN



- We use convolution neural network called CVN (Convolutional Visual Network).
- Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic.





A. Aurisano et. al, JINST 11, P09001 (2016)

Neutrino cross-sections tuning

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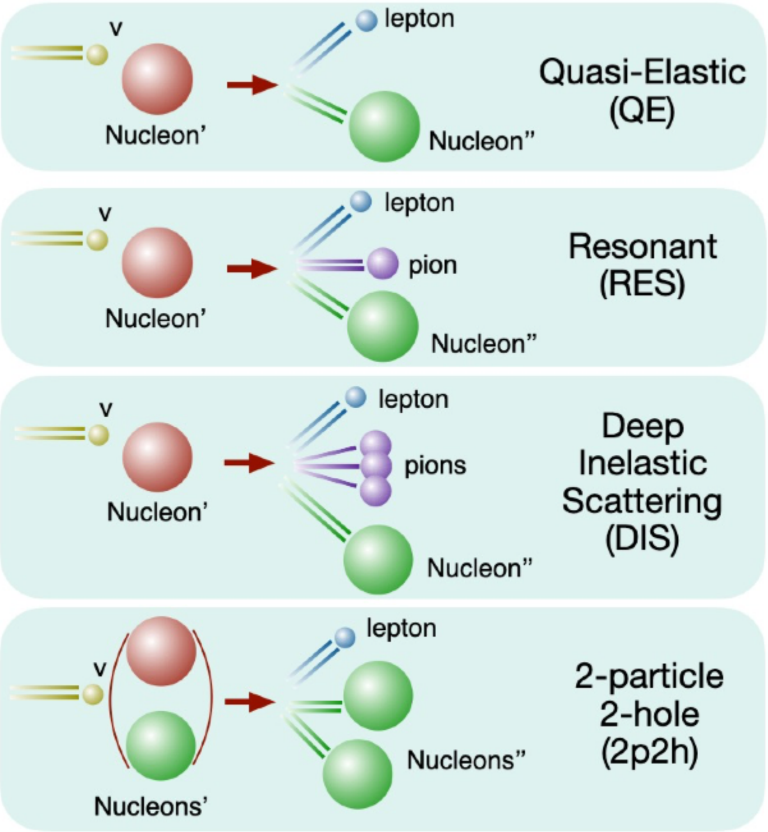
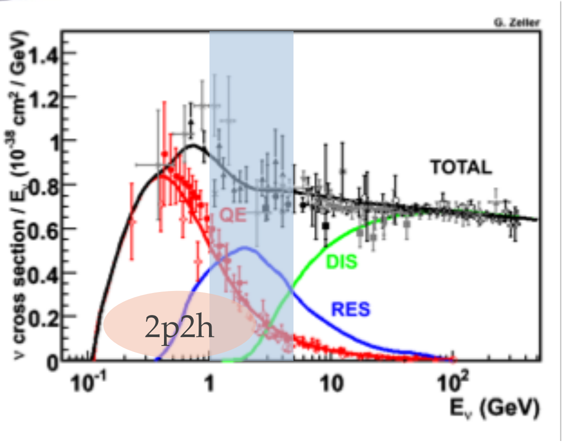
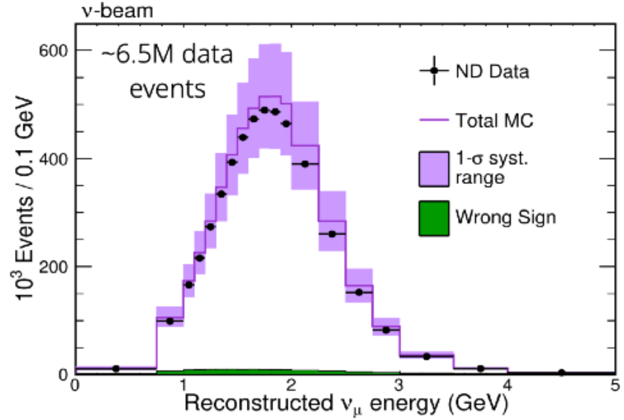


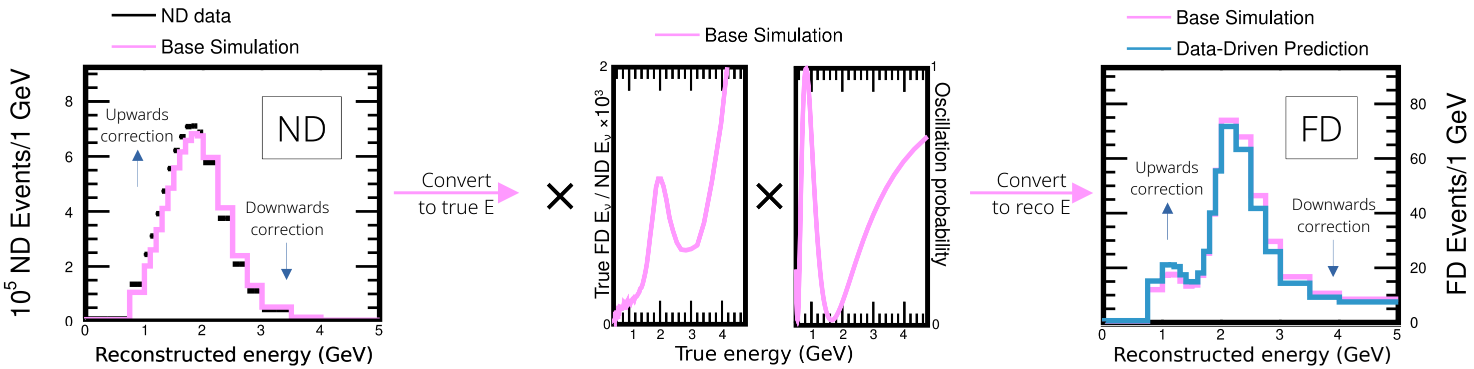
- Base simulation: GENIE 3.0.6
- No stock comprehensive model configuration (CMC) agrees well with data
- We choose a "theory-driven" set of models and make *post hoc* adjustments to improve agreement





J.Wolcott @ Neutrino-2024

Data driven ND to FD extrapolation



Correcting ND simulation to agree with data in reco E_ν…

… **via Far/Near transformation** that comprises **well understood effects** (beam divergence, detector acceptance) **+ oscillations**

… results in **constrained FD E_ν prediction** highly correlated with ND correction

Constrain nominal prediction *and* effect of **systematic uncertainties**

- Shift *all* elements of sim., then redo constraint
- Since post-correction all variations forced to agree at ND, spread at FD is reduced
- Effects that are not shared between detectors unaffected, or increase in some cases (e.g.: calibration)

Subdivide or **use different samples** to better account for ND/FD differences:

- **ν_μ: differences in resolution, acceptance**
  subdivide by E_{had}/E_ν × |p_t| [12 bins]
- **ν_e bknds: different oscillation behavior**
  constrain νs' parent π and K (beam ν_e);
  subdivide by Michel electron multiplicity (ν_μ, NC)

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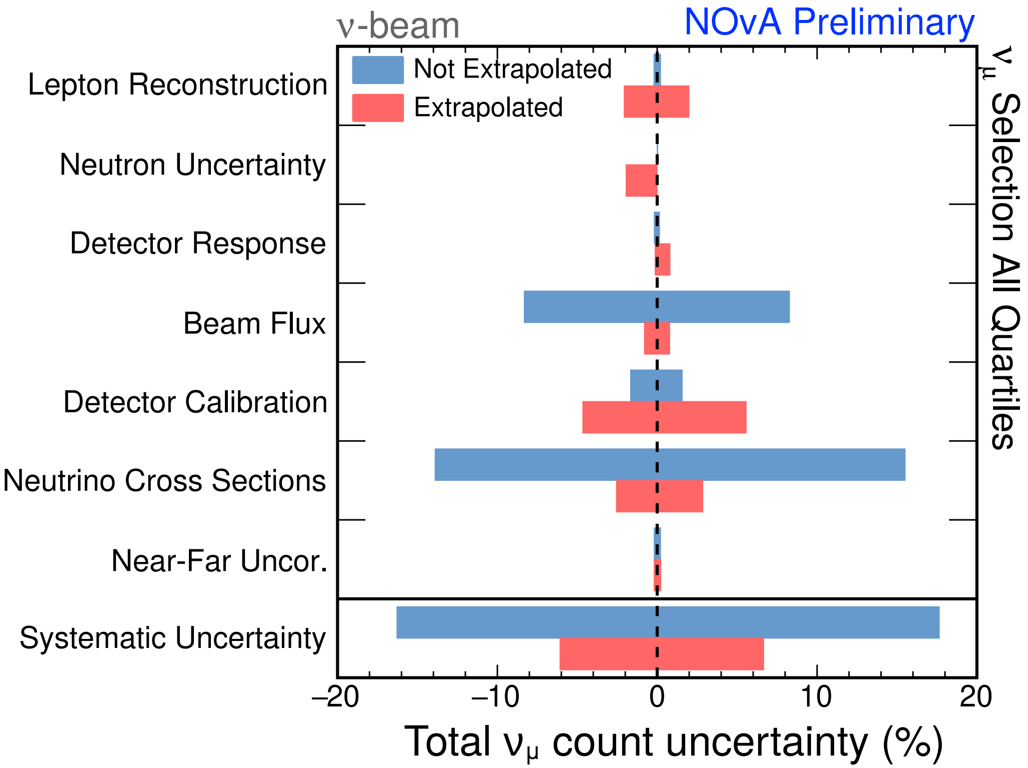
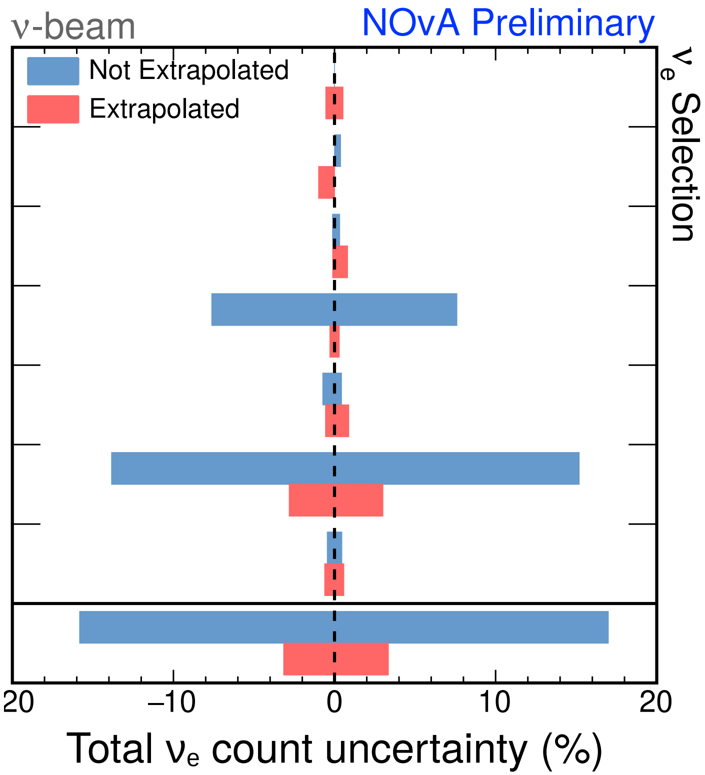
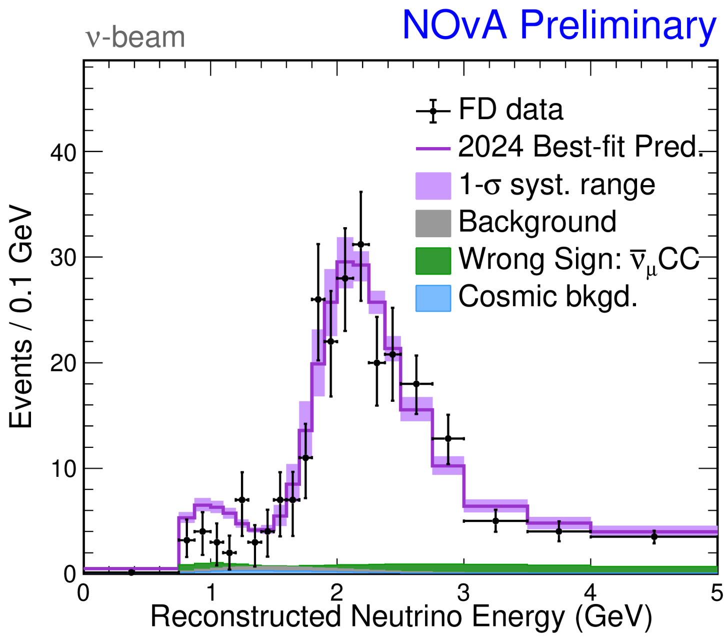
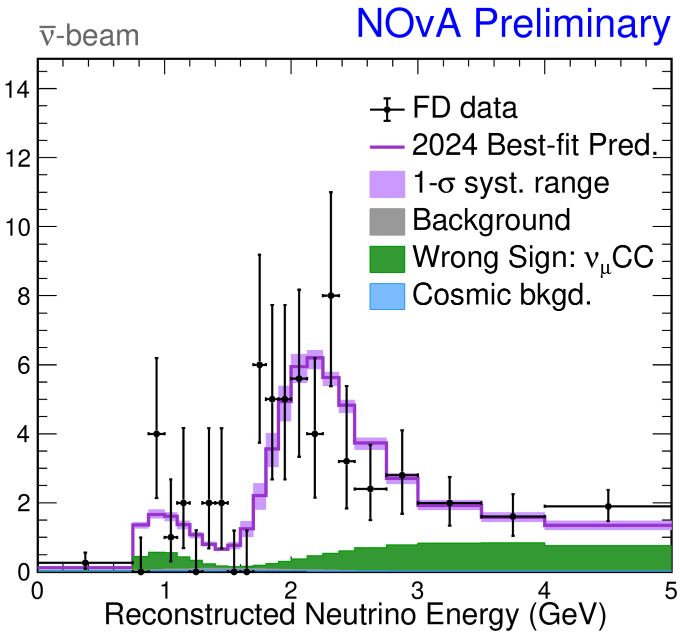
Systematic uncertainties





Neutrino Oscillation





384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

3-flavor oscillations describe these data well: Bayesian posterior predictive *p*-value = 0.54

Neutrino Oscillation

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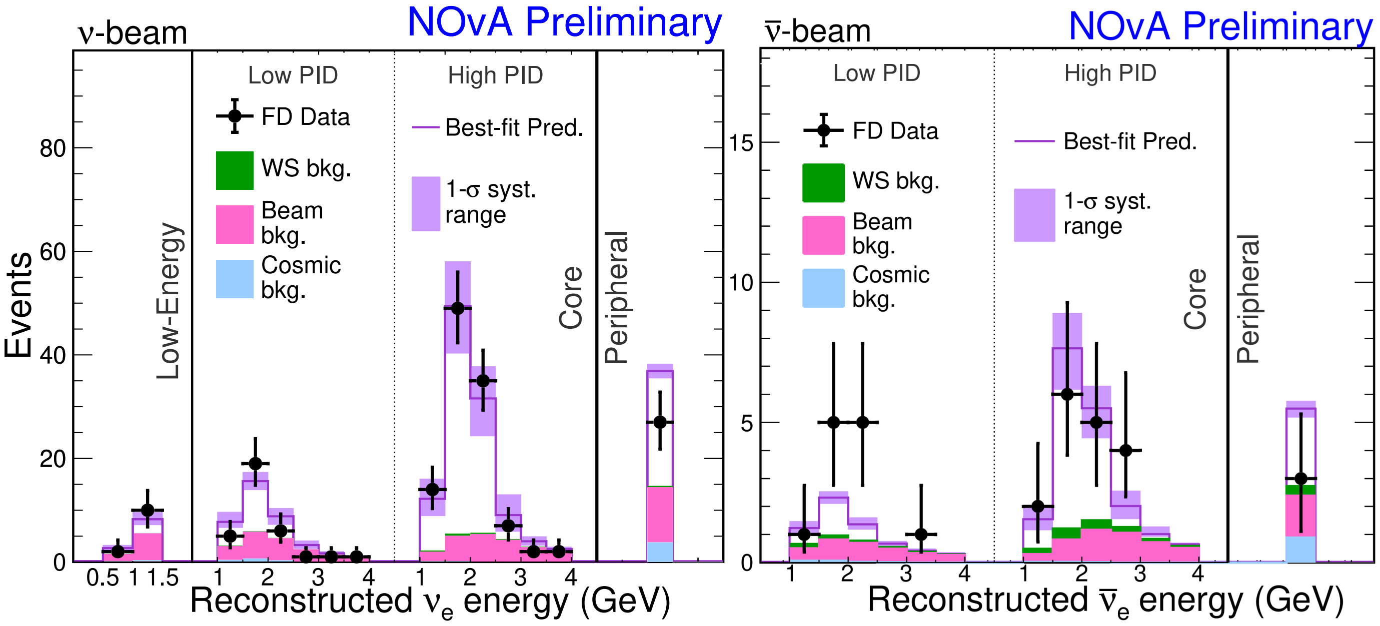
Joint Institute for Nuclear Research



181 ν_e data candidates

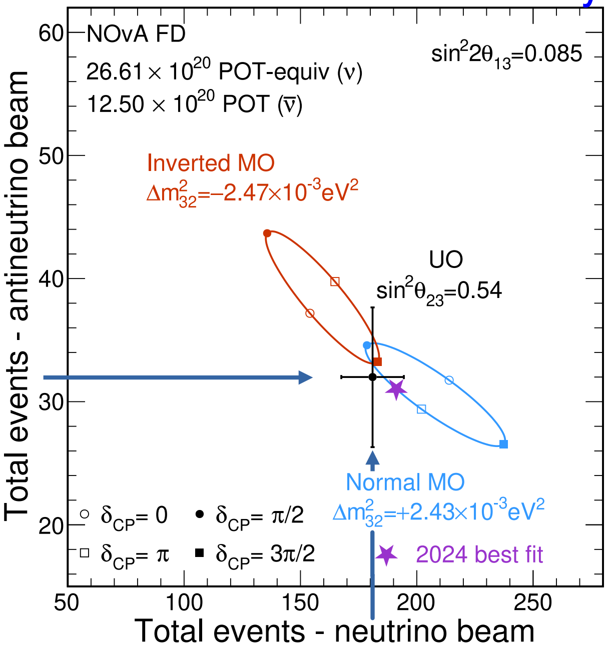
	Best fit	Range
Total pred	186.2	119 – 250
Wrong-sign	1.8	1.6 – 2.8
Beam bknd.	53.7	
Cosmic bknd.	6.2	
Total bknd	61.7	61 – 63

32 $\bar{\nu}_e$ data candidates

	Best fit	Range
Total pred	30.4	28 – 38
Wrong-sign	2.1	1.0 – 3.2
Beam bknd.	9.0	
Cosmic bknd.	1.1	
Total bknd	12.2	11 – 13

Neutrino Oscillation

NOvA Preliminary



32 $\bar{\nu}_e$ data candidates

181 ν_e data candidates

Data favors region where **matter & CP violation effects oppose one another**

Future $\bar{\nu}$ data will be critical for disentangling

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Neutrino Oscillation Results

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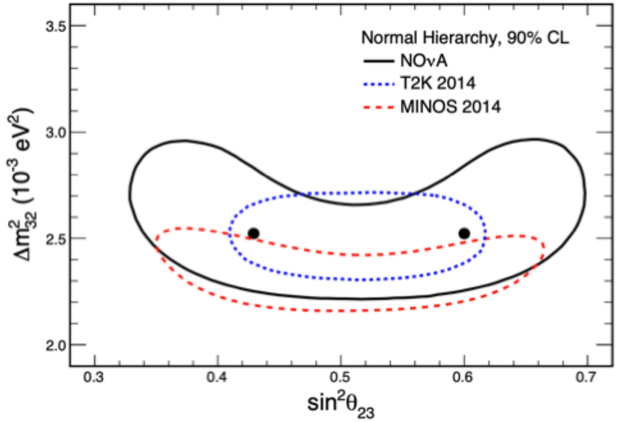
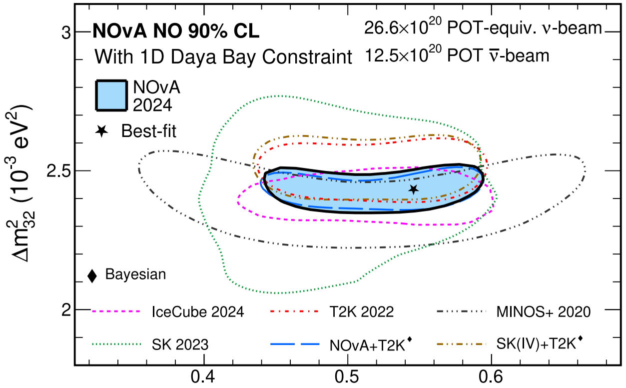
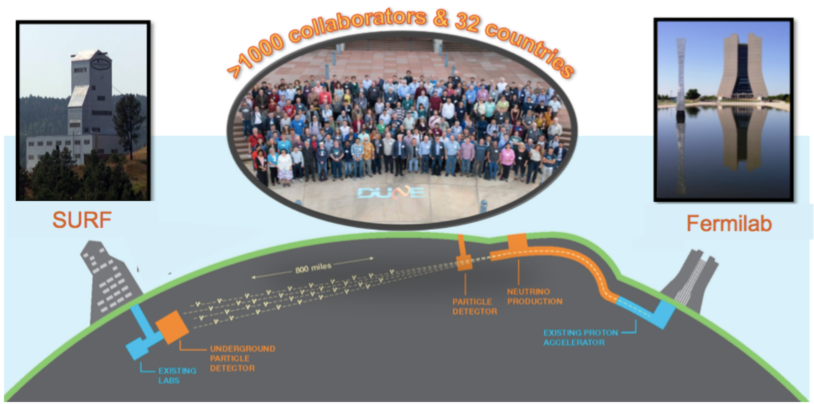
- First measurement of muon-neutrino disappearance in NOvA. Phys. Rev. D 93, 051104(R) – Published 25 March, 2016
- First Measurement of Electron Neutrino Appearance in NOvA. Phys. Rev. Lett. 116, 151806 – Published 13 April, 2016
- Measurement of the Neutrino Mixing Angle θ_{23} in NOvA. Phys. Rev. Lett. 118, 151802 – Published 10 April, 2017
- Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA. Phys. Rev. Lett. 118, 231801 – Published 5 June, 2017
- New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment. Phys. Rev. D 98, 032012 – Published 24 August, 2018
- First measurement of neutrino oscillation parameters using neutrinos and antineutrinos by NOvA. Phys. Rev. Lett. 123, 151803 – Published 11 October, 2019
- Improved measurement of neutrino oscillation parameters by the NOvA experiment. Phys. Rev. D 106, 032004 – Published 3 August, 2022
- The Profiled Feldman-Cousins technique for confidence interval construction in the presence of nuisance parameters. [arXiv:2207.14353]
- Expanding neutrino oscillation parameter measurements in NOvA using a Bayesian approach. Phys. Rev. D 110, 012005 – Published 10 July, 2024



NOvA Preliminary



Future LBNE: T2HK и DUNE



Hyper-K

- Advanced neutrino beam from J-PARC (Tokai)
- Water Cherenkov detector Hyper-Kamiokande
- 8× larger fiducial mass
- 2.5× more intense beam

DUNE

- Significant upgrade to the NuMI accelerator complex (Fermilab)
- Liquid Argon Time Projection Chamber (TPC)
- Oscillation baseline of 1300 km
- Sanford Underground Laboratory

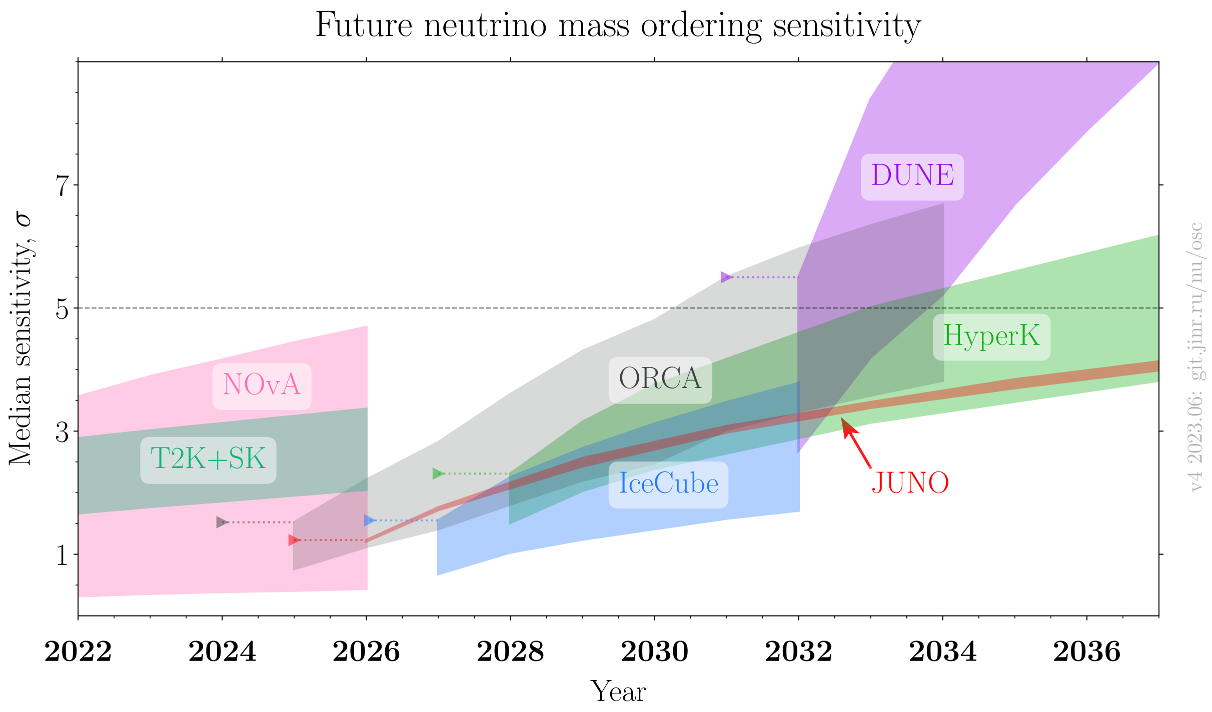
Three-flavo(u)r oscillations

L.Kolupaeva

Future landscape: neutrino mass ordering

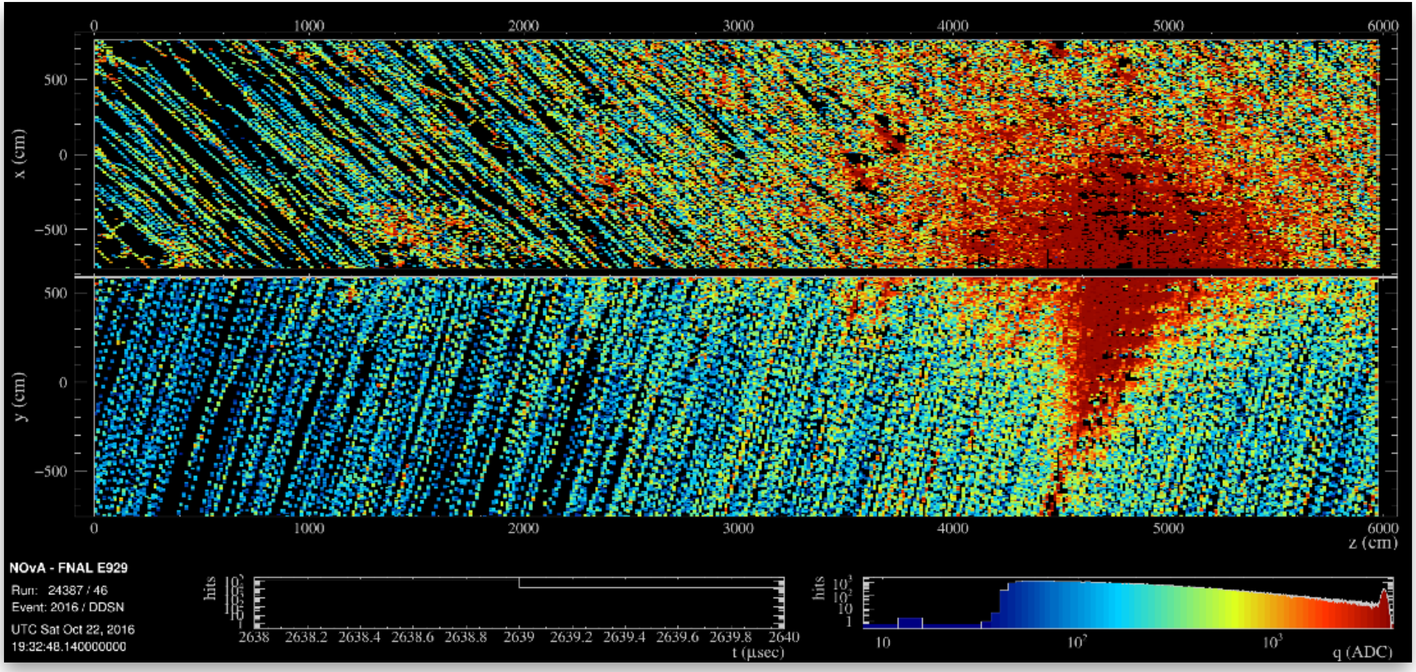
- ✳ NOvA's sensitivity is 2020 ana projection.
- ✳ Realistically ~2σ along for currently running experiments (w/o joint analyses).

- ✳ There is a good chance that NOvA's result will be still very impactful measurement up to ~2028.
- ✳ Future is very competitive.



Summary

- Over decade (2014-2024) of operation and data analysis, NOvA has published numerous works on neutrino oscillations.
- Several papers have been published on neutrino interactions with matter and cross-section measurements.
- Research has also been published on the search for exotic phenomena such as sterile neutrinos and magnetic monopoles.
- In addition, NOvA monitors signals from space and Earth's atmosphere, for example, detecting neutrinos from supernovae, gravitational waves, atmospheric neutrinos, and muons.
- List of NOvA publications NOvA has a running total number of **29** (including technical ones).
- Expected Results (by 2027 or so):
- NOvA: Measurement of the neutrino mass hierarchy and δCP with significance levels of $\leq 4\sigma$ and $\leq 2\sigma$, respectively.
- Updated results in other areas.



Backup slides

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