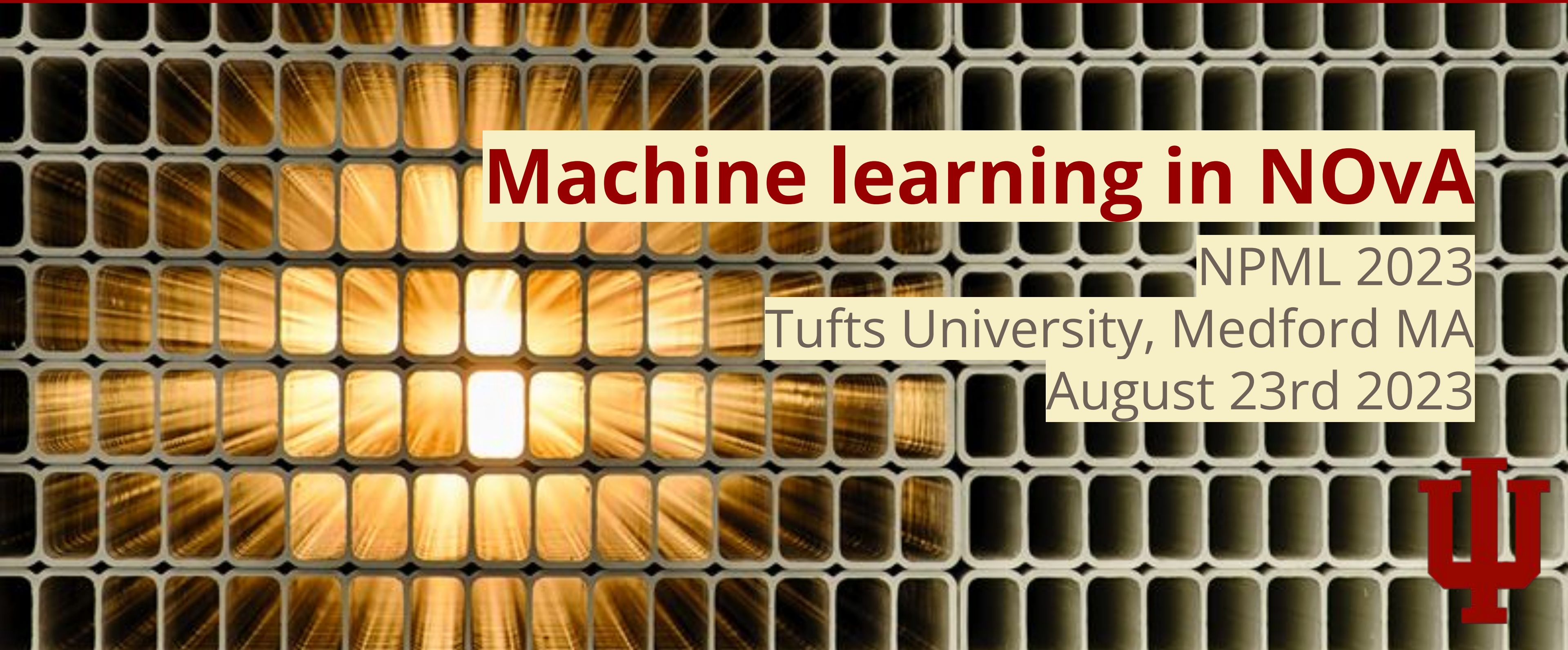
Ashley Back *on behalf of the NOvA Collaboration*

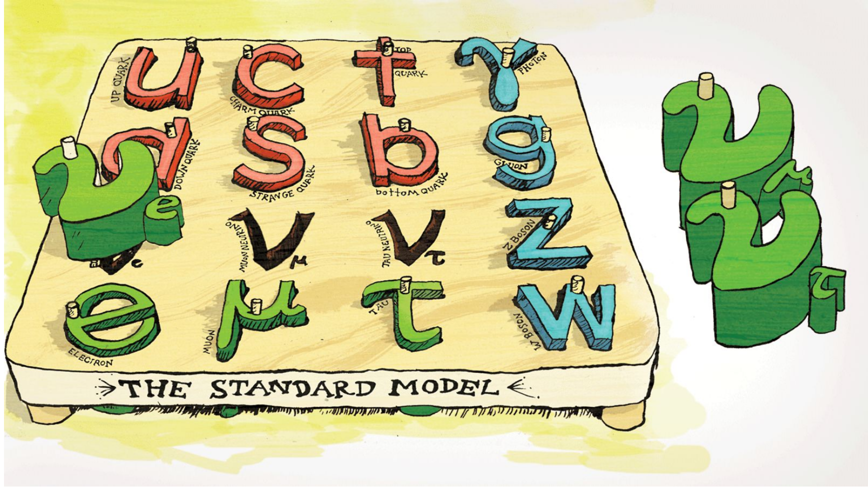
Machine learning in NOvA

NPML 2023
Tufts University, Medford MA
August 23rd 2023



Neutrino oscillation physics

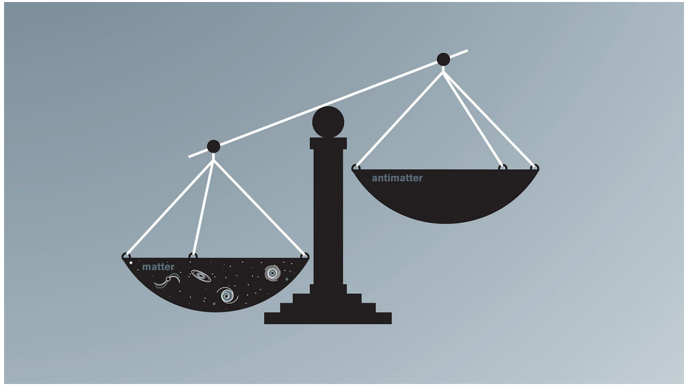
Why study neutrinos?



Credit: Symmetry Magazine / Sandbox Studio, Chicago

- Are neutrinos their own antiparticles? Dirac vs Majorana.
- **Why is there more matter than antimatter in the universe? Is there CP violation in the lepton sector?**

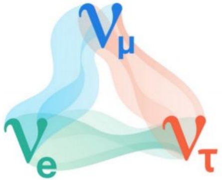
- Neutrino oscillation requires nonzero neutrino masses, but we don't know their absolute mass.
- Do neutrinos get their mass the same way other elementary particles do?



Credit: Symmetry Magazine / Sandbox Studio, Chicago

3-Flavor neutrino oscillations

We know that neutrinos oscillate between (at least) 3 flavor eigenstates as they propagate. This mixing is described by the PMNS matrix:



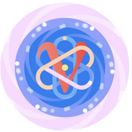
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

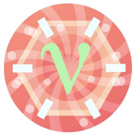
Mixing Matrix

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

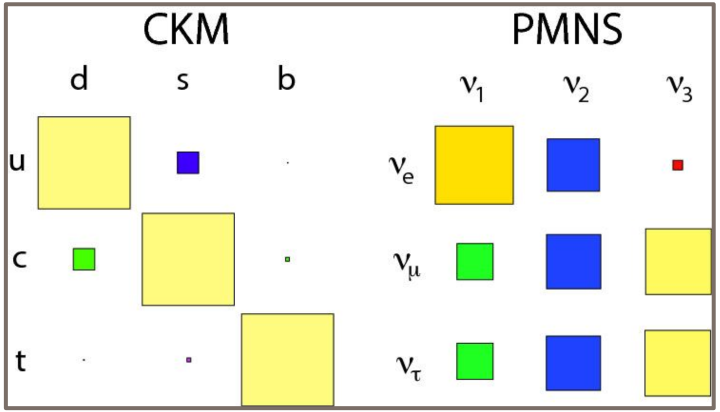
$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$


Solar


Reactor


Accelerator


Atmospheric

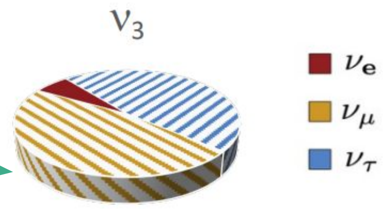


Credit: Fermilab / Sheldon Stone

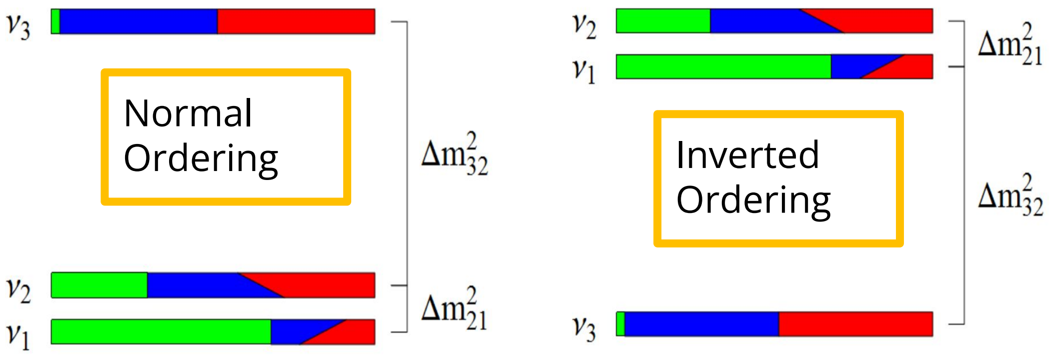
Key questions

Credit: Zoya Vallari, APS April 2022

Is there an underlying **symmetry** in how ν_μ and ν_τ contribute to the mass states? Is θ_{23} **maximal**?



Is is electron flavor associated most with **light** or **heavy** mass states?

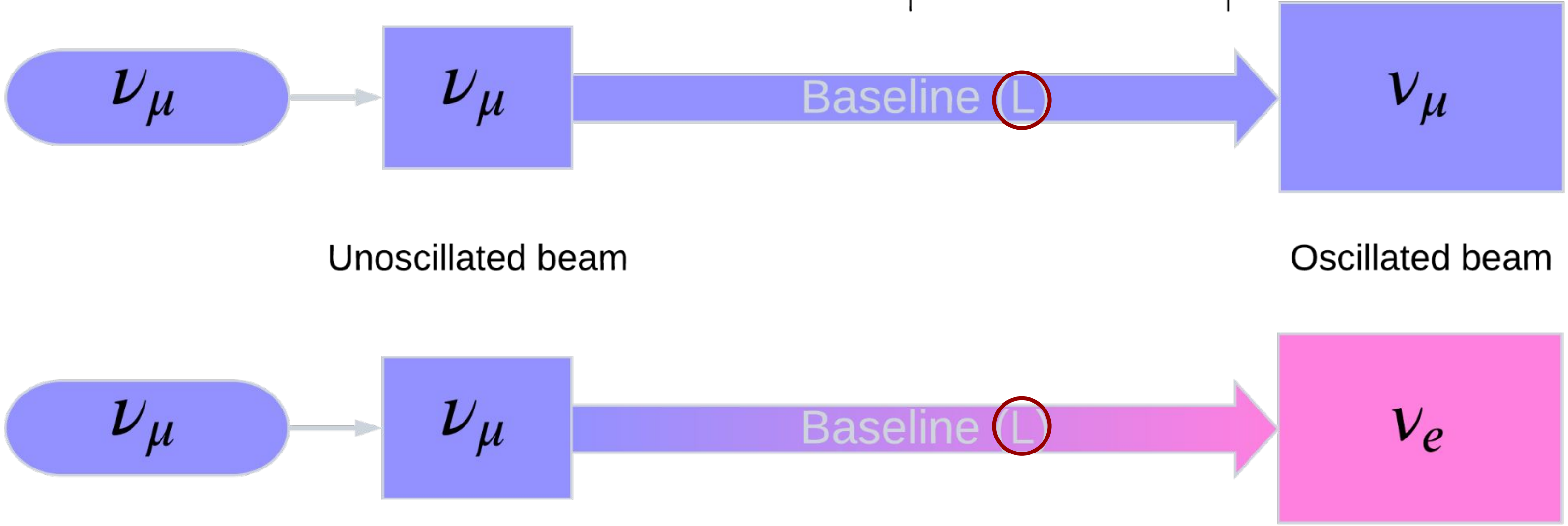


Is there **CP violation** in the lepton sector? What is the value of δ_{CP}? $\sin(\delta_{CP})\neq 0 \rightarrow$ CP violation.

Is our current understanding of neutrino oscillations complete? Are there more than 3 flavor states - existence of **sterile neutrinos**?

Designing a long-baseline experiment

Source (E) ND $P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U^*_{\alpha i} e^{-\frac{m_i^2 L}{2E}} U_{\beta i} \right|^2$ FD

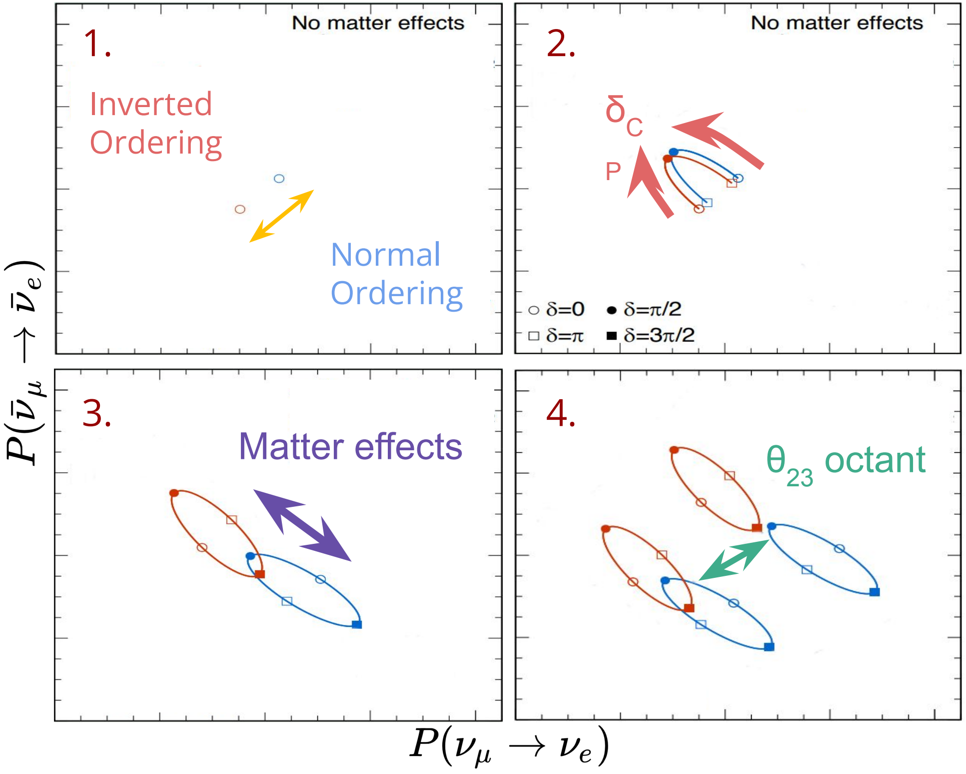


ND also provides opportunity for high-statistics measurements of ν interactions

Neutrinos vs antineutrinos: ν_e appearance

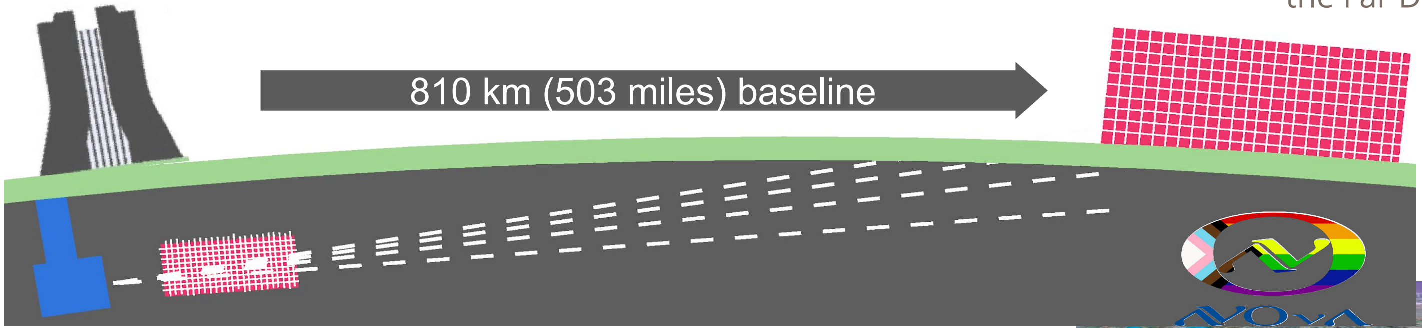
With both beam modes, ν_e appearance gives us access to all parameters:

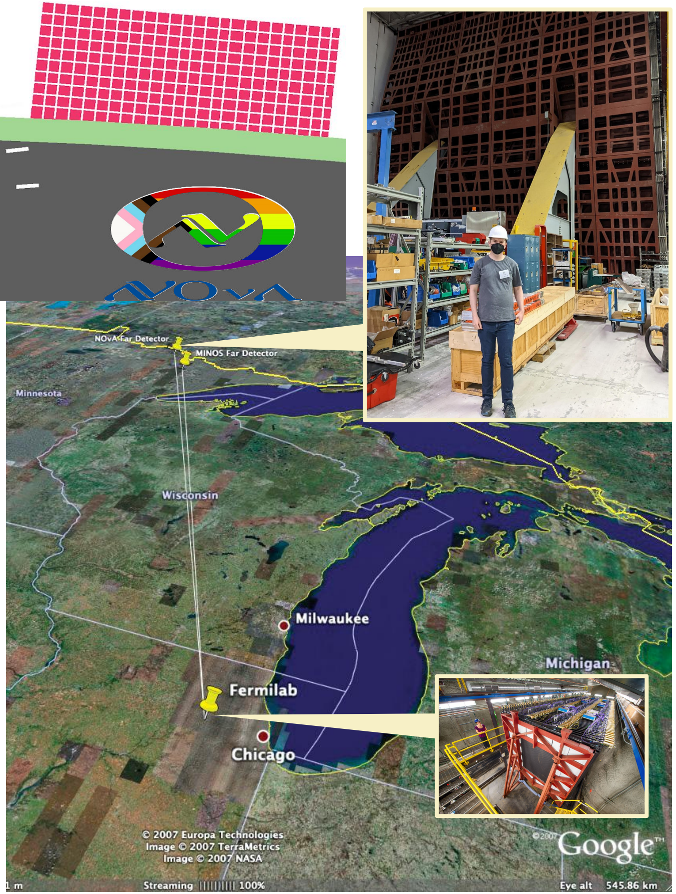
1. Inverted Mass Ordering gives a **slight suppression** in both beam modes.
2. CP violation causes **opposite effects** in each ordering - tracing out ellipses.
3. Matter effects also produce **opposite effects** in neutrinos and antineutrinos.
4. The octant of θ_{23} causes either a **suppression** or **enhancement** in both beam modes.



The NOvA experiment

For scale, me standing in front of the Far Detector in June 2022.





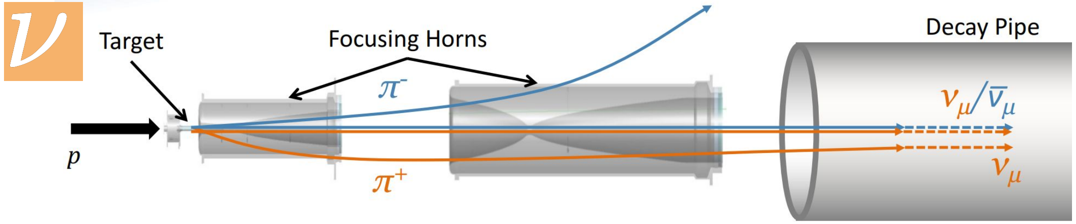
NOvA

- Typical **long-baseline** neutrino oscillation experiment.
- Functionally identical tracking calorimeters.
- **Near detector** (ND) ~100 m underground, at Fermilab.
- 14 kton **far detector** (FD) on surface, northern Minnesota.
- Both positioned **off-axis** (from the beam center), giving a narrow neutrino energy spectrum peaked at ~2GeV.
- Longer baseline → **enhanced matter effects**.

Neutrino beams and datasets

Fermilab’s NuMI beam:

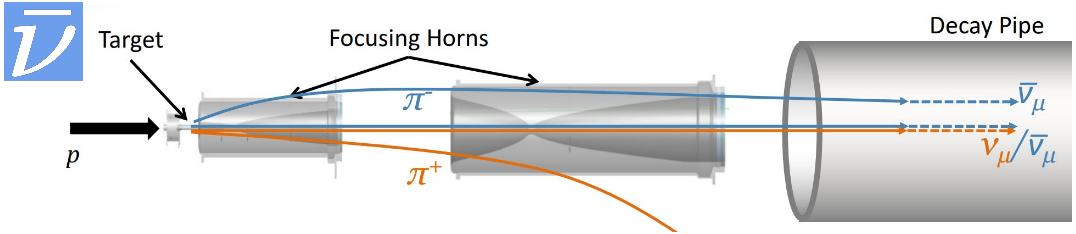
- Protons impinge on a graphite target.
- Charge select pions to get a high purity (anti)neutrino beam.



Neutrino beams and datasets

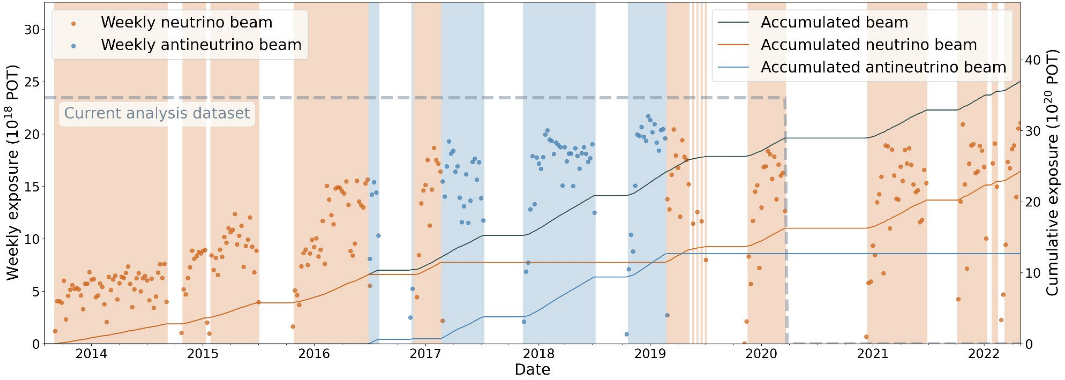
Fermilab's NuMI beam:

- Protons impinge on a graphite target.
- Charge select pions to get a high purity (anti)neutrino beam.



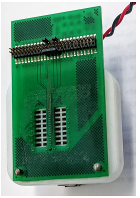
Accumulated beam exposure in both beam modes - 2020 analysis datasets.

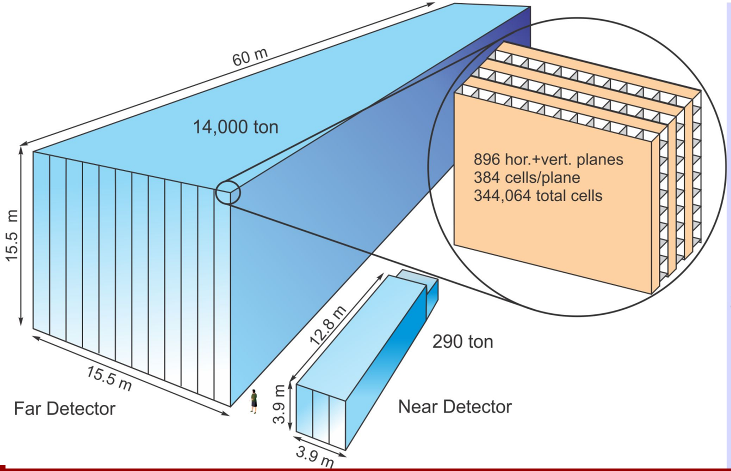
NOvA has continued taking data since 2020. Upcoming analysis will double neutrino beam exposure.

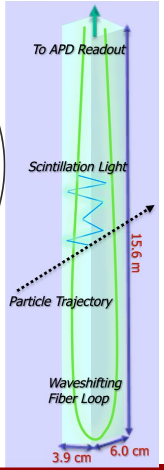


Readout and events

- Highly granular **tracking calorimeters**, orthogonal planes, cells filled with **liquid scintillator.**
- Large target mass - 14 kton FD (~100 FD neutrinos every year).
- Readout via wavelength-shifting fiber loop to **avalanche photodiodes (APDs).**

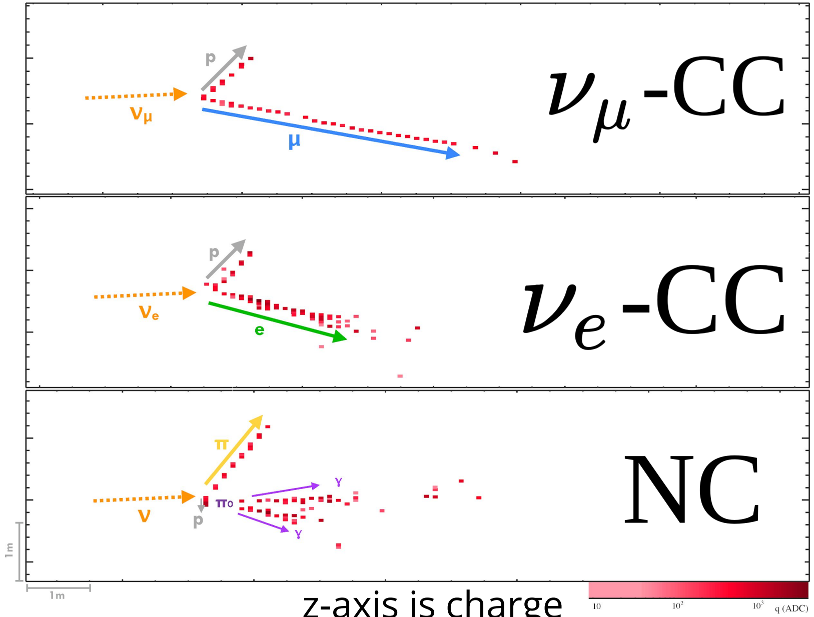




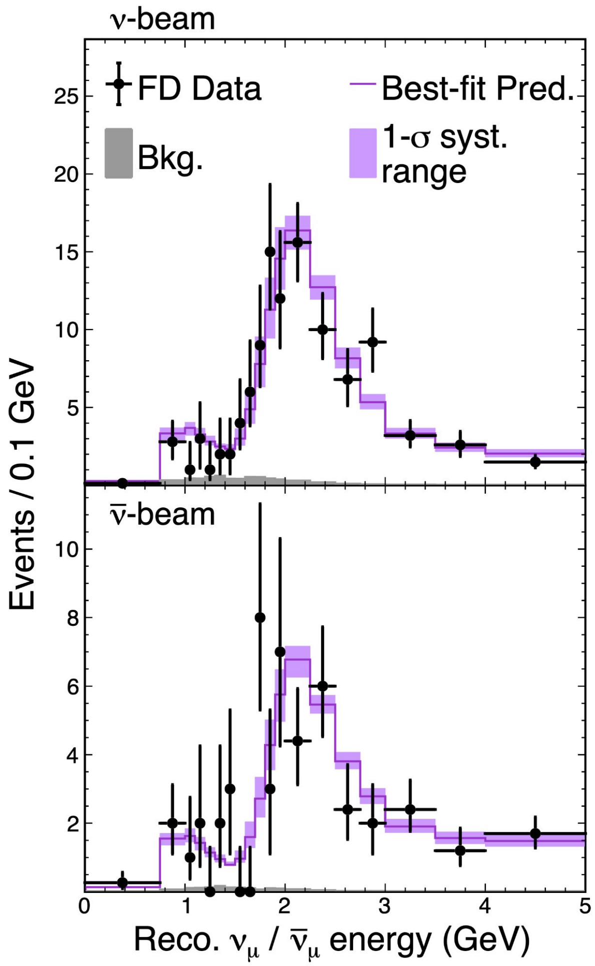


Muons have longer straighter tracks, shorter EM showers are electrons and photons.

Pixelated readout lends itself to reconstruction using techniques from computer vision.



z-axis is charge

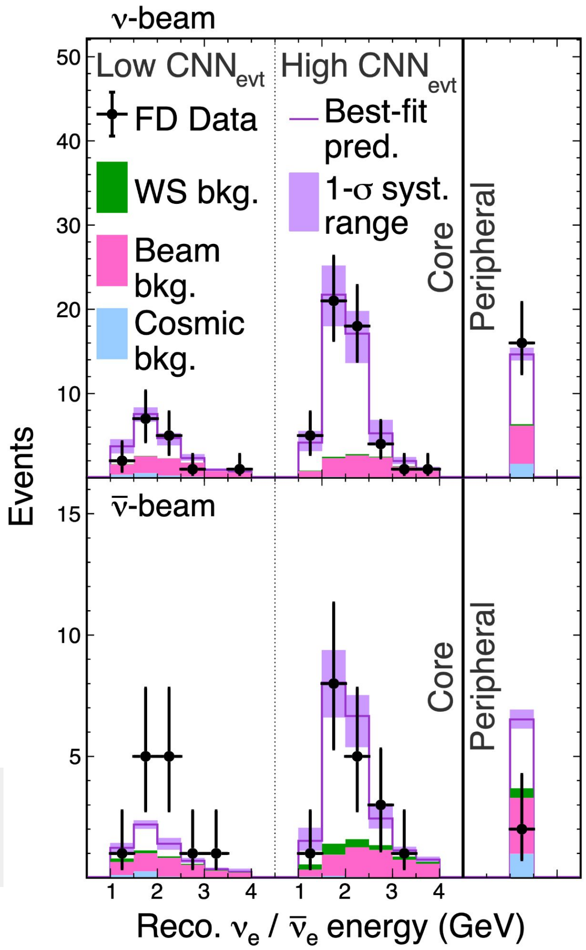


Selected events

	Signal	Background
ν_μ	211	8.2
$\bar{\nu}_\mu$	105	2.1
ν_e	82	26.8
$\bar{\nu}_e$	33	14.0

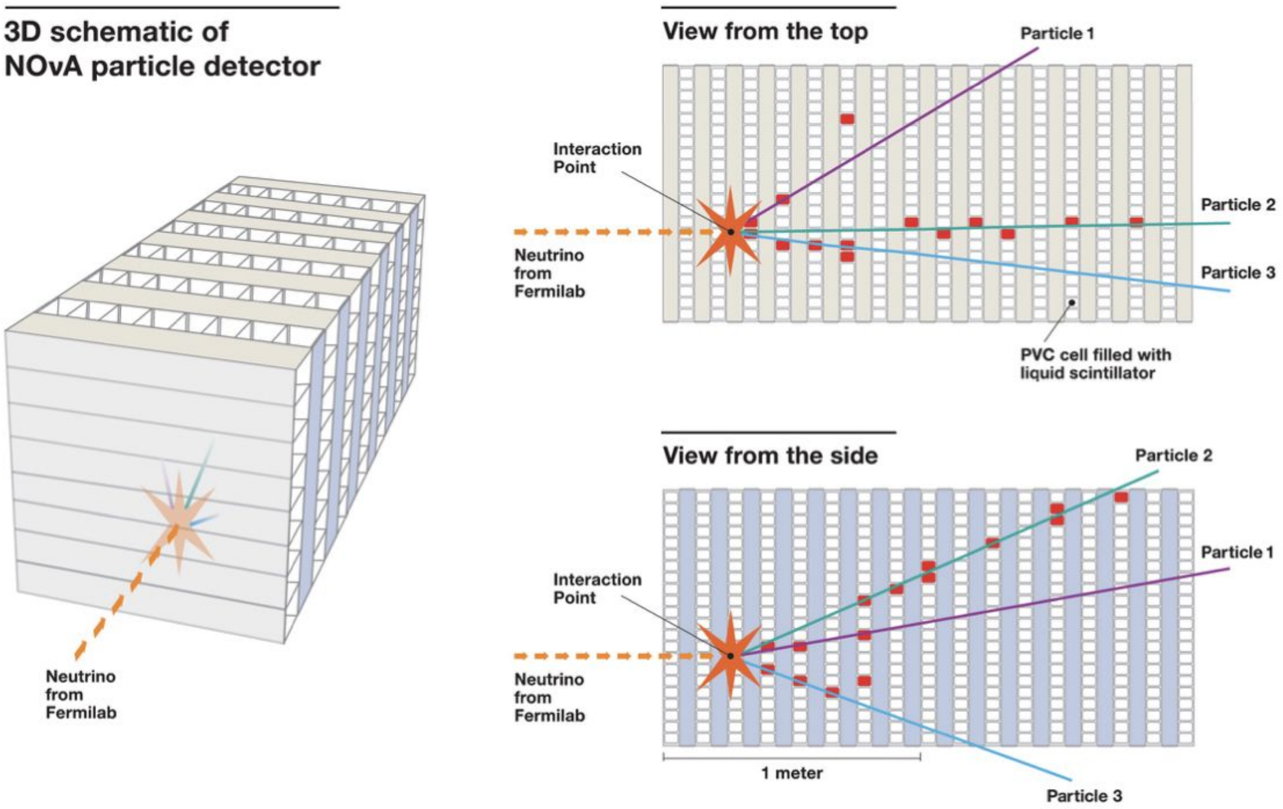
>4σ evidence of electron antineutrino appearance

Phys. Rev. D 106, 032004



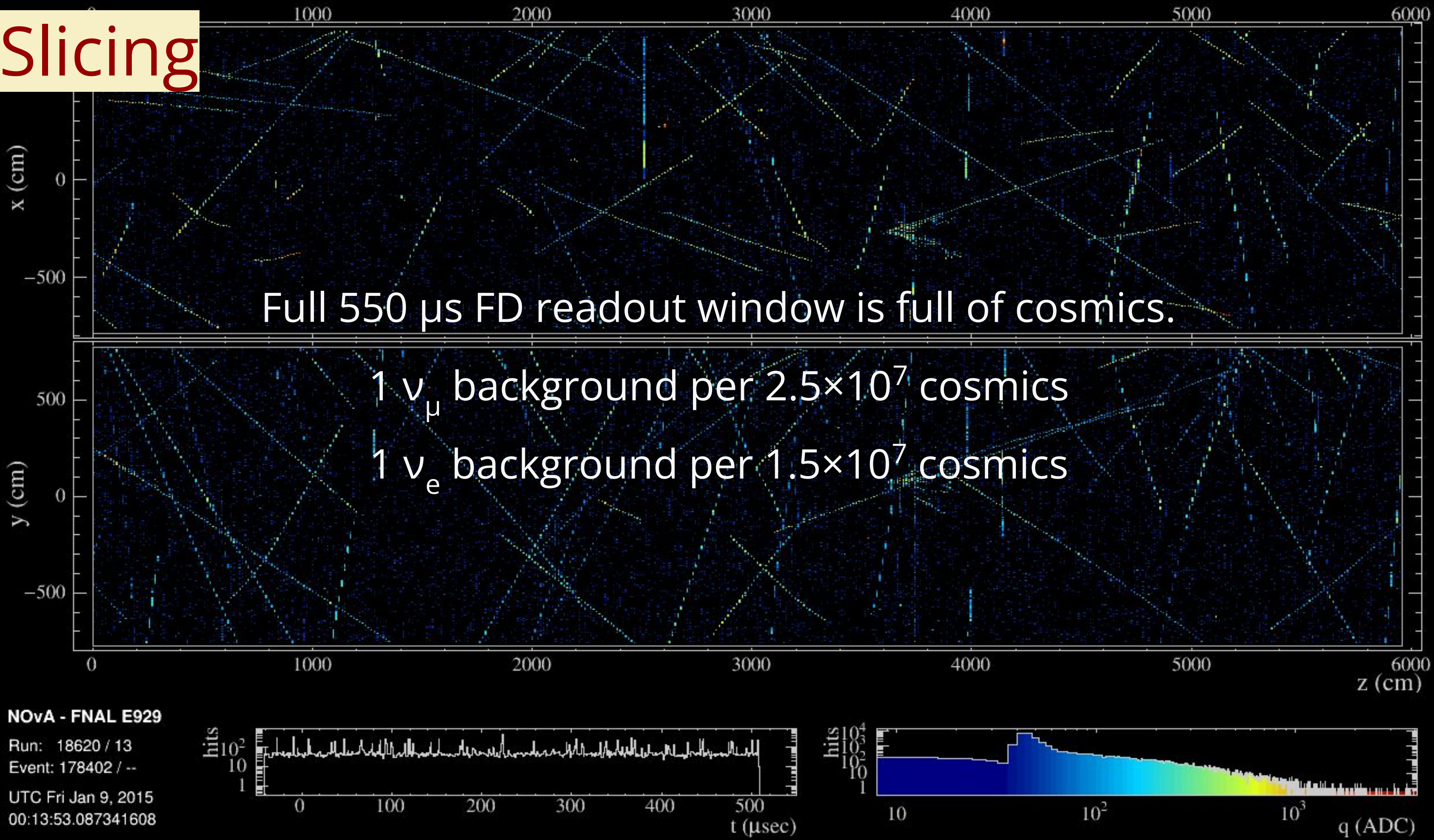
ML in NOvA reconstruction

Detector views



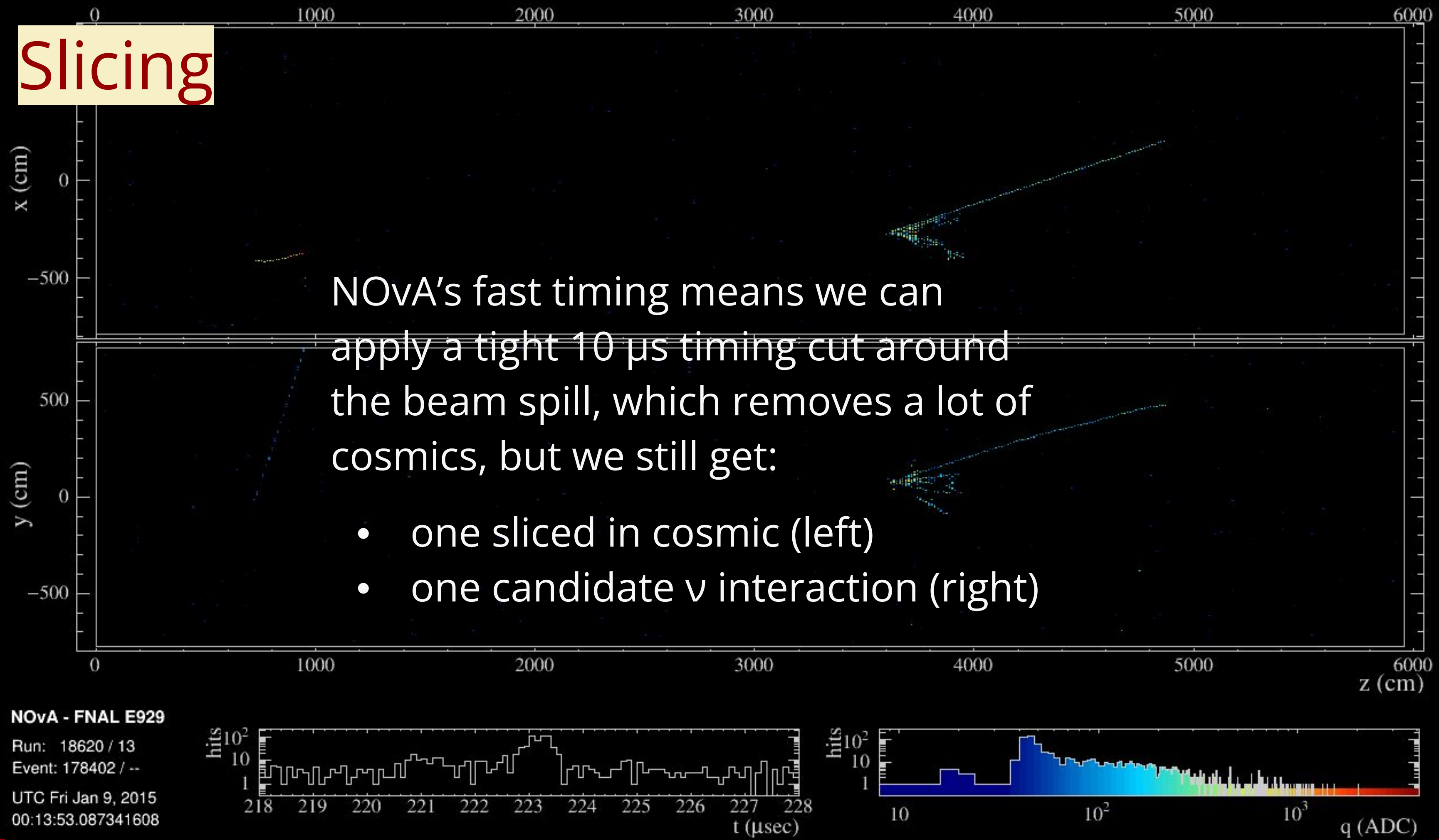
Inputs to ML networks

Slicing



Full 550 μs FD readout window is full of cosmics.
1 ν_μ background per 2.5×10^7 cosmics
1 ν_e background per 1.5×10^7 cosmics
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)

Slicing



NOvA's fast timing means we can apply a tight 10 μs timing cut around the beam spill, which removes a lot of cosmics, but we still get:

- one sliced in cosmic (left)
- one candidate ν interaction (right)

Cosmic filtering with a NN

Runs as a pre-reco step to filter out events that do not contain a neutrino interaction and identified as containing cosmics.

- Network based on ResNet18 backbone with a siamese structure → takes in two event images (top-view and side-view) as input.
- Softmax output with five labels: ν_μ, ν_e , ν_τ, NC, and cosmic score.
  - Only cut on the cosmic score for filtering
- The training sample contained 1M+ ν_μ, ν_e, and NC events in both beam modes and 5M+ cosmic events.
  - Not trained separately for neutrino/antineutrino mode.
- Performs better than traditional cosmic rejection in all samples.

	Traditional Cosmic Rejection (%)	Cosmic Rejection Neural Network (%)
ν_μ	93.21	99.71
$\bar{\nu}_\mu$	92.81	99.82
ν_e	93.22	99.20
$\bar{\nu}_e$	92.82	99.20
ν NC	93.24	97.08
$\bar{\nu}$ NC	92.79	96.82

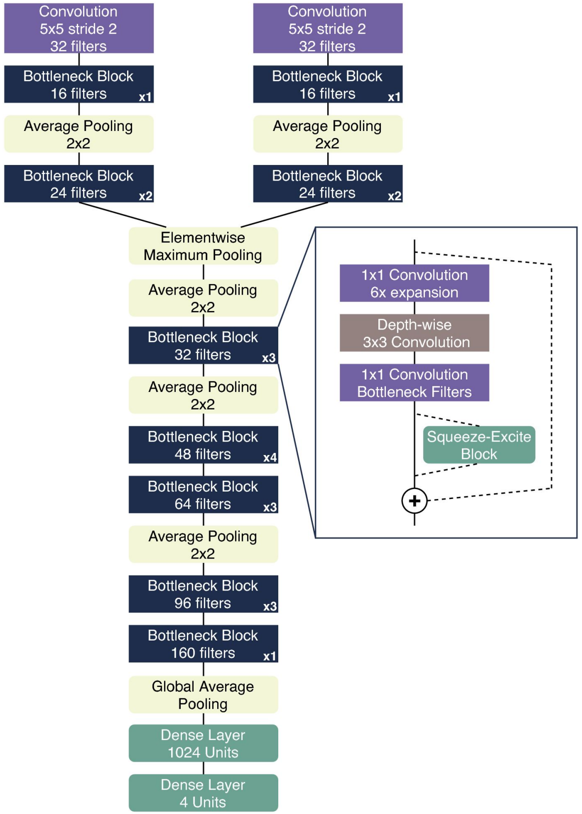
EventCVN (interaction flavor classifier)

NOvA was the first HEP experiment to use a CNN in a physics measurement → classifying candidate neutrino interactions.

"A Convolutional Neural Network Neutrino Event Classifier" (arxiv-1604.0144)

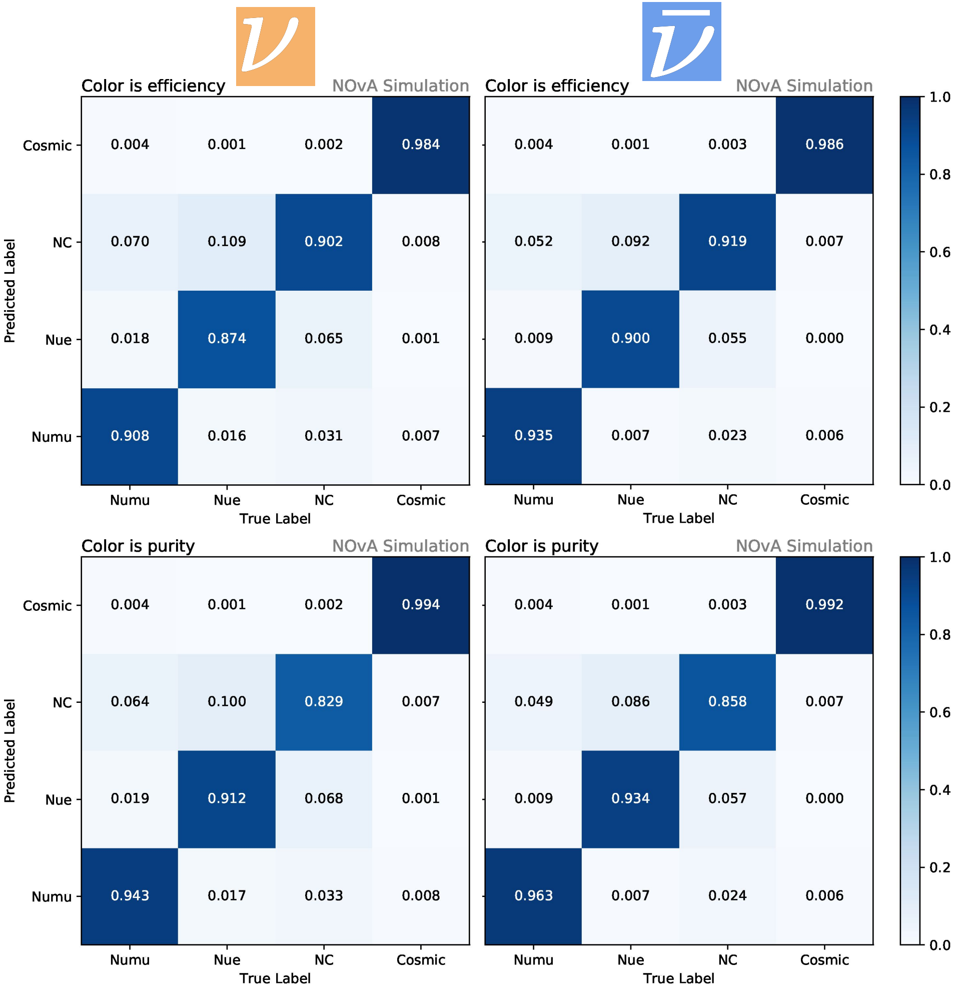
Our current iteration:

- Modified MobileNetv2 architecture
- Removal of tau neutrinos from the training.
- Consideration of key systematics during training.
- Switched to TensorFlow.
- Removed trivial cosmic events from the training sample.



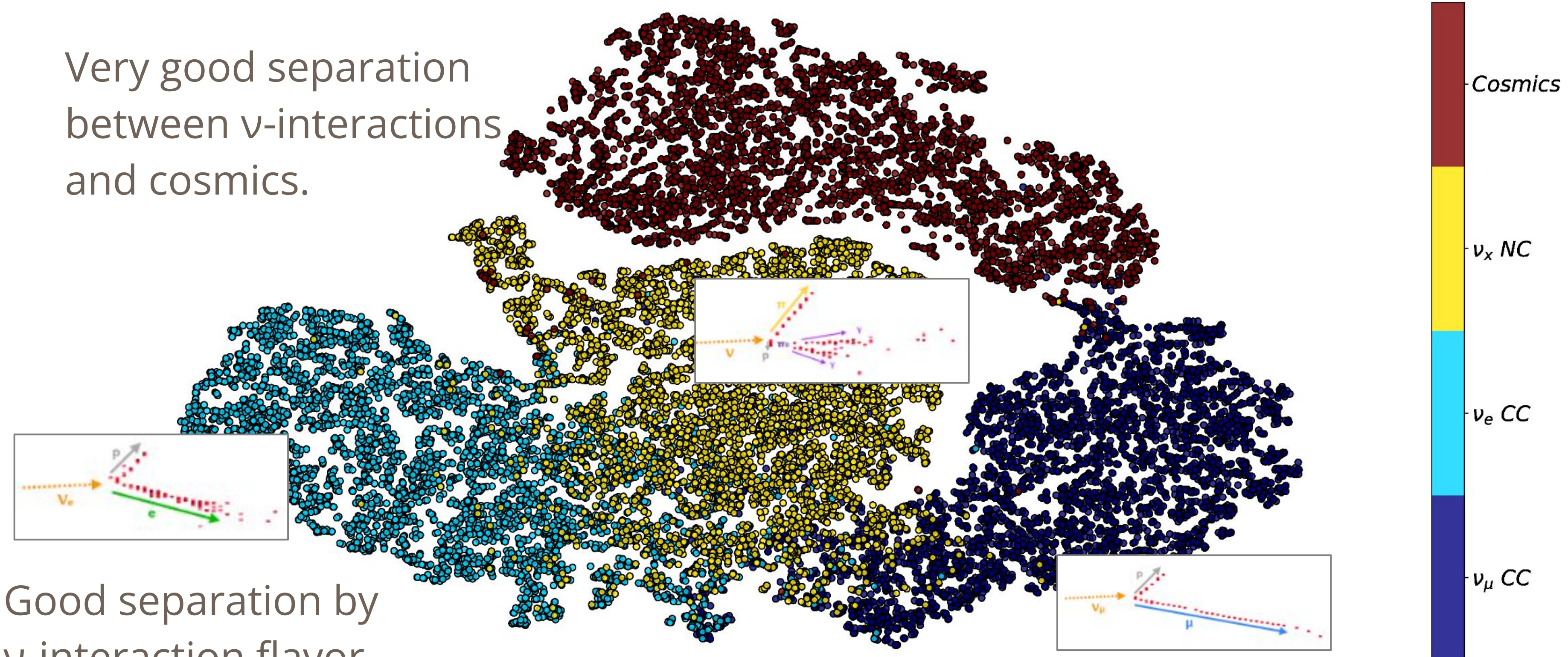
EventCVN performance

- Similar performance for neutrino and antineutrino modes.
- Anti-neutrino mode shows slight increase in efficiency.
- Purity over 90% for all interaction flavors.



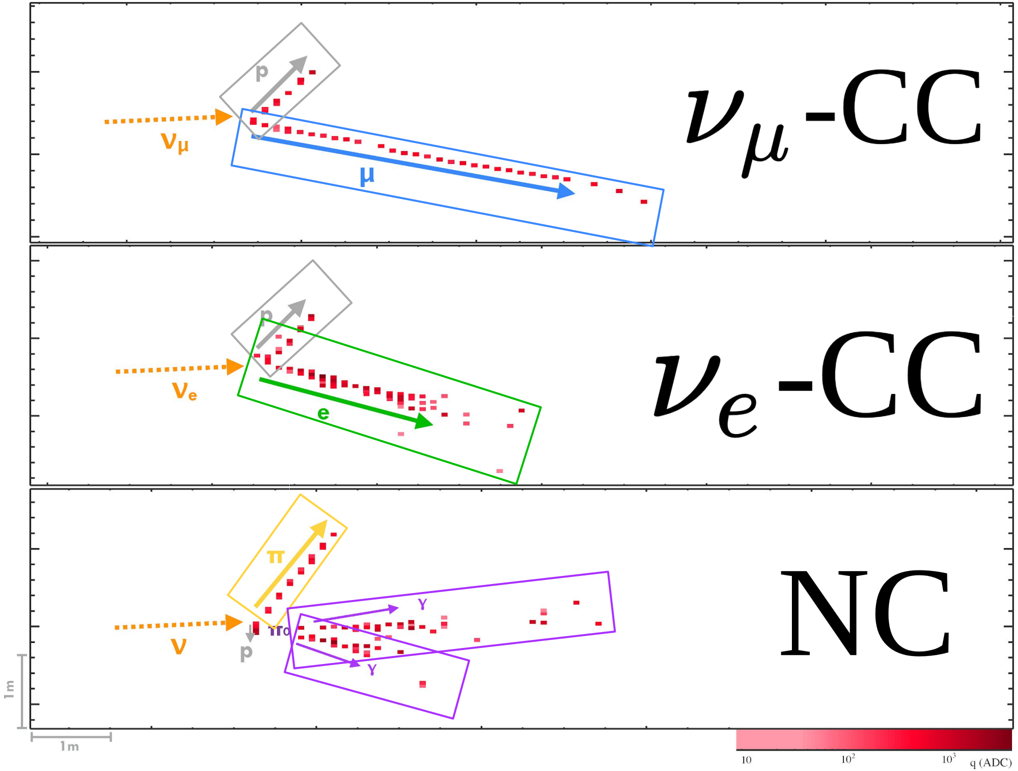
t-Distributed Stochastic Neighbour Embedding

Very good separation between ν-interactions and cosmics.



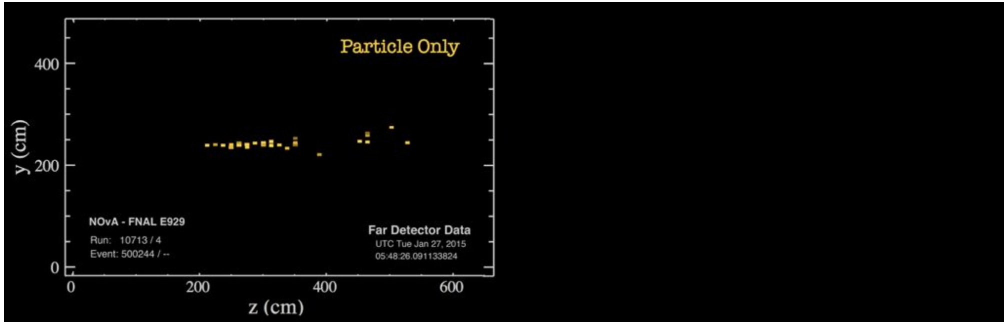
Good separation by ν-interaction flavor.

ProngCVN (particle classifier)



- We also need to be able to classify individual particles with high efficiency and purity.
- We use a fuzzy k-means geometric clustering algorithm to cluster together hits belonging to each particle, forming "prongs".
- ***"Context-Enriched Identification of Particles with a Convolutional Network for Neutrino Events"*** (arxiv-1906.00713)

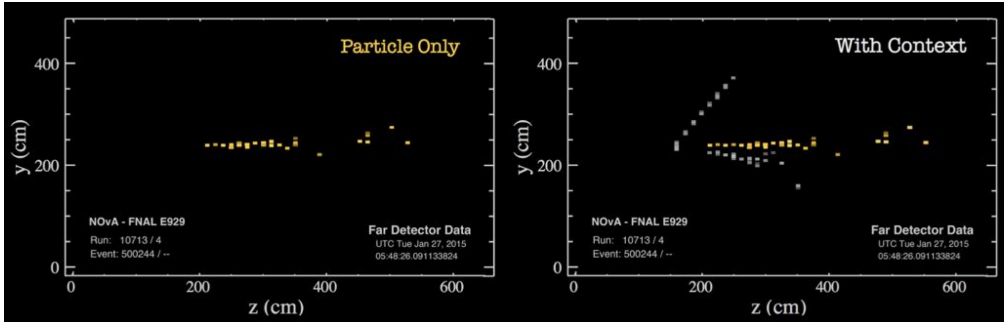
Context enriched ProngCVN



Is this an:

- **Electron**?
- **Photon**?

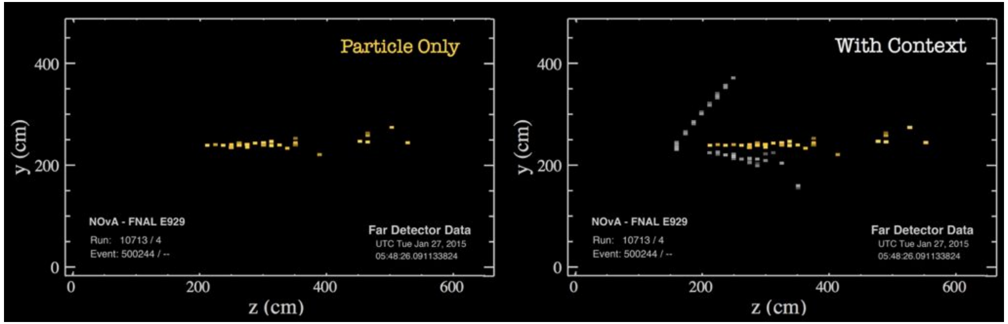
Context enriched ProngCVN



Is this an:

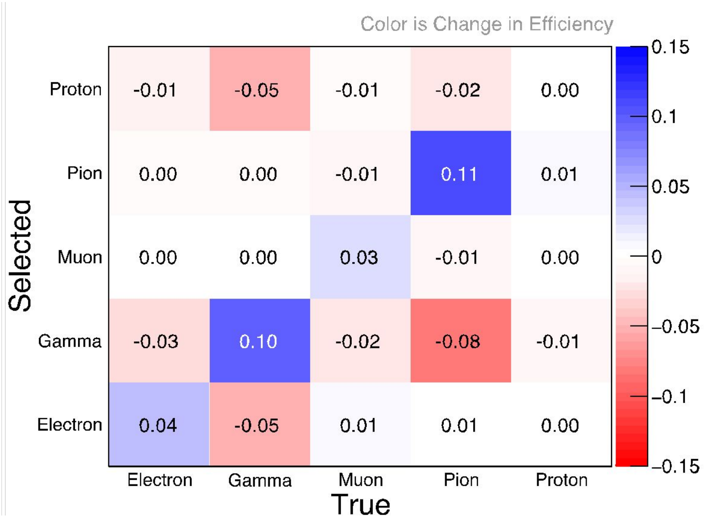
- **Electron**? ✗
- **Photon**? ✓

Context enriched ProngCVN



Is this an:

- **Electron**?
- **Photon**?

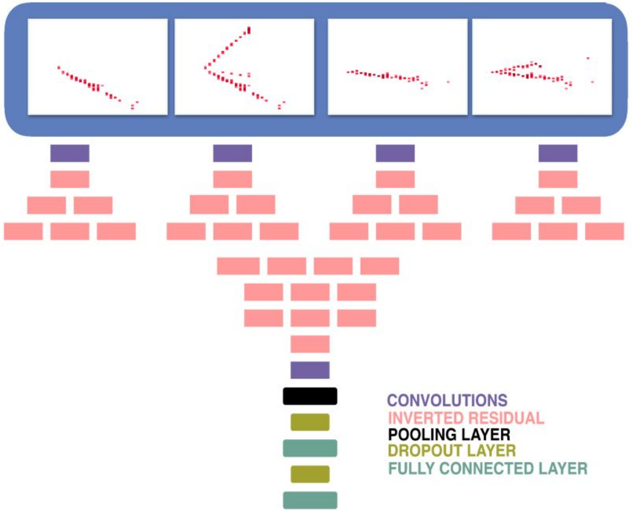


We classify particles using both top and side views of the prongs, plus top and side views of the entire event.

The event views provide extra contextual information.

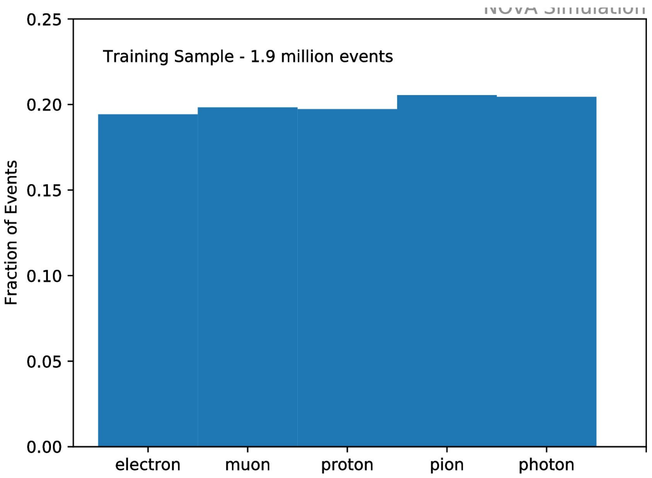
We found that this increase the efficiency by ~10 % in classifying photon and pion candidate prongs.

ProngCVN training



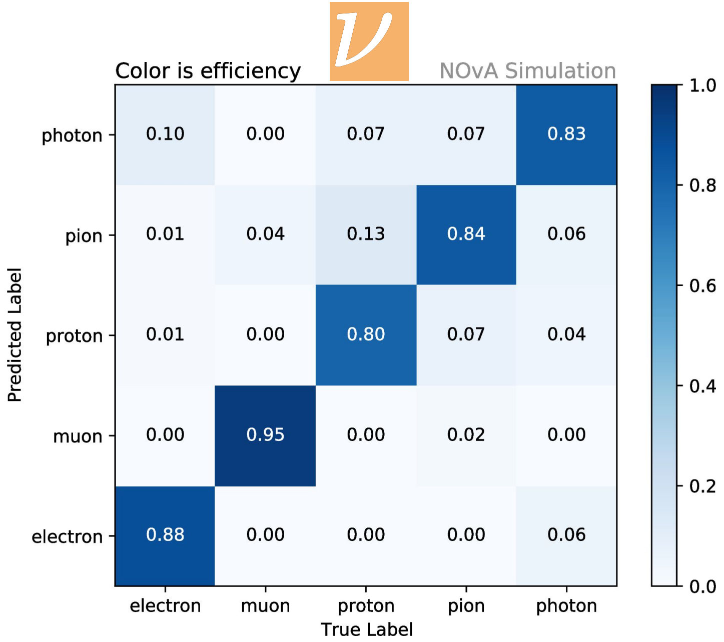
The network architecture uses a CNN based on MobileNetv2 (as for EventCVN), but with a four-tower siamese structure to incorporate each view.

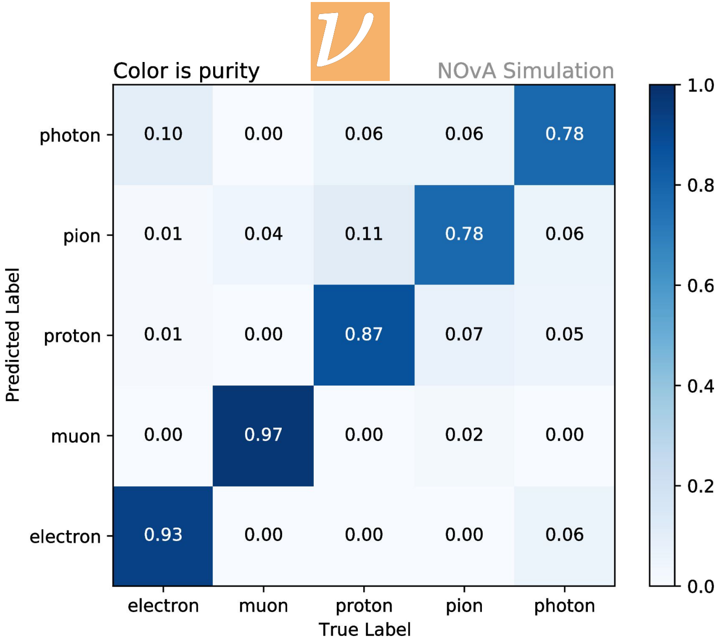
We trained it on a balanced sample of almost 2M prongs, with each of the 5 main particle types NOvA sees representing about ⅕ of the sample.



ProngCVN performance

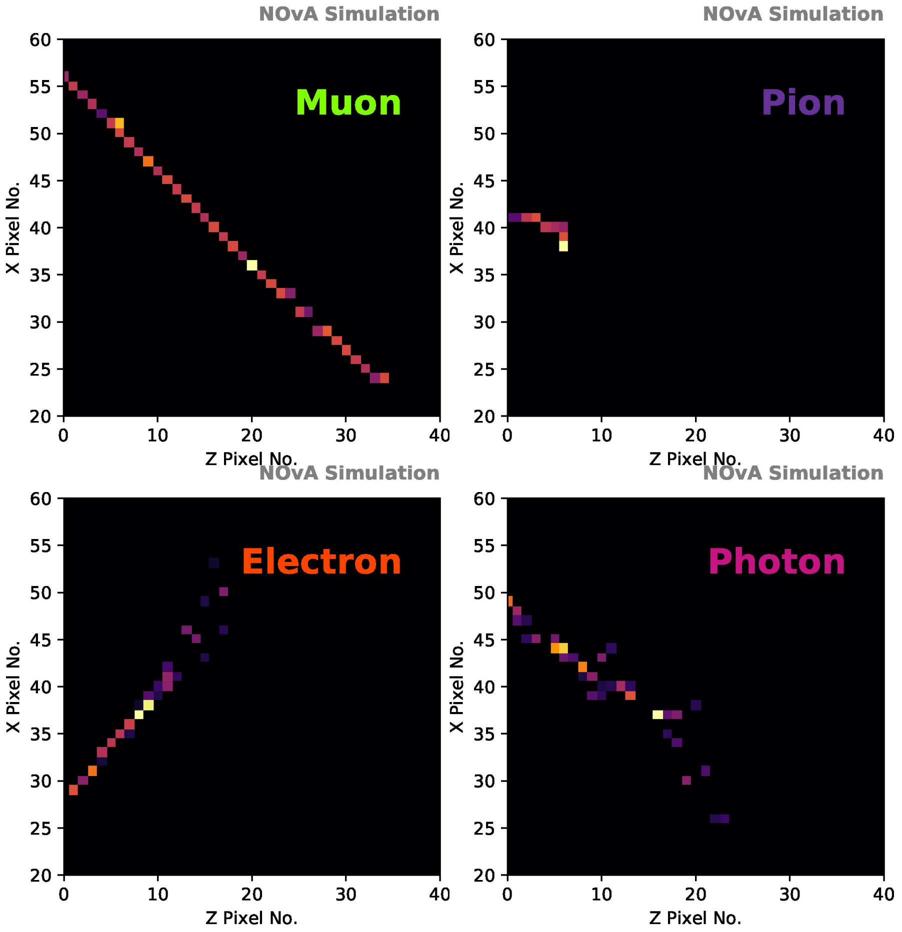
Neutrino mode training performed well for both beam modes. We achieve high purity for all particle types, particularly muons and electrons.





Single particle ID

- We train our context-enriched network is trained on GENIE simulated events.
- Though no-biases have been observed, we also have a network trained using singularly simulated particles for ND analyses → no contextual information can be used.
- We are also developing a network designed for neutron identification using these samples.

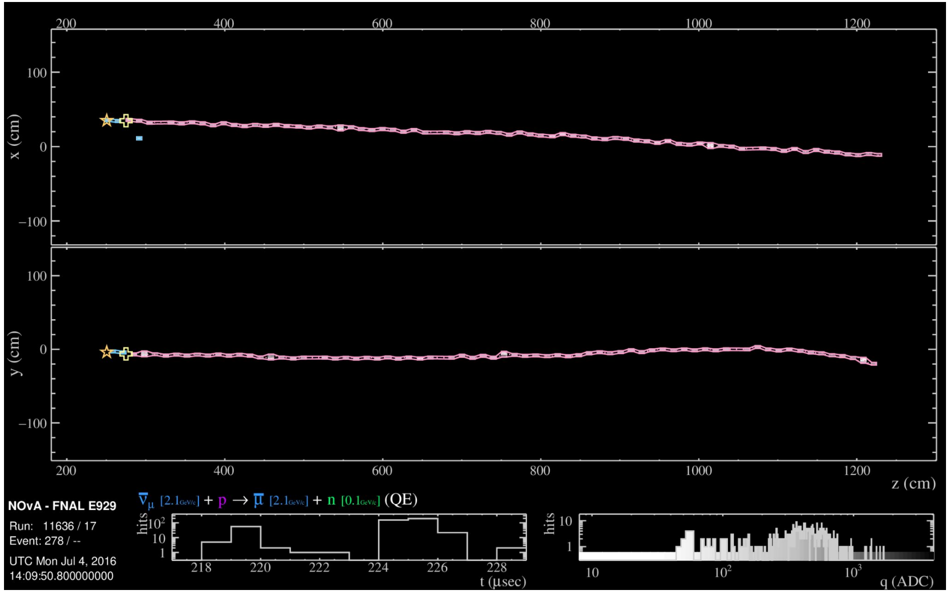


Upcoming ML for NOvA

Why improve our vertexing algorithm?

NOvA has used an Elastic Arms (EA) vertex finding algorithm in all analyses to date.

- Generally the vertex finding is good, but there are some examples of where EA trips up.
- More accurate vertexing, means more accurate:
  - prongs
  - prong ID
  - energy estimation

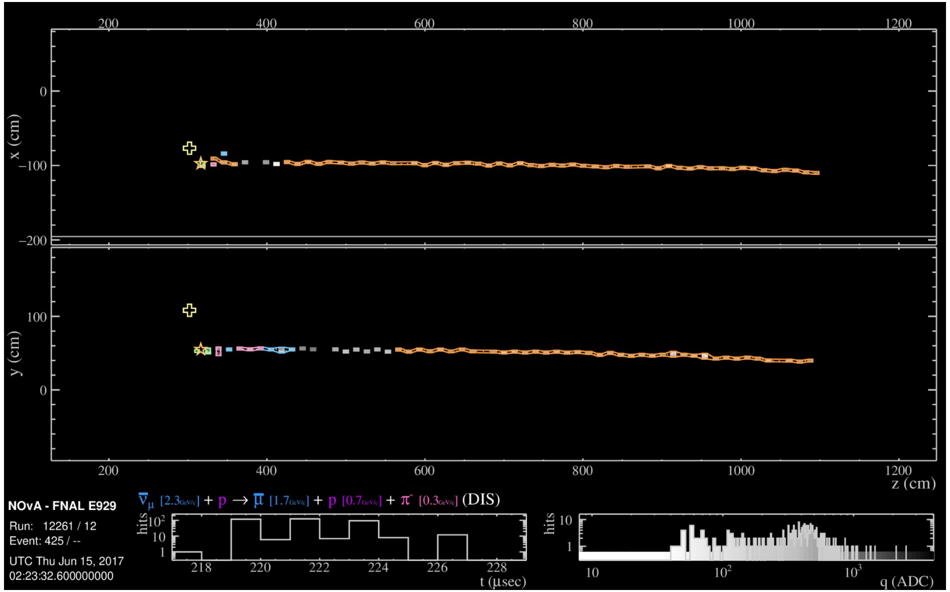


1) Here EA reconstructs the vertex too far forward → one muon prong split into two. Reco is cross, star is true vertex.

Why improve our vertexing algorithm

NOvA has used an Elastic Arms (EA) vertex finding algorithm in all analyses to date.

- Generally the vertex finding is good, but there are some examples of where EA trips up.
- More accurate vertexing, means more accurate:
  - prongs
  - prong ID
  - energy estimation

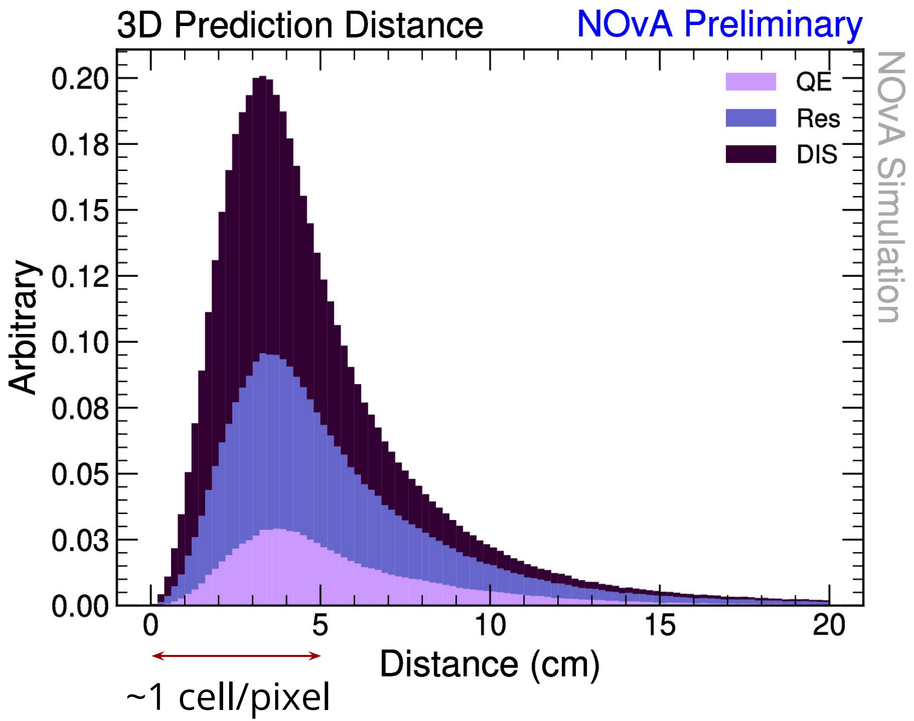


2) Here one hit pulls the vertex to the side, throwing off prong-making. Reco is cross, star is true vertex.

ML vertexing – VertexCVN

Erin Ewart, APS April 2023

- Same network architecture as EventCVN (modified MobileNetv2) – adapted to predict one 3D vertex.
- Originally trained for secondary vertexing but now being trained for primary vertex finding.
- Early training shows good performance across interaction types → vertex resolution within cell width for majority of events.
- Also considering a hybrid approach, where VertexCVN seeds EA.



ML Vertexing – RegVertex

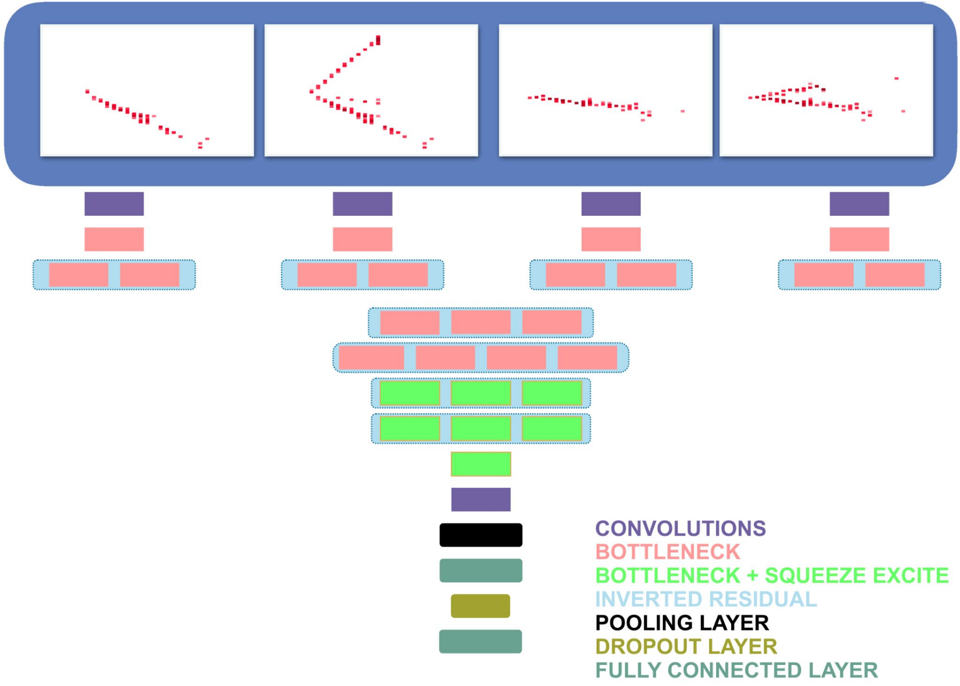
Abdul-Wasit Yahaya

- Parallel vertexing development from our WSU group.
- Model developed using TensorFlow, also based on a CNN.
- Separate trainings for neutrino and antineutrino beam modes.
- Independent networks trained on each coordinate direction: x, y, and z.
    - Combine predicted labels to give one 3D vertex.
- Current training looks promising, but we still need to test at scale.

Improved prongCVN

Akshay Chatla, DAE 2022

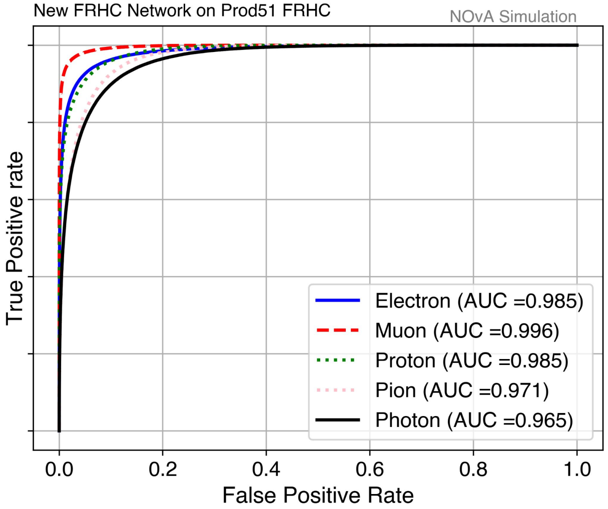
- Modifies ProngCVN (modified MobileNetv2) architecture by adding Squeeze-Excite block for channel attention.
- Trained on a combined sample of neutrino and antineutrino mode data.

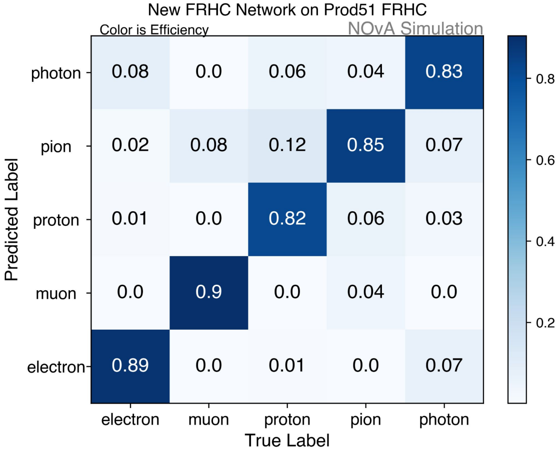


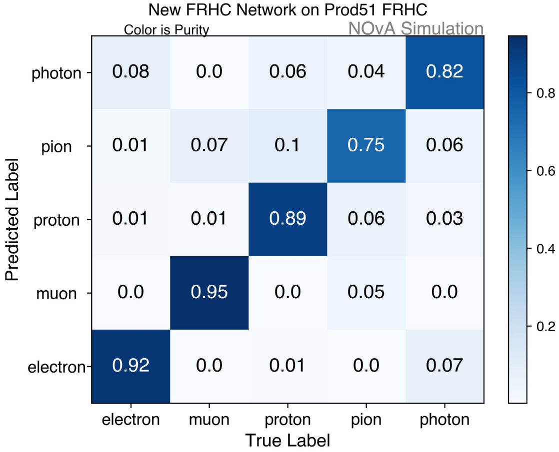
Improved ProngCVN

Akshay Chatla, DAE 2022

- Receiver Operating Characteristic (ROC) curves for particle classification show good performance.
- Improved efficiency for electron, muon, and photon labels.
- Slightly reduced purity.







Transformer network

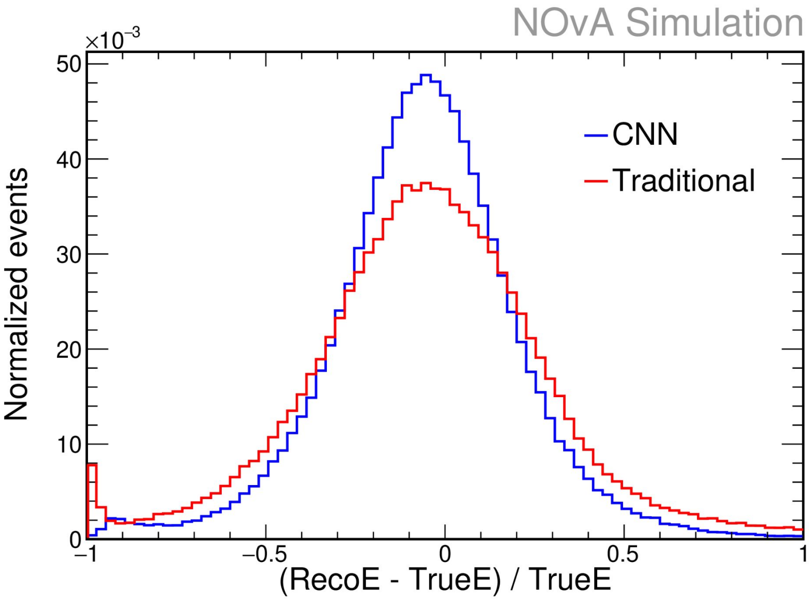
See the next talk by Alejandro!

Energy estimation

Ben Jargowsky, APS April 2022

We are developing a CNN to improve our hadron energy estimation.

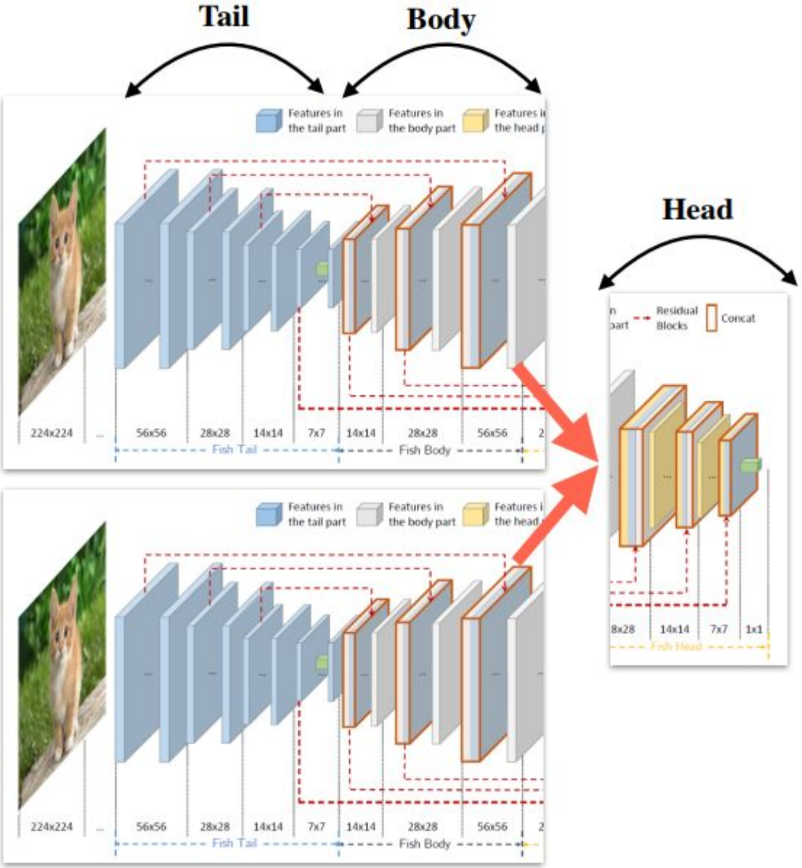
We see an improvement in energy resolution over our traditional calorimetry-based method, when comparing the regression CNN based method.



Sparseness and GNNs

Stella Haejun Oh, APS April 2022

- Sparse FishNet is a modified UNet architecture performing sparse convolutions.
  - Suitable for semantic segmentation and classification.
- Parallel tail->body sections take in detector top and side views.
- These are merged and downsampled in single head section.
- As V mentioned yesterday, we are also in the early stages of developing a GNN for NOvA.



Outlook

- NOvA pioneered the use of CNNs for event classification in HEP and implemented improved networks for recent analyses.

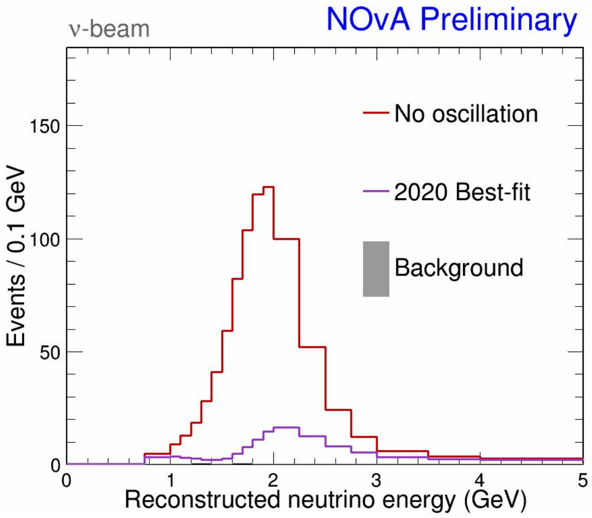
- In the near future we expect to have:
  - ML vertex finding – for improved 3D vertex reconstruction.
  - New transformer network and improved prongCVN.
  - Improved hadronic energy estimation.

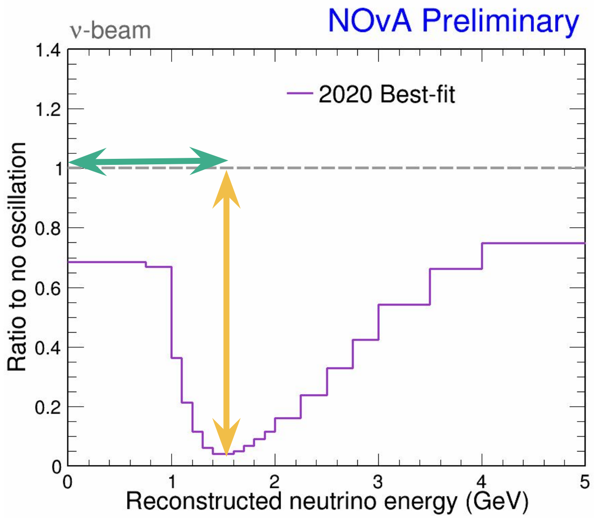
all of which will help NOvA achieve its physics goals.

Thank you!

Extra slides

ν_μ disappearance





The PMNS matrix gives a survival probability for ν_μ as:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \Delta m^2_{32} L}{E}\right)$$

Sensitivity to: $\sin^2(2\theta_{23})$ and Δm^2_{23}

Electron neutrino appearance

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\text{atm}}} e^{-i(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} \left(\cos\Delta_{32} \cos\delta_{CP} \mp \sin\Delta_{32} \sin\delta_{CP} \right)$$

$$P_{atm} = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} (\Delta_{31})^2$$

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

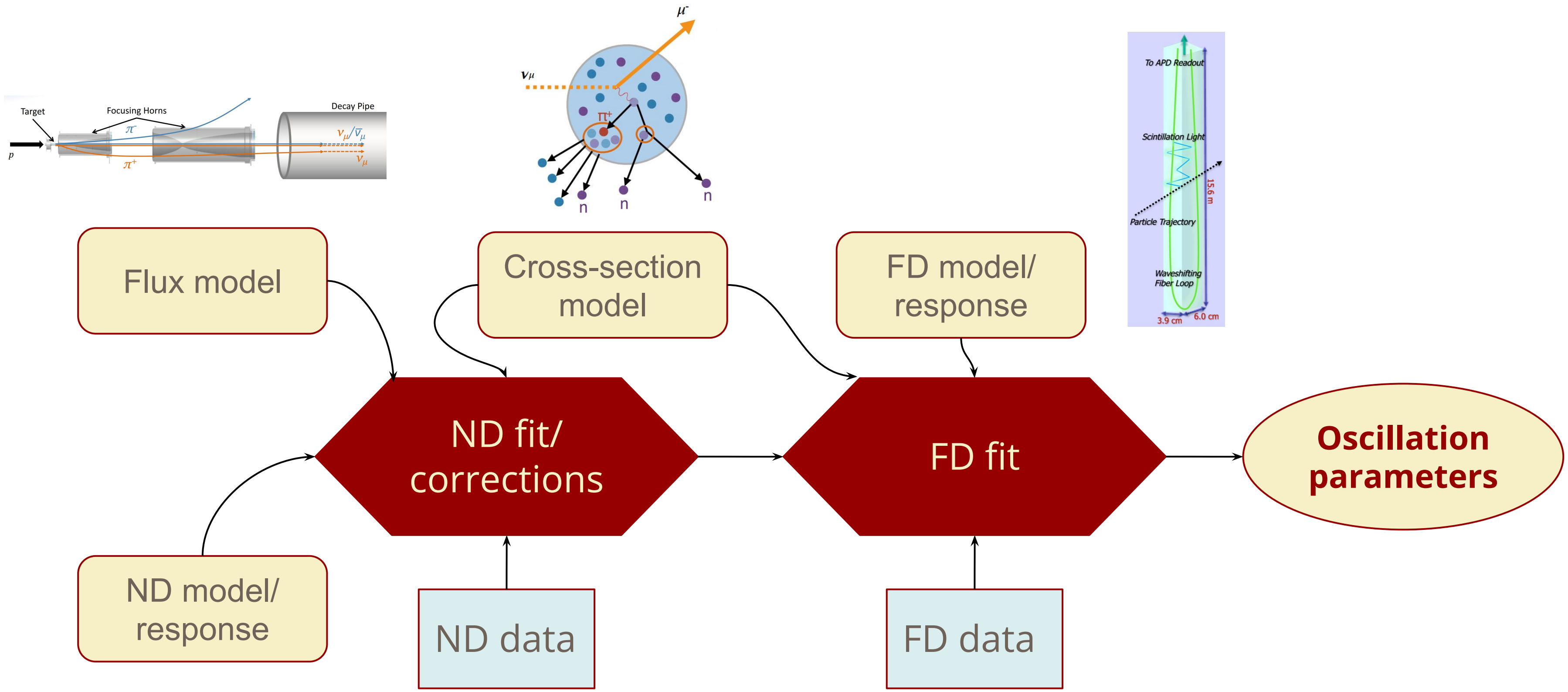
$\Delta_{ij} = (1.27 \Delta m^2_{ij} L)/E$

$a = G_F N_e / \sqrt{2}$

N_e = Earth's electron density

- Gives us access to every oscillation parameter
- Density of the Earth yields different effects for neutrinos and antineutrinos.

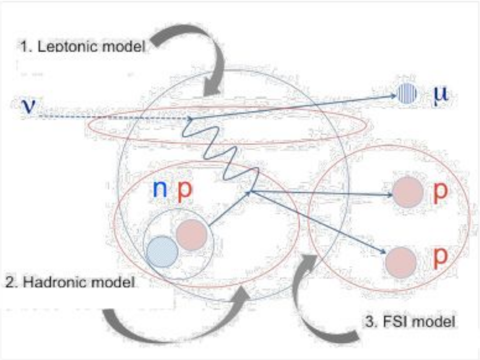
Analysis strategy for oscillation fits



Neutrino interaction model

Slide from A Himmel, Neutrino 2020.

- Constantly evolving understanding of ν interactions.
- Upgrade to GENIE 3.0.6 → freedom to choose models
- Chose the most "theory-driven" set of models plus GENIE's re-tune of some parameters*.
- Some custom tuning is still required.
  - Substantially less than was needed with GENIE 2.12.2, which required tweaks to most models.



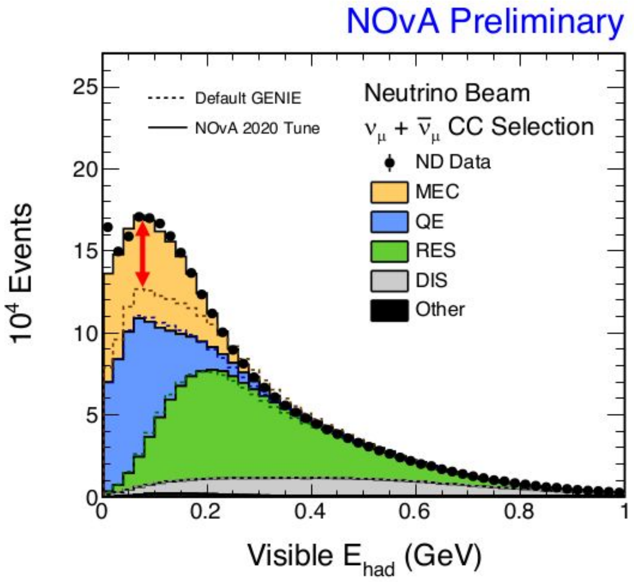
Process	Model	Reference
Quasielastic	Valencia 1p1h	J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C 70 (2004) 055503
Form Factor	Z-expansion	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
Multi-nucleon	Valencia 2p2h	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D 88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D 76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Int.	hN semi-classical cascade	S. Dytman, Acta Physica Polonica B 40 (2009)

* We call our tune N1810j_0211a, and it is built by starting with G1810b_0211a and substituting the Z-expansion form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.
Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

Neutrino interaction model

Slide from A Himmel, Neutrino 2020.

- 2p2h *or* Meson Exchange Current *or* Multi-nucleon Interactions:
  - Disagreement of models with multiple experiments well-known
  - Tuned to **NOvA ND data** with two 2D gaussians in q_0-$|\vec{q}|$ space.
  - Generous systematics covering normalization and kinematic shape
- Final State Interactions
  - Used **external π-scattering data** primarily to set uncertainties
  - Required adjusting central value, change in overall xsec was small.

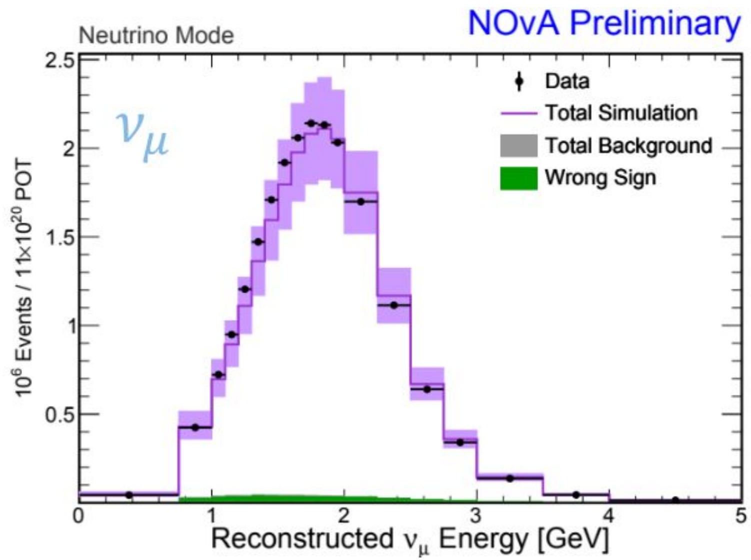


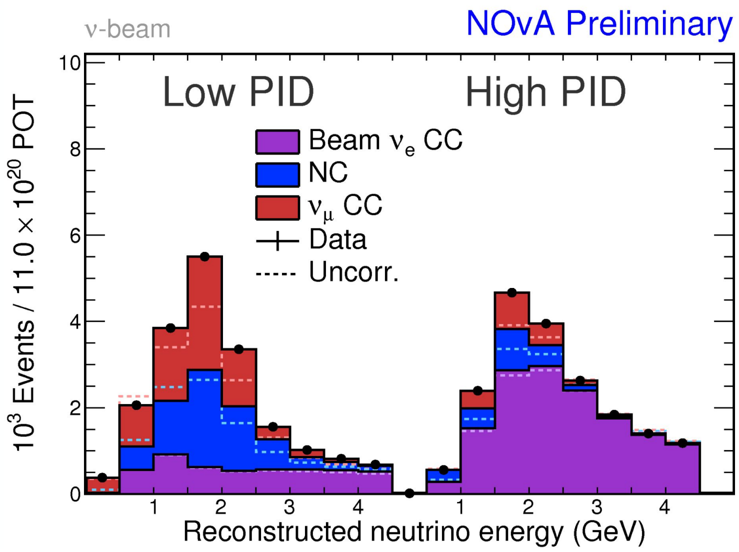
Posters

67. Cross section adjustments for 2p2h
    - Maria Martinez Casales

352. Central value tuning and uncertainties for the hN FSI model in GENIE 3
    - Michael Dolce, Jeremy Wolcott, Hugh Gallagher

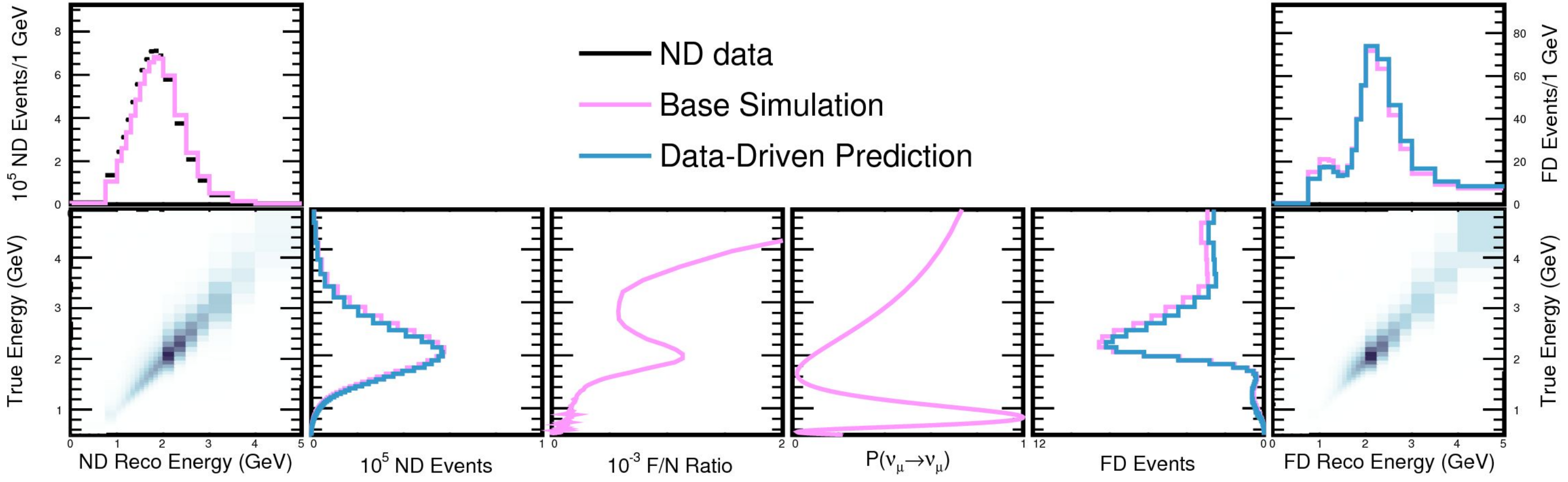
NOvA constraints using ND data





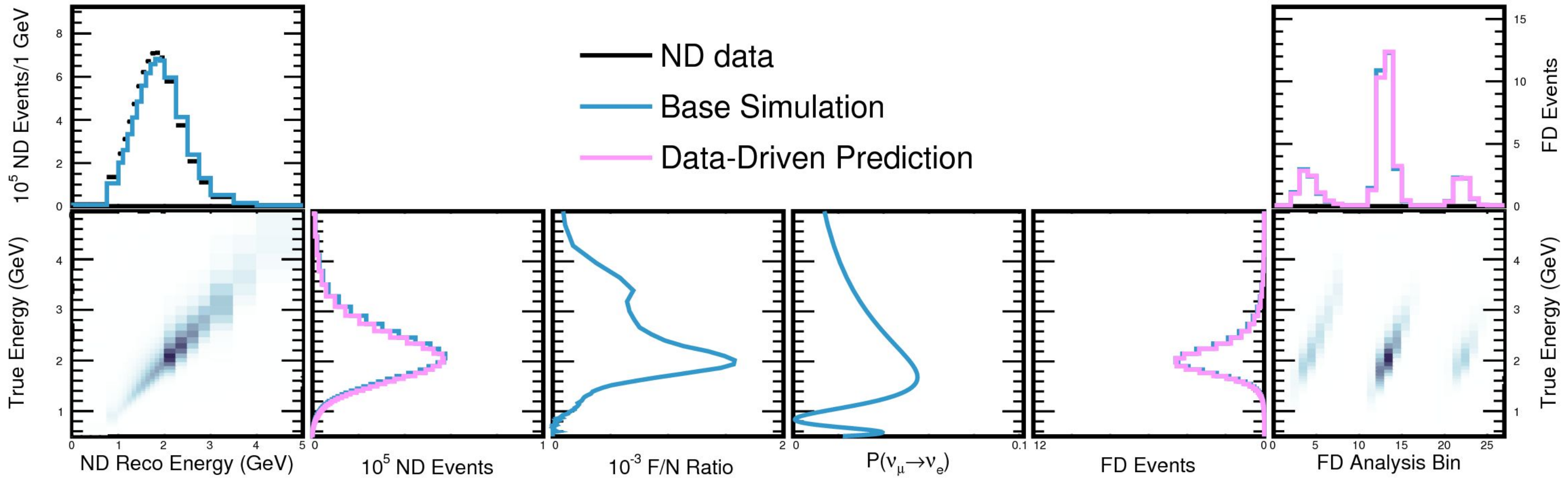
- We scale simulation to ND data to constrain signal and background rates in the FD prediction, with bin-by-bin corrections.
  - We adjust the ν_μCC, ν_eCC and NC components separately in the ND ν_e data.
- The ν_μ ND data constrains the FD **signal** while ND ν_e data constrains the prediction for beam **backgrounds**.

To evaluate the effect of a systematic shifts on our FD prediction, we propagate our nominal MC and each shift through the extrapolation procedure using our corrected ND MC .



- Selected ν_μ ND events (**4 quartiles**) → FD ν_μ signal prediction.

To evaluate the effect of a systematic shifts on our FD prediction, we propagate our nominal MC and each shift through the extrapolation procedure using our corrected ND MC .

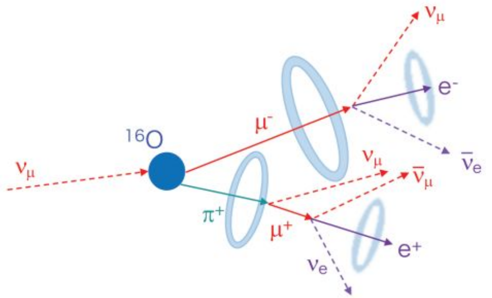


- Selected ν_μ ND events (**4 quartiles**) → FD ν_μ signal prediction.
- Selected ν_μ ND events → FD ν_e signal prediction.
- Selected ν_e/ν_μ/NC ND events → FD ν_e background prediction.

Notable updates

Credit: C. Bronner, Neutrino 2022

- All previous NOvA results use a Feldman-Cousins corrected Frequentist approach.
- Re-interpretation of 2020 data with a new **Bayesian Framework**.
- Access to Jarlskog-Invariant, NOvA-only θ_{13} measurement, and Bayes factors.
- Easier comparison with marginalized and/or Bayesian results from other experiments.



T2K analysis has four main updates:

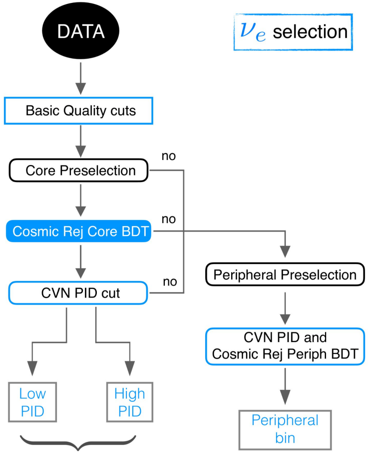
- Updated flux model.
- Improved interaction model and cross-section uncertainties.
- New ND fit including first use of ECAL in oscillation analysis.
- First use of multi-ring events in T2K

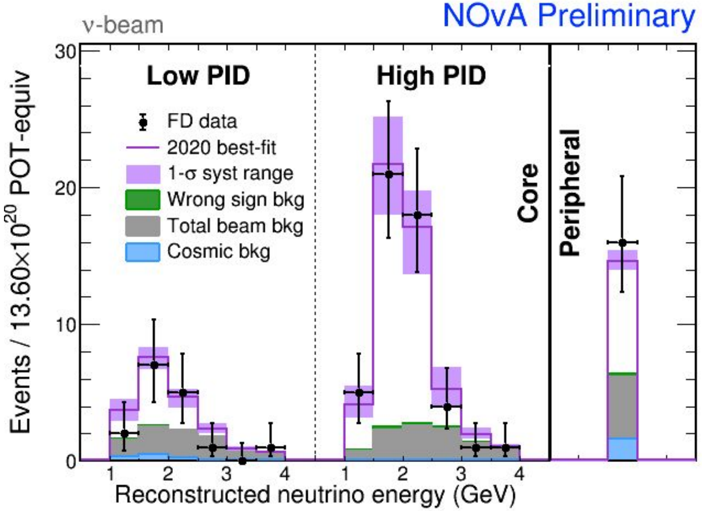
Enhancing sensitivity: ν_e

Sensitivity comes mainly from signal and background separation.

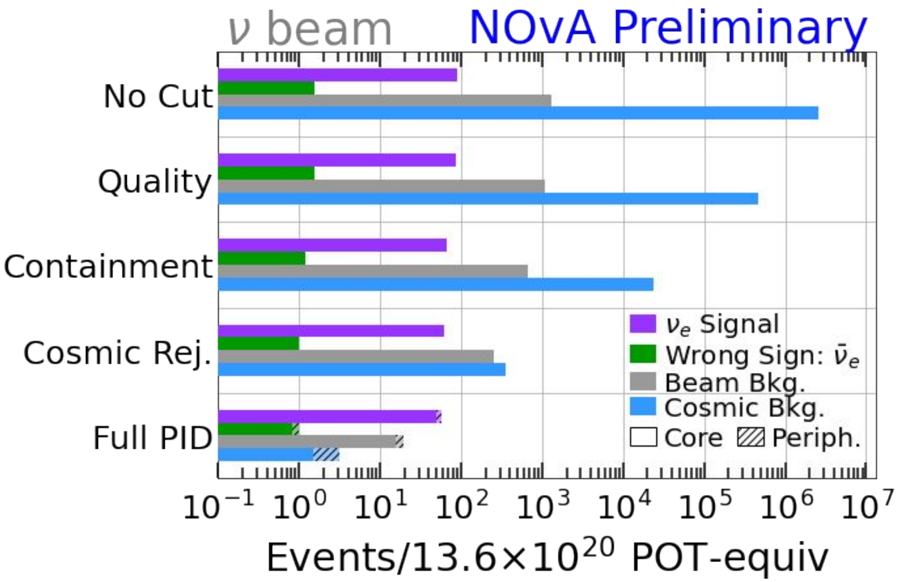
We split into three samples:

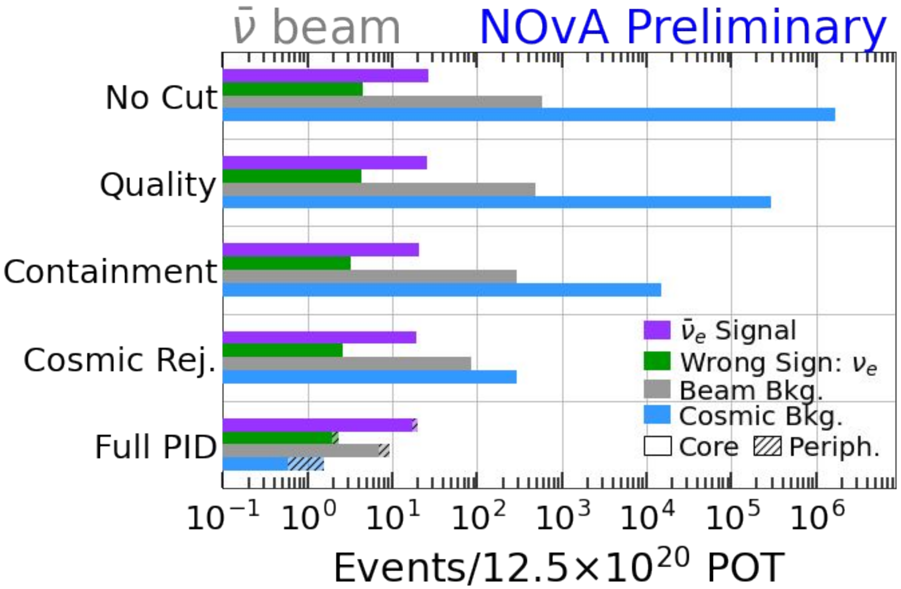
- High and low purity core samples.
- Peripheral sample.
  - Captures highly ν_e-like events (high PID score) that fail initial containment and cosmic rejection cuts.
  - No energy binning.



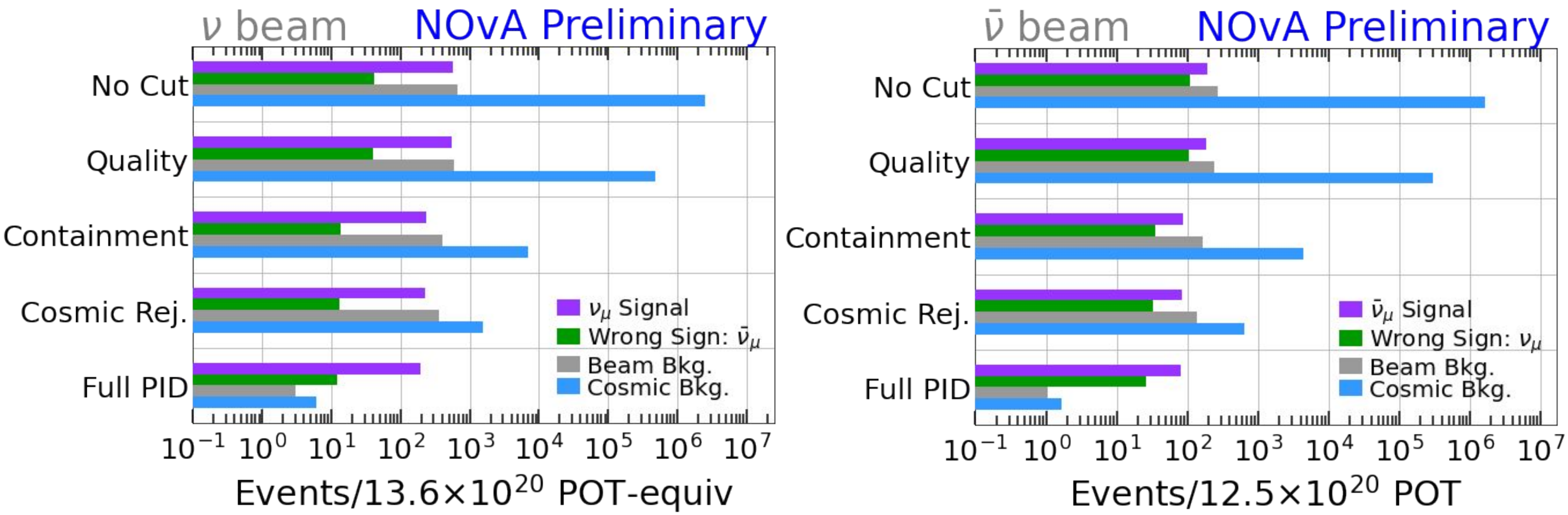


Nue selection: cut-flow





Numu selection: cut-flow

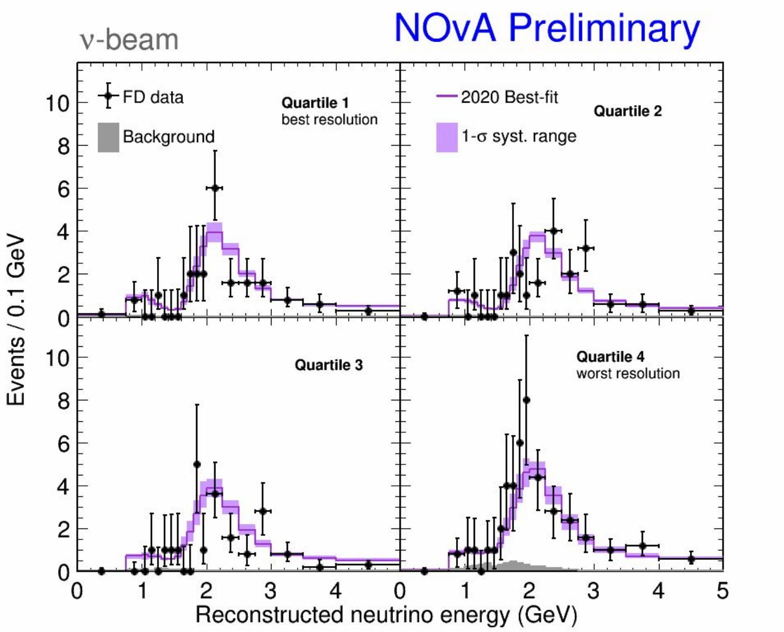


Enhancing sensitivity: ν_μ

Sensitivity comes mainly from the shape of t
particularly in the dip region.

We split into four samples by energy resoluti
hadronic energy.

Resolution varies from ~6 % in Quartile 1 to

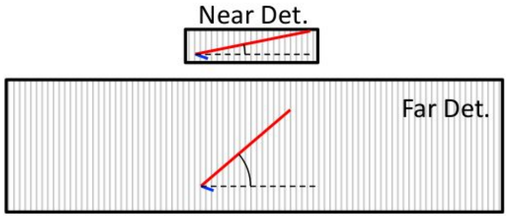


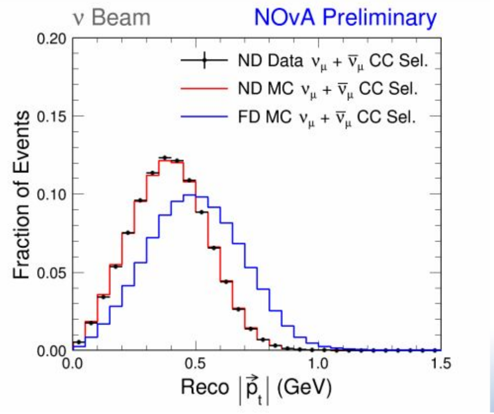
Enhancing sensitivity: ν_μ

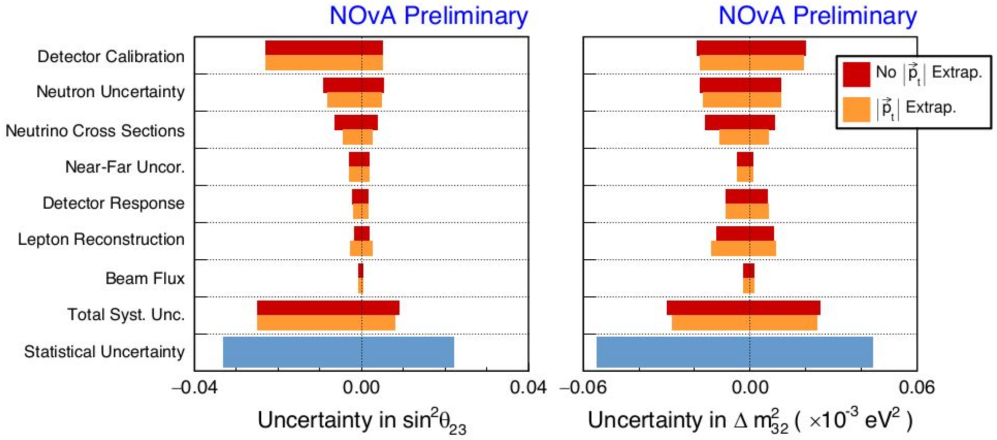
Containment in ND limits range of lepton angles more than in FD.

Mitigate by splitting ND data into 3 samples of transverse lepton momentum and extrapolate to FD.

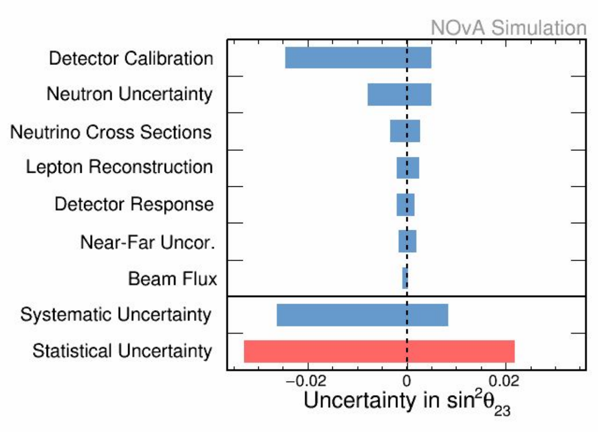
Increases robustness and reduces cross-section systematics by ~30 % (overall reduction in systematics (5-10 %).

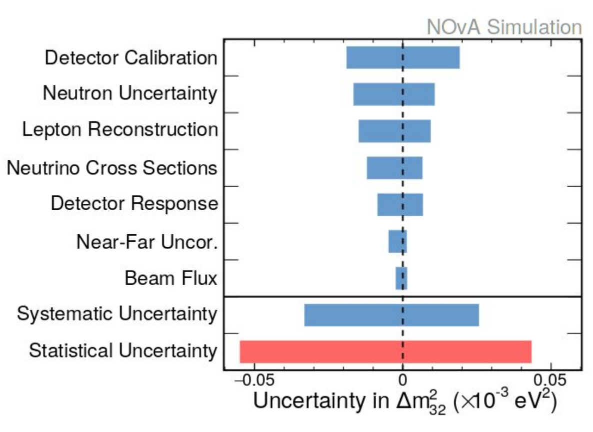


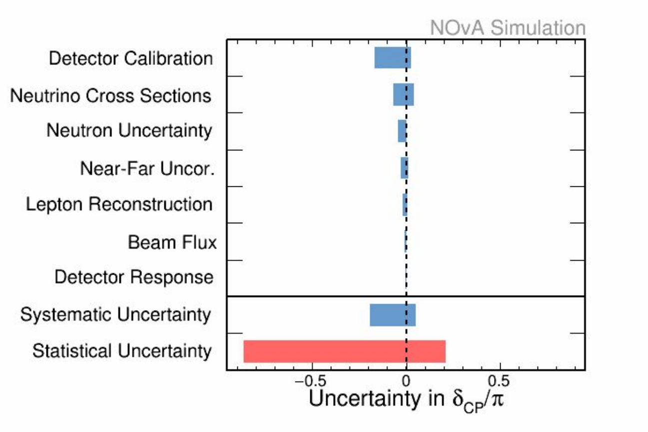




Key systematic uncertainties





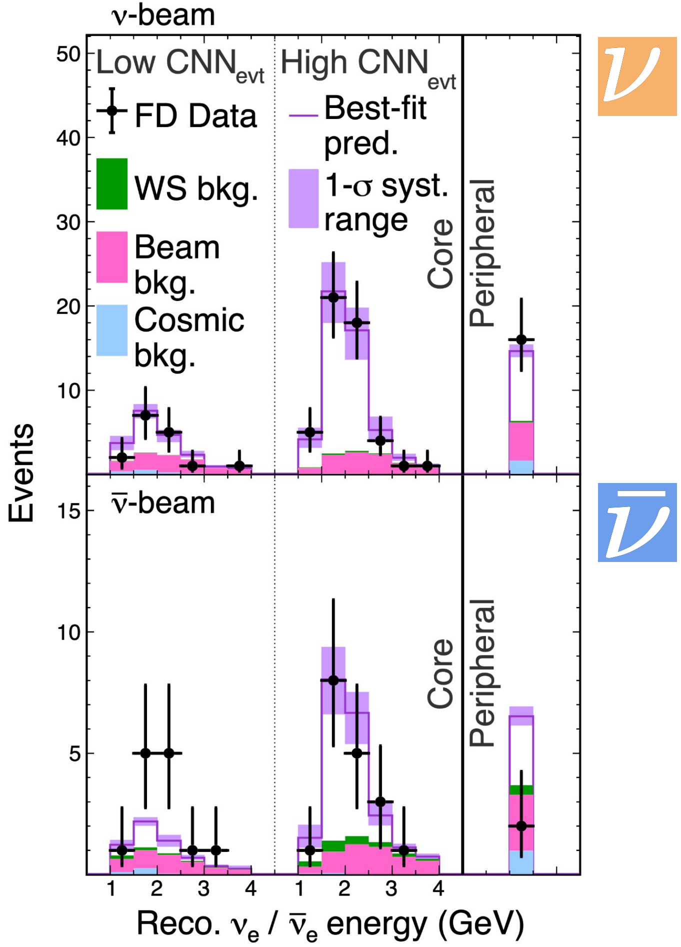


Selected ν_eCC candidates

Total observed	82
Integral at best fit	85.8
Electron antineutrino	1.0
Total beam background	22.7
Cosmic background	3.1

Total observed	33
Integral at best fit	33.2
Electron neutrino	2.3
Total beam background	10.2
Cosmic background	1.6

>4σ evidence of electron antineutrino appearance

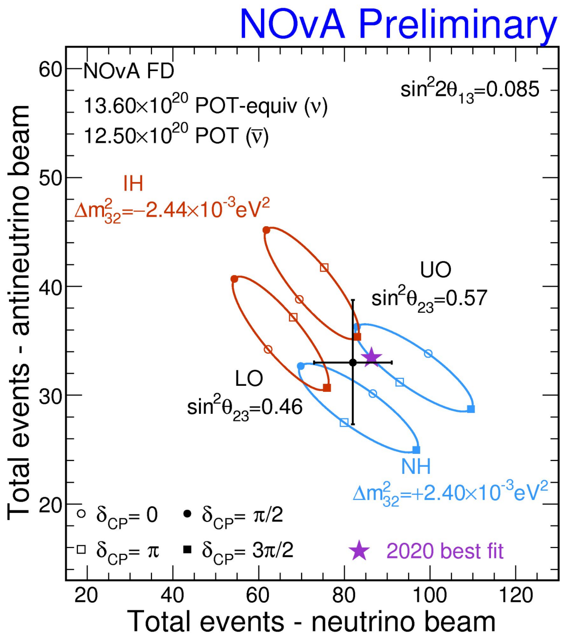


Asymmetry

Plotting number of candidates in neutrino vs antineutrino beam mode, puts observed result in the highly degenerate central region.

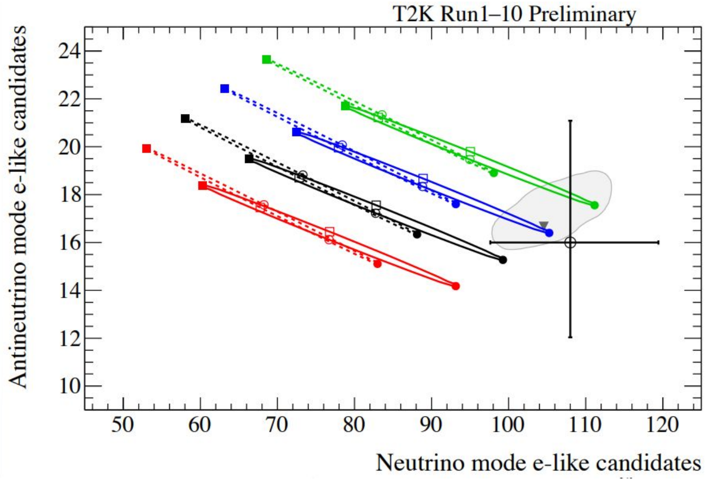
NOvA sees **no strong asymmetry** in the appearance rates → consistent with slightly negative and slightly positive asymmetries, but disfavoring more extreme asymmetries.

T2K favors **stronger asymmetry** and less degeneracy.

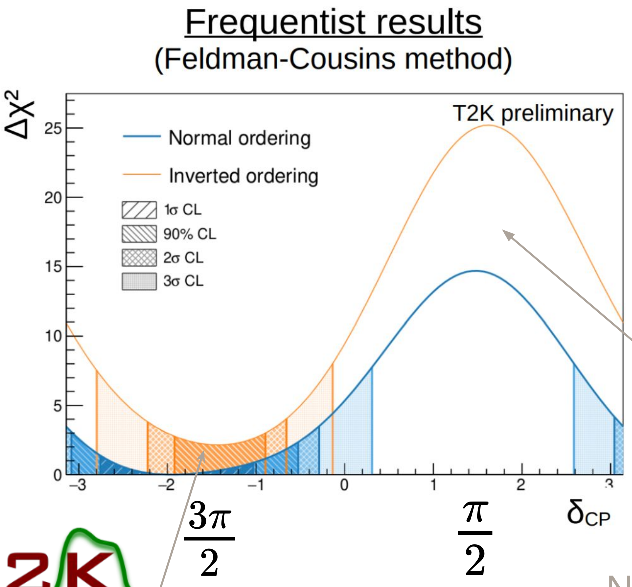


$$\frac{P(\nu) - P(\bar{\nu})}{P(\nu) + P(\bar{\nu})}$$

T2K

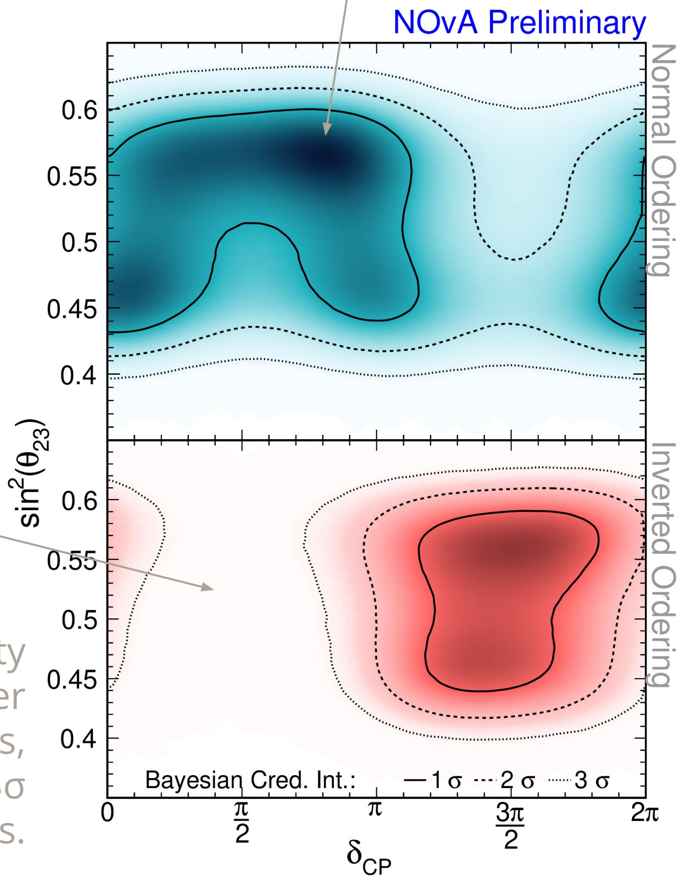


Fit to oscillation parameters



Most probable

Excluded

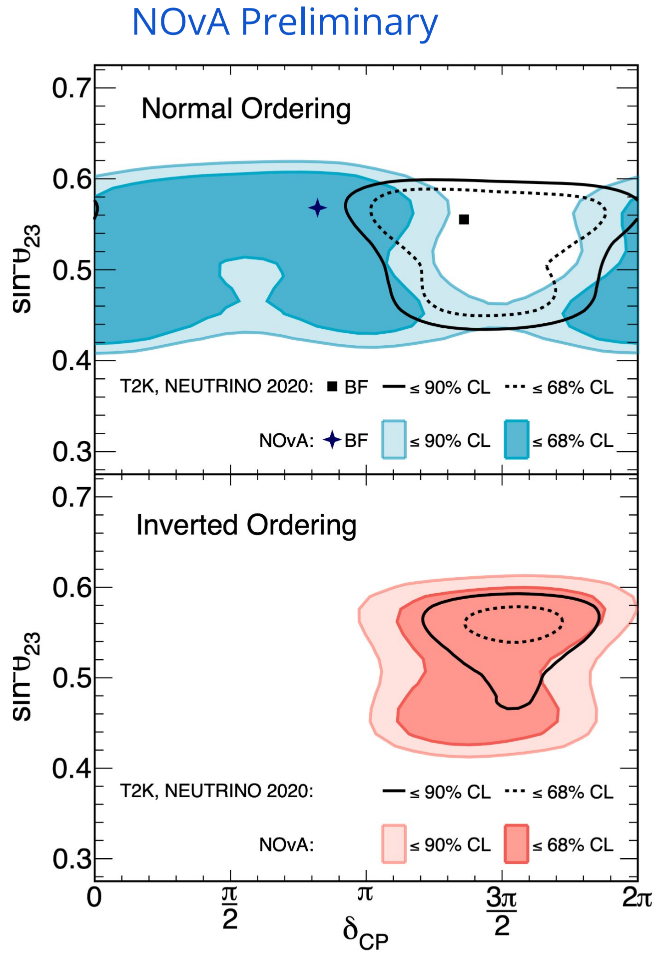


Most probable

NOvA Posterior probability density, marginalized over both mass orderings, showing 1, 2, and 3σ credible regions.

NOvA-T2K joint analysis

- Overlaid frequestist contours.
- Some tension between preferred regions for the Normal Ordering.
  - Agree on the preferred region in the Inverted Ordering.
- A joint fit of the data from the two experiments is needed to properly quantify consistency.
  - Significant progress made on a joint-fit → coming this year!



J_{CP} measurement

$$J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} s_{CP}$$

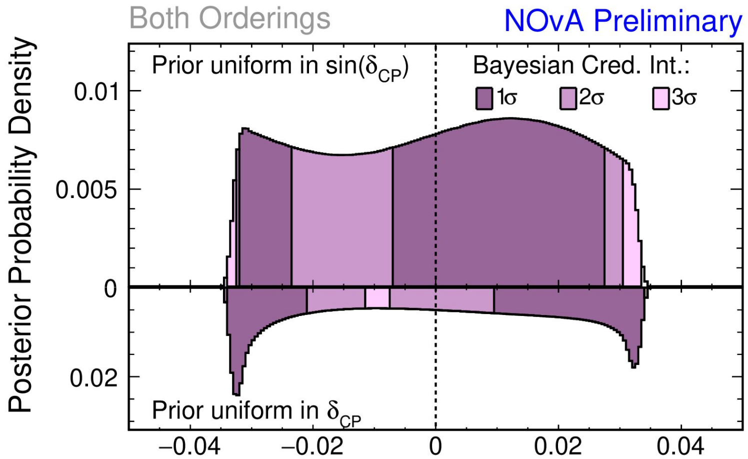
Jarlskog-Invariant (J_{CP}) is a measure of CP-violation that is independent of parameterization → allows for direct comparison with quark sector.

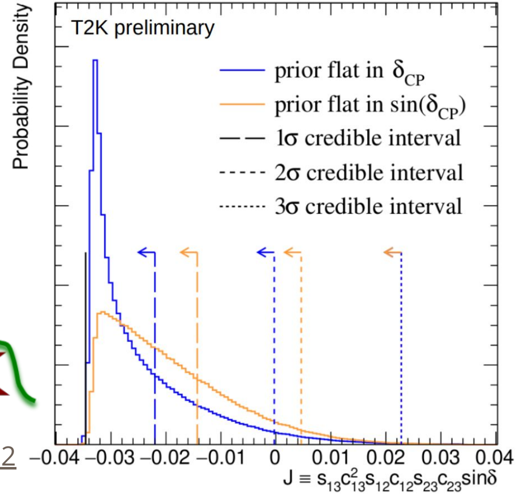
J=0: CP-Conservation, J≠0: CP-Violation.

NOvA and T2K both use two priors:

- Flat in sin(δ_{CP}) → data preference
- Flat in δ_{CP} → bias away from minimal CP violation
  - has some theoretical motivation.

For NOvA both priors are consistent with a wide range of δ_{CP} values. T2K favors nonzero J.

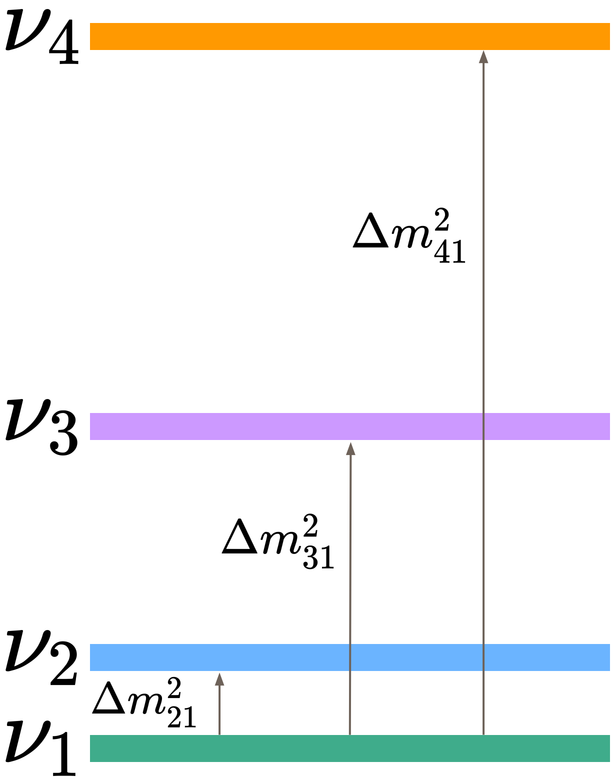




Credit: C. Bronner, Neutrino 2022

3+1 flavor oscillations

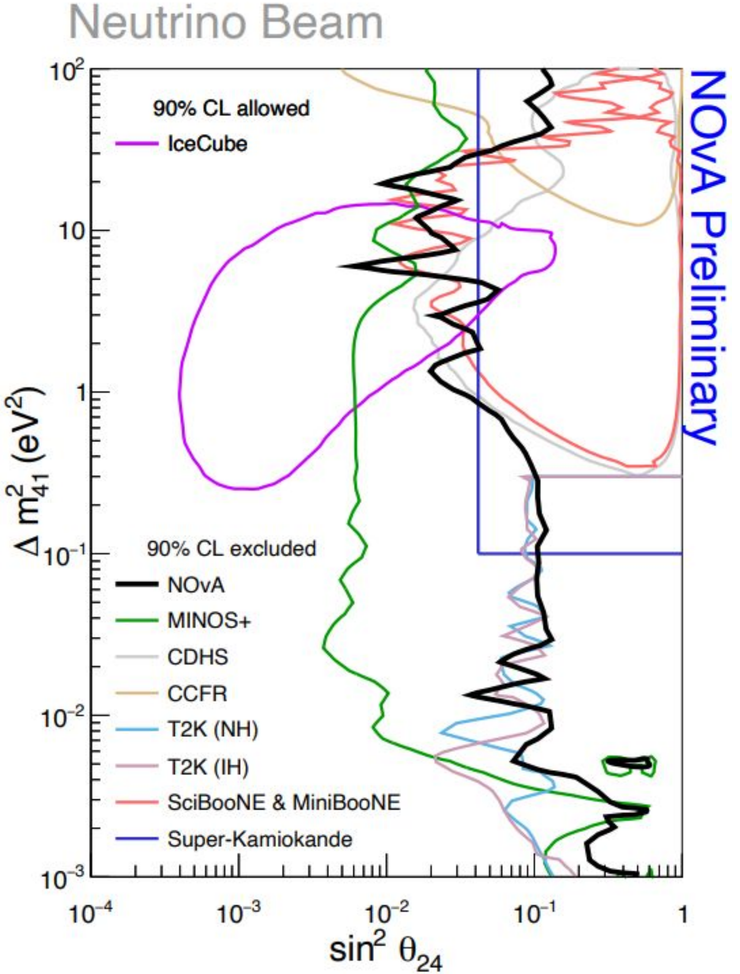
- Expands the 3-flavor PMNS model by adding a new flavor state ν_s, and mass state ν_4.
- Given LEP's Z-width measurement, this state must be sterile.
    - does not couple to the standard model forces but does modify the oscillation probability for active neutrino states.
- Usually we can re-use the ν_e-CC, ν_μ-CC and NC selections for the 3-Flavor PMNS analysis.
- Showing results from NOvA's first dual-baseline (simultaneous ND and FD fit) sterile analysis (see: ν Hewes, Fermilab JETP seminar).



$\sin^2\theta_{24}$ vs Δm_{41}^2

- Profile θ_{23}, Δm_{32}^2 , θ_{34} and δ_{24}.
  - Other 3-flavor PMNS parameters fixed at recent NuFIT values.
  - θ_{14} fixed at zero by reactor constraints.
  - Loose Gaussian constraint applied to Δm_{32}^2.
- 90% CL critical values corrected using Profiled Feldman Cousins approach.

NOvA and T2K have comparable and competitive limits, particularly in lower Δm_{41}^2 region.

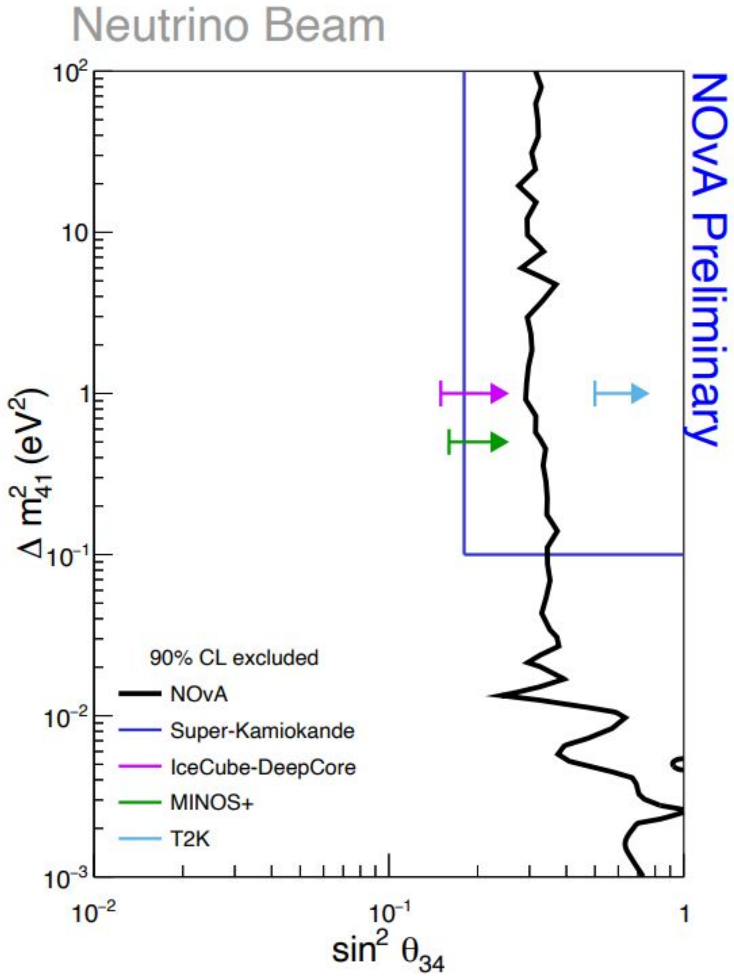


Credit: ν Hewes, Fermilab JETP seminar

$\sin^2\theta_{34}$ vs $\Delta m_{41}^{\ 2}$

- Profile θ_{23}, $\Delta m_{32}^{\ 2}$, θ_{24} and δ_{24}.
  - Other 3-flavor PMNS parameters fixed at recent NuFIT values.
  - θ_{14} fixed at zero by reactor constraints.
  - Loose Gaussian constraint applied to $m_{32}^{\ 2}$.
- 90% CL critical values corrected using Profiled Feldman Cousins approach.

NOvA has world-leading limit in smaller $\Delta m_{41}^{\ 2}$ region. T2K limit is less competitive.



Credit: v Hewes, Fermilab JETP seminar

The future

Future of NOvA

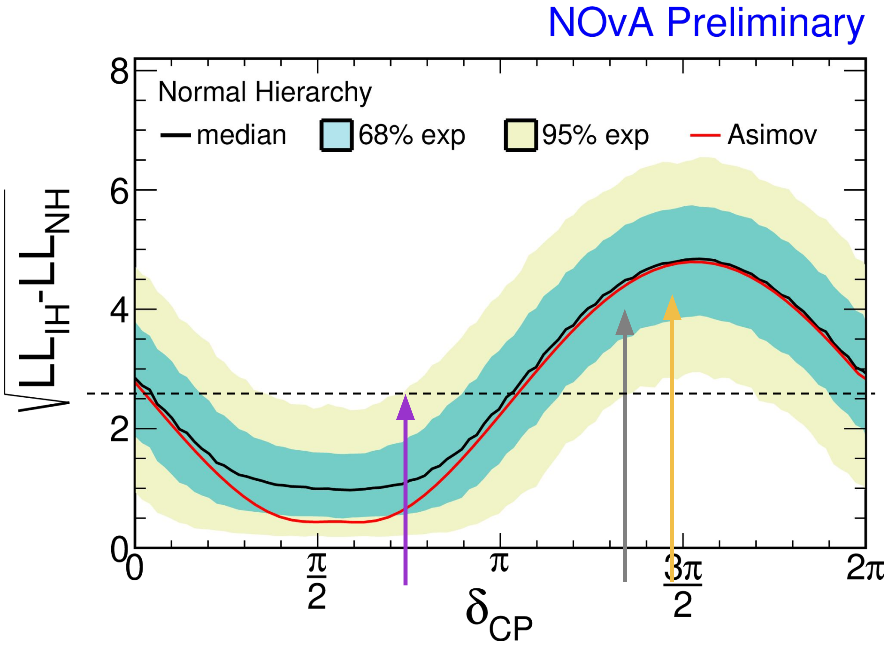
NOvA will continue taking data until 2026.

- equal exposure in both beam modes.
- >2x current (2020) POT.

Sensitivity to mass ordering depends on the value of δ_{CP}.

- NOvA best-fit (δ_{CP}=0.82π) has ~2.5% chance of 3σ.
- Most favourable parameters/T2K best-fit (δ_{CP}=1.37π) have ~50% chance of 4σ.

NOvA's successful Test Beam program will help reduce detector systematics.

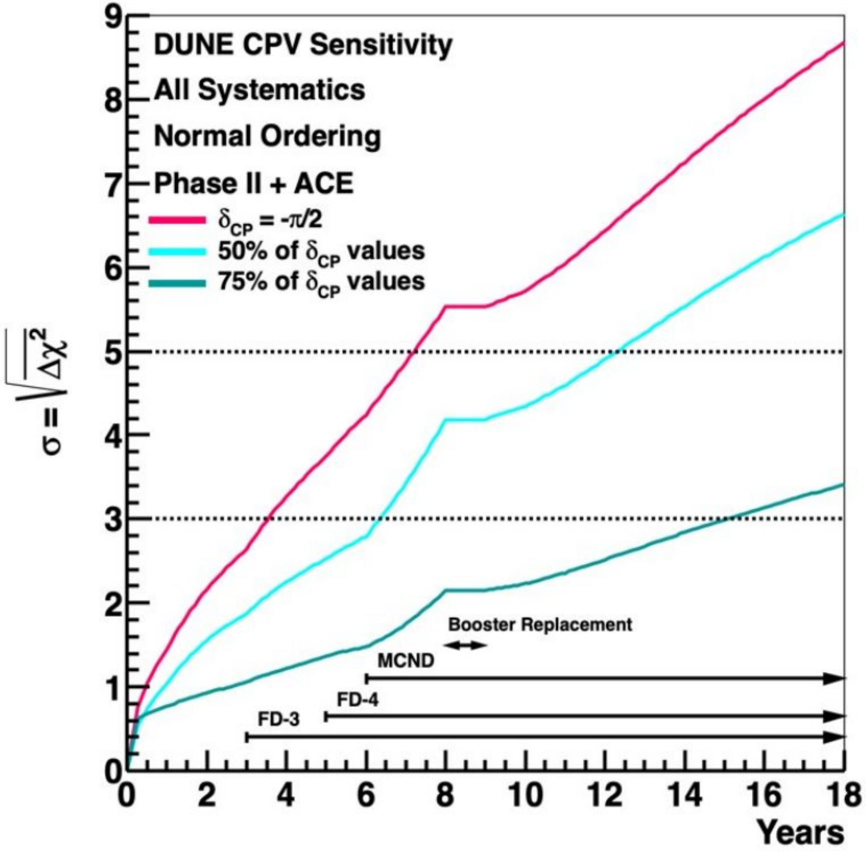


DUNE and Hyper-K

Credit: Chris Marshall, P5 Town Hall

Sensitivity depends on the value of δ_{CP}:

- For δ_{CP} = ±π/2 DUNE reaches 3σ in <4 years and 5σ in ~7 years.
  - Hyper-K will likely reach 5σ first.
- For δ_{CP} = ±23° establishing CP violation above 3σ is challenging. DUNE and Hyper-K sensitivity is comparable.



More details on DUNE:

H11.5: Long-baseline Neutrino Oscillation Sensitivity with DUNE

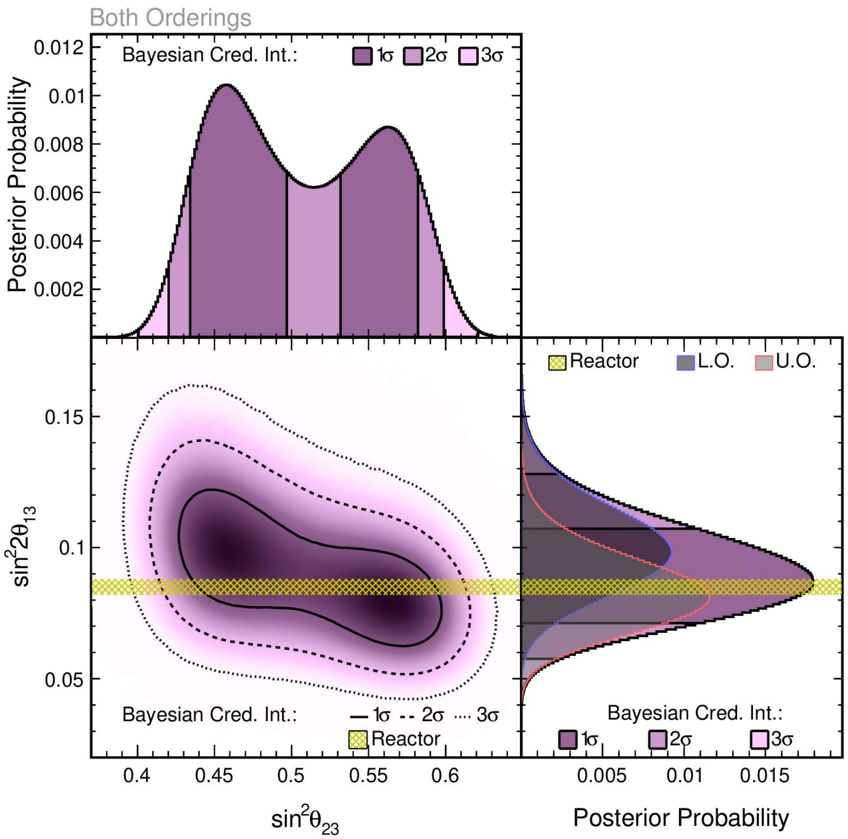
⊟ Hide Details

Sun. April 16, 2:18 p.m. – 2:30 p.m. CDT

Chair: Jeremy A Fleishhacker (Carleton College)

Marquette II - 2nd Floor

NOvA measurement of θ_{13}

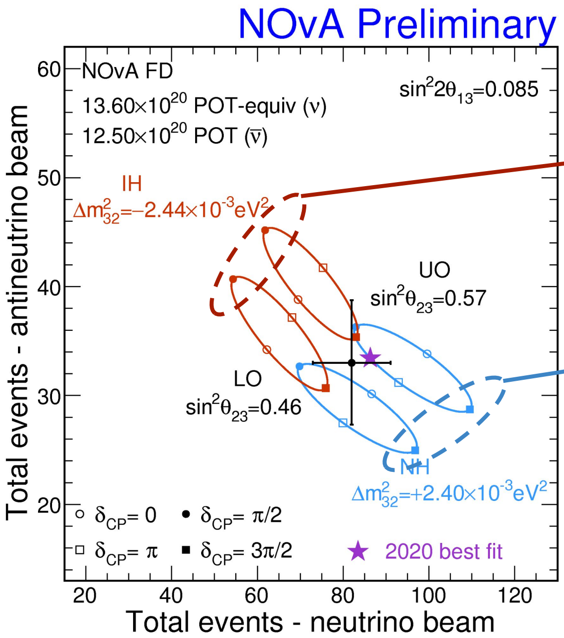


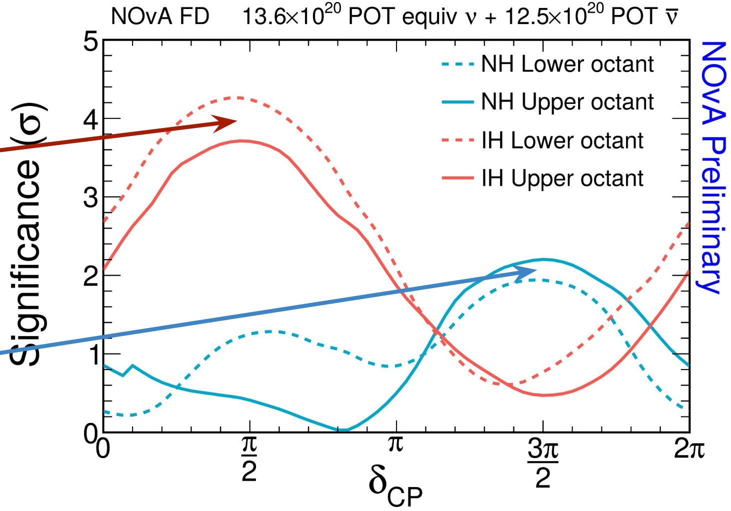
- The results so far all use a constraint on θ_{13} from reactor experiments.
- The Bayesian interpretation of our data allows us to drop this constraint and make a NOvA measurement of θ_{13}.

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

- Consistent with the measurements from reactor experiments.
- Good test of PMNS consistency → NOvA measurement uses a very different strategy to reactor experiments.

Fit to oscillation parameters - Frequentist

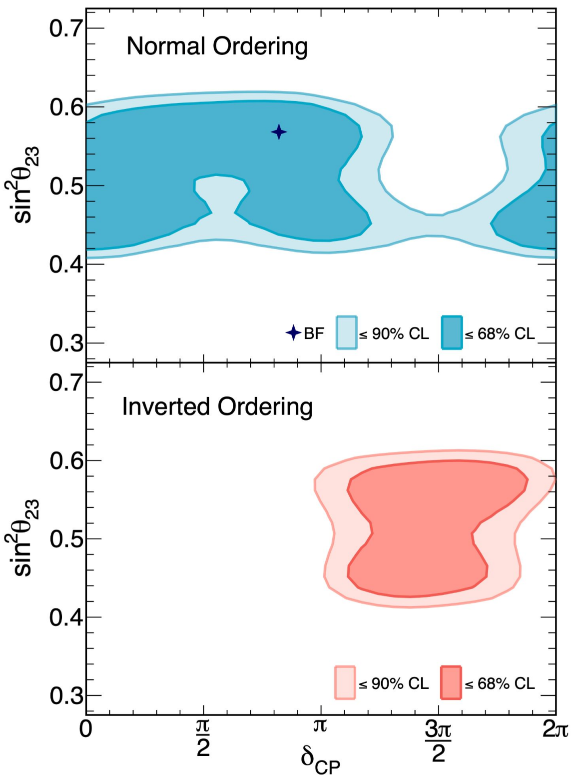


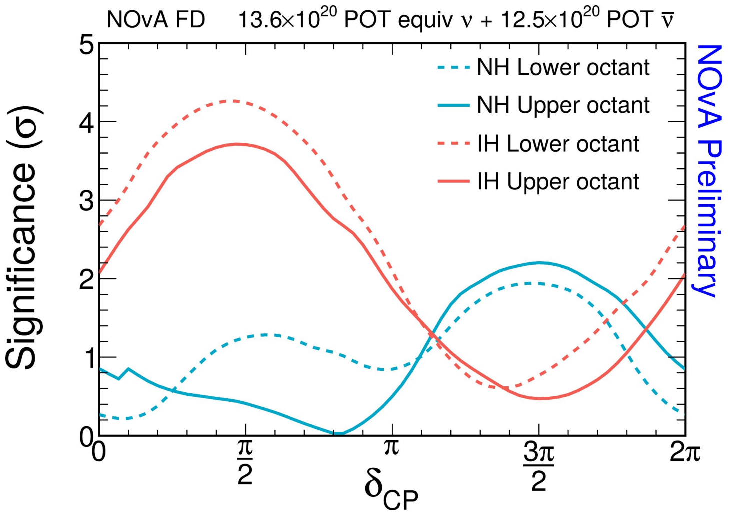


Exclude IH $\delta = \pi/2$ at $>3\sigma$
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer:
Normal Hierarchy at 1.0σ
Upper Octant at 1.2σ

Fit to oscillation parameters - Frequentist





Exclude IH δ = π/2 at >3σ
Disfavor NH δ = 3π/2 at ~2σ

Prefer:
Normal Hierarchy at 1.0σ
Upper Octant at 1.2σ