Long-baseline Neutrino Oscillation Results and Machine Learning in NOvA

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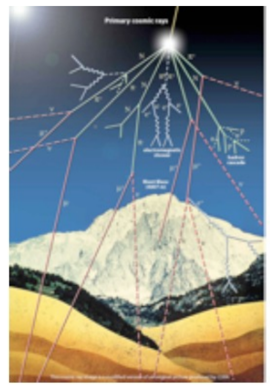
CCEPP Summer School 2021 on Neutrino Physics

Neutrino

- Neutrinos are elementary particles with little mass and no charge
- Postulated by Pauli in 1930 to reconcile beta decay with energy conservation, first observed in 1950s by Cowan and Reines
- Very abundant, many sources can generate neutrinos
- But very elusive → need gigantic detectors to find them

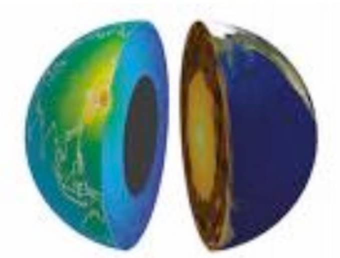
Nuclear Reactors



Cosmic Ray Showers

The Sun

Astrophysical (SuperNova/Big Bang)



The Earth (Radioactive Elements)

Accelerators

NOvA and DUNE

Neutrino

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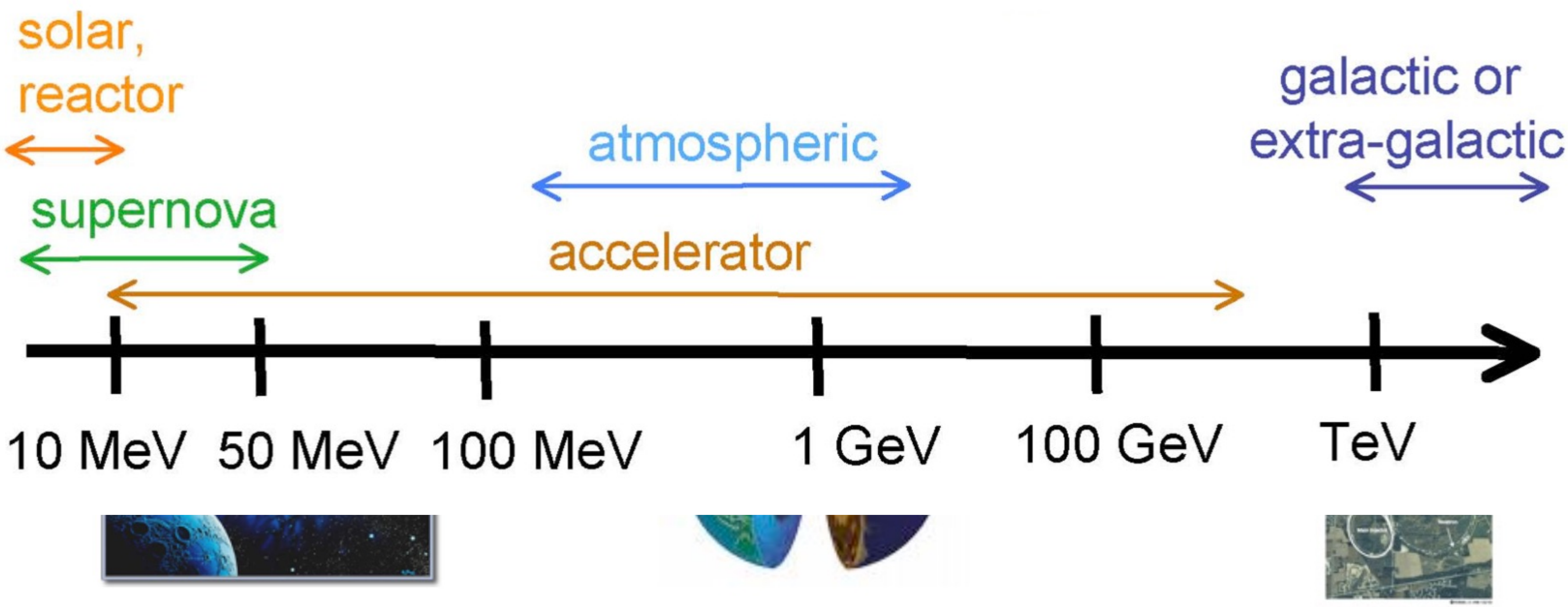
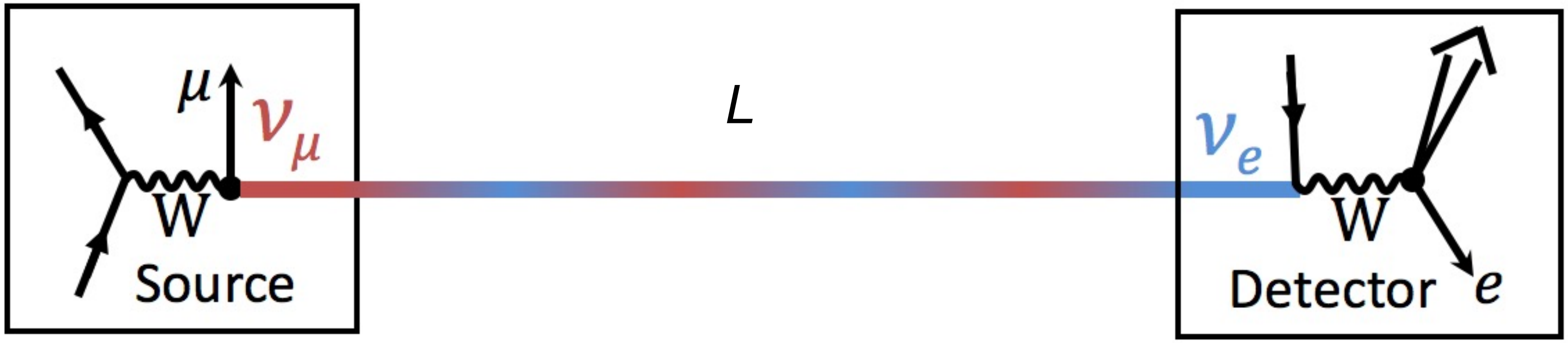


Astrophysical (SuperNova/Big Bang) The Earth (Radioactive Elements) Accelerators

NOvA and DUNE

Neutrino Oscillation

- There are 3 flavors of neutrinos: ν_e, ν_μ, ν_τ, their antiparticles: $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$
- Neutrino oscillation: neutrinos produced in a specific lepton flavor can change to a different flavor during their travel (2015 Nobel Prize)
- The rate of change depends on the neutrino energy E and travel distance (baseline) L



Neutrino Oscillation

- The neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are not mass eigenstates (ν_1, ν_2, ν_3):

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$U_{\alpha i}$: an element of the PMNS mixing matrix

- As neutrinos propagate, the phases of the three mass states $|\nu_{i=1,2,3}>$ advance at different rates. Therefore the flavor eigenstates oscillate:

$$|\nu_\alpha(L)\rangle = U_{\alpha 1} e^{-im_1^2 L/2E} |\nu_1(0)\rangle + U_{\alpha 2} e^{-im_2^2 L/2E} |\nu_2(0)\rangle + U_{\alpha 3} e^{-im_3^2 L/2E} |\nu_3(0)\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \left| \sum U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E} \right|^2$$

$|\nu_\alpha>$, $\alpha = e, \mu$ *or* τ *- flavor eigenstates*

$|\nu_i>$, $i = 1,2,3$ *- mass eigenstates with a definite mass* m_i

Neutrino Oscillation

- Oscillation probability depends on squared mass differences $\Delta m^2_{ij}=m^2_i-m^2_j$ and PMNS mixing matrix U

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}L/4E)$$
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}L/2E)$$

For anti-neutrinos,

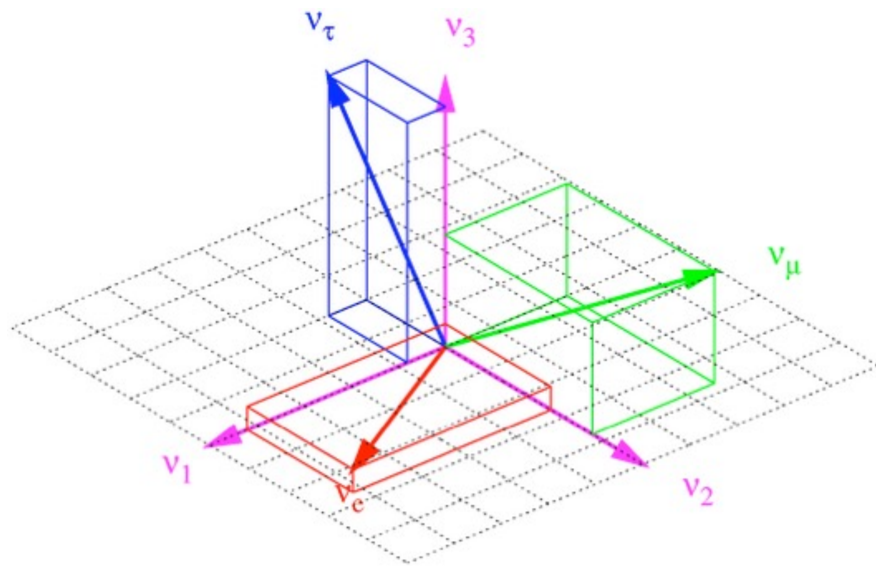
$$P(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = P(\nu_\alpha \to \nu_\beta, U^*)$$

(Assuming CPT invariance)

- In the case of CP violation $P(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = P(\nu_\alpha \to \nu_\beta, U^*) \neq P(\nu_\alpha \to \nu_\beta, U)$, need a non-zero phase δ_{CP} in the mixing matrix U

Neutrino Oscillation

- For the three-flavor case the PMNS matrix is most commonly parameterized by three real mixing angles θ_{12}, θ_{23} and θ_{13} and a single phase δ_{CP}



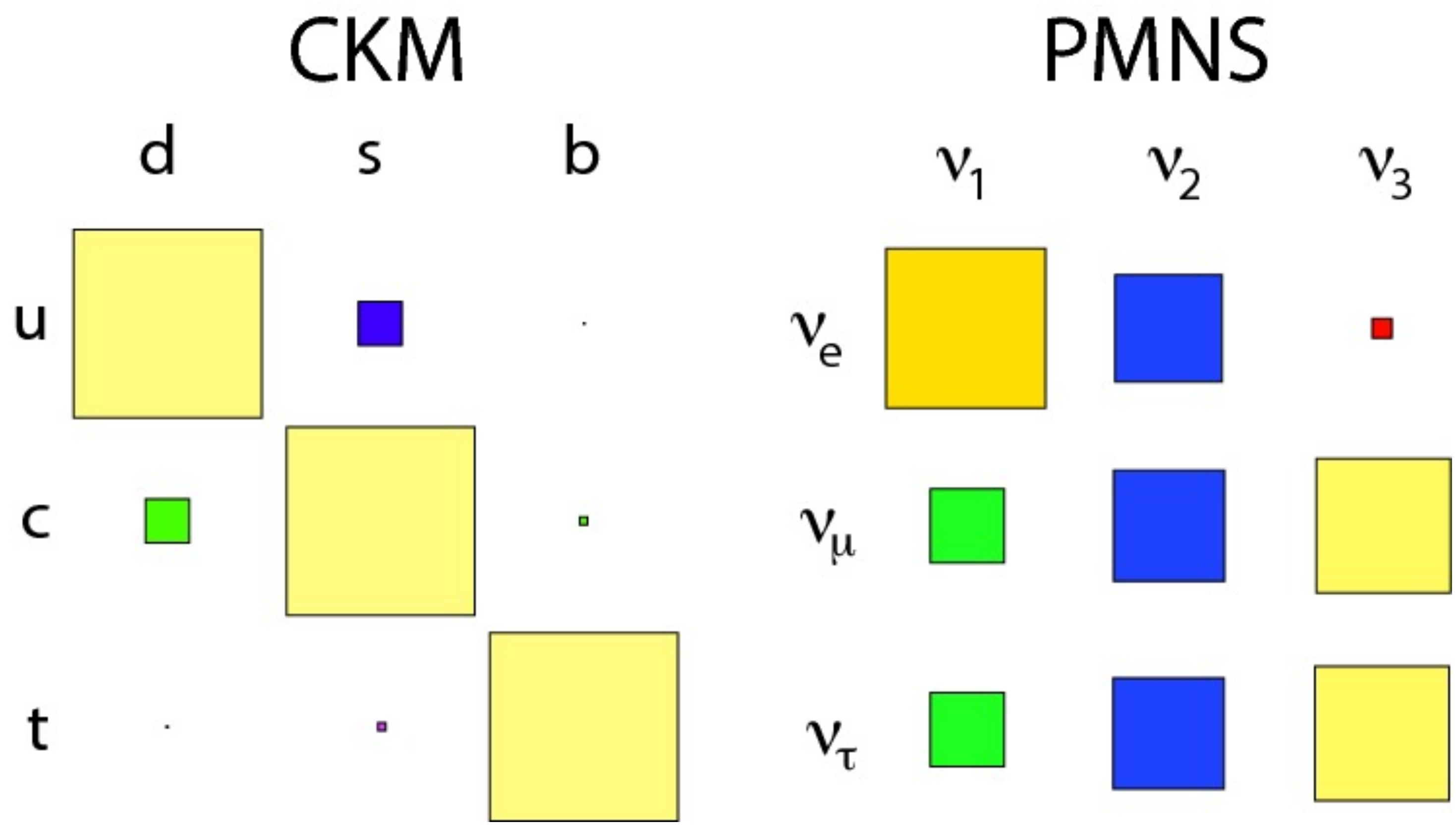
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix}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

Including two independent squared mass differences $\Delta m^2_{21}=m^2_2-m^2_1$ and $\Delta m^2_{32}=m^2_3-m^2_2$, there are 6 free parameters that determine the neutrino oscillation.

Neutrino Oscillation Parameters

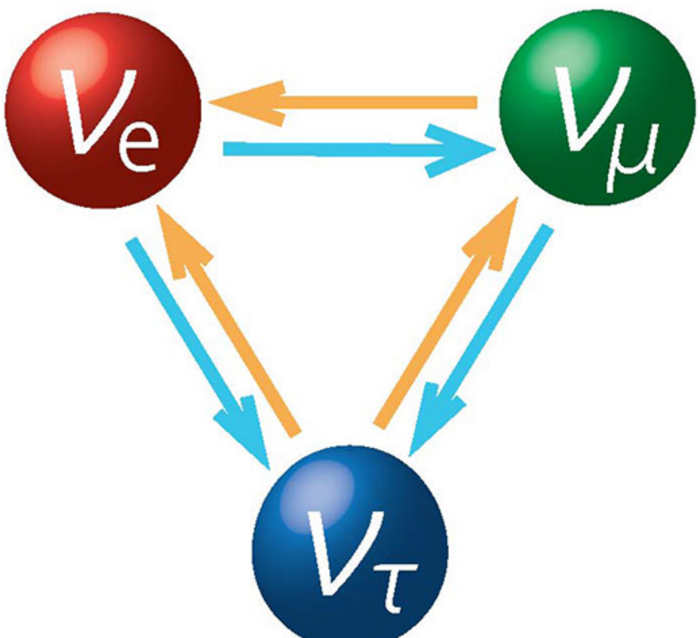
From previous experiments:

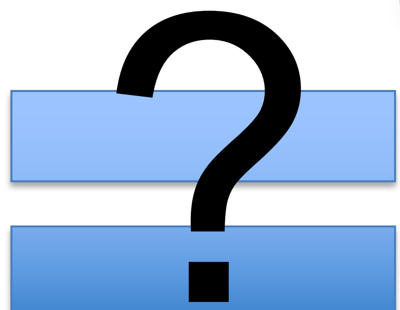
- $\sin^2 2\theta_{12}$, $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{23}$ have been measured
- Δm^2_{21} and $|\Delta m^2_{32}|$ have been measured, we know that m_1 and m_2 are very close, but difference in m_3 and $m_{1,2}$ is much larger
- $\Sigma m < 0.3$ eV (total mass of the 3 generations of neutrino)

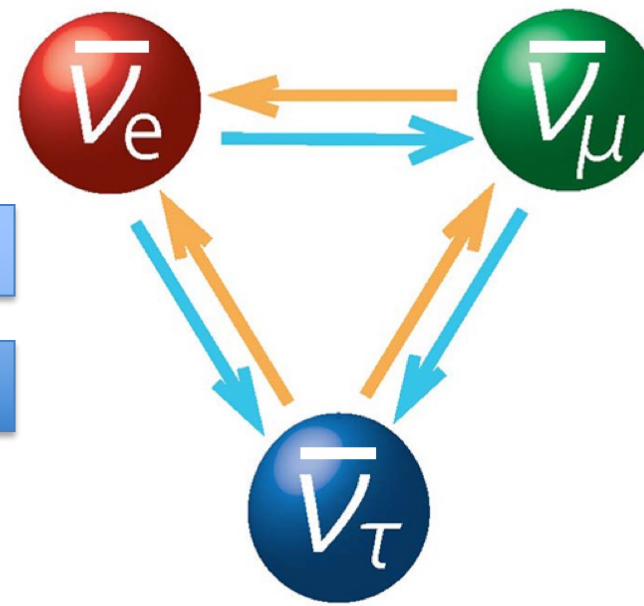


Remaining Fundamental Questions

- CP phase δ_{CP}: whether neutrinos and antineutrinos behave the same way in oscillation? Implications for matter-antimatter asymmetry in the universe





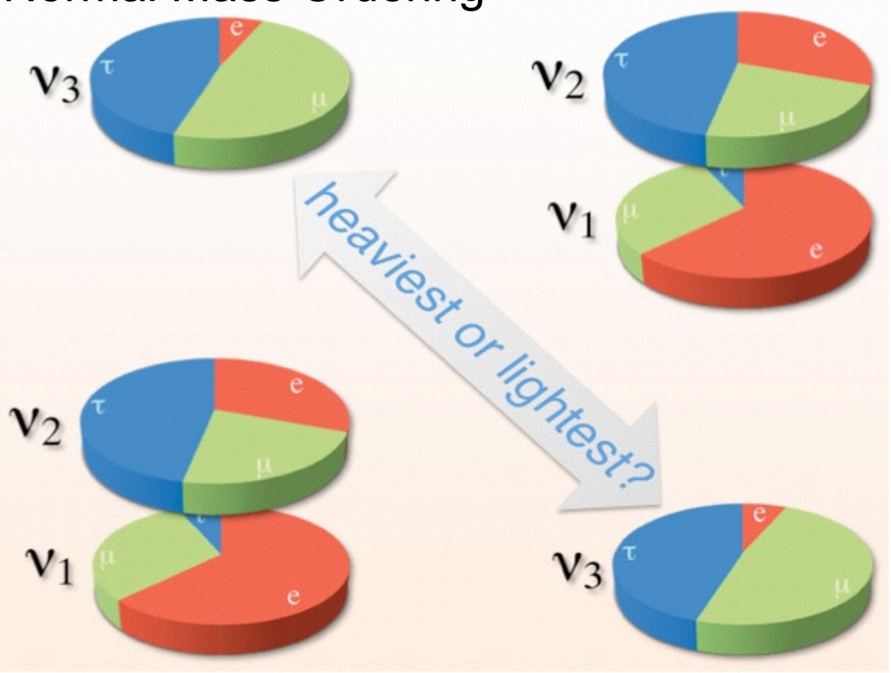


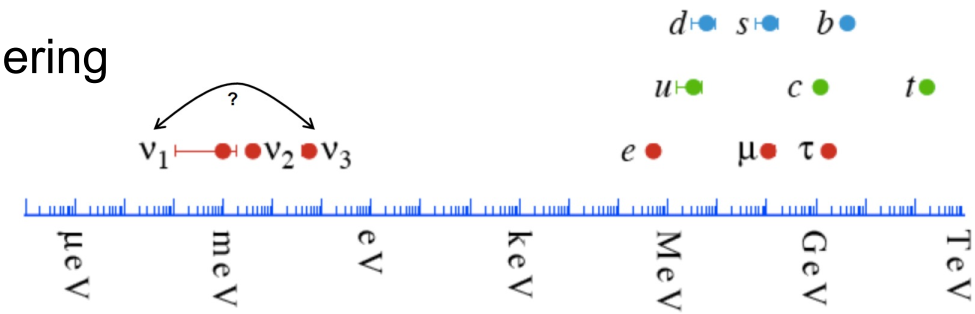
Remaining Fundamental Questions

- Mass ordering (hierarchy): sign of $\Delta m^2_{31(2)}=m^2_3-m^2_{1(2)}$, $m_3>m_{1,2}$ or $m_{1,2}>m_3$? Implications for absolute neutrino masses, grand unified theories and neutrino-less double beta decay searches

Δm^2_{21} and $|\Delta m^2_{32}|$ have been measured, we know that m_1 and m_2 are very close, but difference in m_3 and $m_{1,2}$ is much larger

Normal Mass Ordering　　Inverted Mass Ordering



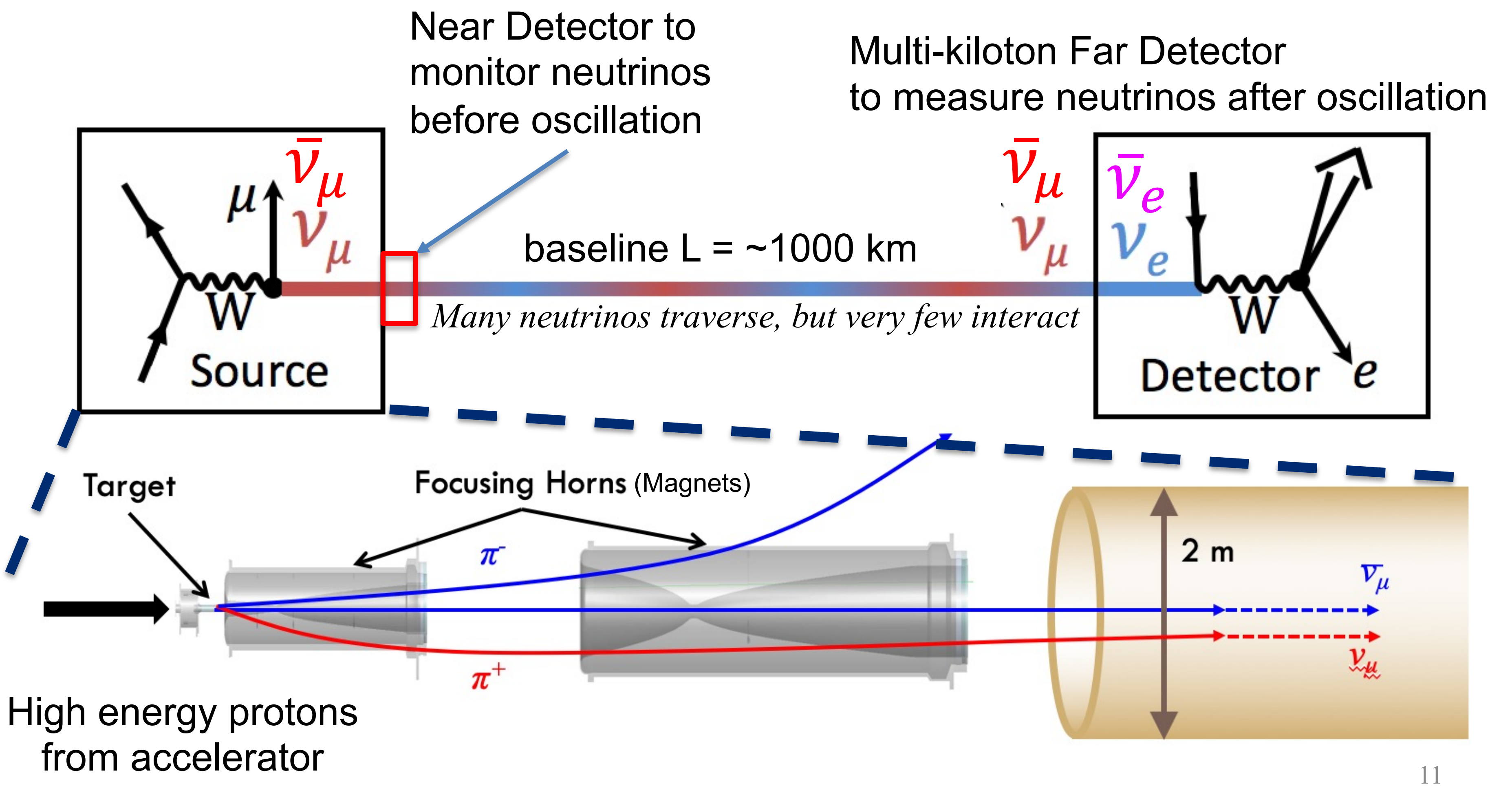


Octant of θ_{23} : Is θ_{23} exactly 45°? Is ν_3 more strongly coupled to ν_τ or ν_μ?

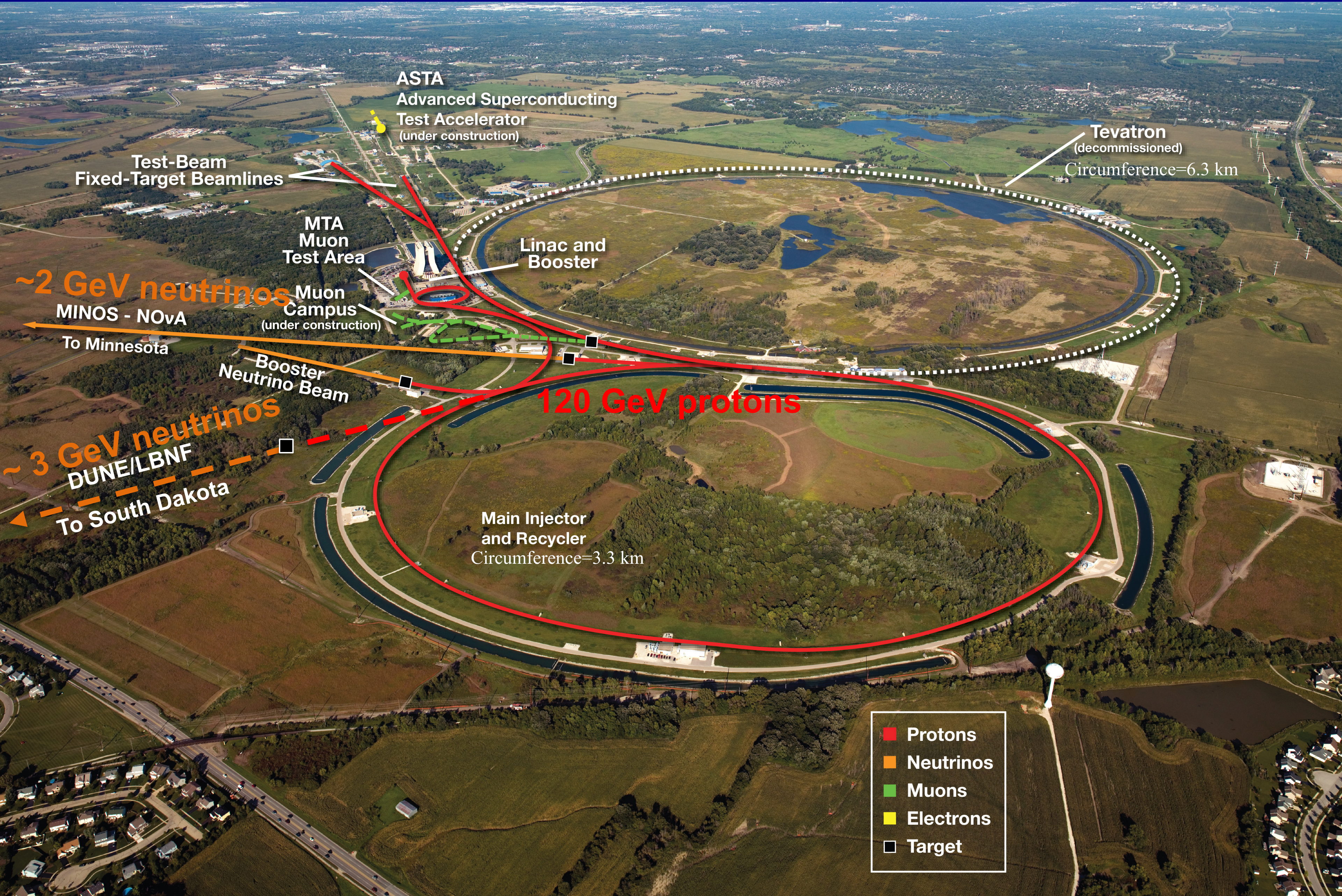
Long baseline accelerator neutrino experiments are designed to solve these questions

Long-Baseline Accelerator Neutrino Oscillation Experiments

Use man-made neutrino beam with known flavor to measure oscillation probability as function of neutrino energy



Accelerator Neutrino Beams at Fermilab Near Chicago



Accelerator Neutrino Beams at Fermilab Near Chicago

Long-Baseline Neutrino Oscillation

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- Measure ν_μ (anti-ν_μ) survival probability with ν_μ and anti-ν_μ neutrino beam
- Provide high precision $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} L/4E)$$
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Long-Baseline Neutrino Oscillation

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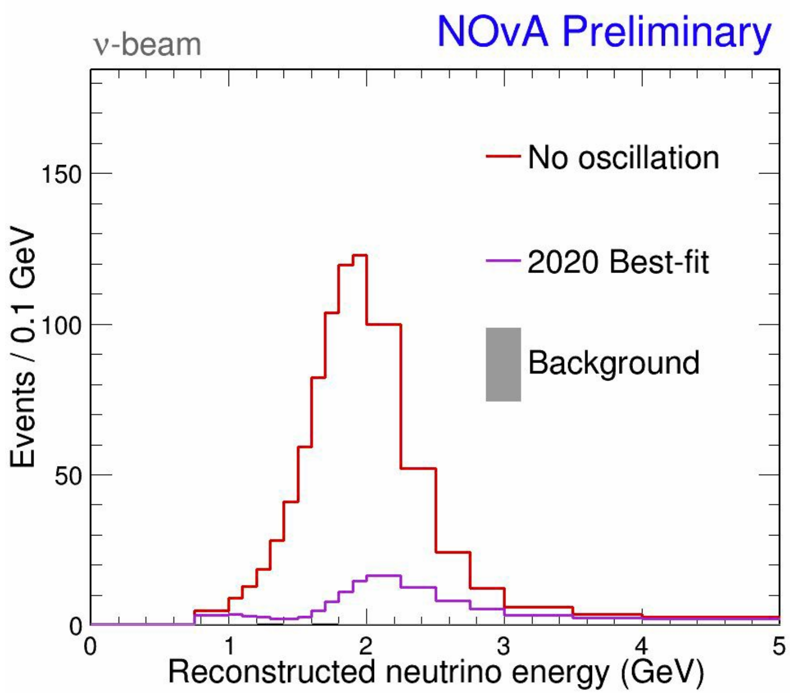

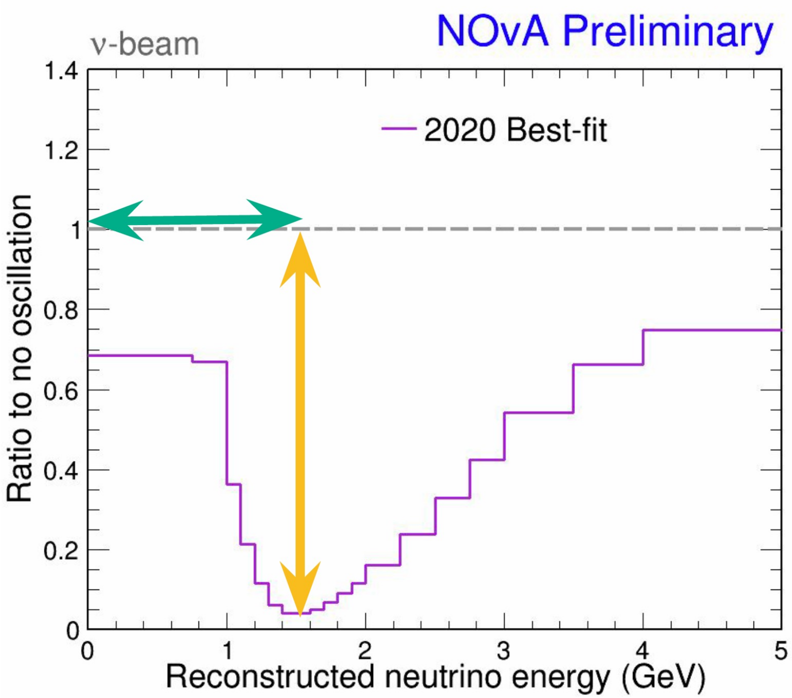

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+ \; 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

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G_f=Fermi constant
N_e =electron density

- Measure ν_e (anti-ν_e) appearance probability with ν_μ and anti-ν_μ neutrino beam
- Determine mass hierarchy, δ_{CP} and octant of θ_{23}

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Depends on θ_{13}

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Depends on θ_{13}

Depends on δ_{CP}

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Depends on θ_{13}
Depends on δ_{CP}
Depends on octant of θ_{23}

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G_f=Fermi constant
N_e =electron density

Matter effect is the correction to neutrino effective masses, when they travel through matter and scatter on electrons

Depends on $\Delta m^2{}_{31}$
The difference between normal hierarchy (Δ>0) and inverted hierarchy (Δ<0) is enlarged by matter effect (A)
Matter effect increases with travel distance L

ν_e appearance

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

$$+ \quad 2\alpha \sin\theta_{13} \cos\left(\boxed{-\delta_{CP}}\right) \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

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G_f=Fermi constant
N_{e} =electron density

For anti-neutrinos, flip signs on δ_{CP} and matter effect A

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

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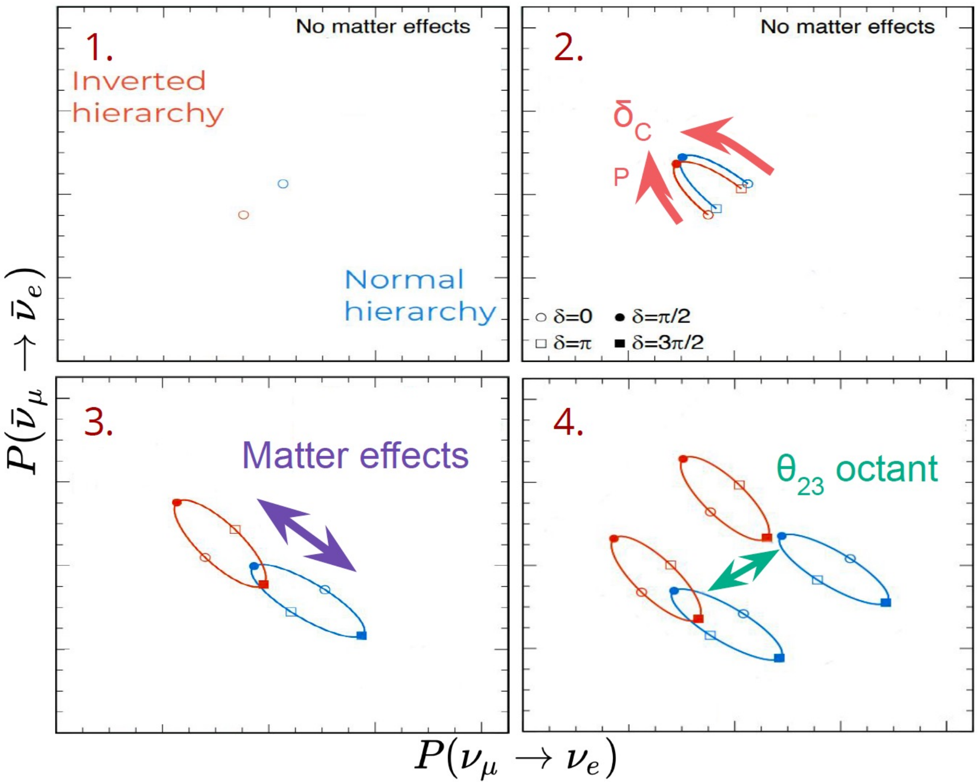
N_e =electron density

- Measure ν_e (anti-ν_e) appearance probability with ν_μ and anti-ν_μ neutrino beam
- Determine mass ordering, δ_{CP} and octant of θ_{23}
- $\sin^2 2\theta_{13}$ measured by reactor experiments
- $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$ constraint by ν_μ disappearance
- $P(\nu_\mu \longrightarrow \nu_e)$ difference between $\Delta m^2_{31}>0$ and $\Delta m^2_{31}<0$ enlarged by matter effect ($\propto L$)

Matter effect is the correction to neutrino effective masses, when they travel through matter and scatter on electrons

ν_e appearance - ν_e vs anti-ν_e events

1. Inverted hierarchy gives a **slight suppression** in both.
2. CP violation causes **opposite effects** in neutrinos and antineutrinos.
3. Matter effects also produce **opposite effects** in neutrinos and antineutrinos.
4. The octant of θ_{23} causes either a **suppression** or **enhancement**.



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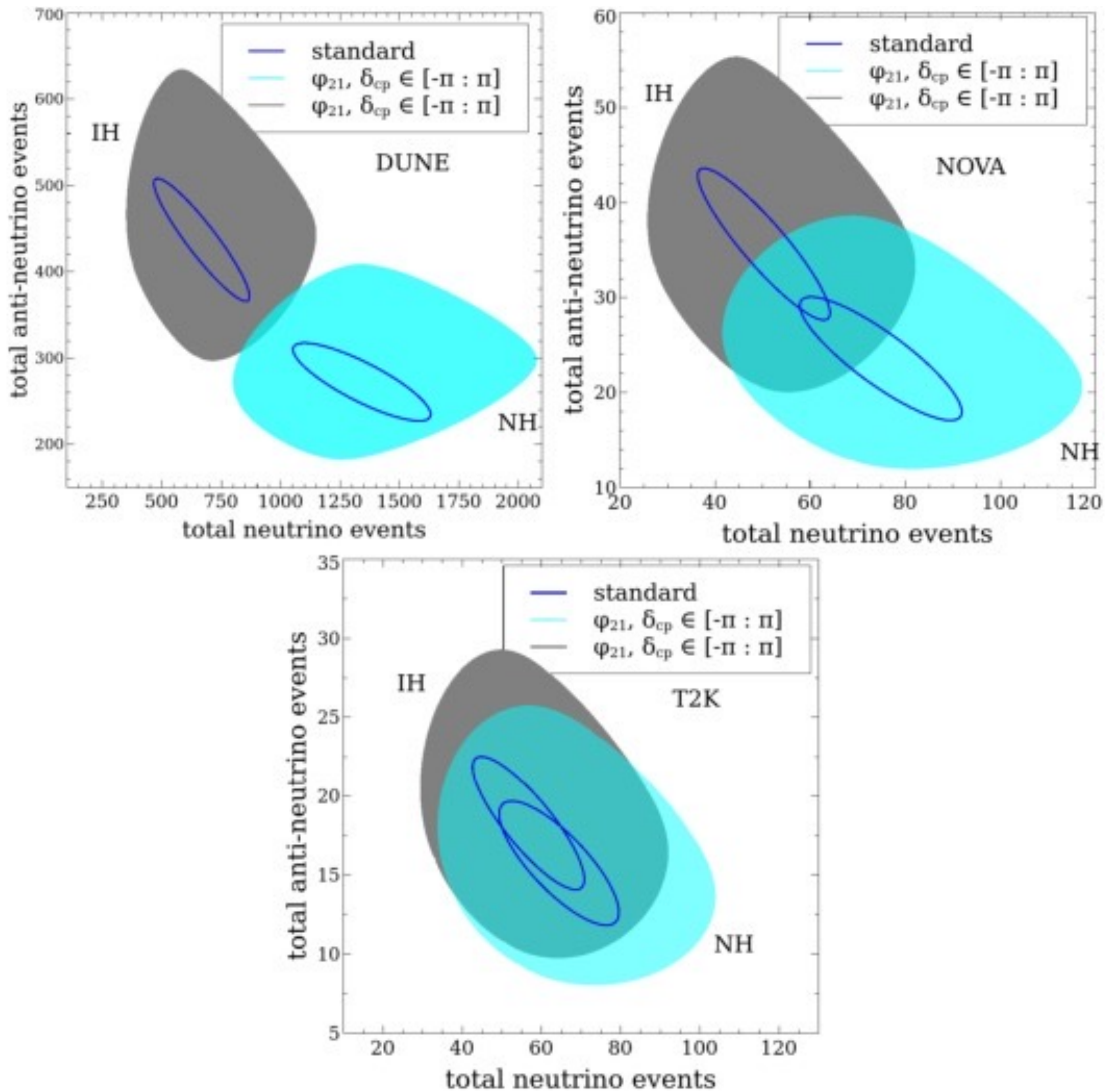
ν_e appearance - ν_e vs anti-ν_e events



Neutrino Detection (~MeV)

- Inverse beta decay (IBD) – Cowan-Reines Experiment (first observation of neutrinos), DayaBay (θ_{13}), JUNO (mass hierarchy), etc
- Neutrino capture on radioactive nuclei (Davis experiment in South Dakota 1970-1994, first to detect and count solar neutrinos, discrepancy in results created the solar neutrino problem → neutrino oscillation)
- Coherent scattering (recently developed, high cross-section, low energy signal)

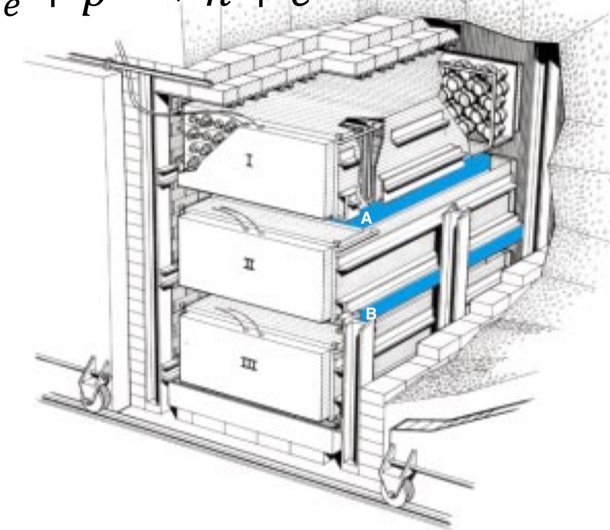
Source (beta decay)

$$n \rightarrow p^{+} + e^{-} + \bar{\nu}_e$$

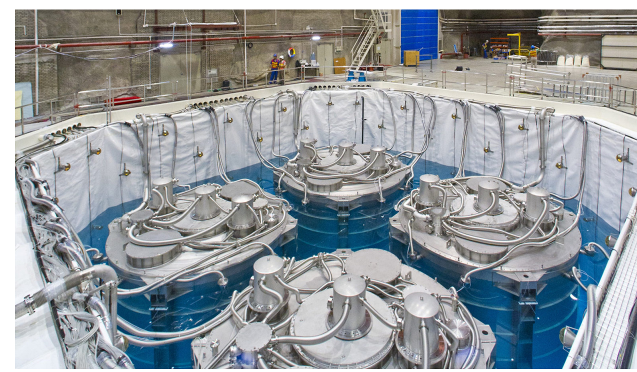
Nuclear Reactors

Detector (inverse beta decay)

$$\bar{\nu}_e + p^{+} \rightarrow n + e^{+}$$



1995 Cowan-Reines experiment:
$CdCl_2$ target + liquid scintillator
Cd capture neutrons, ~10 tons



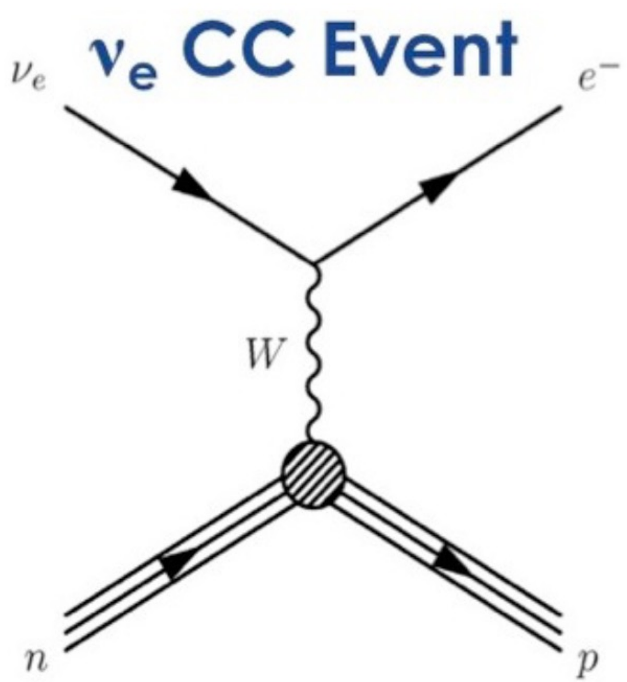
DayaBay: liquid scintillator, ~8x20 tons, first measured θ_{13} in 2012

↓

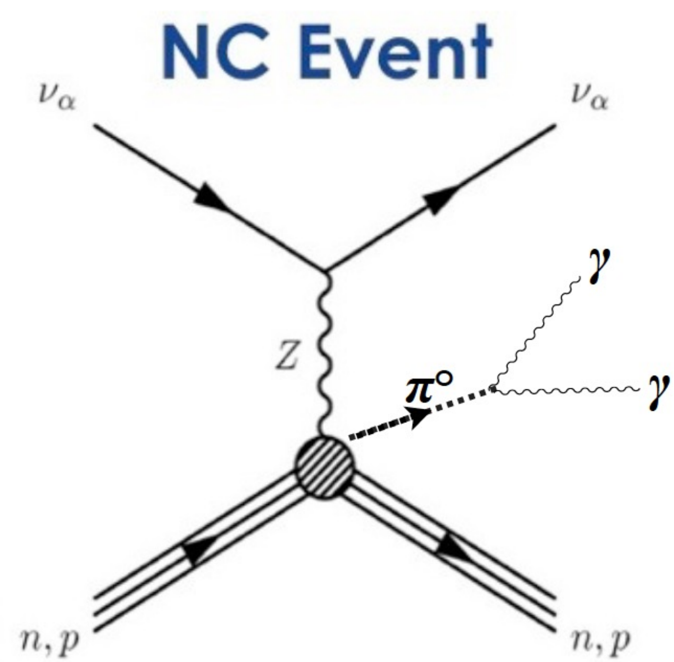
JUNO ~ 20kt

Neutrino Detection (~GeV)

- Charged-Current interactions are the "signal" events that allow the neutrino flavor to be identified, via identification of the charged lepton flavor
- Due to the small $\nu_\mu \rightarrow \nu_e$ probability (~5%), background processes can greatly confuse ν_e appearance measurements
- For example, Neutral Current (NC π^0) events where a π^0 is produced can fake CC ν_e

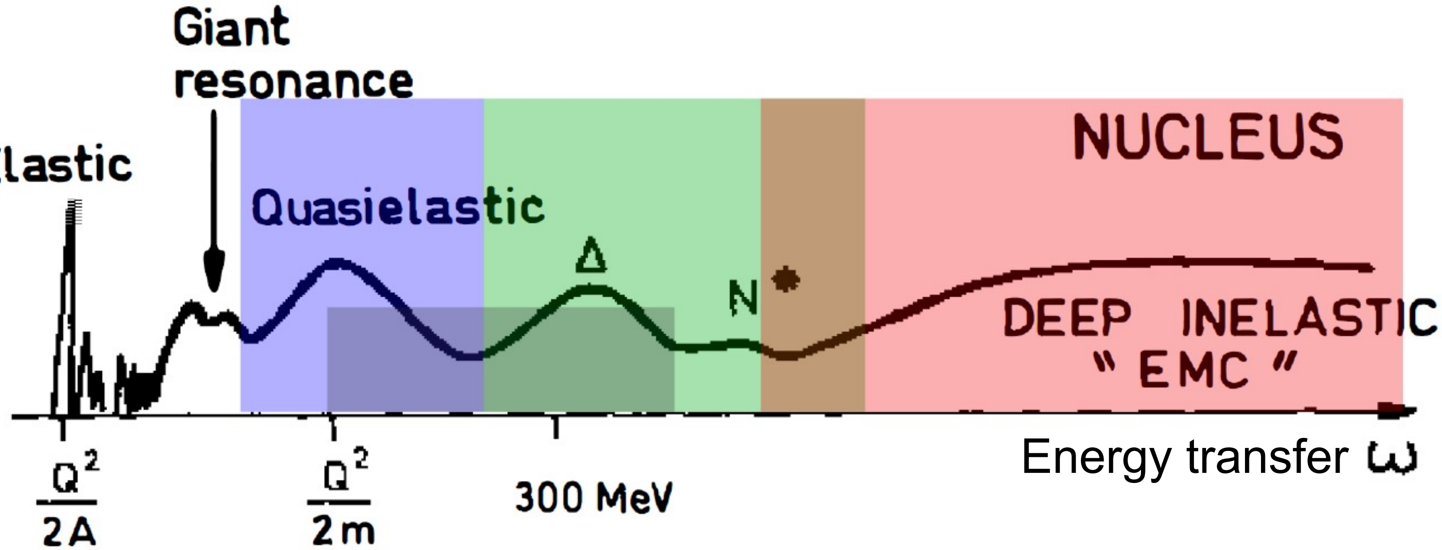


"appearance" signal

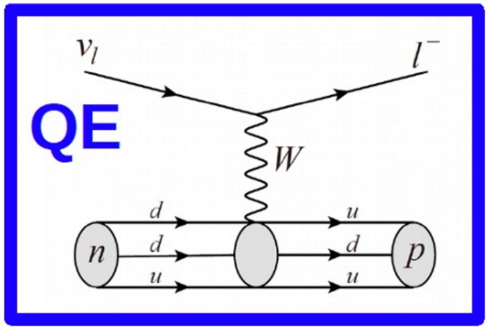


"appearance" background

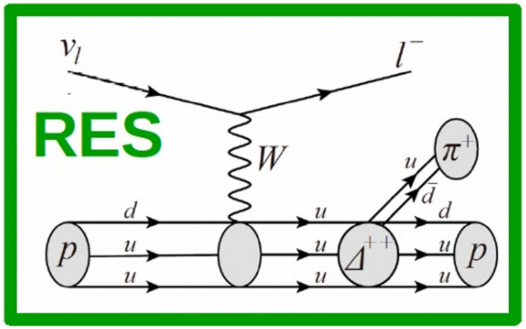
Charged-Current Signal - Interaction Modes



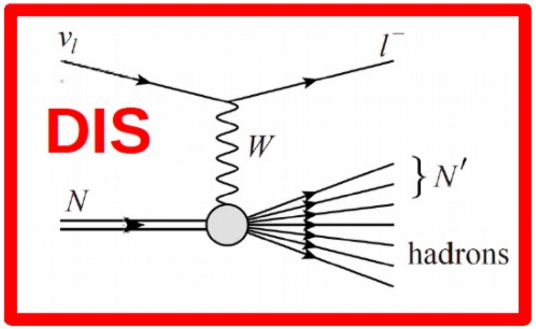
Quasi elastic

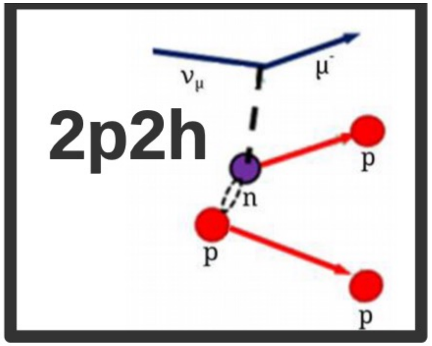


Resonance



Deep Inelastic

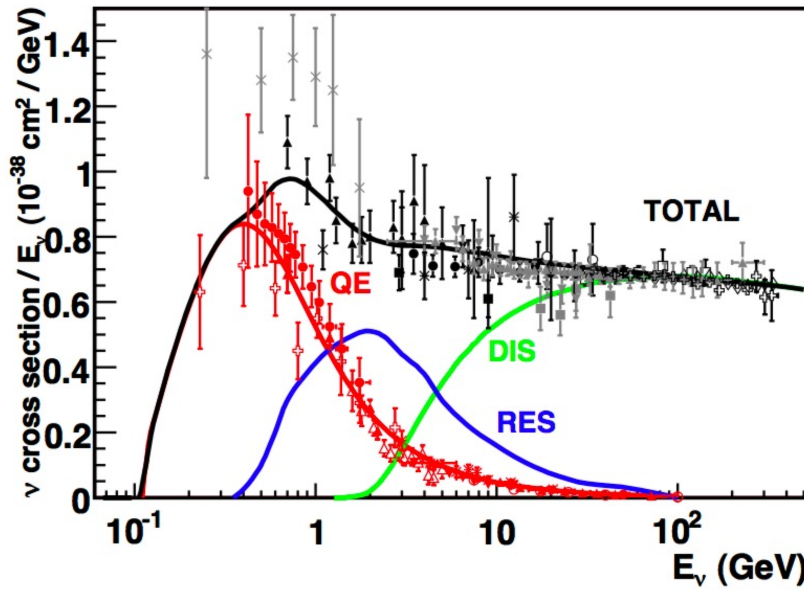


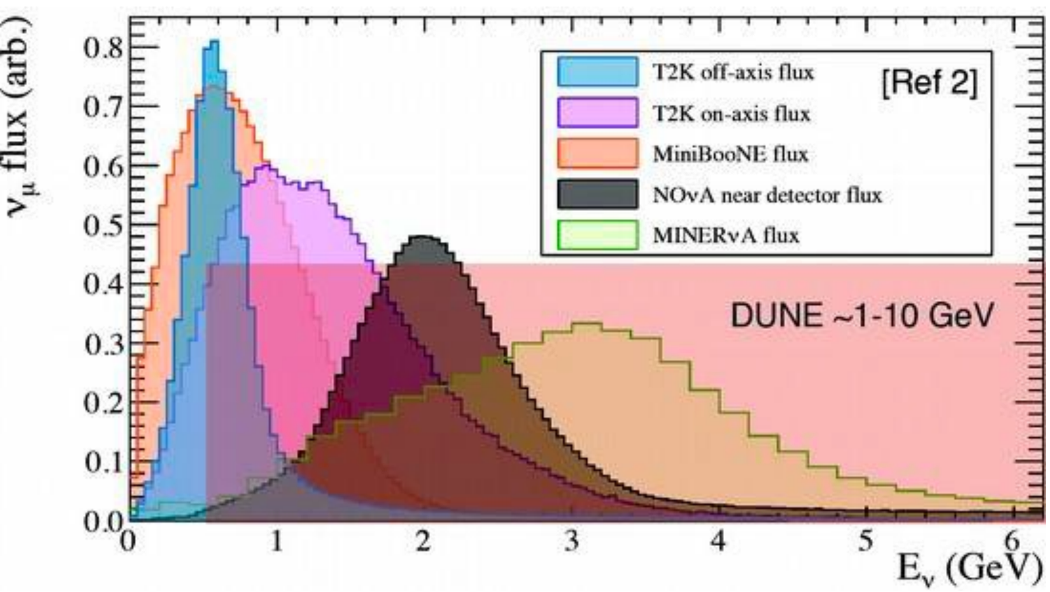


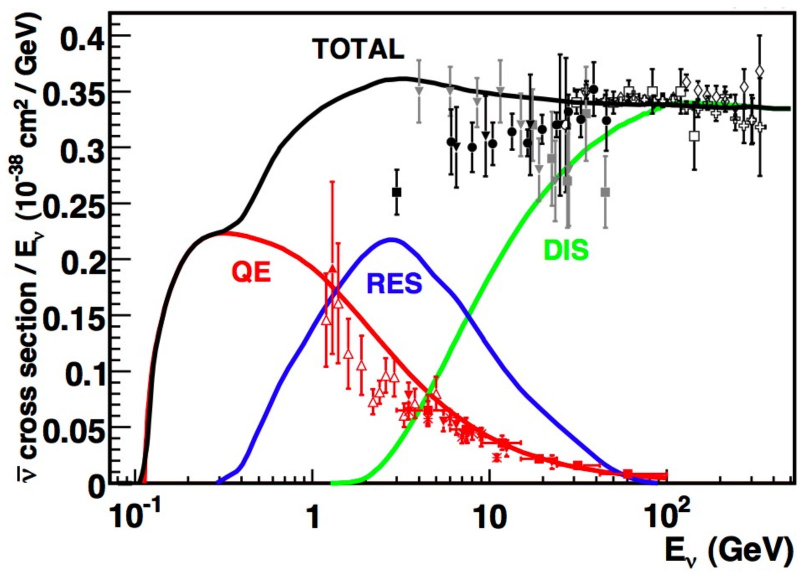
2 particle-2 hole (2p-2h) effect: dominated by Meson Exchange Current (MEC), Interactions with more than one nucleon contribute

Charged-Current Signal- Cross Sections

- Accelerator neutrino oscillation experiments in the 0.1-10GeV transition region
- Multiple types of interactions with complicated final states and topology
- Requirements:
  - High performance detector
  - Excellent Event reconstruction
  - Well understood neutrino flux and interaction models

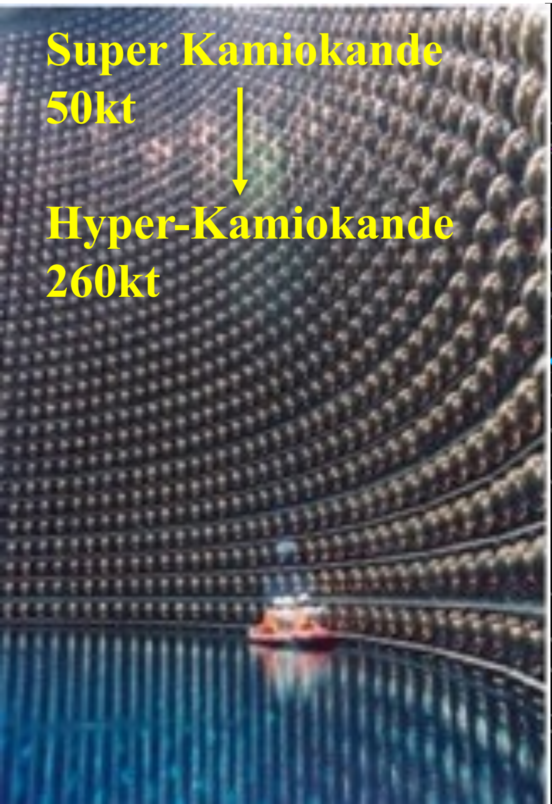


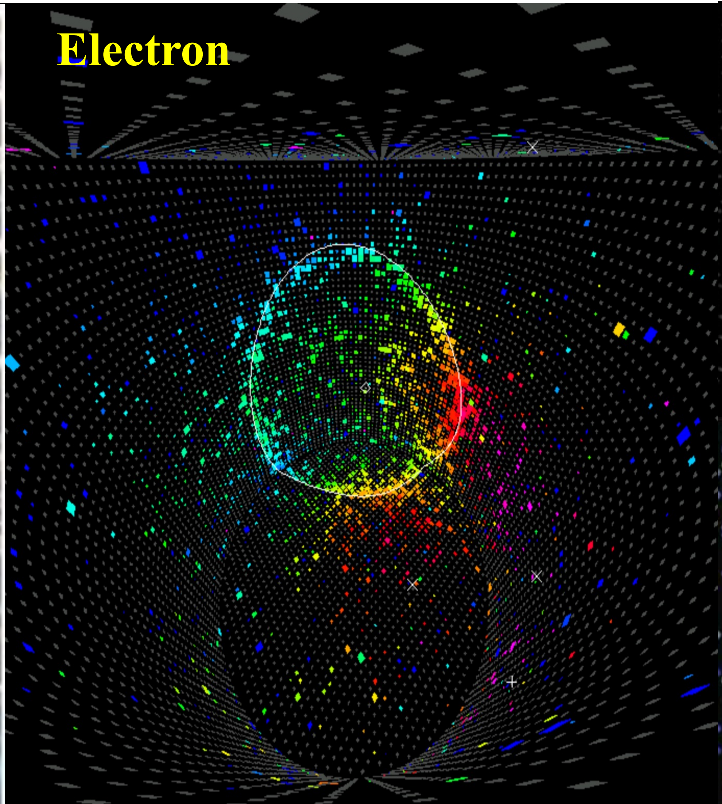


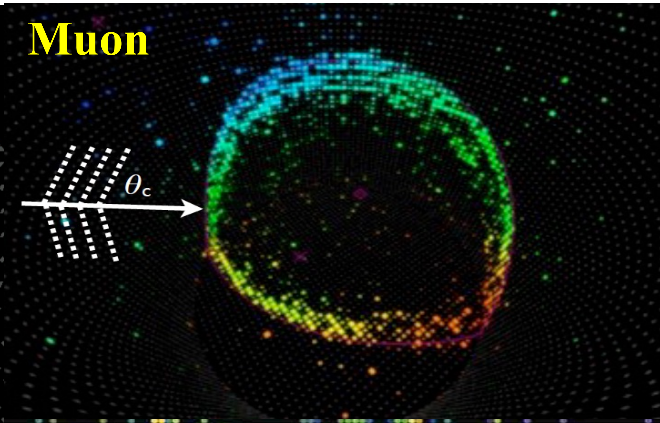


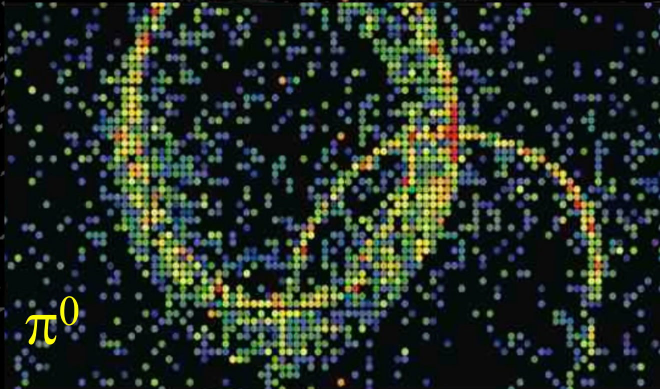
Cherenkov Detectors

- Particles traversing medium faster than light ($v>c/n$) emit Cherenkov light at a characteristic angle.
- Cherenkov light collected and produces signals on PhotoMultiplier Tubes (PMTs)
  - Muons: straight trajectories lead to crisp rings
  - Electrons: showering and multiple scattering produce fuzzy rings
  - π^0s: decay into two gammas, which each appear as electron-like rings



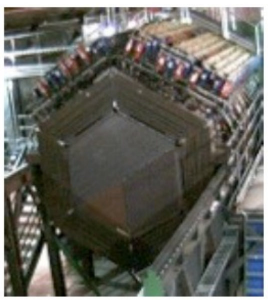




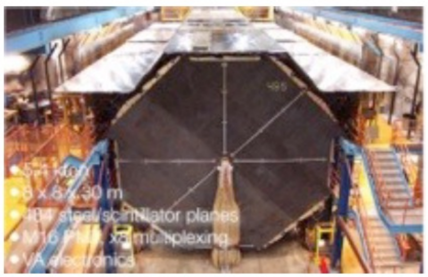


Scintillator Tracking Detectors

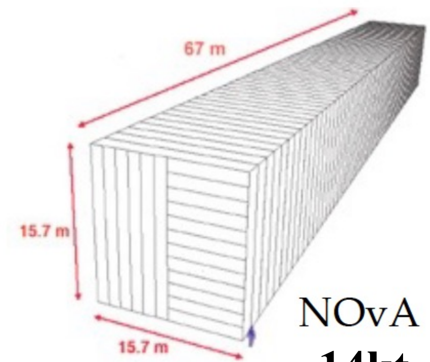
- Use scintillator distributed throughout detector that produces light when particles pass through
- Collect scintillator light via fiber optic readout that connects to a APD
- Reconstruct event in 3D by merging information from alternate coordinate views
- Low-Z and low-density, good for e^- vs π^0 separation



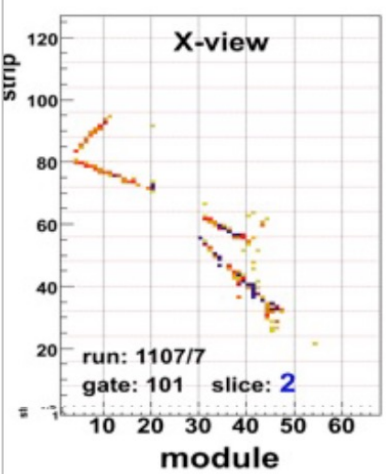
MINERvA

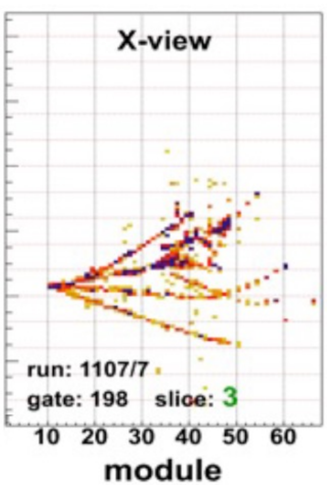


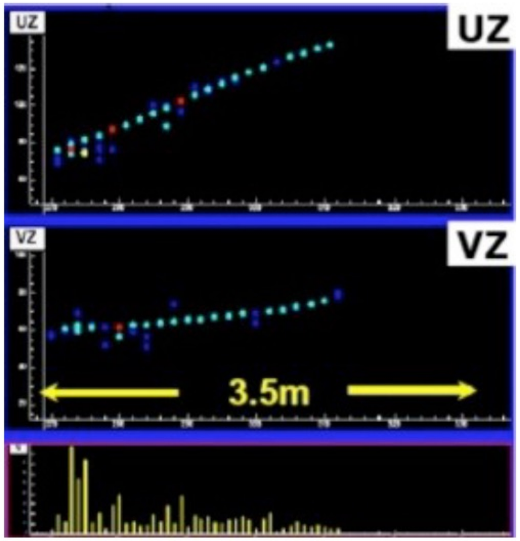
MINOS

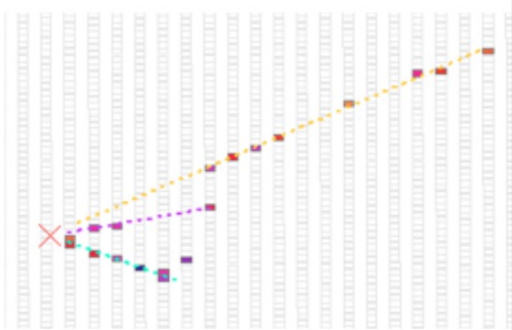


NOvA
14kt

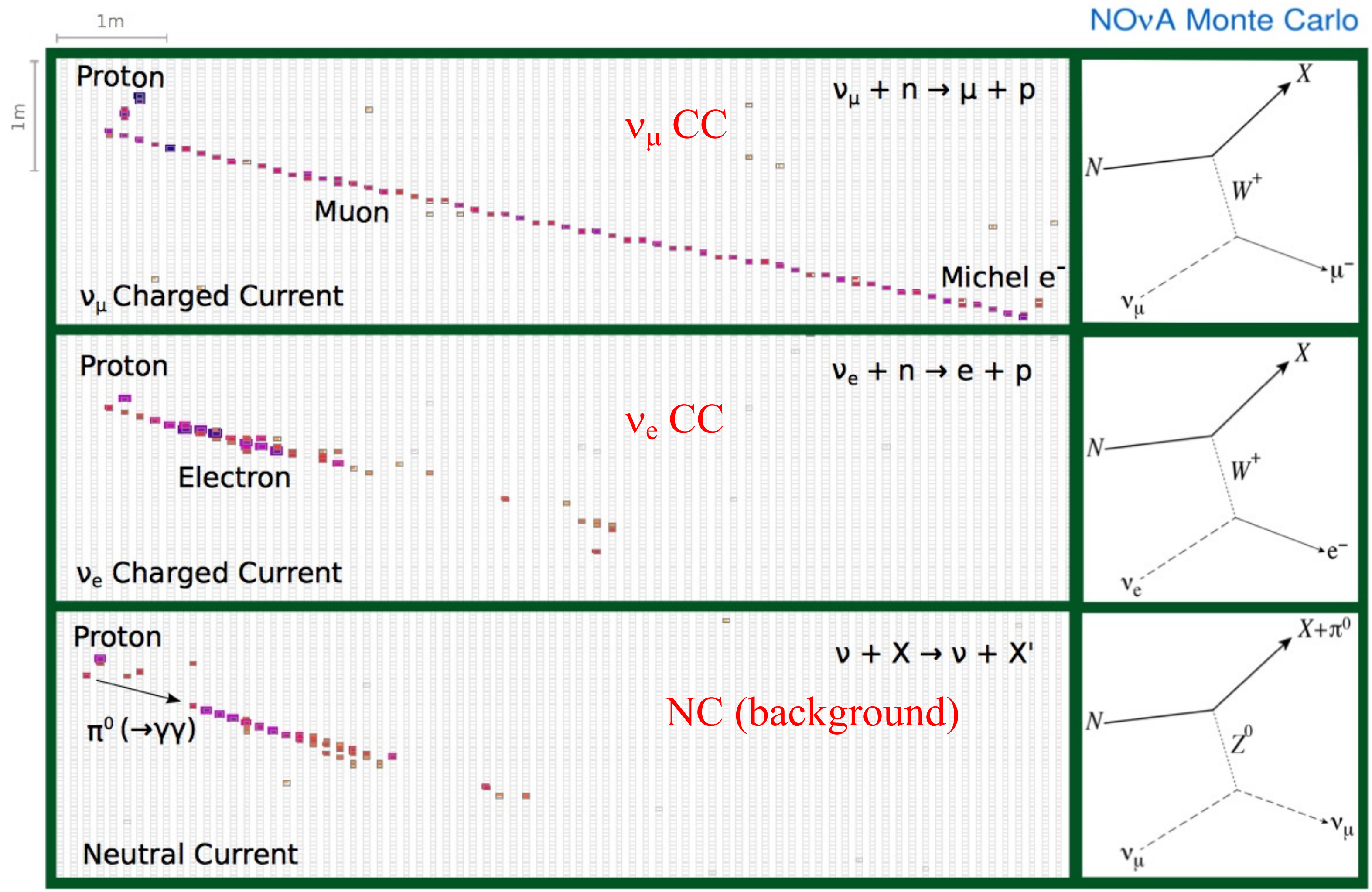








Neutrino Interaction in scintillator detector (NOvA)

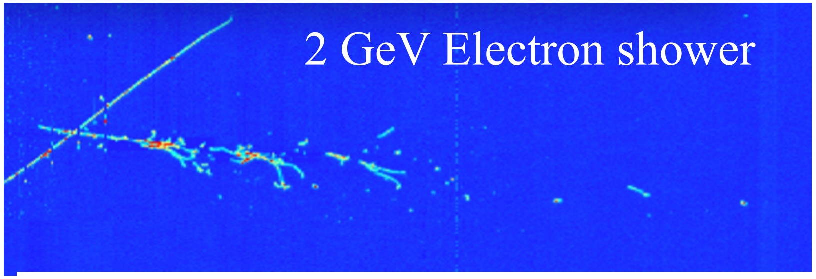


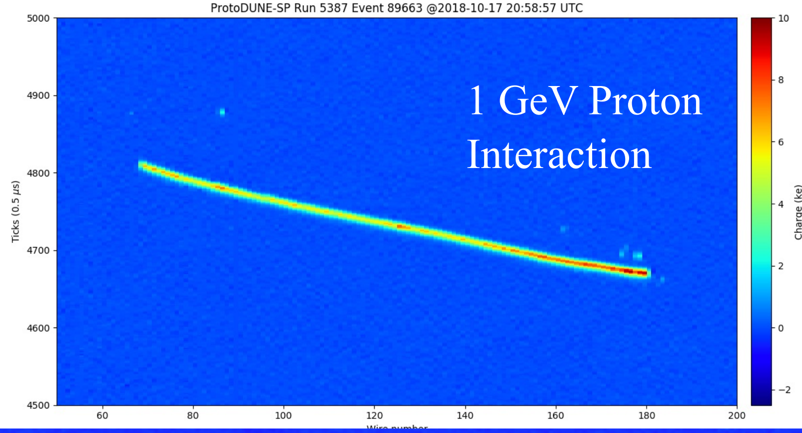
The muon is a long minimum ionizing particle, the electron ionizes in the first few planes then starts to shower and the photon is a shower with a gap in the first few planes.

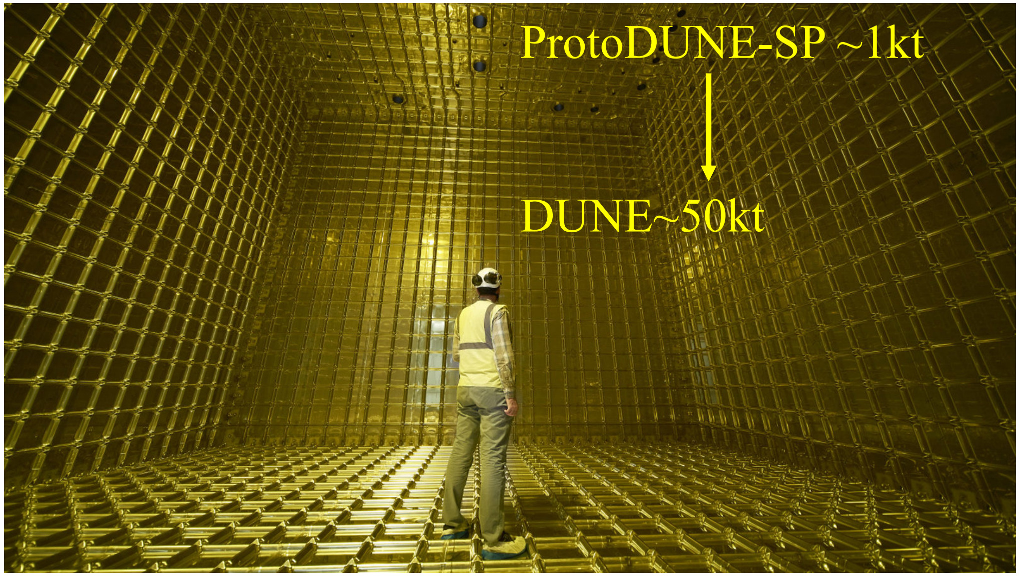
Liquid Argon Time Projection Chamber (LArTPC)

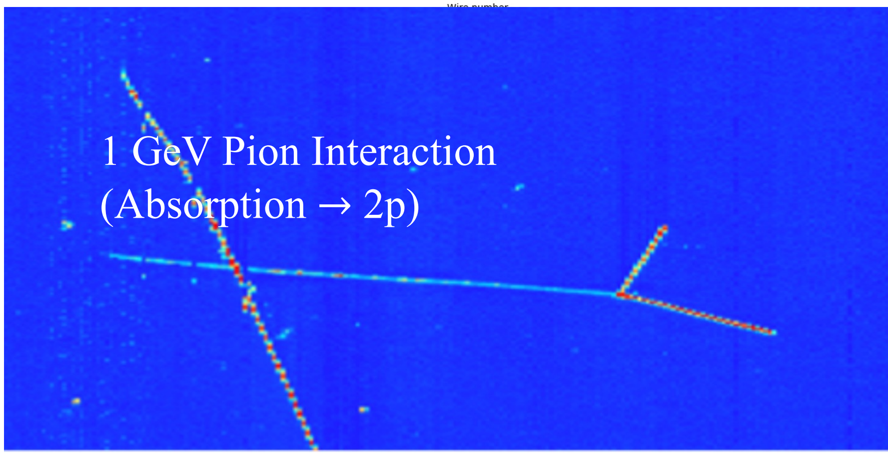
- Liquid Argon Time Projection Chamber (LArTPC) is promising for the next generation of neutrino experiments
  - Image quality of a bubble-chamber, improving sensitivity by better background rejection and resolution
  - Scalable to multi-kiloton detectors
  - Not infinitely expensive
  - Fast electronic readout

ProtoDUNE-SP

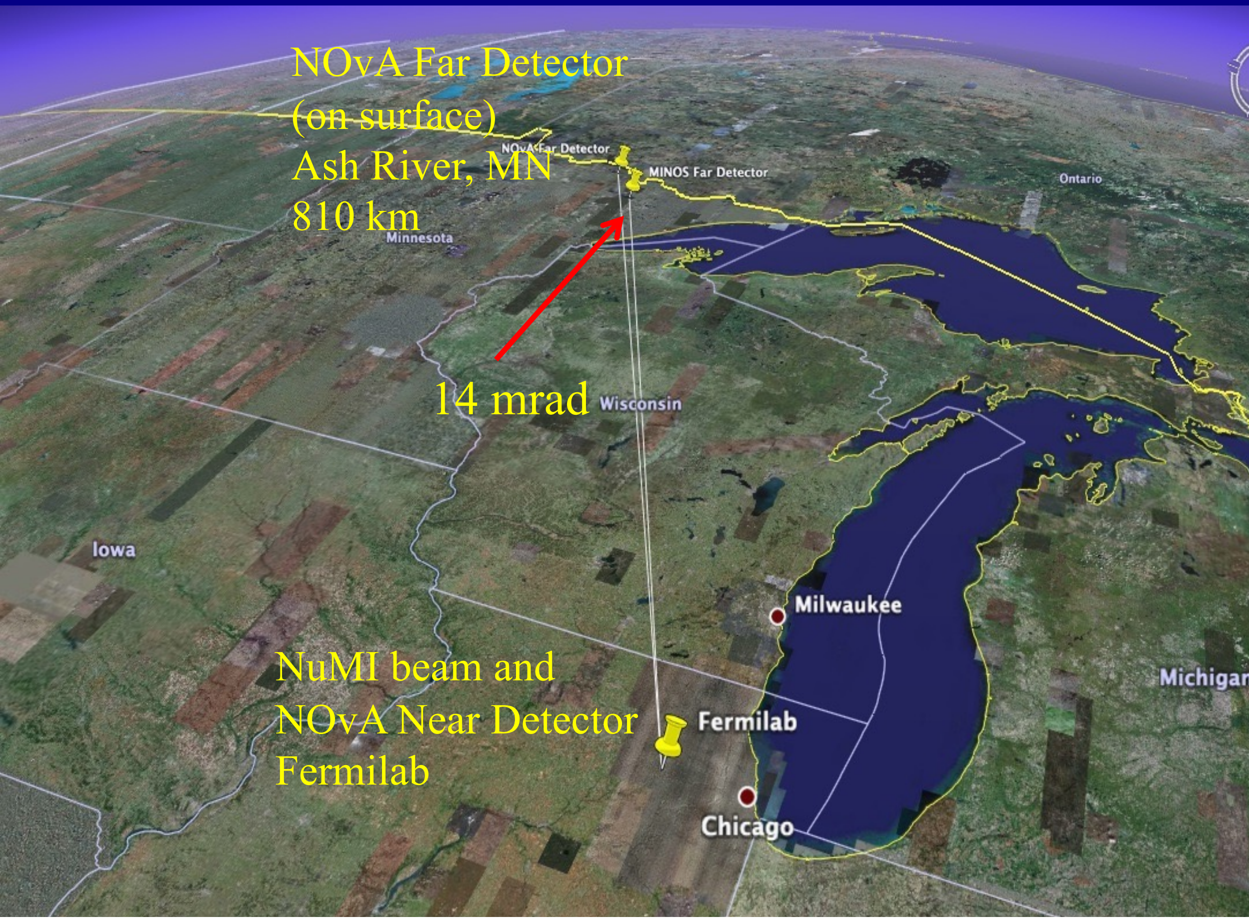


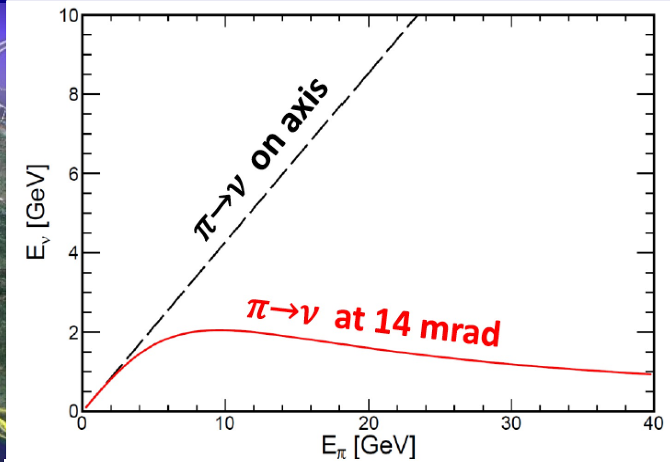


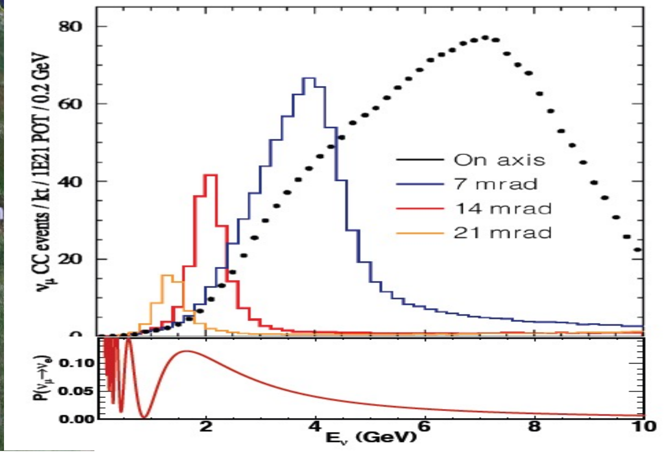




NuMI Off-Axis ν_e Appearance Experiment (NOvA)



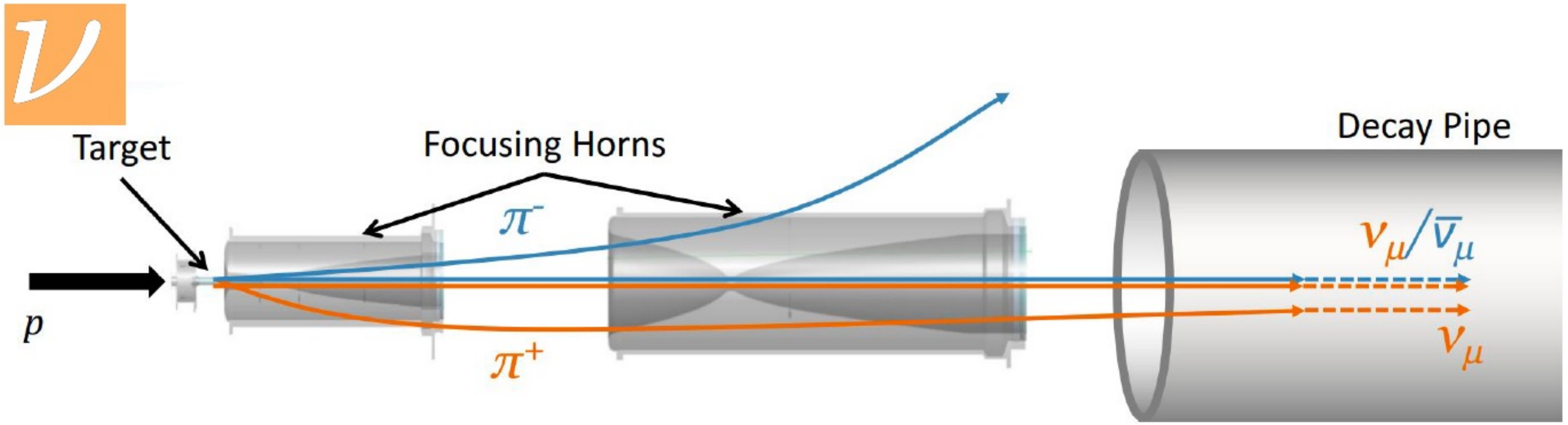


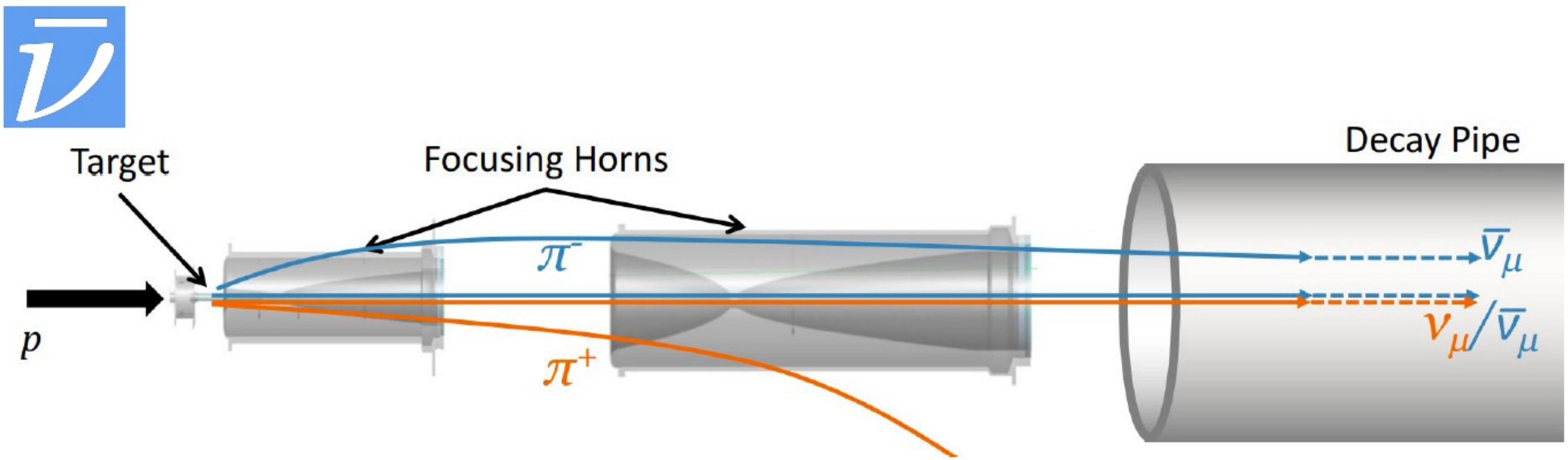


- Muon neutrino beam at Fermilab near Chicago
- Longest baseline in operation (810 km), large matter effect, sensitive to mass ordering
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum

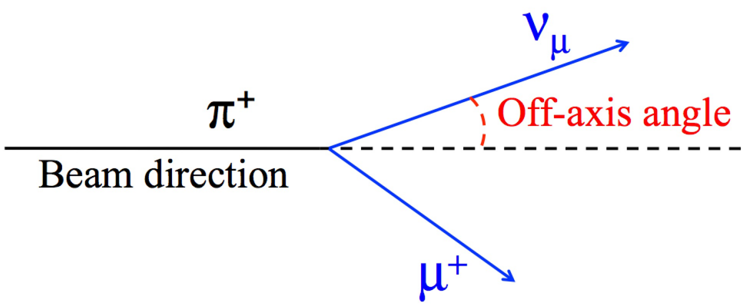
NuMI Off-Axis Beam

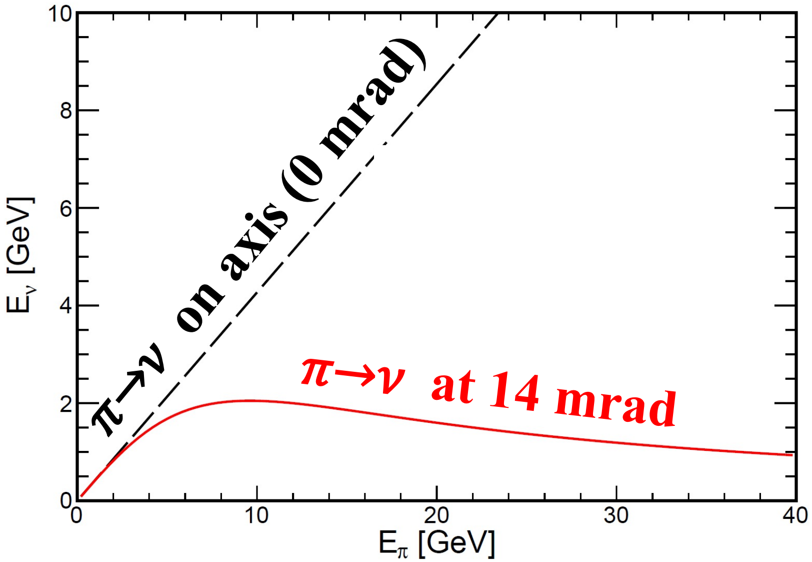
Charge select pions to get 96% (83%) pure muon-neutrino, (anti-muon-neutrino) beam.





NuMI Off-Axis Beam



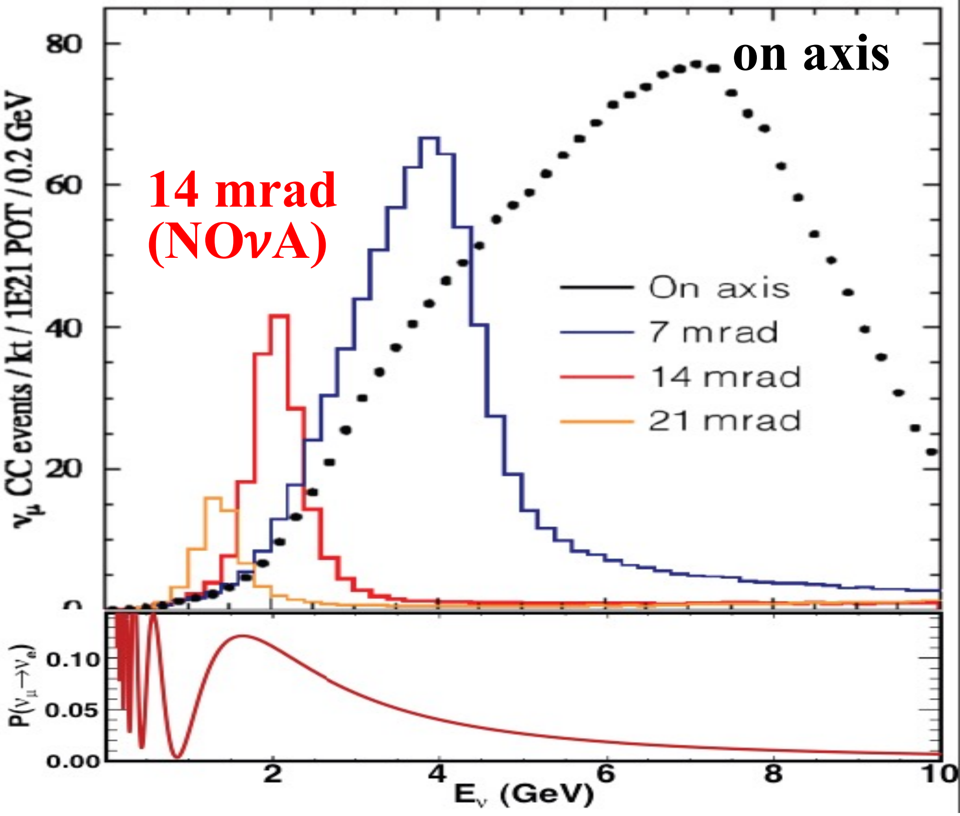


- NOvA detectors are sited 14 mrad off the NuMI beam axis

- Beam ν are produced by π and K decays. Neutrino energy depends on the decay angle and π/K energy

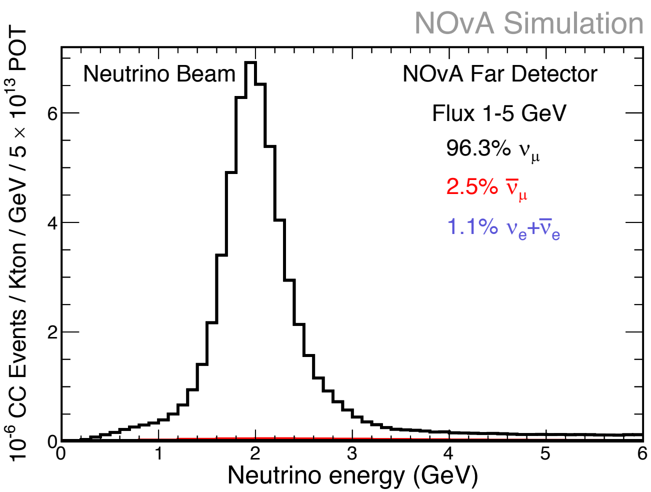
- The off-axis angle provides a narrow 2-GeV ν energy spectrum around the $\nu_\mu \rightarrow \nu_e$ oscillation maximum

- Reduces beam NC and ν_eCC backgrounds while maintaining high ν_μ flux at 2 GeV for the oscillation signal

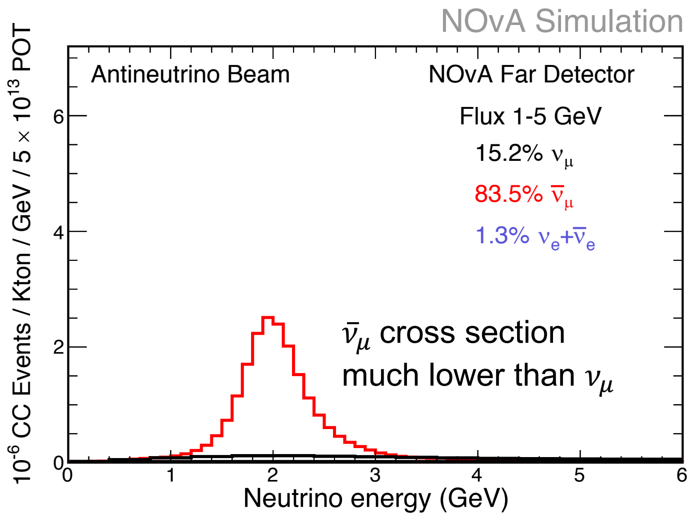


Neutrino Beam Performance

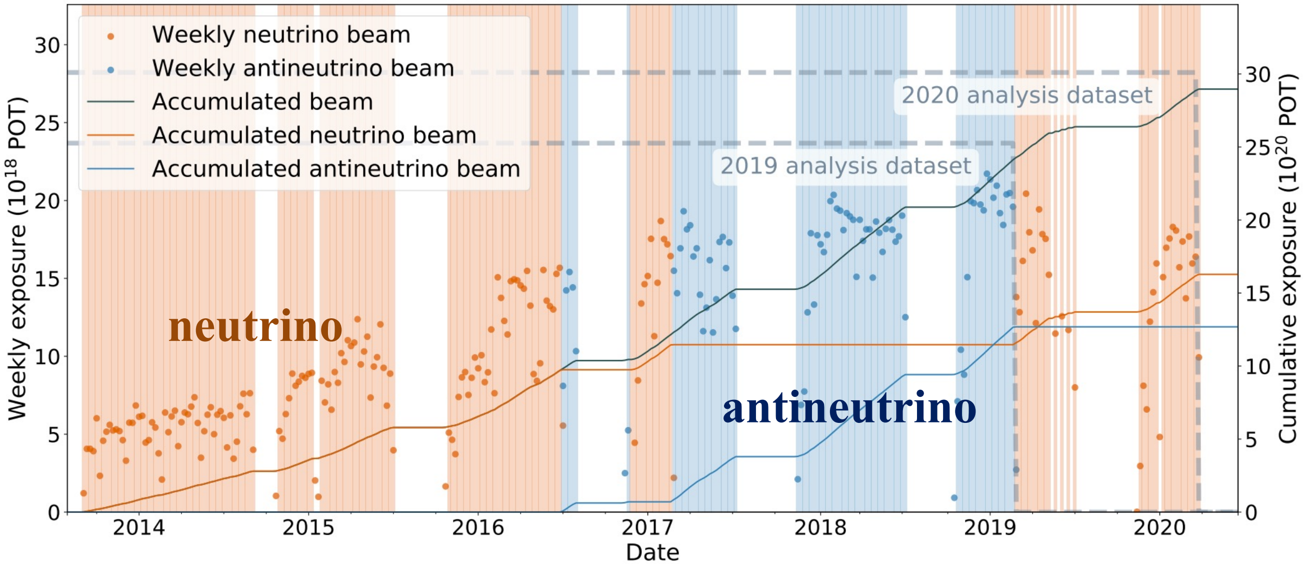
ν_μ event rates at FD in neutrino beam



anti-ν_μ event rates at FD in antineutrino beam



Neutrino beam data: 13.6x10^{20} Protons on Target (POT), (+54% over 2019)
Antineutrino data: 12.5 x 10^{20} POT



Exceed 700 kW design goal since Jan 2017

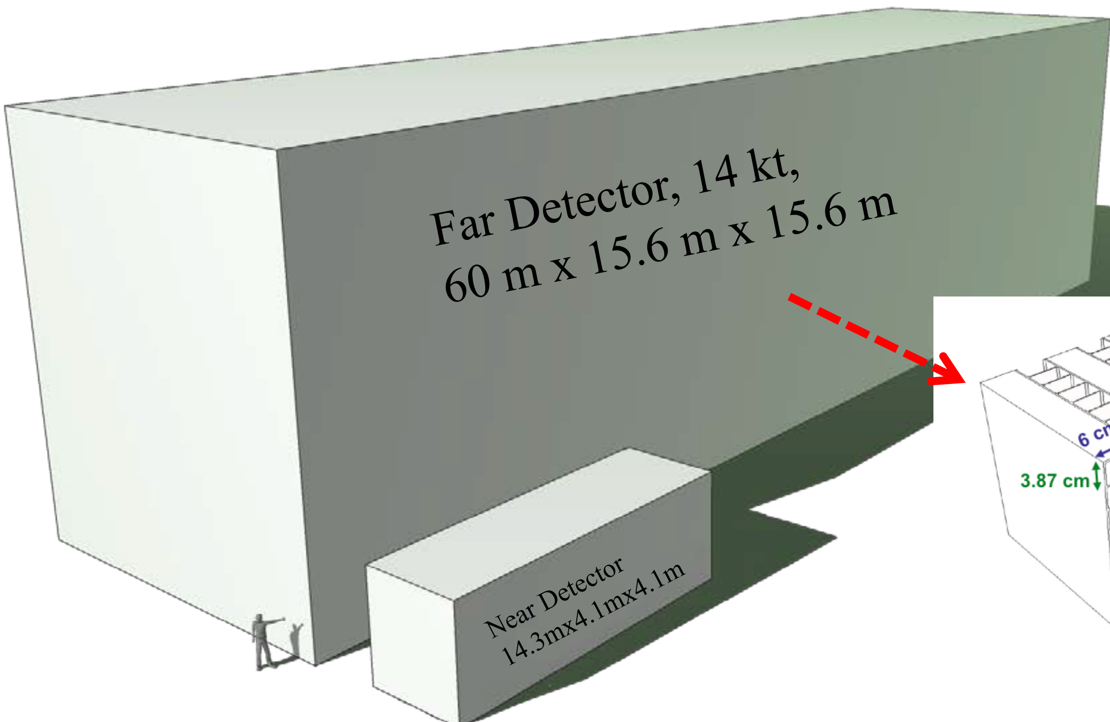
Upgrading beamline targets, horns and accelerator to achieve >=900 kW

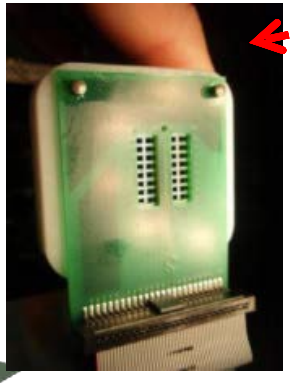
NOvA Detectors

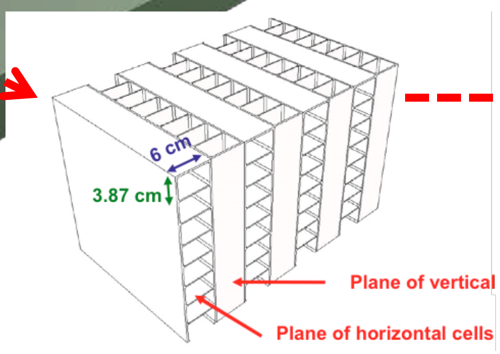
Far Detector (FD):

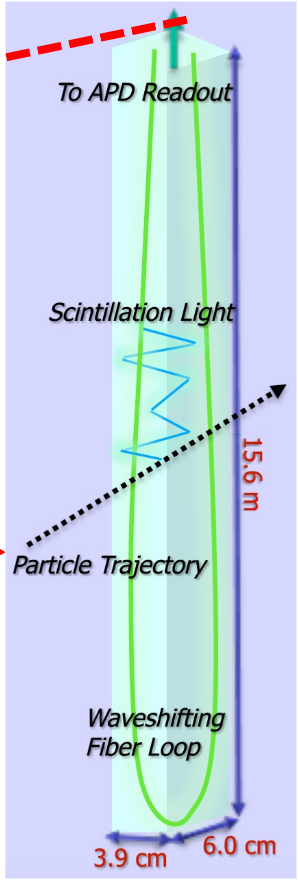
- 14-kton, fine-grained
- 344k detector cells

0.3-kton functionally identical Near Detector (ND), ~20k cells









- Detectors are composed of PVC modules extruded to form long tube-like cells
- Each cell: filled with liquid scintillator, has wavelength-shifting fiber (WLS) routed to Avalanche Photodiode (APD)
- Cells arranged in planes, assembled in alternating vertical and horizontal directions → 3-D information of neutrino interactions

NOvA Detectors

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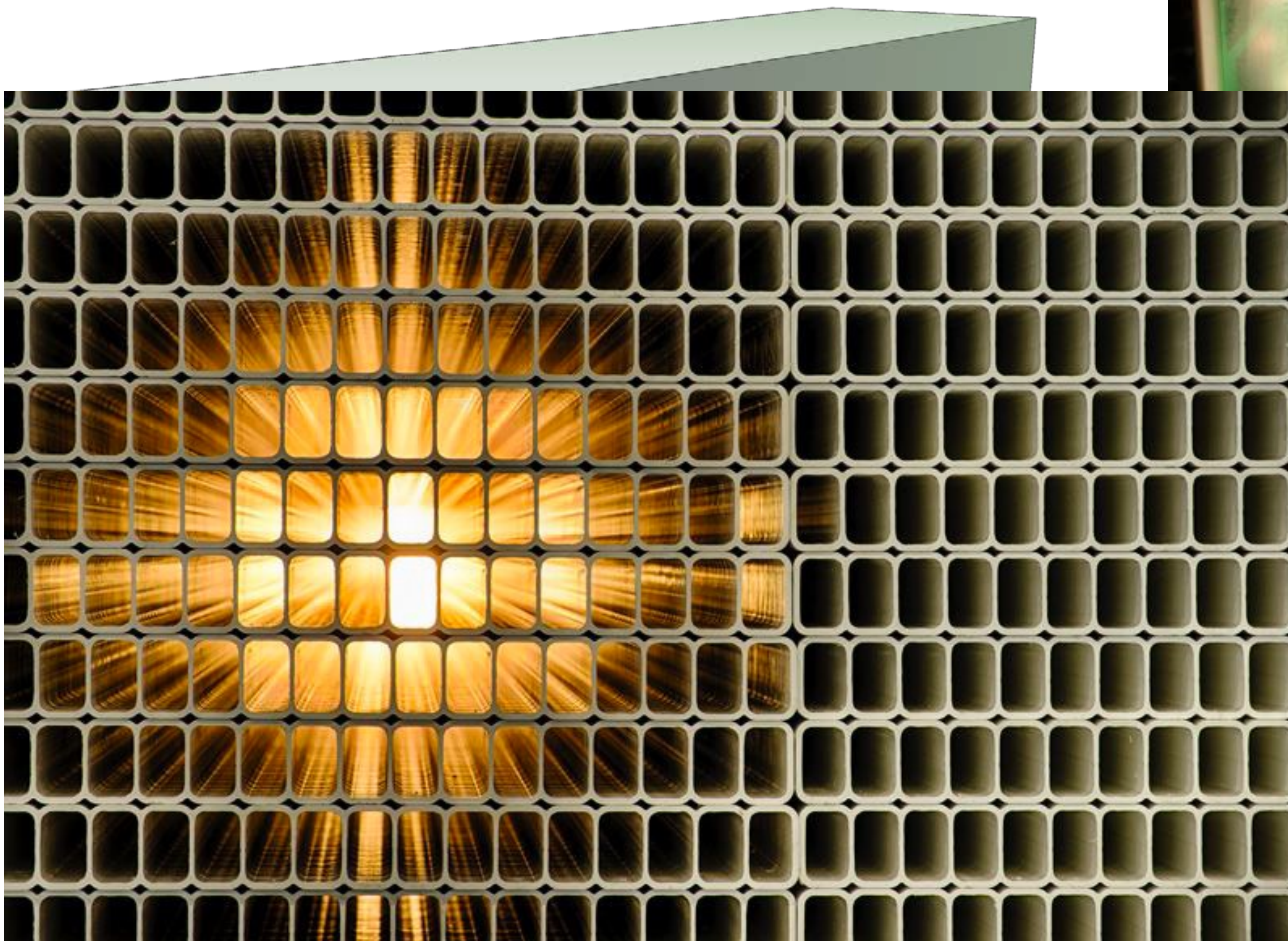

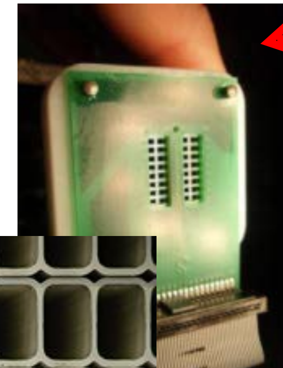

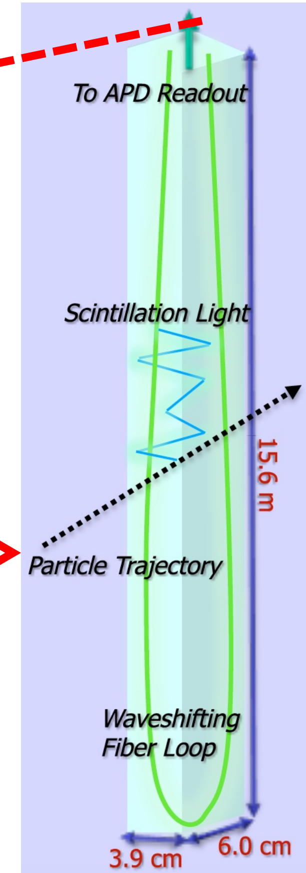

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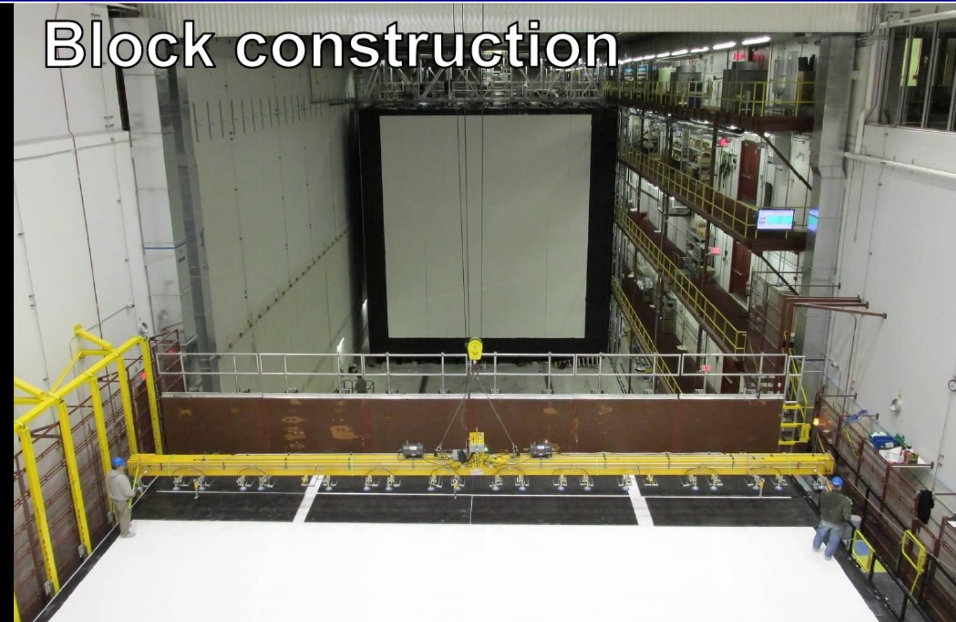
-like cells

r (WLS) routed

ontal directions

NOvA Detectors



Oscillation Analysis Process

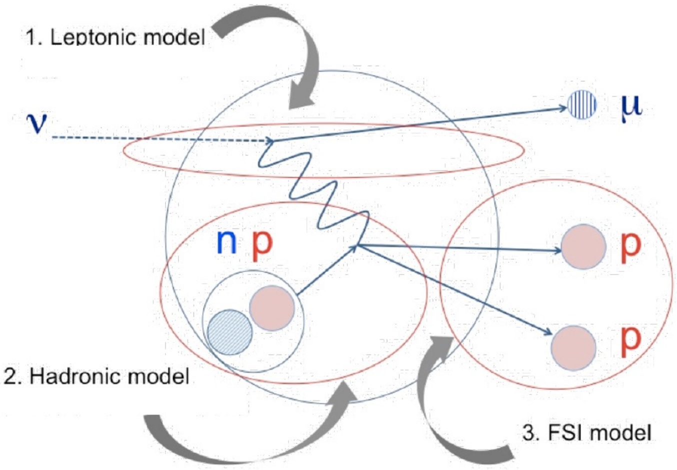
Measure neutrino flavor change vs. energy over a long travel distance to determine oscillation parameters:

- Identify ν_e and ν_μ charge current events from cosmic rays and beam backgrounds (PID)
- Reconstruct neutrino energy and other kinematic variables
- Observe differences between data and MC simulation at Near Detector (ND), extrapolate them to Far Detector (FD) to correct FD MC
- Infer oscillation parameters by fitting oscillation-weighted FD MC to FD data

+ Tune interaction models based on ND data and external data, mitigating uncertainties on neutrino flux, cross sections, and detector response

Neutrino Interaction Tuning

- Upgrade to GENIE 3.0.6 in 2020 (more models)
- Chose the most "theory-driven" available set of models along with GENIE's re-tune of some parameters
- Custom tuning for both central values and systematics:
  - Final State Interactions: external π-scattering data
  - Meson Exchange Current (MEC, Multi-nucleon interaction, 2p2h): amount tuned in 2D space to match NOvA ND data ($q_0 = E_\nu - E_\mu$, $|q| = |p_\nu - p_\mu|$)



T. Katori, AIP Conf. Proc. 1663, 030001 (2015)]

Process	Model	Reference
Quasielastic	Valencia plus Z-expansion form factor	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
MEC	Valencia w/ custom tune	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Interactions	hN w/ custom tune	S. Dytman, Acta Physica Polonica B 40 (2009)

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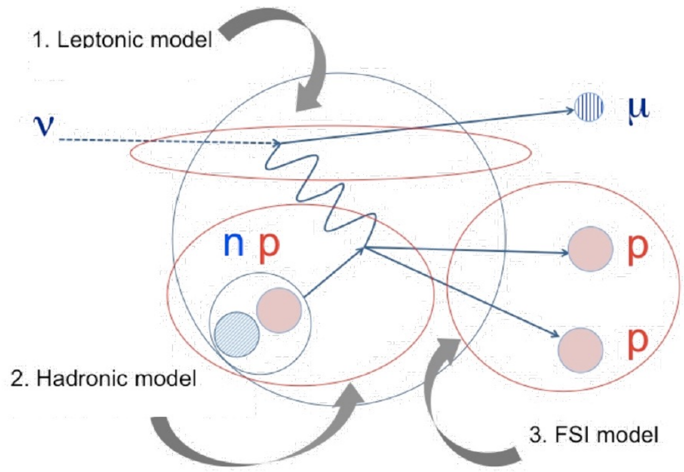
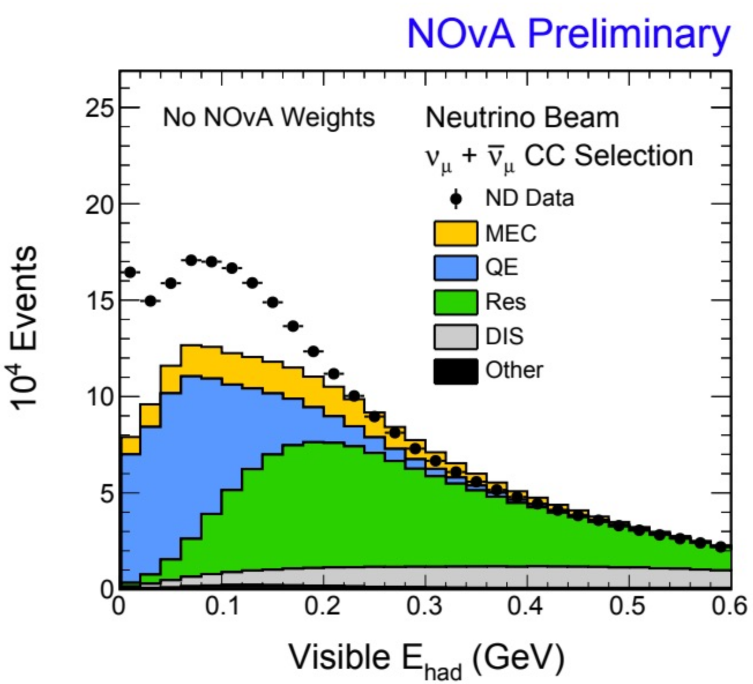
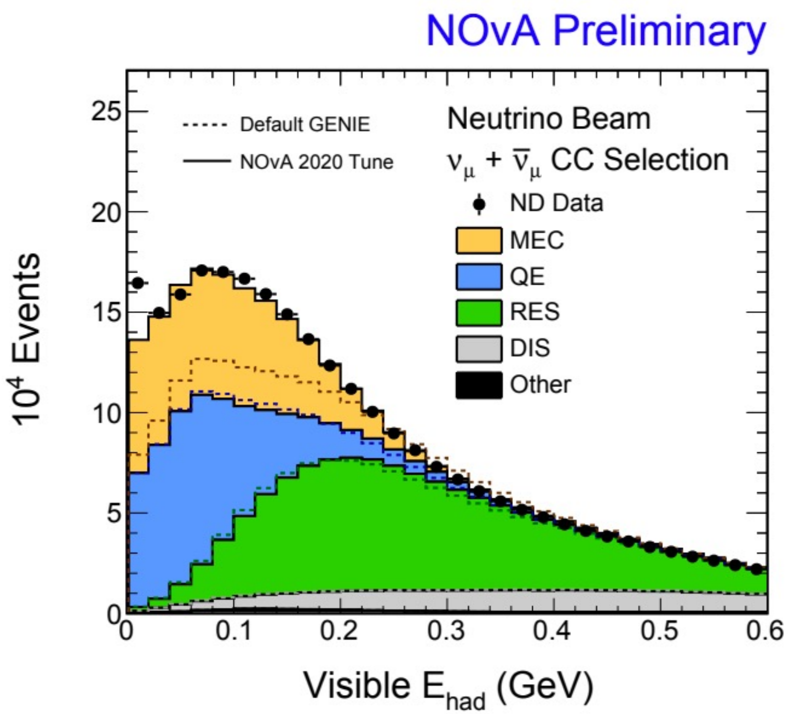
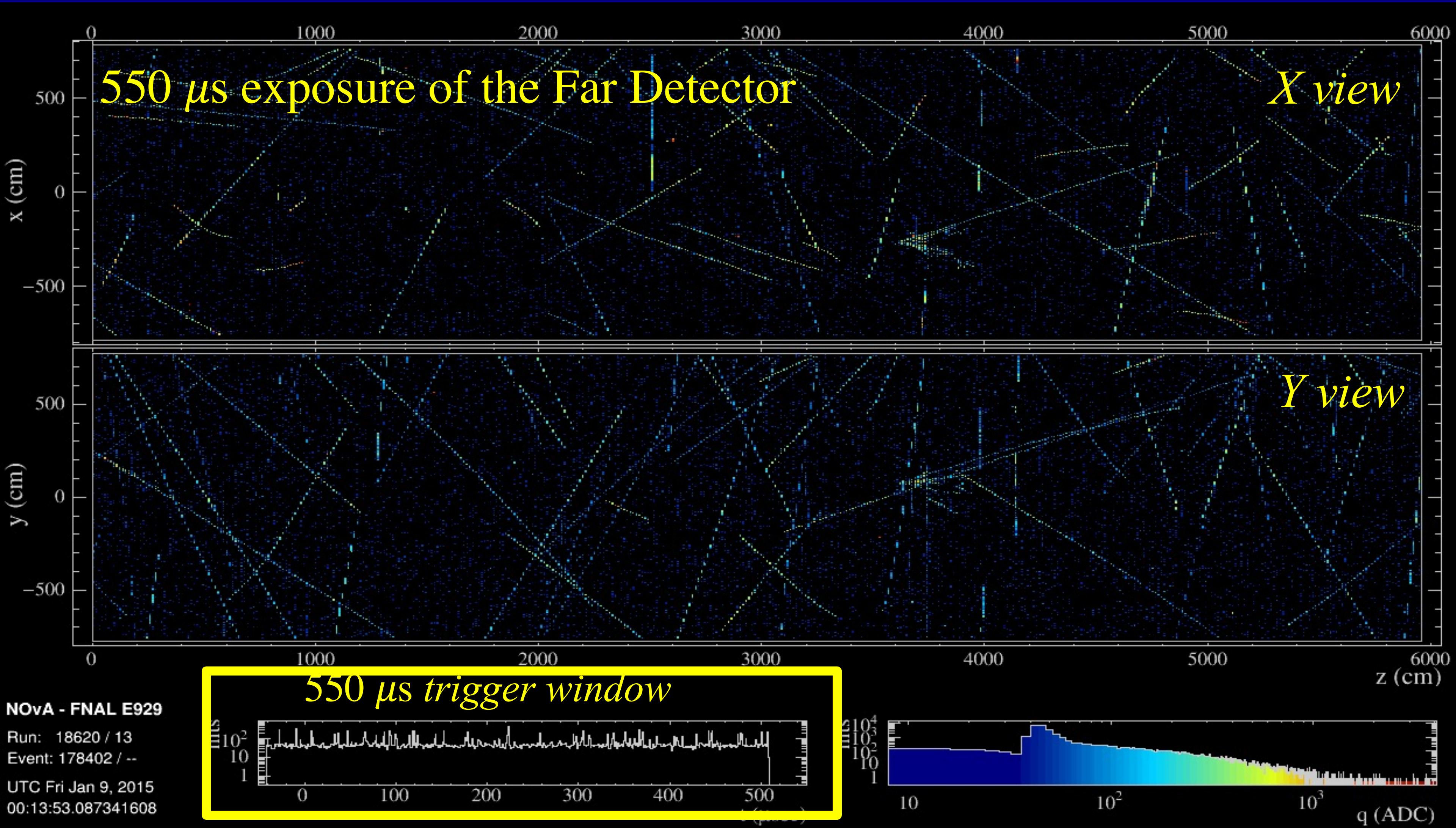


T. Katori, AIP Conf. Proc. 1663, 030001 (2015)]



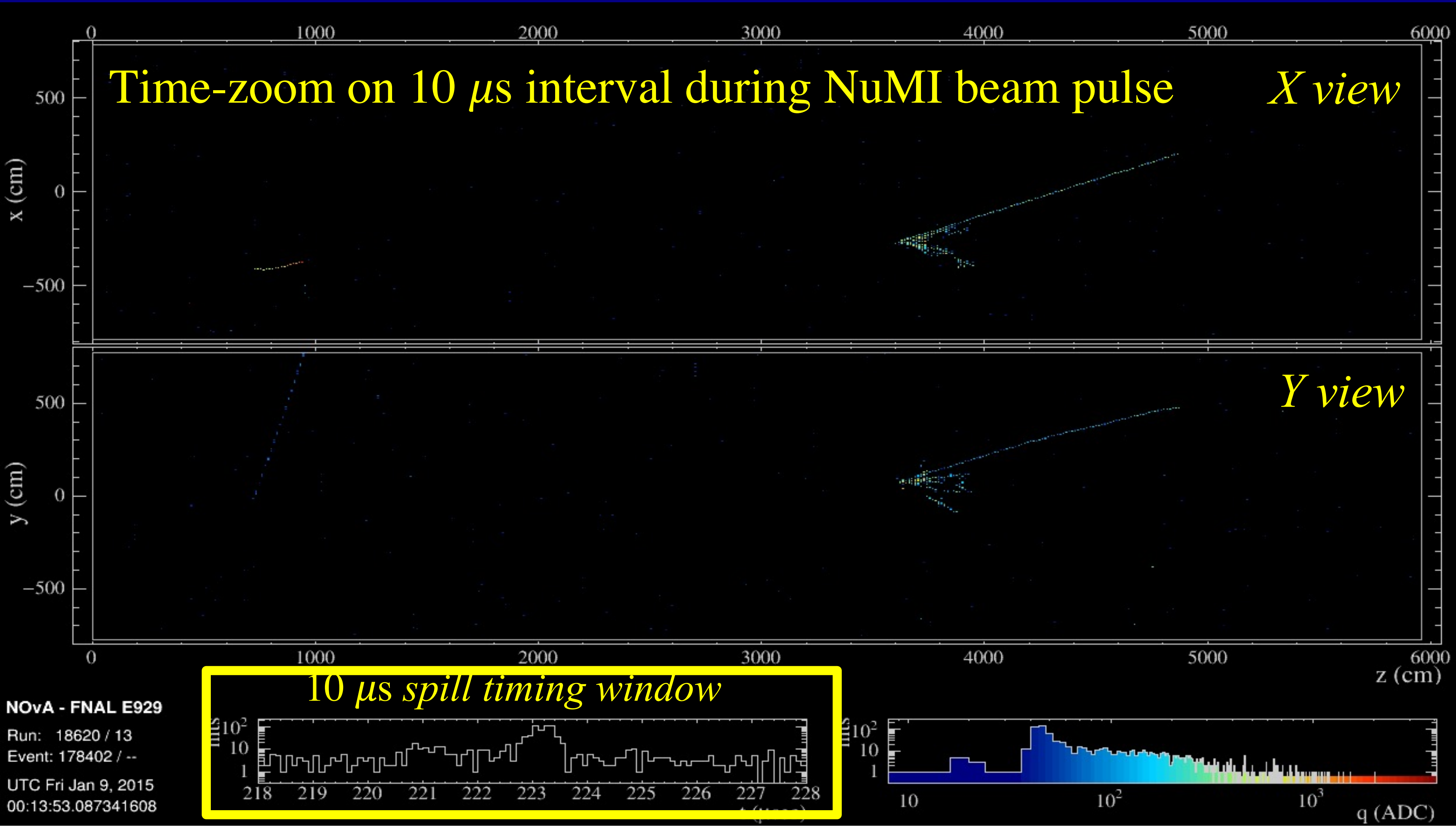


Event clustering



- Because NOvA is on surface, hits in a trigger window are a combination of cosmic and beam events.
- First step in reconstruction is to cluster hits by space-time coincidence to separate neutrino hits and cosmic hits.

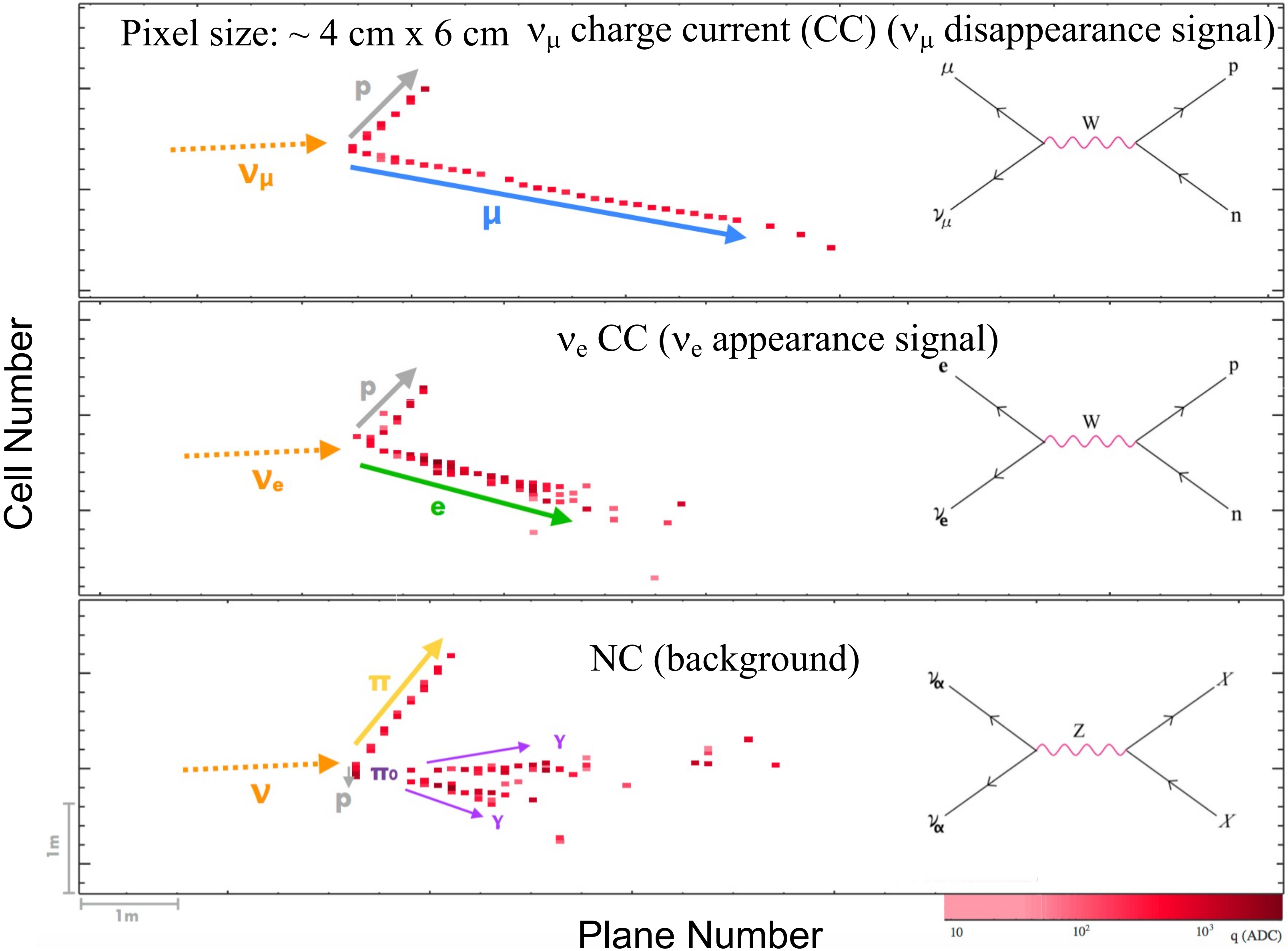
Event clustering



Event clusters that contain neutrino interactions can be correctly selected in the neutrino spill timing window

NOvA Event Topologies

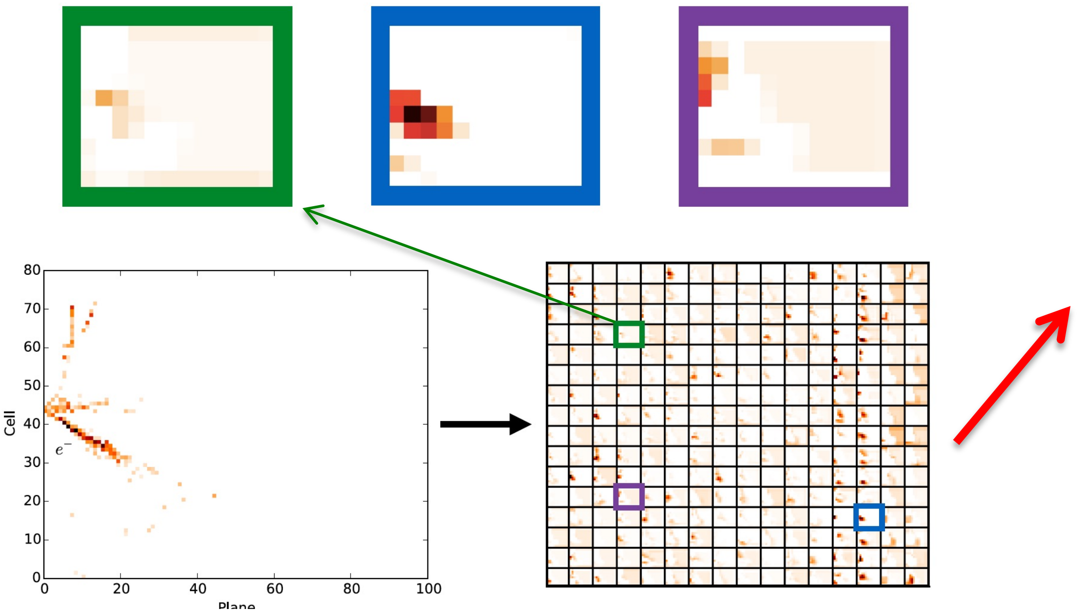
X-View only



Deep-Learning based neutrino classifier (PID)

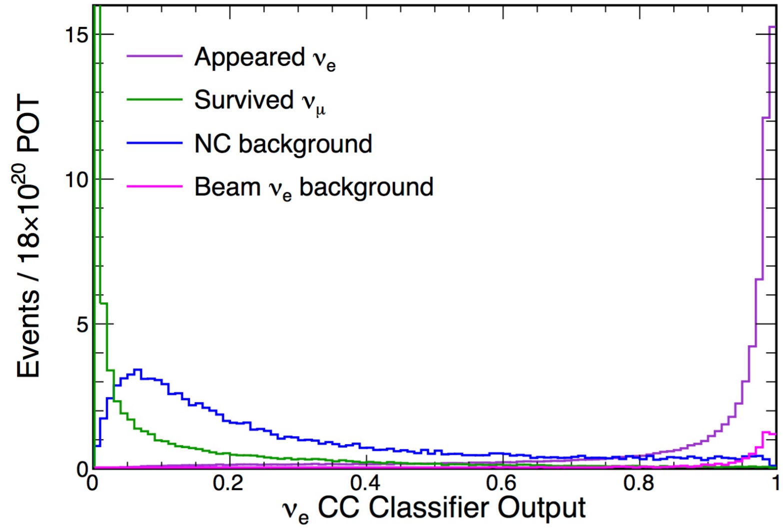
- CVN: a convolutional neural network (CNN), based on modern image recognition technology
- Extract features directly from pixel maps
- Statistical power equivalent to 30% more exposure than previous neutrino classifiers

Outputs of convolutional filters (features)



Hit map of a ν_e CC event

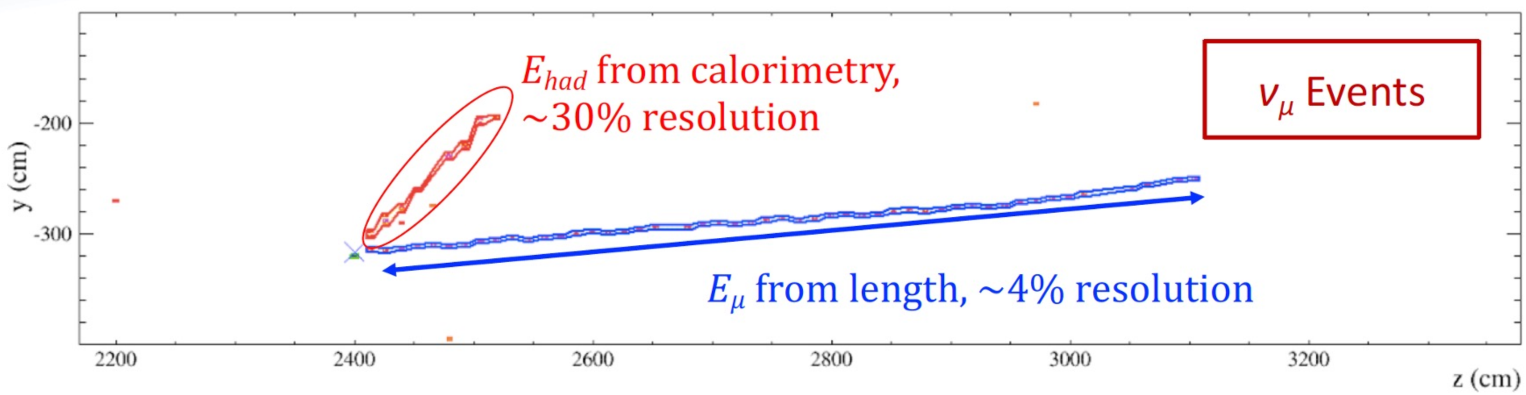
CVN output in the far detector MC

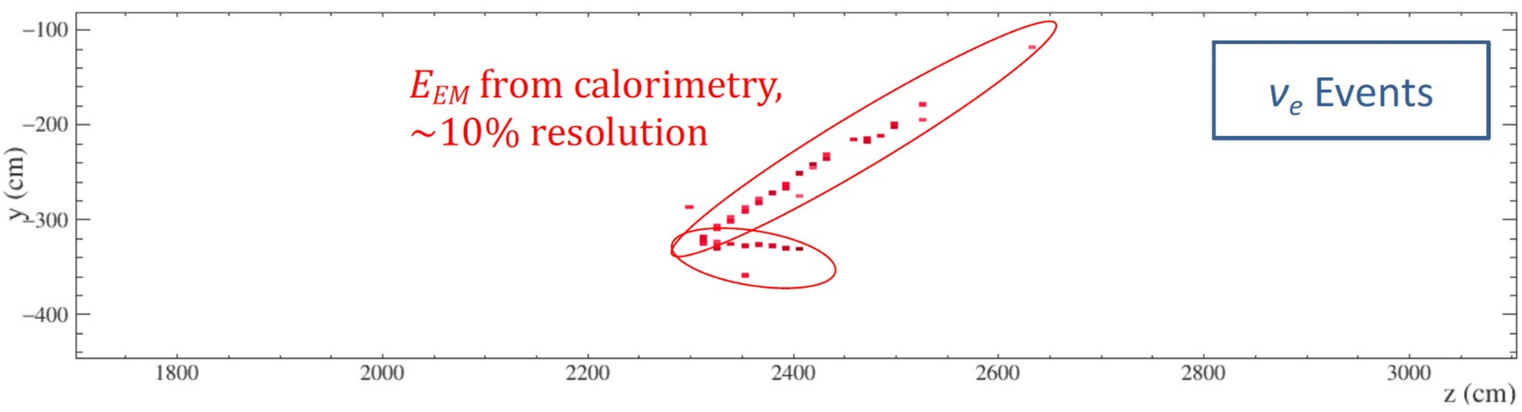


A. Aurisano et. al, JINST 11, P09001 (2016)

Select ν_μ ($\bar{\nu}_\mu$) CC and ν_e ($\bar{\nu}_e$) CC candidates from neutrino (antineutrino) beam with CVN in Near Detector (ND) and Far Detector (FD)

Event Reconstruction



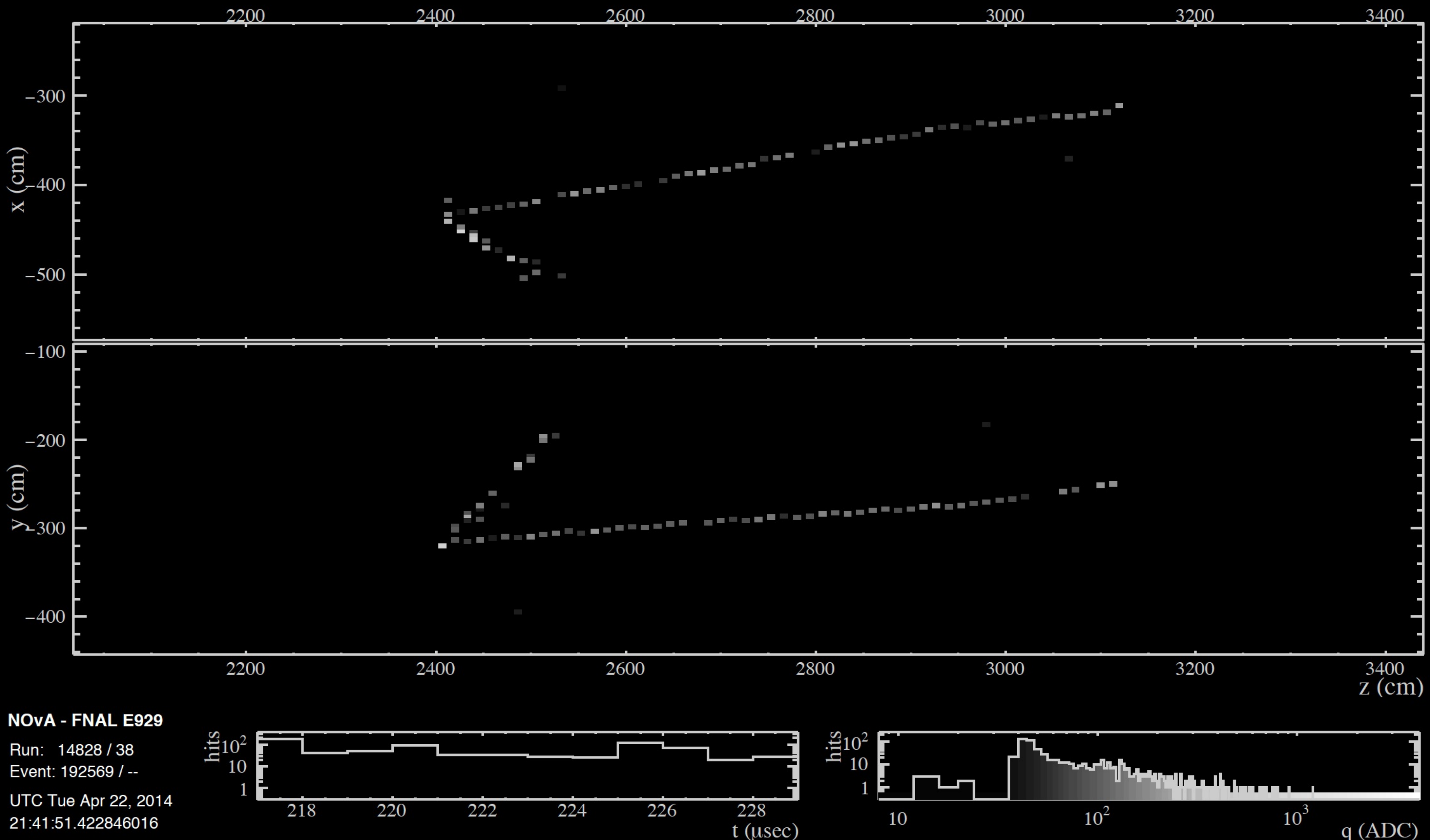


Vertexing: Find lines of energy depositions with Hough transform. Then determine the vertex that all lines converge to

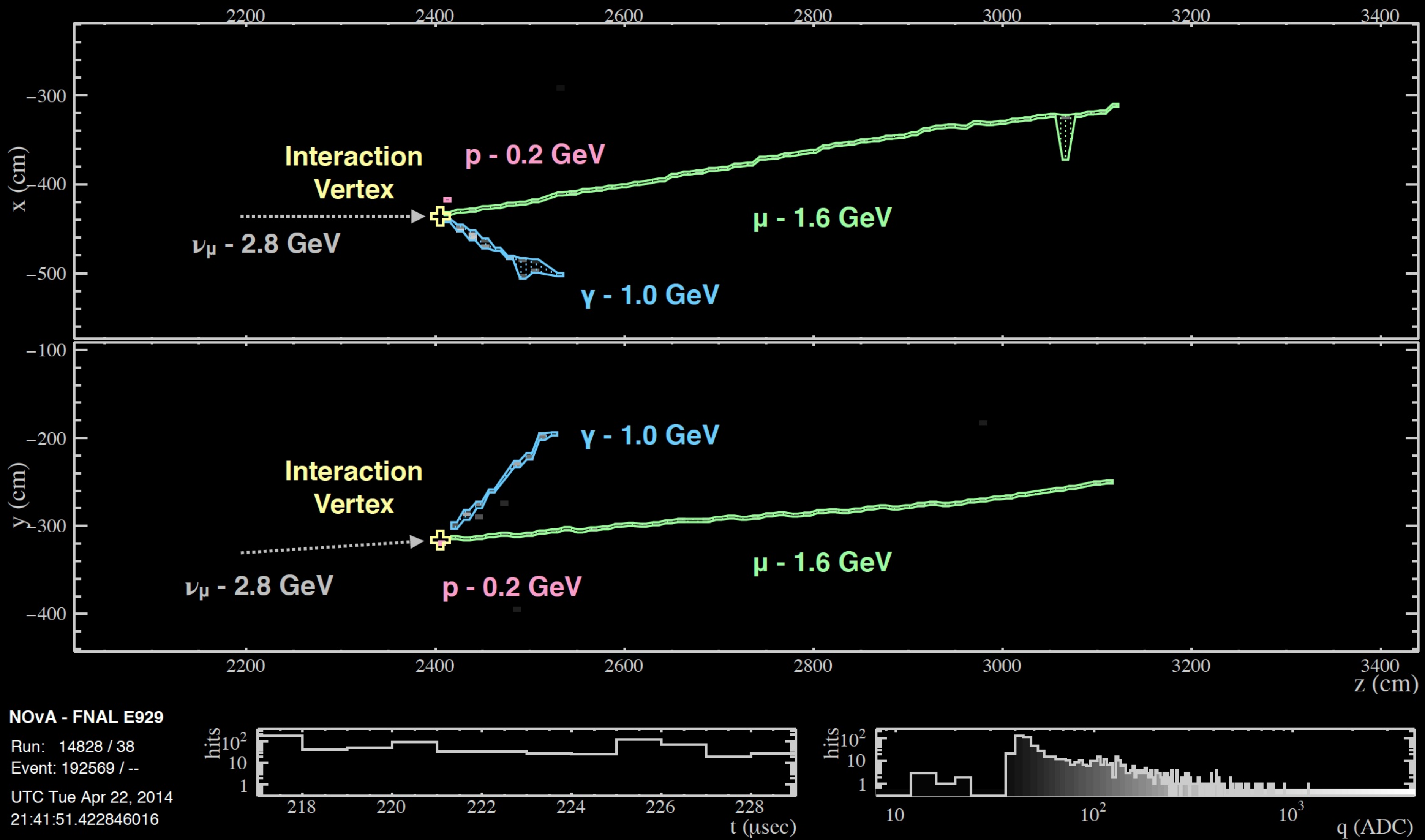
Shower Clustering: Based on the vertex and the lines, showers are reconstructed by angular clustering

Tracking: Trace particle trajectories with **Kalman filter** tracker

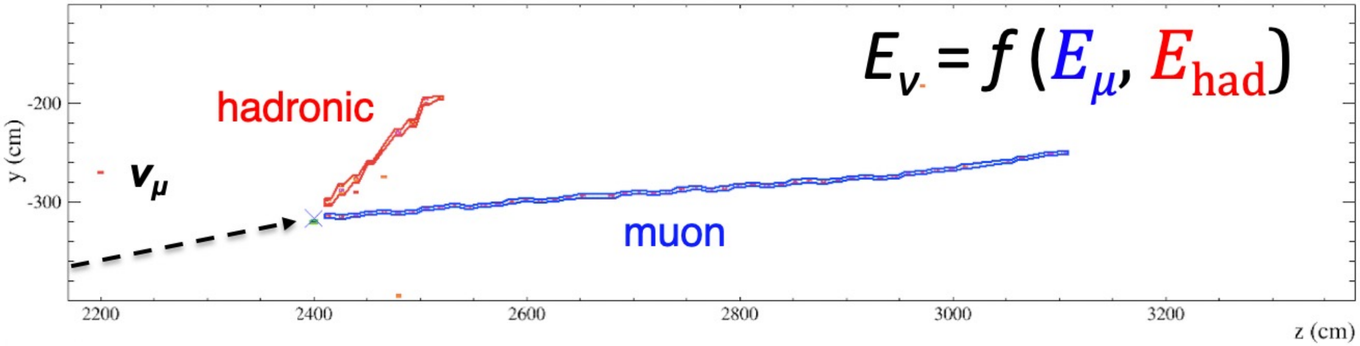
NOvA Events

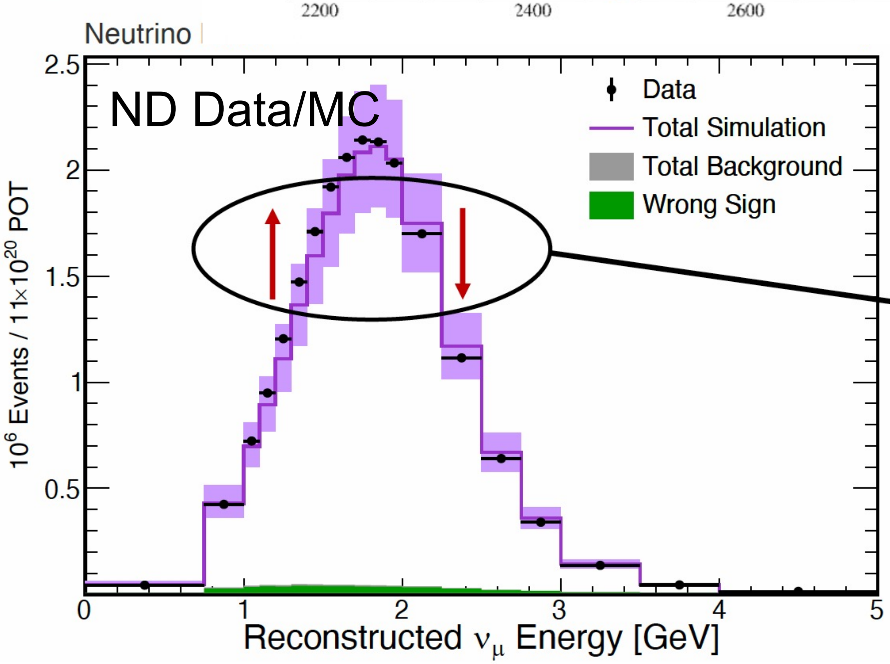

x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 14828 / 38
Event: 192569 / --
UTC Tue Apr 22, 2014
21:41:51.422846016
hits
t (μsec)
q (ADC)

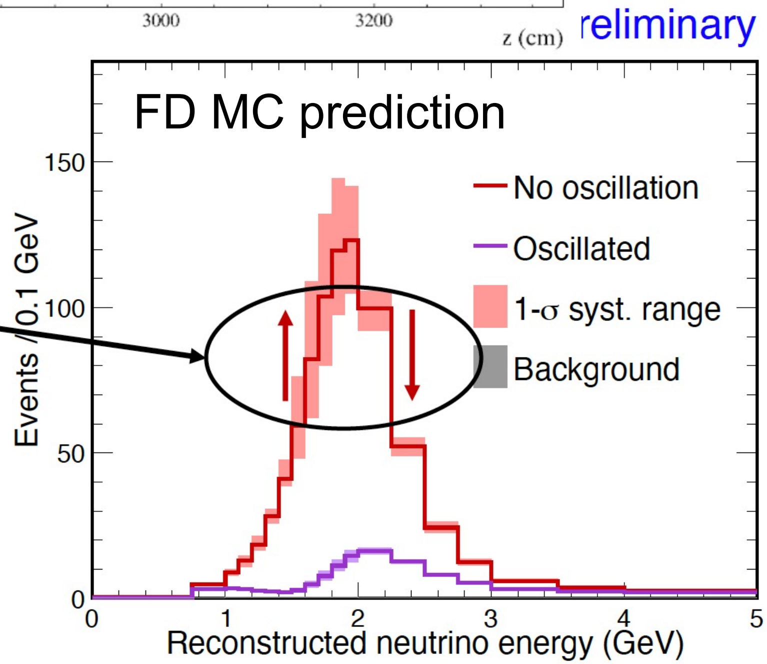
Reconstruction



Energy Reconstruction and Extrapolation

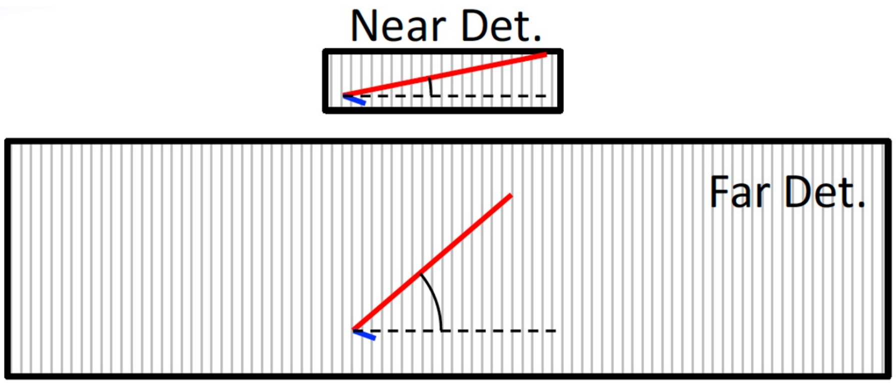


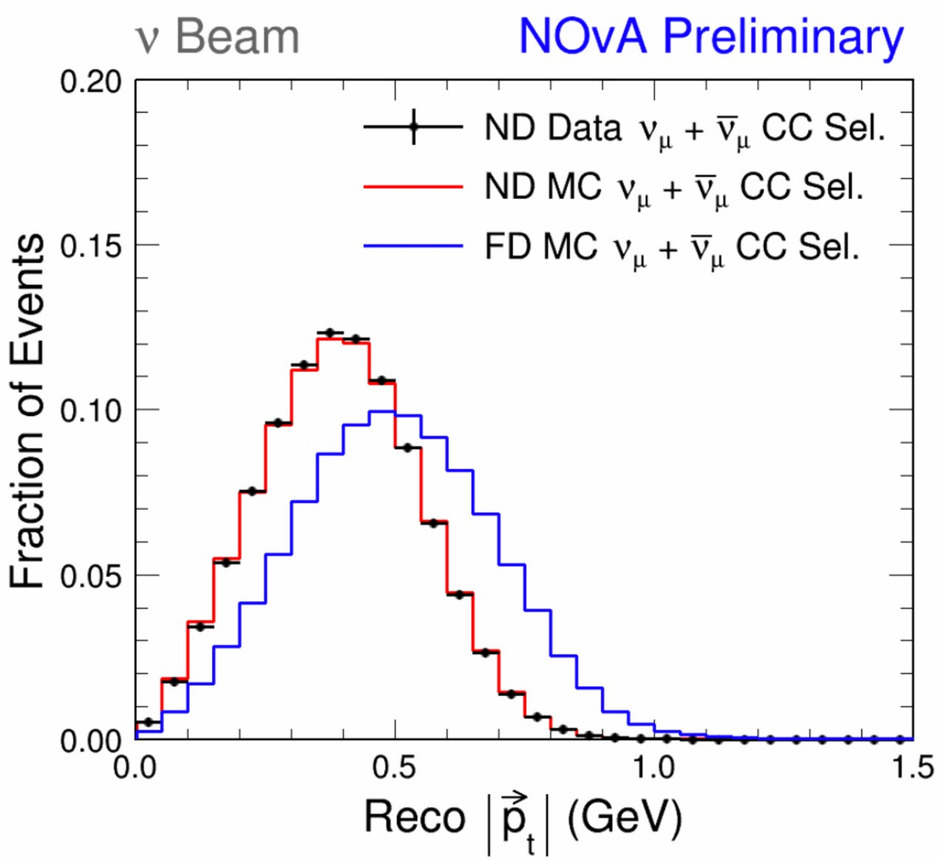




- Signal neutrino energy is the sum of muon/electron and hadronic energy.
- Observe data-MC differences in neutrino energy spectrum at the ND, extrapolate them to modify the FD MC prediction (significantly reduce systematics)
- Systematic uncertainties determined in ND also extrapolated to FD

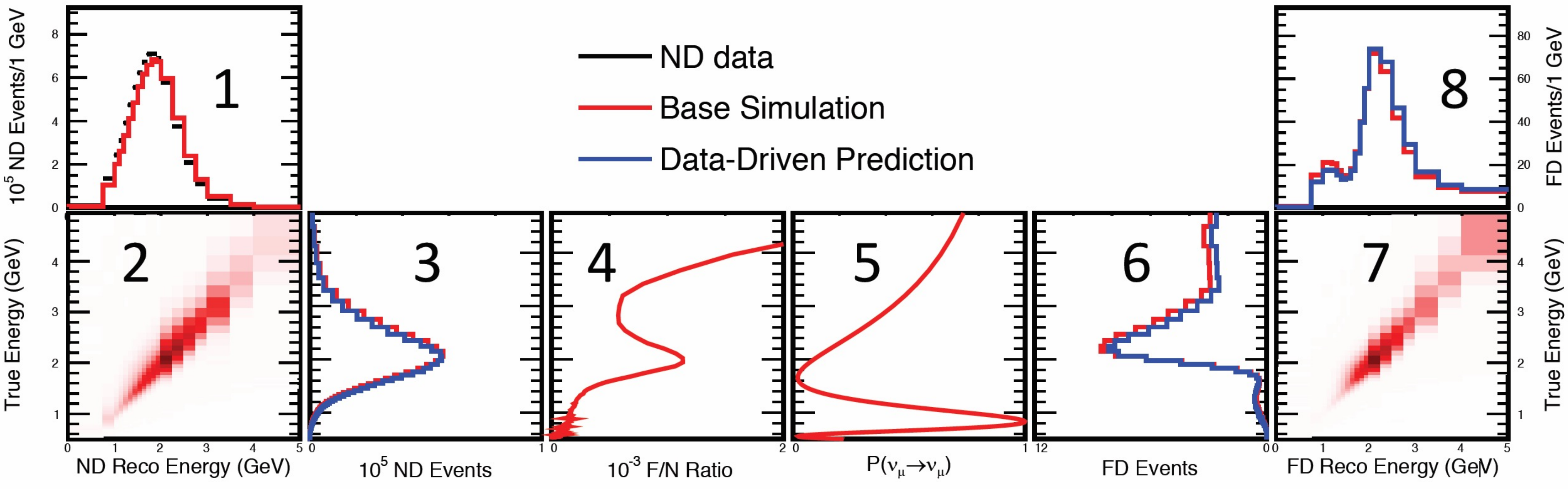
Energy reconstruction and Extrapolation





- "Functionally identical" is not "identical" – the ND and FD are very different sizes.
- Containment limits the range of lepton angles more in the ND than in the FD.
  - An avenue for cross-section mismodeling to not cancel between detectors.
- Can be mitigated by extrapolating in bins of **transverse momentum, p_t.**
  - Component of the *lepton's* momentum transverse to the ν-beam direction.
  - Split the ND sample into 3 bins of p_t, extrapolate each separately to the FD.

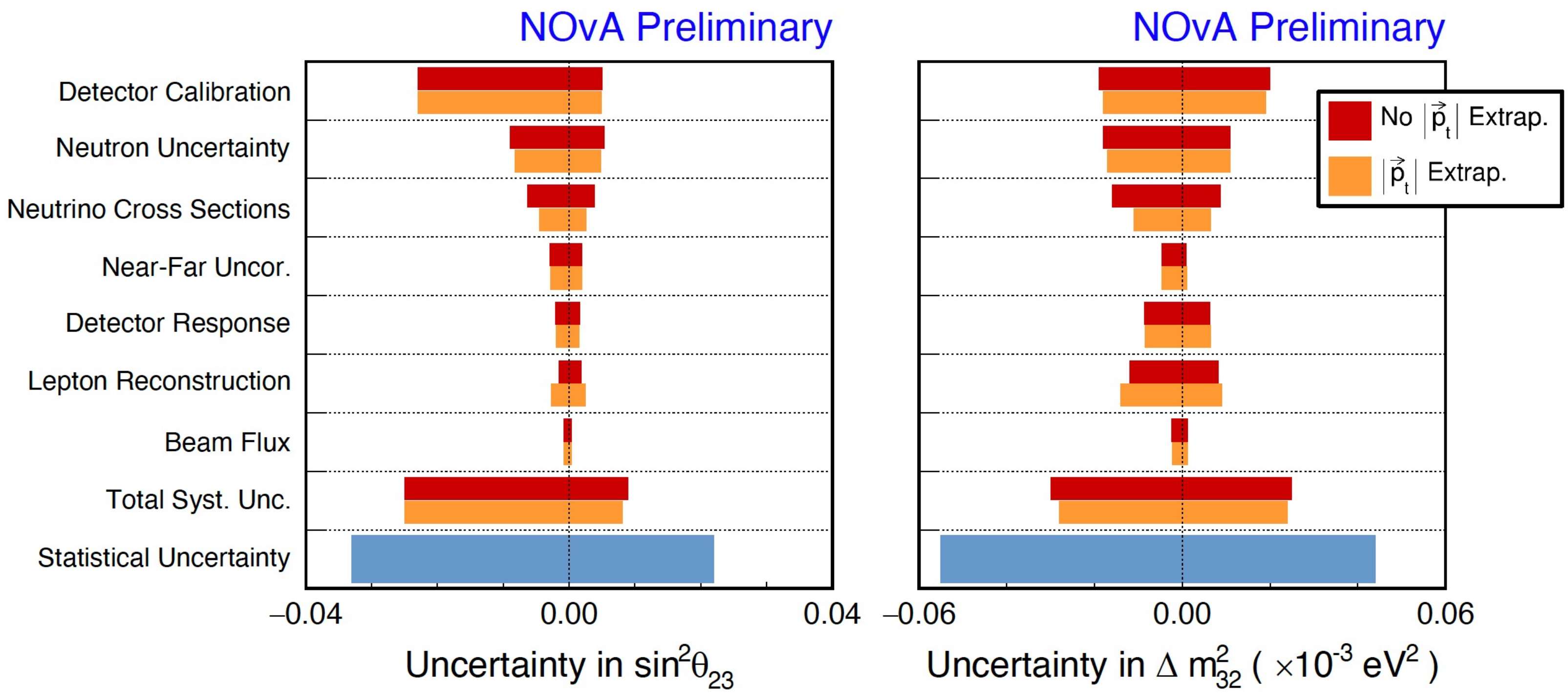
Energy reconstruction and Extrapolation



1. ND Data Reco E_ν 2. ND Reco-to-True E_ν Weighting 3. ND True E_ν 4. Far / Near Ratio 5. Oscillations Probability 6. FD True Eν 7. FD True-to-Reco E_ν Weighting 8. Predicted FD Reco E_ν

- The extrapolation for ν_μ disappearance is divided into 4 bins in hadronic energy fraction called quartiles, each bin
- For ν_e appearance the ND ν_μ CC data and intrinsic beam ν_e background are extrapolated separately

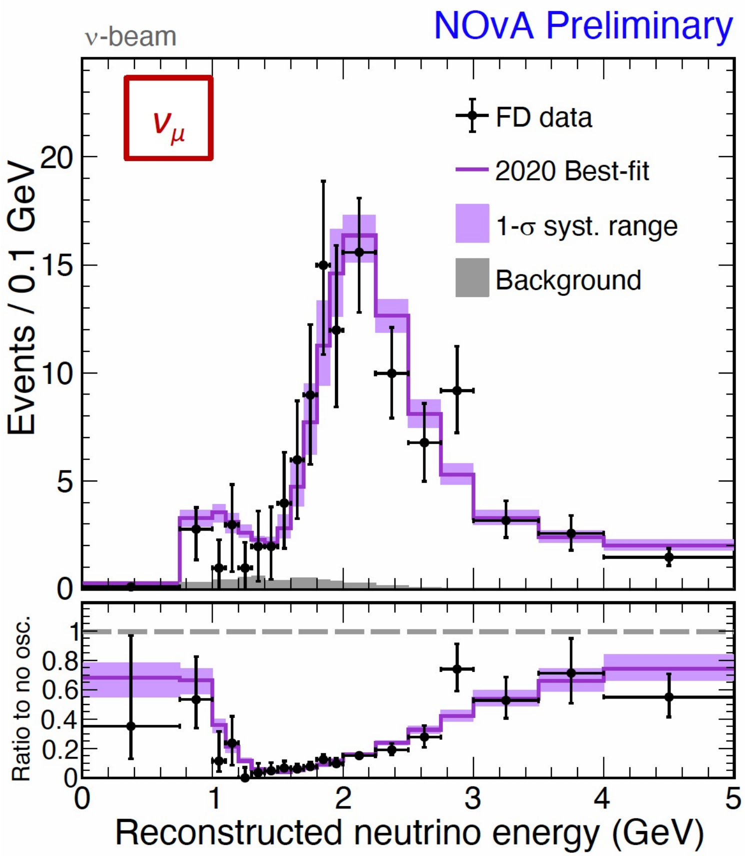
Energy reconstruction and Extrapolation

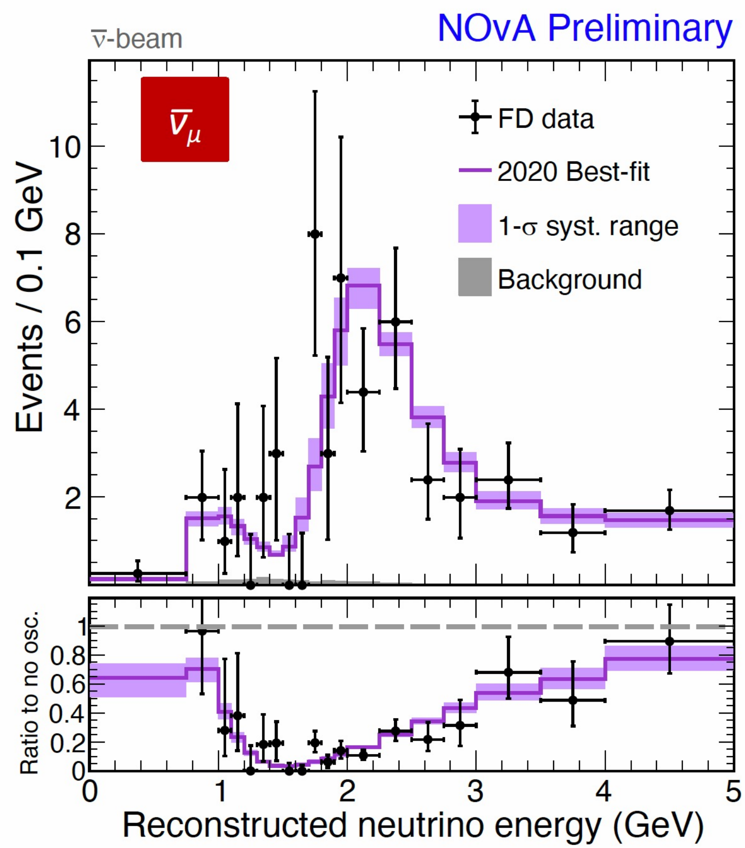


- Signal neutrino energy is the sum of muon/electron and hadronic energy.
- Observe data-MC differences in neutrino energy spectrum at the ND, extrapolate them to modify the FD MC prediction (significantly reduce systematics)
- Systematic uncertainties determined in ND also extrapolated to FD

ν_μ and $\bar{\nu}_\mu$ Data at Far Detector

- FD selection:
  - Additional Boosted Decision Tree (BDT) to reduce cosmic backgrounds





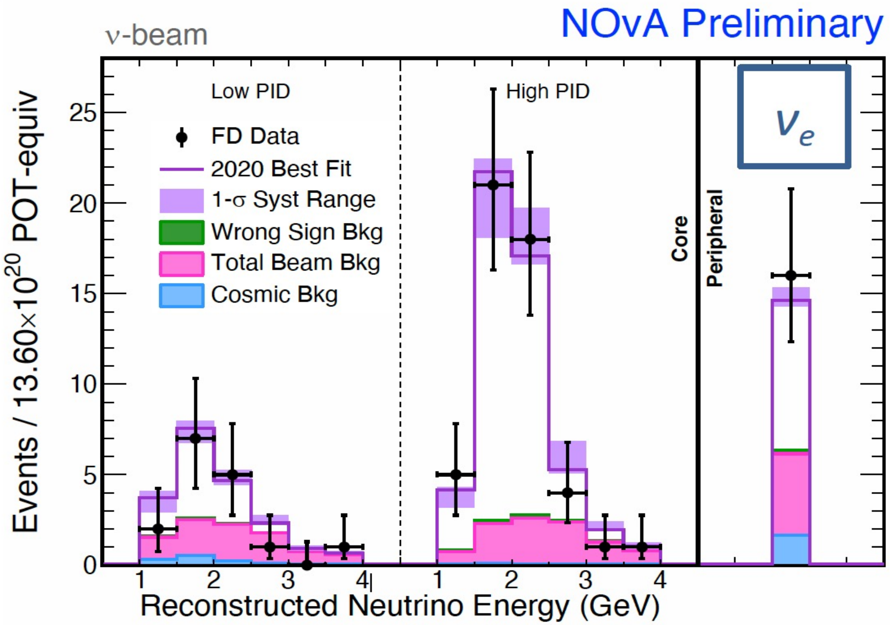
Neutrino beam:

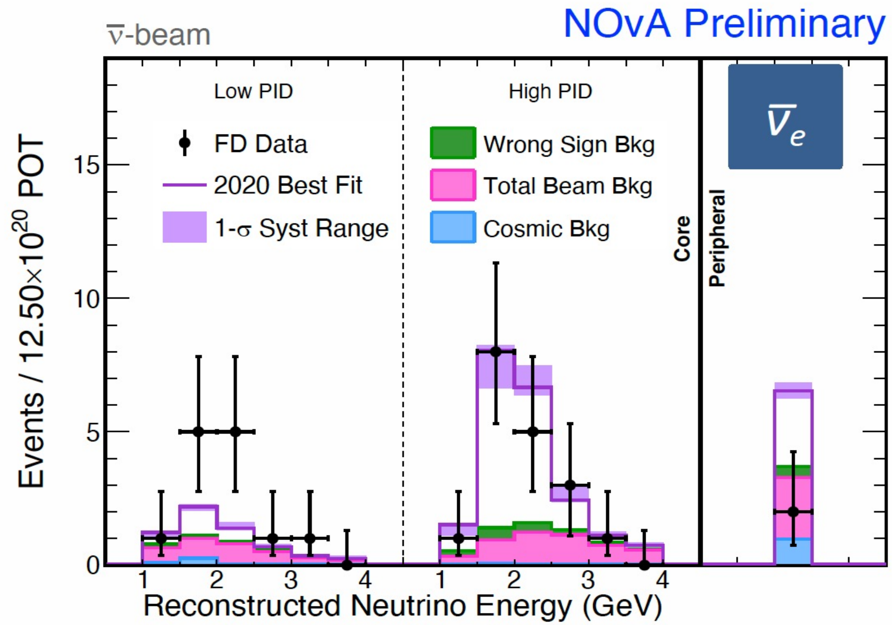
- Observe 211 events
- Total bkg prediction: 9.3 events

Anti-Neutrino beam:

- Observe 105 events
- Total bkg prediction: 2.8 events

ν_e and $\bar{\nu}_e$ Data at Far Detector





- ND data split into low and high PID ranges and extrapolate to FD
- FD selection: Add a region close to detector top with tighter cosmic ray cuts to count more signal events

Neutrino beam:

- Observe 82 ν_e like events
- Total bkg prediction: 26.8:1.0 wrong sign, 22.7 beam bkg, 3.1 cosmic

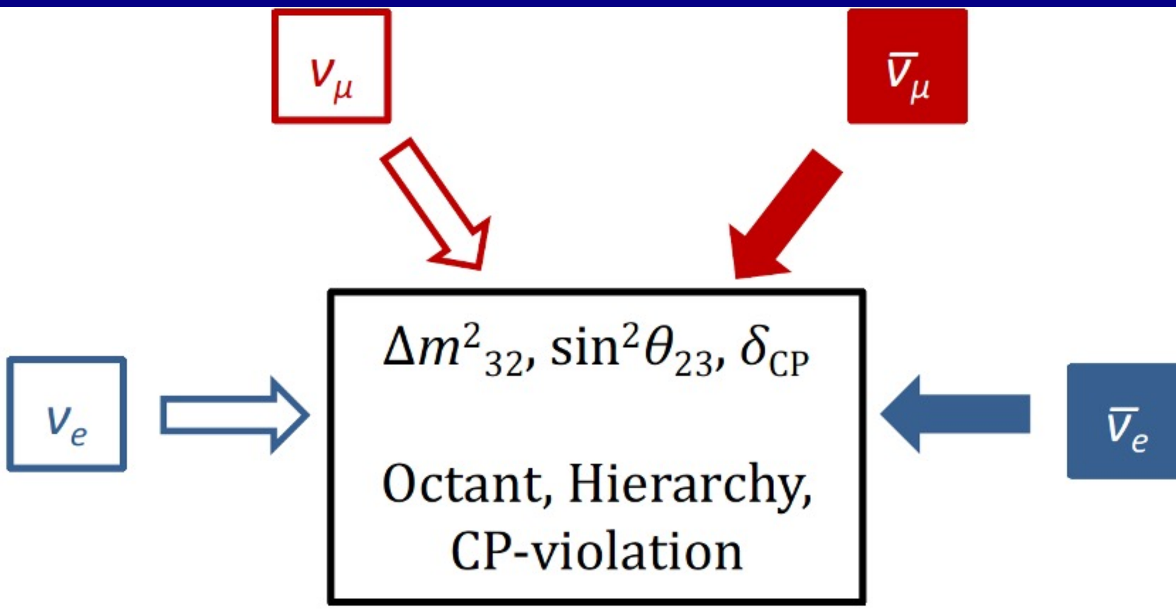
Anti-Neutrino beam:

- Observe 33 $\bar{\nu}_e$ like events
- Total bkg prediction: 14.0: 2.3 wrong sign, 10.2 beam bkg, 1.6 cosmic

>4 σ $\bar{\nu}_e$ appearance

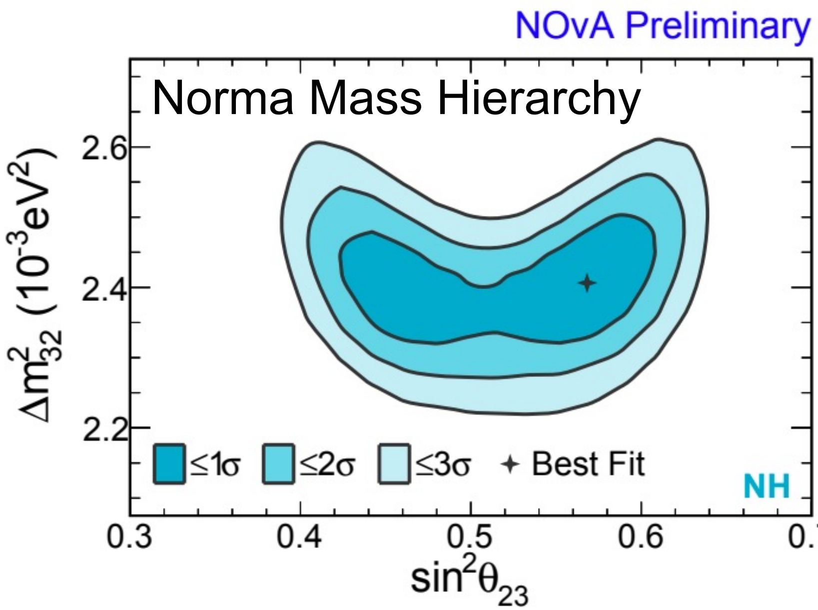
Extract oscillation parameters by fitting oscillation-weighted FD MC to FD data

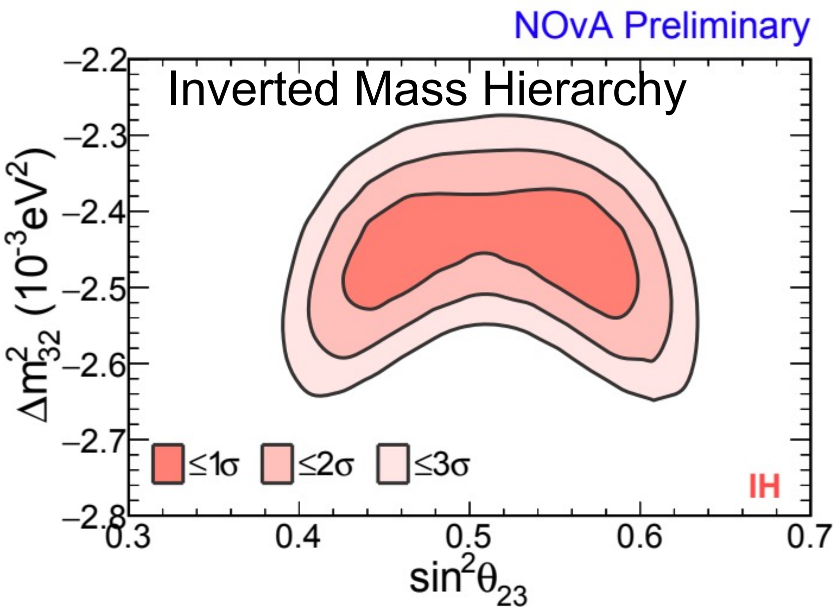
Oscillation parameter fit



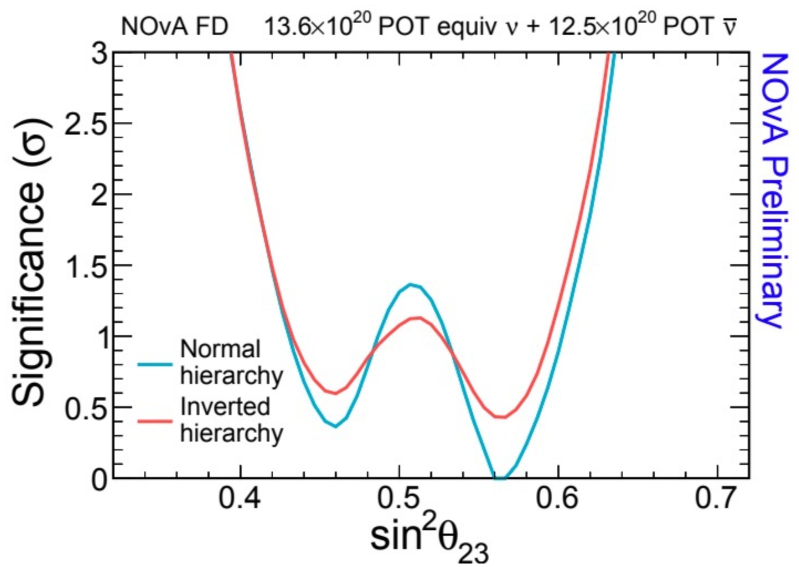
- All results come from a joint fit to neutrinos + antineutrinos, $\nu_e + \nu_\mu$, reactor-constrained $\sin^2 2\theta_{13} = 0.085 \pm 0.003$.
- We perform a frequentist analysis and use the Feldman-Cousins method to ensure proper coverage in all contours and intervals.
- We perform blind analyses, finalizing all analysis elements before looking at the FD data.

Joint Appearance and Disappearance

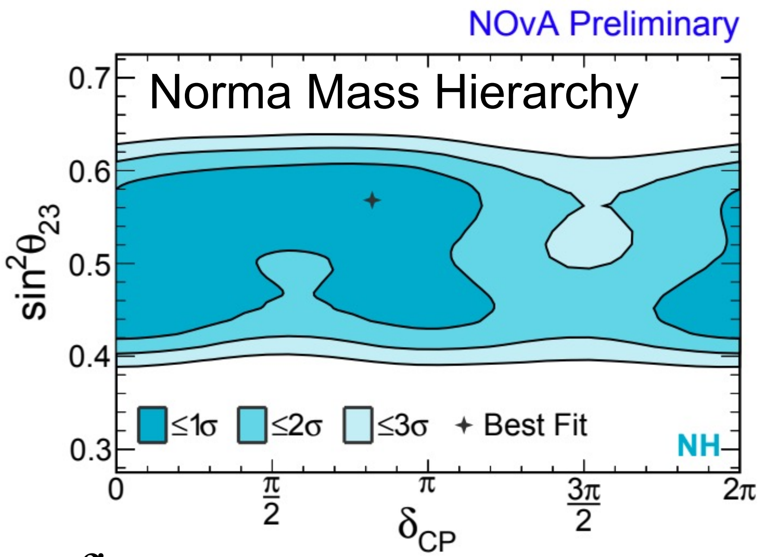


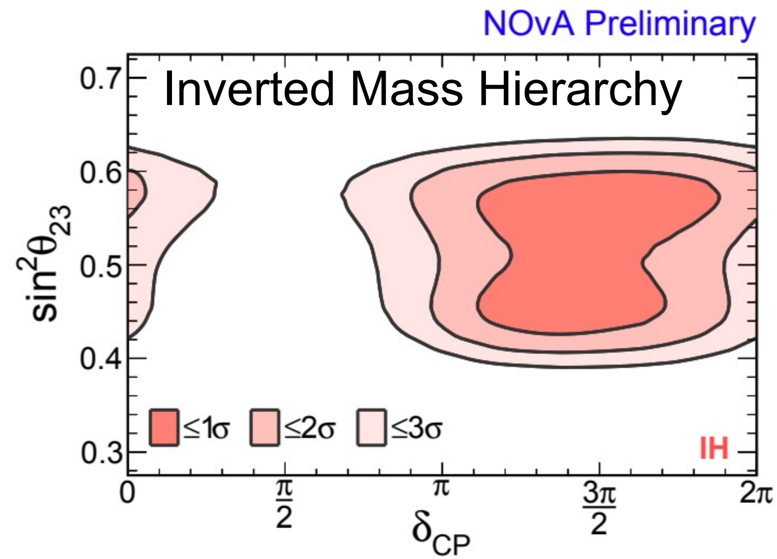


- Use frequentist analysis Feldman-Cousins method to infer oscillation parameters
- $\sin^2\theta_{13} = 0.085$+-0.005 from PDG avg. of reactor data
  - Best fit:
    - Normal Mass Hierarchy
    - $\sin^2\theta_{23} = 0.57+0.03-0.04$ (UO)
    - $\Delta m^2_{32} = (2.41+0.07-0.07)*10^{-3}\ eV^2$
- Disfavor maximal mixing ($\theta_{23}=45^o$) at 1.1 σ
- Disfavor lower octant ($\theta_{23}<45^o$) at 1.2 σ

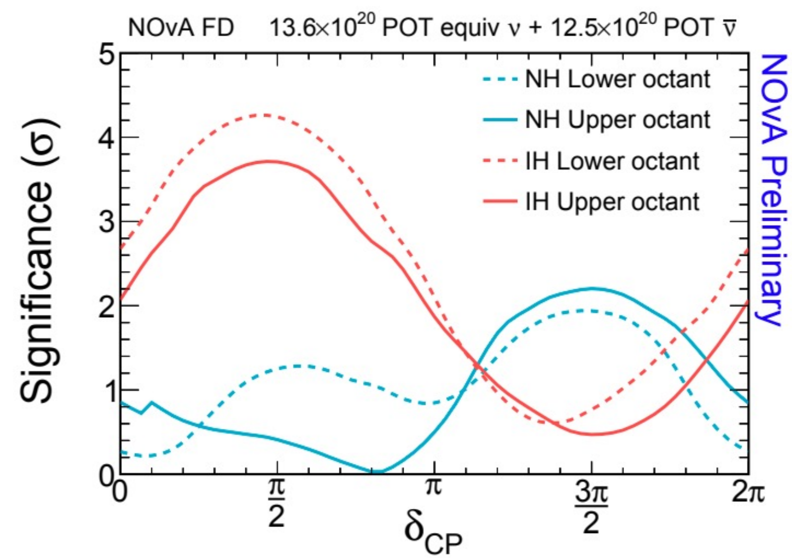


Joint Appearance and Disappearance



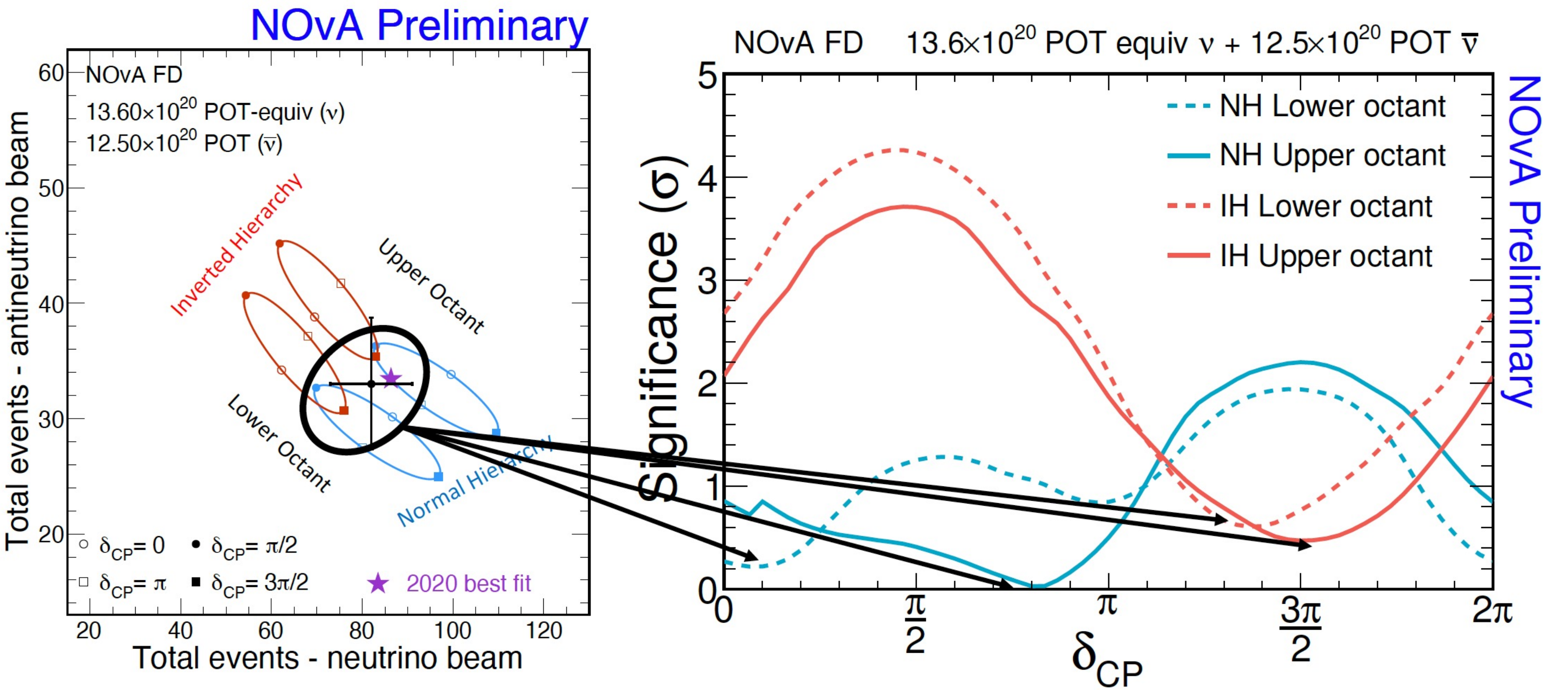


- Best fit:
  - Normal Mass Hierarchy ($m_3 > m_{1,2}$)
  - $\delta_{CP} = 0.82\ \pi$
  - $\sin^2\theta_{23} = 0.57{+}0.03{-}0.04$ (UO)
  - $\Delta m^2_{32} = (2.41{+}0.07{-}0.07)*10^{-3}\ \text{eV}^2$



- Exclude $\delta_{CP}=\pi/2$ in IH at > 3σ
- Disfavor (NH, $\delta_{CP}=3\pi/2$) at ~2σ
- Consistent with all δ_{CP} values in Norma Mass Ordering at < 1.1σ
- Disfavor Inverted Mass Ordering at 1.0σ

Joint Appearance and Disappearance



- We see no strong asymmetry between the appearance of ν_e and $\bar{\nu}_e$.
- Strongly disfavor "extreme" *combinations*, but can be consistent with any δ, hierarchy, or octant if probed individually.

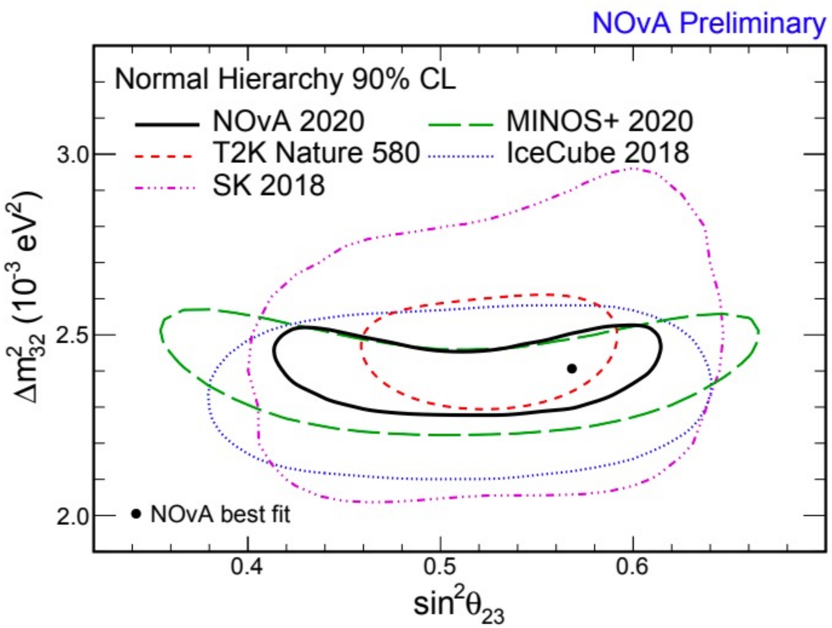
Exclude IH $\delta = \pi/2$ at $>3\sigma$

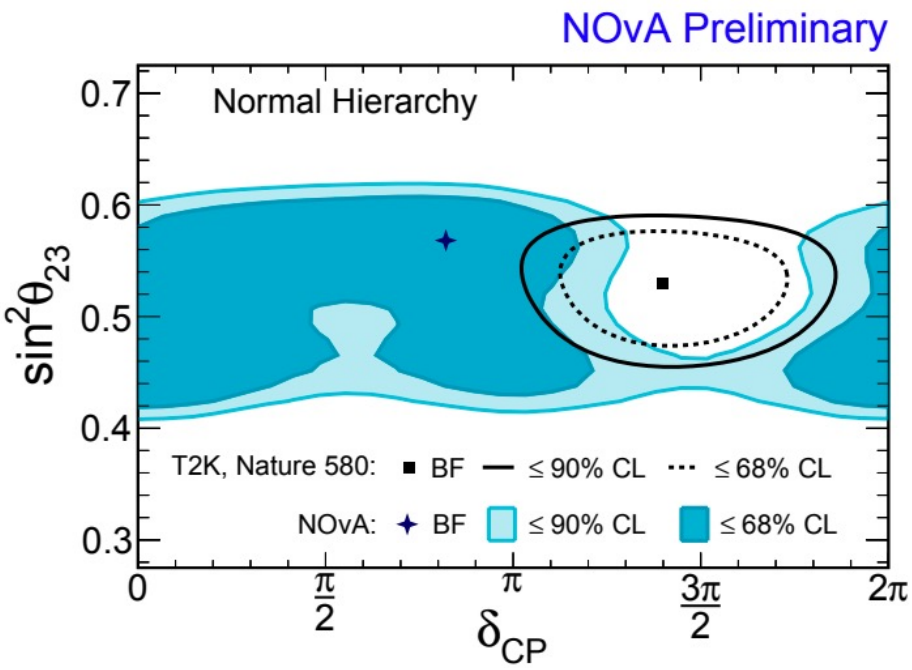
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer...	
Normal Hierarchy at	1.0σ
Upper Octant at	1.2σ
Non-maximal Mixing at	1.1σ

Compare with Other Experiments

NOvA's allowed 90% C.L. regions are compatible to other experiments

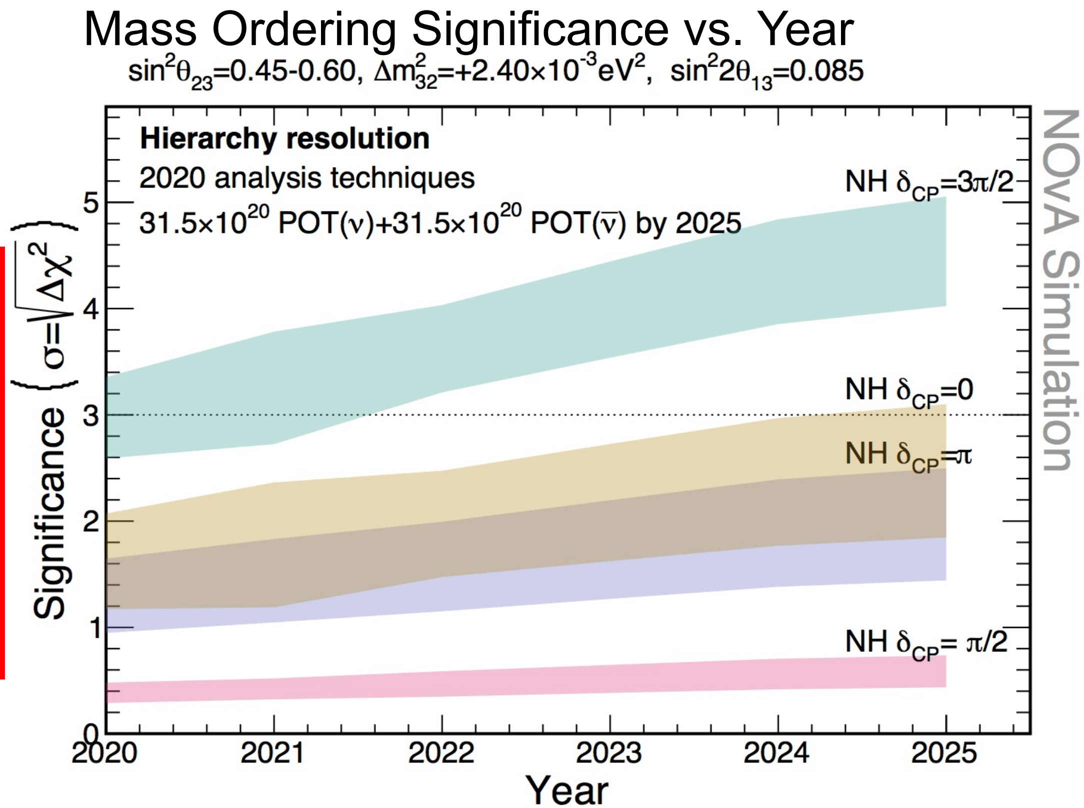




Agreement across many precision measurements about values of "atmospheric" parameters

- Apparent tension in allowed values of δ_{CP}
- NOvA & T2K are working on a fully self-consistent joint fit (including systs)

NOvA Results Summary

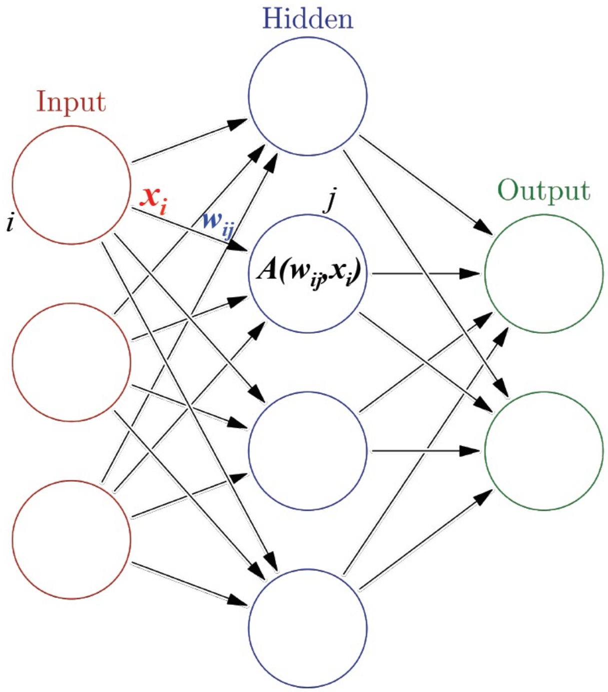


- NOvA new results
  - Precisely measured $\sin^2\theta_{23}$ = 0.57+0.03-0.04 and Δm_{23}^2 = (2.41+0.07-0.07)*10^{-3} eV^2
  - Exclude δ_{CP}=π/2 in IH at > 3σ
  - Disfavor (NH, δ_{CP}=3π/2) at ~2σ

- NOvA is running through 2025, test beam program and potential accelerator improvement to enhance ultimate reach
- Optimistically, if δ_{CP}=3π/2, 4-5 σ sensitivity to Mass Ordering by 2025
- >=3σ sensitivity to Mass Ordering for 30-50% of δ_{CP} values (depends on θ_{23} and true ordering)

Artificial Neural Network (ANN)

- Artificial Neural Network (ANN) provides a general framework for estimating non-linear functional mapping between a set of input variables $x(x_1, x_2, \ldots x_N)$ and a set of output variables without requiring a prior mathematical description of how the output formally depends on the inputs.
- All layers in a traditional ANN are fully connected, meaning that the inputs of the activation function in each node are the weighted sums of the outputs of all nodes in the previous layers.
- The weights and biases are determined by training ANN with large simulated data samples in which true outputs values are known (supervised learning).



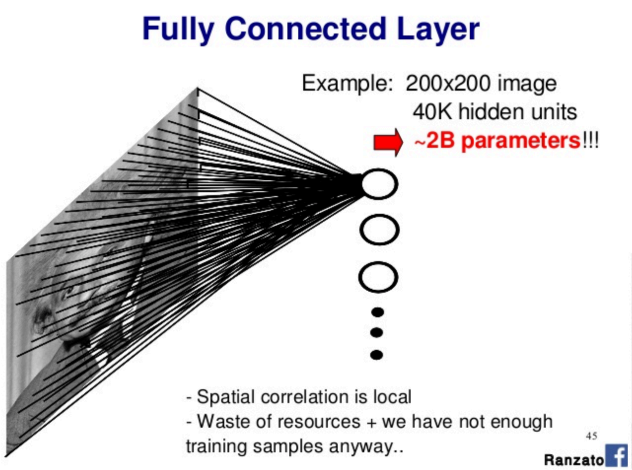
$$x_j^k = A(w_{0j}^k + \Sigma_{i=1}^{M_{k-1}} w_{ij}^k \cdot x_i^{k-1})$$

- Traditional ANNs can not use raw data (e.g., the pixels of a image) directly as inputs because of the computational complexity and over fitting problems, encountered when the number of layers increases.

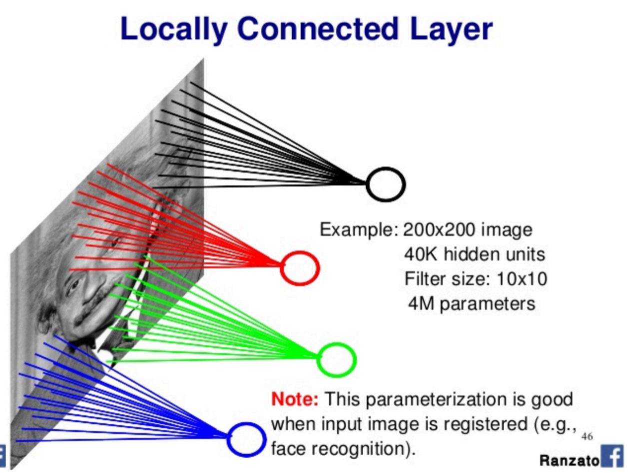
Convolutional Neural Network

- CNNs are convenient for taking images as inputs, as they use translationally invariant filters to look for features
- CNNs can be utilized in 2 ways:

1. Classification (Particle ID, Event ID): Output layer will have a sigmoid activation function, which outputs a number between 0 and 1, or softmax, it's generalization to an arbitrary number of classes
2. Regression (Particle Momentum/Energy, Event Energy, Vertex): Output layer has a linear activation function



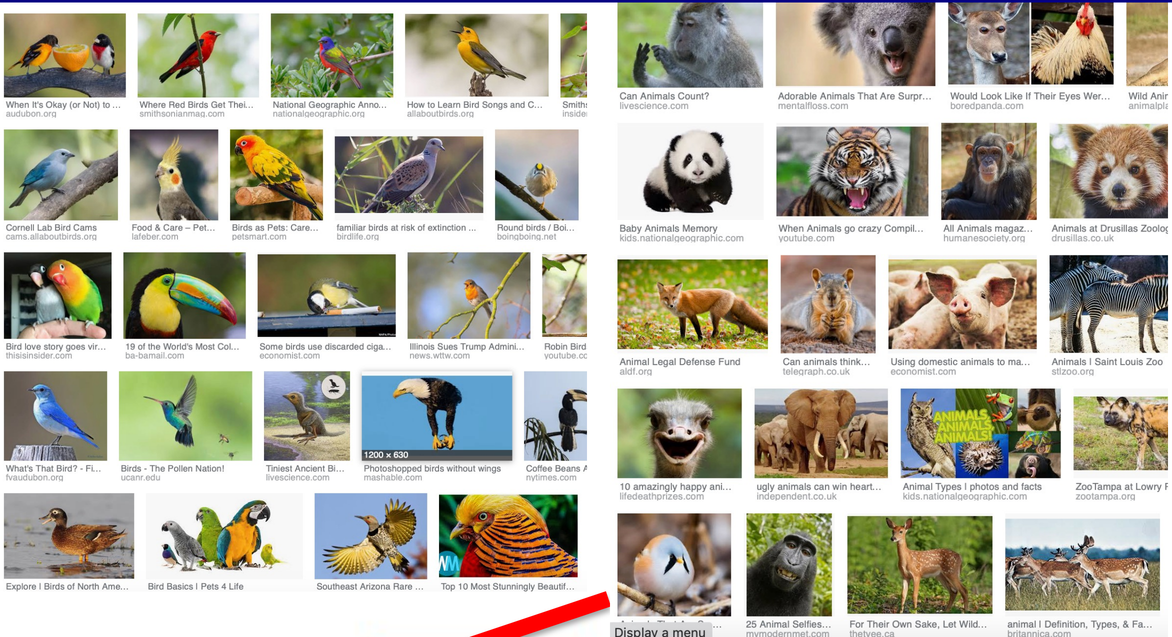
Traditional artificial neural network



Convolutional neural network

CNNs take raw pixel inputs, using all detector information with acceptable computing cost

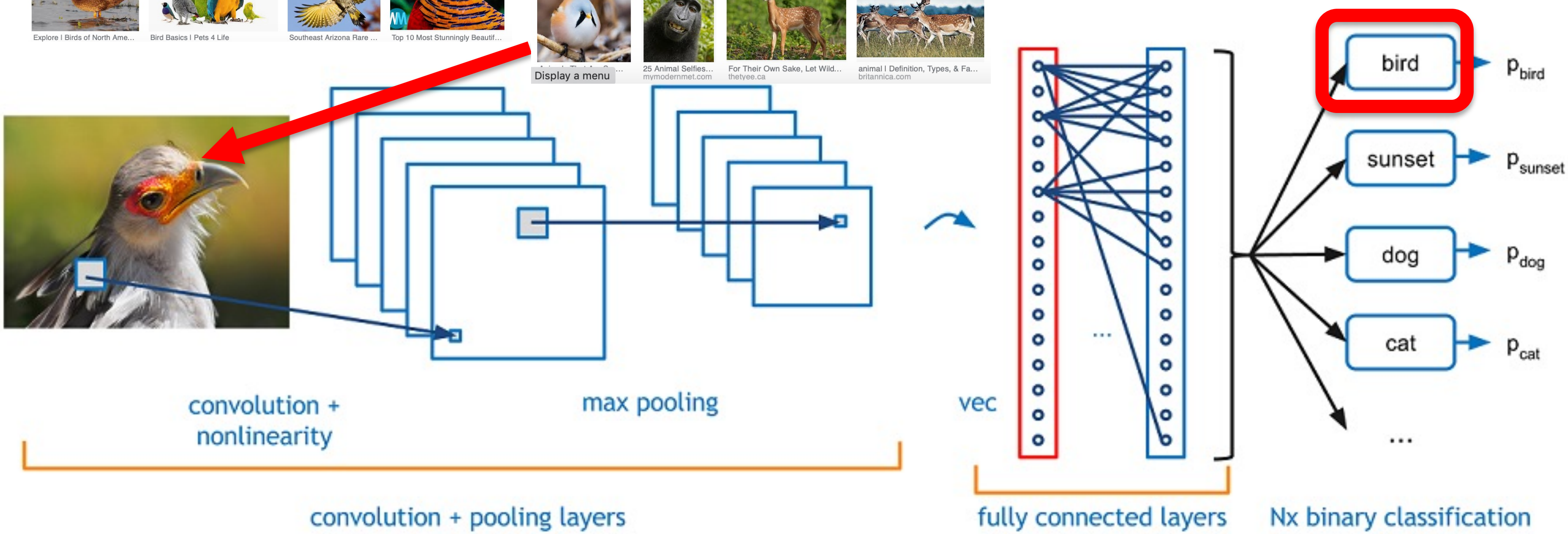
Convolutional Neural Network



1. Design neural network architecture

2. Provide many bird and non-bird examples to train CNN

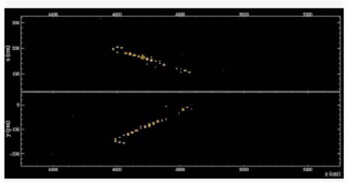
3. Parameters in neural network trained to give a score for birds

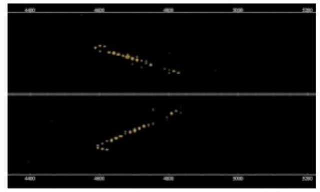


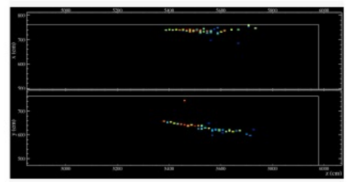
Convolutional Neural Network

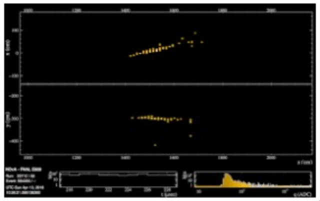
1. Design neural network architecture

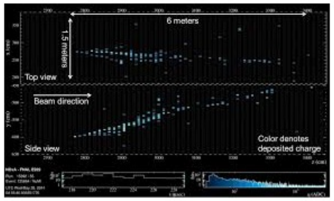
2. Provide many simulated neutrino examples to train neural network


electron neutrino data from NOvA E…
phys.org


electron neutrino data from NO…
phys.org

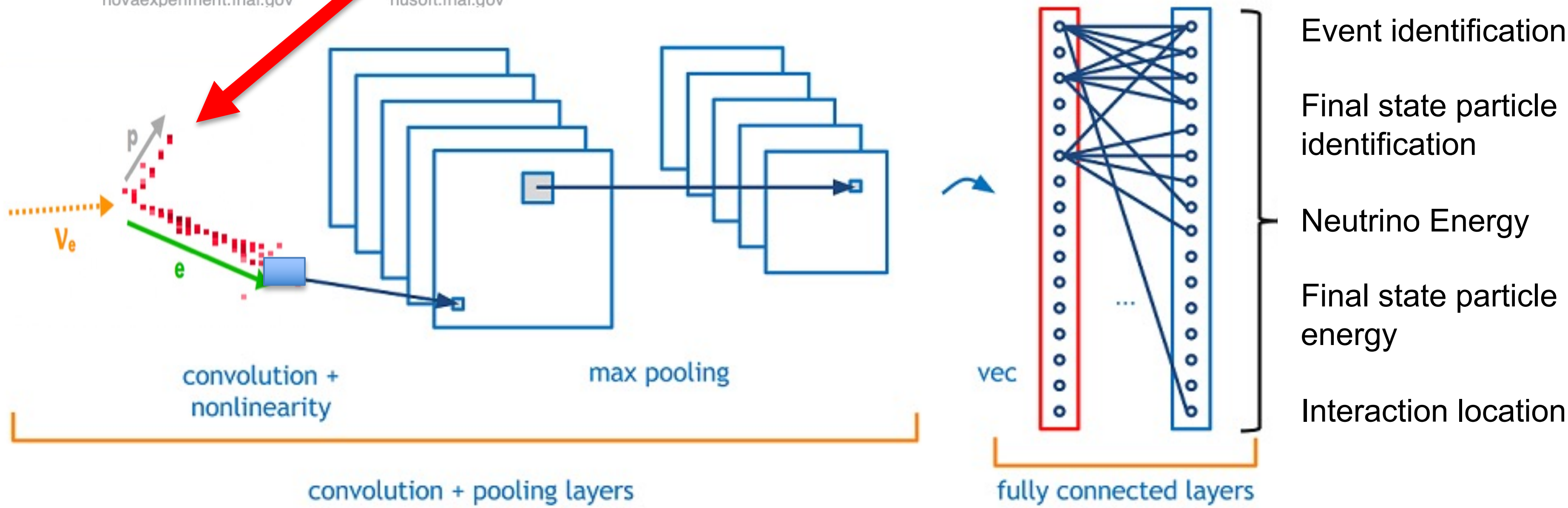

antineutrino oscillation
phys.org


NOvA
novaexperiment.fnal.gov



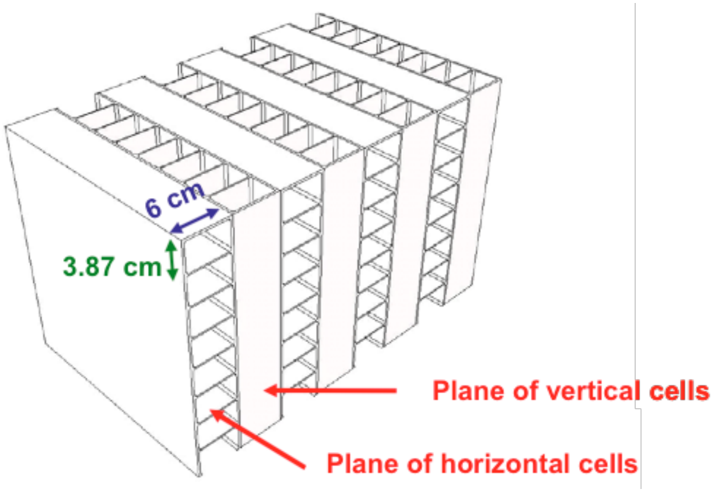
Finding Neutrinos in NOvA's Ev…
nusoft.fnal.gov

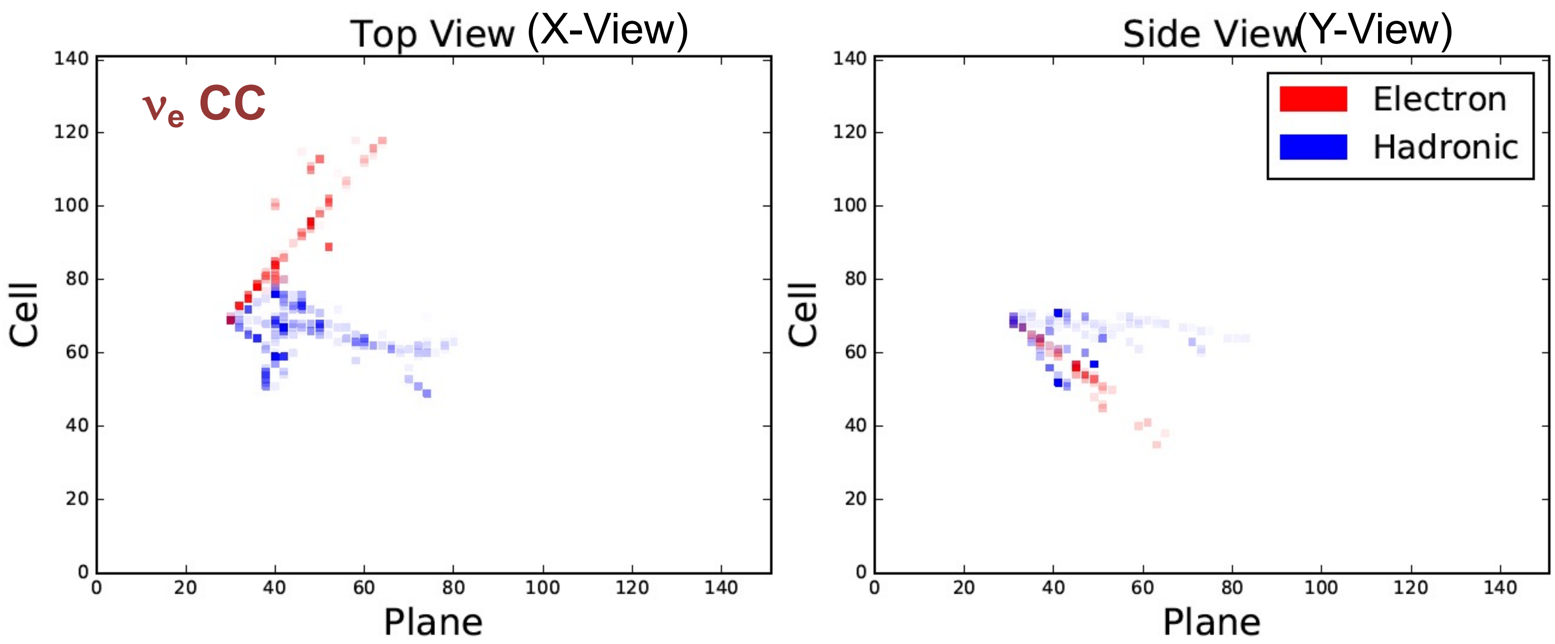
3. Parameters in neural network trained to give event identification, neutrino energy, interaction position etc.



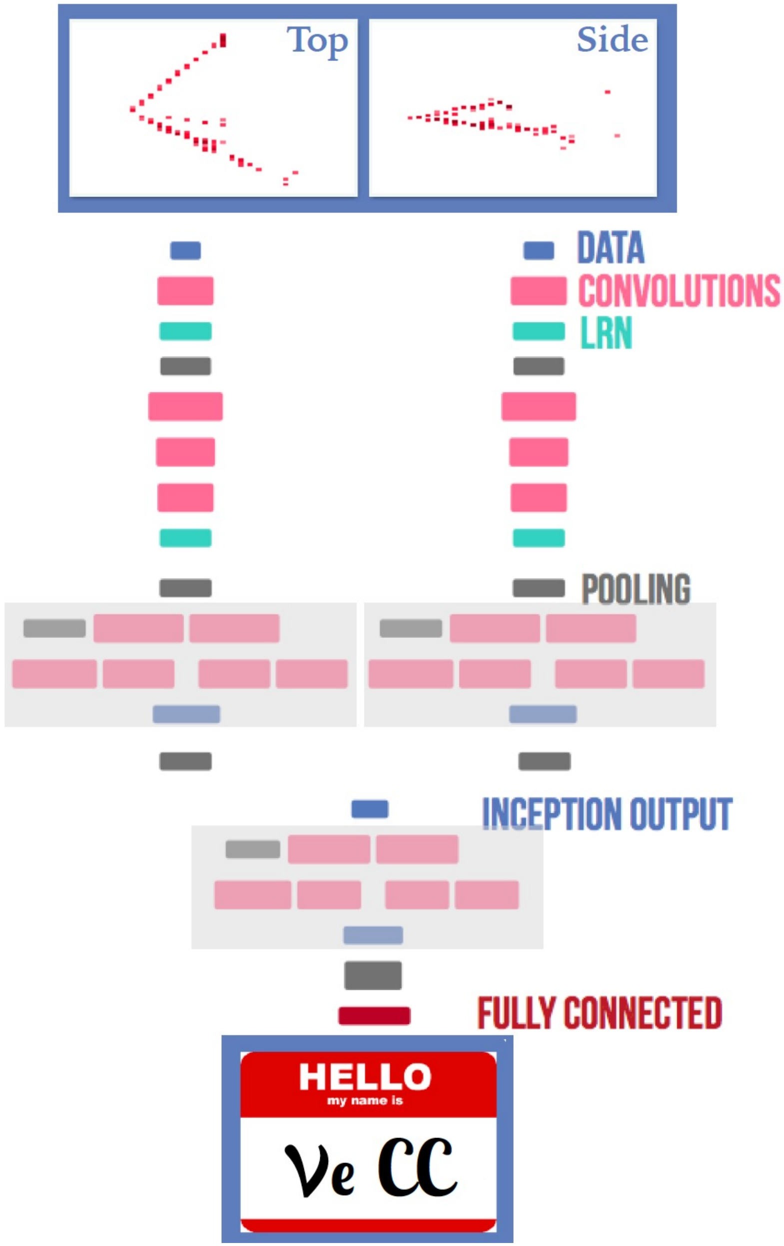
Input Images - NOvA

- NOvA detector cells arranged in planes, assembled in alternating X and Y directions
- Produce a pair of pixel maps (Cell Number vs. Plane Number) for the X and Y view of each interaction
- Input images are 151 cells by 141 planes





CNN based Event Classifier (CVN)



Classify neutrino events using two tower network, **Convolutional Visual Network**, based on googlenet.

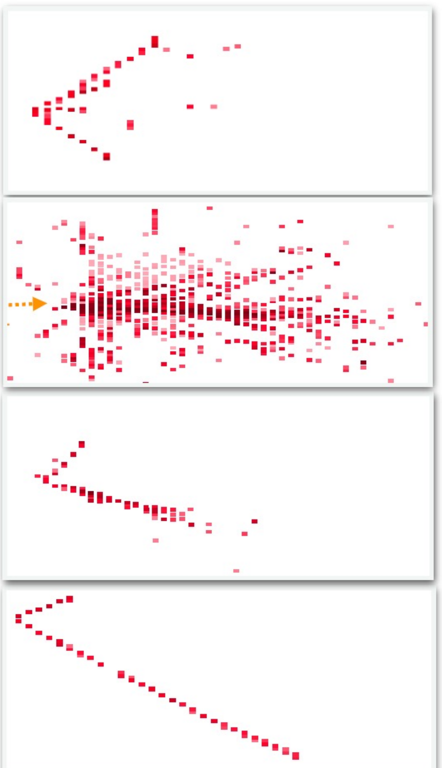
Each view of the event is examined separately for most of feature extraction.

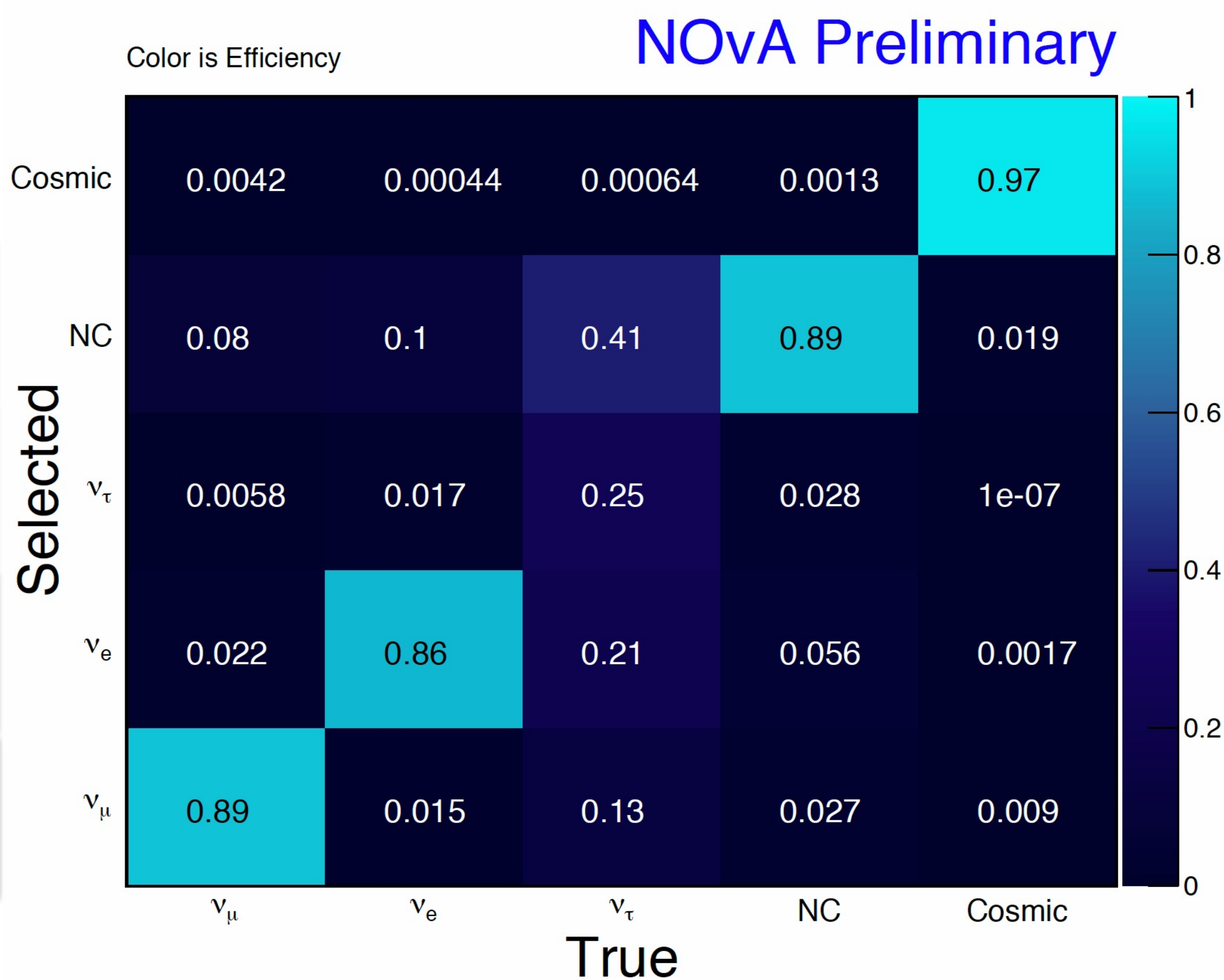
NOvA was the first experiment to apply CNNs to a HEP result in its 2016 analysis.

Yielded an effective **30%** increase in exposure.

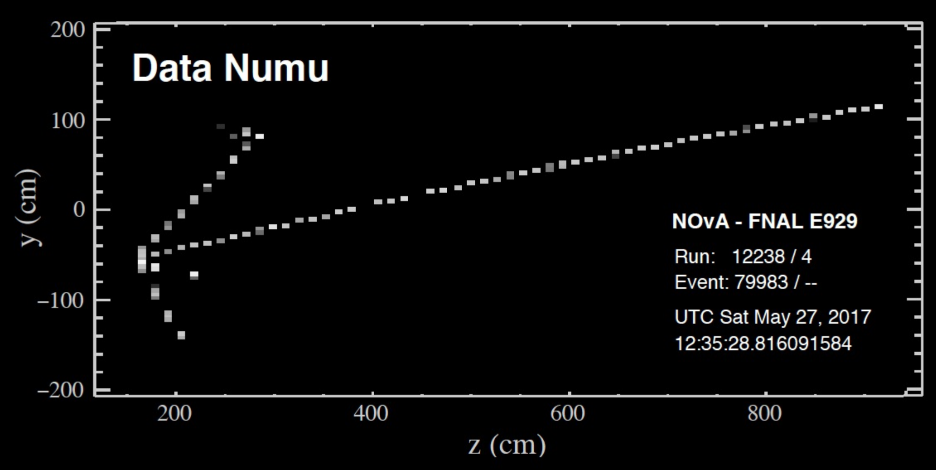
Aurisano et al., “A Convolutional Neural Network Neutrino Event Classifier”, JINST 11, P09001 (2016).

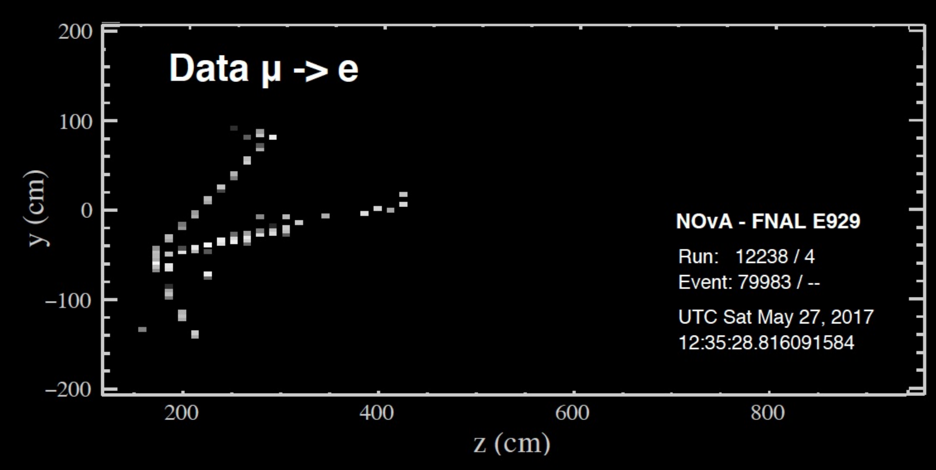
CNN based Event Classifier (CVN)

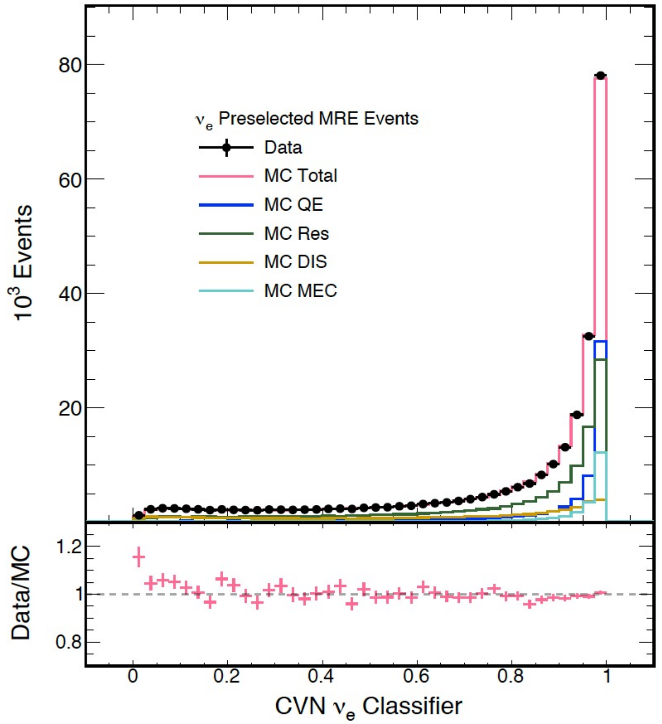




Example Data Check: MRE







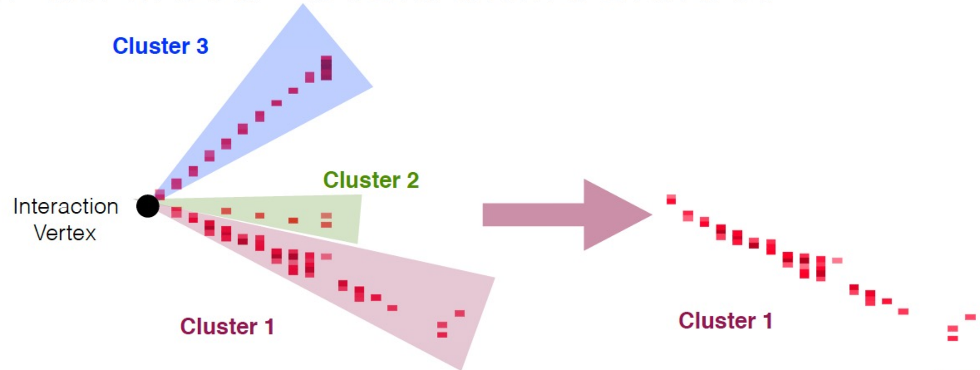
Muon Removed - Electron Added:

Select a muon neutrino interaction.

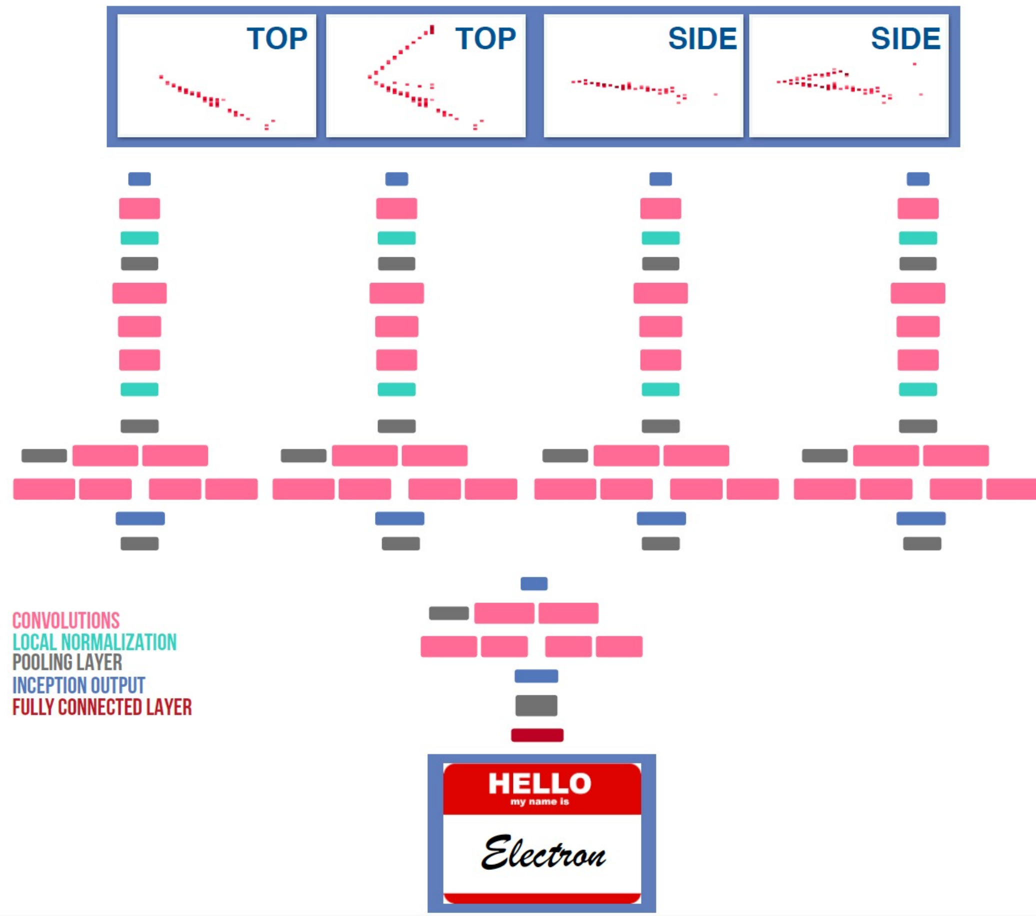
Remove the muon hits and replace with a simulated electron.

	Pre Selection	Full Selection	Efficiency
Data Events	486083	316009	0.6501
MC Events	511287	341119	0.6672

Particle Classification



Single particles are currently separated using geometric reconstruction methods.

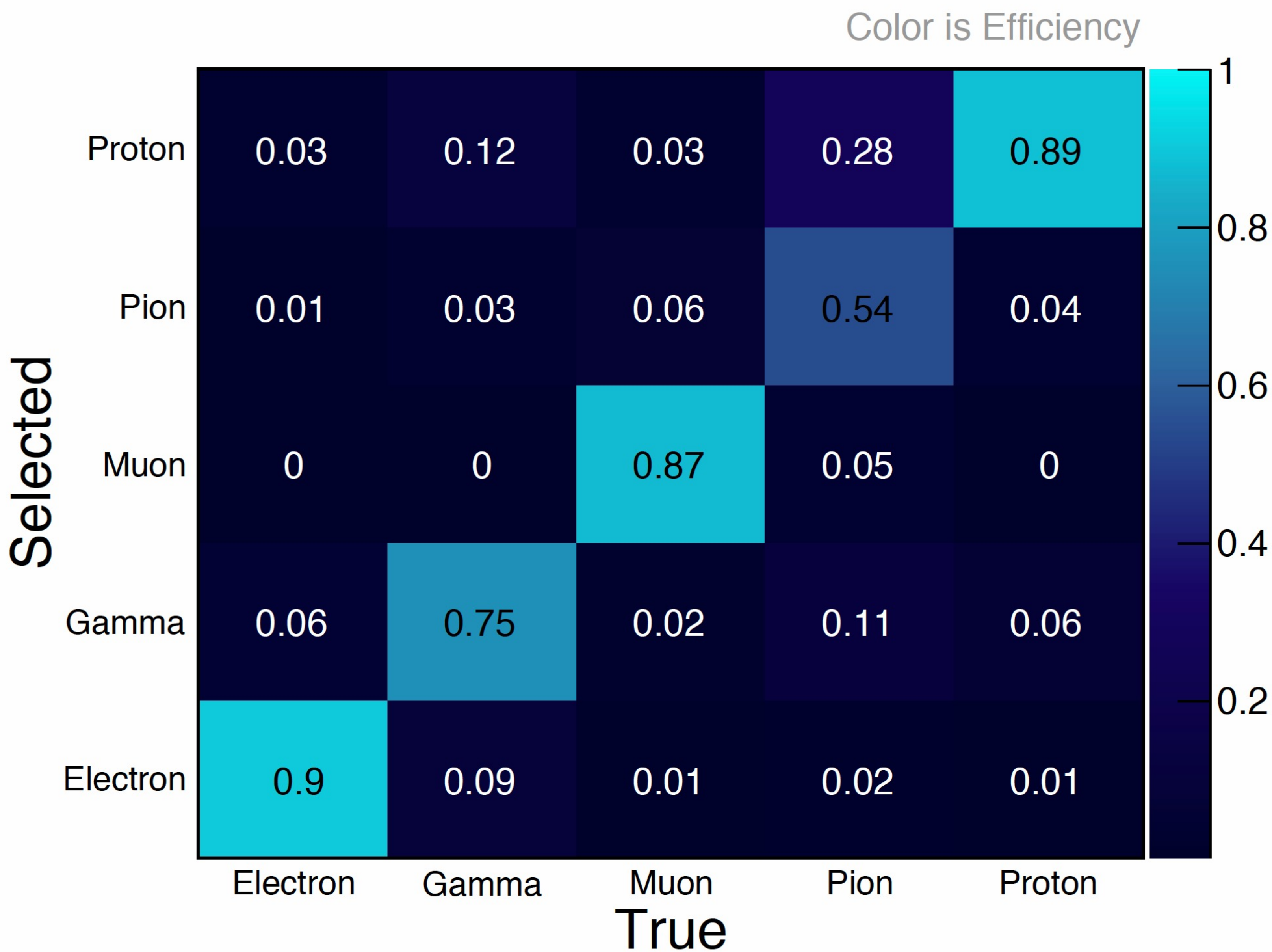


Classify particles using both views of the **particle** and both views of the entire **event.**

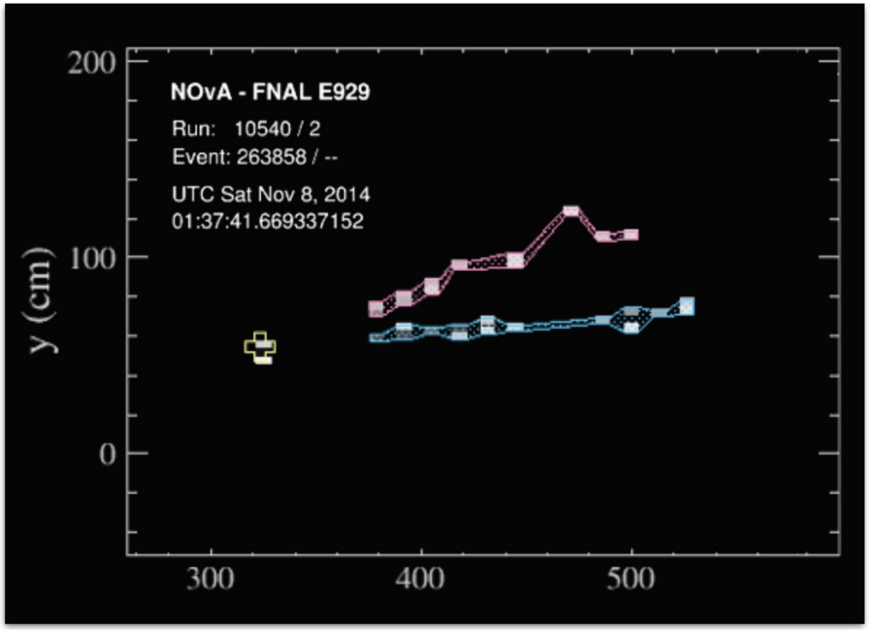
This shows the network **contextual information** about single particles.

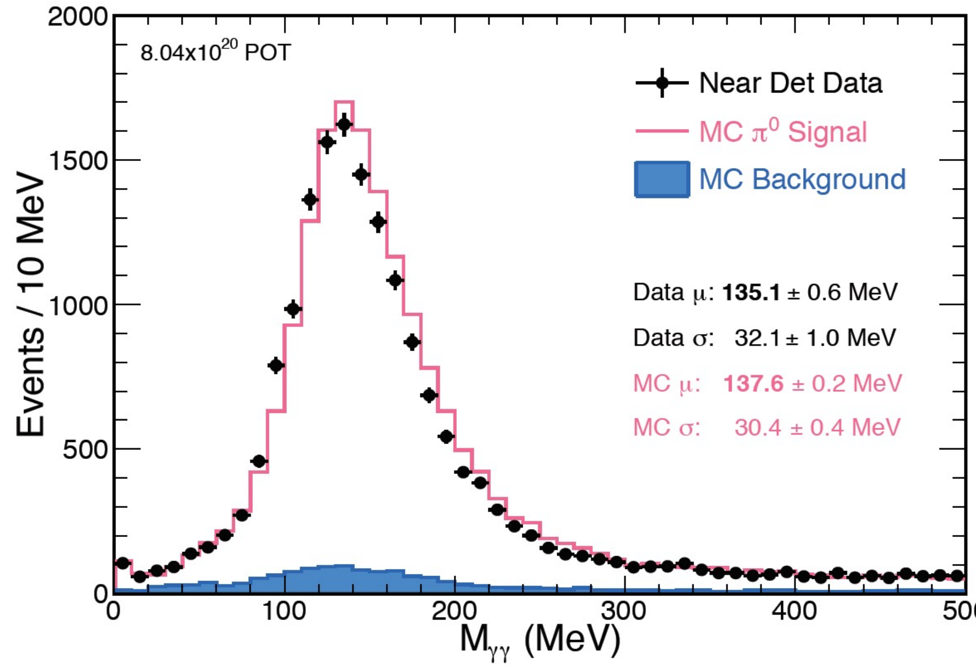
Phys.Rev.D 100 (2019) 7, 073005

Particle Classification



Example Data Check: π^0 Mass Peak





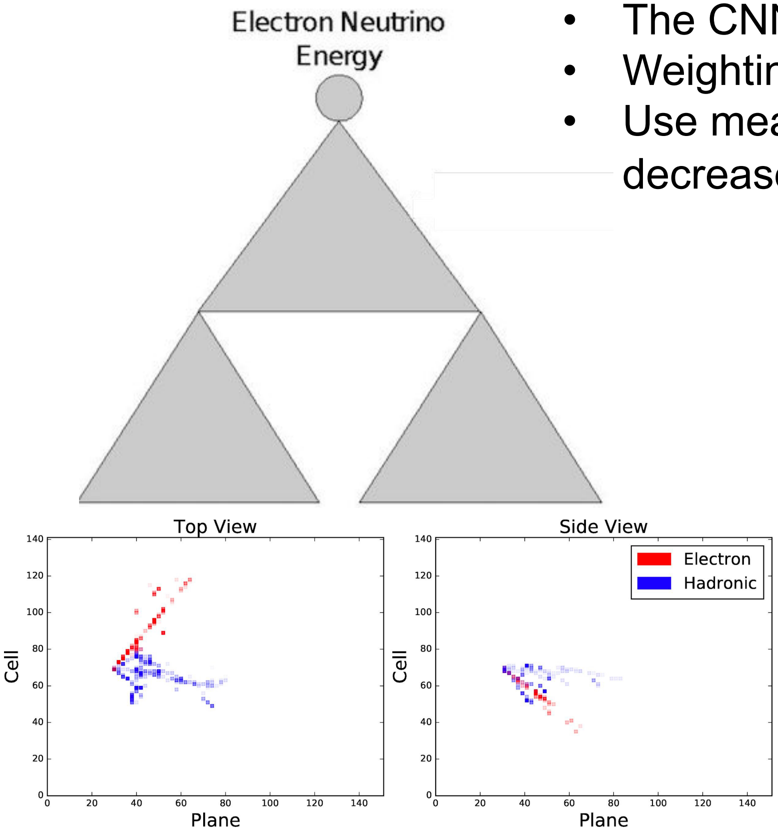
π^0 mass reconstructed using invariant mass of pairs of photons identified using the single particle classifier.

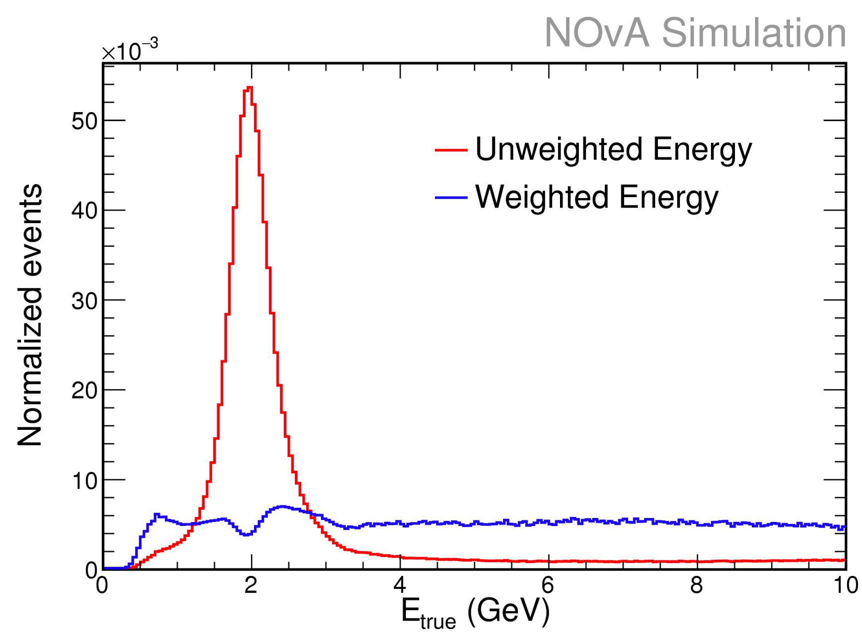
Shows a 60% reduction in backgrounds over previous techniques.

Regression CNNs for Energy Estimation

- Feed the two 80x100 image images of the event, one for each view, to the 2 inputs of the CNN which estimate event energy
- The CNN architecture used is an adapted ResNet
- Weighting scheme so the loss function sees a flat distribution
- Use mean absolute percentage error instead of square of errors to decrease the effects of outliers

$$L(\mathbf{W}, \{\mathbf{x}_i, y_i\}_{i=1}^{n}) = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{f_{\mathbf{W}}(\mathbf{x}_i) - y_i}{y_i}\right|$$

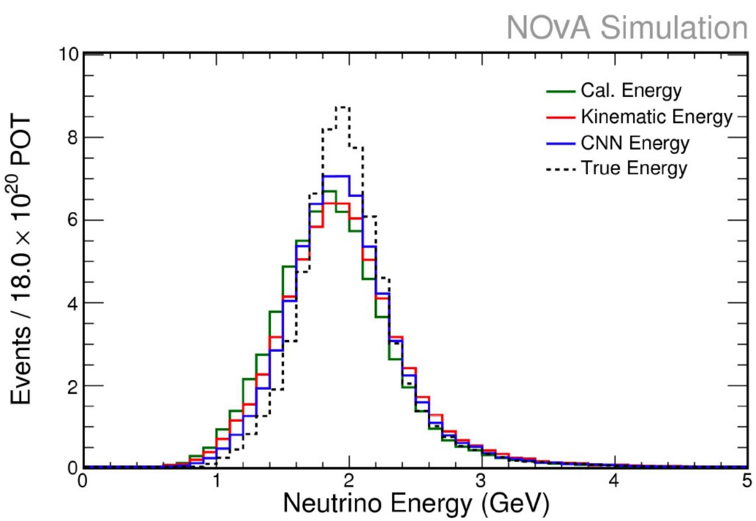


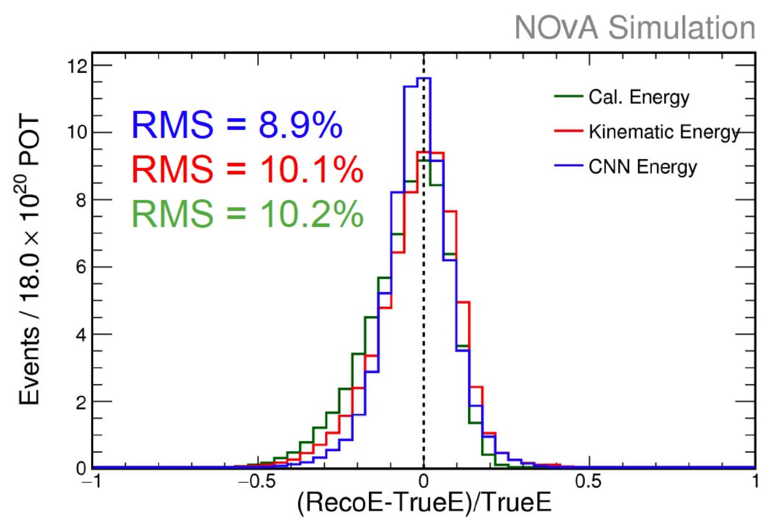


Phys. Rev. D **99**, no. 1, 012011 (2019)
doi:10.1103/PhysRevD.99.012011

ν_e Energy Performance

- Energy regression results for ν_e CC results are shown here
- Calorimetric method is based on adding up calorimetric energy per cell and applying an overall factor
- The kinematic method is based on a fit using electromagnetic and hadronic clustering:
- $E(\nu_e) = A\,E_{EM} + B\,E_{hadron} + C\,E_{EM}^{2} + D\,E_{hadron}^{2}$



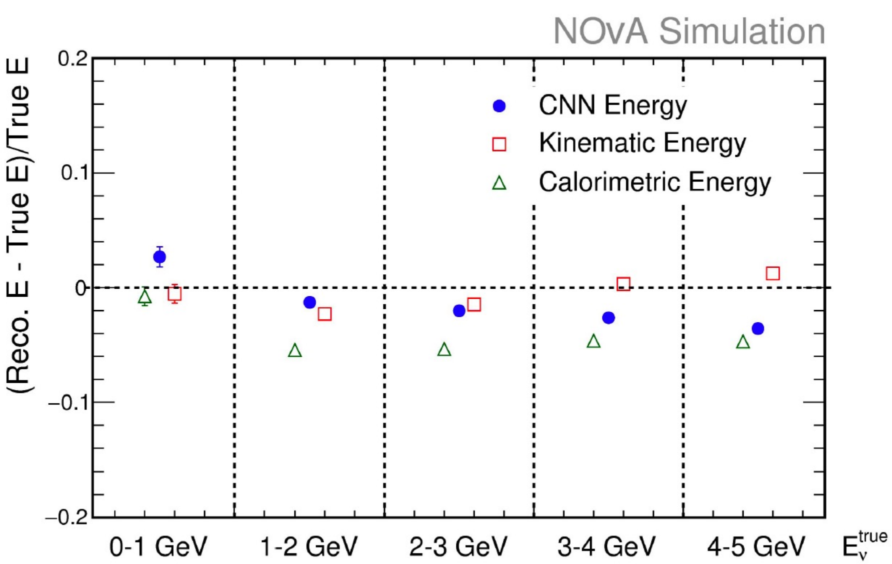


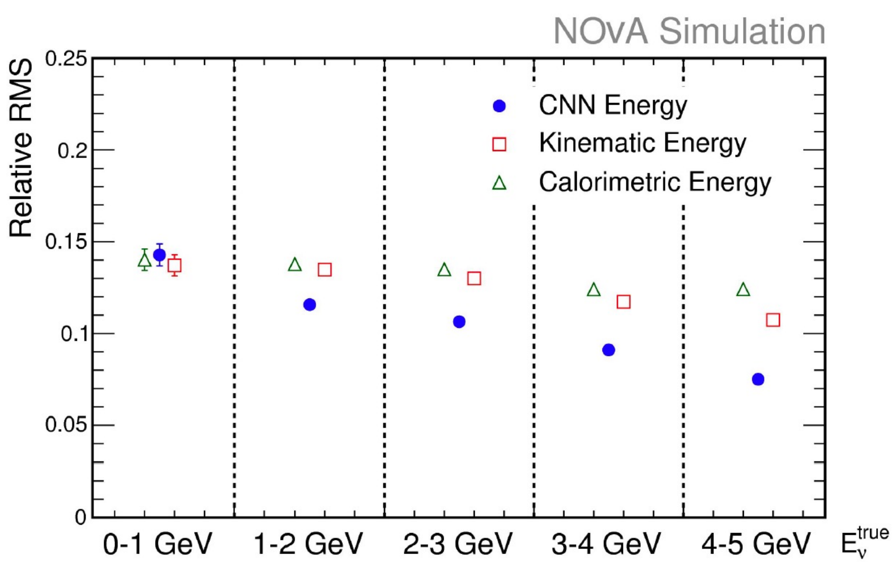
6

Also trained for electron energy, hadronic energy, ν_μ Energy, etc

ν_e Energy Performance

- The CNN resolution keeps the edge over calorimetric and kinematic based energy estimators from 1 GeV and up

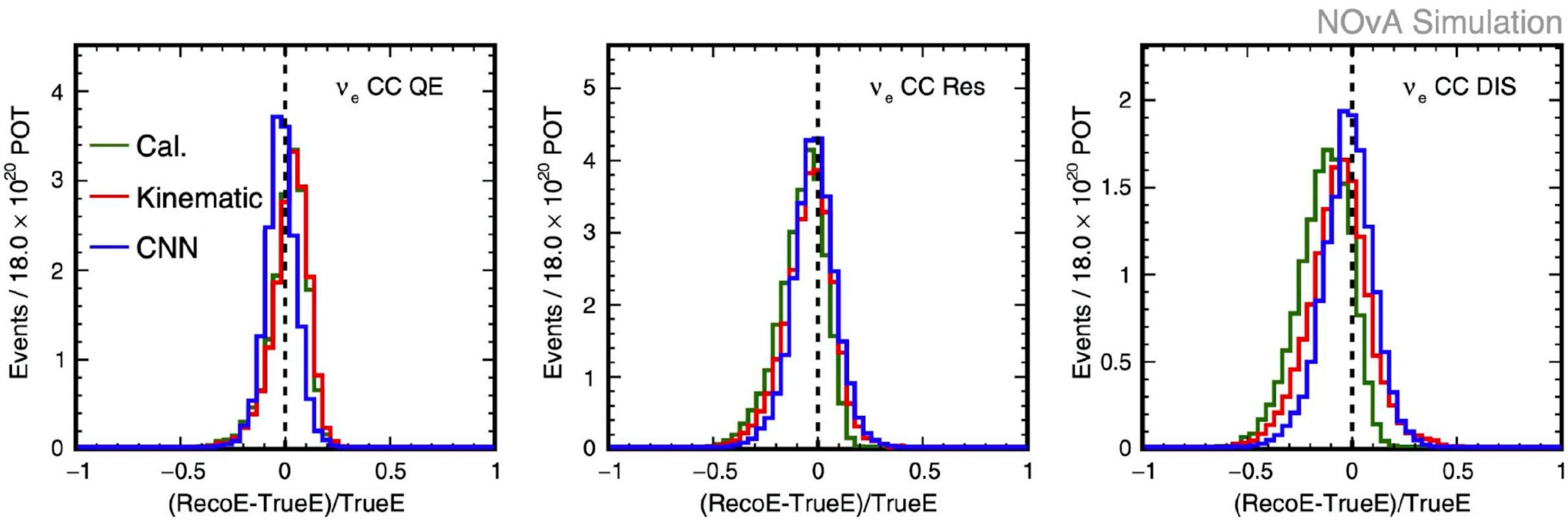




7

ν_e Energy Performance

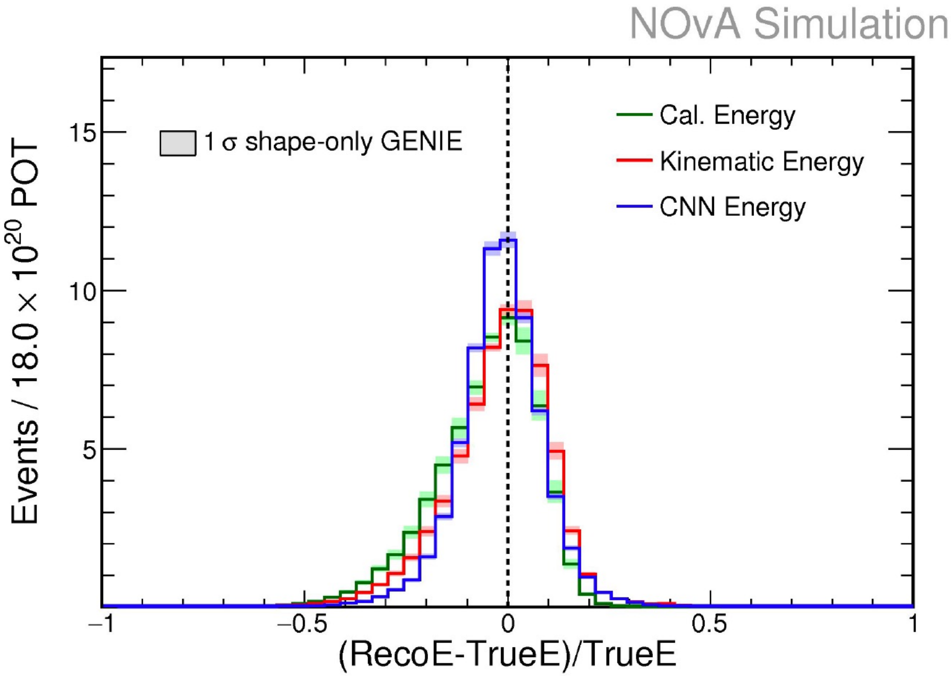
- CNN based method shows good stability over different interaction types
- This shows robustness a CNN model can provide with a large degrees of freedom



8

ν_e Systematics

- To quantify systematic uncertainties arising from simulation, we vary cross section uncertainties
- CNN event energy estimator is also very robust to cross section systematics, as well as the better performance



9

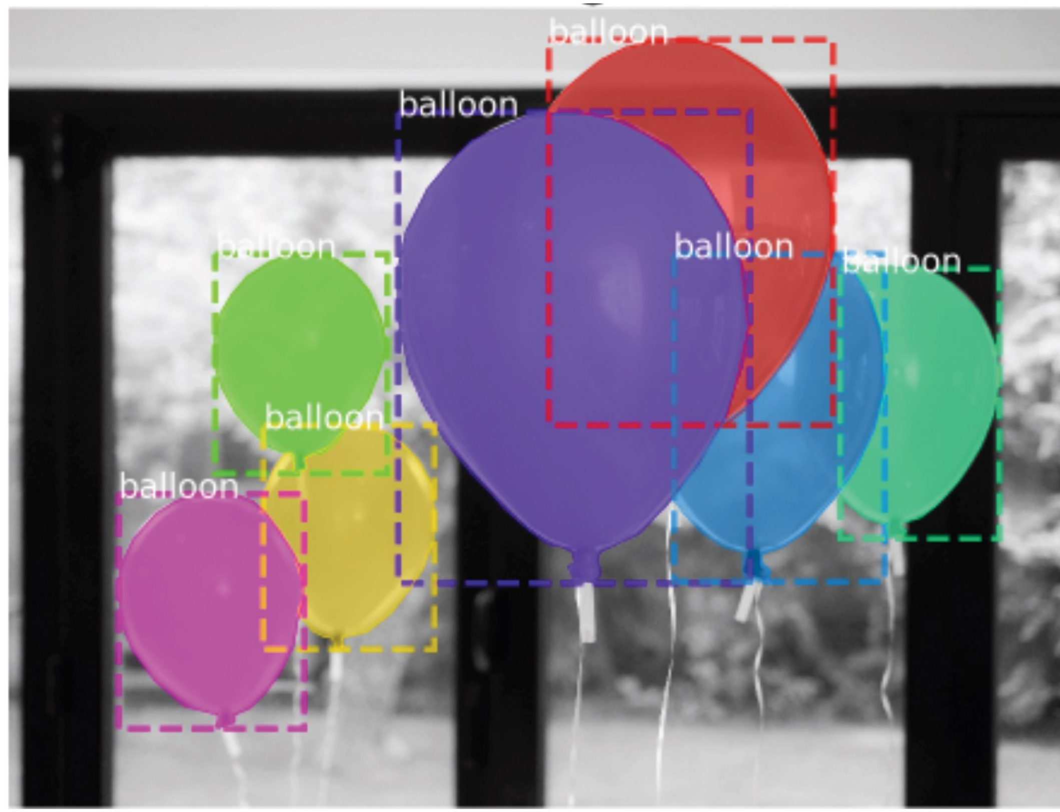
Full Event Reconstruction

Cluster and **classify** objects simultaneously using **instance aware semantic segmentation**.

Use machine learning to reconstruct an event **hit by hit**.

Three outputs:

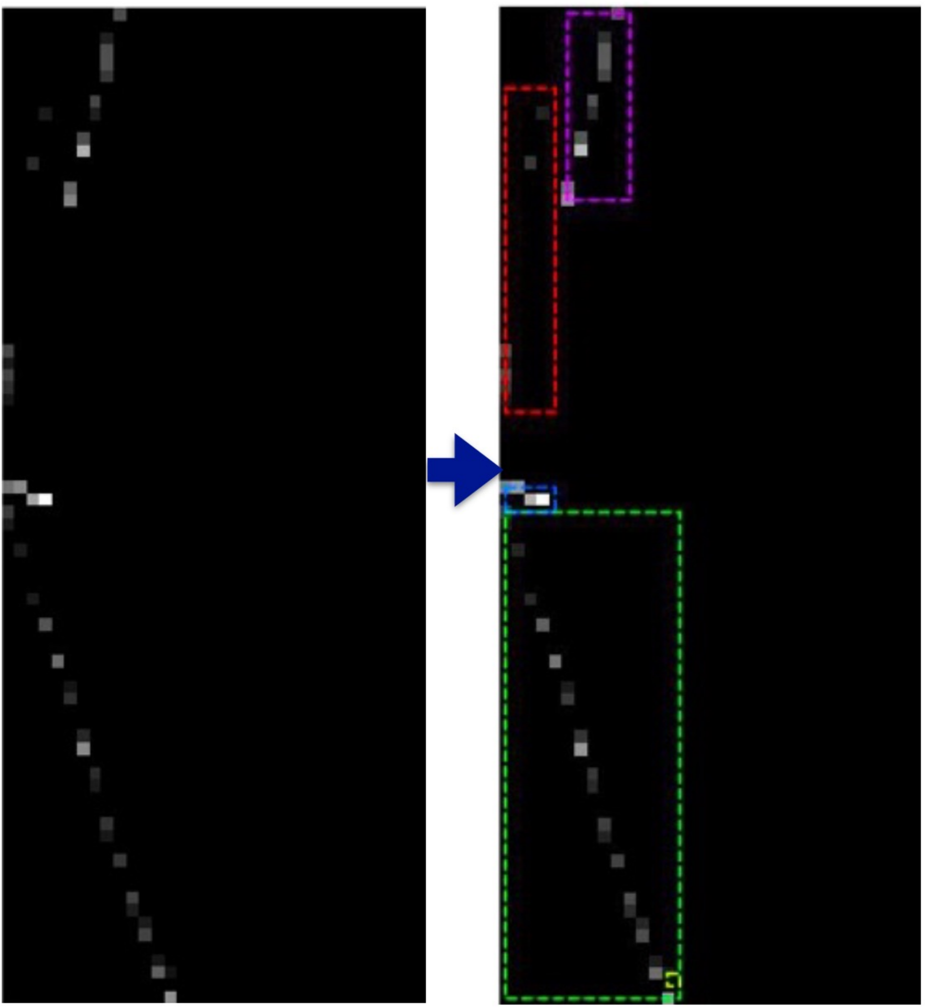
1. **Bounds**
2. **ID Score**
3. **Clusters**



Using an implementation of Mask R-CNN:
K. He, G. Gkioxari, P. Dollar, and R. Girshick. Mask R-CNN. arXiv:1703.06870, 2017.

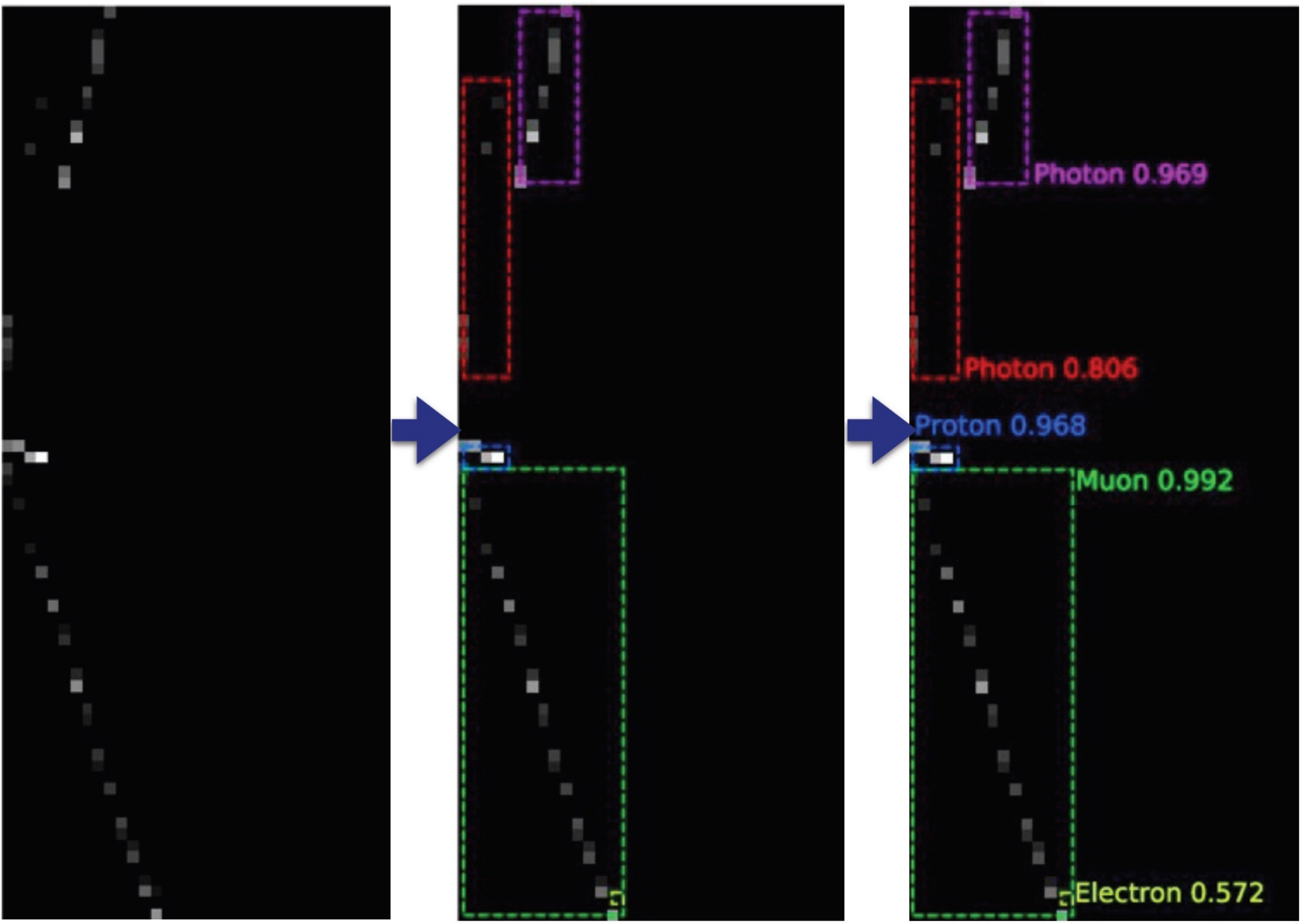
Full Event Reconstruction

Bounds - Look for individual particles within the event and construct bounding boxes containing each.



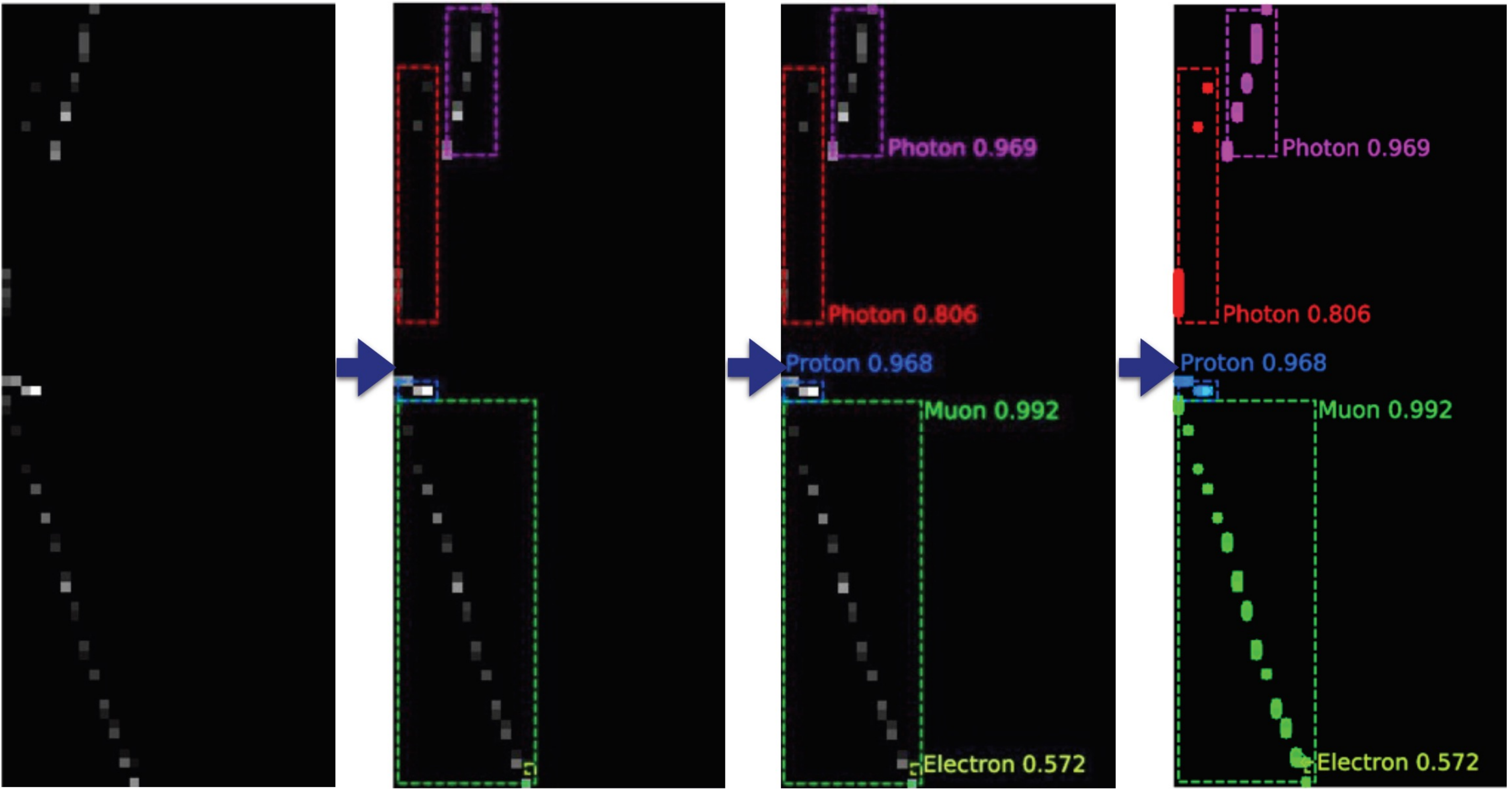
Full Event Reconstruction

ID Score - Use a softmax function to classify the particle contained within each box.

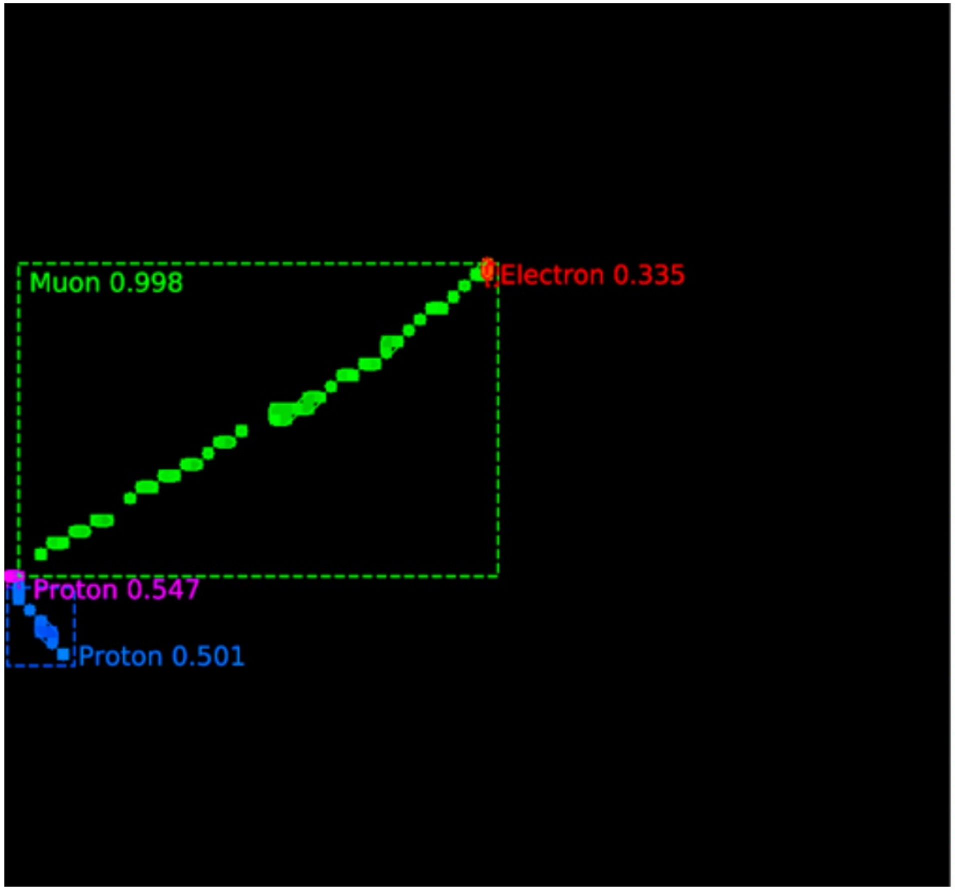


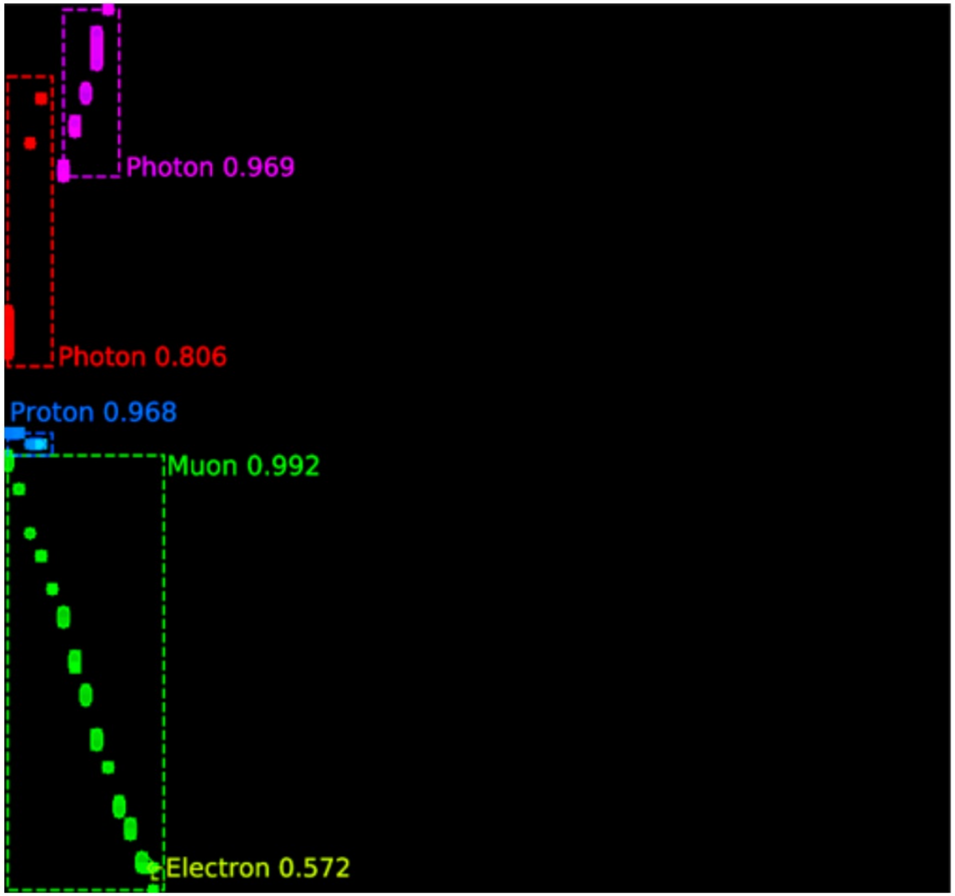
Full Event Reconstruction

Clusters - Group together hits within each box to make clusters for each particle.



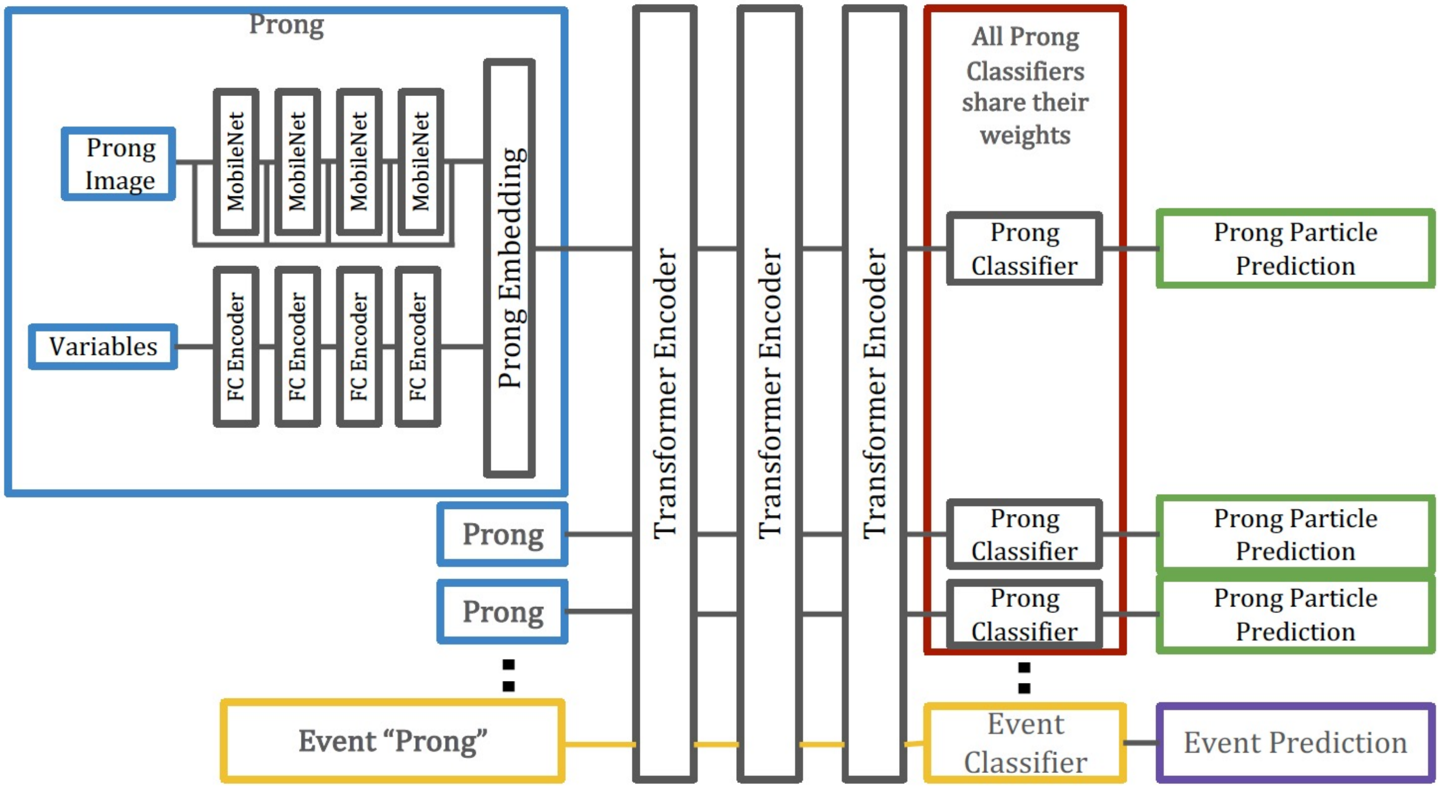
Full Event Reconstruction



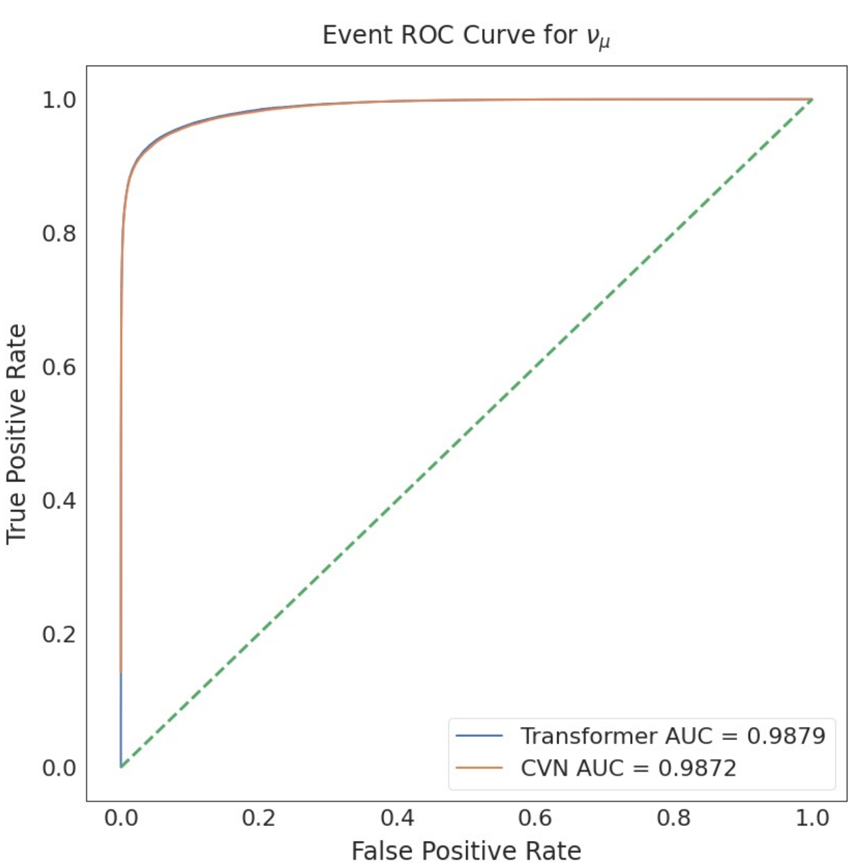


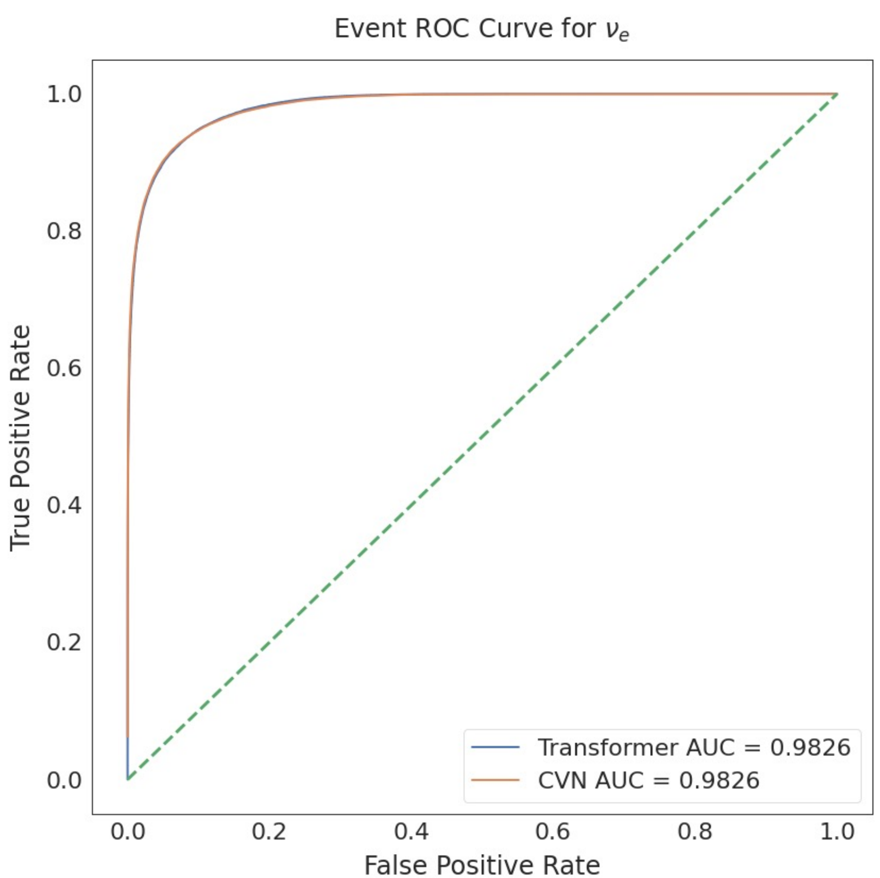
Transformer

- Recently developed for Natural Language Processing in CS
- Deals with variable number of inputs to combine particle level information
- Ideal to combine kinematics/ID of final state particles, make each step in ML/AI based reconstruction checkable and explainable



Comparing Networks





A receiver operating characteristic (ROC) curve shows the network performance for one event class vs all others. The transformer's ROC curves for event predictions are nearly identical to those of NOvA's CNN.

Oscillation parameter fit: Confidence Interval

- Typically, using Likelihood Ratio Test (LRT) to estimate confidence interval

$$\Delta\chi^2 = -2\log\frac{L(\theta_0)}{\arg\max_\theta L(\theta)}$$

- In asymptotic case (large sample, etc), test statistic $\Delta\chi^2$ following a χ^2 distribution (Wilks Theorem), so confidence interval can be directly calculated from $\Delta\chi^2$

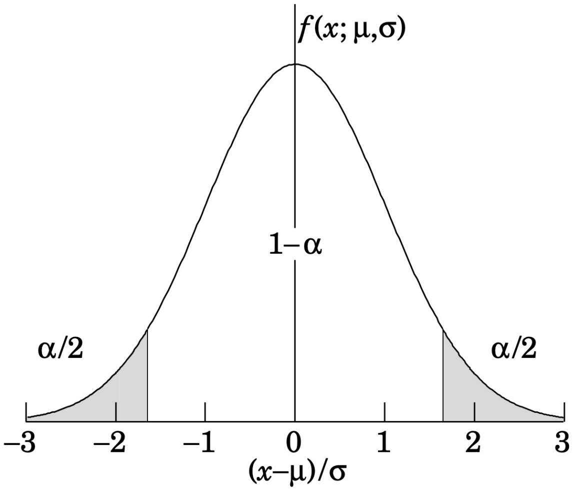


Figure 40.4: Illustration of a symmetric 90% confidence interval (unshaded) for a Gaussian-distributed measurement of a single quantity. Integrated probabilities, defined by $\alpha = 0.1$, are as shown.

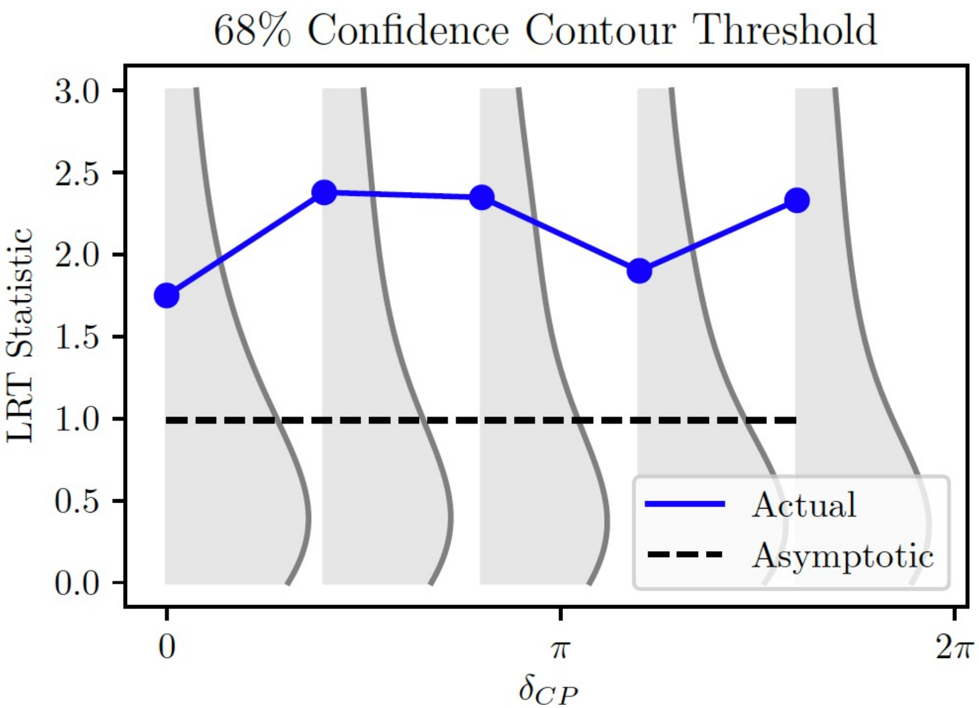
Table 38.2: Values of $\Delta\chi^2$ or $2\Delta\ln L$ corresponding to a coverage probability $1-\alpha$ in the large data sample limit, for joint estimation of m parameters.

	$(1-\alpha)$ (%)	$m=1$	$m=2$	$m=3$
1σ	68.27	1.00	2.30	3.53
	90.	2.71	4.61	6.25
	95.	3.84	5.99	7.82
2σ	95.45	4.00	6.18	8.03
	99.	6.63	9.21	11.34
3σ	99.73	9.00	11.83	14.16

From the PDG Review on Statistics

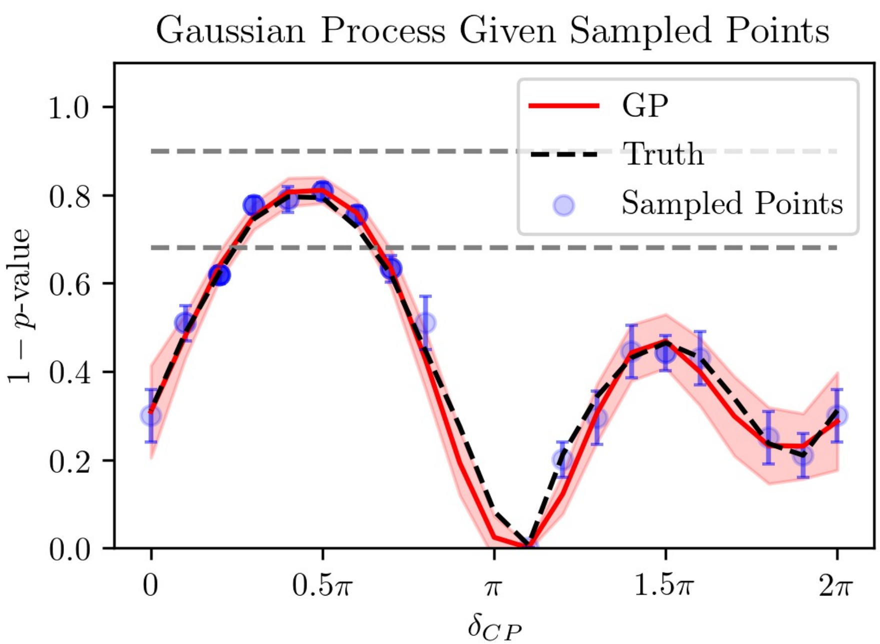
Feldman-Cousins (FC) Method

- Due to the small sample size in neutrino data and physical boundaries on the oscillation parameters, the asymptotic distribution is unreliable
- Explicitly simulate distribution using lots of pseudo-experiments
- Find p-value associated with for each point in parameter space
- In practice, FC conducts a grid-search over the entire parameter space with many toy Monte-Carlo (MC)

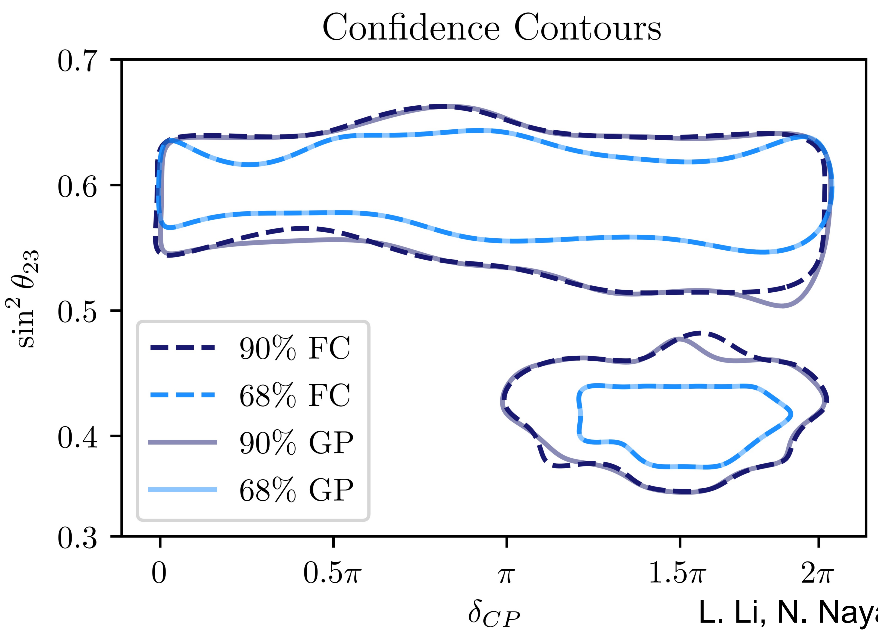


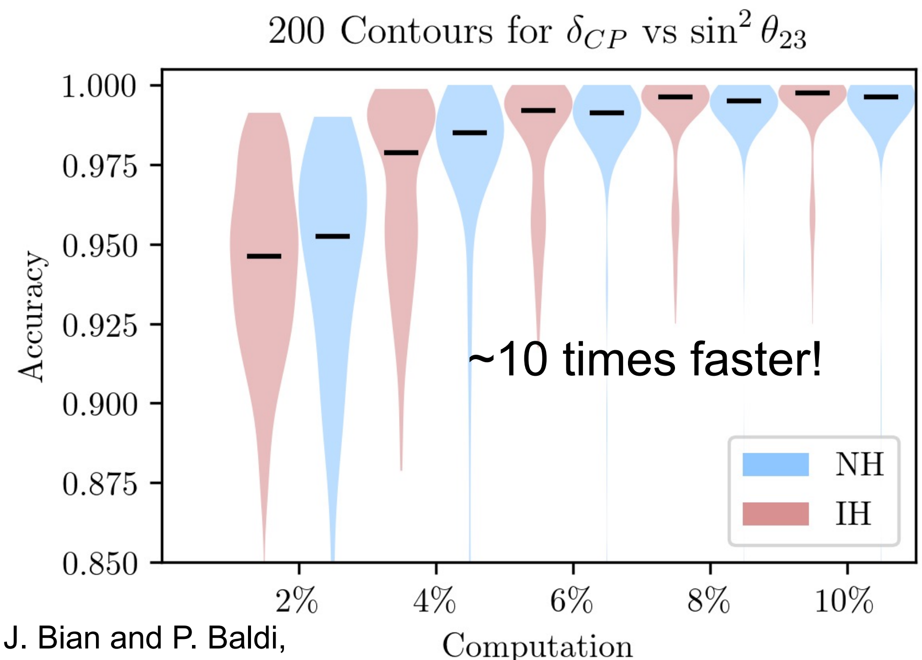
Gaussian Process to Enhance Oscillation Parameter Inference

- The Feldman-Cousins (FC) approach is a frequentist method widely used by neutrino experiments for oscillation parameter inference.
- FC search a grid over the entire parameter space with many toy simulated events to integrate and obtain p-values → very time- and computing resource-consuming.
- A Gaussian Process (GP) is a special case of Bayesian learning that can use existing data points to predict the values for unseen points with posterior mean and posterior standard deviation.
- Use GP to approximate the FC P-value surface non-parametrically based on a small fraction of grid points and toy simulated events



Gaussian Process to Enhance Oscillation Parameter Inference





L. Li, N. Nayak, J. Bian and P. Baldi,
Phys. Rev. D 101, 012001 (2020)

- Oscillation contours produced by GP 10 times faster than the standard FC algorithm while keeping the accuracy at 99%.
- GP algorithm implemented in NOvA's software framework, working on parallelize the algorithm to fit NOvA oscillation parameters at DOE’s National Energy Research Scientific Computing Center (NERSC)

Machine Learning to Boost Neutrino Oscillation Measurements

Measure neutrino flavor change vs. energy in over a long travel distance to determine oscillation parameters:

- Identify ν_e and ν_μ charge current events from cosmic rays and beam backgrounds (PID)
- Reconstruct neutrino energy and other kinematic variables
- Observe differences between data and MC simulation at Near Detector (ND), extrapolate them to Far Detector (FD) to correct FD MC
- Infer oscillation parameters by fitting oscillation-weighted FD MC to FD data

BLUE: Apply machine learning

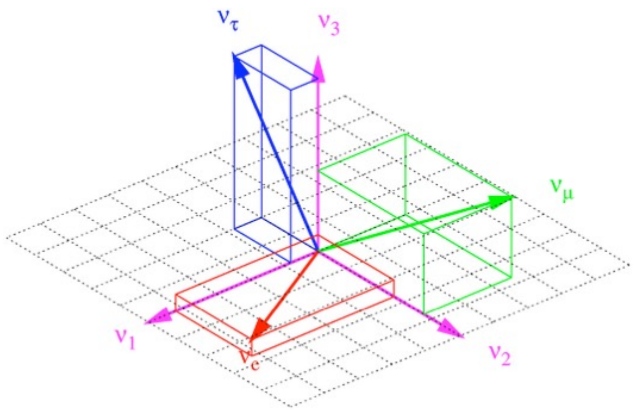
Backup

Neutrino Oscillation

- Neutrino oscillate because their flavor (interaction) eigenstates (ν_e, ν_μ, ν_τ) are not mass eigenstates (ν_1, ν_2, ν_3)
- As neutrinos propagate, the phases of the three mass states $|\nu_{1,2,3}>$ advance at different rates. Therefore the flavor eigenstates oscillate.

3-flavor standard model neutrinos

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



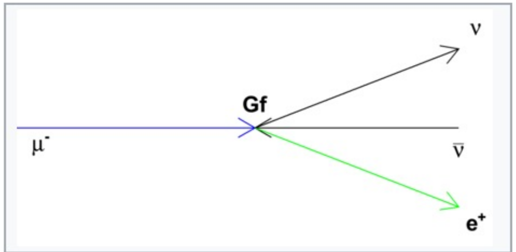
PMNS matrix

Parameterized by mixing angles θ_{12}, θ_{23} and θ_{13} and phase δ_{CP}

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

Including two squared mass differences $\Delta m^2_{21} = m^2_2 - m^2_1$ and $\Delta m^2_{32} = m^2_3 - m^2_2$, there are 6 free parameters that determine neutrino oscillation probabilities.

Fermi Constant G_f



Fermi's interaction showing the 4-point fermion vector current, coupled under Fermi's Coupling Constant G_F. Fermi's Theory was the first theoretical effort in describing nuclear decay rates for β decay.

The most precise experimental determination of the Fermi constant comes from measurements of the muon lifetime, which is inversely proportional to the square of G_F (when neglecting the muon mass against the mass of the W boson).[19] In modern terms:[3][20]

$$G_F^0 = \frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2 c^4} = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \approx 4.5437957 \times 10^{14}\ \mathrm{J}^{-2}\ .$$

Here g is the coupling constant of the weak interaction, and M_W is the mass of the W boson, which mediates the decay in question.

In the Standard Model, the Fermi constant is related to the Higgs vacuum expectation value

$$v = \left(\sqrt{2}\, G_F^0\right)^{-1/2} \simeq 246.22\ \mathrm{GeV}.$$ [21]

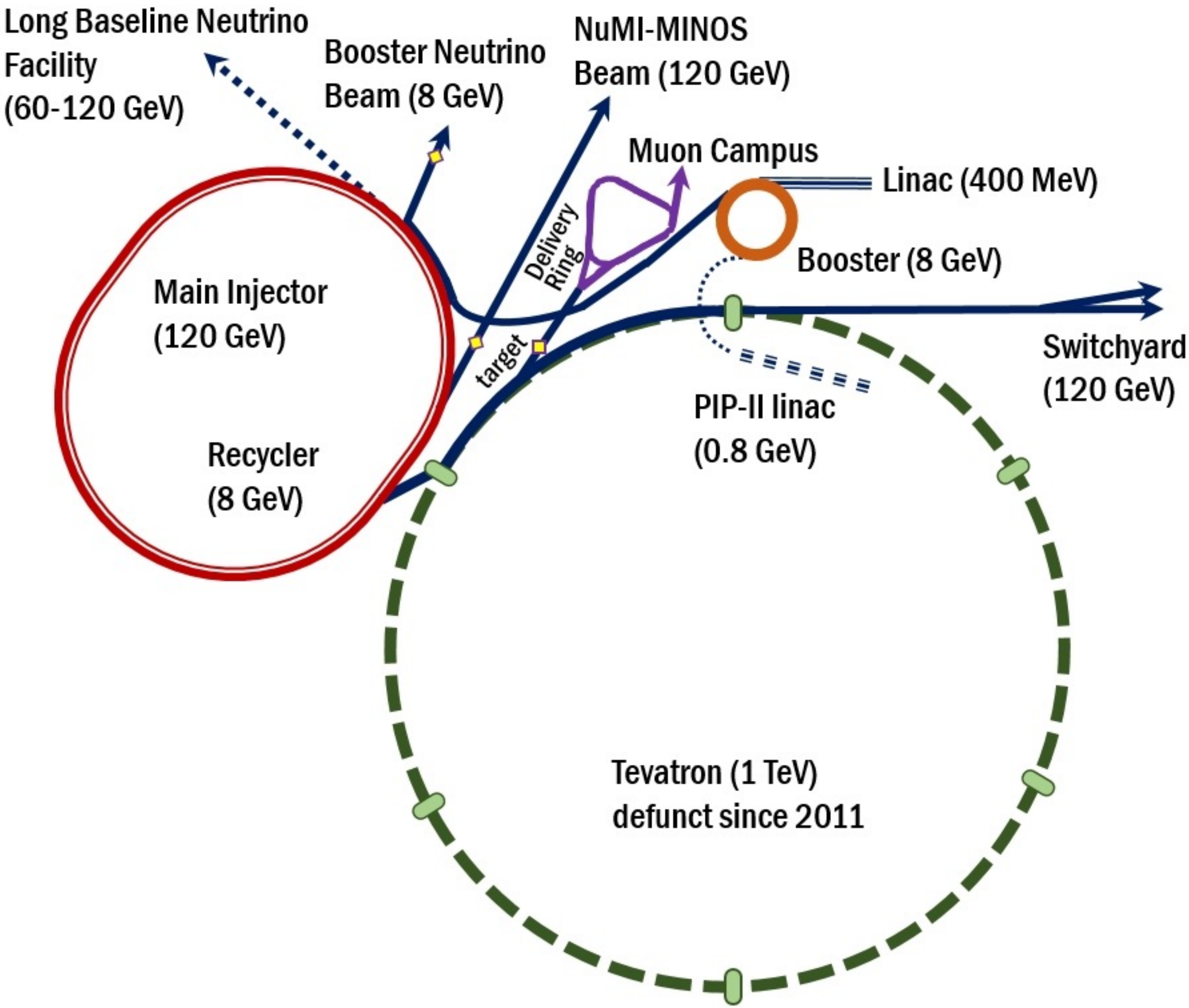
More directly, approximately (tree level for the standard model),

$$G_F^0 \simeq \frac{\pi\alpha}{\sqrt{2}\, M_W^2 (1 - M_W^2/M_Z^2)}.$$

This can be further simplified in terms of the Weinberg angle using the relation between the W and Z Bosons with $M_Z = \dfrac{M_W}{\cos\theta_W}$, so that

$$G_F^0 \simeq \frac{\pi\alpha}{\sqrt{2}\, M_Z^2 \cos^2\theta_W \sin^2\theta_W}.$$

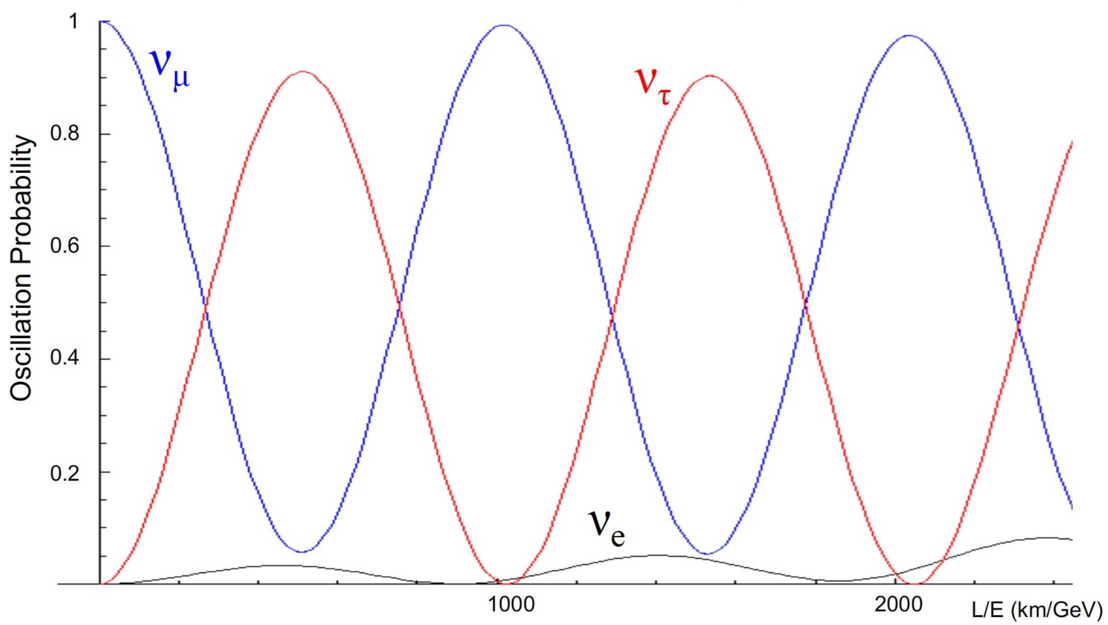
Accelerator Neutrino Beams at Fermilab Near Chicago



Neutrino Oscillation

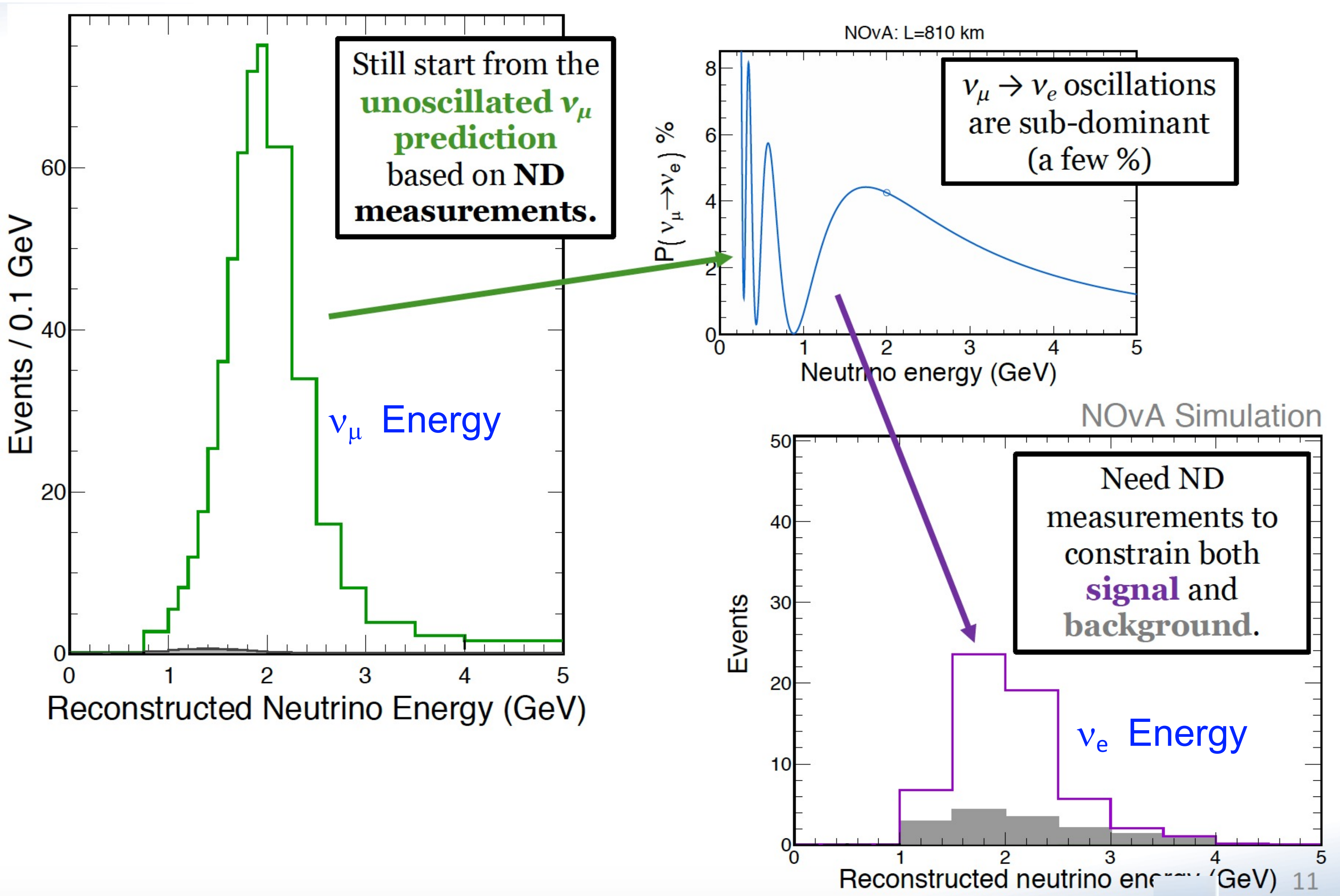
- There are 3 flavors of neutrinos: ν_e, ν_μ, ν_τ, their antiparticles: $\bar{\nu}_e$, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$
- Neutrino oscillation: a neutrino created with a certain flavor has a probability of being detected later with a different flavor during their travel

Starting with ν_μ



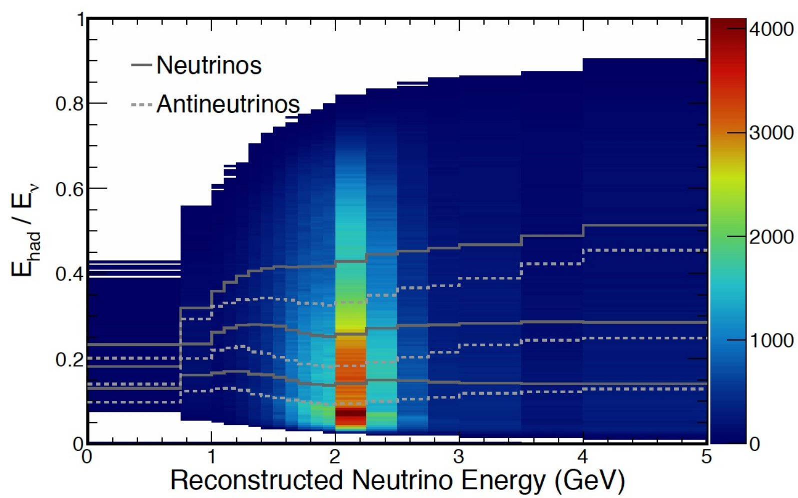
Neutrino Energy

- Second task: Reconstruct Neutrino Energy

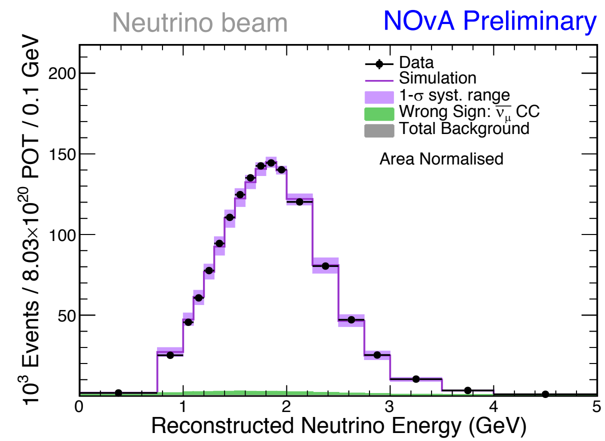


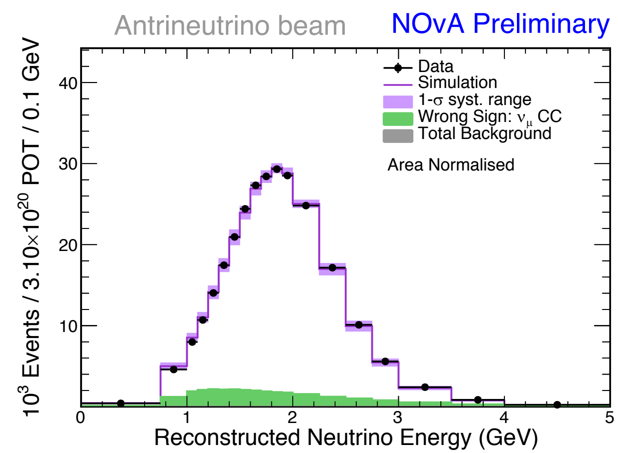
ν_μ Near Detector (ND) Spectrum

- Select ν_μ ($\bar{\nu}_\mu$) CC in ND from neutrino (antineutrino) beam with CVN
- E_ν = E_μ+ E_{had}, data split in 4 equal energy quartiles based on E_{had}/E_ν, resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.
- Normalize ND simulation to data in each E_ν bin, then extrapolate the 4 quantiles to FD



Reco ν_μ ($\bar{\nu}_\mu$) energy, all Quartiles





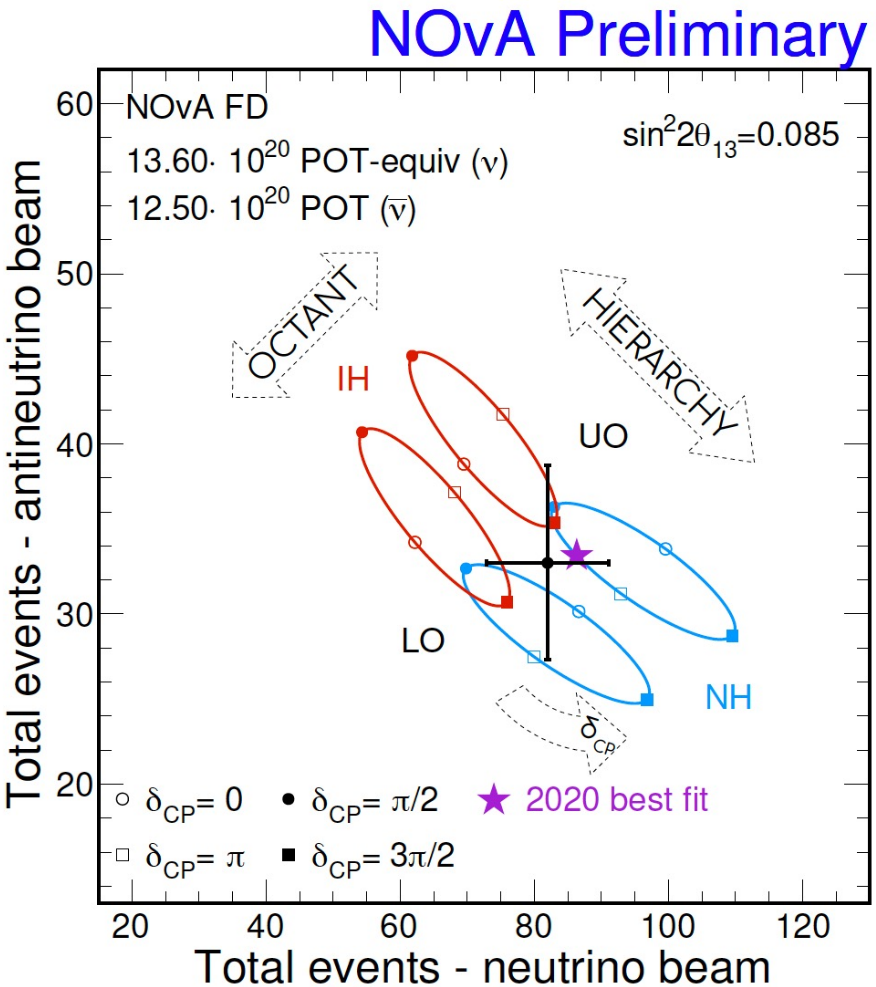
Area-normalized, shape-only systematics

Data/MC normalization difference:

1.3% and 0.5% for ν_μ and $\bar{\nu}_\mu$

Joint Appearance and Disappearance

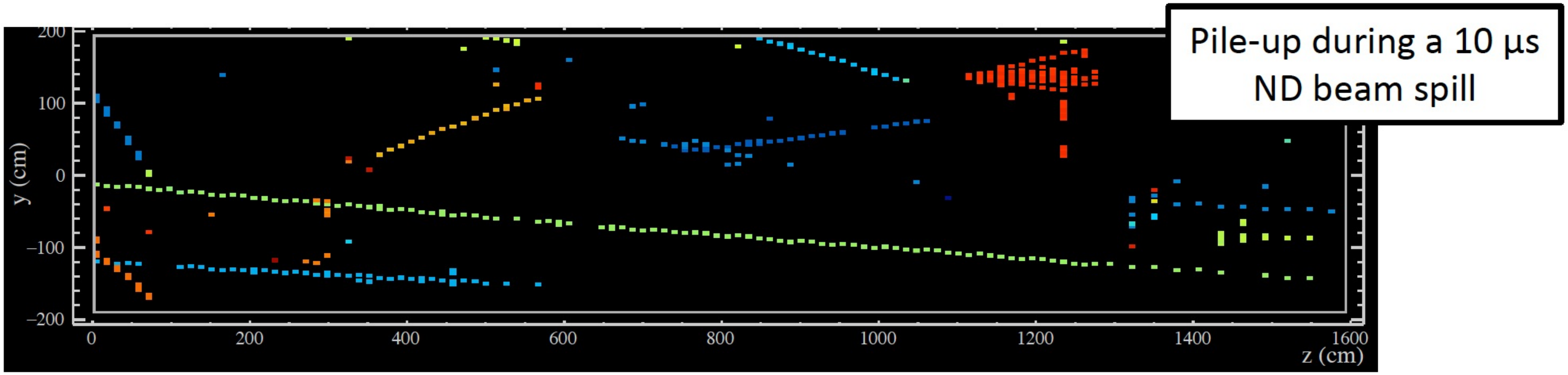
$\nu_e/\bar{\nu}_e$ appearance event counts and best fit from $\nu_e/\bar{\nu}_e + \nu_\mu/\bar{\nu}_\mu$ combined analysis



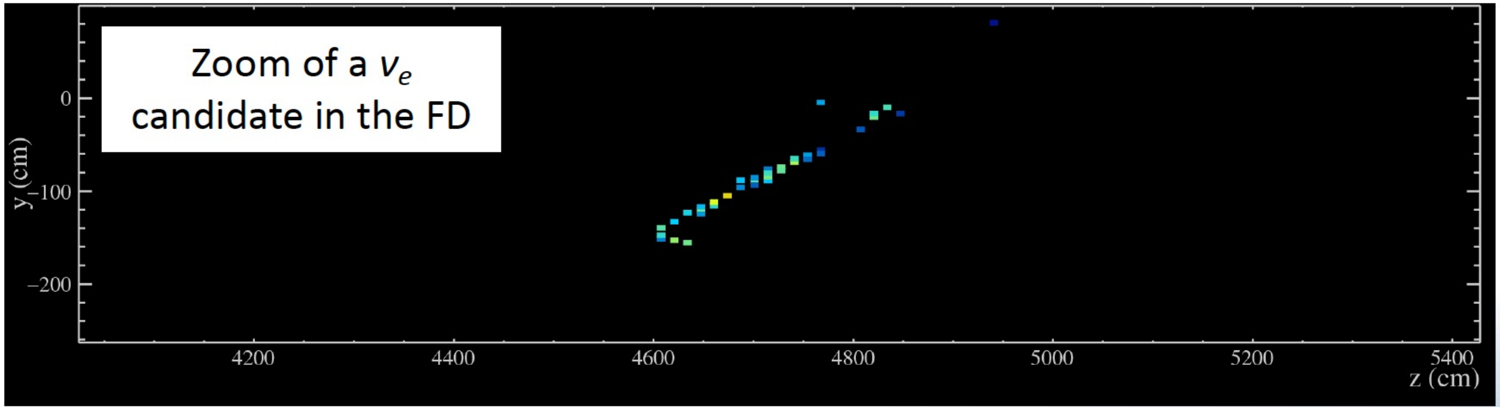
- Disfavor maximal mixing (θ_{23}=45°) at 1.1 σ
- Disfavor lower octant (θ_{23}<45°) at 1.2 σ
- Consistent with all δ_{CP} values in NH at < 1.1σ
- Exclude $\delta_{CP}=\pi/2$ in IH at > 3σ
- Disfavor (NH, $\delta_{CP}=3\pi/2$) at ~2σ
- Disfavor inverted mass ordering at 1.0σ

NOvA Detectors

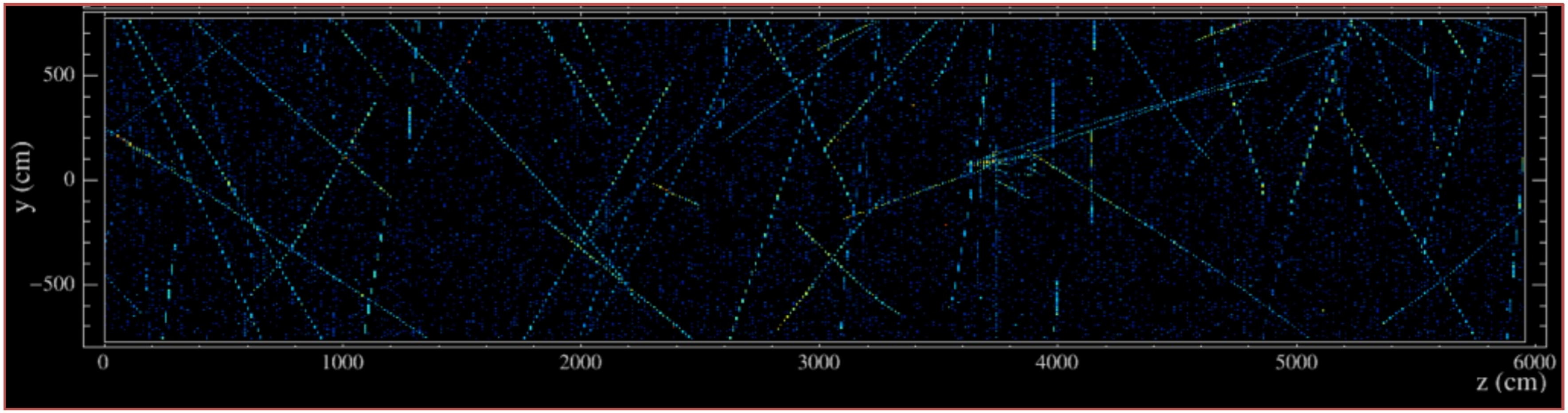
- Segmented liquid scintillator detectors.
  - Allows both 3D tracking and calorimetry
- Good time resolution (few ns) and spatial resolution (few cm)
  - Allows clear separation of individual interactions



- Optimized for electron showers: ~6 samples per X_0 and ~60% active



Selection: Cosmic Rejection



- **Cosmic rejection** is critical at the Far Detector.
  - 11 billion cosmic rays/day in the Far Detector on the surface.
- We require:
  - Vertices in the fiducial volume, events contained in the detector.
  - Pass a BDT tuned to reject cosmics.
- For the **ν_e sample,** we add a second “peripheral” sample which contains high-confidence ν_e events close to the detector walls.

t-SNE

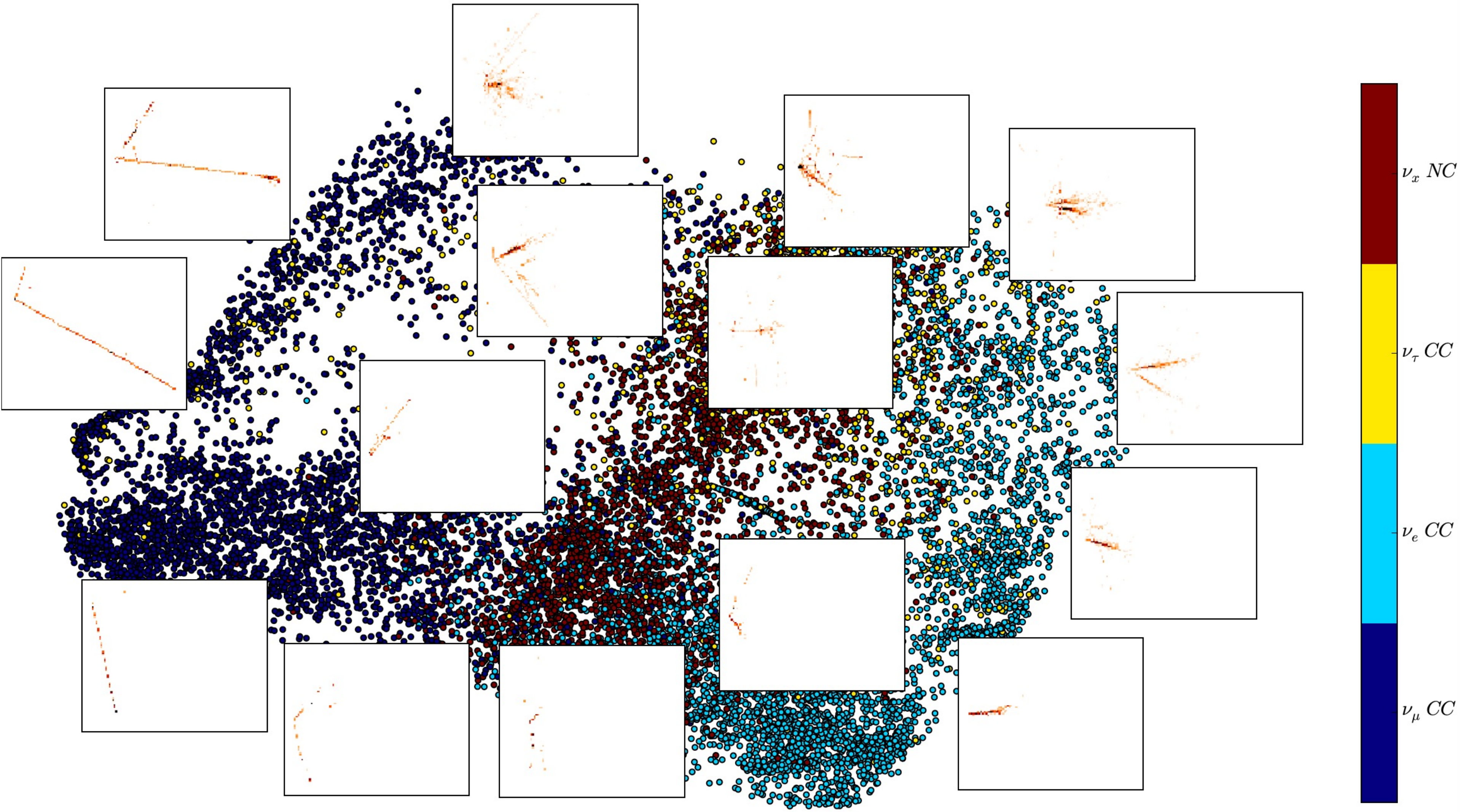
t-Distributed Stochastic Neighbor Embedding

https://indico.io/blog/visualizing-with-t-sne/

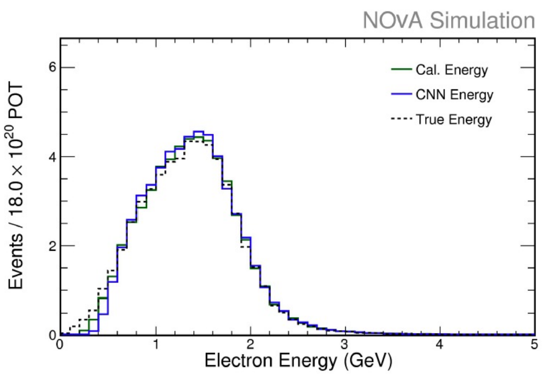
https://www.nature.com/articles/s41586-018-0361-2

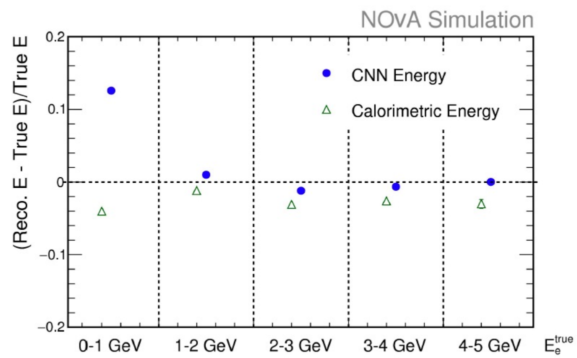
t-SNE

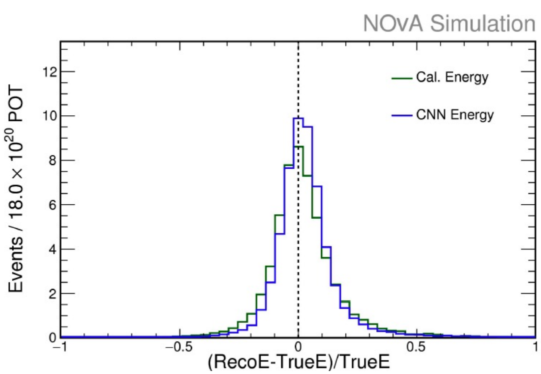
Example Event Topologies

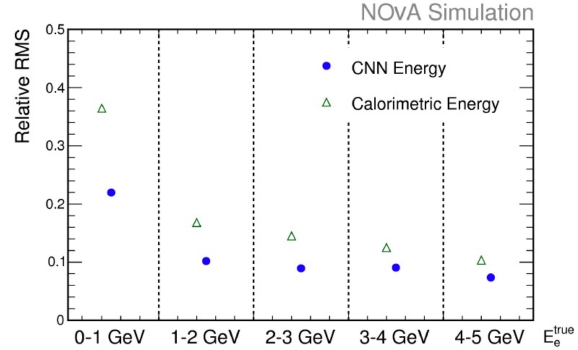


ν_e CC Electron Energy









- An electron energy estimator was also developed
- The input images for this estimator are only hits from the electron part of ν_e CC events
- The CNN based estimator sees an improvement over the traditional method based on summing up calibrated hit energy

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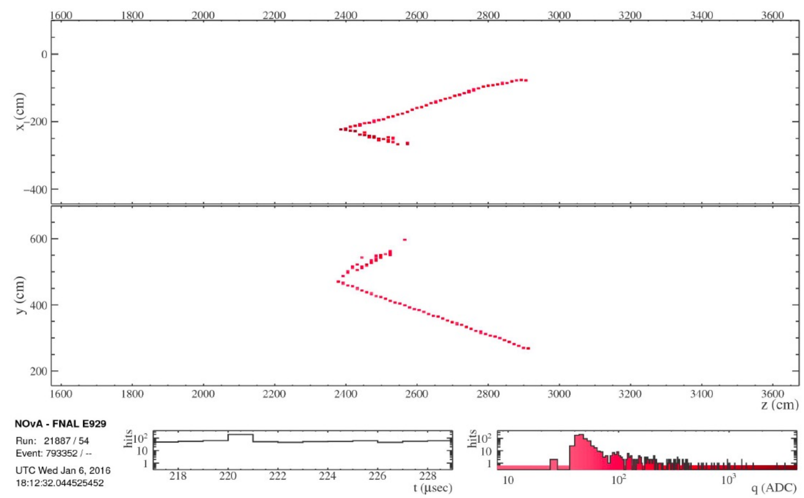
ν_μ CC Events

- We can also apply regression CNNs to ν_μ CC events
- Muon tracks are long, so the ν_e pixelmap size would not contain the full event
- We can specialize to estimating the hadronic part of energy, then use:
- $E(\nu_\mu) = E_\mu + E_{hadronic}$
- Then we combine our CNN hadronic energy estimator with the traditional, length based muon energy estimator to estimate ν_μ event energy



Here is a simulated ν_μ CC event, with a long muon track and hadronic shower

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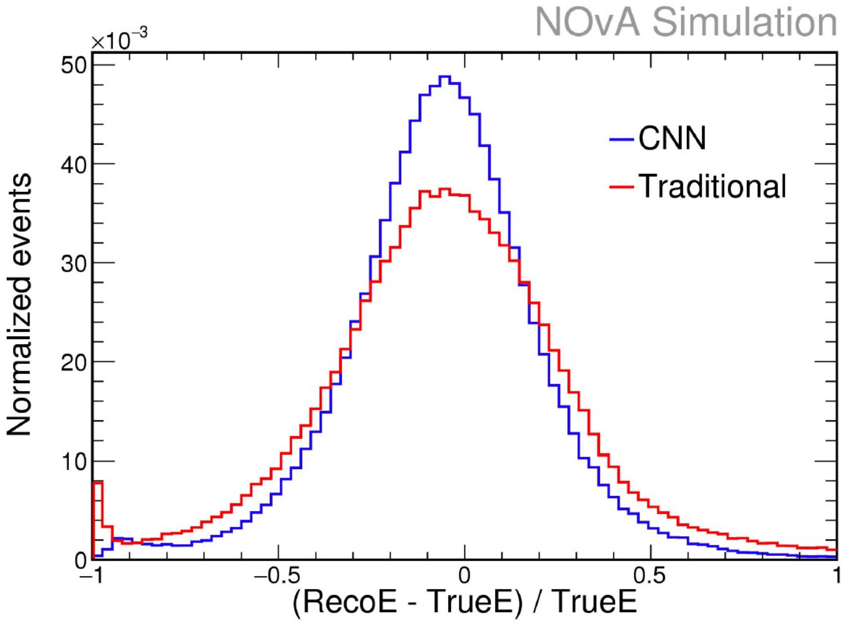
Hadronic Energy

- Here we show the resolution of the hadronic energy
- We apply a weighting to the hadronic energy spectrum
- The traditional method is found by adding up visible calorimetric energy from the hadron, then applying a calibration factor



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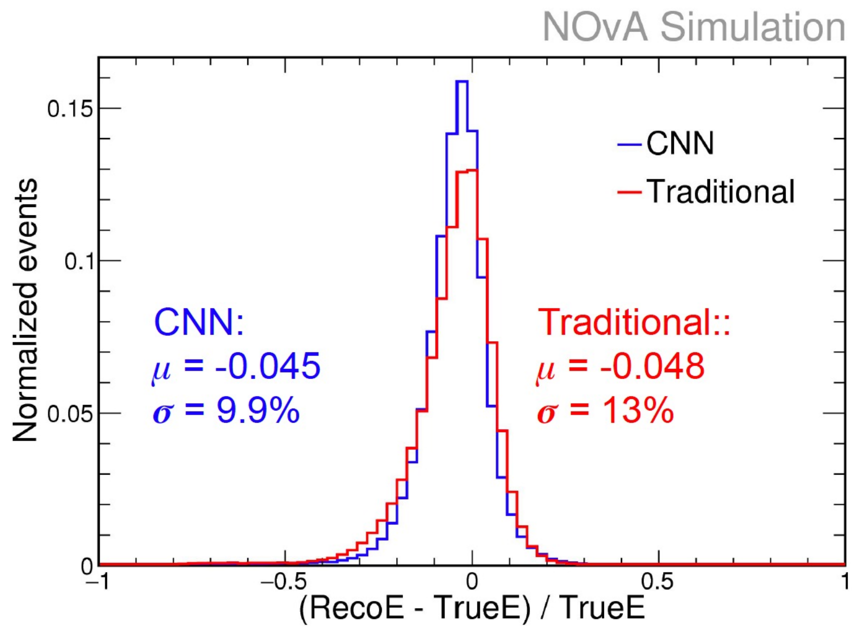
ν_μ Energy

- We estimate the ν_μ event energy with:
- $E(\nu_\mu) = E_\mu + E_{hadronic}$
- Traditional method of muon energy is based on length of muon prong
- We do this using both the traditional and CNN reconstructed hadron energy



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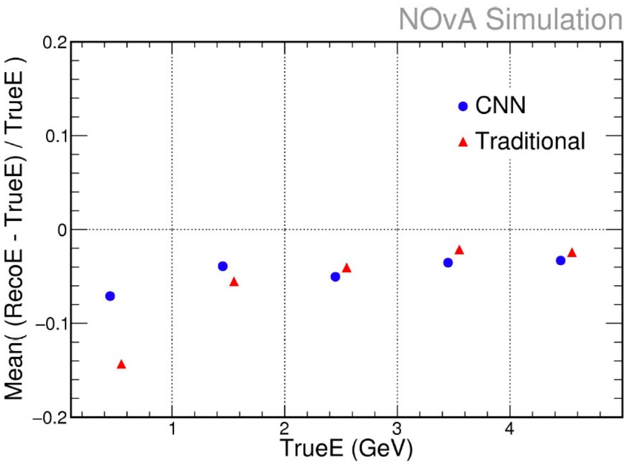
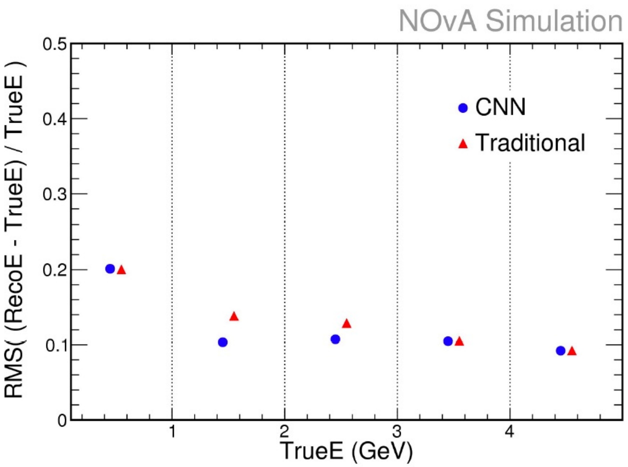
ν_μ Energy





- Here we look at Mean and RMS of ν_μ energy resolution over ranges of true ν_μ energy
- The CNN has a smaller bias at lower energies
- The CNN's RMS does about as well or better everywhere

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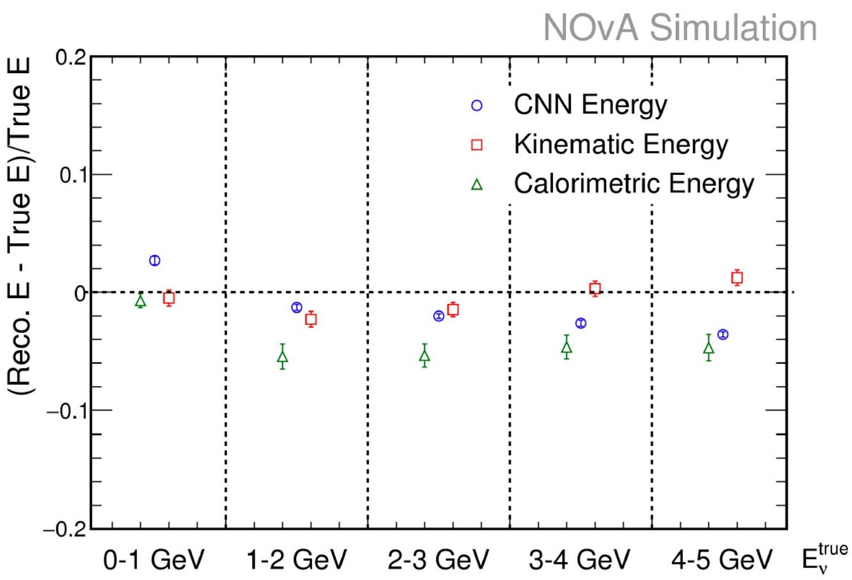
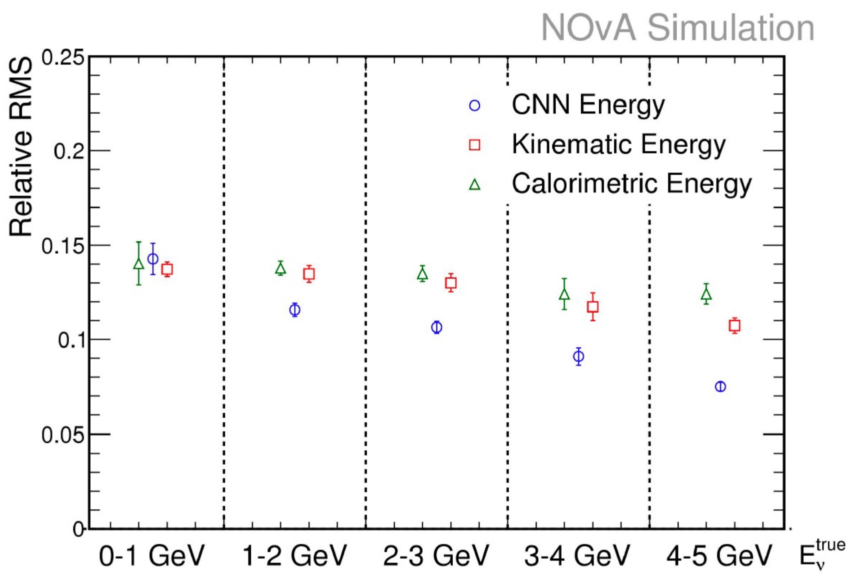
ν_e Systematics





- Energy bars here are systematic uncertainties
- CNN is more robust to cross section systematics from 1 GeV onward

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