http://novaexperiment.fnal.gov

Latest 3-flavor neutrino oscillations results from the NOvA experiment

Steven Calvez on behalf of the NOvA collaboration

EPS HEP 2021

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EUROPEAN PHYSICAL SOCIETY HEP2021 VIRTUAL EDITION

NOvA

COLORADO STATE UNIVERSITY

What are the main goals of the NOvA experiment?

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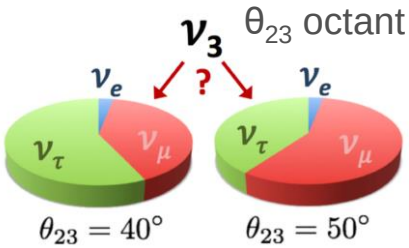

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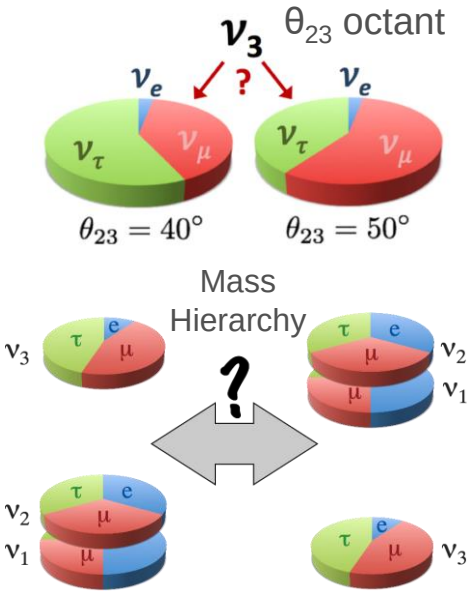

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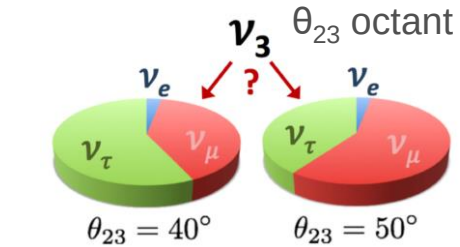

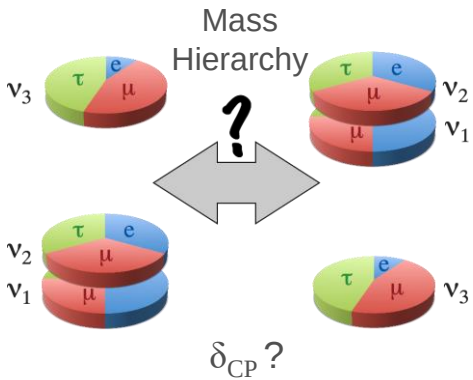

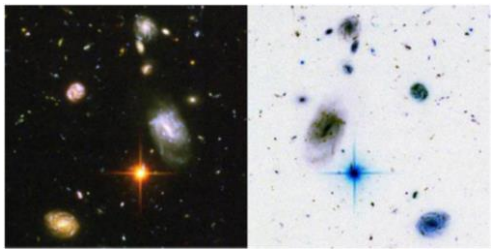

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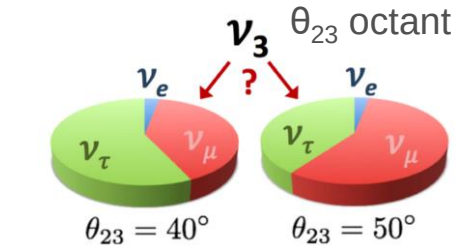
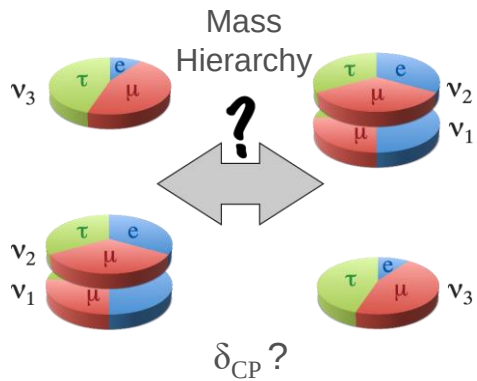
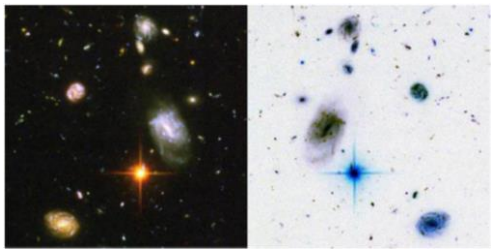


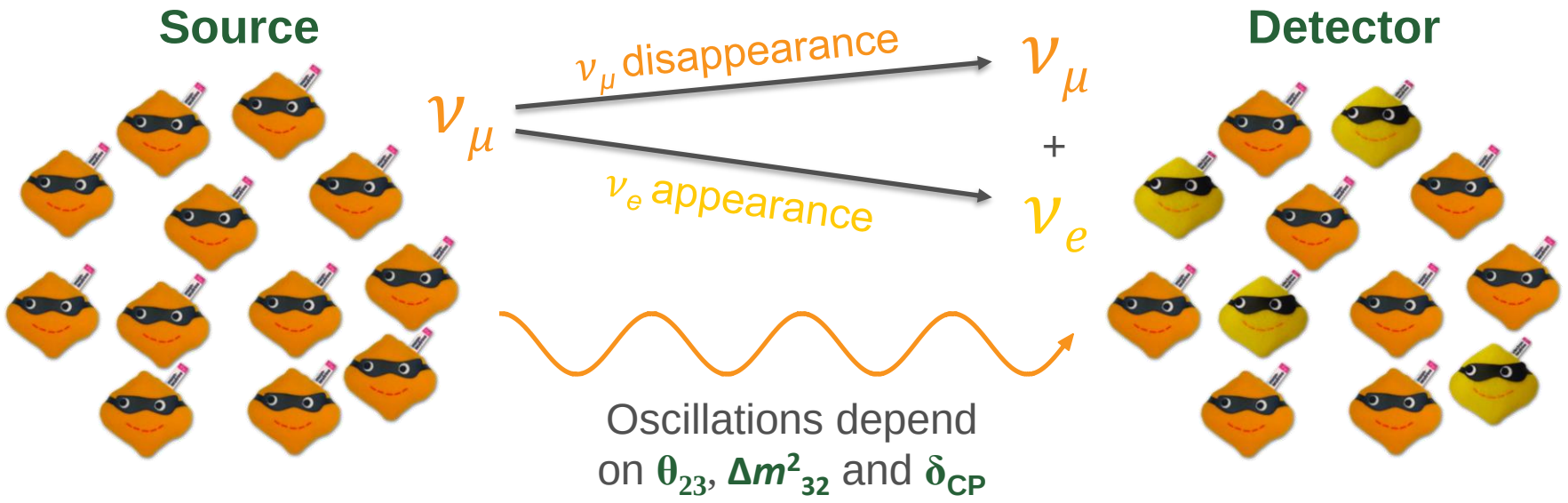


- NOvA has a **rich physics program**:
  - **Neutrino cross-section** measurements.
  - Search for **sterile neutrinos**.
  - Investigate **astrophysical** and **exotics** phenomena: *see Peter Filip's poster in Session T10.*



How can NOvA measure neutrino oscillation parameters?

- NOvA measures the **rate, energy and flavor of neutrinos detected** both near its **source** and in its **detector** far away.
- Perform a joint **disappearance** $\nu_\mu \rightarrow \nu_\mu$ and **appearance** $\nu_\mu \rightarrow \nu_e$ analysis.



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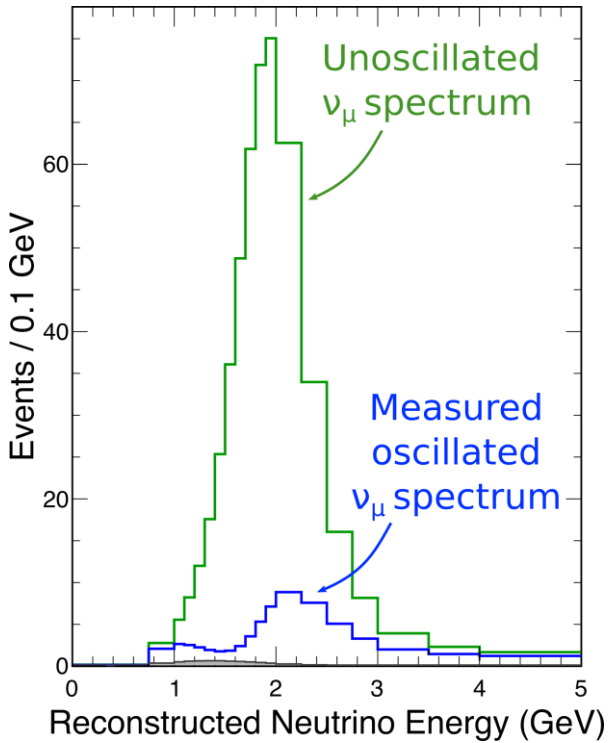
- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_\mu}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}}$ **disappearance** to constrain $\boldsymbol{\sin^2 2\theta_{23}}$ and $\boldsymbol{|\Delta m^2_{32}|}$:
  - ν_μ survival probability:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



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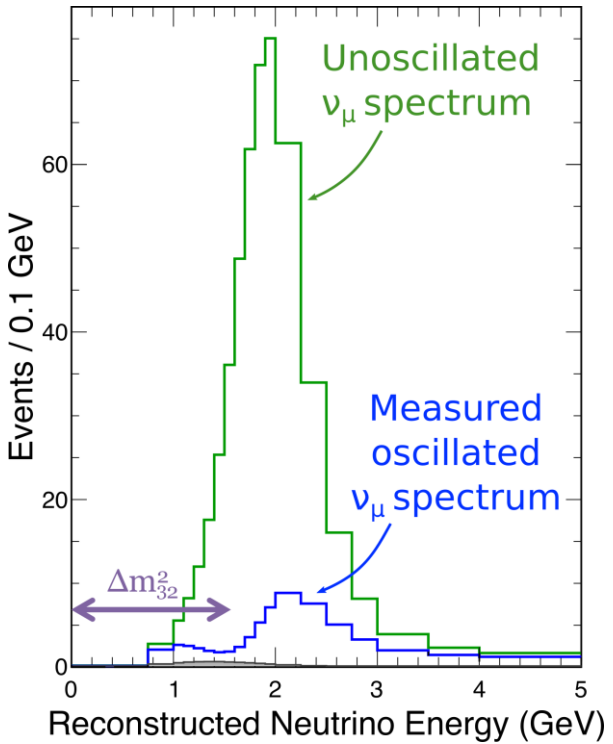

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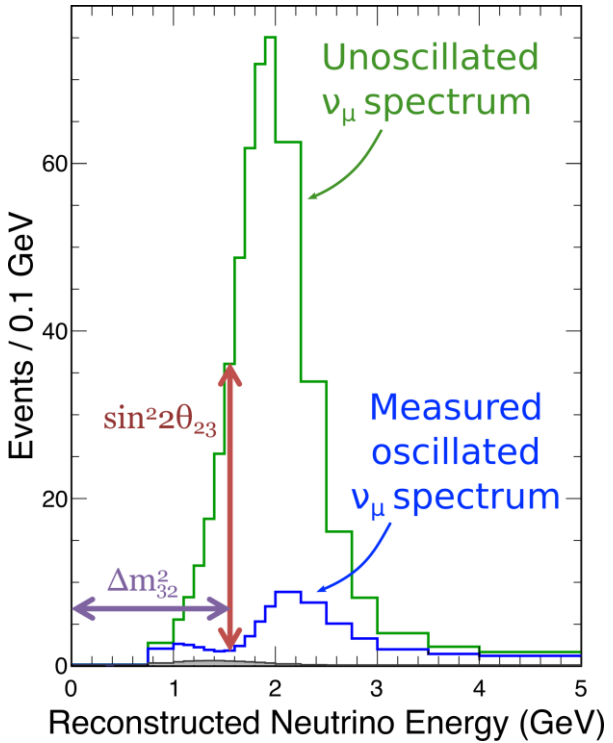
  - Location of dip → $\boldsymbol{|\Delta m^2_{32}|}$
  - Amplitude of dip → $\boldsymbol{\sin^2 2\theta_{23}}$



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- Measure $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ **appearance** to constrain **$\sin^2\theta_{23}$**, **Δm^2_{32}** and **δ_{CP}**:

  - ν_e appearance probability:

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

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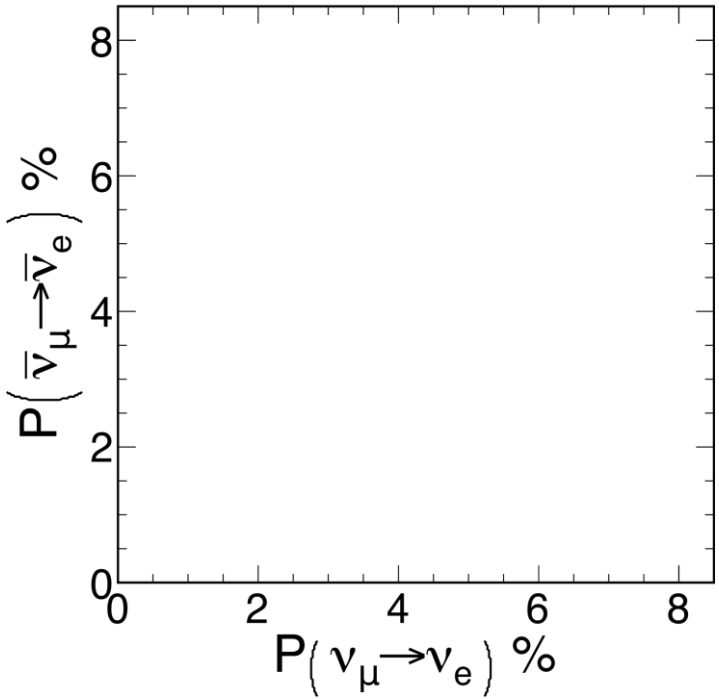

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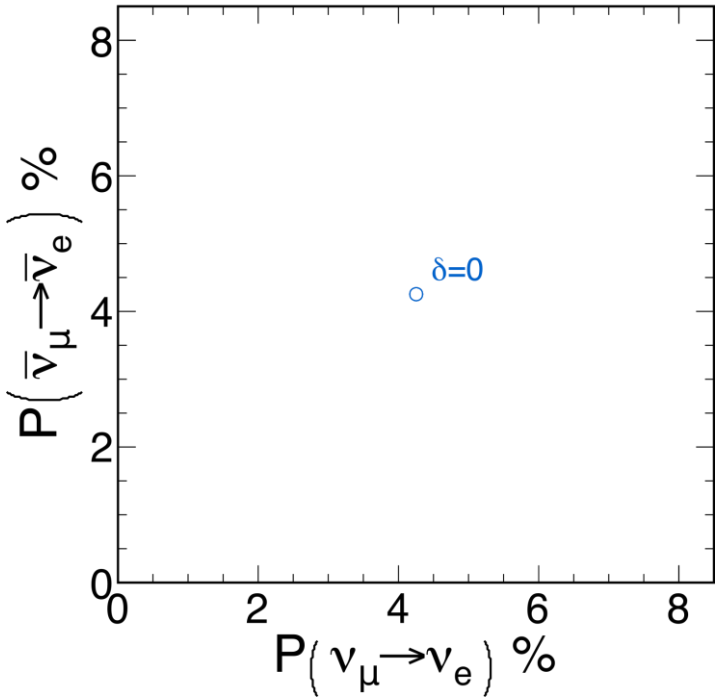

➢ In a vacuum and with no CP-violation, ν and $\overline{\nu}$ oscillation probabilities are **equal**.

How can NOvA measure neutrino oscillation parameters?

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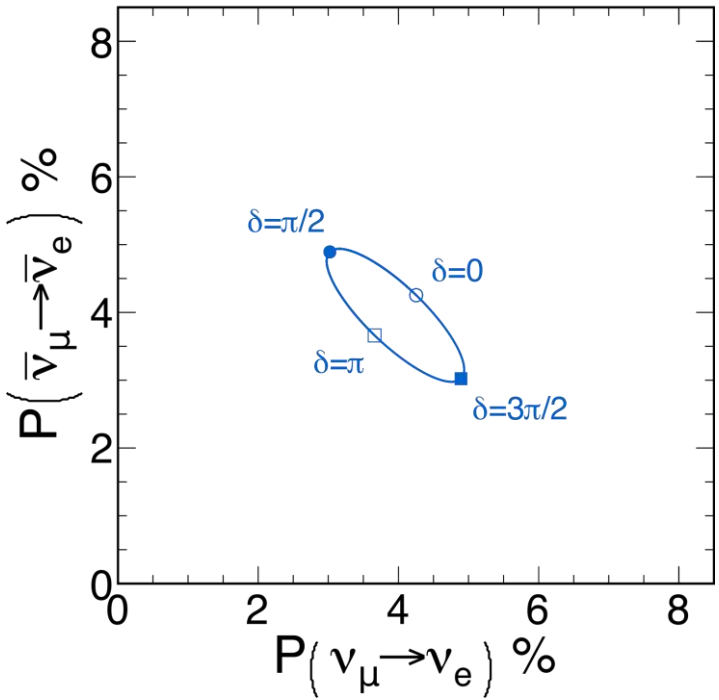

➢ **CP-violation** generates **opposite effects** in ν and $\overline{\nu}$ oscillation probabilities.

How can NOvA measure neutrino oscillation parameters?

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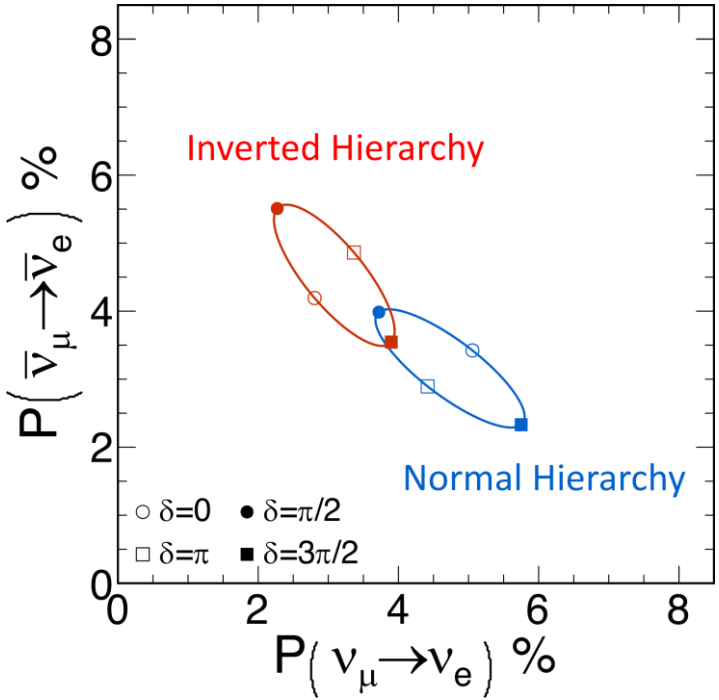

➢ **Matter effects** also generate opposite effects in ν-$\overline{\nu}$ oscillations depending on the **Mass Hierarchy.**

How can NOvA measure neutrino oscillation parameters?

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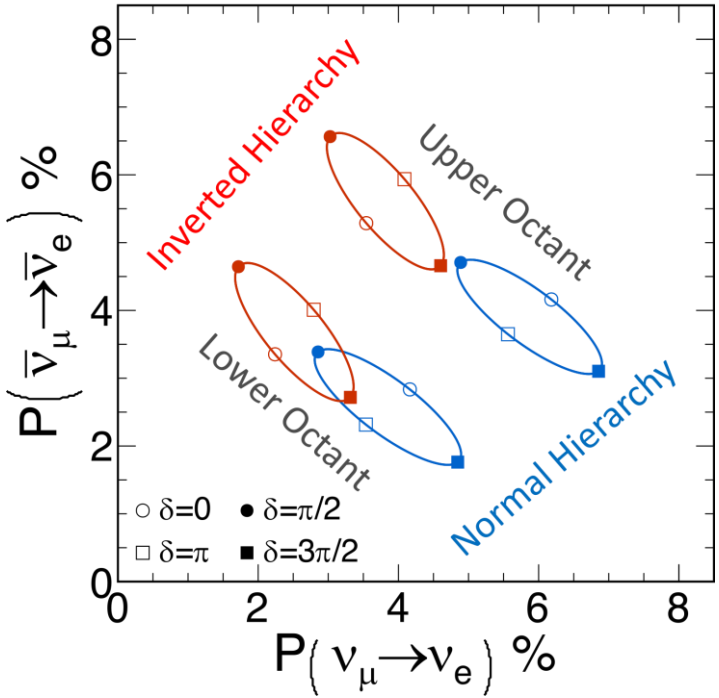
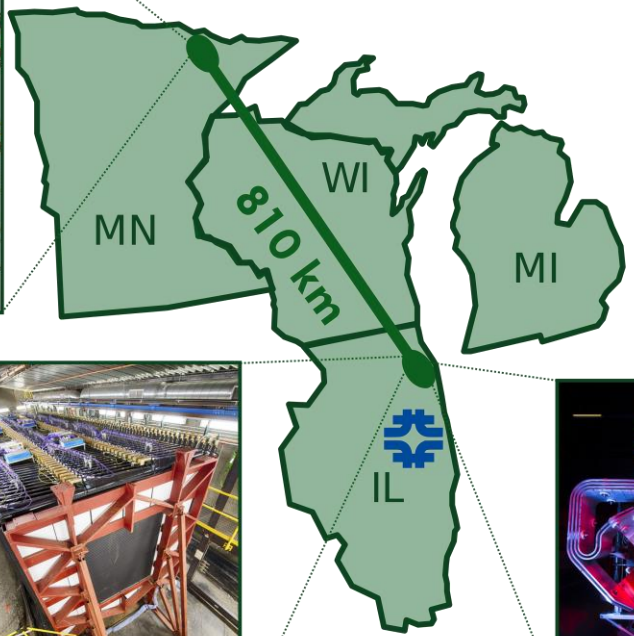


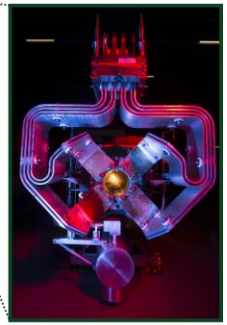
➢ **θ_{23}** can increase or decrease **ν** and **$\overline{\nu}$** oscillations probabilities.

What is the NOvA experiment?

Far Detector



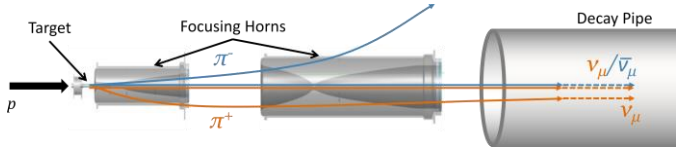
Near Detector

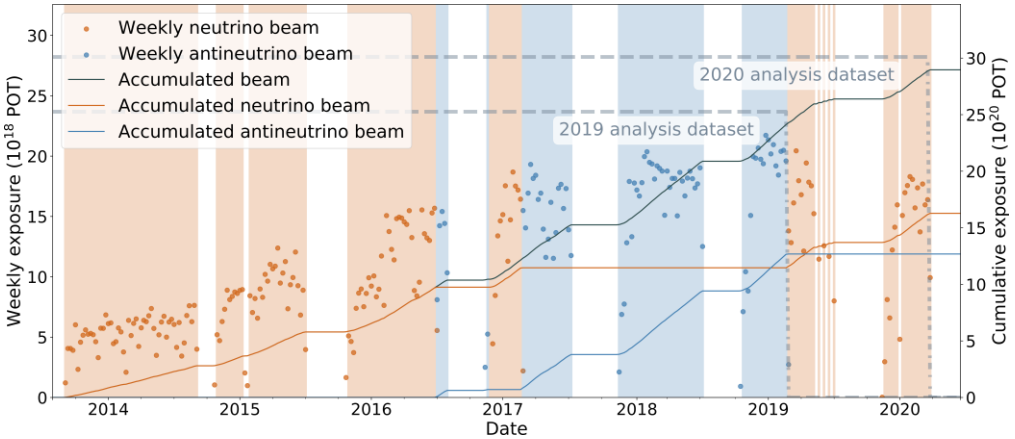


NuMI beam

How are neutrinos produced?

- **NuMI beam** can produce both ν_μ and $\overline{\nu_\mu}$.
- **World most powerful neutrino beam:** peak hourly average of 805kW.
- **+50% neutrino** mode exposure between 2019 and 2020 analyses.
- Ongoing **improvements** to reach **900kW.**

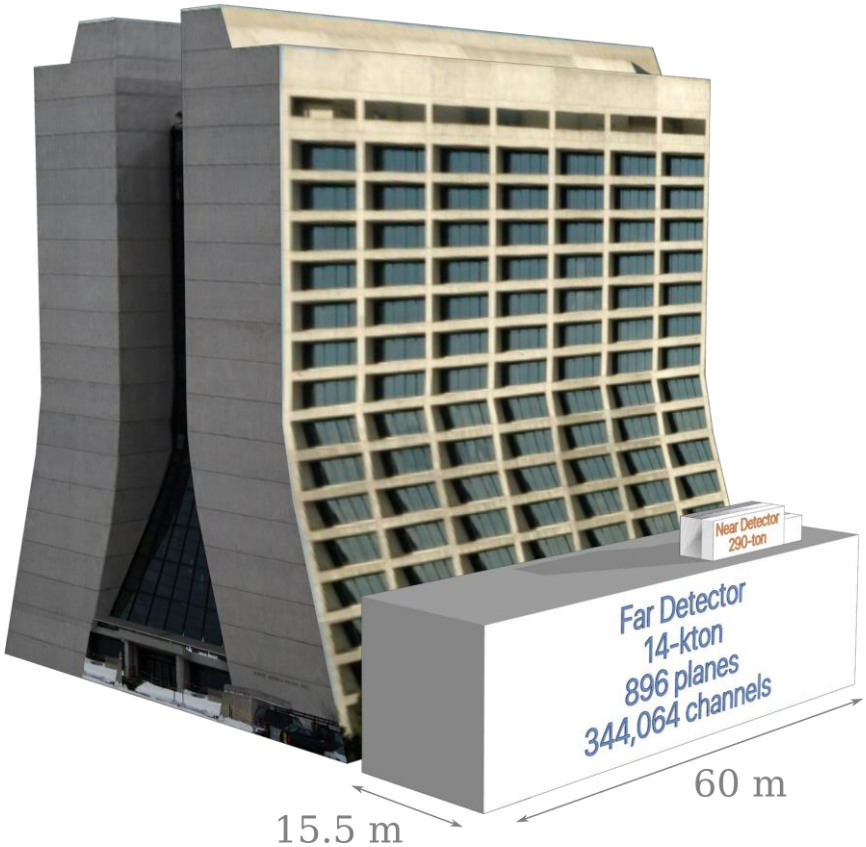




MW-capable target

MW-capable horn

How are neutrinos detected?



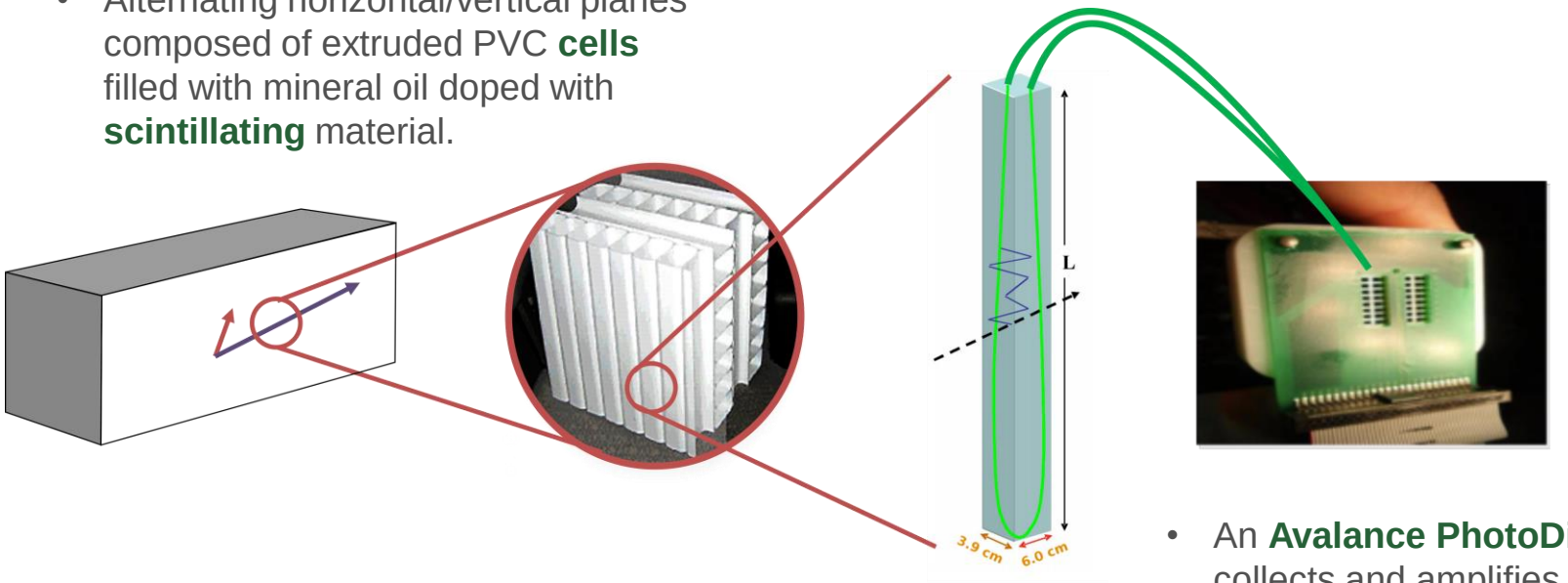
- The NOvA **Near Detector** and **Far Detector** are both **segmented liquid scintillator** detectors providing **3D tracking** and **calorimetry**.

- **Near Detector**:
  - 290 tons.
  - >100 m underground at Fermilab.

- **Far Detector**:
  - 14 ktons.
  - 810 km away on the surface in Minnesota.

How are neutrinos detected?

- Alternating horizontal/vertical planes composed of extruded PVC **cells** filled with mineral oil doped with **scintillating** material.

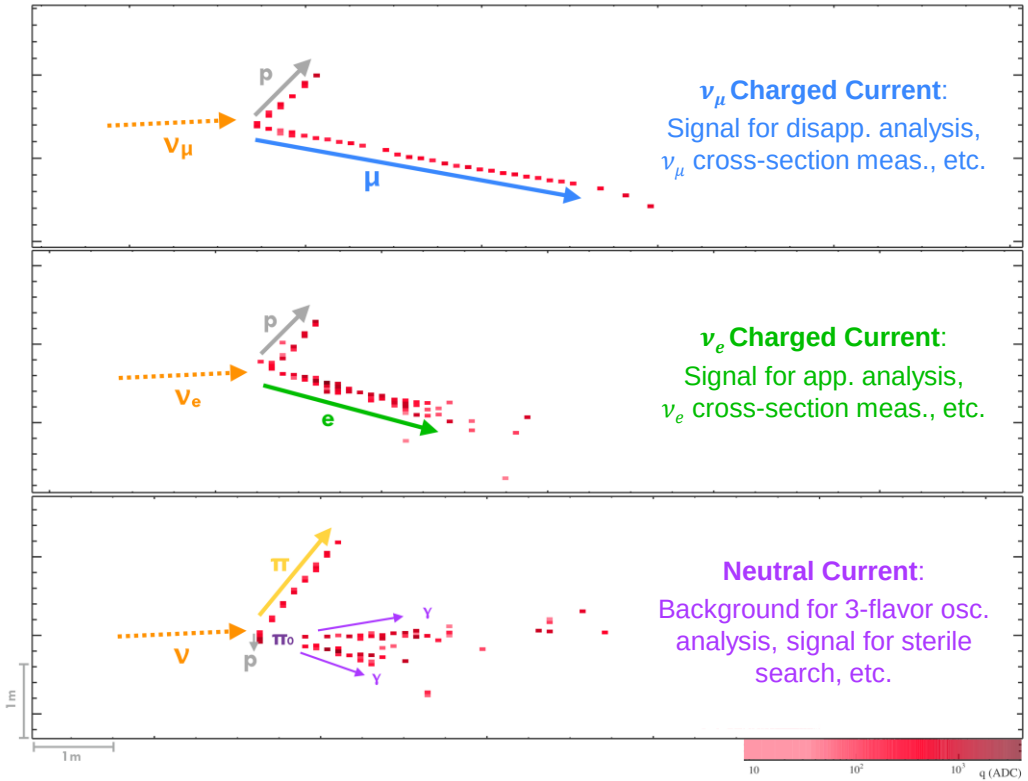


- **Charged particles** ionize the medium and produce **scintillation light**. The light is picked up by **wavelength shifting fibers**.

- An **Avalance PhotoDiode** collects and amplifies the **light signal**.

What do neutrino events look like in NOvA?

- Use **Machine Learning** techniques to **select** and **identify** neutrino interactions.
- **Particles energies** are reconstructed from the track length, the calorimetric energy deposits, or from dedicated Deep Learning algorithms.

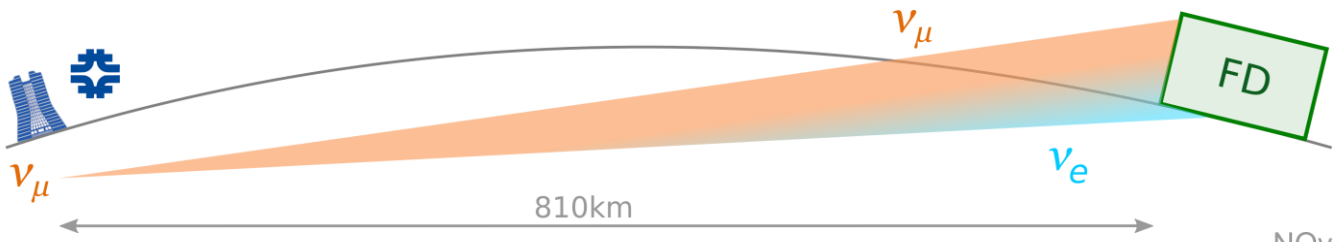


ν_μ Charged Current:
Signal for disapp. analysis, ν_μ cross-section meas., etc.

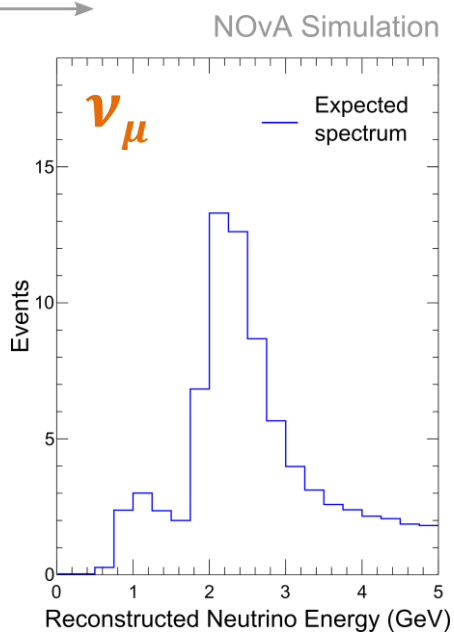
ν_e Charged Current:
Signal for app. analysis, ν_e cross-section meas., etc.

Neutral Current:
Background for 3-flavor osc. analysis, signal for sterile search, etc.

How does NOvA measure neutrino oscillation parameters?



- Measure ν_μ / $\overline{\nu_\mu}$ and ν_e / $\overline{\nu_e}$ **energy spectra** in **FD.**



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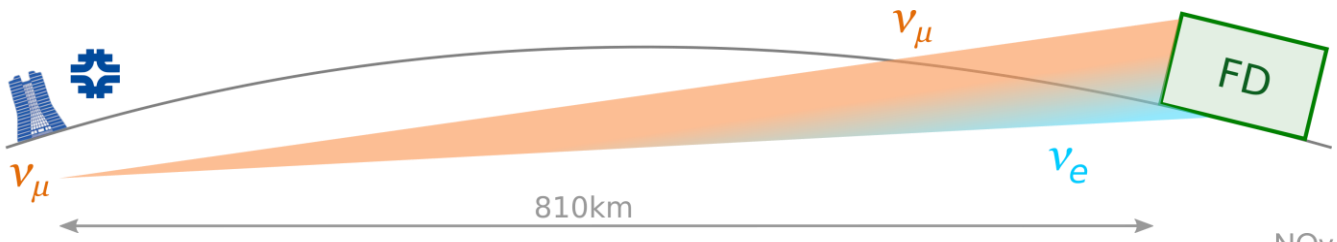
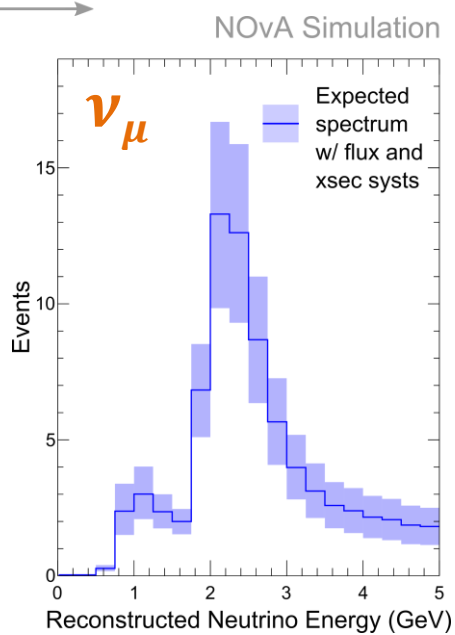


- Measure ν_μ / $\overline{\nu_\mu}$ and ν_e / $\overline{\nu_e}$ **energy spectra** in **FD.**
- Large **flux** and **cross-section uncertainties**.



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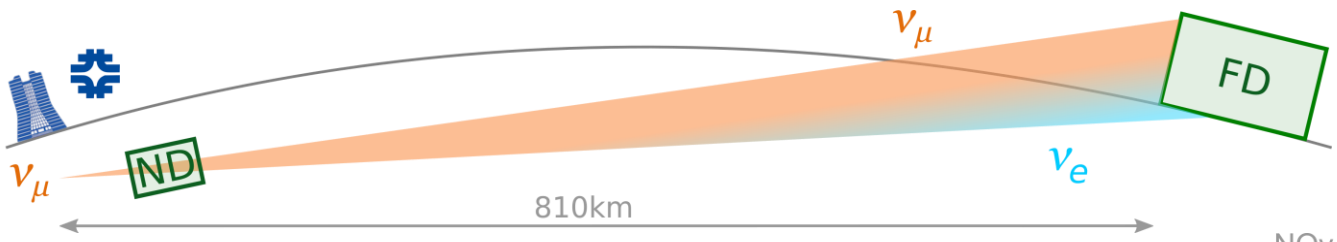
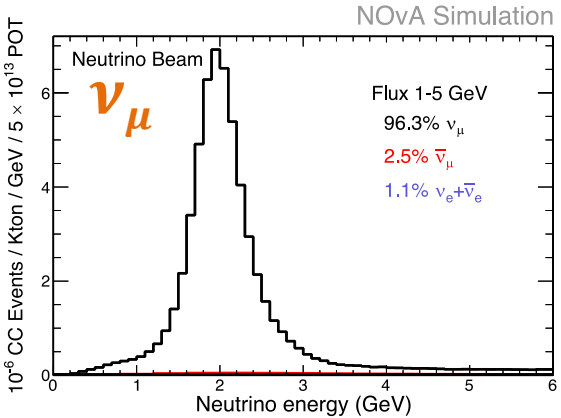
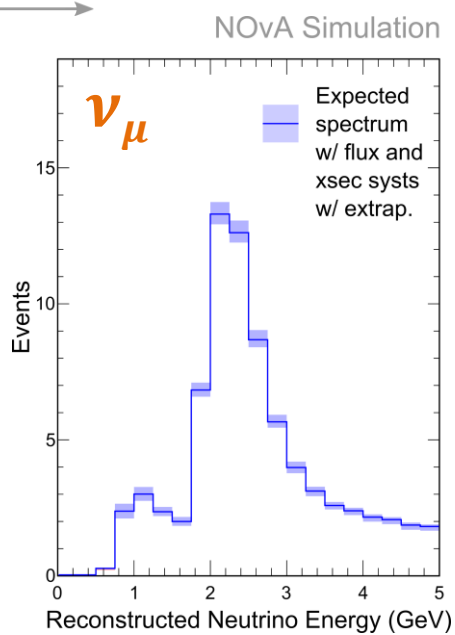




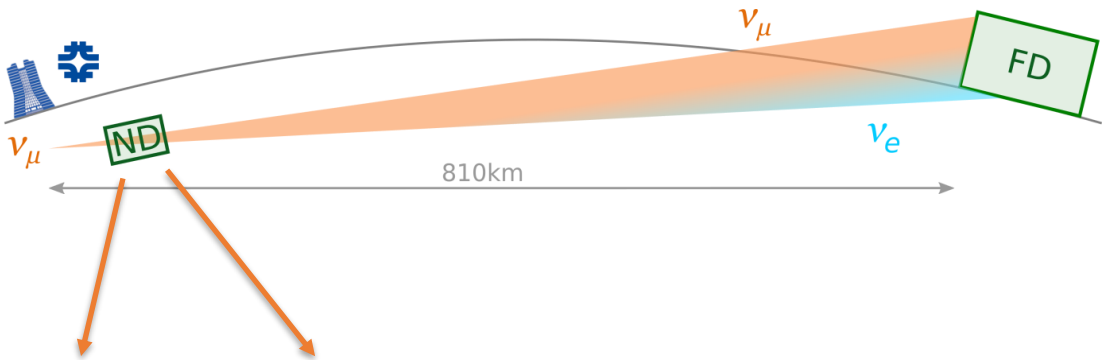
- Measure ν_μ / $\bar{\nu}_\mu$ and ν_e / $\bar{\nu}_e$ **energy spectra** in **FD.**

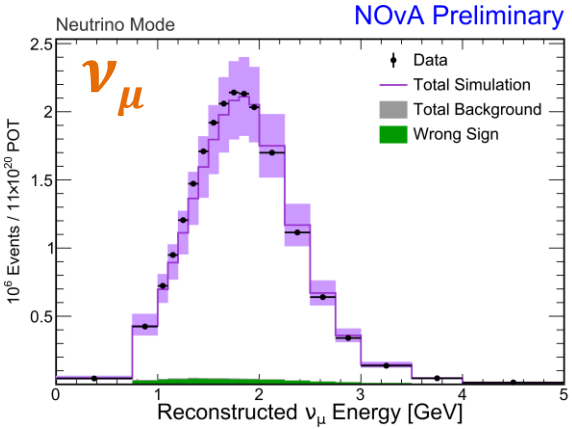
ND to FD Extrapolation

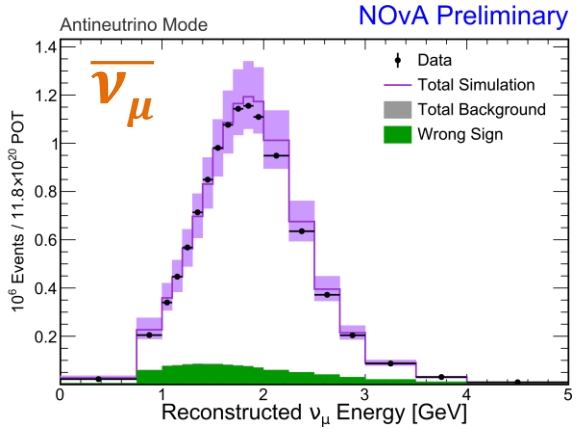


- Measure ν_μ / $\bar{\nu}_\mu$ in the **ND** and extrapolate to greatly **cancel** the **flux** and **cross-section uncertainties**.

How does NOvA measure neutrino oscillation parameters?







- Large statistics.
- Systematic bands come from **flux** and **cross-section** uncertainties

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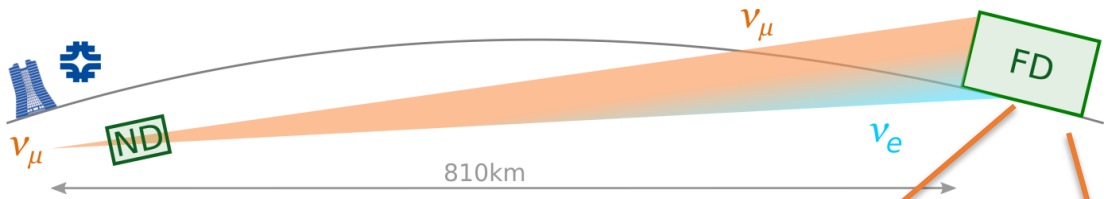
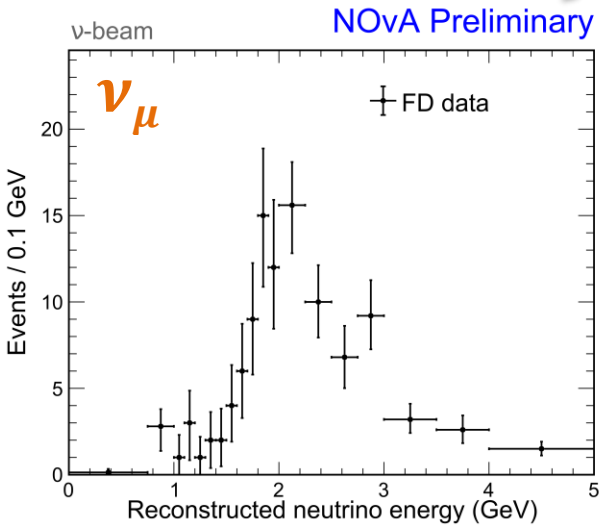
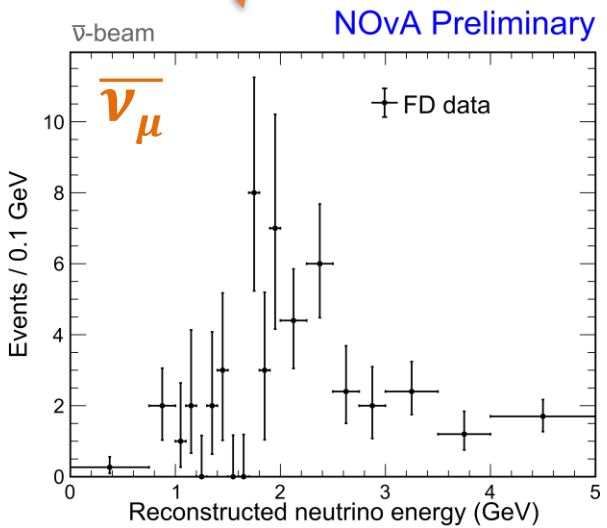
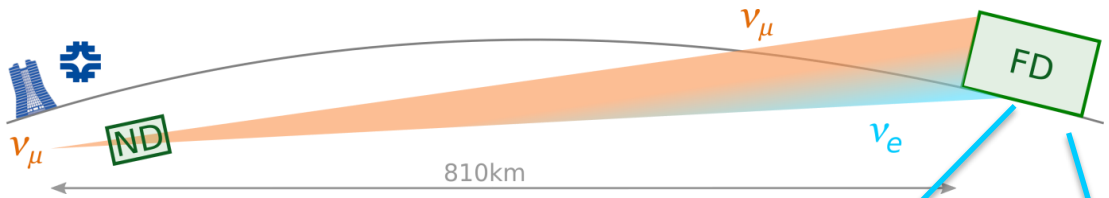


- Surviving ν_μ / $\bar{\nu}_\mu$ spectra
  - **211 ν_μ candidates**
  - **105 $\bar{\nu}_\mu$ candidates**
- Without oscillations, would expect >1000 ν_μ and ~500 $\bar{\nu}_\mu$ candidates.

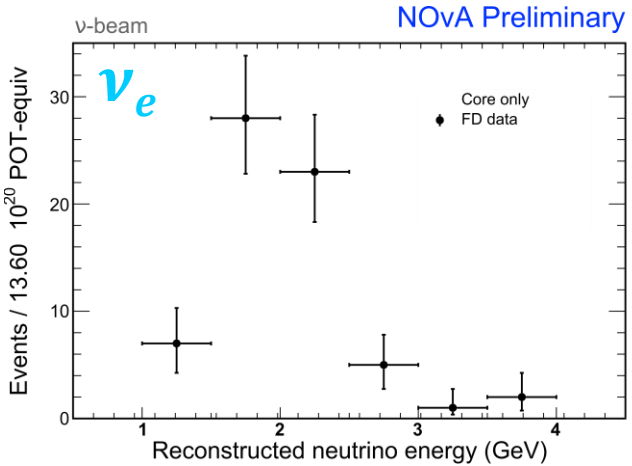


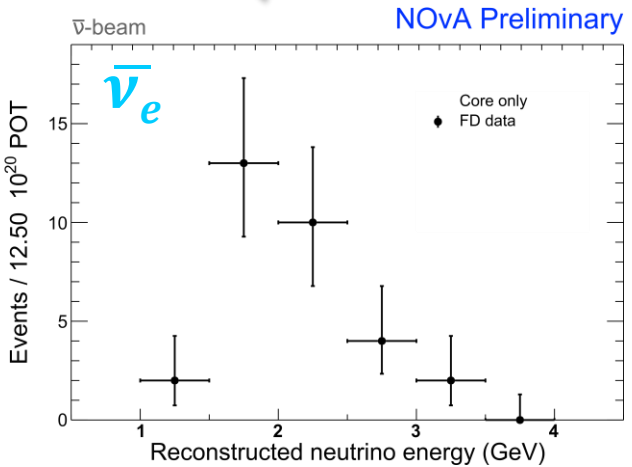


How does NOvA measure neutrino oscillation parameters?

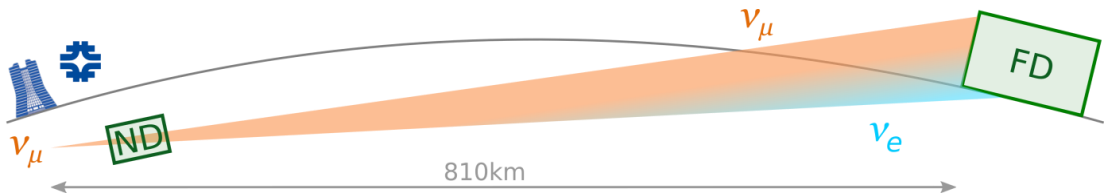


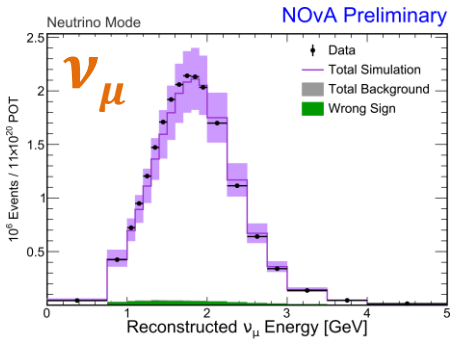
- Appearing ν_e / $\bar{\nu}_e$ spectra
  - **82 ν_e candidates**
  - **33 $\bar{\nu}_e$ candidates**

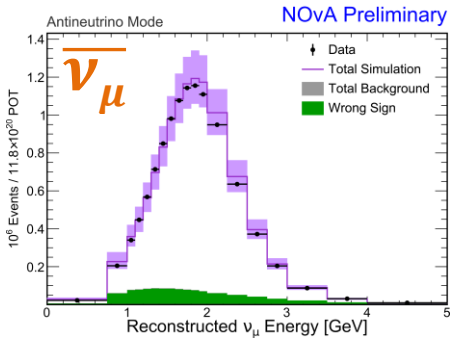




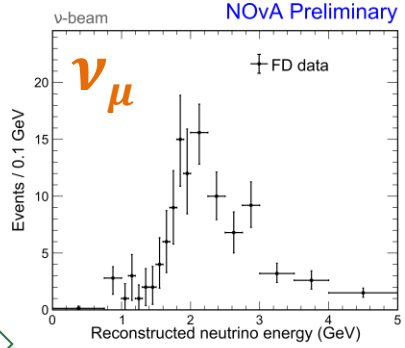
What are NOvA's latest 3-flavor oscillation results?

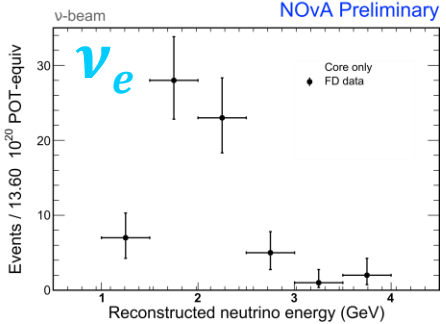


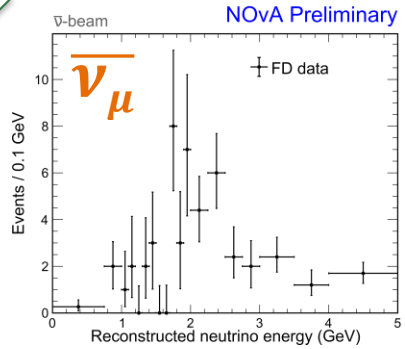


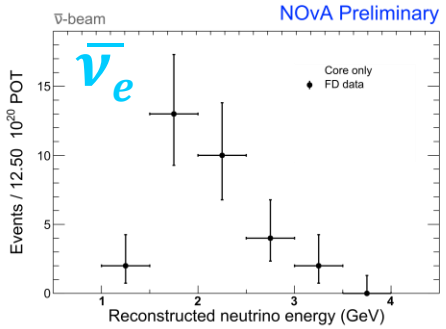


Which set of oscillation parameters generate predictions closest to data?









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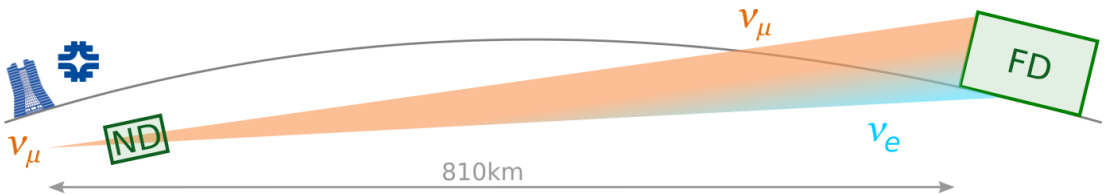
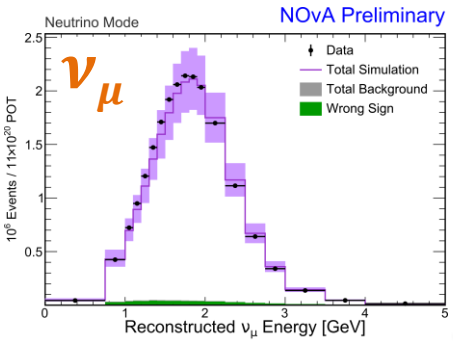
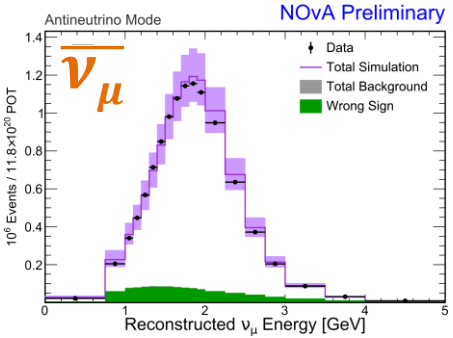




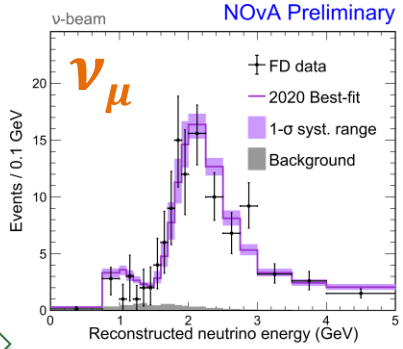


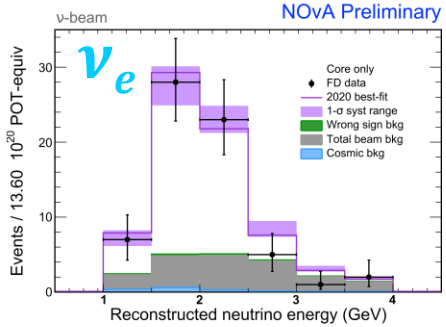
Best fit prediction

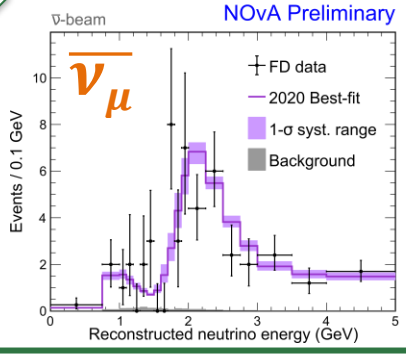
$\Delta m^2_{32} = +2.41 \times 10^{-3}\ \text{eV}^2$

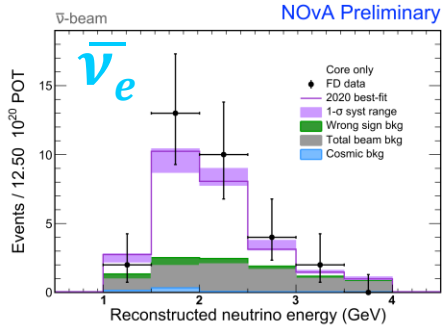
$\sin^2\theta_{23} = 0.57$

$\delta_{CP} = 0.82\pi$

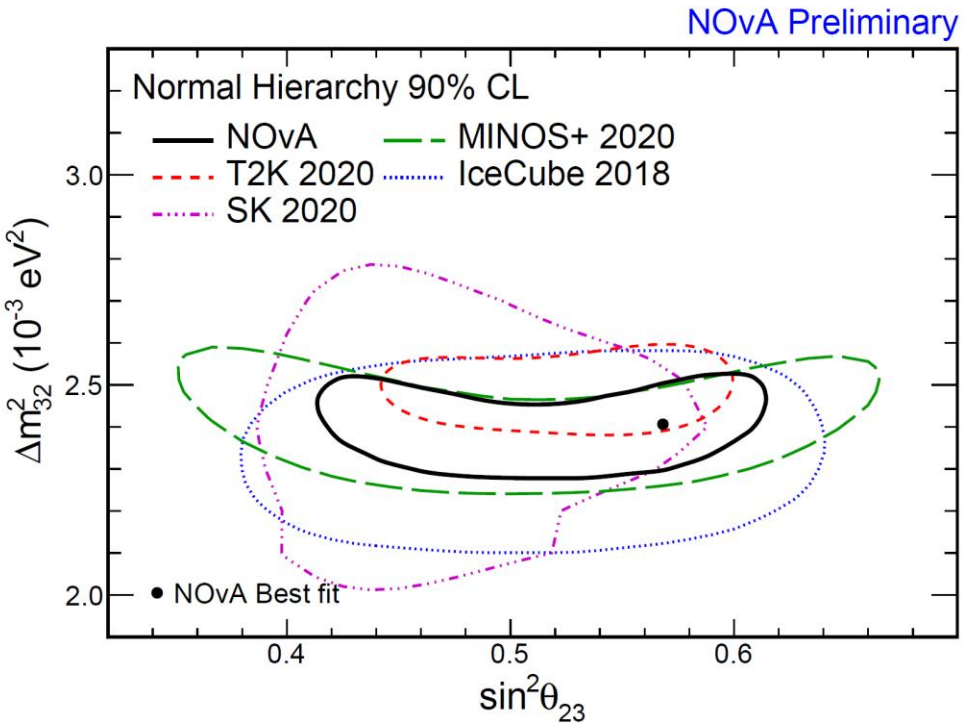








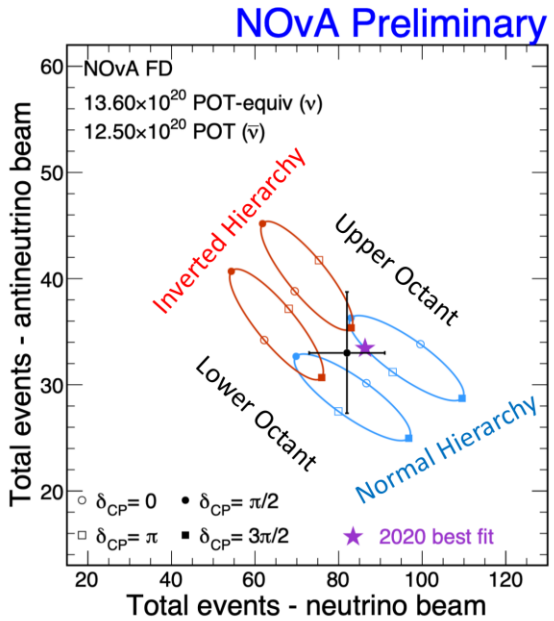
What is NOvA's constraint on $\sin^2\theta_{23}$ and Δm^2_{32} ?



- Best fit in **Normal Hierarchy** and **Upper Octant** ($\theta_{23} > 45^o$).
- **Precision measurements**:
  - $\Delta m^2_{32} = 2.41 \pm 0.07 \times 10^{-3}$ eV^2 ($\pm 3\%$)
  - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$ ($\pm 7\%$)
- Preference for:
  - **Normal Hierarchy** at 1.0σ
  - **Upper Octant** at 1.2σ
  - Non-maximal mixing at 1.1σ

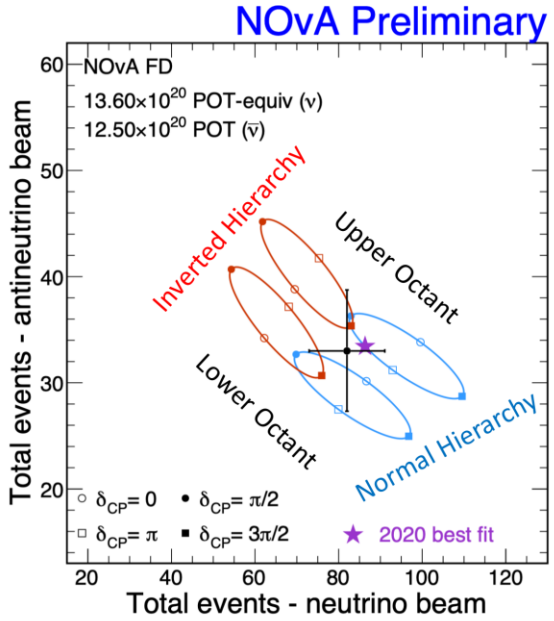
What is NOvA's constraint on δ_{CP} ?

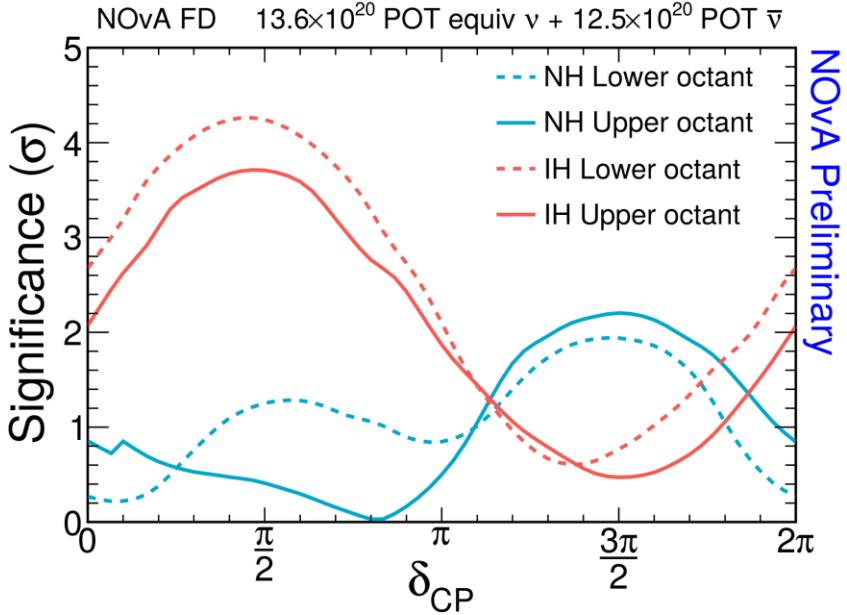
- Observed ν_e - $\bar{\nu}_e$ **appearance** rates fall in a degenerate region of the param. space.



What is NOvA's constraint on δ_{CP} ?

- Observed ν_e - $\bar{\nu}_e$ **appearance** rates fall in a degenerate region of the param. space.
- No significant ν_e - $\bar{\nu}_e$ asymmetry observed.





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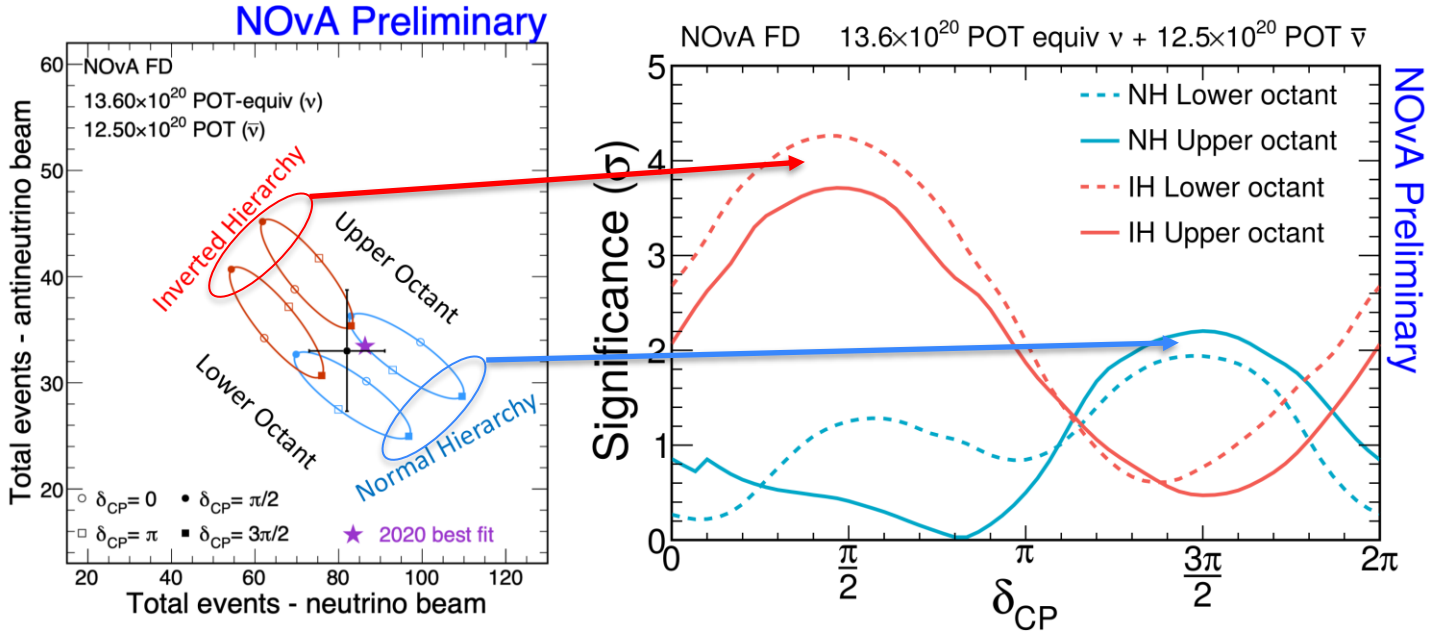
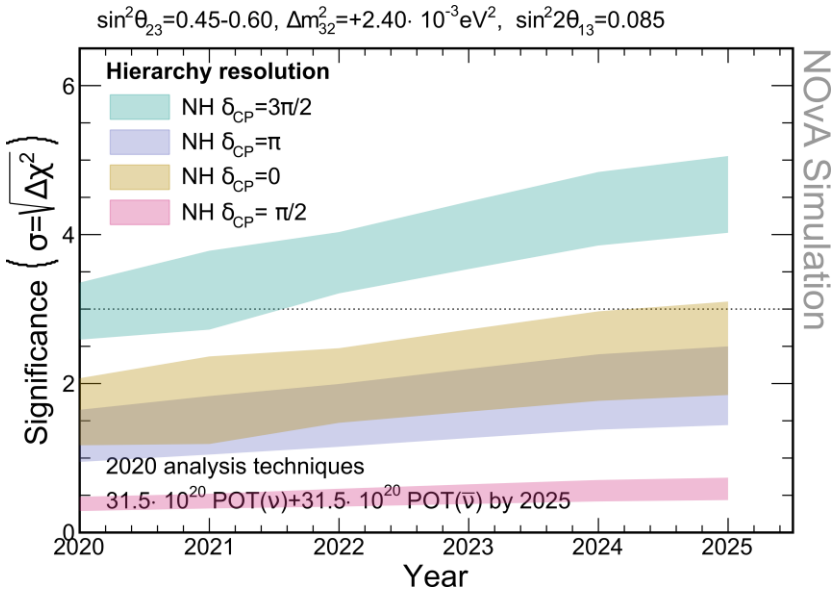
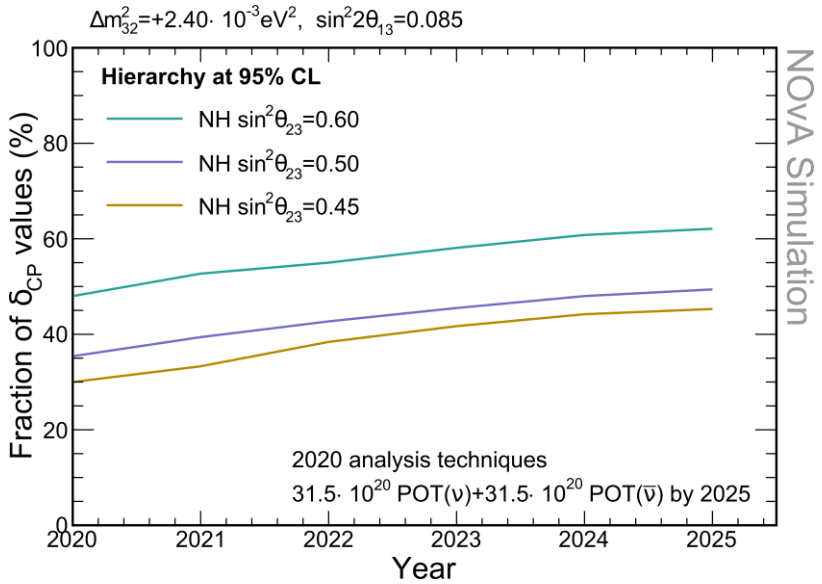
- Disfavor **IH $\delta_{CP}=\pi/2$ at >3σ** and **NH $\delta_{CP}=3\pi/2$ at 2σ**.



What is NOvA's future sensitivity?

- Run until **2026**, accumulating more than **3×10^{21} POT** in both ν and $\bar{\nu}$ modes.
- Could reach **5σ sensitivity** to **Mass Hierarchy** for the most favorable parameter.
- Probe the majority of δ_{CP} **values** at **2σ-level**.





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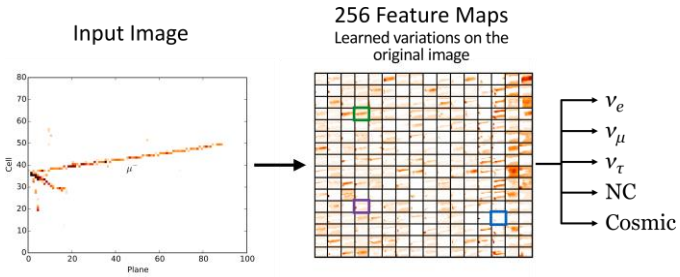

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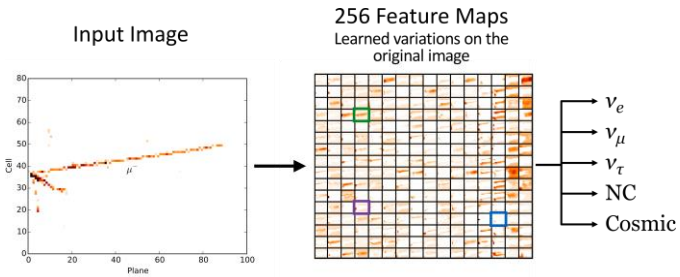
- **NOvA Test Beam** program is ongoing at **Fermilab Test Beam Facility**: reduce our largest systematics.



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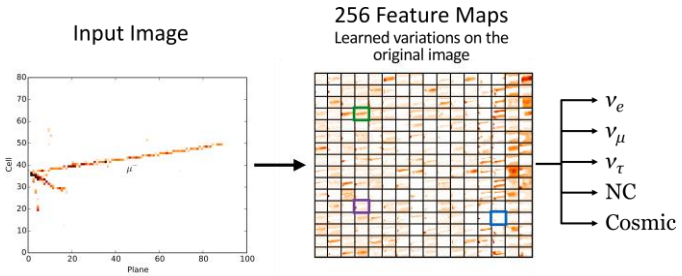
- **NOvA Test Beam** program is ongoing at **Fermilab Test Beam Facility**: reduce our largest systematics.
- Many important **neutrino cross-section** measurements from NOvA are coming.
- **NOvA-T2K** joint fit effort ongoing.



Conclusions

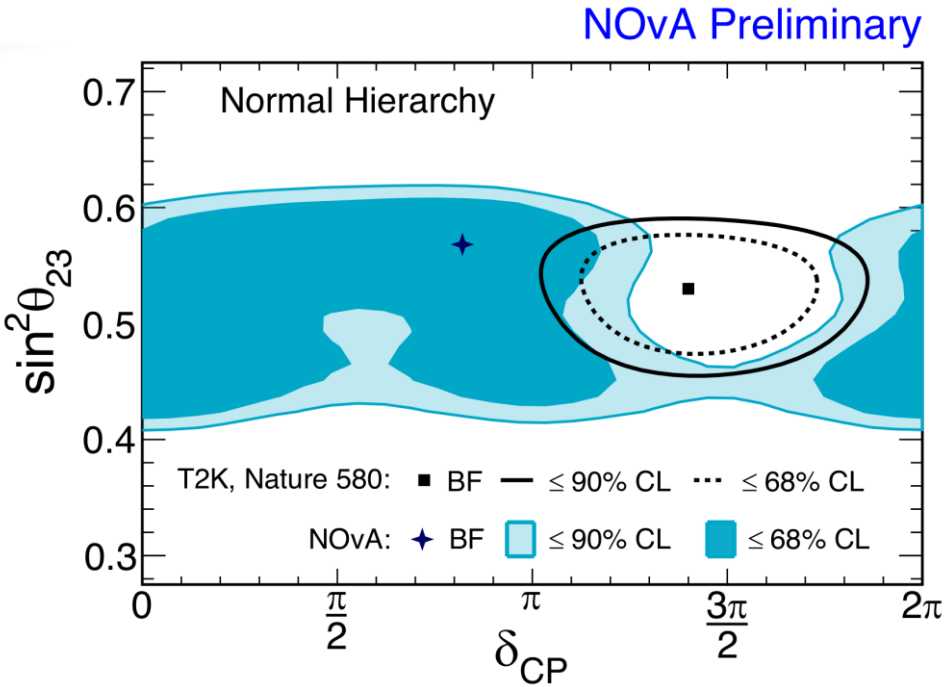
- **Latest results** with **50% more neutrino** mode exposure and **updated analysis**.
- Preference for **Normal Hierarchy** (1.0σ) and **Upper Octant** (1.2σ).
- Achieved some of the **most precise measurement** of:
  - $\Delta m^2_{32} = 2.41 \pm 0.07 \times 10^{-3}$ eV^2
  - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
- Exclude **IH $\delta_{CP}=\pi/2$ at >3σ** and disfavor **NH $\delta_{CP}=3\pi/2$ at 2σ**.
- Stay tuned for many **interesting papers** to appear soon!

Questions?

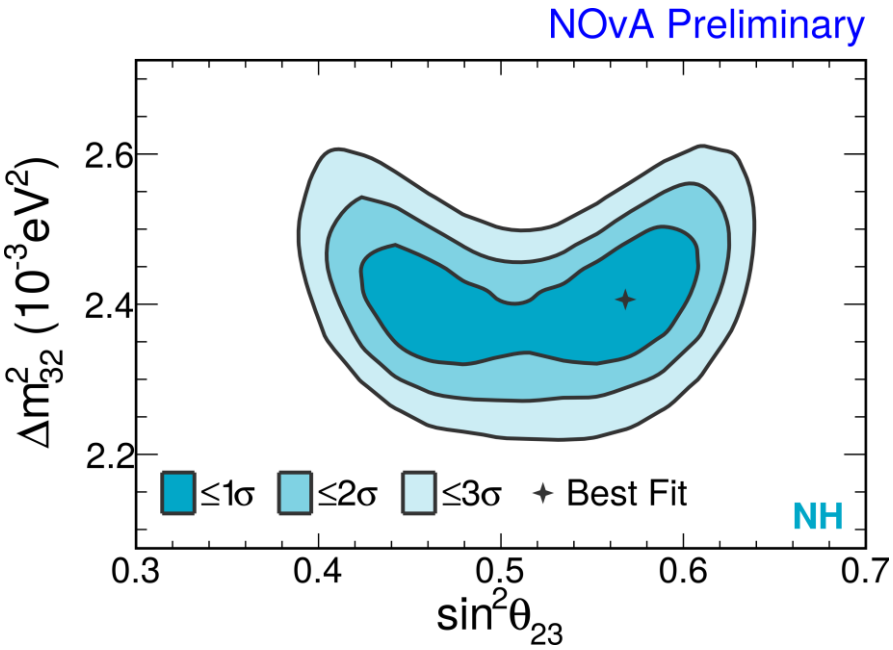
Backup

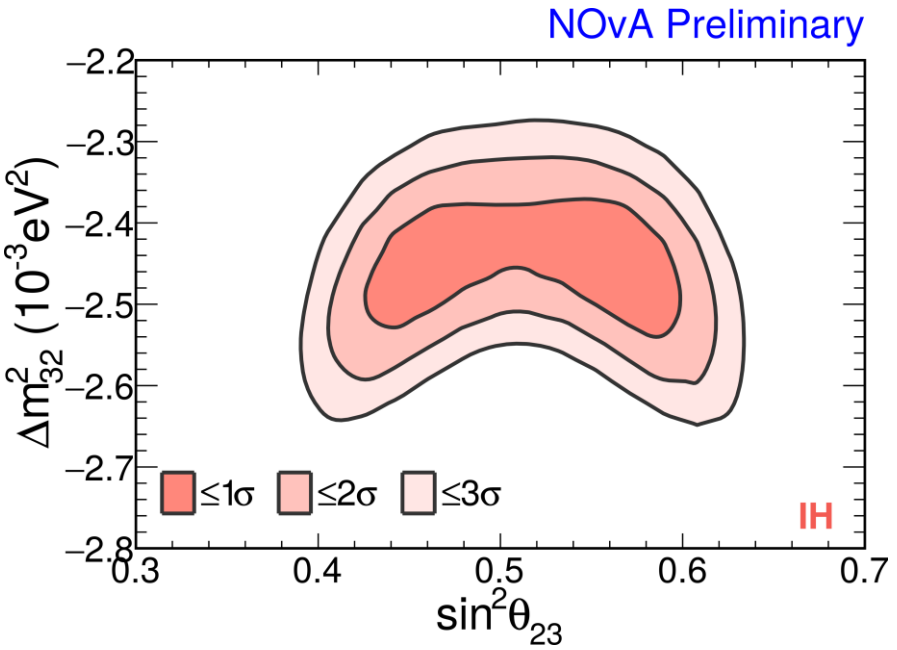
Joint NOvA-T2K analysis

- **T2K results** are statistically compatible with ours.
- Ongoing effort towards a joint NOvA-T2K fit.

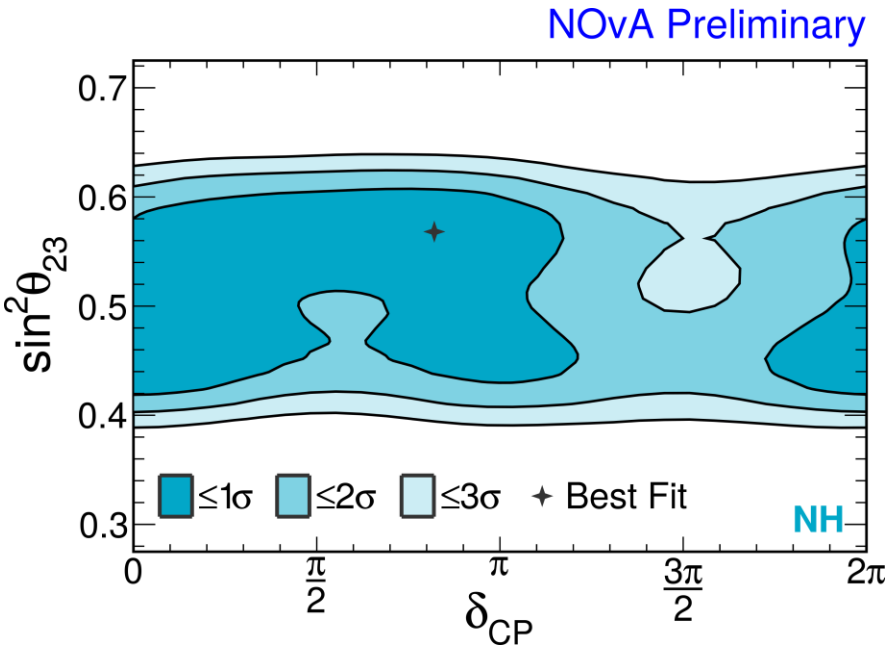


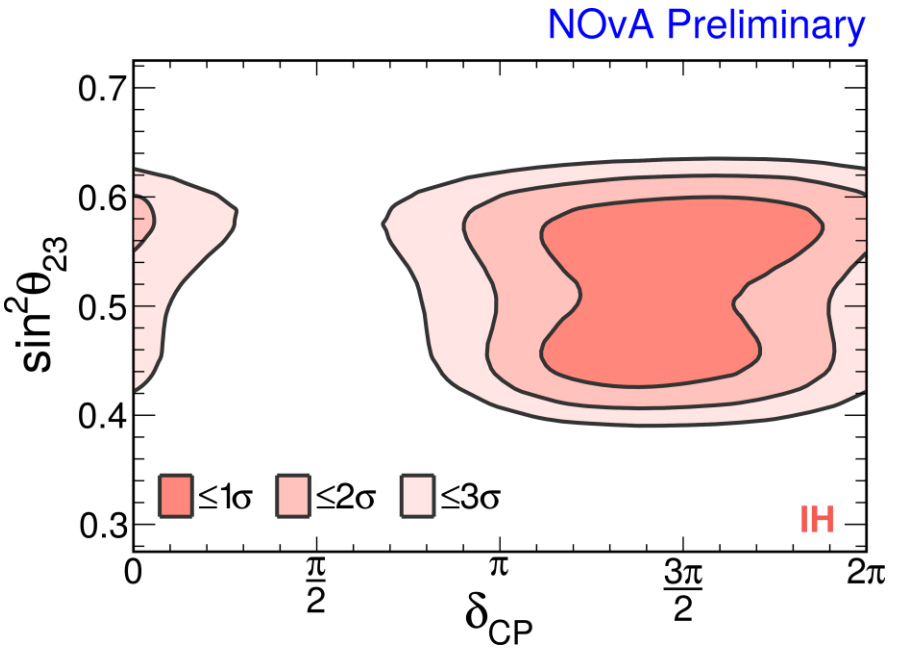
Δm^2_{32} vs. $\sin^2\theta_{23}$



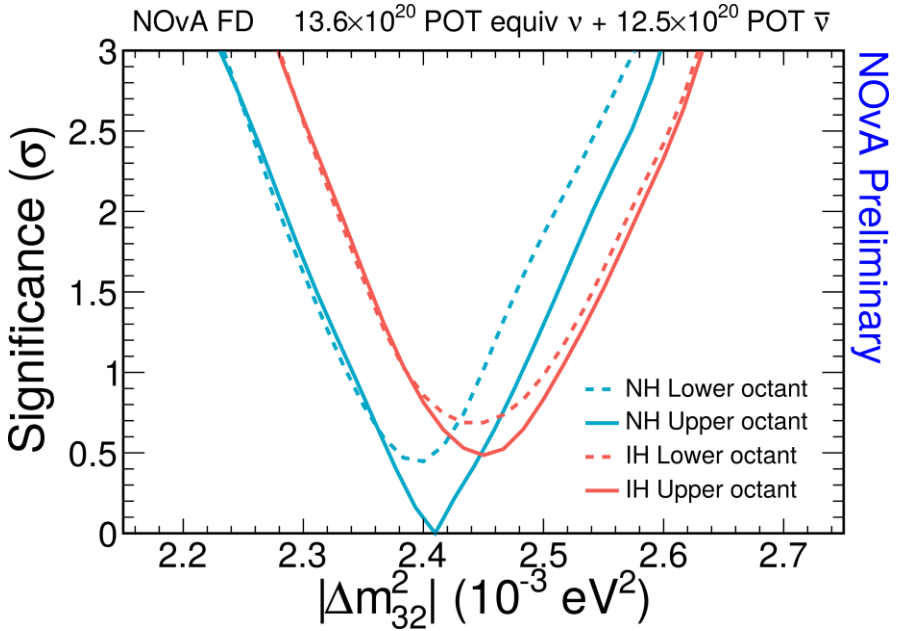


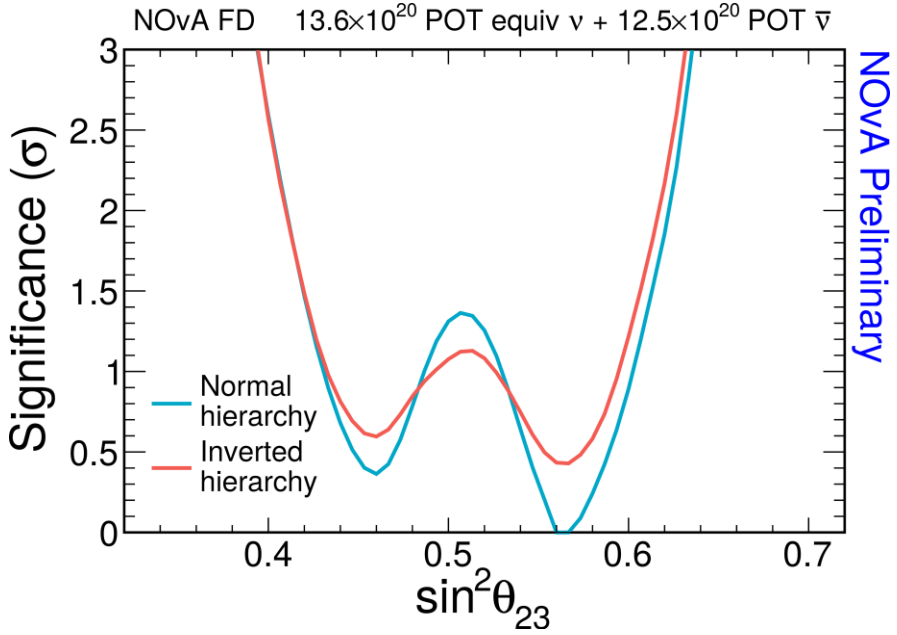
$\sin^2\theta_{23}$ vs. δ_{CP}





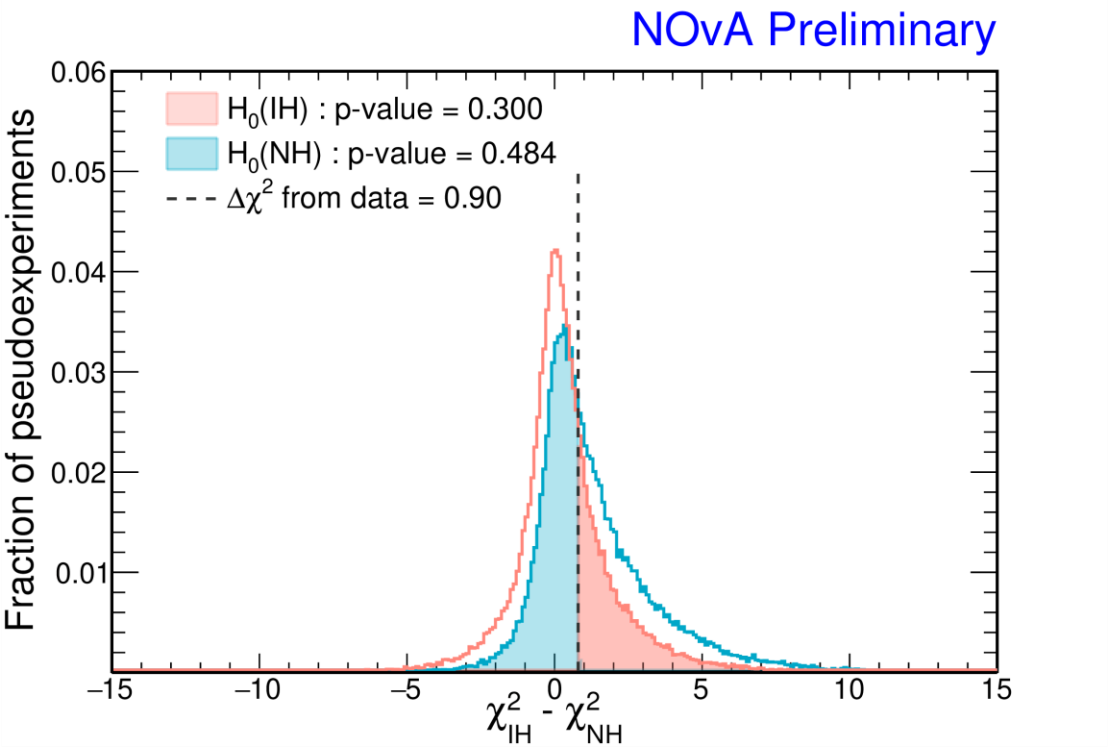
Δm^2_{32} and $\sin^2\theta_{23}$





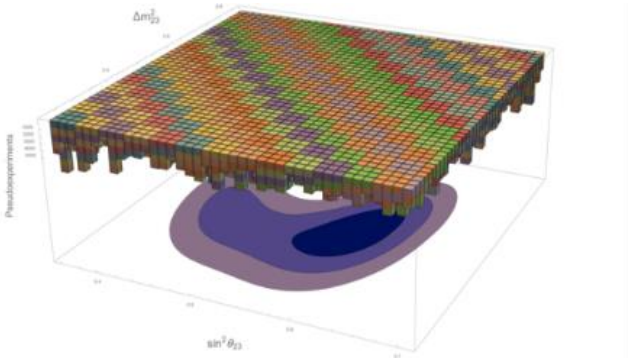
Mass hierarchy CL_S

- **CL_S** factor : 0.620



How are confidence intervals built?

- Generate and fit **millions of pseudoexperiments** to build empirical χ^2-distributions: **Feldman-Cousins approach**.
- Extremely **computationally expensive**.
- Implemented a **massive parallel framework** on **High Performance Computing** platforms like **NERSC**, in collaboration with the SciDAC-4 HEP Data Analytics program.
- Time to results brought from **6 months** on FermiGrid and OpenScience grid down to a **few days/weeks** on NERSC machines.



SciDAC
Scientific Discovery through Advanced Computing

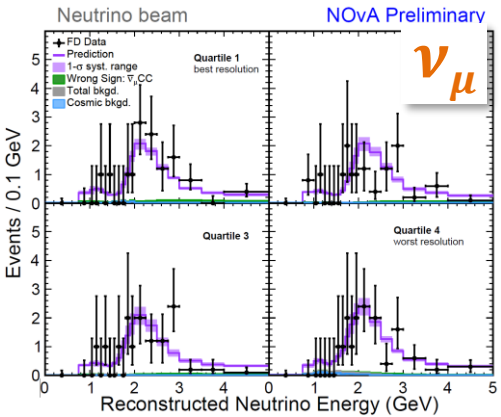
NERSC

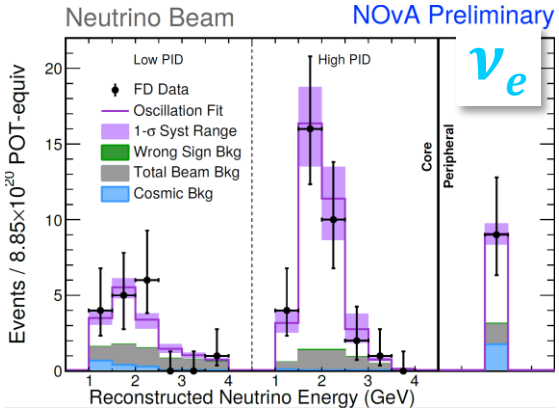
Sensitivity optimization

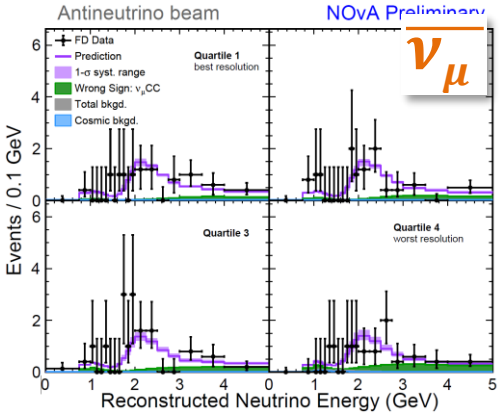
- Measurement **sensitivity** can be **increased** by splitting:
  - ν_μ / $\overline{\nu_\mu}$ events into quartiles depending

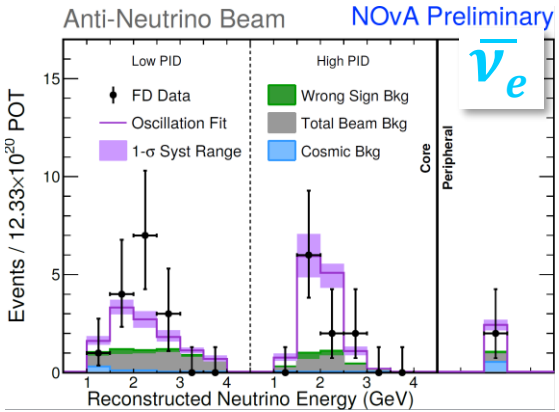
    on their **energy resolution**.
  - ν_e / $\overline{\nu_e}$ events into levels of confidence

    in the **event classifier**.



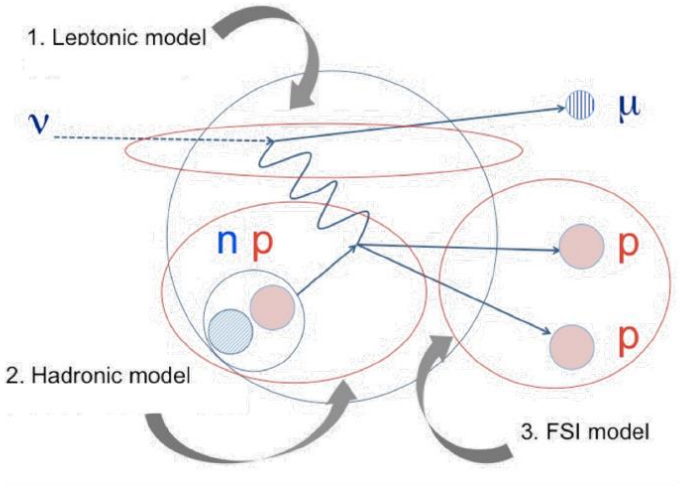






GENIE Tune

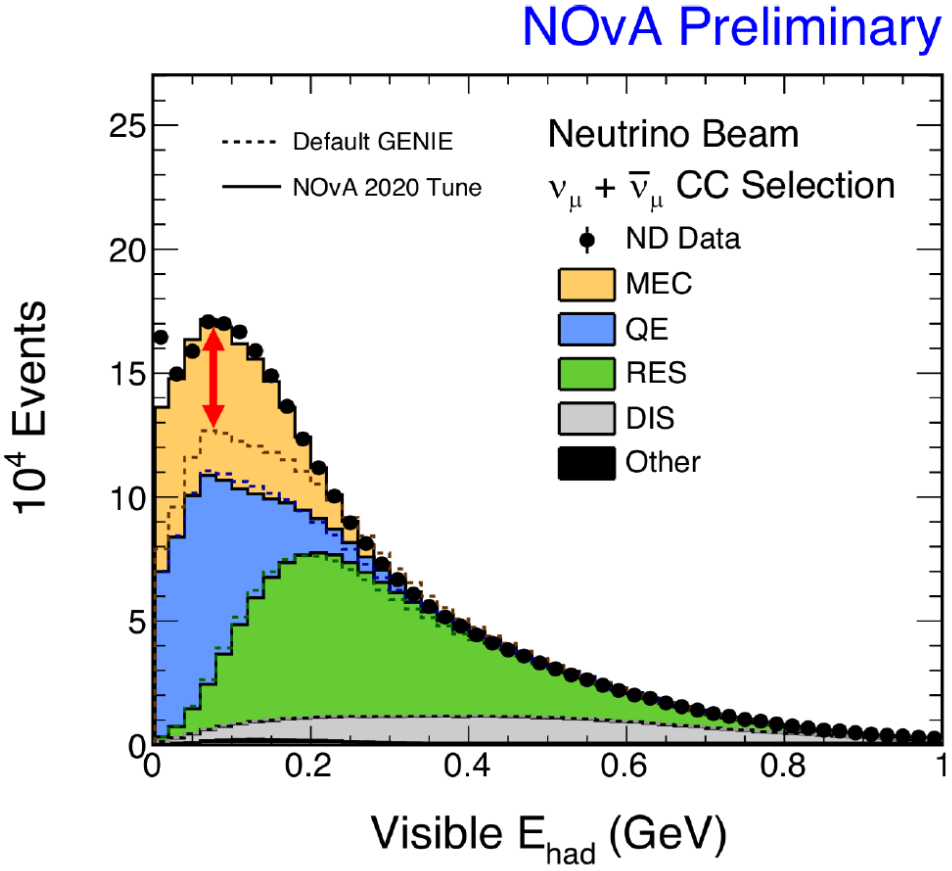
- Used **GENIE 3.0.6** in NOvA 2020 analysis: choose the most theory-driven models and retune some parameters to better match ND data.



Process	Model
Quasielastic	Valencia 1p1h
Form Factor	Z-expansion
Multi-nucleon	Valencia 2p2h
Resonance	Berger-Sehgal
DIS	Bodek-Yang
Final State Int.	hN semi-classical cascade

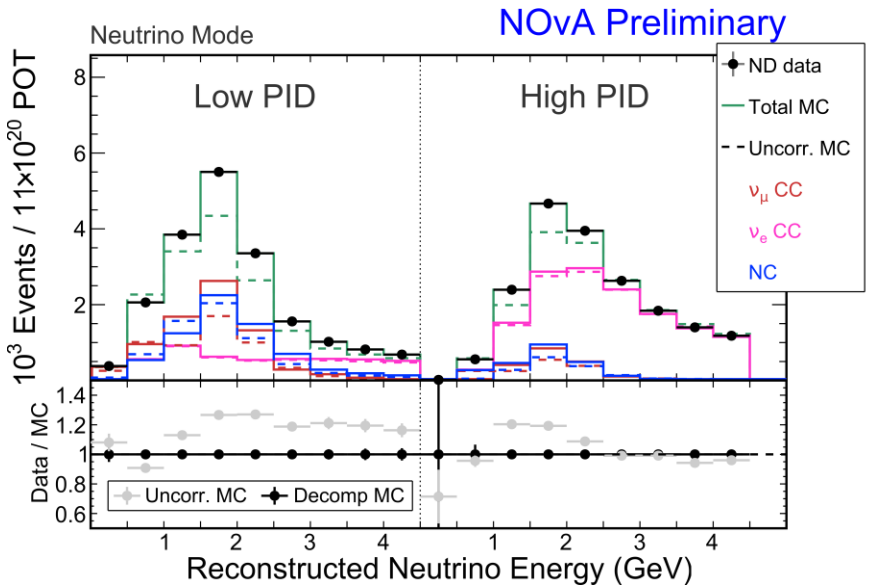
GENIE Tune

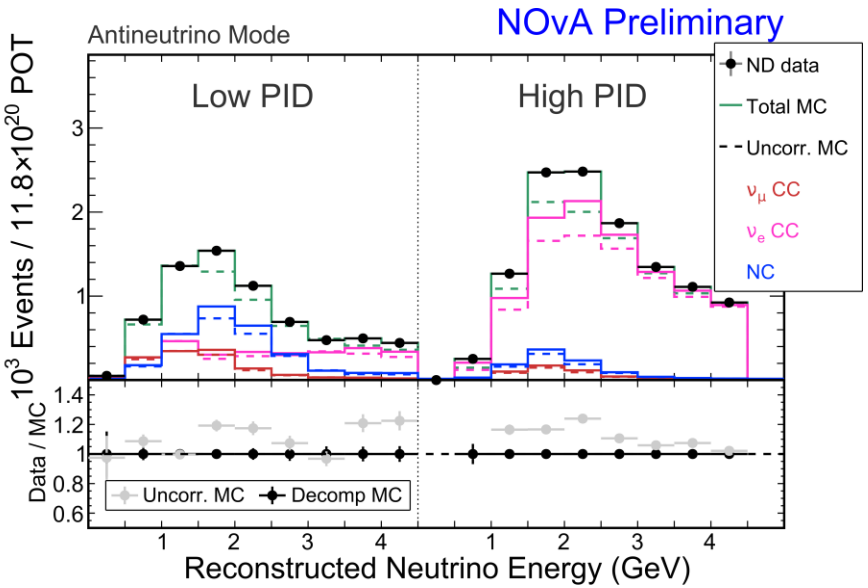
- Largest **tunes**:
  - Meson Exchange Current (MEC or 2p2h): tune to **ND data**
  - Final State Interactions (FSI): use external **π-scattering data**



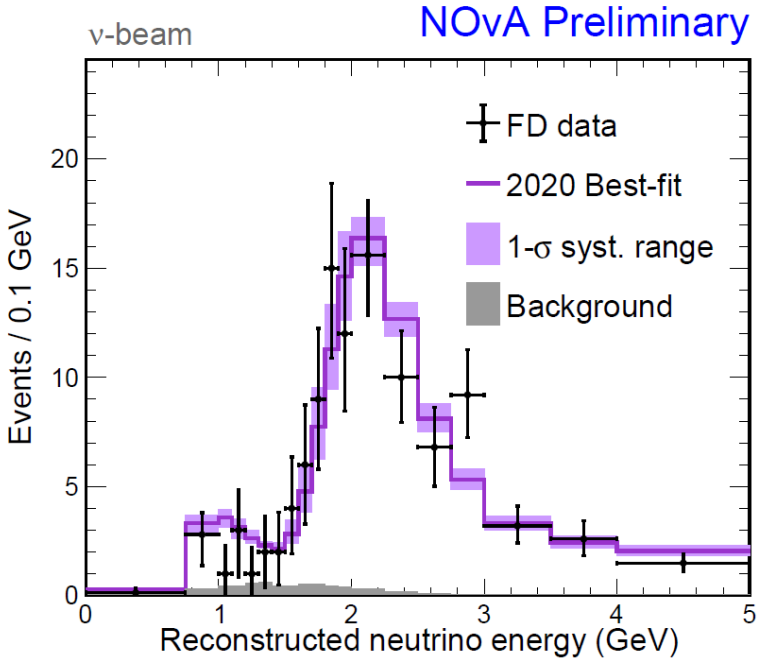
Data driven corrections

- Data-driven techniques lead to small adjustments to the ν_μ CC, ν_e CC and NC rates.

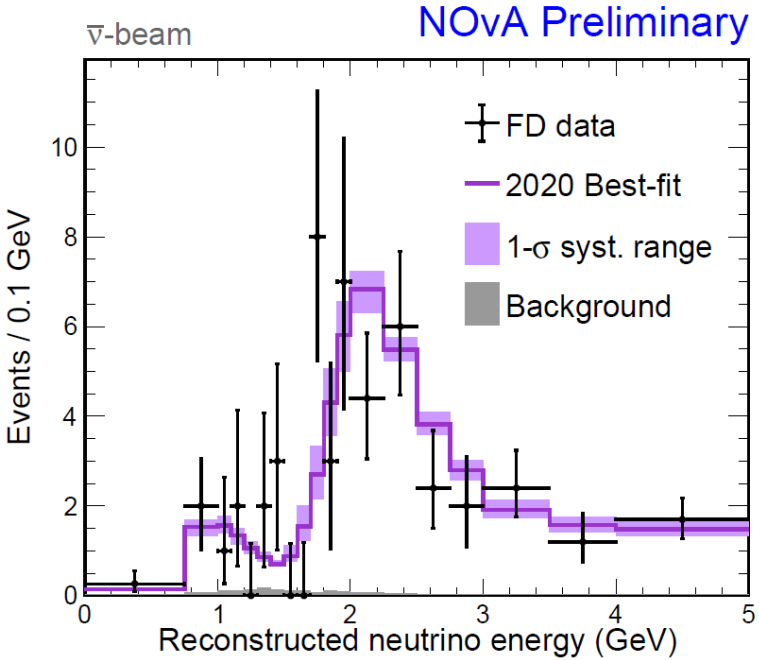




FD ν_μ data

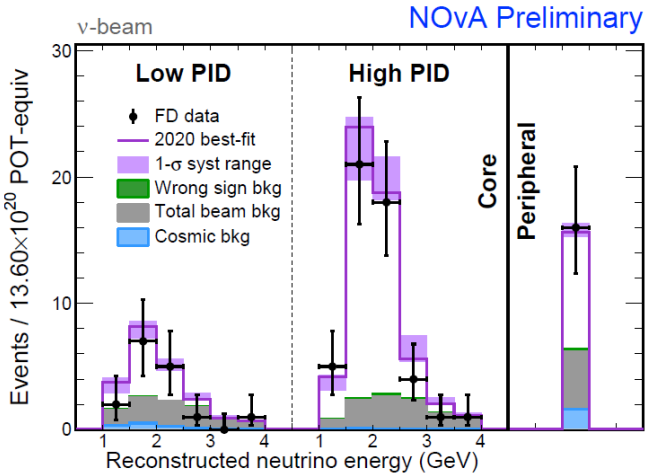


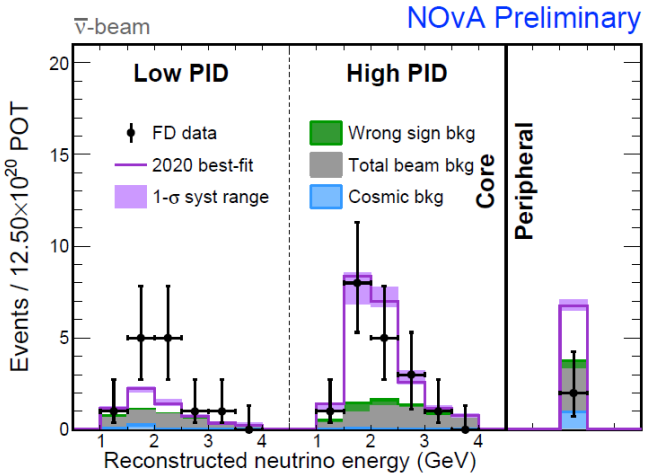
Obs. ν_μ candidates	211
Total background	8.2



Obs. $\overline{\nu}_\mu$ candidates	105
Total background	2.1

FD ν_e data



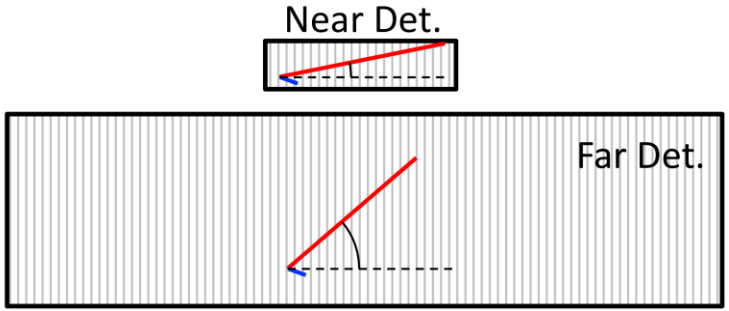


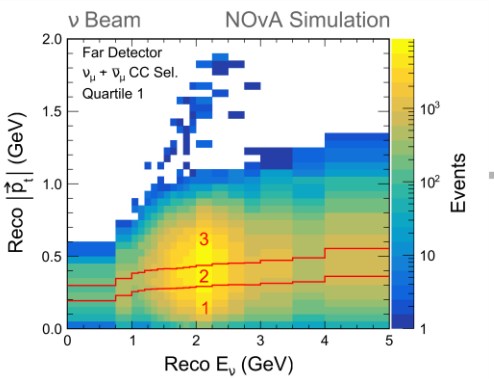
Obs. ν_e candidates	82
Best fit prediction	85.8
Total background	26.8
Beam bkg	22.7
Cosmic bkg	3.1
Wrong sign	1.0

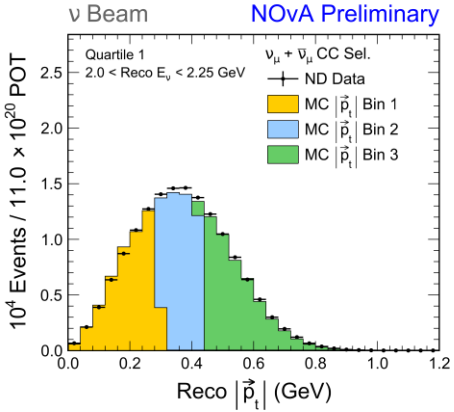
Obs. ν_e candidates	33
Best fit prediction	33.2
Total background	14.0
Beam bkg	10.2
Cosmic bkg	1.6
Wrong sign	2.3

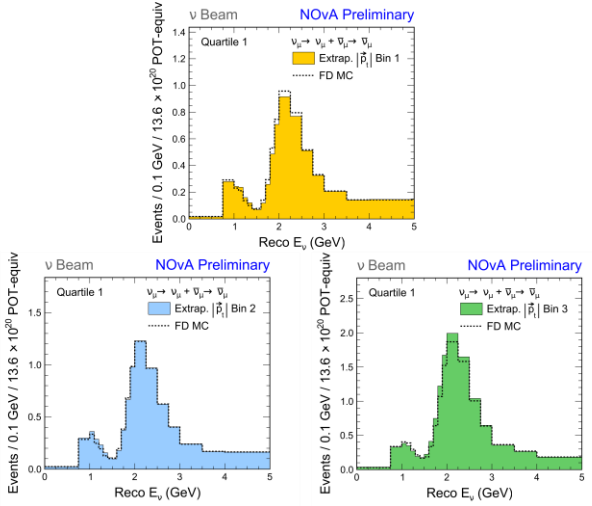
p_t extrapolation

- ND/FD containment difference.
- Split ND samples into 3 bins of transverse momentum and extrapolate separately.
- Reduce cross-section uncertainty by 30%. Overall systematics reduction is 10%.



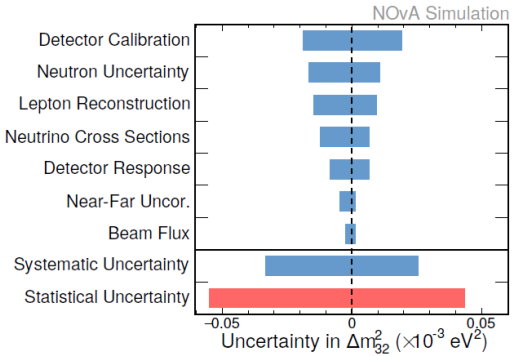


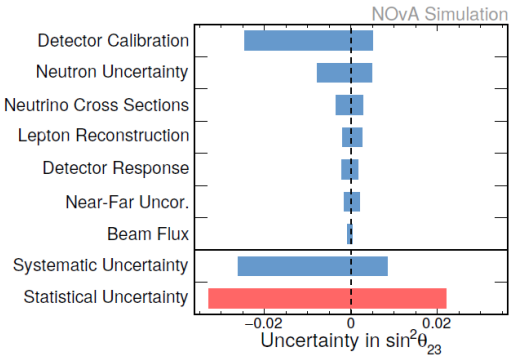


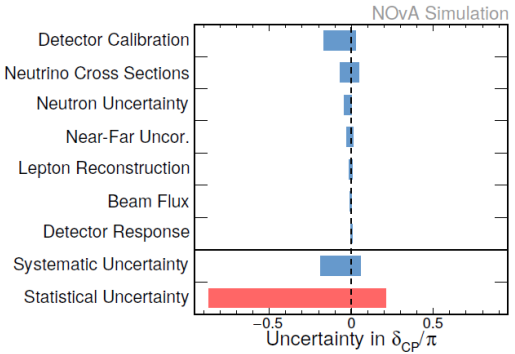


Systematics

- **Detector calibration**: will be improved by the ongoing test beam program at FNAL.
- **Neutron uncertainty**: cover discrepancies observed in low-energy $\overline{\nu}$ data. Ongoing work to improve our simulation and understanding of neutrons in the detectors.
- **Neutrino cross-sections**: use own tuning but still noticeable nuclear effects (RPA, MEC).







Systematics

- Without the ND to FD extrapolation technique, **cross-section and flux uncertainties** would be **dominant**, especially for the appearance analysis which is extremely **rate sensitive**.