Latest results from the NOvA experiment

Steven Calvez

53rd Fermilab Users Meeting

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NOvA

COLORADO STATE UNIVERSITY

What are the main goals of the NOvA experiment?

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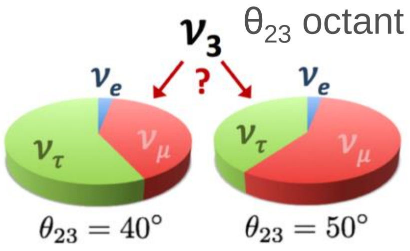

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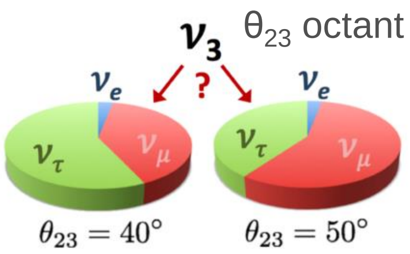

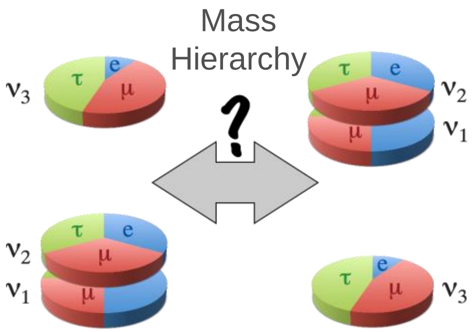

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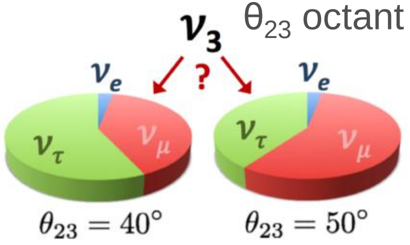
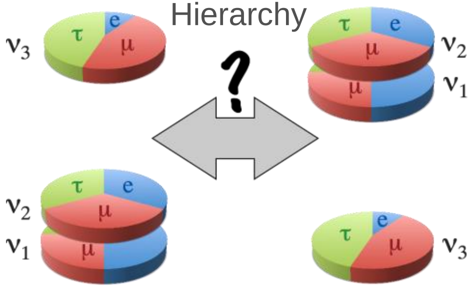
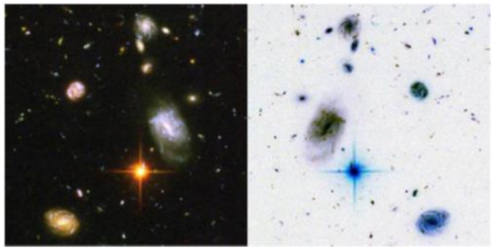
θ_{23} octant



Mass Hierarchy



δ_{CP} ?



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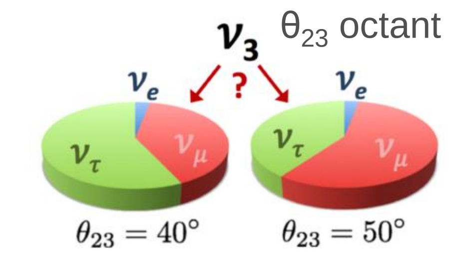

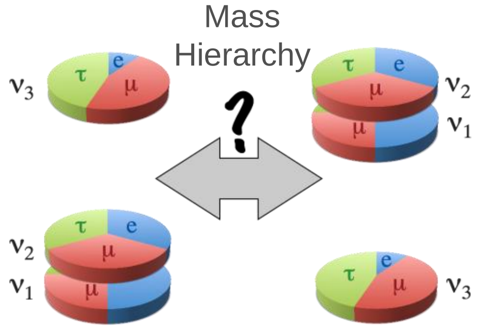

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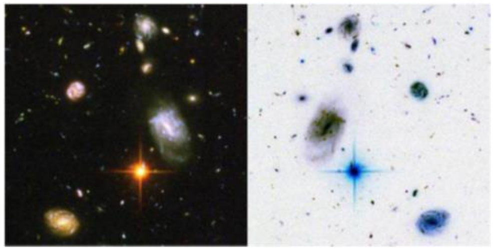
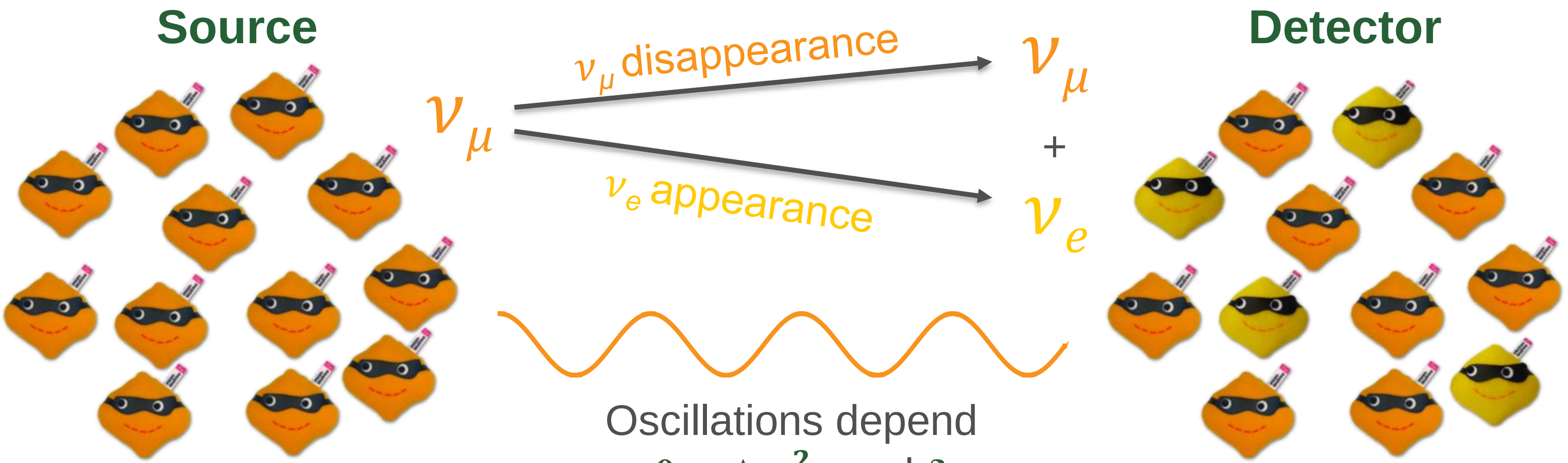


- NOvA has a **rich physics program**:
  - **Neutrino cross-section** measurements. *See Steven G.'s talk.*
  - Search for **sterile neutrinos**. *See Gianluca's talk.*
  - Investigate **astrophysical** and **exotics** phenomena.

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.



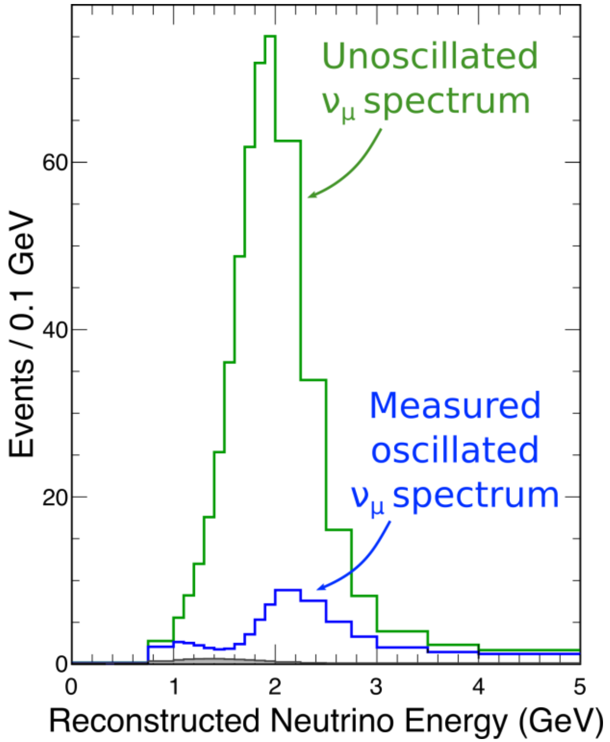
Oscillations depend on θ_{23}, Δm^2_{32} and δ_{CP}

How can NOvA measure neutrino oscillation parameters?

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

  - ν_μ survival probability:

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



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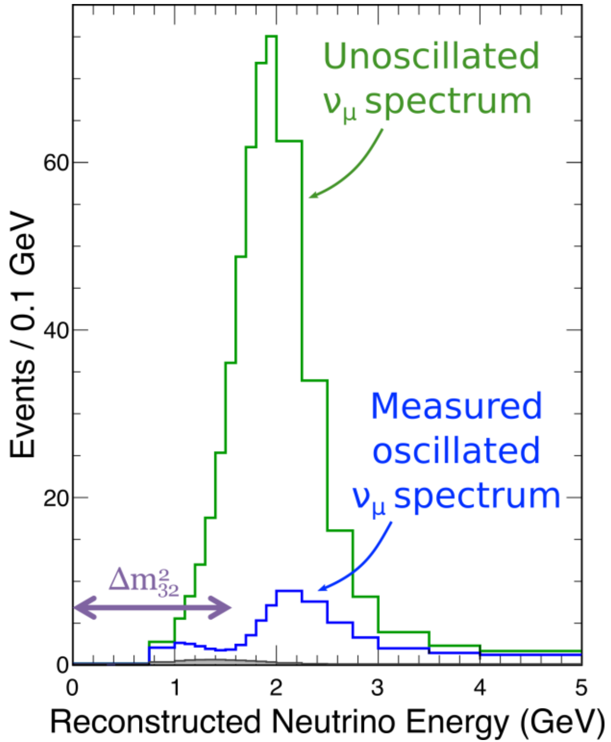

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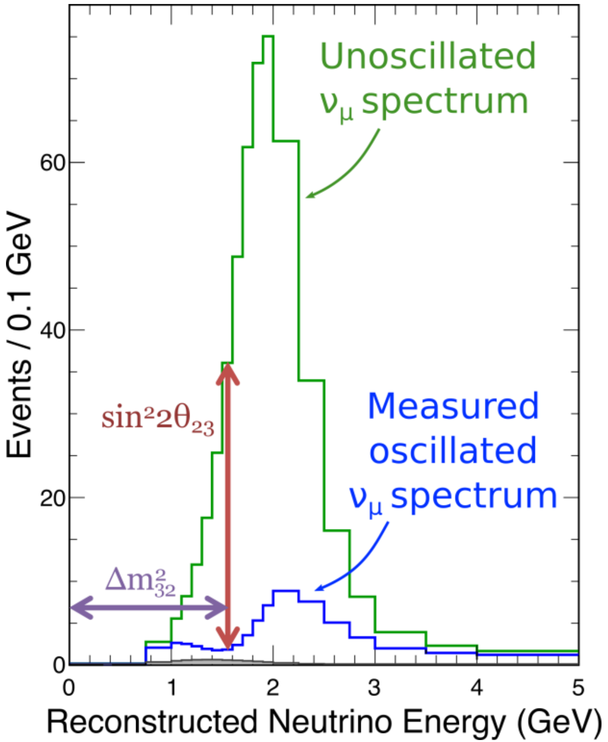
  - Location of dip $\rightarrow$ $|\boldsymbol{\Delta m^2}_{32}|$

  - Amplitude of dip $\rightarrow$ $\mathbf{sin^2 2\theta_{23}}$



How can NOvA measure neutrino oscillation parameters?

- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \bar{\nu}_e}$ **appearance** to constrain $\mathbf{sin^2\theta_{23}}$, $\boldsymbol{\Delta m^2_{32}}$ and $\boldsymbol{\delta_{CP}}$:

  - ν_e appearance probability:

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

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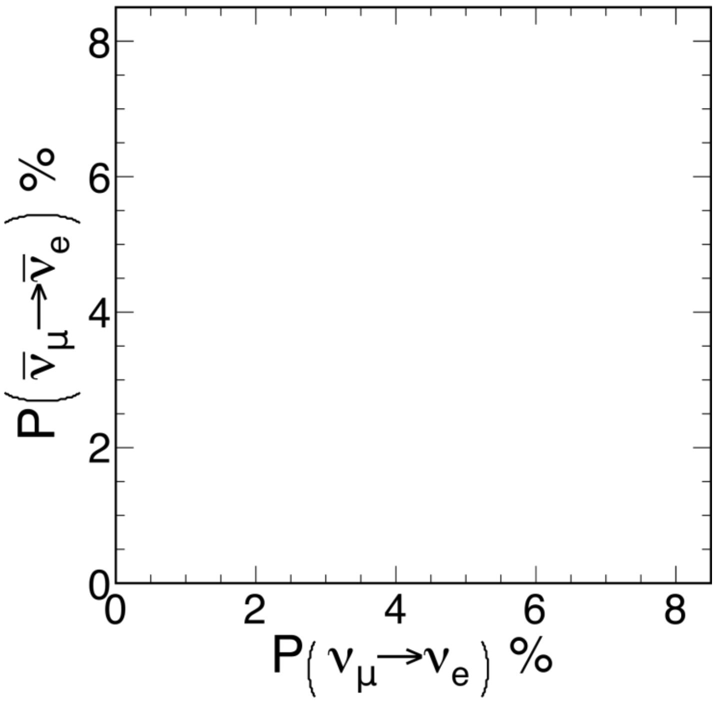

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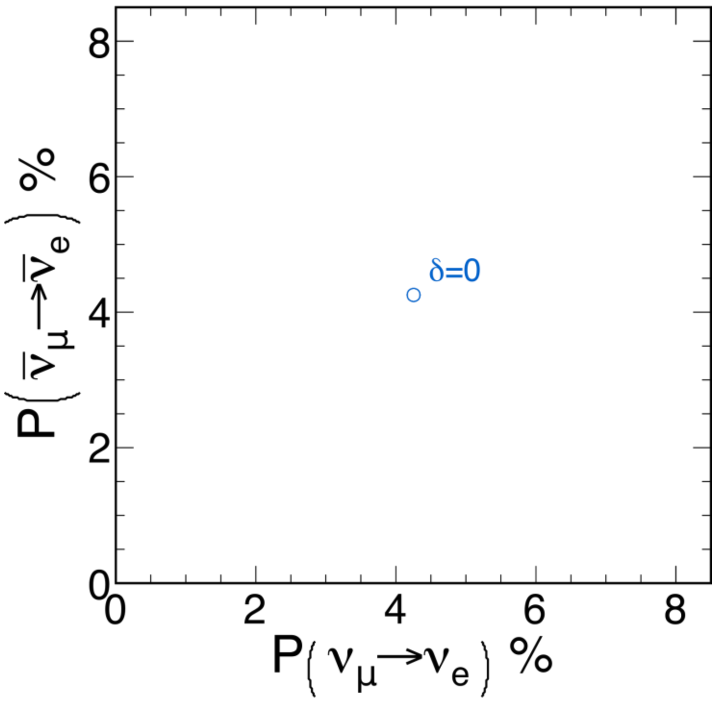
➢ In a vacuum and with no CP-violation, **ν** and $\boldsymbol{\overline{\nu}}$ oscillation probabilities are **equal**.



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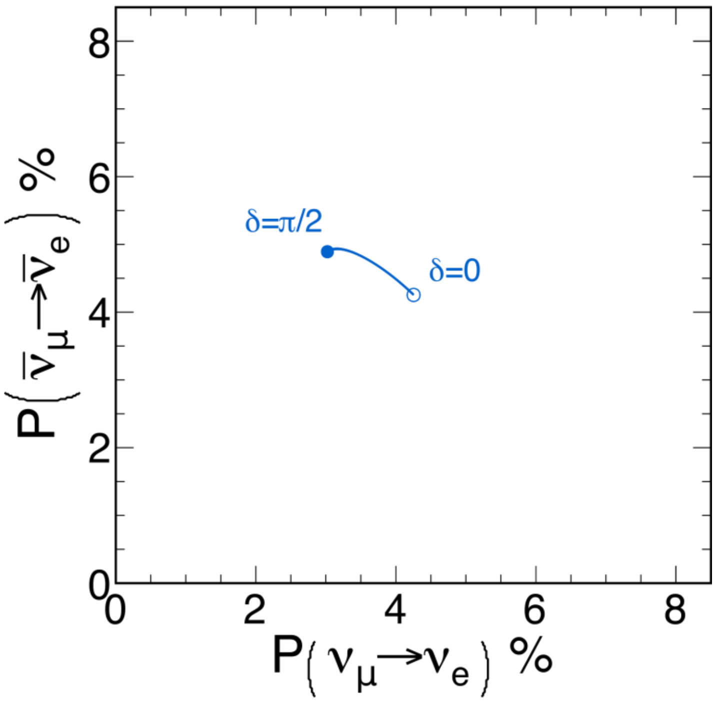
➢ **CP-violation** generates **opposite effects** in $\boldsymbol{\nu}$ and $\boldsymbol{\bar{\nu}}$ oscillation probabilities.



How can NOvA measure neutrino oscillation parameters?

- Measure $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\overline{\nu_\mu} \rightarrow \bar{\nu}_e}$ **appearance** to constrain **$\sin^2\theta_{23}$, $\Delta m^2{}_{32}$** and **δ_{CP}**:

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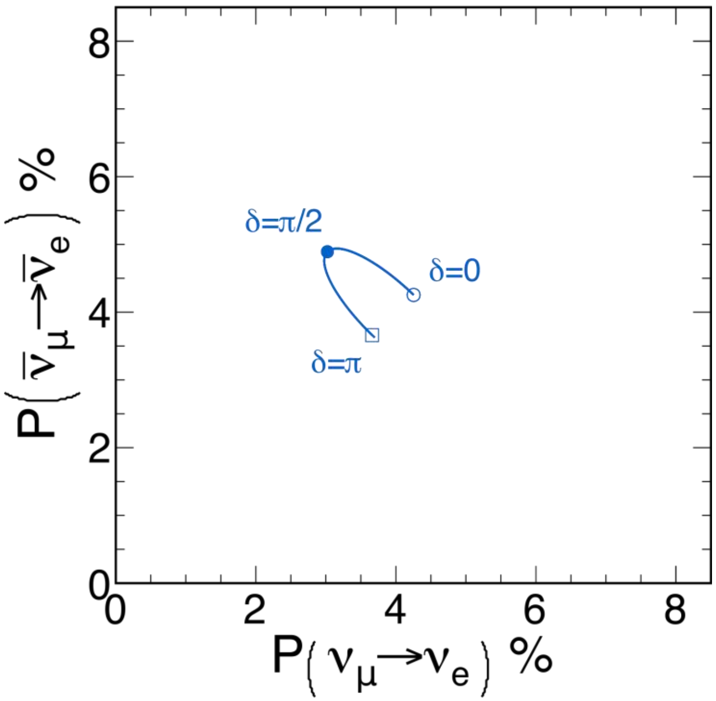
➢ Other **CP-conserving phase** yields slightly different oscillation probabilities.



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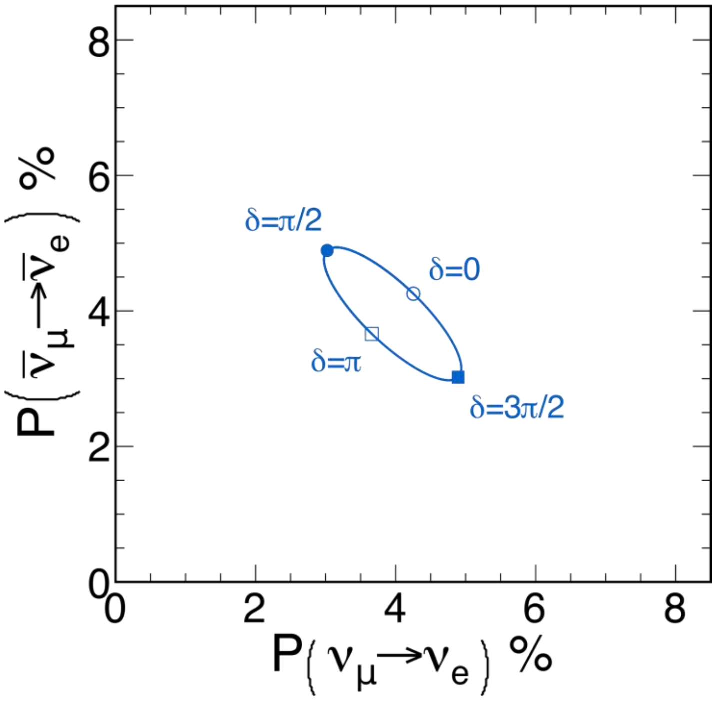

➢ Other maximum violating **CP phase enhances $\boldsymbol{\nu_e}$ appearance.** $\boldsymbol{\delta_{CP}}$ is cyclical.

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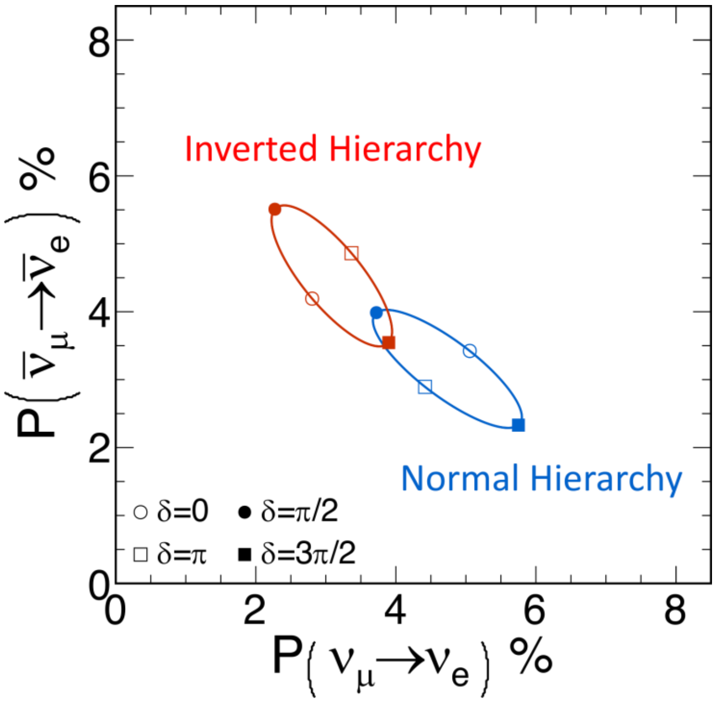

➢ **Matter effects** also generate opposite effects in $\boldsymbol{\nu}$-$\boldsymbol{\bar{\nu}}$ oscillations depending on the **Mass Hierarchy.**

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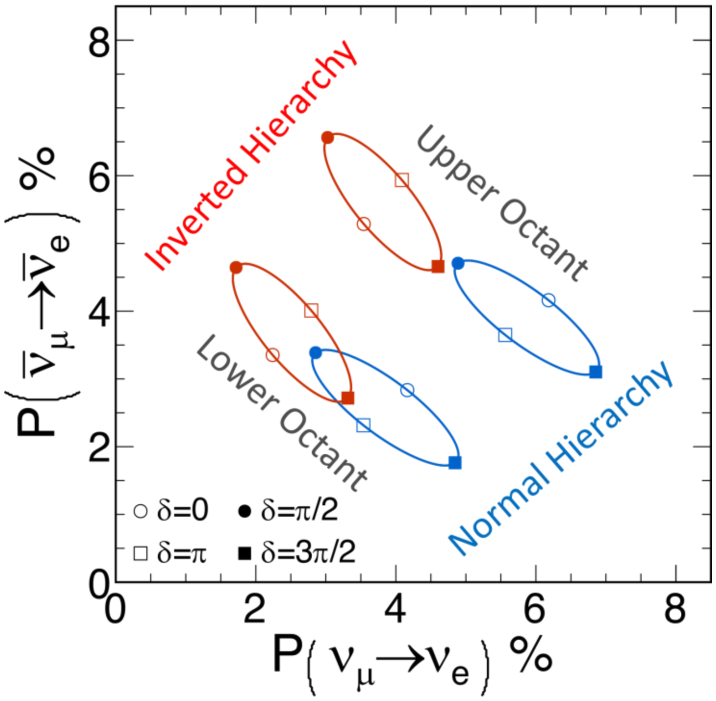
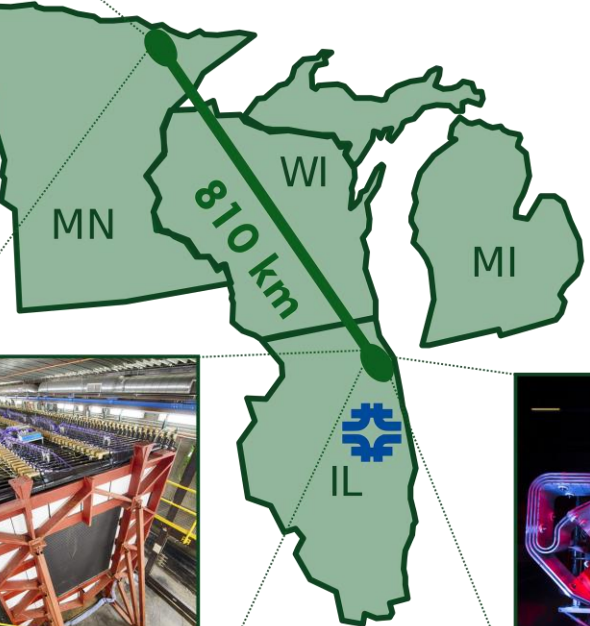


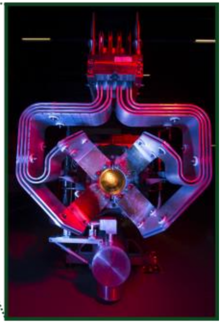
➢ θ_{23} can increase or decrease ν and $\bar{\nu}$ oscillations probabilities.

What is the NOvA experiment?

Far Detector



NuMI beam



Near Detector

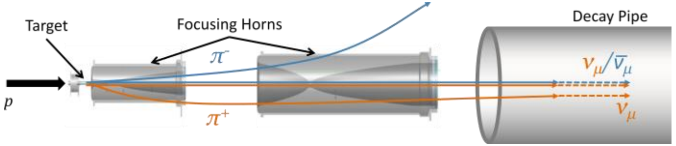
How are neutrinos produced?

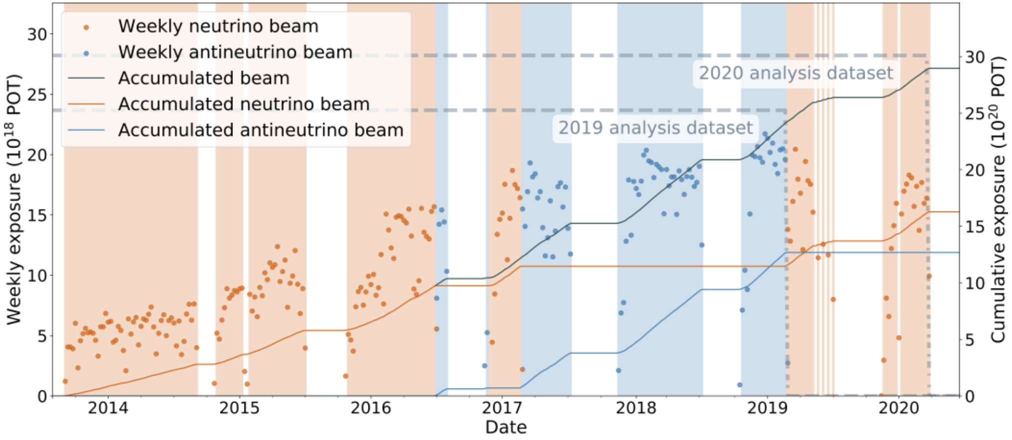
- **NuMI beam** can produce both $\boldsymbol{\nu_\mu}$ and $\boldsymbol{\overline{\nu_\mu}}$.

- **World most powerful neutrino beam:** typical power of 670kW (peaks >750kW).

- **+50% neutrino** mode exposure last year.

- Ongoing **improvements** to reach **900kW.**

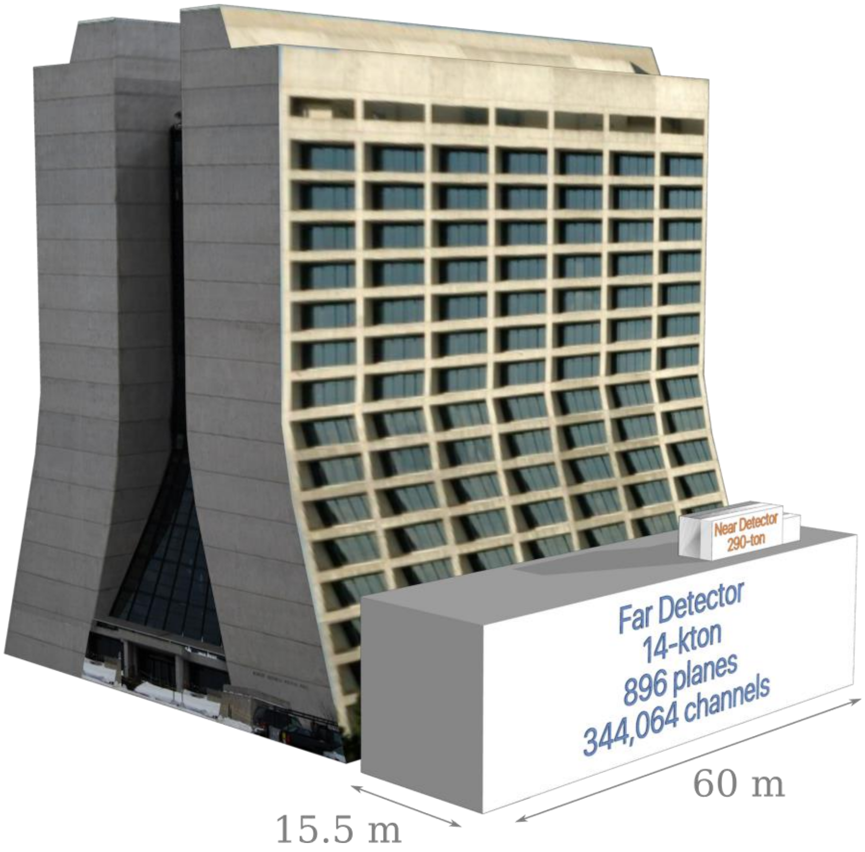





MW-capable target


MW-capable horn

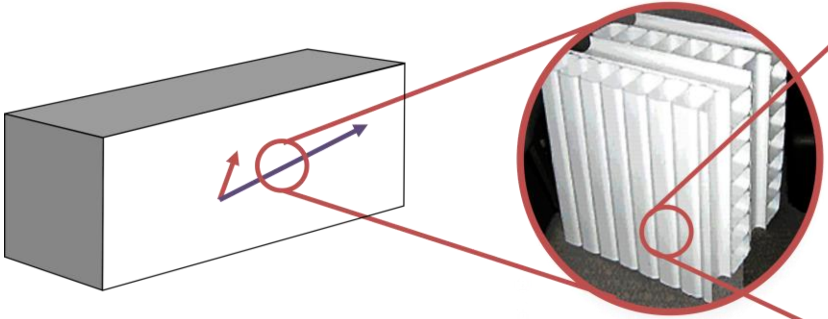
How are neutrinos detected?

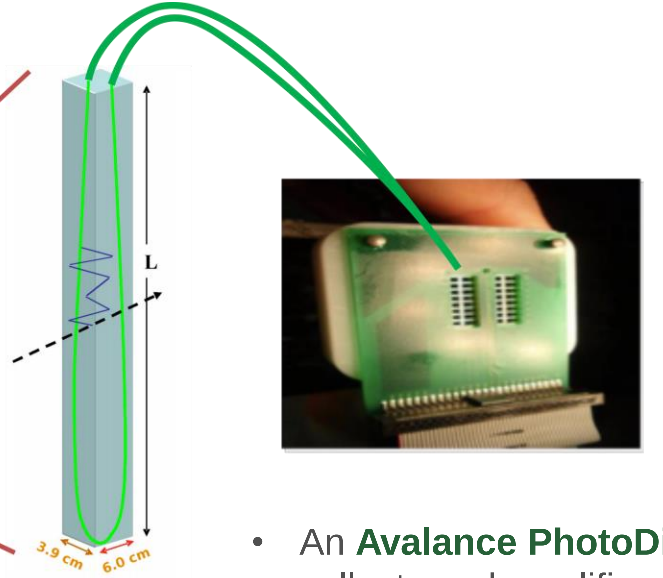


- The NOvA **Near Detector** and **Far Detector** are both **segmented liquid scintillator** detectors providing **3D tracking** and **calorimetry**.
- **Near Detector**:
  - 290 tons.
  - 350 ft underground at Fermilab.
- **Far Detector**:
  - 14 ktons.
  - 810km away on the surface in Minnesota.

How are neutrinos detected?

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





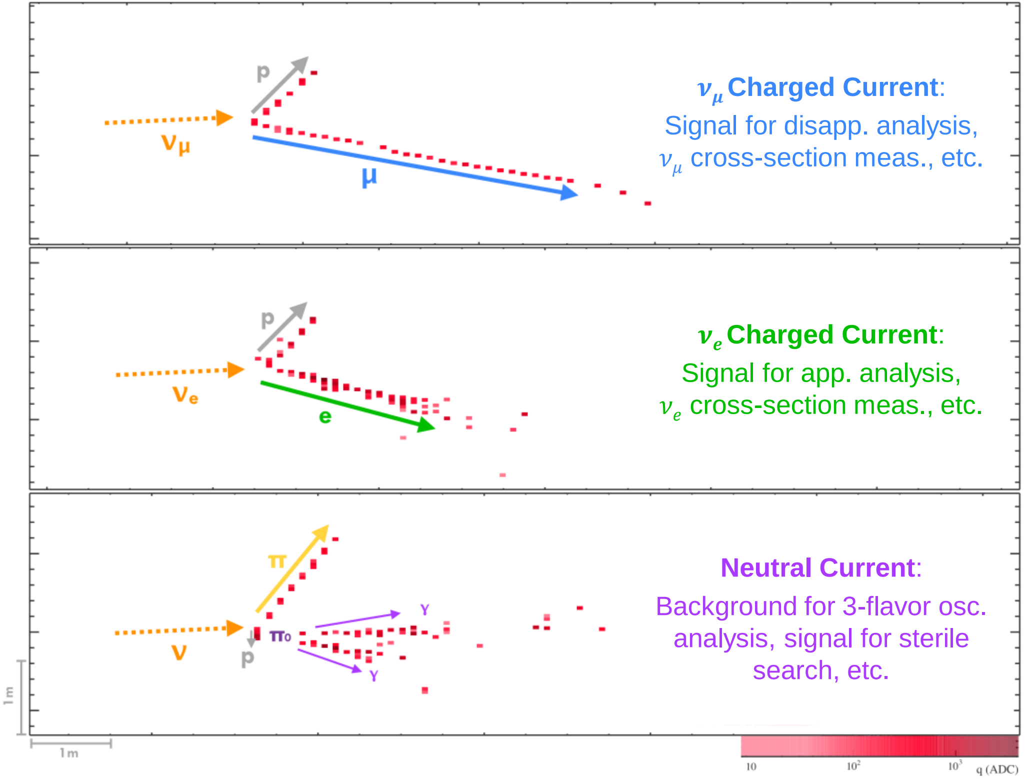
- **Charged particles** ionize the medium and produce **scintillation light**. The light is picked up by **wavelength shifting fibers**.

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

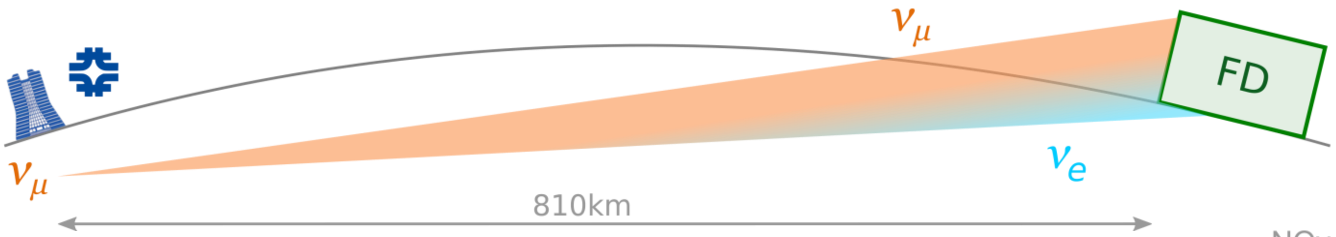
What do neutrino events look like in NOvA?

- Use **Machine Learning** techniques to **select** and **identify** neutrino interactions.

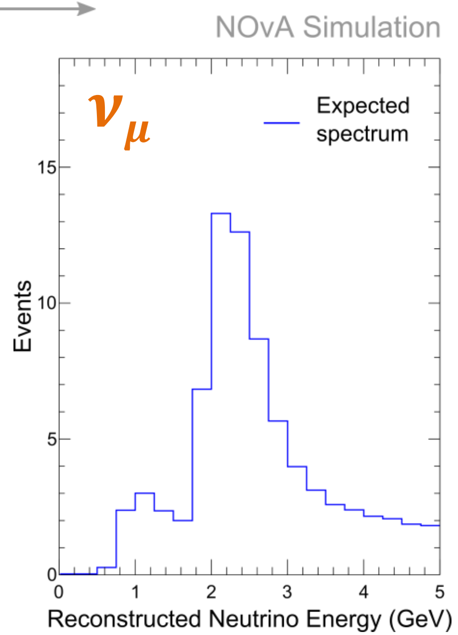
- Data processing, simulations, event reconstruction, network training: performed thanks to **Fermilab computing resources**.



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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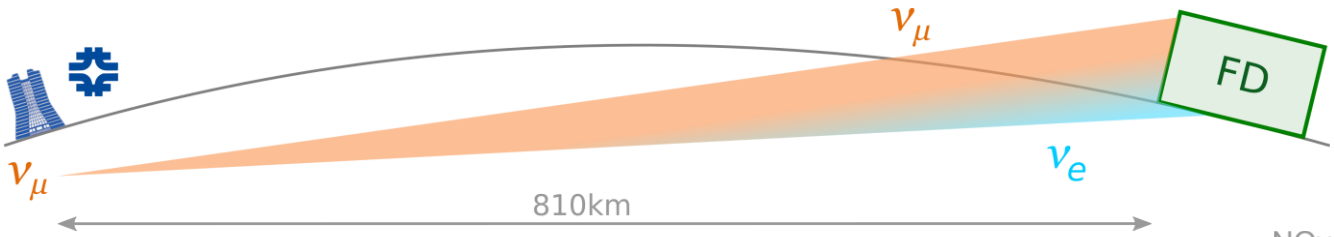
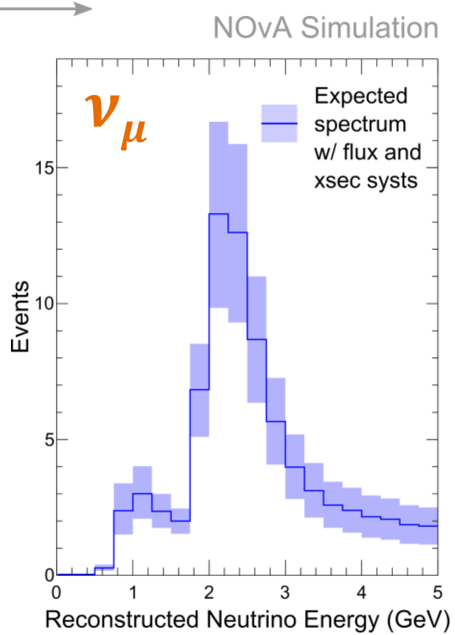


- Measure ν_μ / $\overline{\nu_\mu}$ and ν_e / $\overline{\nu_e}$ **energy spectra** in **FD.**

- Large **flux** and **cross-section uncertainties**.



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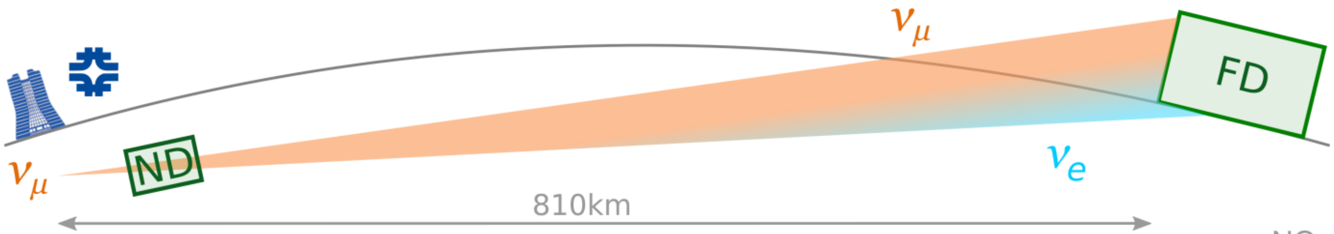

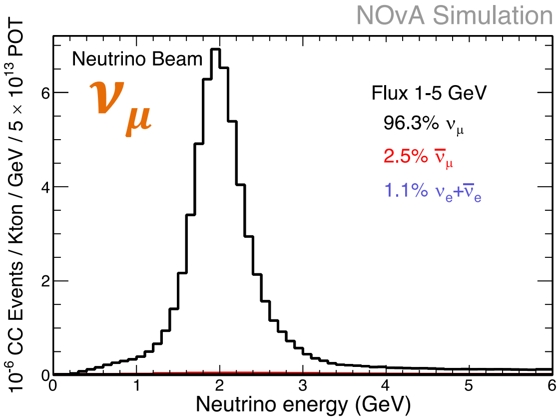

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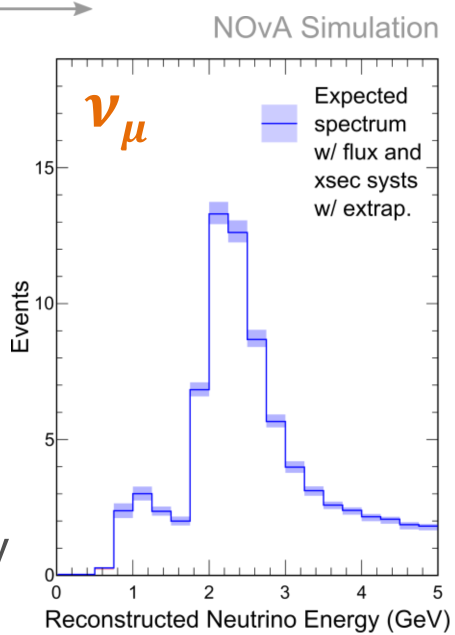

Measure ν_μ / $\overline{\nu_\mu}$ in the **ND** and extrapolate to greatly **cancel** the **flux** and **cross-section uncertainties**.

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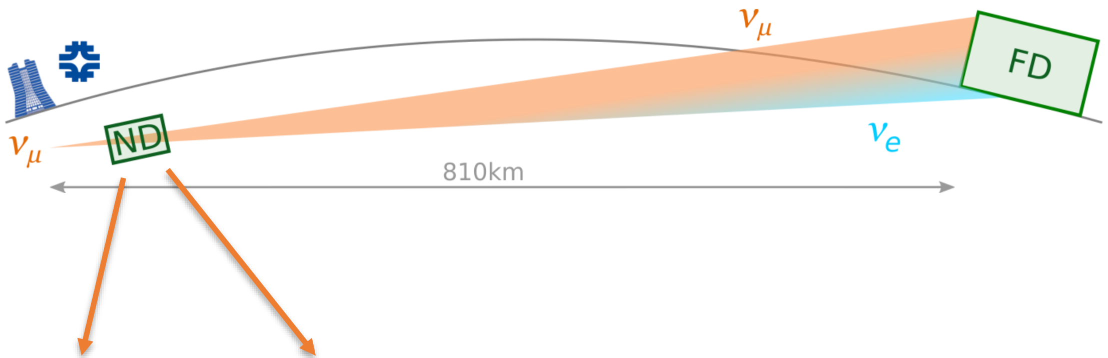

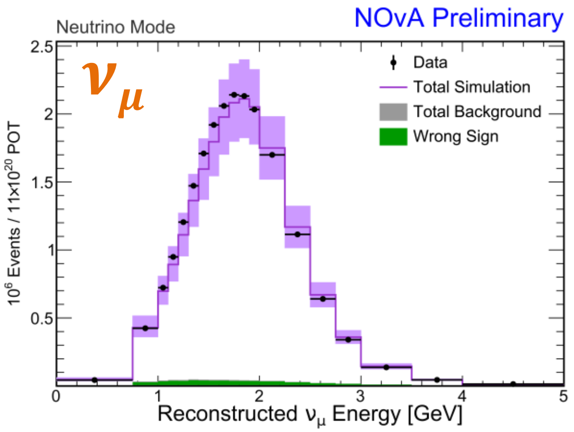

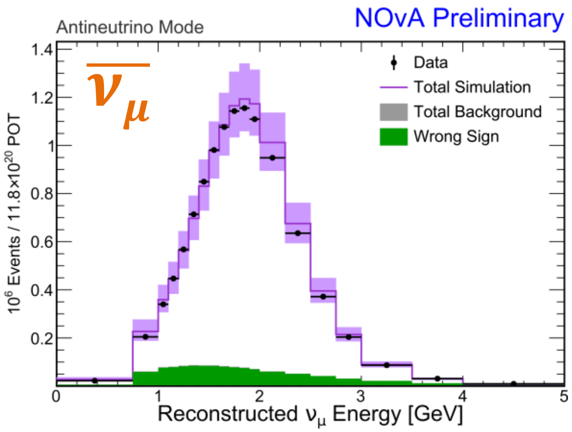

- Large statistics.
- Systematic bands come from **flux** and **cross-section** uncertainties

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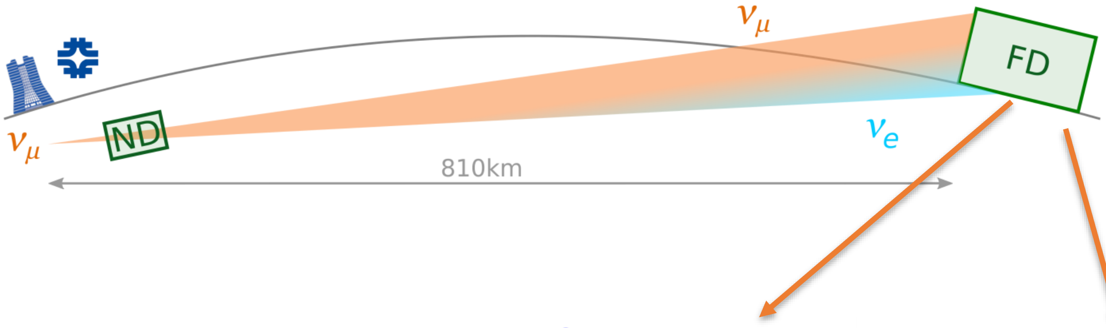
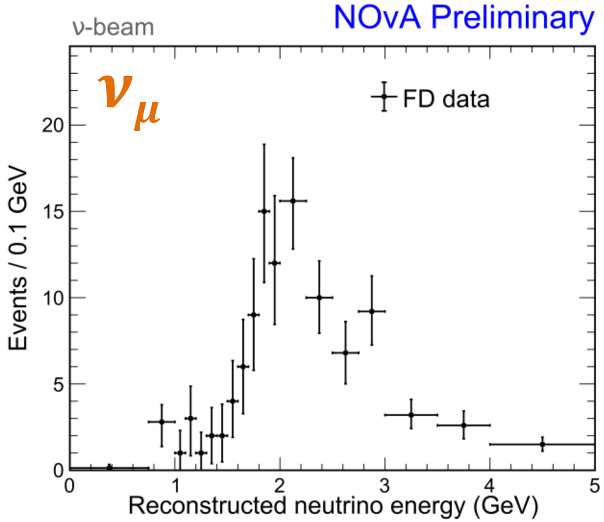
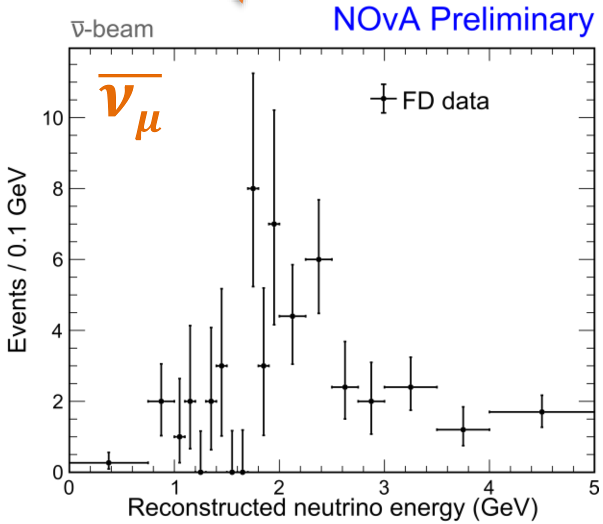
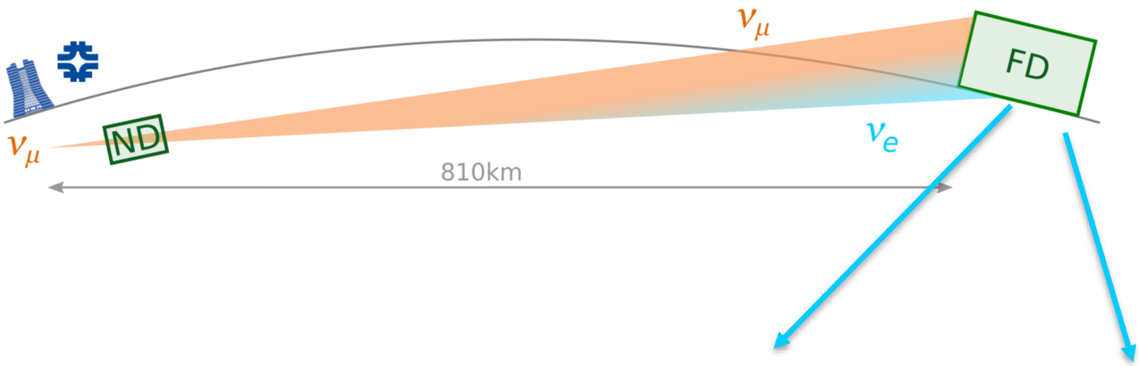


- Surviving ν_μ / $\overline{\nu}_\mu$ spectra
  - **211 ν_μ candidates**
  - **105 $\overline{\nu_\mu}$ candidates**
- Without oscillations, would expect >1000 ν_μ and ~500 $\overline{\nu}_\mu$ candidates.

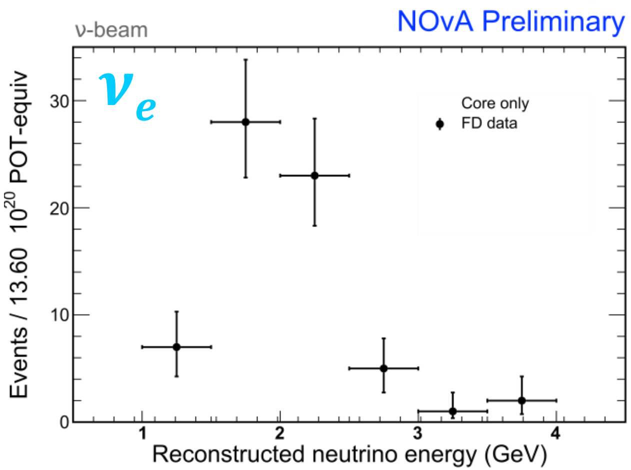


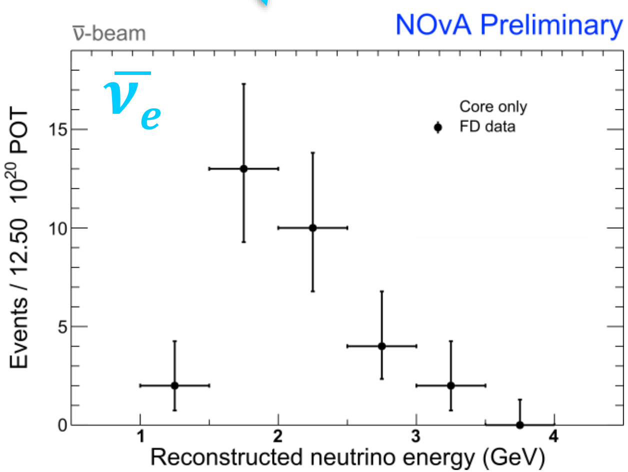


How does NOvA measure neutrino oscillation parameters?

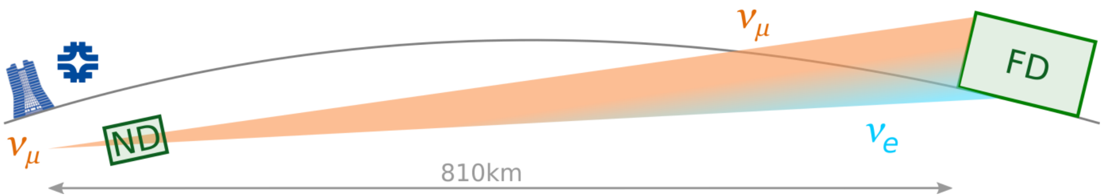


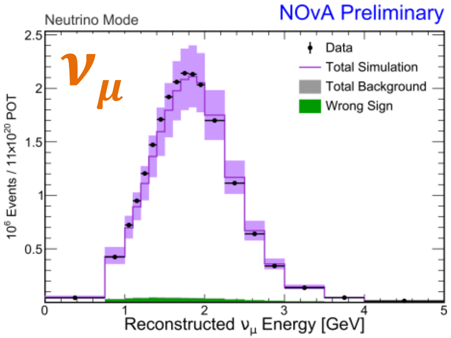
- Appearing ν_e / $\bar{\nu}_e$ spectra
  - **82 ν_e candidates**
  - **33 $\bar{\nu}_e$ candidates**

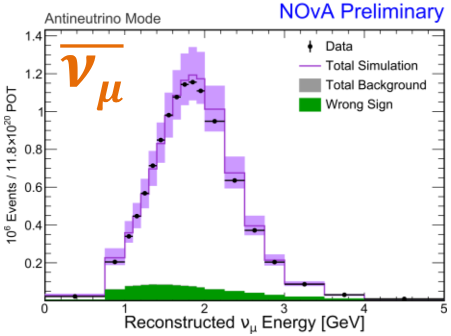




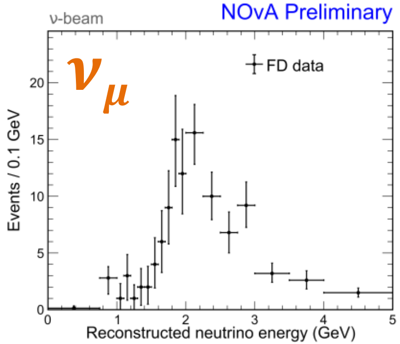
What are NOvA's latest 3-flavor oscillation results?

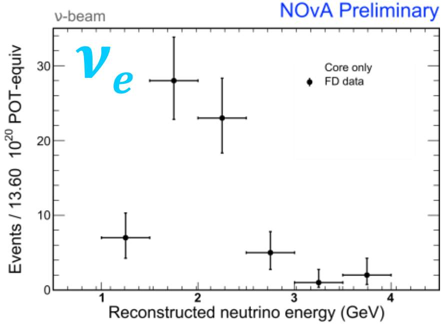


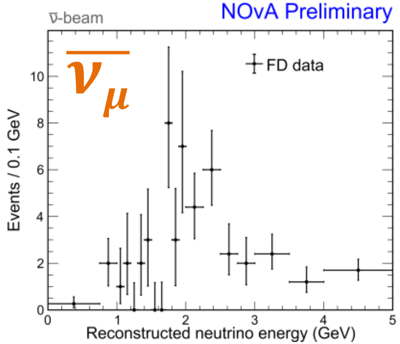


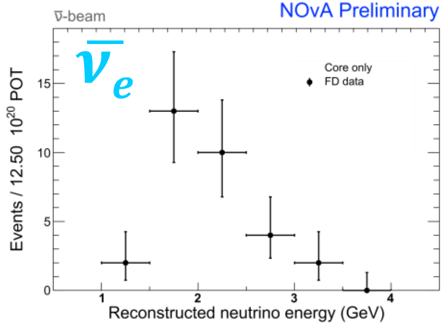


Which set of oscillation parameters generate predictions closest to data?









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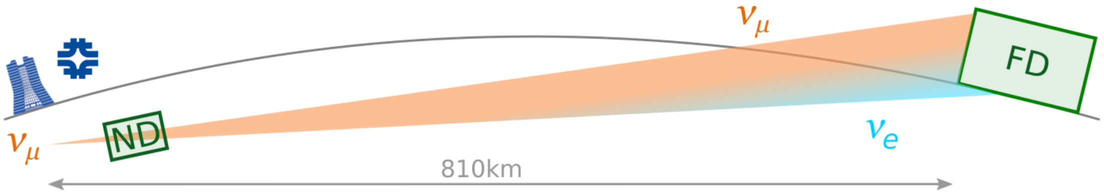
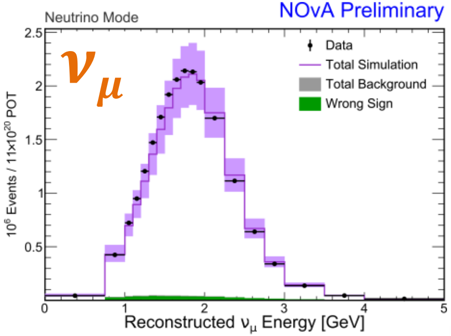
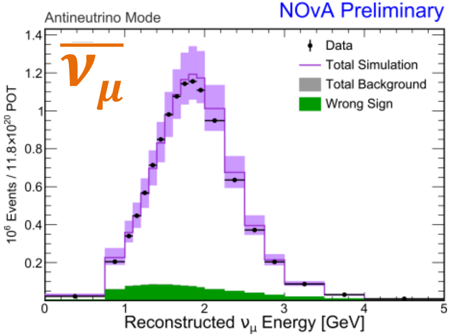




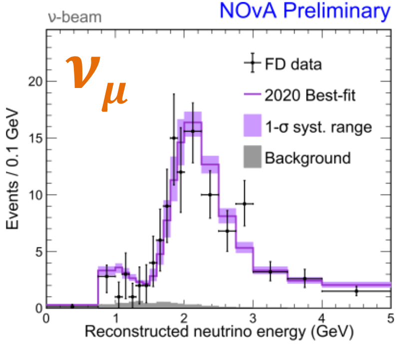


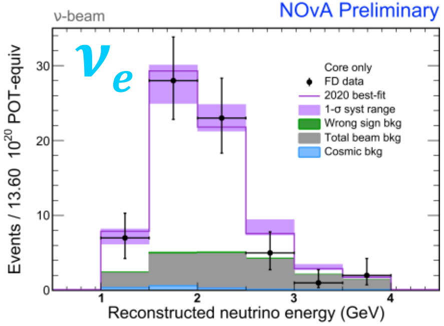
Best fit prediction

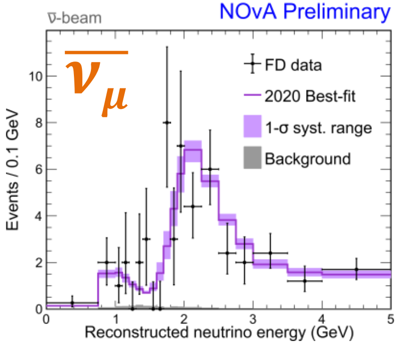
Δm^2_{32}=2.41×10^{-3} eV^2

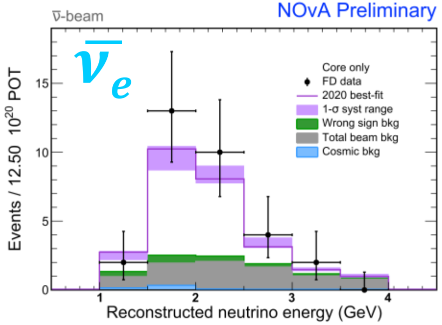
$\sin^2\theta_{23}$=0.57

δ_{CP}=0.82π



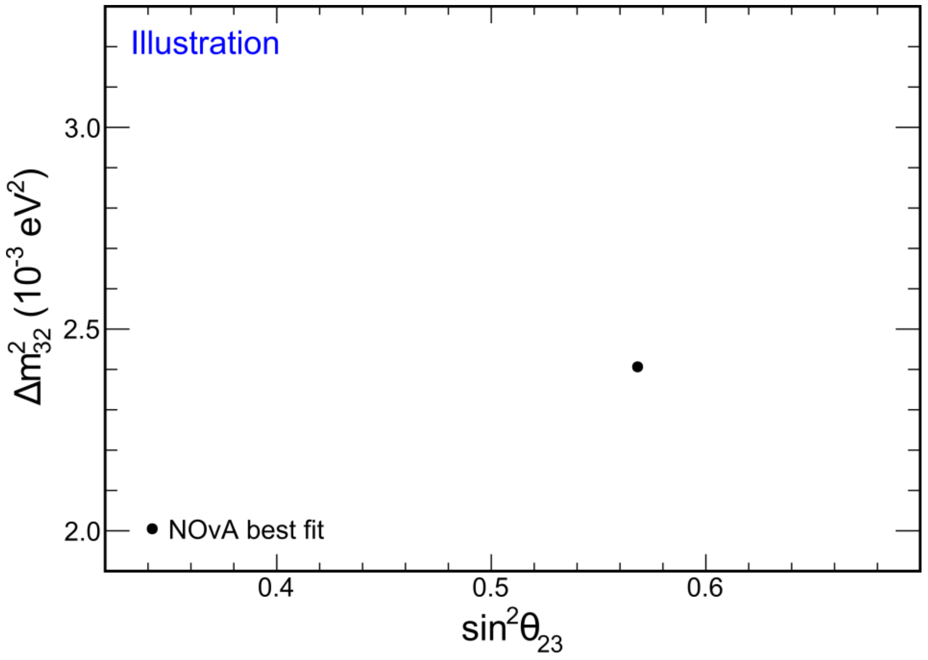






How confident are we in the results?

- The measurement is sensitive to **statistical fluctuations.**



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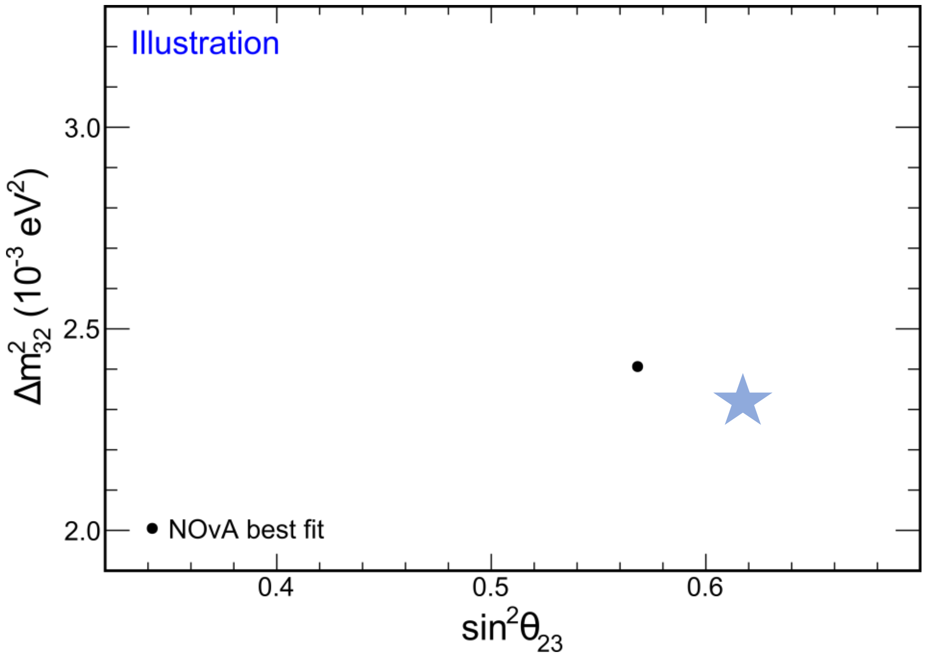

★ : With a few more events in the $\boldsymbol{\nu_\mu}$ oscillation dip.

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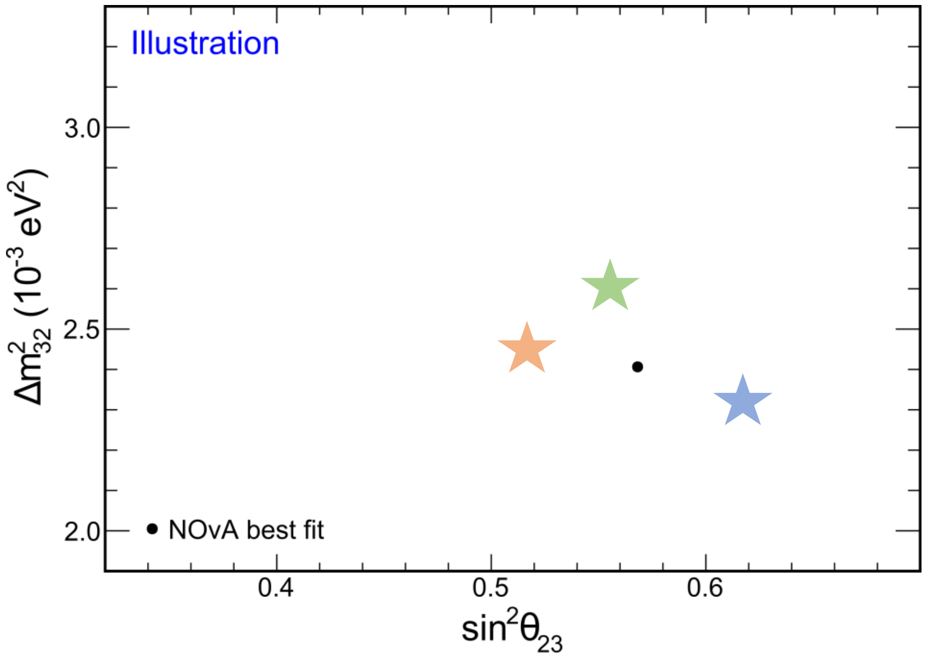
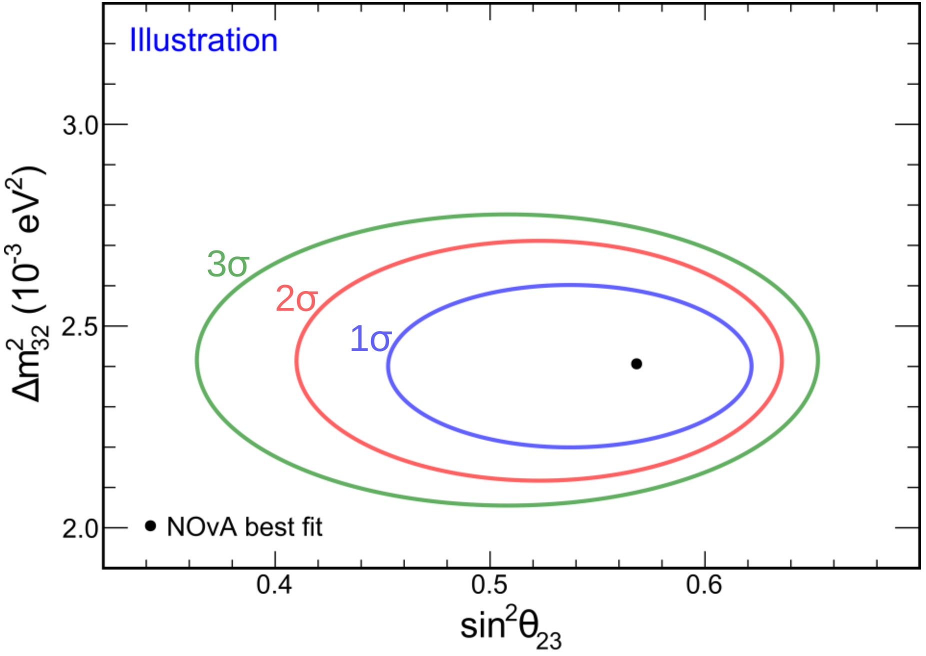


★ : With a few more events in the ν_μ oscillation dip.

★ ★ : With a few less events in the ν_μ oscillation dip.

How confident are we in the results?

- The measurement is sensitive to **statistical fluctuations**
  → Need to report **confidence intervals.**



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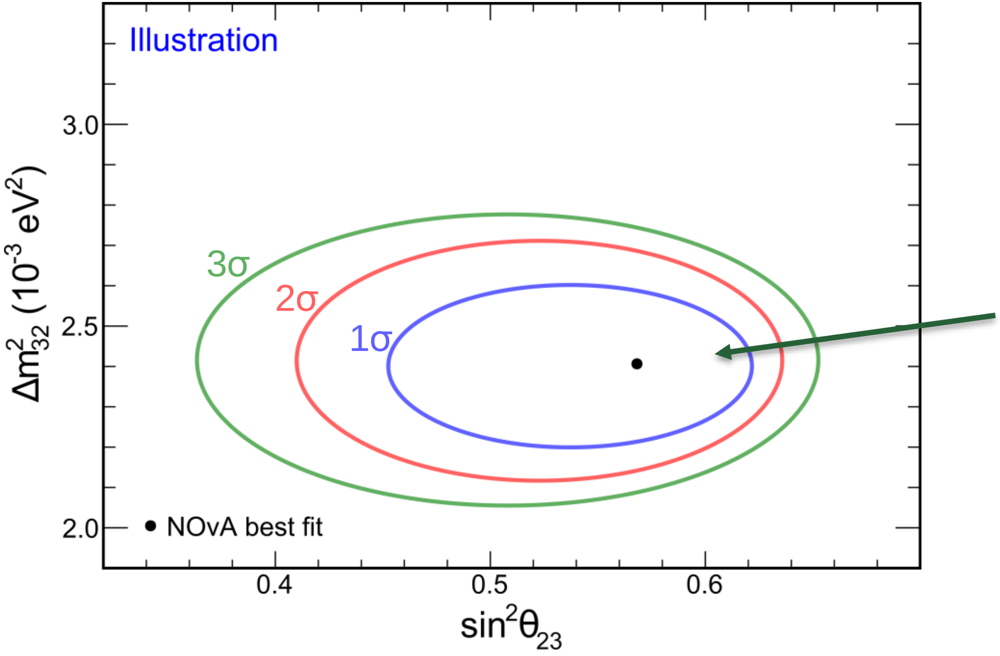

"True" values are "more likely than not" in the 1σ interval.

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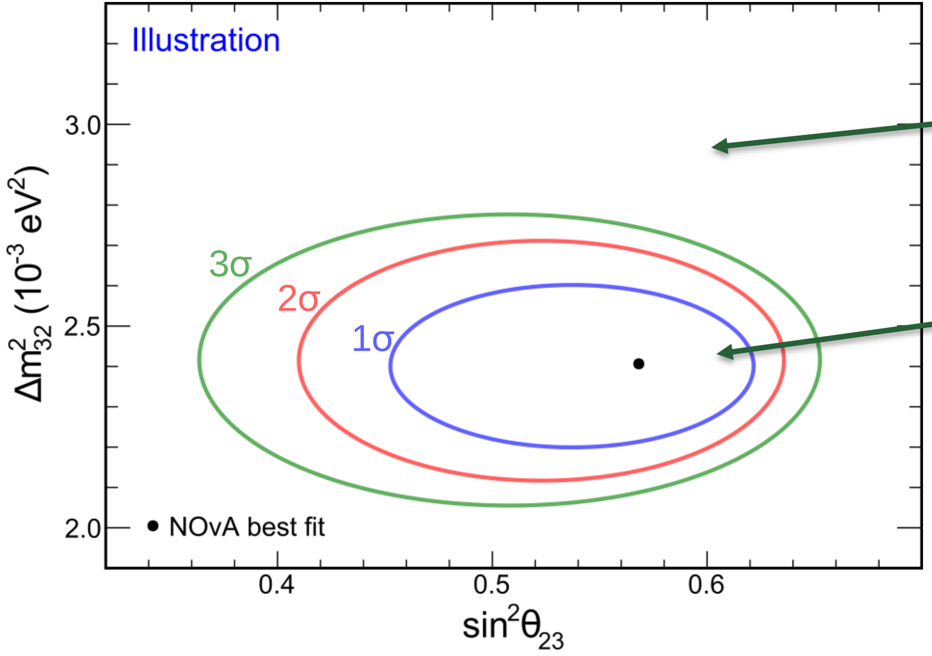

"True" values are "very unlikely" to be outside the 3σ interval.

"True" values are "more likely than not" in the 1σ interval.

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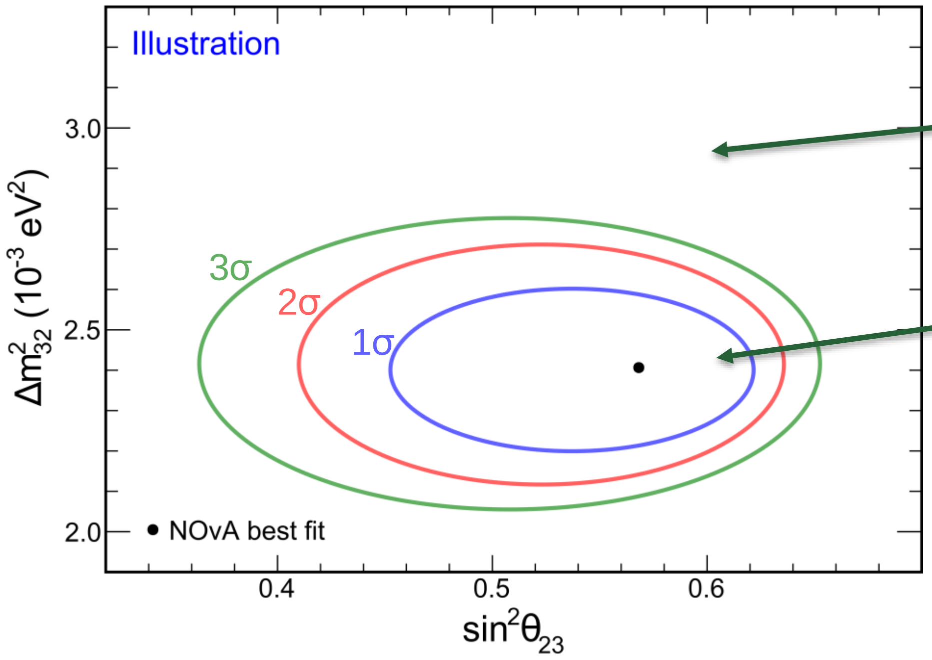
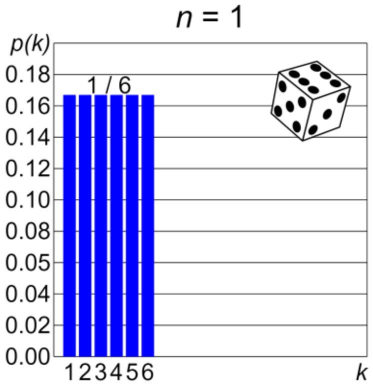


"True" values are "very unlikely" to be outside the 3σ interval.

"True" values are "more likely than not" in the 1σ interval.

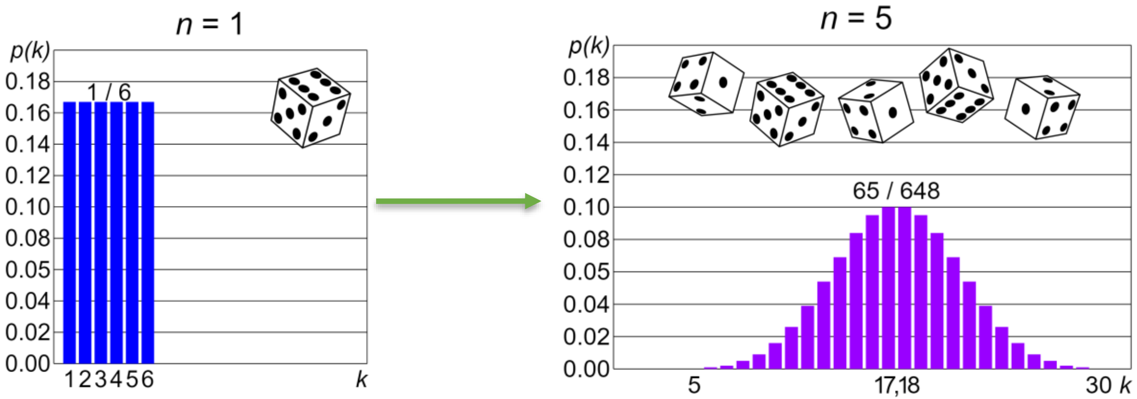
- Because of the **low statistics** and the presence of **physical boundaries**, building statistically accurate **confidence intervals** is very challenging.

How are confidence intervals built?



With a regular die, distribution of outcomes is flat.

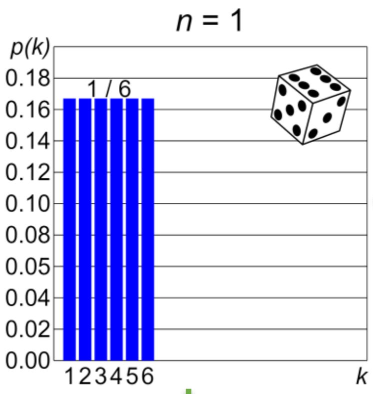
How are confidence intervals built?

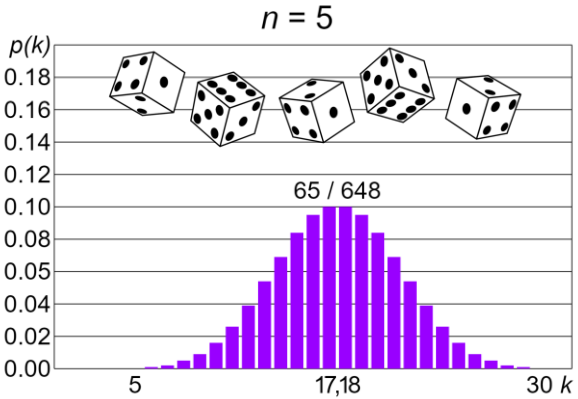


The sum of many dice follows a **normal distribution**.

The square of the sum is χ^2**-distributed** → can **mathematically predict** the probability to throw ≥25.

How are confidence intervals built?





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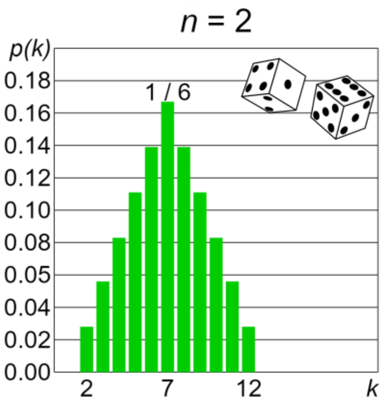
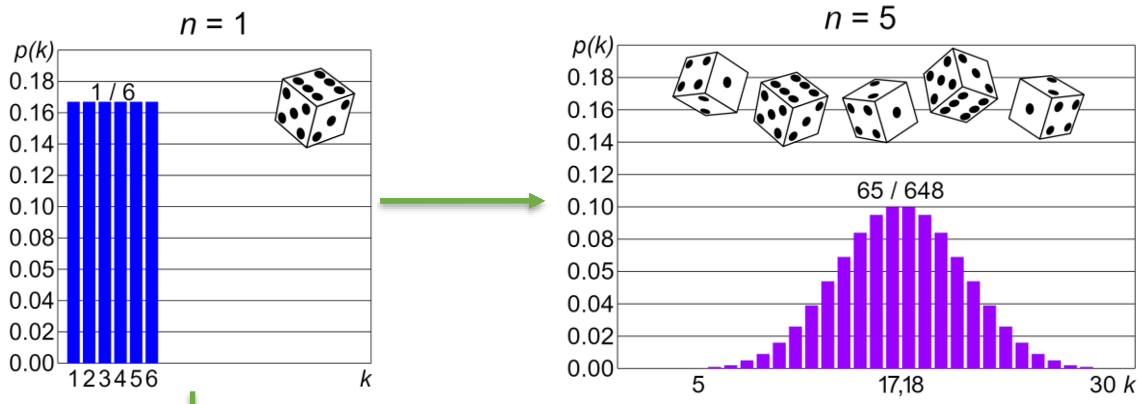


The sum of two dice is not normal distributed or “gaussian”.

How are confidence intervals built?



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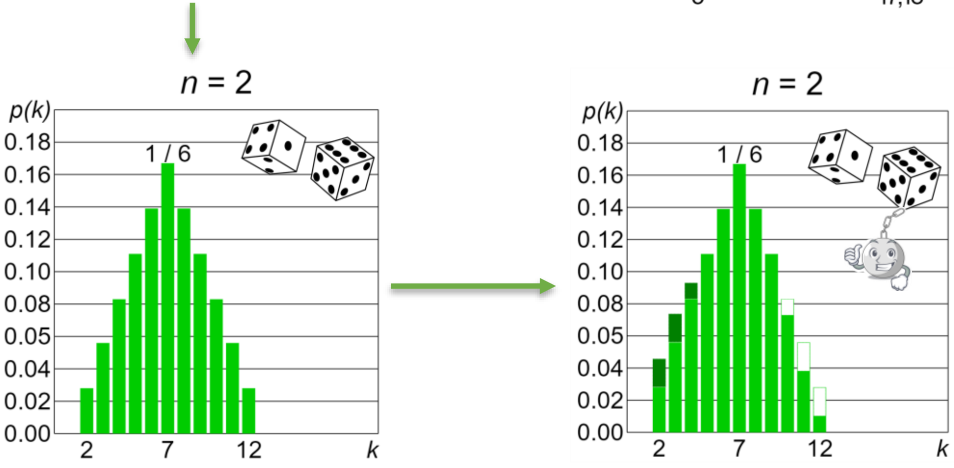

In addition, if the two dice are loaded, the only way to **predict** the distribution of outcomes is to throw the dice many times, i.e. throw **pseudoexperiments**.

How are confidence intervals built?

- Generate and fit **millions of pseudoexperiments** to build empirical χ^2-distributions: **Feldman-Cousins approach**.
- Extremely **computationally expensive**.

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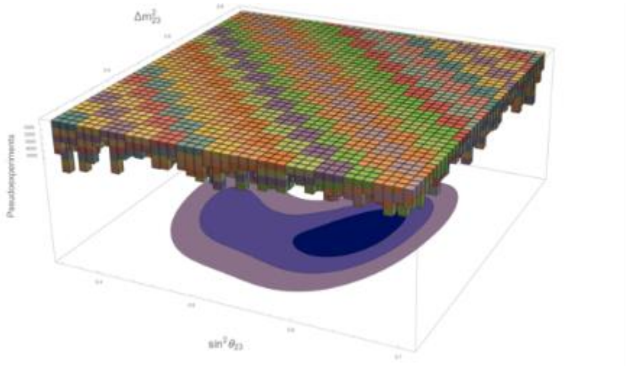
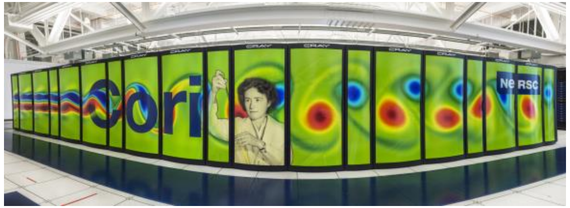
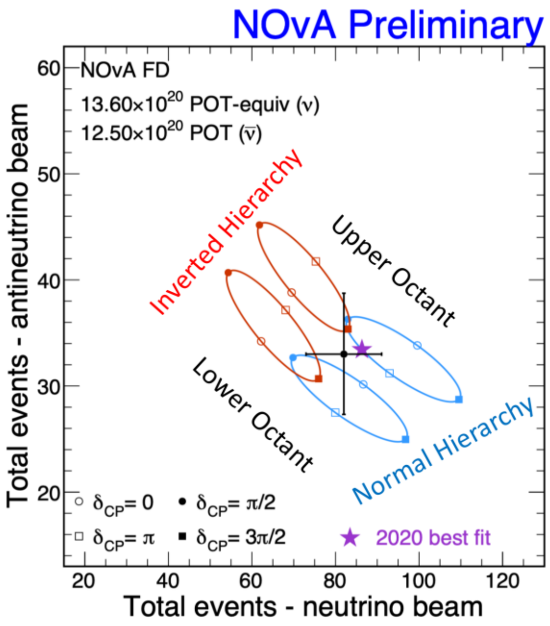


- Extremely **computationally expensive**.
- Implemented a **massive parallel framework** on **High Performance Computing** platforms like **NERSC**, in collaboration with the SciDAC-4 HEP Data Analytics program.
- Time to results brought from **6 months** on FermiGrid and OpenScience grid down to a **few days/weeks** on NERSC machines.



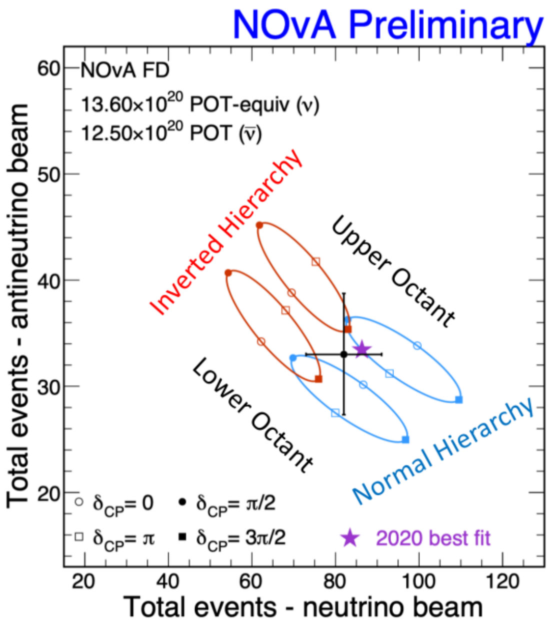
What is NOvA's constraint on δ_{CP} ?

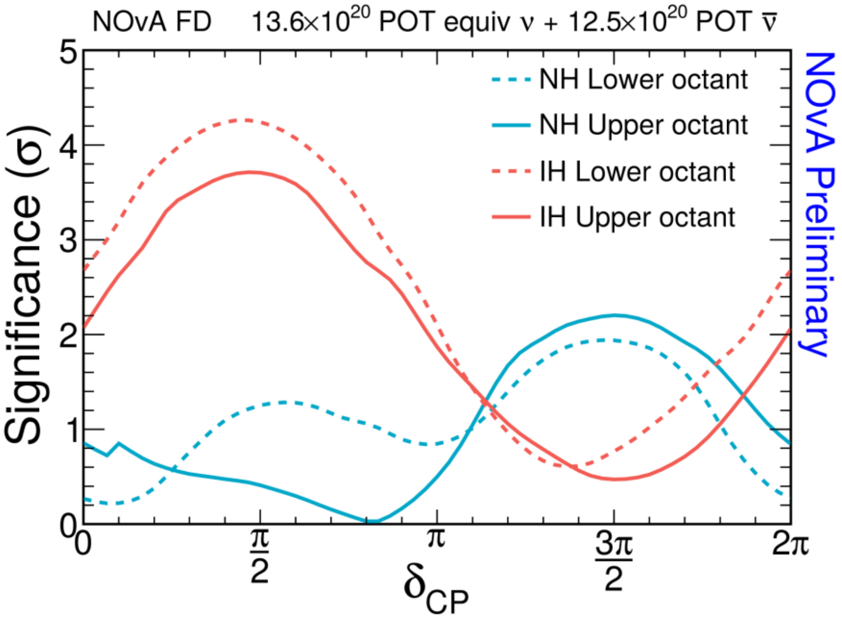
- Observed ν_e - $\bar{\nu}_e$ **appearance** rates fall in a degenerate region of the param. space.



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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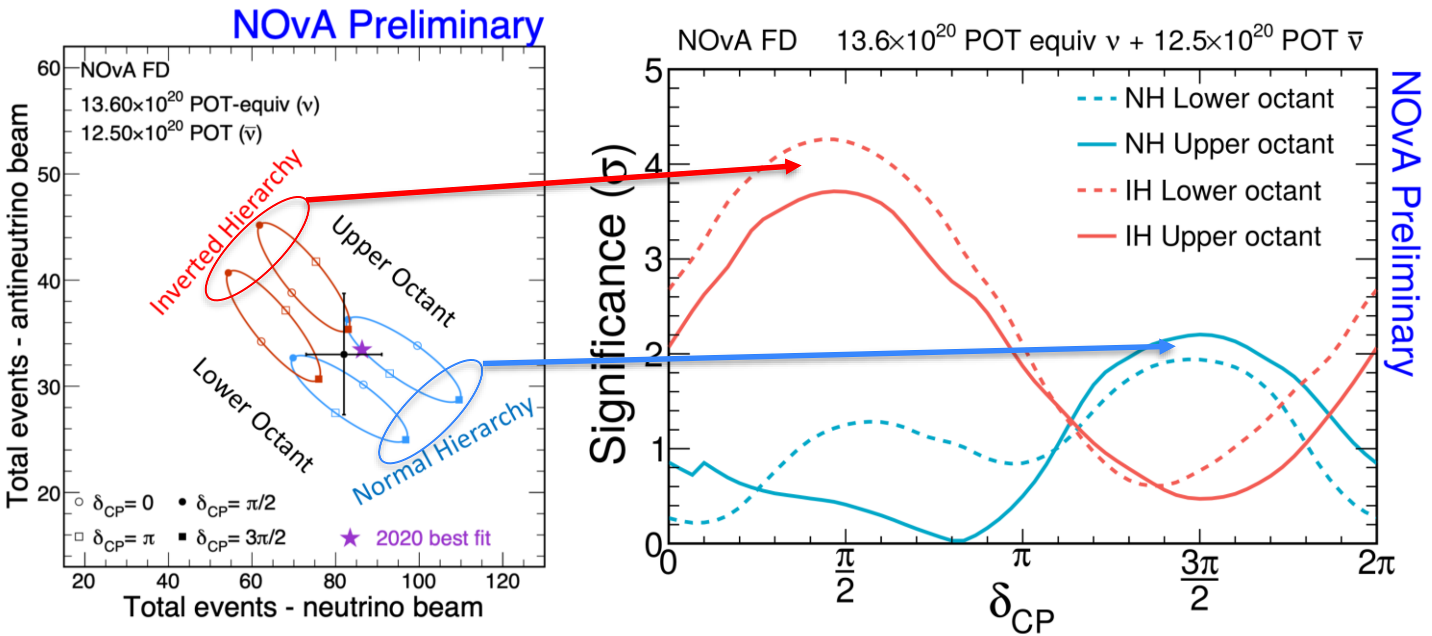
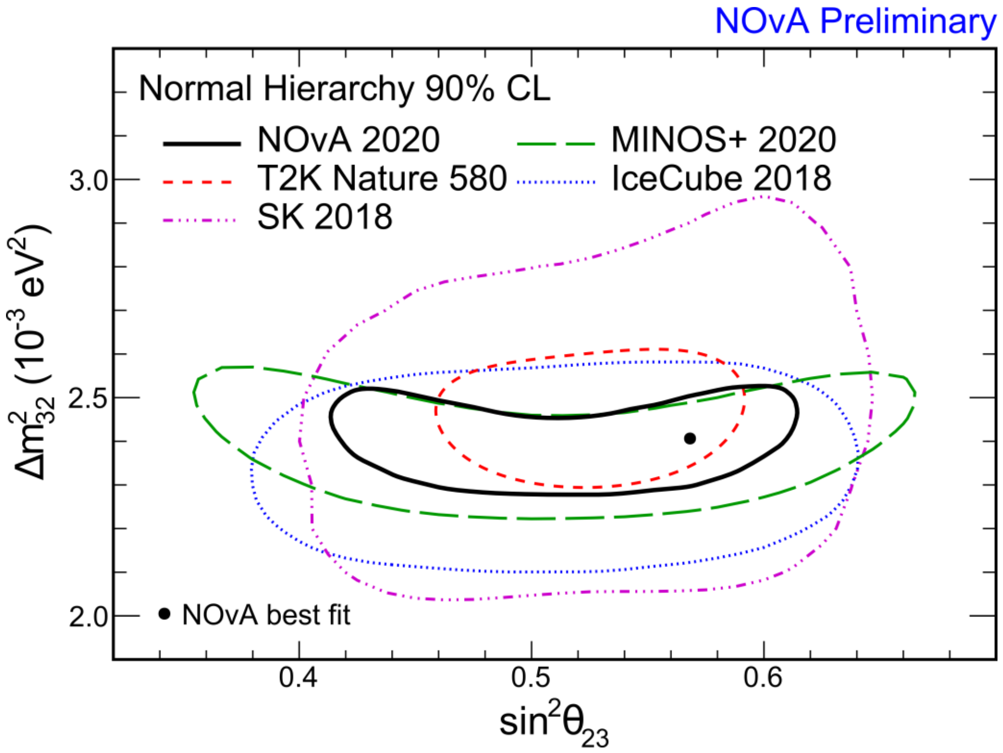
- Observed ν_e - $\bar{\nu}_e$ **appearance** rates fall in a degenerate region of the param. space.
- No significant ν_e - $\bar{\nu}_e$ asymmetry observed.
- Disfavor **IH $\delta_{CP}=\pi/2$ at >3σ** and **NH $\delta_{CP}=3\pi/2$ at 2σ**.



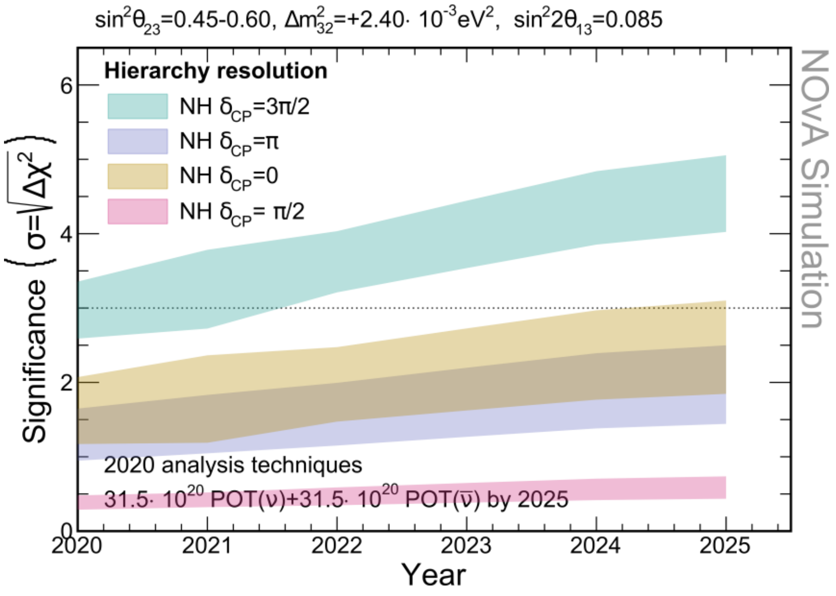
What is NOvA's constraint on $\sin^2\theta_{23}$ and Δm^2_{32} ?

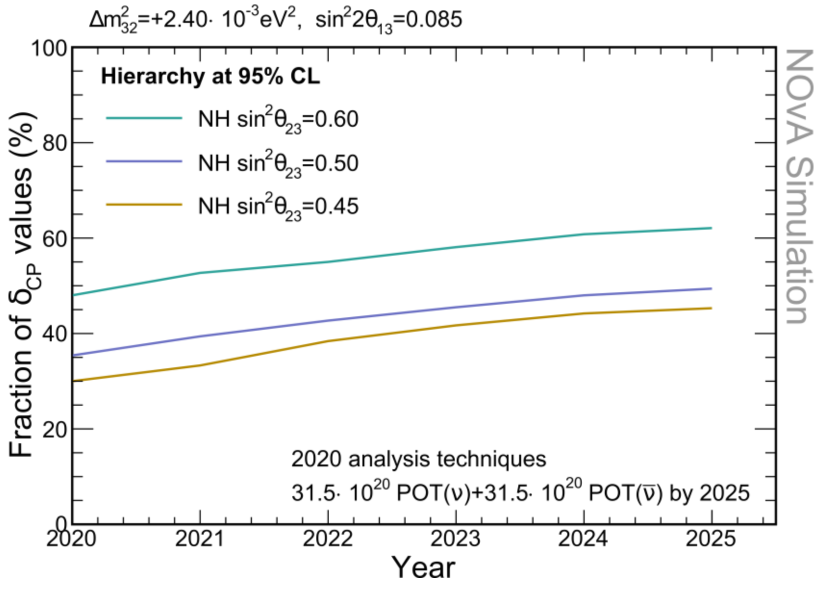


- Best fit in **Normal Hierarchy** and **Upper Octant** ($\theta_{23} > 45^o$).
- **Precision measurements**:
  - Δm^2_{32}=2.41±0.07×10^{-3} eV^2 (±3%)
  - $\sin^2\theta_{23}=0.57^{+0.04}_{-0.03}$ (±7%)
- Preference for:
  - **Normal Hierarchy** at 1.0σ
  - **Upper Octant** at 1.2σ
  - Non-maximal mixing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

What is NOvA's future sensitivity?

- Run until **2025**, accumulating more than **3×10^{21} POT** in both $\boldsymbol{\nu}$ and $\boldsymbol{\bar{\nu}}$ modes.
- Could reach **5σ sensitivity** to **Mass Hierarchy** for most favorable parameters.
- Probe the majority of **δ_{CP} values** at **2σ-level**.





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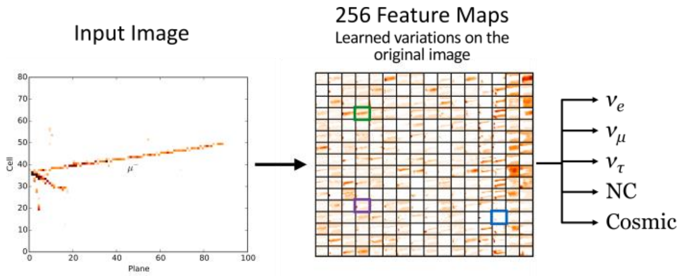
- Development of **Machine Learning** tools to address some of the biggest reconstruction challenges, like pion energy estimation, etc.



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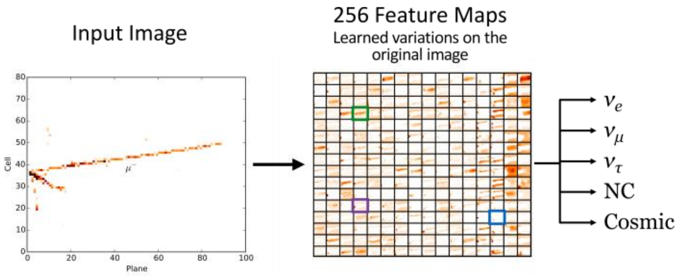
- Development of **Machine Learning** tools to address some of the biggest reconstruction challenges, like pion energy estimation, etc.
- **NOvA Test Beam** program is ongoing at **Fermilab Test Beam Facility**: reduce our largest systematics.



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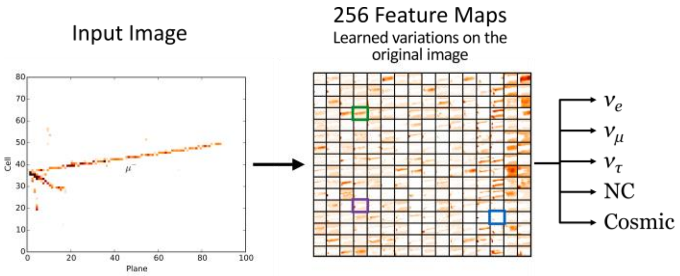
- **High Performance Computing** enables great **speed ups** and previously computationally prohibitive analysis techniques to be explored.
- Development of **Machine Learning** tools to address some of the biggest reconstruction challenges, like pion energy estimation, etc.
- **NOvA Test Beam** program is ongoing at **Fermilab Test Beam Facility**: reduce our largest systematics.
- Expect more **neutrino cross-section** measurements from NOvA: see past two weeks JTEP seminars on the **ν_μ and ν_e charged current** inclusive measurements.



Conclusions

- **New 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:
  - Δm^2_{32}=2.41$\pm$0.07$\times$10^{-3} eV^2
  - $\sin^2\theta_{23}$=$0.57^{+0.04}_{-0.03}$

- Exclude **IH δ_{CP}=π/2 at >3σ** and **NH δ_{CP}=3π/2 at 2σ**.

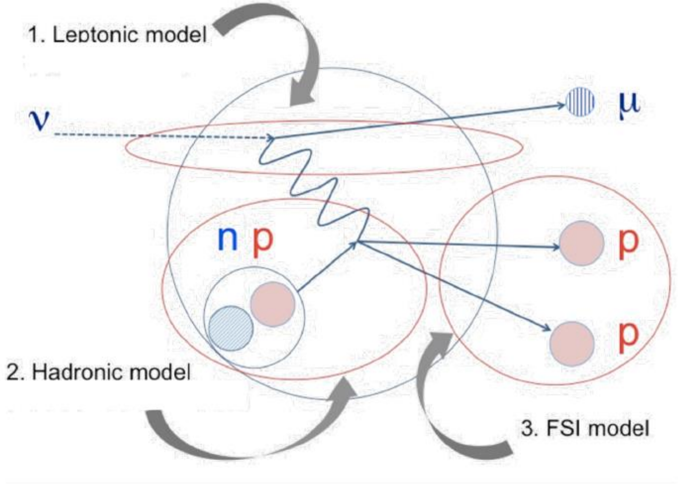
- **Fermilab** played a critical role in **NOvA's latest results!** Grateful for continued support.

Questions?

Backup

GENIE Tune

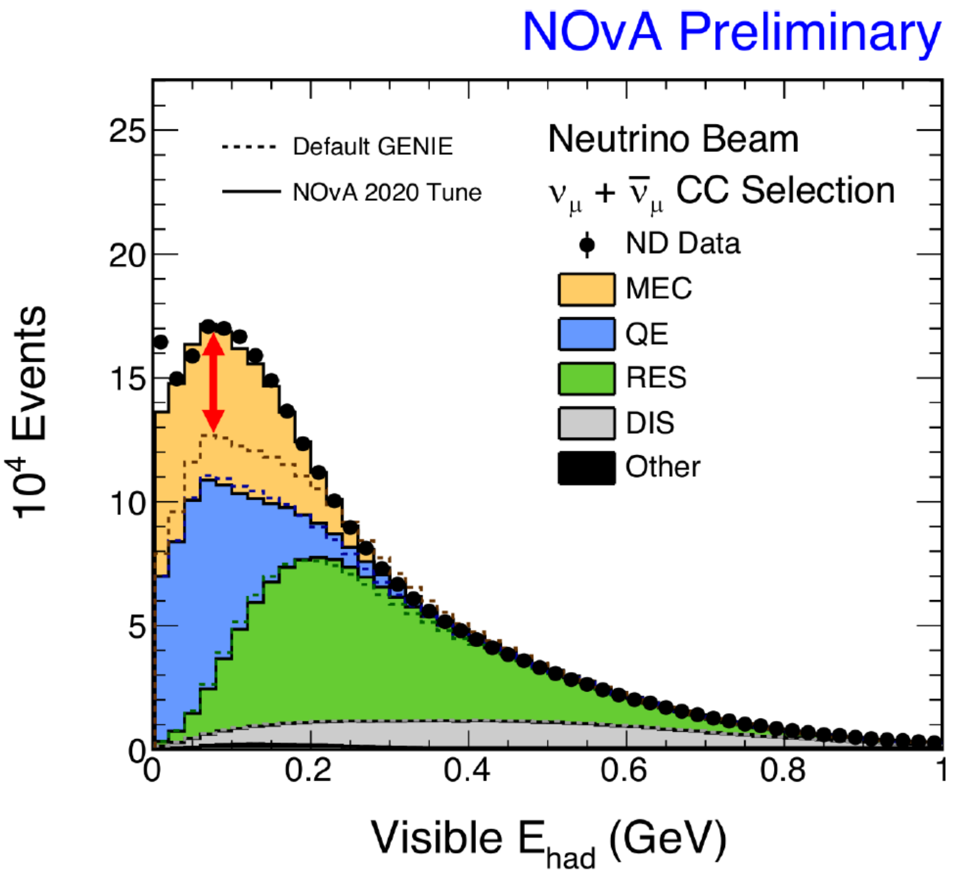
- Used **GENIE 3.0.6** in NOvA 2020 analysis: choose the most theory-driven models and retune some parameters to better match ND data.



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

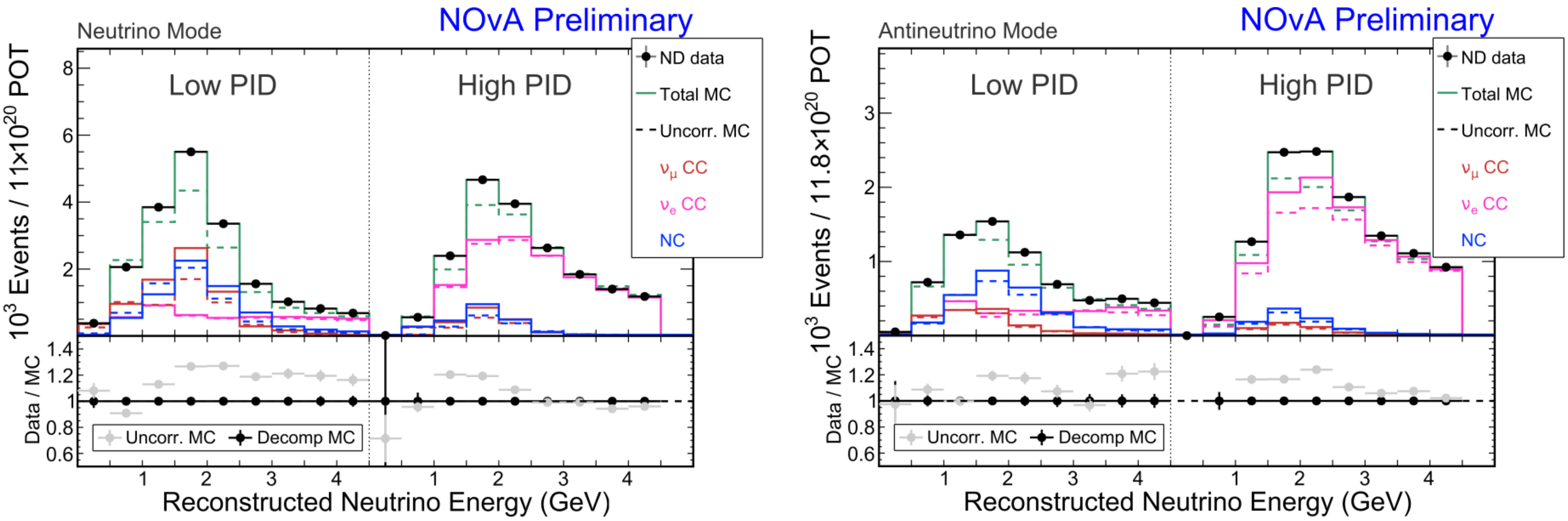
GENIE Tune

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

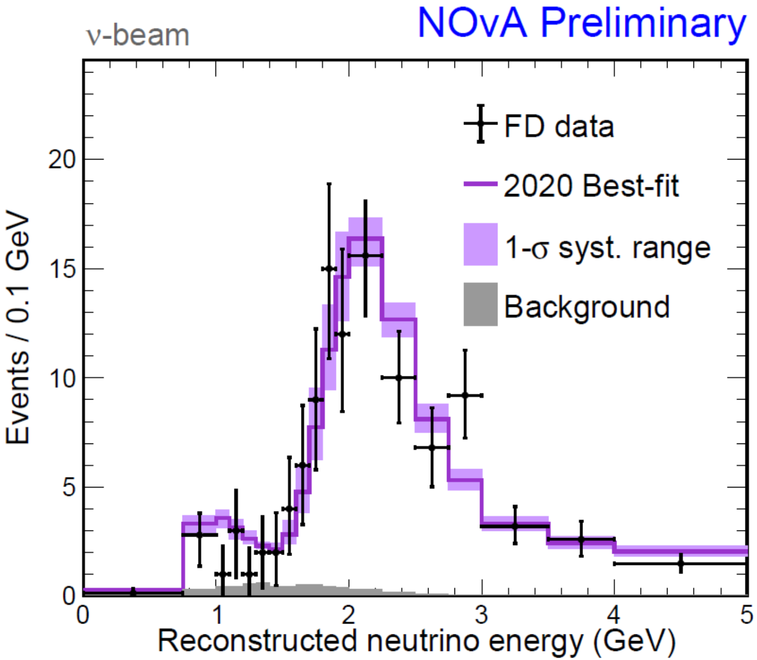


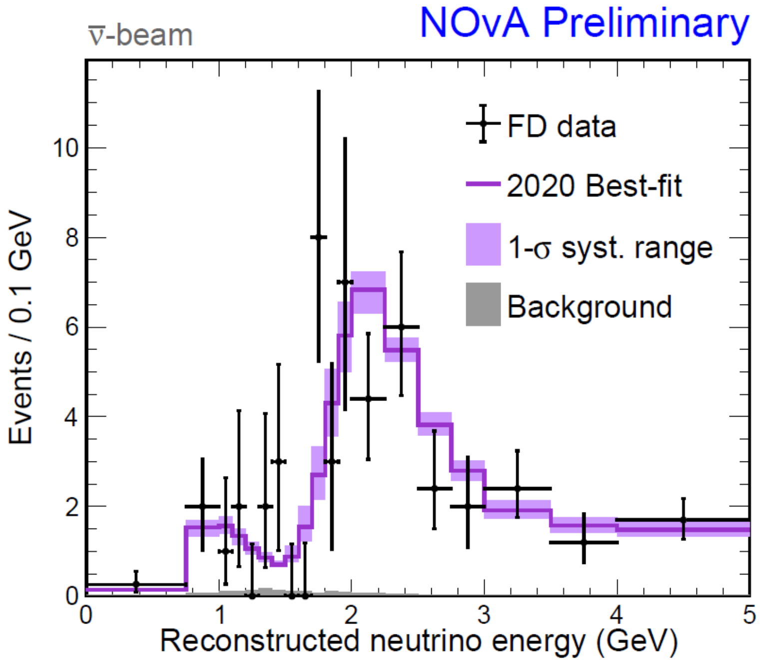
Joint NOvA-T2K analysis

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



FD numu

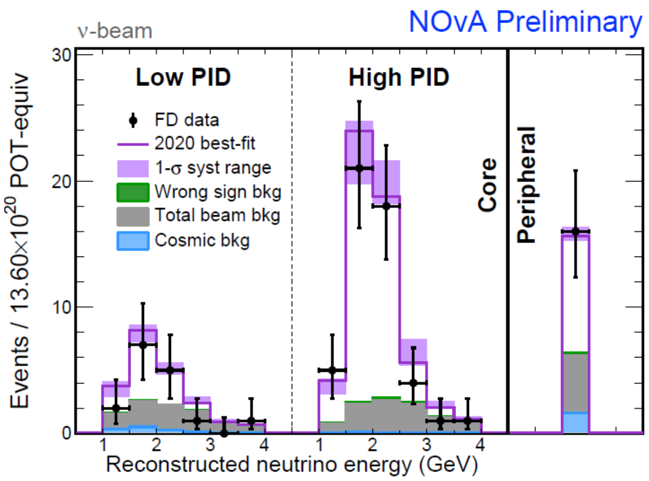


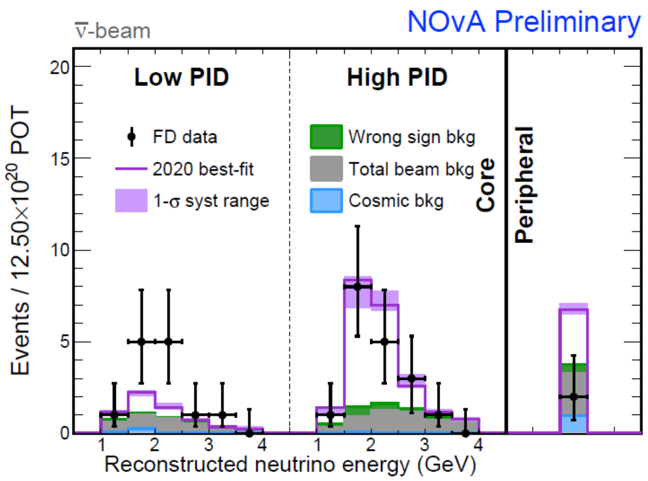


Obs. ν_μ candidates	**211**
Total background	8.2

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

FD nue



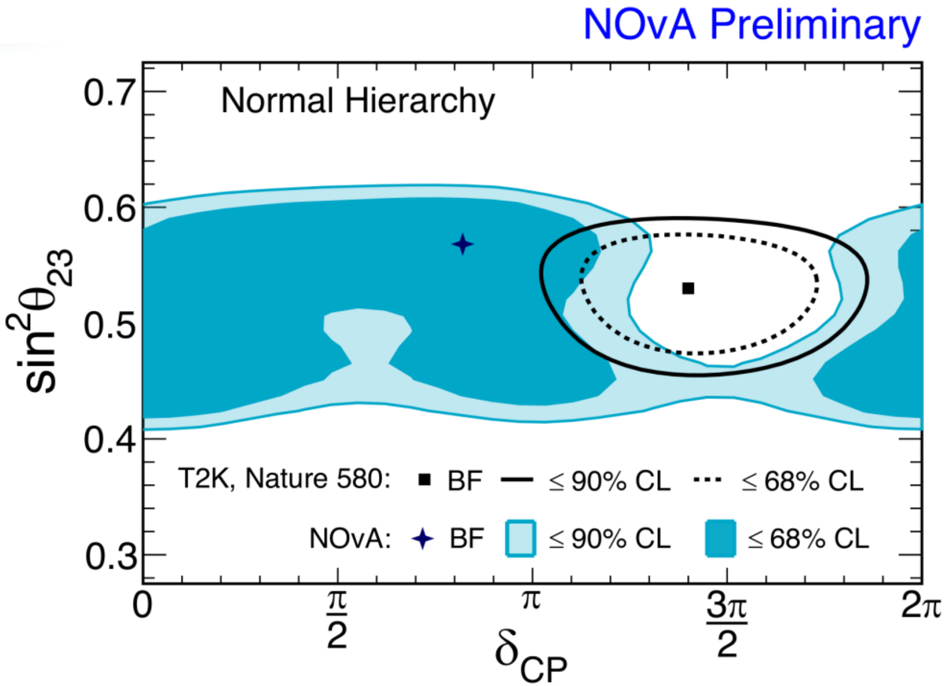


Obs. ν_e candidates	82
Best fit prediction	85.8
Total background	26.8
Beam bkg	22.7
Cosmic bkg	3.1
Wrong sign	1.0

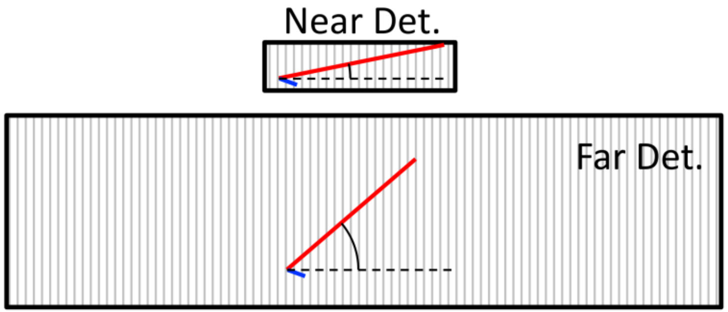
Obs. ν_e candidates	33
Best fit prediction	33.2
Total background	14.0
Beam bkg	10.2
Cosmic bkg	1.6
Wrong sign	2.3

Joint NOvA-T2K analysis

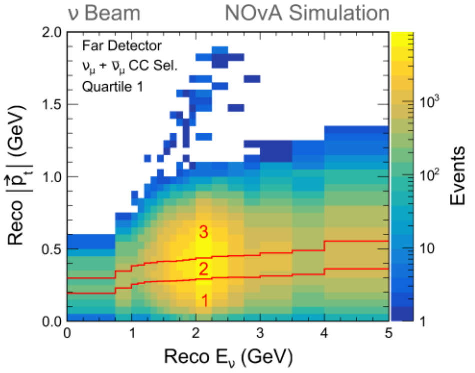
- **T2K results** are statistically compatible with ours.
- Ongoing effort towards a joint NOvA-T2K fit.

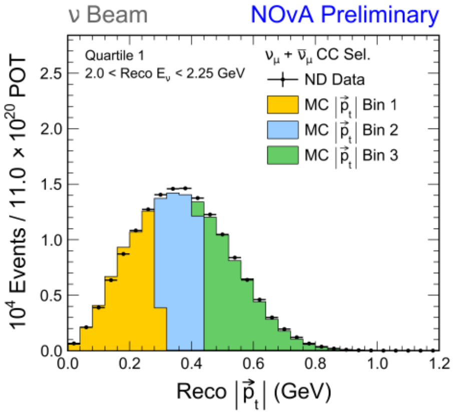


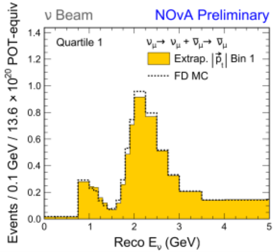
p_t extrapolation

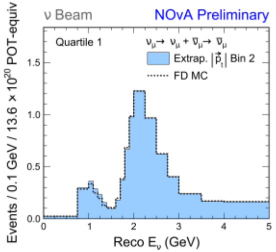


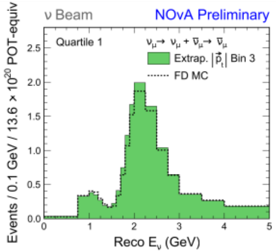
- ND/FD containment difference.
- Split ND samples into 3 bins of transverse momentum and extrapolate separately.
- Reduce cross-section uncertainty by 30%. Overall systematics reduction is 10%.





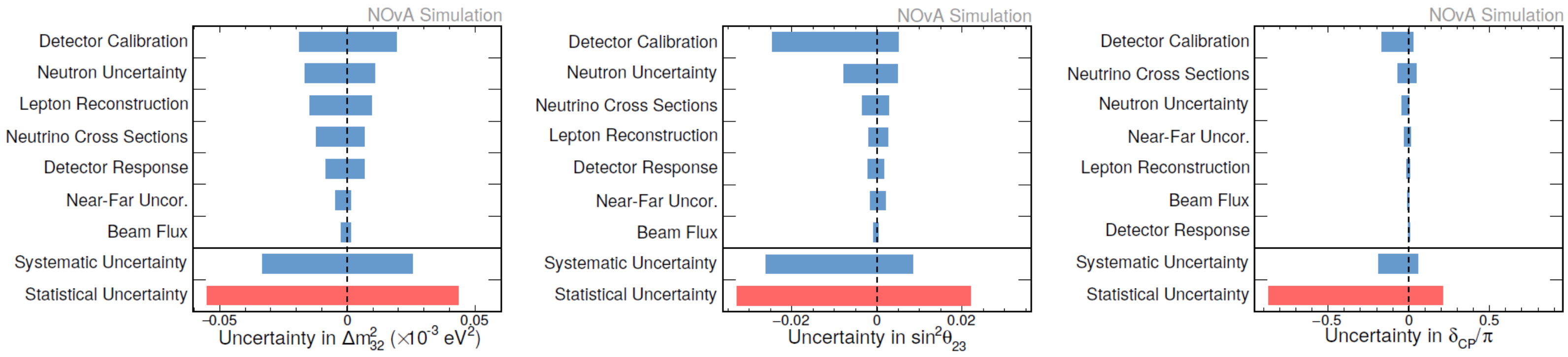






Systematics

- **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**.