DUNE oscillation physics overview

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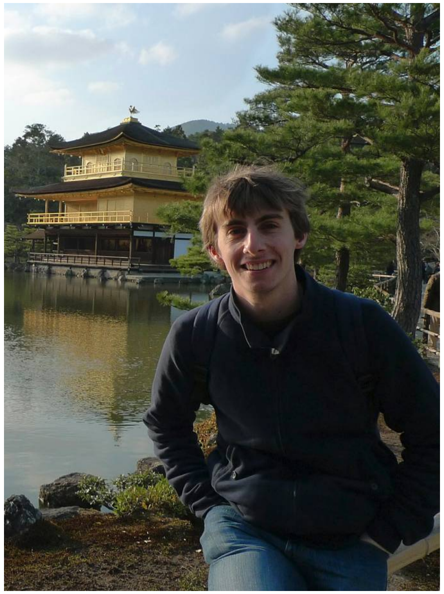
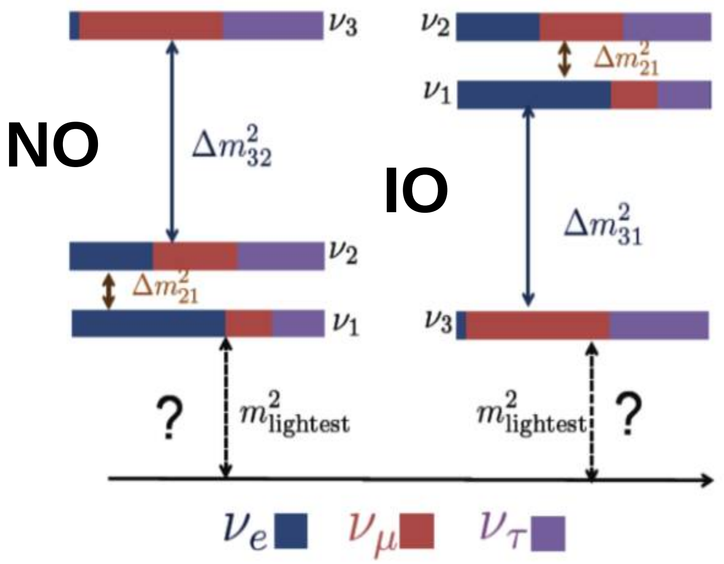
Lawrence Berkeley National Laboratory
Snowmass CSS, 19th July 2022



Open questions in neutrino physics



Two mass scales

$|\Delta m^2| \sim 2 \times 10^{-3}\ \text{eV}^2$

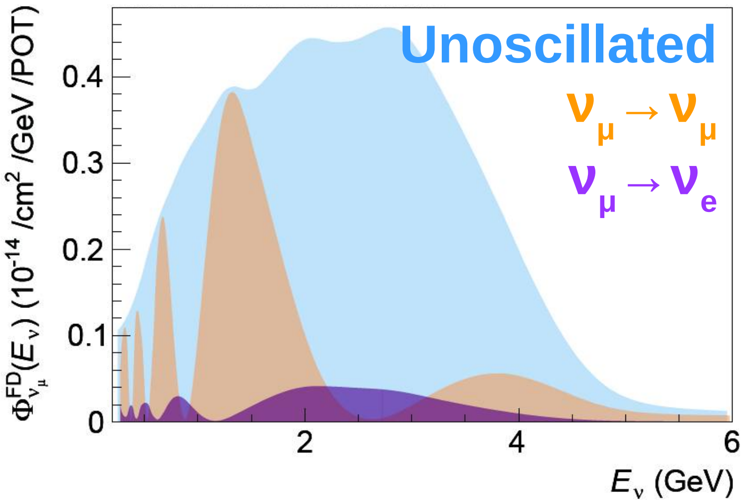
$\Delta m^2_{21} \sim 7 \times 10^{-5}\ \text{eV}^2$

- What is the neutrino mass ordering?
- Is there leptonic CP violation?
- Is this picture complete? E.g. >3 flavors? Non-unitary U_{PMNS}, …
- Connected to many interesting theoretical questions

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

Long-baseline oscillation experiments

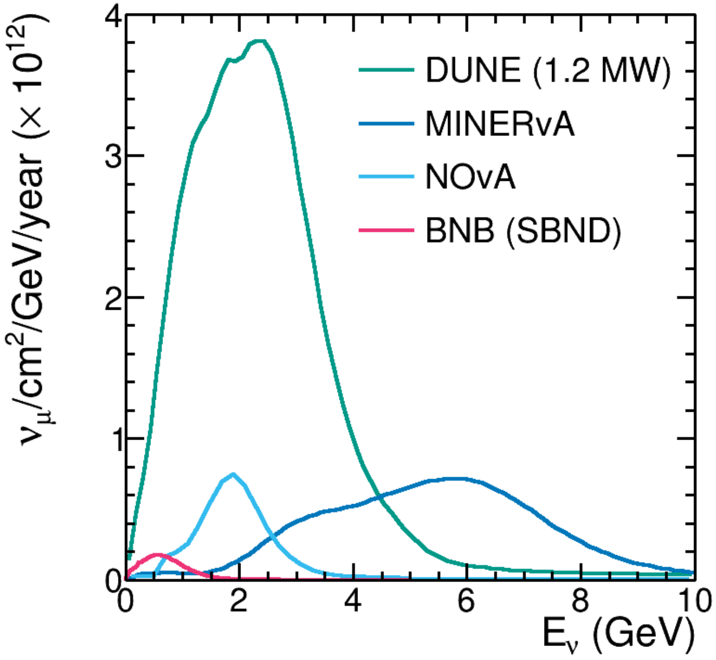
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \to \nu_B)}_{\text{Far}}$$

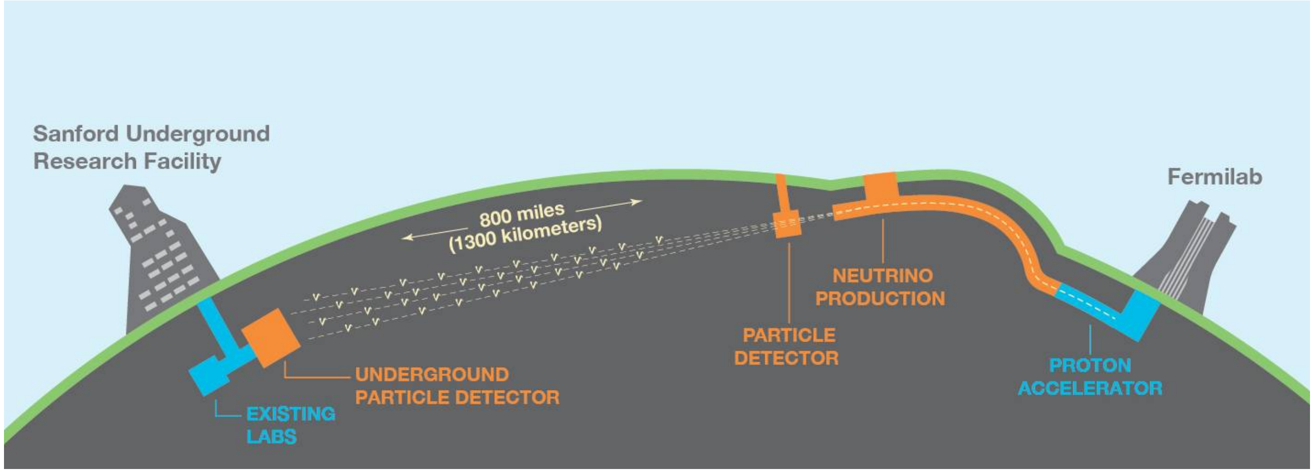


- Complex inference of **oscillation probability** from measured **event rate**
- Near detector to constrain **neutrino flux** and **cross-section*** models/systematics
- Different near and far detector fluxes mean uncertainties do not neatly cancel
- High-fidelity detectors reduce ambiguities due to **detector smearing**

See K. McFarland's talk later!

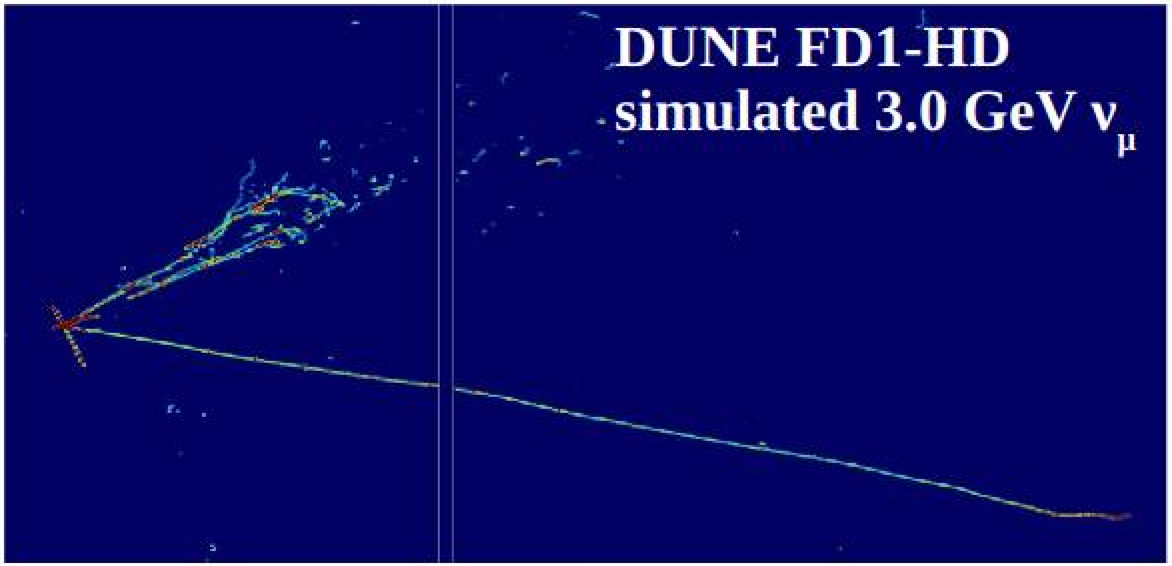
DUNE

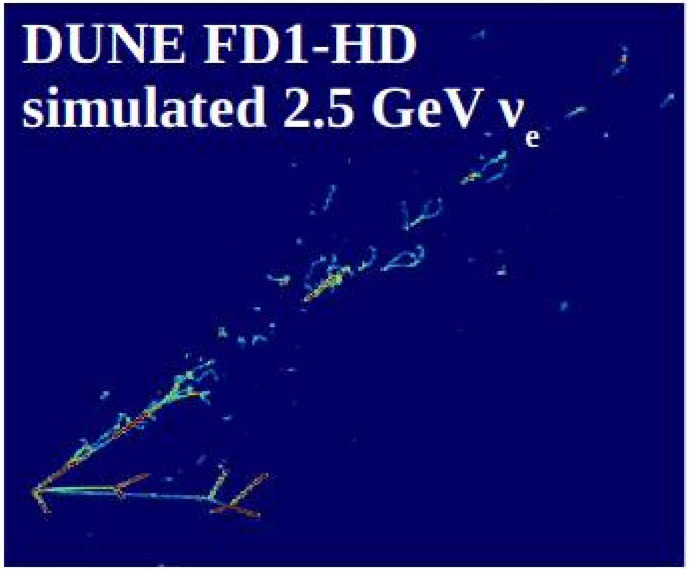




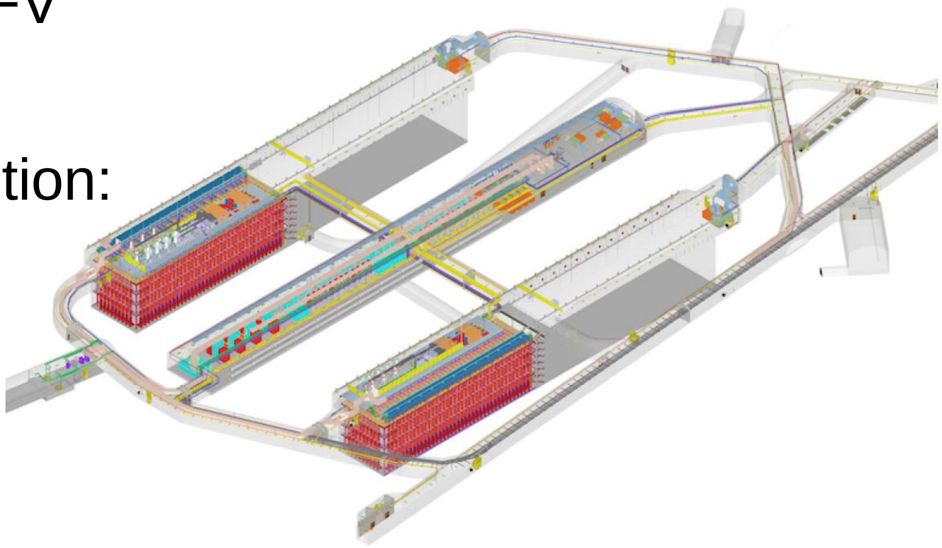
- L ≈ 1285 km; E_ν ≈ 2.5 GeV (*broad band*); liquid argon time projection chamber (LArTPC)
- Unprecedented intensity neutrino beam (1.2 → 2.4 MW)
- Near detector system at Fermilab
- 4 x 17 kt far detector modules at SURF

Far Detector (FD)

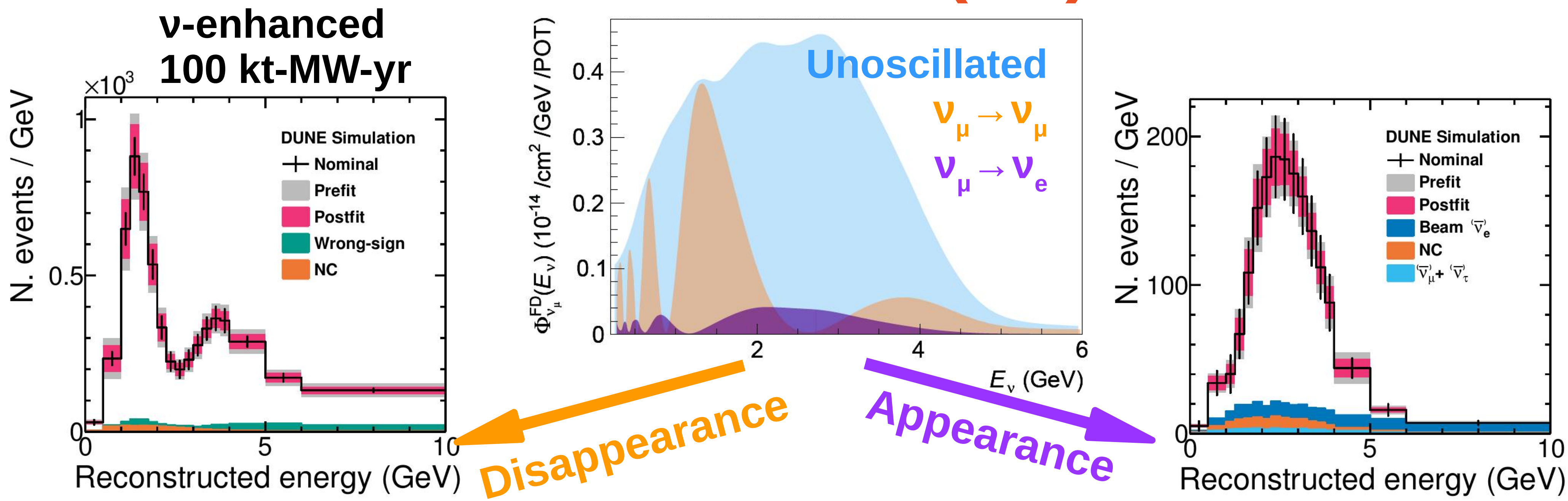




- 4 x 17 kt modules, minimum 10 kt FV each (2 x LAr in phase I)
- Full FD1 simulation and reconstruction: PRD102, 092003 (2020)
- Four samples in analysis: ν_μ & ν_e in ν and $\bar{\nu}$ enhanced modes



Far Detector (FD)



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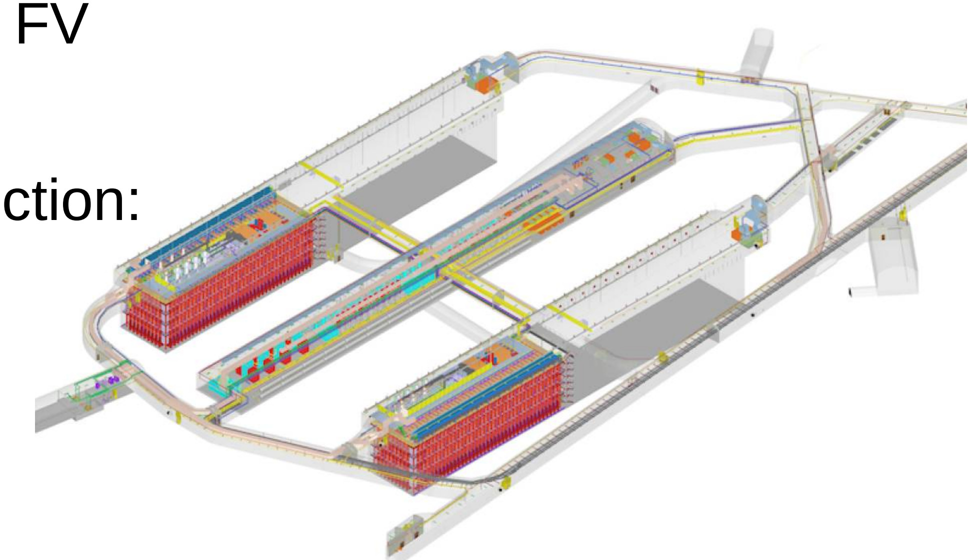
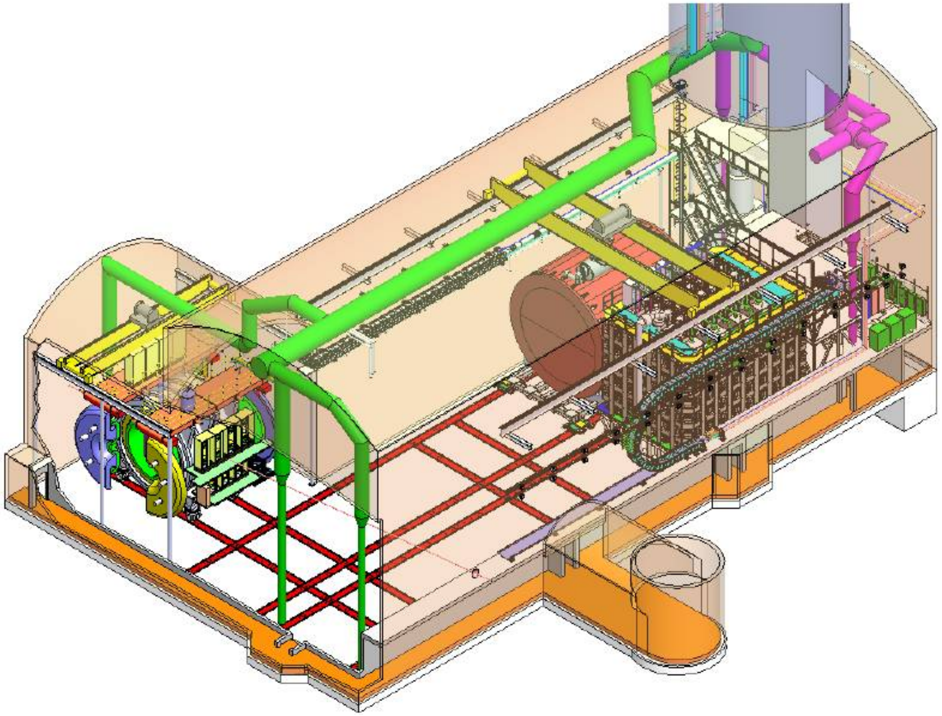


Near Detector (ND)

Core requirements:

- Constrain neutrino flux
- Constrain $\nu/\bar{\nu}$-Ar interactions
- Exceed FD energy resolutions
- Tolerate high rate environment



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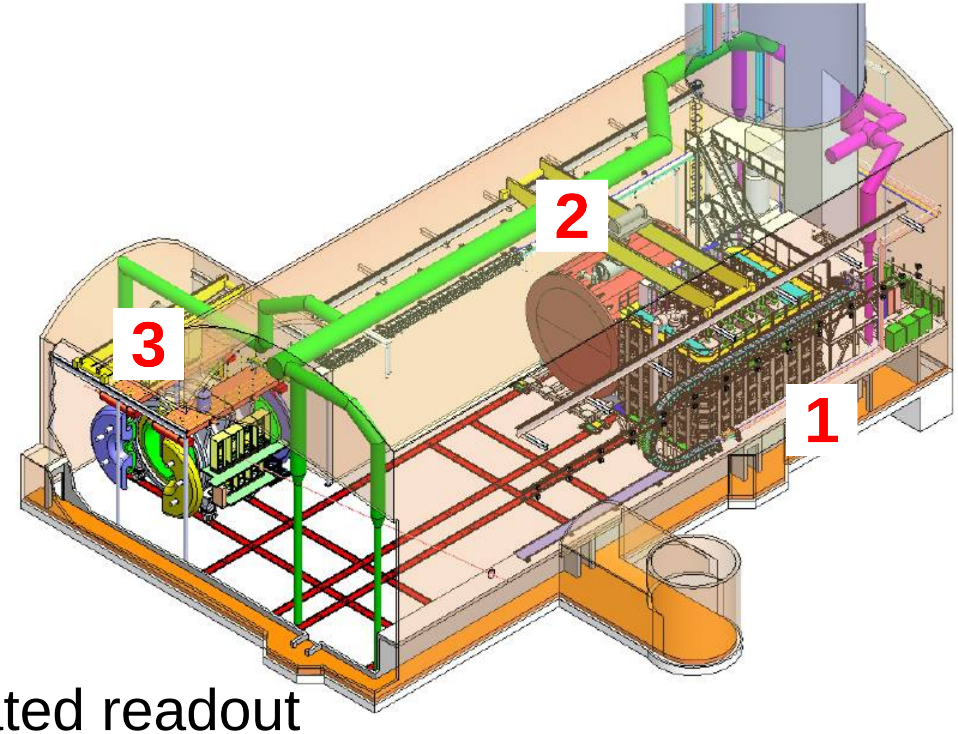

Three major components:

1 - Core 150 t LArTPC with pixelated readout

2 - Downstream magnetized tracker

- Phase I physics with muon range stack
- Phase II with GArTPC for finer precision

3 - SAND: dedicated beam monitor

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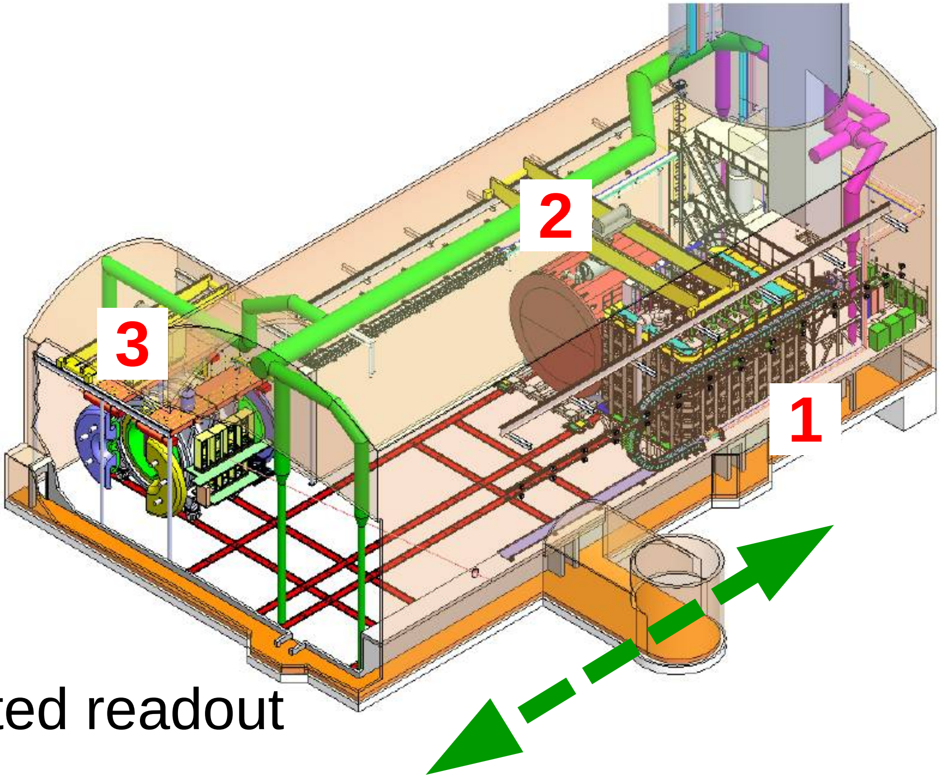

Moveable

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- Phase II with GArTPC for finer precision

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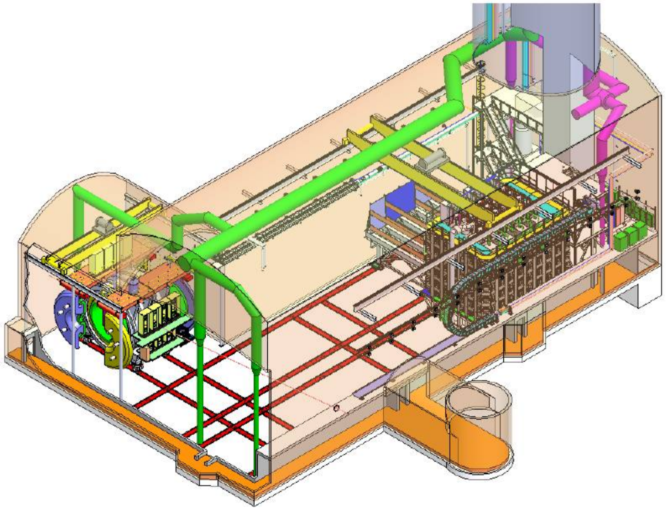
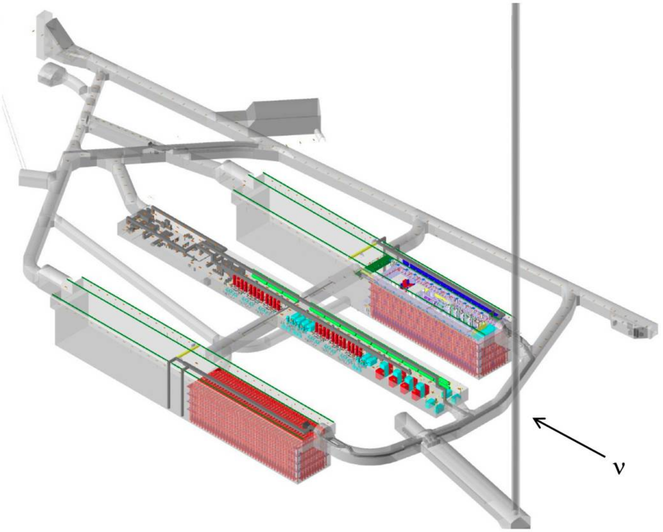
See D. Cherdack's talk later!

Phased DUNE construction

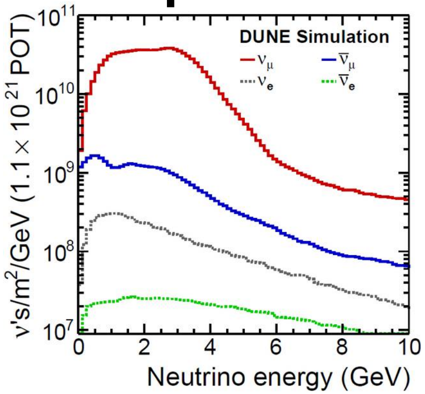
- Construction schedule funding limited:
  - FD late 2020s
  - Beam and ND by 2031
- **Phase I:**
  - Ramp up to 1.2 MW beam intensity
  - 2x 17 kt LArTPC FD modules
  - Near detector: ND-LAr + TMS + SAND
- **Phase II:**
  - Proton beam 1.2 MW → 2.4 MW
  - 4x 17kt FD modules
  - TMS → MCND





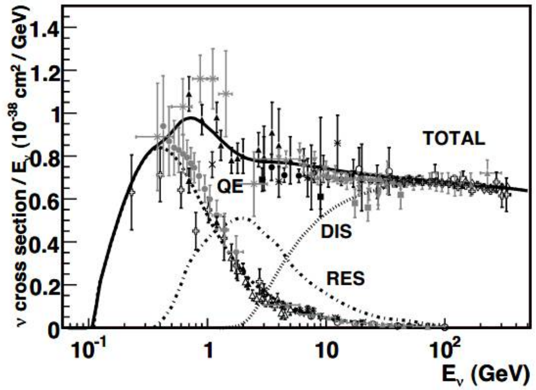
Analysis summary

Flux prediction

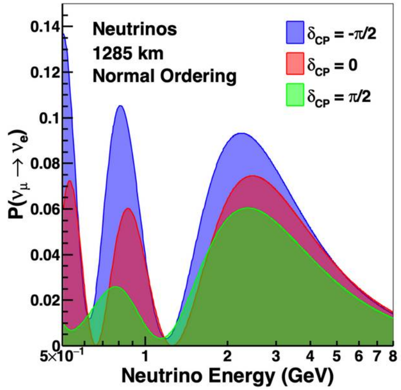


X

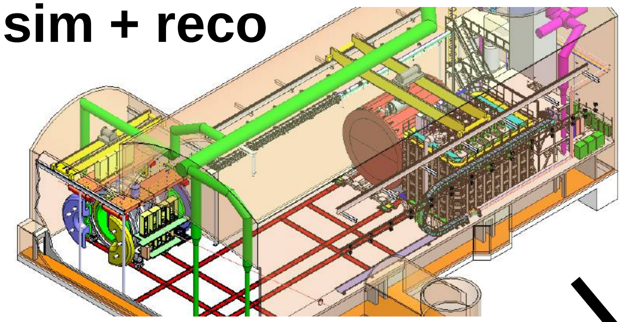
Interaction model



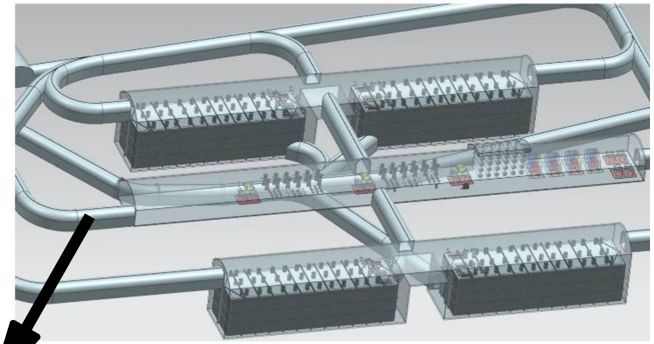
Oscillations



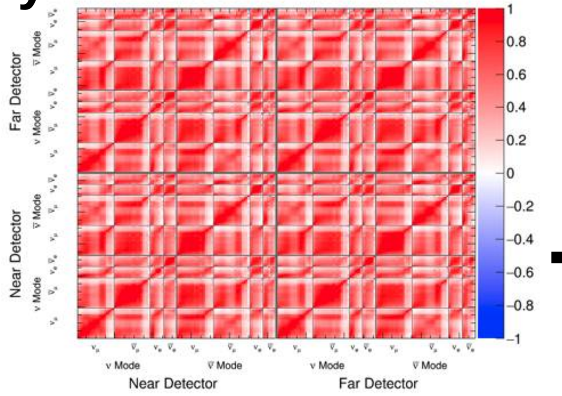
ND sim + reco



FD sim + reco



Systematic uncertainties



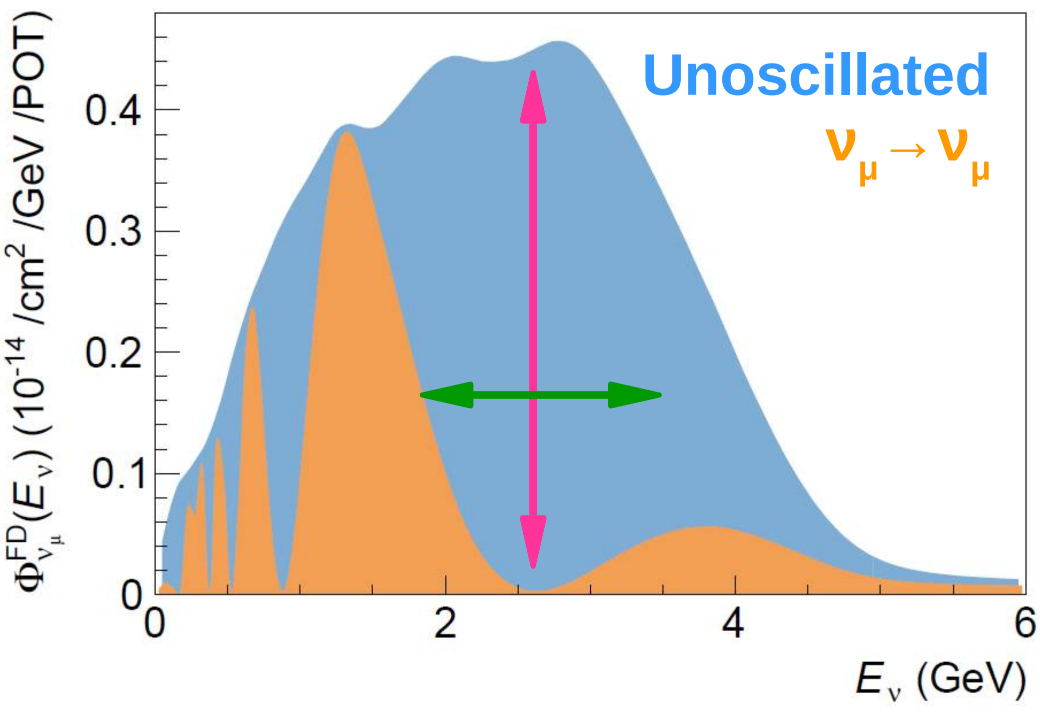
Fitting framework

$$\chi^2(\vec{\vartheta},\vec{x}) = 2\sum_{i}^{N_{\text{bins}}}\left[M_i(\vec{\vartheta},\vec{x}) - D_i + D_i \ln\left(\frac{D_i}{M_i(\vec{\vartheta},\vec{x})}\right)\right] + \sum_{j}^{N_{\text{systs}}}\left[\frac{\Delta x_j}{\sigma_j}\right]^2$$

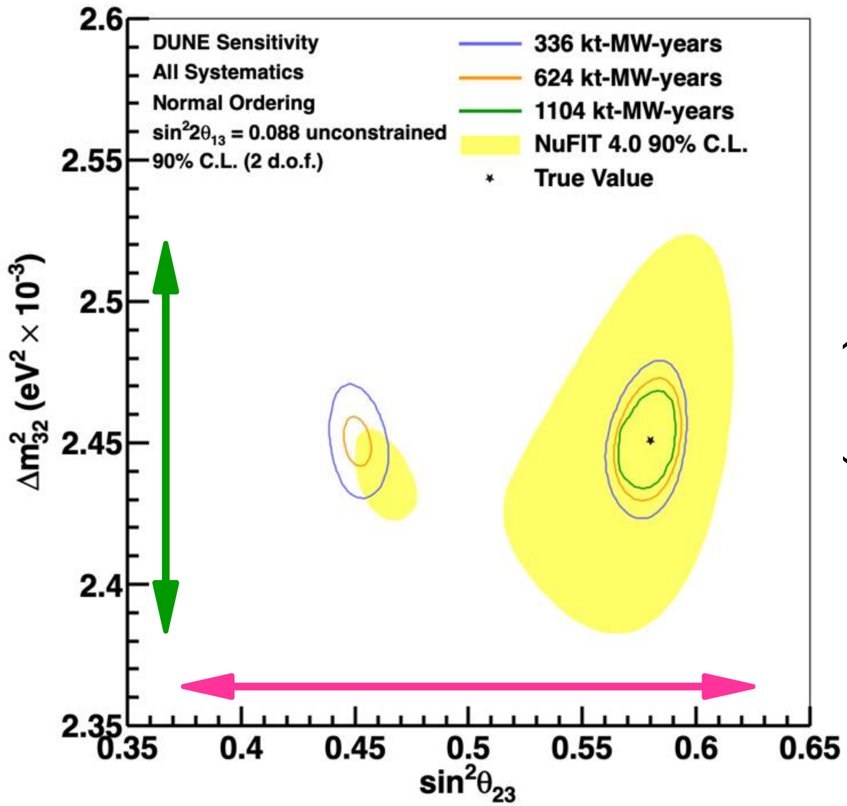
Muon (anti)neutrino disappearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) = 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Phi_{32} + \ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$



90% confidence



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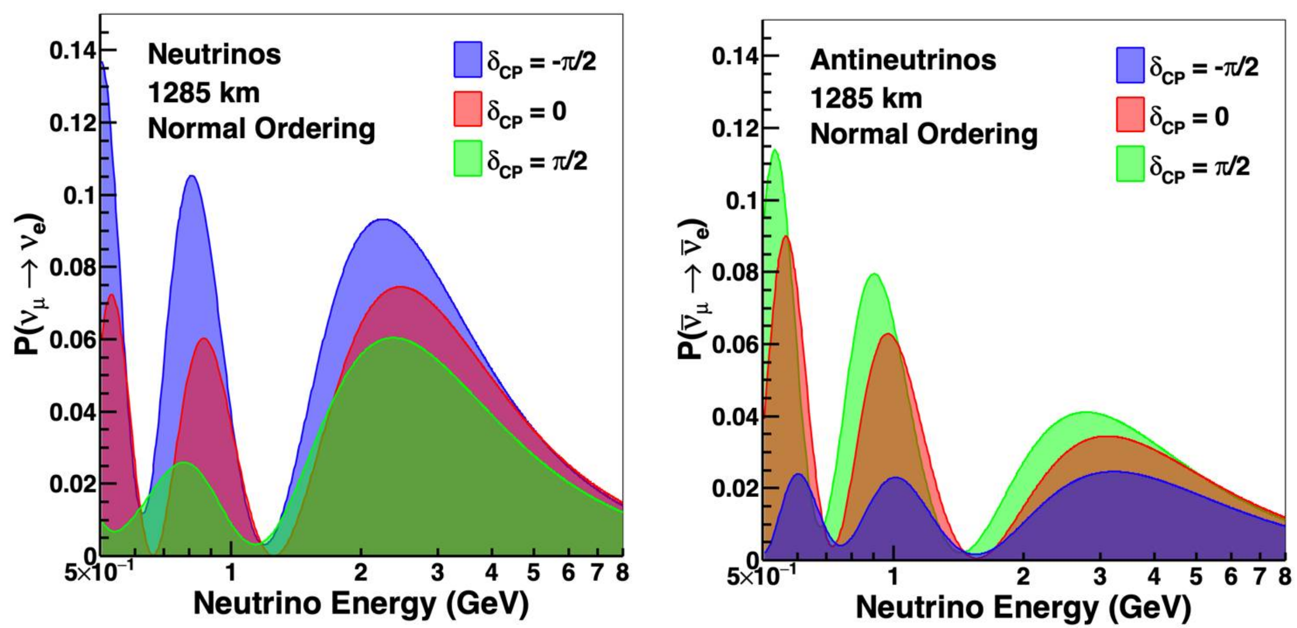
Electron (anti)neutrino appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Phi_{31}-aL)}{(\Phi_{31}-aL)}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\cos(\Phi_{31}\pm\delta_{CP})$$
$$+\ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m_{ji}^2 L}{E_\nu} \qquad a = \pm\frac{G_F N_e}{\sqrt{2}}$$

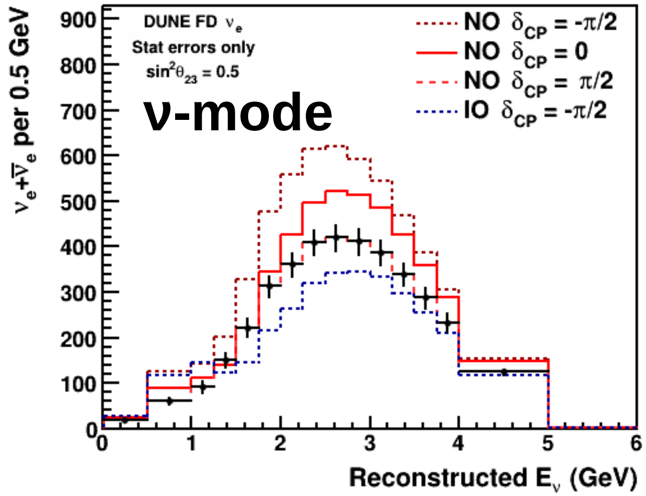
Sign change for ν_e and $\bar{\nu}_e$

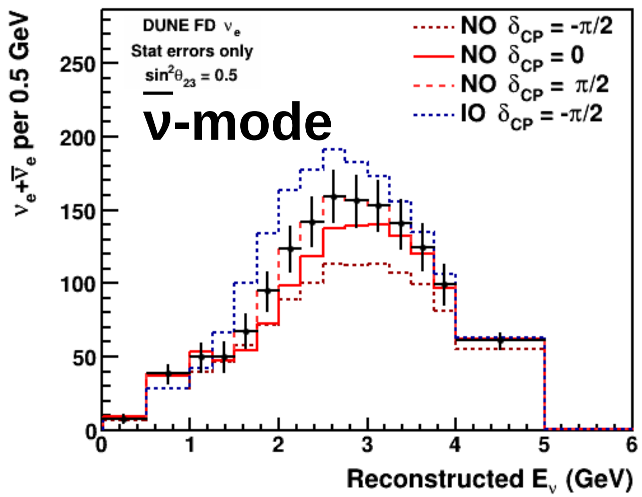
Interplay between mass ordering and CP-phase

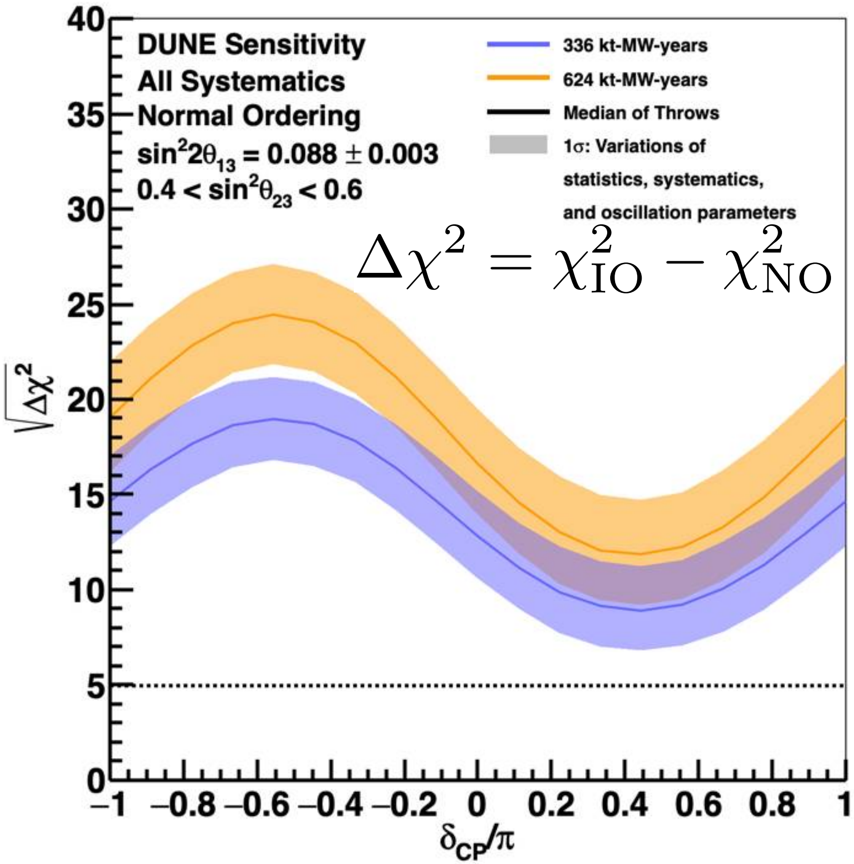


Spectral measurement allows DUNE to disentangle effects

MO sensitivity







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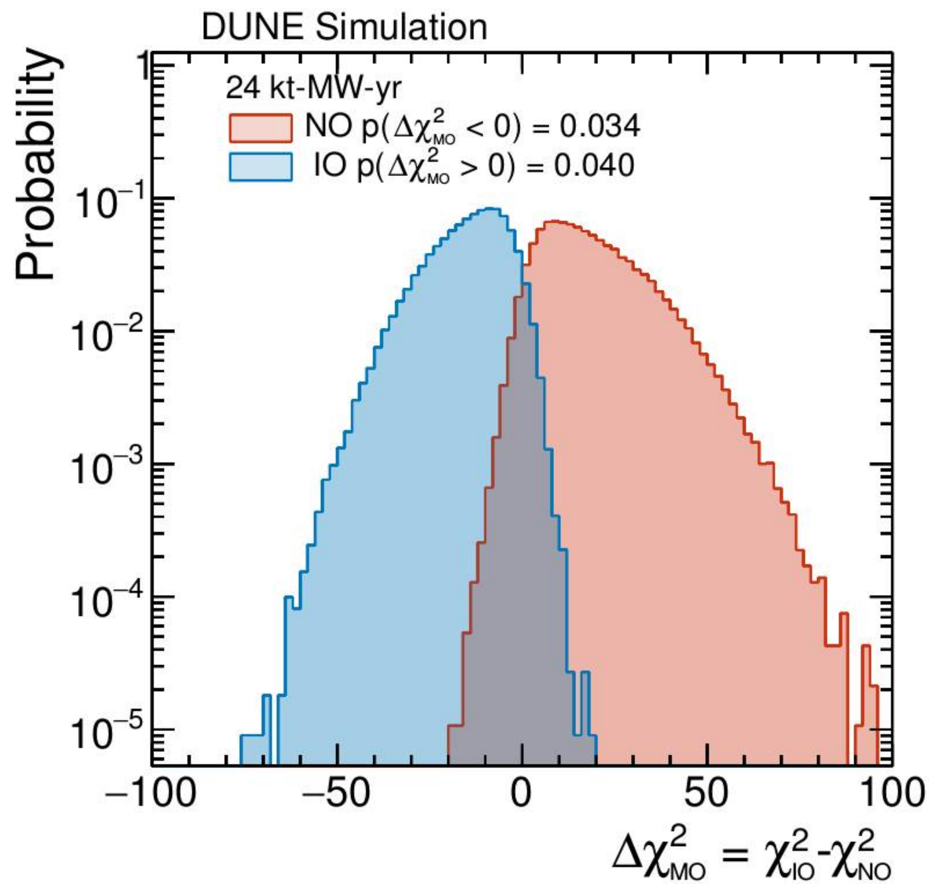
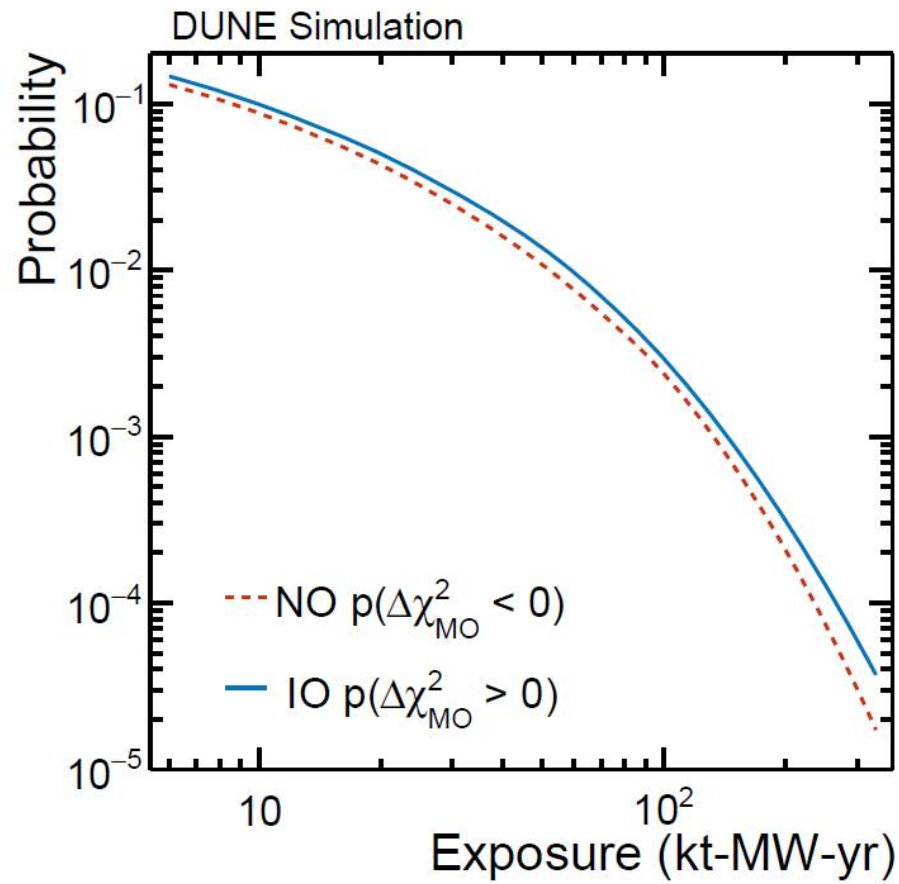
Unrivaled ability to resolve the mass ordering:

- Regardless of other parameter values
- Without reliance on other oscillation parameter inputs

MO sensitivity





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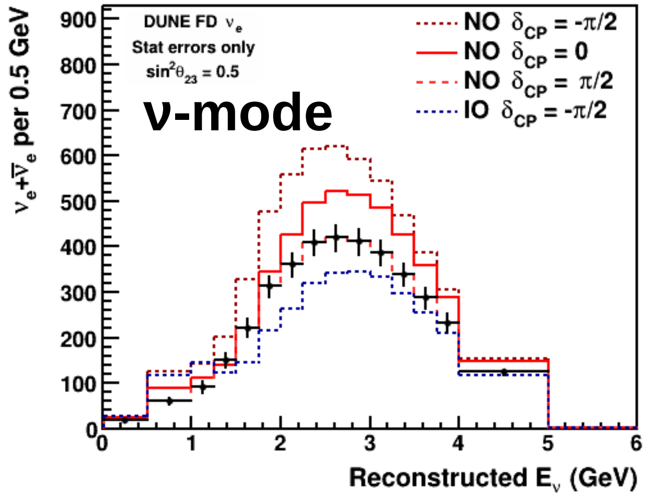
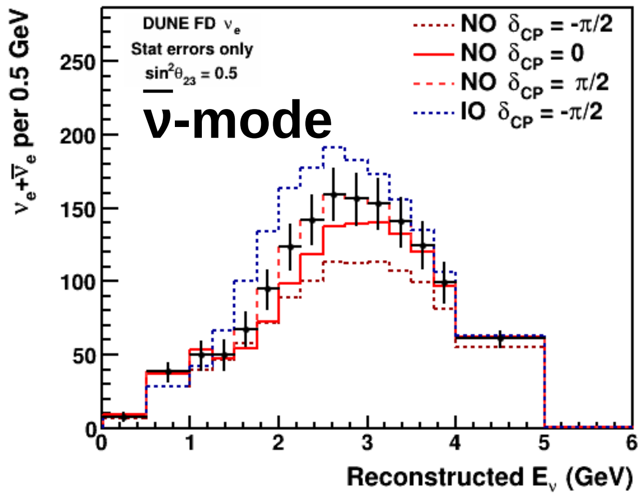
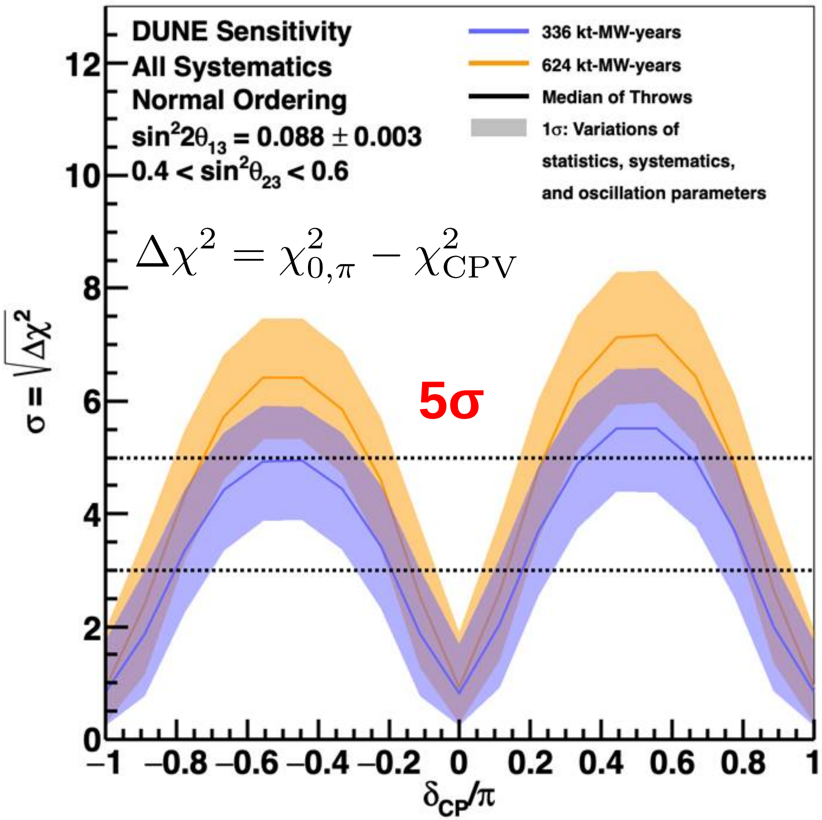
Phase I: strong MO potential with <u>short exposures</u>

Probability < 0.01 to prefer the wrong neutrino mass ordering after 66 kt-MW-yr

CPV sensitivity







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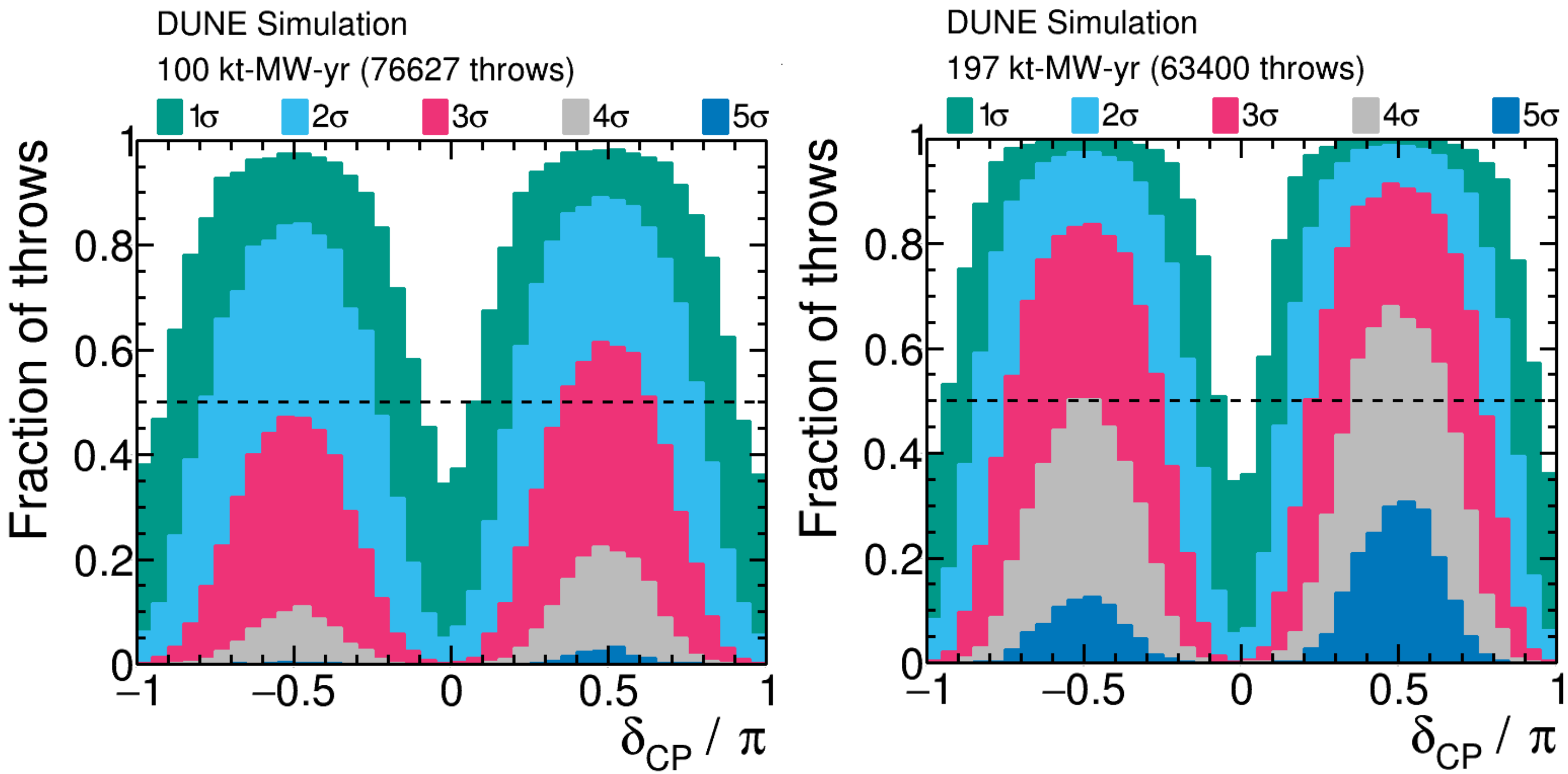
Phase II: >5σ discovery potential for >50% of δ_{CP} values

No reliance on external oscillation parameters

CPV sensitivity



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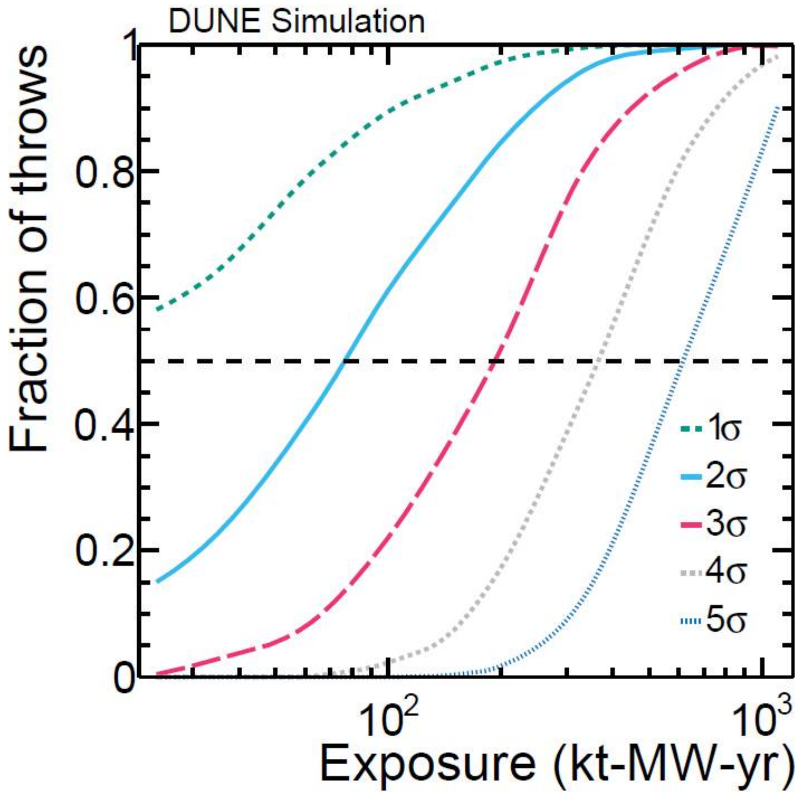
Syst.+stat. throws exceeding 1-5σ significance thresholds

- Late phase I: ≈100 kt-MW-yr, 3σ at maximal δ_{CP}
- Early phase II: ≈200 kt-MW-yr, 3σ for 50% of δ_{CP} values

CPV sensitivity over time



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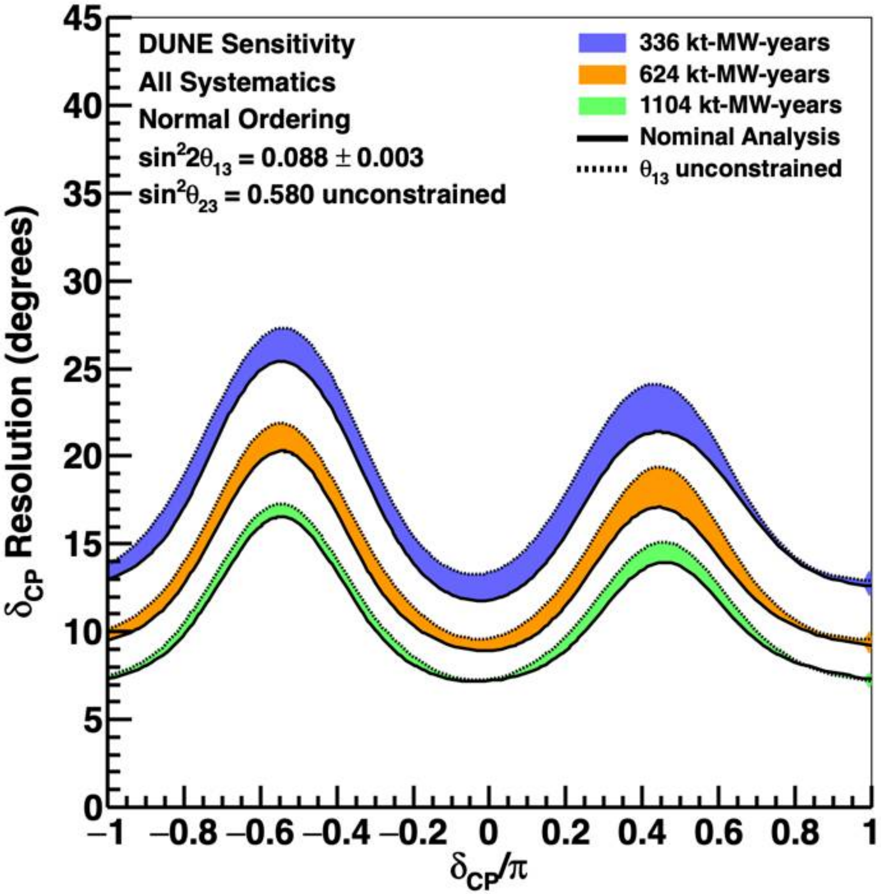
Phase II: by 646 kt-MW-yr >5σ median sensitivity for 50% δ_{CP} values

δ_{CP} resolution



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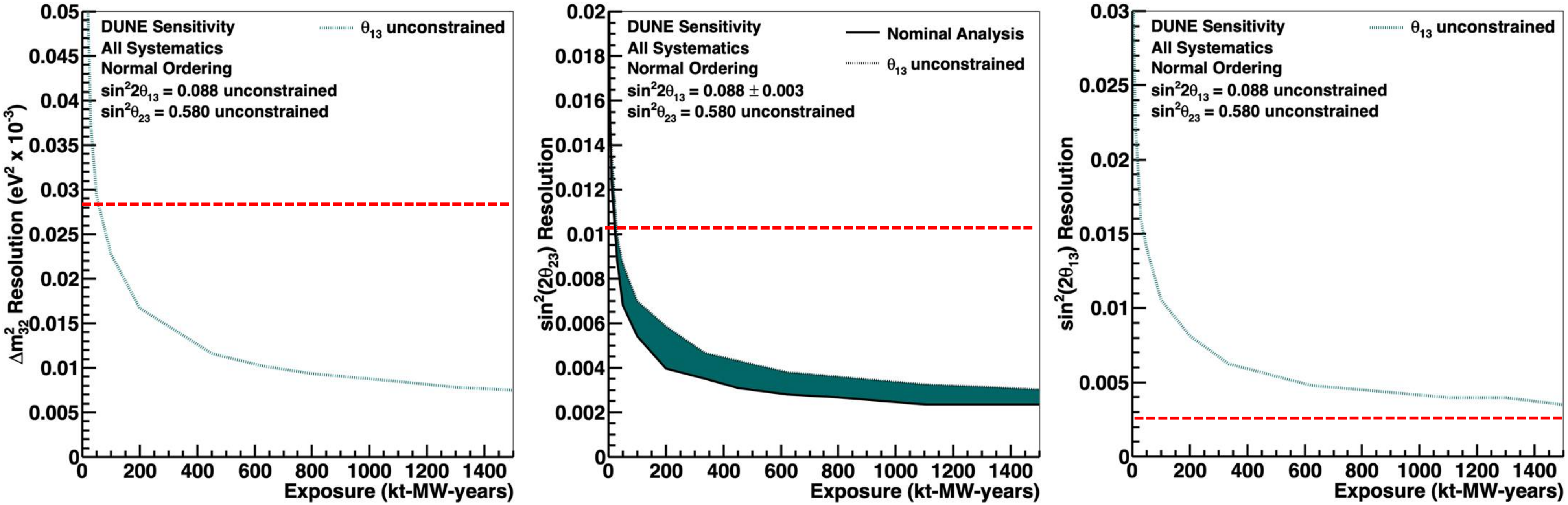
Phase II: 7–16° δ_{CP} resolution **regardless of true value**

Not just CPV!

DUNE precision measurements



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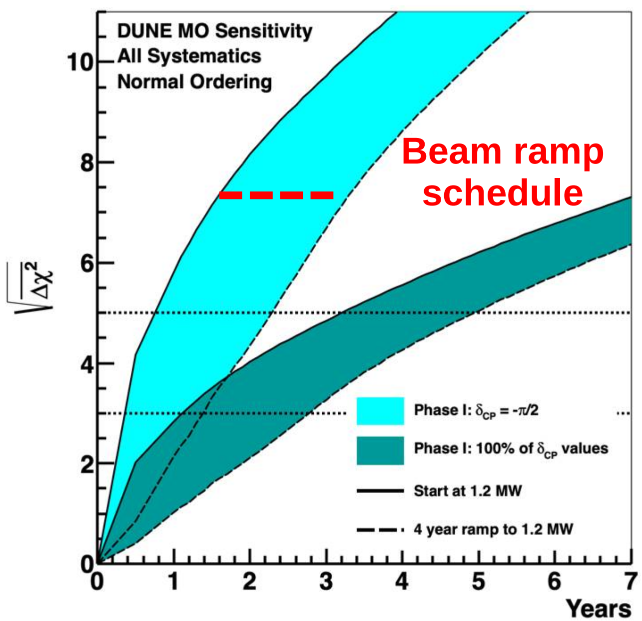
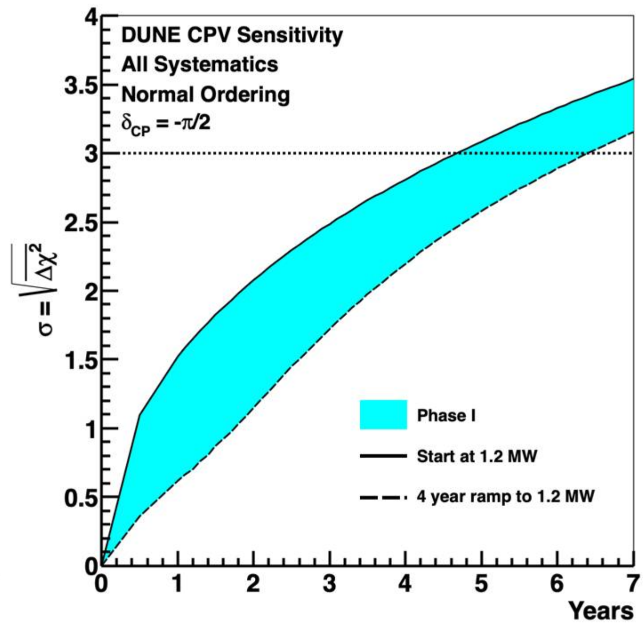
- Expected DUNE resolution vs exposure and **current global fit** (NuFit 5.0: JHEP 09 (2020) 178)
- Ultimate sensitivity approaches reactor θ_{13}
- Constrain δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13} and MO with a single experiment

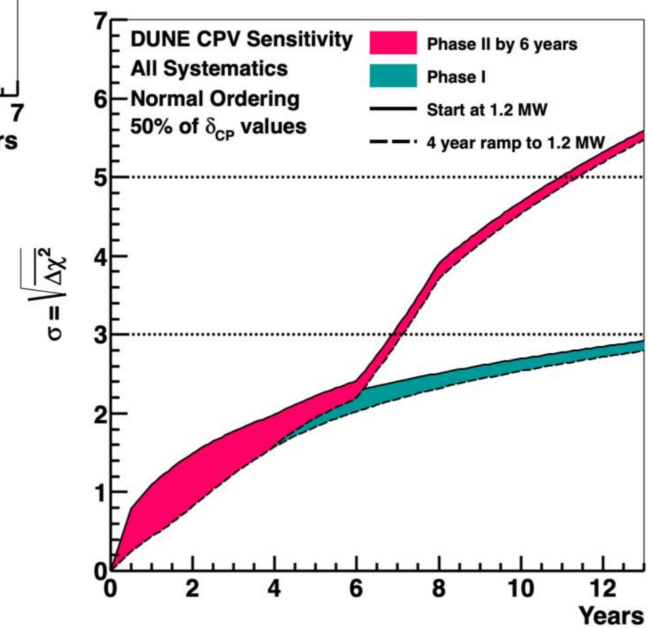
DUNE staging summary





Phase I:

- ✔ Unambiguous MO
- ✔ 3σ CPV at maximal δ_{CP}



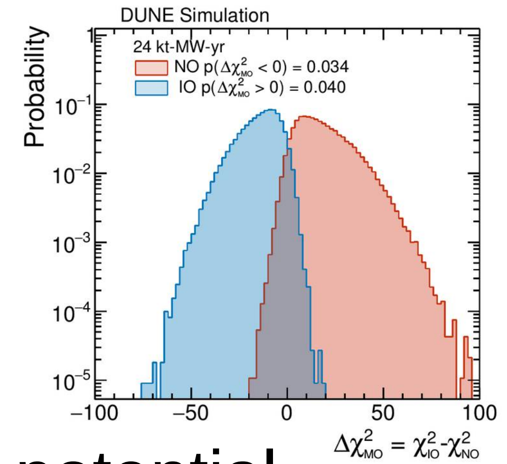
Phase II:

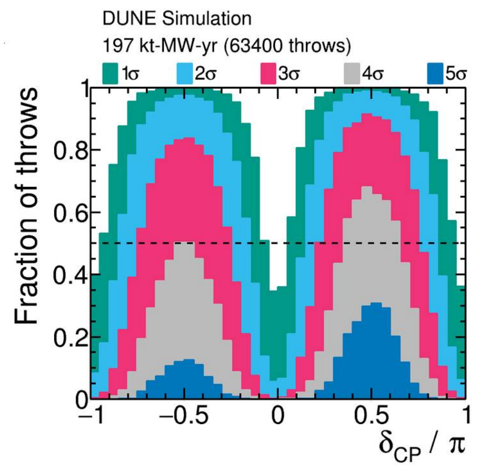
- ✔ 5σ CPV for 50% of δ_{CP}
- ✔ Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}

Requires 2.4 MW, 4 x FD modules + full ND

DUNE oscillation summary

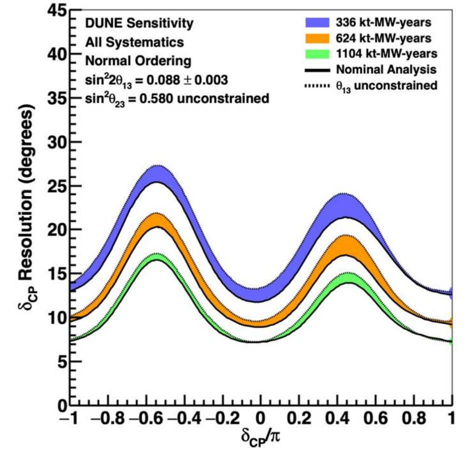
Unambiguous MO measurement





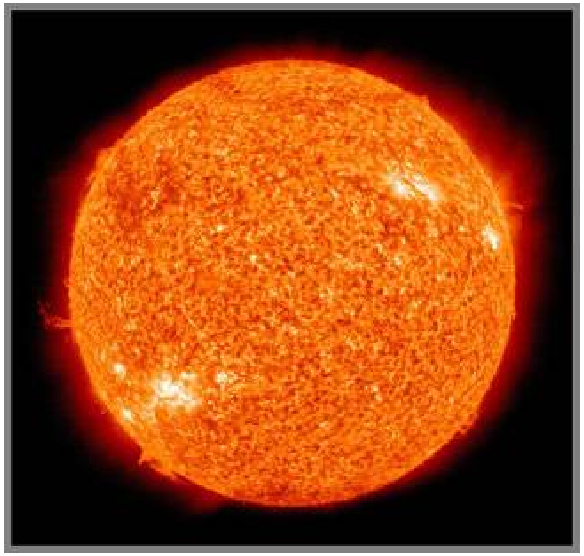
Strong CPV discovery potential

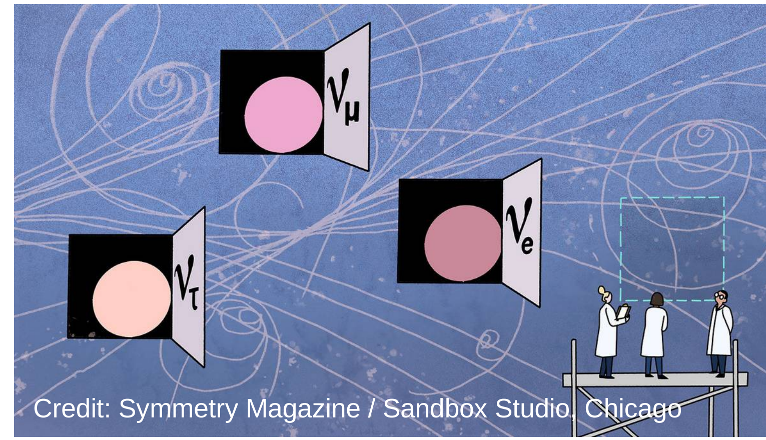
Precision osc. parameter measurements



Broad spectral measurements will stress test the U_{PMNS} model – ***is anything missing?***

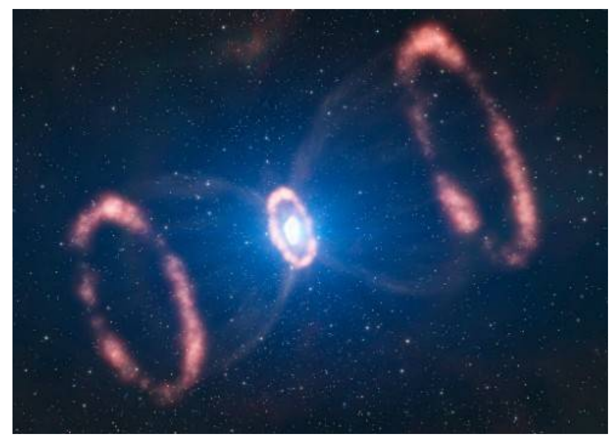
Part of a broader physics program!





Credit: Symmetry Magazine / Sandbox Studio, Chicago

Credit: Higgstan



See additional DUNE talks in other sessions!