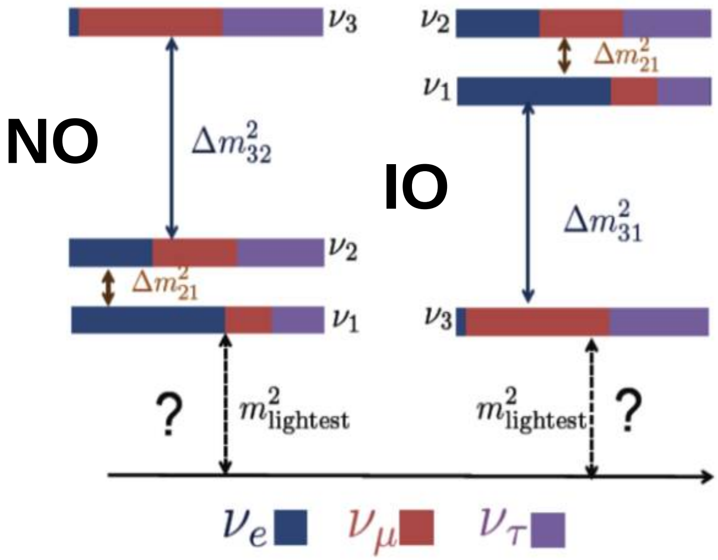
DUNE oscillation physics overview

Snowmass CSS, Seattle
19th July 2022
Callum Wilkinson

Open questions in neutrino physics



Two mass scales

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

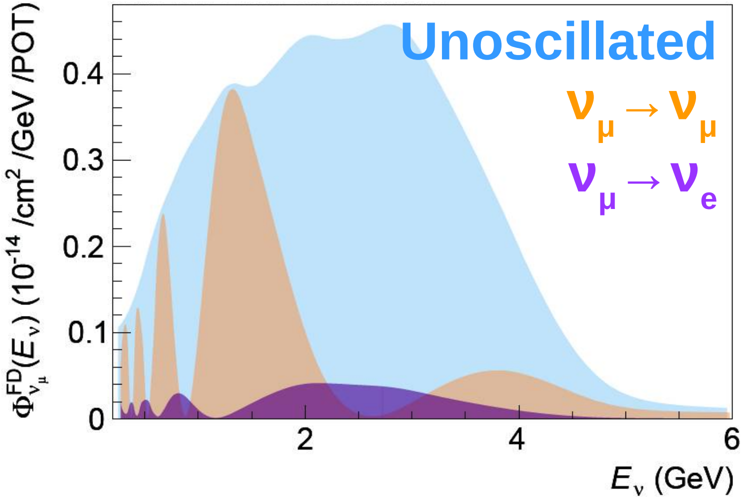
$\Delta m^2_{21} \sim 7 \times 10^{-5}\ \text{eV}^2$

- 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

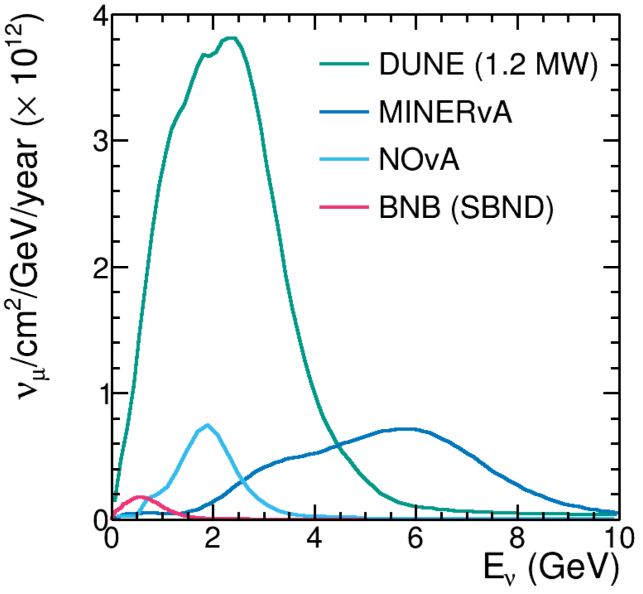
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \rightarrow \nu_B)}_{\text{Far}}$$

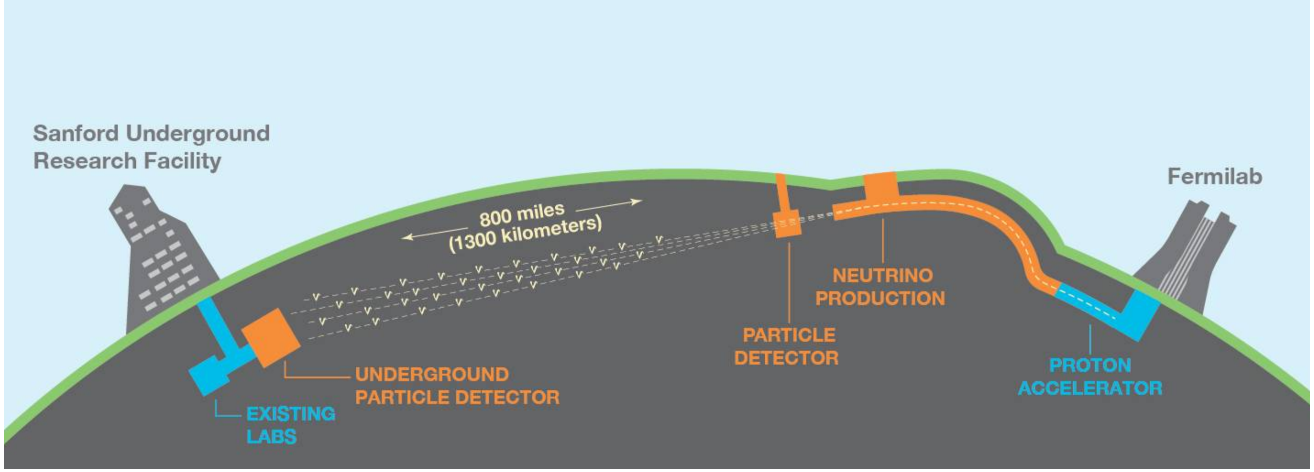


- Complex inference of **oscillation probability** from measured **event rate**
- Near detector to constrain **neutrino flux** and **cross-section*** models/systematics
- Different near and far detector fluxes mean uncertainties do not neatly cancel
- High-fidelity detectors reduce ambiguities due to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

****See K. McFarland's talk later!***

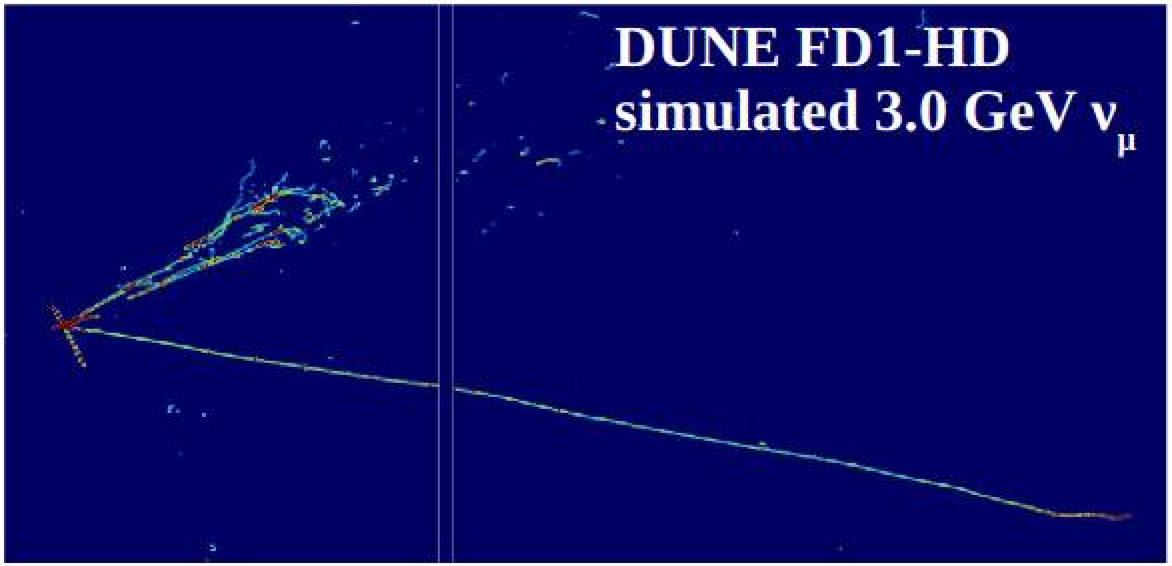
DUNE

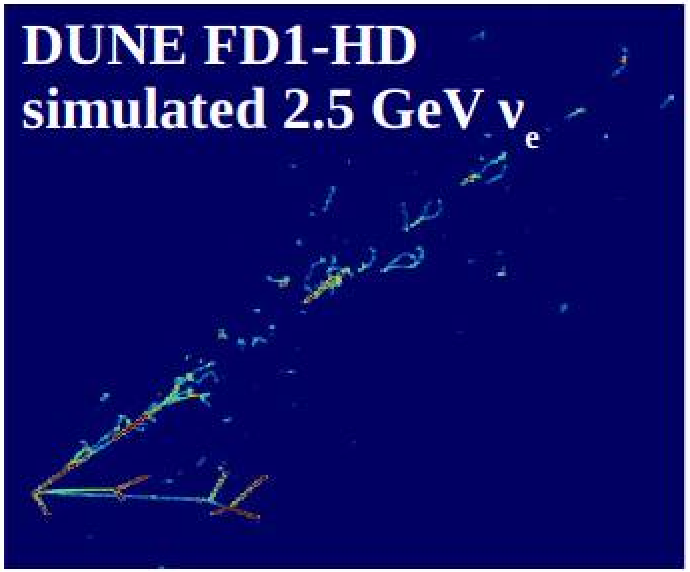




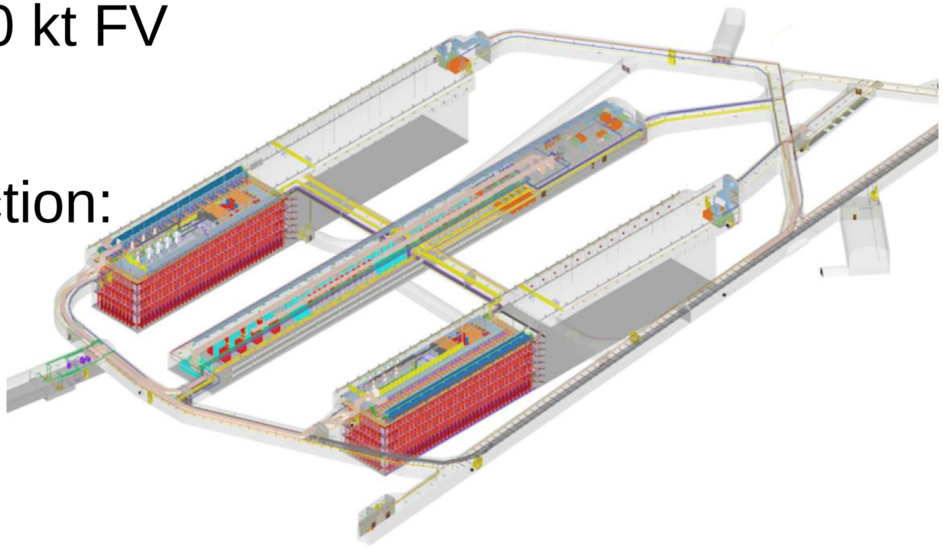
- L ≈ 1285 km; E_ν≈ 2.5 GeV (*broad band*); liquid argon time projection chamber (LArTPC)
- Unprecedented intensity neutrino beam (1.2 → 2.4 MW)
- Near detector system at Fermilab
- 4 x 17 kt LAr far detector modules at SURF

Far Detector (FD)

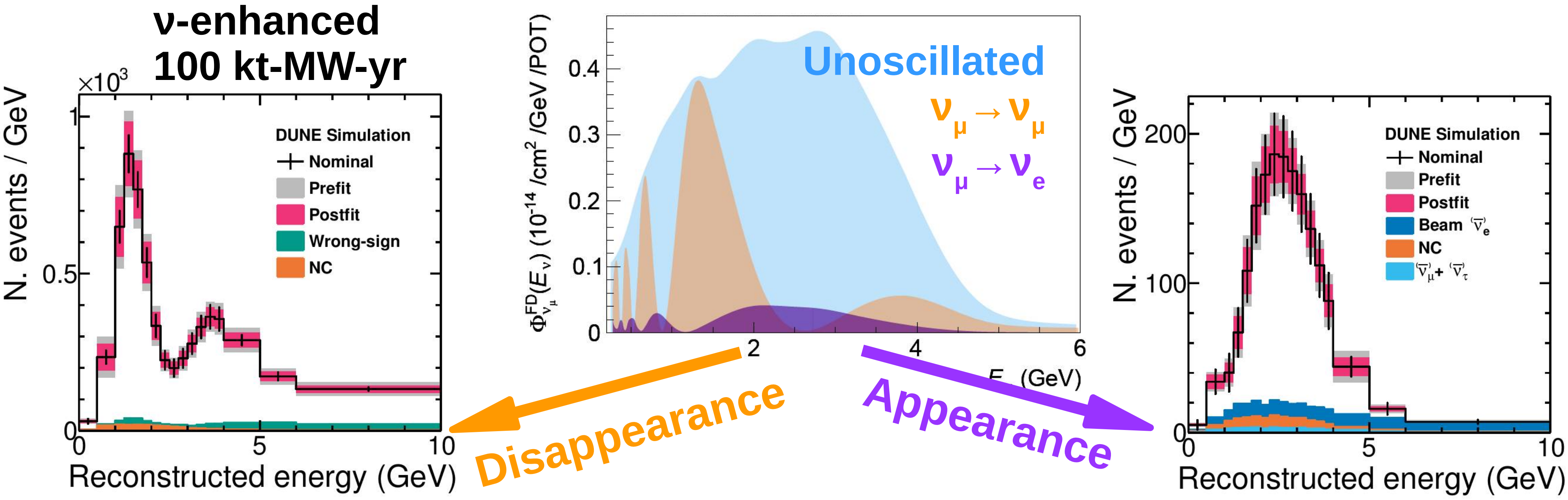




- 4 x 17 kt LAr modules, minimum 10 kt FV each (2 in phase I)
- Full FD1 simulation and reconstruction: PRD102, 092003 (2020)
- Four samples in analysis: ν_μ & ν_e in ν and $\bar{\nu}$ enhanced modes



Far Detector (FD)



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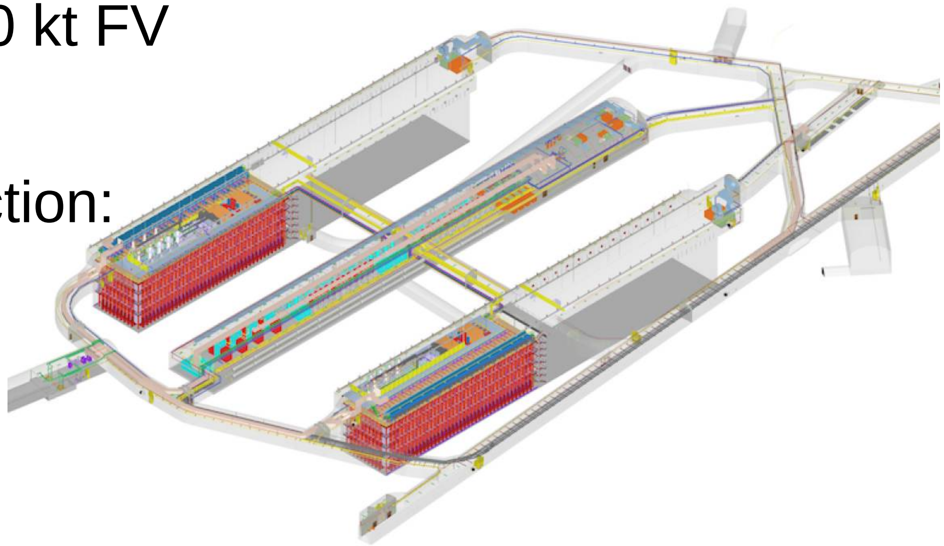
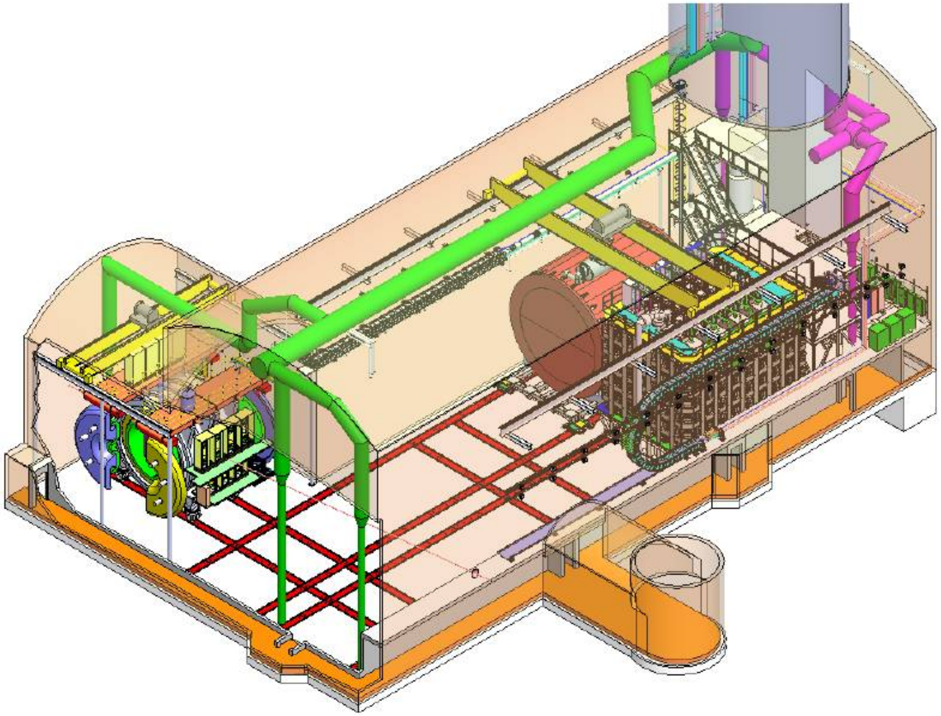


Near Detector (ND)

Core requirements:

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



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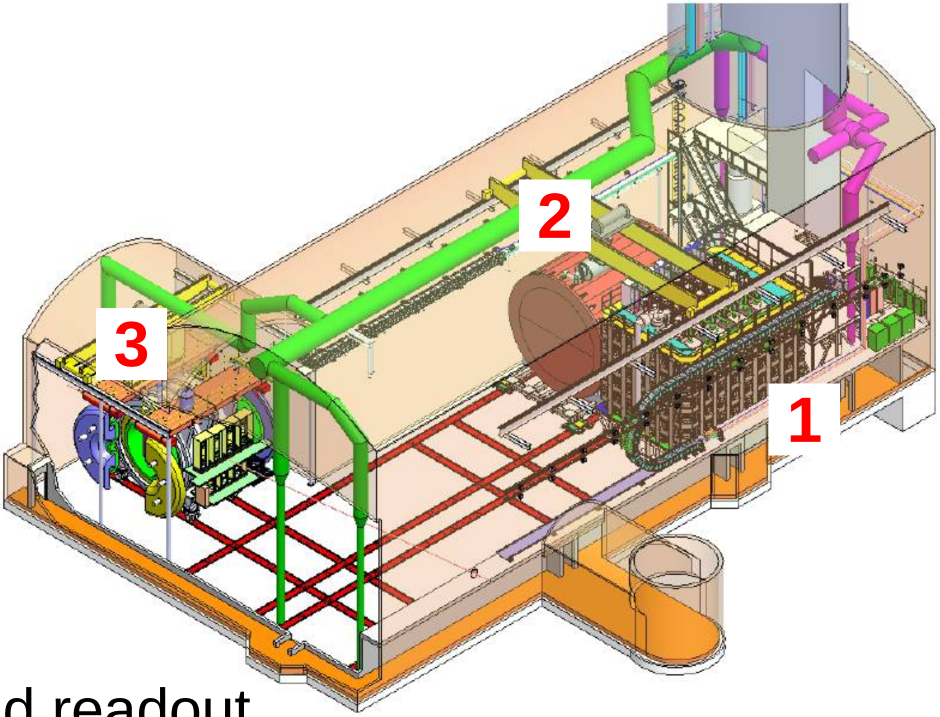

Three major components:

1 - Core 67 t LArTPC with pixelated readout

2 - Downstream magnetized tracker

- Early physics with muon range stack
- GArTPC for finer precision in full deployment

3 - SAND: dedicated beam monitor

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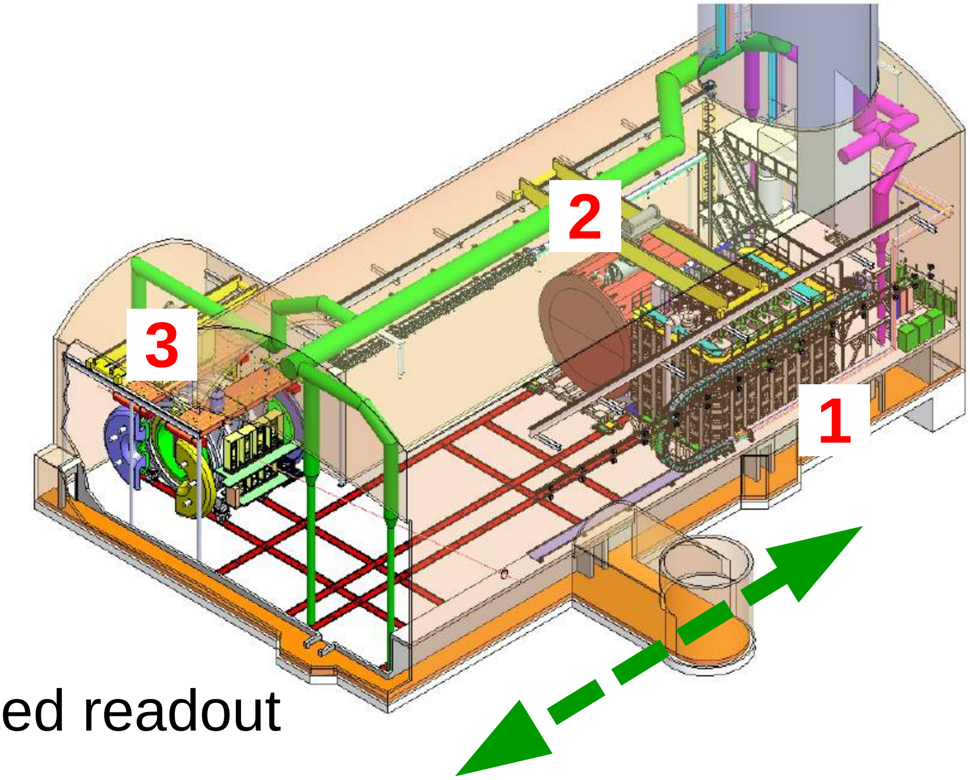


Moveable

Three major components:

1 - Core 67 t LArTPC with pixelated readout

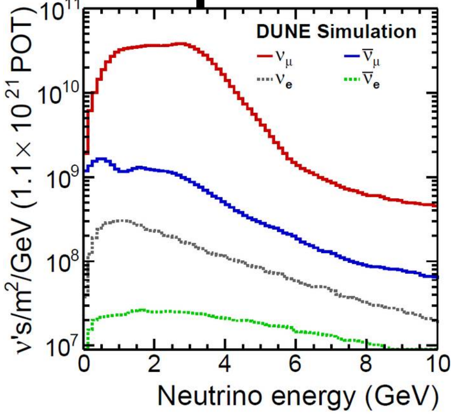
2 - Downstream magnetized tracker
  - Early physics with muon range stack
  - GArTPC for finer precision in full deployment

3 - SAND: dedicated beam monitor

See D. Cherdack's talk later!

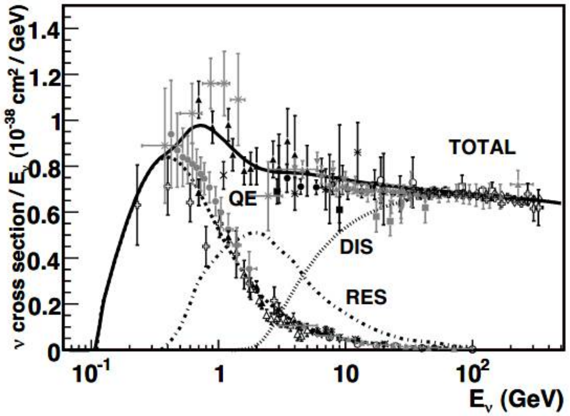
Analysis summary

Flux prediction

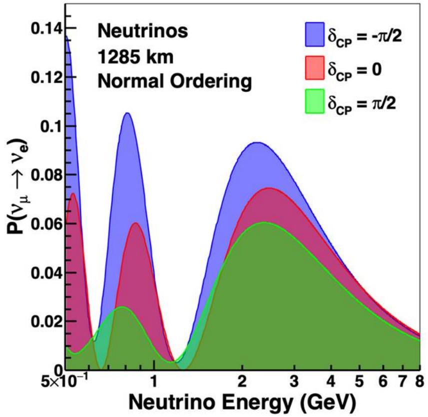


X

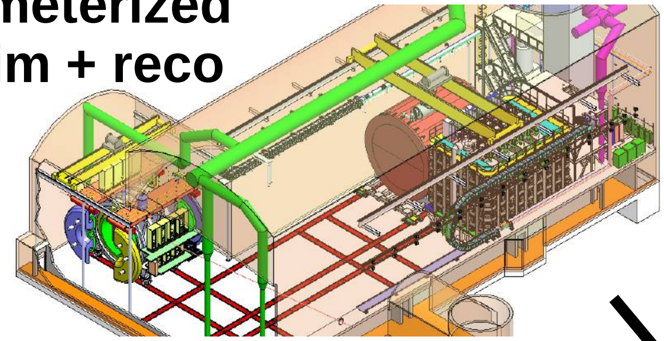
Interaction model



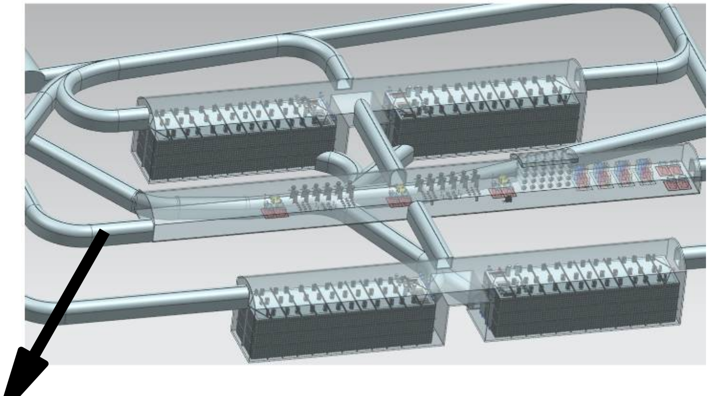
Oscillations



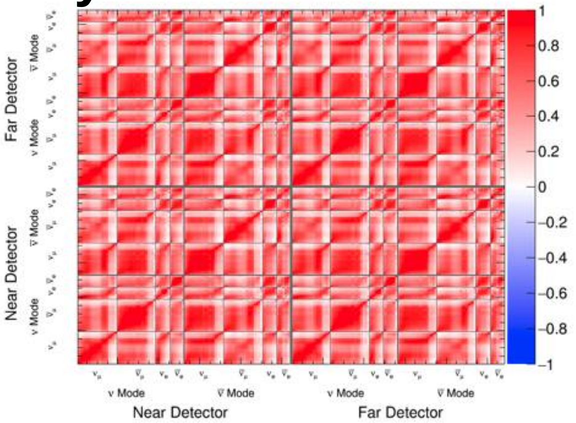
Parameterized ND sim + reco



FD sim + reco



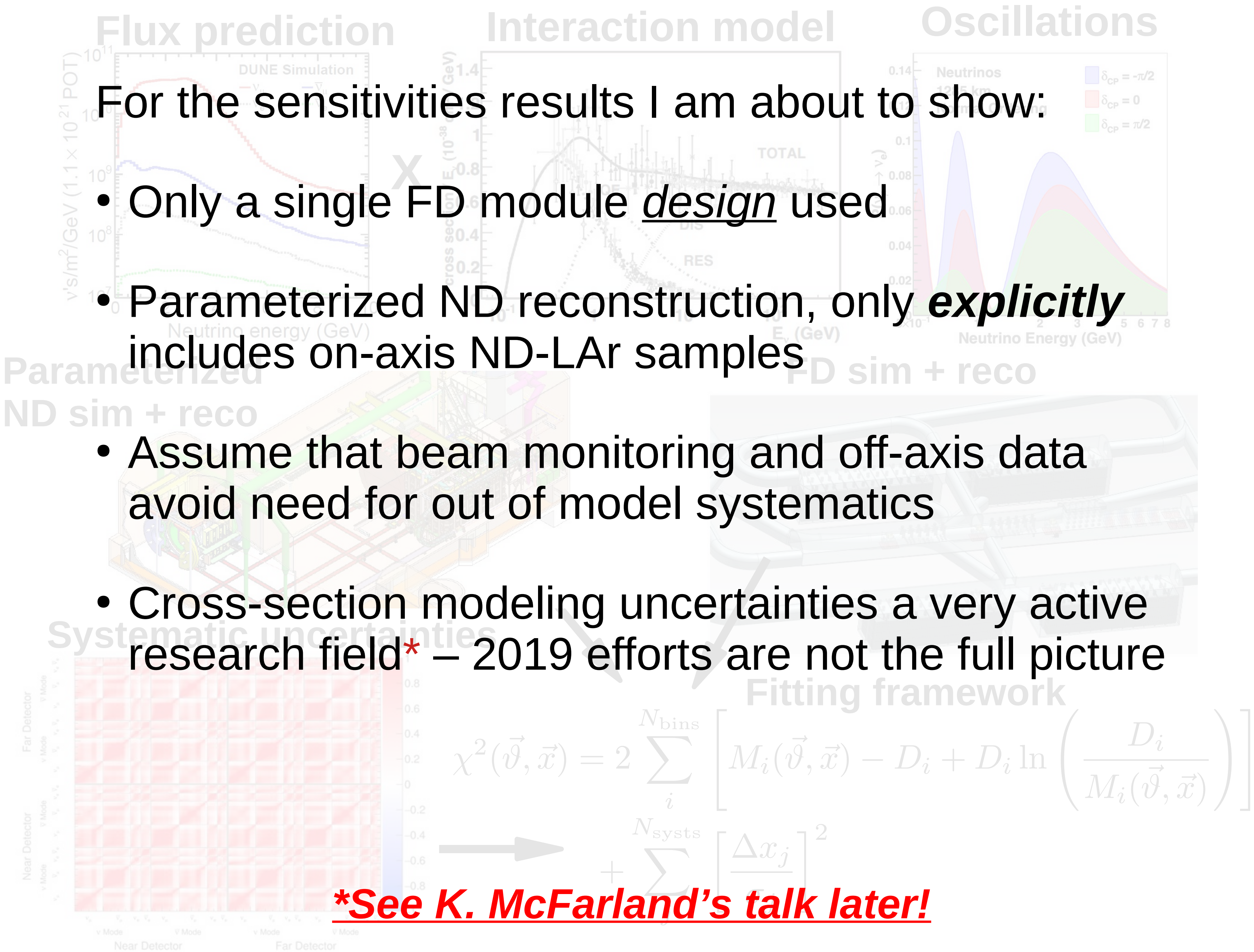
Systematic uncertainties



Fitting framework

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

Analysis **caveats**



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For the sensitivities results I am about to show:

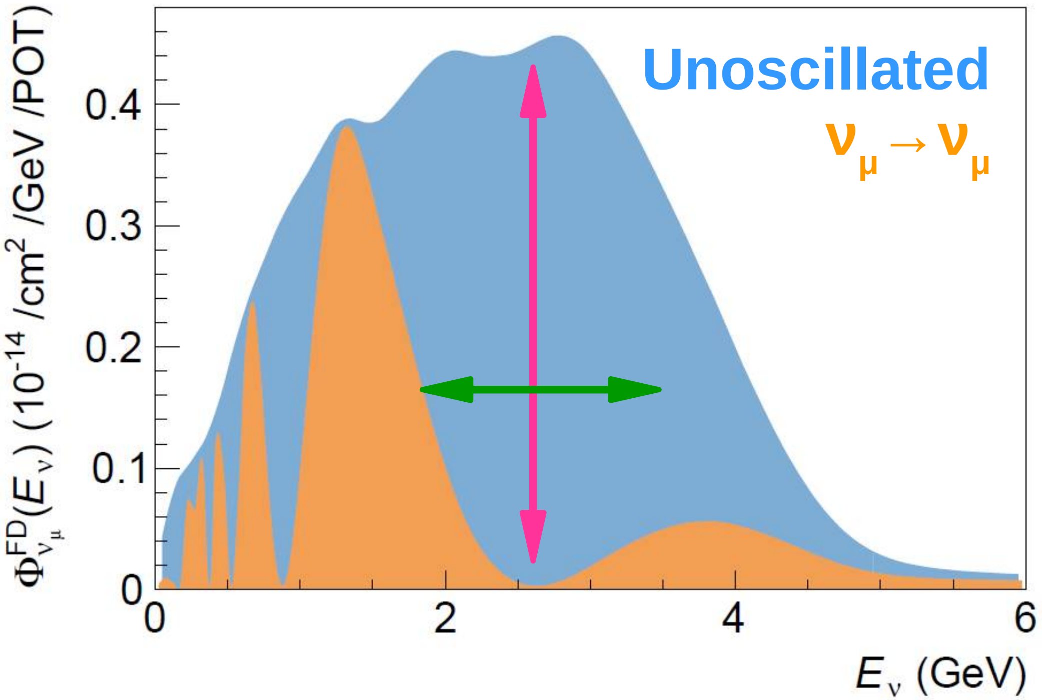
- Only a single FD module *design* used
- Parameterized ND reconstruction, only ***explicitly*** includes on-axis ND-LAr samples
- Assume that beam monitoring and off-axis data avoid need for out of model systematics
- Cross-section modeling uncertainties a very active research field* – 2019 efforts are not the full picture

****See K. McFarland's talk later!***

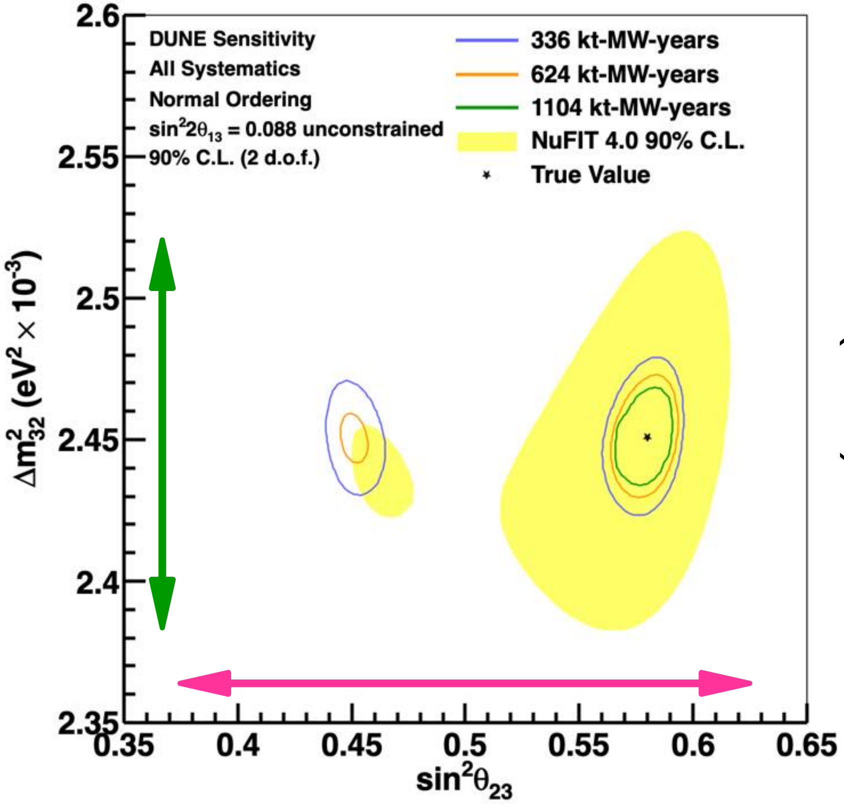
Muon (anti)neutrino disappearance

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

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



90% confidence



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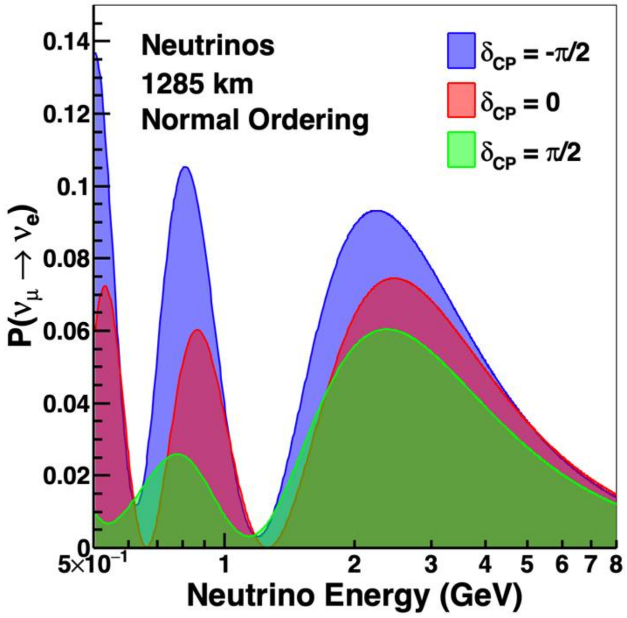
Electron (anti)neutrino appearance

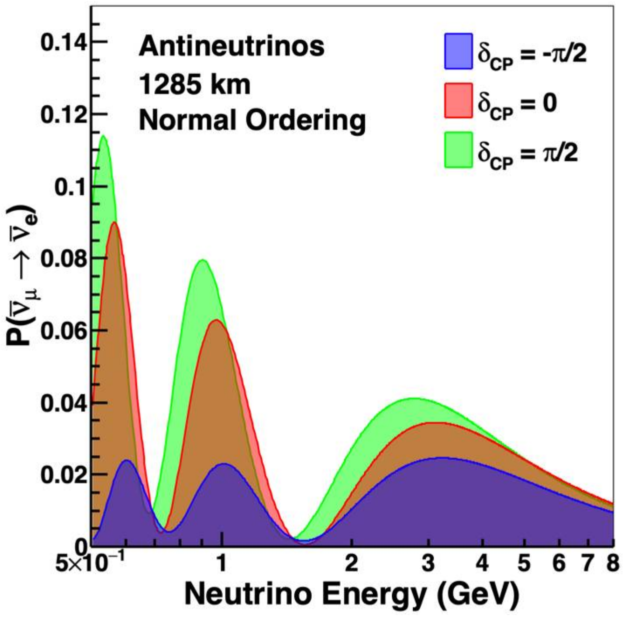
$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) &= \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2 \\
&+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Phi_{31}-aL)}{\underline{(\Phi_{31}-aL)}}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\cos(\underline{\Phi_{31}\underline{\pm}\delta_{\mathrm{CP}})} \\
&+ \dots
\end{aligned}
$$

$$
\Phi_{ji} = \frac{1.27\Delta m^2_{ji}L}{E_\nu} \qquad a = \underline{\pm}\frac{G_\mathrm{F}N_e}{\sqrt{2}}
$$

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

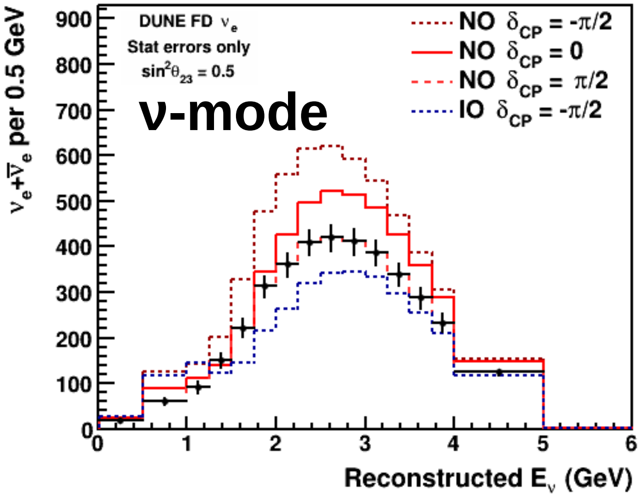
Interplay between mass ordering and CP-phase

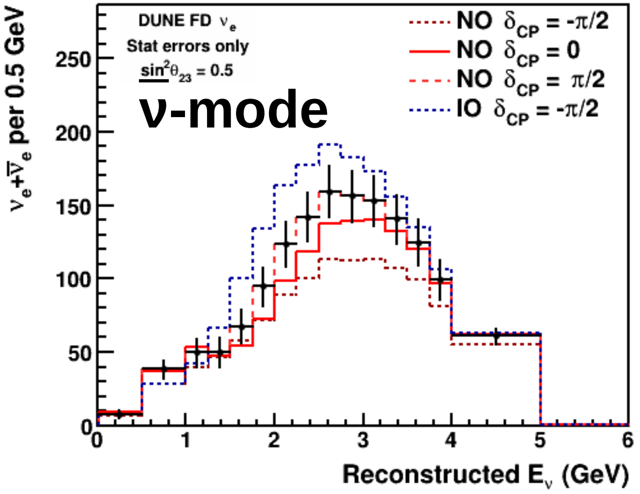


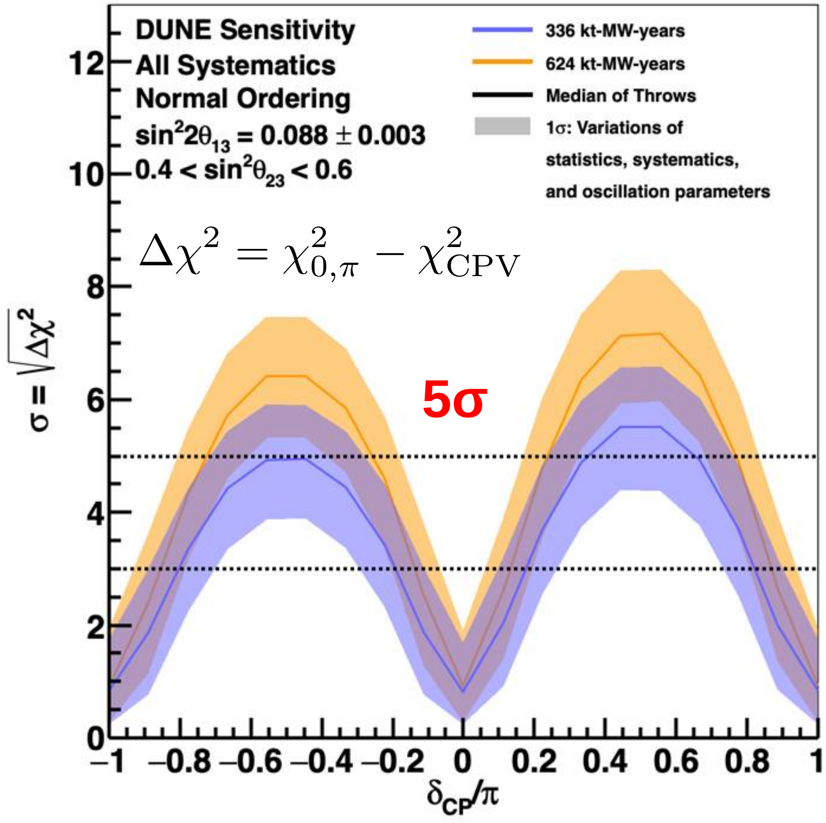


Spectral measurement allows DUNE to disentangle effects

DUNE CPV







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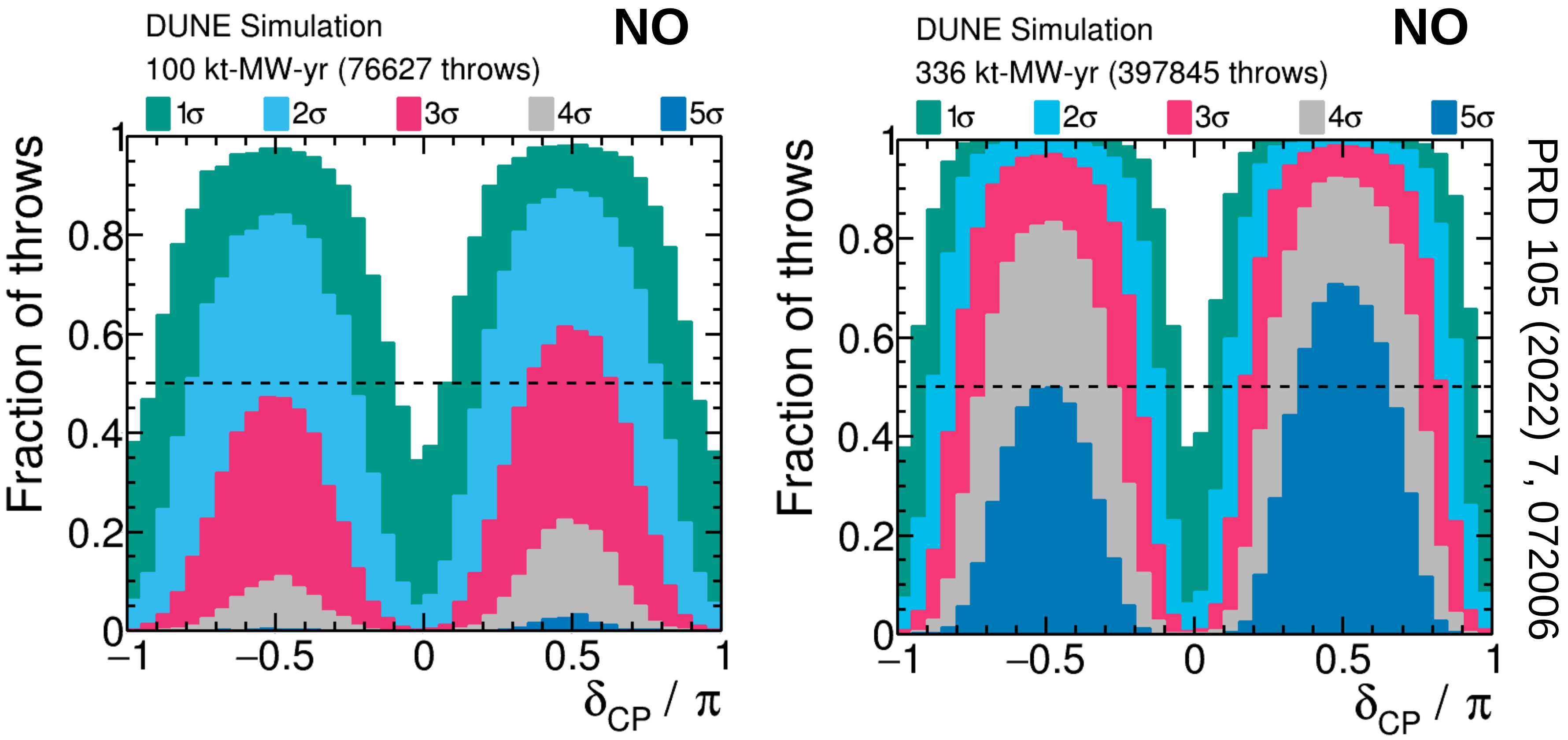
>5σ discovery potential for >50% of δ_{CP} values

No reliance on other experiments

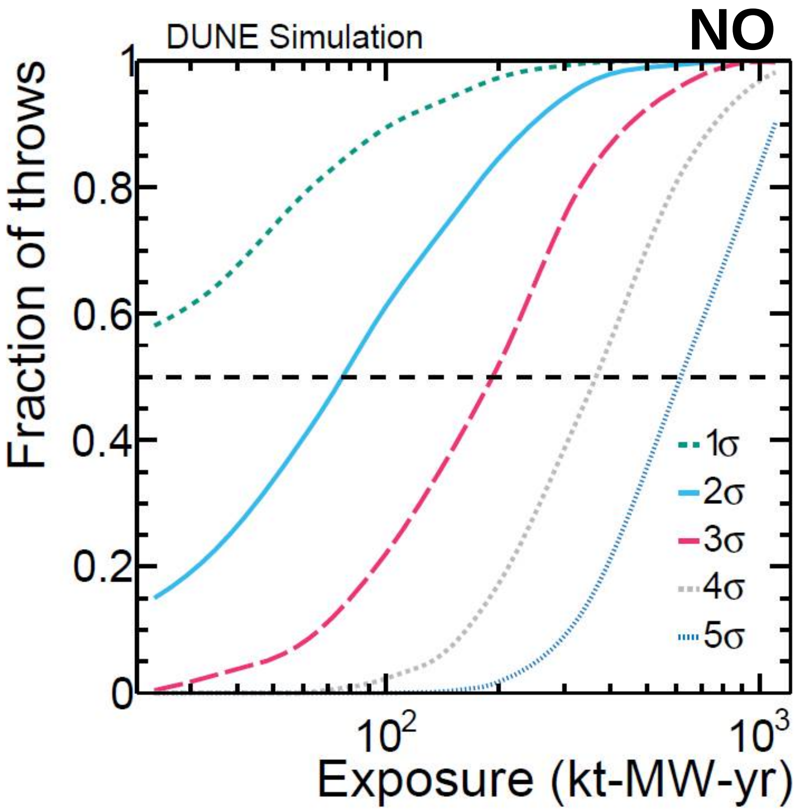
CPV sensitivity



PRD 105 (2022) 7, 072006

Fraction of throws that exceed each 1-5σ significance threshold as a function of true δ_{CP} for two exposures

CPV sensitivity over time



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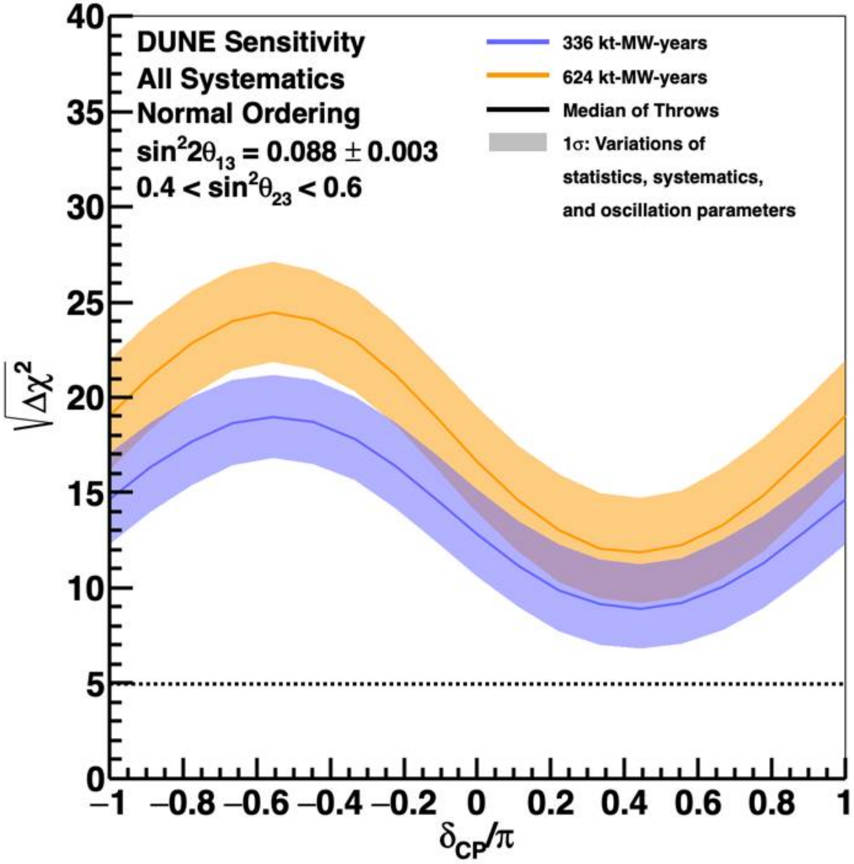
Behaviour as a function of exposure can be extracted, here shown for 50% of true δ_{CP} values

Median sensitivity for 50% δ_{CP} values above 3σ (5σ) after 197 (646) kt-MW-yr

DUNE MO

$$\Delta\chi^2 = \chi^2_{\mathrm{IO}} - \chi^2_{\mathrm{NO}}$$



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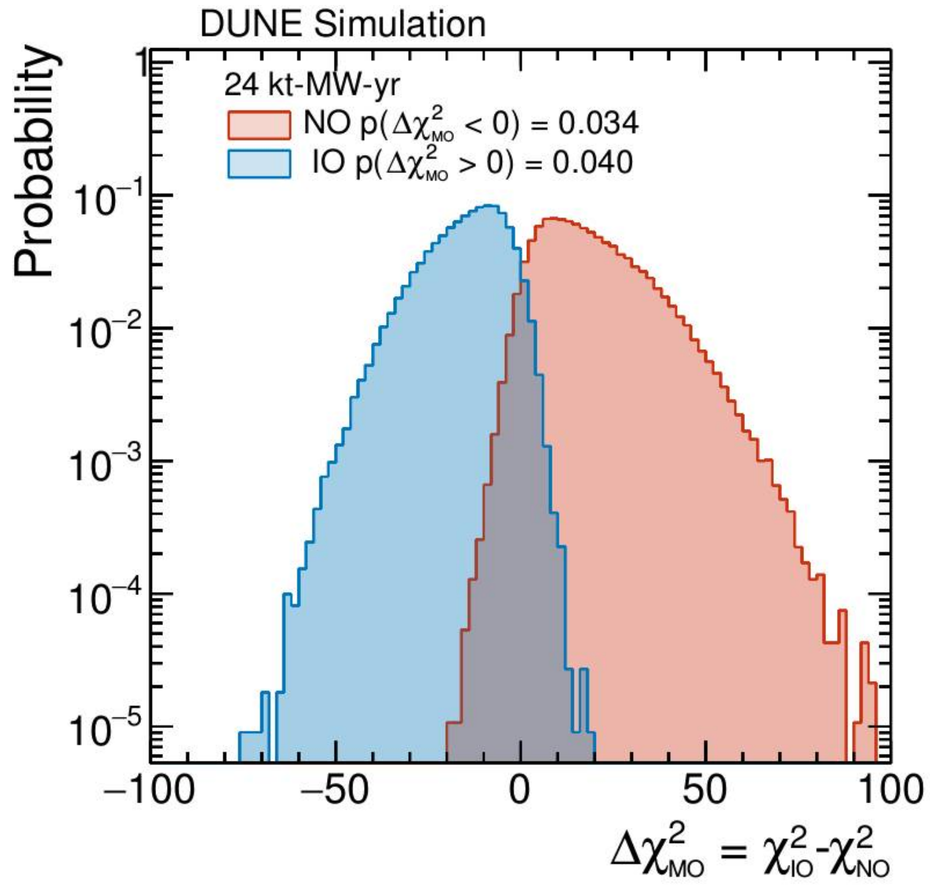
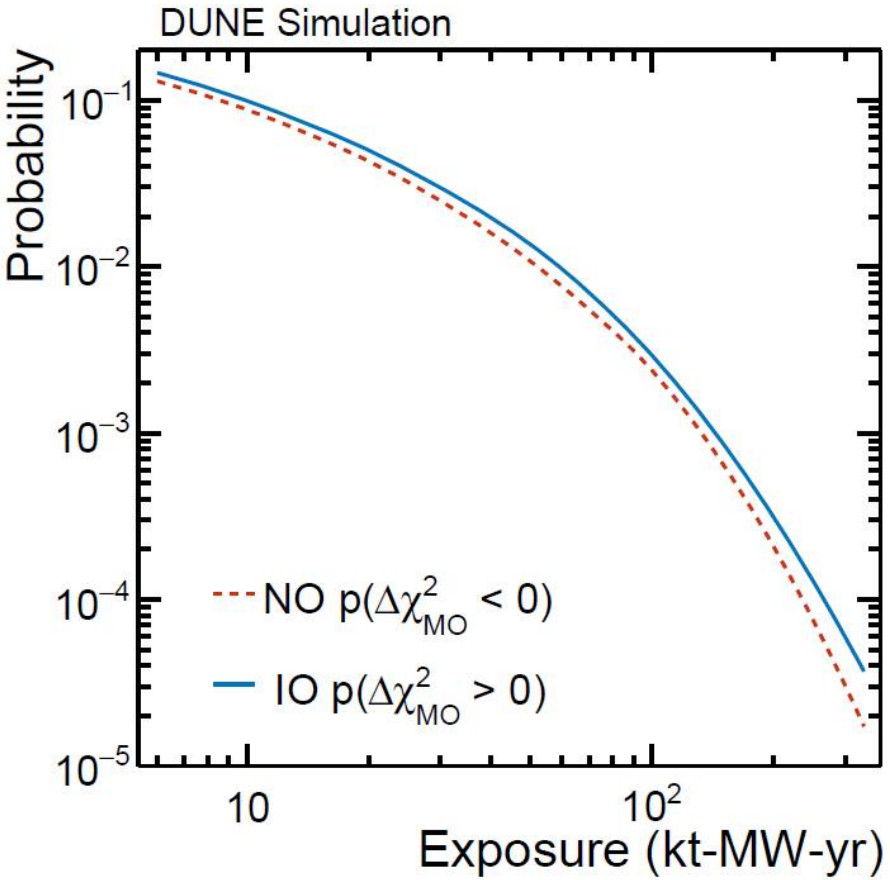
Unrivaled ability to resolve the mass ordering:

- Regardless of other parameter values
- Without reliance on other experiments

DUNE MO





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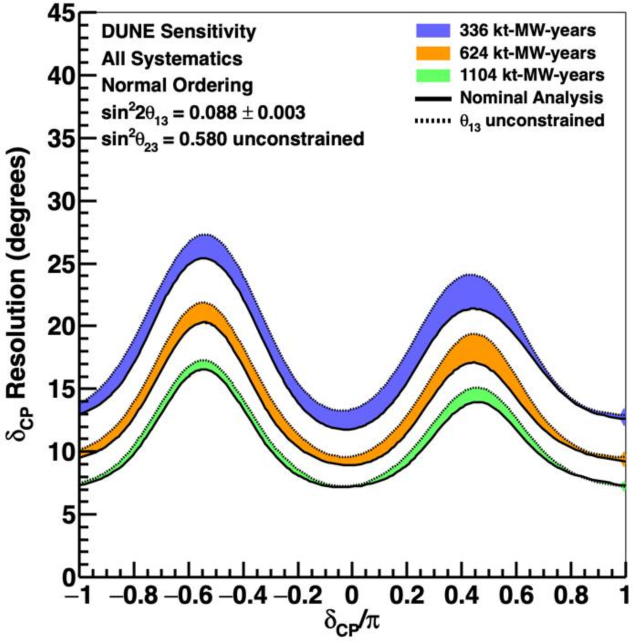
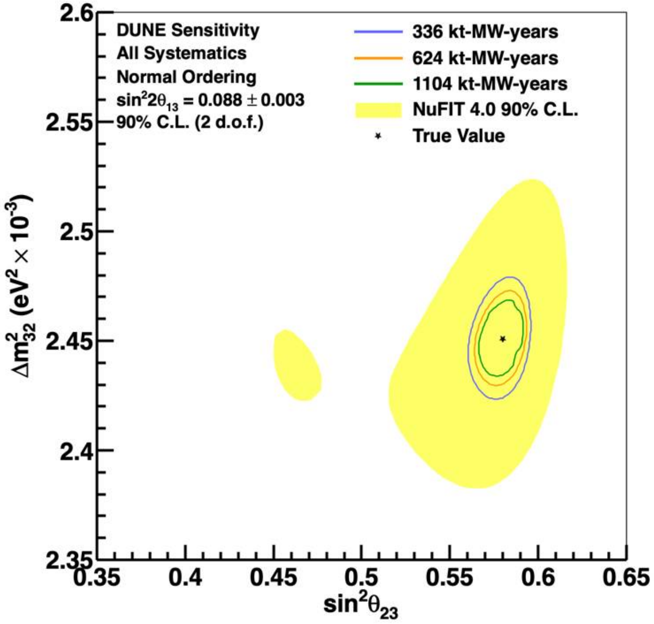
Strong MO potential with very short exposures

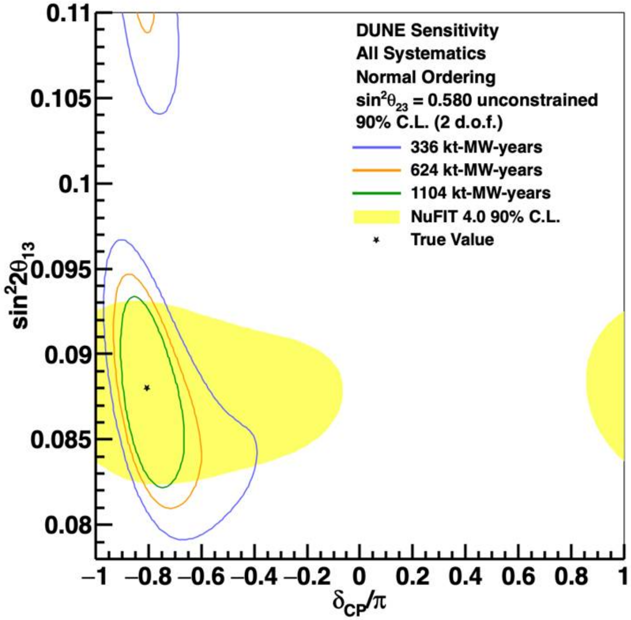
Probability < 0.01 to prefer the wrong neutrino mass ordering after 66 kt-MW-yr

DUNE precision measurements

NuFit 4.0: JHEP 01 (2019) 106







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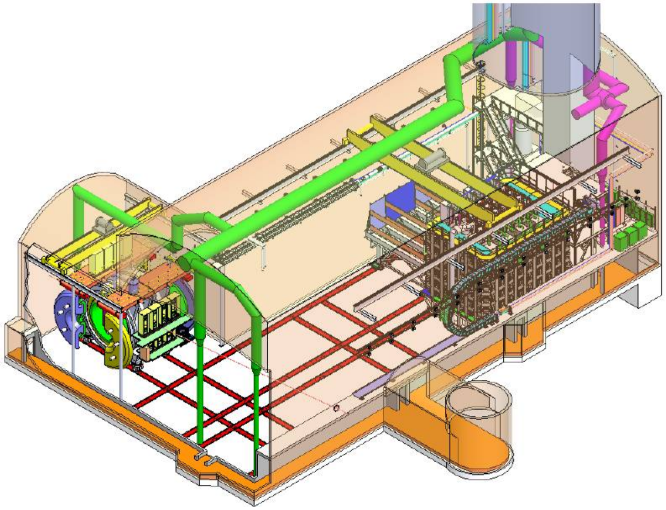
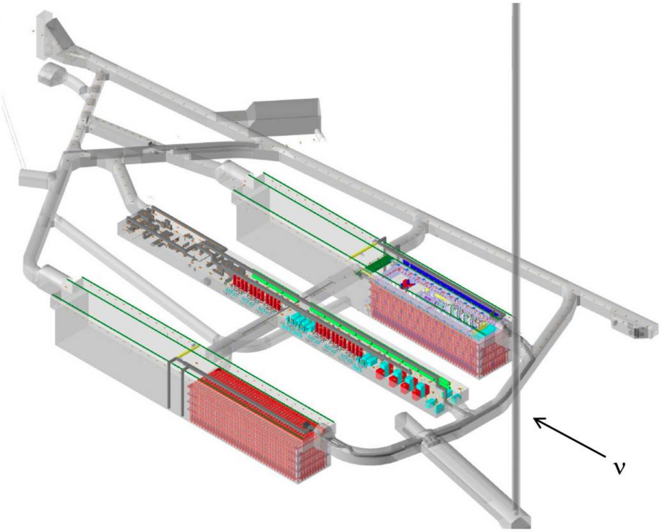
- 7–16° δ_{CP} resolution, world-leading Δm^2-$\sin^2\theta_{23}$
- Ultimate sensitivity approaches reactor θ_{13}
- **Constrain all parameters with one experiment**
  → probe unitarity / completeness of the PMNS

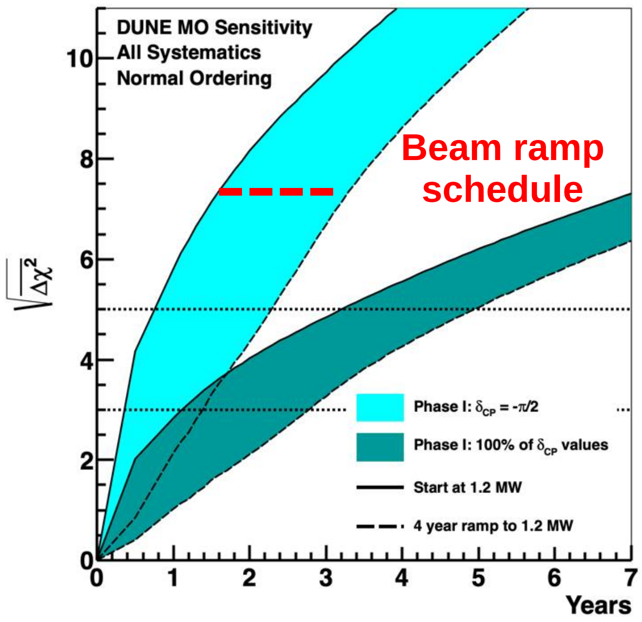
Phased DUNE construction

- 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 (movable) + SAND
- **Phase II:**
  - Proton beam 1.2 MW → 2.4 MW
  - 4x 17kt LArTPC FD modules
  - Full ND complex

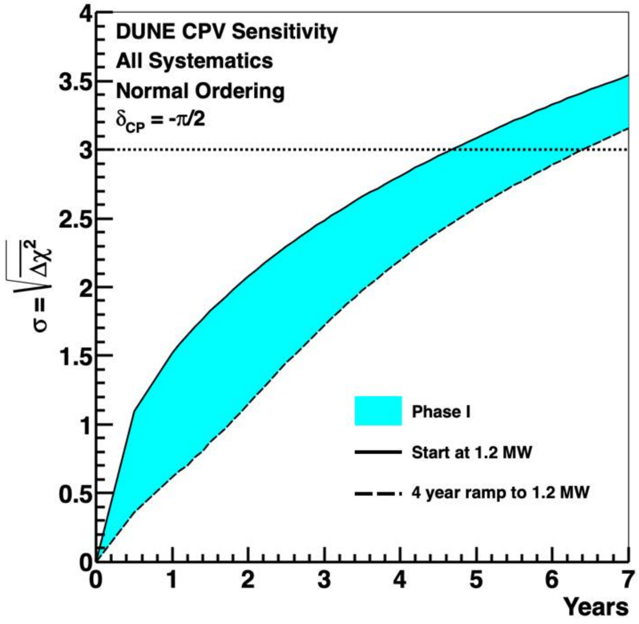




DUNE staging



Beam ramp schedule



Phase I:

✔ Unambiguous MO

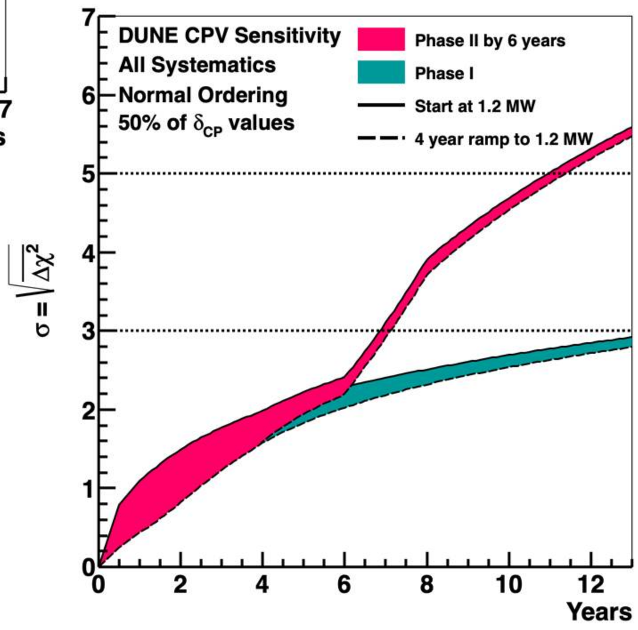
✔ 3σ CPV at maximal δ_{CP}

Phase II:

✔ P5 goal of 5σ CPV for 50% of δ_{CP}

✔ Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}

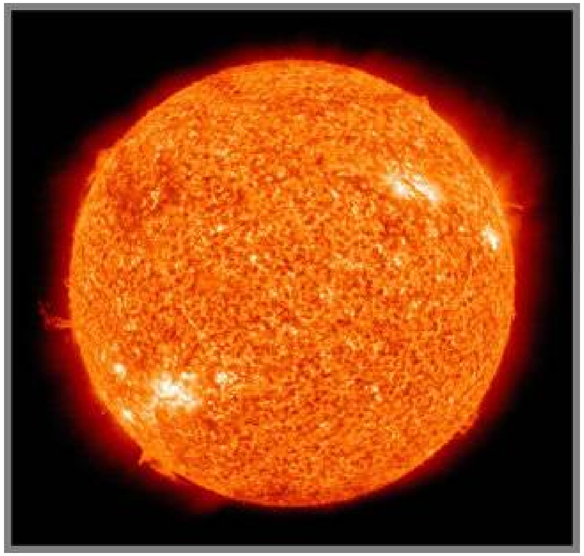
Requires 2.4 MW, 40 kt and full ND

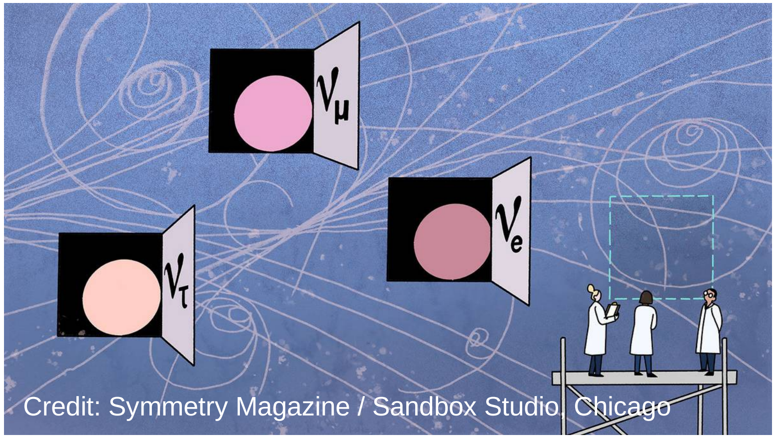


DUNE oscillation summary

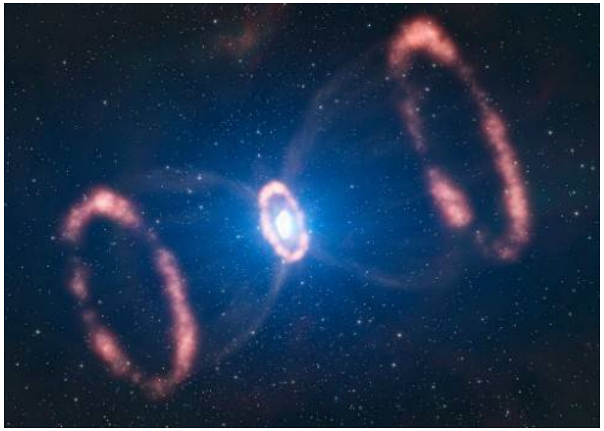
- Unambiguous MO measurement
- Strong CPV discovery potential
- Precision measurements of key oscillation parameters
- Broad spectral measurements will stress test the U_{PMNS} model – *is anything missing?*
- No reliance on constraints from other experiments

Part of a broader physics program!





Credit: Symmetry Magazine / Sandbox Studio, Chicago

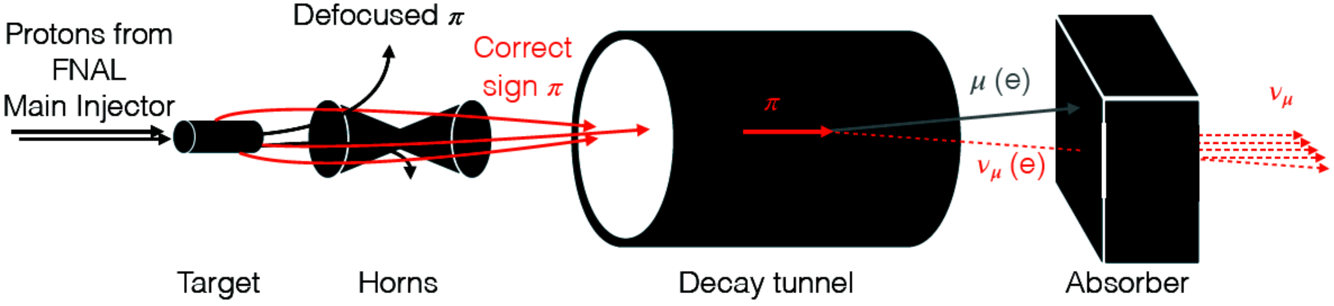


Credit: Higgstan

See additional DUNE talks in other sessions!

Backup

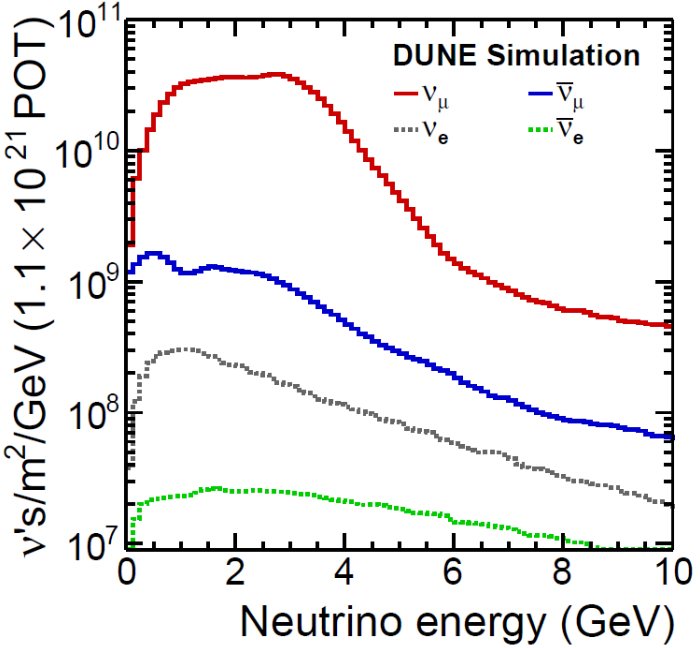
Beam



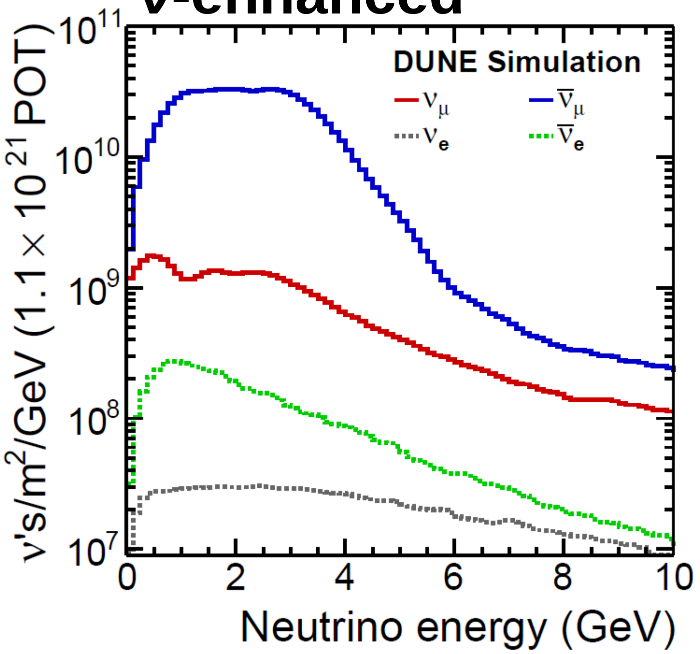
$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

- Produce neutrino beam by focusing charged pions and allowing them to decay
- Can operate in neutrino and antineutrino enhanced modes
- 1.2 MW with planned 2.4 MW upgrade – ramp-up schedule under development

ν-enhanced

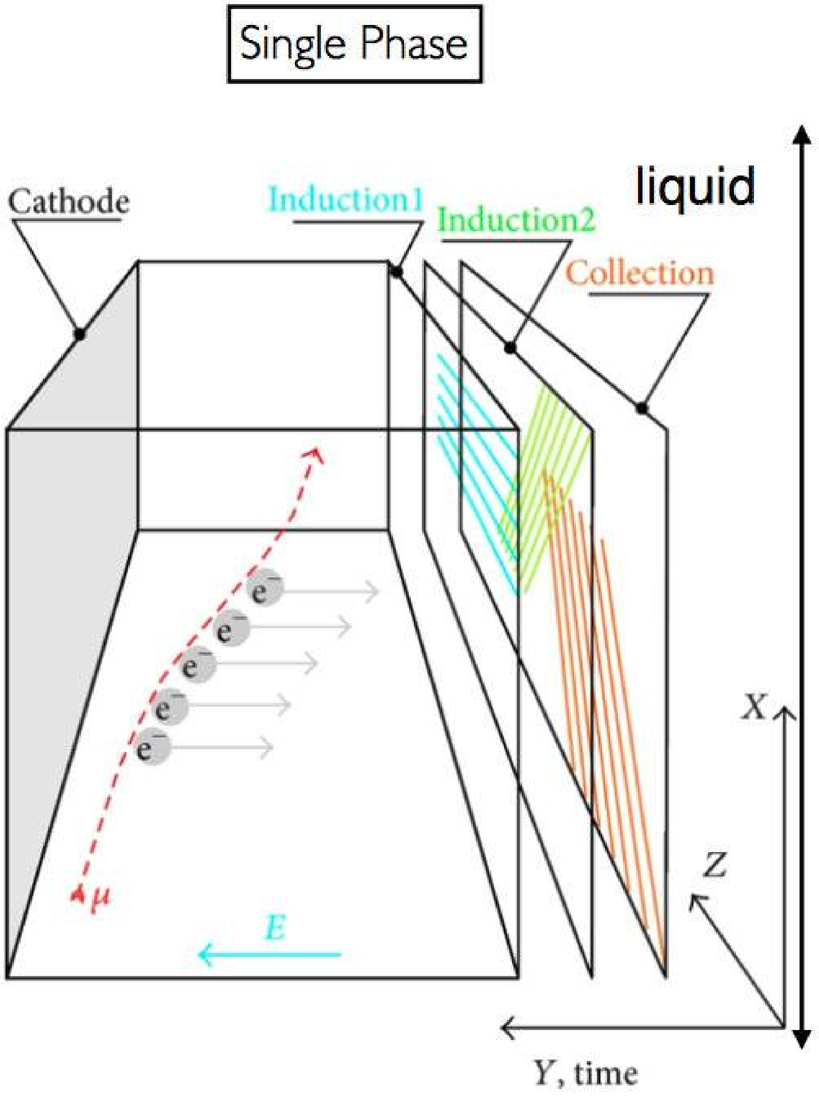


$\bar{\nu}$-enhanced

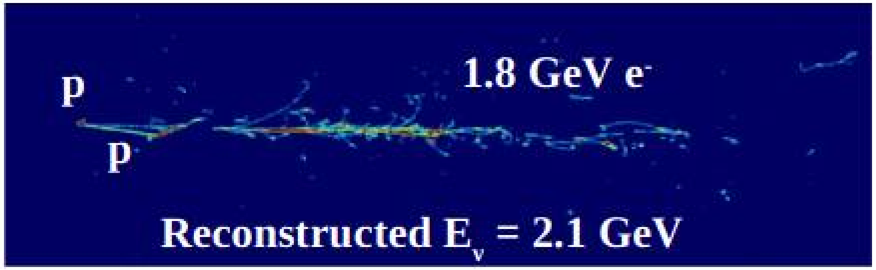


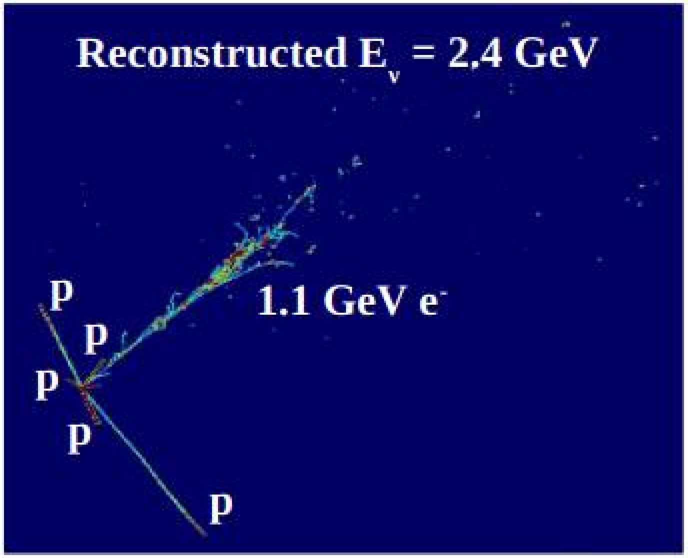
Liquid Argon Time Projection Chambers (LArTPCs)

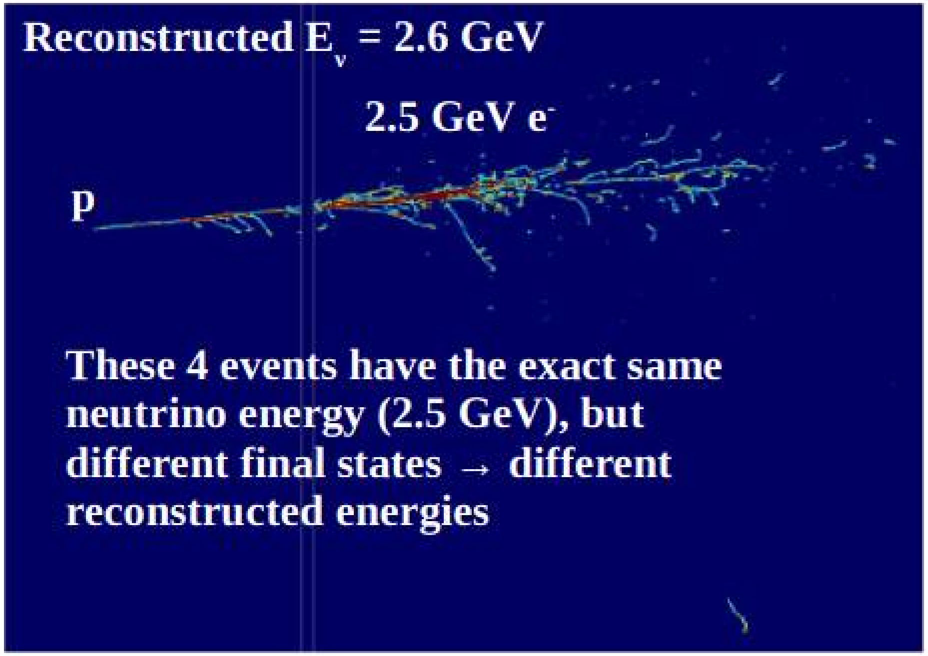
- Charged particles ionize liquid argon (LAr)
- Uniform electric field drifts ionization electrons to anode
- Electrons collected and readout (wires/pixels)
- Argon produces and is transparent to its scintillation light



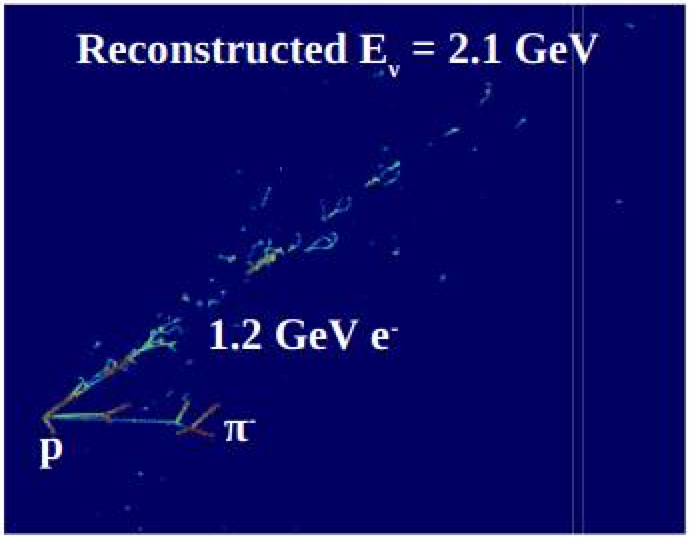
Why LArTPCs?



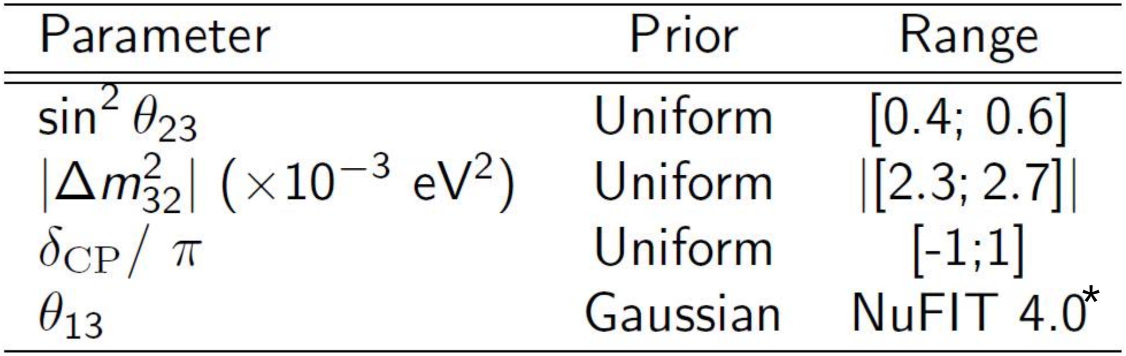




These 4 events have the exact same neutrino energy (2.5 GeV), but different final states → different reconstructed energies



Toy throw study method



Parameter	Prior	Range
$\sin^2\theta_{23}$	Uniform	[0.4; 0.6]
$\|\Delta m^2_{32}\|$ ($\times 10^{-3}$ eV^2)	Uniform	|[2.3; 2.7]|
δ_{CP}/π	Uniform	[-1;1]
θ_{13}	Gaussian	NuFIT 4.0*

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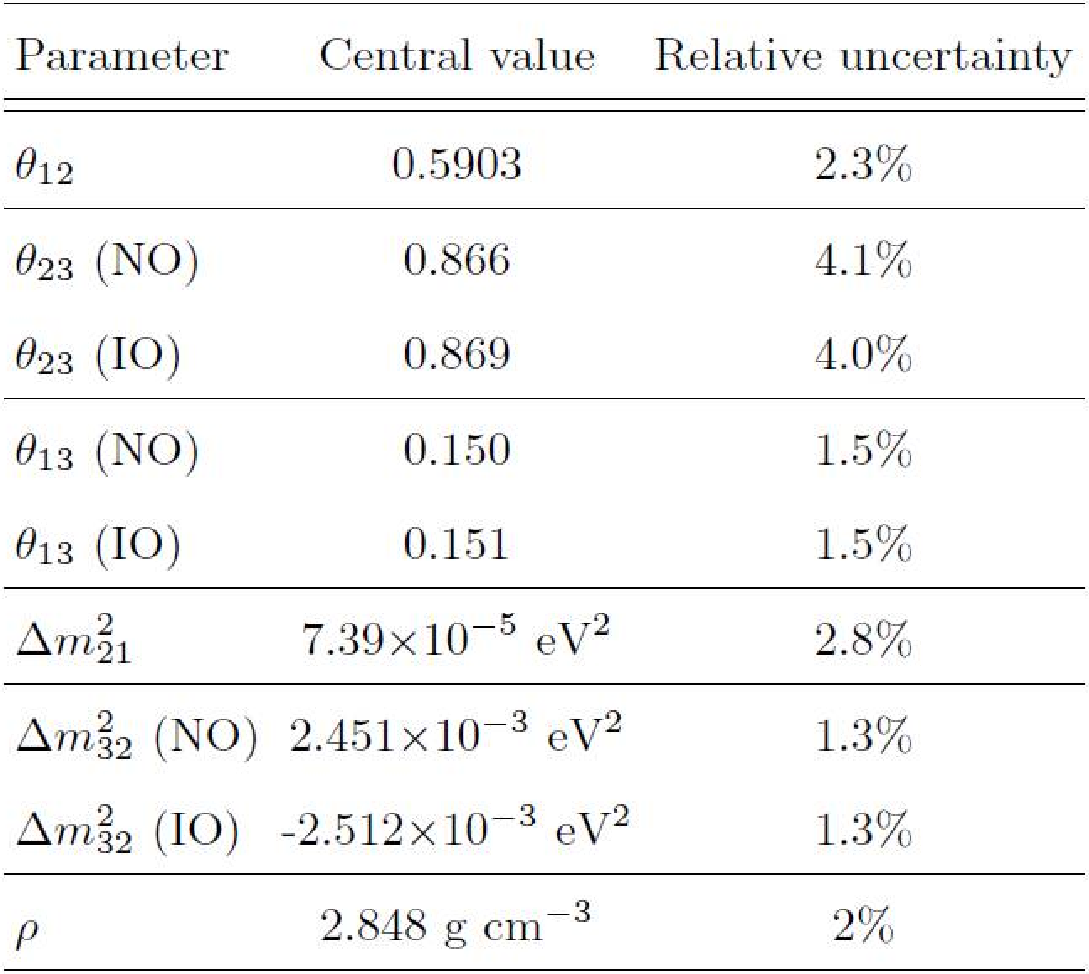
- For each toy throw:
  - Flux, detector and cross-section systematics thrown according to their prefit Gaussian uncertainty
  - Oscillation parameters thrown according to the table
  - Statistical throw applied
  - All parameters are allowed to vary
- All fits use all ND+FD samples, equal $\nu:\bar{\nu}$ running, and apply a Gaussian penalty to θ_{13}

NuFit4.0 uncertainties



Parameter	Central value	Relative uncertainty
θ_{12}	0.5903	2.3%
θ_{23} (NO)	0.866	4.1%
θ_{23} (IO)	0.869	4.0%
θ_{13} (NO)	0.150	1.5%
θ_{13} (IO)	0.151	1.5%
Δm^2_{21}	7.39×10^{-5} eV^2	2.8%
Δm^2_{32} (NO)	2.451×10^{-3} eV^2	1.3%
Δm^2_{32} (IO)	-2.512×10^{-3} eV^2	1.3%
ρ	2.848 g cm^{-3}	2%

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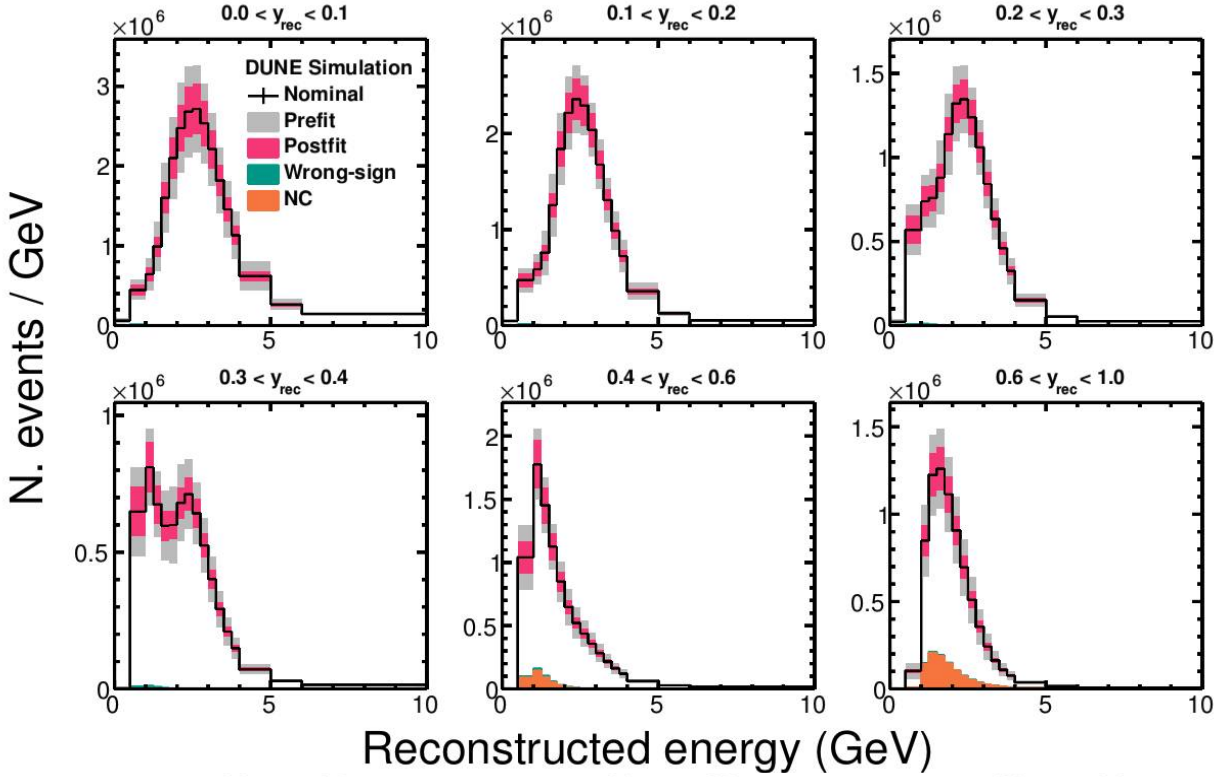
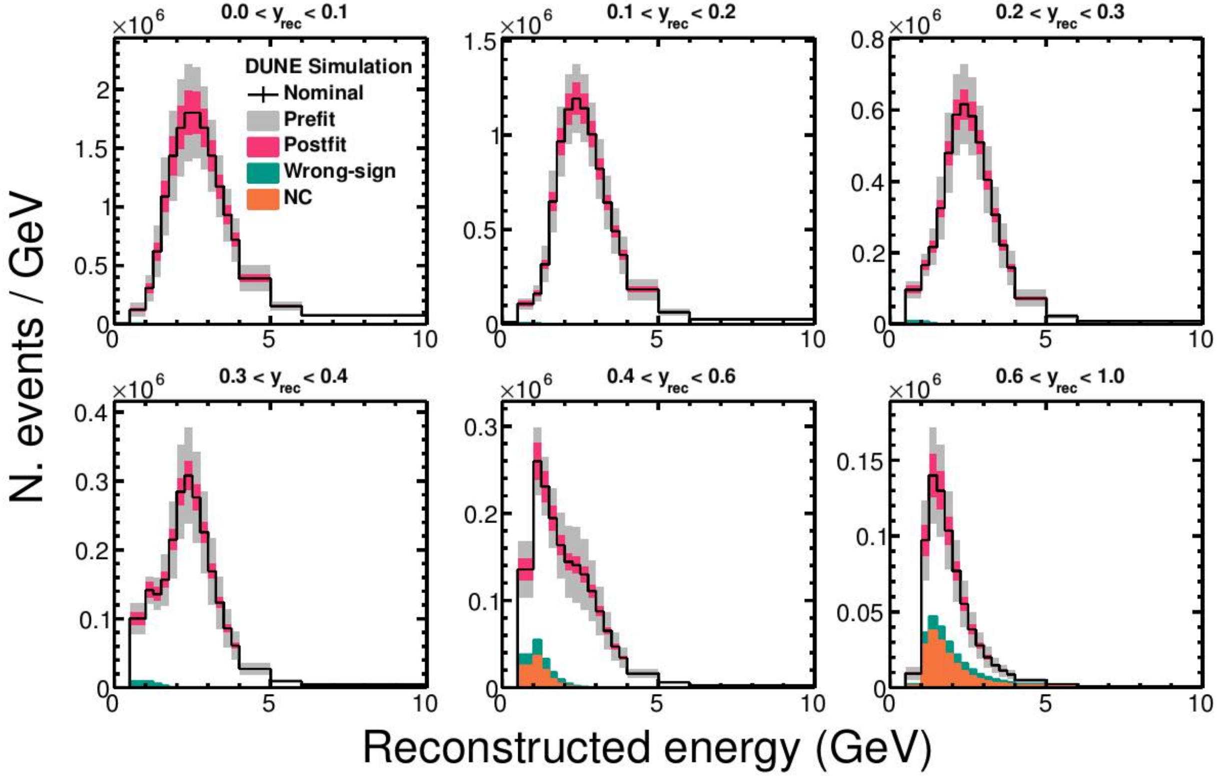
nu-fit.org/?q=node/177

ND samples
(105 t-MW-yr)

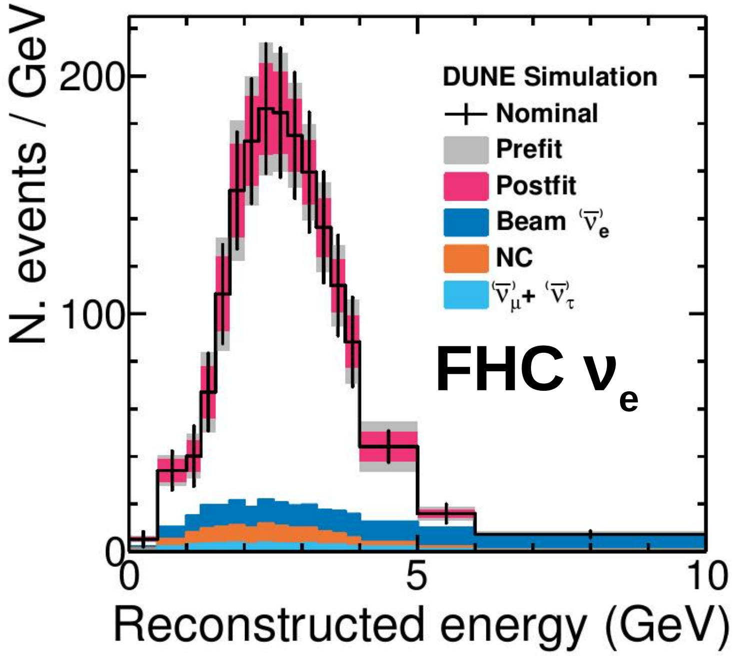
FHC ν_μ

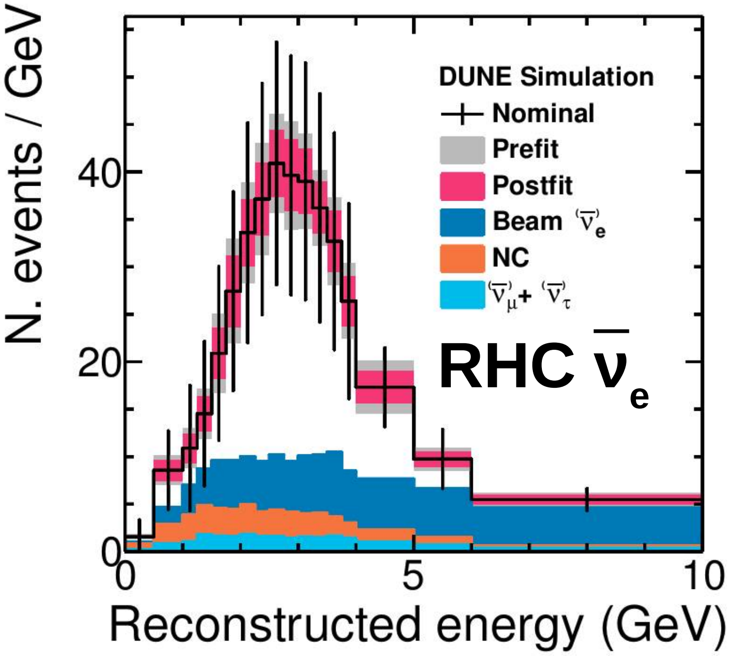


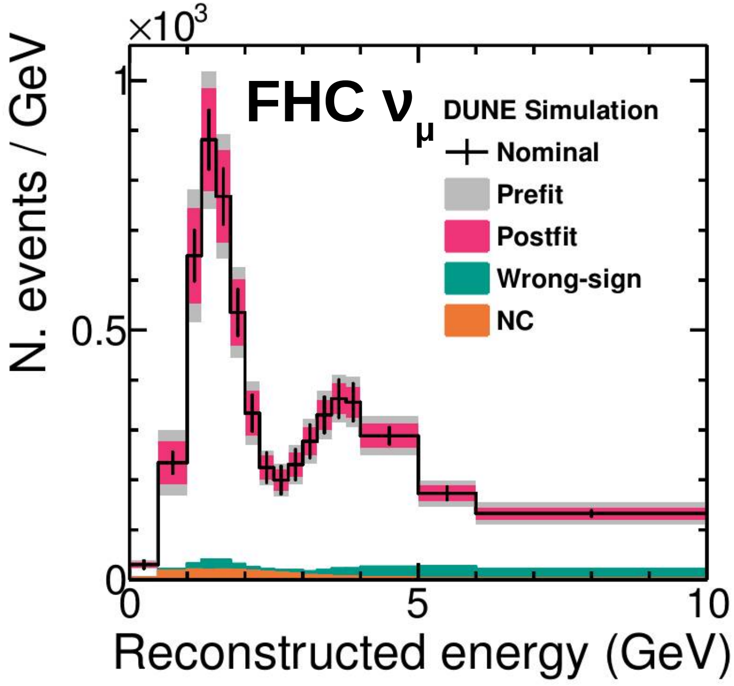
RHC $\bar{\nu}_\mu$

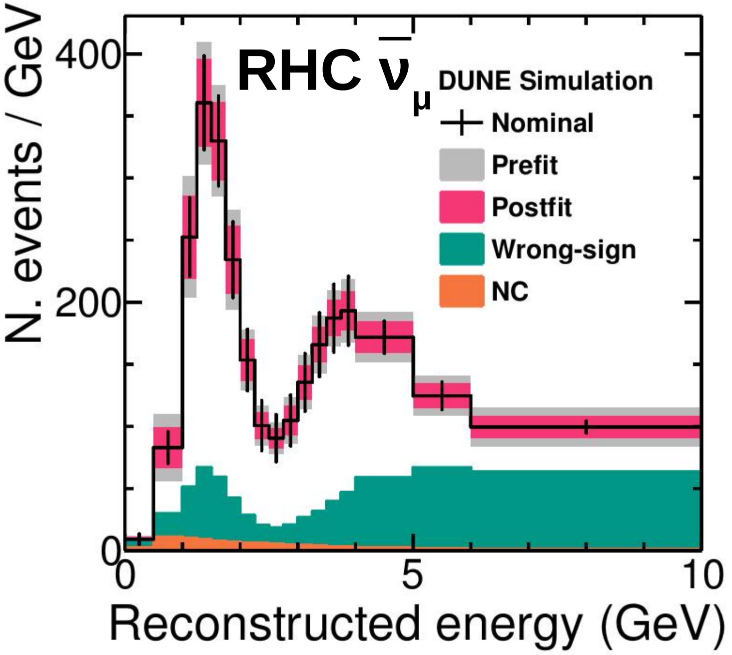


FD samples (100 kt-MW-yr)

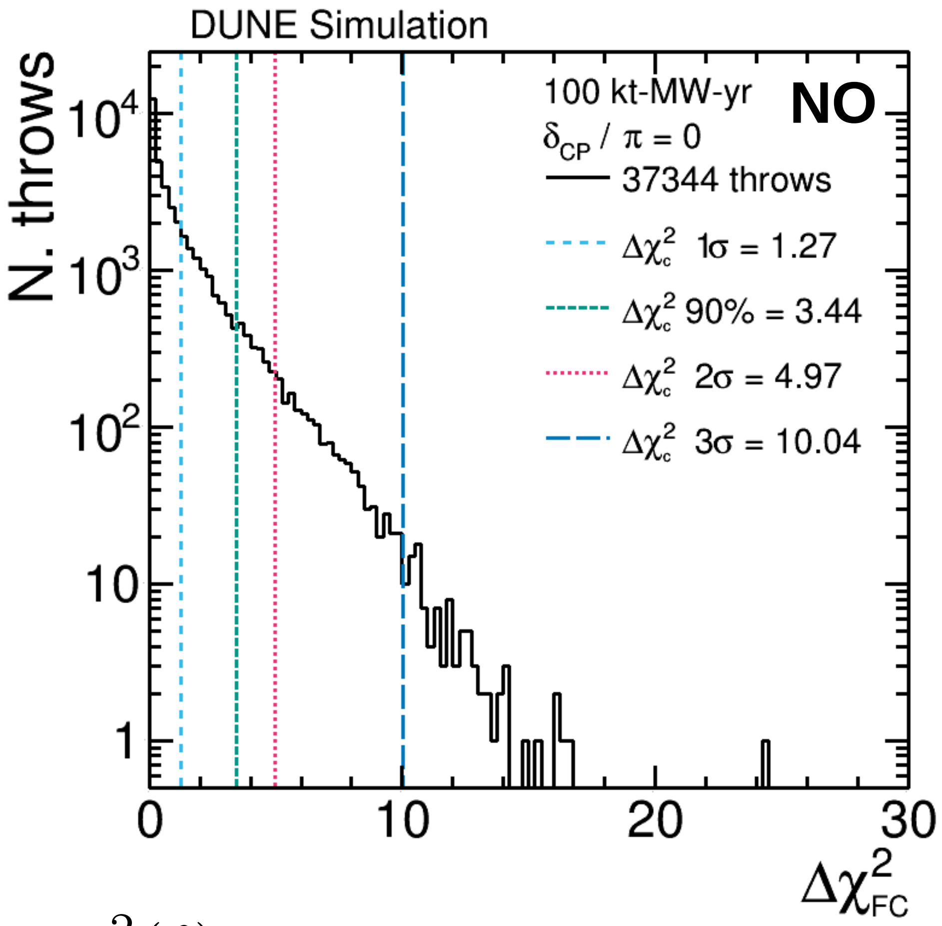








Feldman-Cousins* (FC)



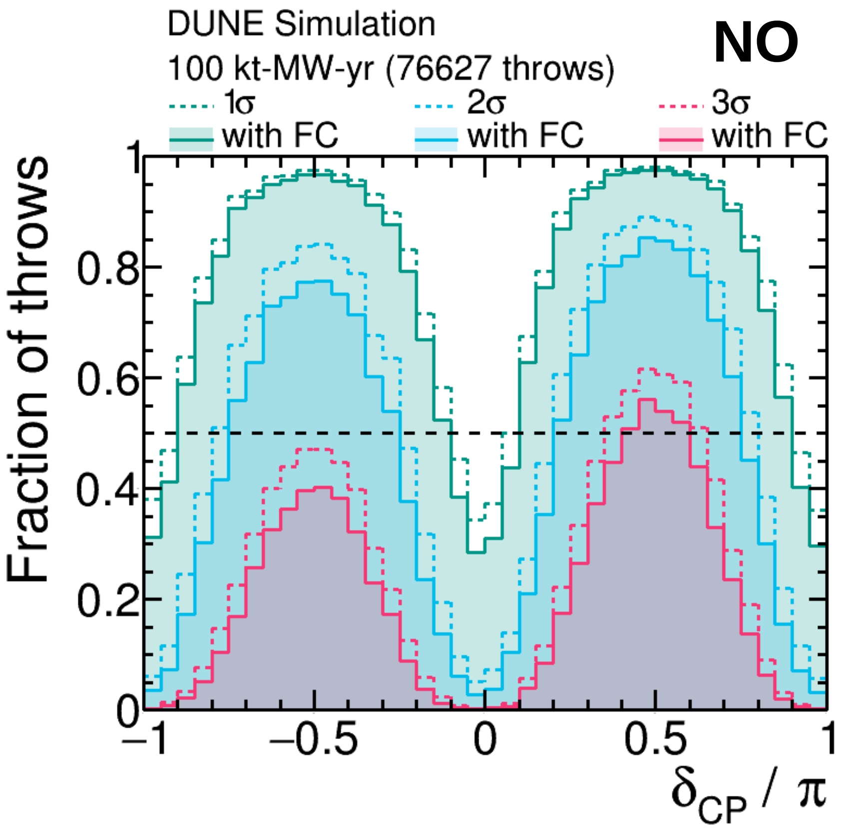
- Constant $\Delta\chi^2$ breaks down:
  - Around physical boundaries
  - For cyclic parameters
  - If there are degeneracies
- Numerical method for confidence intervals with correct coverage
- Fix parameter of interest, throw other parameters and statistics
- Build up distribution of:

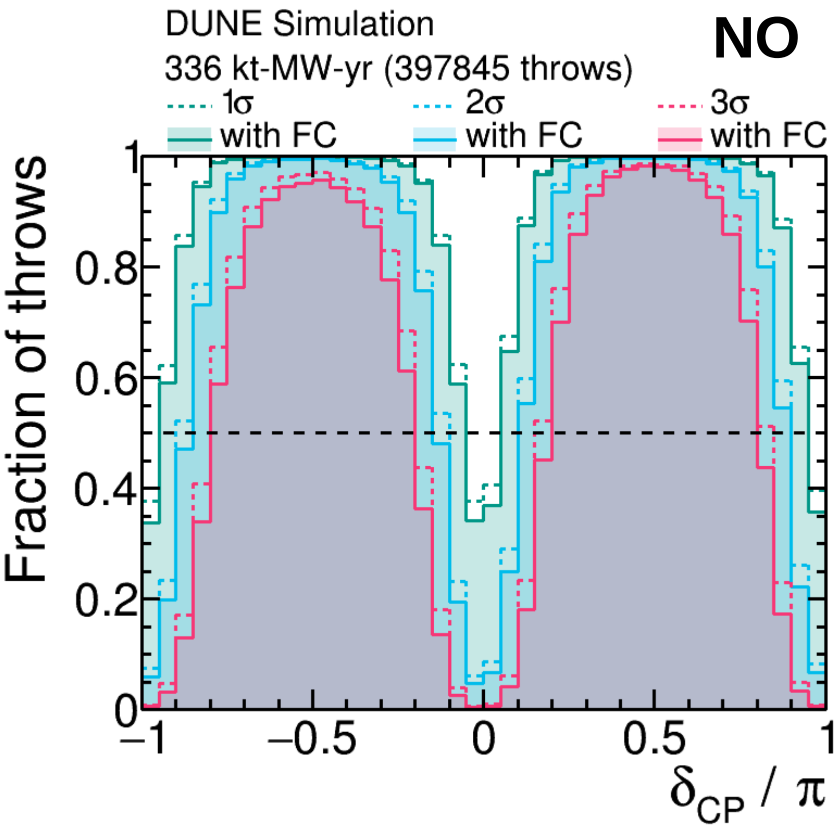
$$\Delta\chi^2_{\mathrm{FC}} = \chi^2(\theta_{\mathrm{true}}) - \min_{\theta} \chi^2(\theta)$$

- Find the critical value $\Delta\chi^2_c$ that gives the intended coverage

*G. J. Feldman and R. D. Cousins, PRD 57, 3873 (1998)

FC-corrected CPV sensitivity

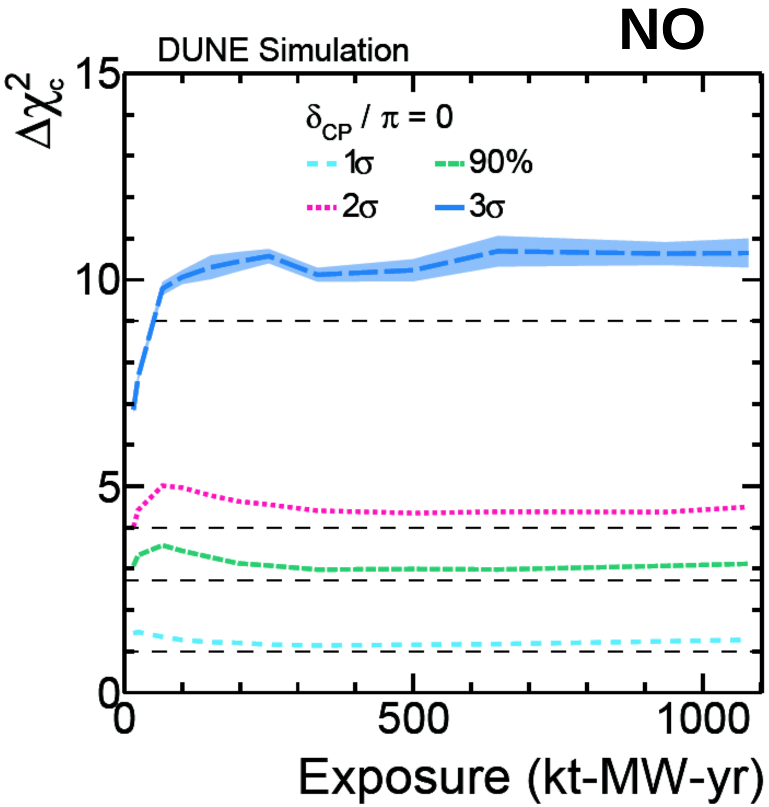


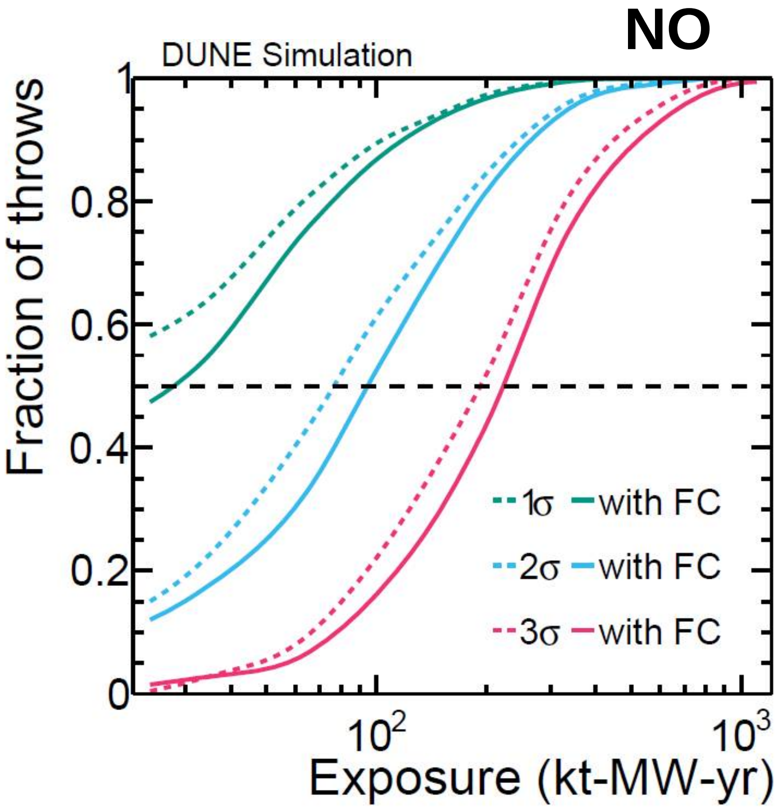


Fraction of throws that exceed each 1-3σ significance with and without FC corrections

FC corrections computationally prohibitive above 3σ

FC CPV sensitivity over time





Fraction of throws that exceed 1-3σ for 50% of true δ_{CP} values, as a function of exposure, with and without FC corrections

Uncertainty on $\Delta\chi^2_c$

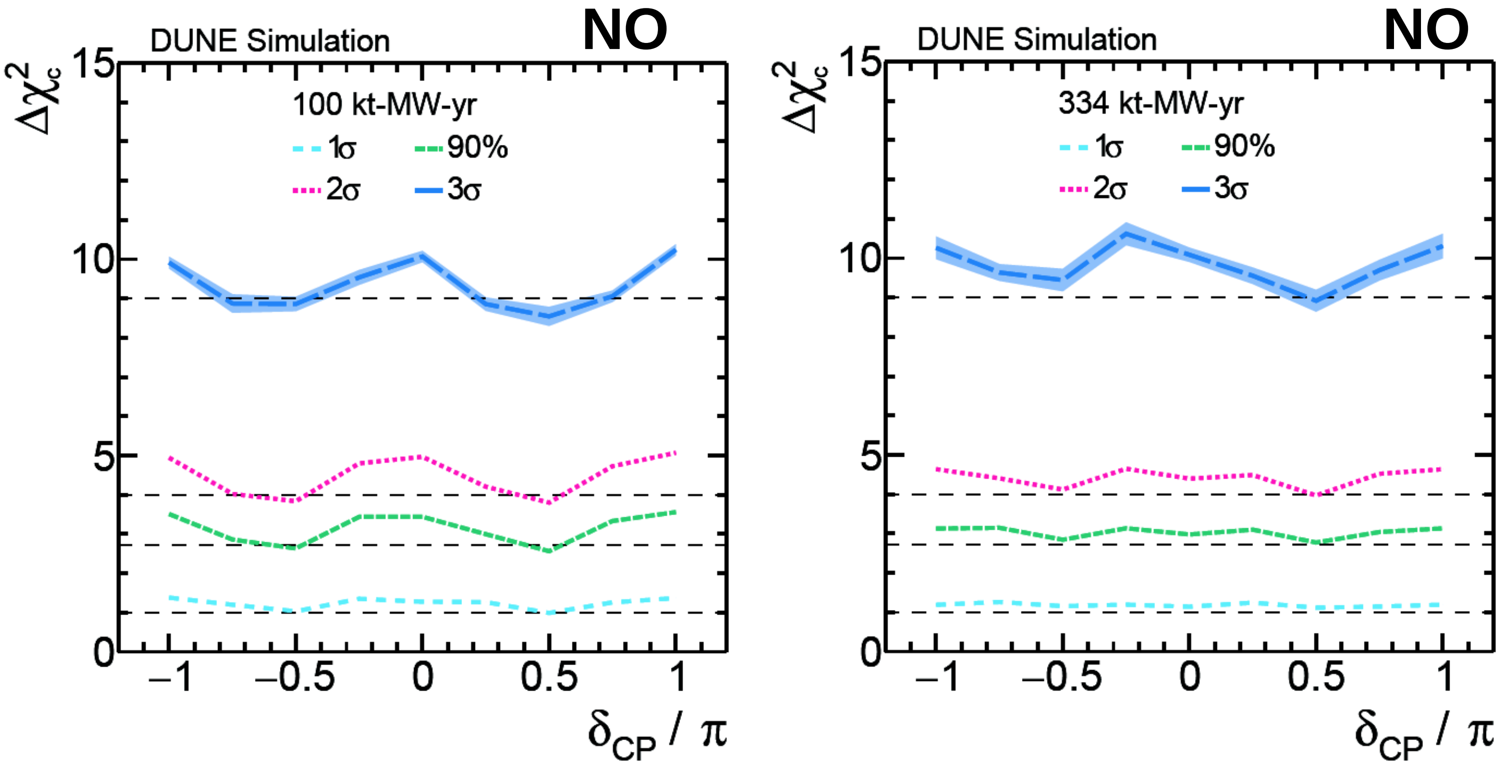
Calculated using a bootstrap rethrowing method:

- Treat PDF from *n* FC throws as the true PDF, and draw *B* independent samples of size *n* from it (with replacement)
- Calculate the value of interest for each of the *B* samples, and then calculate the standard deviation with:

$$s_{\hat{\theta}} = \sqrt{\frac{1}{B}\sum_{i=0}^{B}(\theta_i^* - \bar{\theta}^*)^2}$$

Additional toys were produced to ensure the uncertainty on all $\Delta\chi^2_c$ values was less than 5%

FC vs δ_{CP}



$\Delta\chi^2_c$ values as a function of δ_{CP} for 100 and 334 kt-MW-yr

Horizontal lines indicate the constant-$\Delta\chi^2$ equivalent