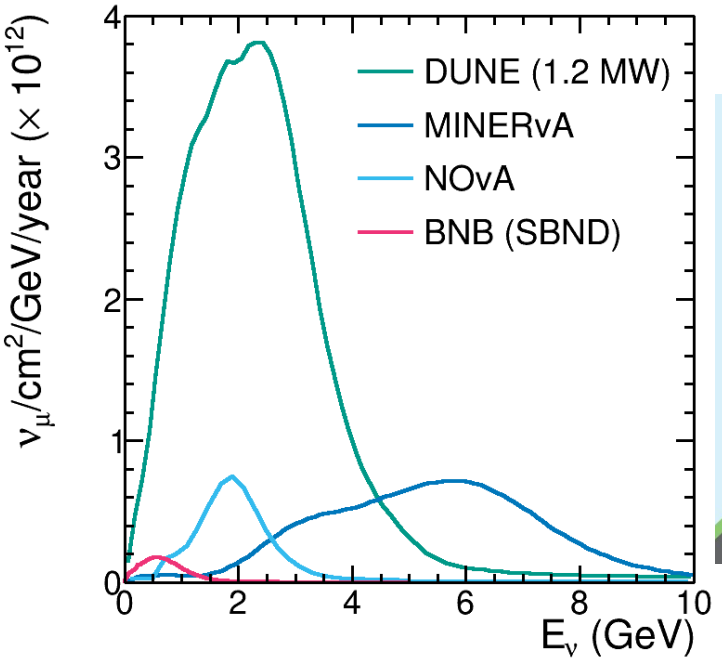
DUNE systematics challenges

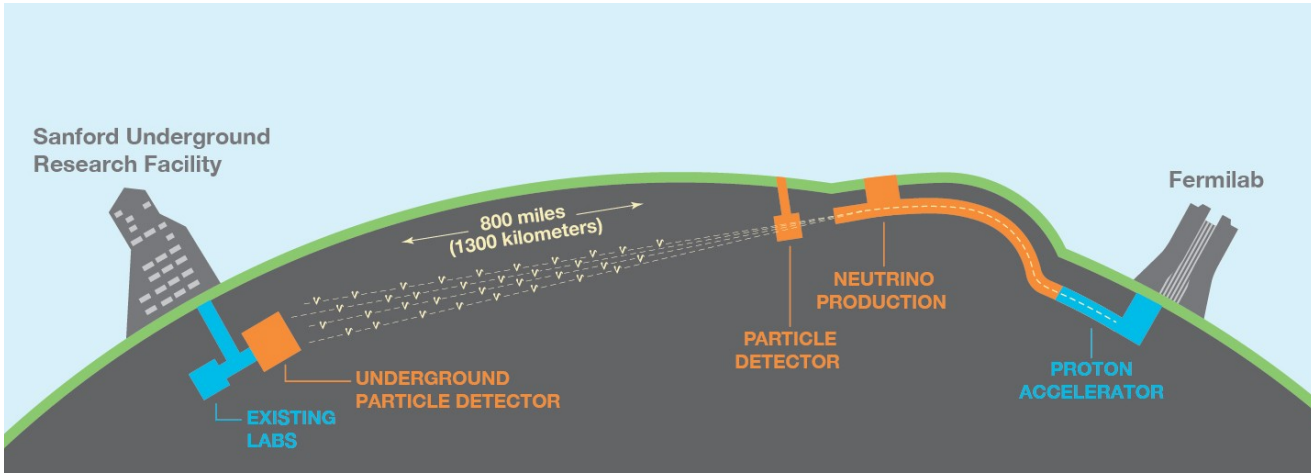
Callum Wilkinson on behalf of the DUNE collaboration
Lawrence Berkeley National Laboratory
Workshop on Neutrino Event Generators
FNAL, 16th March 2023

BERKELEY LAB

DUNE

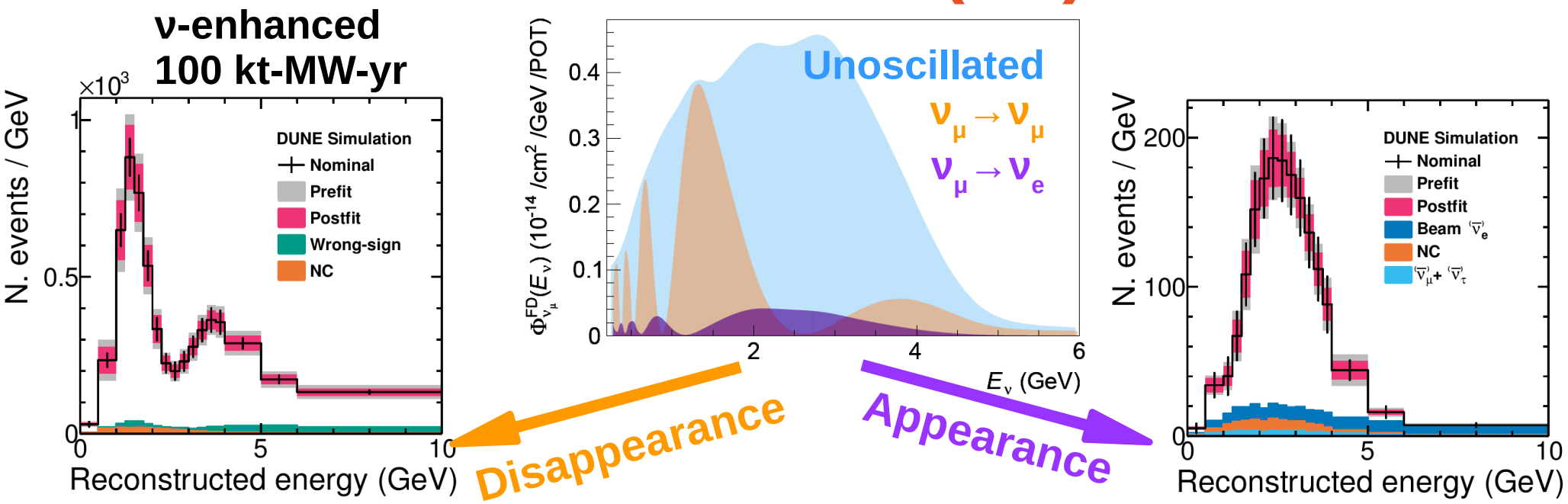
DUNE



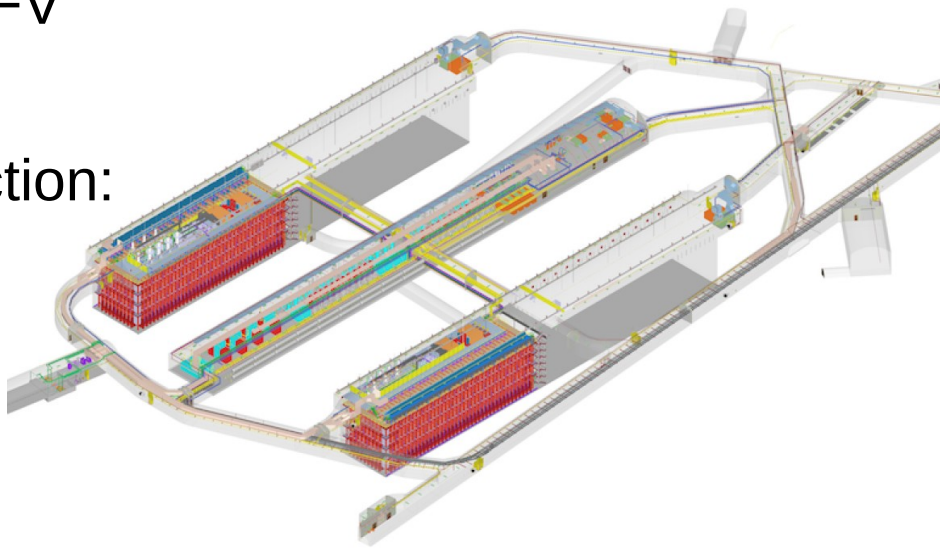


- L ≈ 1285 km; E_ν ≈ 2.5 GeV (*broad band*); liquid argon time projection chamber (LArTPC)
- Unprecedented intensity neutrino beam
- Near detector system at Fermilab
- 4 x 17 kt far detector modules at SURF

Far Detector (FD)



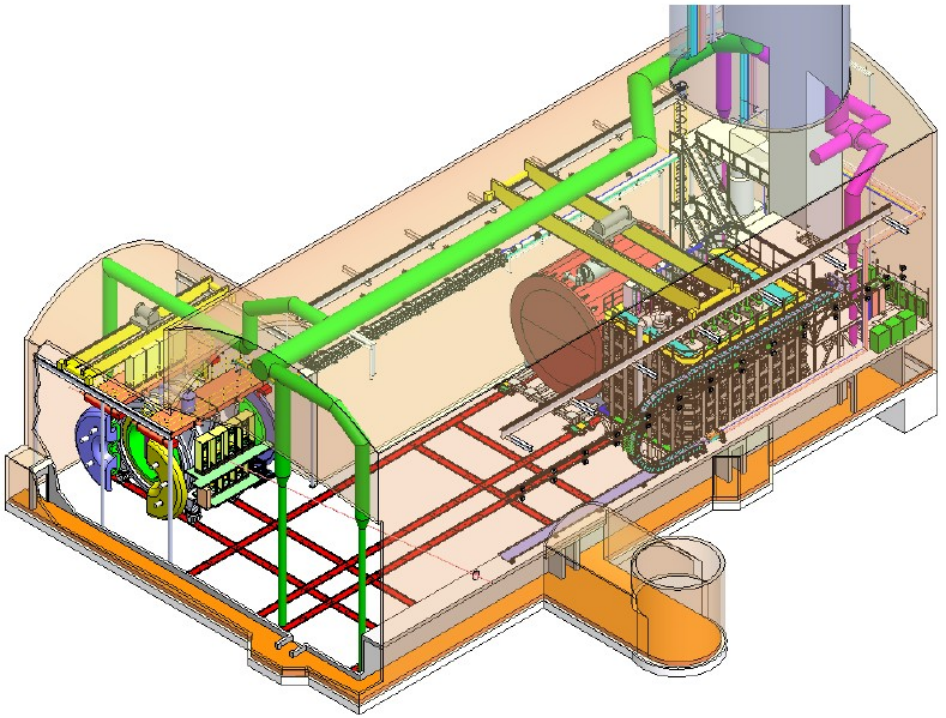
- 4 x 17 kt modules, minimum 10 kt FV each (2 x LAr in phase I)
- Full FD1 simulation and reconstruction: PRD102, 092003 (2020)
- Four samples in analysis: ν_μ & ν_e in ν and $\bar{\nu}$ enhanced modes



Near Detector (ND)

Core requirements:

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



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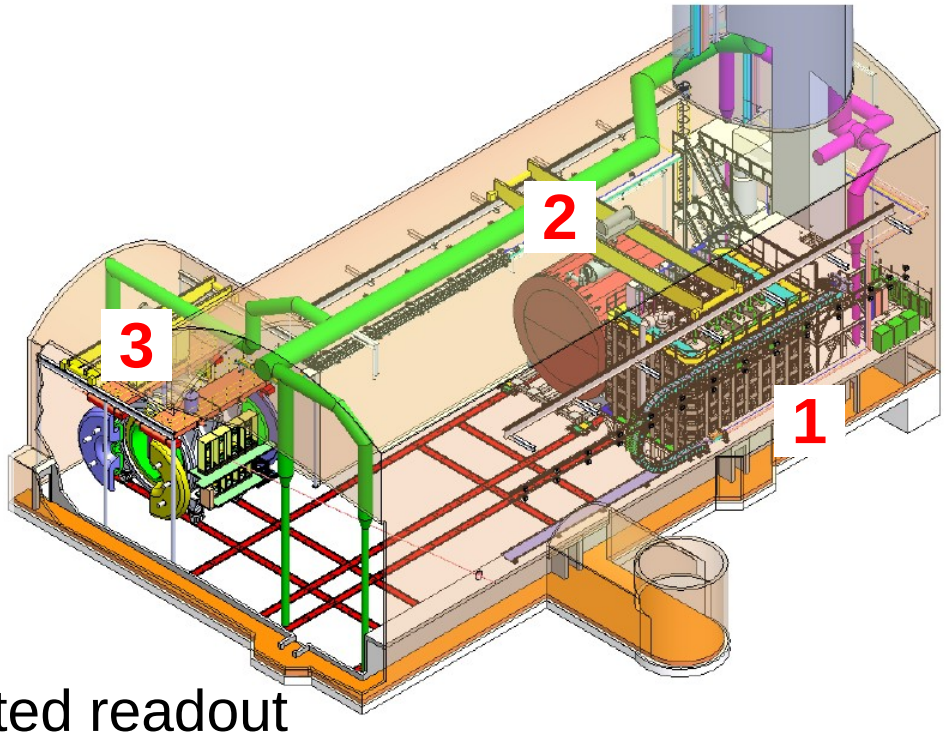

Three major components:

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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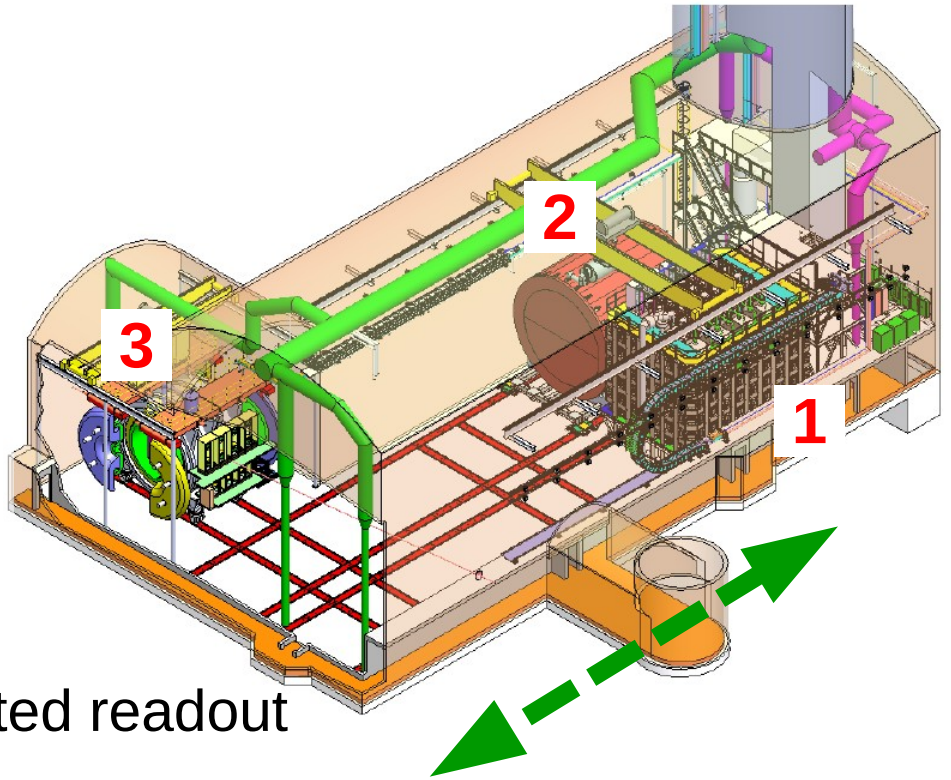

Three major components:

Moveable

1 - Core 150 t LArTPC with pixelated readout

2 - Downstream magnetized tracker

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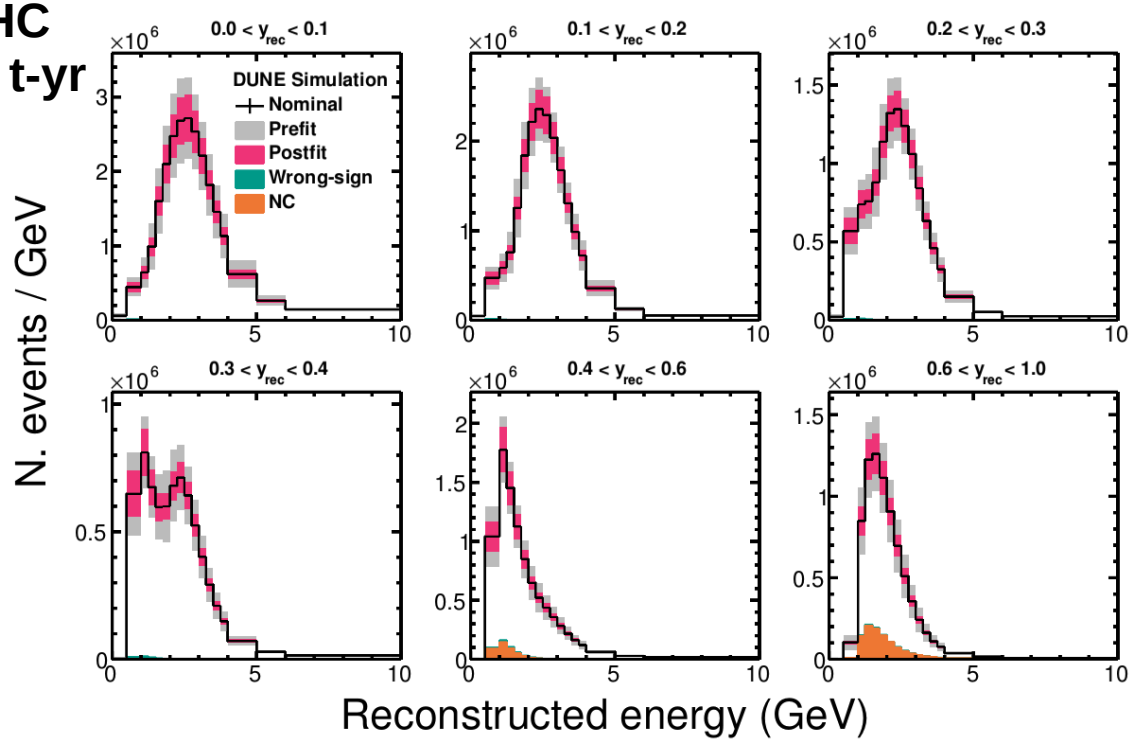
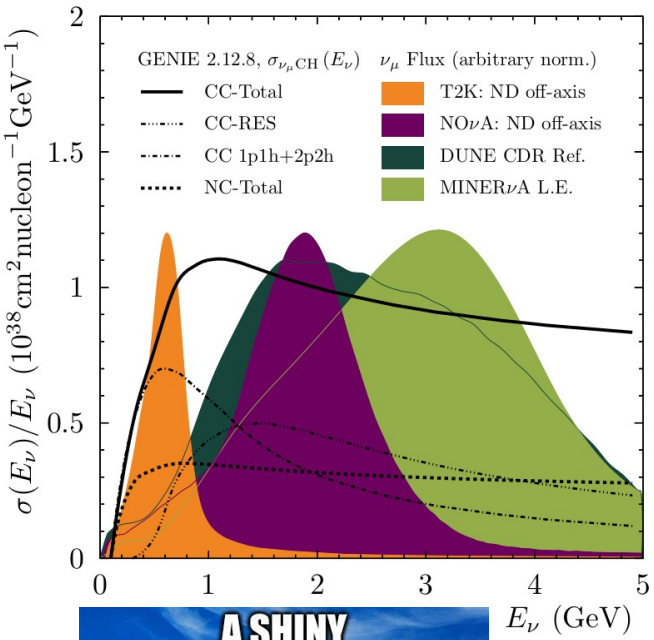
ND systematics challenges

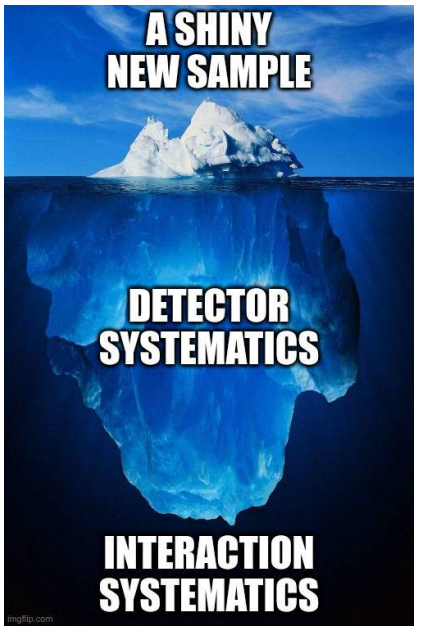
Two obvious points:

- ≈100 million events/year at the ND, no stat. uncertainty to hide behind
- DUNE events span QE → RES → DIS

FHC
105 t-yr



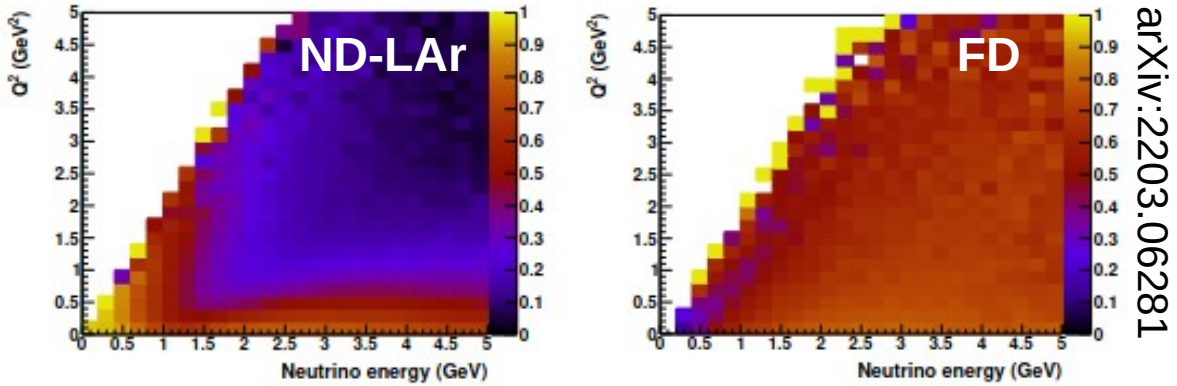




ND systematics challenges

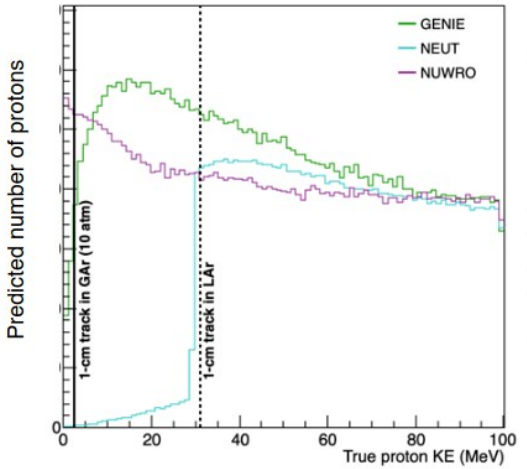
1) SAND is mostly composed of hydrocarbon targets, although other targets can and will be added (including LAr)

2) Different ND-LAr acceptance to FD



arXiv:2203.06281

3) Lower thresholds in GArTPC
→challenge and opportunity



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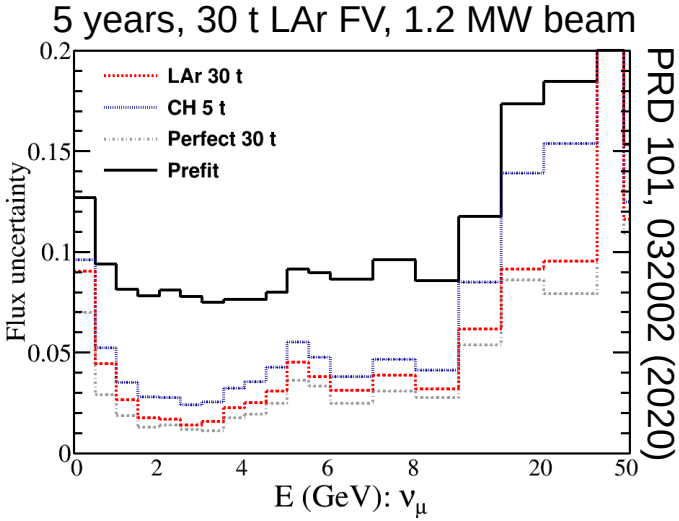
ND standard candles?

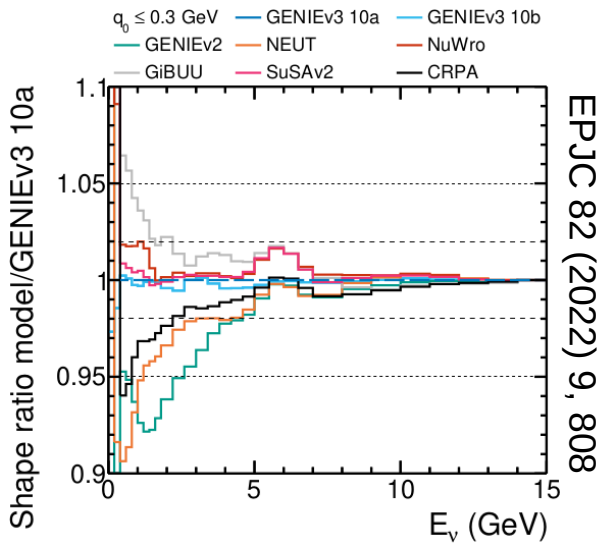
With ≈100 million events/year in DUNE NDs, possible to utilize (faint) standard candles:

- $\nu + e \rightarrow \nu + e$ elastic scattering
- Inverse muon decay: $\nu_\mu + e \rightarrow \mu + \nu_e$
- The low-ν technique
- Isolating hydrogen events (CH_2–C in SAND)

Rely on: a known cross section and/or isolating an unusual region of phase space

New/extra challenges for systematic modeling





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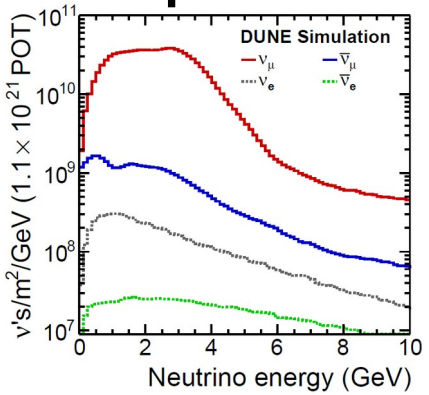
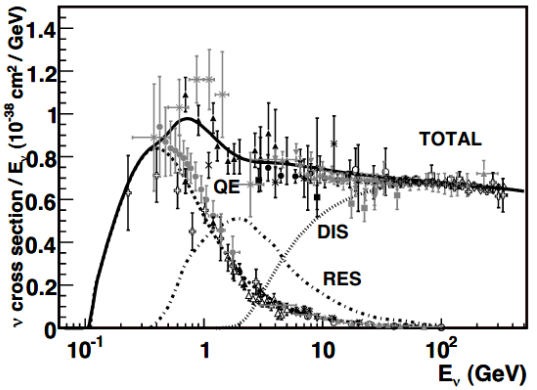
(On-axis) analysis

Flux prediction

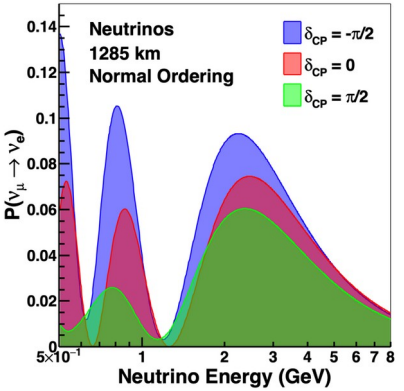


X

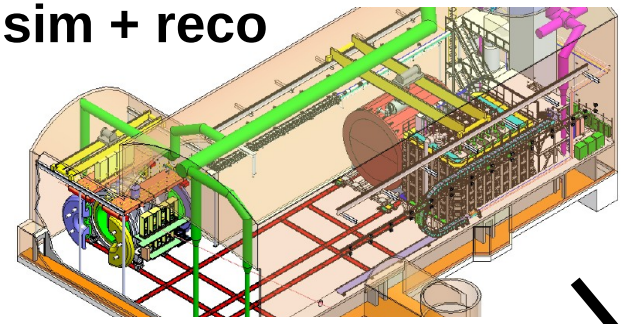
Interaction model



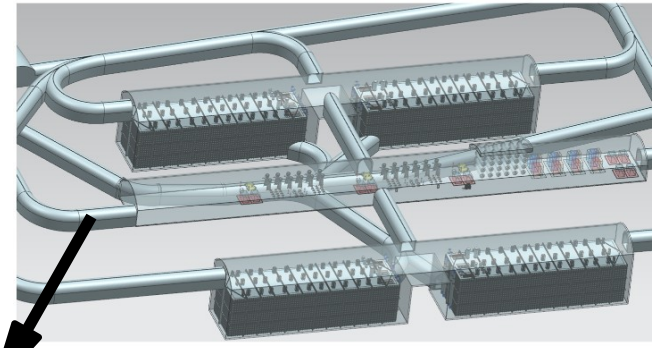
Oscillations



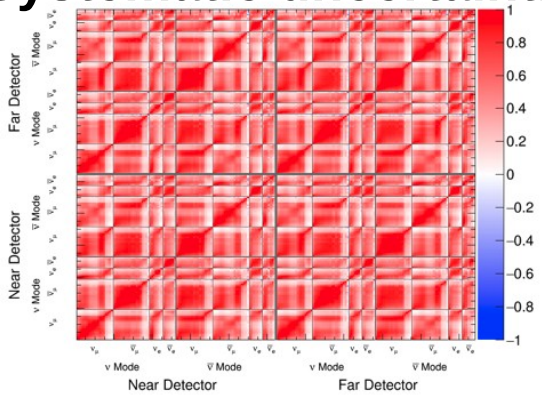
ND sim + reco



FD sim + reco



Systematic uncertainties



Fitting framework

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

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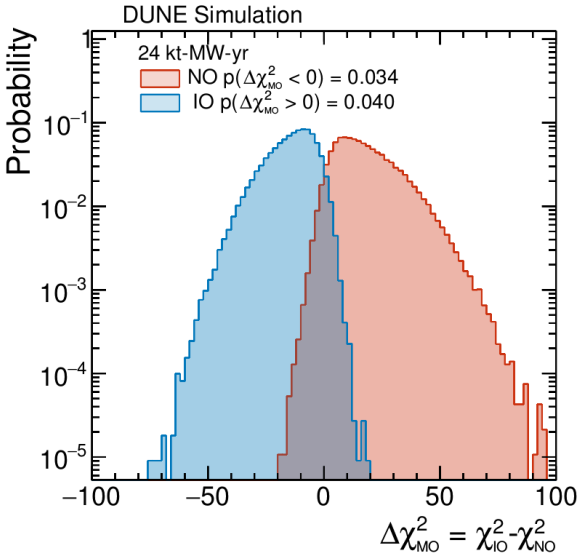
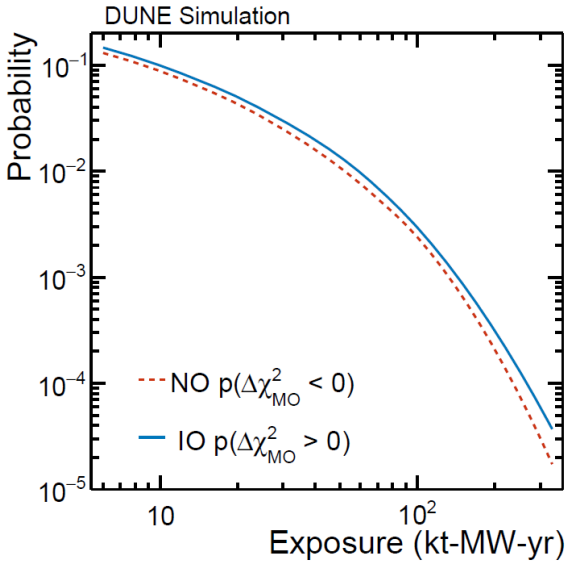
Oscillation sensitivities



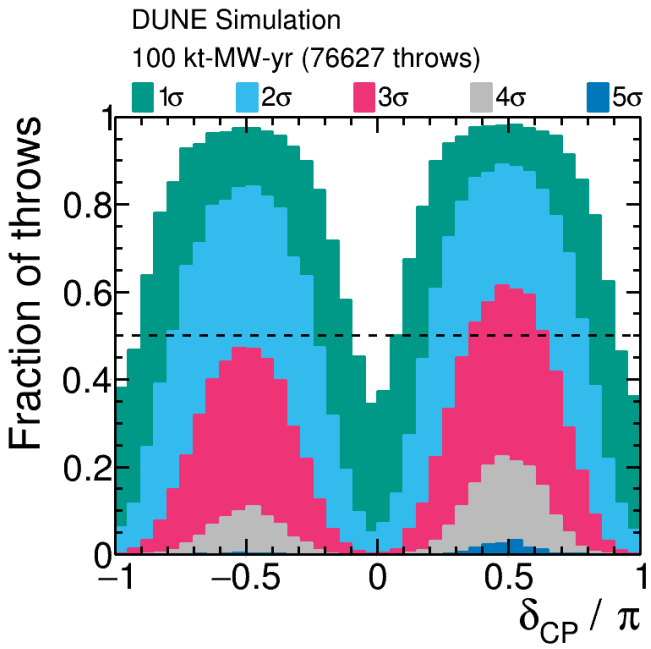


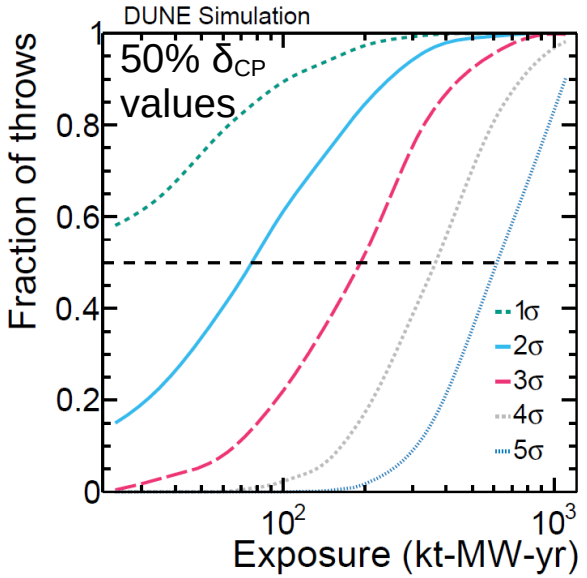
Phase I:

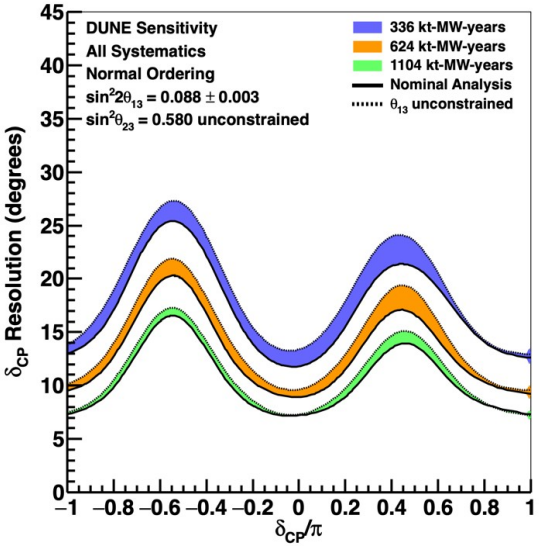
- MO to >5σ
- 3σ CPV if δ_{CP} ±π/2

Phase II:

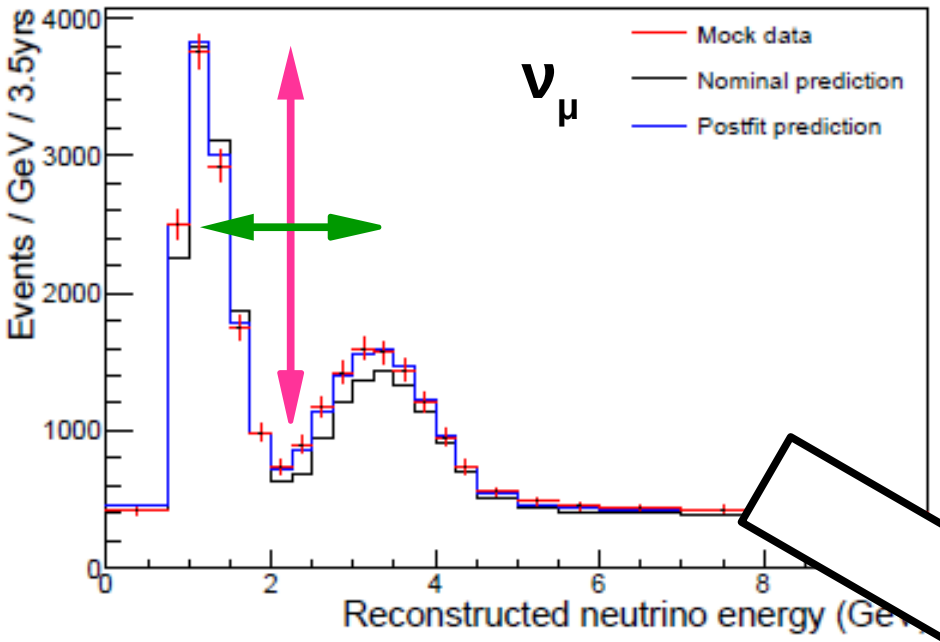
- >5σ CPV, >50% δ_{CP} values
- >3σ CPV, >75% δ_{CP} values
- Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}





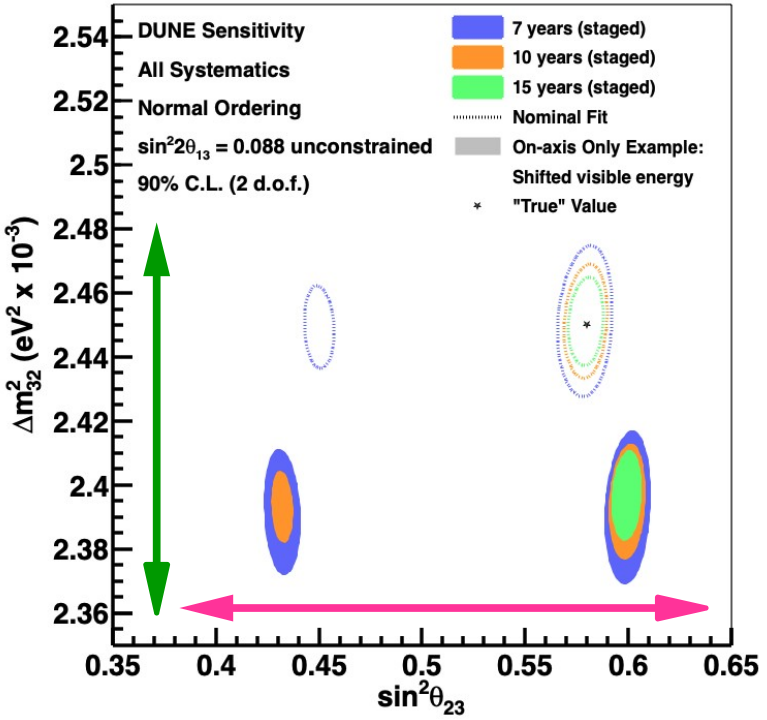


Bias studies: cross-section mismodeling



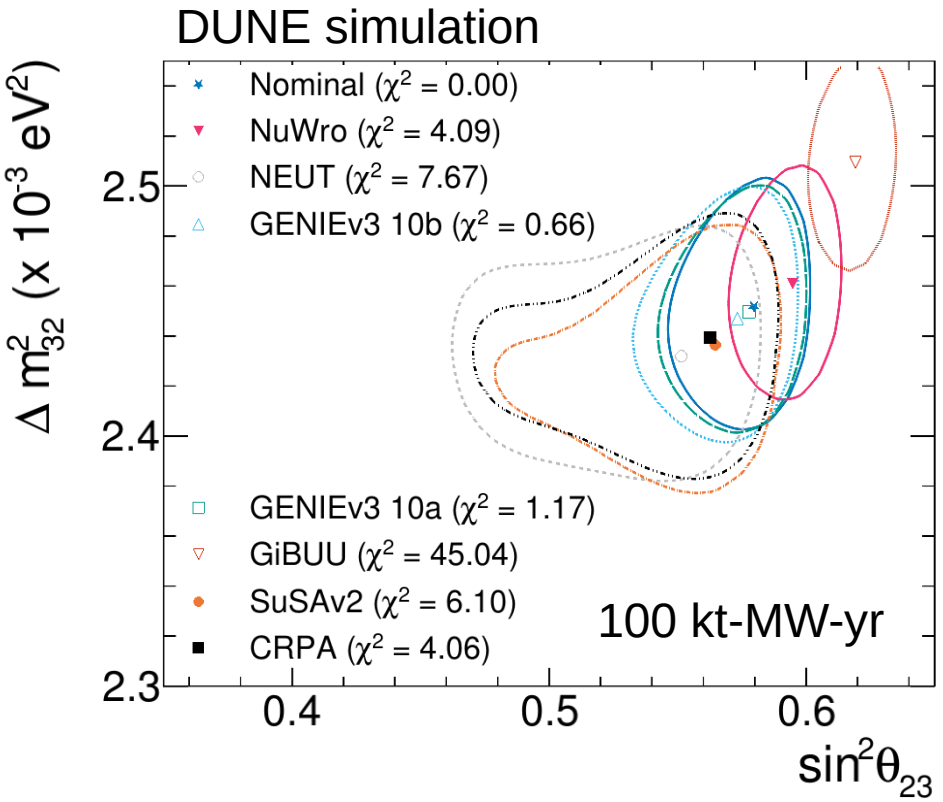
- Shift 20% of proton energy to neutrons (for all E_ν)
- Subtle impact on spectra, but large bias in oscillation parameters

90% confidence



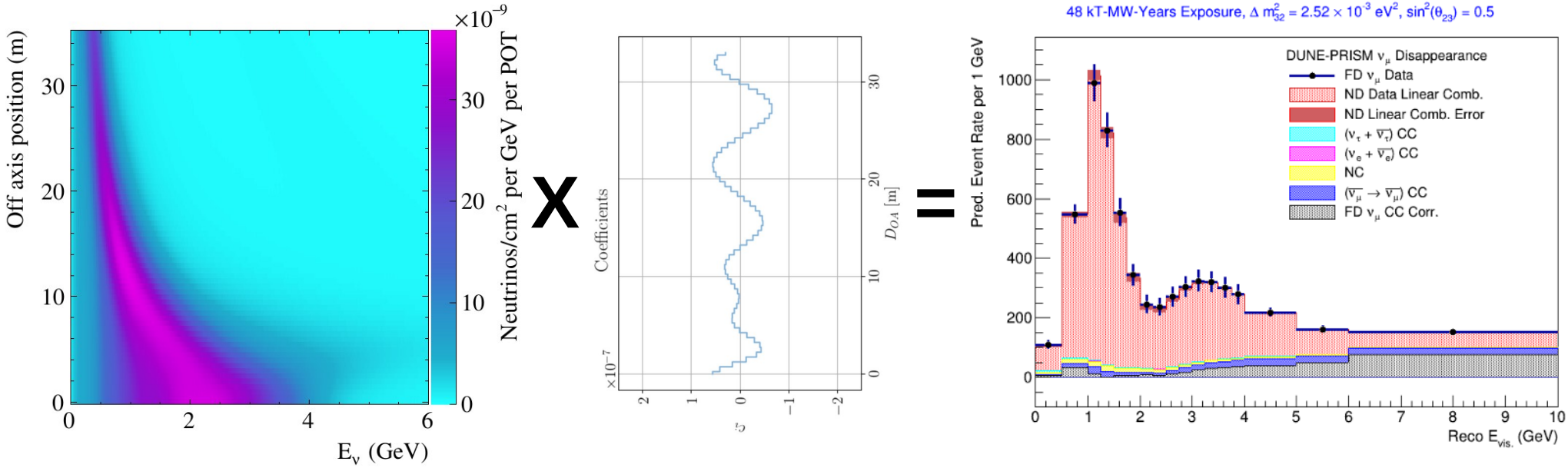
Bias studies: cross-section mismodeling

- Not all model differences are reweightable; significant cost to propagate multiple models through the full sim+reco chain
- Used high-dimensional BDT (Instruments 5 (2021) 4, 31) for approximate model→model reweighting for fake data studies



- On one hand, this is a failure of the systematics model...
- But… it's also a reality, DUNE will use FDS extensively for the OA
- Not necessarily an acceptable solution for BSM… divergent systematics needs?

DUNE-PRISM



- Linear combinations of off-axis data approximate the oscillated FD flux
- *Reduces* cross-section model dependence relative to on-axis extrapolation analysis
- Different off-axis slices provide additional capability to probe modeling issues

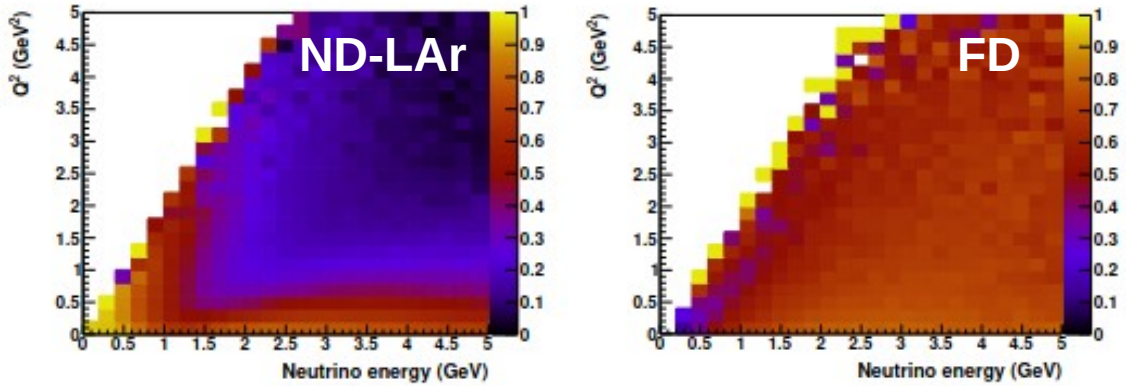
Doesn’t DUNE-PRISM solve everything?

Hugely important part of the DUNE **OA** strategy, but **no**:

1) Linear combination analysis cannot *quite* reach the same sensitivity as model-dependent fit

(trade ND stat. and flux for XSEC uncertainties)

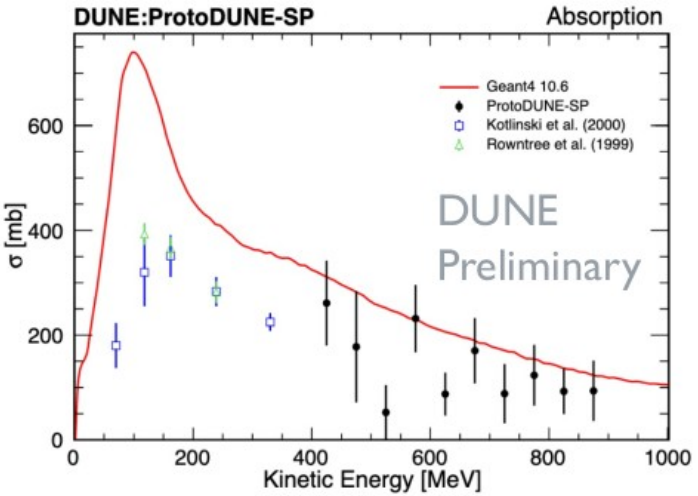
2) ND and FD acceptances and performance will be different, model-dependent corrections required

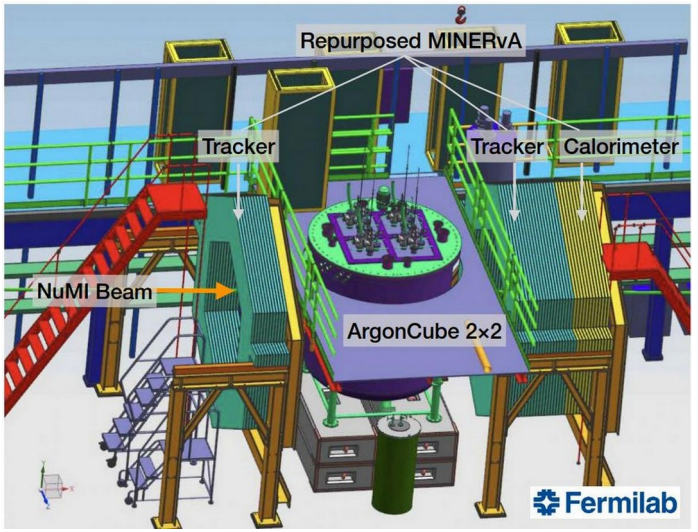


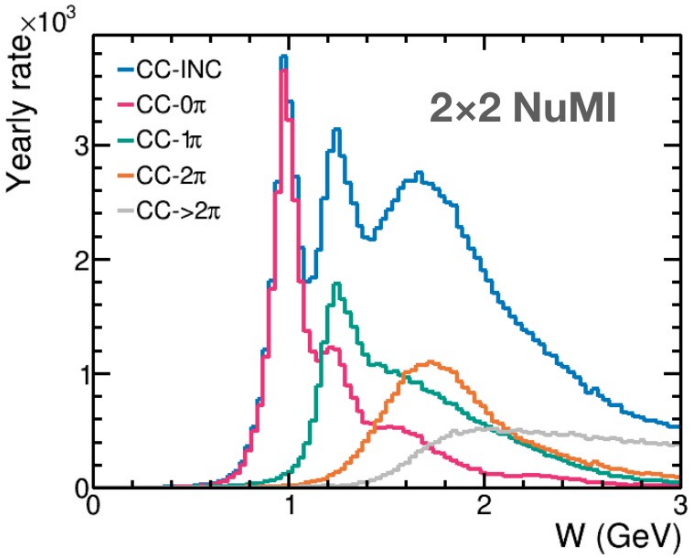
Note that leading XSEC uncertainties will be different to on-axis analysis, will require careful thought!

DUNE: not just sensitivity studies

- Prototype experiments produce useful information for developing systematics
- ProtoDUNE $\pi^{\pm}/K^{\pm}/p$ – argon scattering
- ArgonCube 2x2 in NuMI ME beam







Concluding thoughts

- DUNE has a broad band beam (and broad physics program) so all processes matter...
- Methods to reduce uncertainties and potential for bias introduce new challenges: PRISM, standard candles
- Sensitivity studies show that systematics we currently include are insufficient to cover model variation
- Improvements ongoing may mitigate that (see next talk!)
- However, ability to rapidly deploy and test variety of models will be essential for robust results
- OA focus, but… is it really sufficient for other searches?