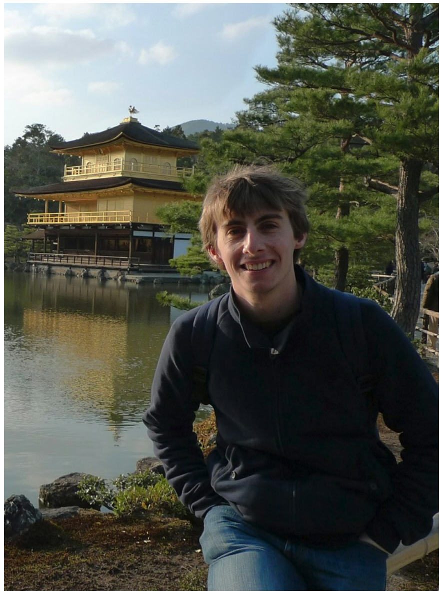
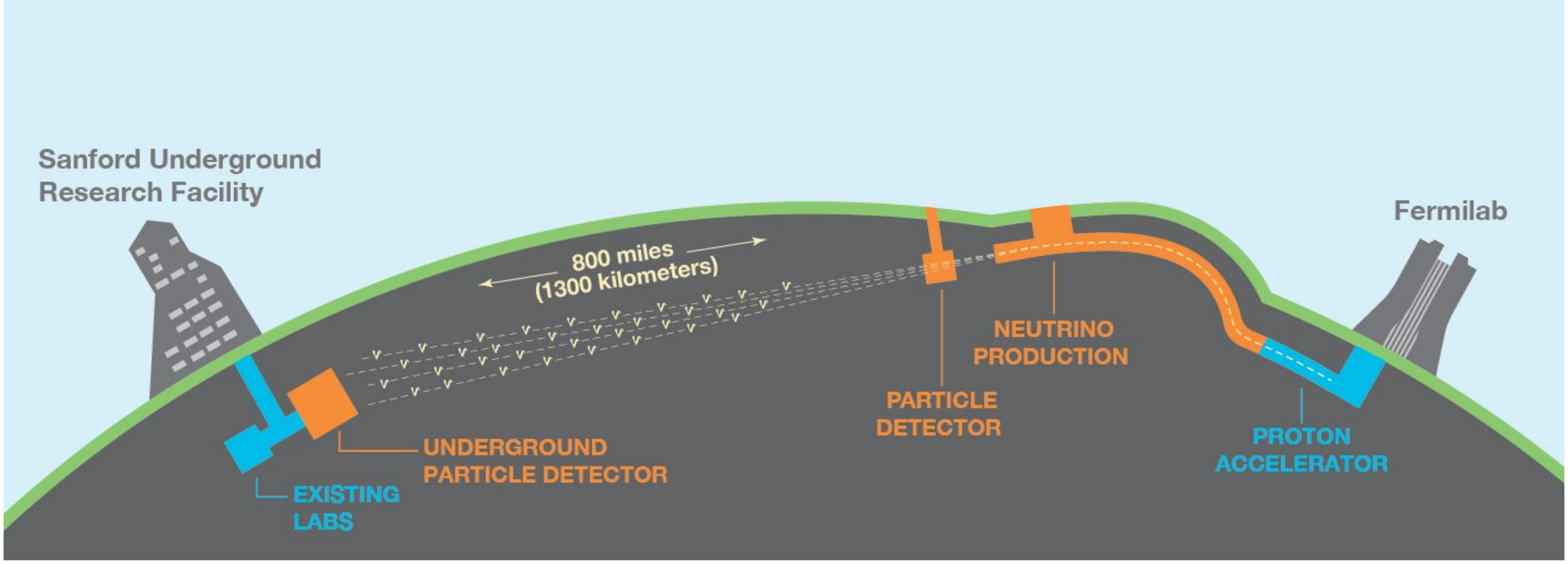
LBL physics and the DUNE ND

Callum Wilkinson on behalf of the DUNE collaboration
Lawrence Berkeley National Laboratory
DUNE Phase II ND workshop
ICL, 20th June 2023



DUNE



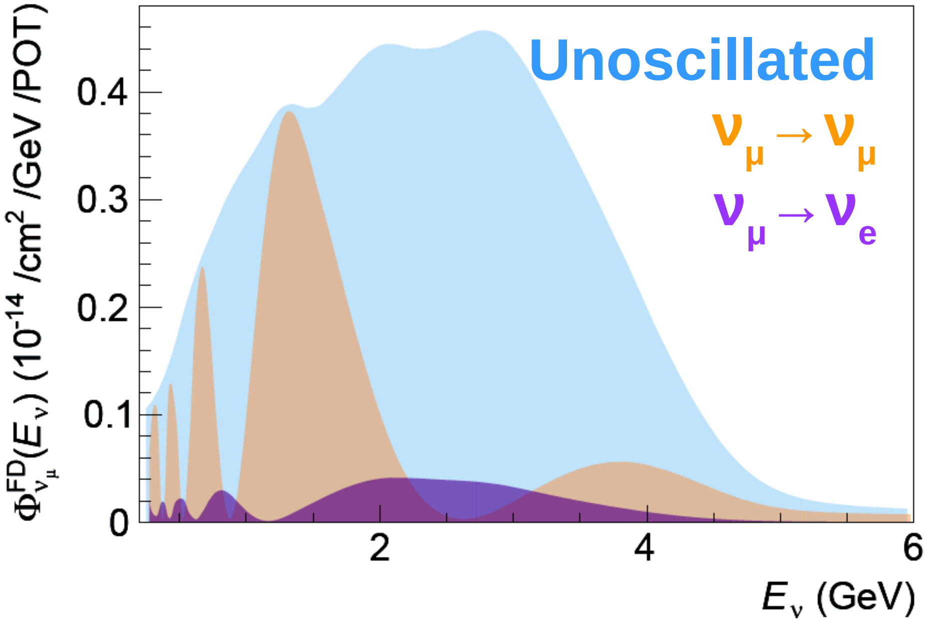
- L ≈ 1285 km; E_ν≈ 2.5 GeV (*broad band*); liquid argon time projection chamber (LArTPC)
- Unprecedented intensity neutrino beam
- Near detector system at Fermilab
- 4 x 17 kt far detector modules at SURF

Function of the ND for LBL

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

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

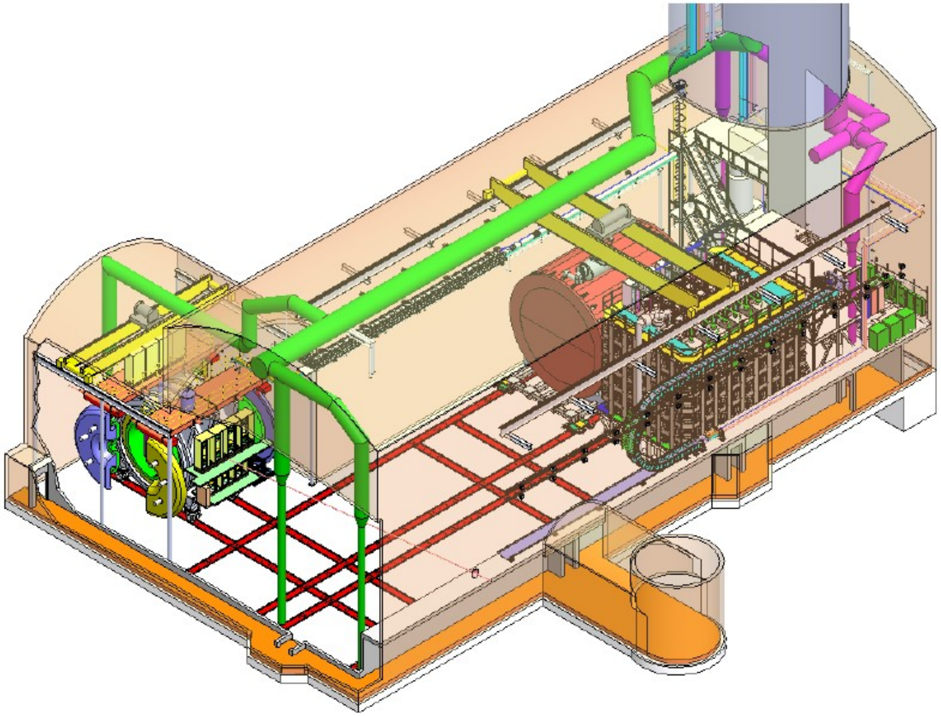
- Fundamentally, the ND breaks degeneracies
- By location, it breaks the degeneracy between **P** and **Φ** x **σ**
- By design, we want it to break degeneracies between **Φ** and **σ**
- Limited by the detector resolution and efficiency **ε**



Phase I 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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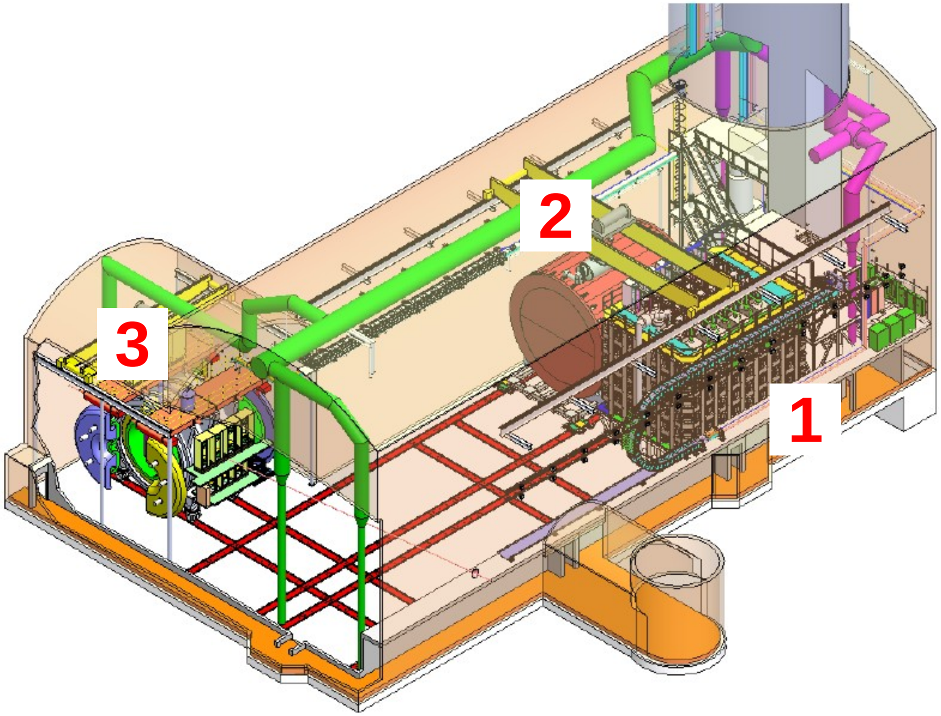

Three major components:

1 - Core 150 t LArTPC with pixelated readout

2 - Downstream magnetized tracker

3 - SAND: dedicated beam monitor

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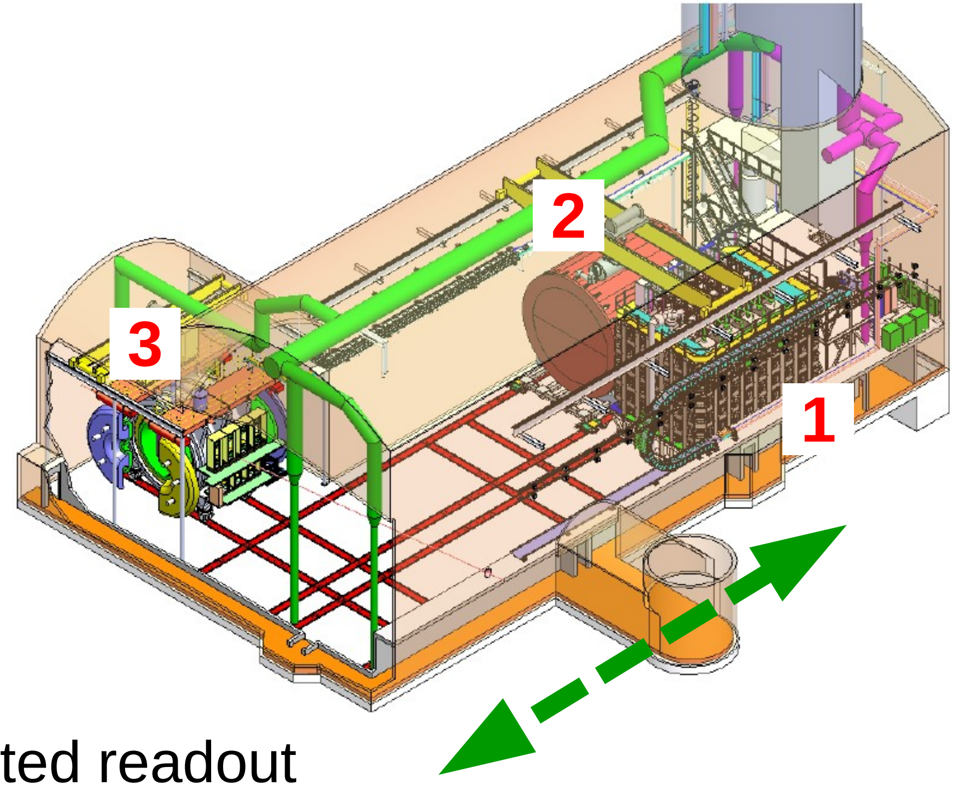


Three major components:

Moveable

1 - Core 150 t LArTPC with pixelated readout

2 - Downstream magnetized tracker

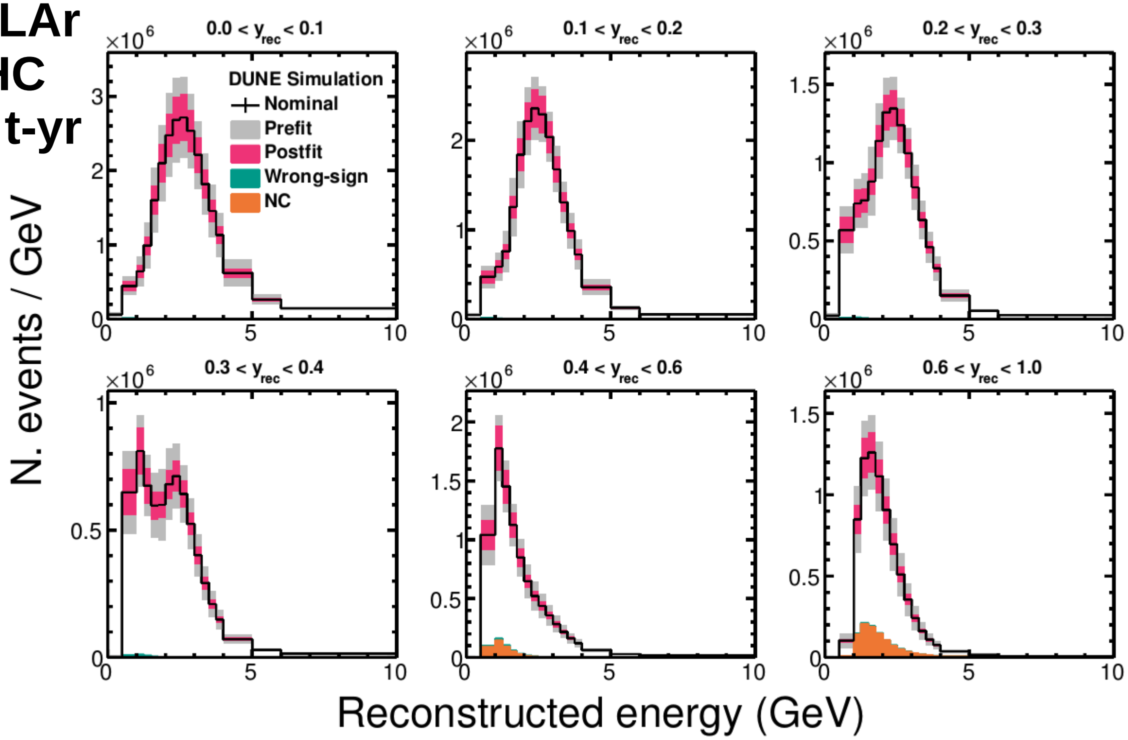
3 - SAND: dedicated beam monitor

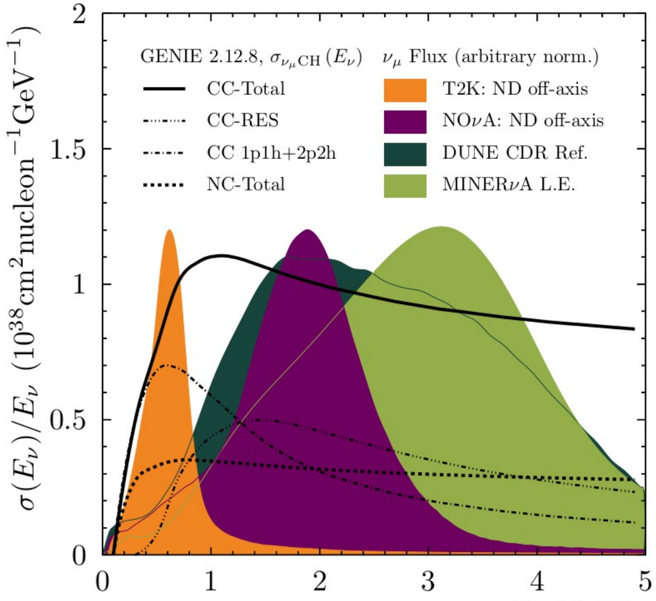
DUNE ND will be systematics-limited

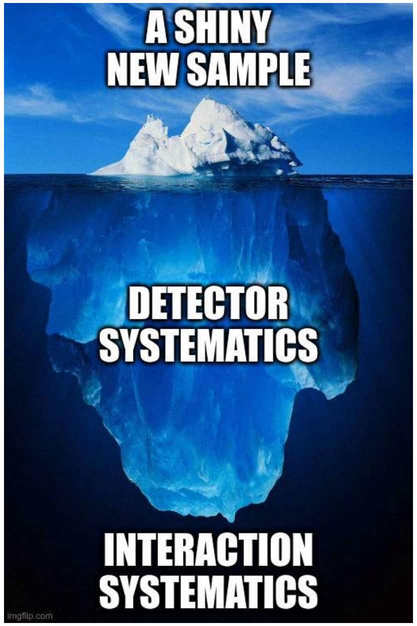
Two (obvious) points:

- ≈100 million events/year at the ND, no stat. uncertainty to hide behind
- DUNE spans complex region of phase space: QE → RES → DIS

ND-LAr
FHC
105 t-yr

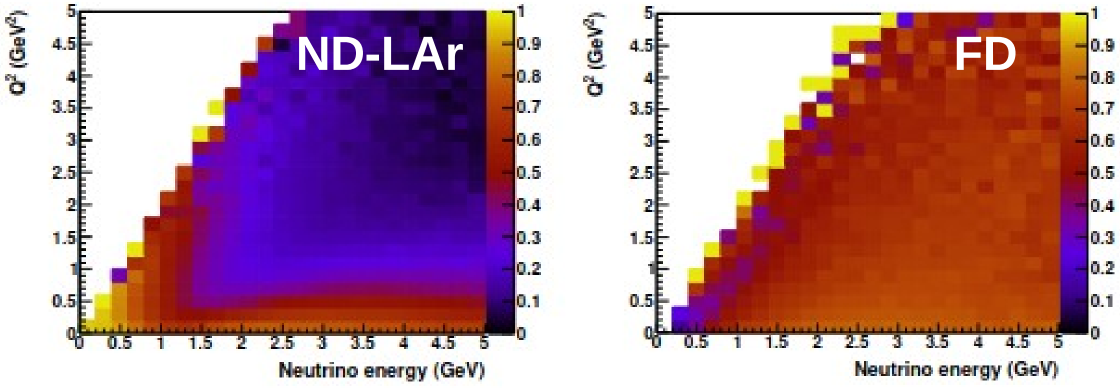






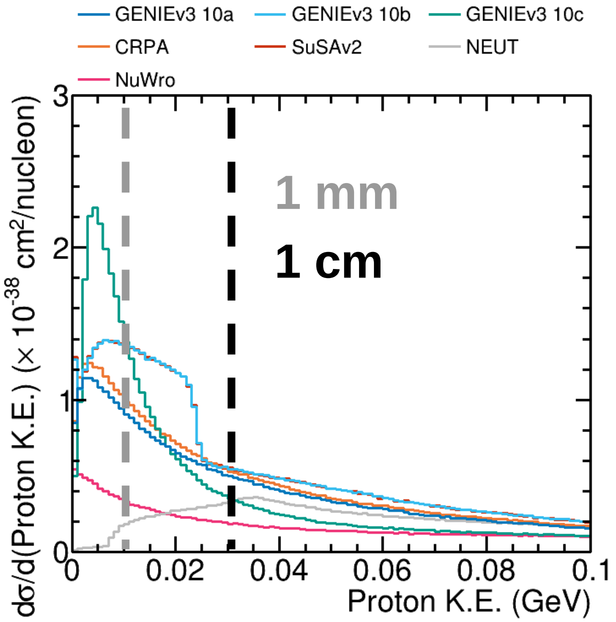
DUNE ND Phase I challenges

1) Different ND-LAr acceptance to FD

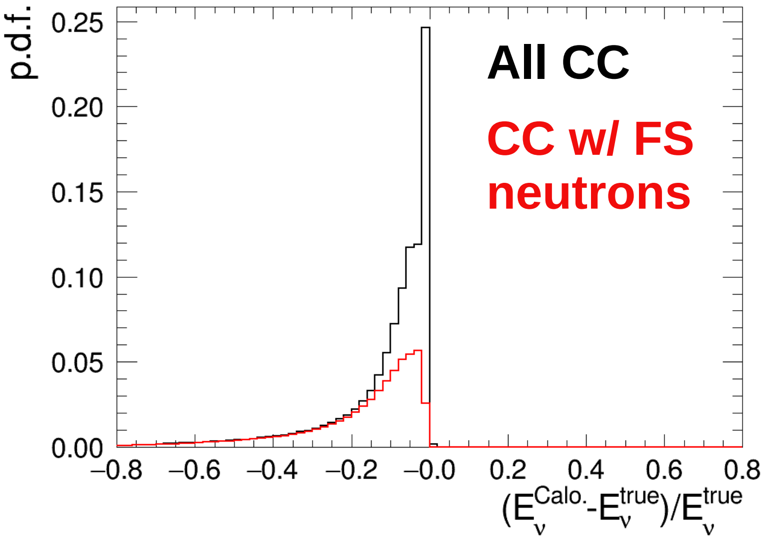


arXiv:2203.06281

2) Particle tracking threshold may hide important information



3) Neutrino energy reconstruction limits precision measurements – neutrons are a particular challenge



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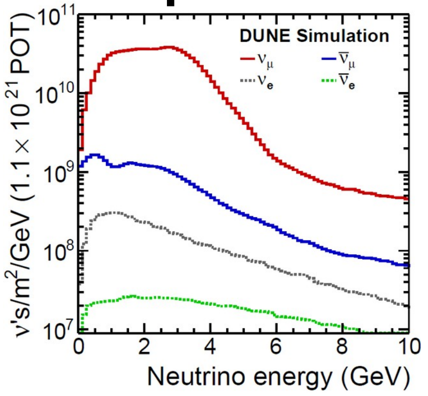
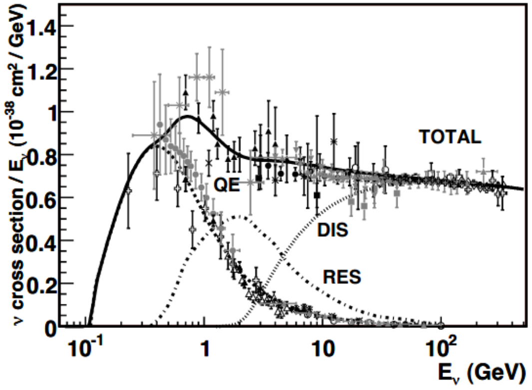
(On-axis) analysis

Flux prediction

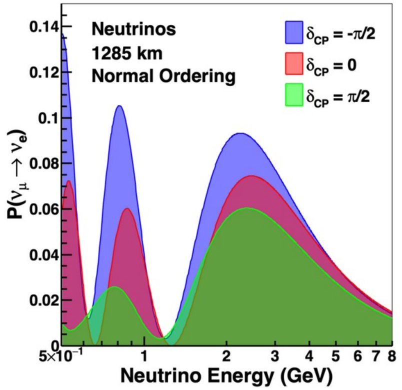


X

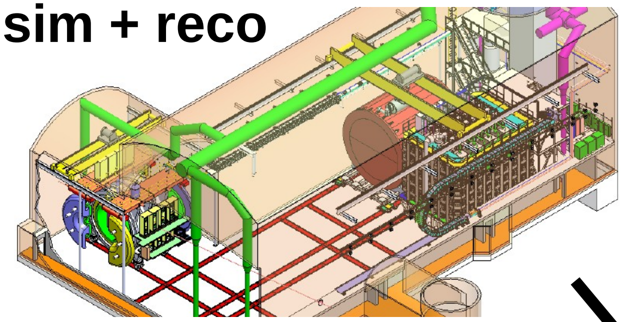
Interaction model



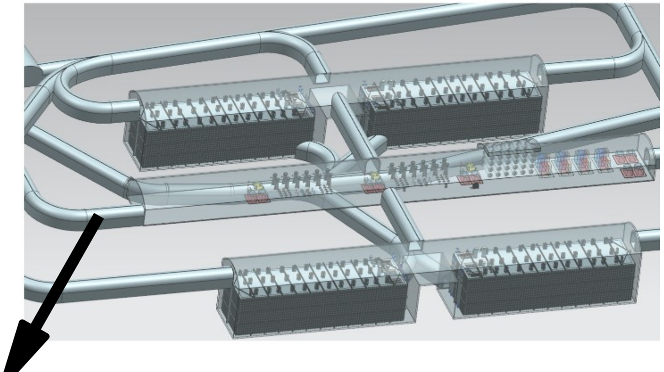
Oscillations



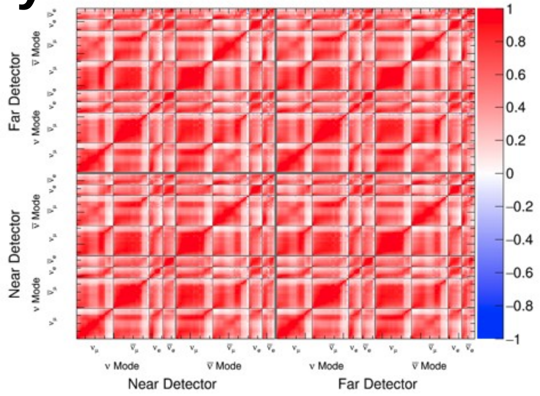
ND sim + reco



FD sim + reco



Systematic uncertainties



Fitting framework

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

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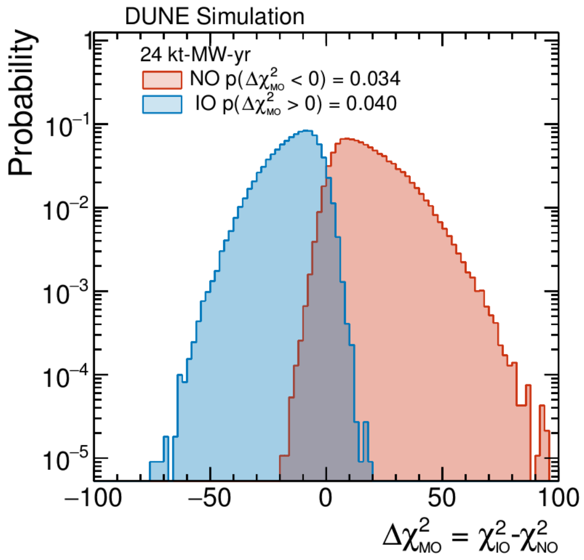
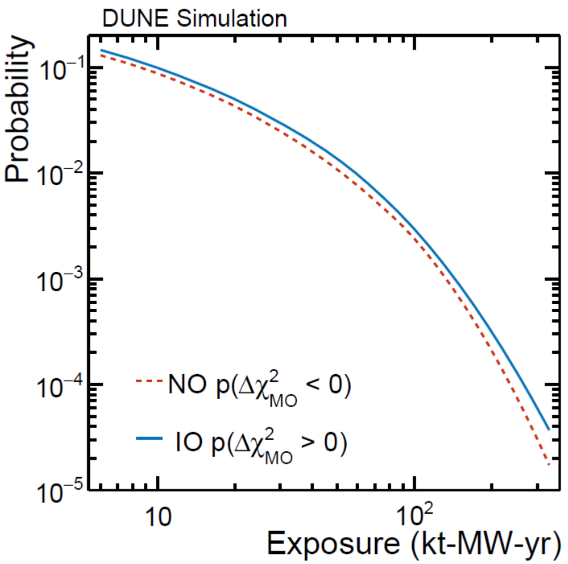
Oscillation sensitivities



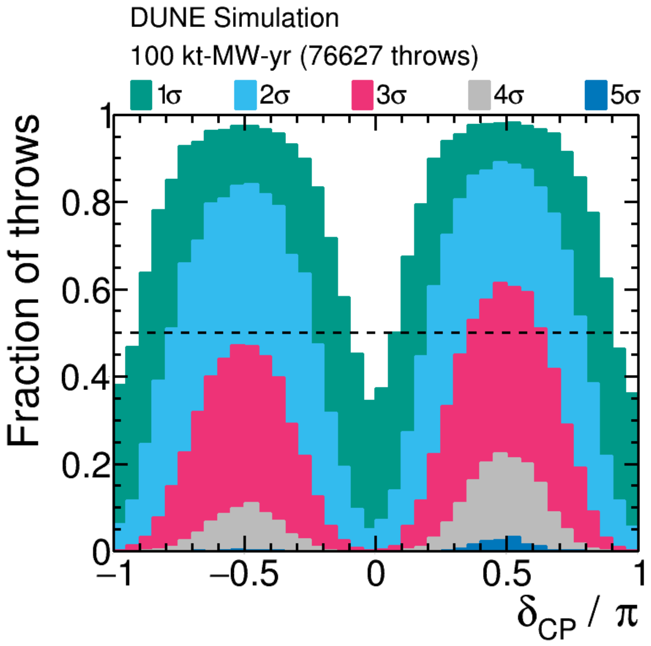


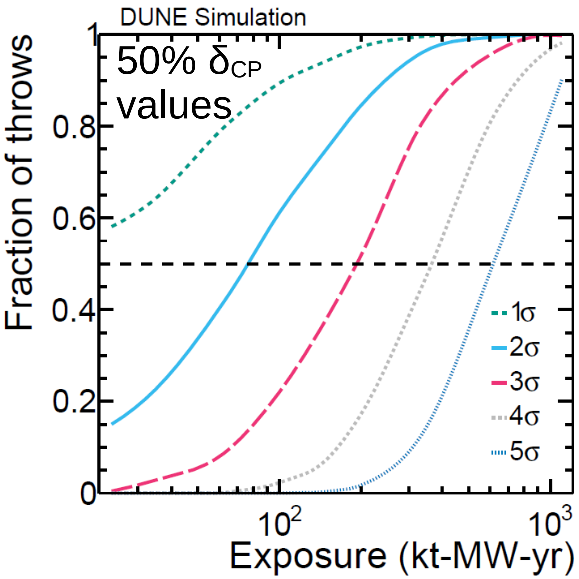
Phase I (100 kt-MW-yr):

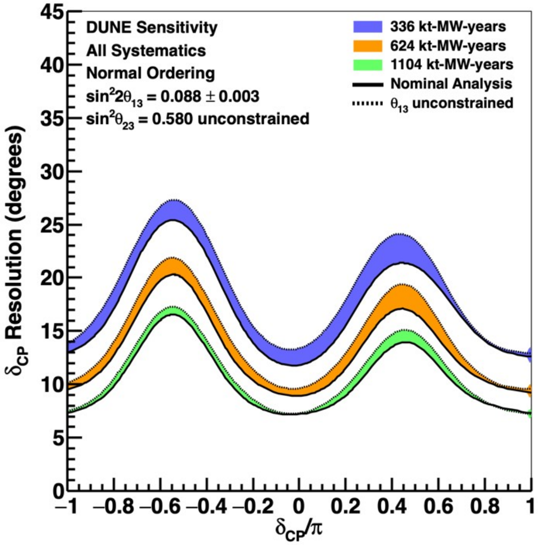
- MO to >5σ
- 3σ CPV if δ_{CP} ±π/2

Phase II (1000 kt-MW-yr):

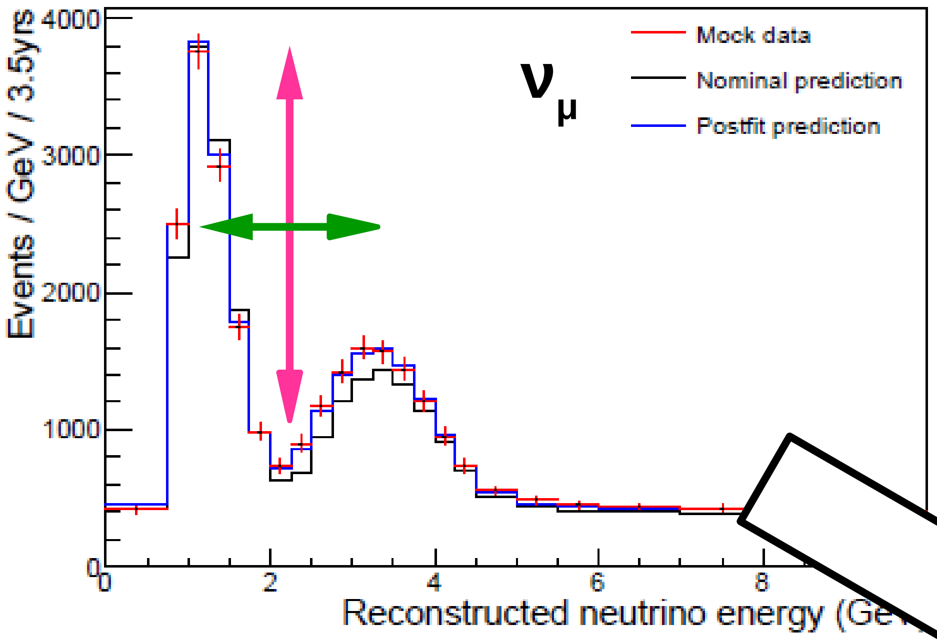
- >5σ CPV, >50% δ_{CP} values
- >3σ CPV, >75% δ_{CP} values
- Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}





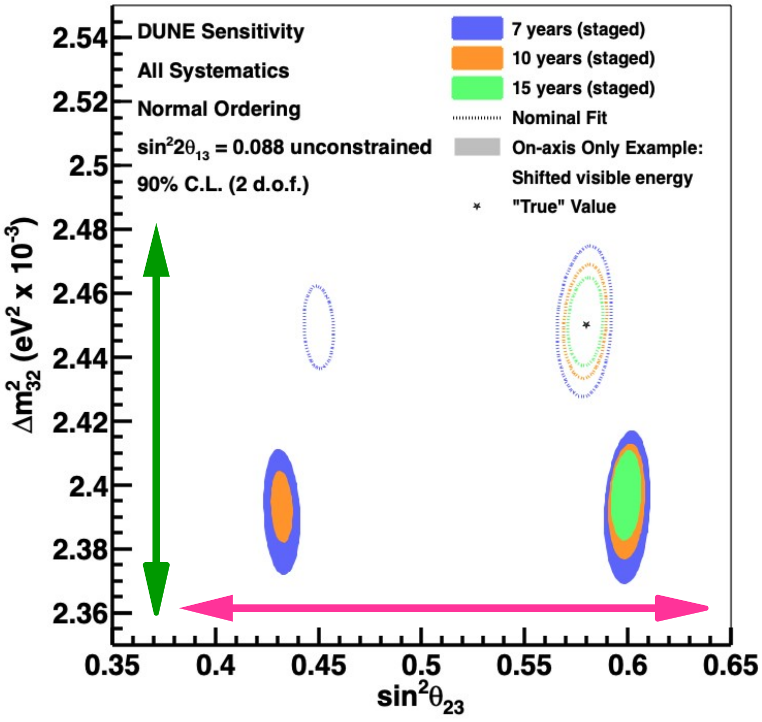


Bias studies: cross-section mismodeling



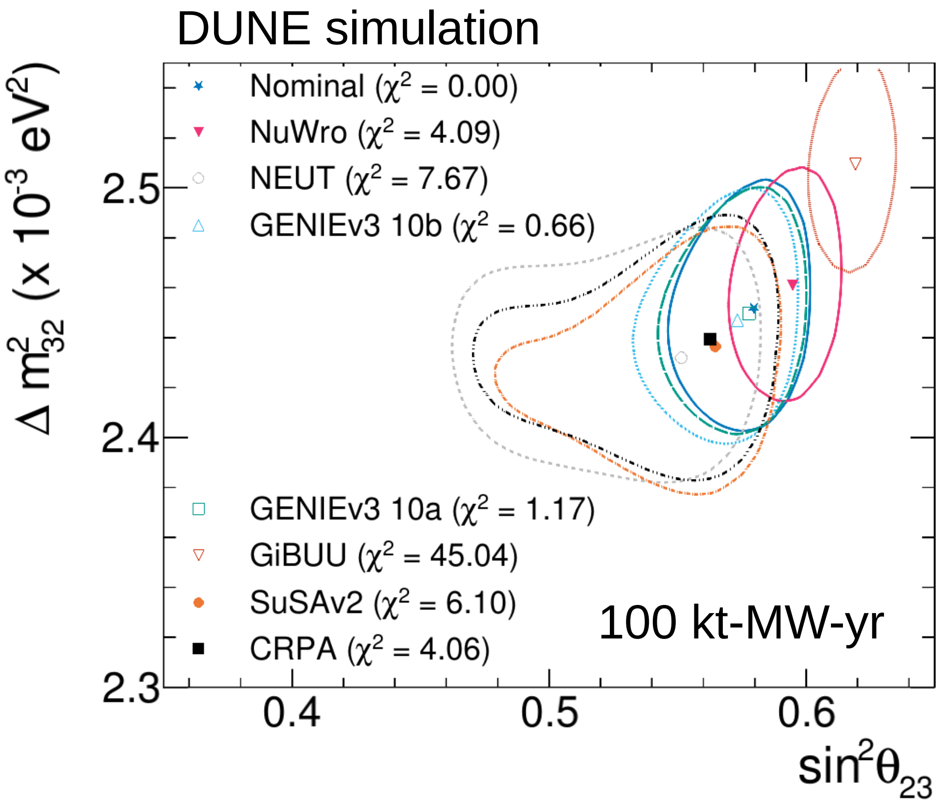
- Shift 20% of proton energy to neutrons (for all E_ν)
- Subtle impact on spectra, but large bias in oscillation parameters

90% confidence



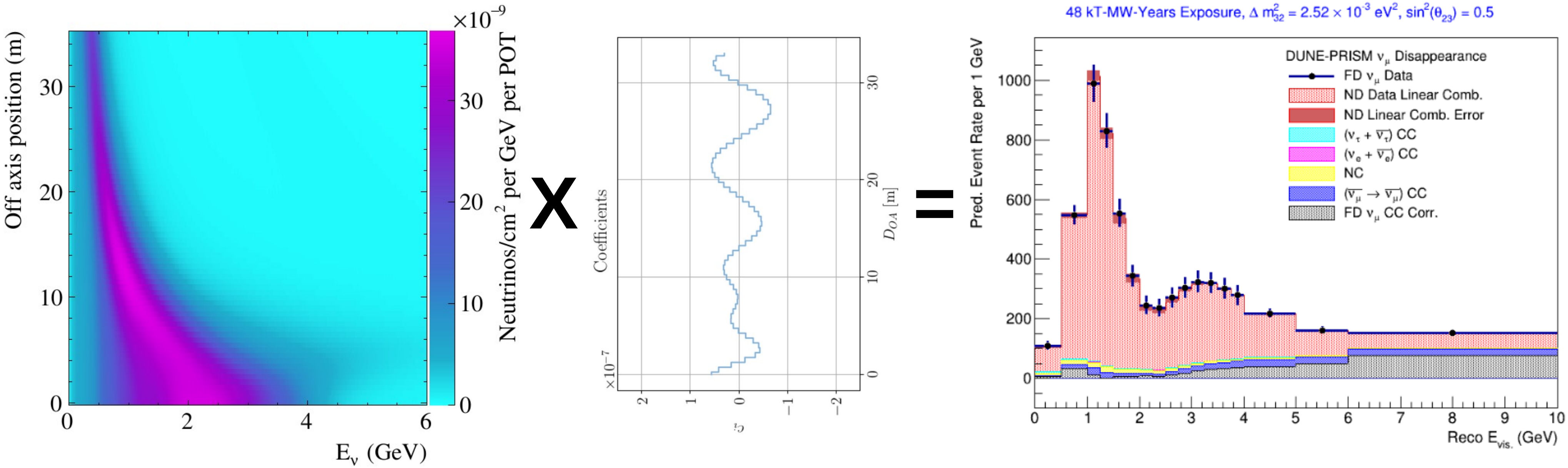
Bias studies: cross-section mismodeling

- Many theoretical/phenomenological models for neutrino interactions on the market → further potential for bias
- ND finds okay™ agreement by pulling parameters of nominal model → leads to biases in osc. parameters



- **Φ** x **σ** degeneracies, limited by **ε**, are responsible
- Avoiding **degenerate solutions** will be an experimental and theoretical challenge
- Precision (phase-II) DUNE measurements may be limited by these issues

DUNE-PRISM: breaking E_ν degeneracies



- 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

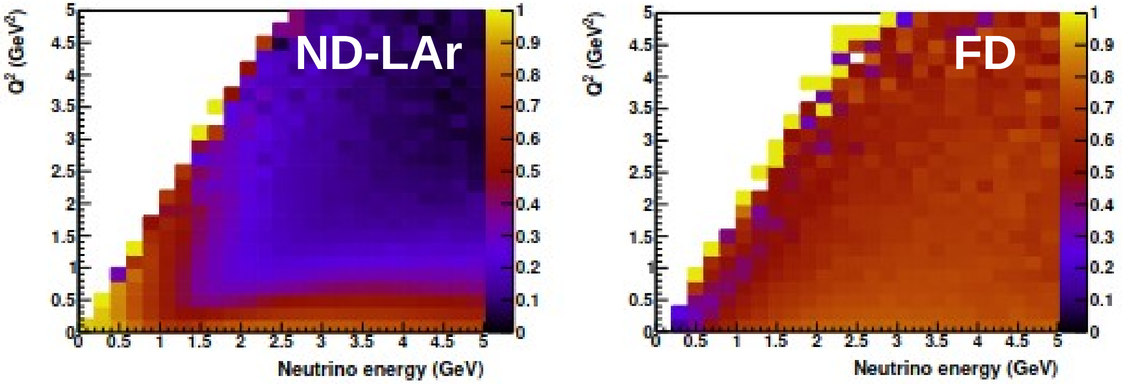
Doesn't DUNE-PRISM solve everything?

Hugely important part of the DUNE strategy, but no:

1) Linear combination analysis unlikely to 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



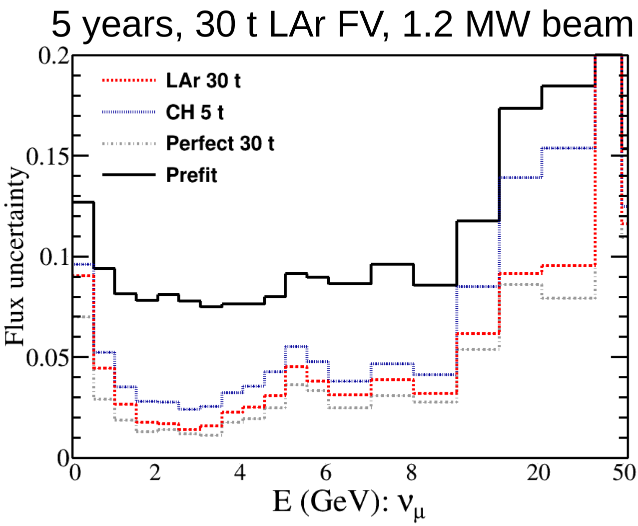
But, DUNE-PRISM breaks important degeneracies, shown with FDS → a good way to frame other ND improvements

Standard candles to break $\Phi \times \sigma$ degeneracy

Rely on a known cross section by isolating an unusual region of phase space

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

New challenges for systematic modeling, but potential to break flux/XSEC degeneracies



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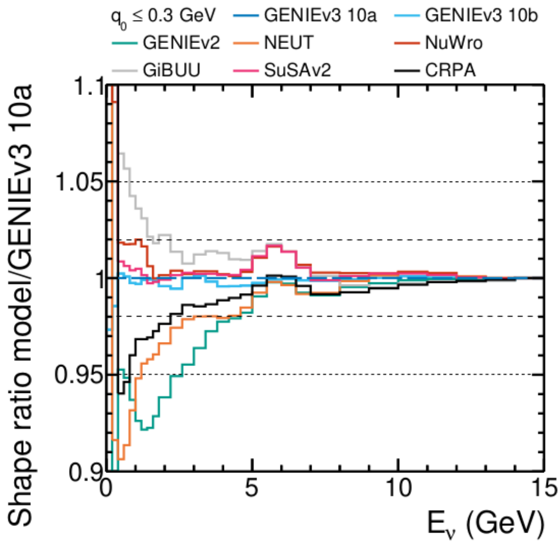

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Concluding thoughts

- ND design breaks **Φ** x **σ** x **ε** degeneracies that limit LBL
- Phase I ND will become systematics limited, highlighted by bias studies → problematic **Φ** x **σ** degeneracies exist
- Some ND features not fully incorporated into analysis: Standard candle samples; DUNE-PRISM
- Multiple ways to improve DUNE’s sensitivity: ancilliary measurements; theory; ND hardware improvements
- A useful way to frame the discussion about the ND phase II is to ask what degeneracy a new feature will break