Impact of MeV signatures on oscillation physics

Callum Wilkinson for the DUNE Collaboration

30th November 2020

BERKELEY LAB

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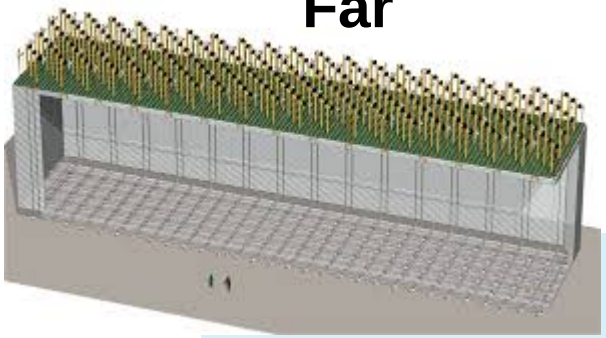
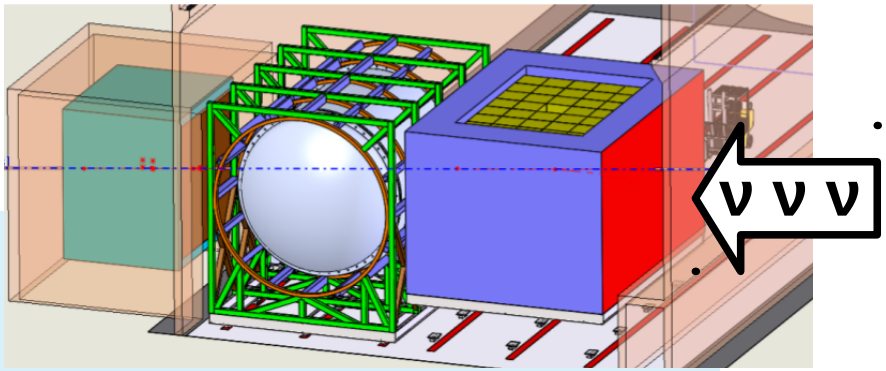
DUNE

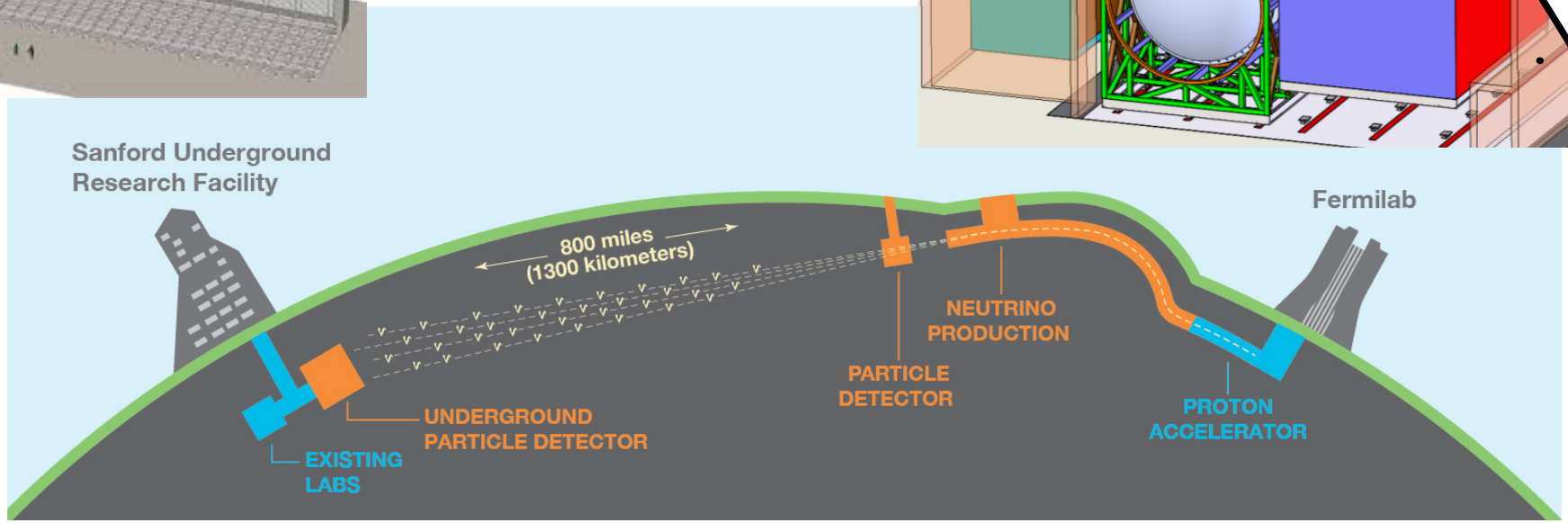
Far



10 kt x4

Near





- Unprecedented intensity neutrino beam at Fermilab
- 40 kt (FV) LAr far detector, 1300 km baseline
- Near detector system at Fermilab
- Start main cavern excavation: Summer 2021
- Start of detector far site detector installation: 2024

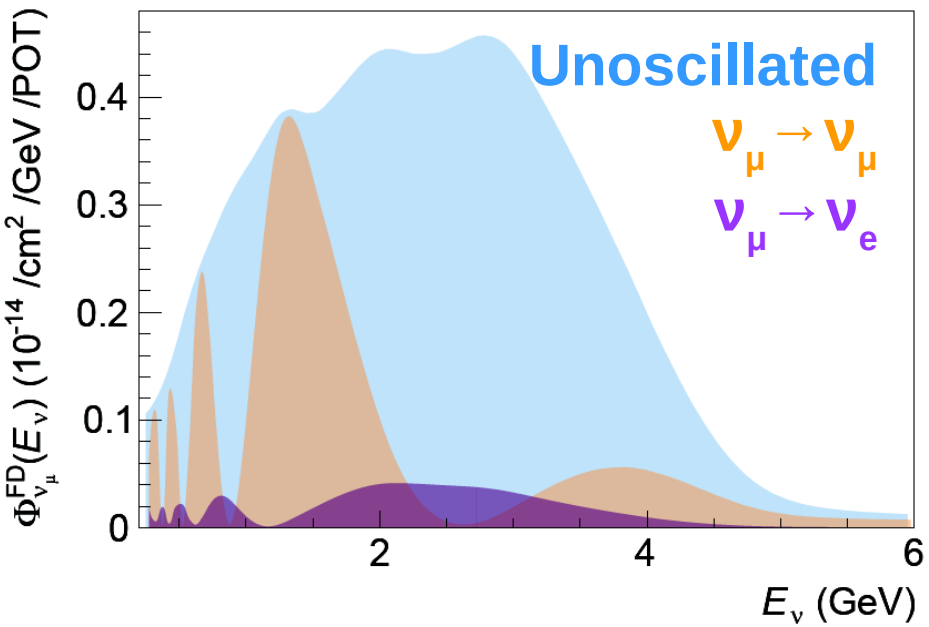
DUNE oscillation analysis basics

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

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

Far

- Some uncertainties cancel or are reduced by the near-far extrapolation
- But still rely on a good understanding of the neutrino flux, and the cross-section model

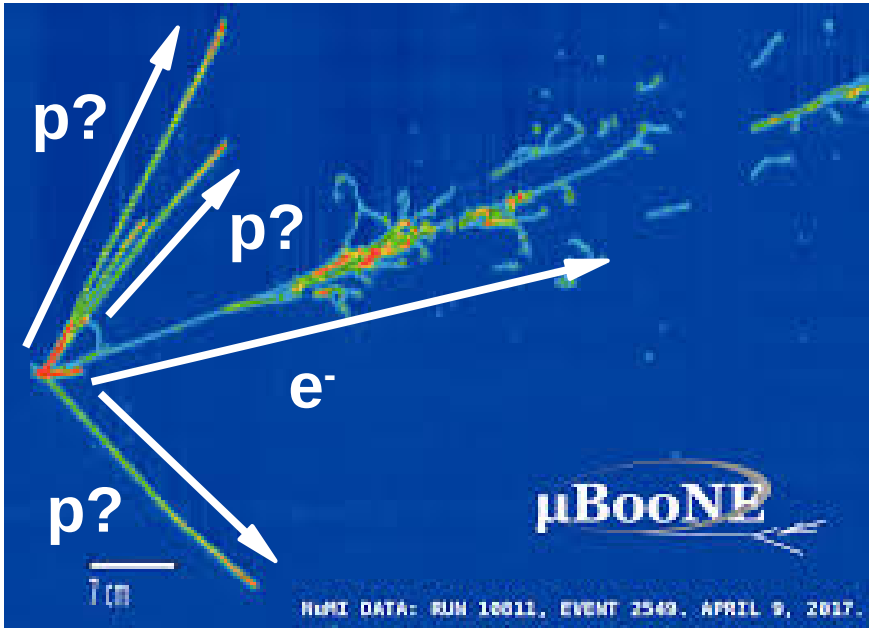


Neutrino energy reconstruction

Use **leptonic** and **hadronic** information:

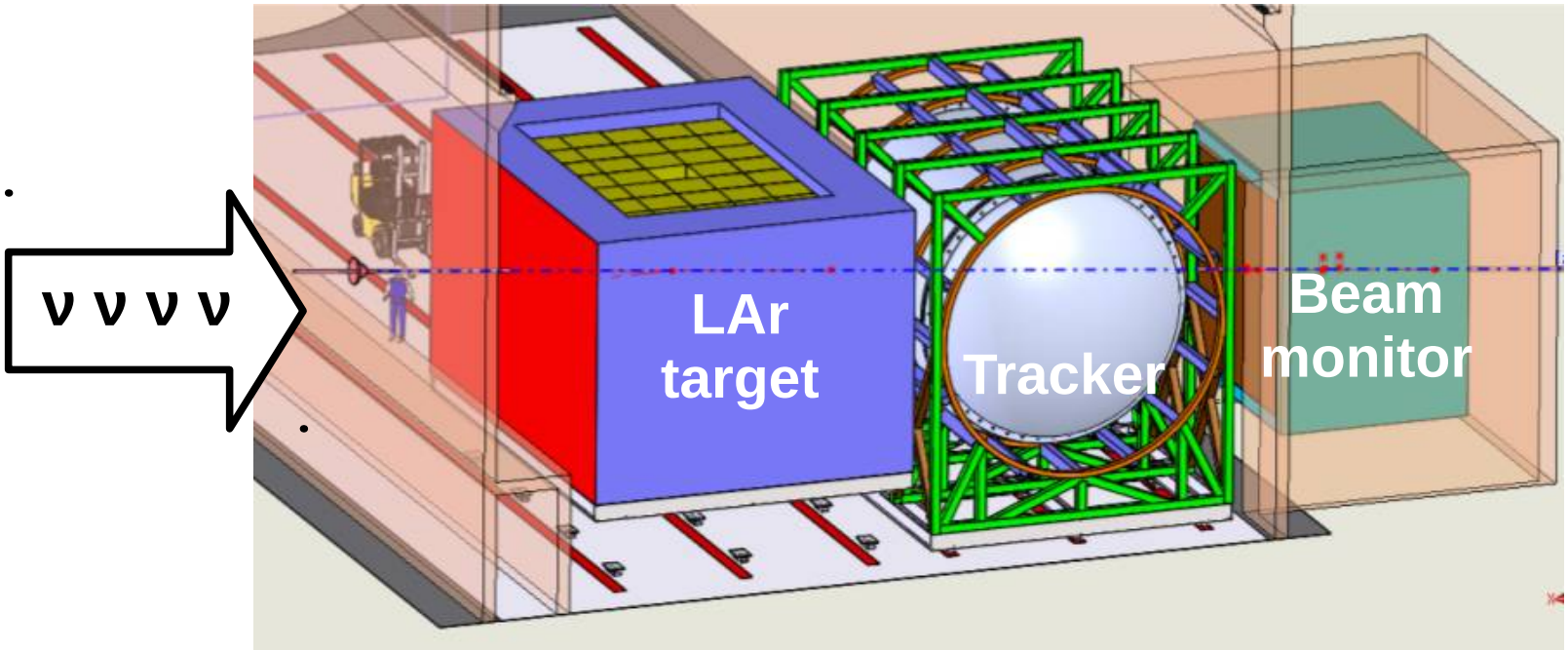
$$E_{rec} = E_{lep} + \sum E_{had}$$

- Smearing from initial nuclear state
- Mis-ID of pions (e.g. < tracking threshold) misses pion mass
- Miss (most) neutrons
- Lower energy, ~100 MeV, structure of events is important



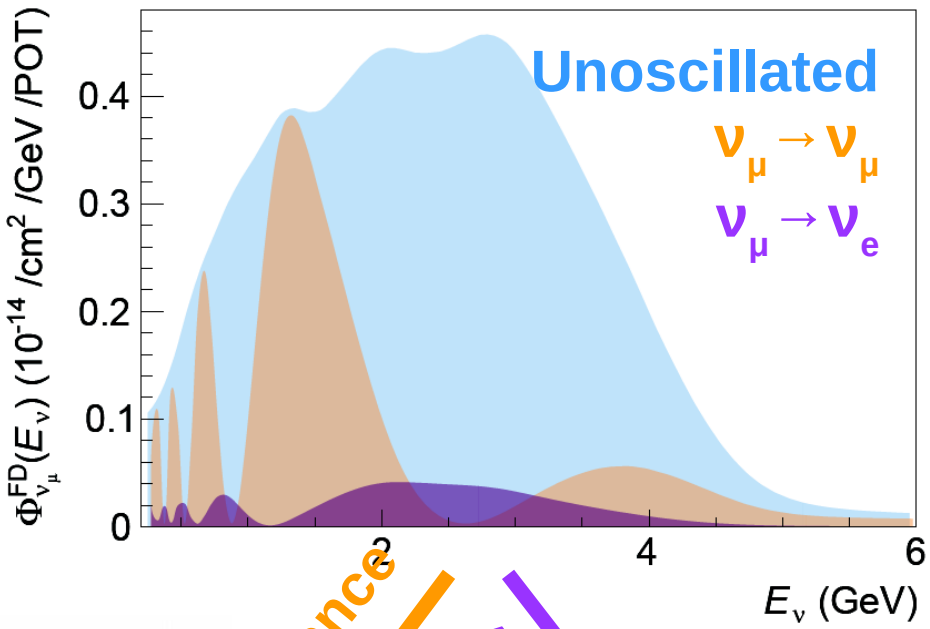
MicroBooNE event display
(purely illustrative)

DUNE near detector



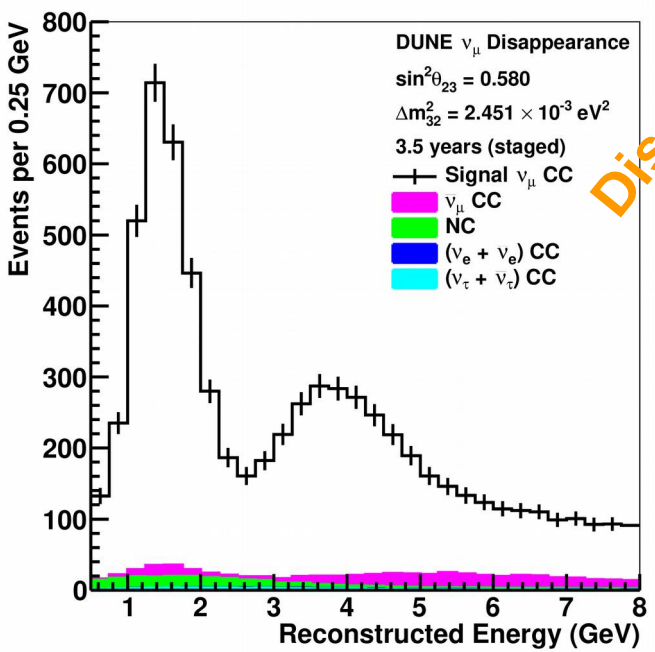
- Controls flux and cross-section systematics for oscillation analysis by sampling the unoscillated beam
- **Unprecedented event rates:**
  - 3.5 years neutrino enhanced: **~50M events**
  - 3.5 years antineutrino enhanced: **~30M events**

DUNE oscillation analysis

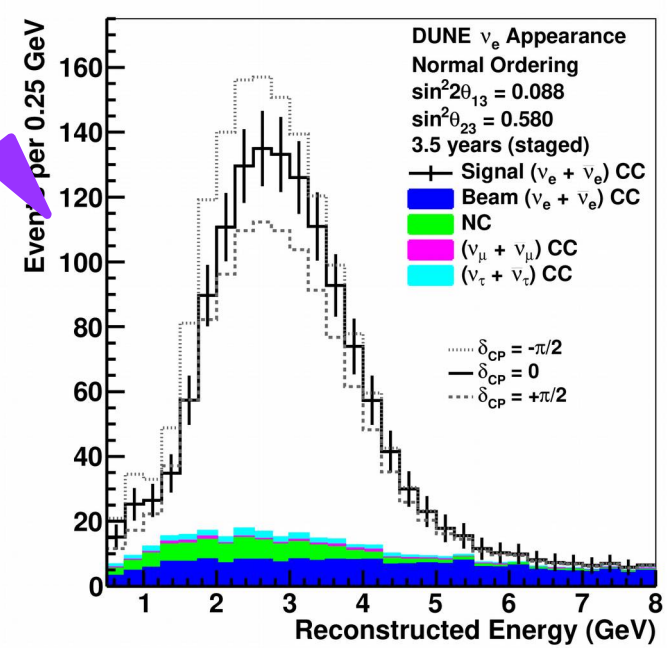


Disappearance

Appearance



(7 years)



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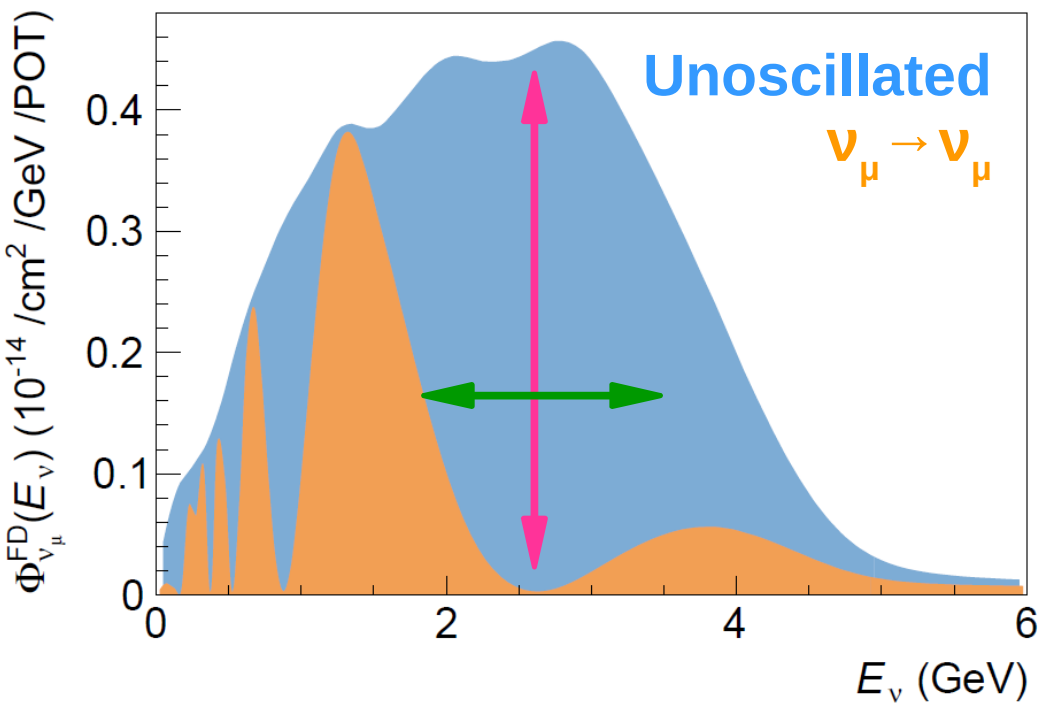
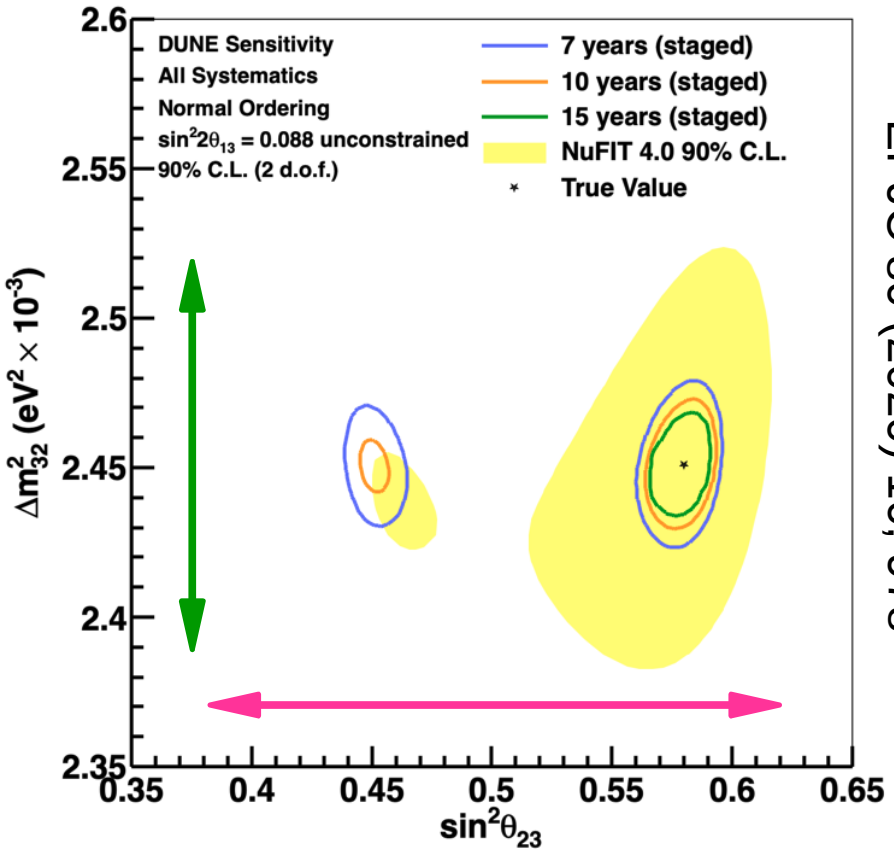
Disappearance parameters

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\vartheta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



90% confidence



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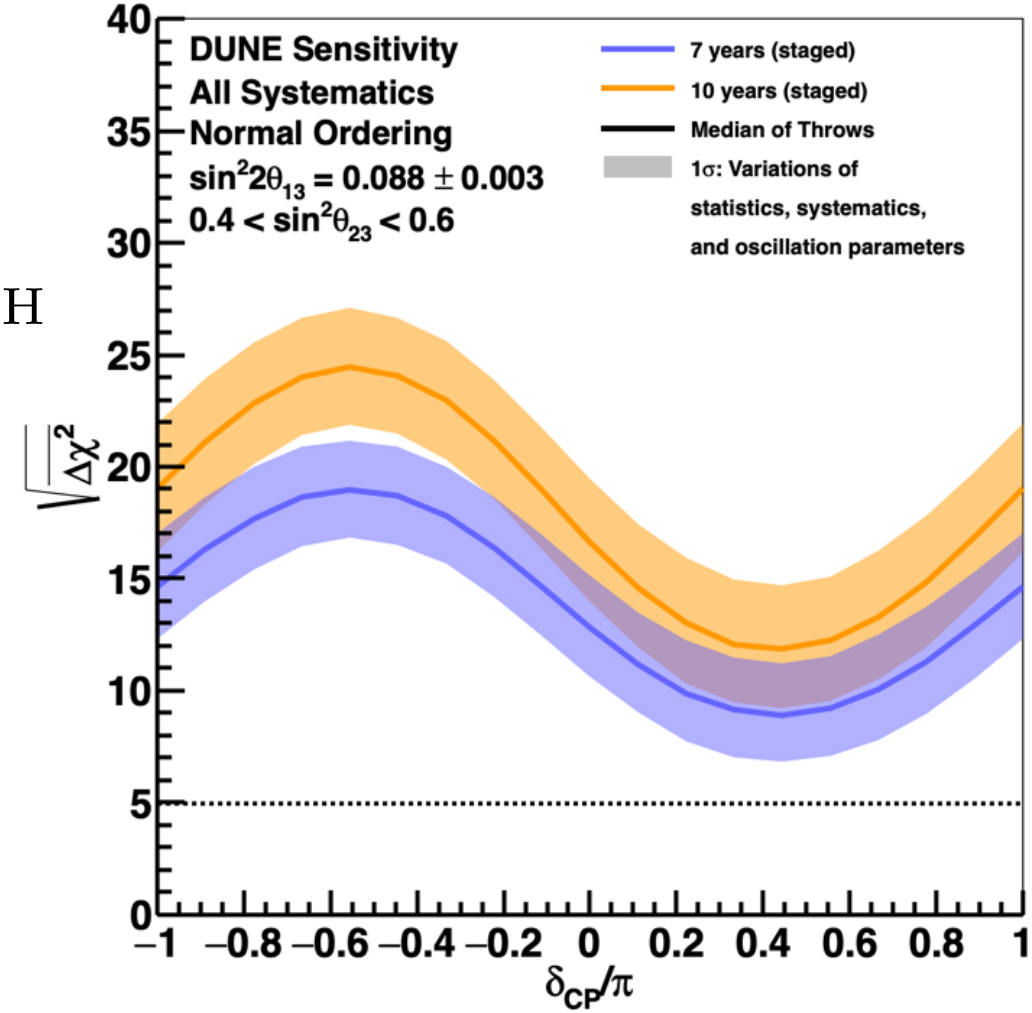
Mass hierarchy sensitivity

$$\Delta\chi^2 = \chi^2_{\mathrm{IH}} - \chi^2_{\mathrm{NH}}$$



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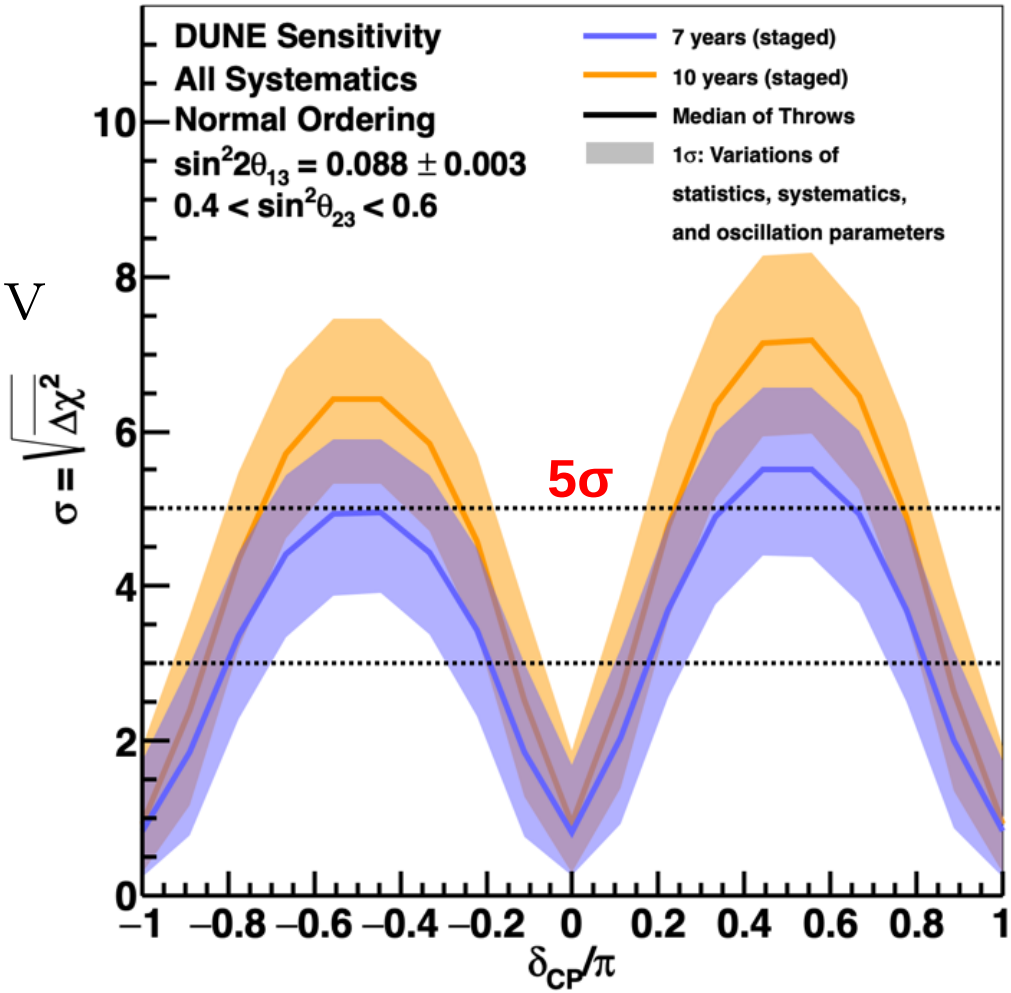
Median and central 68% of parameter throws are shown

CP violation sensitivity

$$\Delta\chi^2 = \chi^2_{0,\pi} - \chi^2_{\mathrm{CPV}}$$



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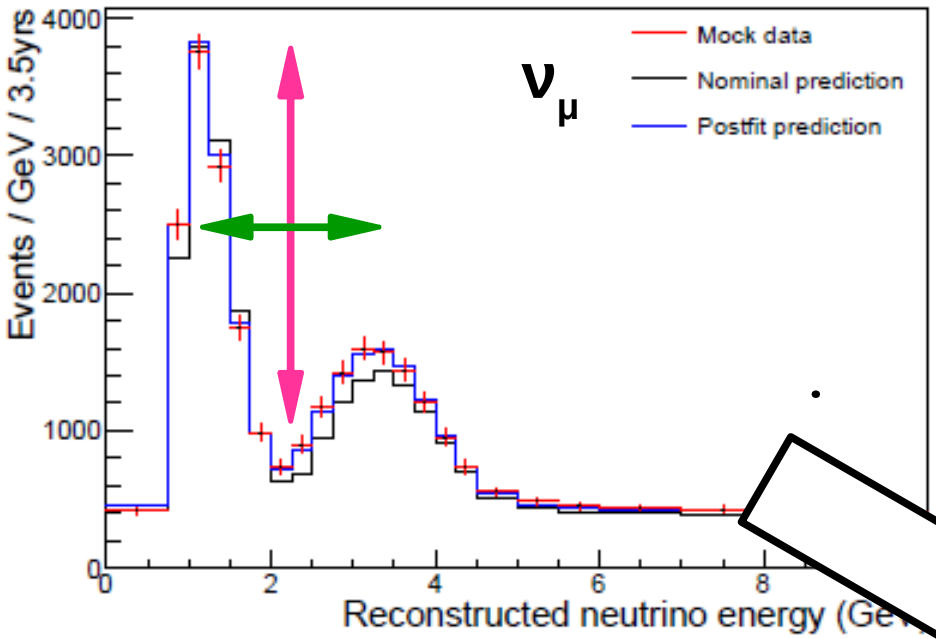
Median and central 68% of parameter throws are shown

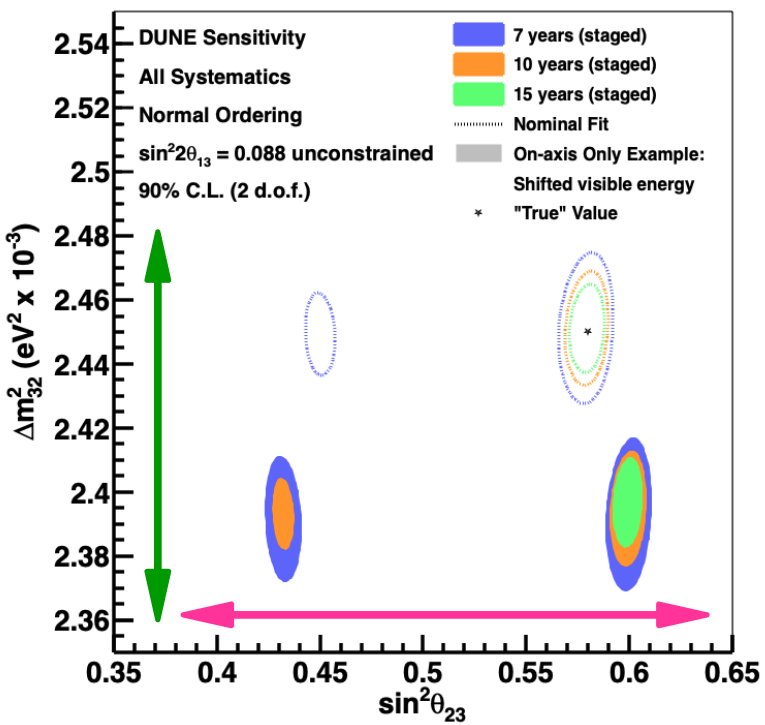
Proton missing energy

arXiv:2002.03005



- Poor knowledge of energy loss to neutrons
- Check the effect of shifting 20% of proton energy to neutrons

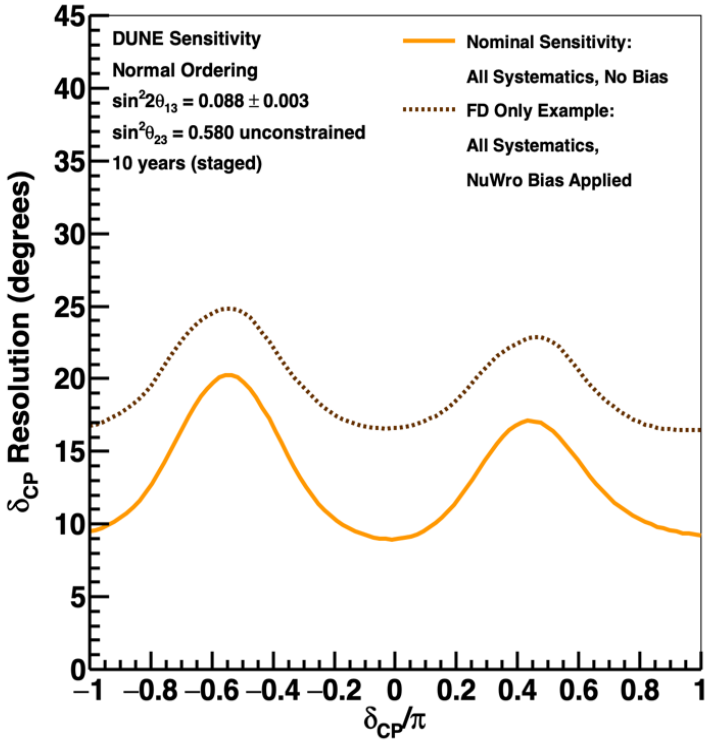
90% confidence

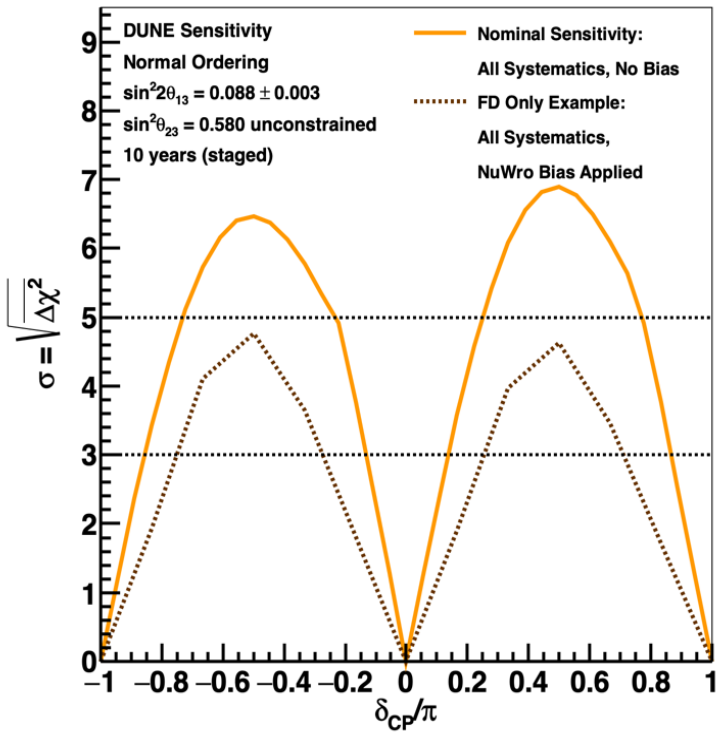


arXiv:2002.03005

- Large bias seen in the oscillation parameters!
- Smaller scale structure of events is clearly important here

Alternative generator model





arXiv:2002.03005

- Moving from the nominal **<u>GENIE</u>** model to **<u>NuWro</u>** varies many aspects of the outgoing particle momentum spectra

- *<u>If uncontrolled</u>* (here, FD-only), taking the induced bias on δ_{CP} as an additional uncertainty degrades the CPV sensitivity

Flux constraints

- The high statistics DUNE-ND environment is well suited to using additional techniques for flux monitoring
- These aren't currently included in the DUNE sensitivity analysis, but are starting to be explored
- An example used by a number of past experiments has been the "low-ν" method:

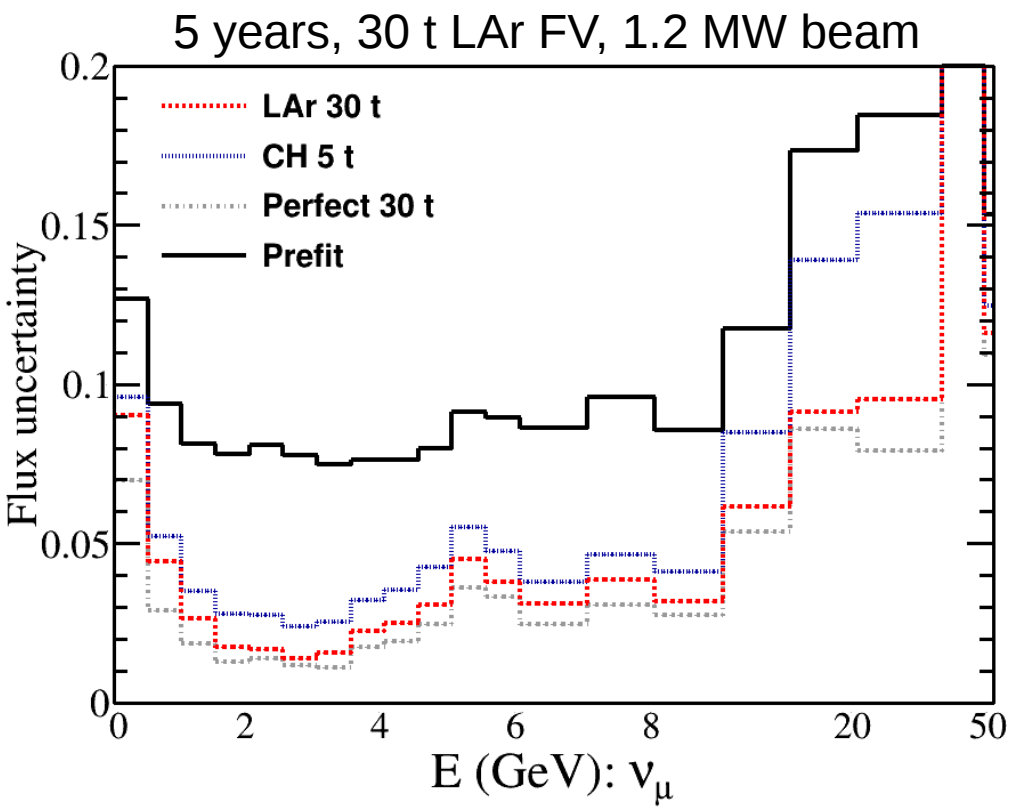
$$\frac{d\sigma}{d\nu} = A + B\frac{\nu}{E} - C\frac{\nu^2}{2E^2}$$

- The inclusive XSEC can be written as above, at low ν/E, the cross section is independent of neutrino energy
- Depends on a good understanding of the low-ν (<100 MeV) response

Neutrino-electron elastic scattering

- The known, but small, cross section can be used to constrain the flux. ~5000 LAr ND events/year
- A powerful additional tool for achieving DUNE's sensitivities, and resolving flux ↔ cross section ambiguities

PRD 101, 032002 (2020)



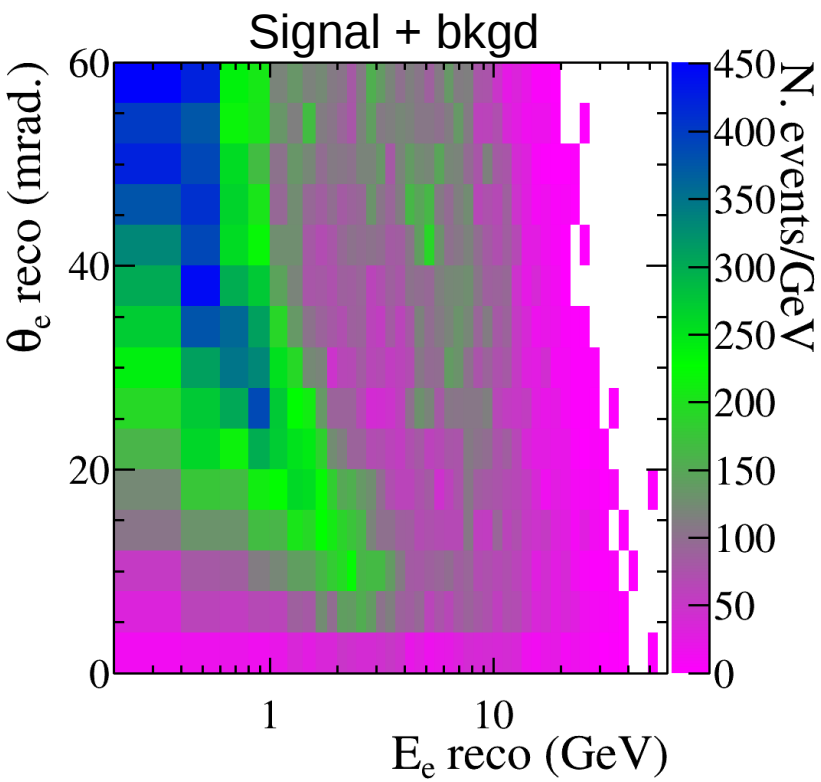
$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}}$$

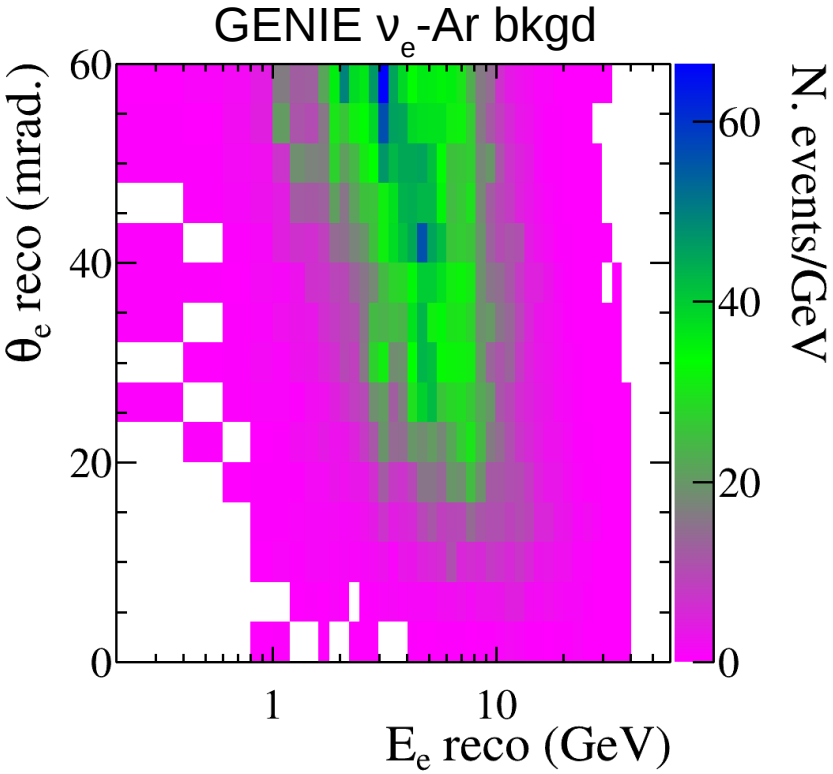
- Strong normalization contraint due to known XSEC
- Weak shape constraint due to detector smearing and beam divergence

Neutrino-electron elastic scattering

- Relatively clean signal of a very forward electron
- Key background from very low-energy transfer ν_e-Ar scattering (also NC1π^0 with a single reconstructed photon)
- Potential for a small region of phase-space to have an oversize impact on the DUNE program

PRD 101, 032002 (2020)





Summary

- Neutrino oscillation physics at DUNE is strongly connected to understanding sub-GeV features of neutrino interactions
- In particular, ~100 MeV scale features of the hadronic system are important. Unclear exactly what the lowest energy features of importance are without further work
- Additionally, low energy transfer events (<100 MeV) are important for various flux monitoring techniques which will be used to further refine the DUNE analysis in the future

Backup

NuFit4 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%

JHEP 01 (2019) 106 [arXiv:1811.05487]

http://www.nu-fit.org/?q=node/177

DUNE staging assumptions

FD event rates are calculated with a nominal deployment plan, based on a technically limited schedule:

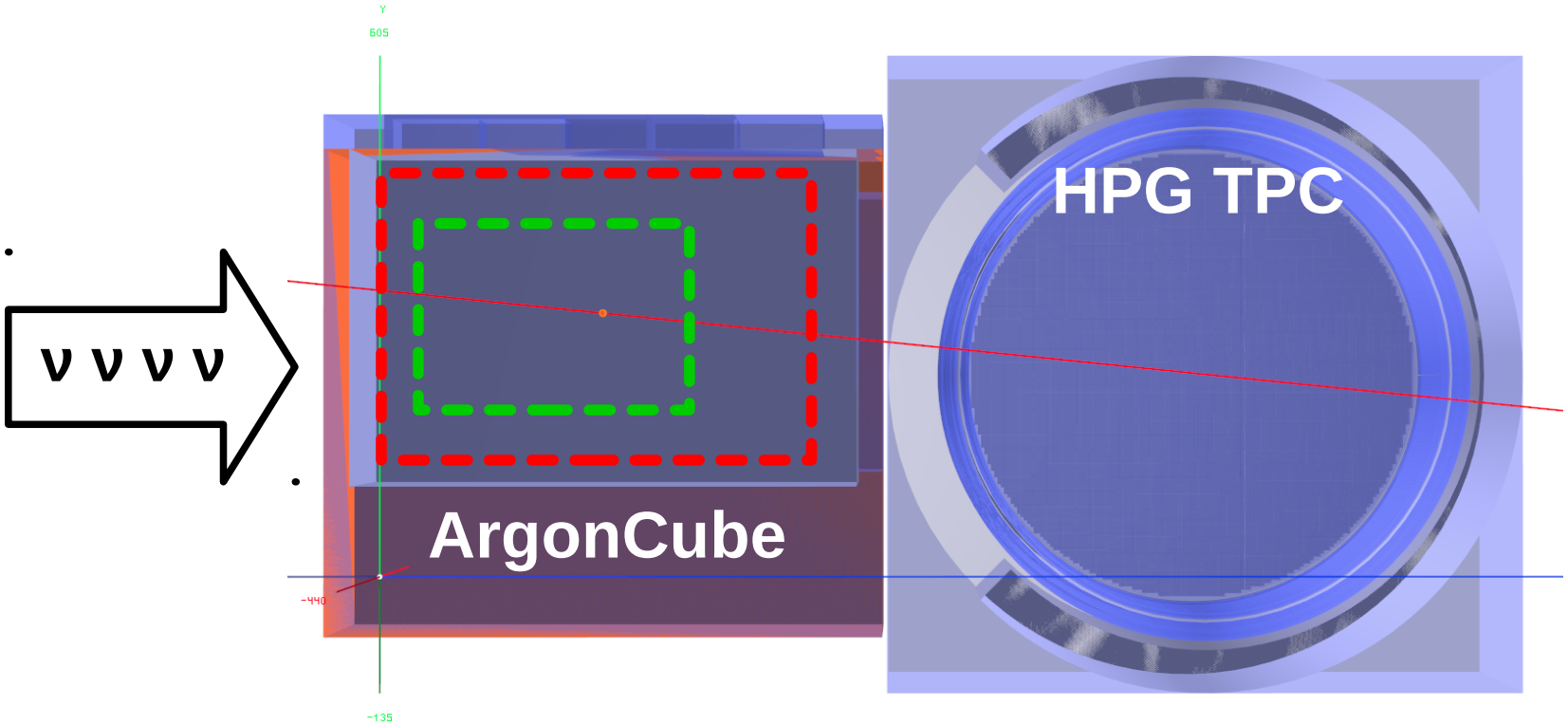
- Beam start: two FD modules with a total fiducial mass of 20 kt, 1.2 MW beam
- +1 year: add one FD module for total fiducial mass of 30 kt
- +3 years: add one FD module for total fiducial mass of 40 kt
- +6 years: upgrade to 2.4 MW beam

Years	kt-MW-years
7	336
10	624
15	1104

Detector systematics

- Energy scale uncertainties for each particle species:
  - Muons 2% (1%) in LAr (exiting downstream in Gar)
  - Protons, pions, 5%
  - EM showers, 5%
  - Visible energy from neutrons, 20%
- Additional energy-dependent energy-scale uncertainties
- Resolution uncertainties, uncorrelated between different particle species
- Additional uncertainty on CC event acceptance for the ND (from variations in muon/hadronic response)

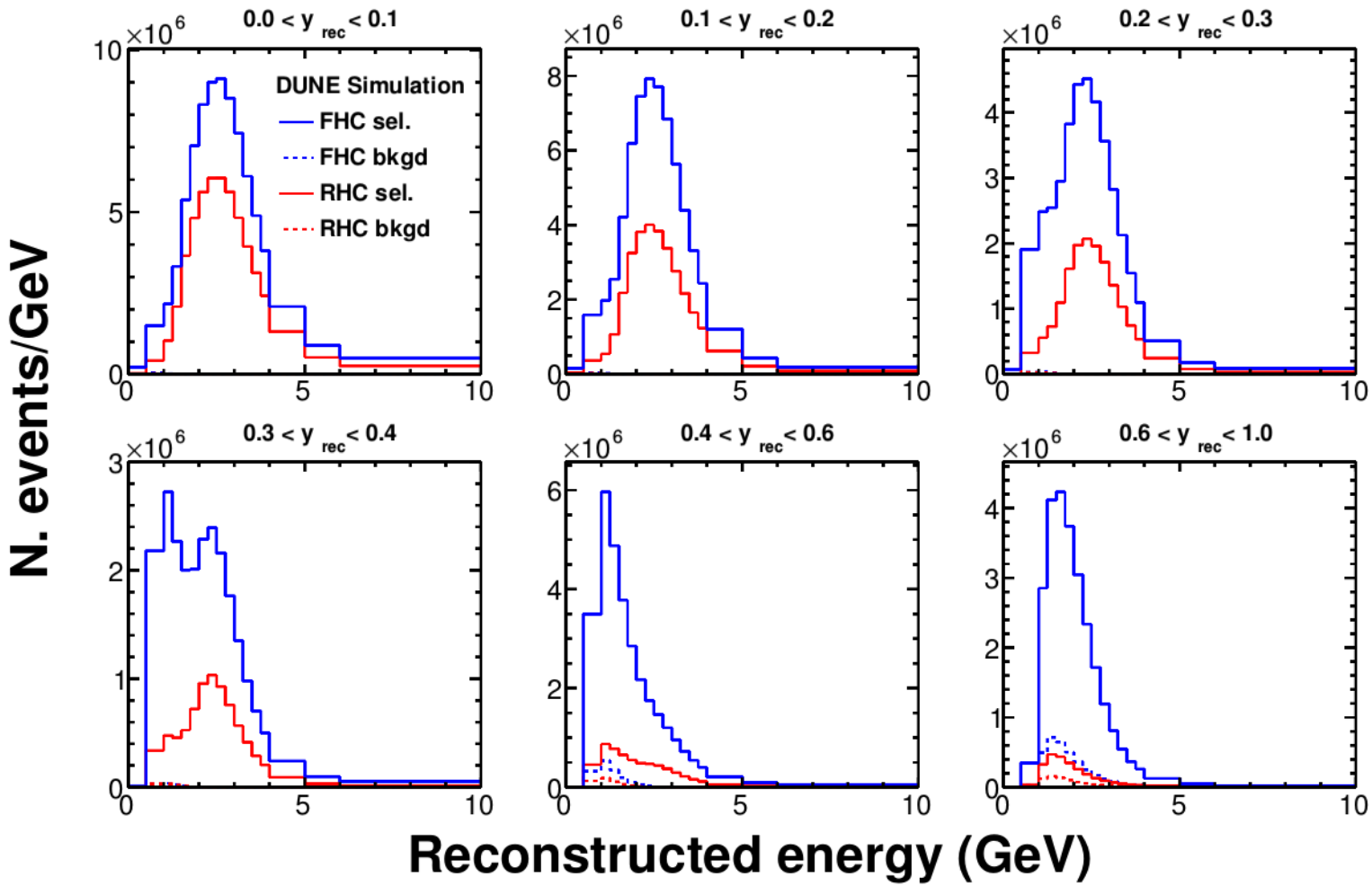
Simplified near detector samples



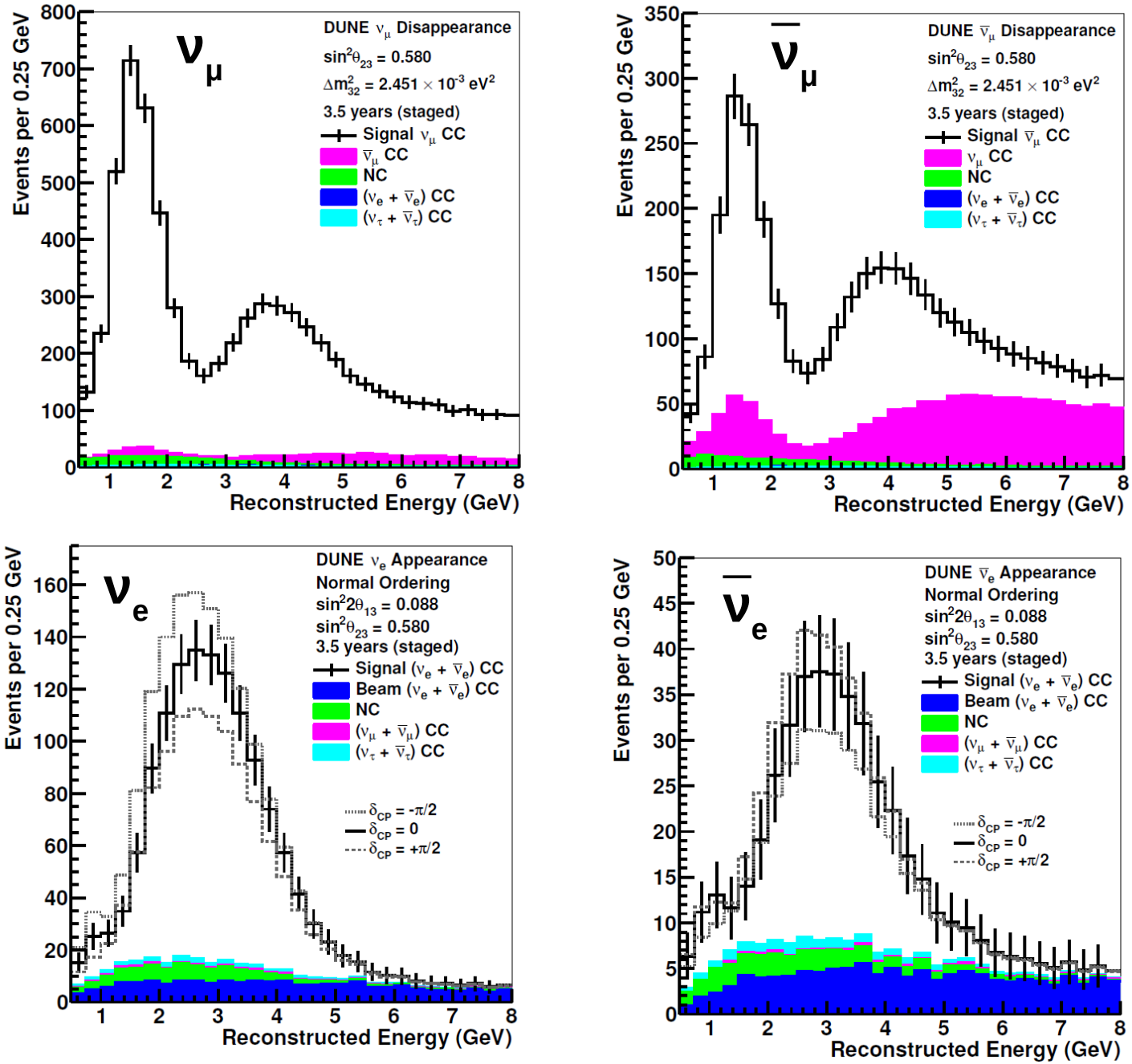
- Simulate events in simplified ArgonCube + HPG TPC geometry
- **Restrictive LAr FV**, require hadronic containment in **large volume**, and muon **contained**, or passing into HPG TPC
- Simplified reconstruction and detector systematics

ND samples (7 years)

$$y_{\mathrm{rec}} = 1 - \frac{E_\mu}{E_{\mathrm{rec}}}$$



Far detector (FD) samples (7 years)



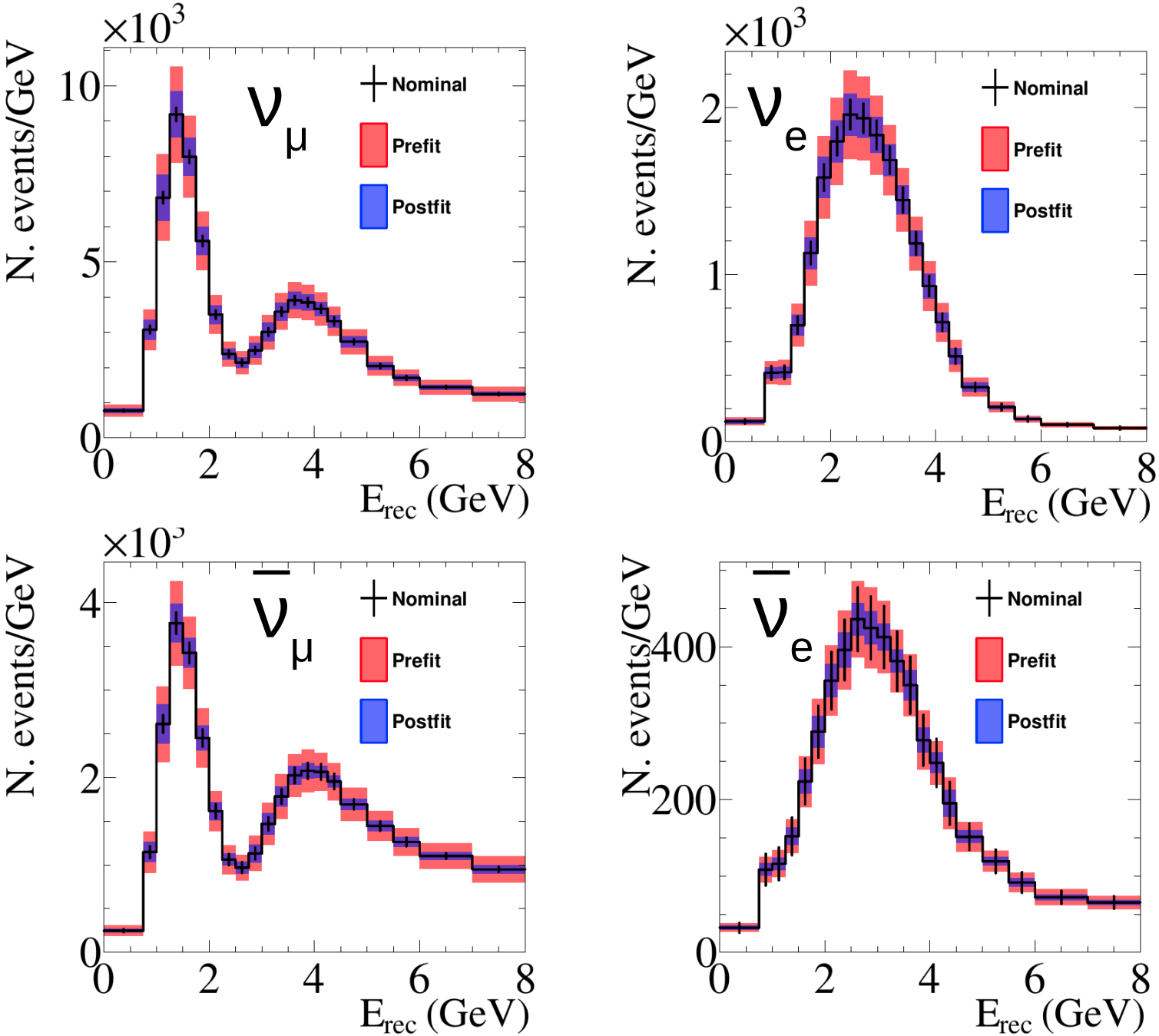
Sample event rates

All numbers for 3.5 FHC + 3.5 RHC year exposures

ND rates:

- FHC: 53.70M events
- RHC: 32.28M events

FD rates (normal hierarchy, $\delta_{CP} = \pi/2$):

- FHC ν_e: 1436 events
- FHC ν_μ: 10839 events
- RHC ν_e: 680 events
- RHC ν_μ: 6553 events

All FD samples (15 years)