Capabilities of the DUNE Near Detector

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on behalf of the DUNE Collaboration

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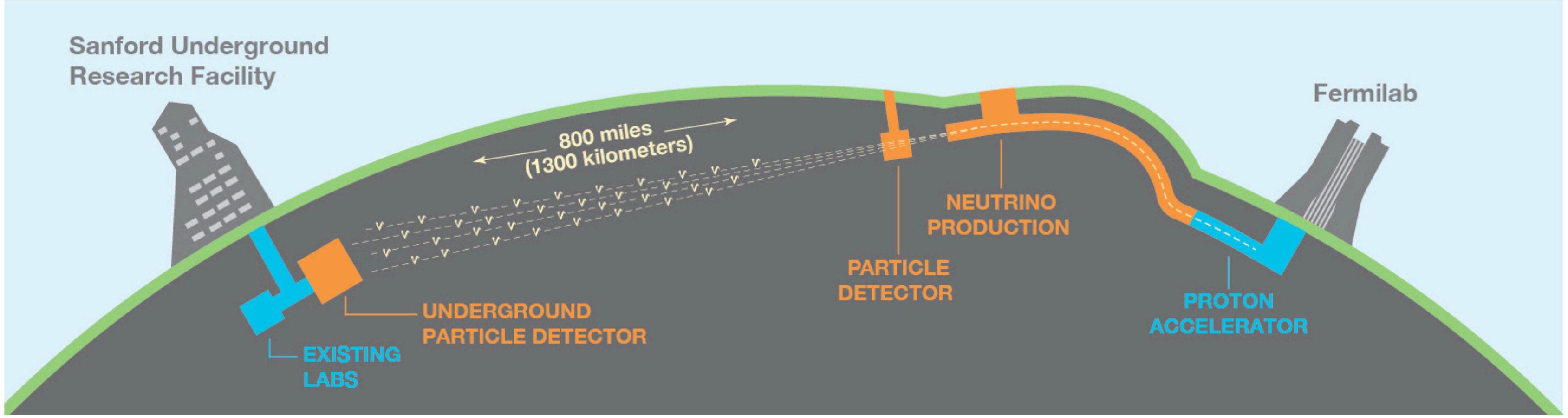
Outline

- Requirements for the DUNE near detector
- Design Concepts
- Integrated Near Detector

Near Detectors and Oscillation Analyses

- Near detector sees beam near source, before significant oscillations.
- Goal is to measure flux and neutrino interactions, and to inform modeling of response of the far detector.
- Near detector rate = $\int$ flux$\otimes$cross-section$\otimes$detector response.
- Detector must provide methods to deconvolve these elements.



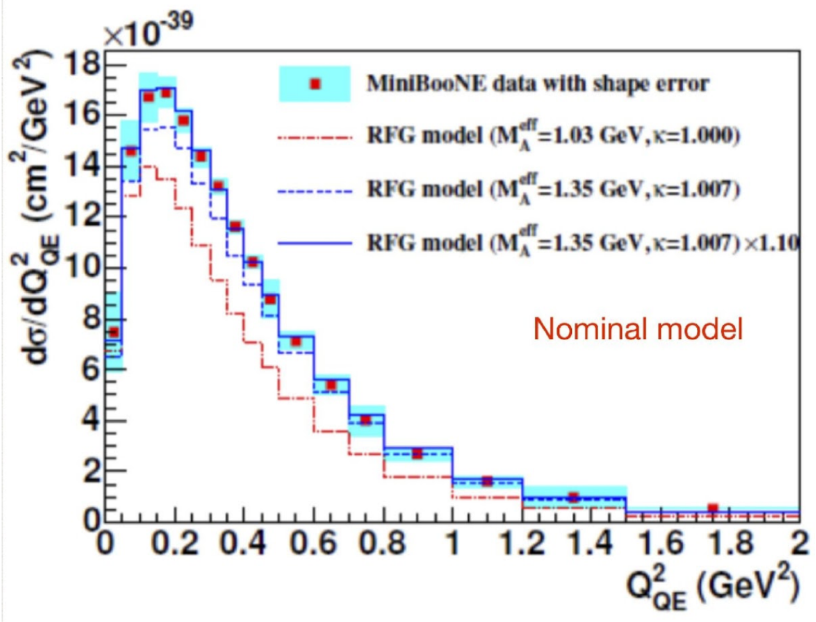
Challenges

- Neutrino flux is difficult to measure.
  - "Standard candle" reactions have been either dim or unreliable.
- Neutrino oscillation probability, $P(\nu_\mu \to \nu_\ell) = \mathcal{F}\left[parameters, \frac{L}{E_\nu}\right]$.
  - The detector measures E_ν from final state particles.
  - But the detector response in ionization to leptons, π^0, protons, π^+, π^-, neutrons, nuclear remnant are all different (rough ordering by visibility).
- Rate at the near detector is much higher than rate at far detector.
  - 1.5M ν_μ CC events/ton/yr at the on-axis location in neutrino beam.
  - LAr readout by drifting ionization in a TPC is a slow detector technology. Pileup of neutrino interactions at near detector is a problem.
- Deconvolution is an ill-posed problem.

Historical (but recent) example of a failure of deconvolution

- MiniBooNE observed a discrepancy in its "CCQE" events vs Q^2.
  - Attributed to axial form factor and Pauli blocking, just an event distortion in Q^2.
  - We understand now this is, at least in part, due to multinucleon production with a different energy-momentum transfer relationship.
- Attributing the difference in form factor meant misreconstructing E_ν.
- Lesson: need multiple observables to diagnose an incorrect deconvolution.

$F_A(Q^2)=F_A(0)/(1+Q^2/M_A^2)^2$



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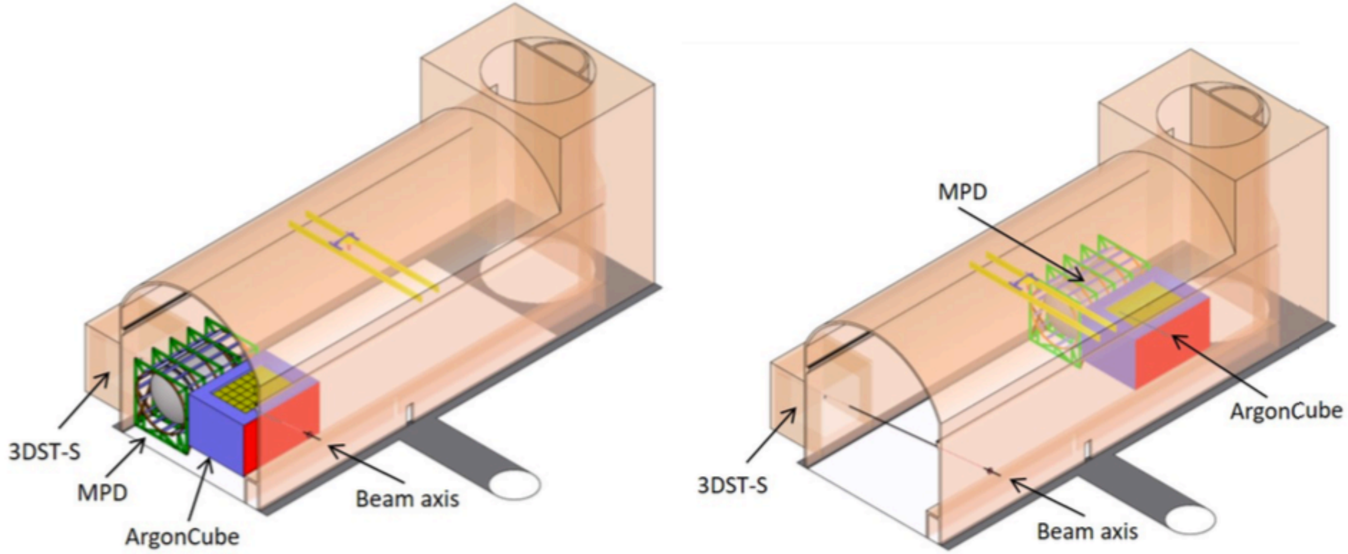
Overview of Near Detector Concept

- Four main components, working together:
  1. Liquid argon detector (ArgonCube)
  2. Downstream tracker with gaseous argon target (MPD)
  3. LAr and GAr systems can move to off-axis fluxes (DUNE PRISM)
  4. On-axis flux monitor with neutron detection capability (3DST-S)

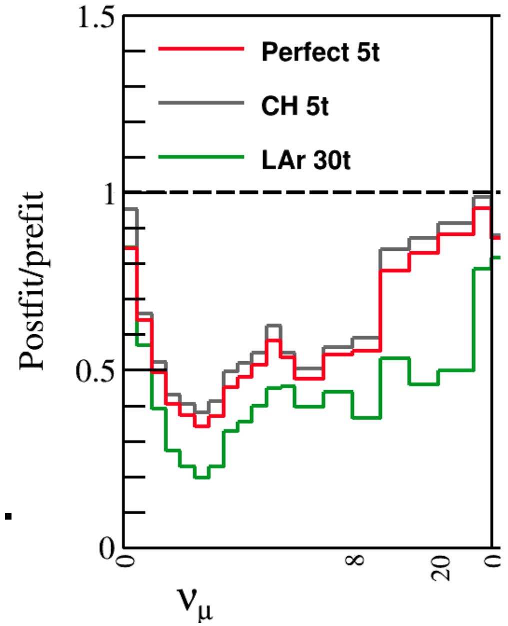


Neutrino Electron Scattering

- $\nu e^- \rightarrow \nu e^-$, cross-section uncertainties below 1% but reaction is only a few parts in 10^4 of total on nuclei.
- Events/year in ν beam
  - Rates sufficient in a LAr TPC (50 ton) for a measurement of total rate to better than 1% (stat).

Detector	LAr TPC	HPg Ar TPC	3D Scint Tracker
$\nu_\mu + e$ (E_e>500 MeV)	6600	130	1100

- Simulated analysis, including leading interaction systematics on backgrounds, shows reduction in flux uncertainties.
  - 8% to 1-2% uncertainties at flux peak
  - Limited, but useful, capacity to probe spectrum.

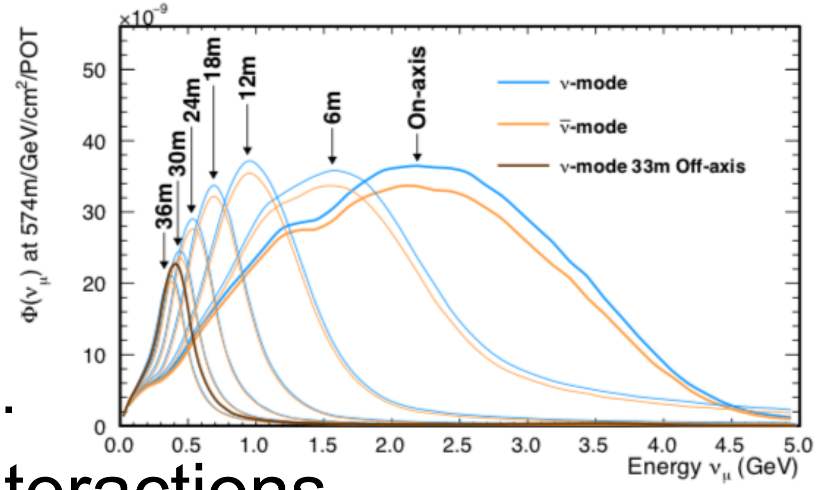


Bins of E_ν

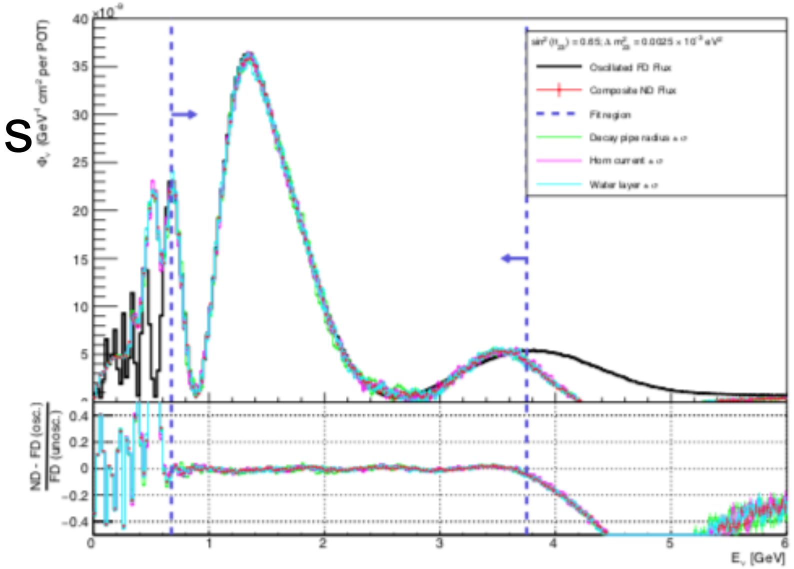
$\nu e^- \rightarrow \nu e^-$ flux constraint previously demonstrated by MINERvA, [Phys. Rev. D 93, 112007](), and [arXiv:1906.00111]()

DUNE PRISM

- If near detector is movable…
- Flux at near detector location varies with transverse position: range of “off axis” fluxes.
  - Exploit this to make a pseudo “monochromatic” beam by combinations of fluxes at different locations.

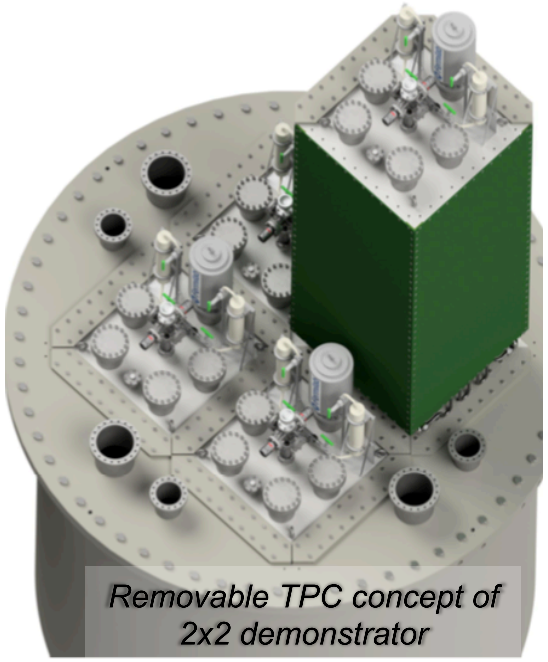


- Monochromatic beam can directly measure interactions vs. true E_ν to understand relationship to reconstructed E_ν^{reco}.
  - One analysis strategy: form directly the expected flux of muon neutrinos after oscillations that should be observed at the far detector.
  - Then measure the observed response and translate to far detector.
  - Interaction model independent, by construction.

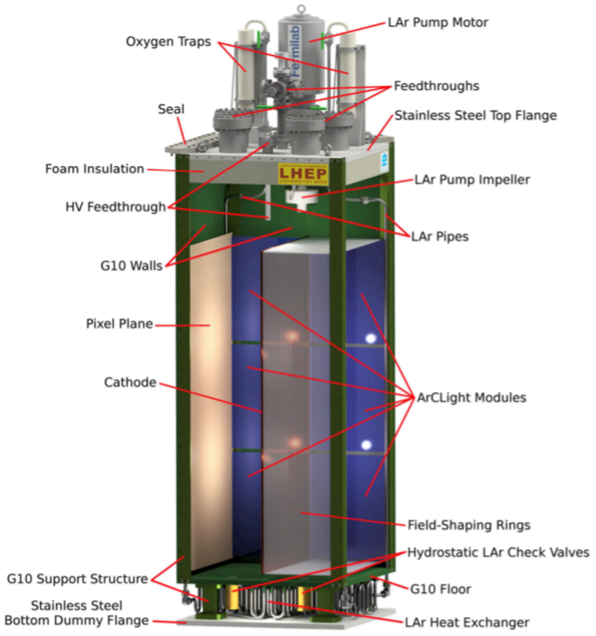


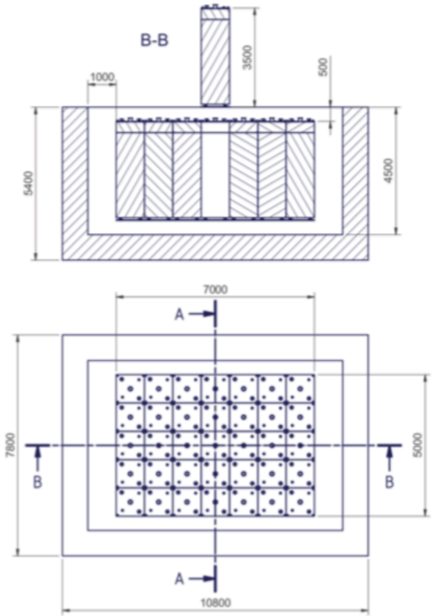
Segmented Liquid Argon (ArgonCube)

- Want a detector as similar as possible to far detector (liquid argon TPC).
  - But TPCs are slow, and neutrino flux is very high. Overlapping events are a problem.
  - Segment TPCs and light collection into $1x1x3m^3$ volumes. Pixel readout of TPC.
  - Minimize material between volumes to allow for continuous event reconstruction.



Removable TPC concept of 2x2 demonstrator

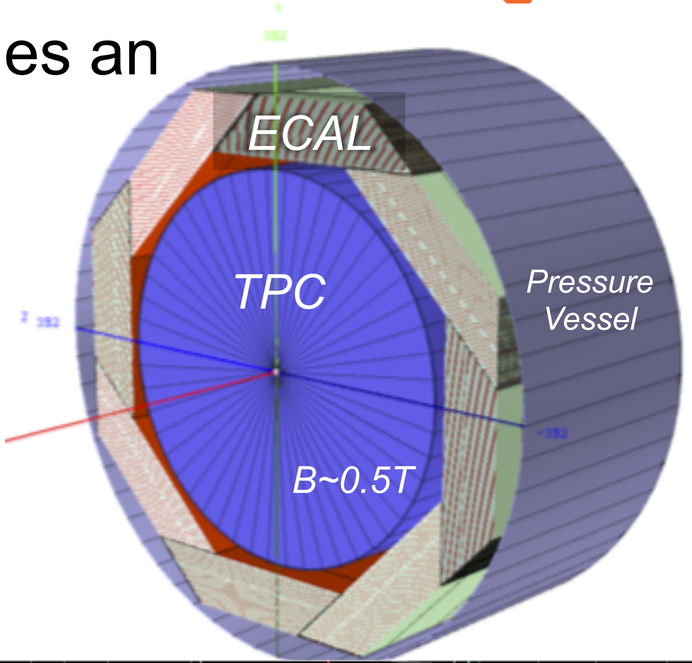


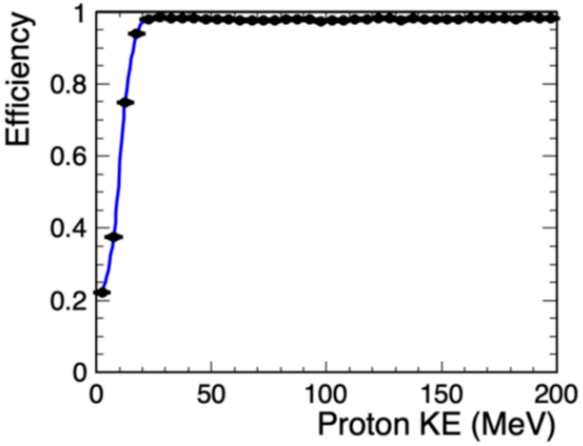


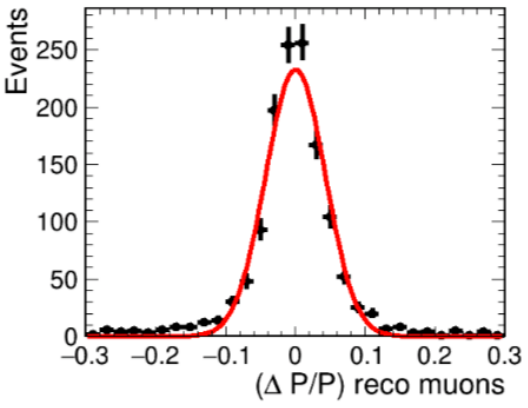
- 5m depth provides good hadronic containment
- 3m height of each TPC
- 7m transverse to beam… more than needed for hadrons, but eliminates need for side-going muon spectrometer.
- 50 ton fiducial volume.
- This design, however, does not contain enough forward muons…

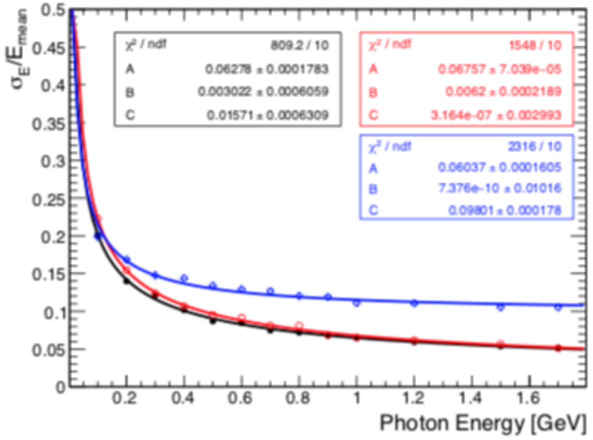
Multi-Purpose Detector (MPD): Gas Tracking in Magnetic Field

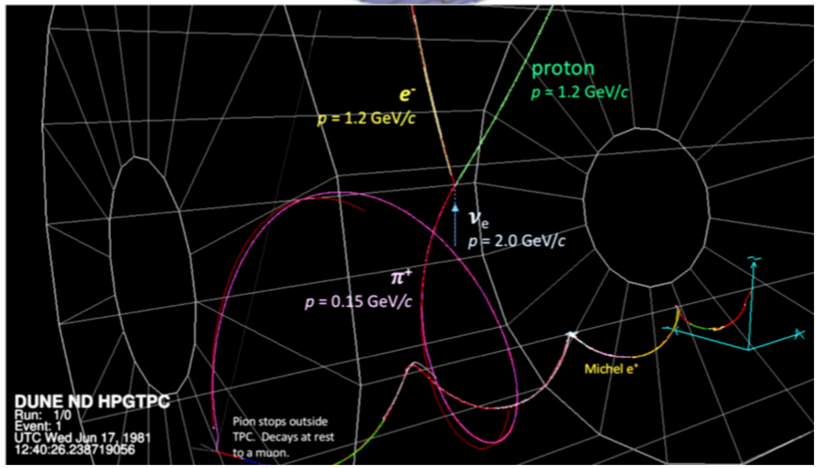
- Accordingly, downstream of ArgonCube the MPD provides an open geometry gas tracker (TPC) in a magnetic field.
  - Combination of two detectors together allows for containment.
- In addition, the TPC gas is 97% Ar. Sample of events from the TPC with improved reconstruction.
  - Requires high pressure (10 atm), and ECAL for detection of $e^{\pm}, \pi^0$.
- 1t fiducial mass, but still 1.5M CC ν_μ events per year.
  - Thresholds much lower than LAr, and $\nu_e/\bar{\nu}_e$ separation.





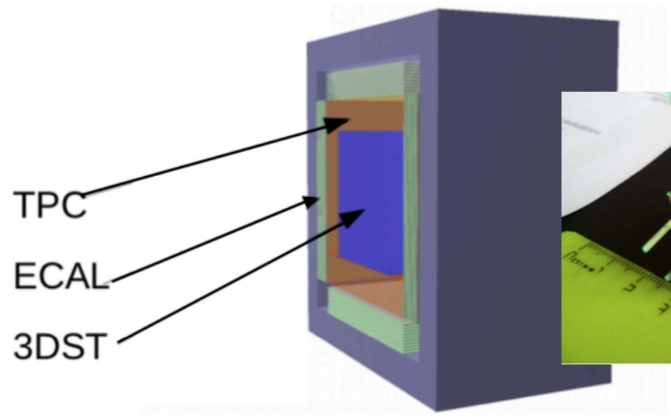


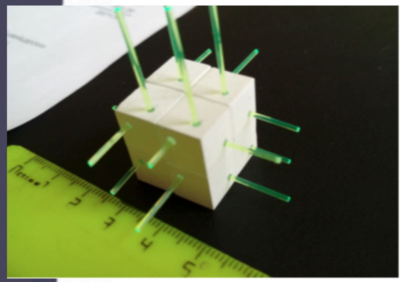


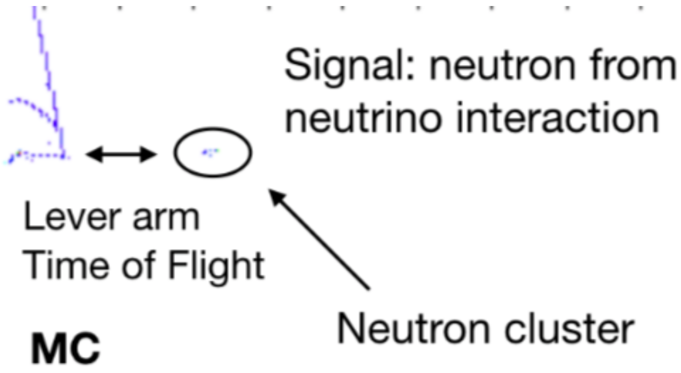


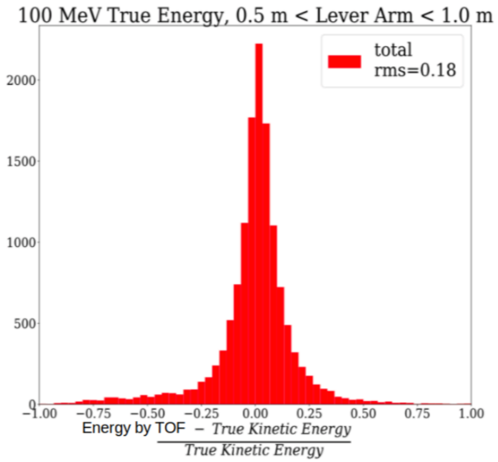
3DST-S: On-axis and neutrons

- Two weakness in movable ArgonCube+MPD
  - Need to monitor beam stability over time as DUNE-PRISM moves.
  - Ar detectors are (largely) blind to neutrons.
- Address with an on-axis (fixed) scintillator detector with magnetized tracking surrounding it.
  - Segmented 1cm^3 scintillator cubes detect proton recoils from fast neutrons.
  - Application of fast neutron measurement builds on data from MINERvA, NOvA, T2K on hydrocarbons, comparison with Ar results from SBN, DUNE.



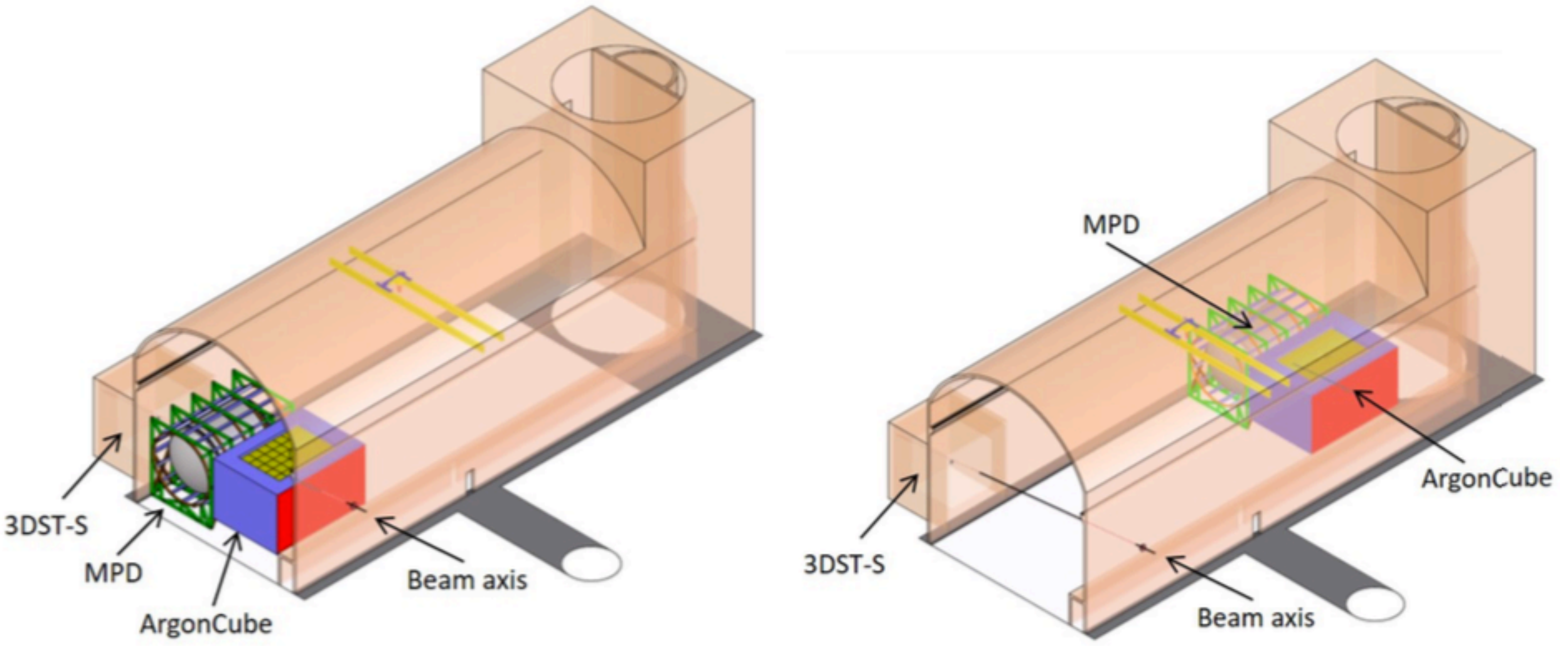






Integrated Near Detector Concept

- Movable ArgonCube (LAr TPC) and MPD require a wide hall to support moving the detector off axis. 3DST-S remains in alcove.
  - Run plan would require significant on-axis running for $\nu e^- \rightarrow \nu e^-$ measurement.



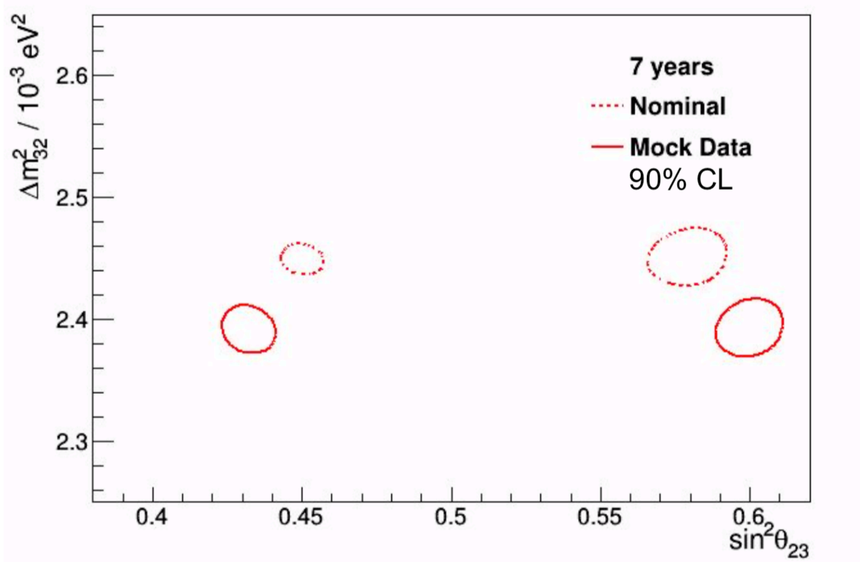
Conclusions

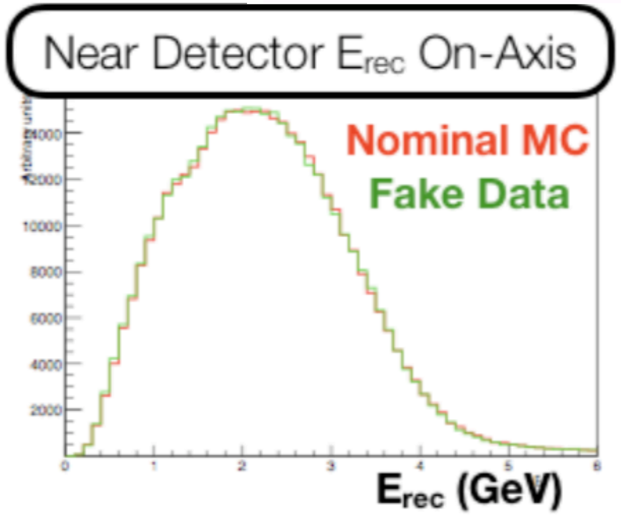
- The DUNE experiment has specified and designed a complex of near detectors to address the needs for the oscillation analysis.
  - Detectors can independently measure flux and cross-section, as a function of energy, through the weak standard candle of $\nu e^- \rightarrow \nu e^-$ and DUNE-PRISM.
  - Detectors measure all individual particles in the final state, except the recoiling nucleus, and their correlations with the leptonic system to build comprehensive interaction models.
- Simulation studies of ND+FD analysis are well underway.
- Prototyping of detectors has begun.
  - Planning for 2x2 ArgonCube demonstrator in NuMI beam now.
  - 3DST-s reuses technology of T2K's "SuperFGD", soon under construction.
  - HPgTPC R&D for MPD ongoing in US, UK, and India.

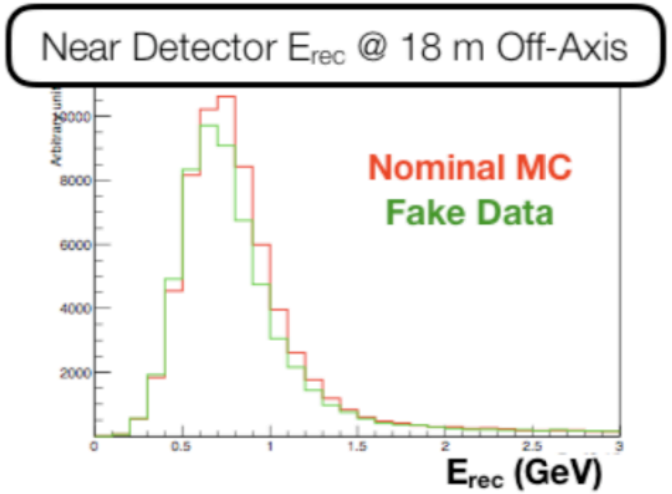
BACKUP

Deconvolution Example

- Can DUNE-PRISM detect a conspiracy?
  - Adjust interaction model so 20% of energy in protons instead appears as neutrons while keeping the visible energy on-axis fixed.
- As expected, oscillation parameters are biased.
- However, change in off-axis visible energy is significant.
  - 3DST would also likely see unexpected neutrons.

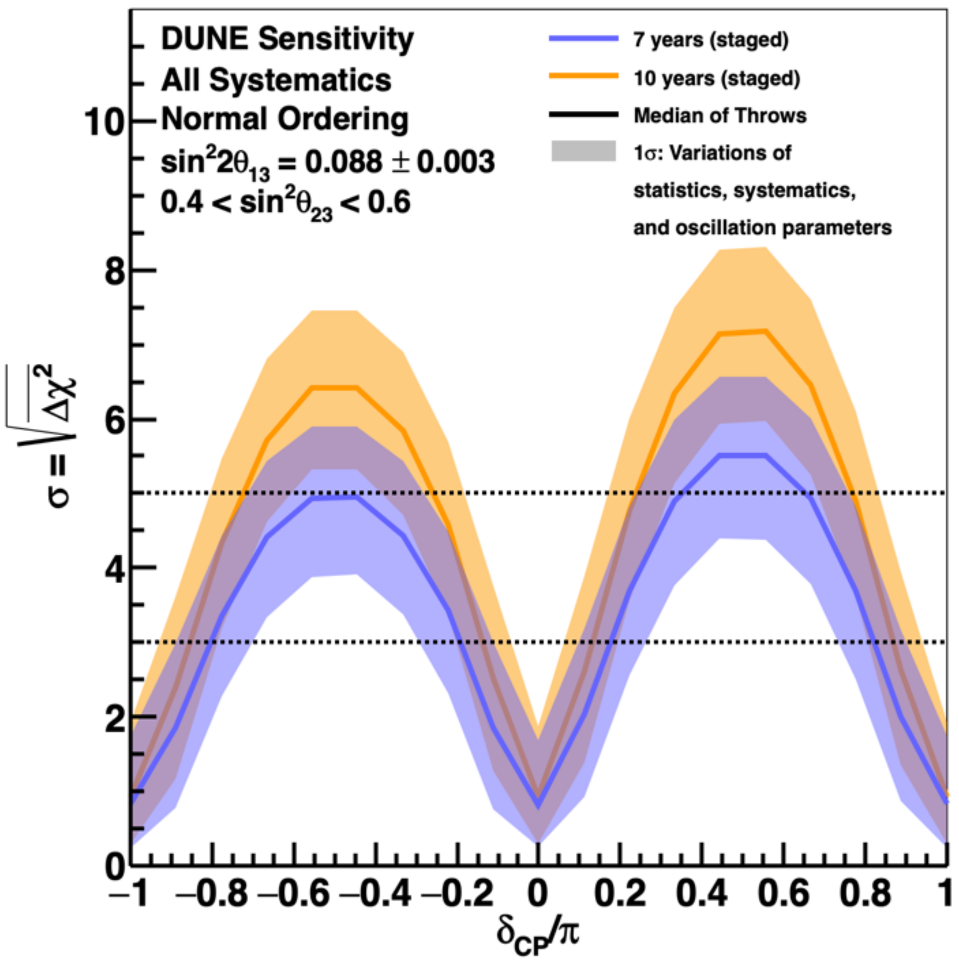




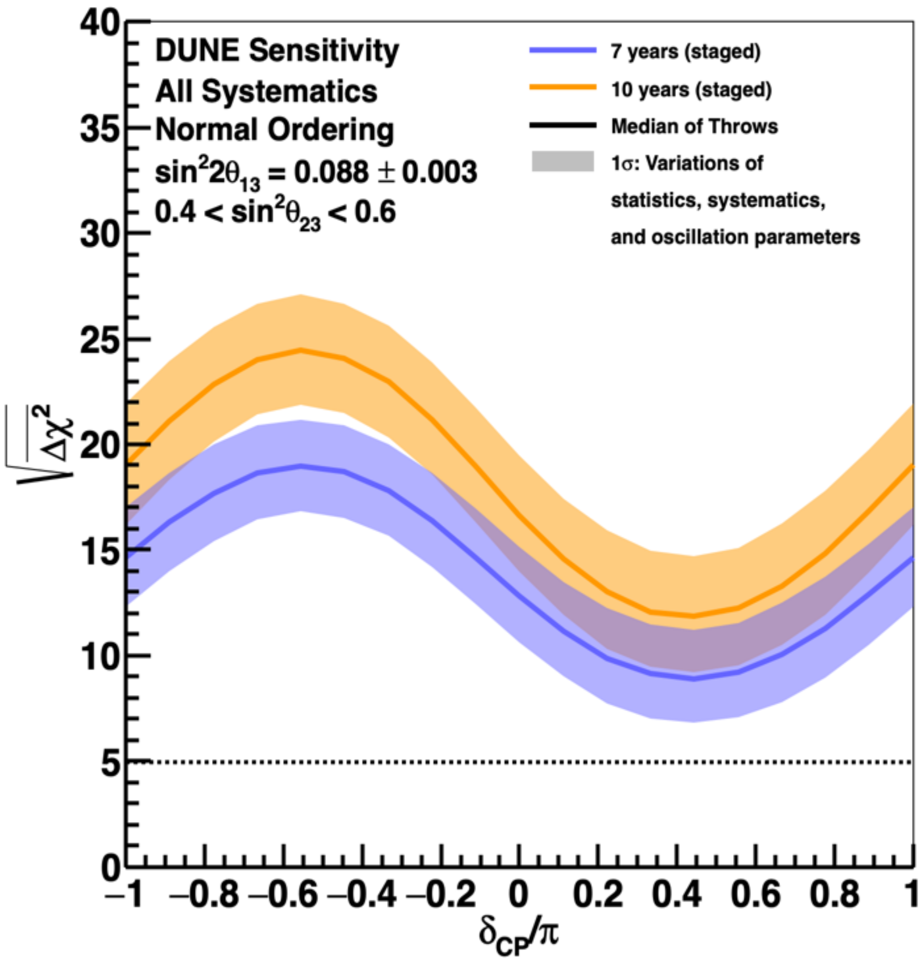


CP Violation and Mass Ordering Sensitivity

CPv sensitivity



Mass ordering sensitivity



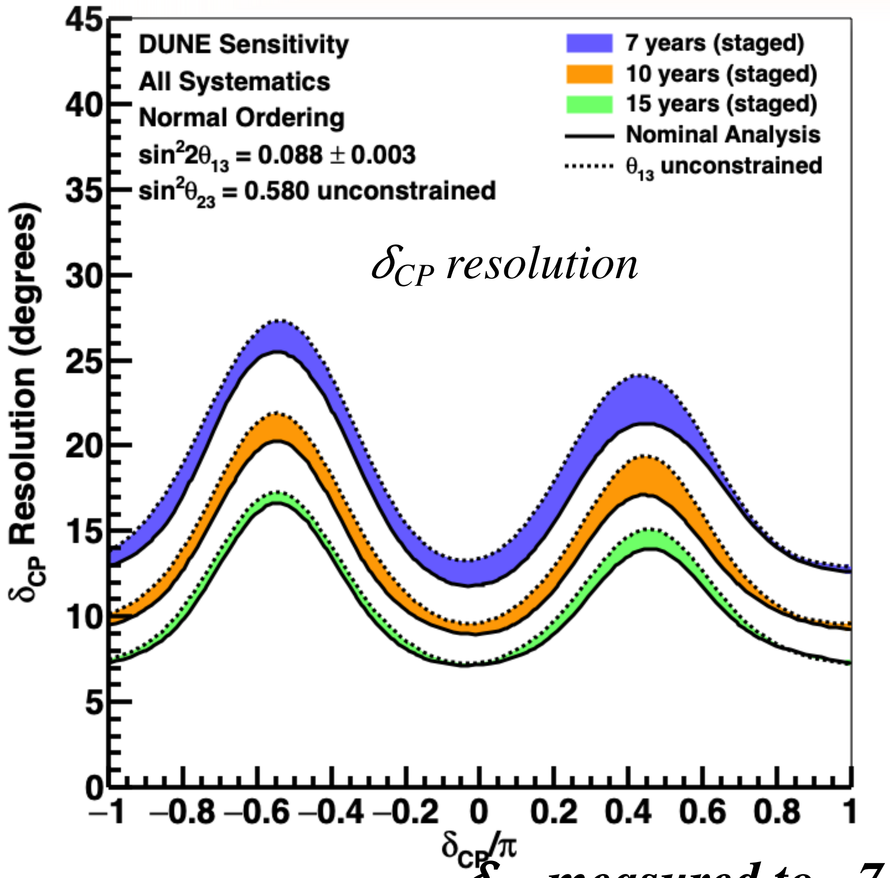
Updated sensitivities!

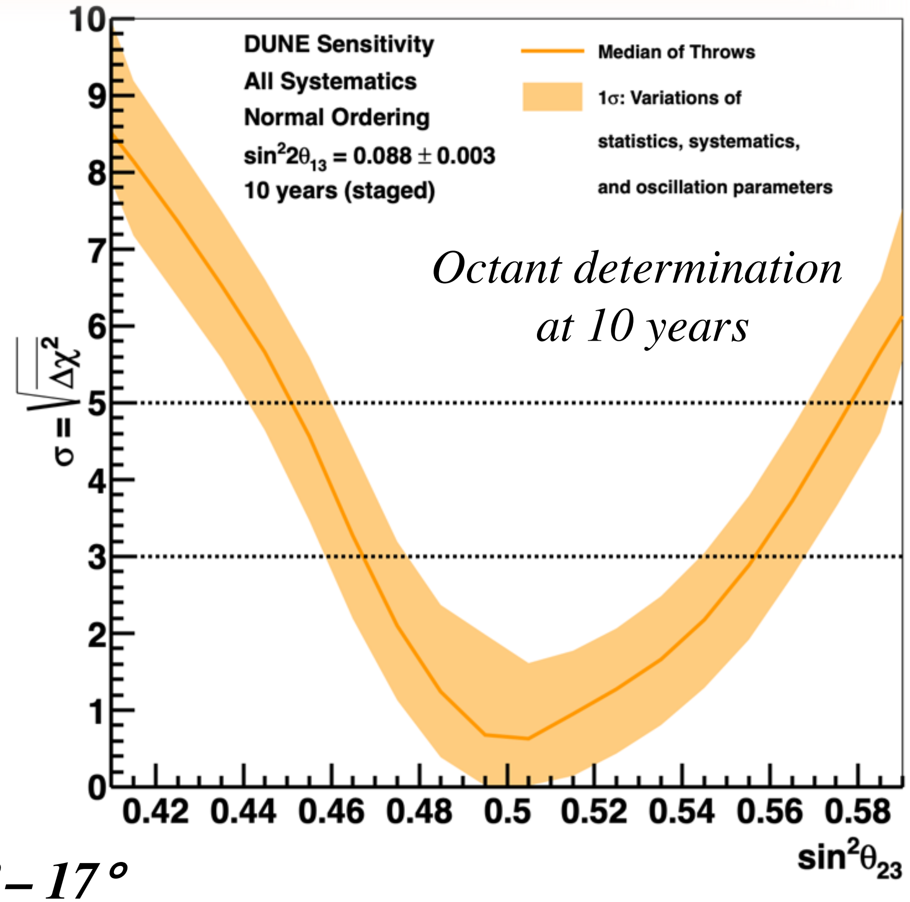
→ *Move quickly to potential* ***CP violation discovery***

→ *Rapid, definitive* ***mass ordering determination >5σ*** *regardless of any other parameter choices*

→ *Relies on Near Detector input*

Precision PMNS





δ_{CP} measured to ~7°– 17°

***>5σ octant determination** possible*

Single-experiment*
precision oscillation measurement!

**solar parameters θ_{12} and Δm^2_{21} are still inputs*