Fermilab accelerator enhancement: DUNE Physics impact

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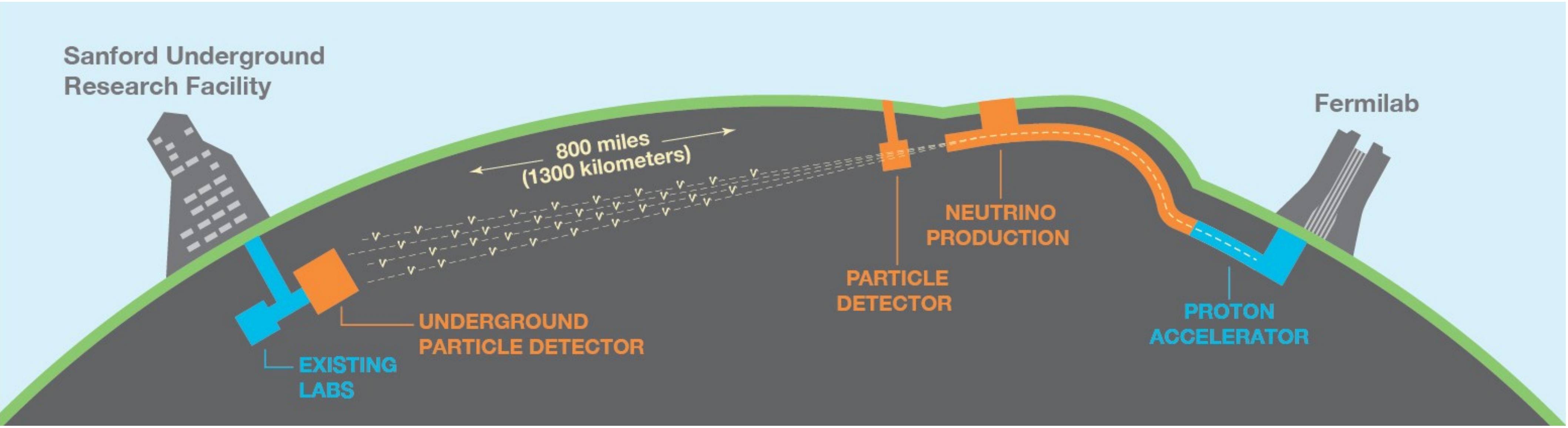
Outline

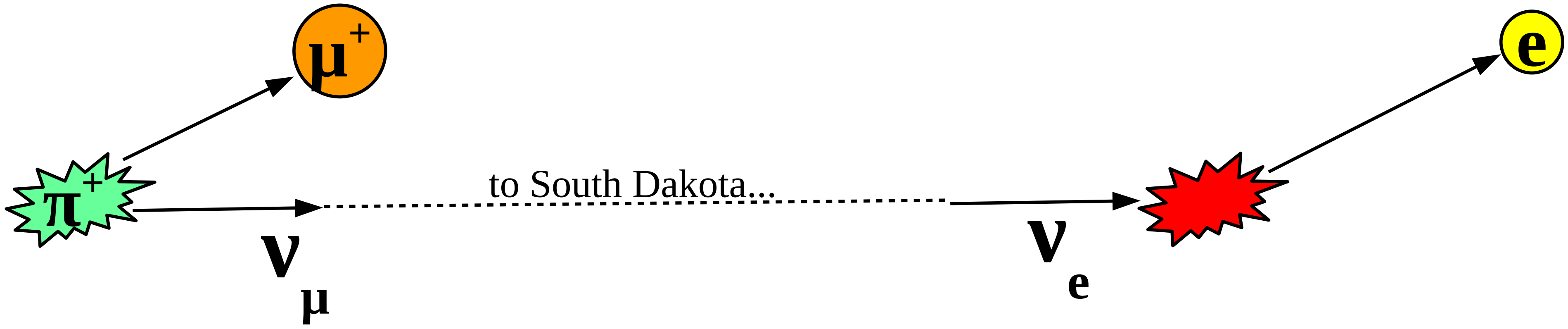
- Introduction: why we want to measure neutrino oscillations, and how we do it
- DUNE oscillation sensitivities, and how “Option 0” would affect physics milestones
- Impact on Near Detector: beam pile-up
- Conclusions: “Option 0” would be very good for DUNE physics

DEEP UNDERGROUND NEUTRINO EXPERIMENT



- Next-generation international neutrino & underground science experiment hosted in the United States (37 countries + CERN)
- **High intensity neutrino beam**, near detector complex at Fermilab
- Large, deep underground LArTPC far detectors at SURF
- Precision neutrino oscillation measurements, MeV-scale neutrino physics, broad program of physics searches beyond the Standard Model

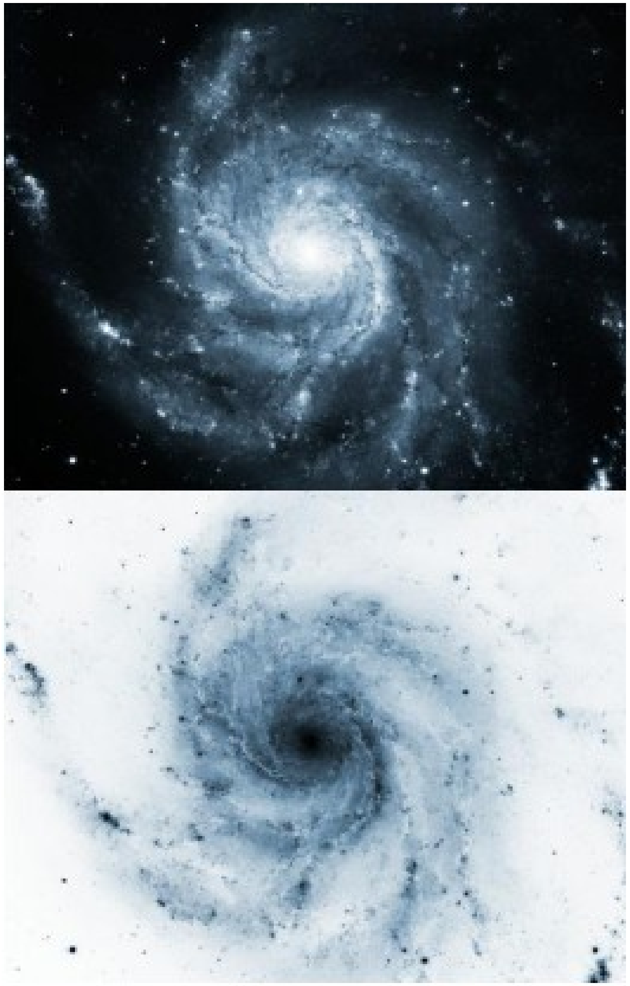
What we do with the beam: measuring neutrino oscillations



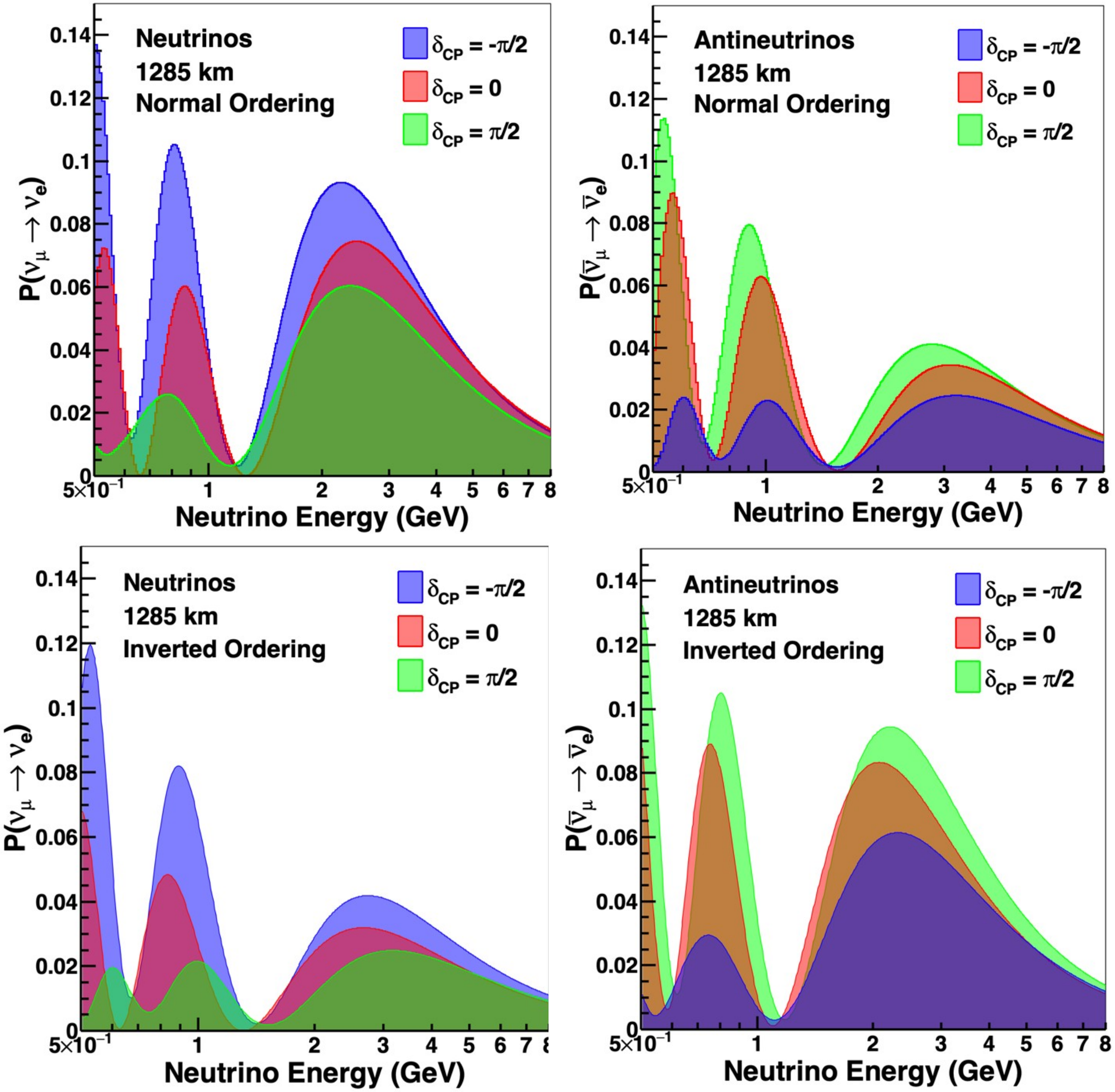
- Produce muon neutrinos at Fermilab, and look for those neutrinos to change flavor en route to South Dakota
- Measure all flavors of neutrino, but especially electron neutrinos, in the Far Detector

Why we measure neutrino oscillations: big open questions

- What is the origin of neutrino mixing? Is there an underlying flavor symmetry, and how is it broken?
- What is the origin of the neutrino masses? Why are the neutrinos so light?
- Is leptogenesis a viable explanation of the baryon asymmetry of the Universe?
- Is the νSM complete? Are there additional neutrinos?

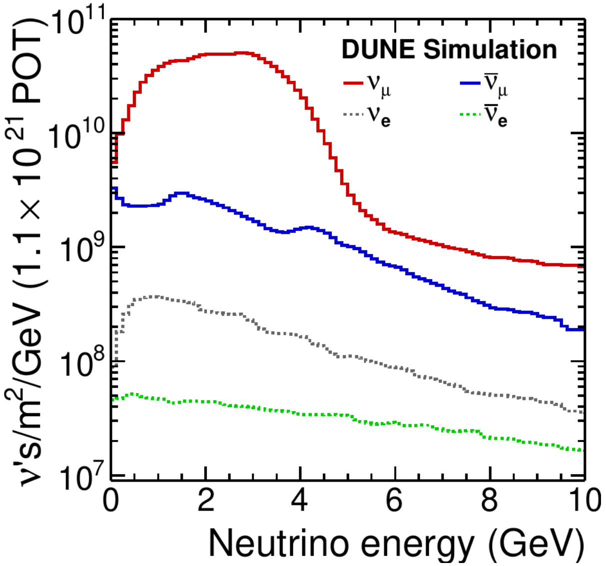


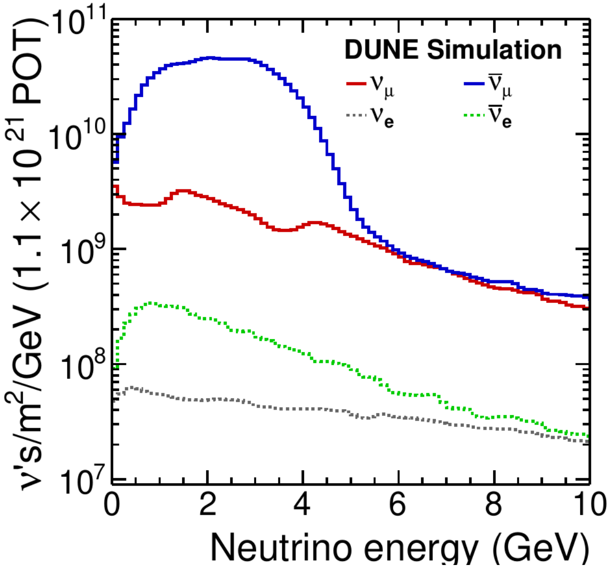
DUNE measures oscillations as a function of energy in broad beam



- DUNE measures $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino energy in a wideband beam, over more than a full oscillation period
- DUNE can simultaneously resolve CP violation, mass ordering, and other parameters, but effects are subtle → requires **very precise measurements**

Key ingredient #1: Very high beam intensity → small stat errors

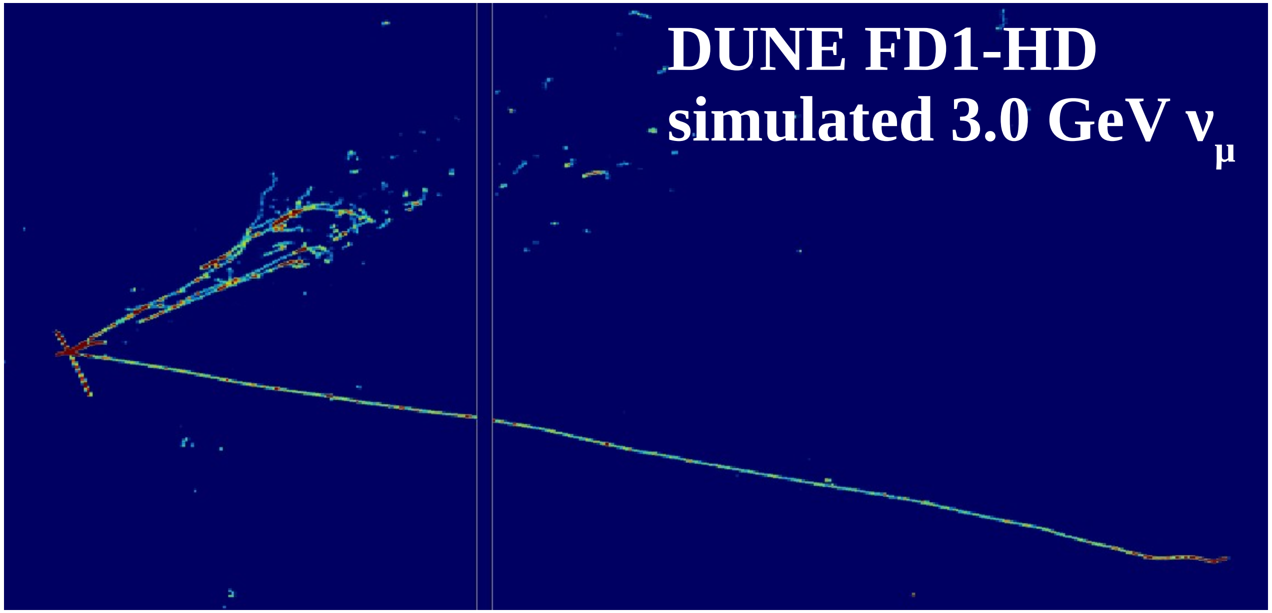


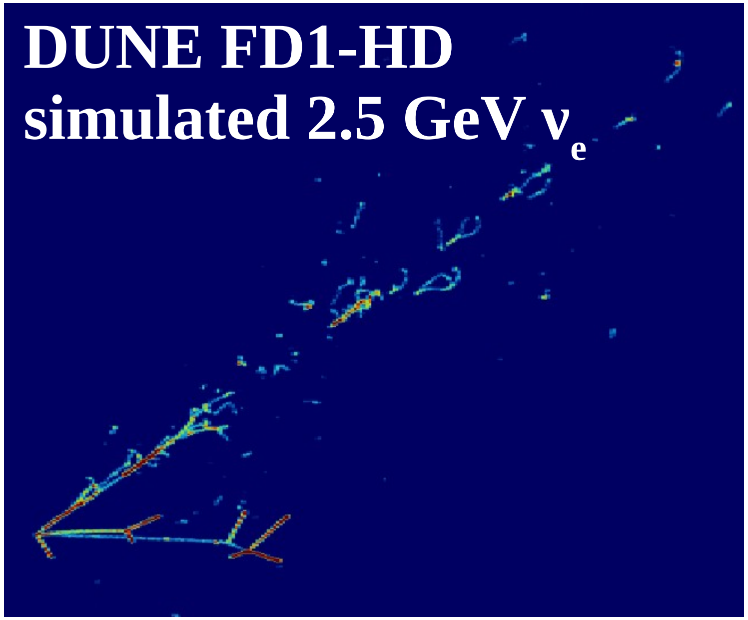


- DUNE's physics goals require thousands of oscillated ν_e at the Far Detector → very high neutrino flux
- Number of neutrinos scales more like power than POT because we get more neutrinos per proton at higher proton energy
- Even with multi-MW intensity, FD observes only one beam neutrino every few hours
- More is better – DUNE wants as much beam power as the accelerator can provide and the target & focusing system can handle

Key ingredient #2: ability to distinguish μ/e, measure energy

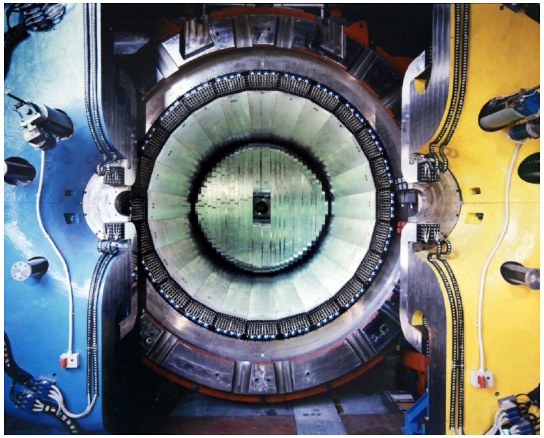
- LArTPC provides clean separation of ν_μ and ν_e charged currents
- Ability to measure both the lepton and the hadronic system → precise energy reconstruction over broad E_ν range
- Also sensitivity to low-energy physics

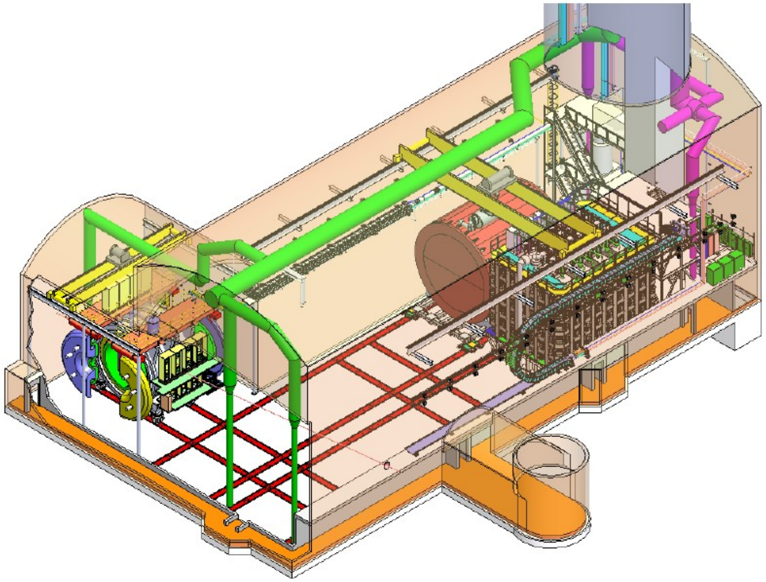


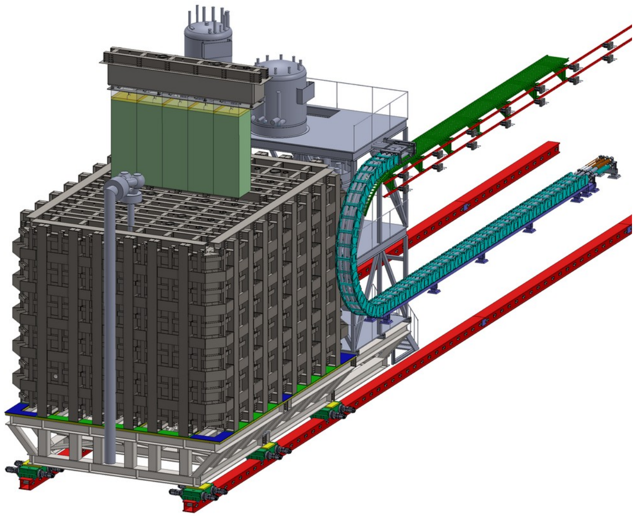


Key ingredient #3: precise systematic constraints from ND

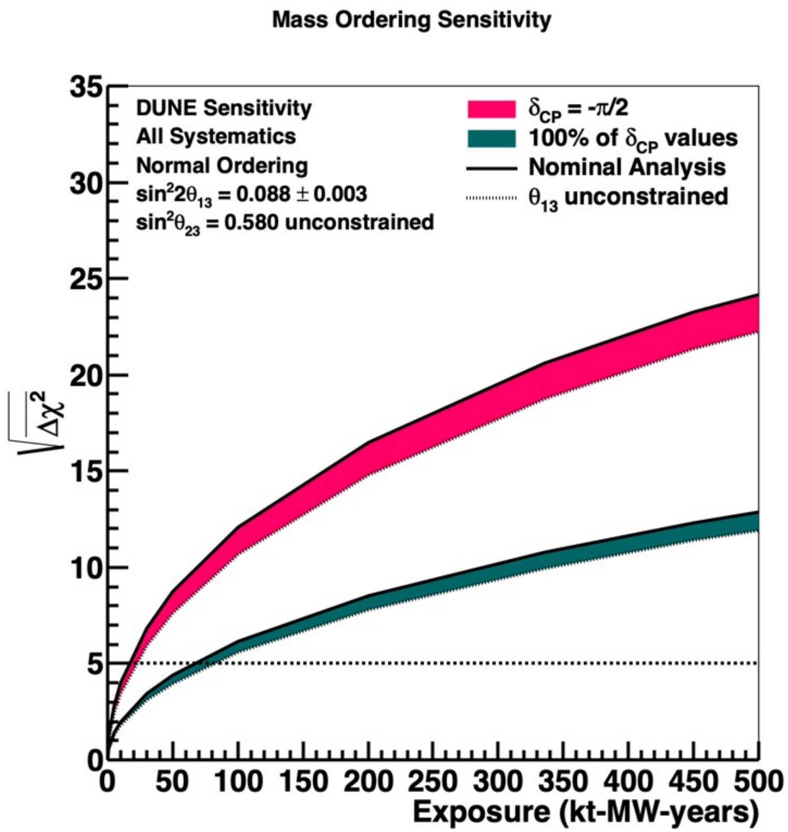
- LArTPC detector: same nuclear target and detector technology near & far
- Movement system to facilitate measurements in different neutrino fluxes
- On-axis magentized low-density tracker and spectrometer

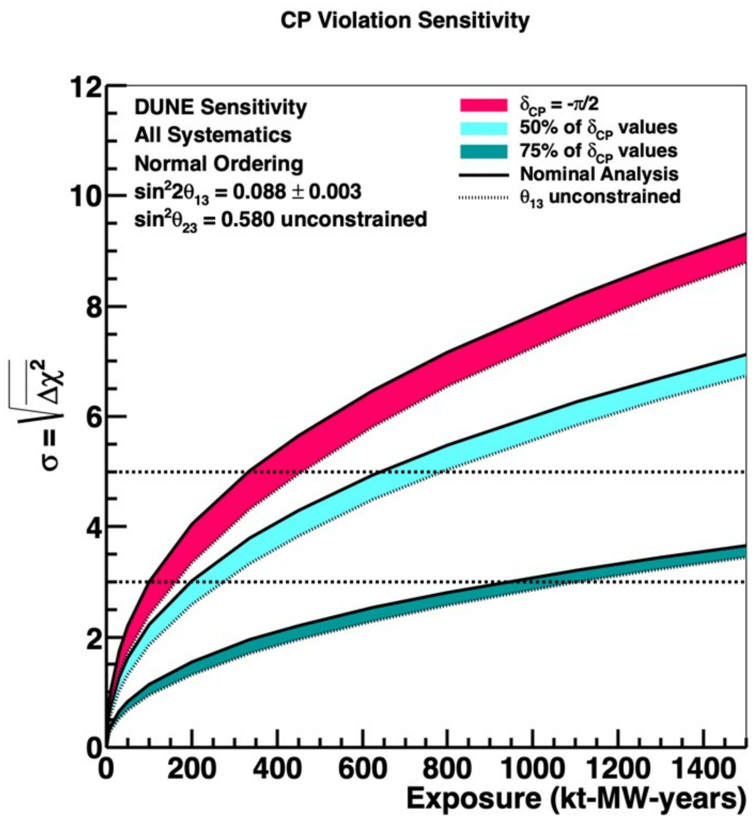






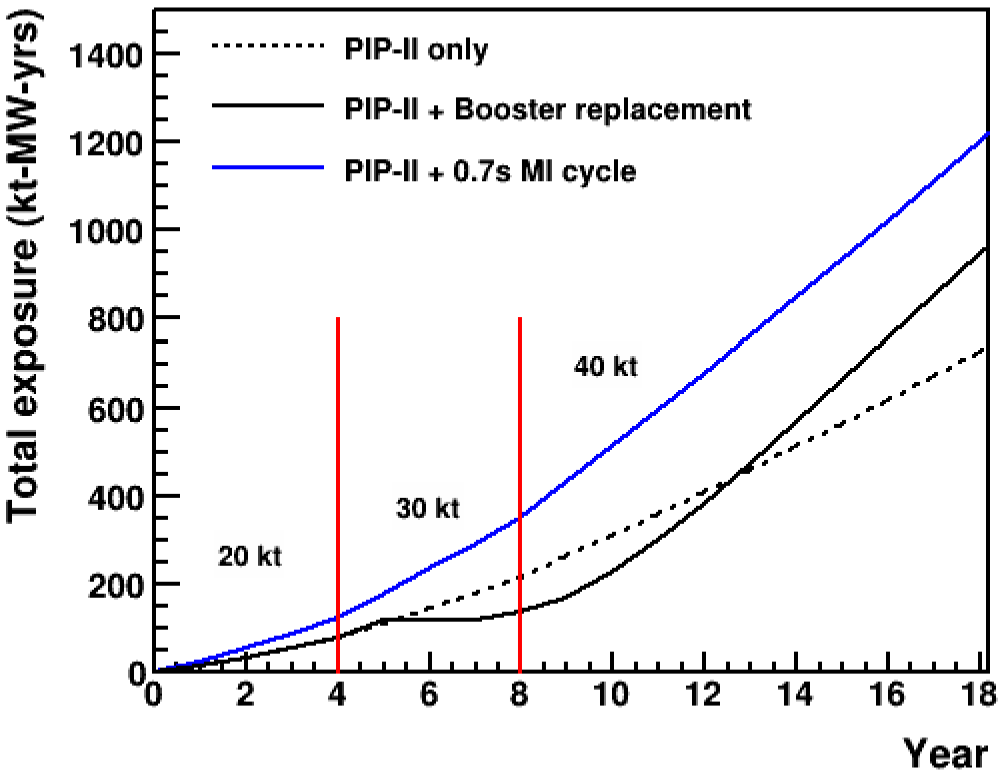
DUNE sensitivities depend on exposure (kt*MW*yrs)





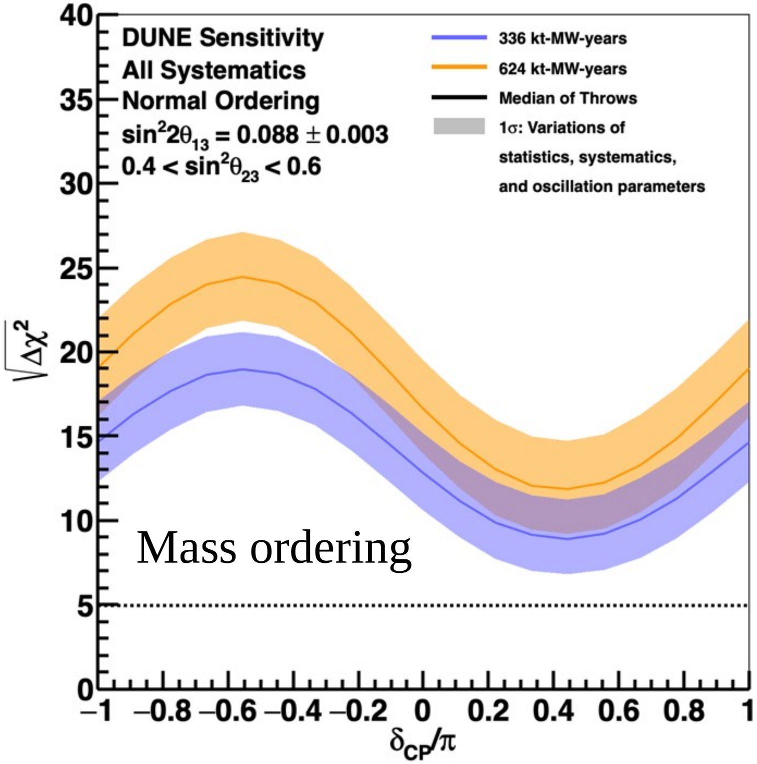
- Because Near Detector constraints are not statistically limited, oscillation sensitivities depend on the total Far Detector exposure
- This assumes a particular beam configuration (120 GeV + focusing system)

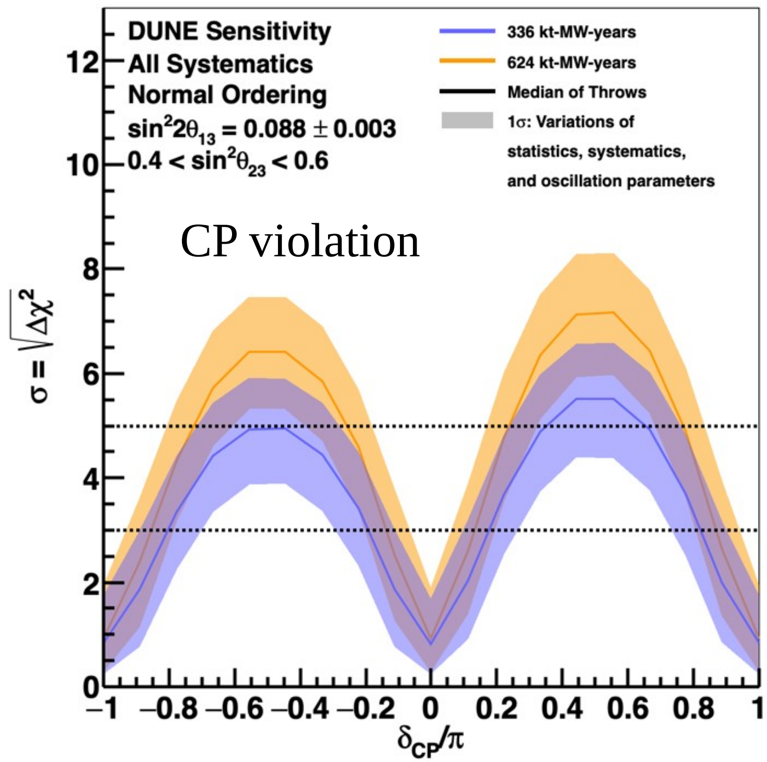
Converting from POT → exposure requires a FD staging scenario



- Blue curve is “option 0”, compared to PIP-II only and Booster replacement scenarios
- For this plot, we assume 20 kt initially (Phase I; 2 FD modules), additional 10 kt module in year 4 and year 8
- One can already see that “Option 0” will be beneficial for DUNE physics compared to alternatives – we see a higher integrated exposure throughout the run

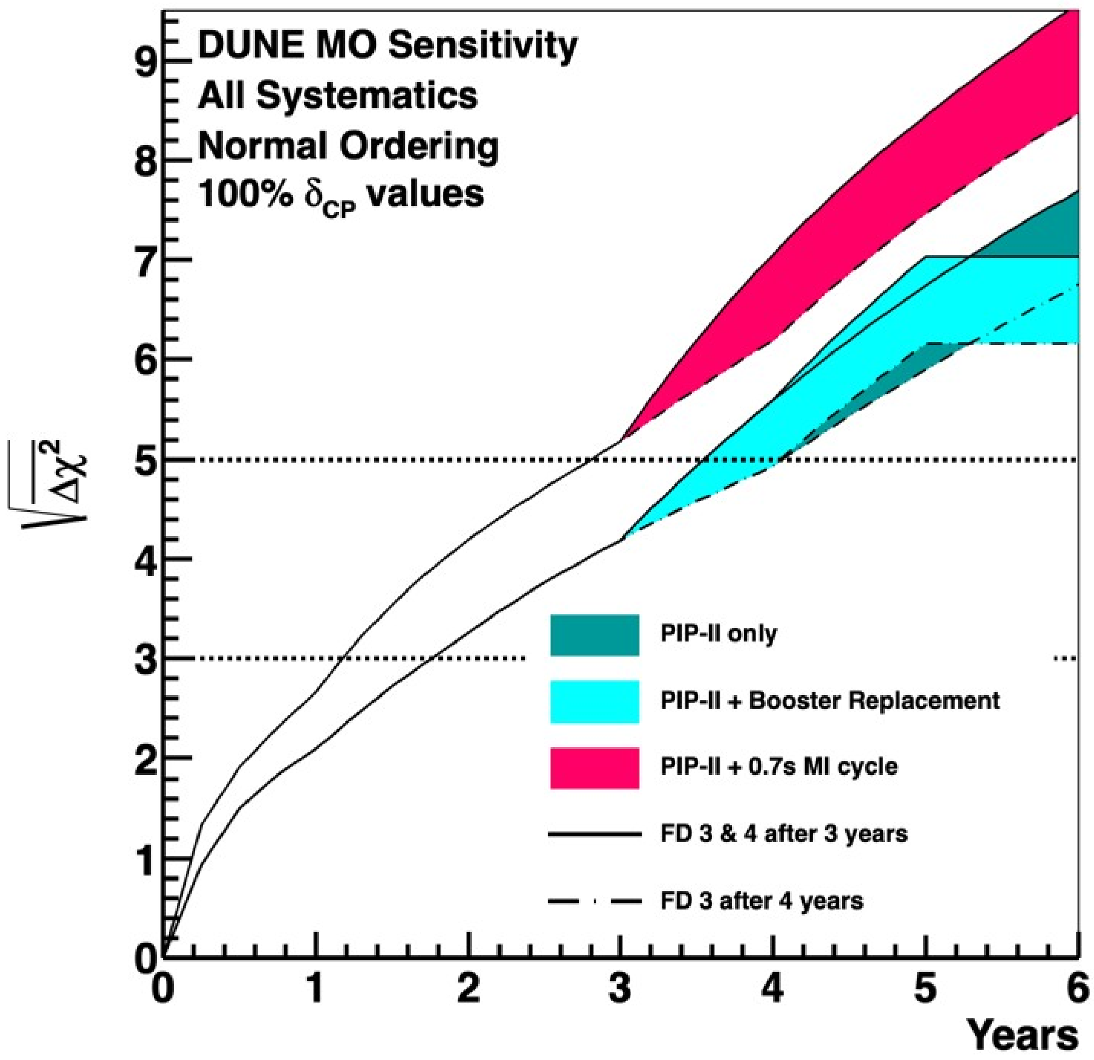
Oscillation sensitivities depend strongly on what nature gives us





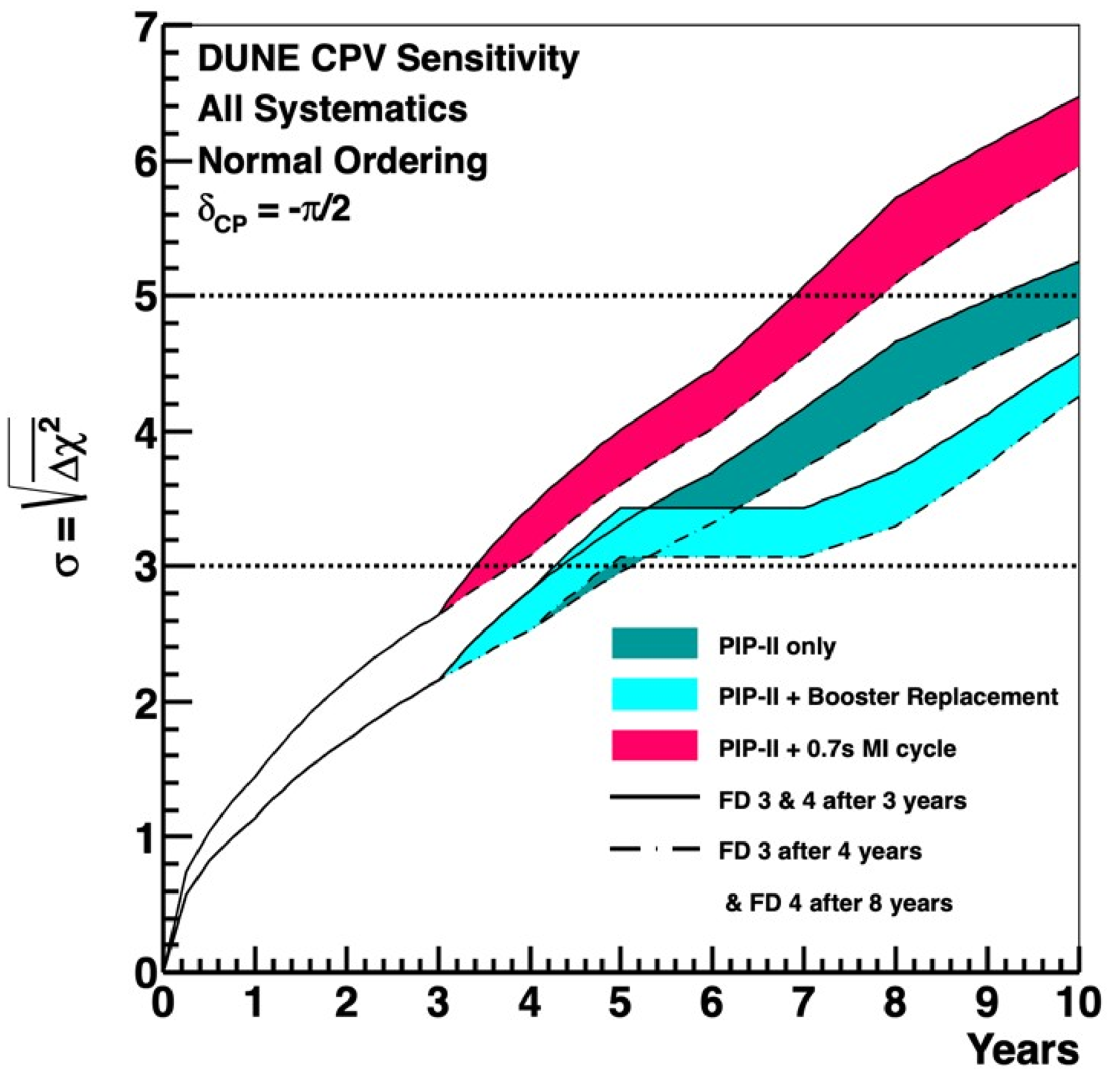
- It is easier to establish CP violation if the effect is large, and easier to determine the mass ordering if the asymmetries due to CPV and MO go in the same direction
- Bands represent variations due to other parameters; median sensitivities shown in upcoming slides comparing different beamline scenarios
- DUNE’s strength is its ability to make these measurements **even if nature is unkind**

Mass ordering sensitivity with updated beamline scenarios



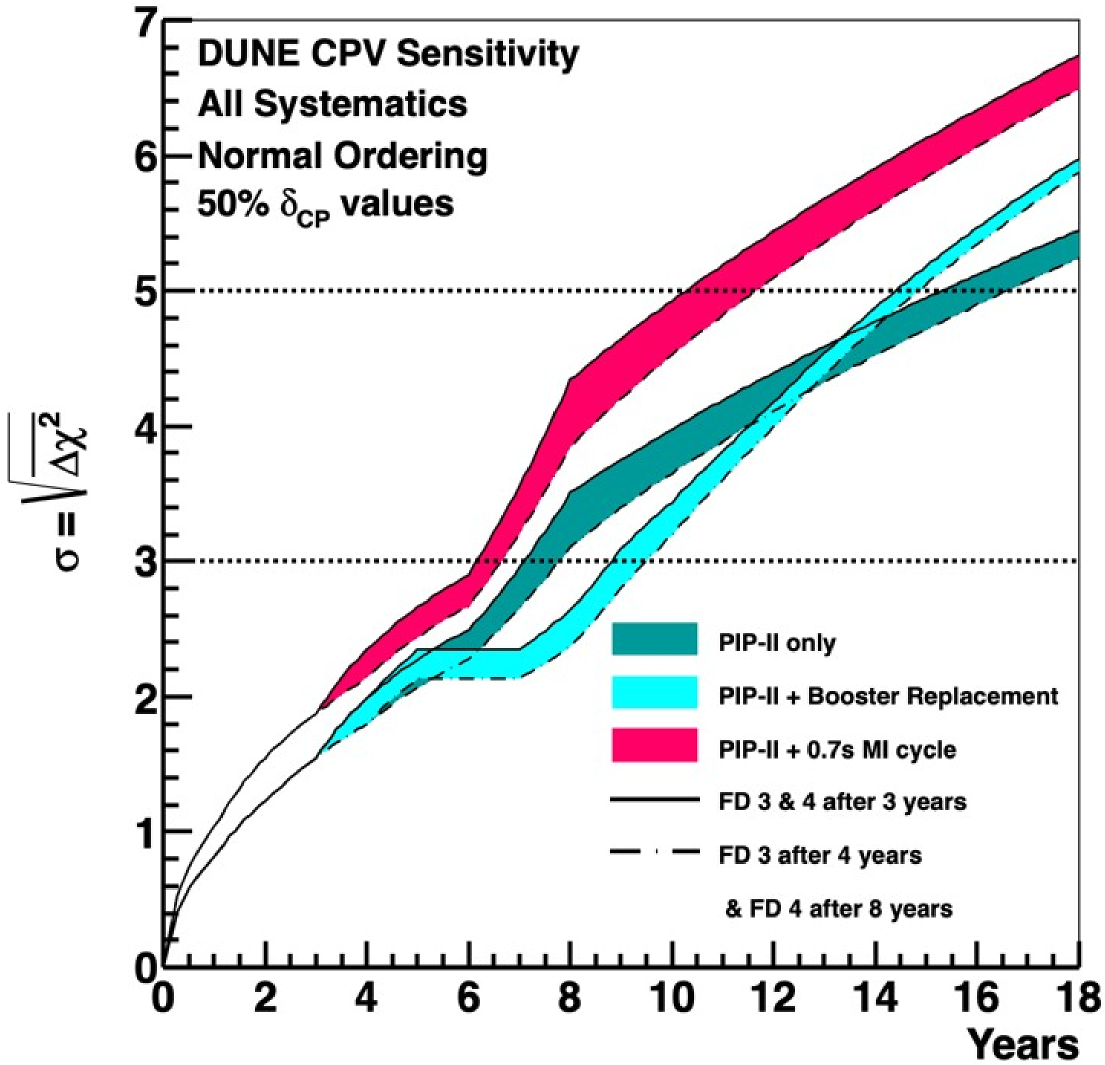
- Band corresponds to different FD staging scenarios
- This is shown for the **worst case** scenario in other oscillation parameters
- **DUNE determines the mass ordering at >5σ in Phase I no matter what**
- Option 0 pushes milestones earlier by ~1 year

CP violation sensitivity for maximal CPV (easiest case)



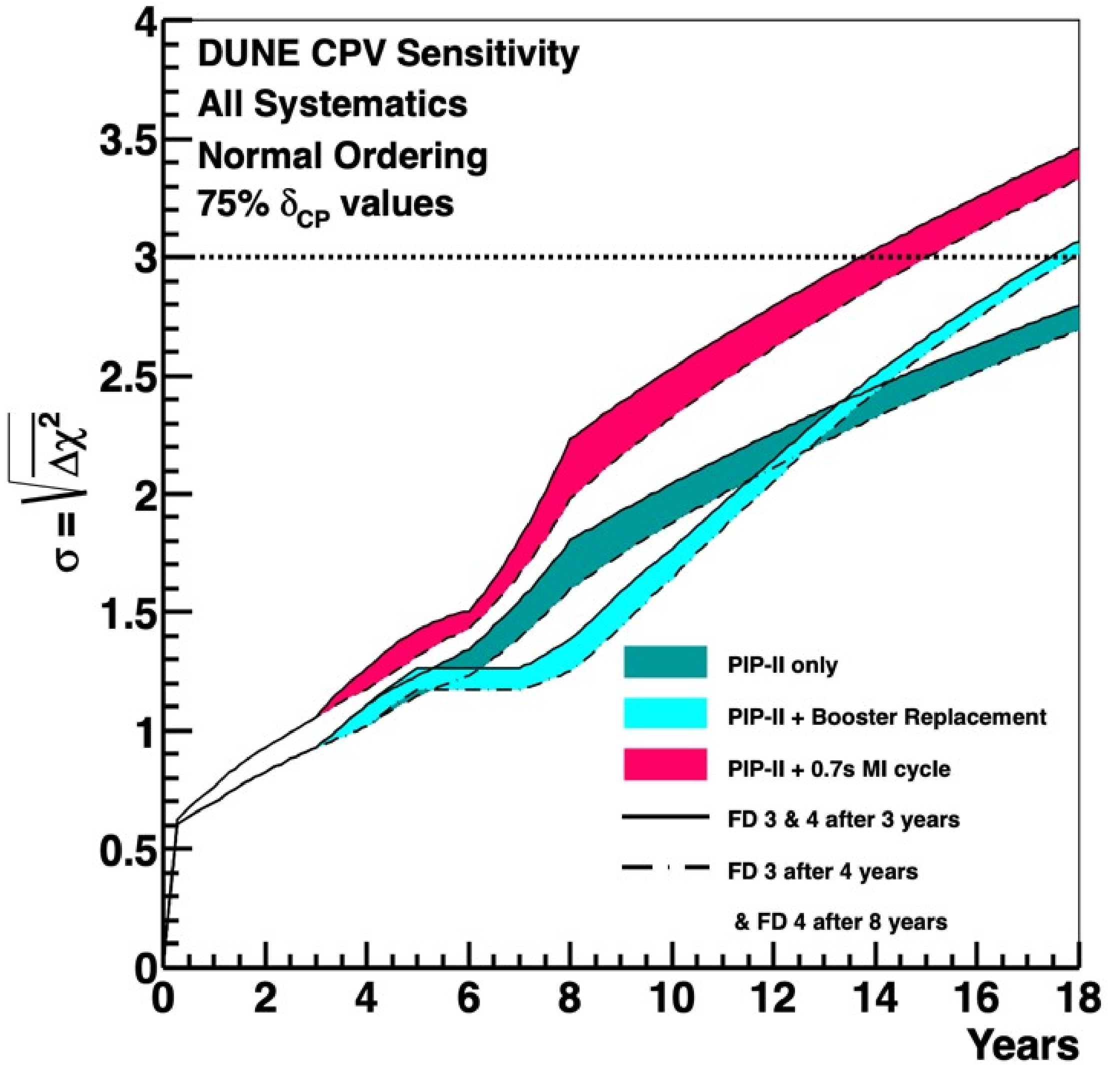
- Scenario where δ_{CP}= -π/2, the easiest possible scenario for establishing CPV
- **3σ milestone is achieved DUNE Phase I**
- Option 0 pushes milestone forward by ~1 year

CP violation sensitivity in more challenging case: 50% δ values



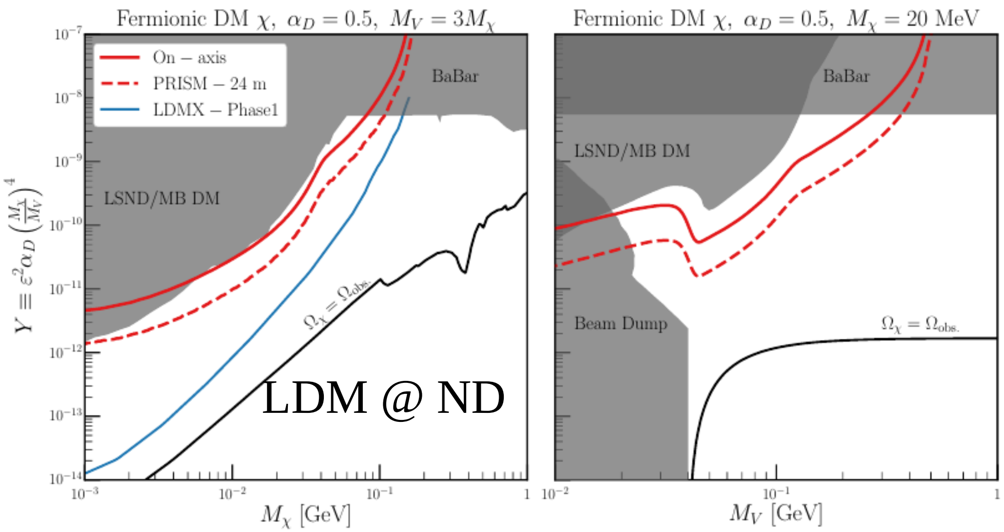
- CP violation significance over 50% of possible δ_{CP} values, essentially the median significance if you have a flat prior on true δ_{CP}
- DUNE could be competitive with Hyper-K if 5σ can be achieved in 10 years
- Kinks at 6-8 years are due to incorporation of constraint from upgraded Near Detector installed by year 6
- **Option 0 significantly increases DUNE's competitiveness**

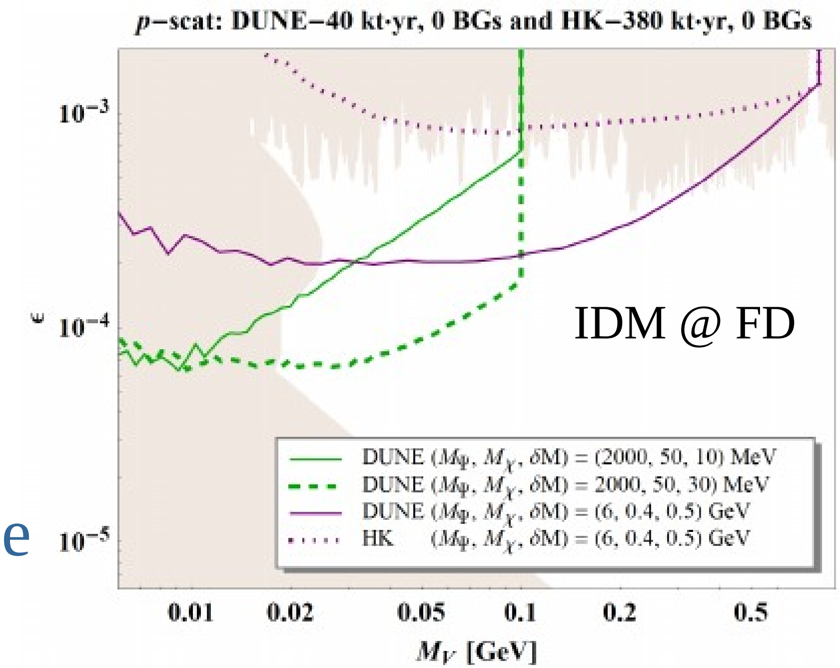
Even more challenging scenario: 75% δ values



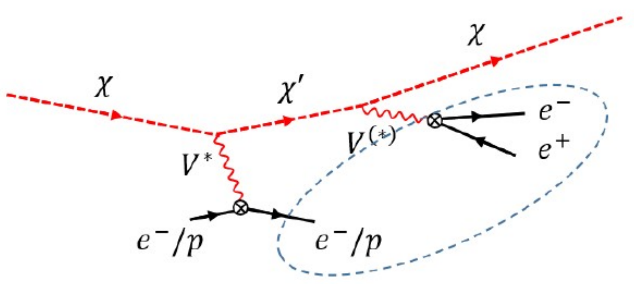
- CP violation significance over 75% of possible δ_{CP} values
- This is the primary physics goal established in the 2014 P5 recommendations
- It is extremely challenging to establish CPV at 3σ in this scenario
- **DUNE and Hyper-K are competitive in this scenario, and Option 0 significantly increases DUNE's competitiveness**

Impact on BSM physics program

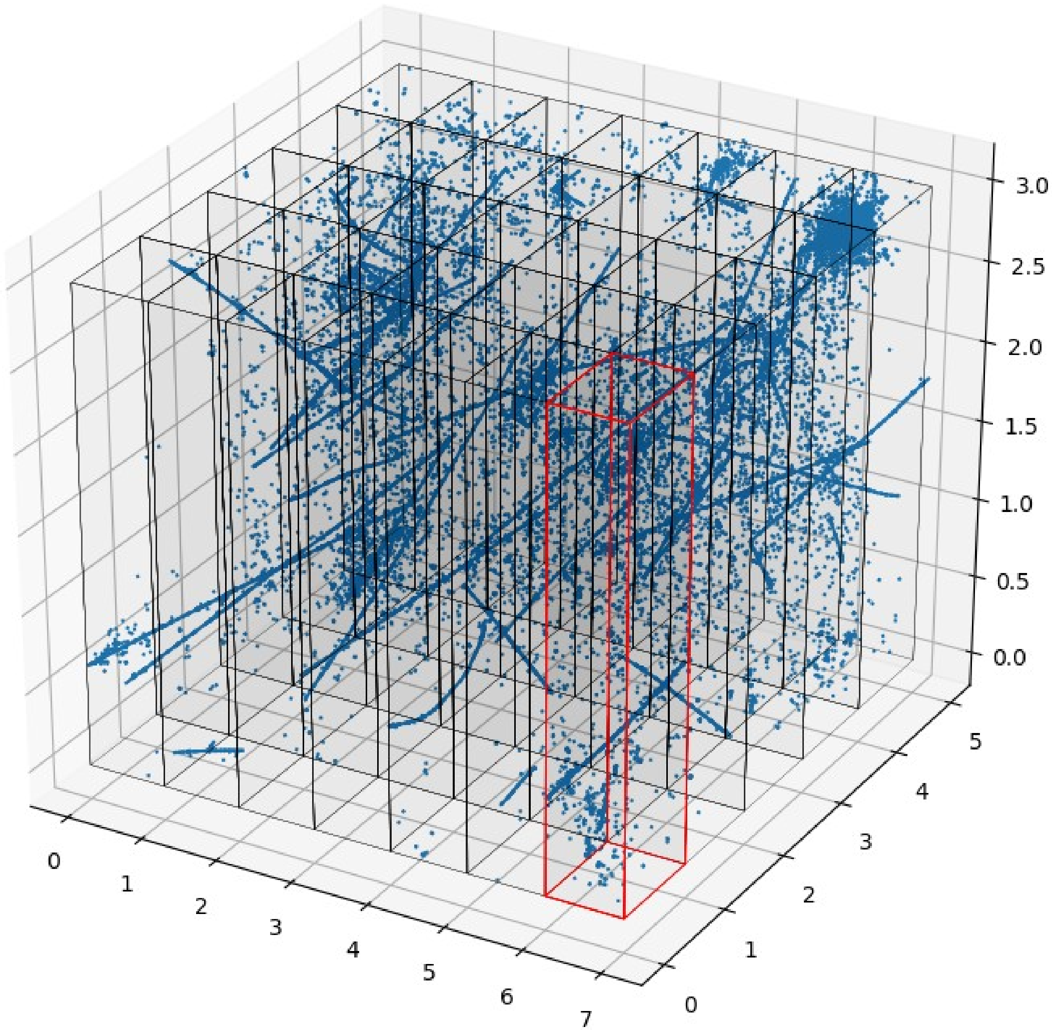




- Increased POT will generally increase sensitivity to BSM signatures produced in the beam and detected at the ND (LDM, HNL, etc.)
- Increased POT will have no effect on BSM signatures of cosmic origin detected in the FD, or low-energy non-beam physics (e.g. Supernovae)

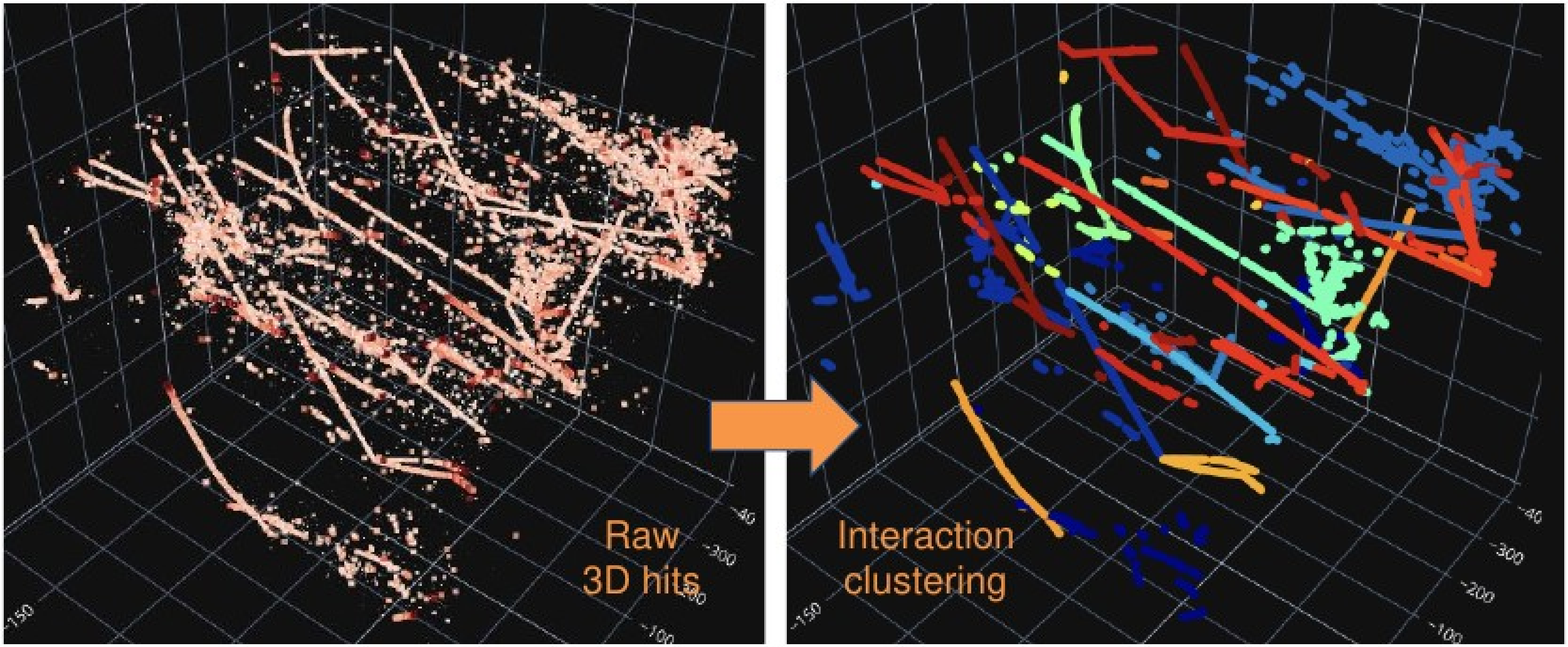


Impact on Near Detector: beam pile-up and reconstruction



- FD measures one neutrino every few hours
- ND measures one neutrino per 10t material per 10μs beam spill (7.5E13ppp = 1.2MW), plus rock muons
- Charge drift in LArTPC is O(m/ms) → readout window is much longer than 10μs beam spill, so ND-LAr sees activity from ~50 neutrino interactions "at once"

ND-LAr is designed to cope with pile-up, but it is challenging



- ND-LAr uses pixel readout → natively 3D hits for pattern recognition
- ND-LAr is optically segmented, with light collection along entire module wall → scintillation signals for fast timing
- Event reconstruction algorithms are able to resolve pile-up at 7.5E13 protons per spill
- **Shortening the cycle time is better than doubling the spill intensity for the ND**

Conclusions

- DUNE can establish CP violation at high significance, **even if nature gives us a challenging scenario**
- For more challenging oscillation scenarios, **DUNE and Hyper-K are competitive**, even if Hyper-K begins physics several years ahead of DUNE
  - Hyper-K will make first CPV measurements if CPV is large
  - DUNE has unique sensitivity to mass ordering, and slightly better ultimate resolution to other parameters
- "Option 0" provides more POT, and provides **earlier physics milestones throughout the DUNE program**, but especially for longer-term goals where DUNE is most competitive and difference is ~4 years
- Shortening the cycle time is better than increasing the spill intensity for the ND
- If it can be achieved technically, the 0.7s MI cycle scenario is **very beneficial for DUNE physics**
- **DUNE strongly endorses further study of this possibility**