# REQUIREMENTS FOR THE DUNE NEAR DETECTOR

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DUNE Near Detector 30% Design Review

14-16 July 2020

# Who am I

- Researcher at SLAC, Stanford University
- Member of DUNE since 2018
- Participant in some other neutrino experiments, such as T2K

# OUTLINE

- DUNE long baseline physics goals . . .  particularly CP violation
- The role of the DUNE Near Detector
- Quick overview of DUNE Near Detector
  - a few important features . . . .
- Review of Requirements
- Summary

# PHYSICS GOALS OF DUNE

- Scope: CP violation in long-baseline neutrino oscillations
- **“Initial” goal**
  - **Reach 3 σ significance for maximal CPV ($\delta_{CP}$= -π/2)**
  - Advance world knowledge on DUNE’s primary physics goal
- **“Nominal” goals:**
  - (3,5) σ observation for (75, 50)% of $\delta_{CP}$ values (“P5 goal”)
  - $\delta_{CP}$ precision 10°, 20° for $\delta_{CP}$ = 0,-π/2
- $\Longrightarrow$ **Initial/Nominal requirements:**

- *n.b.*:
  - Additional physics topics where the near detector is relevant/central
    - these will not be discussed here
  - TDR Staging Assumptions:
    - Beam Power : Year 1: 1.2 MW, Year 6- 2.4 MW
    - Detectors: Y1: 20 kt, Y2-3: 30 kt, Y4-: 40 kt

| Physics Milestone | Exposure (staged years, $\sin^2\theta_{23} = 0.580$) |
|---|---|
| $5\sigma$ Mass Ordering<br>$\delta_{CP} = -\pi/2$ | 1 |
| $5\sigma$ Mass Ordering<br>100% of $\delta_{CP}$ values | 2 |
| $3\sigma$ CP Violation<br>$\delta_{CP} = -\pi/2$ | 3 |
| $3\sigma$ CP Violation<br>50% of $\delta_{CP}$ values | 5 |
| $5\sigma$ CP Violation<br>$\delta_{CP} = -\pi/2$ | 7 |
| $5\sigma$ CP Violation<br>50% of $\delta_{CP}$ values | 10 |
| $3\sigma$ CP Violation<br>75% of $\delta_{CP}$ values | 13 |
| $\delta_{CP}$ Resolution of 10 degrees<br>$\delta_{CP} = 0$ | 8 |
| $\delta_{CP}$ Resolution of 20 degrees<br>$\delta_{CP} = -\pi/2$ | 12 |
| $\sin^2 2\theta_{13}$ Resolution of 0.004 | 15 |

# MORE FORMALLY

O(10%) uncertainty in each component

$$N_{FD}(\nu_\alpha \rightarrow \nu_\beta, E_{REC}) = \int dE_\nu \times \Phi(\nu_\alpha, E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta, E_\nu) \times V \times n \times R(\nu_\beta, E_{REC}, E_\nu) \times \sigma(\nu_\beta, E_\nu)$$

DUNE global science requirement

ND measurements shall be of sufficient precision to ensure that when extrapolated to FD to predict the FD event spectra, the associated systematic error must not dominate the measurement precision.

- *n.b.:*
  - The far detector (FD) is a LArTPC
  - ND operates in the near detector hall
  - What FD measures involves both R and σ
    - R depends on what particles emerge, how the detector responds
    - each must be modelled accurately to predict the observables
  - Backgrounds introduce additional considerations
    - Predicting the signal has critical systematic uncertainties that must be addressed as shown here

DUNE ND Overarching Requirements

→ **ND-O0** • **Predict the observed spectrum of neutrino interactions at FD**

ND-O1 • Transfer measurements to the FD

ND-O2 • Constrain the cross section model

ND-O3 • Measure the neutrino flux

ND-O4 • Obtain measurements with different fluxes

ND-O5 • Monitor time variation of the neutrino beam

ND-O6 • Operate in high rate environment

# STRUCTURE OF DUNE ND REQUIREMENTS

- **Overarching:**
  - Broad statements on needed “deliverables” from the ND for the DUNE long baseline analysis
- **Measurements:**
  - What measurements are performed at the ND to fulfill the overarching requirements? and how well?
  - These are in principle subsystem agnostic but are assigned to specific subsystems to carry out
  - I will introduce **10 measurement requirements (ND-MX)** to fulfill the overarching requirements
- **Capabilities**:
  - What capabilities do the ND systems need to perform the measurements?
  - These capabilities are assigned to specific subsystems which will carry out the measurements
  - I will **breeze through these (ND-CX)** and leave further discussion to system-specific talks.
- **Technical**:
  - What technical/physical characteristics does the subsystem need to have these capabilities?
  - **These are still in development . . . . and will be addressed in the following talks**

# TARGET UNCERTAINTIES:

**FHC (“$\nu$-mode”) 3.5 Staged Years**

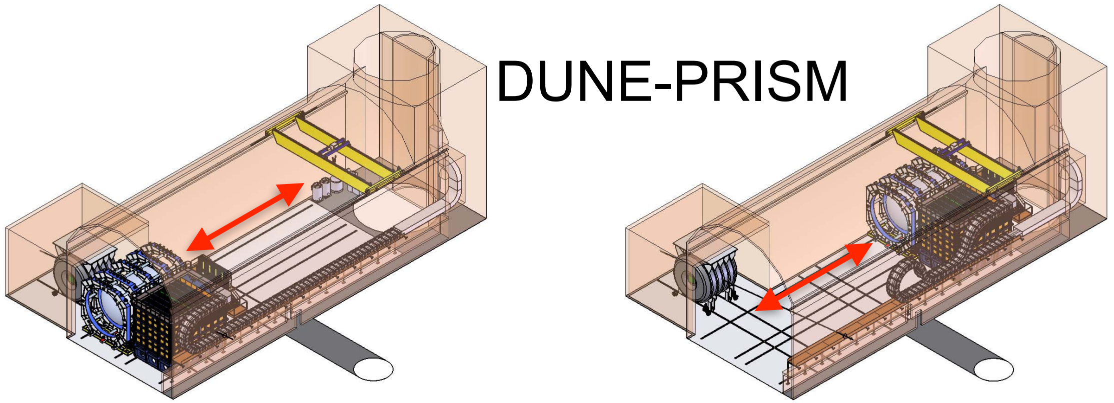
| | normal ordering | | |
|---|---|---|---|
| | δCP=0 | δCP=-π/2 | Variation |
| $\nu_\mu \rightarrow \nu_e$ | 1155 | 1395 | **0.21** |
| $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | 19 | 14 | |
| Beam $\nu_e + \bar{\nu}_e$ | 228 | 228 | |
| Other bkg | 135 | 134 | |
| Total | **1537** | **1771** | **0.15** |

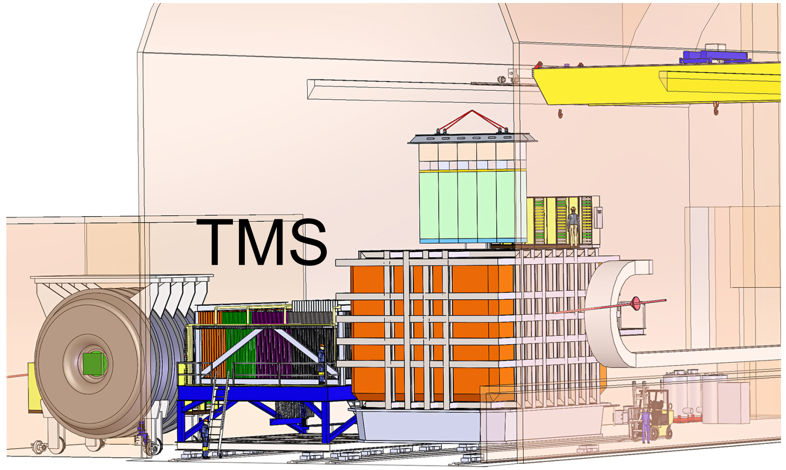
**RHC (“$\bar{\nu}$-mode”) 3.5 Staged Years**

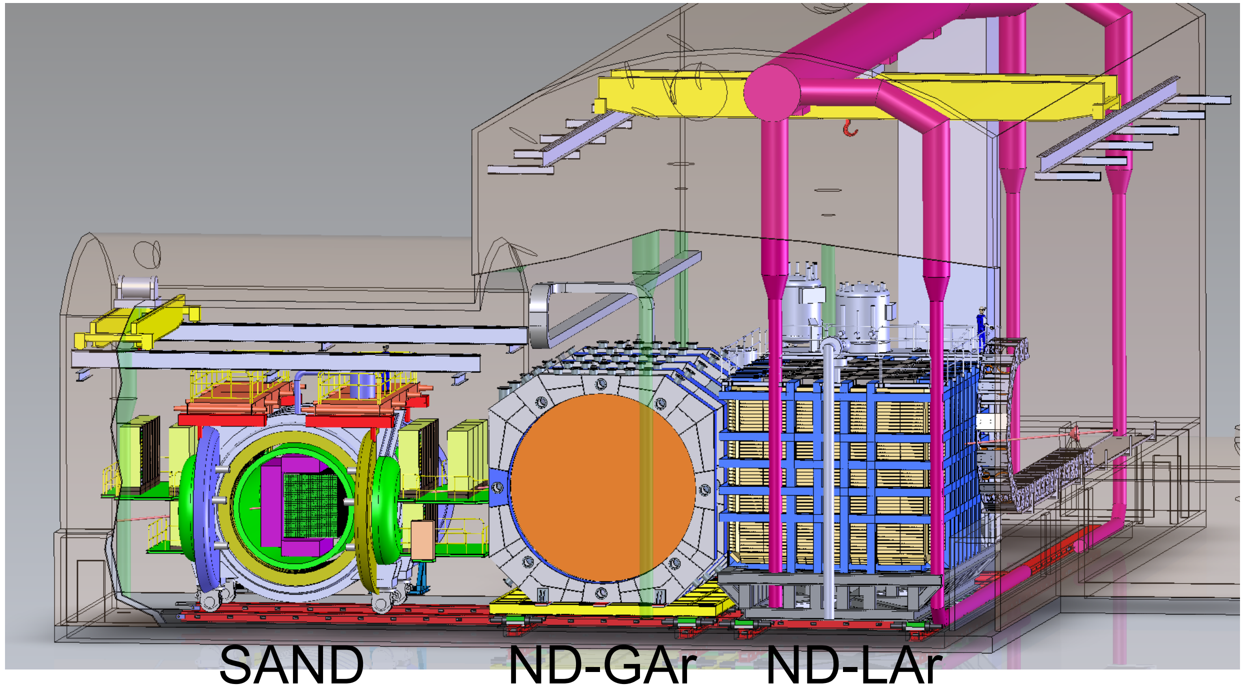
| | normal ordering | | |
|---|---|---|---|
| | δCP=0 | δCP=-π/2 | Variation |
| $\nu_\mu \rightarrow \nu_e$ | 81 | 95 | |
| $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | 236 | 164 | **0.44** |
| Beam $\nu_e + \bar{\nu}_e$ | 145 | 145 | |
| Other bkg | 68 | 68 | |
| Total | **530** | **475** | **0.12** |

- **Maximal CPV is in principle a large effect**
  - diluted to ~15% variation in $\nu_e/\bar{\nu}_e$ events by backgrounds
- To detect this, one roughly needs:
  - <5% total (stat. + sys.) error to achieve 3 σ significance
  - <3% total (stat. + sys.) error to achieve 5 σ significance
- aim for balance of statistical/systematic error
  - **Initial target for total systematic error: < ~3%**
  - **Nominal target for total systematic error: < ~2%**
- *n.b.*:
  - T2K/NOvA achieve **~7-8% uncertainty** in this metric after O(decade) of operation/analysis
- This will guide the measurement requirements in what follows

# The DUNE NEAR DETECTOR (ND)



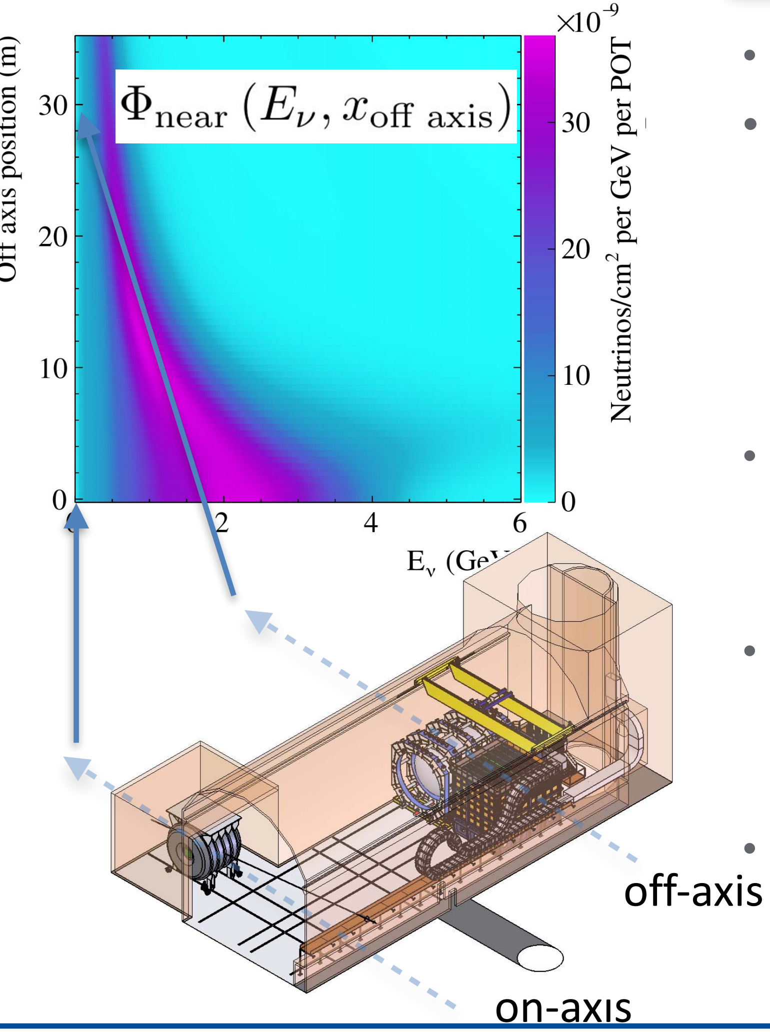




- ND-LAr:
  - LArTPC in 1 (w) x 3 (h) x 1 (d) $m^3$ modules
  - 67 tons of fiducial mass in a 7x5 array
- ND-GAr:
  - Magnetized 10 Atm GAr TPC (~1 ton of target)
  - Electromagnetic calorimetry and muon detection system
  - **Downstream muon spectrometry for ND-LAr**
    - can be temporarily fulfilled with magnetized iron spectrometer (**TMS**) in “initial” requirements.
- SAND:
  - On-axis beam monitoring system
  - Plastic scintillator target surrounded by gaseous tracking chambers in the KLOE magnet+ECAL system
- DUNE-PRISM
  - Movement of ND-LAr/(TMS/ND-GAr) up to 30.5 meters to sample off-axis neutrino fluxes

# DUNE-PRISM

$$N_{FD}(\nu_\alpha \rightarrow \nu_\beta, E_{REC}) = \int dE_\nu \times \Phi(\nu_\alpha, E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta, E_\nu) \times V \times n \times R(\nu_\beta, E_{REC}, E_\nu) \times \sigma(\nu_\beta, E_\nu)$$

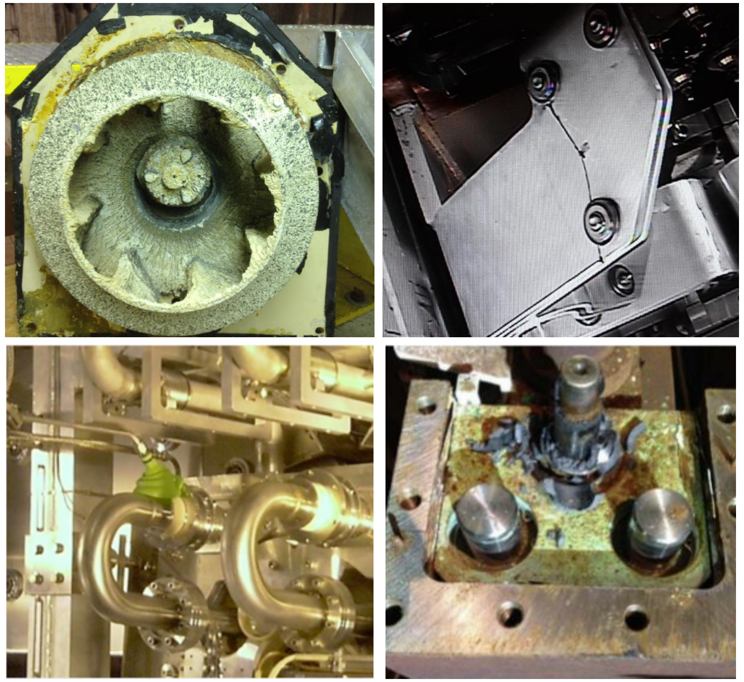



- **DUNE-PRISM (ND-O4) is an initial requirement**
- Neutrino oscillations depend on the true neutrino energy
  - (Model dependence/uncertainty in neutrino energy reconstruction)
  - Modelling must be correct with respect to $E_\nu$ to correctly incorporate oscillations
  - It is **not** sufficient for observables to "agree" in ND and FD
    - These are convolutions over the spectrum that can hide/obscure mismodelling.
- The "Off-axis" effect (aka 2-body decay kinematics)
  - breaks the correlation between the parent pion energy and the child neutrino
  - spectrum moves to lower energy and narrows
- The ability to expose the near detector to different neutrino fluxes
  - reveals mismodelling that cannot be detected with a single spectrum measurement
  - by sampling multiple positions/fluxes, measures $E_\nu$-dependence of observables
- Plausible mismodelling scenarios can impact the initial goals

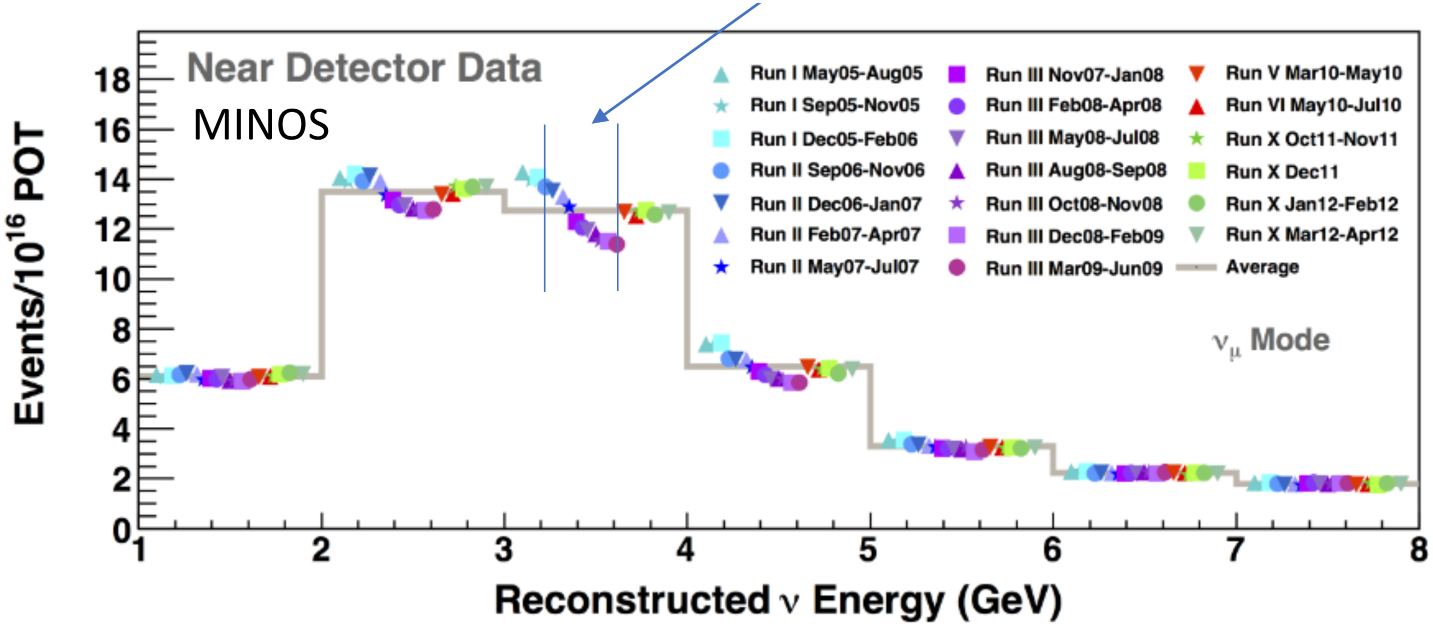
not DOE Scope

# BEAM MONITORING

- A high intensity neutrino beamline with ~1 MW proton beam is a vibrant environment



- each picture has a story that either stopped or changed the neutrino beam




- Most dramatically, components can fail and stop operations
- However, they also just change without failing, changing the neutrino flux
  - As we scale the intensity frontier, beam monitoring will be more important than ever

# ND-O1/O2: TRANSFER MEASUREMENTS TO FD, CONSTRAIN MODEL

| | | |
|---|---|---|
| ND-O1 | Transfer measurements to the FD | Measurements at the ND must be transferable to the FD in order to minimize systematic uncertainties |

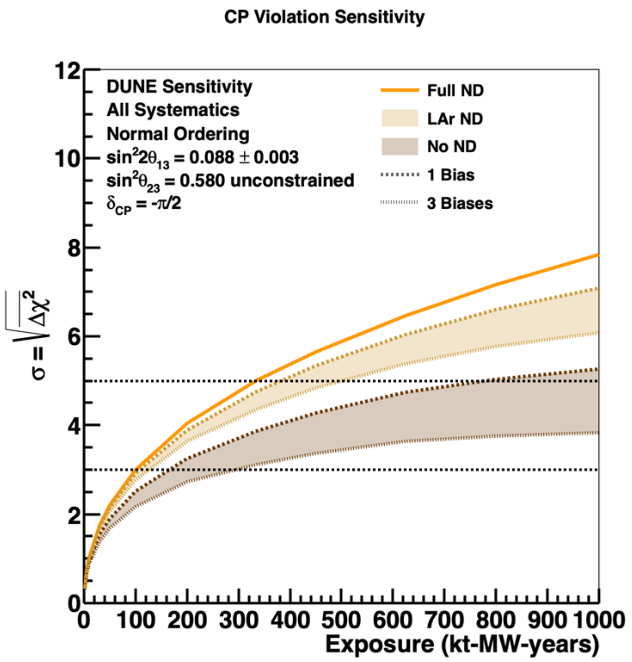
| Label | Description | Spec. | Rationale | System | Ref. Req. |
|---|---|---|---|---|---|
| ND-M1 | Classify interactions and measure outgoing particles in a LArTPC with performance comparable to or exceeding that of the FD | N/A | The ND must have a LArTPC with reconstruction capabilities comparable/exceeding the far detector in order to effectively transfer measurements. | ND-GAr, ND-LAr | ND-O1, ND-O2 |
| ND-M2 | Measure outgoing particles in $\nu$-Ar interactions with uniform acceptance, lower thresholds than a LArTPC, and with minimal secondary interaction effects | N/A | The ND must measure outgoing recoil particles ($\pi$, $p$, $\gamma$) in $\nu$-Ar interactions to ensure that sensitive phase space is properly modeled. | ND-GAr | ND-O1, ND-O2 |

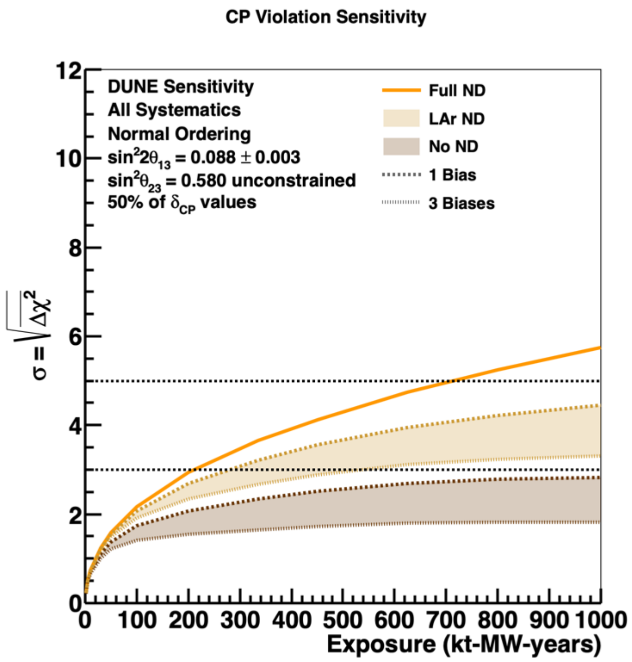
- **ND-M1:** address “transferability” by ensuring relevant FD observables can be reproduced in ND
  - Presupposes a LArTPC component of the ND (ND-LAr)
    - requirements pertain to events observed in ND-LAr
    - performance must be comparable/better than FD
- **ND-M2:** address limitations of LArTPC to probe neutrino interactions that arise generically from density of LAr
  - secondary interactions, thresholds, sign selection, etc.
  - more specific issue arise from size constraints of ND-LAr

- **Capability requirements for ND-M1 (ND-LAr) :** based on that currently demonstrated in FD
  - Efficiency, purity, $E_\nu$ resolution for $\nu_\mu/\nu_e$ CC events, detection thresholds for individual particles
  - Containment requirements for muons and hadrons:
    - **muons: requires spectrometer downstream with resolution comparable/better than LAr range**
    - hadrons: full containment for a fraction of events across phase space of $E_\nu$, $E_{had}$ → requirements on ND-LAr active volume

# ND-O1/O2: TRANSFER MEASUREMENTS TO FD, CONSTRAIN MODEL

- Case study of discrepancy in pion production model in two generators (NuWRO, GENIE)
  - introduces large biases/systematics into extraction of $\delta_{CP}$
- ND-LAr will allow a limited correction for these channels (ND-M1)→ large biases/systematics remain
- ND-GAr can make clean channel specific corrections (ND-M2)→ biases significantly reduced




## Takeaways:

- Initial goals can be met without ND-M2
  - TMS can deliver the required muon spectrometry capabilities for ND-LAr
- Anything beyond detecting maximal CPV requires ND-M2 (ND-GAr)

**Impact on Initial goal:**

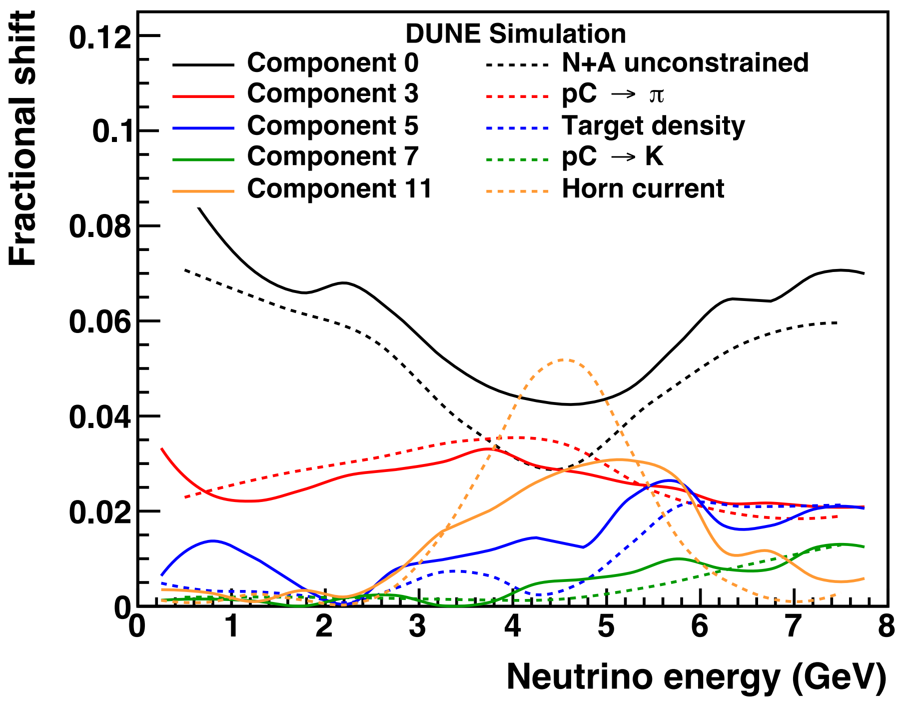
- 3 σ for maximal CP violation: not much
- 5 σ: 30% more exposure (note staging)

**Impact on Nominal goals: for non-maximal CP:**

- Year 5: 3 σ for 50% $\delta_{CP}$ requires **significantly more exposure**
- Year 10: 5 σ for 50% $\delta_{CP}$ possibly **never met**

# ND-O3: FLUX MEASUREMENTS

| | | | | | |
|---|---|---|---|---|---|
| ND-O3 | Measure the Neutrino Flux | | The ND must constrain the flux beyond what is achieved by *ab initio* modeling of the neutrino beam | | |
| ND-M3 | Measure the $\nu$ flux using neutrino-electron scattering | N/A | The ND must measure the flux with $\nu$-e scattering, a standard candle that provides a normalization measurement. | ND-LAr | ND-O3 |
| ND-M4 | Measure the neutrino flux spectrum using the 'low-$\nu$' method | N/A | The ND must identify/measure low recoil events which have flat energy dependence in order to measure the spectrum. | ND-LAr, ND-GAr | ND-O3 |




- Expected *ab initio* uncertainties on absolute neutrino flux is ~5-7%
  - Relative flux at ND/FD constrained to ~1.5%
- **ND-M3: constrain the total flux* with v-e scattering**
  - ***leptonic "standard candle" providing flux normalization***
  - **initial:** verify ab initio model to ~5%
  - **nominal:** constrain flux to 2% (cf. target of 3% total uncertainty)
- Capability Requirements (ND-LAr) for ND-M3:
  - sufficient fiducial mass: very small cross section
  - reconstruct forward lone electron (energy/angle resolution)
  - reject: photons from $\pi^0$s, $\nu_e$ CC interactions

- ND-M4: use "low-v" method
  - ~constant σ for low-$E_{had}$ events to measure shape of flux
  - initial: no requirements
  - nominal: 5% measurement >1 GeV

*decomposition of flavor is needed to verify primary $\nu_\mu$ (FHC), $\bar{\nu}_\mu$ (RHC) flux (see next slide)

# ND-O3: FLUX MEASUREMENTS

| | | | | | |
|---|---|---|---|---|---|
| ND-O3 | Measure the Neutrino Flux | | The ND must constrain the flux beyond what is achieved by *ab initio* modeling of the neutrino beam | | |

| | | | | | |
|---|---|---|---|---|---|
| ND-M5 | Measure the wrong sign contamination | N/A | The ND must measure and validate the modeling of wrong-sign interactions that dilute the oscillation asymmetries at the FD. | ND-GAr | ND-O3 |
| ND-M6 | Measure the intrinsic beam $\nu_e$ component | N/A | The ND must measure and validate the modeling of this irreducible background | ND-LAr, ND-GAr | ND-O3 |

## FHC ($\nu$) 3.5 Staged Years

| | normal ordering | |
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| Beam $\nu_e + \bar{\nu}_e$ | 145 | 145 |
| Other bkg | 68 | 68 |
| Total | 530 | 475 |

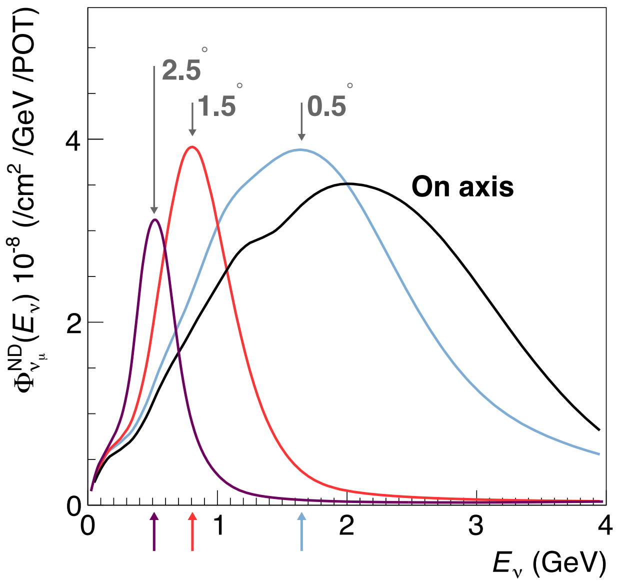
Two ~irreducible backgrounds in FD:

- **ND-M5: "wrong-sign" contribution**
  - much worse in RHC
    - **initial:** (10/40*)% in RHC/FHC
    - **nominal:** (5/20*)% in RHC/FHC
  - Capability requirements (ND-LAr, TMS):
    - *sign-selected measurement of $\nu_\mu$-CC at ND-LAr in spectrometer*
- **ND-M6: beam $\nu_e$ component**
  - Dominant background for $\nu_e$ analysis
    - **initial:** 5%
    - **nominal:** 2%
  - Capabilities requirements (ND-LAr):
    - *fulfilled by related ND-M3 requirements to identify $\nu$-e events*

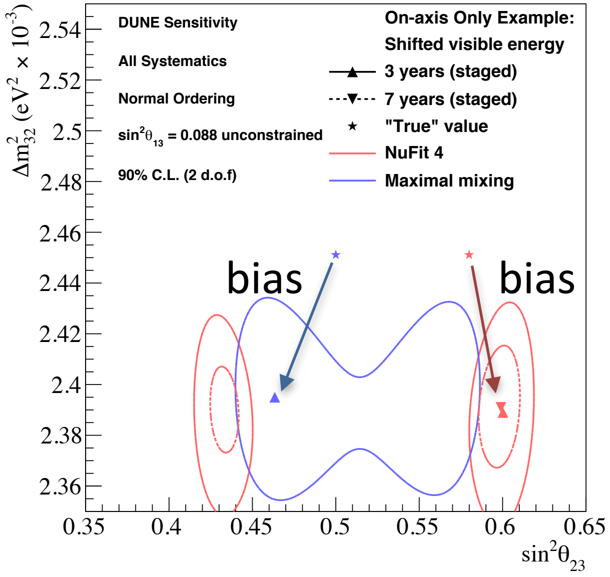
*FHC requirements are driven by verifying $\nu_\mu$ flux in conjunction with $\nu - e$ elastic measurement, not the wrong sign contribution to the $\nu_e$ appearance

# ND-O4: MEASUREMENTS WITH DIFFERENT FLUXES

| | | | | | |
|---|---|---|---|---|---|
| ND-O4 | Obtain measurements with different fluxes | | The ND must verify that model predictions are robust with different neutrino fluxes. | | |
| ND-M7 | Take measurements with off-axis fluxes with spectra spanning region of interest | 0.5-3.0 GeV | The ND must be able to move off the beam axis to take data with different neutrino spectra. | ND-LAr, ND-GAr, DUNE-PRISM | ND-O4 |




Neutrino flux vs. off-axis angle




Oscillation parameter bias

- ND, FD observations are convolutions over the spectrum of incident neutrinos
  - breaking degeneracy requires control over incident spectrum
  - ND-M7: move ND-LAr+TMS/ND-GAr to off-axis positions
  - "DUNE-PRISM"
- Case study shows bias in $\sin^2\theta_{23}$, $P(\nu_\mu \rightarrow \nu_e)$, beyond initial error budget
  - resolvable by taking data off-axis
  - **DUNE-PRISM is needed for initial goals**
- Capability Requirements for ND-M7 (DUNE-PRISM):
  - span region of interest (0.5-3.0 GeV)
  - maintain uniform measurement capability (~1%)
  - place ND-LAr/ND-GAr with sufficient granularity/precision
  - minimize downtime for motion (<8 hours)
  - regular suite of measurements (~1 year)

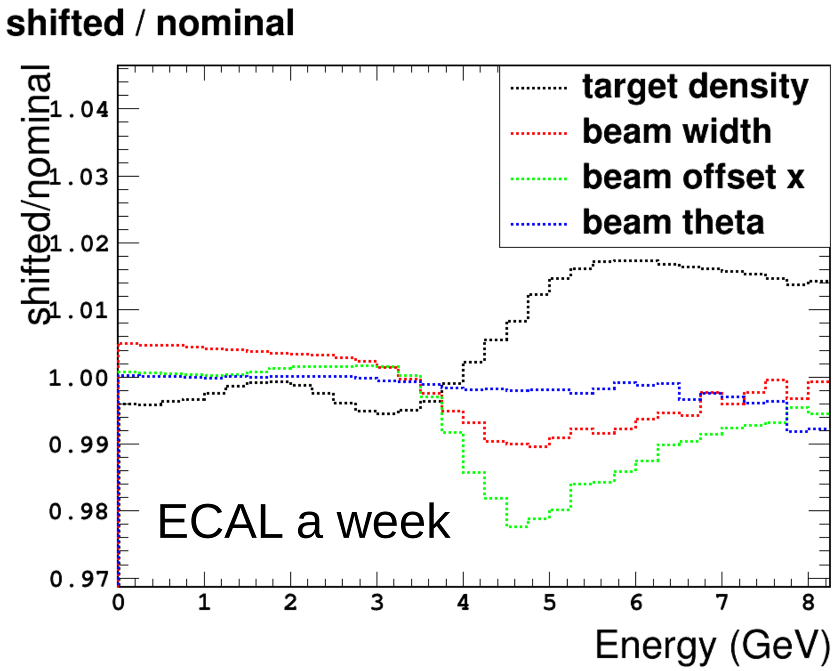
# ND-O5: BEAM MONITORING

| | | | | | |
|---|---|---|---|---|---|
| ND-O5 | Monitor time variation of the neutrino beam | | The ND must detect potential variations in the neutrino flux. | | |
| ND-M8 | Monitor the beam rate on-axis | N/A | The ND must have a component that remains on-axis where beam monitoring is most sensitive and collects a sufficient number of $\nu_\mu$ CC events. | SAND | ND-O5 |
| ND-M9 | Monitor the beam spectrum on-axis | N/A | The ND must use spectrum information to detect representative changes in the beam line. | SAND | ND-O5 |

- High statistics neutrino-based monitoring needed to "quickly" (~1 week) identify variations
  - Rate needs to
  - On-axis spectrum is important to identify variations
    - some variations do not change overall rate
  - Due to DUNE-PRISM, a dedicated on-axis monitor is required (SAND)

- Requirements studied with representative potential beam variations informed from past experience
  - n.b. the requirement is to detect variations, not to diagnose them

- Capability requirements for ND-M8, M9 (SAND):
  - $p_\mu/E_\nu$ resolution: better than ~1 GeV to resolve features
  - higher statistics/mass required if monitoring with $p_\mu$ only
  - sufficient mass: (20/5) tons $p_\mu/E_\nu$ based monitoring
  - vertexing: place interaction left/right, above/below beam center



# ND-O6: HIGH RATE ENVIRONMENT

- Due to the intense 1.2 MW LBNF beam, expect ~0.2 interactions/ton of material
  - Backgrounds from external interactions
    - hall, inactive detector elements, other detectors, etc.
  - Pileup from interactions within the active/fiducial volume of a detector
  - Measurement requirement (ND-M10):
    - subsystems must be able to verify that the backgrounds are adequately modeled
- Primary means for reducing backgrounds/isolating interactions is timing

- Capability requirements:
  - 10 µsec spill with O(100) interactions → 20 nsec on products from an individual interactions
    - commensurate inter-detector timing (modules in ND-LAr, between ND-LAr, TMS/ND-GAr)
  - ND-GAr has further timing requirements for $t_0$ determination for the TPC (under study)
  - KLOE ECAL timing requirements driven by directionality determination

# SUMMARY

- Initial and nominal requirements are considered based on the corresponding DUNE physics goals
  - “initial” = 3 σ sensitivity to maximal CP violation
  - “nominal” = further goals, including CP coverage at 3,5 σ (“P5”) and $\delta_{CP}$ precision
  - Even “initial” goals require systematic error well beyond what is currently achieved.
    - Each source of error must be addressed by DUNE-ND to meet the goals
- ND requirements are hierarchical
  - start with the global science requirement to predict the observed spectrum of neutrino interactions at FD
  - overarching → measurements → capabilities (→ technical)
  - These have recently been approved by the DUNE Executive Board
- The reference design LBNC and a conceptual design review
- Initial and nominal requirements are presented
  - **Initial requirements should be satisfied by the proposed “Day 1” system to meet the initial goal of 3 σ sensitivity to maximal CP violation**
    - Notably, the muon spectrometry capabilities requirements of TMS are sufficient
  - Reaching nominal goals on CP violation require additional capabilities beyond the “Day 1” system