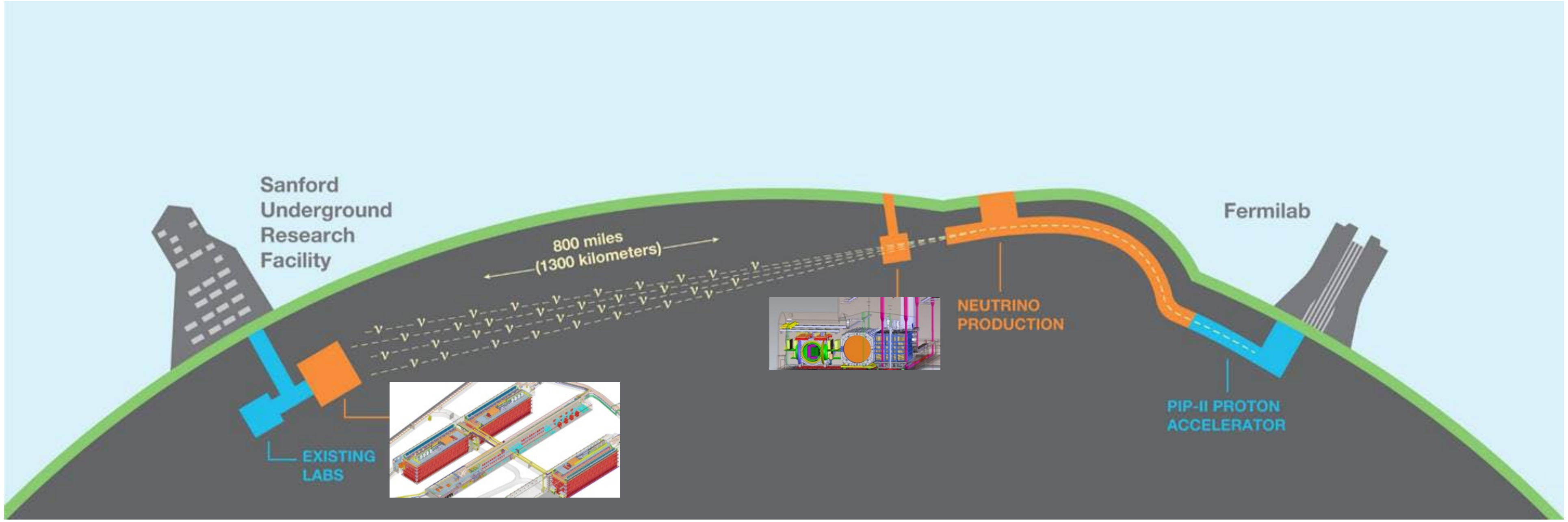
DUNE Status and Plans for Phase II ND Workshop

Mary Bishai

DUNE Phase II Near Detector Workshop, Imperial College, London UK

June 20, 2023

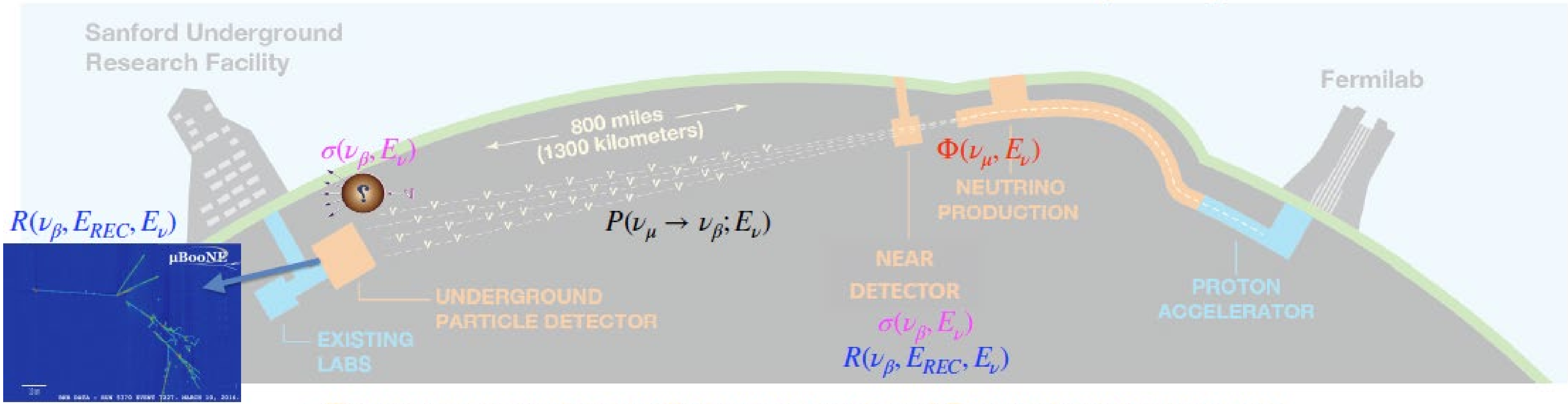
Reminder: Full DUNE scope

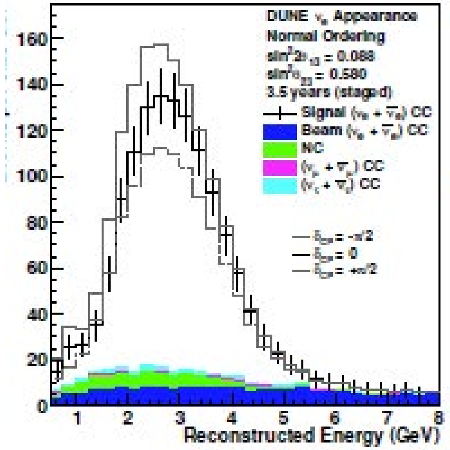


- The <u>complete</u> DUNE detector
  - ***<u>Four Far Detector 17 kton LAr TPC modules</u>*** with ≥ 40 kt fiducial volume.
  - A Near Detector system which includes a liquid-argon TPC.
  - A 1.2 MW beam <u>upgradeable to 2.4 MW</u>.

PURPOSE OF NEAR DETECTOR (ND)

From H. Tanaka

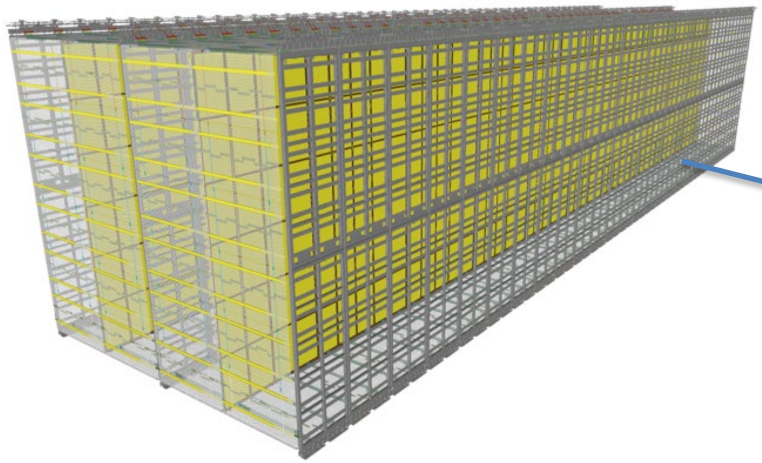


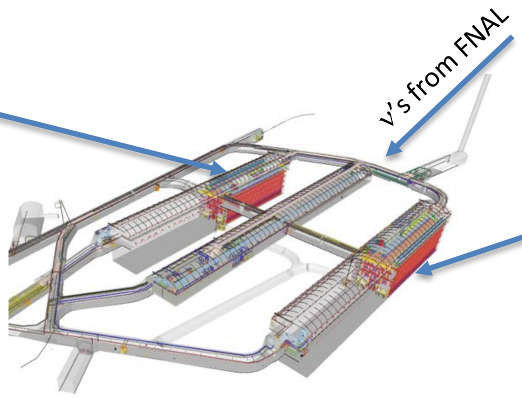


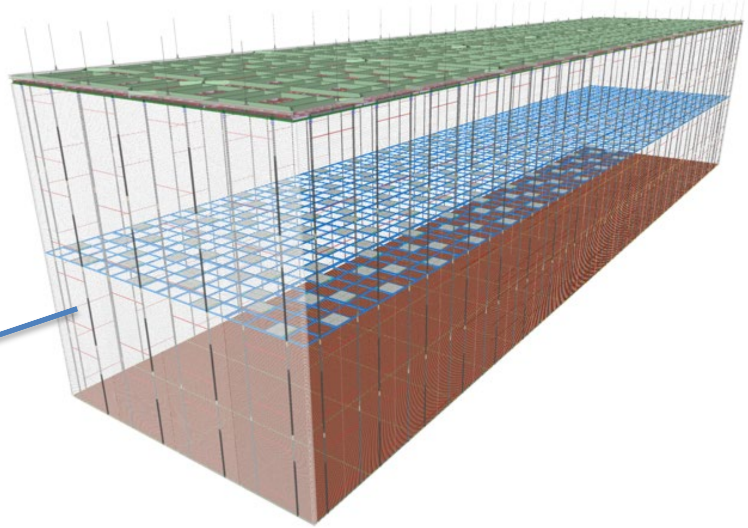
- To measure neutrino oscillation parameters, LB experiments compare:
  - Observed energy spectrum of flavor-tagged neutrinos at the far detector
  - Prediction as a function of neutrino oscillation parameters (both "signal" and background).
- This requires :
  - "following" neutrinos: production (Φ), oscillation (P), interaction (σ), detection (R) in far detector (FD)
  - The measurement is only as good as the prediction:
    - Systematic errors in the prediction result in degradation in precision/sensitivity
- Each element is critical in producing the prediction

DUNE – Phase I Far Detectors

- ***LBNF will provide caverns at SURF + most of the cryogenic infrastructures for 4 detector modules (each with a FV ≥ 10Kt) in Phase I***
  - 1st detector to be installed in NE cavern has horizontal drift (like ICARUS and MicroBooNE)
  - 2nd detector will go into SE cavern and has vertical drift (capitalizing on elements of the dual phase development)







APA* Horizontal Drift

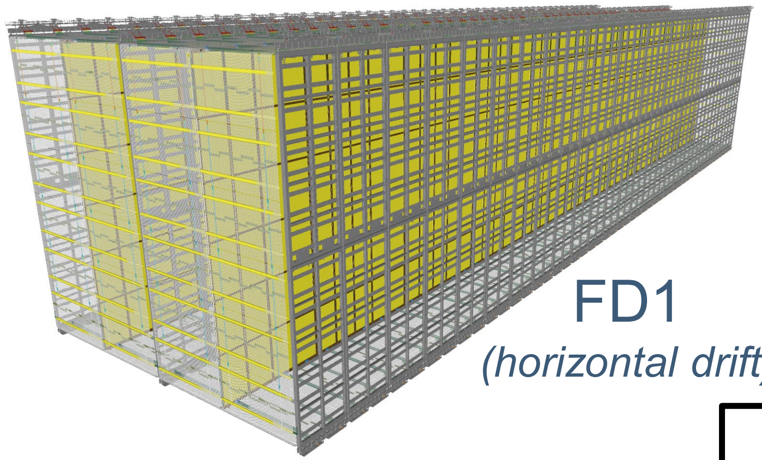
*Anode Plane Assemblies

Note : DUNE Science begins when FD1 is filled and turned on and recording tracks

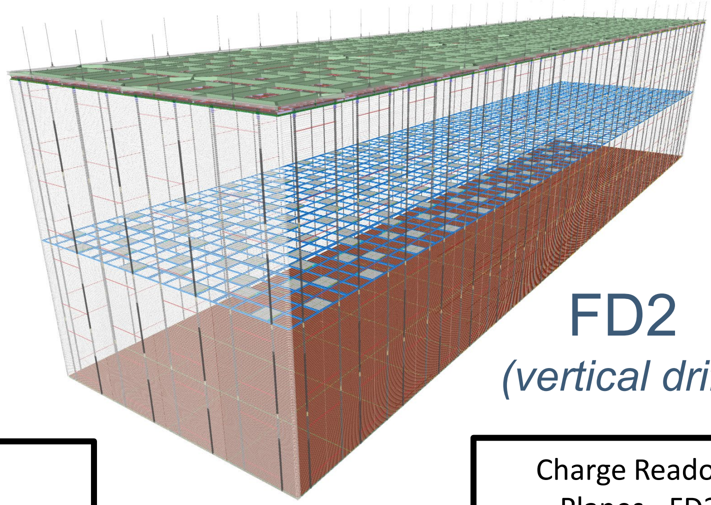
CRP** Vertical Drift

**Charge Readout Planes

DUNE – Far Detector Partnerships



FD1
(horizontal drift)



FD2
(vertical drift)

High Voltage
FD1, FD2

Anode Plane
Assemblies - FD1

TPC
Electronics
FD1, FD2-B

Photon Detection
FD1, FD2

Data Acquisition
FD1, FD2

Charge Readout
Planes - FD2

CALCI
FD1, FD2

Electronics
FD2-T

Brookhaven National Laboratory

Argonne National Laboratory

Los Alamos National Laboratory

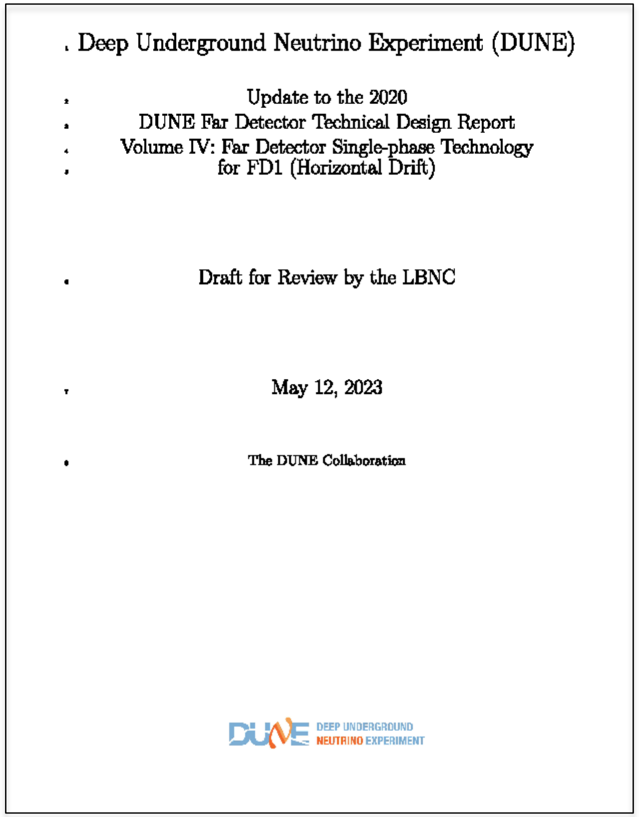
Fermilab

Berkeley Lab

FD1 Status

- Final Design Reviews completed

FD1 System Review	Date
FD DAQ FDR for Timing System	July 21, 2020
FD TPC Electronics FDR for ASICs	July 21, 2021
FD1 APA FDR	August 31, 2021
FD1 TPC Electronics FDR	September 29, 2022
FD1 High Voltage System FDR	October 12, 2022
FD Cryogenic Instrumentation FDR	January 18, 2023
FD DAQ FDR	February 22, 2023
FD1 Photon Detector FDR	March 14, 2023
FD Installation FDR	April 25, 2023


Deep Underground Neutrino Experiment (DUNE)

Update to the 2020
DUNE Far Detector Technical Design Report
Volume IV: Far Detector Single-phase Technology
for FD1 (Horizontal Drift)

Draft for Review by the LBNC

May 12, 2023

The DUNE Collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Updated FD1 Design Report
submitted to LBNC on May 12, 2023

- Installation of the ProtoDUNE-HD-Module 0 TPC in the NP04 cryostat was completed in 2022

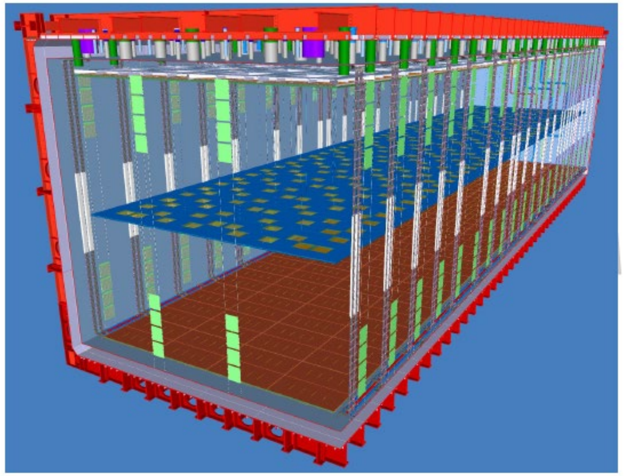
FD2: Vertical Drift

- ProtoDUNE-VD
  - TPC installation complete mid-June, 2023
- TDR
  - First draft to LBNC December 2022
  - Second draft March 2023
- FDRs complete
- MoUs are with funding agencies

Deep Underground Neutrino Experiment
Technical Design Report

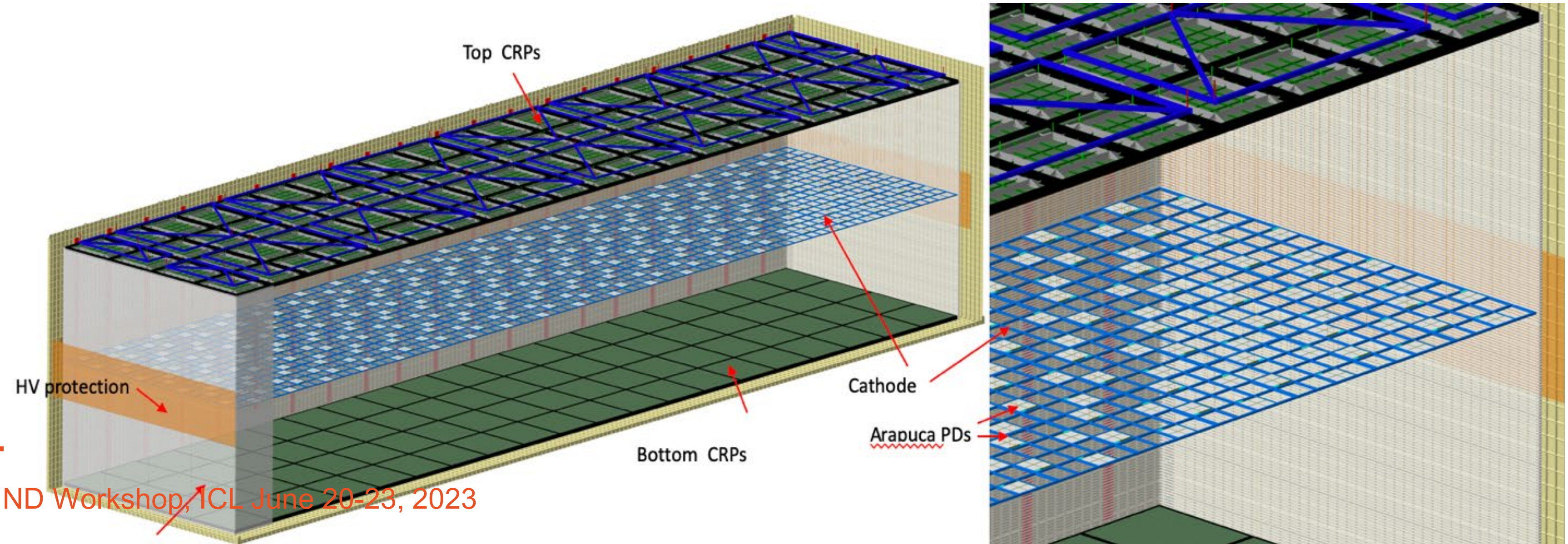
Single-Phase Vertical Drift Technology for
Far Detector Module 2 (FD2-VD)

March 16, 2023



DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

TDR submitted March 16, 2023

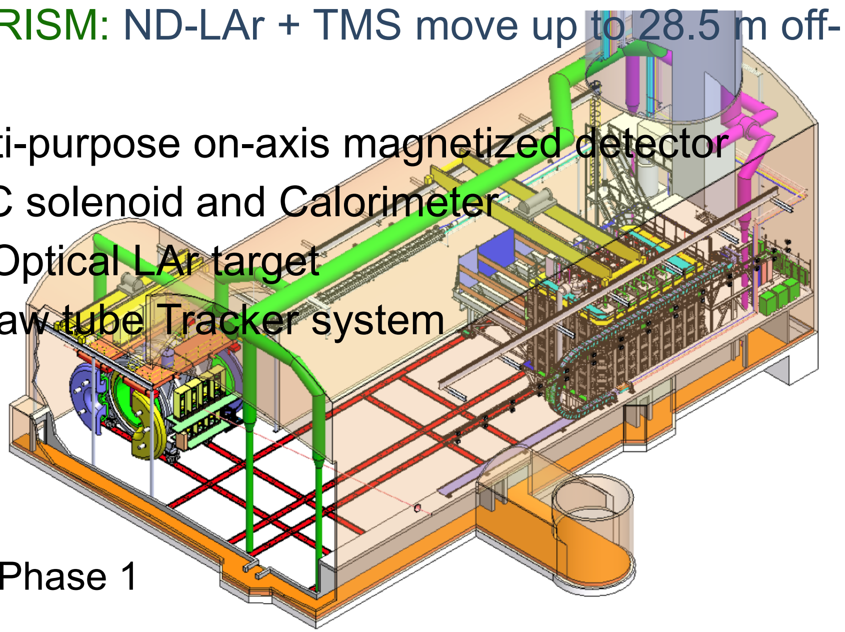


THE PHASE I NEAR DETECTOR (see H. Tanaka's talk next)

	Measurement Requirement (ND Shall . . ..)
ND-M1	Classify interactions and measure outgoing particles in a LArTPC with performance comparable to or exceeding the FD
ND-M2	*Measure outgoing particles in ν-Ar interactions with uniform acceptance, lower thresholds than a LArTPC, and with minimal secondary interactions*
ND-M3	Measure the neutrino flux using neutrino electron scattering
ND-M4	Measure the neutrino flux spectrum using the "low-ν" method
ND-M5	Measure the wrong-sign component
ND-M6	Measure the intrinsic beam ν_e component
ND-M7	Take measurements with off-axis flux with spectra spanning region of interest
ND-M8	Monitor the rate of neutrino interactions on-axis
ND-M9	Monitor the beam spectrum and interaction distribution on-axis
ND-M10	Assess External Backgrounds

Phase 1 Near Detector:

- ND-LAr +TMS with DUNE-PRISM: moveable LArTPC system
  - ND-LAr: 7x5 array of modular 1x1x3 m^3 LArTPCs with pixel readout
  - TMS: Muon spectrometer: magnetized steel range stack to measure μ momentum/sign from ν_μ CC interactions in ND-LAr
  - DUNE-PRISM: ND-LAr + TMS move up to 28.5 m off-axis
- SAND: Multi-purpose on-axis magnetized detector
  - KLOE SC solenoid and Calorimeter
  - GRAIN: Optical LAr target
  - STT: STraw tube Tracker system

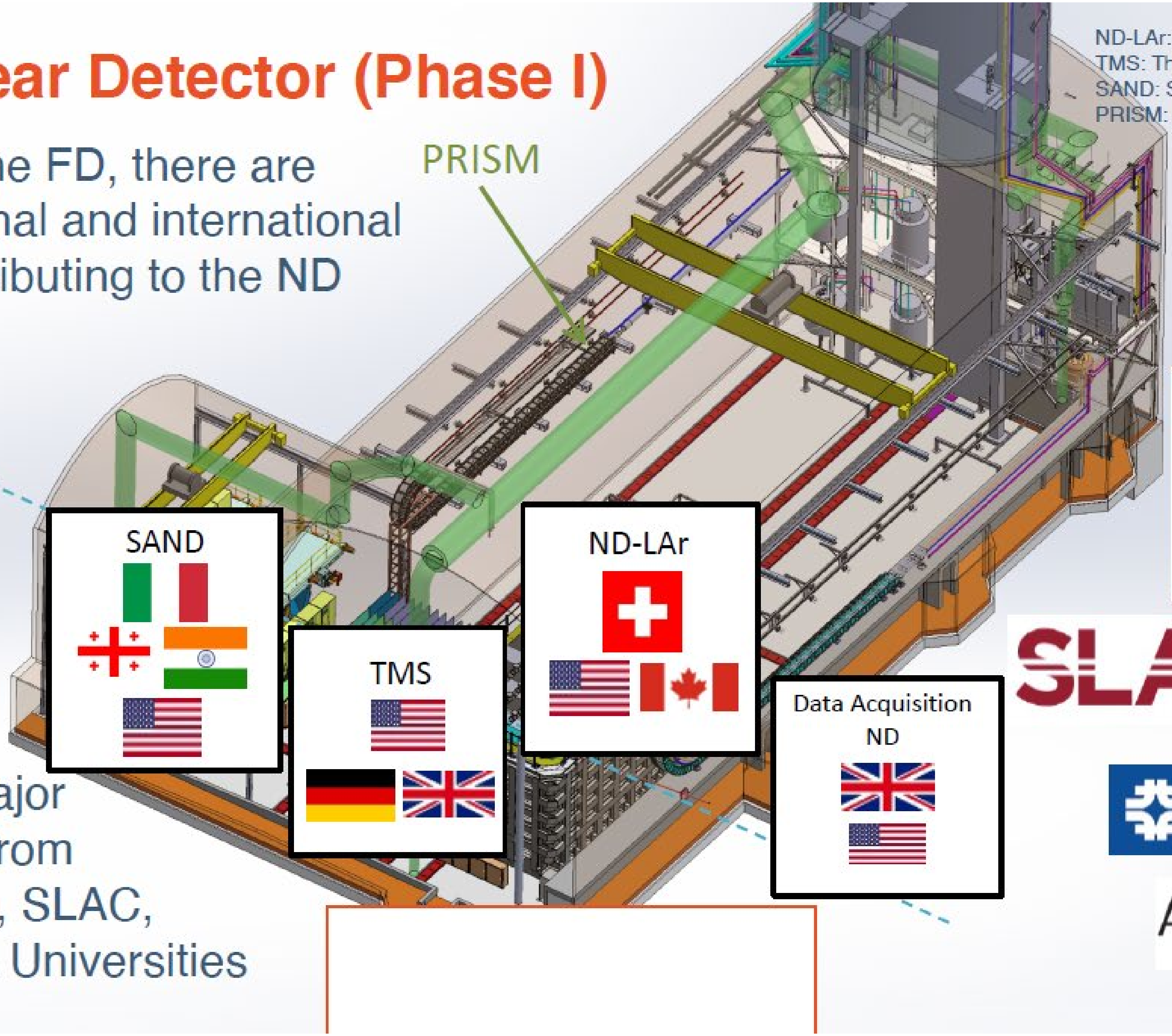


Suitability/necessity of Phase 1 ND affirmed by LBNC

DUNE Near Detector (Phase I)

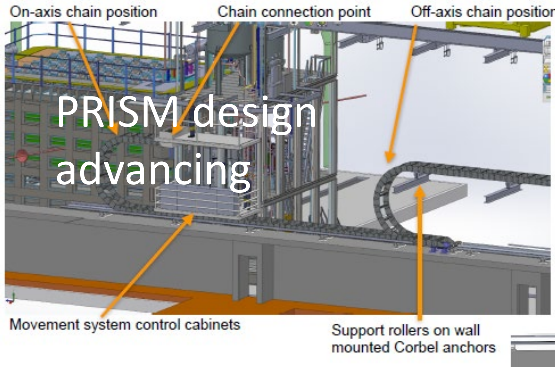
ND-LAr: liquid argon TPC near detector
TMS: The Muon Spectrometer
SAND: System for On-Axis ν Detection
PRISM: off-axis movement system

- Just as with the FD, there are multiple national and international partners contributing to the ND
  - Our partners have been building prototypes & sending detector components
- In the U.S., major contributions from LBNL (pixels!), SLAC, ANL, FNAL, & Universities

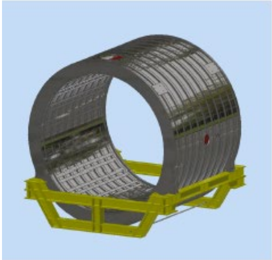


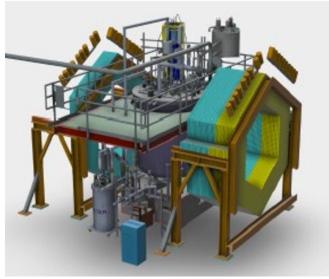
Status of Phase I ND

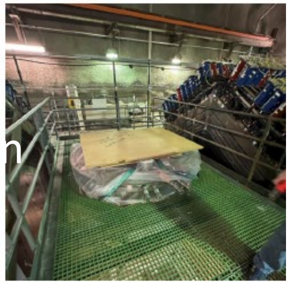
From H. Tanaka



- Steady progress in design and technical development of all subsystems
  - TMS: new short stack design and planning towards preliminary design review
  - SAND: KLOE-to-SAND activities, prototyping of STT and GRAIN
  - ND-LAr: review of 2x2 lessons learned, final stages of 2x2 deployment, preparation for FSD
  - ND-LAr Cryostat: new muon window design, cost analysis with SBND
  - DUNE-PRISM: progression of design and interfaces
  - ND I&I: Detailing of installation plan
- Planning for the Overall Plan:
  - Still working to accommodate US cost cap
  - Overall plan to (US) CD2 and beyond

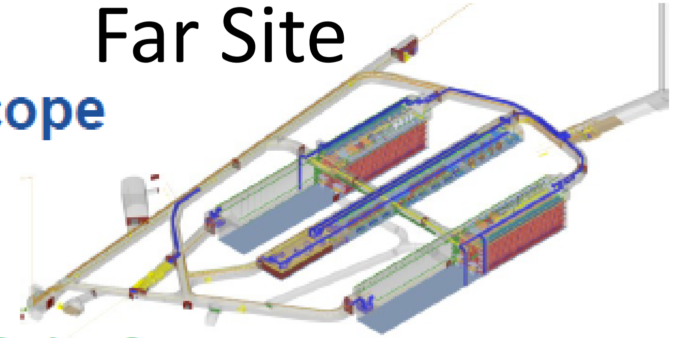


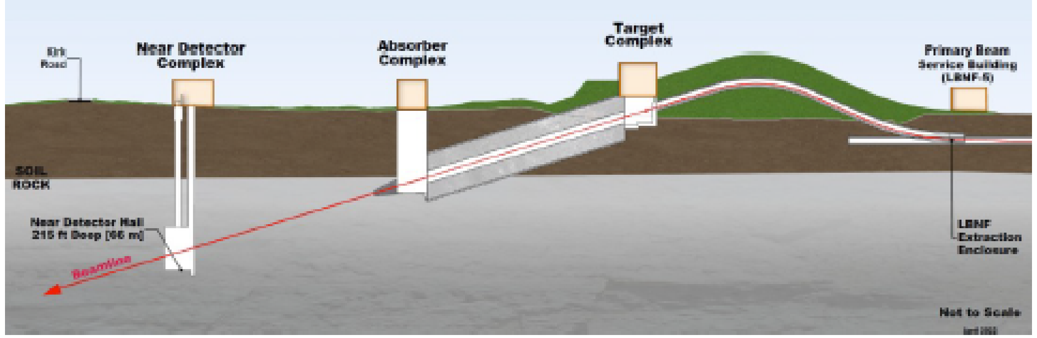




LBNF/DUNE-US Project Scope

Far Site





LBNF/DUNE-US Project Scope Far Site Near Site

	Component	DOE Project Scope (meets 2014 P5 minimum to proceed – Phase I)	Phase II Requirements (meets 2014 P5 goal)
Near Site	Conventional Facilities	• Constructed to support 2.4MW primary and neutrino beamline • Constructed to support underground Ph I & II Near Detector	• None
	Neutrino Beamline	• Wide-band output neutrino beam, 1.2MW initially, designed to be upgradeable to 2.4MW	• 2.4MW capable target and new horns • New decay pipe window • Some additional cooling and instrumentation
	Near Detector	• US contribution to the DUNE Near Detector (Ph I)	• US contribution to more capable Near Detector (Ph II)
Far Site	Conventional Facilities	• Surface and underground facilities & infrastructure for 4 detector modules	• None
	Cryostats	• For 2 detector modules (CERN)	• For 2 detector modules
	Cryogenics	• 3 x nitrogen units; 35 kton liquid argon for detector modules	• 1 x nitrogen unit; 35 kton liquid argon for detector modules
	Far Detector	• US contributions to 2 x DUNE LAr TPC modules	• US contributions to 2 x DUNE LAr TPC modules

Facility scope supports DUNE Phase II

LBNF Update

- Significant progress on DOE Critical Decision milestones
  - ✓ CD-1RR was approved by DOE on 16 Feb 2023.
  - ✓ CD-3a for Far Detectors and Cryogenic Infrastructure (**FDC**) Subproject was approved by DOE on 21 Feb 2023
  - ✓ CD-3a for Near Site Conventional Facilities and Beamline (**NSCFB**) Subproject was approved by DOE on 25 Mar 2023
  - ✓ CD-2/3 for Far Site Conventional Facilities – Building and Site Infrastructure (**FSCF-BSI**) Subproject was approved by DOE on 25 Mar 2023
- Excavation is about 65% complete overall; the central utility cavern has been fully excavated!
  - Safety performance of subcontractors continues to be very good
  - No dust complaints for over one year; mitigation efforts continue to be effective
  - Managing some production challenges due to removal of Yates shaft from service and rock skip capacity – will require some equitable adjustments to contract (cost and time)

LBNF Status - Schedule

	Subproject	CD	Q1 2022	//	Q3 2022	Q4 2022	Q1 2023	Q2 2023	Q3 2023	Q4 2023	Q1 2024	Q2 2024	Q3 2024	//	Q2 2025	//	Q4 2025
	All	CD-1RR			IPR 11-15 Jul		ESAAB 19 Jan										
Far Site	Excavation	CD-2/3	IPR 10 - 12 Jan		ESAAB 19 Aug												
Far Site	Building & Site Infra	CD-2/3				IPR 15-17 Nov	ESAAB 23 Mar										
Far Site	Far Detectors and Cryo	CD-3a				IPR 8 Nov	ESAAB 21 Feb										
Far Site	Far Detectors and Cryo	CD-2/3						DR 20 -23 Jun	IPR 12-15 Sep		ESAAB TBD						
Near Site	Conven. Facilties and Beamline	CD-3a				IPR 6 Dec	ESAAB 23 Mar										
Near Site	Conven. Facilties and Beamline	CD-2/3								IPR TBD		ESAAB TBD					
Near Site	Near Detector	CD-2									IPR TBD		ESAAB TBD				
Near Site	Near Detector	CD-3													IPR TBD		ESAAB TBD

Project focused on next critical milestone for FDC

- Director's review is planned for next month
- DOE IPR is planned for mid-September

DOE critical milestone review

DOE critical decision (ESAAB) timeframe

Notes:

Quarters shown are calendar year

Bolded dates are set with DOE

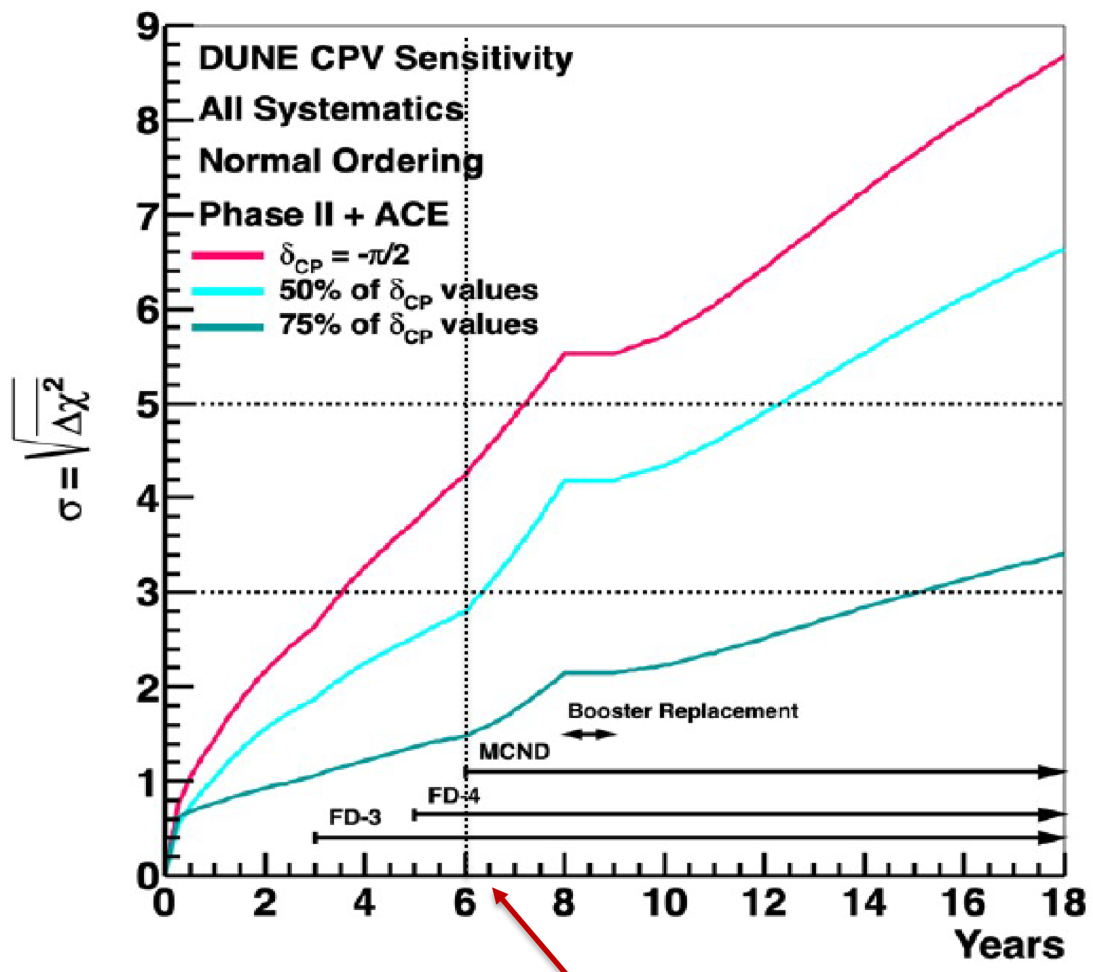
Each subproject will also have a CD-4 milestone review (not shown).

Near Site CF + Beamline update

- Currently analyzing potential impact of a year-long continuing resolution (CR) on ability to start NSCF+B subproject work.
  - Concern:
    - Project is still on steep funding ramp and has two remaining incremental funding increases in FY24 and FY25, +$75M and +$50M respectively
    - NSCFB work requires two major civil construction contract awards in FY25 (~$350 to $450M value)
    - Year-long CR could delay start of construction work, delay project completion, and trigger cost increases
  - Working to understand potential impacts if experience extended CR yet optimize execution capability.
  - Potential mitigation under consideration:
    - Push overall subproject CD-2/3 review to mid-2024 timeframe
      - Assume will have better information on FY24 and FY25 appropriation outlook at this time
    - Request CD-3b approval of certain beamline scope in late 2023 to maintain planned execution schedule

DUNE Phase II Physics and ND Role…....

DUNE Phase II = ultimate CPV reach

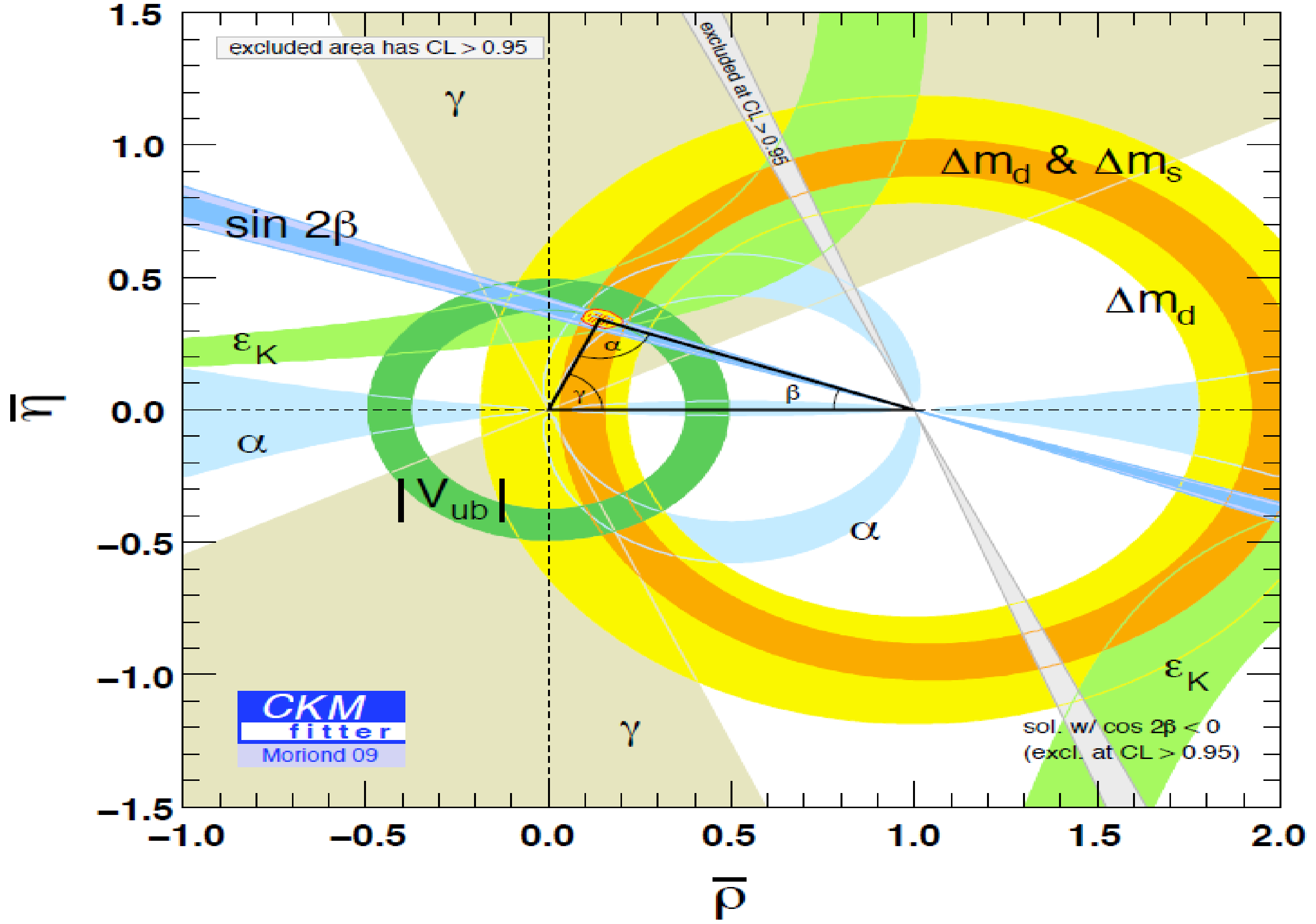


- If $\delta_{CP} = \pm 90°$, DUNE reaches 3σ CPV in 3.5 years, 5σ in 7 years
  - Hyper-K will likely get there first, if/when the mass ordering is known
- If $\delta_{CP} = \pm 23°$, it is extremely challenging to establish CP violation at 3σ → DUNE and Hyper-K are competitive and complementary

Improved systematics constraints from "More Capable" ND necessary to reach osc. physics goals

Ultimate goal for Neutrino Mixing

What we ultimately want to achieve:



We need to do this in the lepton sector!

June 14, 2023 ν Beyond DUNE

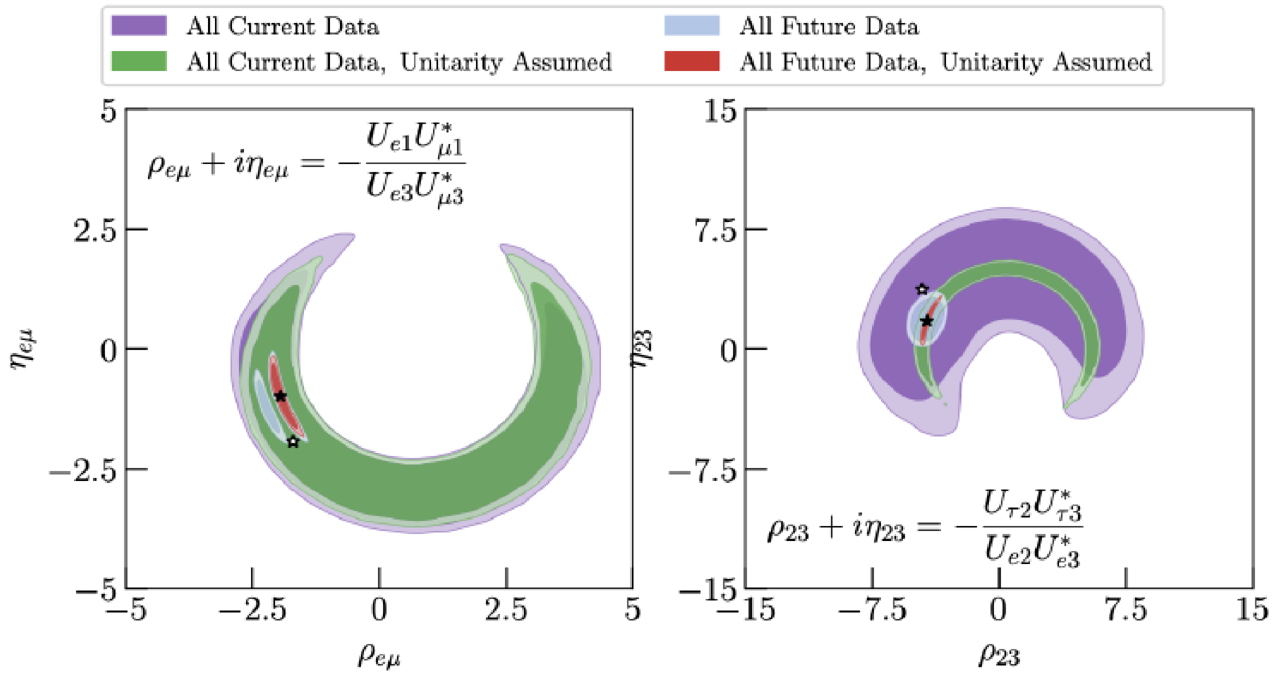


FIG. A1. Current (purple and green) and expected future (pale blue and red) measurements 95% (dark colors) and 99% confidence level (light) of two different unitarity triangles – $\rho_{e\mu}$ vs. $\eta_{e\mu}$ (left) and ρ_{23} vs. η_{23} (right). We contrast two assumptions in this figure, showing the resulting measurements when the unitarity of the leptonic mixing matrix is or is not assumed. Purple and light blue contours display the results when unitarity is not assumed, where green and red contours show the results when it is assumed. The filled-in (open) star indicates the best-fit point of the analysis of current data when unitarity is (not) assumed, corresponding to the green (purple) contours.

DUNE Phase II is the precision phase of mixing parameter measurement.

[Ellis, Kelly, Li, arXiv:2004.13719]

DUNE Phase II and beyond can also provide valuable tests of unitarity

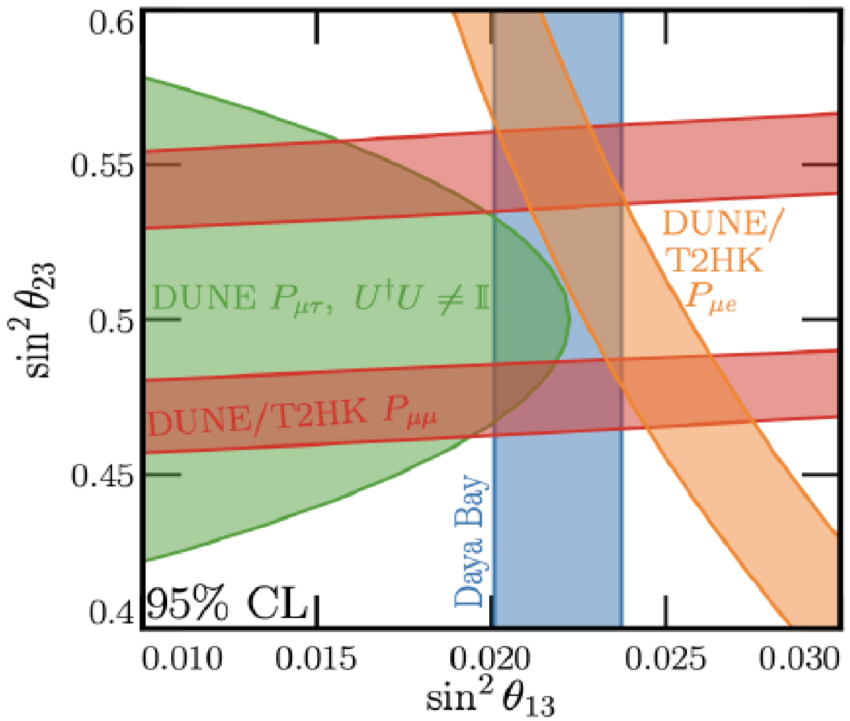
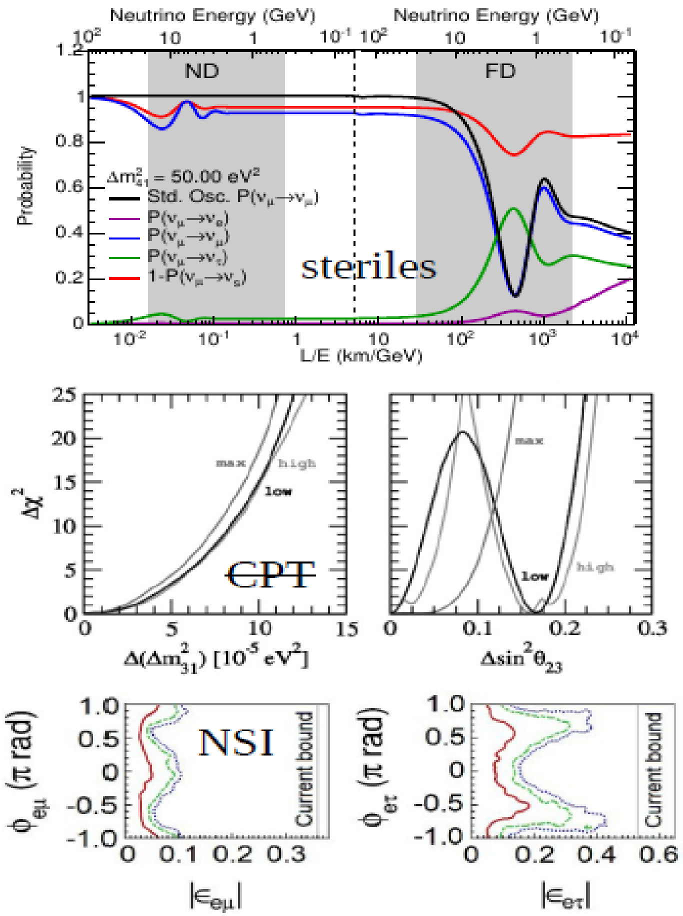


Figure 6. Projected measurements of $\sin^2\theta_{13}$ vs. $\sin^2\theta_{23}$ when unitarity is violated ($N_3 \approx 2$). For DUNE's long-baseline measurement of $P_{\mu\tau}$ (green), we simulate data assuming the underlying mixing matrix is non-unitary, and extract the measurement of these parameters assuming the matrix is unitary.

[Ellis, Kelly, Li, arXiv:2008.01088]

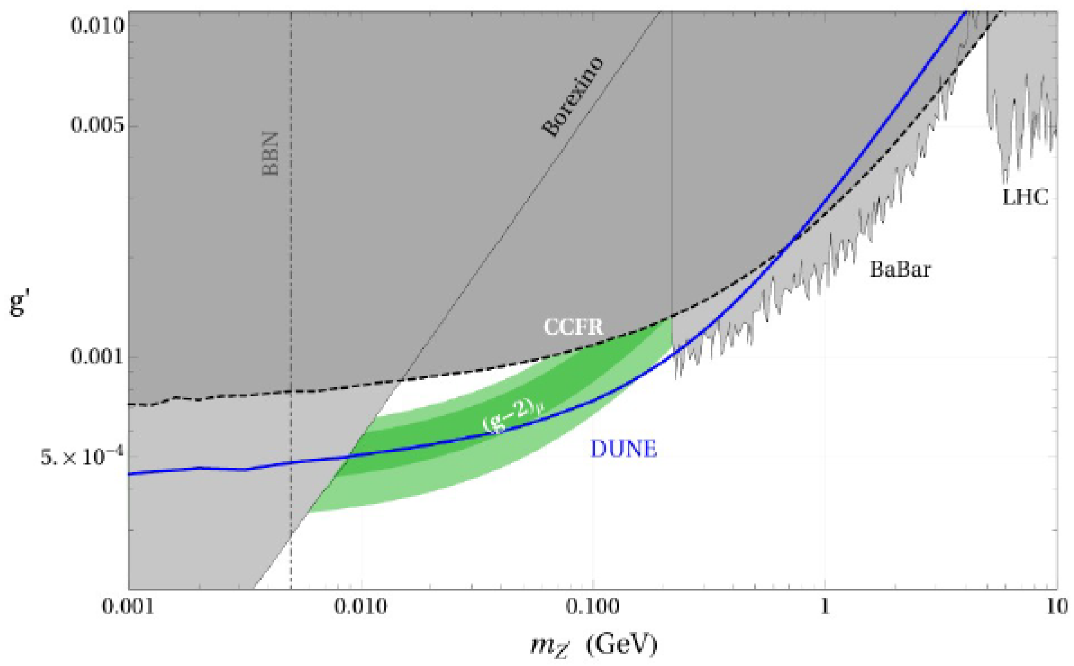
DUNE is sensitive to new physics in neutrino oscillations

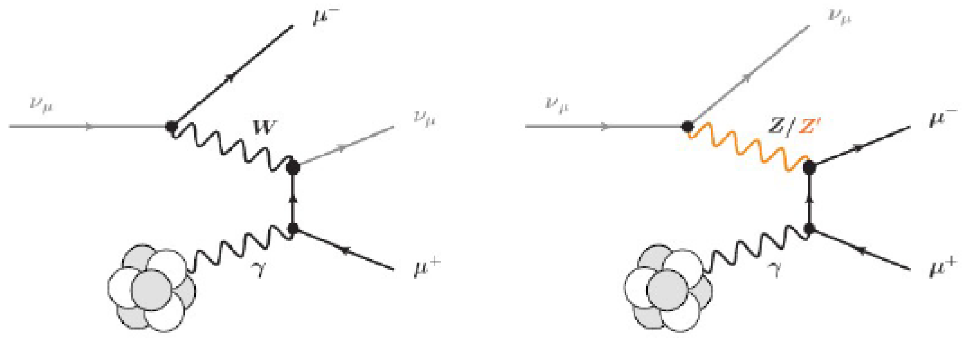


- If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrinos (top), CPT violation (middle), or NSI (bottom)
  - DUNE covers a very broad range of L/E at both the ND and FD
  - DUNE can measure parameters like Δm^2_{32} with neutrinos and with antineutrinos
  - DUNE has unique sensitivity to NSI matter effects due to long baseline
- Characterizing new physics will be challenging: precise measurements with small matter effect in Hyper-K **and** large matter effect in DUNE Phase II likely required

From C. Marshall talk to P5

BSM physics with the LBNF beam: Neutrino tridents at the ND

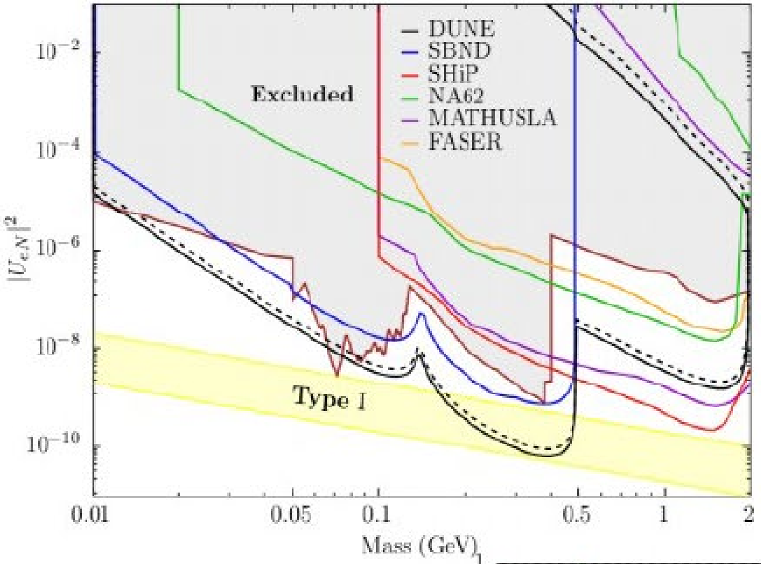


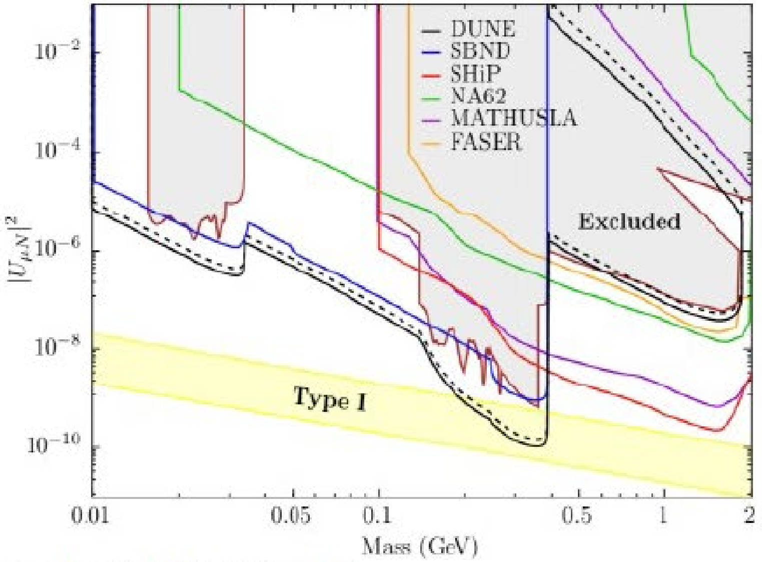


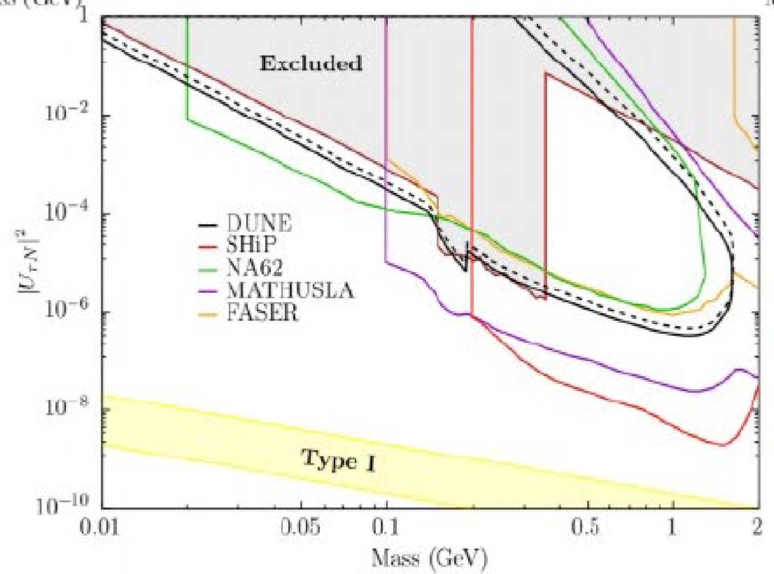
- DUNE ND-LAr will see ~100 μμ tridents per year (at 1.2 MW; XS scales with energy and Z^2)
- Backgrounds (mainly CC1π) can be mitigated by requiring clean vertex, two long, non-scattering tracks
- Tiny SM cross section, DUNE can search for enhancement due to Z'
- World-leading reach at low Z' mass is complementary to collider searches, and covers much of the remaining region that is consistent with a possible $(g\text{-}2)_\mu$ anomaly
- Also at ND (in backups): Heavy neutral leptons, boosted dark matter

From C. Marshall talk to P5

DUNE HNL sensitivity at ND



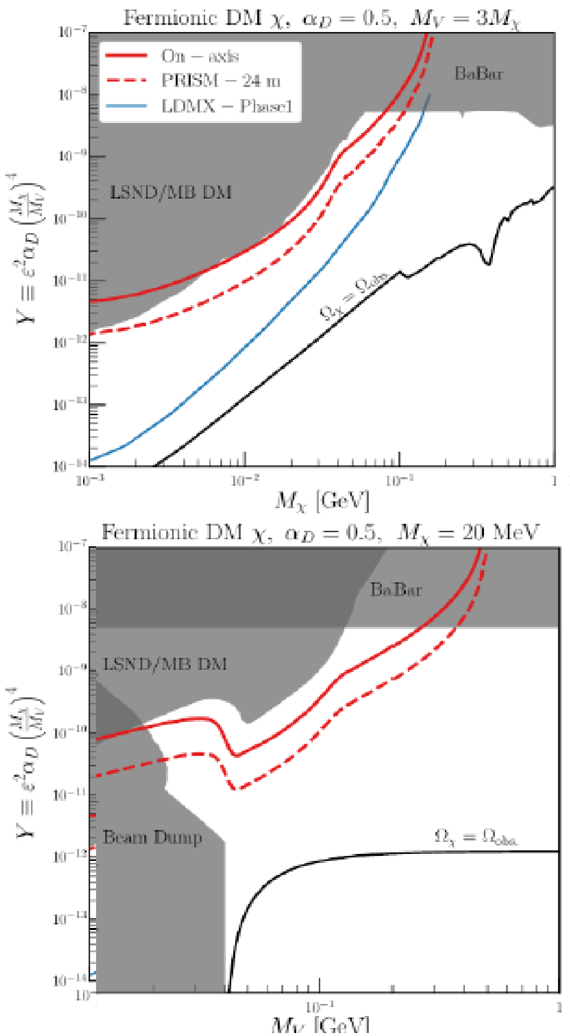




N → νee, $\nu e\mu$, $\nu\mu\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$
Phase II (22 MW-yrs)
no backgrounds → may require ND-GAr to reach zero background

From C. Marshall talk to P5

BDM from the beam



- $\chi e \rightarrow \chi e$ scattering in ND-LAr, from boosted DM produced in the beamline
- Backgrounds from $\nu e \rightarrow \nu e$ have different spectrum
- DM and ν have different dispersion, and looking at off-axis ND-LAr data improves the statistical separation
- Sensitivity at low mass is potentially world-leading

From C. Marshall talk to P5

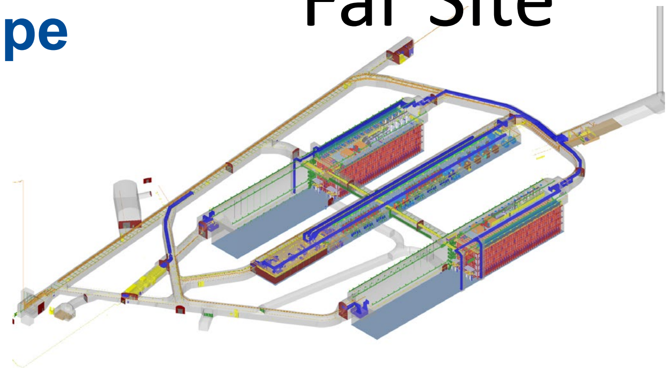
DUNE Phase II and P5

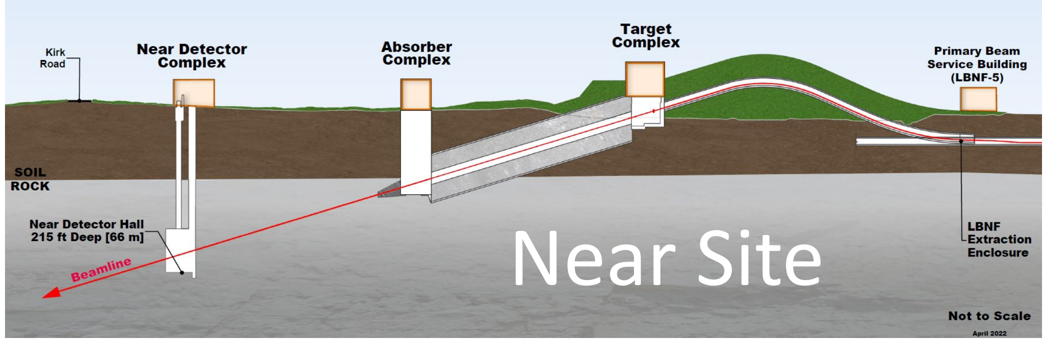
Particle Physics Prioritization Project Panel (P5)

- P5 is a special committee that reports to the High-Energy Advisory Panel (HEPAP) that advises the High-Energy Physics office of the US DOE Office of Science (funds LBNF/DUNE US) and the Division of Physics of the US National Science Foundation (NSF). The P5 is convened every 7-10 years as needed and the committee is charged to build on the "Snowmass" US HEP community study to hash out funding priorities for the next 10 years with a 20-year context
- The 2023 P5 is chaired by Hitoshi Murayama (UC Berkeley and Univ. Tokyo) and deputy Karsten Heeger (Yale)
- P5 held 5 Town Hall style meetings at different US national labs:
  - P5 Town Hall at Lawrence Berkeley National Laboratory, February 22-24, 2023 with a focus on Cosmic Frontier (except for High-Energy Astrophysics)
  - P5 Town Hall at Fermilab/Argonne, March 21-24, 2023 with a focus on Neutrino, Rare Processes and Precision Frontier, High-Energy Astrophysics
  - P5 Town Hall at Brookhaven, April 11-14, 2023 with a focus on Energy, Instrumentation, Computational Frontiers
  - P5 Town Hall at SLAC, May 2-5, 2023 with a focus on Underground, Accelerator, Theory Frontiers, Community Engagement

LBNF/DUNE-US Project Scope

Far Site





LBNF/DUNE-US Project Scope

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Far Site	**Conventional Facilities**	• Surface and underground facilities & infrastructure for 4 detector modules	•NONE
	Cryostats	• For 2 detector modules (CERN)	• For 2 detector modules
	Cryogenics	• 3 x nitrogen units; 35 kton liquid argon for detector modules	• 1 x nitrogen unit; 35 kton liquid argon for detector modules
	Far Detector	• US contributions to 2 x DUNE LAr TPC modules	• US contributions to 2 x DUNE LAr TPC modules

LBNF/DUNE @ P5

Communication with P5 is ongoing and being led by the DUNE Management Team (Spokes, Physics Co-ordinators, Resource Co-Ordinator, Technical Co-ordinators and Phase II Group lead) in co-ordination with Fermilab leadership and LBNF/DUNE-US project leadership.

- Presented our plans for Phase II at the Fermilab P5 Town Hall Meeting (all presentations here) March 21-24, 2023. Several rounds of Q&A on Phase II physics reach and Phase II detector designs and performance – see C. Marshall's presentation
- ACE Workshop Fermilab 14-15 June, 2023: more detail on the Fermilab Accelerator Complex Evolution (ACE) plan which delivers 2.1 (MI ramp upgrade) to 2.4 MW (Booster Replacement) to LBNF/DUNE.
- P5 Townhall SLAC: SURF expansion plans and possible new caverns near the DUNE campus @ the Ross shaft presented and initiated lively discussion.
- P5 cost sub-committee lead by Jay Marx has had 2 rounds of Q&A with LBNF/DUNE

Phase II FD Baseline and Boundary Conditions

- ***For the purpose of planning the DUNE collaboration will assume FD3 and FD4 are vertical-drift LArTPCs similar to FD2 as the baseline options***
- ***DUNE is actively exploring LArTPC detector options for Phase II with enhanced capabilities that could bring in significant contributions from existing partners and/or new partners.***
- ***DUNE is open to different detector proposals for FD4 that demonstrate that the following boundary conditions can be met:***
  - Sensitive to beam neutrinos of different flavor with good flavor separation on par with the Phase-I detector performance
  - Neutrino energy reconstruction with similar performance to LArTPC over the entire beam energy range (500 MeV to ~5 GeV
  - Demonstrate that the near detector complex can be updated to accommodate precision LBL physics if one of the Phase II FDs is not a LArTPC (for e.g. liquid scintillator)

Outcome of MoD workshop in Valencia (Nov. 2022)

(92 participants and R&D from US, Brazil,France,Germany,Israel,Italy,Spain,Switzerland,UK)

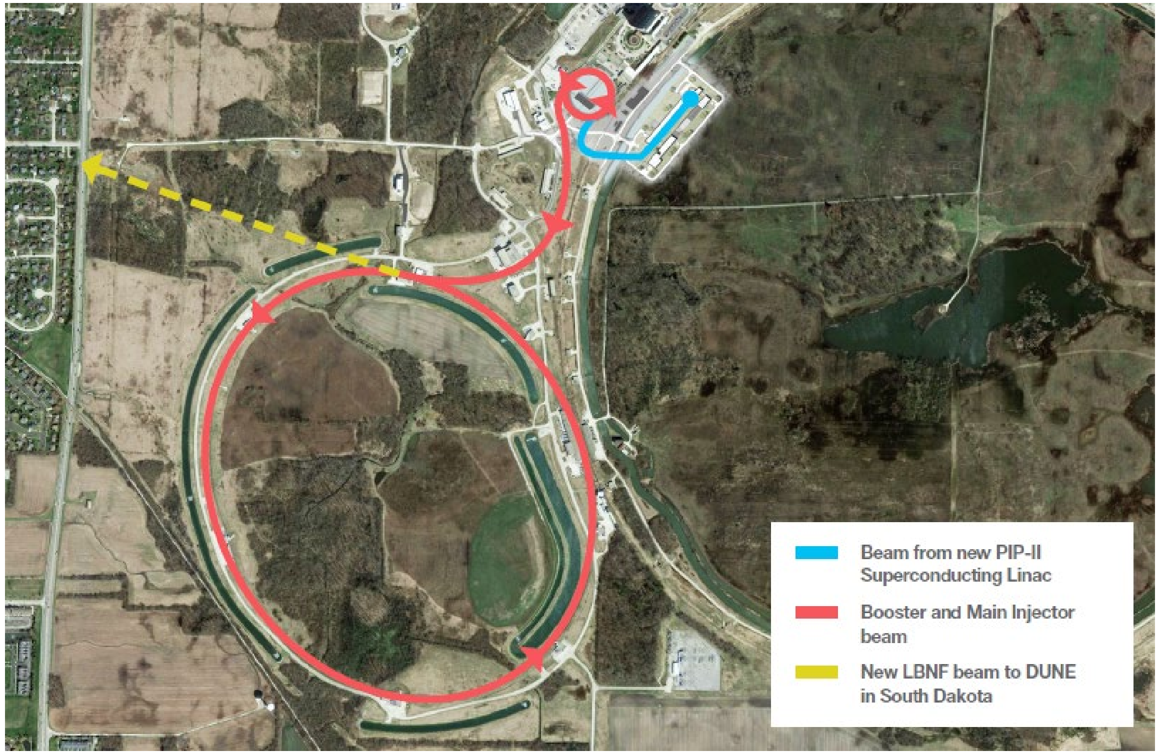
- **Incremental LArTPC R&D on mature options**
  - FD2 like (Vertical Drift) modules with "adiabatic" improvements, mainly in the light detection (baseline option)
  - Scalable options using pixel readout adapted from the near detector LArTPC
- **R&D for vertical drift LArTPC charge, light and combined charge+light readout options**
  - Ariadne: fast optical read-out using cameras, with Arapuca add-on
  - Q-Pix: pixel readout with reset time stamps to reduce data rates and lower thresholds
  - SoLAr/Q-Pix: pixel detector with integrated light pixels, Arapuca
- **R&D on new detector concepts**
  - Water-based liquid scintillator (Theia); separation of Cherenkov and scintilla timing.
  - SloMo: use underground argon in an acrylic vessel, reduce background.
  - "DUNE-β": 2% xenon and photo-sensitive dopant.

We need to develop a similar Phase II ND R&D plan

Fermilab Accelerator Complex Evolution (ACE) Plan and Phase II LBNF Beamline plans

Accelerator Complex in PIP-II / LBNF era (pre ACE plan)

- PIP-II Project provides
  - New SRF linac for injection into Booster at 800 MeV (present 400 MeV)
  - Booster cycle rate upgraded to 20 Hz from 15 Hz
  - Increased proton beam intensity at 8 GeV for 1.2 MW beam power from MI
- LBNF/DUNE-US Project provides
  - New proton beamline for up to 2.4 MW
  - Target systems for 1.2 MW
  - Shielding and absorber for up to 2.4 MW

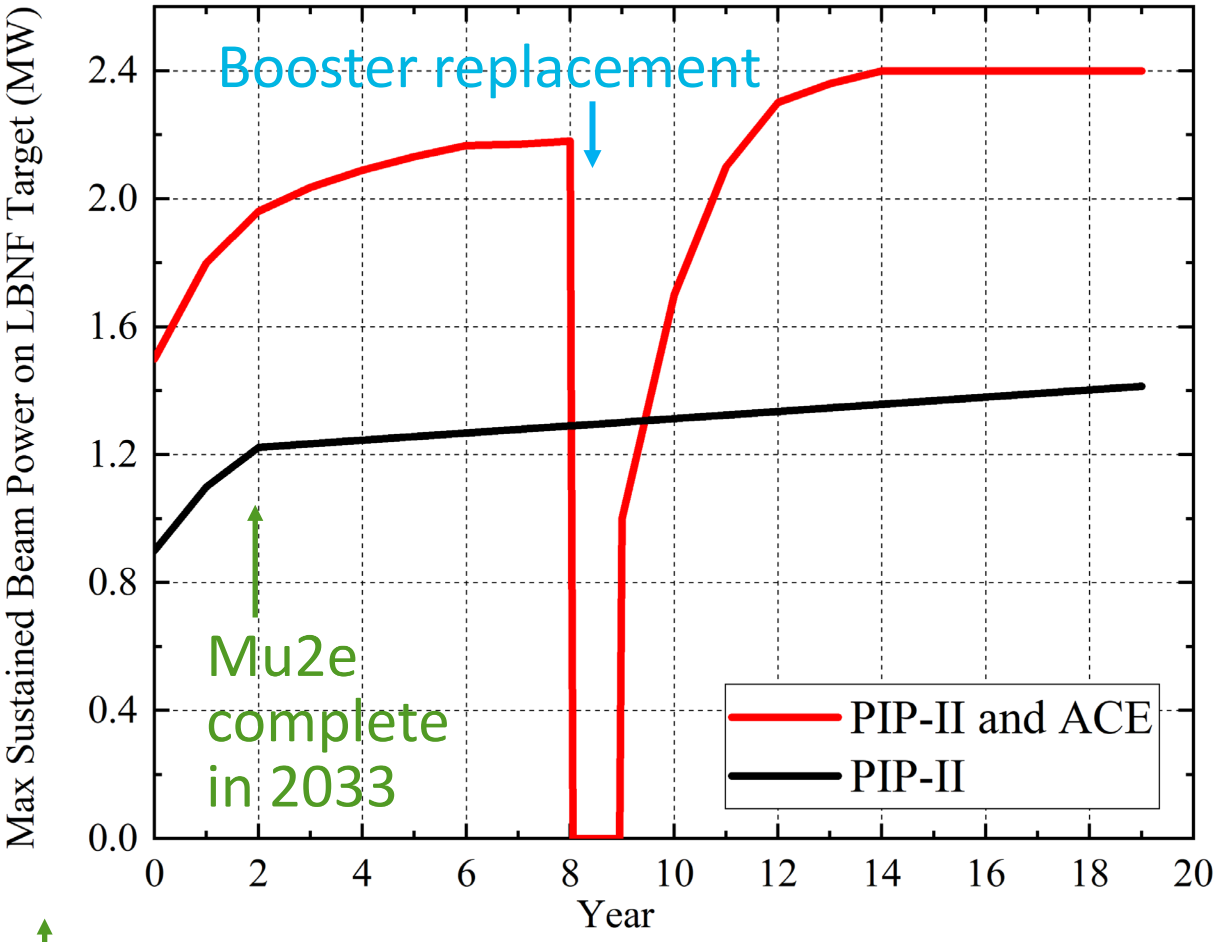


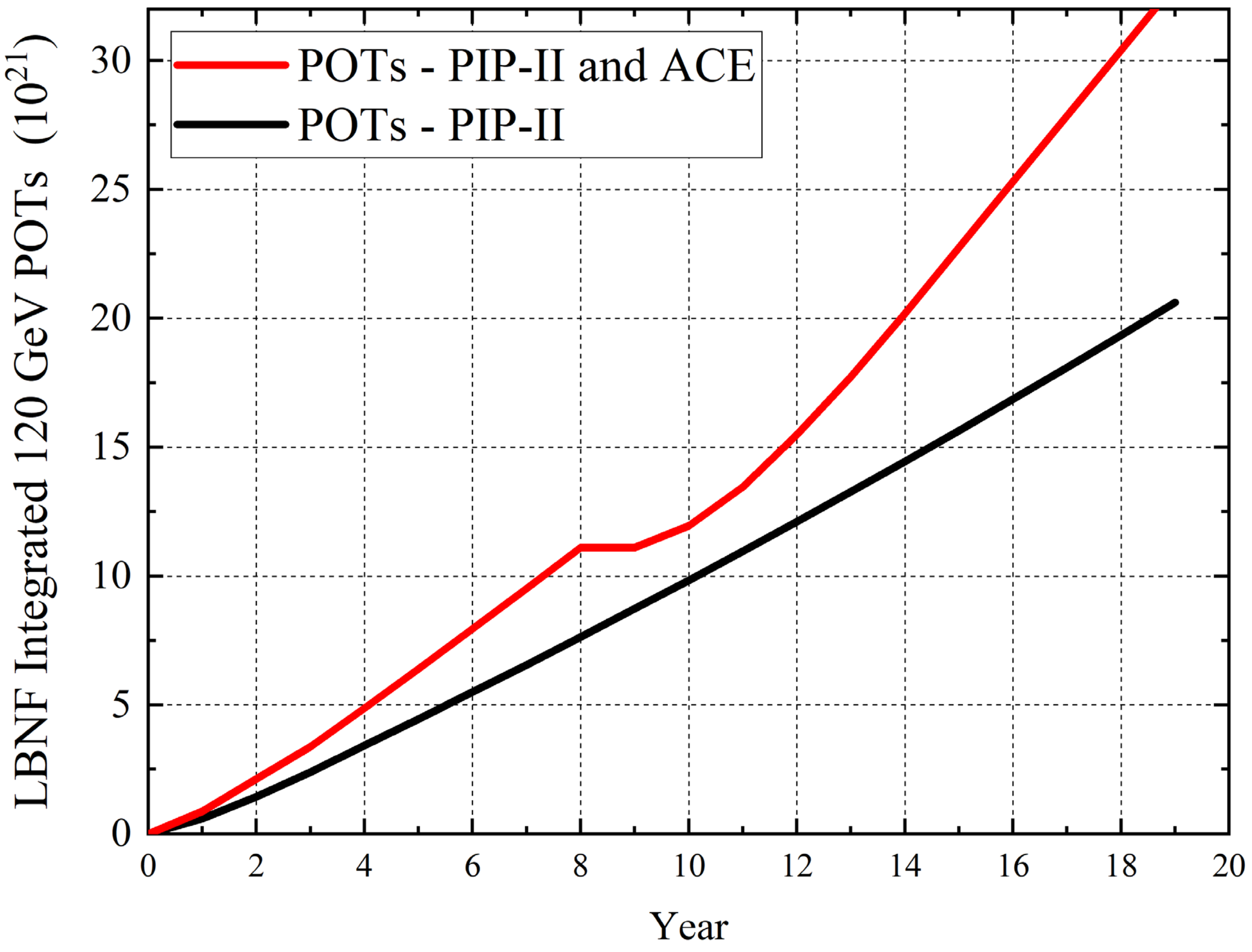
Accelerator Complex Evolution (ACE) plan

- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the Complex
- Establish a project to build a Booster replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

Previously referred to as PIP-III

DUNE power and POT implications

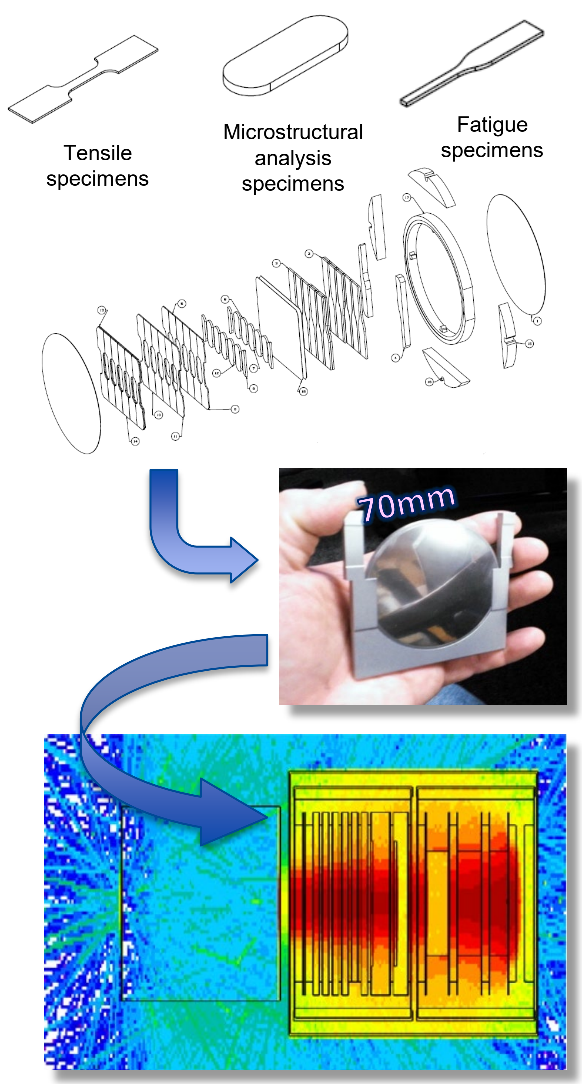




(Mu2e restarts 2029)

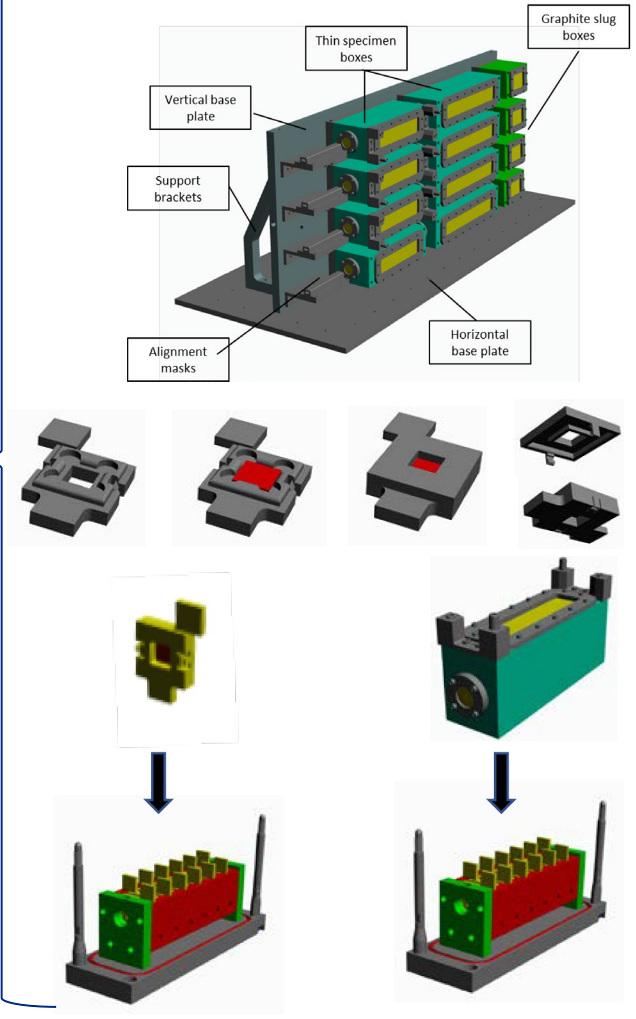
Fermilab

Target materials R&D on critical path to 2+ MW target



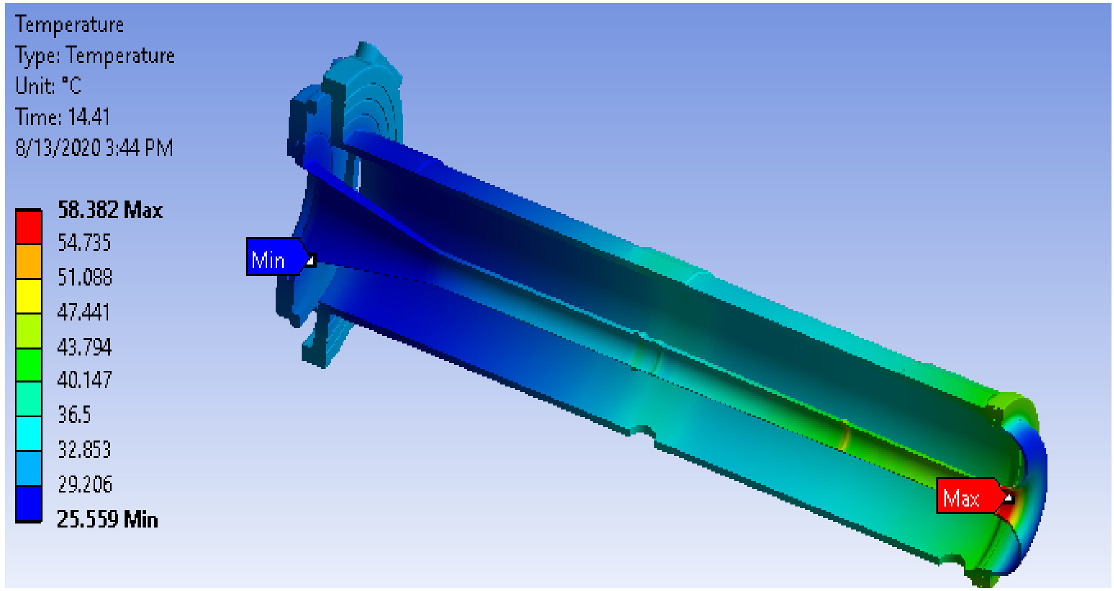
1. Identify candidate materials
2. High-energy proton irradiation of material specimens to reach expected radiation damage
3. Pulsed-beam experiments of irradiated specimens to duplicate loading conditions of beam interactions
4. Non-beam PIE (Post-Irradiation Examination) of specimens
   – Material properties
   – Microscopic structural changes
   – High-cycle fatigue testing

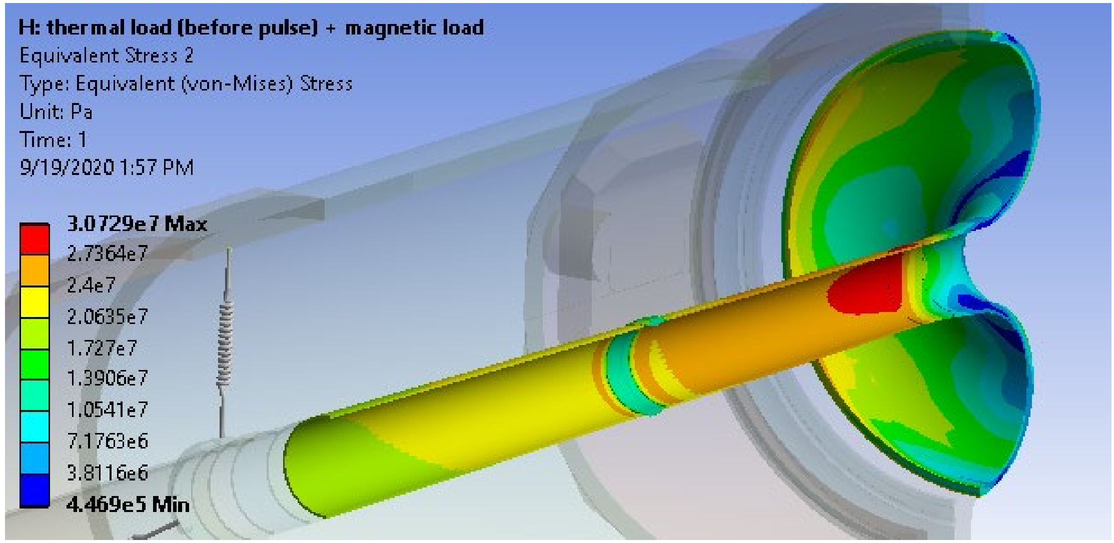
Five-year cycle needs to start ASAP



Horns for 2.4 MW performance

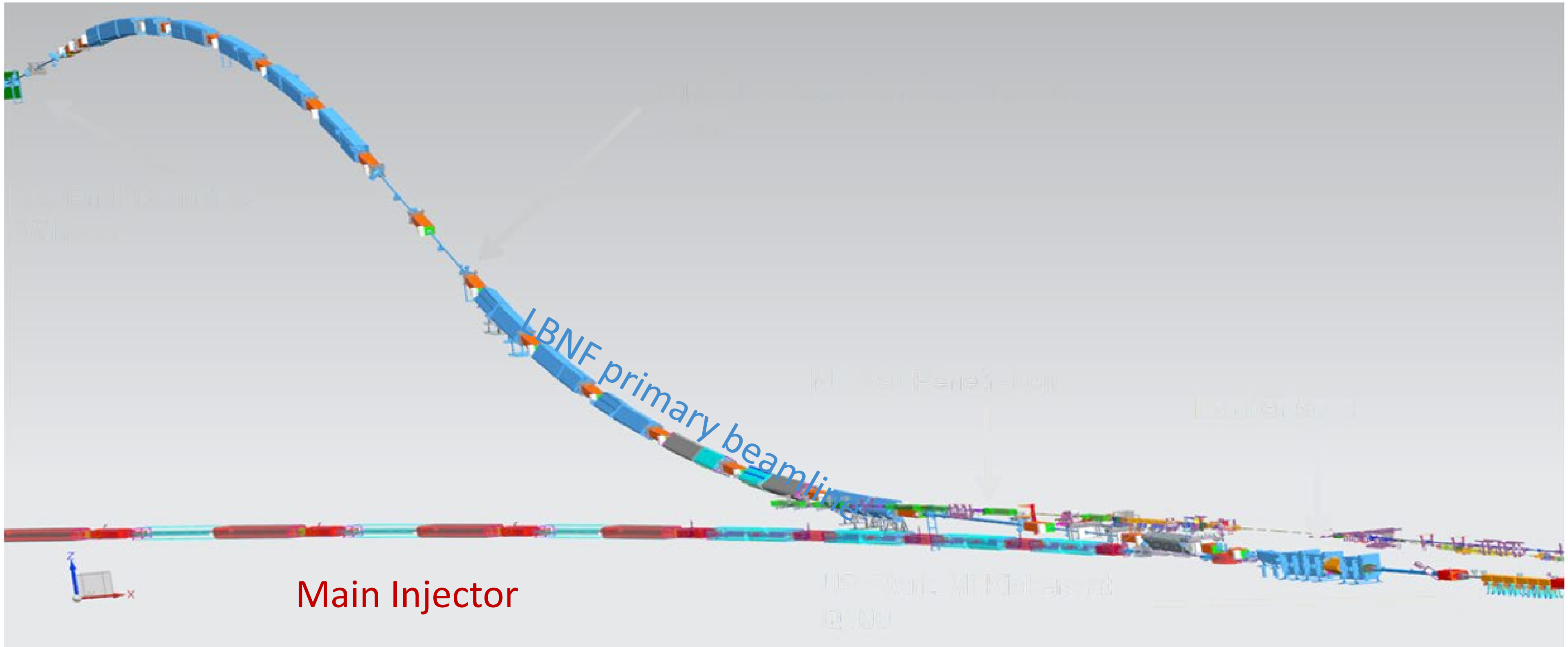
- Horn A requires reanalysis and likely redesign
  - 1.2 MW analysis indicates 2.7 safety factor on fatigue endurance limit
  - Likely redesign to:
    - Avoid beam heating in critical locations
    - Strengthen structure in critical locations
- Horns B&C see less beam heating
  - Safety factor: 7.3 for 1.2 MW operation
  - Require reanalysis, but less likely redesign





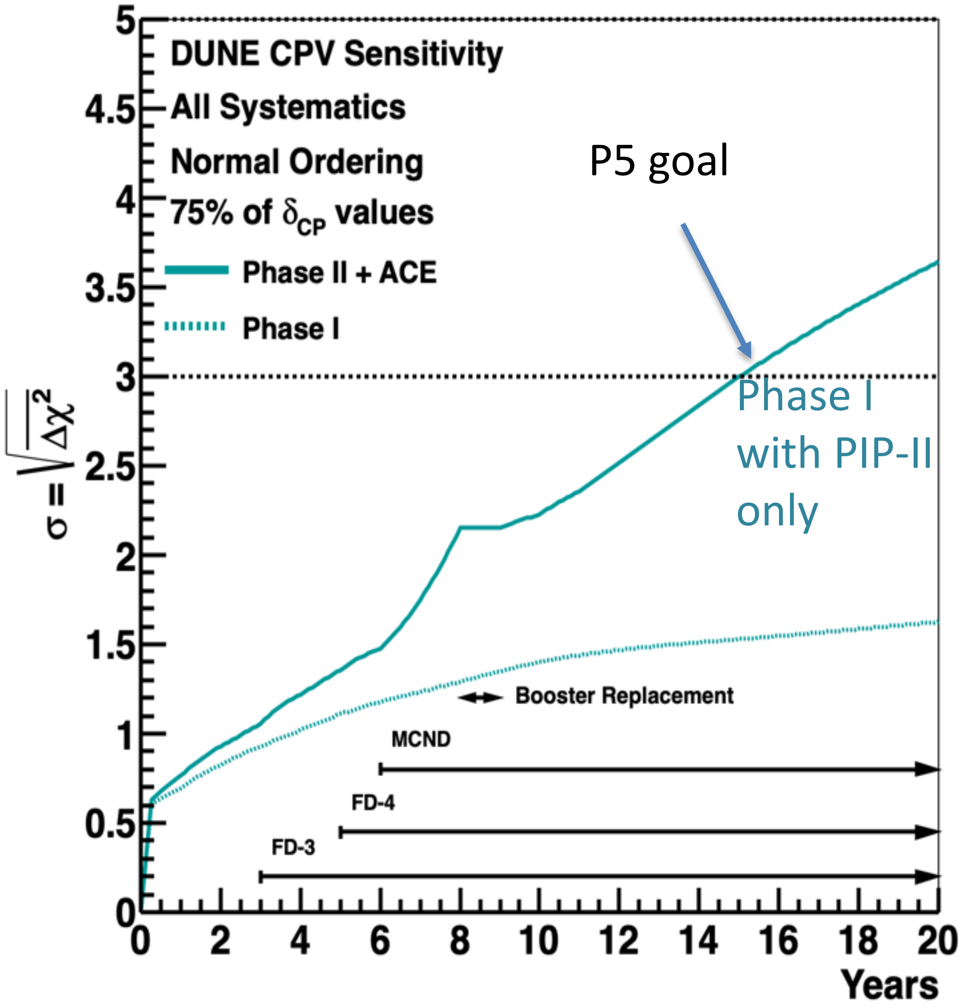
LBNF beamline

- Larger power supplies to ramp twice as fast, may need more building space
- Kicker power supply modifications to charge up faster
- Cooling water: additional pumps to remove and exhaust additional heat

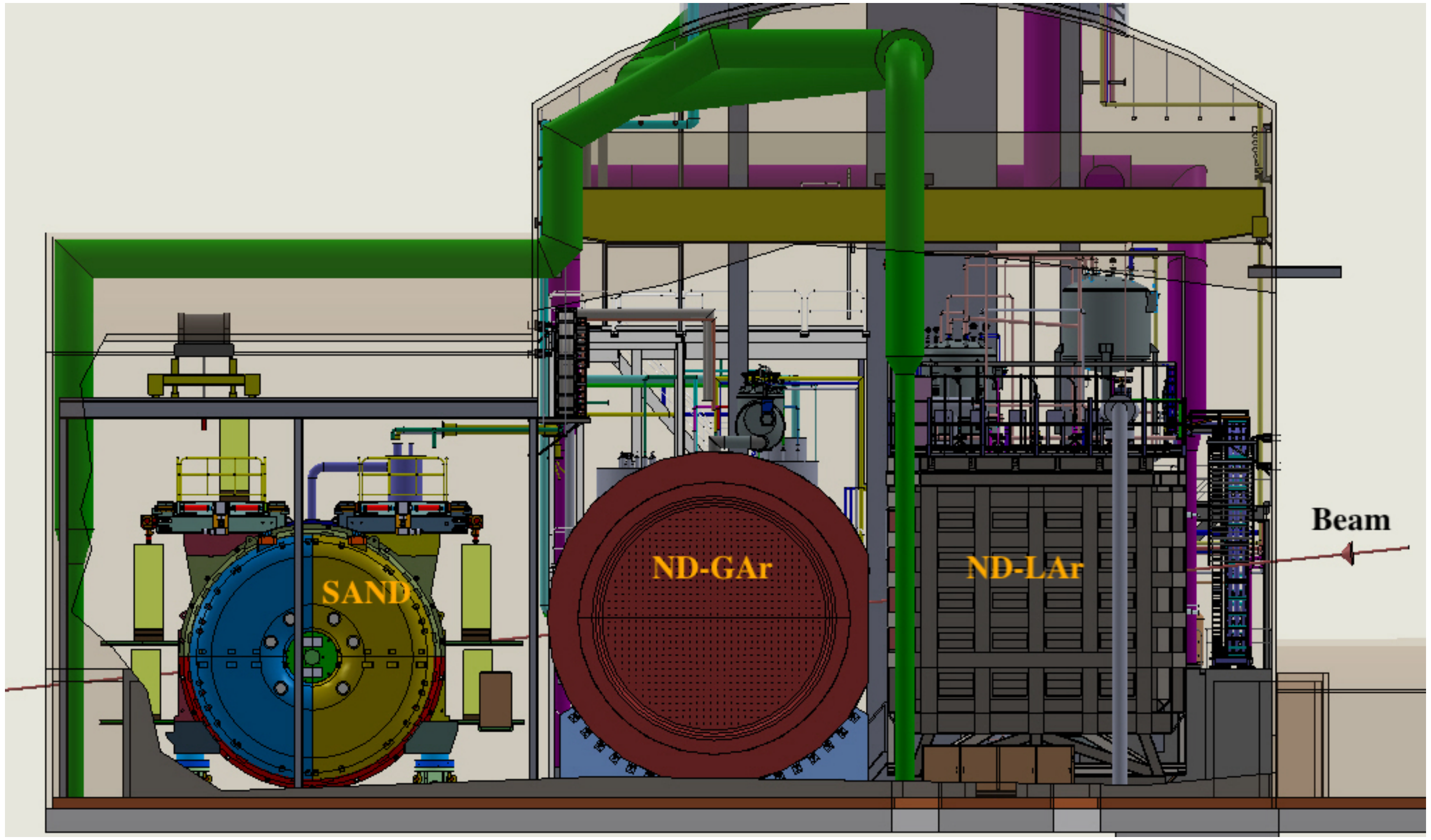


DUNE Message on Phase II to P5

- **DUNE Phase II (beam+detectors) will be essential to complete the DUNE program as outlined by the 2014 P5: reach 3σ sensitivity for 75% of δ_{cp}**
- The DUNE Phase II Far Detector baseline design is based on two vertic drift LArTPC modules which meets all the requirements needed to reach the full DUNE physics goals.The technically driven schedule for Phase I would have FD4 completed by end of 2036
- Several LArTPC R&D lines have been identified that will enhance the physics performance of the DUNE FDs. Non LArTPC options for FD4 su as WbLS detectors could be considered if they meet the performance requirements of DUNE.
- *The enhanced physics potential of DUNE enabled by Phase II far detectors ranges from physics at 10 GeV ($\nu\tau$ appearance) to physics at few MeV (solar ν) and below (DM?)*
- *Phase II More Capable ND (MCND) delivering improved systematics is needed to reach goals – design concepts are not as mature as FD*
- *DUNE Phase II R&D is already engaging potential partners from the existing effort and attracting new communities for both FD and ND.*
- *Reaffirming the US commitment to full DUNE scope would ensure continued support of the international community and the realization a transformational scientific program*



Developing the Phase II ND Concept



Phase II ND Workshop, Imperial College, London June 20-22, 2023.

Phase II ND Planning Goals (this workshop ?)

1) Develop the performance requirements for Phase II ND based on the desired systematics reach to achieve the DUNE long baseline oscillation physics goals in the precision phase
2) Develop a plan and schedule for assessing a more realistic understanding of the performance of the Phase I DUNE ND in reaching the LBL oscillation physics goals: For osc. physics goals is the Phase II ND = Phase I ND + improved reconstruction and a more realistic global analysis?
3) *Identify the minimum ND upgrade needed to reach DUNE LBL osc. physics goals*
4) Identify key physics searches where DUNE ND can be world leading and which are not accessible/competitive with the Phase I ND: BSM, EW precision measurements (?), neutrino scattering physics…etc
5) Identify the Phase II ND design requirements needed to realize the ultimate reach of the DUNE ND physics searches enabled by LBNF Phase II beamline+ACE+ND Facility..
6) Identify candidate Phase II ND designs and assess their maturity and R&D needs: For e.g. NDGAr, SAND upgrades for scattering physics..
7) Identify key metrics to assess and compare Phase II ND candidate detector performances both to Phase I detectors and to other Phase II detector candidates for a) LBL physics reach b) Key BSM searches. *We need apples to apples comparisons*.


Thank You!