Theia Topics in Upcoming DUNE Phase 2 Meetings

Mike Wilking

Theia LBL Meeting

June 9th, 2023

DUNE Phase 2 Meetings

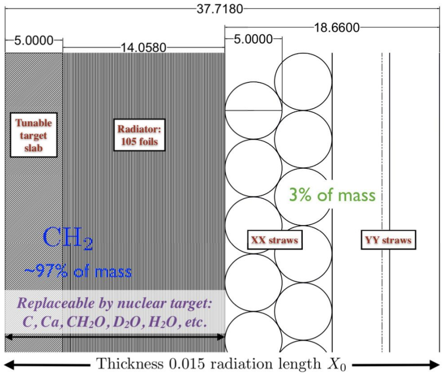
- Next Monday, June 12th at 8am CDT, Michael Wurm will present the ongoing R&D WbLS effort toward Theia
  - Indico: https://indico.fnal.gov/event/60172/
  - Zoom: https://fnal.zoom.us/my/stefansoldner?pwd=M1dBUDFFSHNHbjVqUmJzNlgwTVU4dz09
- Starting June 20th, the 3-day DUNE Phase 2 ND Workshop will begin at Imperial College, London
  - https://indico.fnal.gov/event/58795/
- There will be several talks that potentially include Theia-related content
  - SAND Detector - Phase 2 (Alessandro Montanari)
  - Exploring Nucleons and Nuclei with SAND (Roberto Petti)
  - WbLS targets in the ND-GAr ECAL (M. Wilking)
  - DUNE-PRISM for Phase 2 (M. Wilking)
    - This will include a discussion of the potential hall expansion

Near Detector Concepts

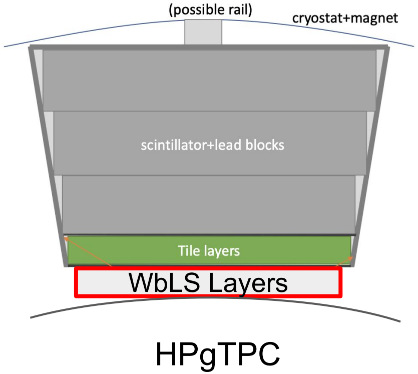
- Several concepts are possible with varying levels of complexity
- SAND already exists, so adding targets for studying WbLS nuclei is possible
  - On-axis only, but this can constrain extended xsec models
- ND-GAr is a primary goal for a DUNE Phase-2 ND
  - Adding WbLS targets in the upstream ECAL is possible
- The extended near detector hall can potentially accommodate more detectors
  - TMS can then be retained instead of scrapped when ND-GAr is installed
  - A new, dedicated detector can be installed upstream of TMS

Least complex

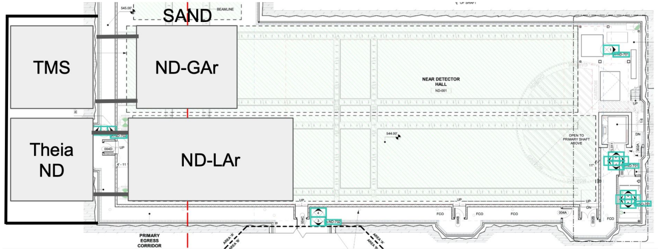
Additional nuclear targets in SAND



WbLS targets in the ND-GAr ECAL



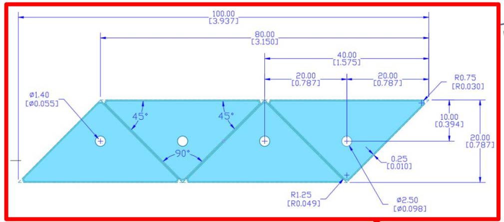
Dedicated Theia ND

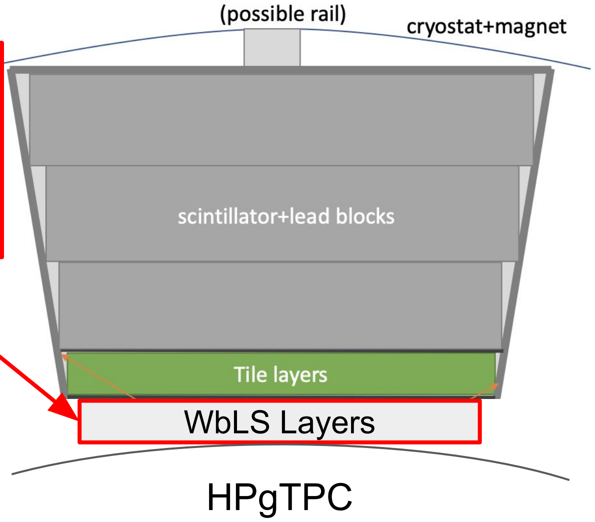


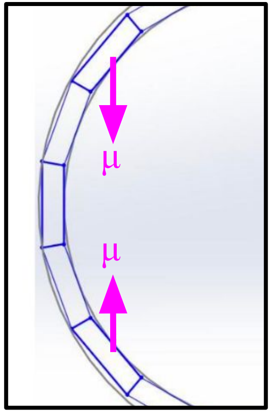
Most complex

WbLS Inside ND-GAr ECAL

- WbLS layers would need to track X & Y positions
  - Optically segmented X & Y bars or 3D cubes
  - Or perhaps a non-segmented LiquidO detector with X & Y fibers
- A few cm WbLS layers provides ~1 ton of target mass
  - A few tons of WbLS in a 2.4 MW beam would produce:
    - ~1M ν_μ-CC events per year on-axis (14 week run)
    - ~100k ν_μ-CC events per year 8m off-axis (2 week run)
    - ~10k ν_μ-CC events per year 28m off-axis (2 week run)
- Additional benefit: variation in detector configurations allows for sampling all of the muon angle phase space
  - The lack of muon acceptance near 90° was an important limitation of the T2K FGD+TPC configuration

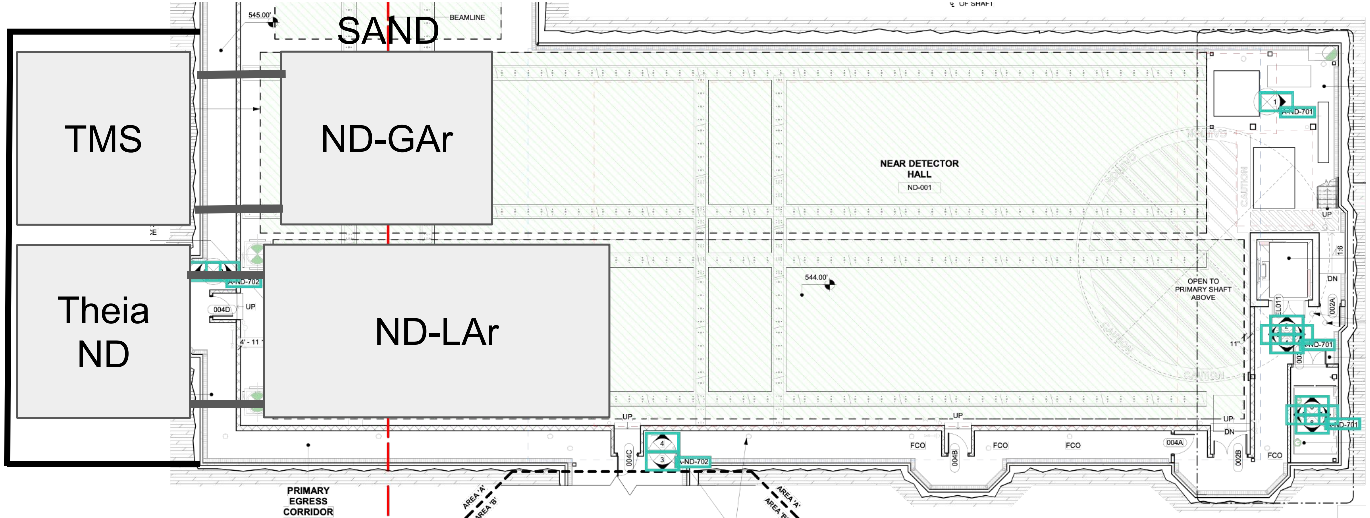






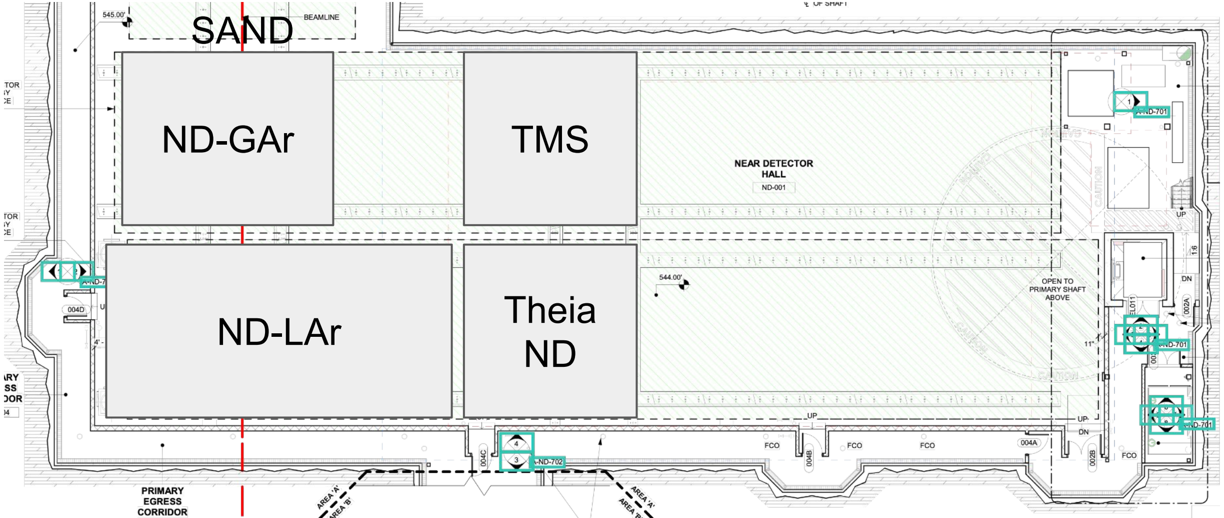
A Dedicated Theia Near Detector

- If the long dimension of the ND Hall can be slightly extended, it may be possible to install a dedicated Theia ND
  - The new alcove need not extend to the full cavern height; just tall enough to insert the detectors
  - This end of the cavern will be mostly bare rock with almost no utilities
- The disassembly of TMS is very time consuming and may delay the installation of ND-GAr
  - Instead, TMS could be reused as the muon catcher for a Theia ND



A Dedicated Theia Near Detector II

- If hall modification proves to be too difficult, one could also consider placing the additional detectors off-axis
  - After O(10) years of DUNE operation, will far-off-axis LAr measurements still be needed?
  - In this configuration, Theia ND would never be on-axis
    - In the current LAr PRISM analysis, brief horn current variations are used to access higher energies
      - Further study would be needed to assess the physics reach of this configuration



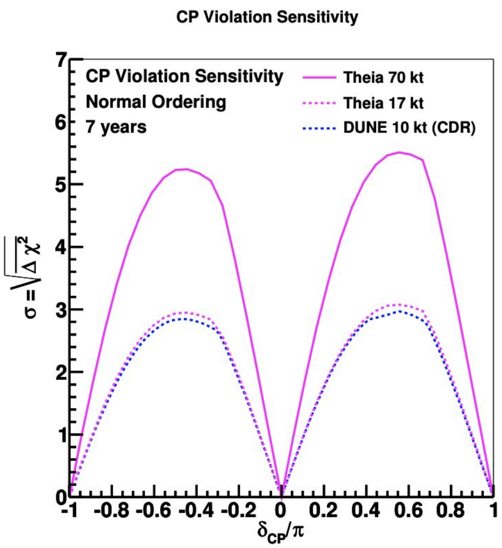
Status / Next Steps

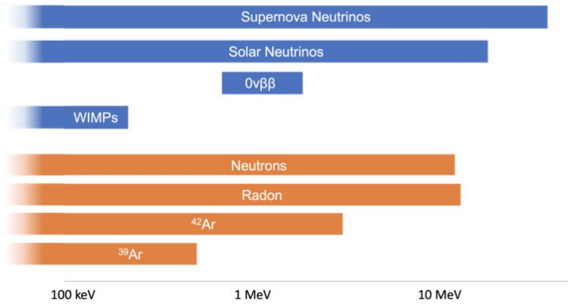
- At the collaboration meeting, it was made clear that some people have already decided that the technology choice (LAr over WbLS) should not wait for a discussion of the physics capabilities of the proposed detectors
  - We will have to have clear, well-motivated presentations, as we will certainly face opposition in these meetings
  - (e.g. comments like “Theia will cost $500M” were made, so we should decide how to address such comments)
- ND Hall expansion will also be controversial (and met with skepticism), so we’ll have to demonstrate that this is plausible
  - The ND subproject has been supporting these inquiries, and have been very helpful with providing critical information to address this issue
  - Related to this, I have a meeting on Monday with the heads of the Near Site Conventional Facilities (Tom Hamernik and Kennedy Hartsfield)
    - Hopefully, some publicly shareable comments can be generated from this discussion to identify plausible paths toward an ND hall upgrade

Backup

FD Module of Opportunity

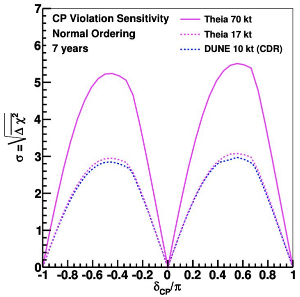
- DUNE Phase 2 goal is to produce 2 new FDs, upgrade the beam, and upgrade the ND
    - Ongoing US P5 process may end up weighing in on these elements with regard to US funding
- Additional funding sources / new collaborators can substantially improve the odds of completing DUNE Phase 2
    - A WbLS detector (Theia) would grow the collaboration and accessible funding sources
- The various proposed enhancements for DUNE Phase 2 all involve improving our access to low energy physics
    - However, many challenges exist to reach low background levels in a future LAr detector
    - Theia is specifically designed for low-E physics and will broaden our physics program (DSNB, SN burst, solar CNO, 0νββ, …) and provide a complementary target nucleus + event reconstruction for the LBL program
- New FD detector technologies require new ND capabilities



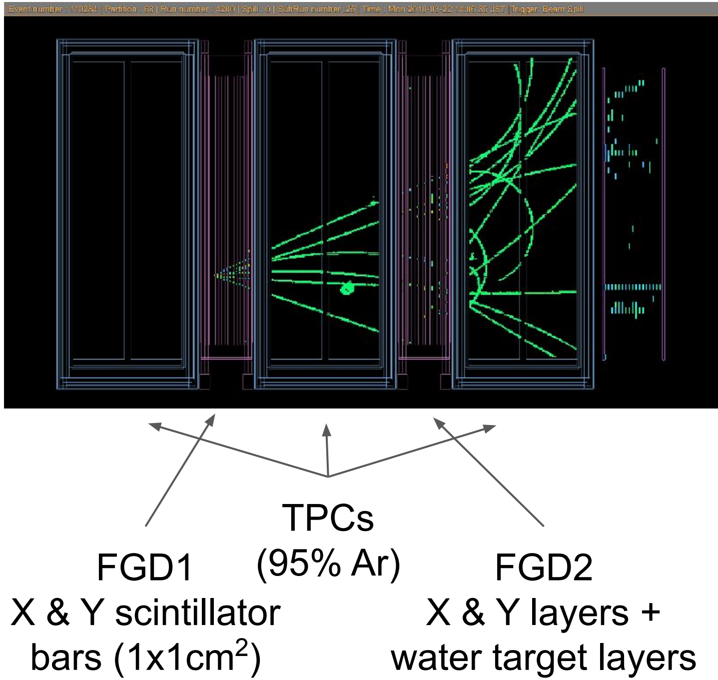


WbLS Near Detector Considerations

- A key component of LAr detectors is hadron calorimetry
  - Neutrino energy is the sum of the reconstructed lepton energy and the (corrected) deposited hadronic energy
- For water Cherenkov detectors, E_ν reconstruction is performed with above-Cherenkov particles
  - The Theia LBL sensitivity studies were performed without utilizing scintillation light
- The primary requirement for a Theia near detector is to measure above-Cherenkov-threshold particles
  - This is the approach used for the primary T2K / Hyper-K near detector
  - Additional external measurements of Cherenkov/scintillation ratio may be helpful
    - Large R&D program with several WbLS detectors is currently underway

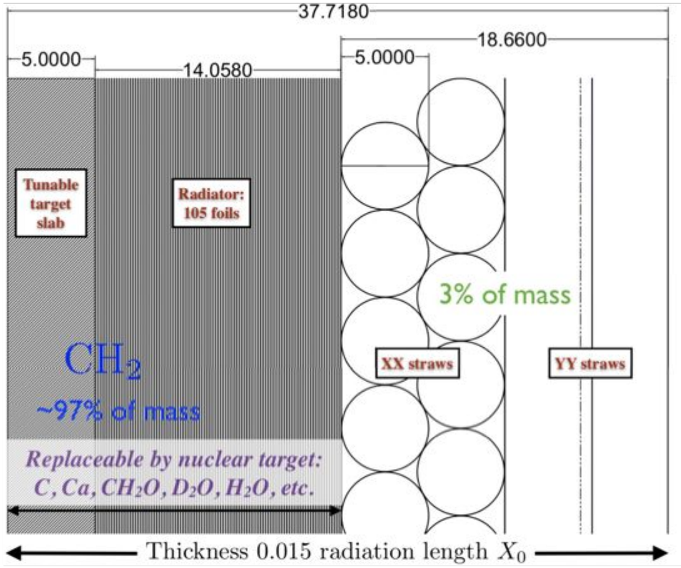


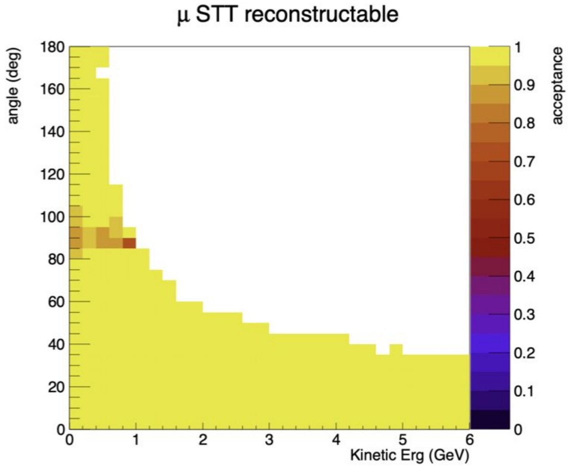
T2K Near Detector (ND280)



C/O/H Targets in SAND

- (See previous talks from R. Petti)
  - https://indico.fnal.gov/event/53965/contributions/258159/attachments/163384/216262/DUNEND-26Jan22-NDnonAr.pdf
  - https://conferences.lbl.gov/event/1227/contributions/7036/attachments/4526/4080/Theia-17Mar23-STTnonAr.pdf
- Identical layers of different target nuclei produce event samples that can be simultaneously fit to constrain differential nuclear effects
  - This approach was tried in T2K with some success (~30% reduction in neutrino cross section uncertainties)
  - SAND should do better, due to more precise tracking, better resolution, better acceptance, and much higher statistics





Target	CP optimized FHC (1.2MW, 2y)				CP optimized RHC (1.2MW, 2y)			
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC
CH_2	13,010,337	624,330	192,118	31,902	2,035,973	4,870,562	91,004	69,278
H	1,222,576	111,574	18,396	5,557	194,216	906,130	8,712	12,434
C	1,547,011	67,294	22,799	3,458	241,710	520,287	10,800	7,460
Ar	3,114,331	121,506	46,384	6,503	480,862	936,489	21,932	13,867
Pb	62,127,600	2,507,940	923,012	130,680	10,375,400	18,222,200	437,284	265,304

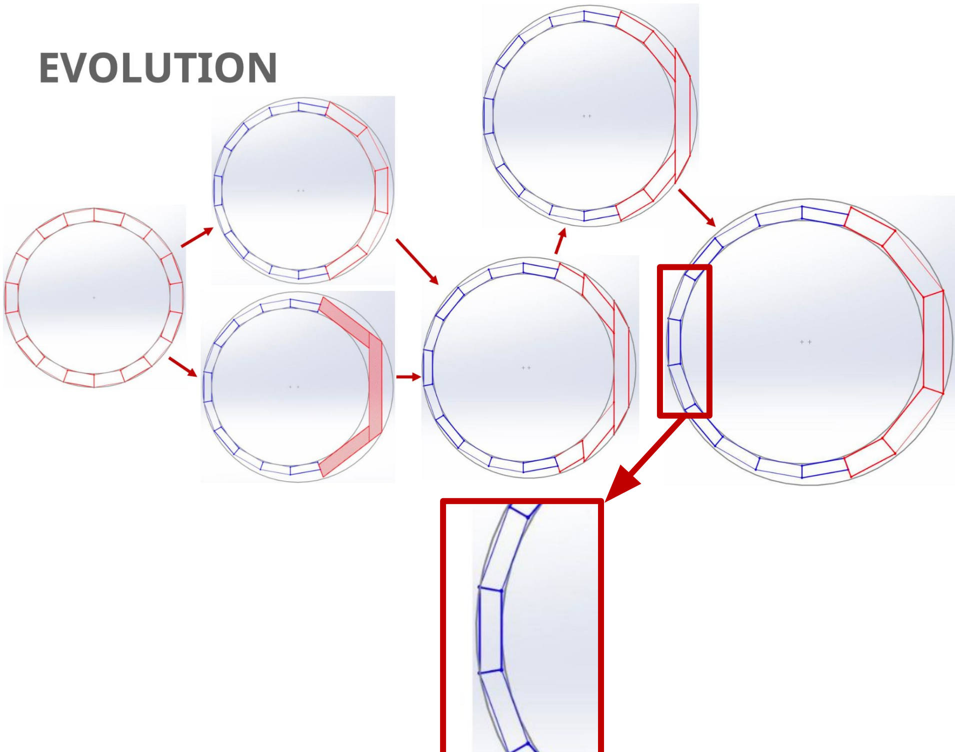
NOTE: 100 kt-MW-years in Phase I FD corresponds to about 2y FHC + 2y RHC with 1.2 MW beam

ND-GAr “Thin” Upstream ECAL

- The ND-GAr ECAL is most needed in the downstream direction
- The upstream portion has been redesigned to be “thin”
  - The thickness requirement of the ECAL as a function of angle is not yet fixed
- WbLS layers placed in the downstream portion of the upstream ECAL can serve as initial ECAL layers (and constitute <1 radiation length)

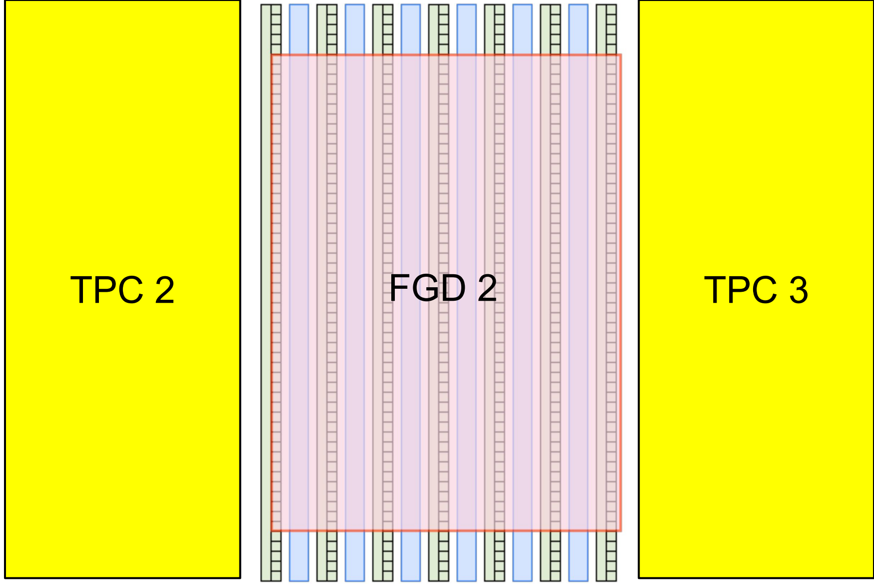
ND-GAr ECAL Design Evolution

https://indico.fnal.gov/event/50217/contributions/241513/attachments/155287/202160/220517_DUNE_CM_Talk_ECAL_Concepts.pdf

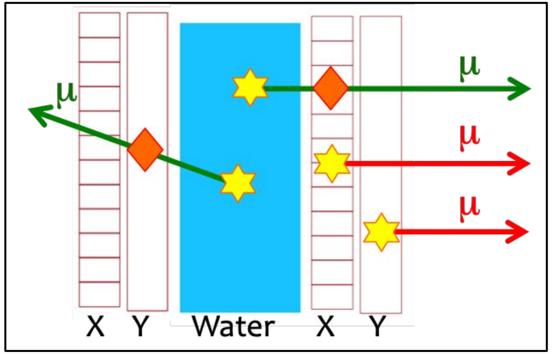


T2K Fine-Grained Detector (FGD2)

- T2K already employs water targets embedded within X & Y layers of scintillator bars
    - This reduced T2K's neutrino interaction uncertainties on water by ~30%
- One of the most important detector uncertainties is disentangling events occurring within water to events occurring in adjacent scintillator layers
- The key difference using WbLS is the water layers themselves can be instrumented
    - Surrounding scintillator layers are no longer a strict requirement
    - Must ensure a sufficient light yield to record MIPs



7 xy + 6 water modules
192x2 bars/layer



Phys. Rev. D 101, 11 (2020) pp.112004

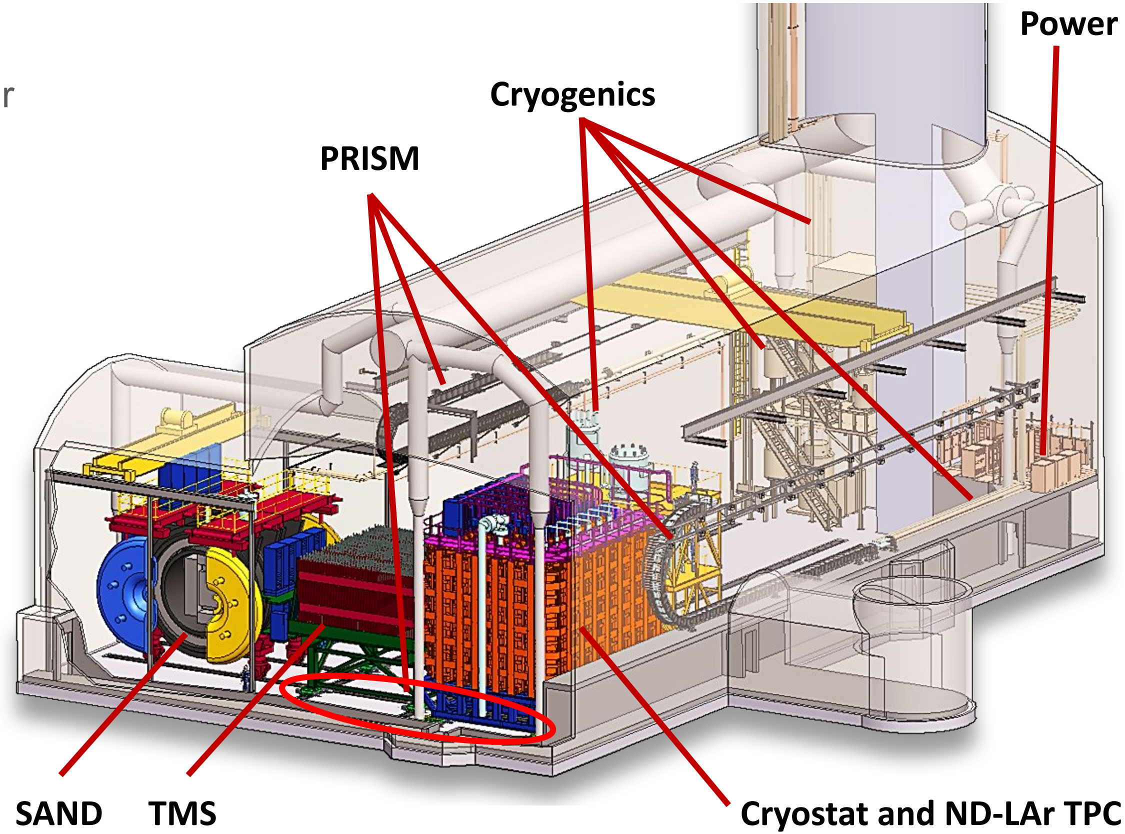
Summary

- Several near detector options exist for a non-Ar 4th FD module
- Least complex: nuclear targets in SAND
  - Pros: straightforward to implement C/O/H targets and/or water targets
  - Cons: no additional handle on Erec vs Etrue from off-axis measurements
- More complex: WbLS layers in the ND-GAr ECAL
  - Pros: provides off-axis data and excellent tracking
  - Cons: must balance with ECAL performance; lower event rates must be studied
- Most complex: A new, dedicated near detector that retains TMS as a muon catcher (ideally with a slight modification to the rock wall)
  - Pros: can be designed for high statistics measurements off-axis; reuse TMS when ND-GAr is installed
  - Cons:
- There are many ND solutions to explore which would enable LBL measurements with a complementary target nucleus and detector technology
- If the LBL sensitivity can be demonstrated, a Theia far detector would broaden DUNE’s physics program (after the first ~10 years of running) to include a variety of interesting low-E physics phenomena

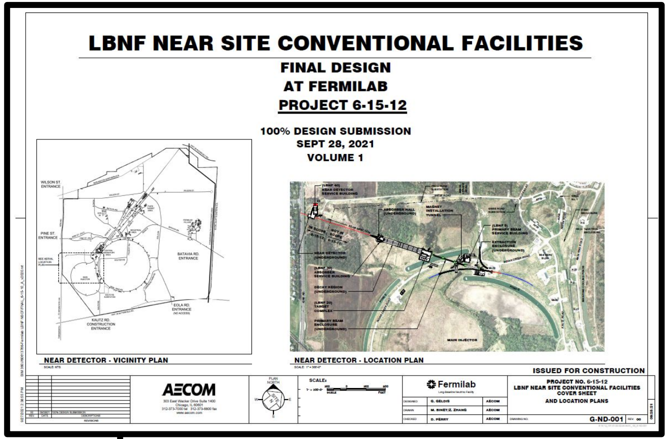
Near Detector Considerations

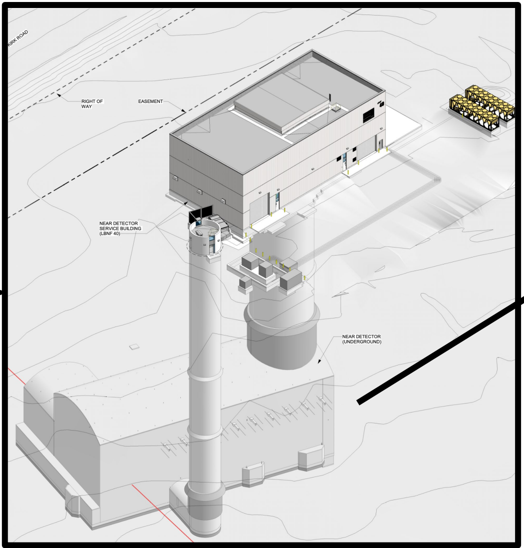
- Near detectors are an essential element of any LBL analysis
  - Measurements on the same nuclear target(s) as the far detector are required
- DUNE ND is currently designed around Ar
  - ND-LAr TPC: ν-Target w/ similar technology to LAr far detectors
  - TMS: Spectrometer for muons escaping ND-LAr
  - PRISM: ND-LAr + TMS move off-axis to sample a variety of E_ν
  - SAND: Beam monitor

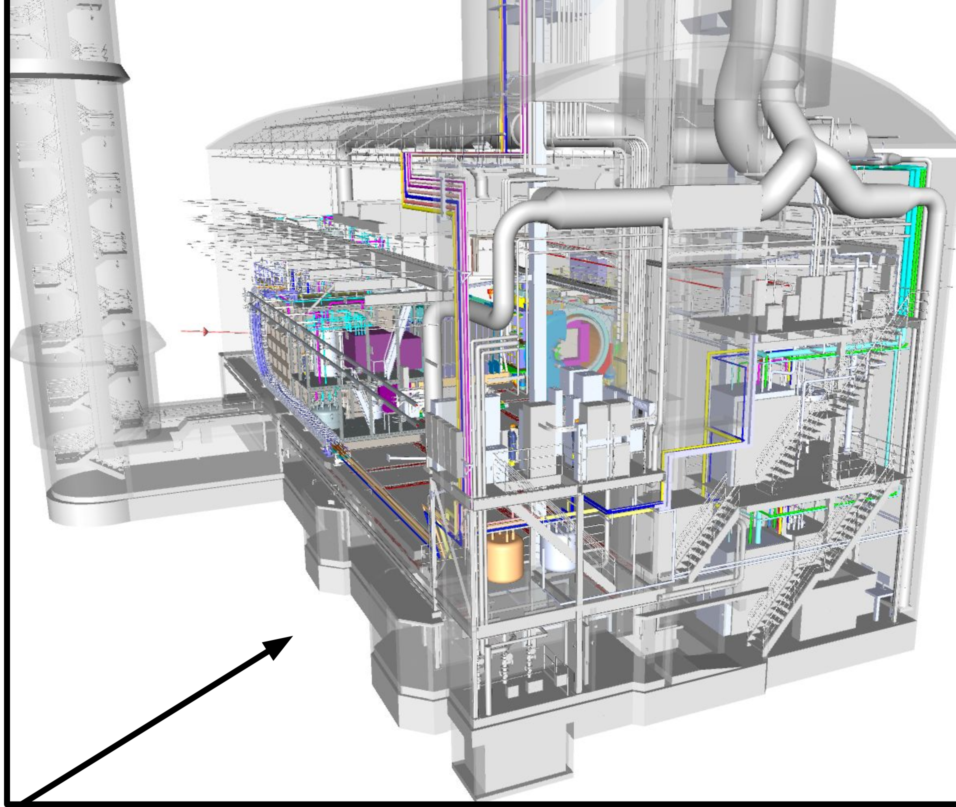
DUNE Near Detector Hall



DUNE Near Detector Hall Design


LBNF NEAR SITE CONVENTIONAL FACILITIES
FINAL DESIGN
AT FERMILAB
PROJECT 6-15-12
100% DESIGN SUBMISSION
SEPT 28, 2021
VOLUME 1
NEAR DETECTOR - VICINITY PLAN
NEAR DETECTOR - LOCATION PLAN
ISSUED FOR CONSTRUCTION
AECOM
Fermilab
PROJECT NO. 6-15-12
LBNF NEAR SITE CONVENTIONAL FACILITIES
COVER SHEET
AND LOCATION PLANS
G-ND-001

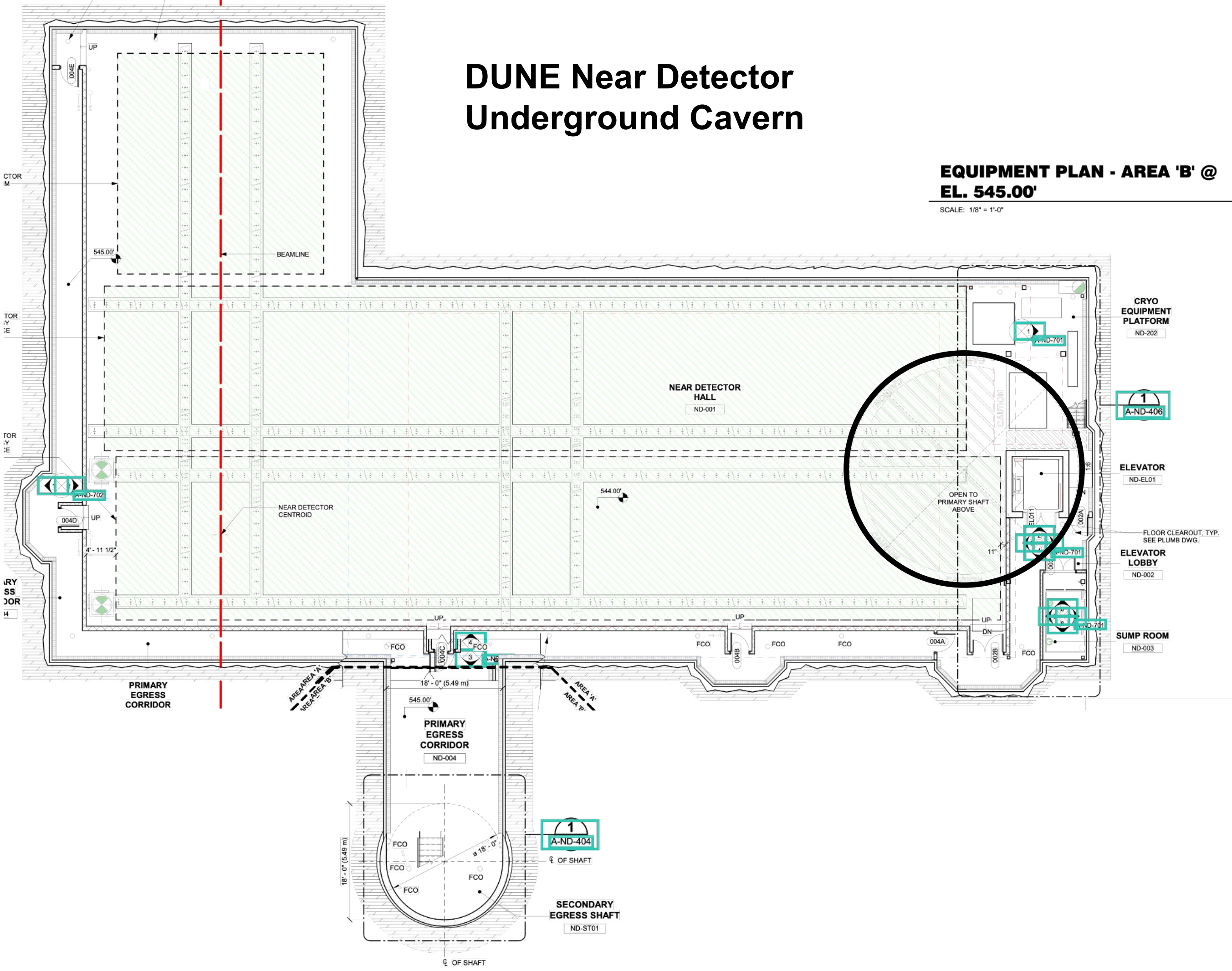




The near detector hall for DUNE Phase 1 is at "100% final design" (i.e. changes to the hall at this point would be very difficult)

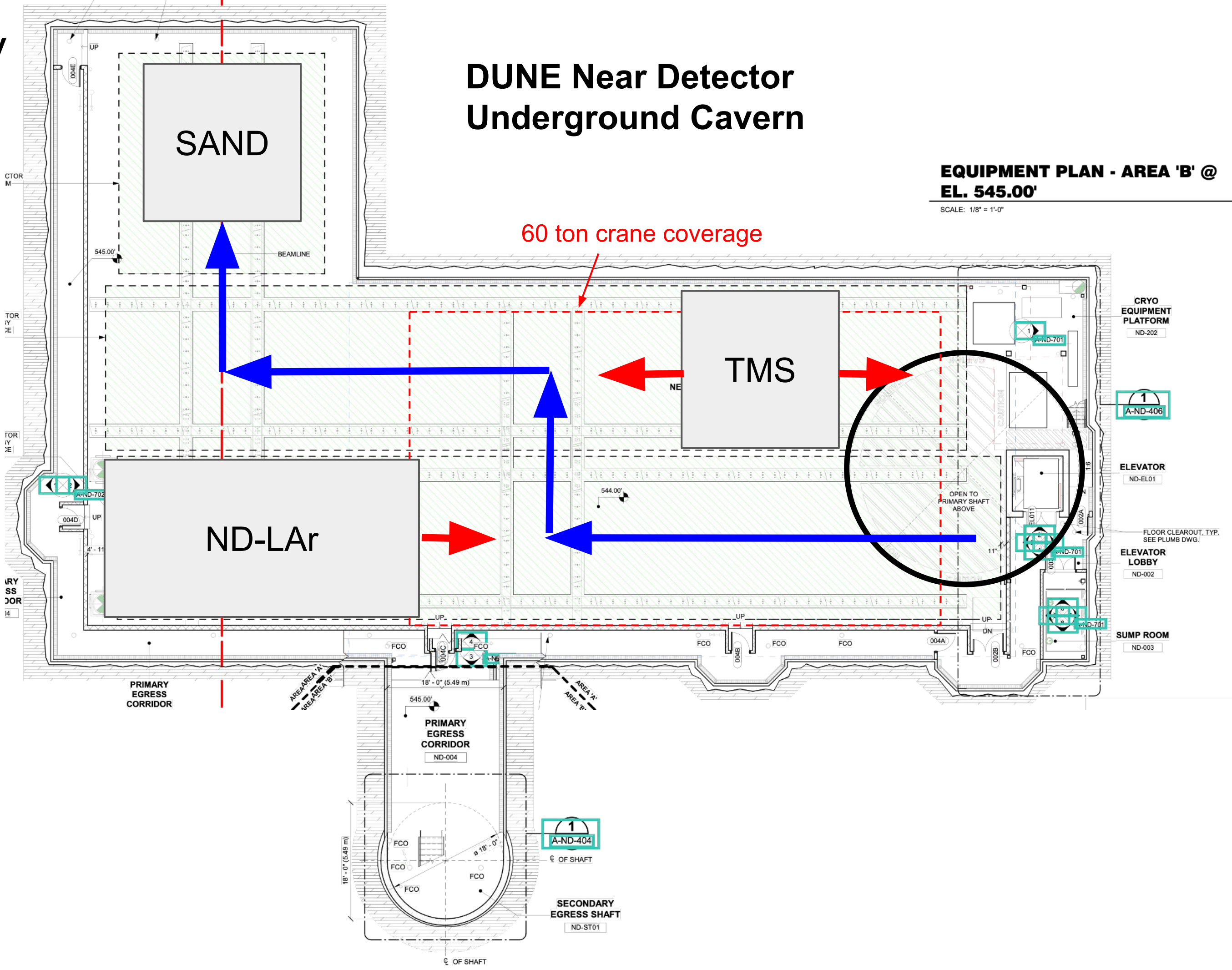
Cavern Layout

- **Red line**: beam axis
- Off-axis travel direction is left-to-right
- 2 pairs of rails for ND-LAr and TMS
- 2 sets of "cross rails" (along the beam direction) for SAND
  - SAND can move between the TMS and ND-LAr rails
- The main shaft, elevator, and equipment mezzanines are on the right side



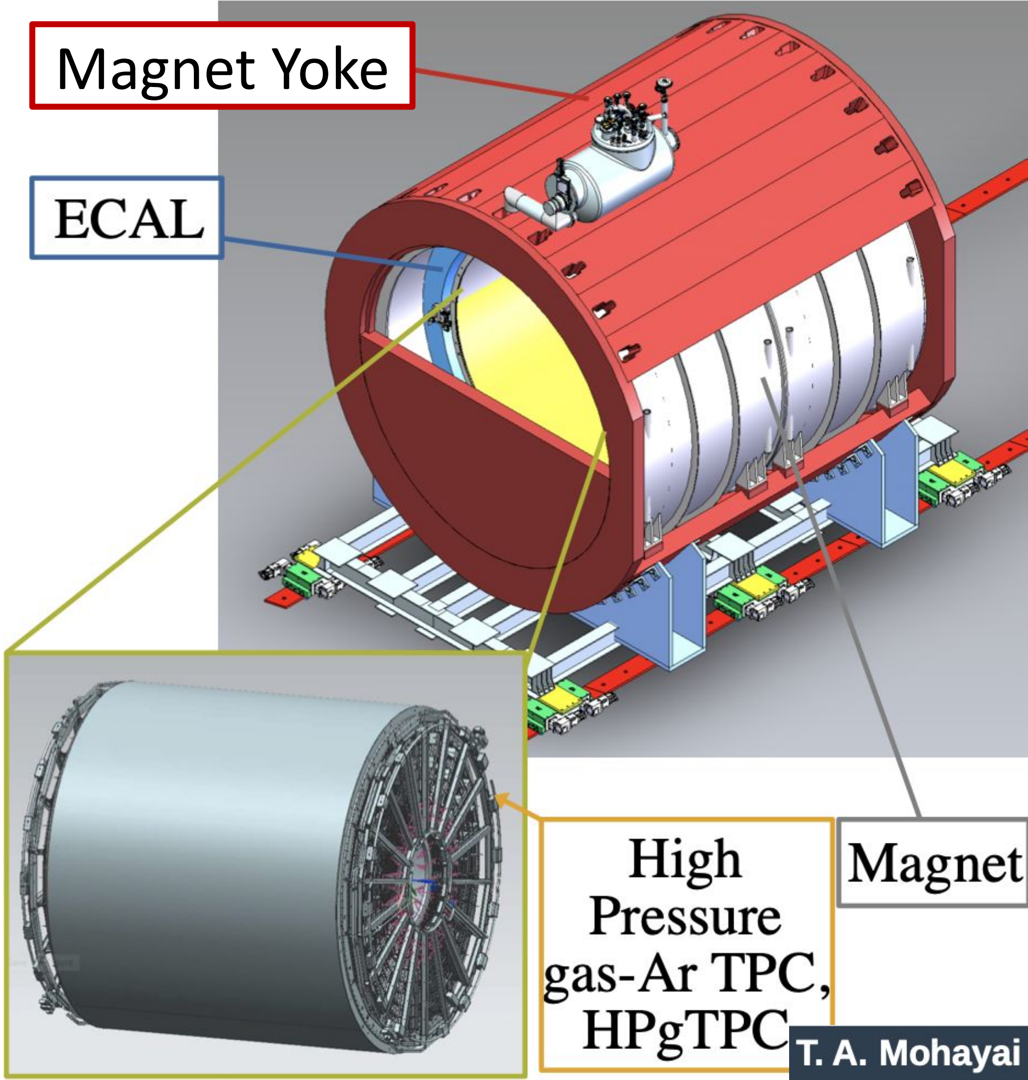
Detector Choreography

- The rail structure is designed to allow SAND to be installed at almost any time
- TMS and ND-LAr can move (via the PRISM system)
  - ND-LAr can temporarily move under the 60 ton crane coverage
  - TMS can temporarily move under the shaft
- Significant flexibility to accommodate a variety of installation scenarios



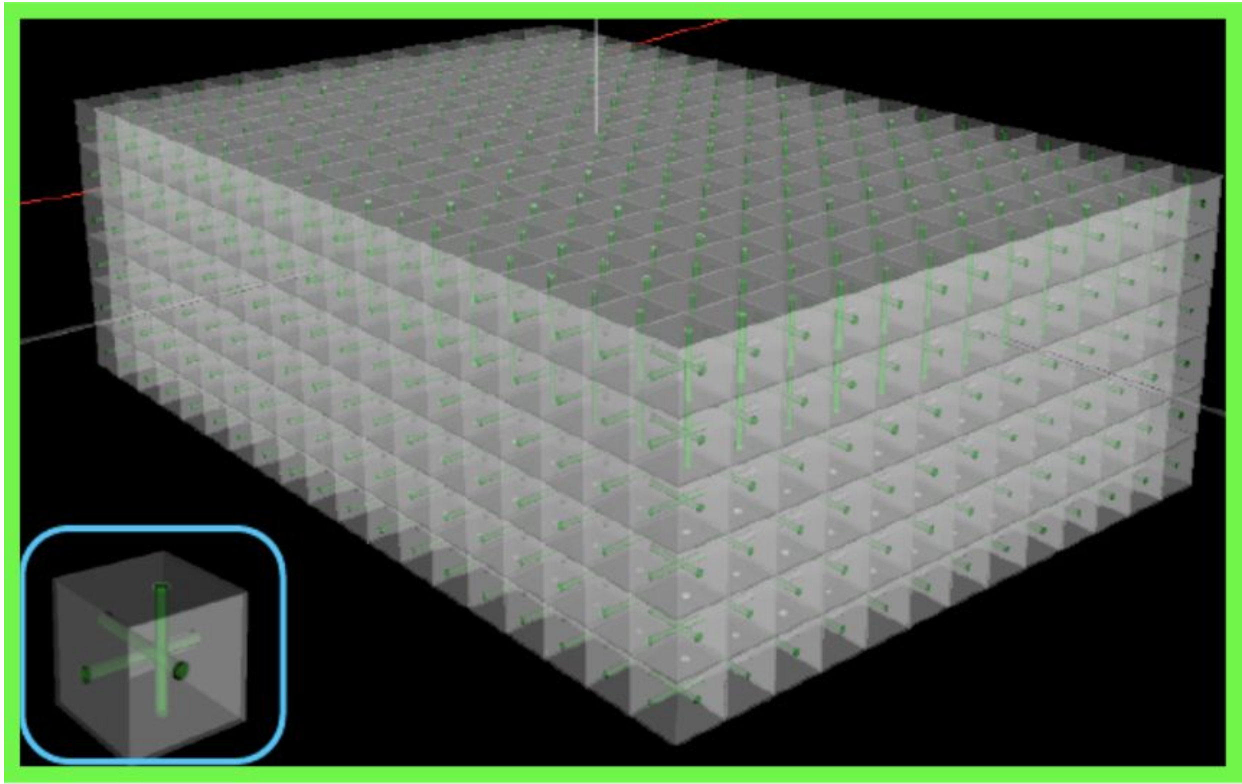
ND-GAr

- DUNE Phase 2 includes plans for an upgraded near detector
- The main option discussed so far is a high-pressure Ar gas TPC in place of TMS
  - Lowers the momentum threshold for detecting particles escaping the Ar nucleus
  - Cleaner measurements of multi-particle final states (e.g. reduces π^+ scattering, γ-conversions, etc.)
- This detector still must function as a muon catcher for ND-LAr
  - Goal is to minimize dead material between ND-LAr and ND-GAr



Super-FGD -> WbLS cubes?

- The Super-FGD currently being constructed for T2K consists of 1 cm^3 scintillator cubes
- Can we incorporate WbLS cubes into a Super-FGD structure for DUNE?
  - For either a dedicated detector or for embedding into ND-GAr?



DUNE FD-TDR Cross Section Model

- Uncertainties included for:
  - Exclusive interactions (QE, Res, SIS/DIS)
  - Final state interactions (FSI)
  - Nuclear effects (RPA, 2p2h)
  - Flavor ratios (ν_e/anti-ν_e)
- A similar set of uncertainties will be needed for C/O/H
  - Fortunately, these nuclei have been studied more extensively
  - Specific expertise in ν-N modeling and GENIE is needed (& communication with DUNE DIRT2/NIUWG)

GENIE Xsec Parameters

Description	1σ
Quasielastic	
M_A^{QE}, Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
QE FF, CCQE vector form factor shape	N/A
p_F Fermi surface momentum for Pauli blocking	±30%
Low W	
M_A^{RES}, Axial mass for CC resonance	±0.05 GeV
M_V^{RES} Vector mass for CC resonance	±10%
Δ-decay ang., θ_π from Δ decay (isotropic → R-S)	N/A
High W (BY model)	
A_{HT}, higher-twist in scaling variable ξ_w	±25%
B_{HT}, higher-twist in scaling variable ξ_w	±25%
C_{V1u}, valence GRV98 PDF correction	±30%
C_{V2u}, valence GRV98 PDF correction	±40%
Other neutral current	
M_A^{NCRES}, Axial mass for NC resonance	±10%
M_V^{NCRES}, Vector mass for NC resonance	±5%

GENIE FSI Parameters

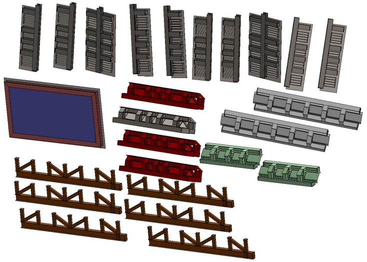
Description	1σ
N. CEX, Nucleon charge exchange probability	±50%
N. EL, Nucleon elastic reaction probability	±30%
N. INEL, Nucleon inelastic reaction probability	±40%
N. ABS, Nucleon absorption probability	±20%
N. PROD, Nucleon π-production probability	±20%
π CEX, π charge exchange probability	±50%
π EL, π elastic reaction probability	±10%
π INEL, π inelastic reaction probability	±40%
π ABS, π absorption probability	±20%
π PROD, π π-production probability	±20%

Additional Xsec Parameters

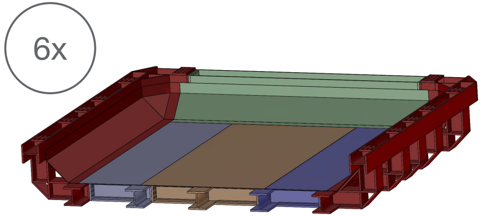
Uncertainty	Mode
BeRPA [A,B,D]	$1p1h$/QE
ArC2$p2h$ [ν,$\bar{\nu}$]	$2p2h$
E_{2p2h} [A,B] [ν,$\bar{\nu}$]	$2p2h$
NR [ν,$\bar{\nu}$] [CC,NC] [n,p] [1π,2π,3π]	Non-res. pion
ν_e PS	ν_e,$\bar{\nu}_e$ inclusive
$\nu_e/\bar{\nu}_e$ norm	ν_e,$\bar{\nu}_e$ inclusive
NC norm.	NC

Eur. Phys. J. C 80, 978 (2020)

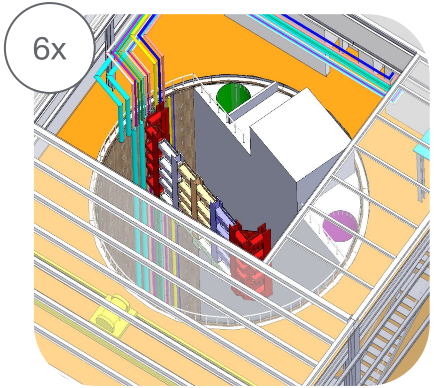
Cryostat Assembly Process Overview



1. Receive 160 metric tons of warm structure parts in 40 pieces



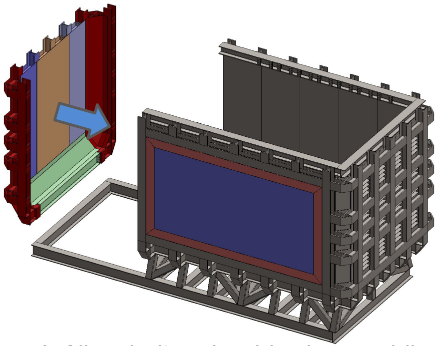
2. Align and bolt pieces into subassemblies



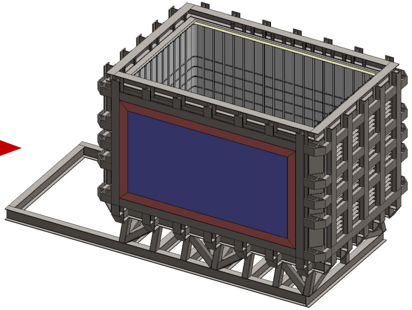
3. Lower 15-50 metric ton subassemblies into cavern

Surface

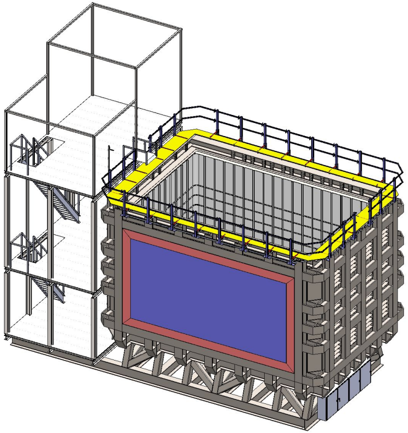
Cavern



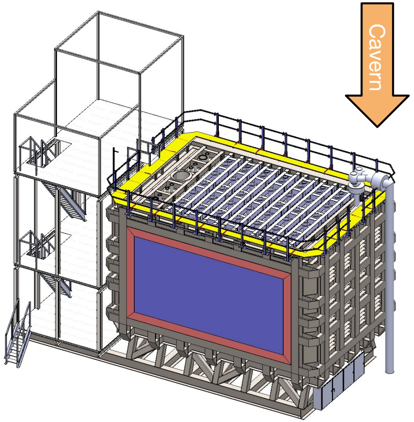
4. Align, bolt and weld subassemblies to form warm structure



5. Install cold membrane

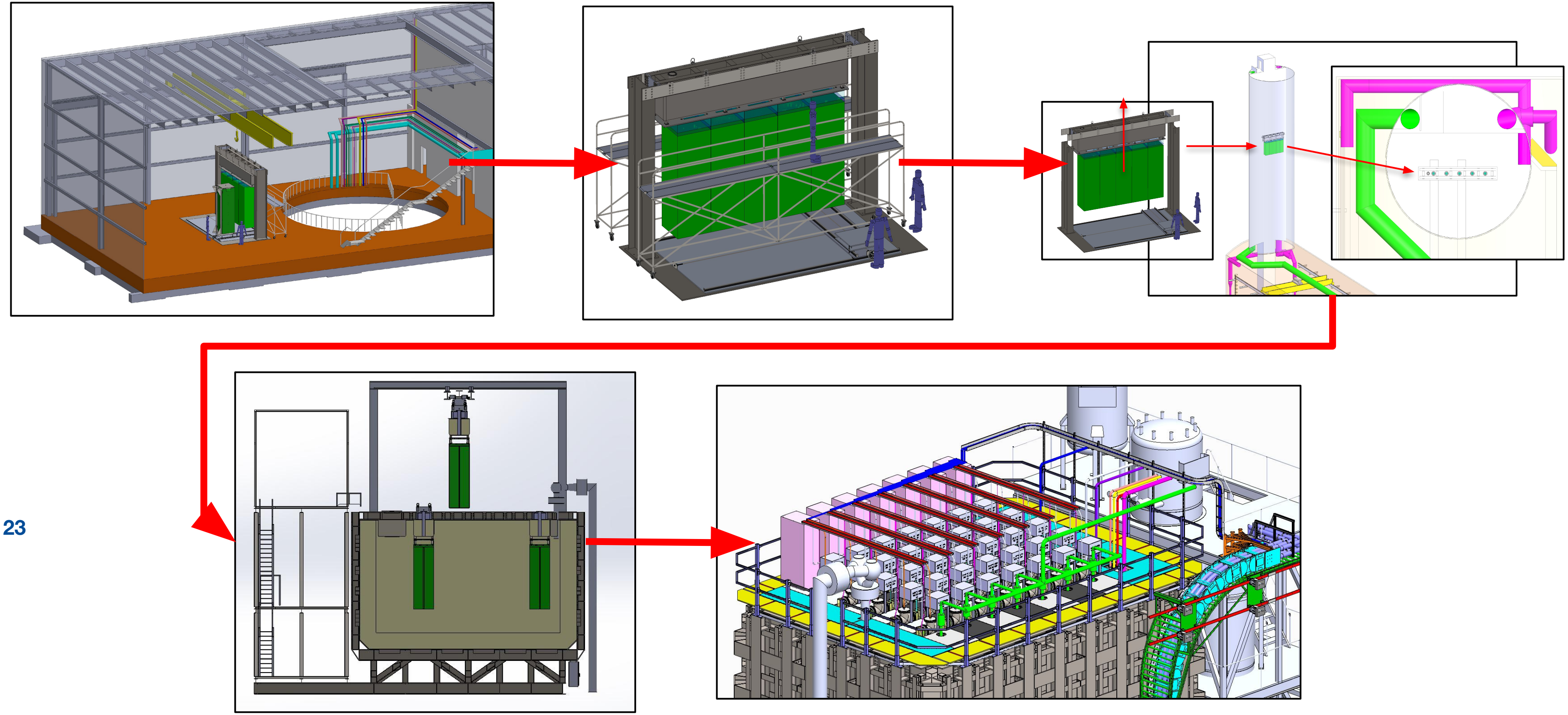


6. Install mezzanines

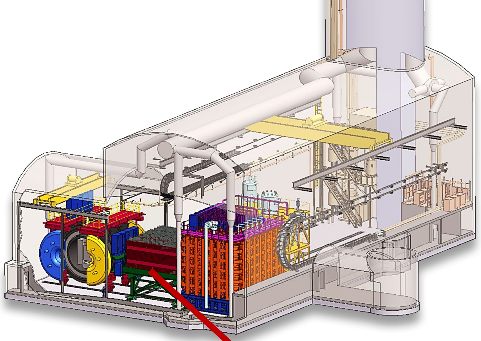


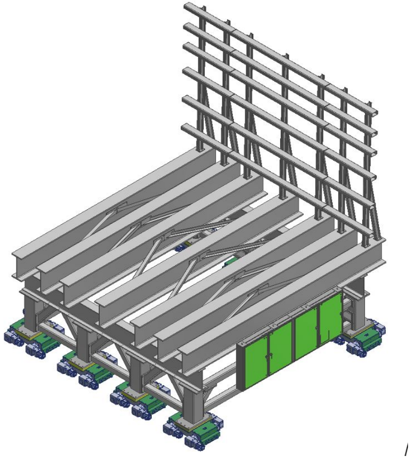
7. Install TPC rows and lid sections

ND-LAr Assembly Process Overview

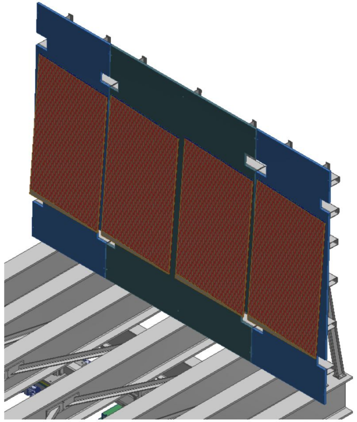


TMS Components and Assembly Overview

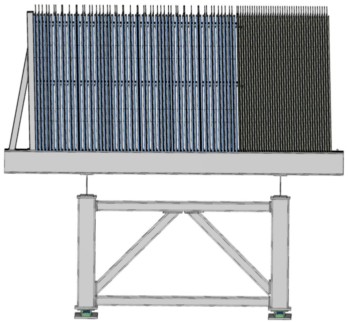




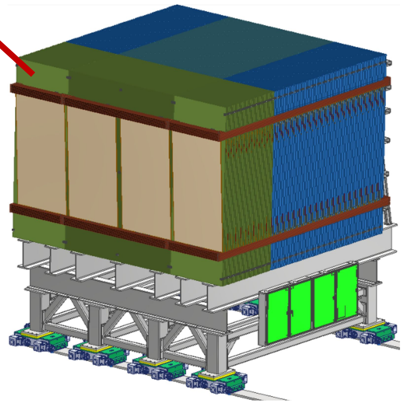
Iron Throne



1st TMS layer



100 TMS layers



Magnet Coils