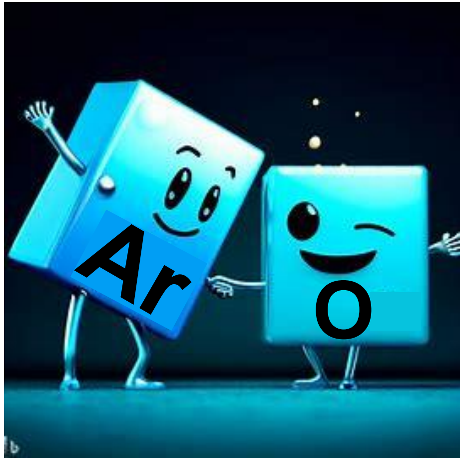
ND-GAr & Theia-ND

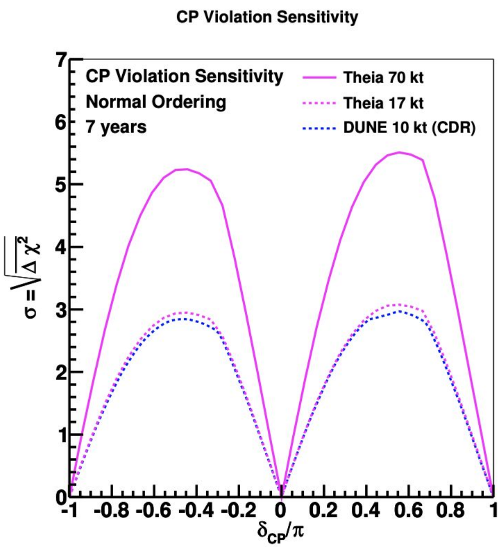
(A Match Made in Cavern?)

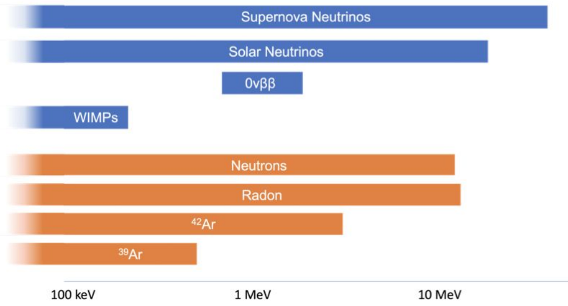
Mike Wilking
DUNE Phase 2 Workshop
Imperial College London
June 21st, 2023



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



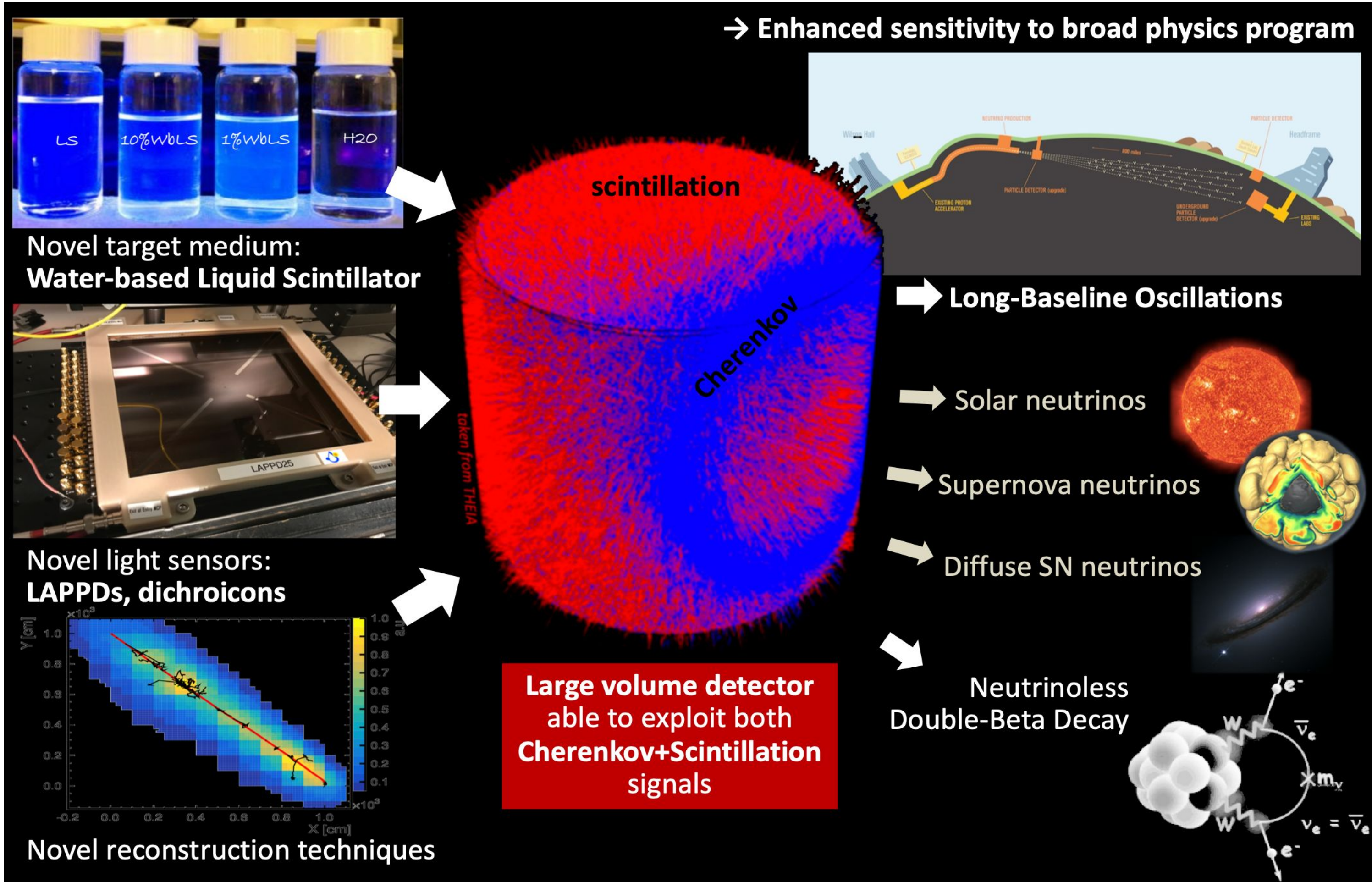


Brief Introduction to Theia

[The European Physical Journal C 80 no. 5, (May, 2020)]

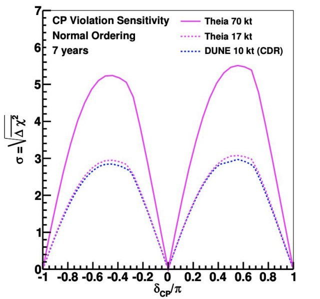
(slide from M. Wurm)

- Observe both Cherenkov and scinitllation light for each event
- At High-E, operates much like Super-K
  - with additional information about below-Cherenkov-threshold hadrons
- Low-E threshold is lowered
  - More photons near and below Cherenkov threshold
- Much more detail in a recent Phase 2 biweekly talk from M. Wurm

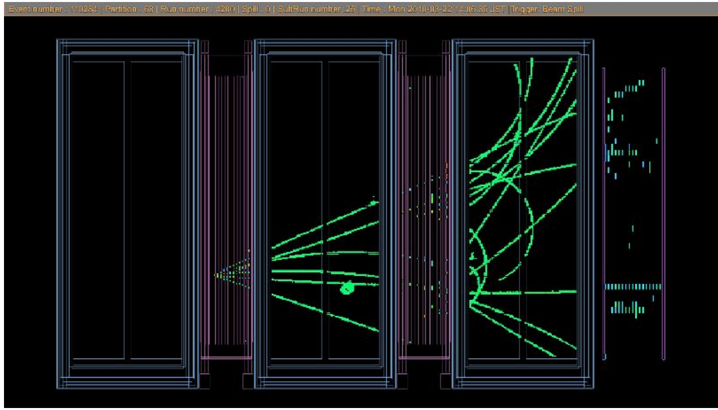


WbLS Near Detector Considerations

- 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)



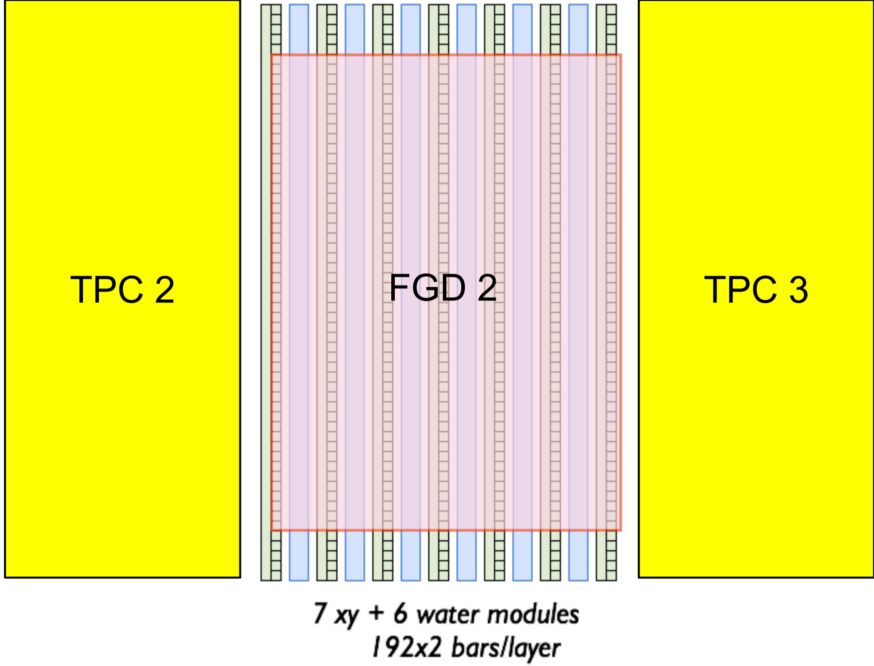
TPCs (95% Ar)

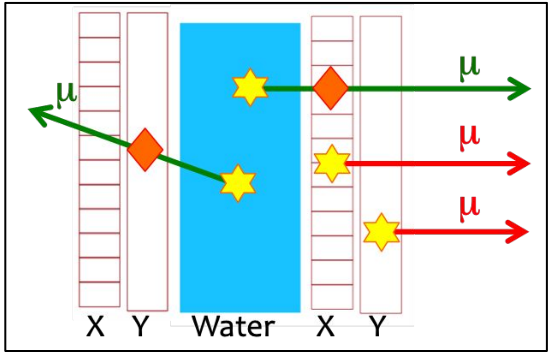
FGD1 X & Y scintillator bars ($1x1 cm^2$)

FGD2 X & Y layers + water target layers

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





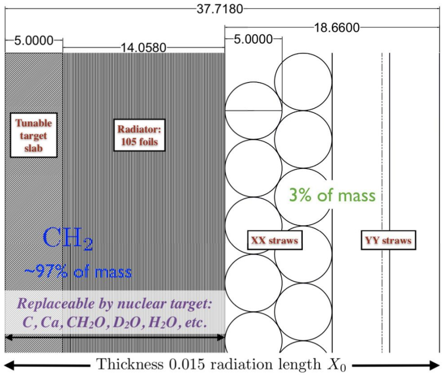
Phys. Rev. D 101, 11 (2020) pp.112004

Near Detector Concepts

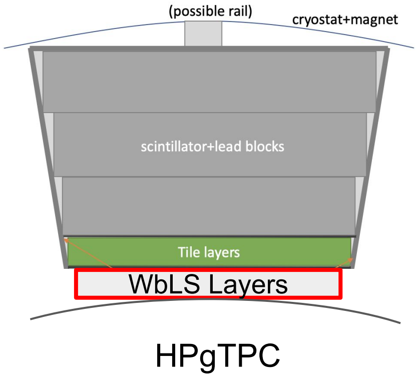
- Several concepts are possible with varying levels of complexity
- SAND already exists, so adding targets for studying WbLS nuclei is possible
  - On-axis only, but this can constrain extended xsec models
- ND-GAr is a primary goal for a DUNE Phase-2 ND
  - Adding WbLS targets in the upstream ECAL is possible
- A dedicated Theia ND
  - e.g. a WbLS Liquid-O
  - e.g. a WbLS NOvA ND

Least complex

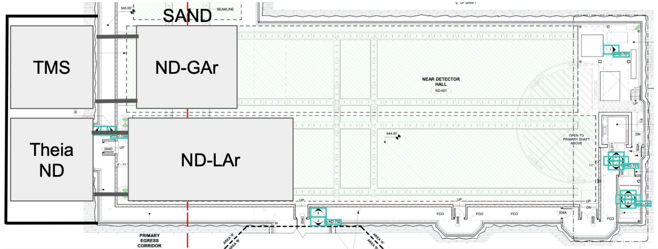
Additional nuclear targets in SAND



WbLS targets in the ND-GAr ECAL



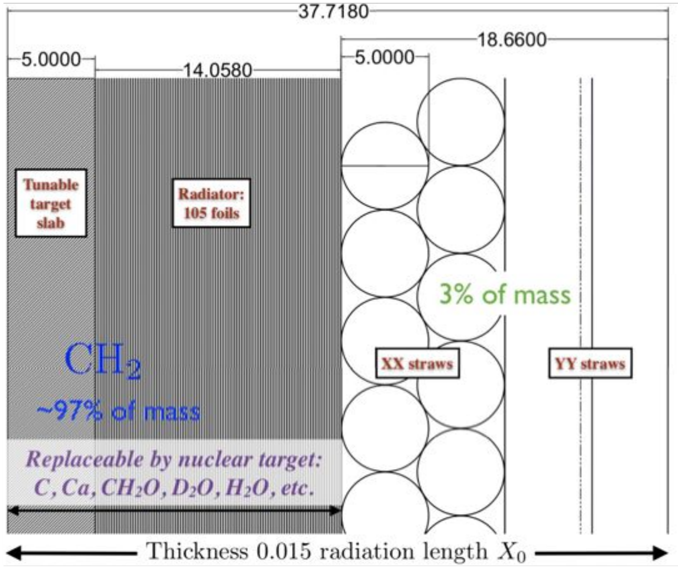
Dedicated Theia ND

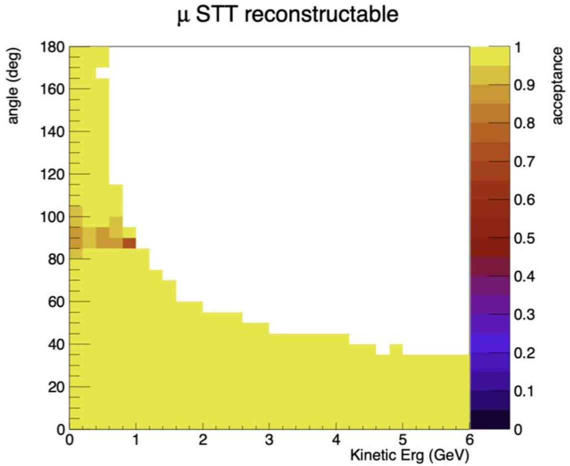


Most complex

C/O/H Targets in SAND

- See previous talk at this workshop from R. Petti
- 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



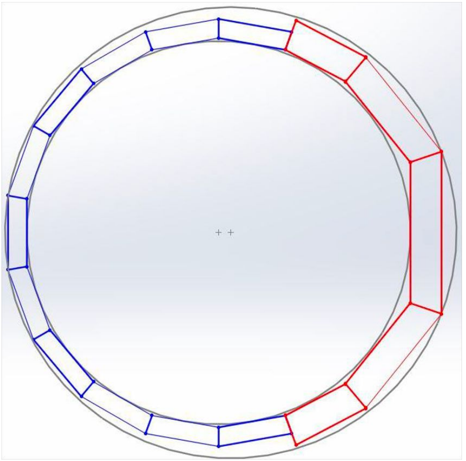


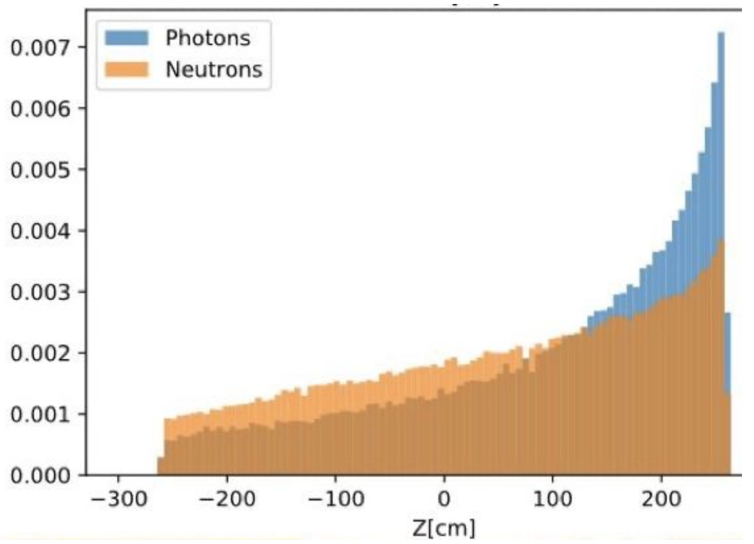
Target	CP optimized FHC (1.2MW, 2y)				CP optimized RHC (1.2MW, 2y)			
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC
CH_2	13,010,337	624,330	192,118	31,902	2,035,973	4,870,562	91,004	69,278
H	1,222,576	111,574	18,396	5,557	194,216	906,130	8,712	12,434
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

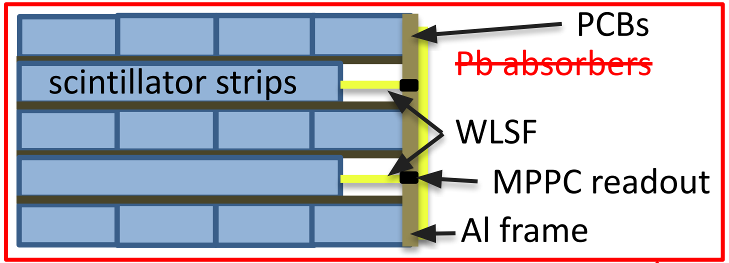
ND-GAr "Thin" Upstream ECAL

- The ND-GAr ECAL is most needed in the downstream direction
- The upstream portion has been redesigned to be "thin"
  - The thickness of the ECAL as a function of angle has not yet been optimized
- WbLS layers could be placed in the downstream portion of the upstream ECAL
  - <1 radiation length (i.e. preshower tracking layers)

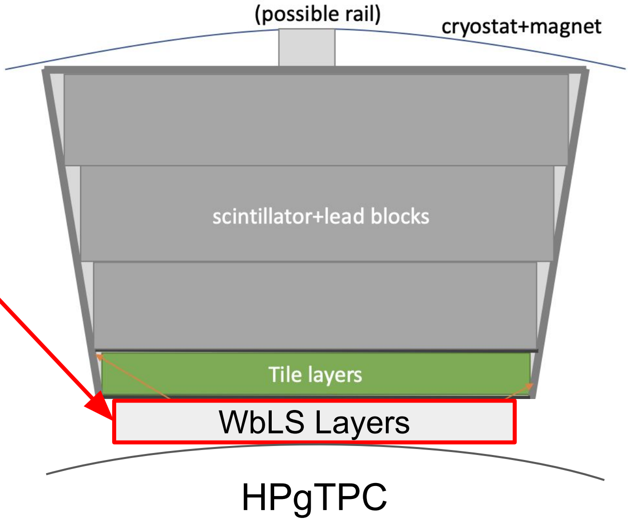


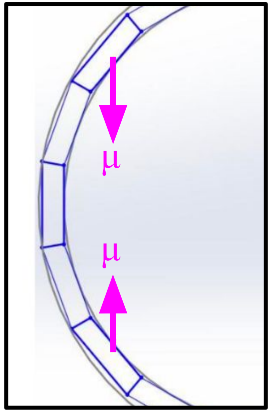


WbLS Inside ND-GAr ECAL



- WbLS layers would need to track X & Y positions
  - Optically segmented X & Y bars (NOvA ND) or 3D cubes (T2K sFGD)
  - 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

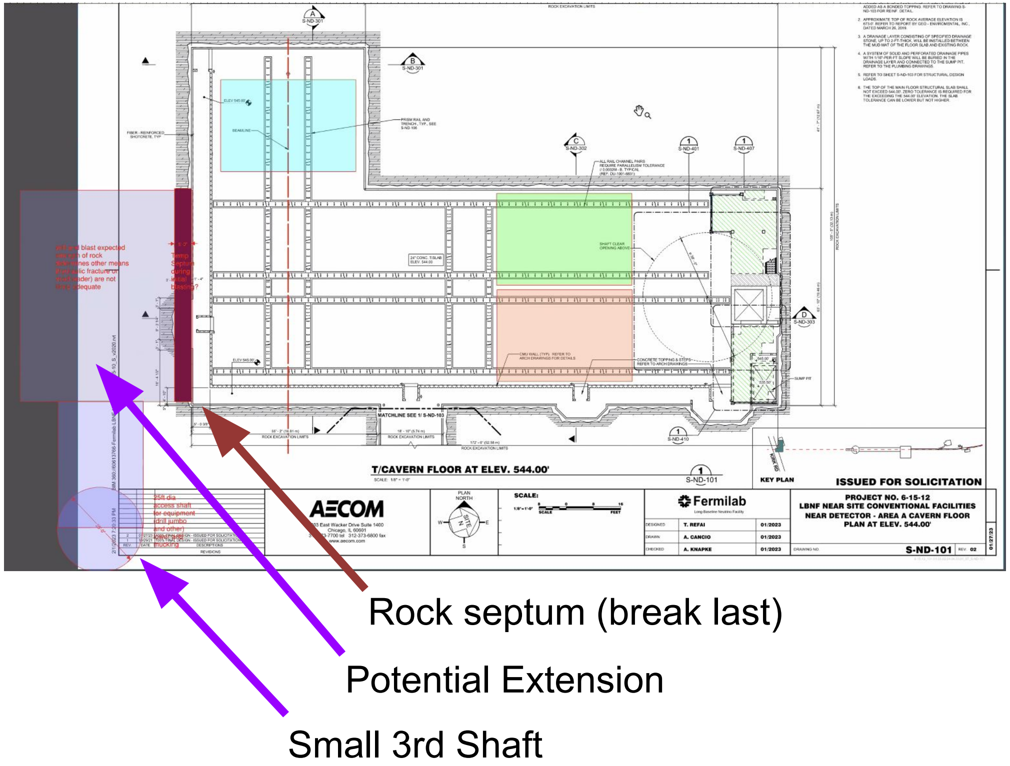




Possible ND Hall Extensions

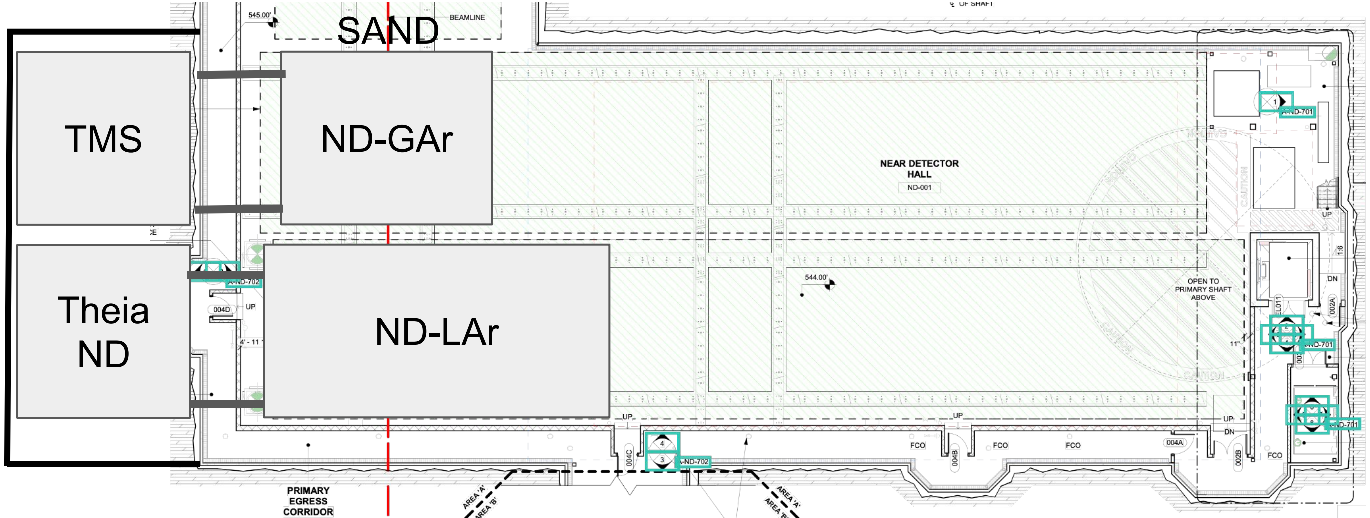
- The Fermilab engineers leading the development of the Phase 1 ND Hall (Tom Hamernik & Kennedy Hartsfield) took a preliminary look at technical feasibility of extending the ND Hall
  - How do we protect detectors that are already installed?
  - Is there enough space to deploy excavation equipment?
- Proposed solution is to create a small 3rd shaft and excavate the additional cavern space (last step: break barrier)
  - Initial look from Fermilab site rock experts revealed no show stoppers
  - Additional study on the impact of vibrations on detectors is needed
- The PRISM range can then be extended, enabling additional detectors

DUNE Near Detector Hall



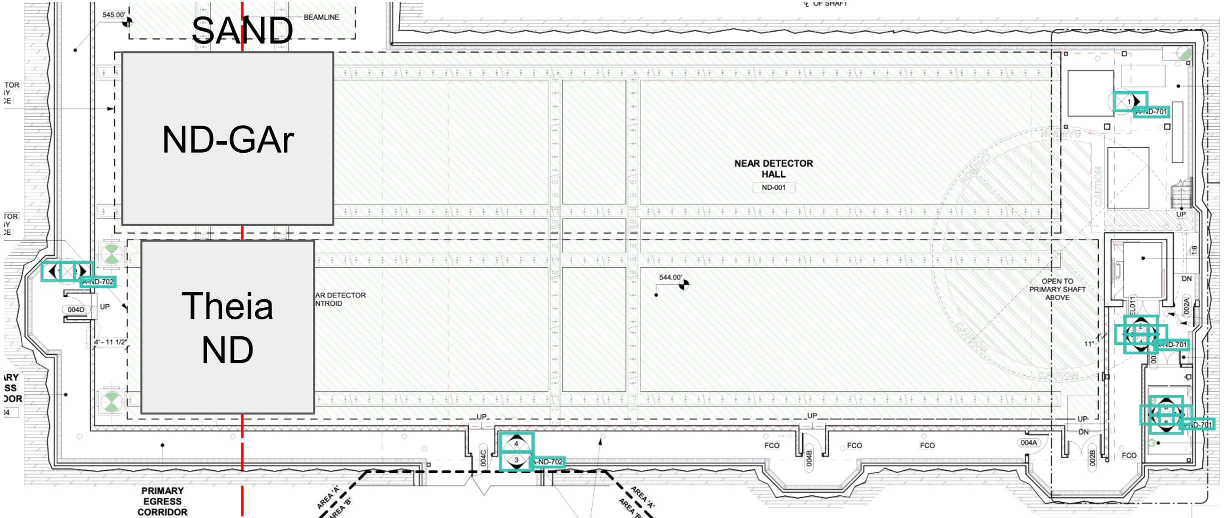
A Dedicated Theia Near Detector

- If the long dimension of the ND Hall can be slightly extended, it may be possible to install a dedicated Theia ND
- The 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
- All 4 detectors could then be moved to different locations along the PRISM rails



A Dedicated Theia Near Detector II

- After many years of Phase 1 running and producing several rounds of DUNE oscillation results, we will likely collect sufficient statistics with ND-LAr for the full duration of DUNE
  - See my DUNE-PRISM talk from earlier today for caveats regarding beam stability
  - It is possible that ND-LAr may not be needed for DUNE Phase 2
- In this scenario, a Theia ND could be placed in front of ND-GAr
  - Any additional measurements required on Ar could potentially be made by ND-GAr

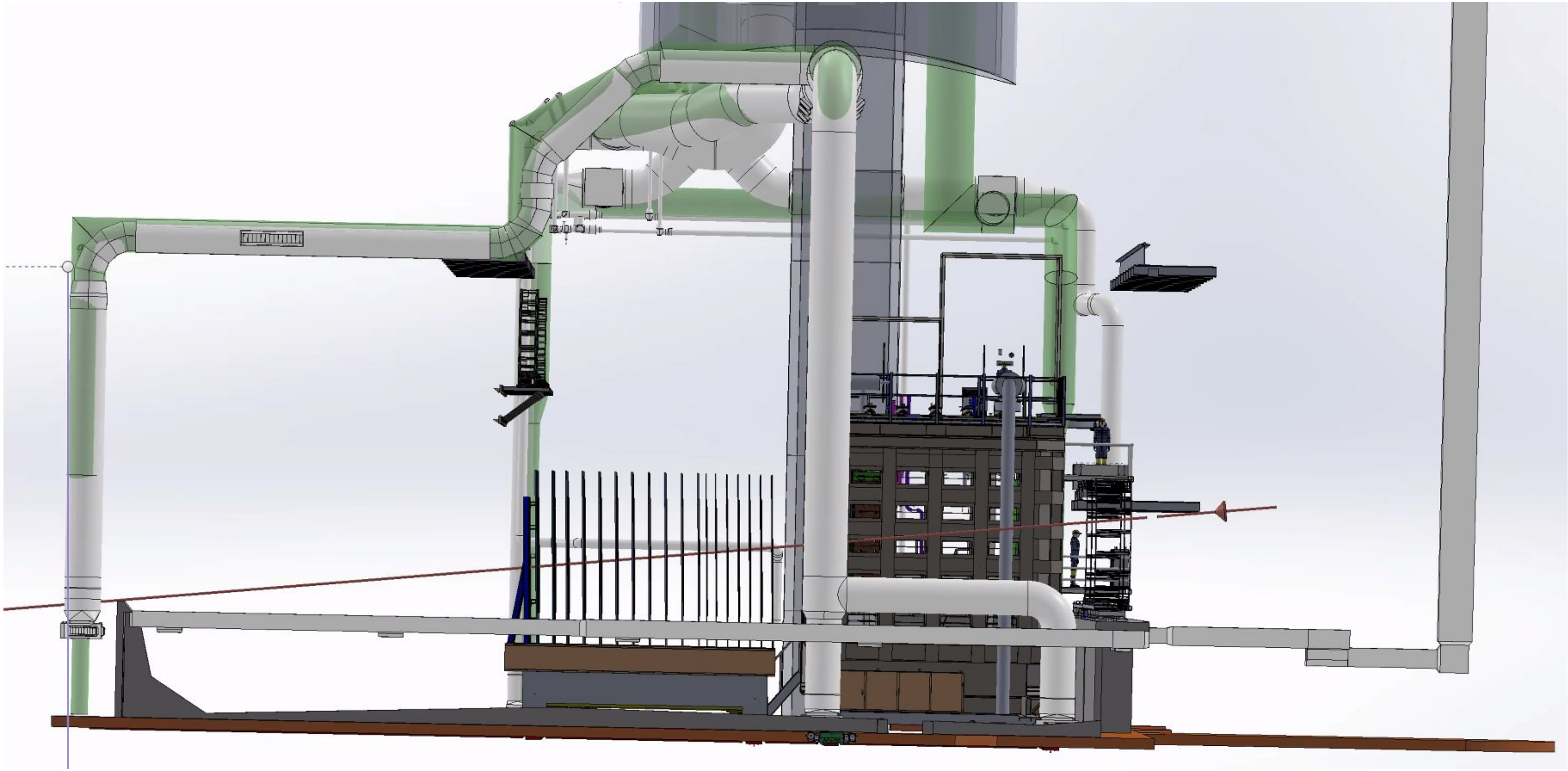


Summary

- Several near detector options exist for a non-Ar 4th FD module
  - and they are all compatible with, and closely coupled to, ND-GAr
- 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 Theia ND (e.g. Liquid-O or NOvA ND)
  - Pros: can be designed for high statistics measurements off-axis; possible reuse of TMS when ND-GAr is installed
  - Cons: Requires additional hall excavation, or removal of ND-LAr after multiple years of Phase 1 running
- If the LBL sensitivity can be demonstrated, a Theia far detector would broaden DUNE's physics program (after many years of Phase 1 running) to include a variety of interesting low-E physics phenomena

Backup

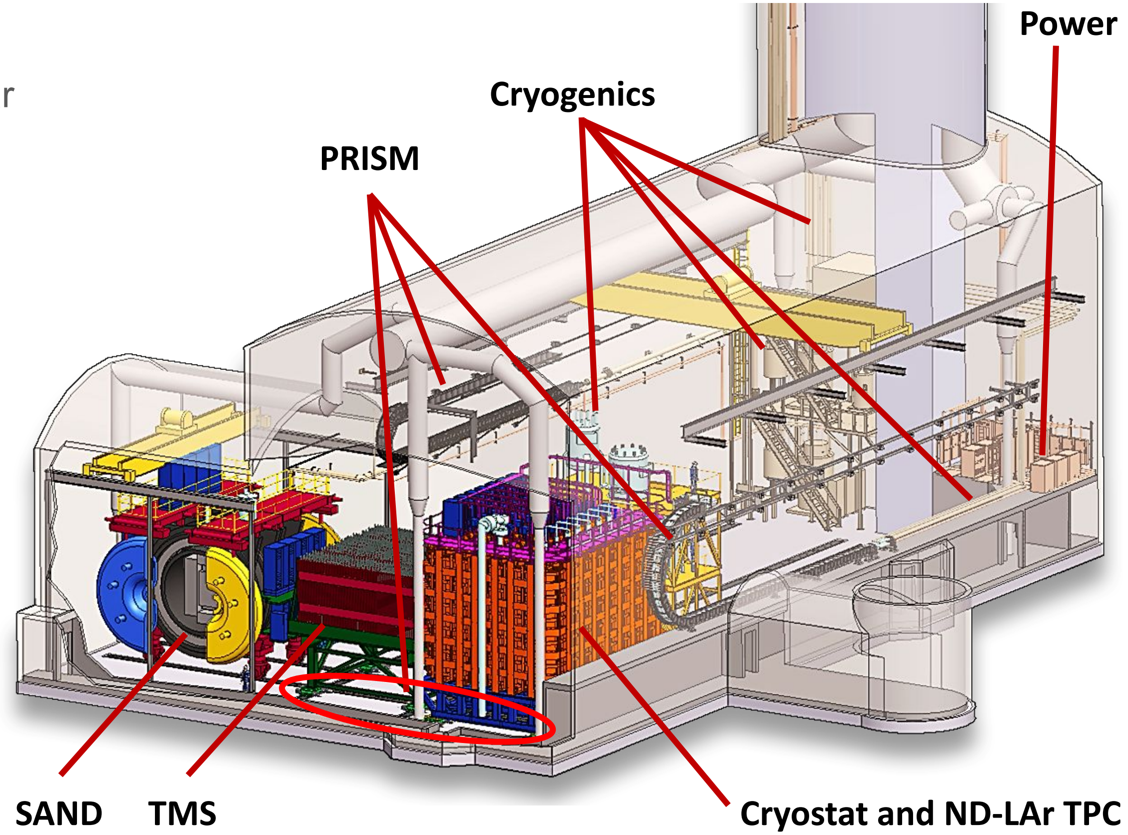
TMS View From Cavern Endwall



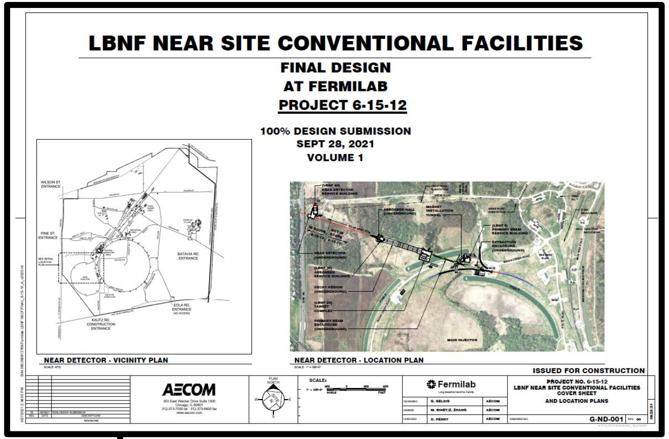
Near Detector Considerations

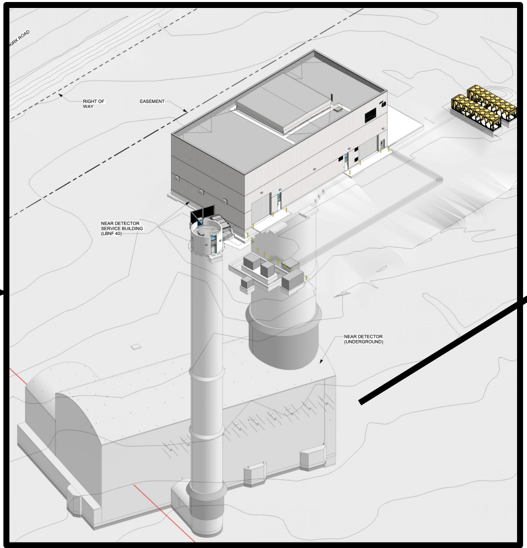
- Near detectors are an essential element of any LBL analysis
  - Measurements on the same nuclear target(s) as the far detector are required
- DUNE ND is currently designed around Ar
  - ND-LAr TPC: ν-Target w/ similar technology to LAr far detectors
  - TMS: Spectrometer for muons escaping ND-LAr
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

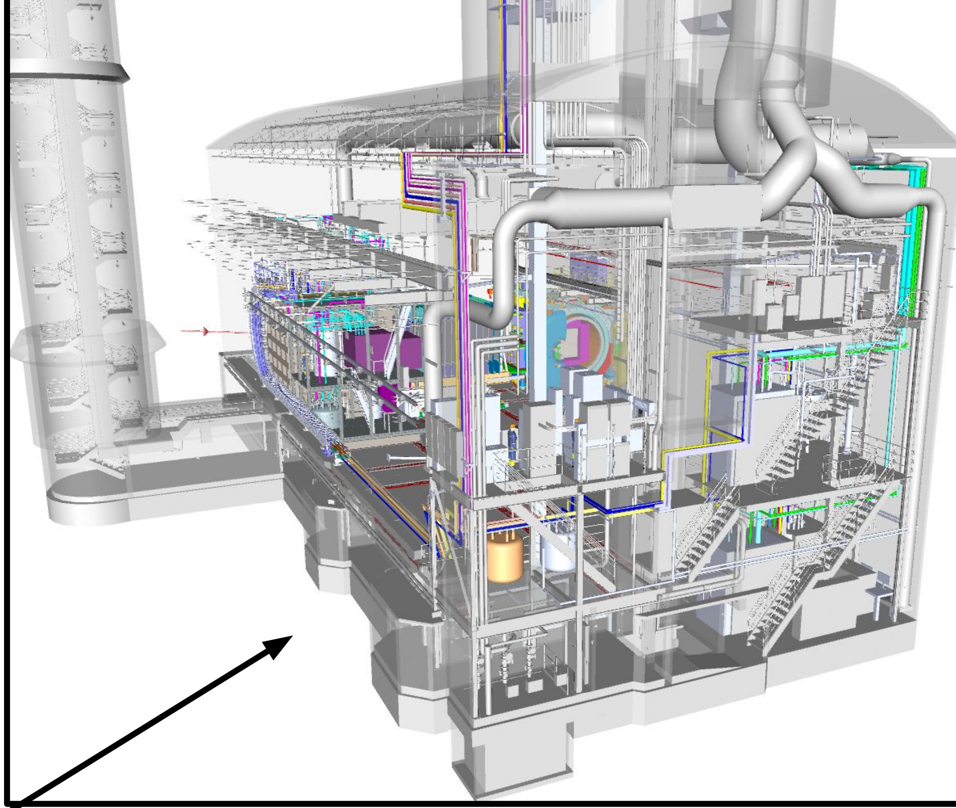
DUNE Near Detector Hall



DUNE Near Detector Hall Design



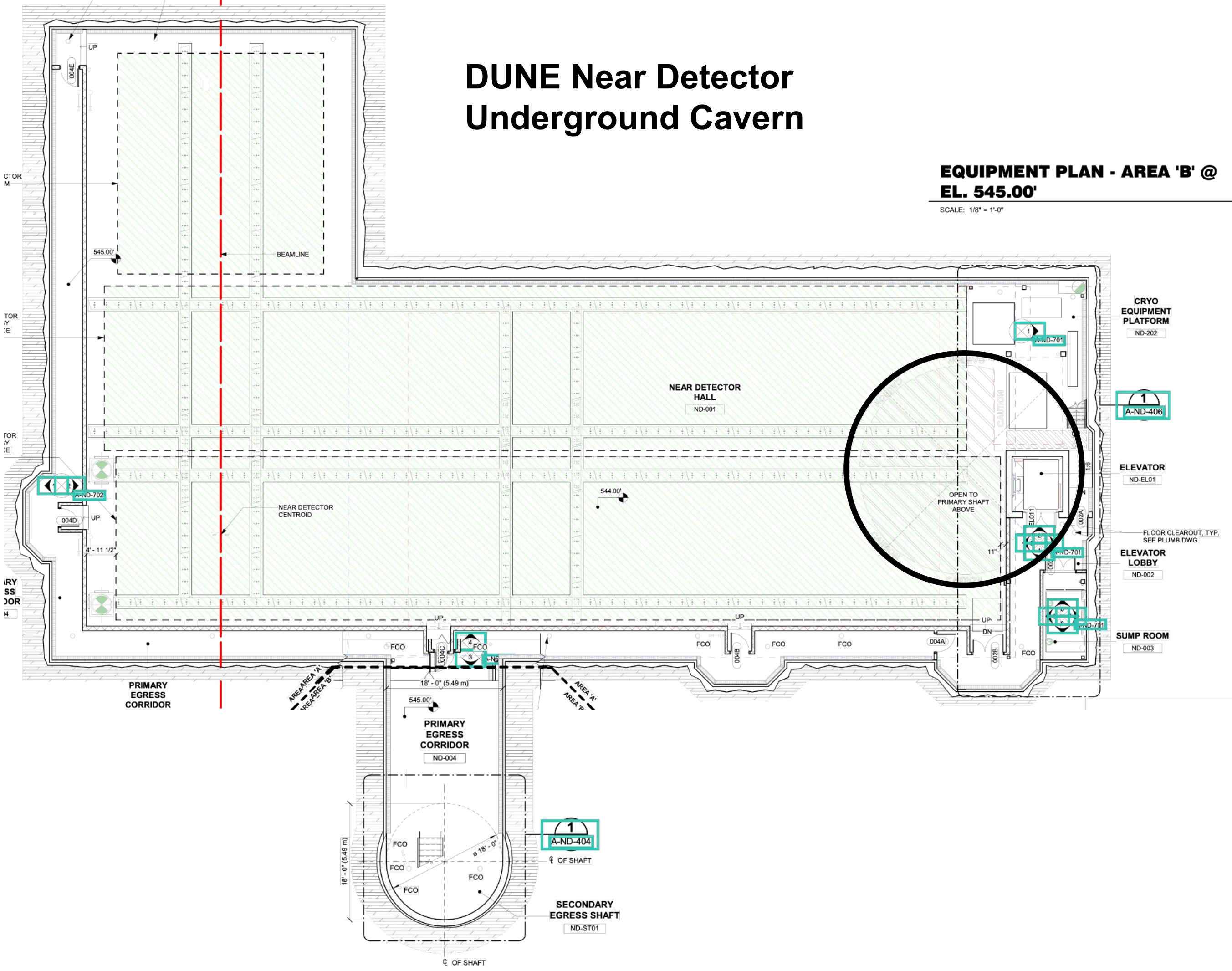




The near detector hall for DUNE Phase 1 is at "100% final design" (i.e. changes to the hall at this point would be very difficult)

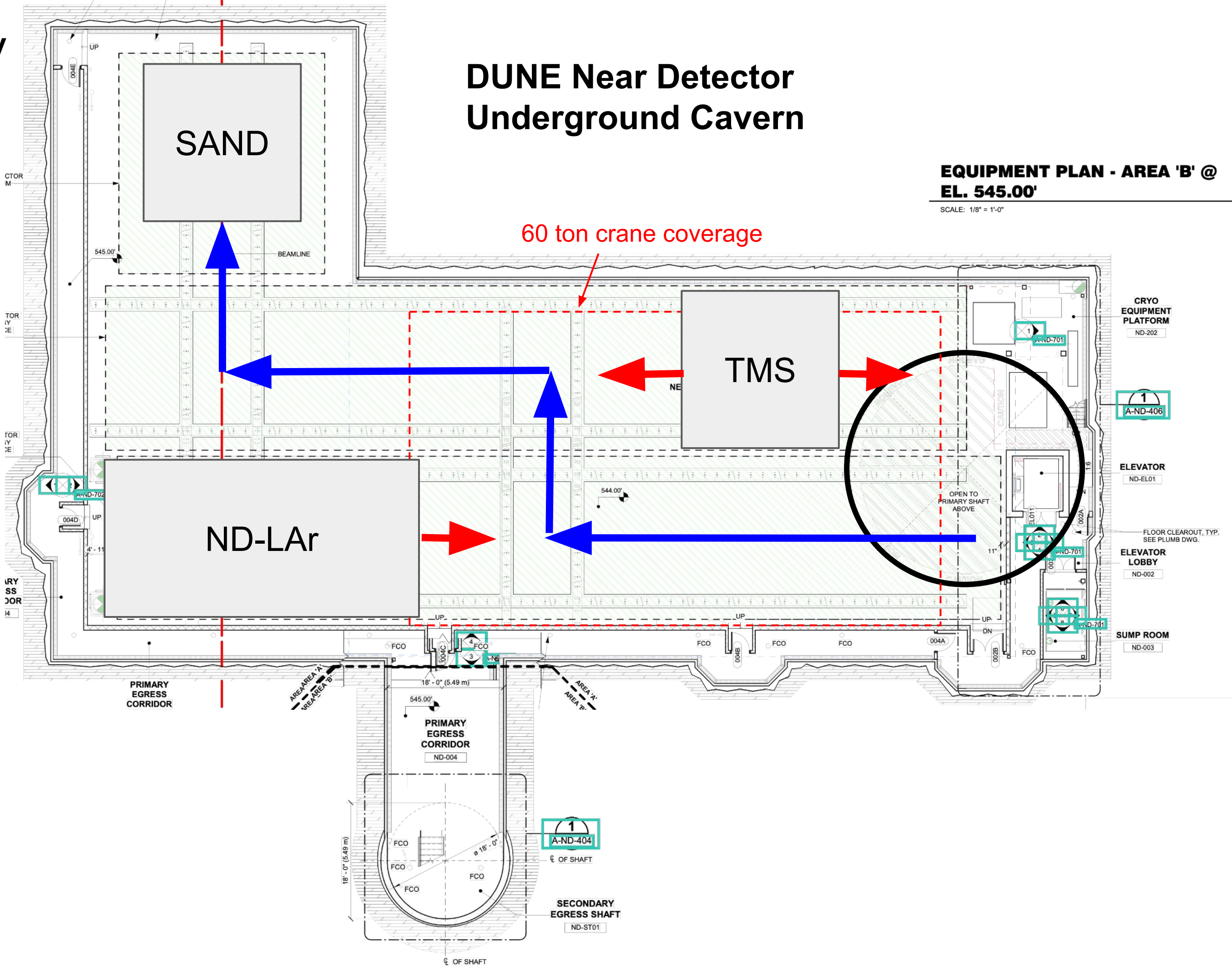
Cavern Layout

- **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



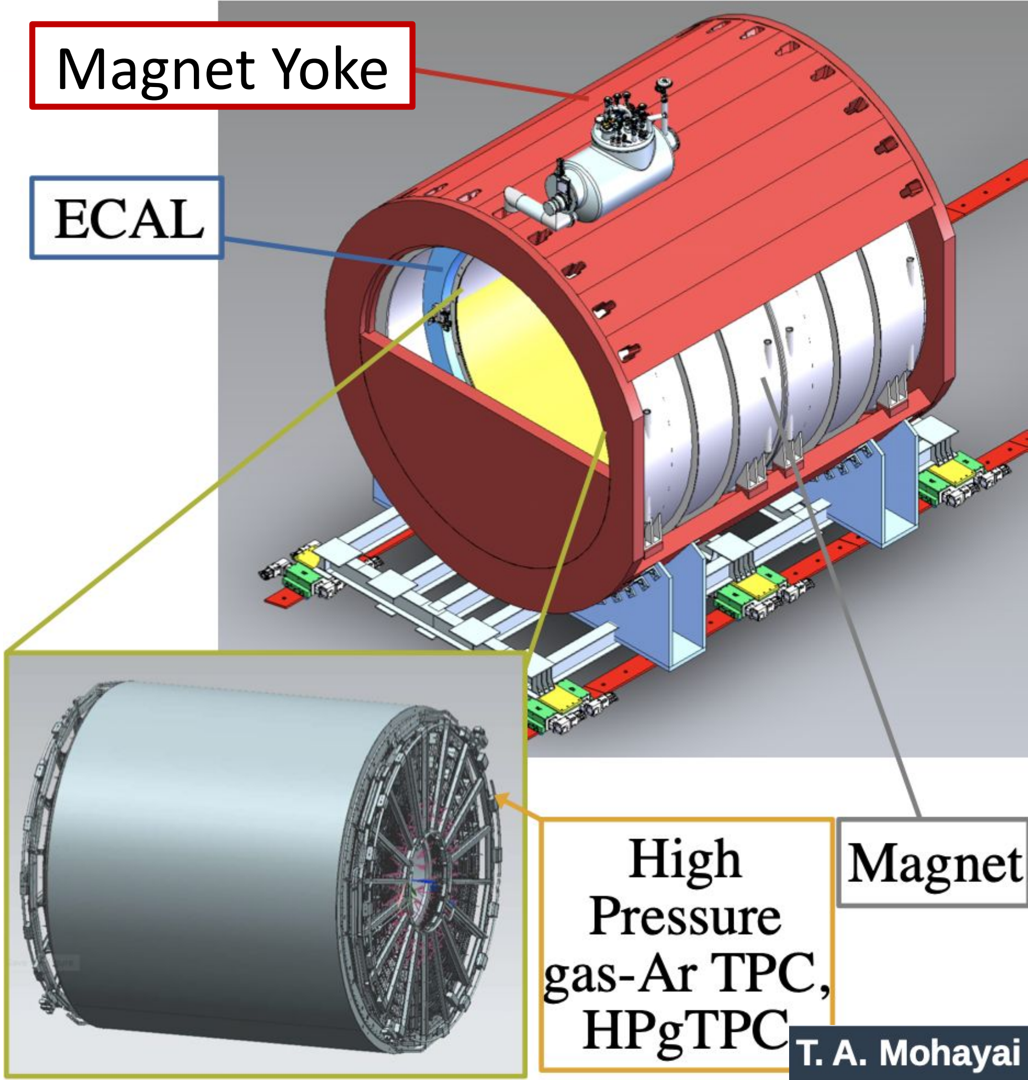
Detector Choreography

- 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



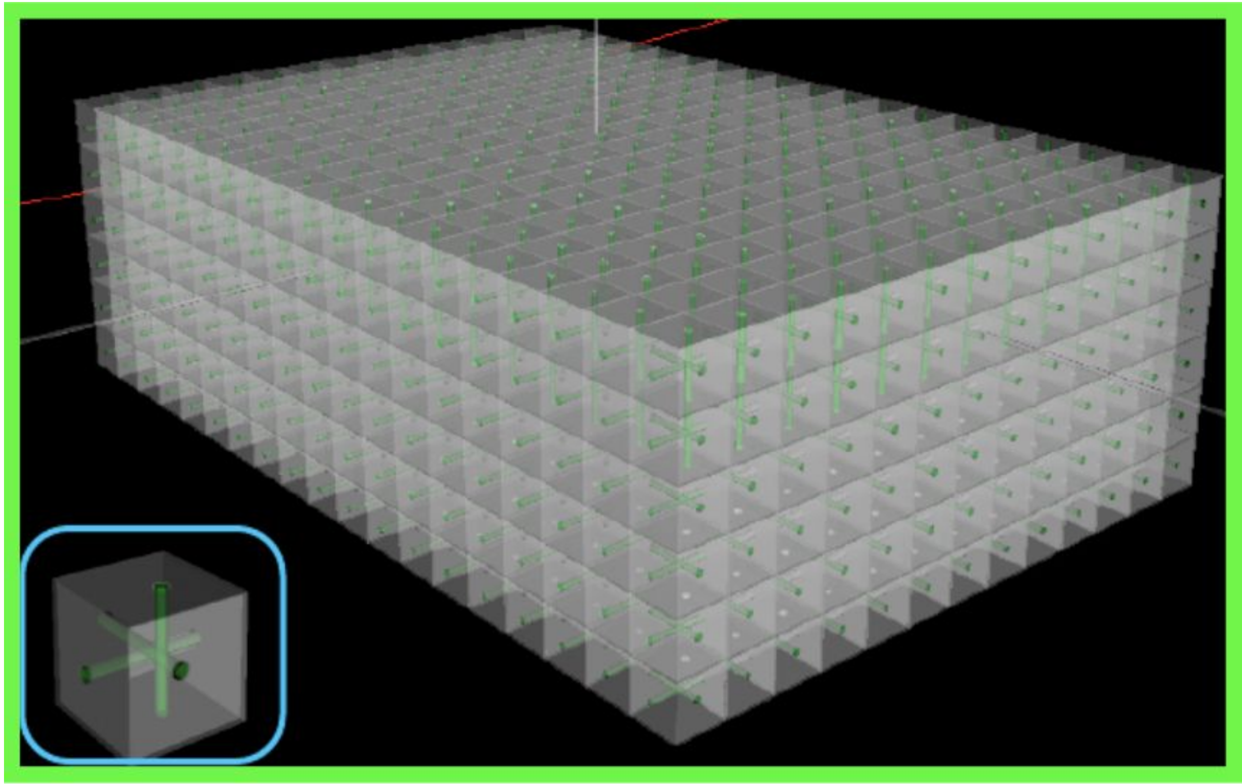
ND-GAr

- 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$p2h$ [$\nu,\bar{\nu}$]	$2p2h$
E_{2p2h} [A,B] [$\nu,\bar{\nu}$]	$2p2h$
NR [$\nu,\bar{\nu}$] [CC,NC] [n,p] [$1\pi,2\pi,3\pi$]	Non-res. pion
ν_e PS	$\nu_e,\bar{\nu}_e$ inclusive
$\nu_e/\bar{\nu}_e$ norm	$\nu_e,\bar{\nu}_e$ inclusive
NC norm.	NC

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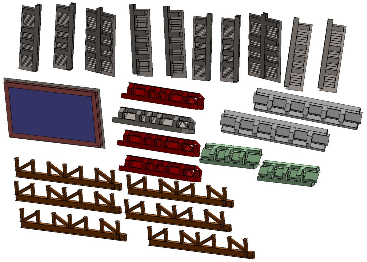
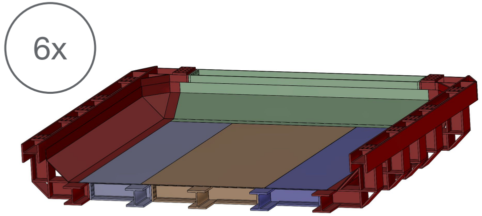
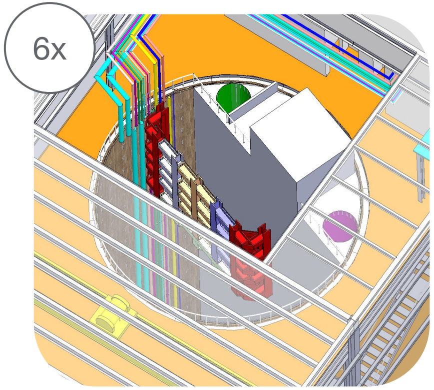
Cryostat Assembly Process Overview



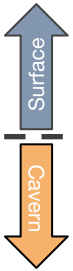
1. Receive 160 metric tons of warm structure parts in 40 pieces

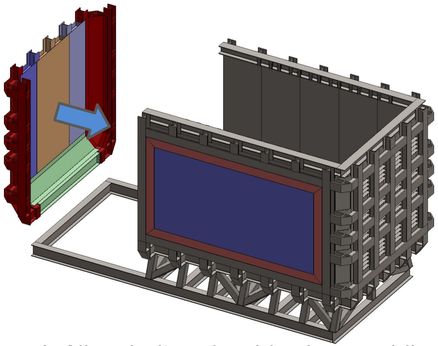


2. Align and bolt pieces into subassemblies

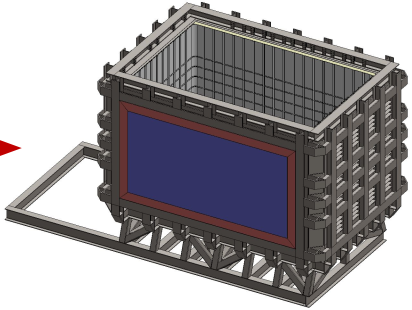


3. Lower 15-50 metric ton subassemblies into cavern

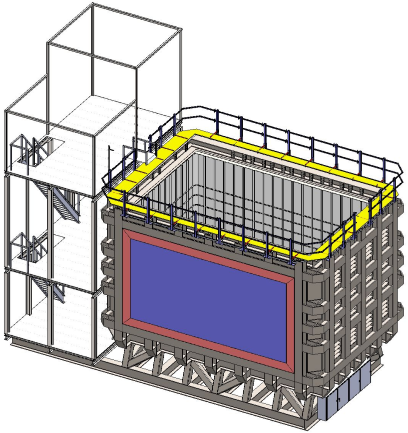




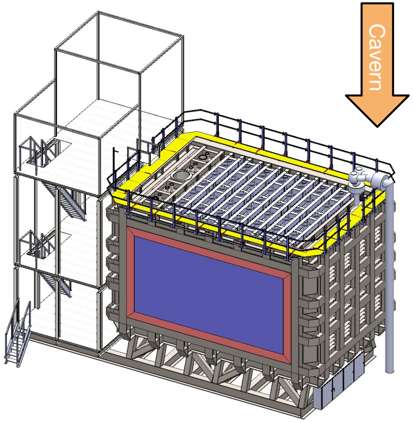
4. Align, bolt and weld subassemblies to form warm structure



5. Install cold membrane

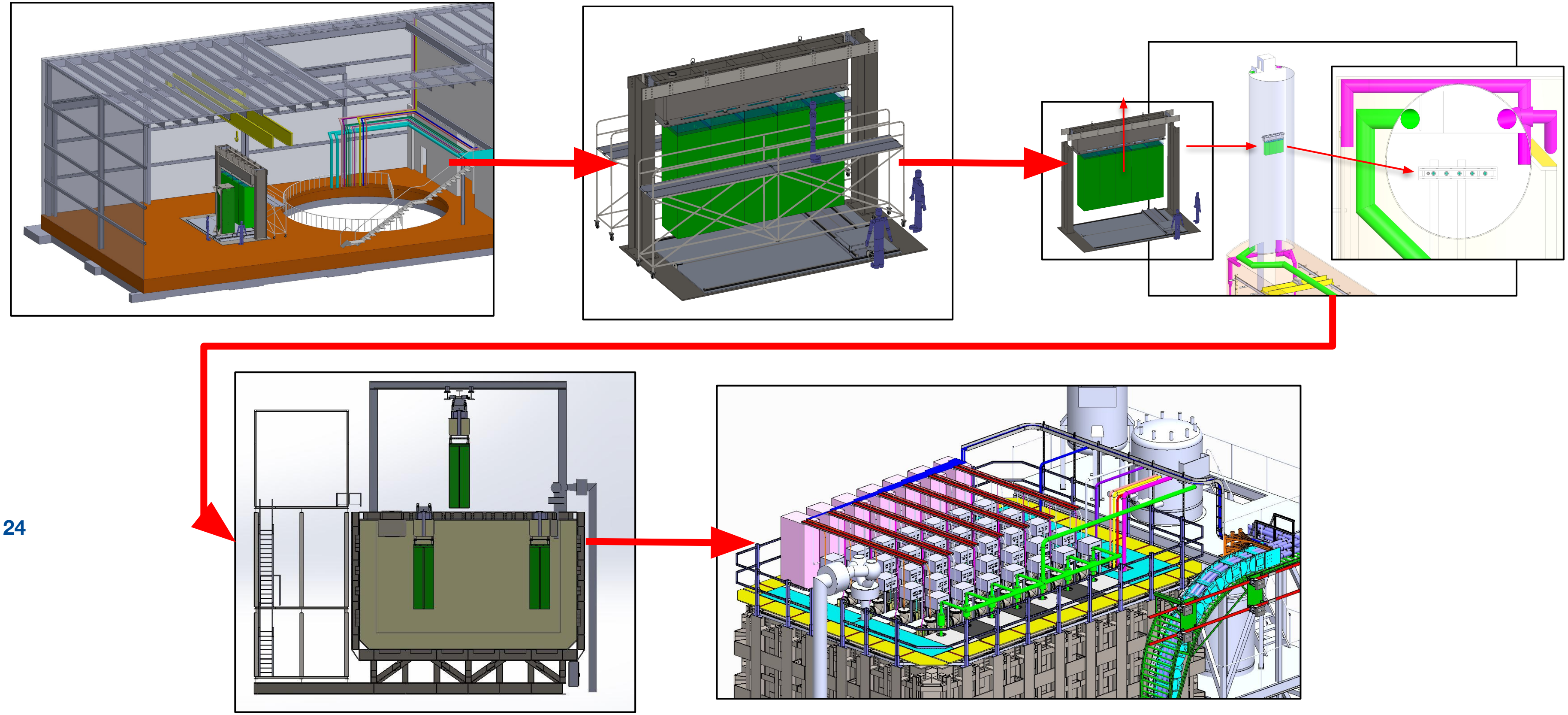


6. Install mezzanines

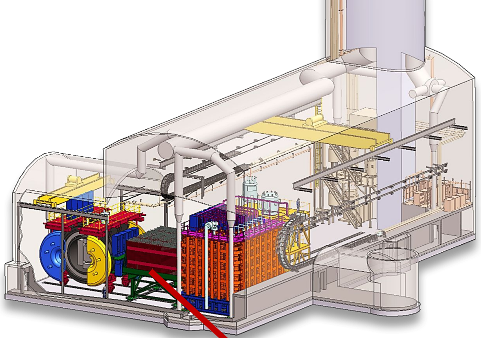


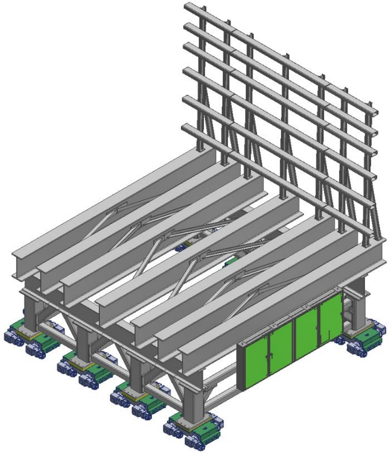
7. Install TPC rows and lid sections

ND-LAr Assembly Process Overview

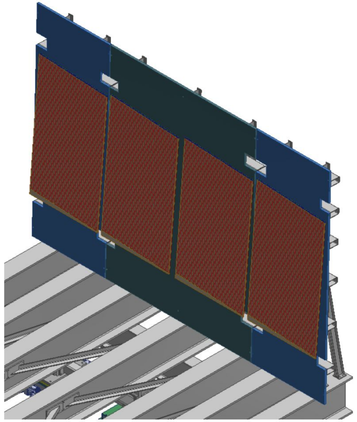


TMS Components and Assembly Overview

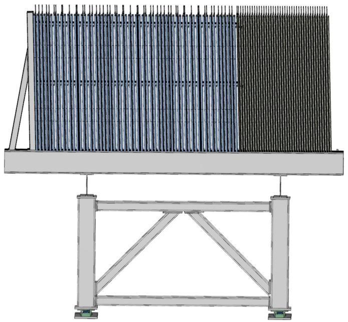




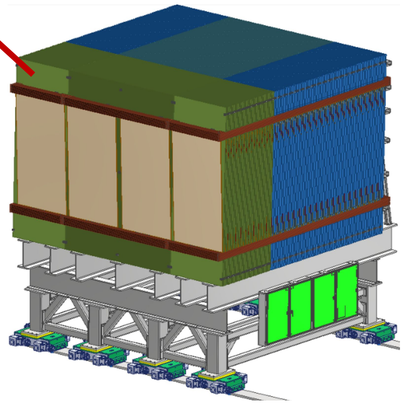
Iron Throne



1st TMS layer



100 TMS layers



Magnet Coils