Toward a Theia Long-Baseline (LBL) Analysis

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Theia LBL Meeting

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Overview

- For the DUNE Far Detector Conceptual Design Report (FD-CDR), LBL sensitivities were produced using GLoBES (https://www.mpi-hd.mpg.de/personalhomes/globes/)
    - This is the same framework (with the same systematic error assumptions) used for the Theia LBL analysis in the Theia white paper (https://arxiv.org/abs/1911.03501)
- For the DUNE Far Detector Technical Design Report (FD-TDR), the analysis was upgraded to include simulated event samples at the ND and FD, and more realistic systematic uncertainties
    - e.g. low-level neutrino-nucleus model parameter uncertainties
- Our goal is to upgrade the Theia LBL analysis to a similar level of sophistication
- Ultimately, our sensitivities must be combined with existing DUNE sensitivities (and will use similar inputs), so we should aim use the DUNE software framework wherever possible
- At the Valencia “Module of Opportunity” workshop, an organization for the DUNE Phase 2 upgrade was formed (FD3, FD4, ND upgrade, beam)
    - We should plan to give regular updates at these meetings as the analysis progresses

DUNE LBL Analysis

- Flux predictions with systematics (hadron production + “focusing”) are available
  - Our analysis should just reuse these
- ν-N uncertainties (next slide)
- Far detector simulation, reconstruction, and first-pass detector uncertainties
  - Guang will tell us about Theia simulation & reconstruction status next
- Near detector simulation (no reconstruction yet), first pass detector uncertainties
  - More on near detectors later

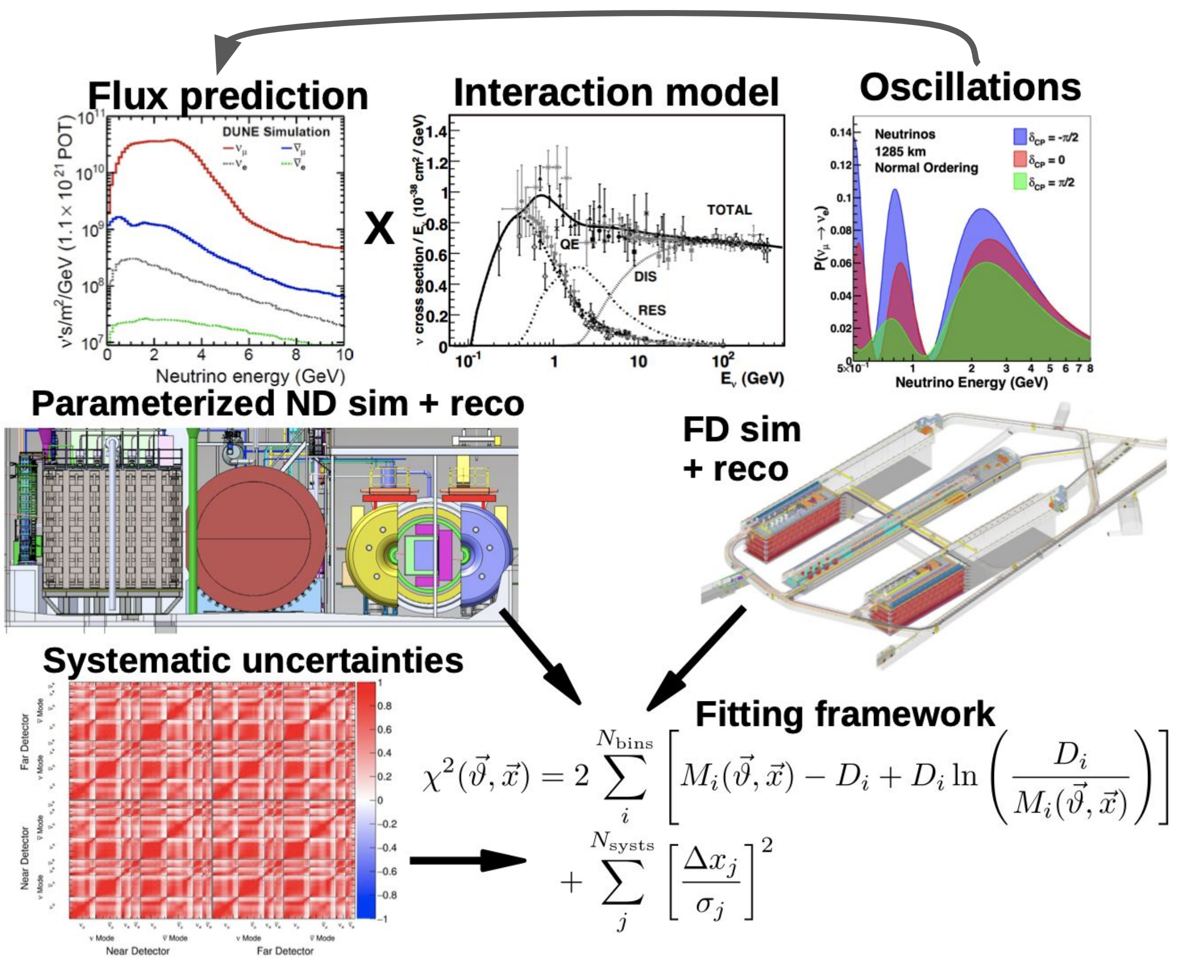

Figure taken from any of ~10 different DUNE talks

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

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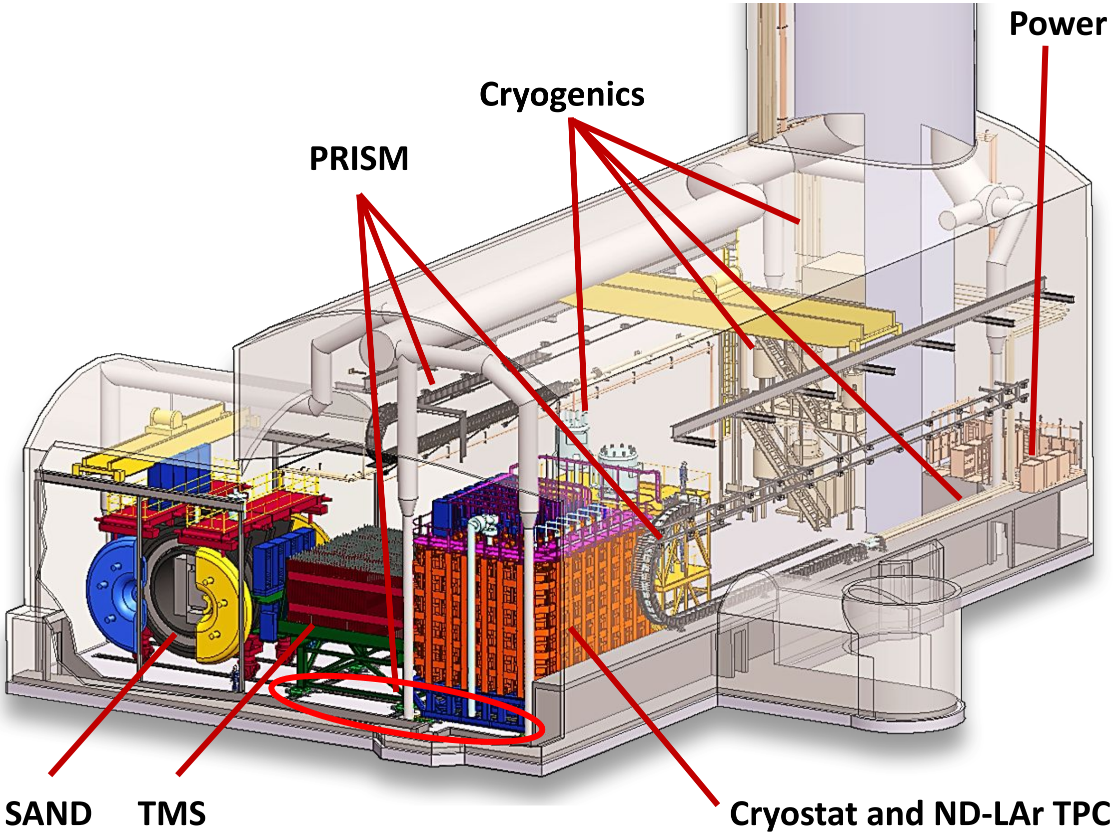
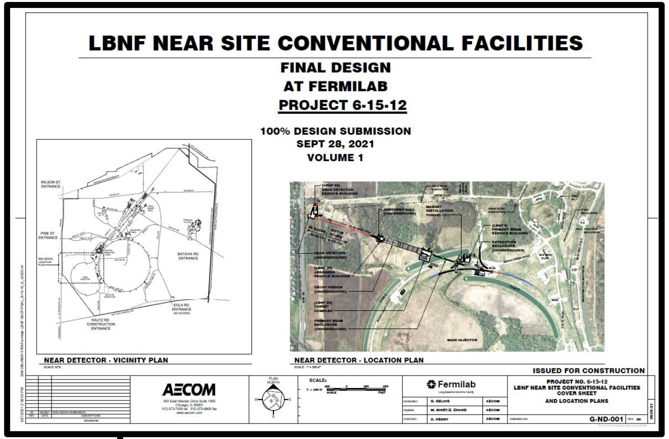
Near Detector Considerations

- 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
- Key question: how can the ND be modified to make measurements necessary for a WbLS far detector?

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

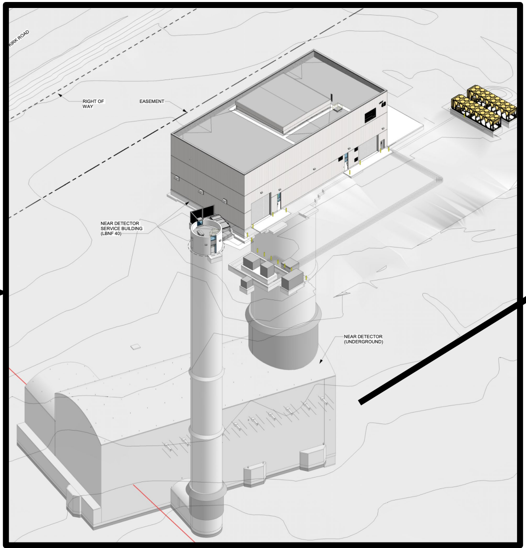
ISSUED FOR CONSTRUCTION

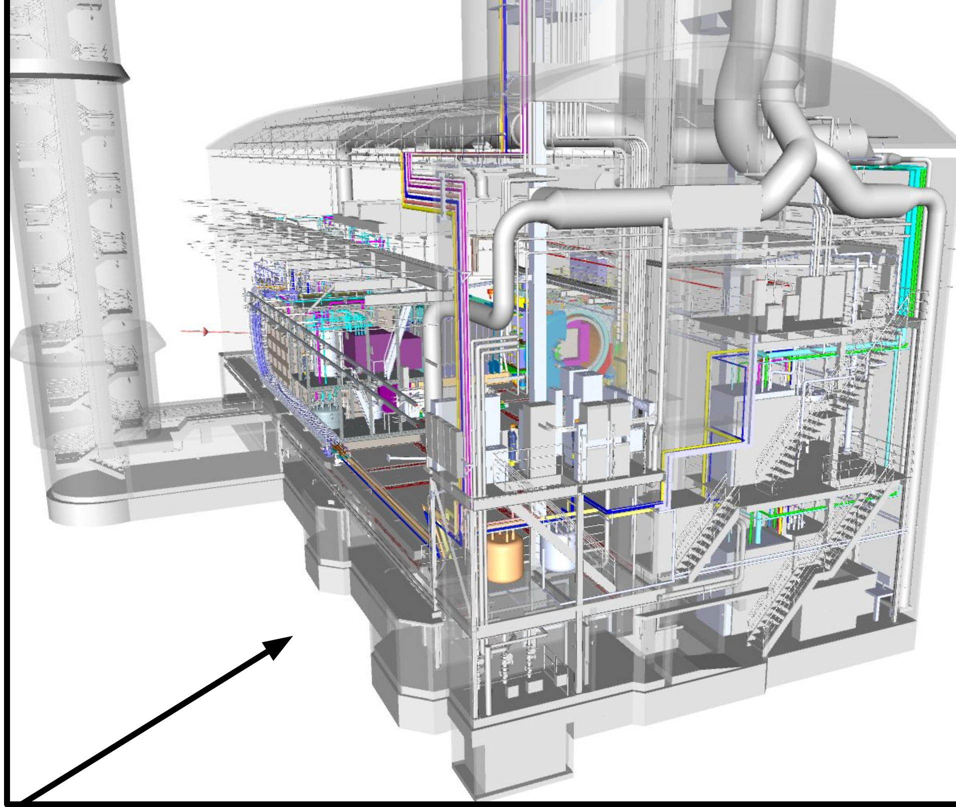
AECOM

Fermilab

PROJECT NO. 6-15-12
LBNF NEAR SITE CONVENTIONAL FACILITIES
COVER SHEET
AND LOCATION PLANS

G-ND-001



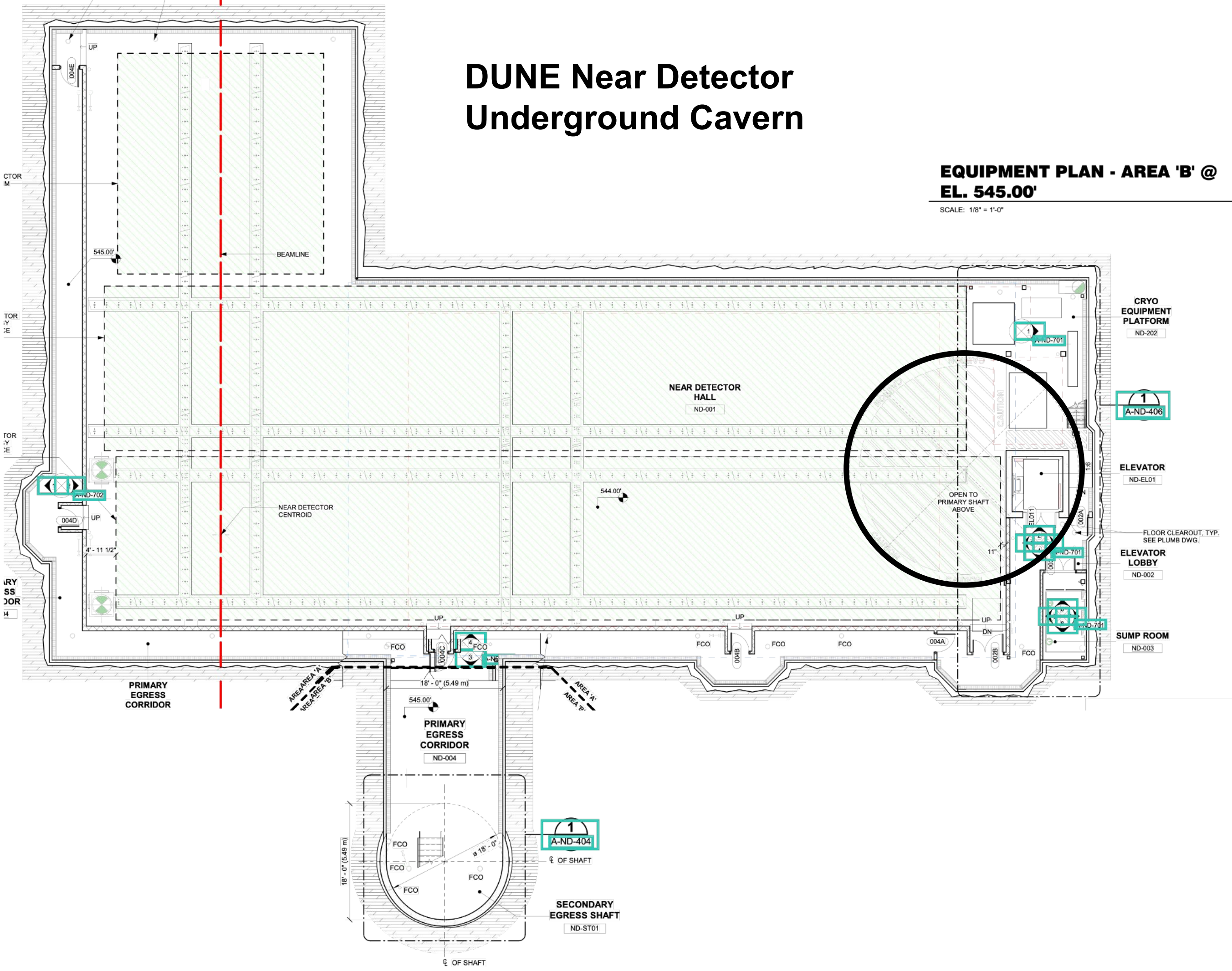


The near detector hall for DUNE Phase 1 is at “100% final design” (i.e. changes to the hall at this point would be very difficult)

Cavern Layout

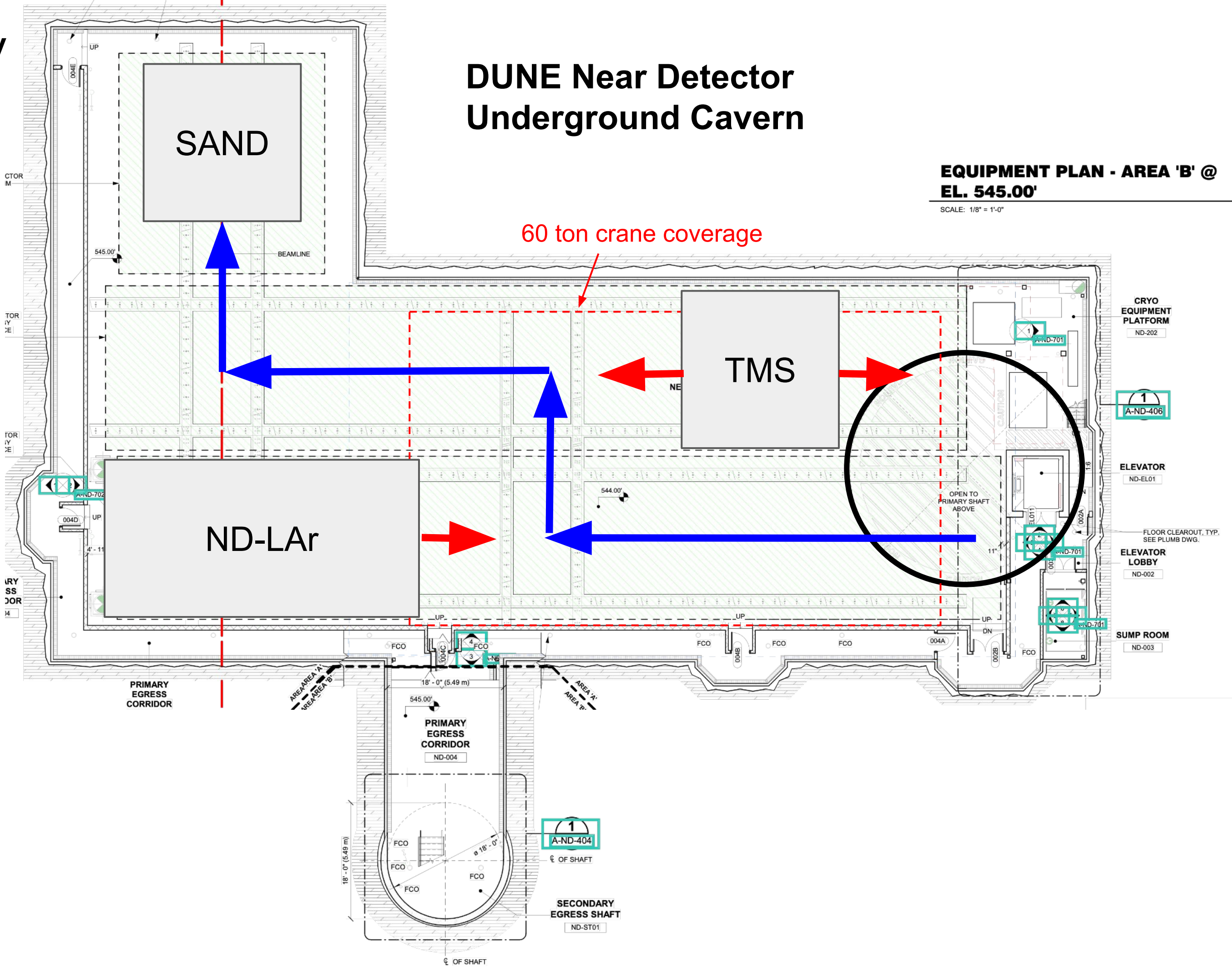
- **Red line**: beam axis
- Off-axis travel direction is left-to-right
- 2 pairs of rails for ND-LAr and TMS
- 2 sets of “cross rails” (along the beam direction) for SAND
  - SAND can move between the TMS and ND-LAr rails
- The main shaft, elevator, and equipment mezzanines are on the right side

DUNE Near Detector Underground Cavern



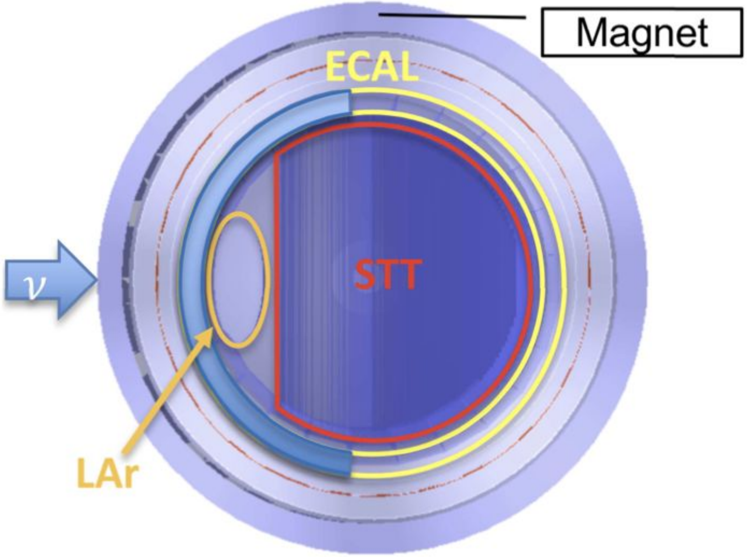
Detector Choreography

- 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



C/O/H Targets in SAND

- The SAND Straw-Tube Tracker (STT) is capable of housing thin (~12 mm) targets of CH_2, C, & CH_2O, which can be used to extract neutrino cross sections on C, O, and H.
- SAND can also hold up to ~1 ton of H_2O to measure water cross sections directly
- High statistics measurements are possible
- More details from R. Petti at an upcoming meeting

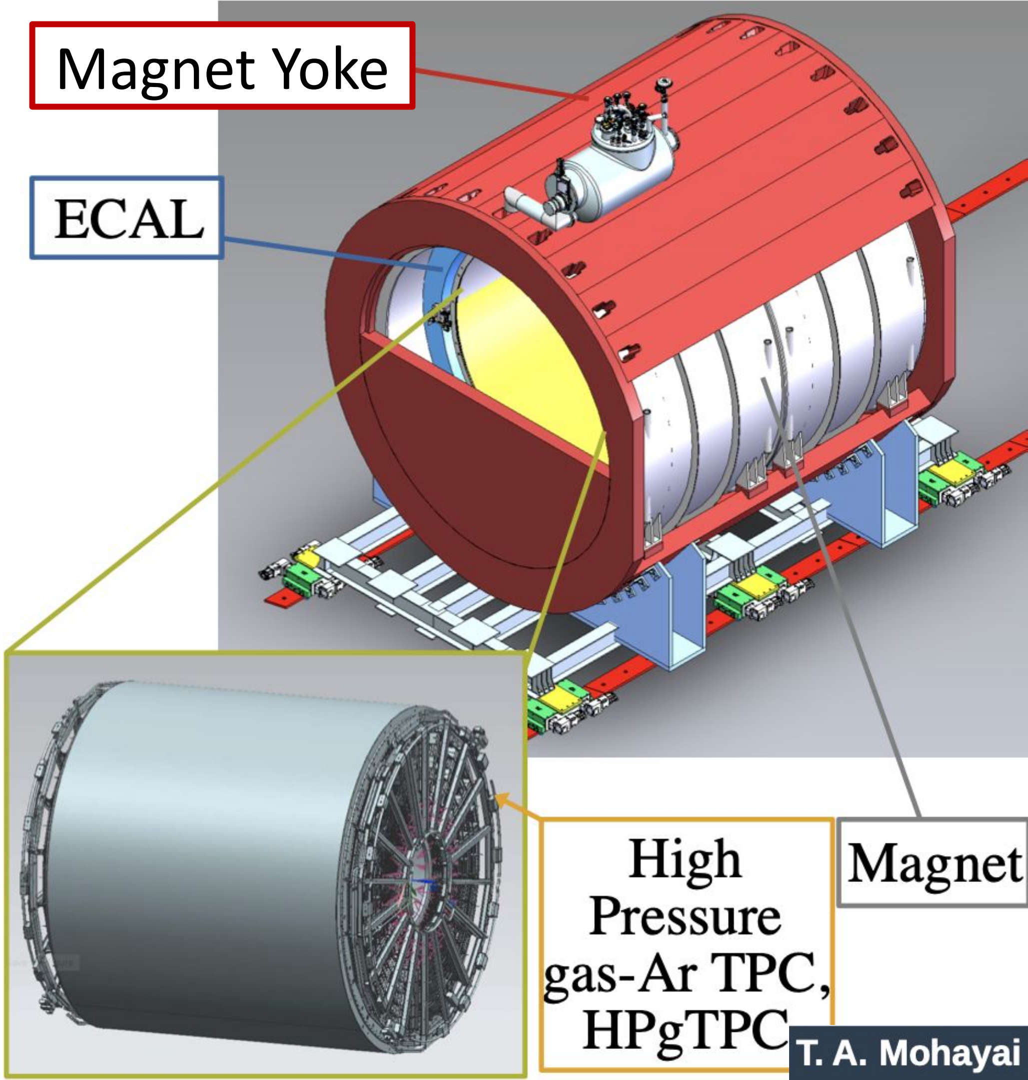


Target	CP optimized FHC (1.2MW, 2y)				CP optimized RHC (1.2MW, 2y)			
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC
CH_2	13,010,337	624,330	192,118	31,902	2,035,973	4,870,562	91,004	69,278
H	1,222,576	111,574	18,396	5,557	194,216	906,130	8,712	12,434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

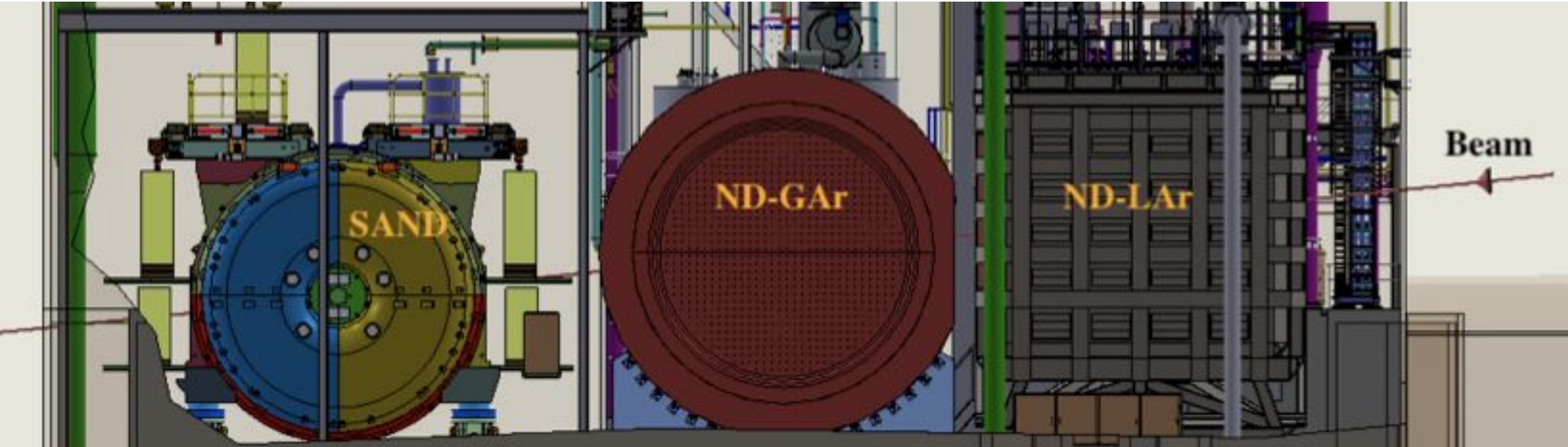
ND-GAr

- Are off-axis WbLS targets possible?
- 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



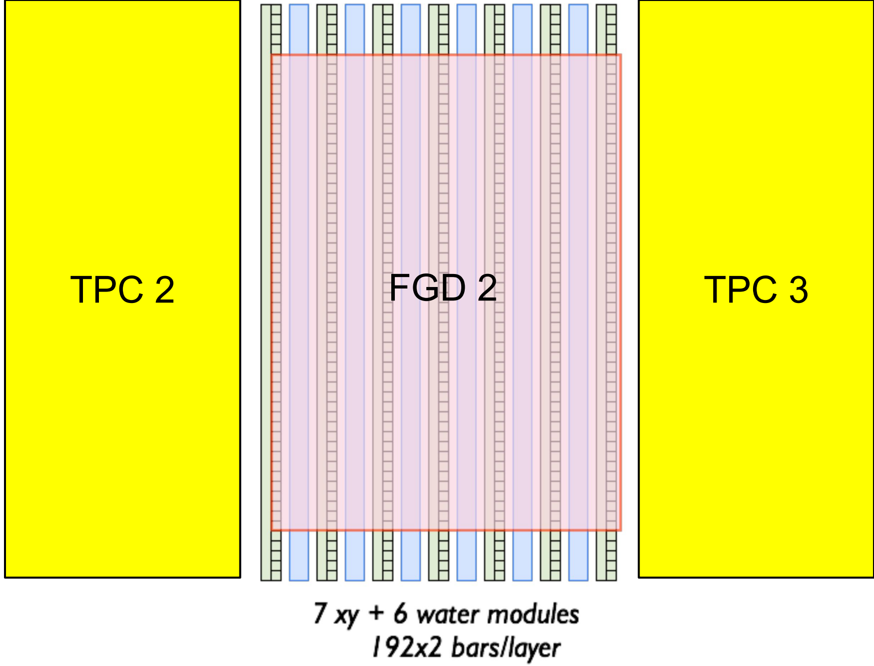
WbLS Targets in ND-GAr

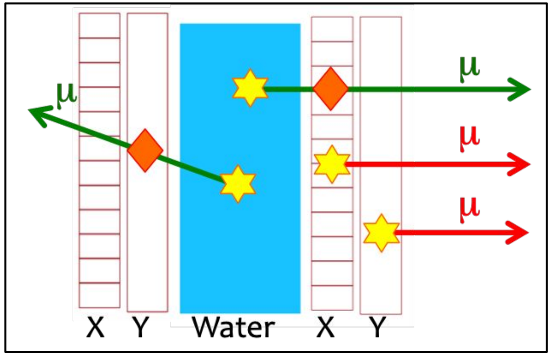
- The most minimally invasive option for off-axis ND WbLS is to incorporate targets into ND-GAr
  - Unlike a LAr detector, which relies on hadronic calorimetry, Theia only requires measurements of particles above Cherenkov threshold (e.g. T2K ND strategy – see next slide)
- The upstream ECAL for ND-GAr is already envisioned to be “thin” to enhance muon catching
  - In this case, it would be possible to incorporate WbLS targets/cells/bars/cubes in the upstream ECAL
- This could also provide useful synergy -> multiple groups working toward a multipurpose ND-GAr



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
- With WbLS, it may be possible to instrument the water layers to reduce these uncertainties
  - A sufficient scintillator fraction / light yield to record MIPs would be needed





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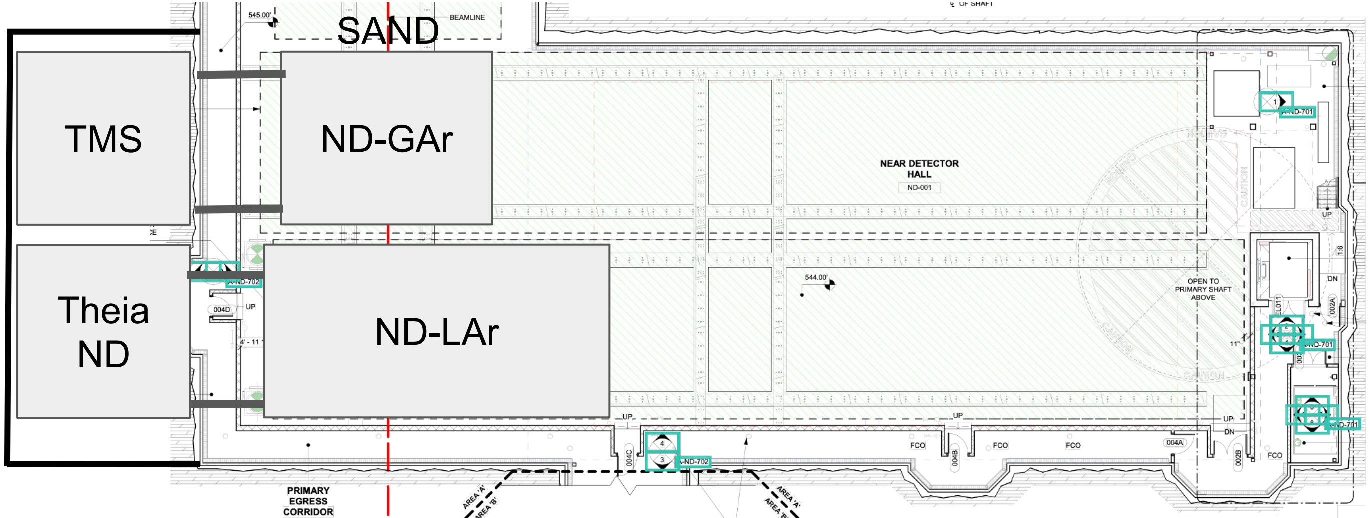
A Dedicated Theia Near Detector?

- The PRISM rail system allows detectors to be moved off-axis during beam running
- If the long dimension of the ND Hall can be further extended, can create a “garage” for a Theia ND
  - The garage need not extend to the full cavern height; just tall enough to fit the detectors
- If ND-GAr is also built, TMS would no longer be needed for ND-LAr, and could become the muon catcher for Theia ND



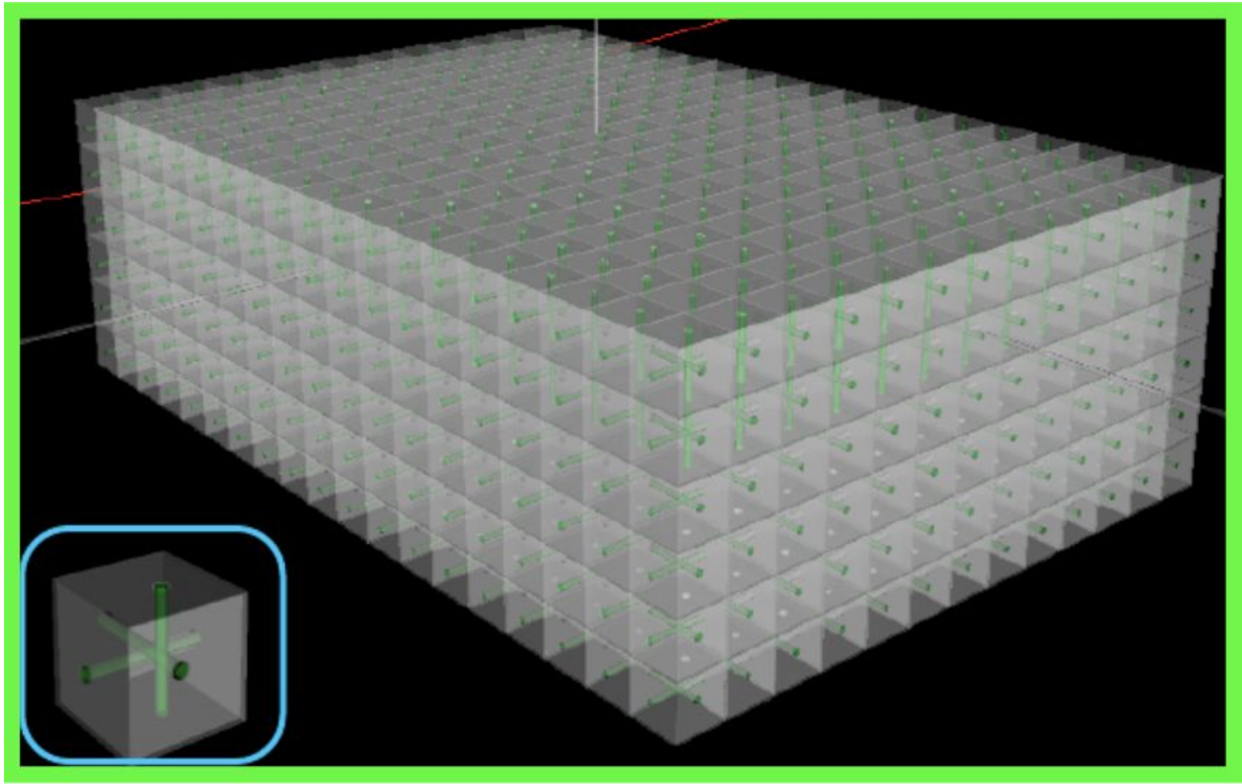
Summary

- Many concurrent activities will be needed to produce a DUNE ND-TDR-level oscillation analysis for a Theia far detector
  - DUNE oscillation analysis tools will need to be extended to incorporate Theia
  - Cross section model development for O/C targets must occur
  - Theia simulation and reconstruction tools will need further development to produce more accurate sample efficiencies and purities
- Many potential avenues to explore for Theia near detector measurements
  - Embedded C/O/H targets within SAND
  - WbLS targets incorporated into the upstream ECAL of ND-GAr
  - A dedicated Theia ND within a slightly expanded ND hall
- There are many places for people to get involved! Please let us know if you are interested in contributing!

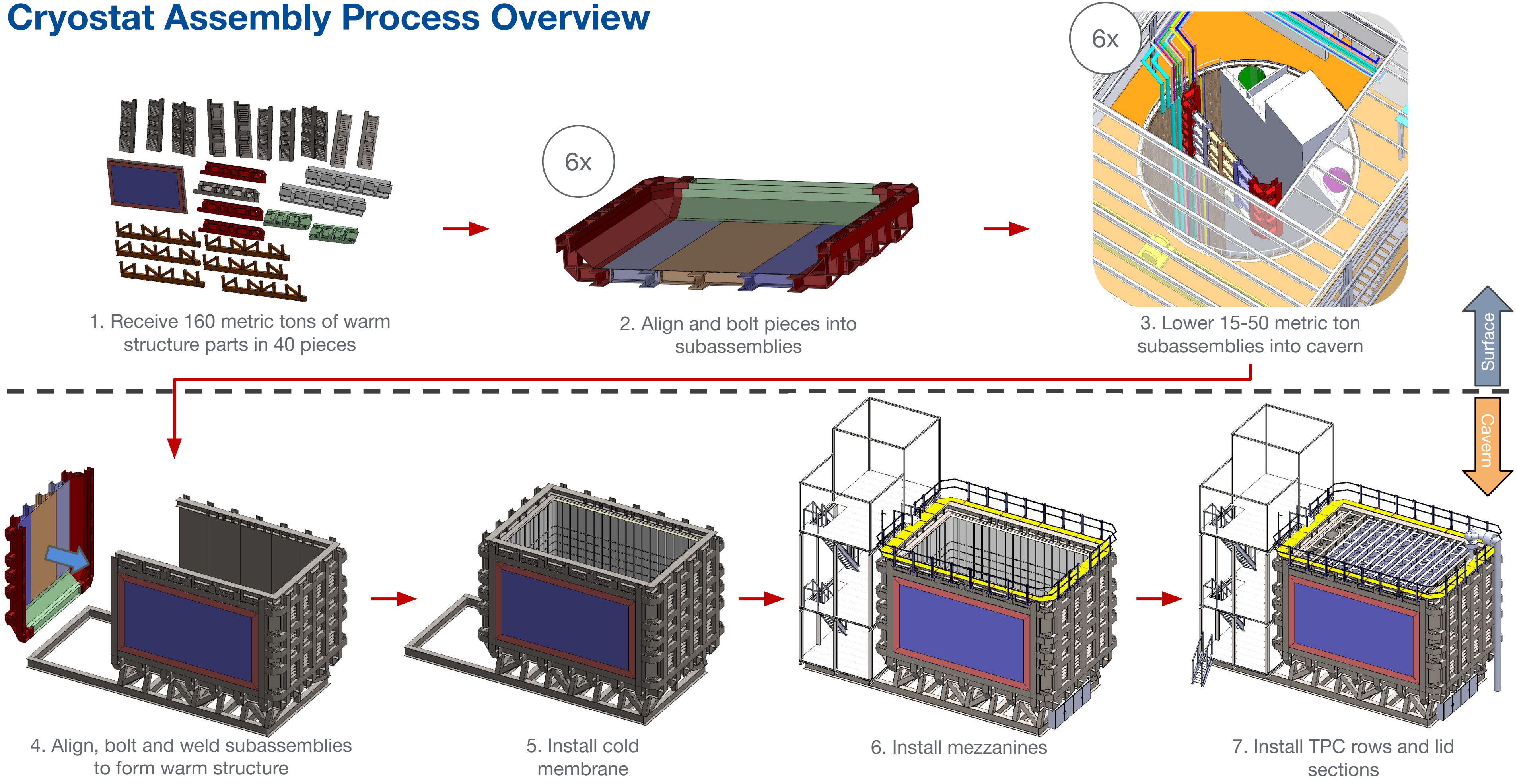
Backup

Super-FGD -> WbLS cubes?

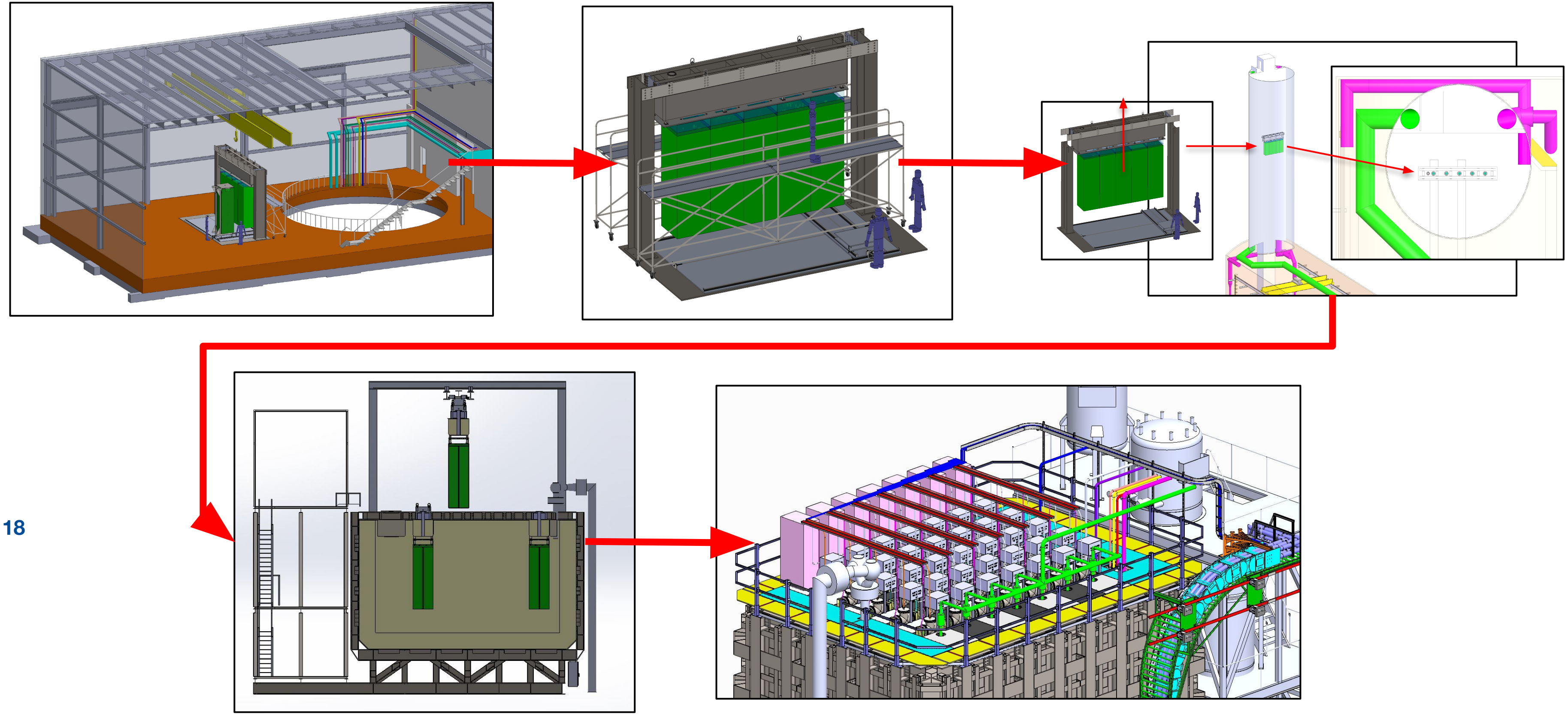
- The Super-FGD currently being constructed for T2K consists of 1 cm^3 scintillator cubes
- Can we incorporate WbLS cubes into a Super-FGD structure for DUNE?
  - For either a dedicated detector or for embedding into ND-GAr?



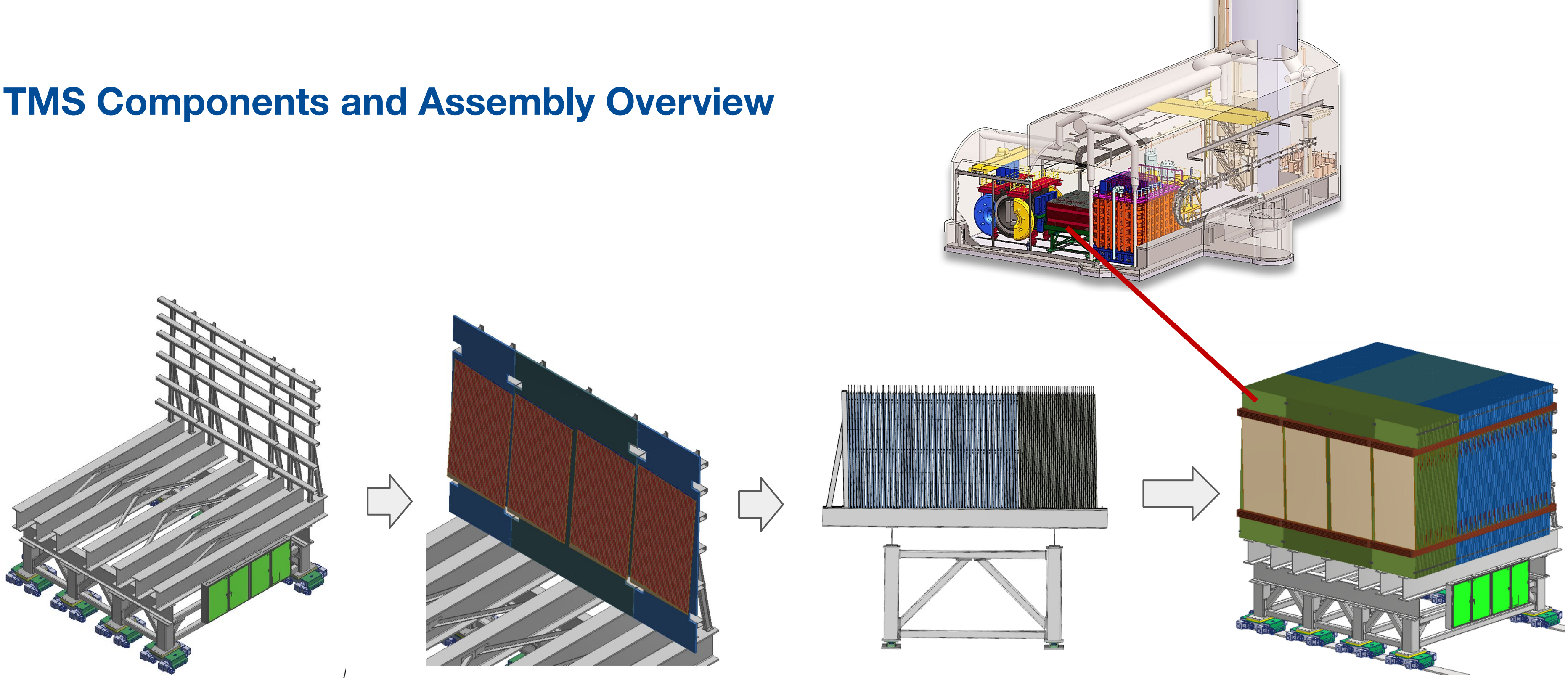
Cryostat Assembly Process Overview



ND-LAr Assembly Process Overview



TMS Components and Assembly Overview



Iron Throne

1st TMS layer

100 TMS layers

Magnet Coils