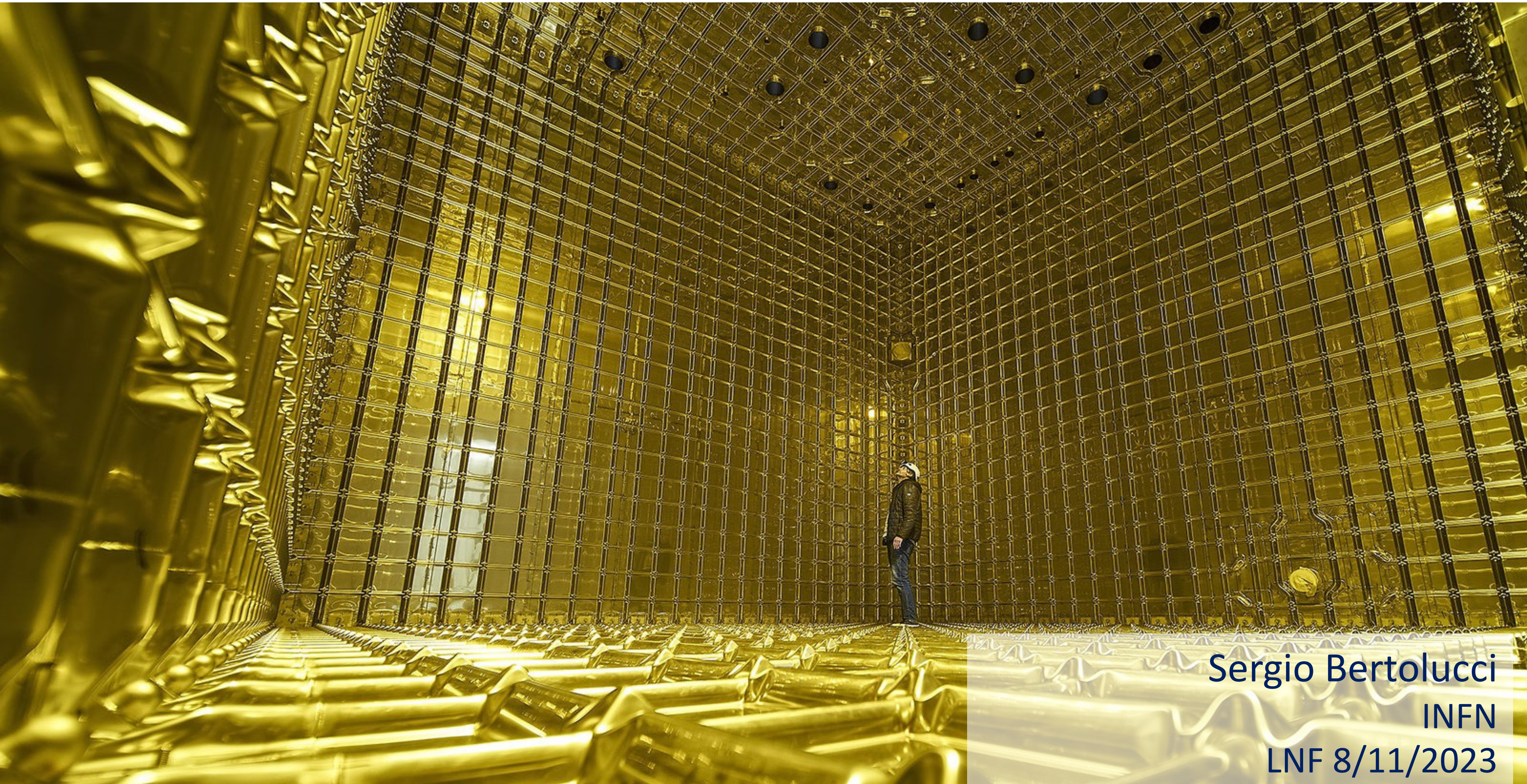
DUNE Status and Outlook



Sergio Bertolucci
INFN
LNF 8/11/2023

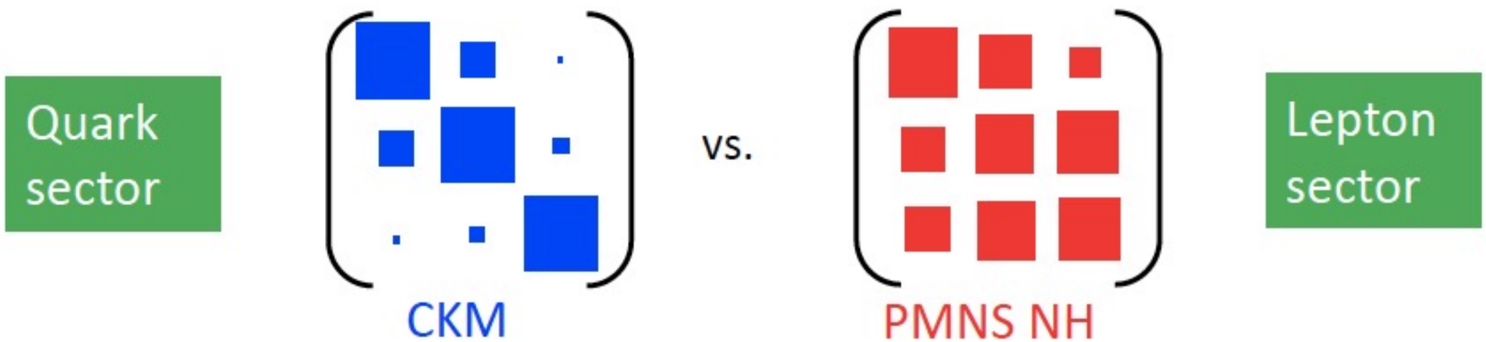
Fermilab INFN DUNE

Key Questions in Neutrino Physics

- Do neutrinos violate CP symmetry?

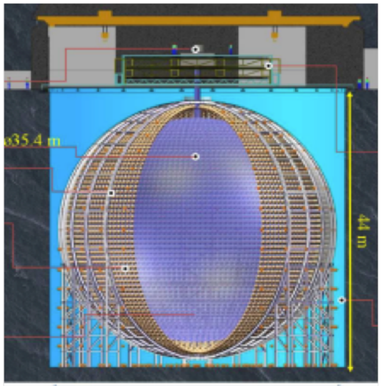
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- What is the mass ordering?
- Why are the quark and neutrino mixing matrices so different?



- Are there additional neutrino states?
- Are neutrinos their own antiparticles?
- What is the neutrino mass?

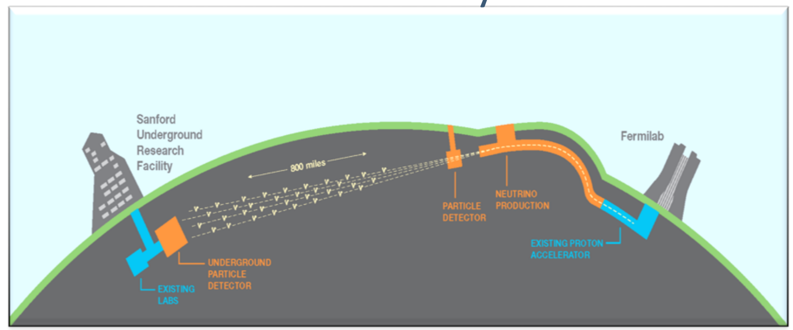
An Exciting Global Initiative to Understand the Most Abundant Known Matter Particle in the Universe

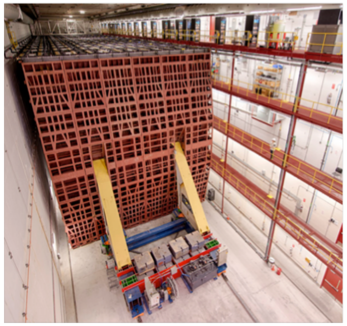


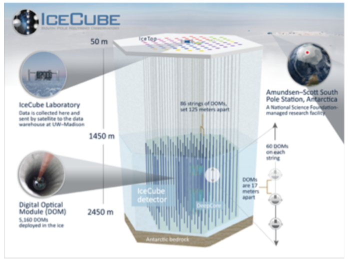
Deep **U**nderground **N**eutrino **E**xperiment

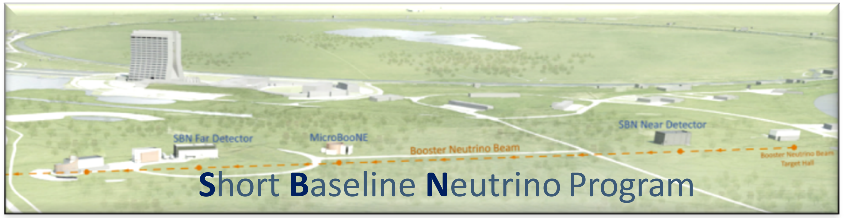
at the

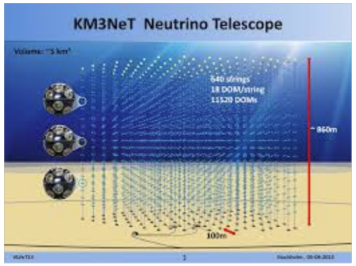
Long **B**aseline **N**eutrino **F**acility

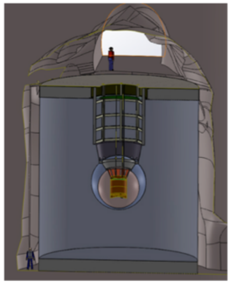


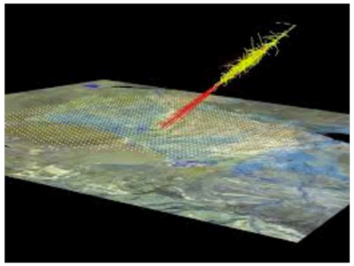


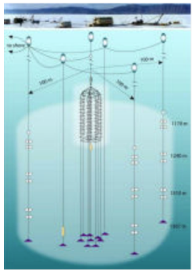












How to search for CP violation

- Compare oscillation oscillation rates for νs and $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

(in vacuum)

- As in quark sector, CP violating effects $\propto J \equiv c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$, and require no degenerate masses

- We know mixing angles and mass differences, so we can measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and determine δ, but there is a complication…

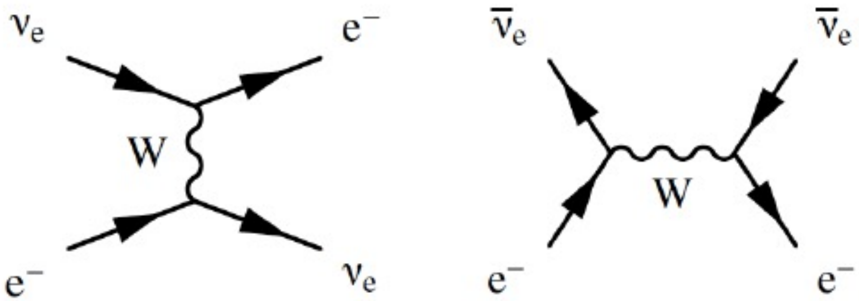
Matter Effects

- In real experiments, even in the absence of CPV,

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq 0$$

Neutrinos travel through material that is not CP symmetric, i.e., matter not antimatter

- In vacuum, the mass eigenstates ν_1, ν_2, ν_3 correspond to the eigenstates of the Hamiltonian:
  - they propagate independently (with appropriate phases)
- In matter, there is an effective potential due to the forward weak scattering processes. **Effect depends on Mass Hierarchy**



$$V = \pm\sqrt{2}G_F n_e$$

Different sign for ν_e vs $\bar{\nu}_e$

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter effects are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

  - Want high flux at oscillation maximum

➡ **Off-axis beam:** narrow range of neutrino energies

OR:

- Make L large (>1000 km): measure the matter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

  - **Unfold CPV from Matter Effects through E dependence**

➡ **On-axis beam:** wide range of neutrino energies

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter eff are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - Want hi tion maximum

➡ **Off- eam:** narrow range of neutrino energies

Hyper-Kamiokande

OR:

- Make L large (>1000 km): measure the atter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - **Unfold CPV from Ma ts through E dependence**

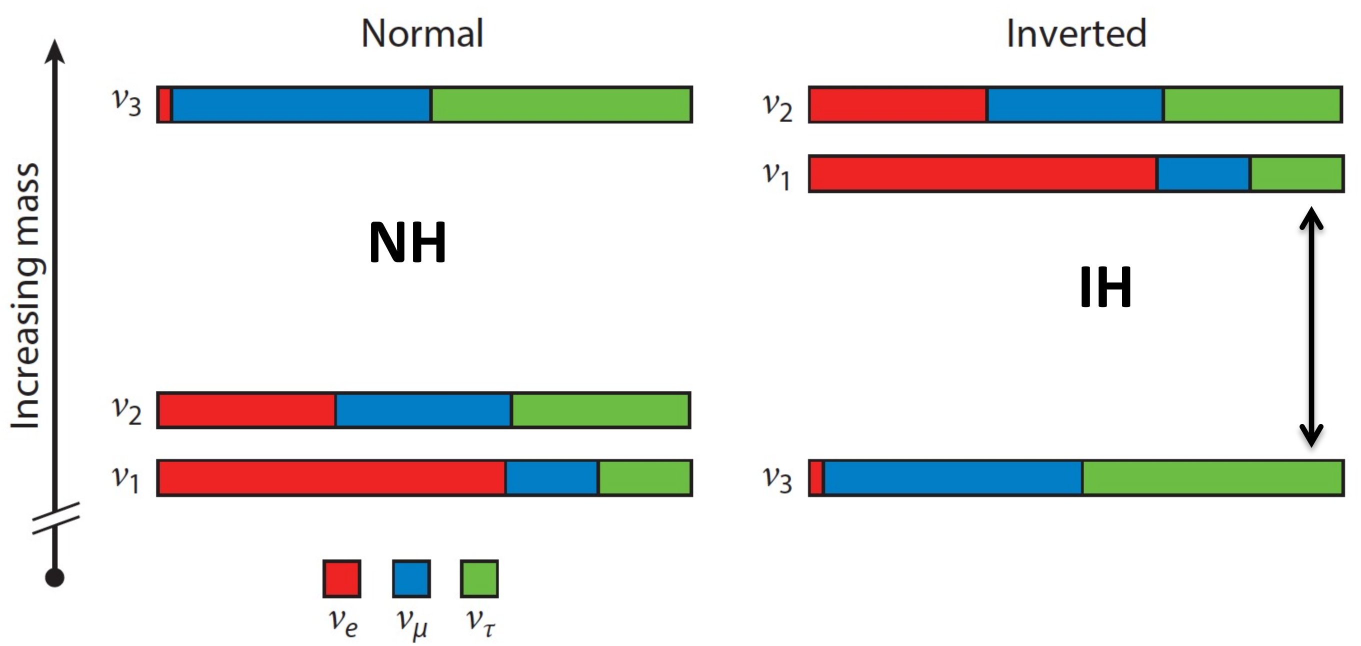
➡ **On-axis beam:** wide range of neutrino energies

DUNE

The present scenario

We are entering in the precision era, but there are still 4 results to be obtained, at least at first order :

1) Leptonic CP violation (phase δ_{CP})
2) Mass ordering (MO)
3) (θ_{23} octant)
4) Presence or not of more (sterile ?) neutrinos states

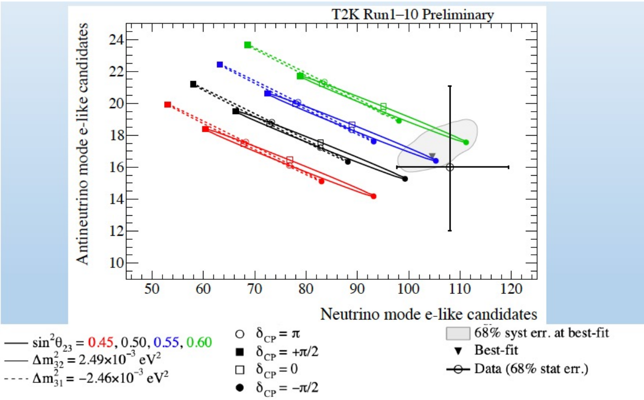


One or two states at higher mass ?

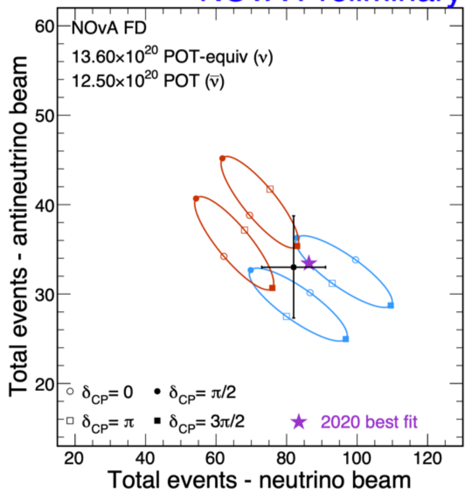
Δm^2_{atm}
||
Δm^2_{32} (NH)
||
Δm^2_{13} (IH)

Comparing scenarios

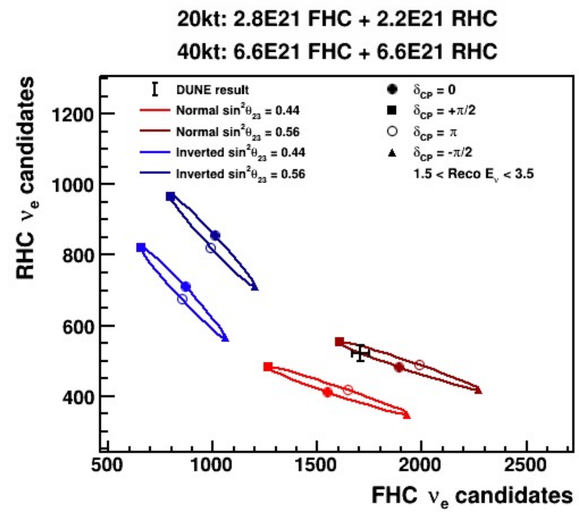
T2K



NOvA Preliminary



DUNE simulation



In Hyper-K only the error bars will shrink

With 2 or 4 dects, 100 kt-MW-y, shared between FHC and RHC, in 3 y ramp-up

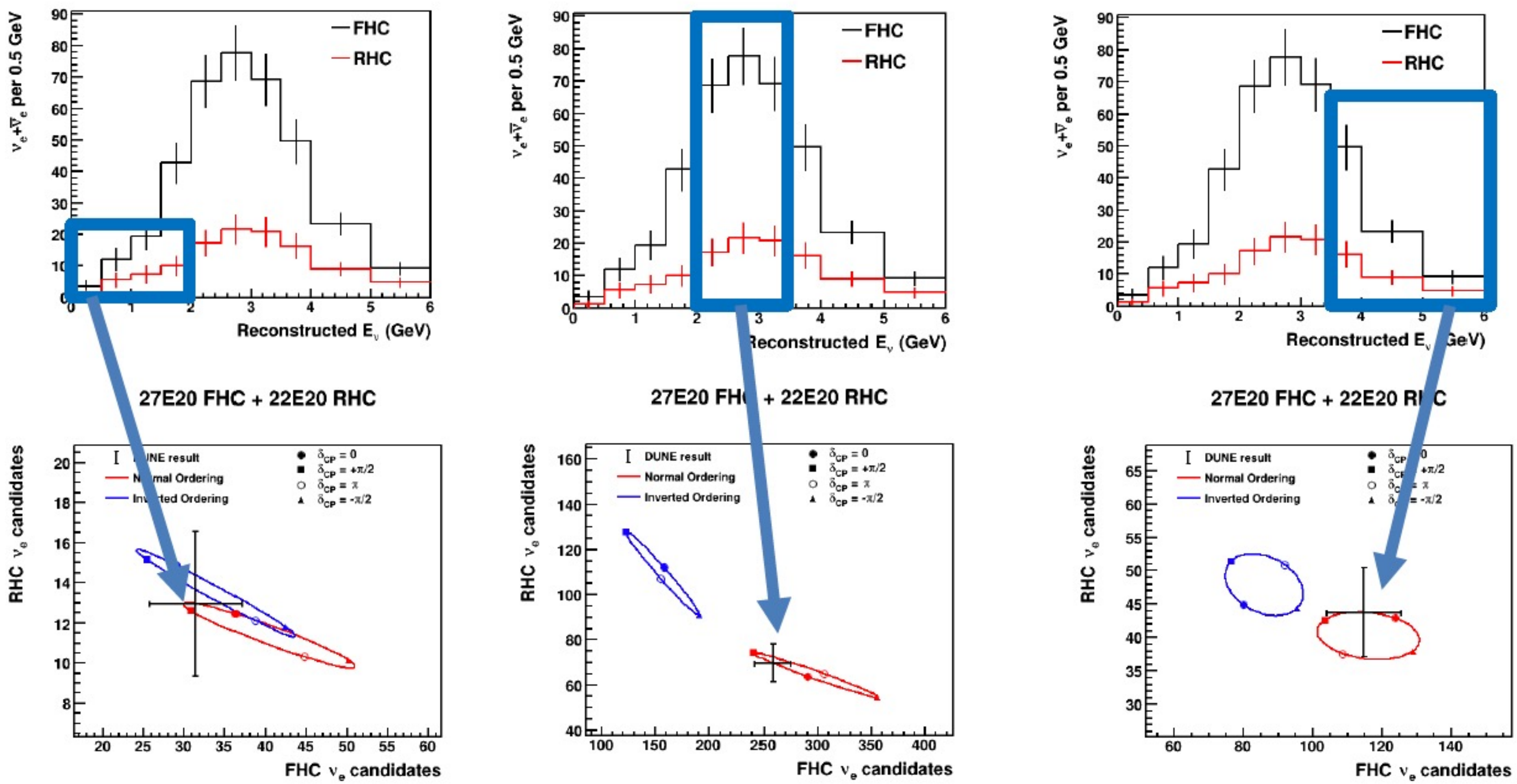
T2K -> Hyper-K:
Same baseline
Same beam spectrum
Same detector technology

NoVA -> DUNE:
Longer baseline
Wideband beam
Better event reconstruction

FHC: Forward Horn Current
RHC: Reverse Horn Current

DUNE : enhanced by the wide-band beam

➡ spectrum shape carries information (need proper energy reconstruction)



100 kt-MW-y,
shared between FHC and RHC,
in 3 y ramp-up

It's not only statistics....

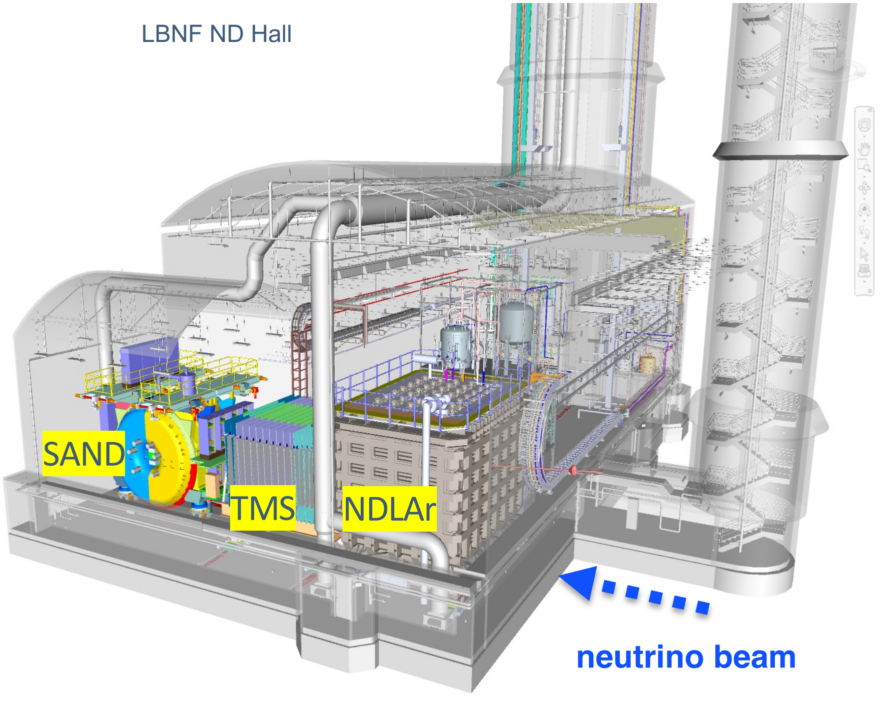
In the experiment we measure:

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

In order to get the physical quantities, we have to control flux, energy distribution/geometry of the beam, efficiencies, acceptances, etc..

Need a sophisticated Near Detector complex to control beam and systematics

Near Detector Complex



- **ND-LAr** (segmented LAr TPC)
- **TMS** (magnetized muon spectrometer)
- **SAND** (on axis magnetized spectrometer)

- Measure the neutrino beam rate & spectrum
- Constrain systematic uncertainties (flux, cross sections, detector response)
- A facility for neutrino physics

ND-LAr and TMS move off-axis to scan over the spectrum of nu energies

DUNE SAND

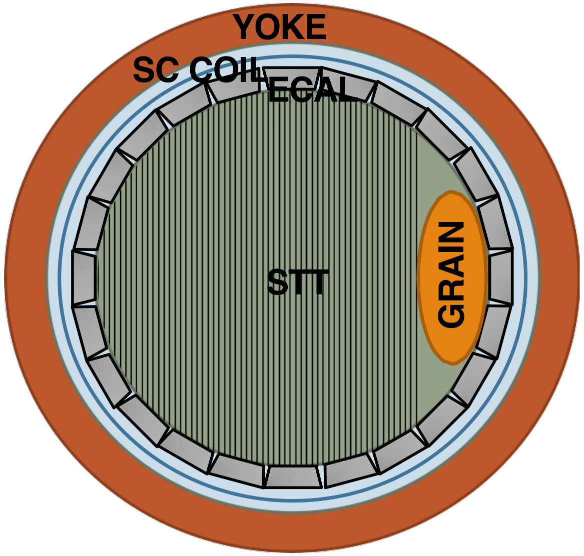
- ECAL/Magnet
- STT
- GRAIN

MAGNET – KLOE 0.6T superconductive coil + Fe Yoke

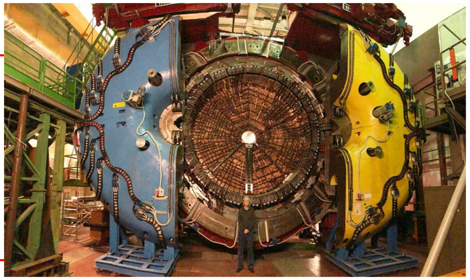
ECAL - KLOE Lead Scintillating Fibers calorimeter (Barrell-23 ton Pb- + EndCaps)

STT – 5 ton Straw-Tube tracker with “solid-H” target CH_2 and C interleaved slabs

GRAIN – 1 ton liquid Argon target with VUV imaging system (fully optical read-out)



SAND, a multipurpose detector with an high-performance ECAL, light-targeted tracker, LAr target, <u>all of them in a magnetic field</u>



SAND Requirements

1. It **must** monitor the (relevant) beam changes on a **weekly basis** with sufficient sensitivity
2. It **must** provide an independent measurement of the **flux** and measure the **flavor** content of the neutrino beam on event-by-event basis.
3. It **should** contribute to remove **degeneracies** when the other components are off-axis (50% of the time)
4. It **would** add robustness to the ND complex to keep **systematics** and **background** under control
5. and while delivering all of the above, it **could** contribute to **oscillation analysis** and enjoy the high statistics to perform a plethora of **other physics** measurements.

As a matter of fact SAND needs to be a multipurpose detector (with challenging compromises between mass, ID and tracking)

Update of KLOE-to-SAND activities

Since last SC meeting:

- Contruction/preparation/test of the dismounting tools for the Barrel ECAL
- Completed the design of the dismounting and transporation tools for the Endcaps. Proceeding to tendering
- Performed a 3D survey of the whole calorimeter
- Defined the solution for the magnet PS replacement/refurbishment
- Narrowed down the choice of the FE electronics. Prototypes being discussed with CAEN.

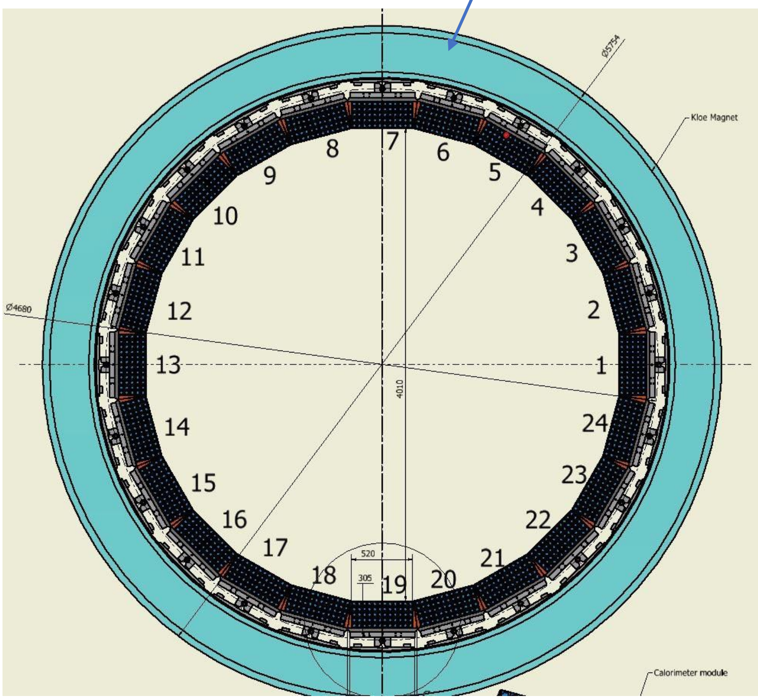
KLOE-to-SAND activities cont.

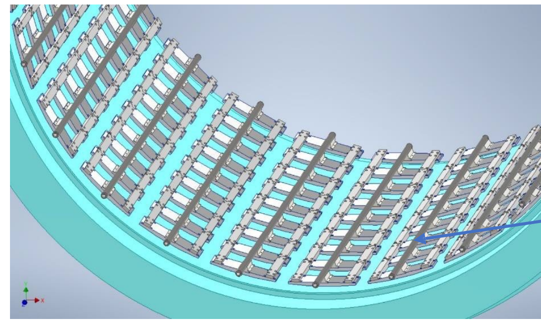
- Cryogenic components for the magnet test being procured
- Coil extraction and transport cradles finalized
- Resource loaded WBS being refined
- …….
- …..

A few excerpts: barrel disassembly procedure

All operations in details has been presented to the safety office of LNF: **Preparatory; Tools and time estimate; Execution works; Number of persons; Tools and time estimate.**

The plan is to start removing the top calorimeter module and subsequently continue symmetrically going downwards.



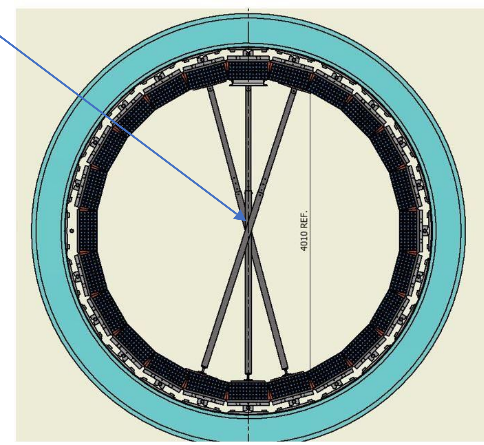


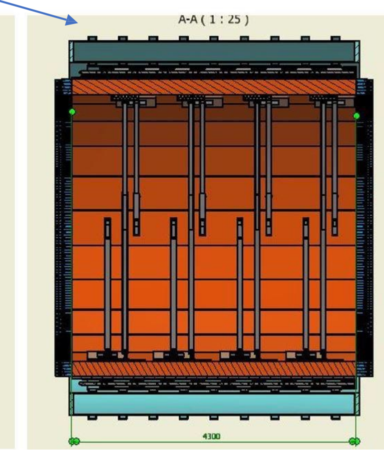
In the lower part of part of the calorimeter we will install a surface of wood boards. On this surface we installed pillars.

Internal structure that hold the calorimeter modules Stainless steel shafts

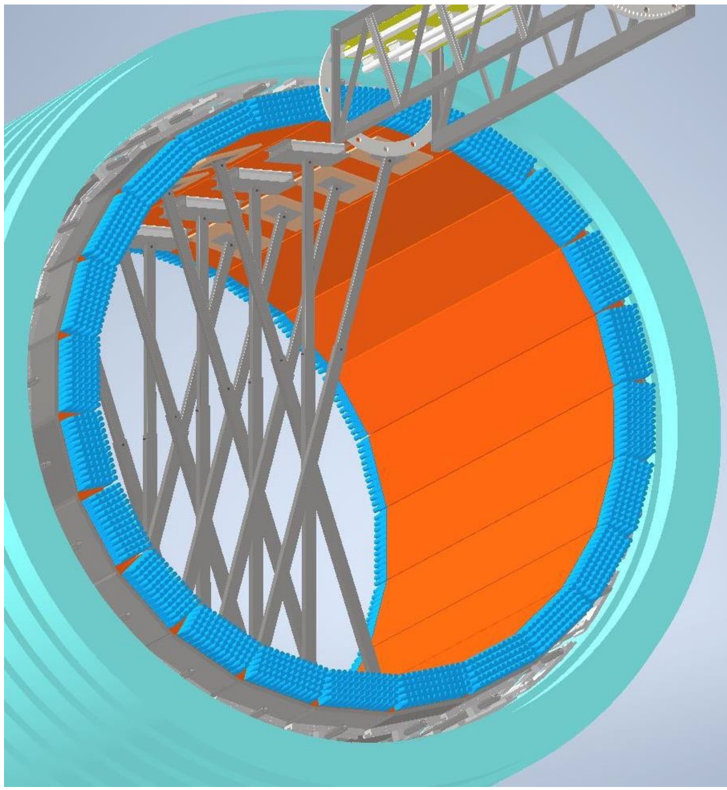
Pillars are considered a safety structure.

Phase 1

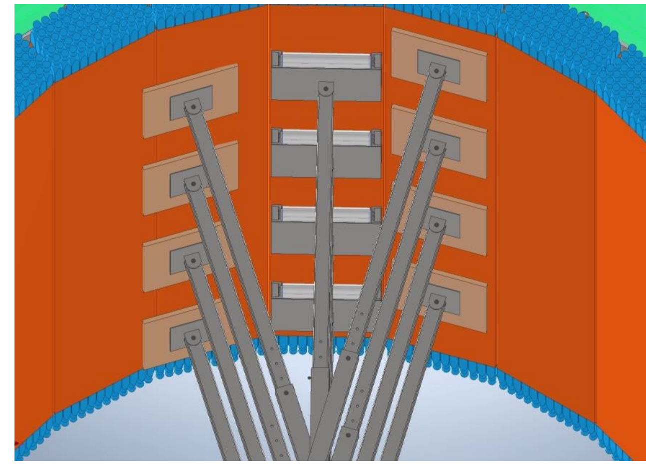


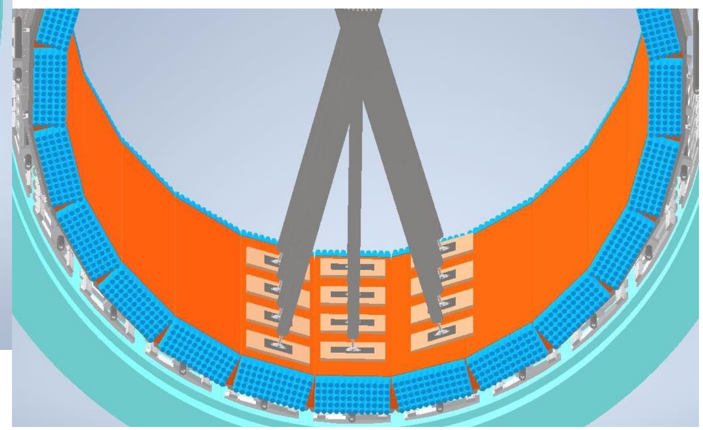


Safety Pillars with Rollers

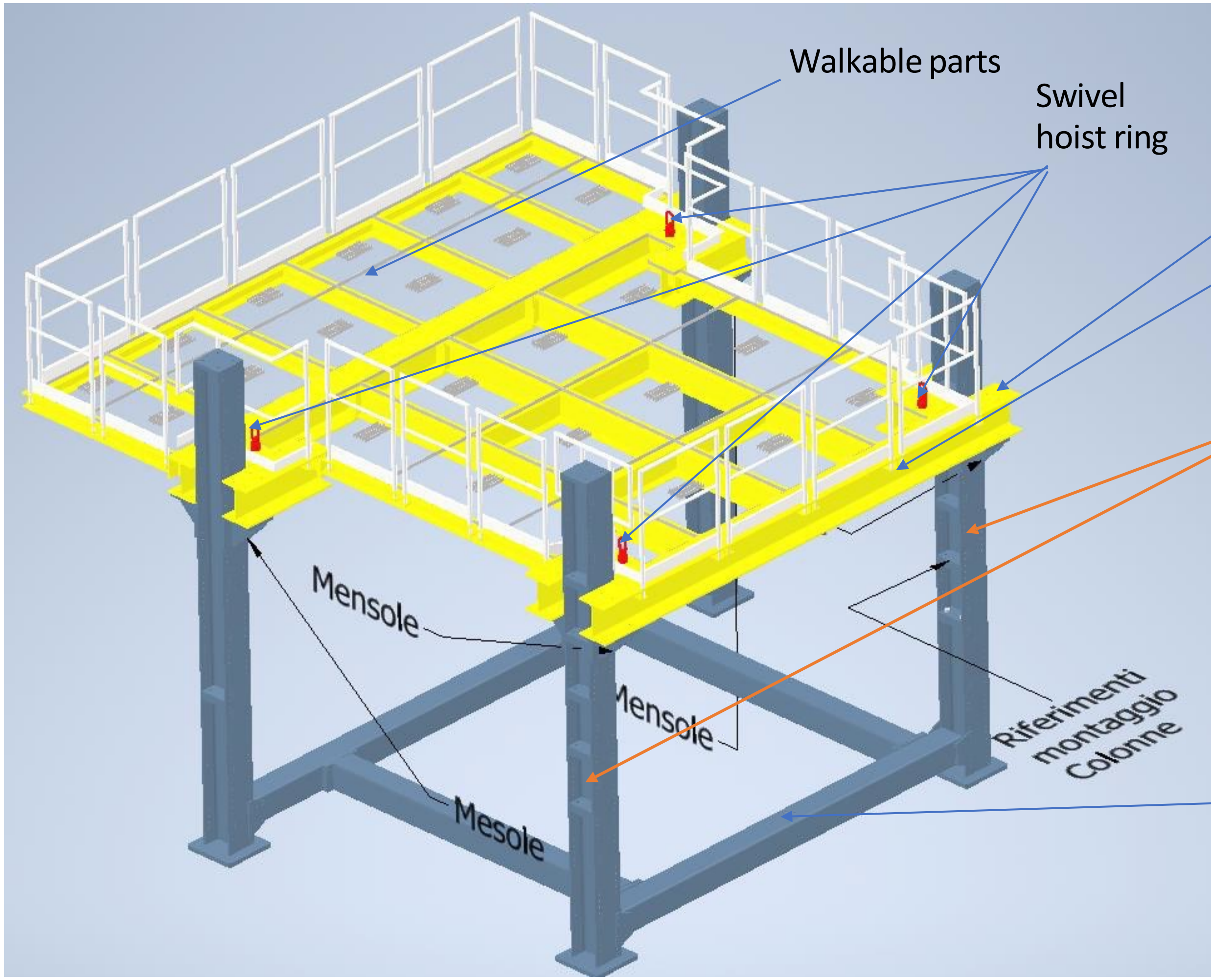


Support are necessary before extracting modules.





Adjustable platform

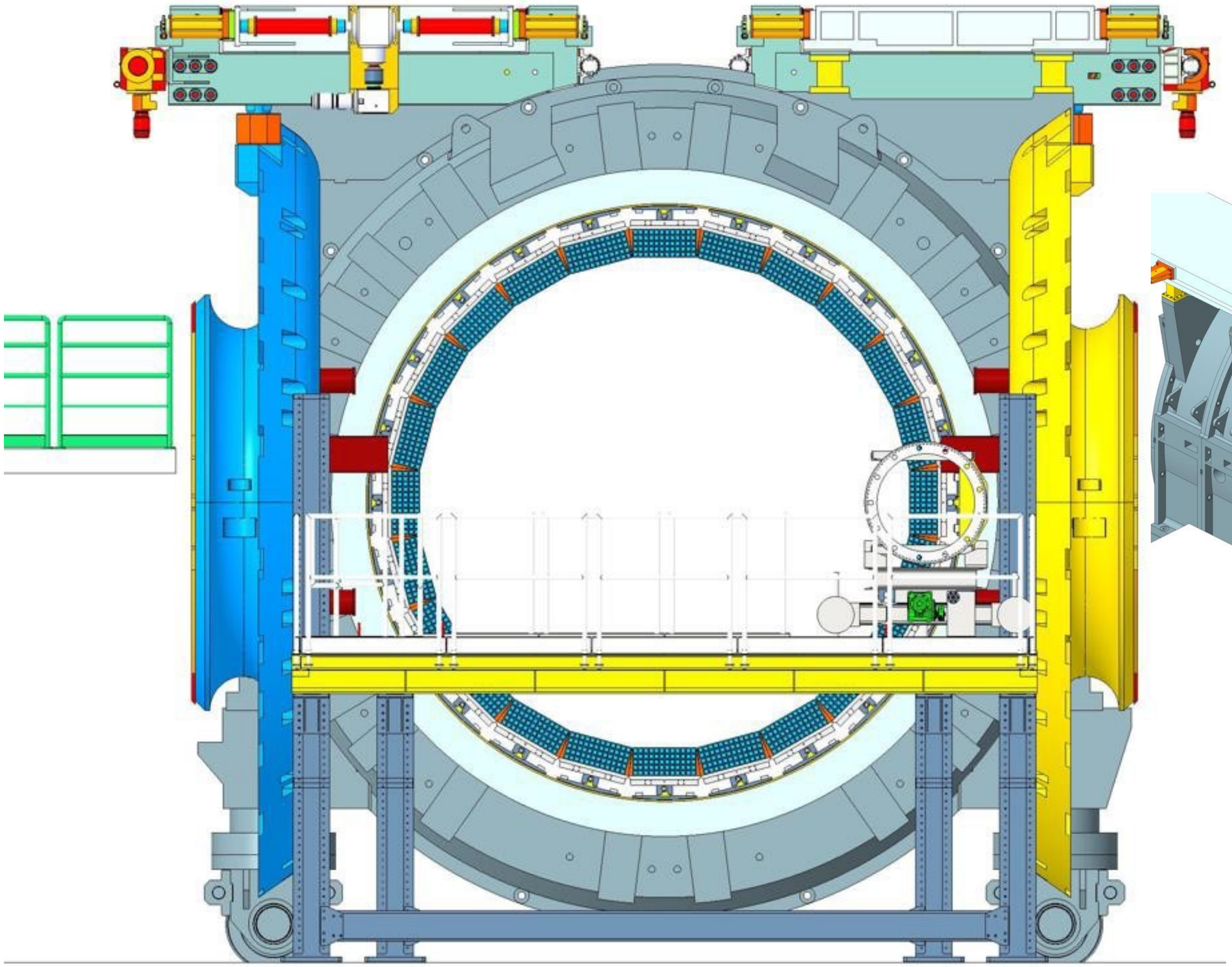


The top part is made in three main parts

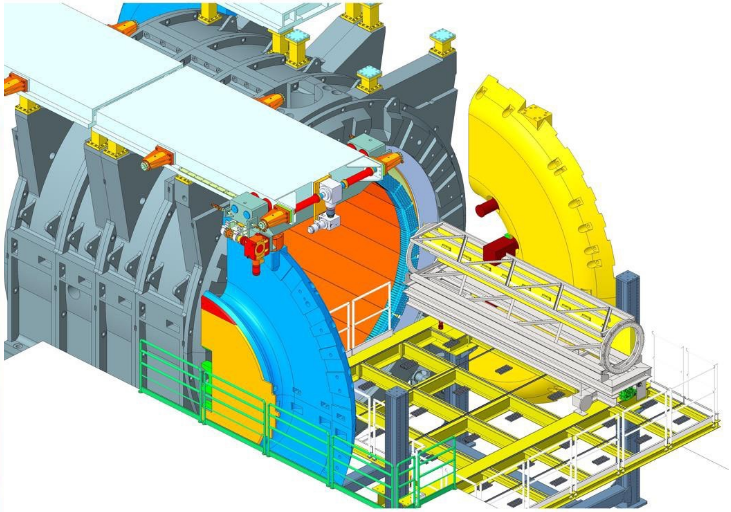
Part that supports the extraction tooling and the calorimeter modules

The two columns closest to the Calorimeter are composed by several pieces that can be removed during the modules dismount.

The lower structure is made in seven main parts: the four vertical columns; the four connecting beams.
The



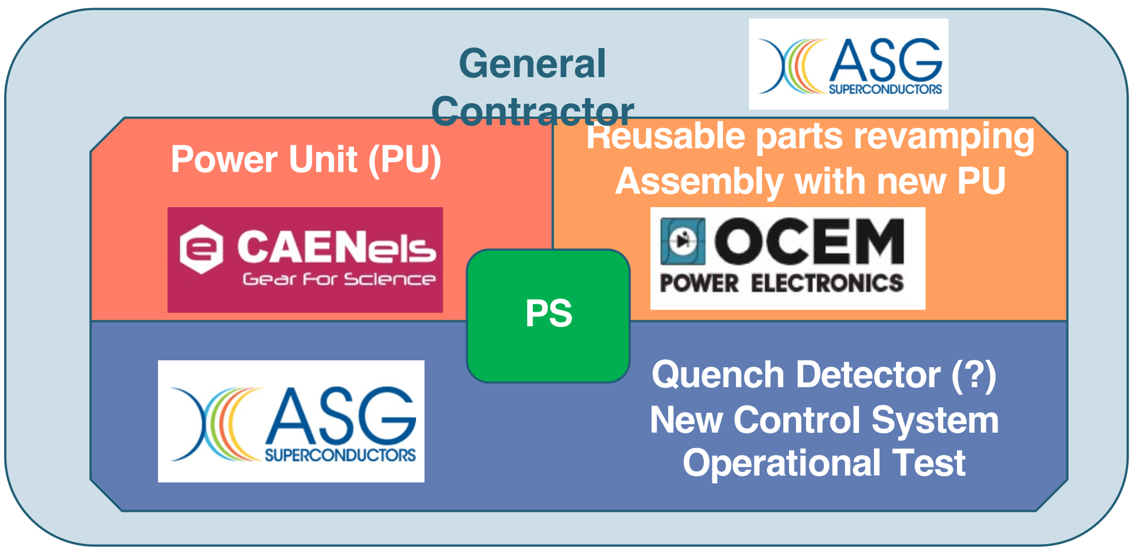
Extraction of the horizontal module



MAGNET New Power Supply Procurement

We want a new Power Supply (PS) keeping the same performances of the old one

to save procurement time, avoiding long EU calls for tenders, we are setting the procurement with 3 partners



Possibly still usable:
busbars, contactors, dump resistor, transformers

Obsolete and/or aged components to replace:
transistors banks, cooling pipe, water loss, elctrolitic capacitors, electronic boards

Estimated PS delivery time 6 months
Possible delivery of PS in second half of 2024

Possible PS+Magnet Test
End od 2024

MAGNET New Power Supply Procurement

Power Unit on blanket order INFN-CAEN

8 TDK-Lambda Genesys+ (375A, 20V) in parallel with CAEN-REGUL8OR regulation unit customized with our interlock interface (all USA standard compliant)

Quench Detector	Dump resistor Filter	Bus bars Contactors	Power Unit Free wheels diodes

Old PS dismounted from Kloe platform and delivered to OCEM for inspections of components possibly saved

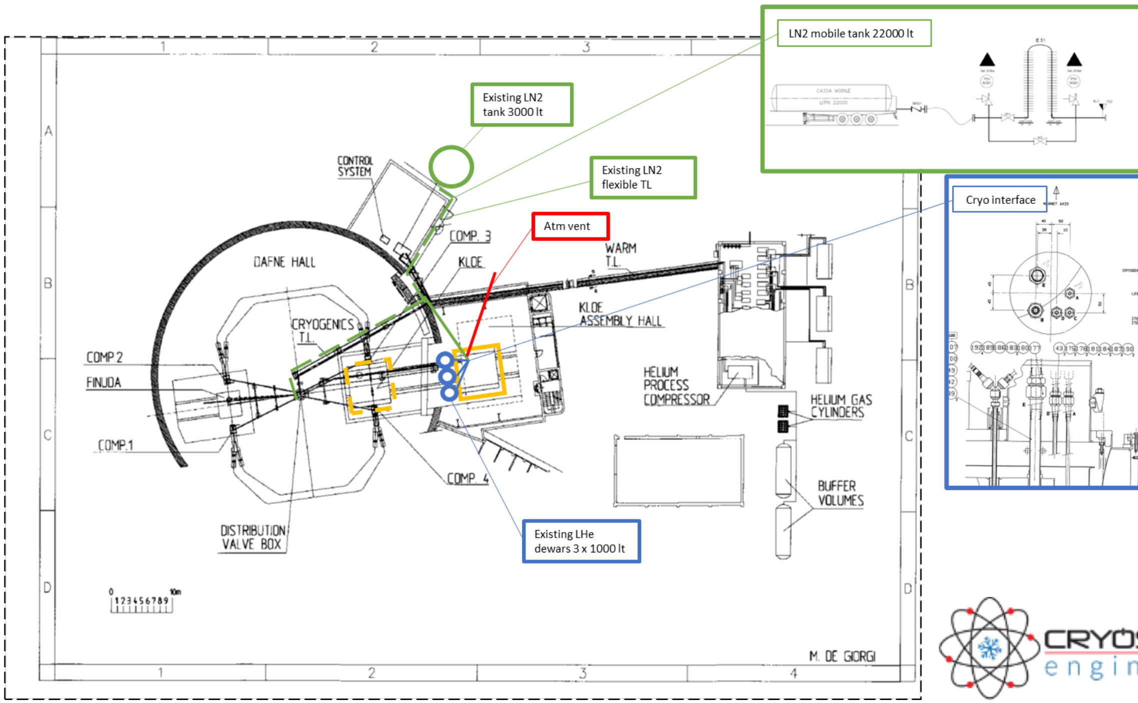
OCEM could also provide its own PU but would not be part of a blanket order.
We asked a PU quotation for a comparison with CAENels

KLOE PS Dump resistor and contactors

KLOE PS delivered to OCEM

Magnet Renovation and Test

Before dismounting and shipping (but after new PS installation) an operational test of the magnet is foreseen to test integration of all parts (PS, Quench Detector, Control System, Software Interface)



Coil cool-down

$36kl\ LN_2$ + 6kl LHe from mobile tanks
No need for DAFNE cryo plant
Noncomplex cryo interface
HW suitable to repeat test in US

Procurement

New cryo interface provided by Cryosystem Engineering
(order placed with 2023 funds)

Cryo liquids provided by AirLiquid
LN_2 funded in 2023
LHe funded SJ in 2024

CRYOSYSTEM engineering
Air Liquide

INFN DUNE

Next steps

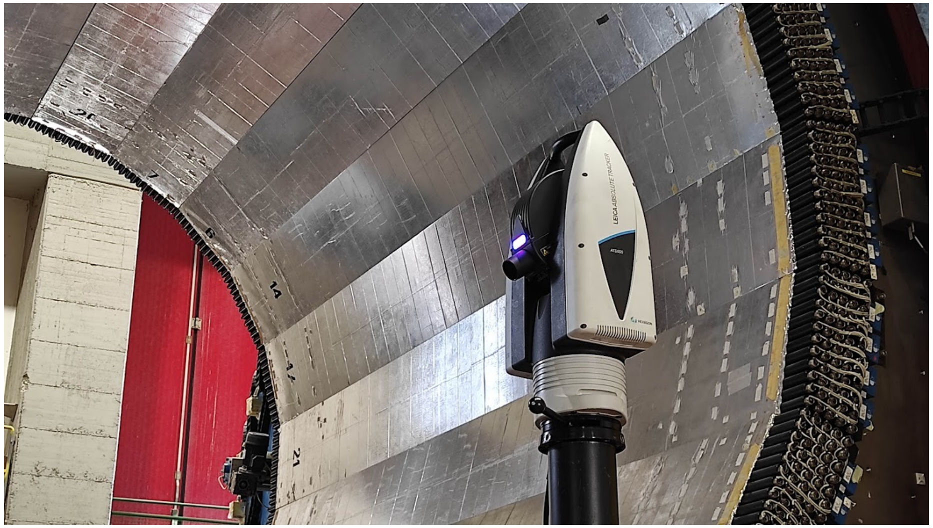
- Preparation phase is approaching conclusion, with satisfactory results and within a reasonably contained delay, well absorbed within the allotted time contingency
- 2024 will see the dismounting of the calorimeters and their refurbishing. Subject to the delivery of the power supply, we might as well perform the magnet test.
- 2025 will be logistically demanding, in view of the extraction of the magnet and the disassembly of the yoke.
- Floor space is presently one of our biggest worries and we have started a discussion with the lab Management, to which we are grateful for the excellent support so far.

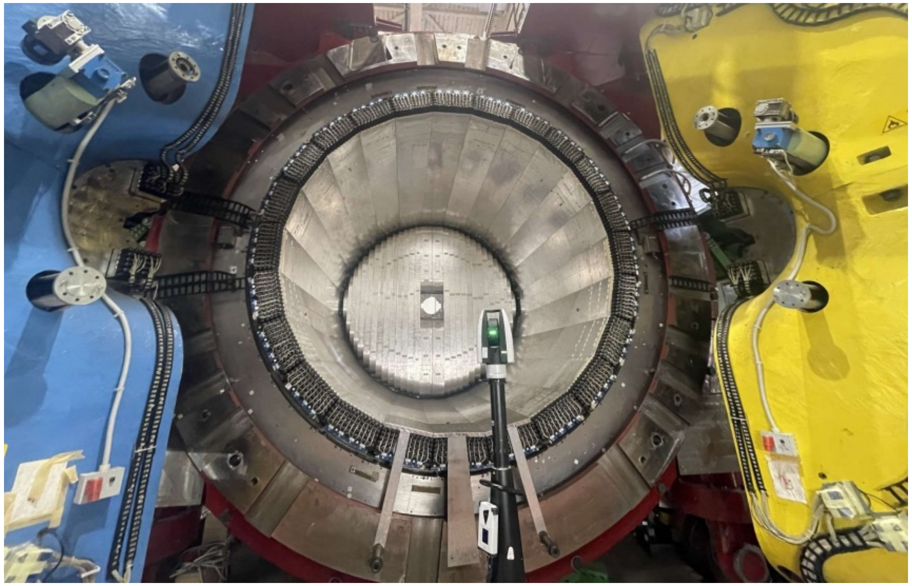
ECAL Dimensional Inspection

HEXAGON
METROLOGY

GEATOP
Metrology & Survey

Organizzazione con sistema di gestione qualità ISO 9001:2015 certificata da Bureau Veritas Italia Spa





2-6 October 2023

All original measurements available

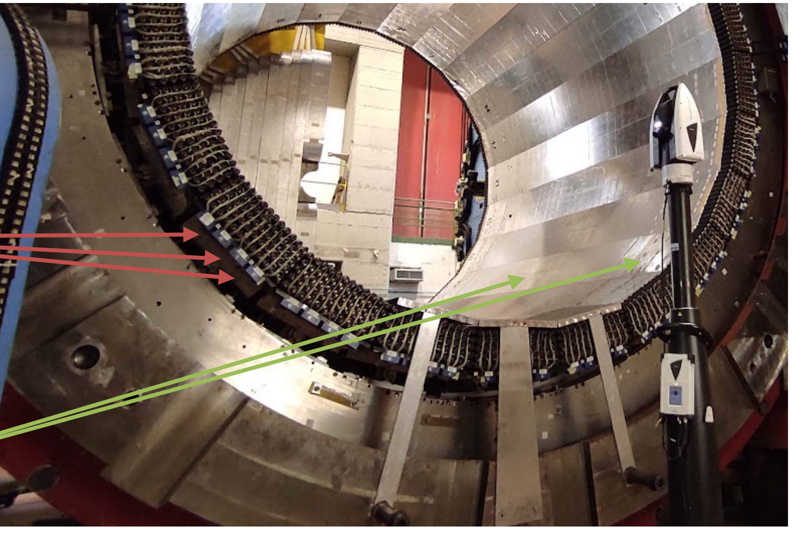
ECAL Dimensional Inspection Report

Analysis of the distance between

Bottom plane reconstructed by accessible points of the Aluminum plate on both module ends

and

Cloud of points (10x10 mm^2 pitch matrix) measured internally



Nominal value should be
230 mm (Pb+SciFi height)
+
25 mm Al plate thickness
=
255 mm

Choice of the calorimeter dynamic range

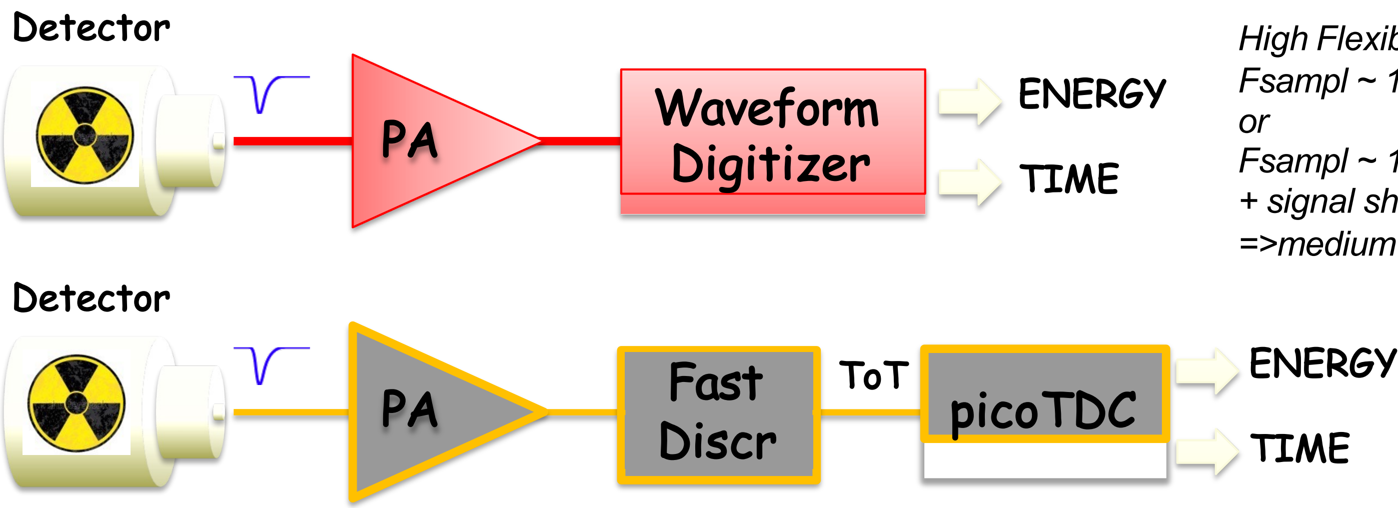
Assuming:

- to increase V_{preamp}(max) by 15% => V_{preamp}(max) = 5.4 V
- (N_{pe} G_{PM})(max) = $95 \cdot 10^7$
- V_{dis}(max) = V_{preamp}(max) • 0.5 • C_{ATT}= 2.0 V
- to have a very low noise environment as in KLOE => lowering (halving) the minimum discriminator/digitizer threshold to V_{TH}= 2.5 mV

G_{PM} ($\times 10^5$)	G_{tot} ($\times 10^6$)	N_{pe}(max)	signal amplitude (mV/pe)	N_{pe}(min) V_{TH} = 2.5 mV	MeV at module center
4.8	1.2	⇠ 2000	1.0	⇠ 3	3.0
6.4	1.6	⇠ 1500	1.3	⇠ 2	2.0
9.5	2.4	⇠ 1000	2.0	⇠ 1	1.0

- Different dynamic ranges can be implemented changing G_{PM} => the final choice should be a compromise between an affordable level of events with energy saturated cells, depending on N_{pe}(max), and an acceptable neutron detection efficiency, depending on N_{pe}(min).

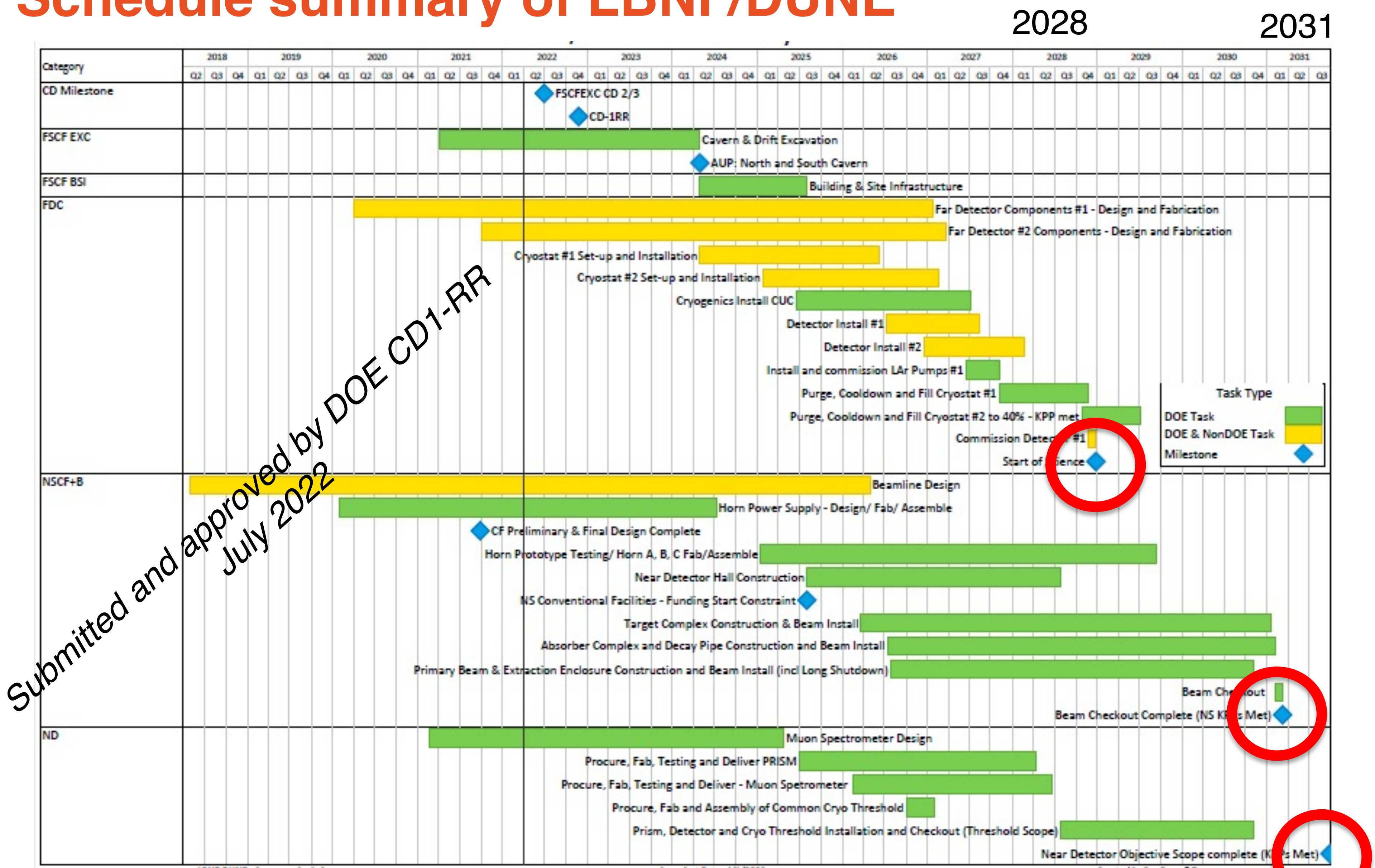
ECAL FEE Solutions



High Flexibility
Fsampl ~ 1 GS/s =>High Cost
or
Fsampl ~ 125-250 MS/s
+ signal shaper
=>medium Cost

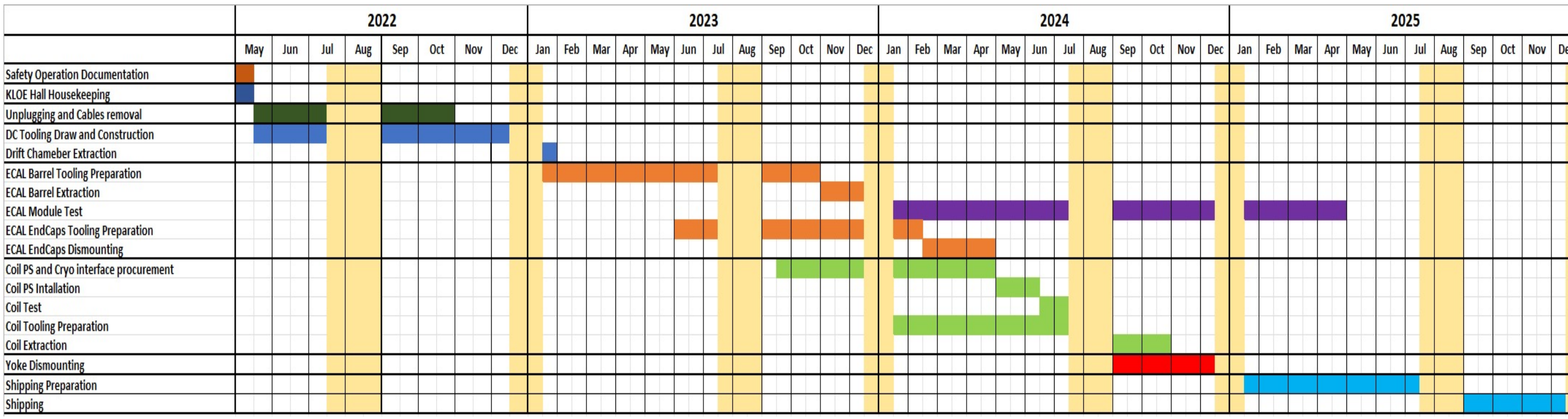
No Flexibility
=>medium cost
energy by ToT
with 2 or more
thresholds not to
worsen energy resol.

Schedule summary of LBNF/DUNE



Fermilab INFN DUNE

KLOE to SAND Summary Schedule



ND-hall availability: 2028

Thank You