ND-SAND
(System for on-Axis Neutrino Detection)

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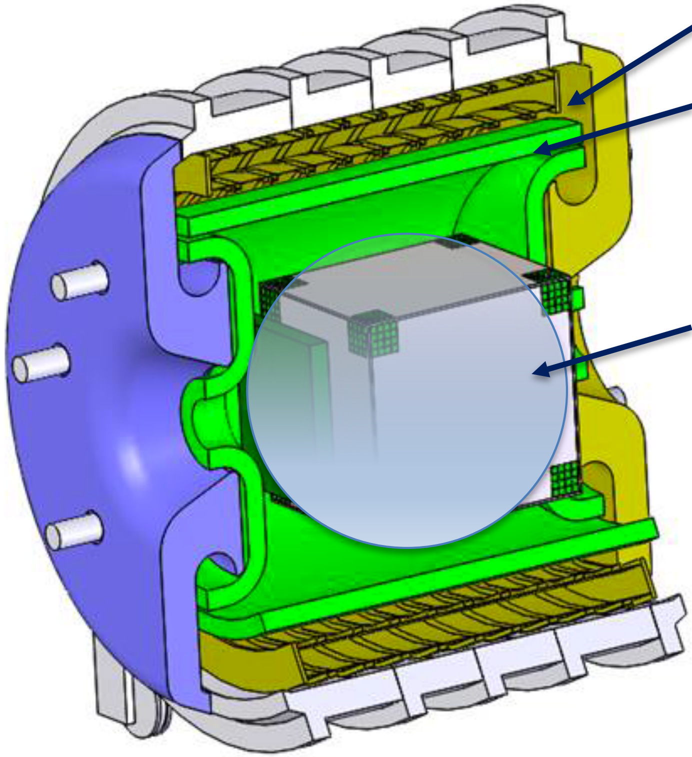
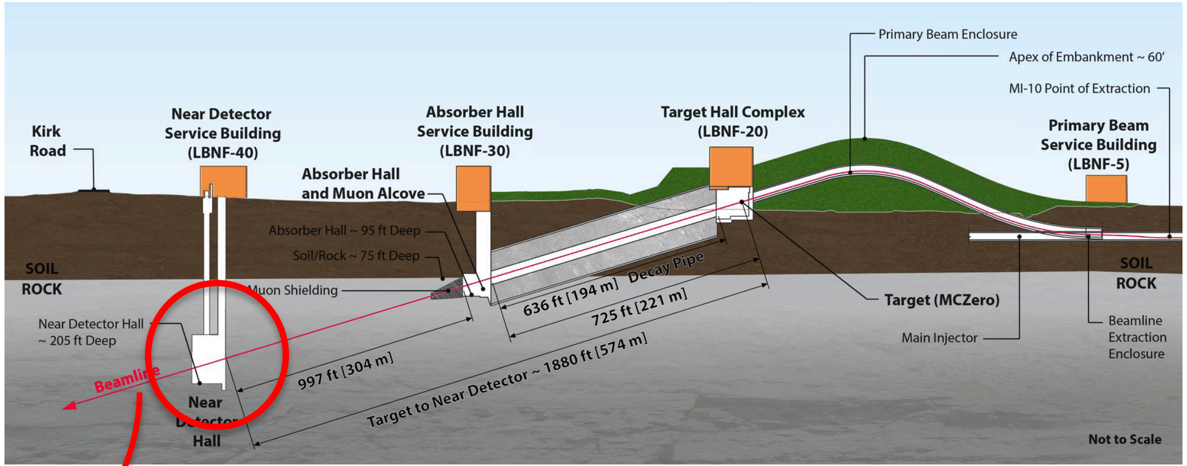
(for SAND)

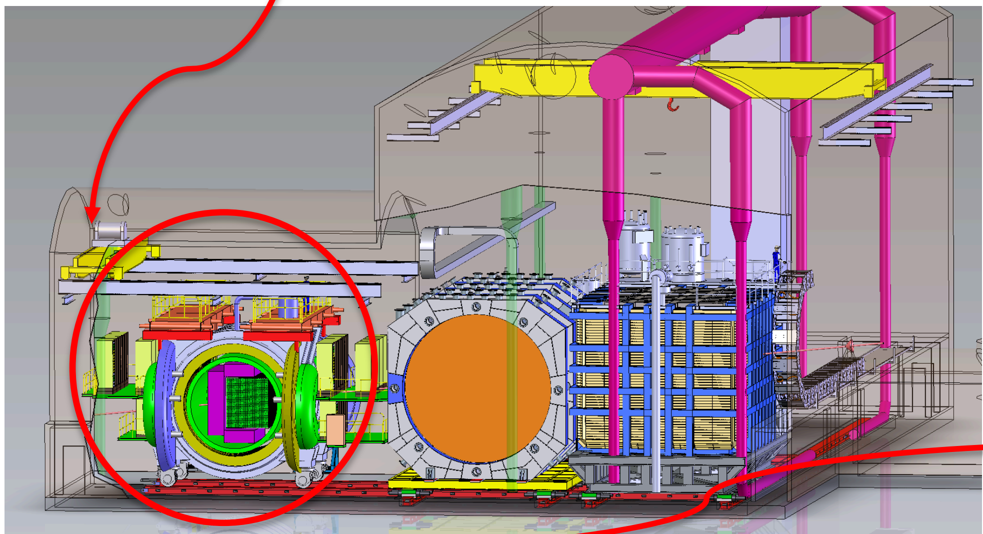


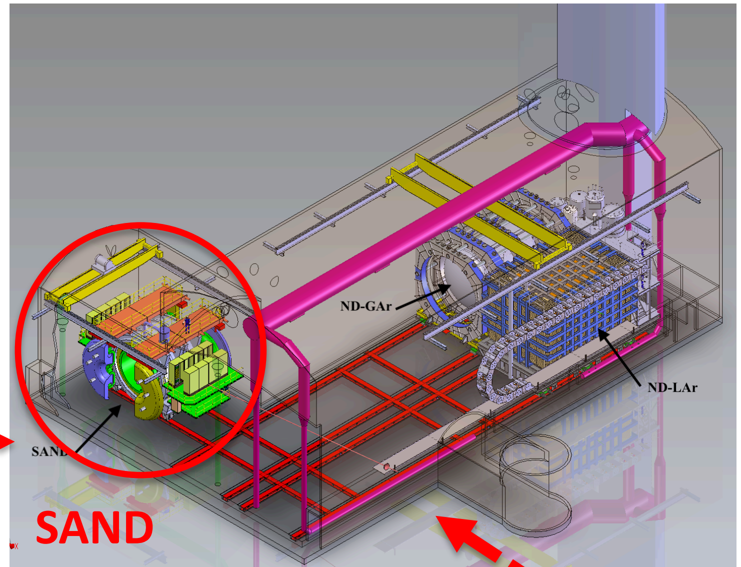
SAND Institutions (> 100 people):
8 Italy
9 US
1 France
1 UK
1 Czech
1 Korea
+ Russia+India+Georgia

Review Office Meeting,
July 7-9, 2020

The Near detector System







SAND

ν

A bit of history

- The final layout of the ND detectors' system took years to be "optimized". Convergence on SAND was reached in September 2019 (Consortium in 2020)
- The PRISM facility (Precision Reaction Independent Spectrum Measurement) implies the necessity of TWO detector systems, one moving across the beam, the other staying on-axis (others comment about LAr)
- A multi-purpose concept is needed for a realistic (not only Monte Carlo based) beam monitoring to get an accurate deconvolution of systematics, resolutions, cross-sections, fluxes, together with beam spectrum.
- The in-kind KLOE magnet and electromagnetic-calorimeter is a unique opportunity (in terms of performances, redundancy, robustness, reliability and availability)
- **The in-kind system must be completed by an excellent tracker** (43 m^3)

Why SAND in the DUNE-ND system?

- The SAND detector is the only component within the near detector (ND) complex that will be permanently located on-axis along the neutrino beam from DAY-1
- ArgonCube and TMS systems will move off-axis for about 50% of the time
- Crucial to have an on-axis beam monitoring to detect time-dependent spectral changes intrinsic to the beam, on a **weekly basis**
- The SAND system will continuously monitor the rate, spectrum and profile of the neutrino beam by measuring the event topology (energy+momentum) of the neutrino interactions on **event-by-event basis**.
- Precision in-situ flux measurements of $\nu\mu$, anti-$\nu\mu$, νe , anti-νe (absolute and relative rates)
- As a side result SAND will be able to do many more things it is supposed to do, like improving the extrapolation of the ν and a-ν fluxes to the far detector, constraining systematics from nuclear effects, neutron detection with ToF, and being very robust against unknown unknowns
  (but it is not our fault…)

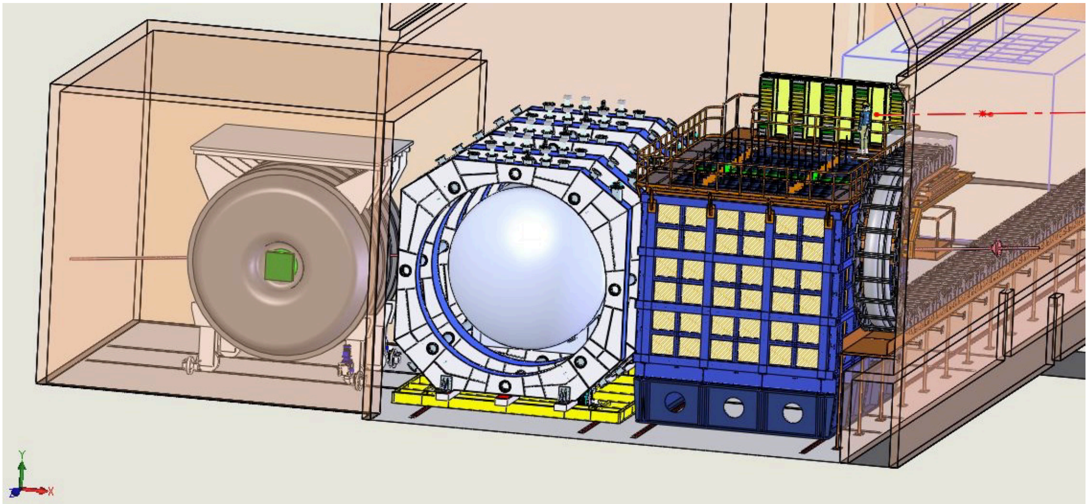
SAND in the ND hall

SAND will be permanently on-axis in a dedicated alcove

A *possible* schematic configuration is:

- a superconducting solenoid magnet
- an Electromagnetic Calorimeter (ECAL)
- a 3D scintillator tracker (3DST) as active neutrino target
- a low-density tracker to measure particles escaping from the scintillator
- a thin active Lar target

TRACKER (different options being studied)



- *An «alternative» configuration based on STT in Dune-docDB: 13262*

Overarching Requirements

ND-O5: Monitor time variations of the neutrino beam

SAND must detect potential variations in the neutrino flux

The flux and spectrum of neutrinos delivered by the beam can vary due to operational variations as well as unexpected component variances or failures. SAND must detect such variations in such a way that they can be identifed promptly and any compromised beam delivery is minimized.

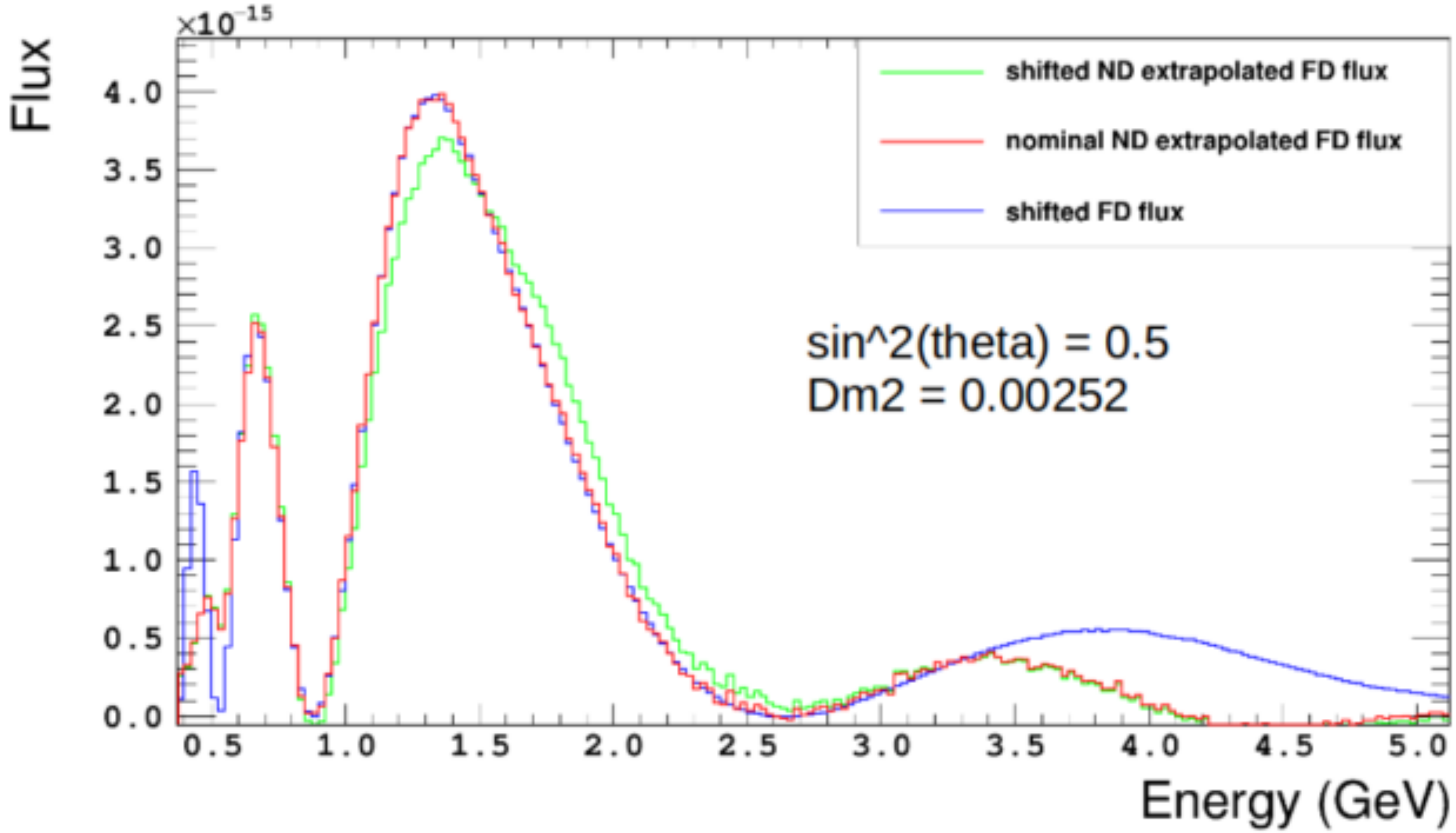
ND-O6: Operate in high rate environment

SAND must fulfill requirements in the presence of cosmics, beam-related backgrounds and pileup.

SAND operates in a significantly different environment from the FD, with higher cosmic ray rates as well as pile up of beam-related activity (including other neutrino interactions). SAND must be robust against this additional activity in fulfilling the other overarching requirement.

ND-O5

How a 3 σ shift on the HC can change the energy flux distribution !



How SAND can take care of beam deviations:

Table 4.2: The beam parameter description as well as the significance to the observation of a change in the beamline are shown. The performance of the SAND spectrometer using 3DST and ECAL as the active targets and the TPC as the low-density tracker with 7-days data taking is compared to a detector system consisting of four non-magnetized 7-ton modules that measure the beam rate and profile at 0, 1, 2, 3 meters from the beam axis position at the ND site.

(similar results for STT)

	Parameter description		Significance, $\sqrt{\chi^2}$	
Beam parameter	Nominal	Changed	Rate-only monitor	SAND
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	5.6
proton beam width	2.7 mm	2.8 mm	0.02	3.6
proton beam offset x	N/A	+0.45 mm	0.09	4.3
proton beam $theta$	N/A	0.07 mrad	0.03	0.5
proton beam $\theta\phi$	N/A	0.07 mrad θ and 1.5707 ϕ	0.00	1.0
horn current	293 kA	296 kA	0.2	11.9
water layer thickness	1 mm	1.5 mm	0.5	4.2
decay pipe radius	2 m	2.1 m	0.5	7.0
horn 1 along x	N/A	0.5 mm	0.5	4.6
horn 1 along y	N/A	0.5 mm	0.1	3.6
horn 2 along x	N/A	0.5 mm	0.02	0.9
horn 2 along y	N/A	0.5 mm	0.00	0.8

ND-O6

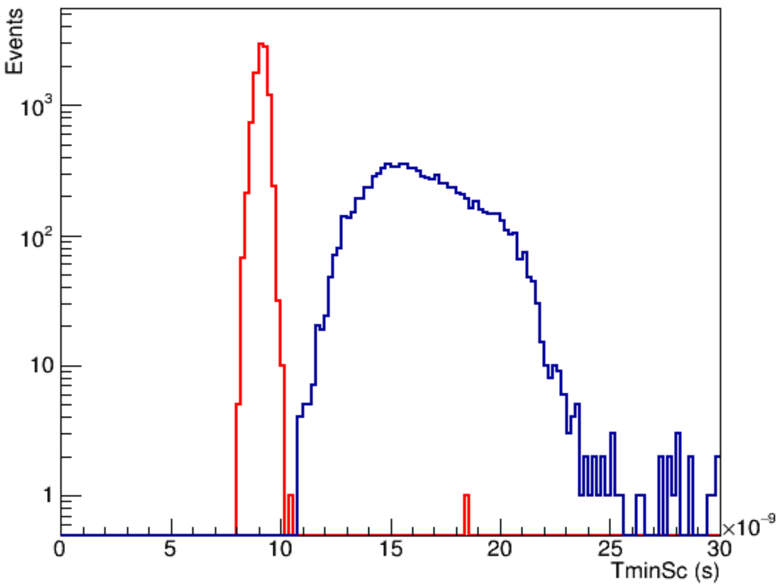
Background from induced external interactions

Active volume: 2.24x2.24x2m³

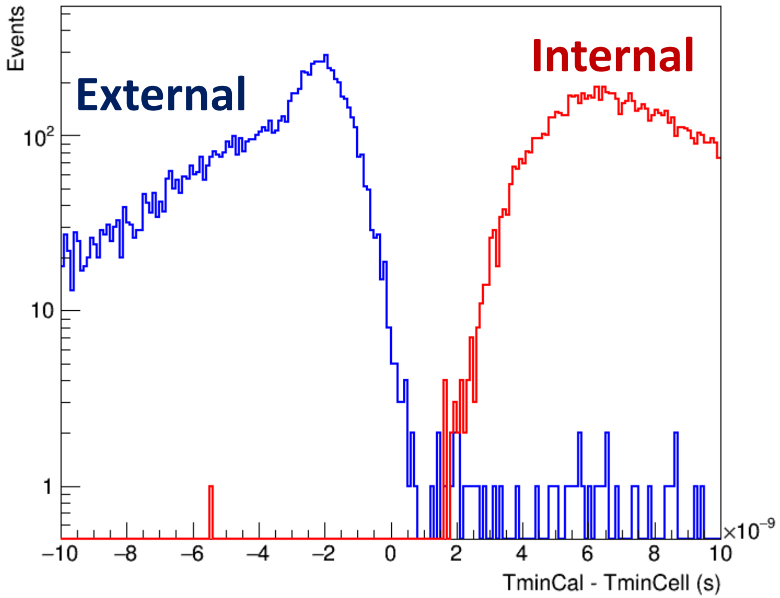
MC samples by FLUKA

T_{1st}^{Sc}, T_{1st}^{Cal} and Time difference ΔT_{1st} before any cut

T_{1st} distribution of Internal evts



$\Delta T_{1st} = T_{1st}^{Cal} - T_{1st}^{Sc}$



Absolute Bck : ~1.2% of External events

Plus FV and N(cells)>30, extrapolated to include NC: : ➢ **Bck : ~1.8%**

(from CC+NC interactions in magnet + ECal)
based on Time difference between Ecal and 3DST

Measurement Requirements

ND-M8: Monitor the rate of neutrino interactions on-axis

SAND remains on-axis where beam monitoring is most sensitive and identifies a sufficient number of $\nu\mu$ CC events

ND-M9: Monitor the beam spectrum on-axis

SAND must use on-axis spectrum information to detect representative changes in the beam line

Rate information alone is insufficient to detect some beam variations that will impact the oscillation analysis. The beam monitoring must use spectrum information from muon/neutrino energy.

ND-M10: Assess External Backgrounds

SAND must be able to measure external backgrounds, which include cosmic rays and beam-induced activity.

ND-M8, ND-M9, ND-M10

Table 4.1: Projected event rates per year for a 2.36 x 2.36 x 2.12 m^3 3DST detector, assuming the 120 GeV, three horn, optimized Long-Baseline Neutrino Facility (LBNF) beam. A 5 cm veto region at each side was required. An * indicates the channel has a statistical uncertainty of about 15%. All other channels have a statistical uncertainty of 3% or less.

(similar results for STT, a factor 4-5 more for front ECAL)

FHC Beam		**RHC Beam**	
Process	**Rate**	**Process**	**Rate**
All ν_μ-CC	1.5×10^7	All $\bar{\nu}_\mu$-CC	5.4×10^6
CC 0π	4.4×10^6	CC 0π	2.4×10^6
CC $1\pi^\pm$	4.3×10^6	CC $1\pi^\pm$	1.5×10^6
CC $1\pi^0$	1.3×10^6	CC $1\pi^0$	5.3×10^5
CC 2π	1.9×10^6	CC 2π	5.0×10^5
CC 3π	8.7×10^5	CC 3π	1.7×10^5
CC other	1.8×10^6	CC other	2.8×10^5
ν_μ-CC COH π^+	1.3×10^5	$\bar{\nu}_\mu$-CC COH π^-	1.0×10^5
$\bar{\nu}_\mu$-CC COH π^-	1.2×10^4*	ν_μ-CC COH π^+	1.7×10^4*
ν_μ-CC ($E_{had} < 250$ MeV)	2.4×10^6	$\bar{\nu}_\mu$-CC ($E_{had} < 250$ MeV)	1.9×10^6
All $\bar{\nu}_\mu$-CC	7.0×10^5	All ν_μ-CC	2.3×10^6
All NC	5.3×10^6	All NC	2.9×10^6
All $\nu_e + \bar{\nu}_e$-CC	2.6×10^5	All $\bar{\nu}_e + \nu_e$-CC	1.7×10^5
$\nu e \rightarrow \nu e$	1.8×10^3*	$\nu e \rightarrow \nu e$	1.5×10^3*

Capabilities Requirements

ND-C5.1: Statistics of identified νμ-CC events

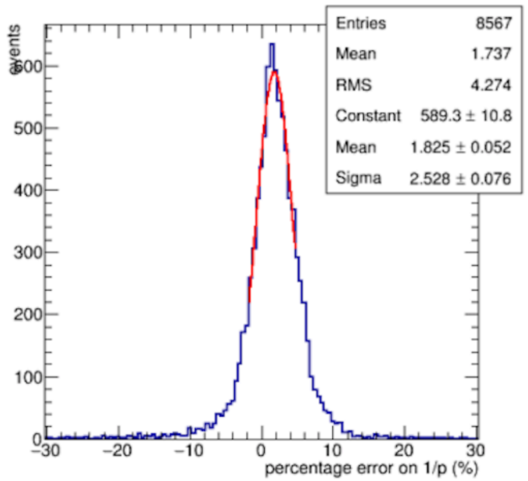
ND-C5.2: pμ/Eν resolution

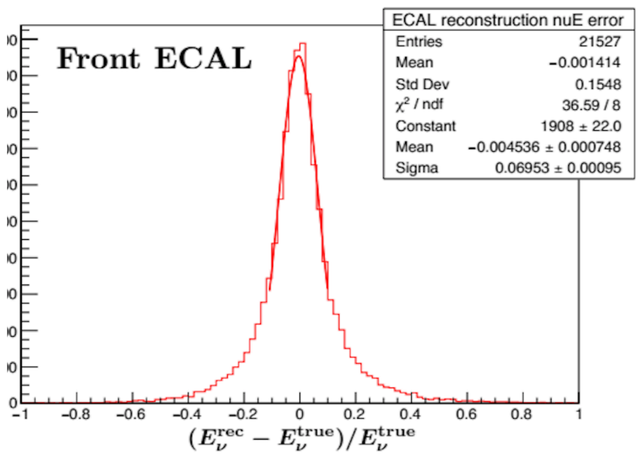
ND-C5.3: Vertex resolution

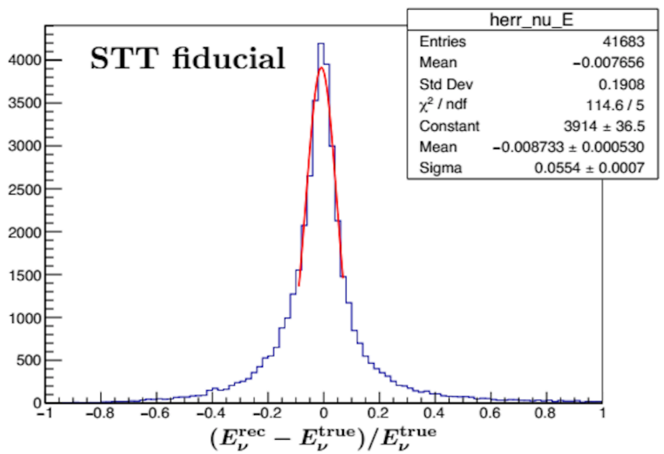
ND-C5.4: Track timing

Detector element	Fiducial volume cuts	Mass	FHC		RHC	
			ν_μ CC	$\bar{\nu}_\mu$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC
Magnet front	$\mid X \mid < 1.69$m, $\mid Y \mid < 2.0$m	45.9 t	2,150,420	105,341	344,801	821,289
ECAL front	$\mid X \mid < 1.69$m, 11 mod.	22.8 t	1,071,506	43,091	178,268	313,091
LAr+STT	$\mid X \mid < 1.59$m, $r < 1.9$m	7.7 t	321,345	17,672	57,842	137,776

Table 20: Number of events expected in one week (7 days, 3.78×10^{19} pot) of data taking in the various detector components used for the beam monitoring.







Time precision for m.i.p = 0.26 ns for ECAL, < 1 ns for 3DST/STT

Conclusions on Requirements

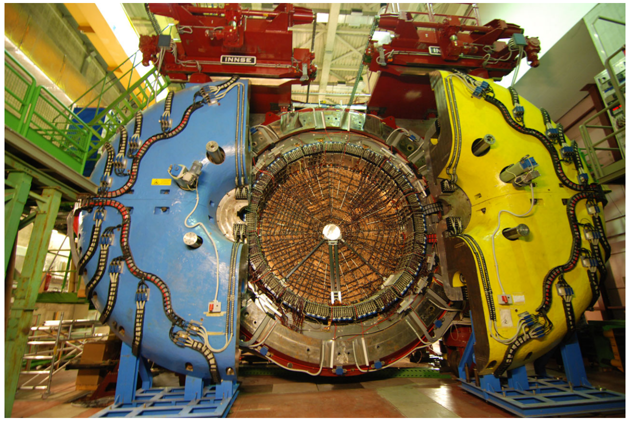
SAND is in a excellent position to overfill* the <<overarching>>, the <<measurement>> and the <<capabilities>> requirements, with all options of the Inner Tracker considered.

* Sorry again, it is not our fault

Technical issues…

November 2019: Two DUNE Near Detector Engineers Visited INFN Frascati To Collect Cavern Design Requirements For SAND Detector


Left Side Detector Utilities




Right Side Detector Utilities


Detector Movement System

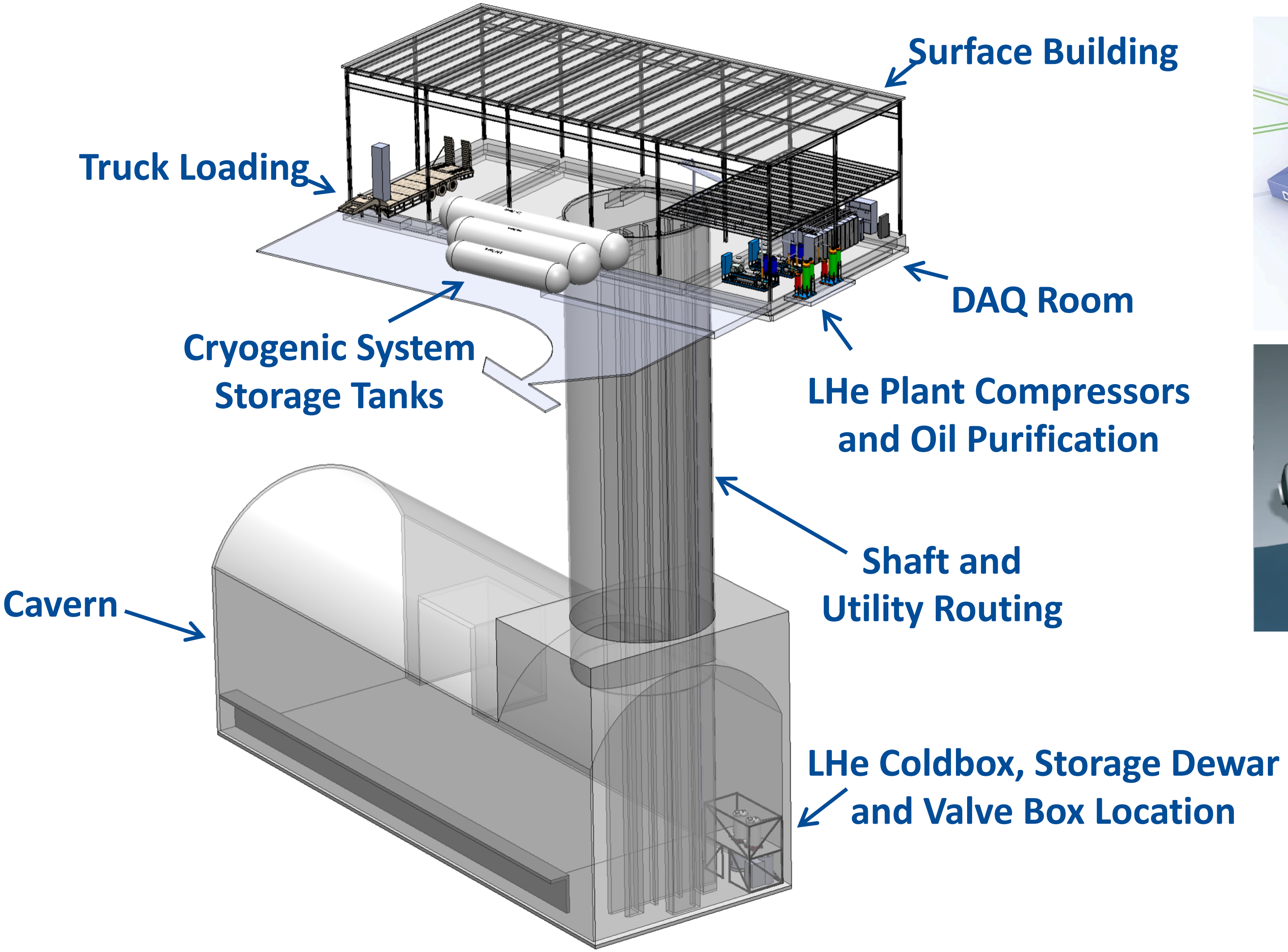

Protrusions From Detector Have Been Recorded In Detail To Ensure Detector Will Fit Within Allocated Alcove Size

DUNE Engineer Bob Flight

Topics Covered During Visit:

- Cavern Interfaces
- Electrical Interfaces
- Cryogenic Interfaces
- Handling Procedures
- Detector Assembly

SAND Liquid-He Coldbox Will Be Located In Underground Cavern



Commercial LHe
Cryosystems

Near Detector Liquid Nitrogen System Will Be Shared Between SAND And LAr-TPC

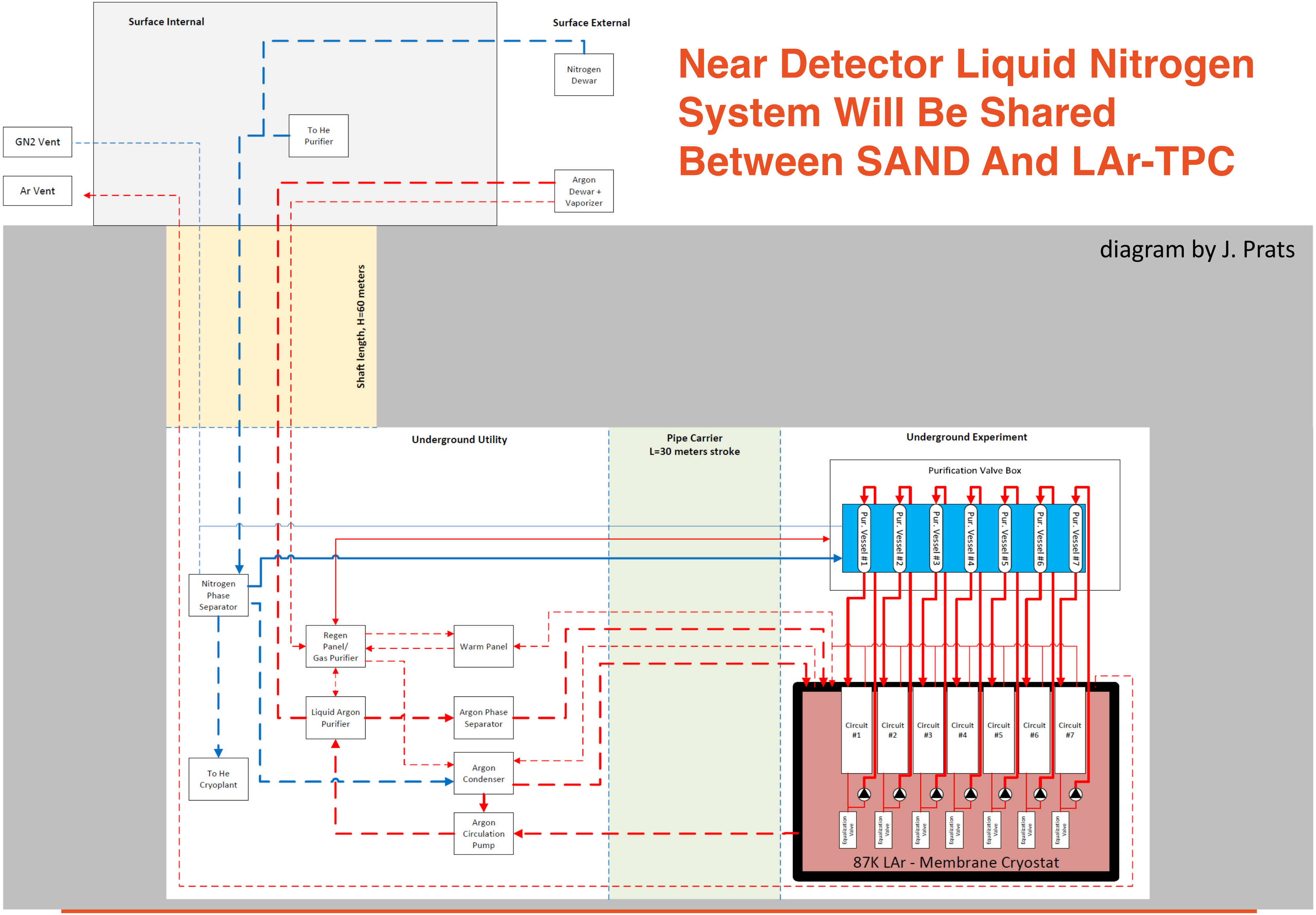
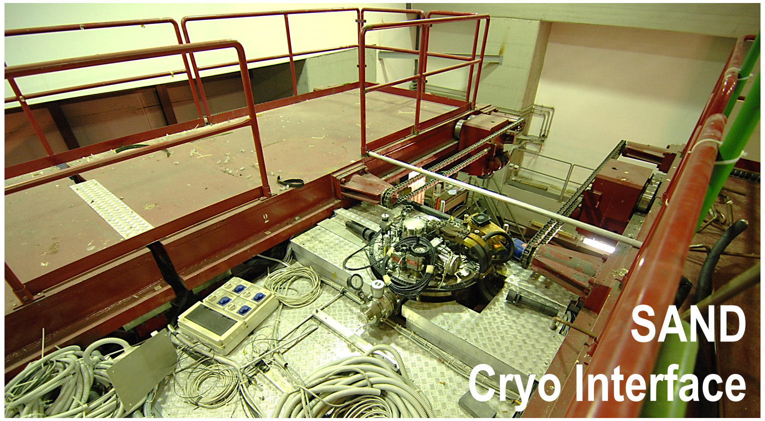


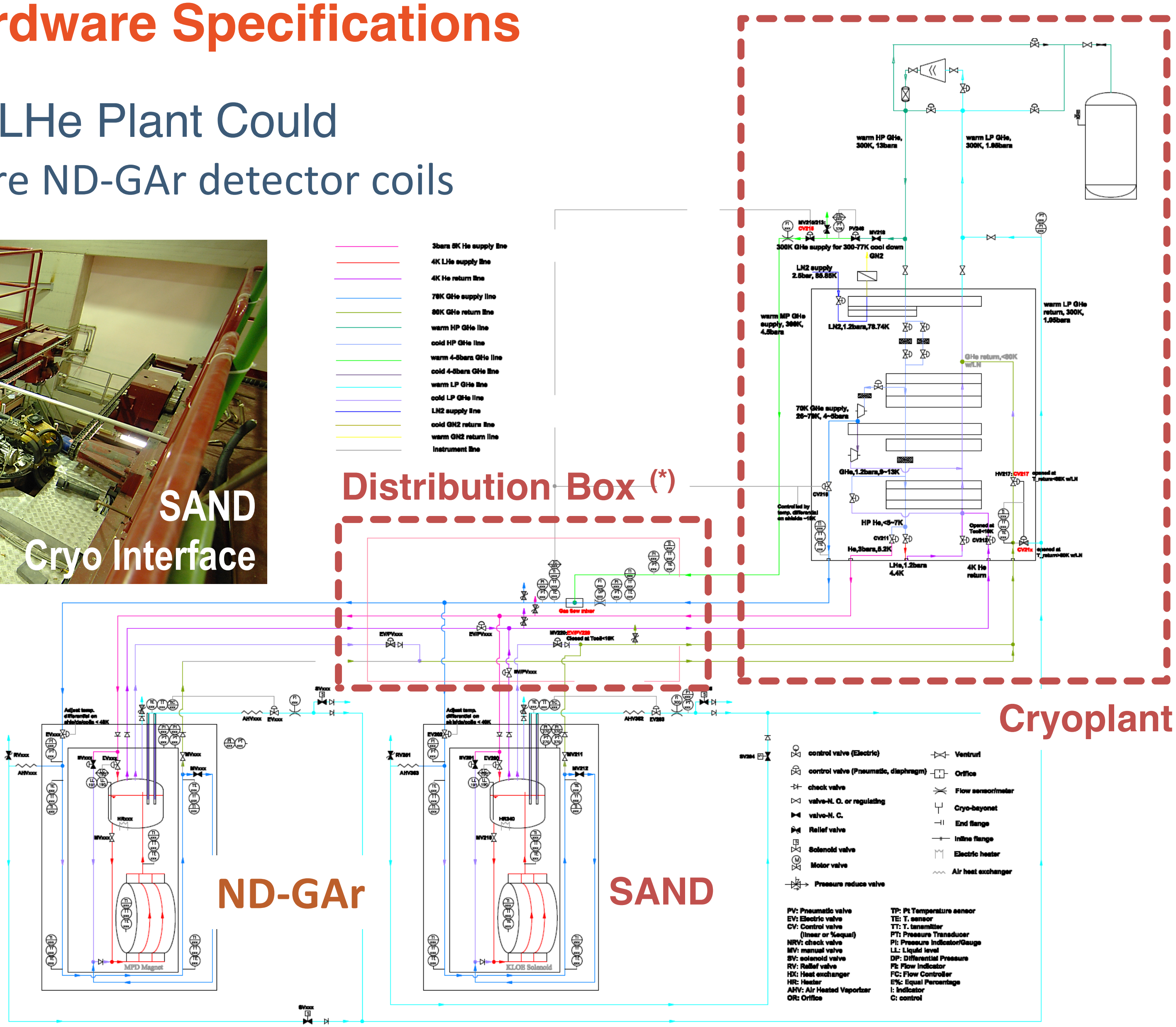
diagram by J. Prats

SAND / DUNE Cavern Cryoplant PID Established: Currently Developing Hardware Specifications

- Near Detector LHe Plant Could Also Cool future ND-GAr detector coils

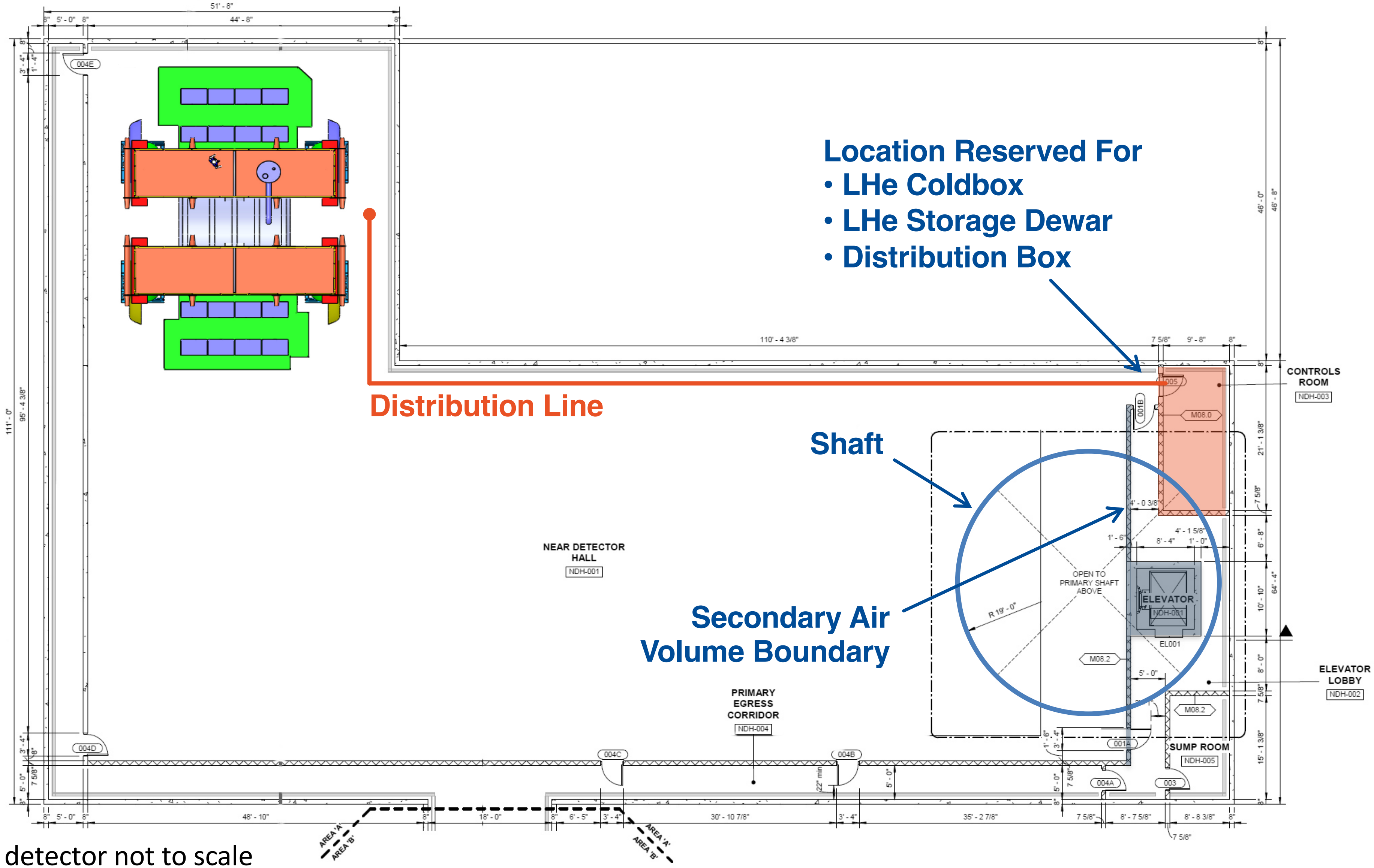


PID by L. Wang



(*) New distribution system will incl. simplified SAND mixing valve connections.

SAND LHe Coldbox Will Be Located In Underground Cavern Interface With Egress Space Remains To Be Defined



detector not to scale

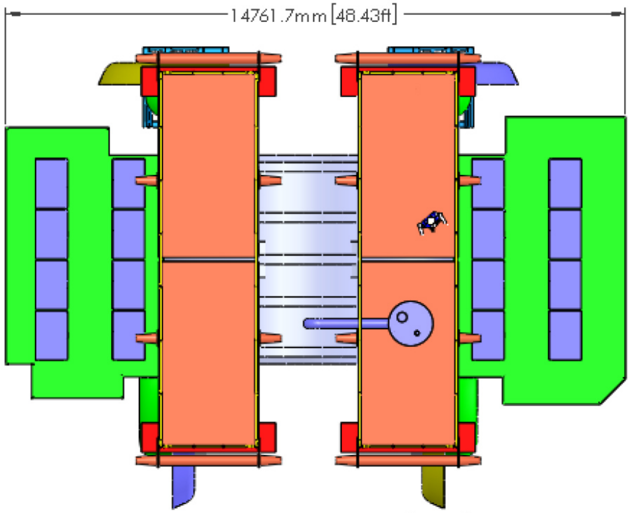
SAND Detector Installation
Will Require 50-ton Crane With Two Hooks

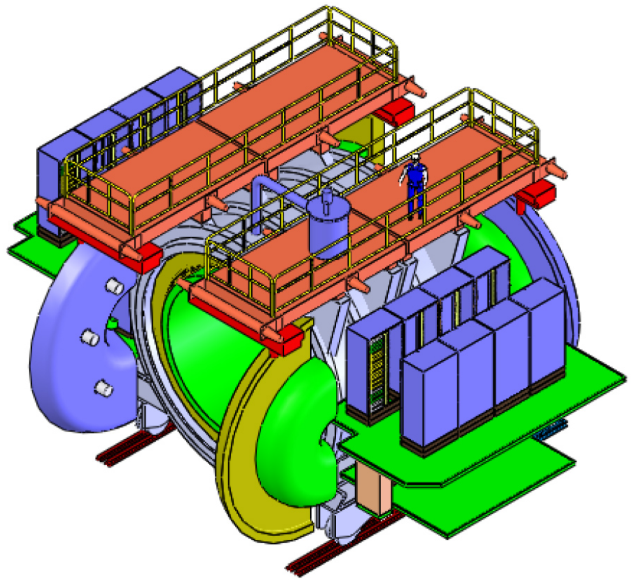
	Volume [m³]	Weight [tonne]
Coil incl. Cryostat	-	42
Yoke[2]	65.2	510
KLOE Existing EmC	21.5	108
Aux. Steel Structures	20	156
New Outside End EmCs	0.4	2
New Inside End EMCs	1.2	6
Low-Density Detector[4]	-	3
3DST Structure	-	15
Racks	-	20
Prism Rollers		10
KLOE-3DST TOTAL WEIGHT		**~900**

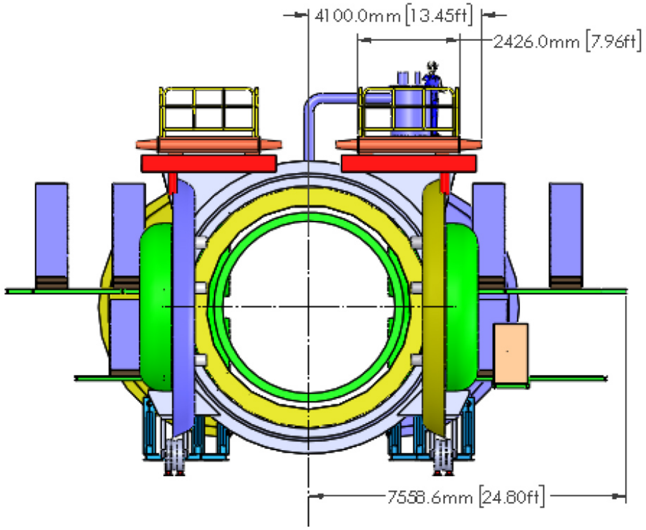
Yoke:
Length = 6 m
Diameter = 7 m

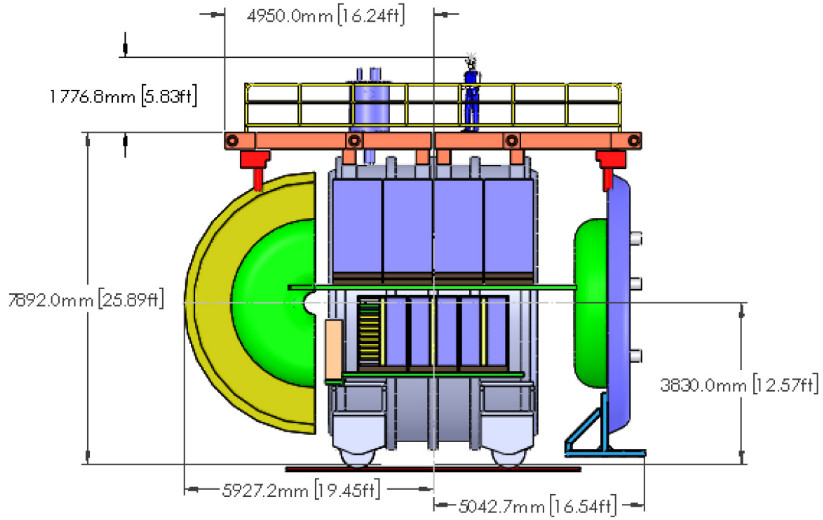
Full Detector Size:
Length ≈ 10 m
Height ≈ 11 m

SAND Magnet assembly consists of several approx. 30 Ton heavy yoke segments and a 42 ton Solenoid Cryostat

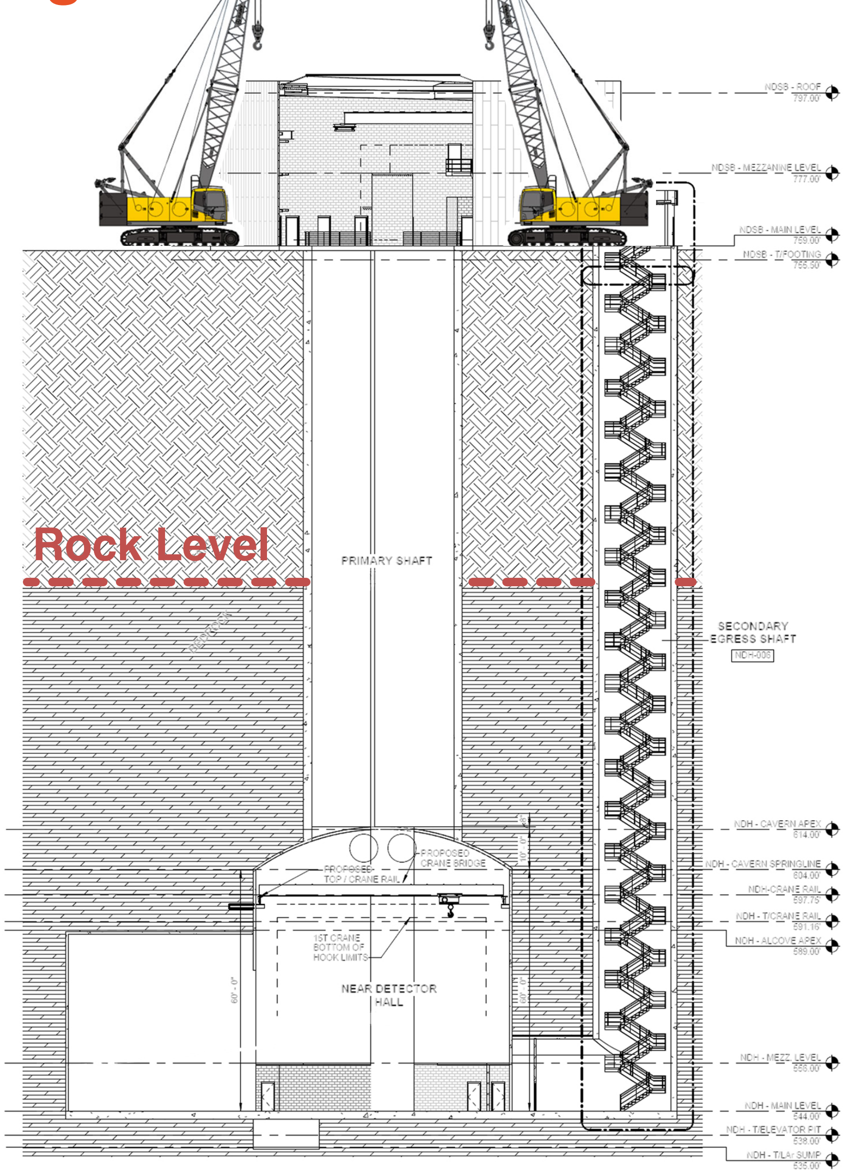


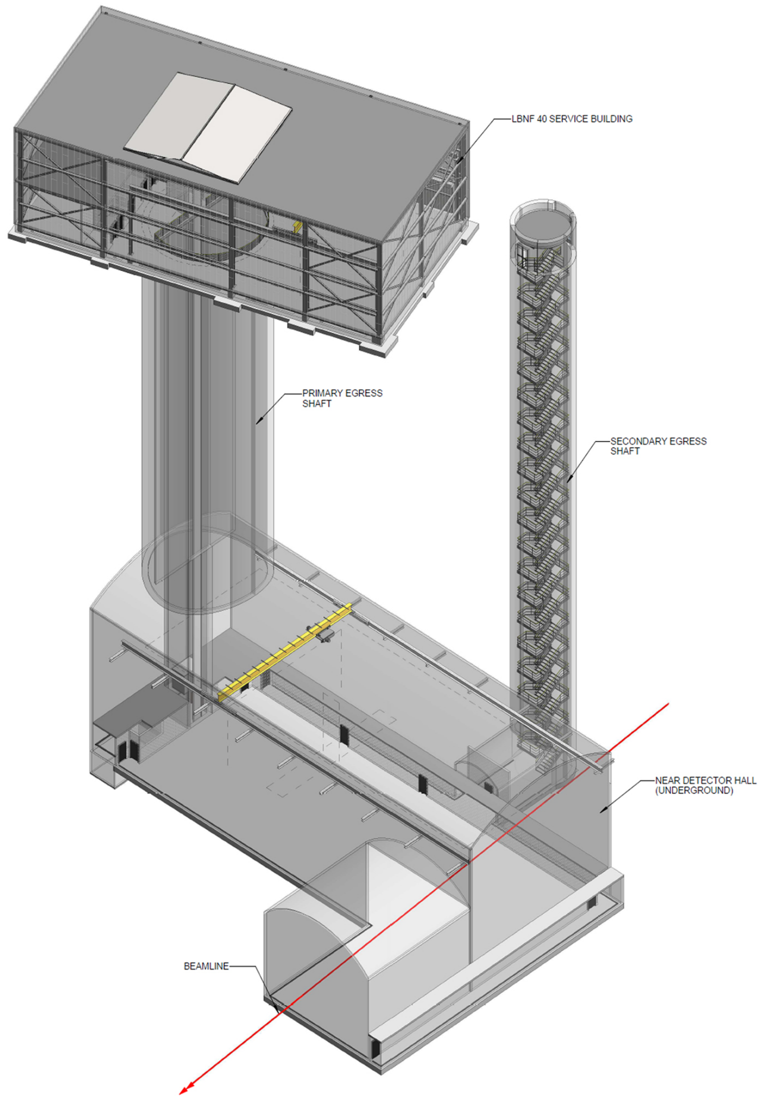




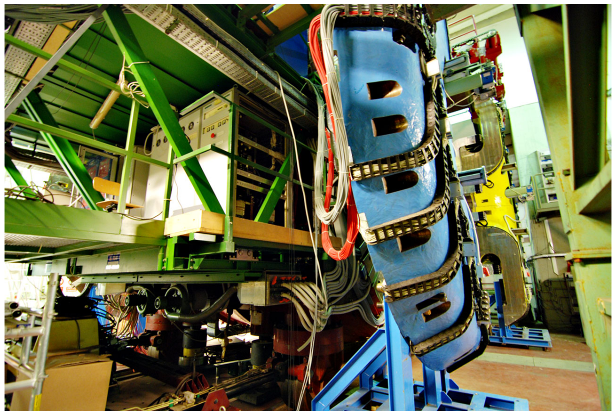


Near Detector Surface Building:
Large component must be lifted through the roof



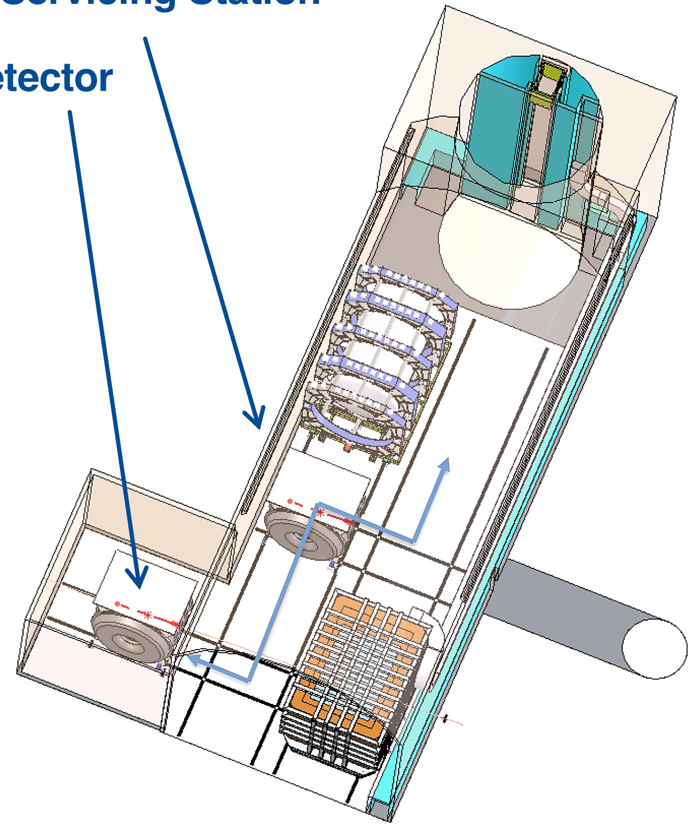


SAND Detector will serve as stationary Beam Monitor, but movement during installation and servicing must be planned



Floor Guides To Assembly And Servicing Station

KLOE Stationary Detector Inside Alcove

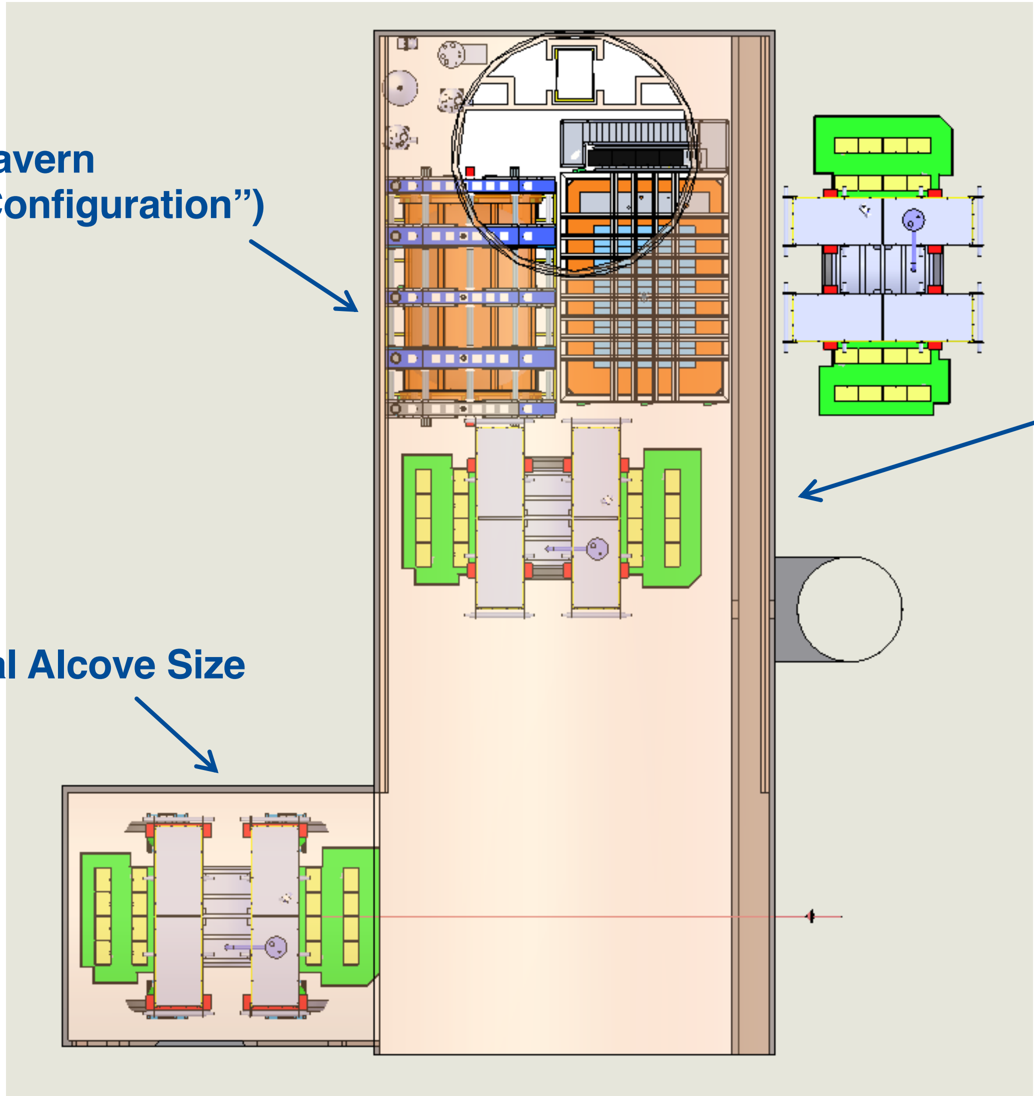


initial movement concept likely not feasible due to SAND detector size

Size of SAND necessitates careful assembly and installation Planning to sequence with assembly of other detectors

Small Cavern
("BCR Configuration")

Final Alcove Size

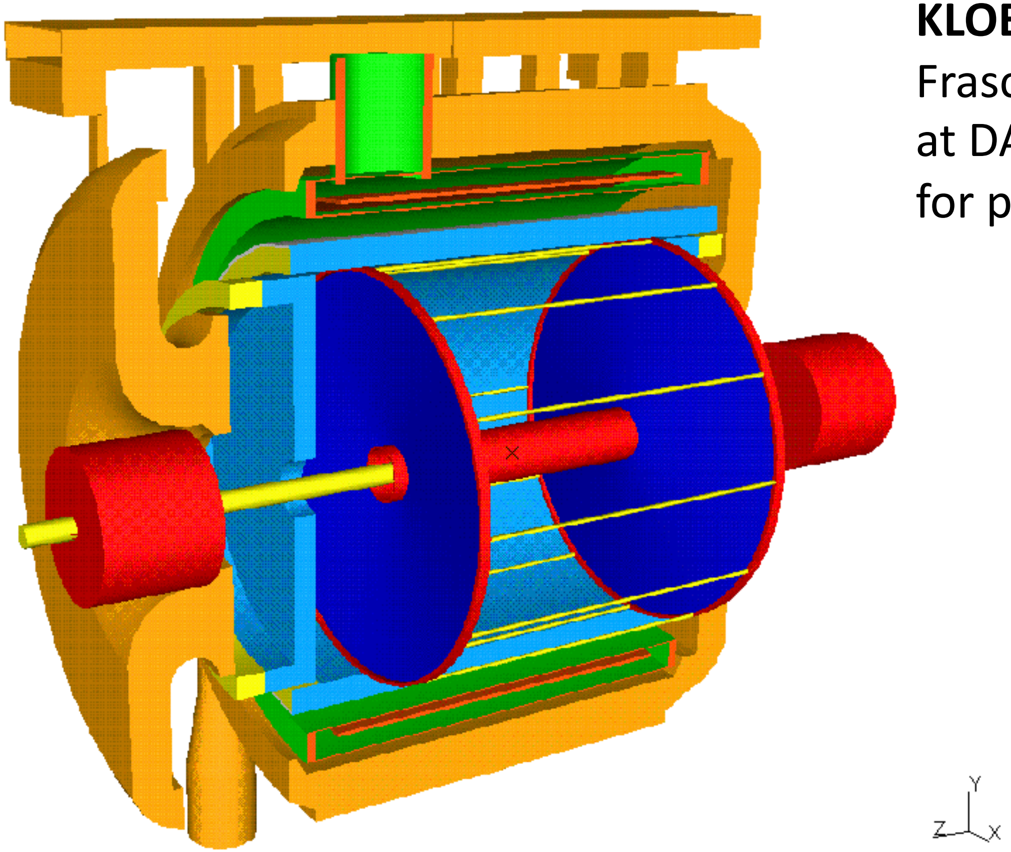


SAND Detector Has To Be Assembled And Installed First Since Detector Size Prohibits Rearranging Once Fully Assembled (*)

(*) NDDG has asked SAND group to evaluate if detector electronics mezzanine structure size could possibly be reduced.

Technical key-points

KLOE: magnet + ECAL + Drift chamber



KLOE experiment run at Laboratori Nazionali di Frascati(Rome) Italy from 1999 until 2018, at DAΦNE e^+e^- collider, for physics of K and Φ mesons.

Electromagnetic calorimeter

- Lead/scintillating fibers
- 4880 PMT's

Superconducting coil (5 m bore)

B = 0.6 T (∫ B dl = 2.2 T.m)

Superconducting Magnet

Coil parameters

Layers	2
Turns/layer	368
Ampere-turns	2.14 MA-T
Operating current	2902 A
Stored energy	14.3 MJ
Inductance at full field	3.4 H
Discharge voltage	250 V
Peak quench temperature	80 K

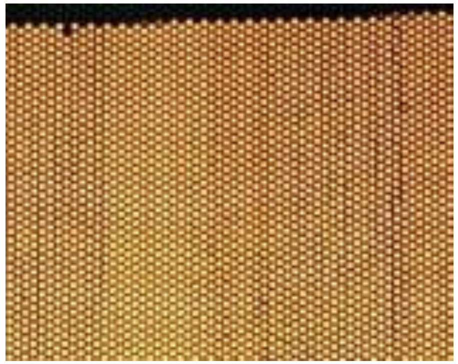
Guaranteed heat loads

Source	**Heat load**
Current leads	0.6 g/s
4 K Radiation and conduction	55 W
70 K Radiation and conduction	530 W

Electromagnetic Calorimeter

Pb - scintillating fiber sampling calorimeter of the KLOE experiment at DAΦNE (LNF):

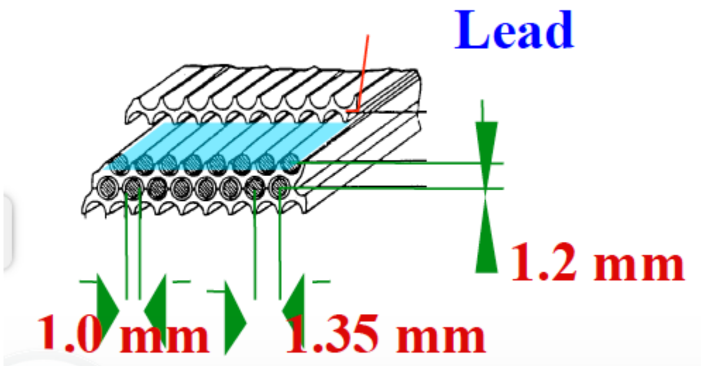
- 1 mm diameter sci.-fi. (Kuraray SCSF-81 and Pol.Hi.Tech 0046)
- Core: polystyrene, ρ =1.050 g/cm^3, n=1.6, λ_{peak} ~ 460 nm



- grooved lead foils from molding .5 mm plates

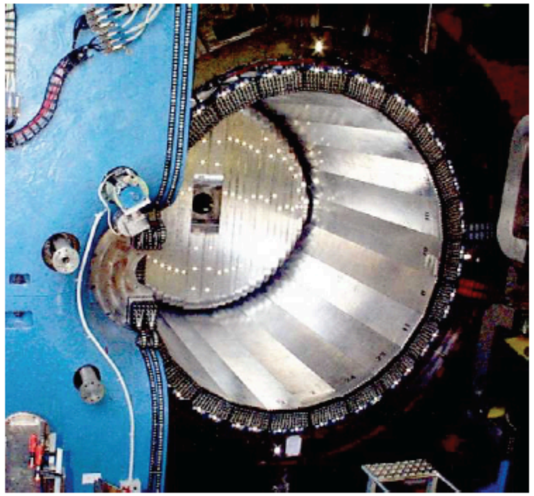
- Lead:Fiber:Glue volume ratio = 42:48:10

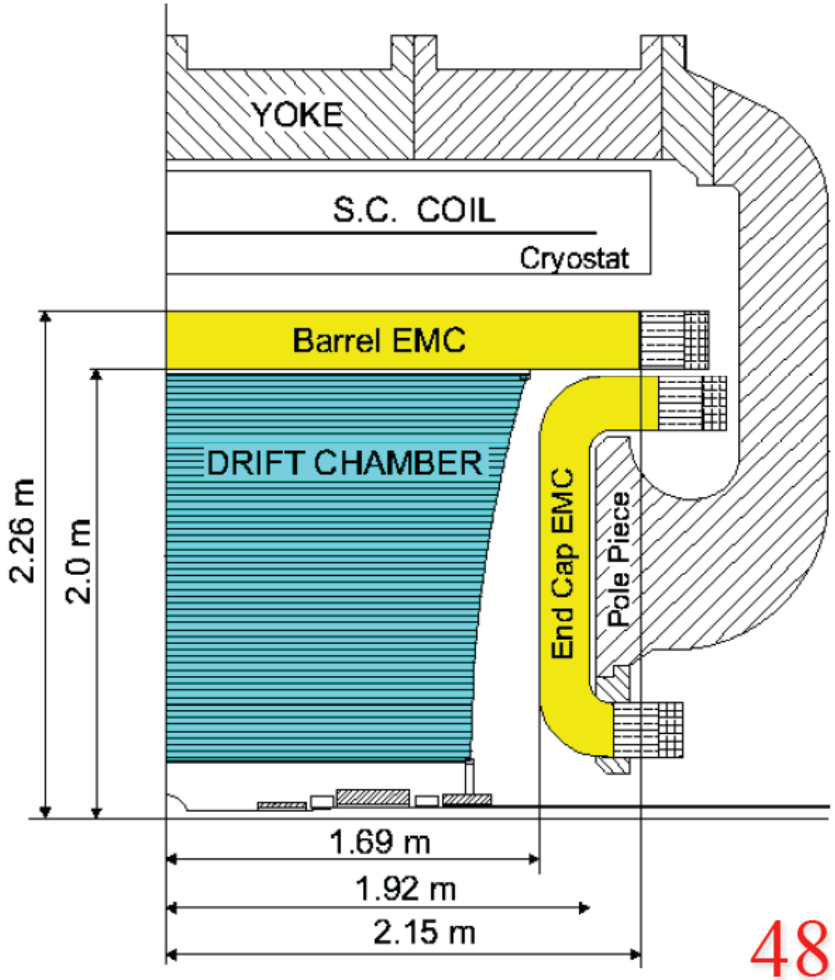
- X_0 = 1.6 cm ρ=5.3 g/cm3
- Calorimeter thickness = 23 cm
- Total scintillator thickness ~ 10 cm



Structure

24 barrel modules
60 cells (5 layers)
4.3m length





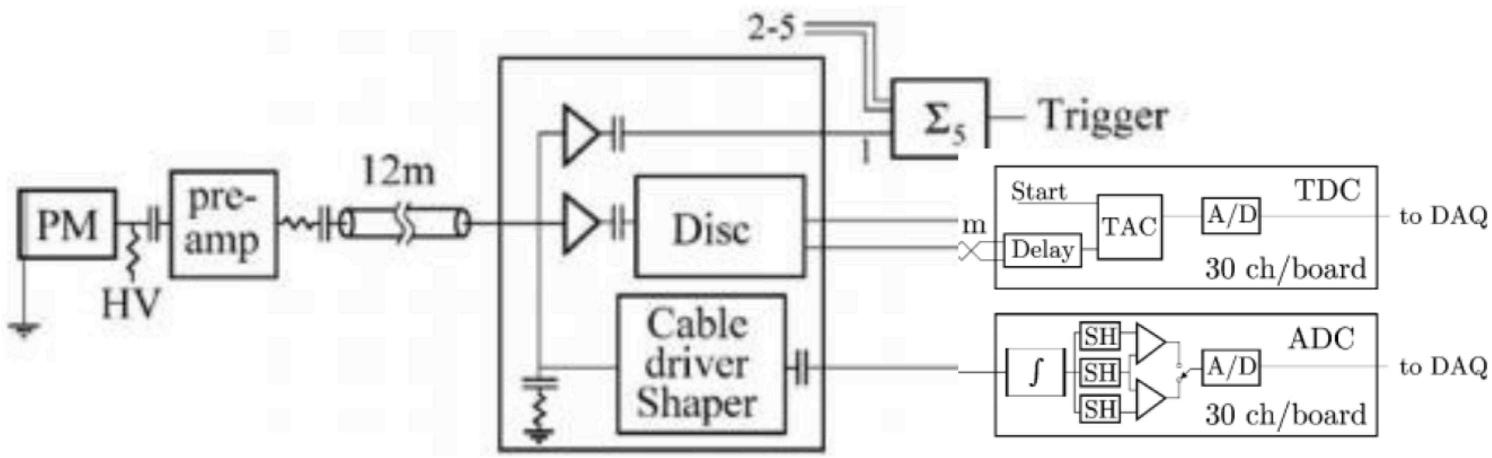
2 × 32 endcap modules
10/15/30 cells

2440 cells total

4880 channels

Electronics

It should/may be improved….if it needs/if it is worth



12 bit TDC 53 ps/count
12 bit ADC 5 counts/MeV

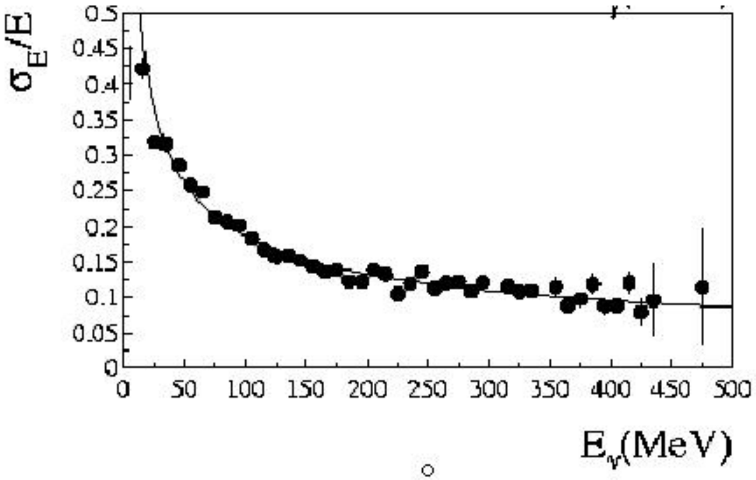
TDC threshold: 4-5 mV (3-4 p.e) → (≈100 keV)

Performances

Operated from 1999 till March 2018 with good performances and high efficiency for electron and photon detection, and also good capability of π/μ/e separation

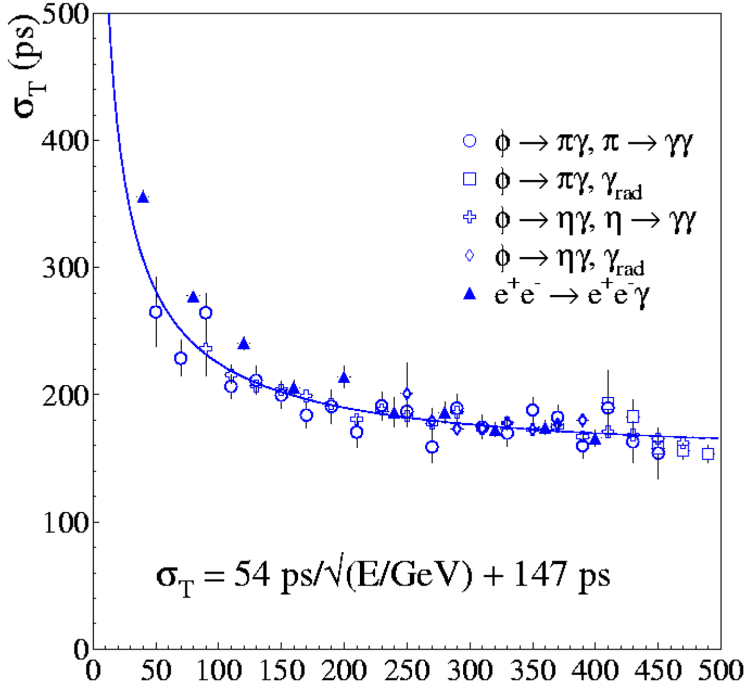
Energy resolution:

$\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$



Time resolution:

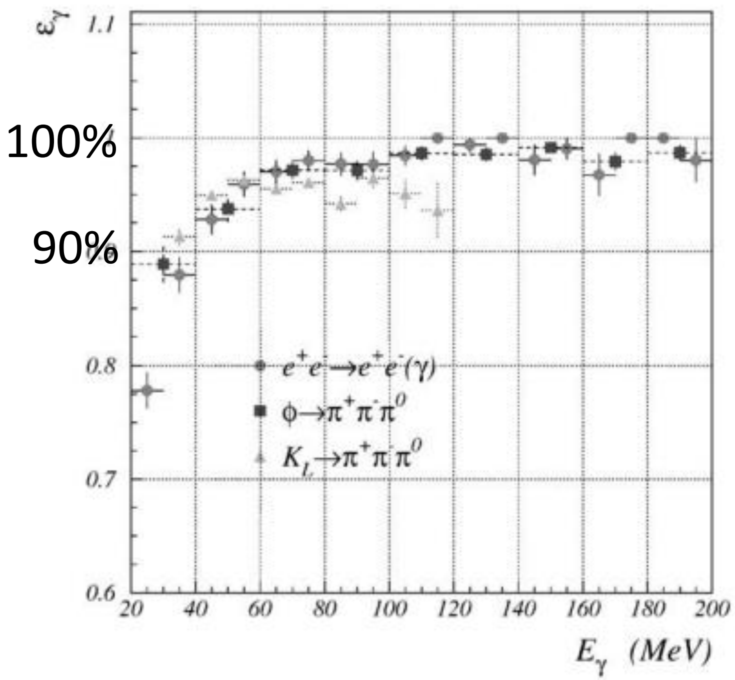
$\sigma_t = 54\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 50\ \mathrm{ps}$



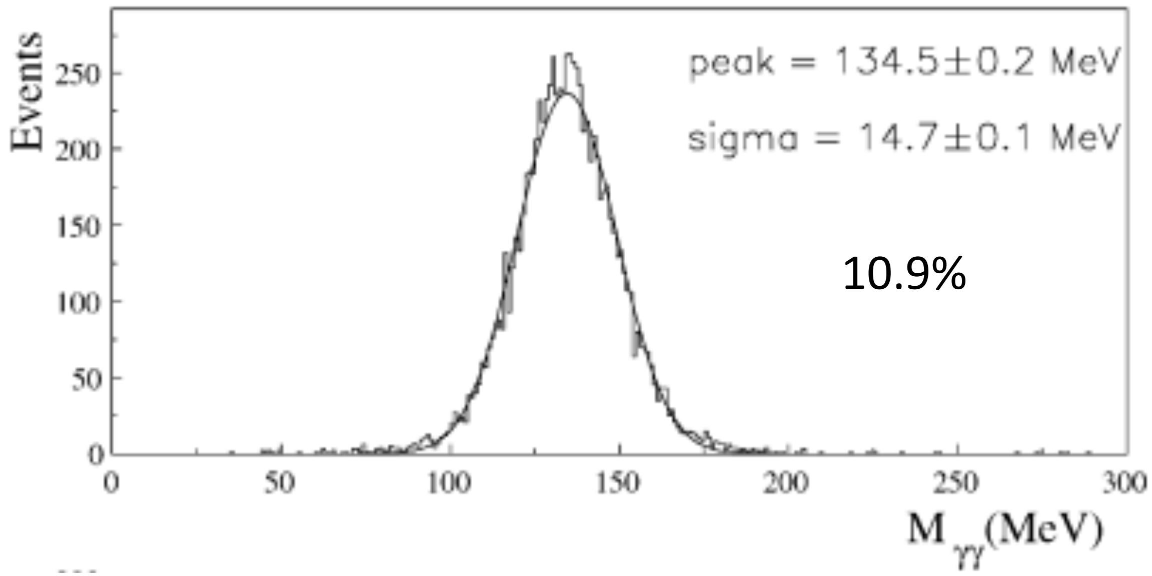
(see KLOE Collaboration, NIM A482 (2002),364)

Performances-II (energy)

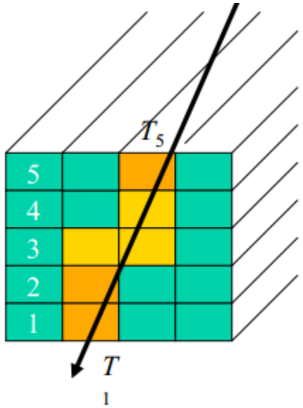
Gamma efficiency detection



π^0 invariant mass

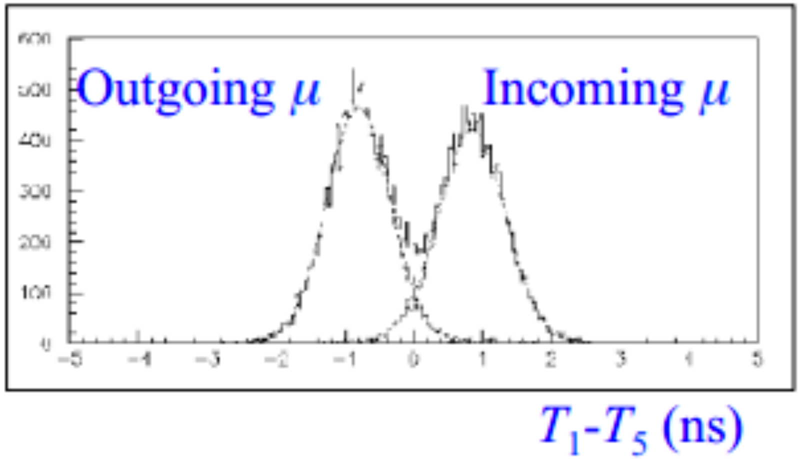


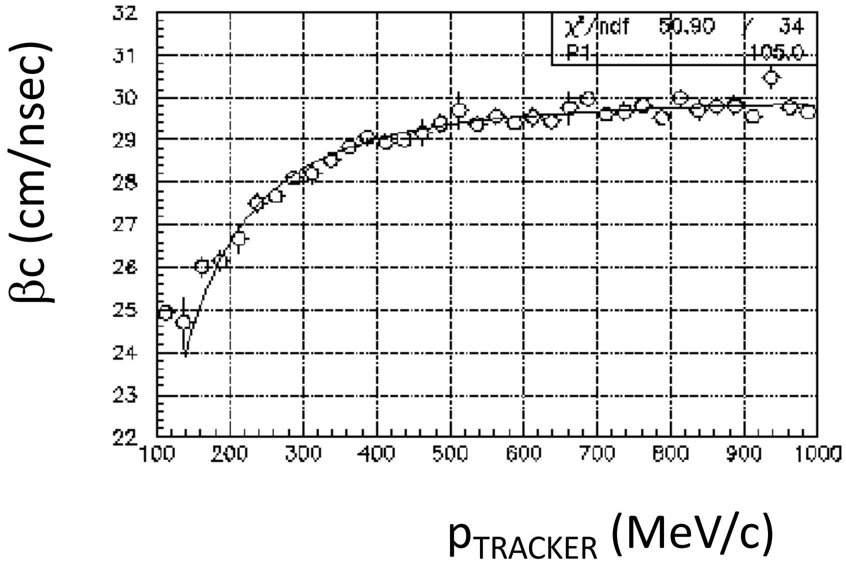
Performances-II (timing)



T_1-T_5 distribution can distinguish incoming/outcoming events

In combination with the TRACKER for L and T_0 : $\beta = L/\Delta T$

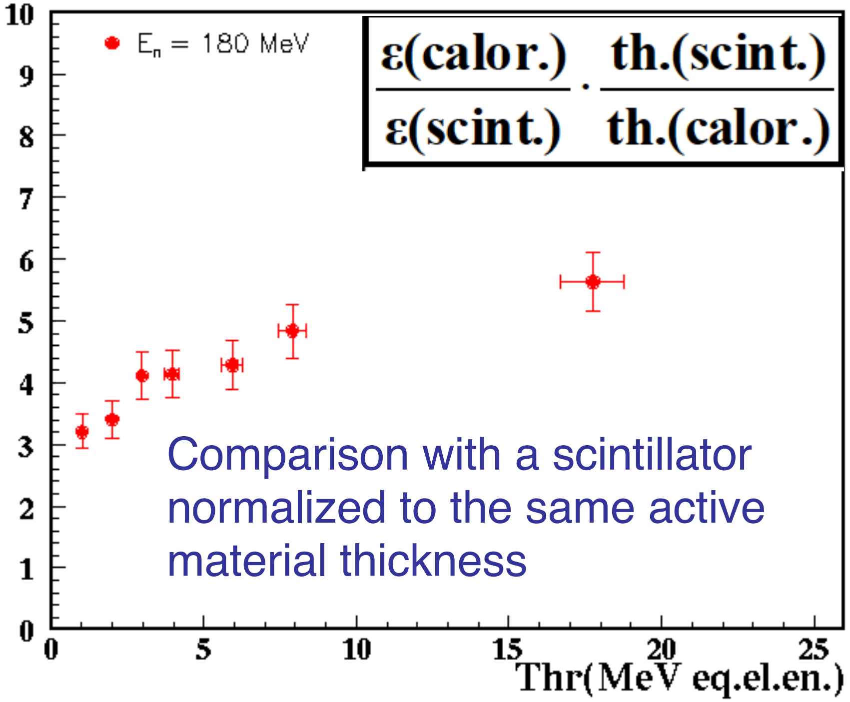


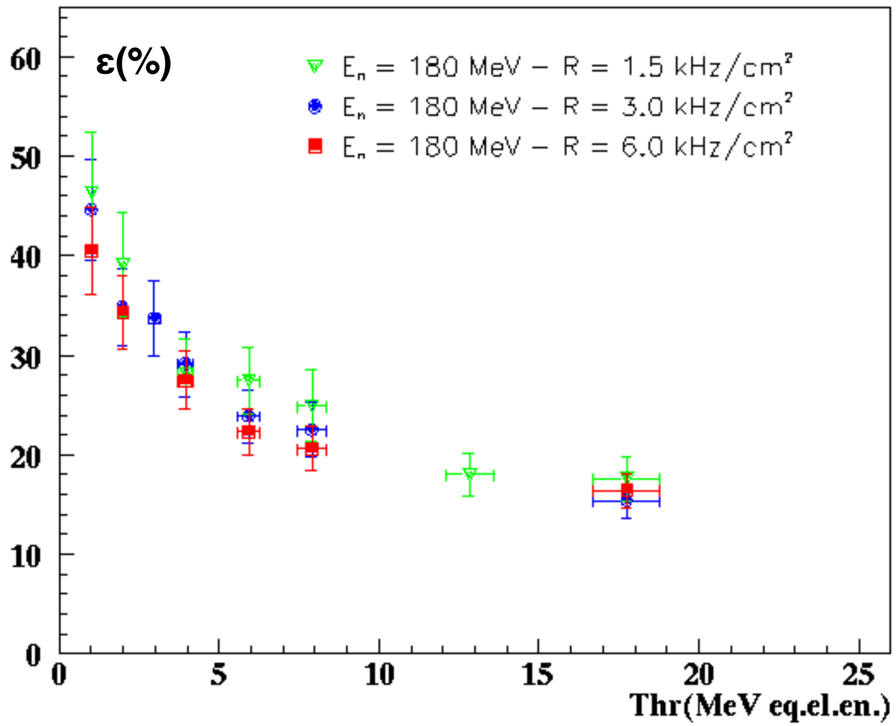


(from fit) m_{μ} = 105.6 MeV/c^2

Performances-III: neutrons!

NIM A 598 (2009) 244–247





Huge inelastic production of neutrons on the lead planes.
Secondary neutrons and protons and photons that contribute to the visible energy

TRACKER: see talks on Thursday

INFN and SAND:

INFN is willing to provide all the needed resources to dismount, refurbish, deliver, reassemble and commission of

- **a fully functional magnet plus**
- **a e.m. calorimeter plus**
- **a LAr active target (~1.5 t)**

within an opening large collaboration with other groups

Review Office charges

1. Are the DUNE-ND requirements sufficiently well understood and documented and are they sufficiently complete for proceeding with the designs of each element?
2. Do the designs address detector requirements? Are the designs feasible? Are the key technical specifications for the major DUNE-ND elements understood and addressed?
3. Have interfaces between detector elements been identified? Are the interfaces with the cryostat, cryogenic systems, facility, and installation sufficiently understood?
4. Are the scope and institutional responsibilities for the major elements defined? Is all essential scope covered?
5. Are plans for prototyping tests sufficient to validate viability of the designs?
6. Do conceptual engineering models or schematics provide sufficient information to ascertain constructability and functionality?
   Do conceptual engineering calculations validate the design?
7. Have installation plans been sufficiently developed to give confidence that the detector elements can be installed?
8. Have appropriate manufacturing methods been identified and have rough cost and schedule estimates been developed? Is the schedule to move forward towards preliminary design, prototyping, and production realistic?

Charges fulfillment

1. Requirements fulfillment: 100%
2. Detector design: 100% for Magnet and EM-Calorimeter
   Trackers: design feasibility 100%, technical specifications: 70% (missing mechanics)
3. Interfaces: 100% overall, at 70% for trackers inclusion
4. Institutional responsibilities for Magnet and EM-Cal: 100%
   Trackers at 30% (missing money-matrix and MoU)
5. Prototypes: 100%
6. Engineering models 100%
7. Installation plans developed at 30%
   Major confidence plans will be ready for 2023.
8. Manufacturing methods identified: 100%
   Precise costs clear for Magnet and EM-Cal,
   Estimation available
   Is the schedule to move forward towards preliminary design, prototyping,
   and production realistic? VERY YES.

Conclusion

1) SAND detector is a well-advanced project for the DUNE-ND
2) A more than excellent ”beam monitoring” system to detect time-dependent beam parameters
3) A performing tracker has to be finalized
4) Its multipurpose concept will allow very extensive studies on neutrino interactions
5) SAND ND-detector is well in-line for starting of data taking at the DUNE-FAR at DAY-1

thanks

Backup slides

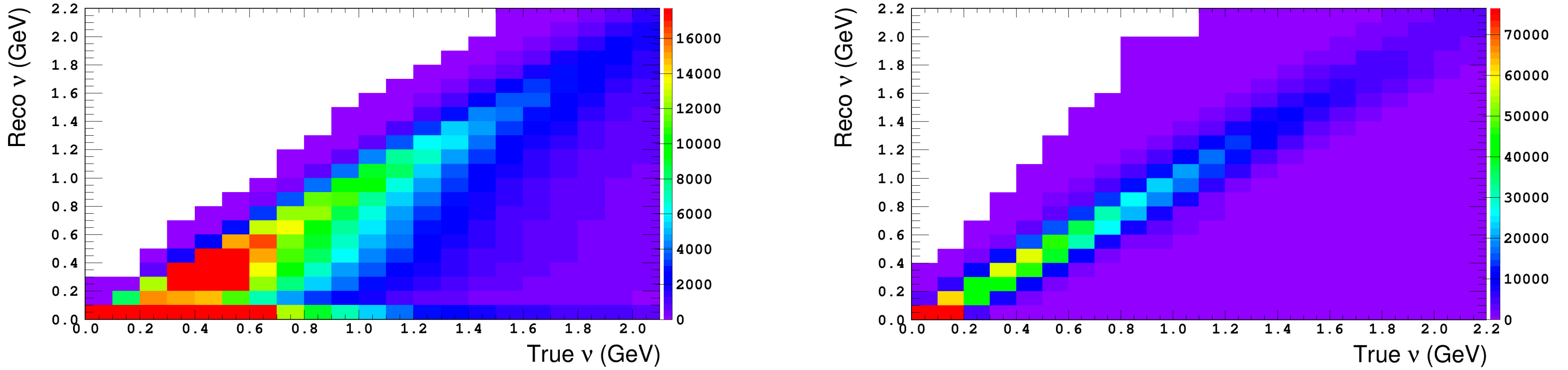
Some Physics performances (more on next talks)

Channel	ν mode	$\bar{\nu}$ mode
ν_μ charged current (CC) inclusive	15.3×10^6	6.1×10^6
CCQE	3.9×10^6	2.4×10^6
CC π° inclusive	5.0×10^6	1.4×10^6
neutral current (NC) total	5.2×10^6	3.3×10^6
ν_μ-e$^-$ scattering	349	190
ν_μ CC coherent	7.49×10^5	4.6×10^5
ν_μ CC low-ν (ν <250 MeV)	1.74×10^6	1.4×10^6
ν_e CC coherent	7.3×10^3	4.3×10^3
ν_e CC low-ν (ν <250 MeV)	1.9×10^4	1.5×10^4
ν_e CC inclusive	2.4×10^5	8.7×10^4

The importance of the neutron detection…

Projected event rates per year for a 2.4 x 2.4 x 2.0 m^3 3DST detector.
A 10 cm veto region at each side was required.

Reconstructed versus true ν transfer energy in 3DST



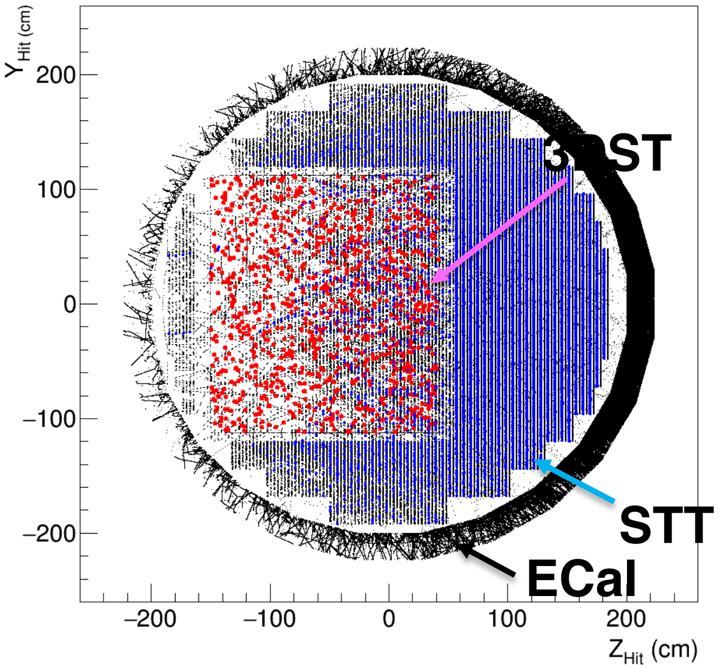
In general, neutron measurement provides an event-by-event reconstruction of neutrino interaction, allowing for the selection of dedicated samples

Physics performances

Background from induced external interactions

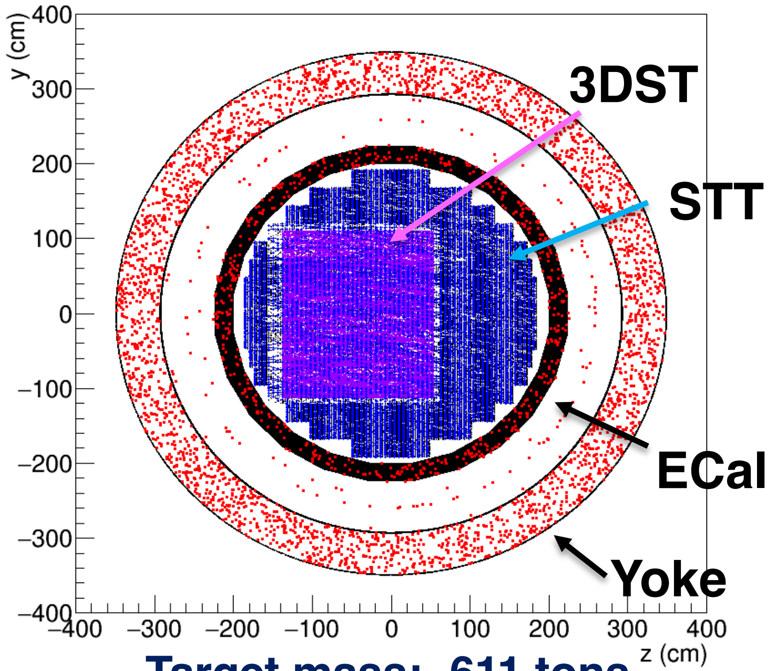
Active volume: 2.24x2.24x2m³ | *MC samples by FLUKA*

"Internal" events: ν_μ (CC) interactions inside 3DST



Target mass: 10.6 tons

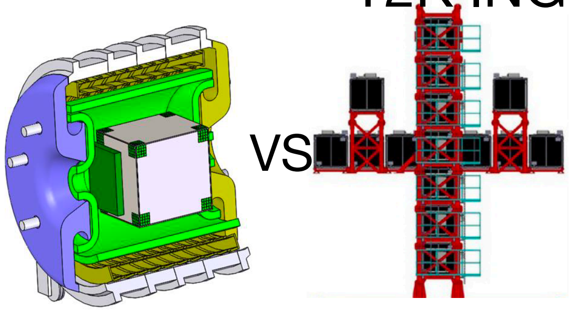
External" events: ν_μ (CC+NC) interactions inside SAND magnet+Calorimeter (ECal)



Target mass: 611 tons

• Interaction vertices

Beam monitoring with 3DST+ECAL



Compared with four 7-ton modules that measure the rate at 0,1,2,3 meters from the on-axis position (28 ton in total)

Beam parameter	Parameter description: Nominal	Parameter description: Changed	Significance, $\sqrt{\chi^2}$: Rate-only monitor	Significance, $\sqrt{\chi^2}$: SAND
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	5.6
proton beam width	2.7 mm	2.8 mm	0.02	3.6
proton beam offset x	N/A	+0.45 mm	0.09	4.3
proton beam $theta$	N/A	0.07 mrad	0.03	0.5
proton beam $\theta\phi$	N/A	0.07 mrad θ and 1.5707 ϕ	0.00	1.0
horn current	293 kA	296 kA	0.2	11.9
water layer thickness	1 mm	1.5 mm	0.5	4.2
decay pipe radius	2 m	2.1 m	0.5	7.0
horn 1 along x	N/A	0.5 mm	0.5	4.6
horn 1 along y	N/A	0.5 mm	0.1	3.6
horn 2 along x	N/A	0.5 mm	0.02	0.9
horn 2 along y	N/A	0.5 mm	0.00	0.8

1 week exposure

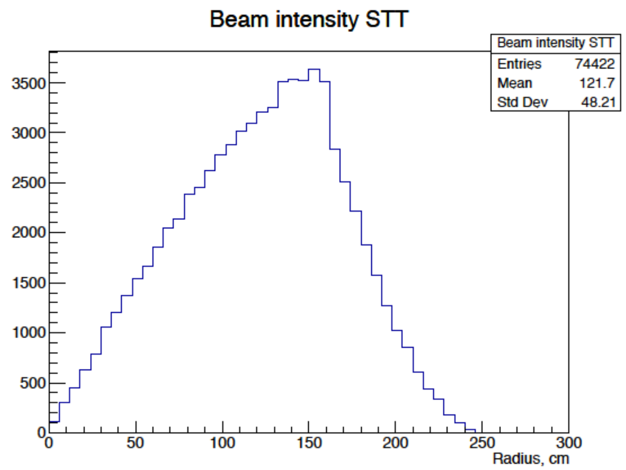
Test statistic: $\Delta\chi^2$ between 1week simulated data and nominal distribution, large data sample

- The SAND spectrometer is very sensitive to even small variations of the beam parameters compared to just measuring the neutrino event rate
- With 3DST module, ~11 cm uncertainty on the beam center can be achieved with 1 week data taking. Improvements are expected by using also ECAL

Beam monitoring with STT+ECAL

Study E_ν and E_μ spectra as a function of the distance from the beam axis using interactions in STT, front ECAL, front magnet.

- Consider sample corresponding to 7 days: 3.78 Å~ 1019 p.o.t.
- events simulated with complete chain dk2nu+GENIE+GEANT4+edep-sim



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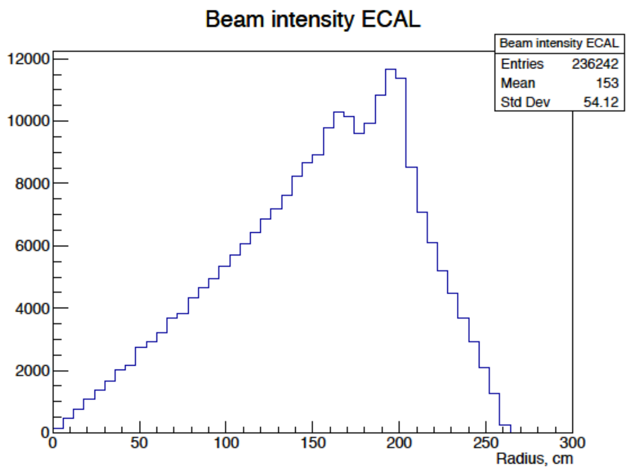
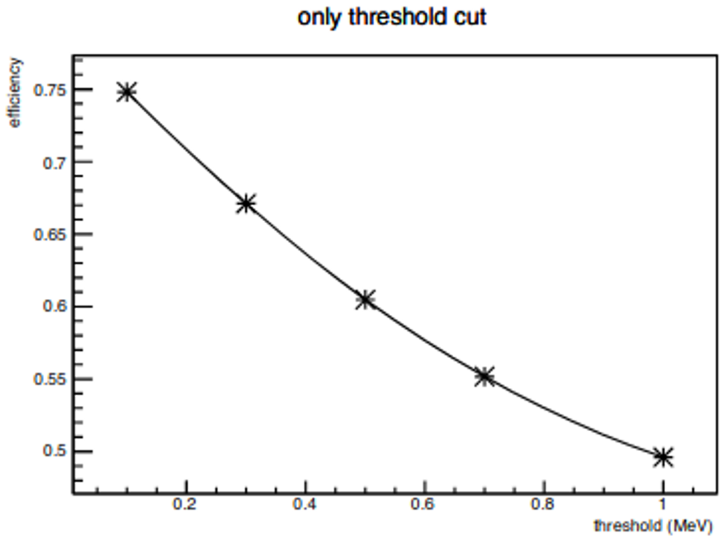


Radial bins used to monitor E_ν and E_μ (ν_μ CC):

- STT: 0-100, 100-150, 150-250 cm
- ECAL: 0-100, 100-150, 150-200, 200-250 cm

Whole range for $\bar{\nu}_\mu$ CC sample

Background cut with topology (3DST)



	cc1pi0p	cc0pi1p
efficiency	0.167	0.042

99% purity

	cc1pi0p	cc0pi1p
efficiency	0.292	0.167

98% purity

	cc1pi0p	cc0pi1p
efficiency	0.403	0.434

95% purity

	cc1pi0p	cc0pi1p
efficiency	0.790	0.891

90% purity

The inefficiency mainly comes from threshold and secondary background cut: 60% and 20%(for 1 pi sample)

«Solid» hydrogen target

Exploit high resolutions & control of chemical composition and mass of targets in STT

✦ "Solid" hydrogen concept: ν(¯ν)-H CC by subtracting CH2 and C thin (1-2%X0) targets:
- STT detector designed to provide, on average, same acceptance for CH2 and C targets;
- Model-independent data subtraction of dedicated C (graphite) target from main CH2 target;
- Kinematic selection provides large H samples of inclusive & exclusive CC topologies with 80-95% purity and >90% efficiency before subtraction.

⇒ Viable and realistic alternative to liquid H2 detectors