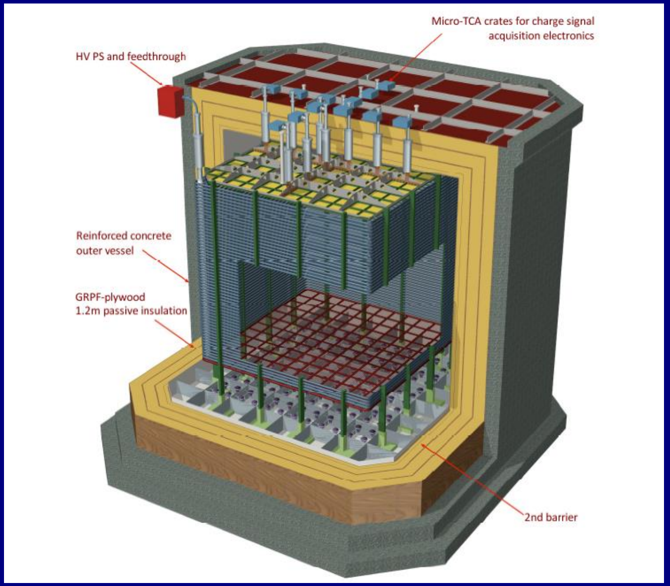
LAGUNA-LBNO

and large-scale prototyping effort at CERN: LBNO-Proto



CS IN2P3, June 27th 2013

APC + OMEGA:

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LAPP:

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LPNHE:

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+ Irfu group: 0.Besida et al., 10 people
→ Discussion at the Irfu CS, June 17th

Neutrinos:

Fundamental role in particle physics, astrophysics and cosmology

Neutrinos mass → presently only evidence of physics beyond the SM

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

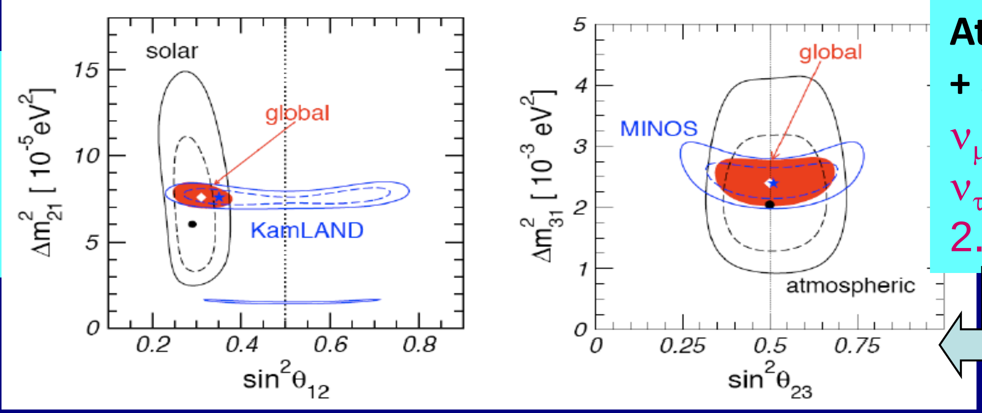
$\alpha = e, \mu, \tau$ (flavor index)

$i = 1, 2, 3$ (mass index)

$U_{\alpha i}$ = unitary mixing matrix

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(1.267\Delta m^2 \frac{L}{E}\right)$$

Solar neutrinos
+ Kamland
ν_e, anti-ν_e disappearance
$7.6 \times 10^{-5}\ eV^2$



Atmospheric neutrinos
+ accelerators
ν_μ disappearance
ν_τ appearance
$2.4 \times 10^{-3}\ eV^2$

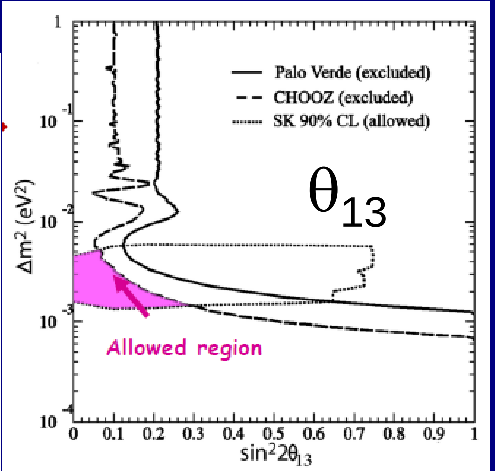
θ_{13}, CP violation?

$$U \equiv U_{23}U_{13}U_{12} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric ν oscillations **Solar ν oscillations**

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

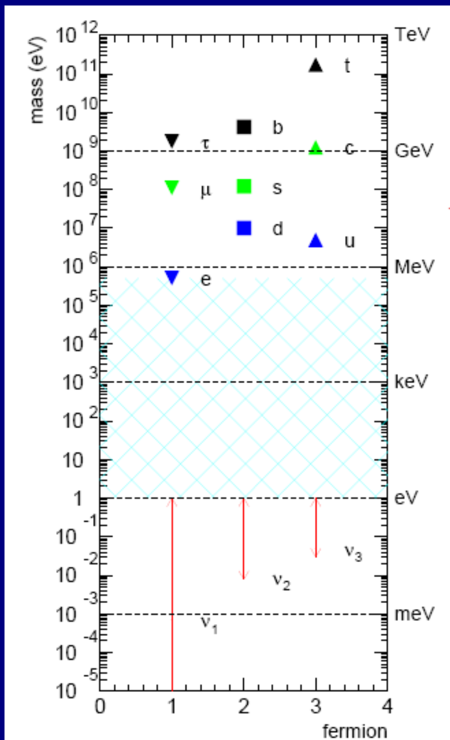
where: $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$.



$\sin^2(2\theta_{13}) < 0.15$ (90% C.L.)

Neutrinos: a window beyond the S.M. → G.U.T.

Fundamental questions related to a deeper description of physics and to the evolution of the universe



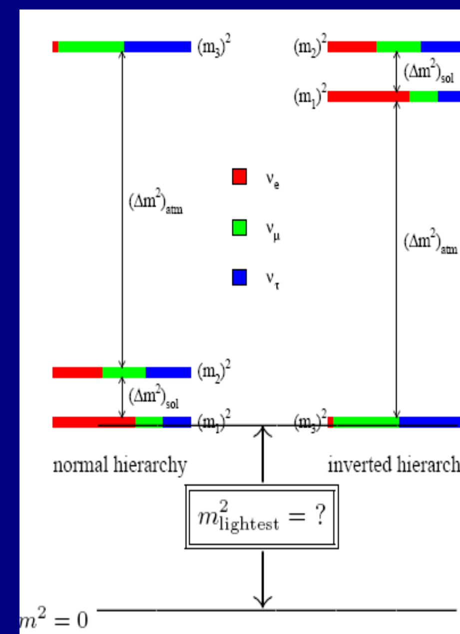
- Why are neutrino masses so small ?
- Why is the mixing matrix so different than the one of the quarks ?

What is this very strange puzzle suggesting us ?

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- How is the hierarchy of the mass eigenstates ?
- Which is the mass of the lightest state
- Are neutrinos Majorana particles ?
- Are there sterile neutrinos … ?

- ~~Is the θ_{13} angle different from zero ?~~
- Is there CP violation in the neutrino sector ?

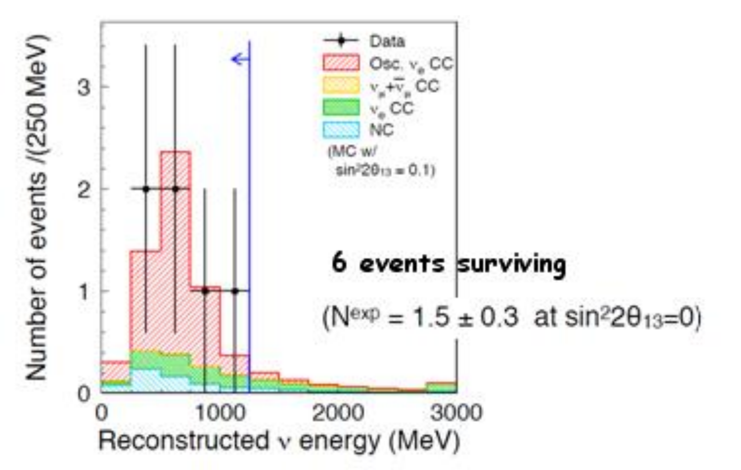


An experimental program for a few decades :
like for CP in quark sector → PMNS matrix to be measured as CKM

Present generation: T2K, NOVA, DCHOOZ, Day-Bay, Reno→ measurement of θ_{13}
Next generation → **search for CP violation and mass hierarchy**
(+ experiments for double beta decay and aimed at measuring the neutrino mass)

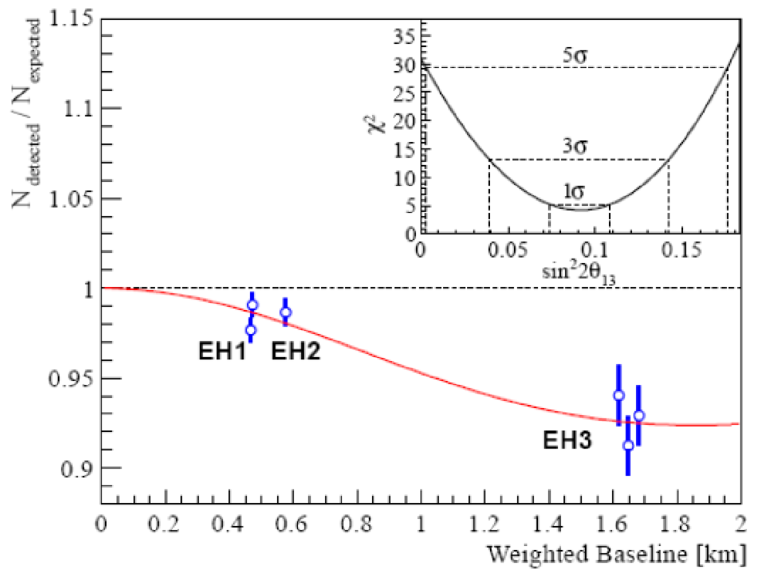
2012: the turning point, $\nu_\mu \rightarrow \nu_e$ oscillations and θ_{13}

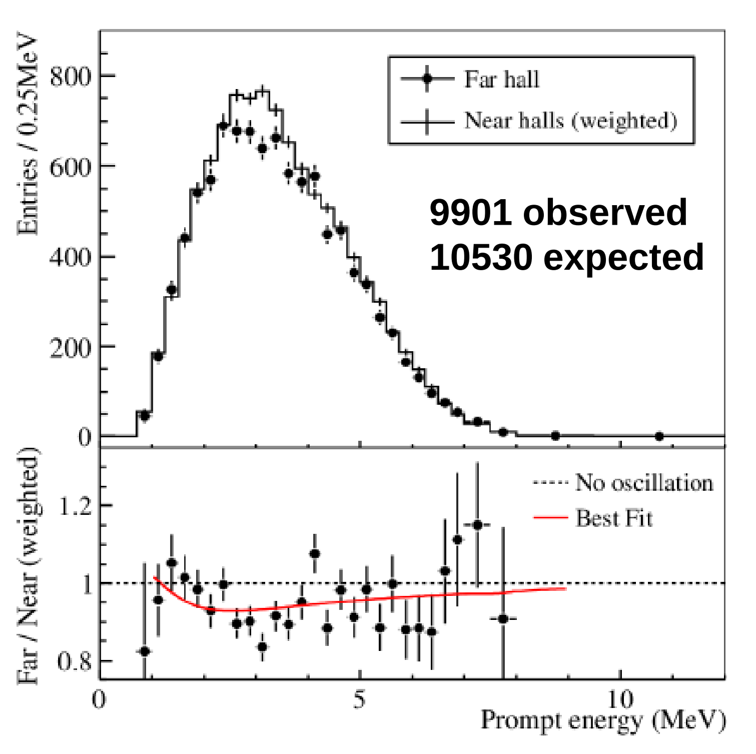
T2K off-axis beam (tuned for osc. max.)
$\nu_\mu \rightarrow \nu_e$ appearance
First result on θ_{13} (June 2011):
6 events observed, 1.5 events bck. → 2.5 σ



March 8th 2012:
Daya Bay reactor anti-neutrinos
$\nu_e \rightarrow \nu_\mu$ (ν_e disappearance)

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$





5.2 σ for non-zero θ_{13}

In March 2012 we entered in a new era !!!

Key measurements of neutrino mixing via the study of $\nu_\mu \rightarrow \nu_e$ oscillations:

- $\theta 13$
- Matter effects and mass hierarchy
- Search for CP violation

Large $\theta 13$ → next steps accessible with standard beams !

Matter effect

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

Leading term

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

CP-terms

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

Solar term

CPV

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

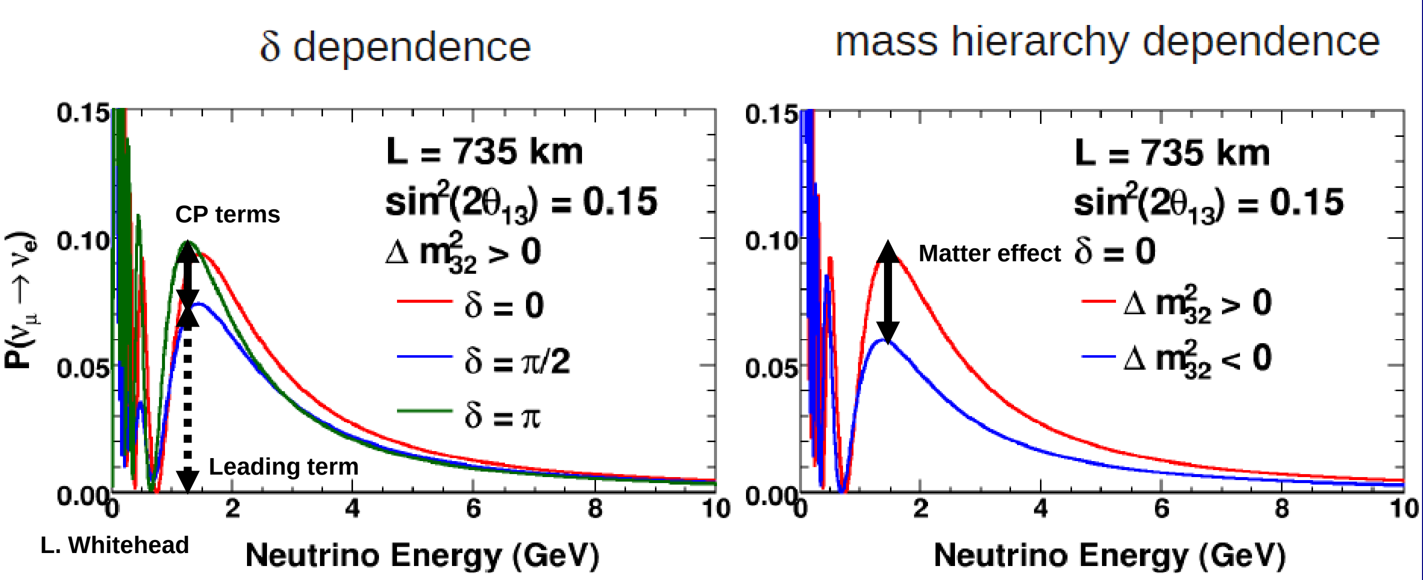
E_ν dependence

$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

Matter effects and CP violation effects degeneracy

Matter effects mimic CP violation

→ They have to be accurately <u>measured</u> and subtracted in order to look for CP



- <u>Difference between neutrinos and antineutrinos:</u>

$$\mathcal{A} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

$$16\frac{a}{\delta m^2_{31}}\sin^2\frac{\delta m^2_{31}L}{4E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

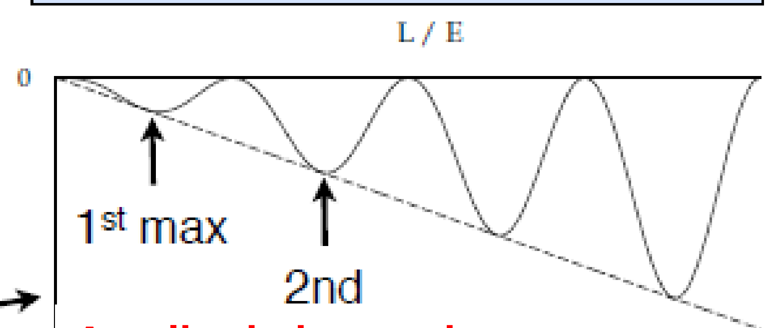
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

Matter terms

$$-8\frac{\delta m^2_{21}L}{2E}\sin^2\frac{\delta m^2_{31}L}{4E}s_\delta c^2_{13}s_{13}c_{23}s_{23}c_{12}s_{12}$$

Pure CP-term

$$\boxed{\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}}$$



Amplitude increasing linearly with L/E

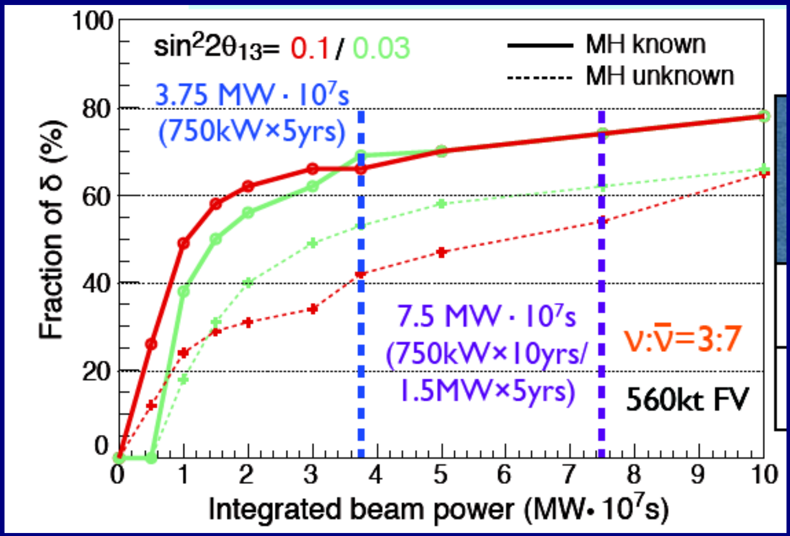
The Water Cerenkov approach (extrapolation ~x25 of SK):

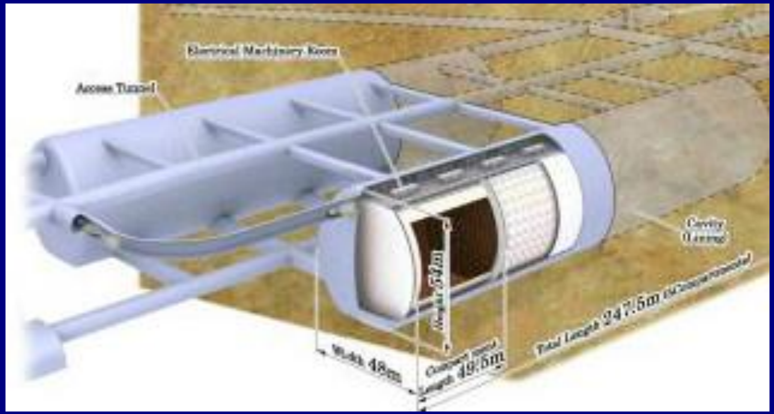
- Carefully studied in LAGUNA-LBNO as a possible option (MEMPHYS) for what concerns the technical implementation, physics performance and costing and classed in second priority

✓ Large water Cerenkov detector *O*(0.5 Mton), 140k 12'' PMT
✓ Low energy narrow beam (0.1-1 GeV) → just lepton reconstruction in QE events
✓ Short baseline (100-300 km) → no mass hierarchy determination
✓ New super-beam needed ~*O*(MW) 4MW SPL beam for Memphys
→ Counting only experiment on neutrinos-antineutrinos asymmetry

- HyperKamiokande project in Japan

0.56 Mton, 99k PMT 20'', 750 kW beam from JPARC (295 km)





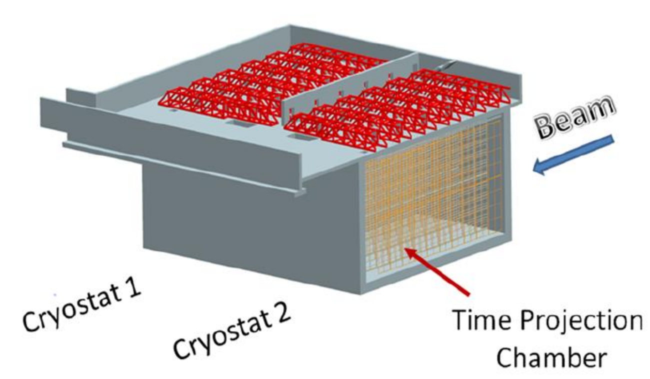
74% (55%) CP coverage (3σ) if MH know (unknown)
In 15 years at 750 kW

The Liquid Argon approach:

- Main option in LAGUNA-LBNO:

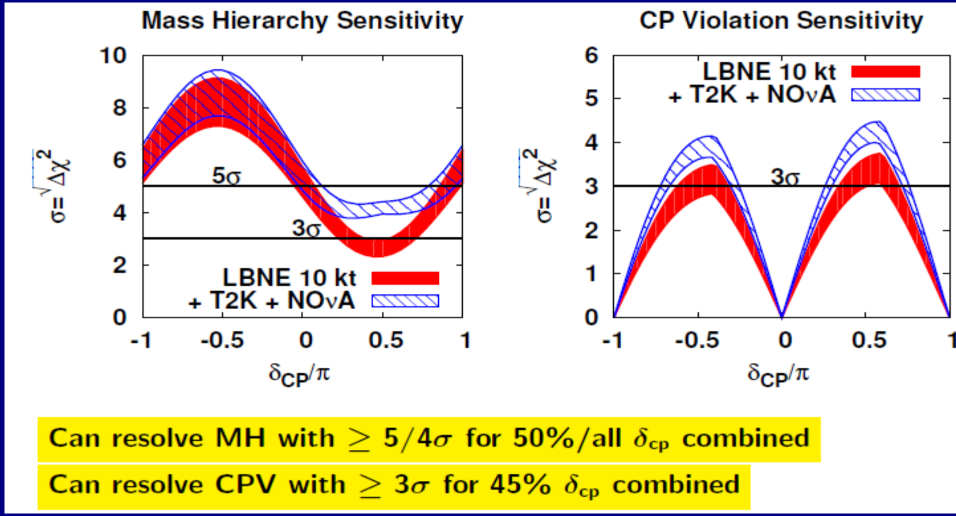
✓ Liquid argon TPC *O*(20kton)
✓ High energy (>1 GeV) beam, all final states accessible
→ L/E pattern and <u>second oscillation maximum</u>
✓ Long baseline (>1000 km) → mass hierarchy measurement (2300km for LBNO)

- LBNE project in USA



→ First phase 2022 (~900 M$):
700 kW beam from FNAL to Homestake,
1300 km → limited matter effects
10 kton LAr far detector on surface (no near detector)

(→ marginal outcome of Phase I)



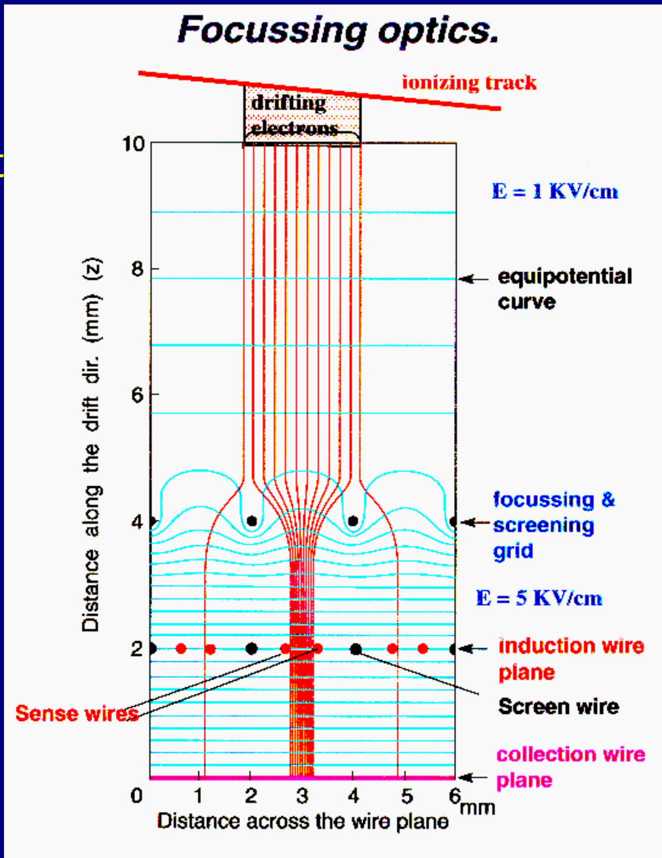
- Sensitivity from only first oscillation max.
- Needs very small syst. errors.

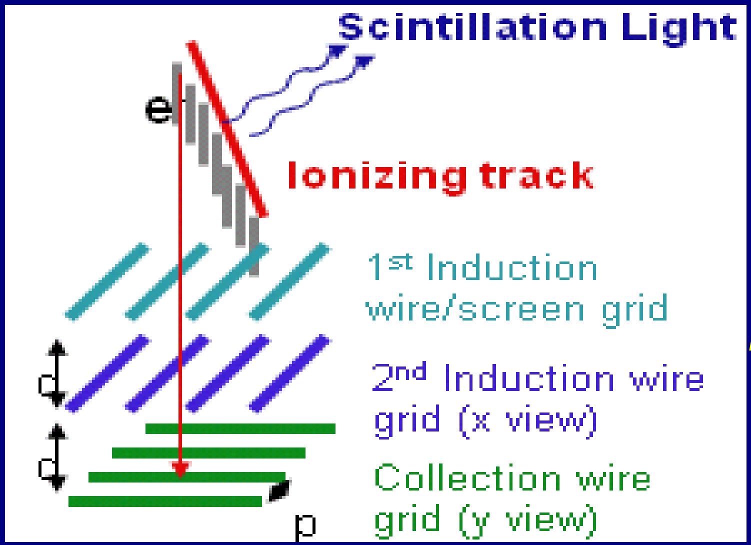
Further stages: underground far detector
35 kton, 2.3 MW beam (Project X)

The Liquid Argon Time Projection Chamber *(C. Rubbia 1977)*

- Homogeneous massive target and ionization detector → electronic bubble chamber
- 3D event reconstruction with ~1 mm resolution, surface readout
- High resolution calorimetry (electromagnetic and hadronic showers)
- Primary ionization in LAr: 1 m.i.p ~ 20000 e- on 3 mm
- Detection of UV scintillation light in Argon (5000 photons/mm @128 nm) to provide t = 0 signal of the event

Ideal detector for neutrino oscillations, supernovae neutrinos and proton decay





Non-destructive multiple readout with induction planes

z = drift time

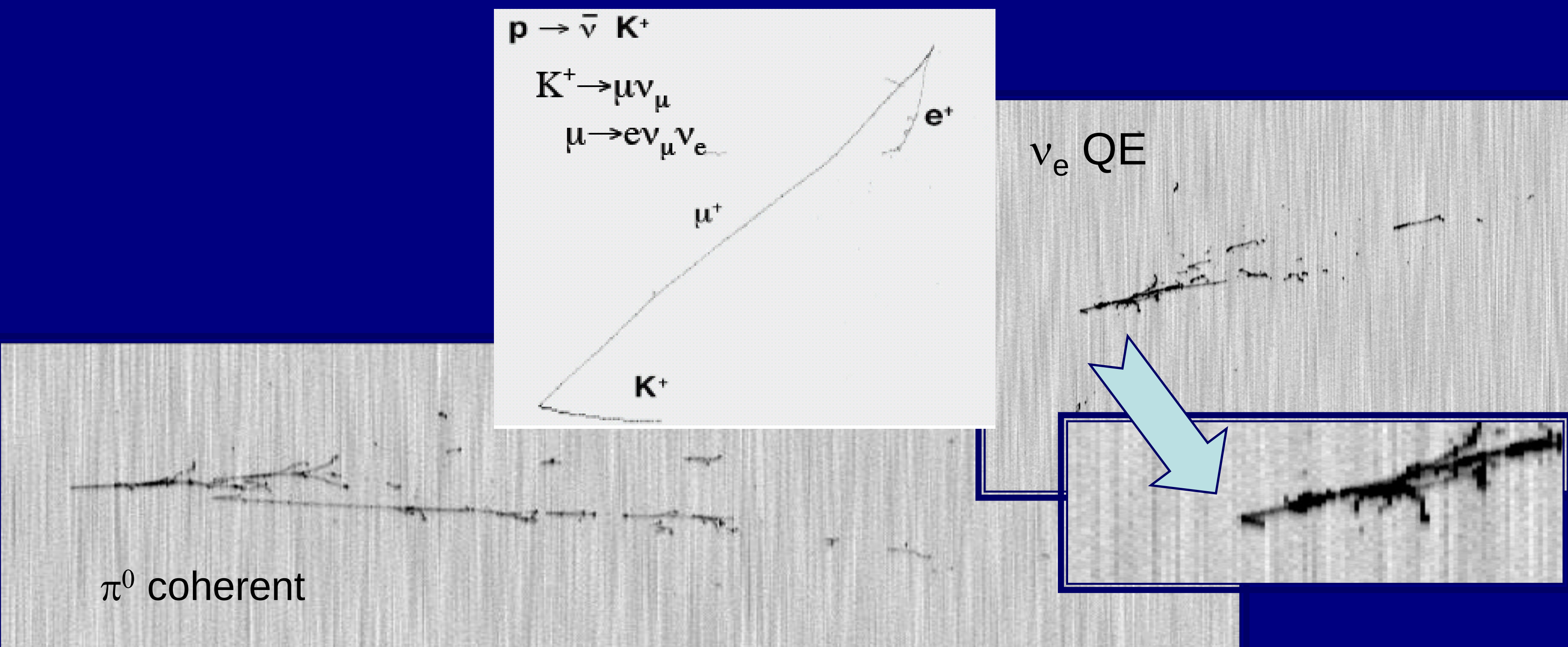
Drift Field: 0.5-1 kV/cm
Drift time:
1.5ms/3m @1 kV/cm

→ drift requiring < 0.1 ppb O_2 equiv. impurities

The LAr TPC as an electronic bubble chamber

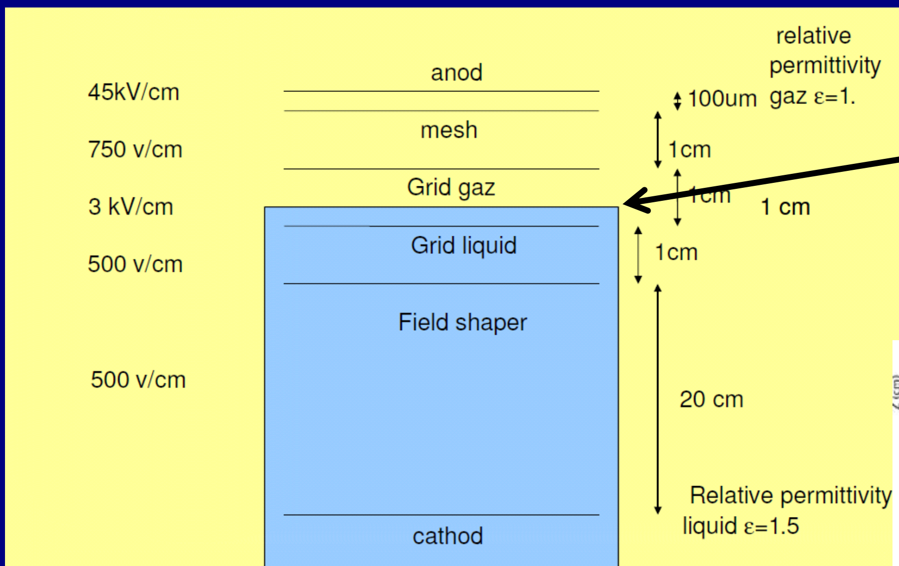
- Large mass, homogeneous detector, low thresholds, exclusive final states
- Tracking + calorimetry (0.02 X0 sampling)
- Electron identification, π0 rejection, particles identification with dE/dx

→ Neutrino physics (electron identification, reconstruction of event kinematics, identificatio of exclusive states, excellent E resolution from sub GeV to multi GeV)
→ Supernovae neutrinos
→ Proton decay search (large mass, particles id.)

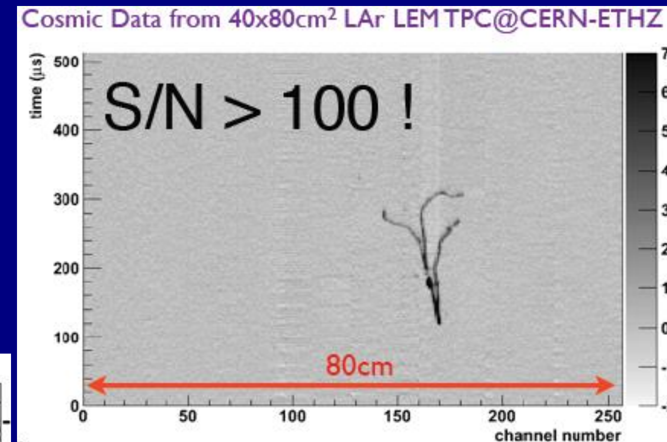


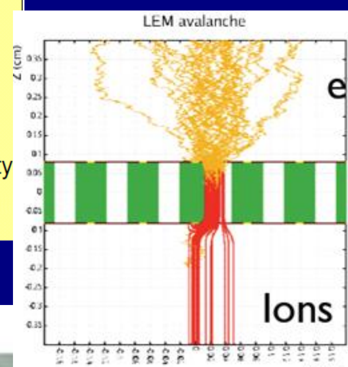
Double phase readout:

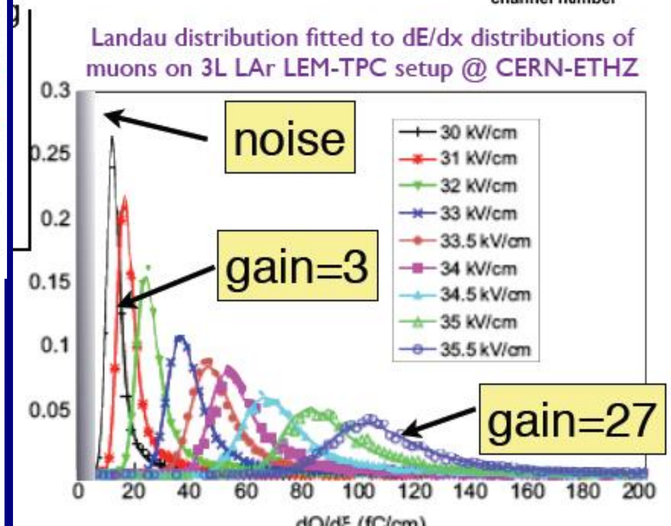
Compensate for long drift: extraction of electrons from the liquid and multiplication with avalanches in pure argon with detectors like LEM or 100 um bulk micromegas.
Low gain (~20), coupling to cold electronics in integrated modules

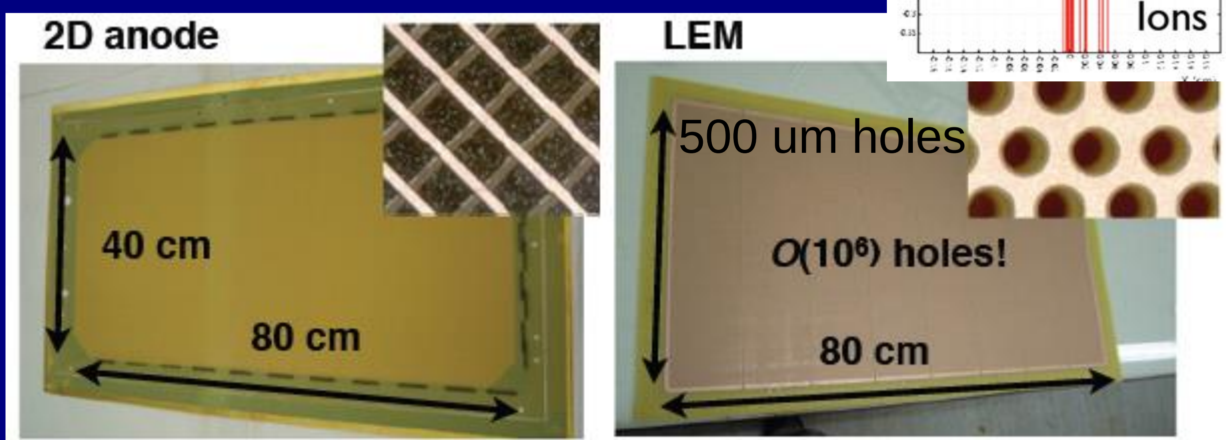


100% extraction efficiency with E> 2.5 kV/cm









LAGUNA (http://www.laguna-science.eu/)

Large Apparatus studying Grand Unification and Neutrino Astrophysics

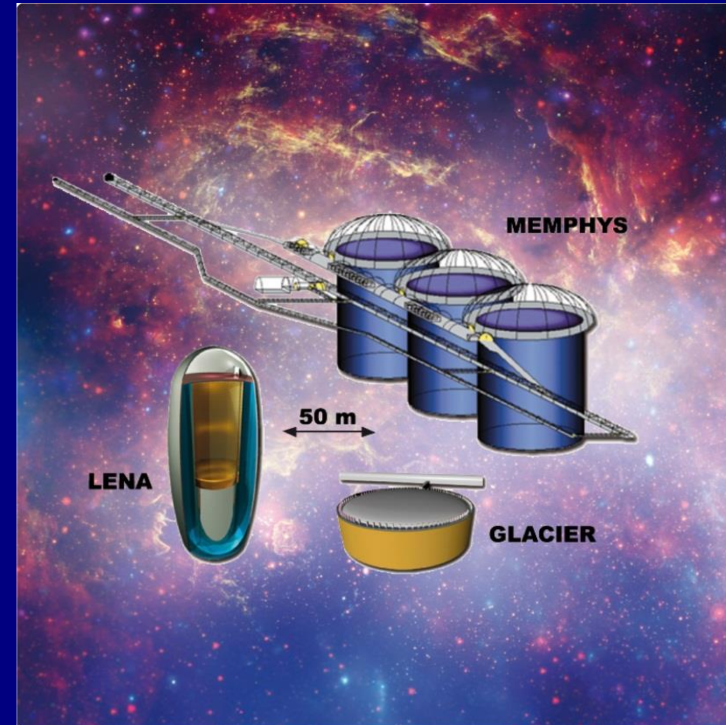
Laguna Design Study 2008-2011
→Feasibility study of a new deep underground research infrastructure

100 members, 10 countries, FP7 funding 1.7Meur

3 detector technologies (WC, LAr, LScint)
x 7 sites (Phyhasalmi, Sieroszowice, Boulby, Slanic, Frejus, Canfranc, Umbria)

- Technical feasibility
- Excavation studies: costs, time, shapes
- Safety
- Infrastructures
- Detectors technologies, tanks

Important contributions of our French groups (proponents of today's proposal) since the beginning

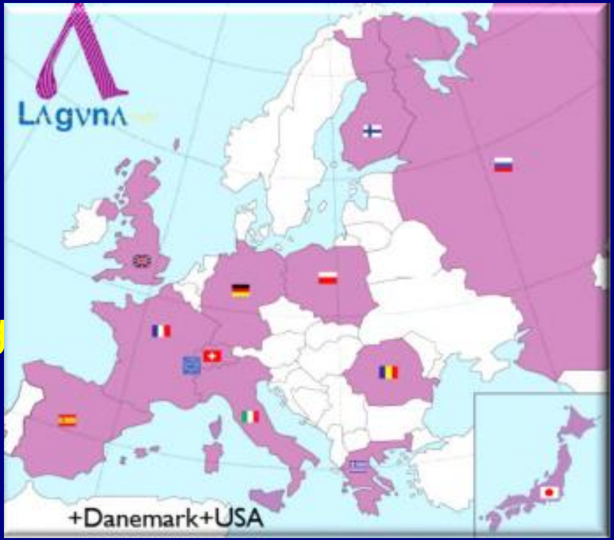


LAGUNA-LBNO (Long Baseline Neutrino Oscillations)

2011-2014 Choice and optimization w.r.t. neutrino oscillations

300 members, 13 countries, (including Japan) FP7 funding 4.9Meur

From 3x7 possibilities → first priority given to:



Pyhasalmi
(most promising site for:
rock quality, infrastructures, feasibility, full availability beyond 2018, depth 4000 m.w.e. and baseline 2300 km)

+ LAr TPC detector
Best physics performance →

Site (baseline)	Complete MH coverage at >5σ CL ?	CPV with beams from CERN (from SPS accelerator unless otherwise noted)	Remark
Fréjus (130km)	No	ν / $\bar{\nu}$ asymmetry	• Beam from HP-SPL (>2030?)
Canfranc (630km)	No	ν / $\bar{\nu}$ asymmetry	• CPV coverage depends on external input on MH
Umbria(665km)-LNGS(732km)	No	ν / $\bar{\nu}$ asymmetry	• CPV coverage depends on external input on MH
Sierozsowice(950km)-Boulby(1050km)	No	L/E shape (1st maximum) and ν / $\bar{\nu}$ asymmetry	• CPV coverage depends on external input on MH
Slanic(1570km)	Yes, after 5 years	L/E shape (1st maximum) and ν / $\bar{\nu}$ asymmetry	• Complete MH coverage in 2028 • No deep underground site
Pyhäsalmi(2300km)	Yes, after 2 years	L/E shape (1st & 2nd maximum) and ν / $\bar{\nu}$ asymmetry	• Complete MH coverage by 2025 then choose optimum sharing between ν & $\bar{\nu}$ for CPV search from 2025 onwards

A new massive deep underground observatory for:
LB neutrino osc. studies, proton decay, atmospheric and astrophysical neutrinos detection

The Pyhäsalmi underground site

- ★ LAGUNA search for the optimal site in Europe for next generation deep underground neutrino detector
  - Very detailed investigations of seven potential sites with three different detector technologies: WCD, LAr and LSc
- ★ Down-selection to top priority site where several optimal conditions satisfied simultaneously: Pyhäsalmi, Finland
  - Infrastructure in perfect state because of current exploitation of the mine
  - Unique assets available (shafts, decline, services, sufficient ventilation, water pumping station, pipes for liquids, underground repair shop...)
  - Very little environmental water
  - Could be dedicated to science activities after the mine exploitation ends (around 2018)
  - One of the deepest location in Europe (4000 m.w.e.)
  - The distance from CERN (2300 km) offers unique long baseline opportunities. It is 1160km from Protvino.
  - The site has the lowest reactor neutrino background in Europe, important for the observation of very low energy MeV neutrinos.
- ★ Second priority: Fréjus, France.
- ★ All other sites are presently considered as backup options for LAGUNA.

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Multi-Gev events, perform L/E analysis around the first and <u>second</u> maxima, wide band beam 0.5-10 GeV, better than 10% energy resolution

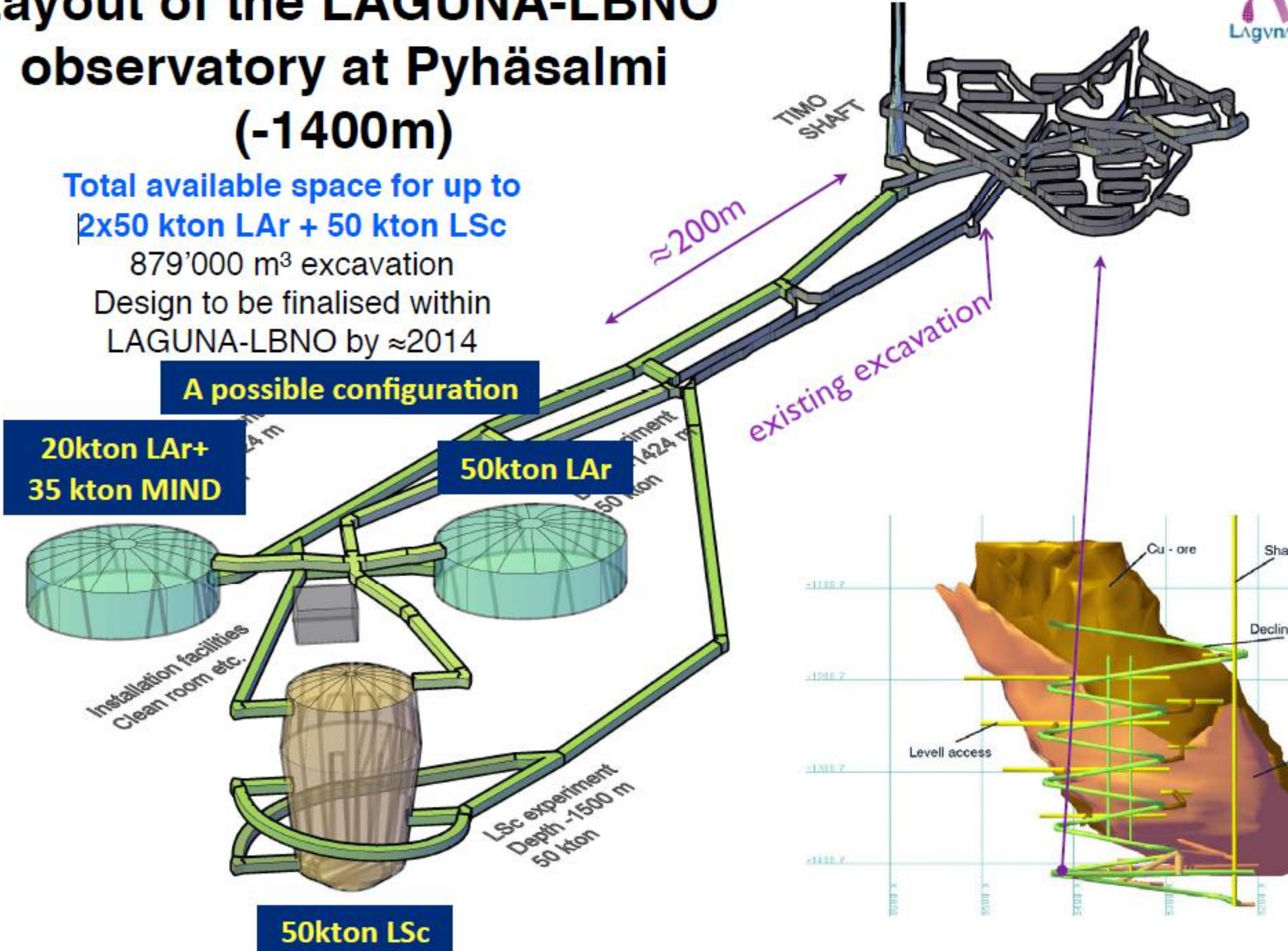
→ Far detector technology: LAr TPC + magnetized muon detector

Layout of the LAGUNA-LBNO observatory at Pyhäsalmi (-1400m)

Total available space for up to 2x50 kton LAr + 50 kton LSc

879'000 m^3 excavation

Design to be finalised within LAGUNA-LBNO by ≈2014



LBNO

Expression of Interest for a very long baseline neutrino oscillation experiment

CERN-SPSC-2012-021 ; SPSC-EOI-007

An incremental approach, based on the findings of LAGUNA

Submitted in June 2012

June 2012: Expression of Interest for the LBNO experiment submitted to the SPSC and the European Strategy Group.

http://cdsweb.cern.ch/record/1457543

150 pages proposal

~230 authors, 51 institutions

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Germany, Finland, France, Italy, Switzerland, Poland, Russia, UK

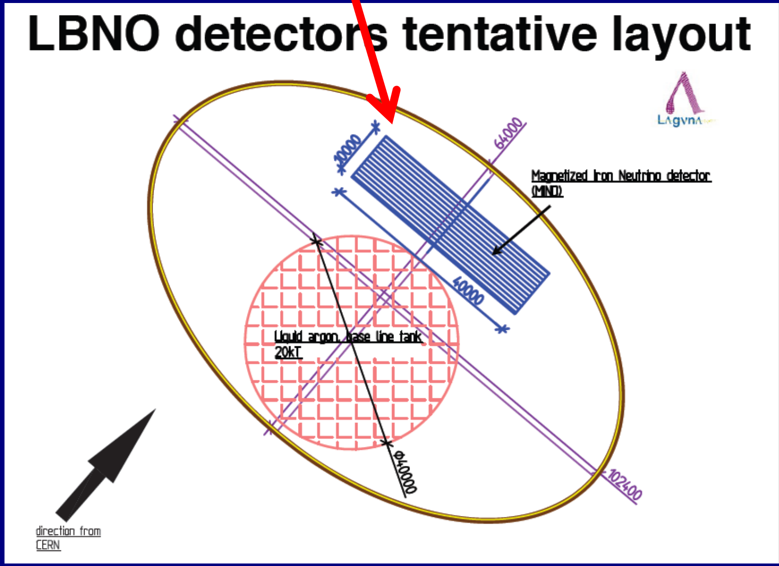
Among which the French physicists proposing today LBNO-Proto:

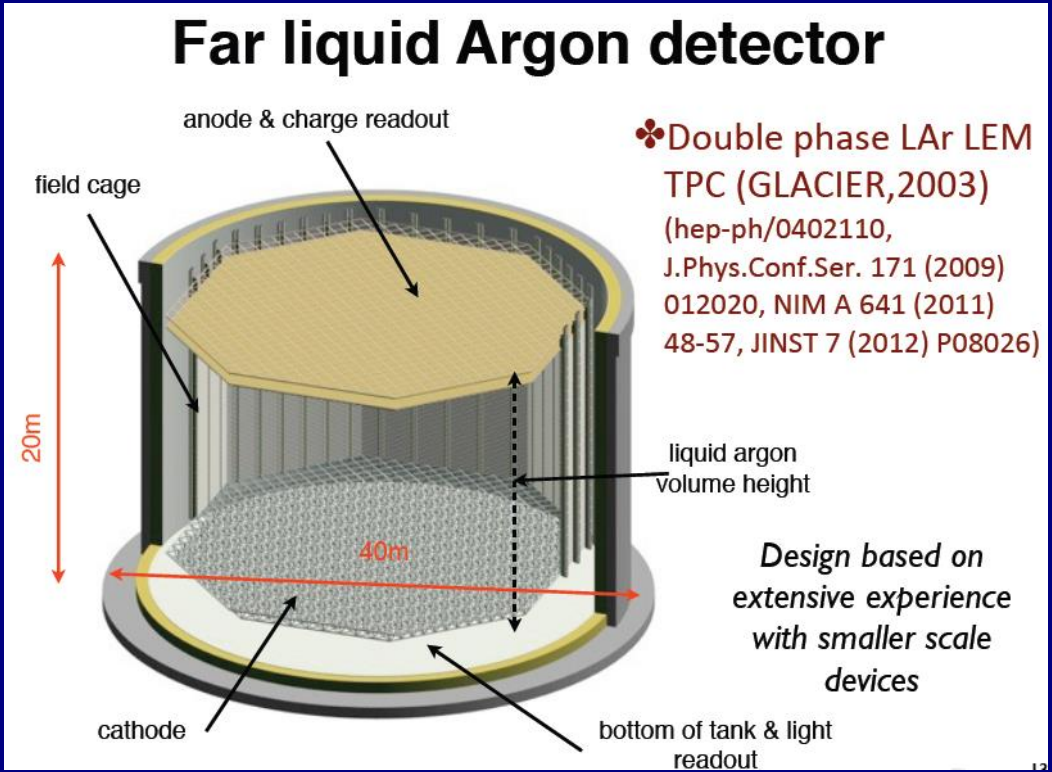
- CEA/IRFU
- APC
- IPNL
- LAPP
- LPNHE

- Start excavation 2016
- Physics program 2023-…
  - Determination of neutrino mass hierarchy
  - Search for CP violation
  - Proton decay
  - Atmospheric and supernovae neutrinos

20 Kton double phase LAr TPC
LNG tank technology

35 kton magnetized muon detector (MIND)





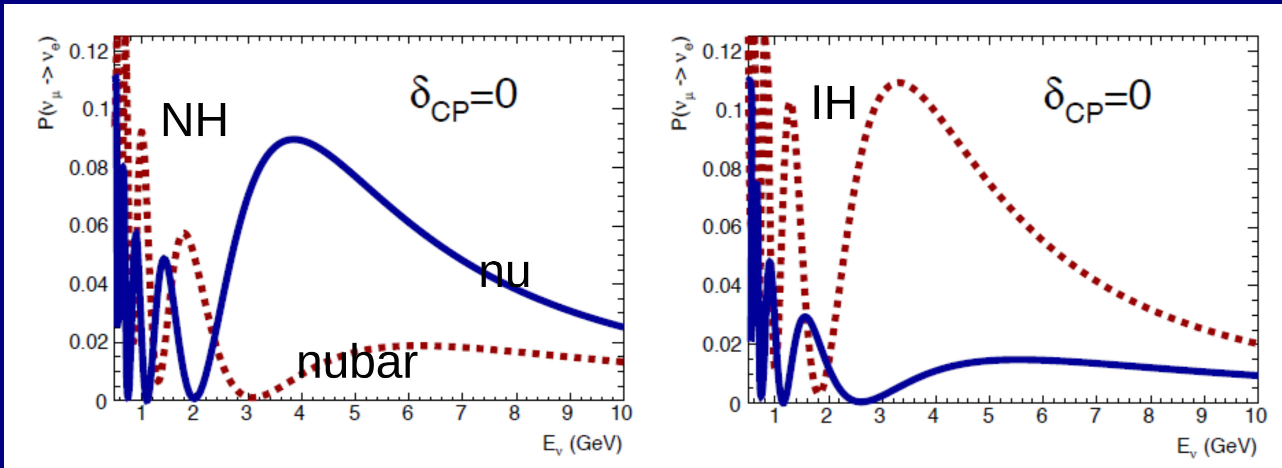
+ near detector at CERN

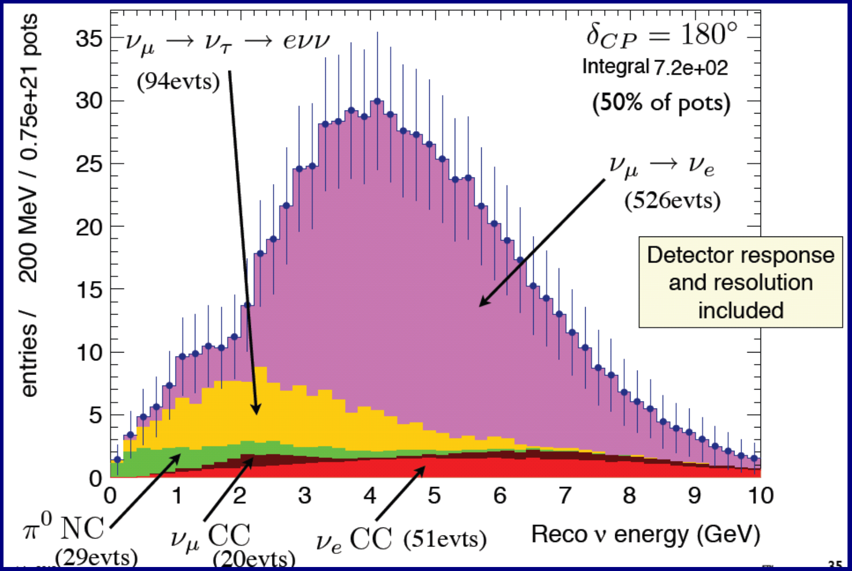
Giant LAr TPC detectors:
Long wires, long drift → Wires + cold electronics (U.S.)
double phase (extra gain) + cold electronics

Unambiguous mass hierarchy determination

L/E shape + nu/nubar

→unique worldwide sensitivity

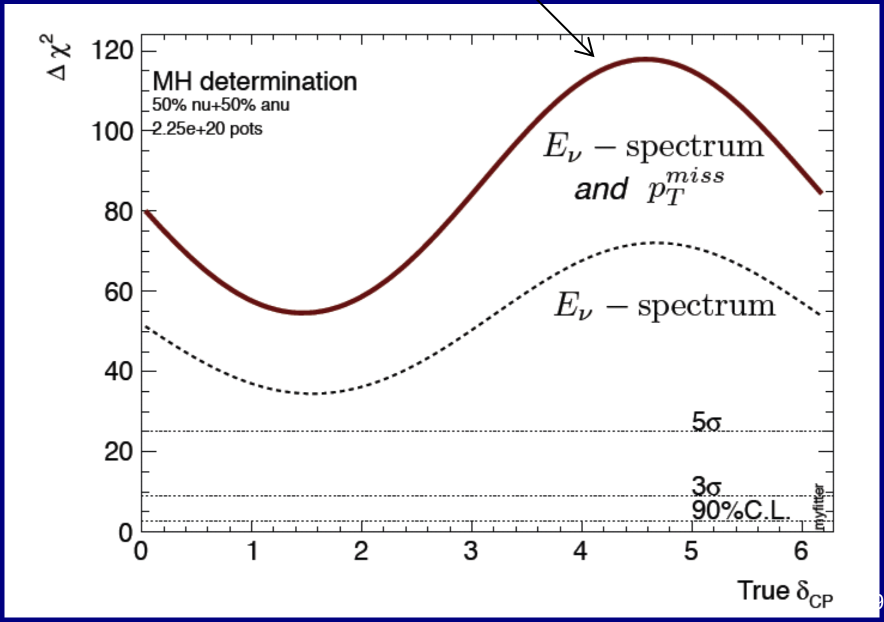




Startup in 2023, MH determination by 2025:

- 2 years, 700 kW
- 2.25×10^{20} pot
- 50% nu, 50% nubar

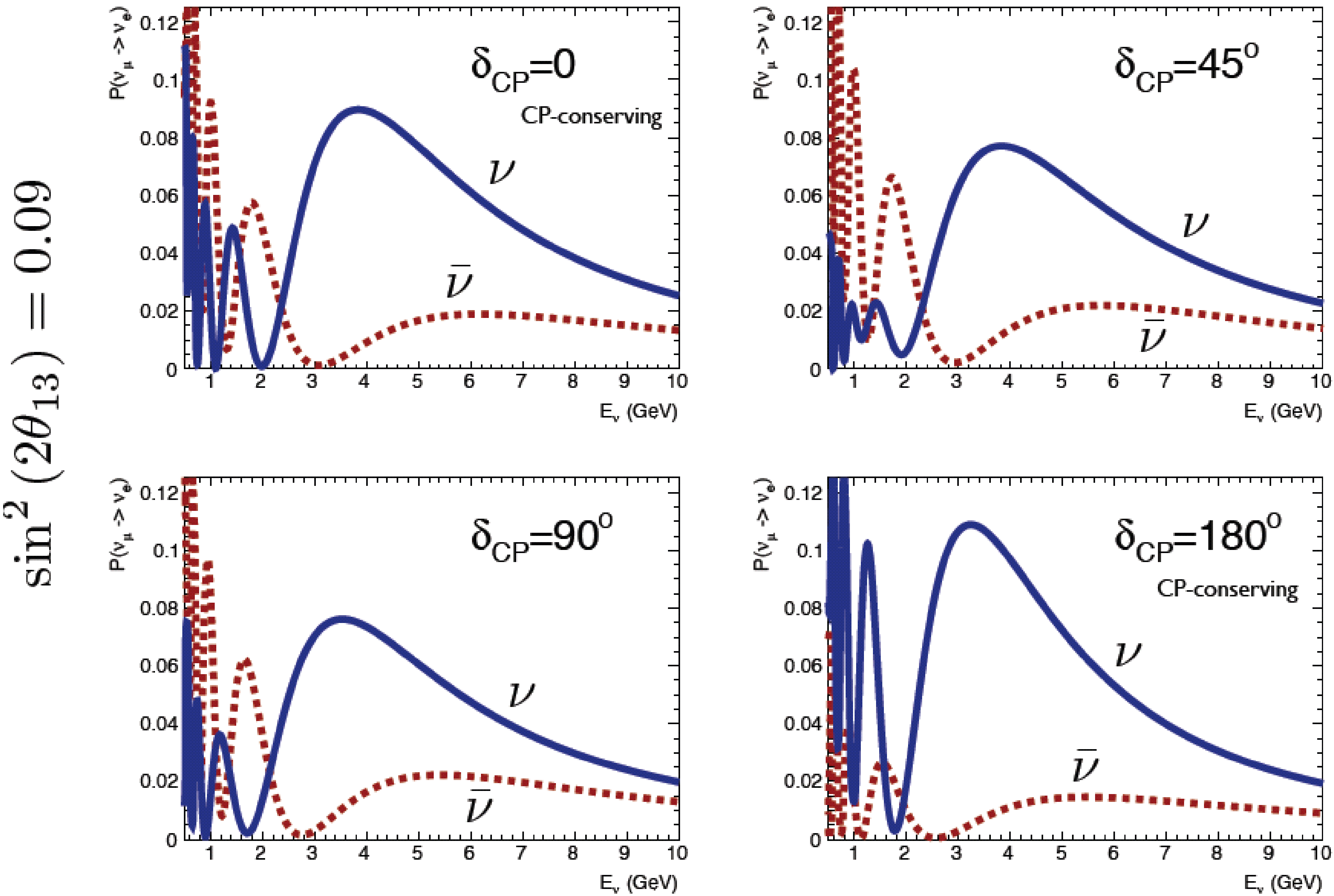
With additional constraint on tau production rate



CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

★Normal mass hierarchy

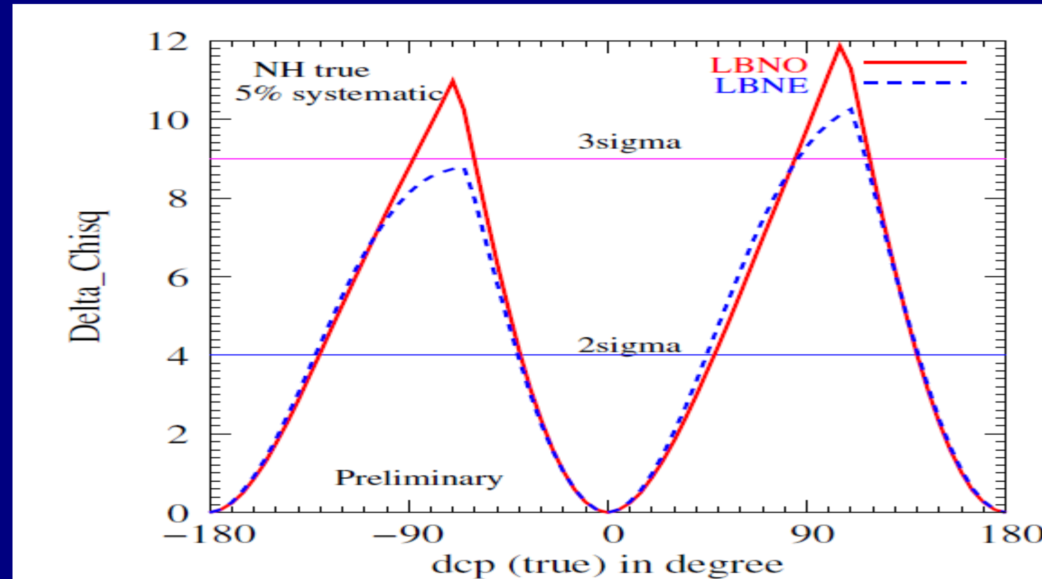
L=2300 km



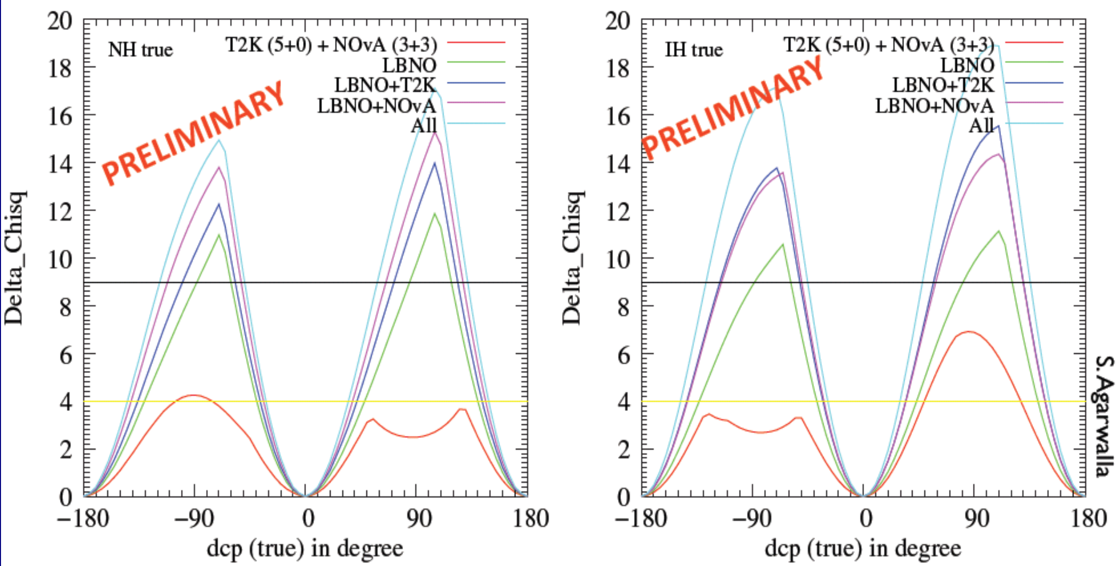
Staged search for CP violation

First phase:
LBNO 20kton
e.g. (5+5 years nu/nubar)
71% (44%) coverage at 90% (3σ)

Second phase:
LBNO 70 kton, 2MW HP-PS

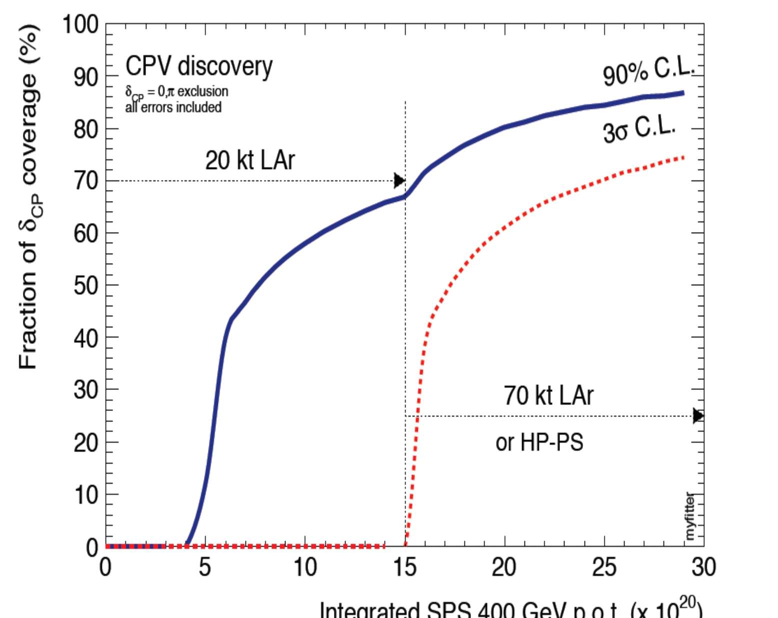


Sensitivity combining T2K(295km), NOvA(810km) and LBNO(2300km)



The power of combining several different baselines L:
LBNO 20kton(5+5) + T2K(5+0) + NOvA(3+3) ≈ 40-45% CPV at >3σ C.L.

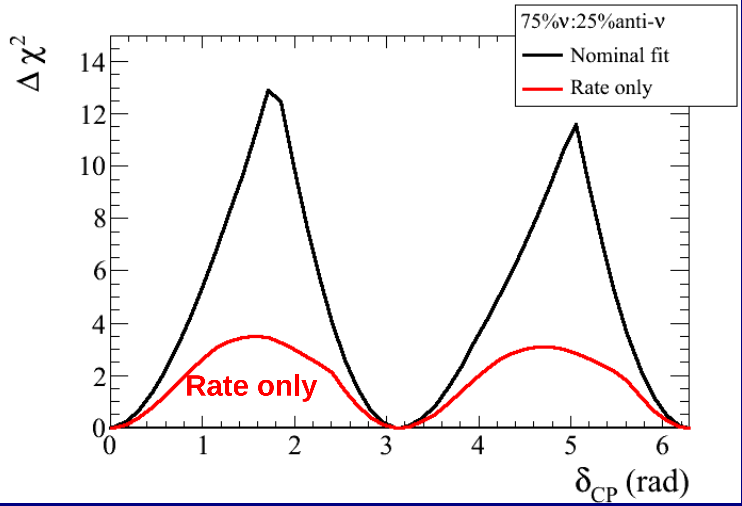
Incremental approach with conventional beams

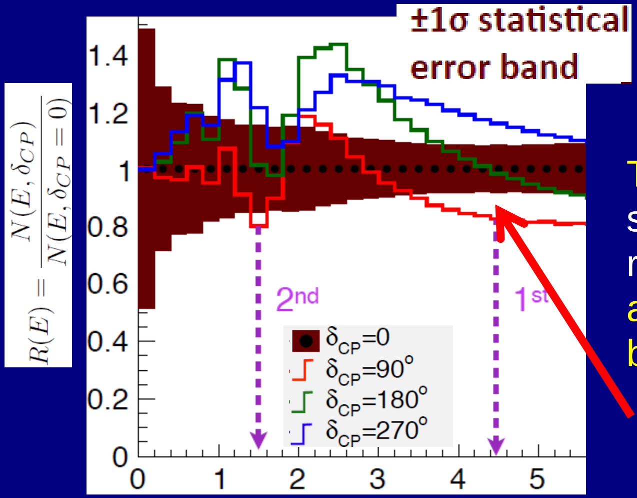


LBNO: high energy LB beam → coverage of two osc. maxima, good energy resolution

A world of useful information and full test of the 3 neutrinos paradigm !

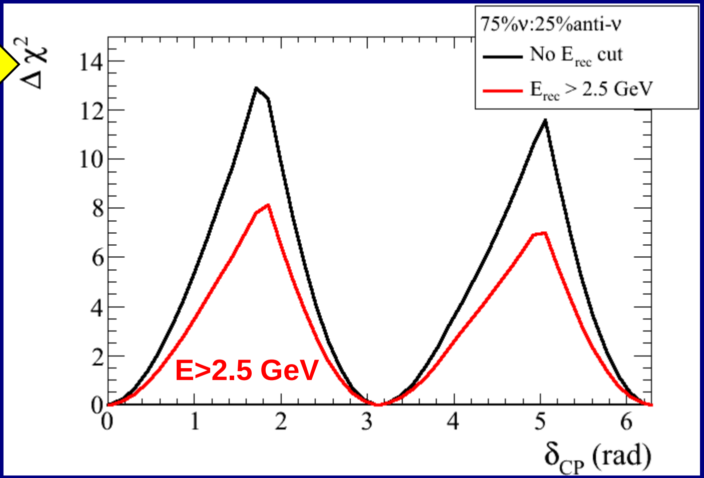
Measurement of L/E pattern independently for nu and nubar for the first and second maxima vs a counting experiment

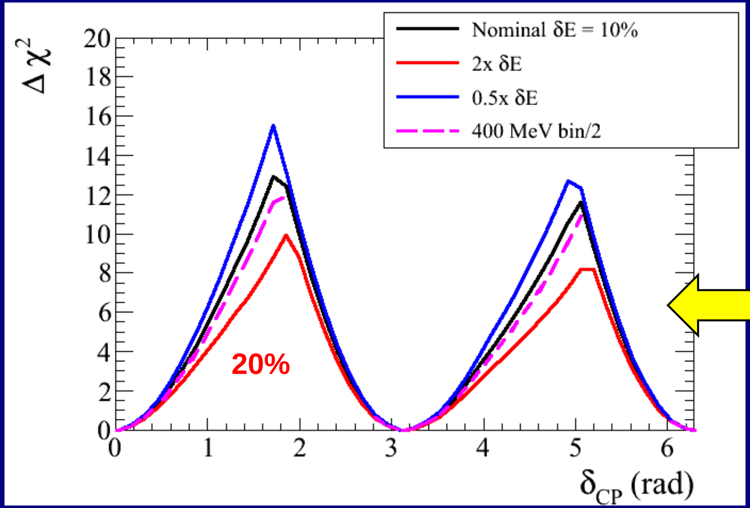




The importance of the second maximum: rather rich CP-dependent features are present at energies below the first maximum

Flatter ''rate dominated'' region larger syst. effects related to normalization



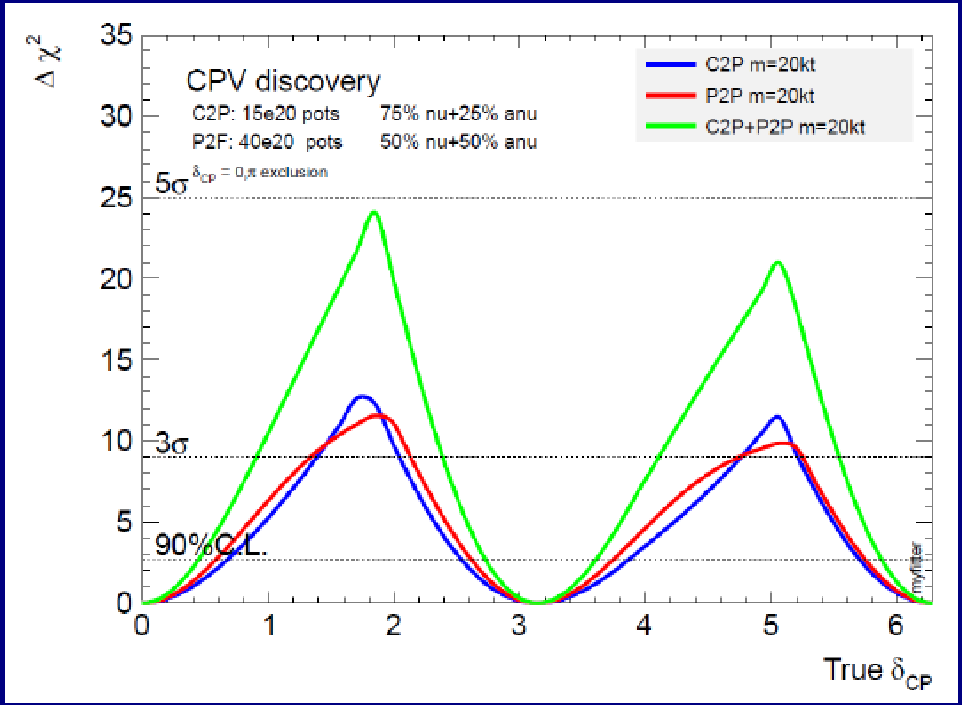


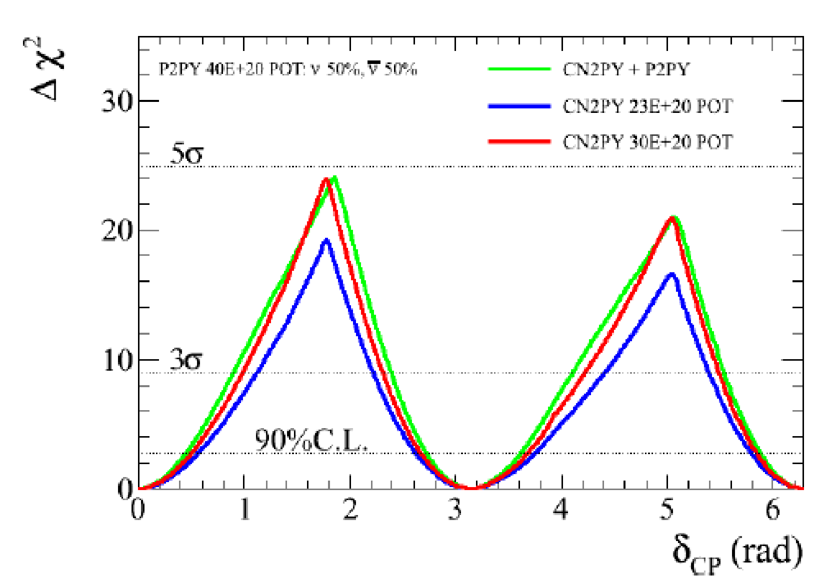
The importance of energy resolution 10% vs 20%

Very fruitful discussions with the SPSC occurring during the last months, full physics paper in preparation

Possible neutrino beam from Protvino

Upgraded beam → 70 GeV, 450 kW
$4^{E}20$ pot/year, 10 years
1160 km baseline

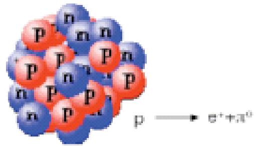




Improvement due to double exposure equivalent to running the CERN beam at $30^{E}20$ pot (~25 years running)

$23^{E}20$ pot at CERN equivalent to C2P and P2P powers added together

Proton decay sensitivity



For an exposure of 10 years (200 kton×year)

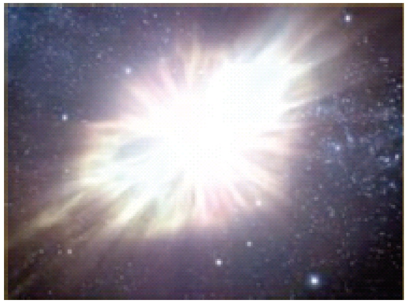
JHEP 0704 (2007) 041

Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	$>3\times10^{34}$ yrs
$p \to e^+\gamma$, $p \to \mu^+\gamma$	$>3\times10^{34}$ yrs
$p \to \mu^-\pi^+K^+$	$>3\times10^{34}$ yrs
$n \to e^-K^+$	$>3\times10^{34}$ yrs
$p \to \mu^+K^0$, $p \to e^+K^0$	$>1\times10^{34}$ yrs
$p \to e^+\pi^0$	$>1\times10^{34}$ yrs
$p \to \mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n \to e^+\pi^-$	$>0.8\times10^{34}$ yrs

Expect ≈linear sensitivity improvement with exposure until 1000 kton×year

x10 sensitivity increase, comparable to HK

Supernova detection channels



JCAP 0310 (2003) 009

JCAP 0408 (2004) 001

For a SN explosion at the distance of 5 kpc

$\langle E_{\nu_e} \rangle = 11 MeV, \langle E_{\bar{\nu}_e} \rangle = 16 MeV, \langle E_{\nu_x} \rangle = \langle E_{\bar{\nu}_x} \rangle = 25 MeV$

Events:

$\nu_e \; {}^{40}Ar \rightarrow e^- \; {}^{40}K^*$	(E_ν > 1.5 MeV)	≈23820
$\bar{\nu}_e \; {}^{40}Ar \rightarrow e^+ \; {}^{40}Cl^*$	(E_ν > 7.48 MeV)	≈2420
$\nu_x \; {}^{40}Ar \rightarrow \nu_x + \; {}^{40}Ar^*$		≈30440
$\nu_x \; e^- \rightarrow \nu_x \; e^-$		≈1330

- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Combined analysis of all reaction modes
- Neutrino mass via TOF

The LBNO strategy:

- A very long baseline (2300 km) to measure matter effects and determine the MH at $>5\sigma$ within *two years*, better than any other proposed experiment → immediate important physics outcome
- 20 kton deep underground double phase LAr detector with full astro-particle physics program
- Conventional beam 700 kW from CERN SPS (no interference with LHC)

- If the findings from stage I require → upgrade path for the detector (+50 kton) and proton intensity 700kW (SPS) → 2MW HP-PS
- Possibly a second beam (from Protvino) with medium baseline to reduce the systematic errors and shorten the time to discover CP

- The Pyhasalmi site is extremely convenient (baseline, infrastructures, depth, excavation aspects)
- The LAGUNA LBNO collaboration is in the most advanced state for what concerns all technical implementation and site studies, costing and prototyping

→ We believe that LBNO is still the most competitive project in the world

- The extended site investigation is progressing well (750 m drilled)
- Discussions will continue with Finland in order to define its real contribution, after last year misunderstanding

Conclusions (LBNO)

- ➢ Neutrinos are key particles for the understanding of the universe and fundamental laws of physics

- ➢ The next generation of massive underground detectors will be a the forefront of particle physics and astro-particle physics with a very rich program going from the determination of the mass hierarchy, search for CP violation the study of supernovae neutrinos and the search for proton decay

- ➢ The saga of neutrino oscillations started in 1968. Nature had been kind enough for the third time after solar neutrinos and atmospheric neutrinos to provide a large theta13 value, just below the CHOOZ limit. We just entered in the era of the hierarchy determination and CP violation searches in the neutrino sector. This activity has now received an enormous boost

- ➢ LBNO appears as the most competitive worldwide project to pursue this research line

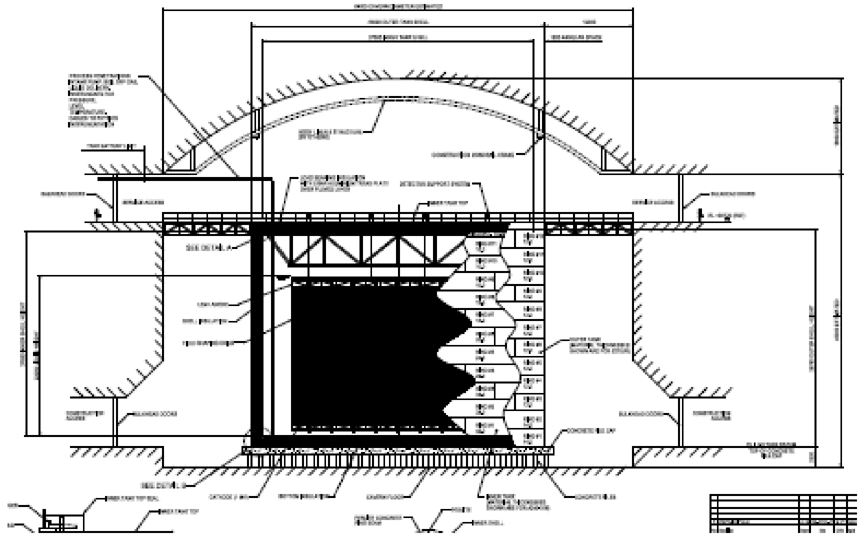
- ➢ Strategy group statement: "CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan”.

→ Decision to open the discussion with LBNE to study a possible merging on equal foot of the two projects in a new global one LBNx (physics optimization, technical issues, liquid argon double phase technology)

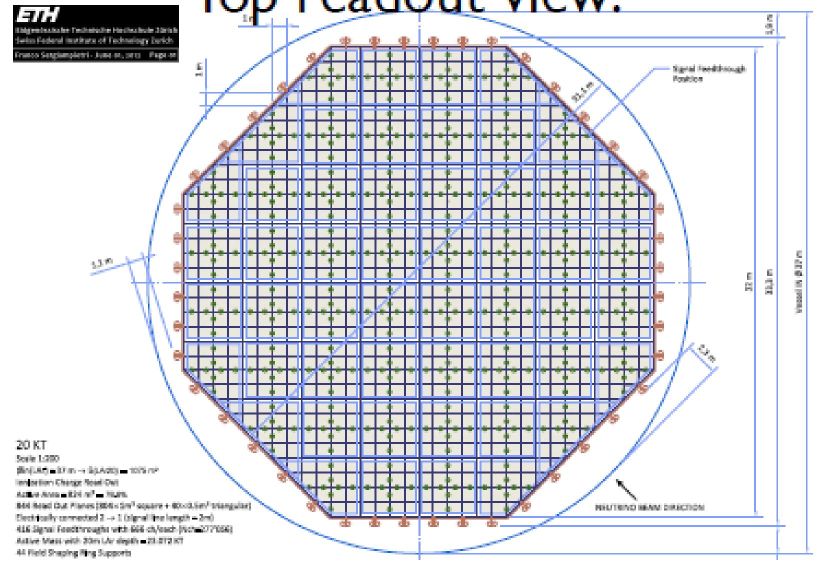
→ Proposal to build at CERN a large scale prototype of the 20 kton far detector (LBNO-Proto)

GLACIER detector design

- ★ Concept unchanged since 2003: Simple, scalable detector design, from one up to 100 kton (hep-ph/0402110)
- ★ Single module non-evacuable cryo-tank based on industrial LNG technology
  - industrial conceptual design (Technodyne, AAE, Ryhal engineering, TGE, GTT)
  - two tank options: 9% Ni-steel or membrane (detailed comparison up to costing of assembly in underground cavern)
  - three volumes: 20, 50 and 100 kton
- ★ Liquid filling, purification, and boiloff recondensation
  - industrial conceptual design for liquid argon process (Sofregaz), 70kW total cooling power @ 87 K
  - purity < 10 ppt O_2 equivalent
- ★ Charge readout (e.g. 20 kton fid.)
  - 23'072 kton active, 824 m^2 active area
  - 844 readout planes, 277'056 channels total
  - 20 m drift
- ★ Light readout (trigger)
  - 804 8" PMT (e.g. Hamamatsu R5912-02MOD) WLS coated placed below cathode
- ★ The concept and the designs are reaching the required level of maturity for submission to SPSC.



Top readout view:

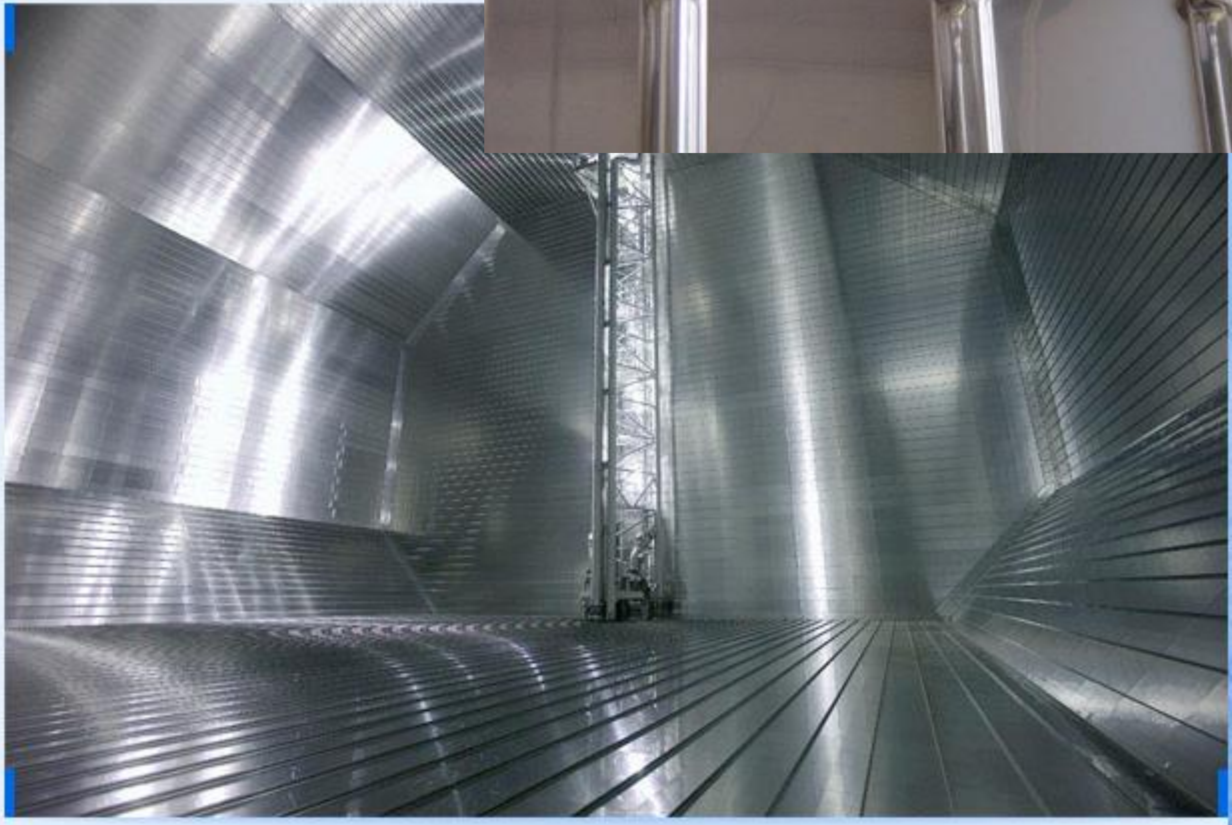


Technical aspects being finalized in the LAGUNA/LBNO study as deliverables

LNG Carrier Containment Systems

NO96 System

NO 96 Membrane System
is a cryogenic liner directly supported by the ship's inner hull. This liner includes two identical metallic membranes and two independent insulation layers:



Primary & secondary Invar membranes

The primary and secondary membranes are made of Invar, a 36% nickel-steel alloy, 0,7 mm thick. The primary membrane contains the LNG cargo, while the secondary membrane, identical to the primary, ensures a 100 % redundancy in case of leakage. Each of the 500 mm wide invar strakes is continuously spread along the tank walls and is evenly supported by the primary and the secondary insulation layers.

Primary & secondary thermal insulation

The primary and secondary insulation layers consist in a load bearing system made of prefabricated plywood boxes filled with expanded perlite. The standard size of the boxes is 1m x 1.2m. The thickness of the primary layer is adjustable from 170mm to 250mm, to fulfill any B.O.R. requirements ; the typical thickness of the secondary layer is 300 mm. The primary layer is secured by means of the primary couplers, themselves fixed to the secondary coupler assembly. The secondary layer is laid and evenly supported by the inner hull through load-bearing resin ropes, and fixed by means of the secondary couplers anchored to the inner hull.

LBNO LAr prototype at CERN (LBNO-Proto)

Configuration: $6 \times 6 \times 6\,m^3$ active volume LAr TPC detector with double phase
+ charge amplification + 2-D collection readout PCB anode.
Exposure to charged hadrons beam (1-20 GeV/c)

Purpose:

1) Test a full size proof prototype of the LBNO far detector (20 kton in 2023)

- **LNG tank construction technique**
- **Purification system**
- **Long drift**
- **HV system 300-600 KV**
- **Double-phase readout**
- **Readout electronics**

2**) Assess the TPC performance in reconstructing hadronic showers** (the most demanding task in reconstructing neutrino interactions).

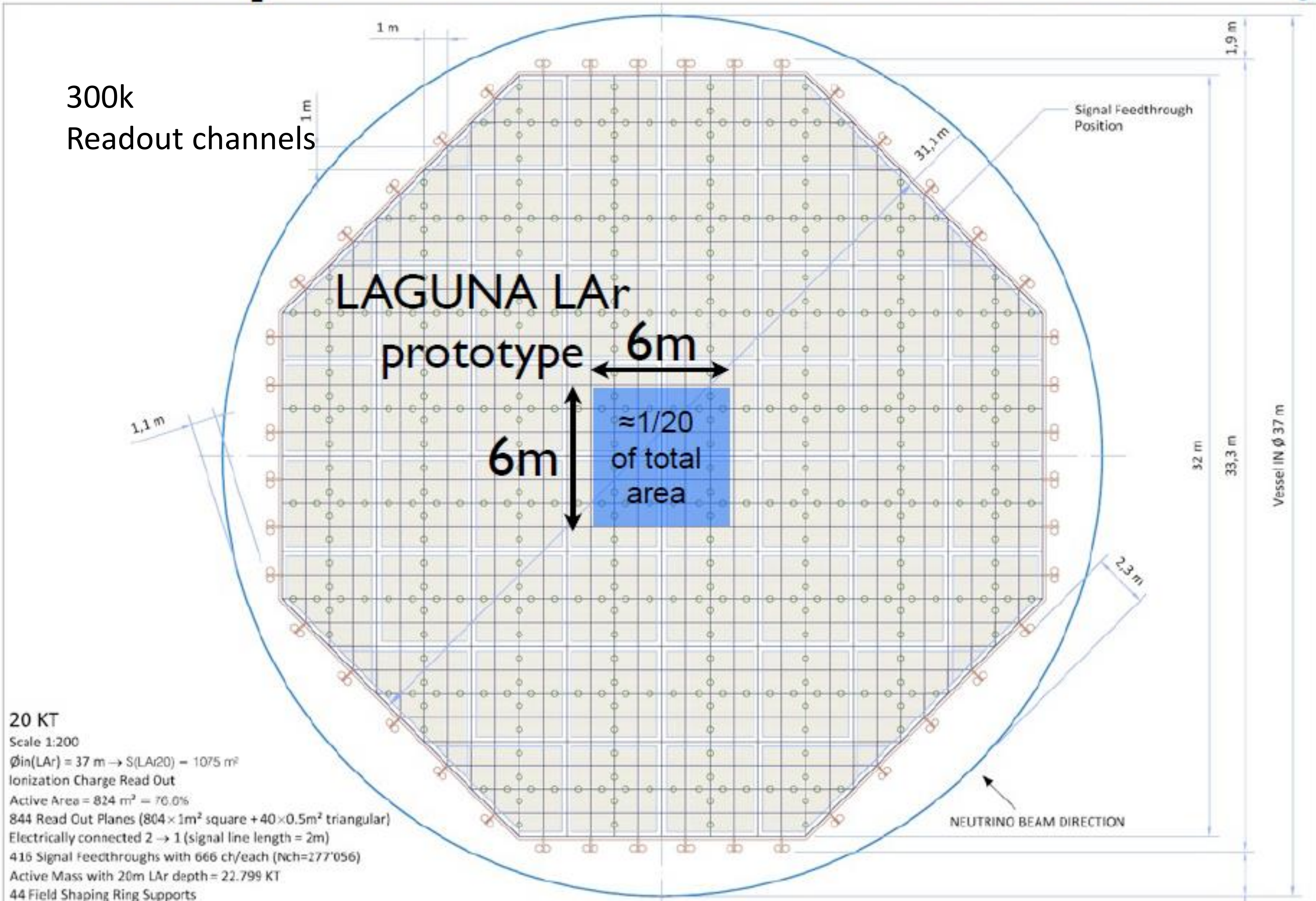
- Measurements in hadronic and electromagnetic calorimetry and PID performance
- Full-scale software development, simulation and reconstruction to be validated and improved

→ Fundamental step for the construction of the final LBNO detector

- The most advanced prototyping program which has no equivalent in the world
- Experience with this prototype module scalable to future LBNO detectors, putting the European groups in a very advanced and strong position for the participation to a world-wide joint program (prototype initiative supported also by the US and Japan groups)

Compared to GLACIER 20 kton

300k
Readout channels



Scenario of installation: EHN1 extension

North area extension, supported by CERN,
Extension activities already started, completion middle 2014 ?

Prototyping activity strongly supported by the European Strategy group, the SPSC and CERN

North area facility: supported by CERN. Activity for the extension works of the EHN1 hall already started since the fall of 2012, involvements of technical services for civil engineering and cryogenics

Time-scale:

- Now: submission of the LBNO-Proto proposal (addendum to LBNO LOI) to the SPSC

>130 pages detailed technical document (preliminary version distributed to the CS IN2P3)

- Detector Construction: 2014-2015:
  - Middle of 2014: completion of extension and infrastructure in EHN1 (?)
  - Tank construction 9 months → after tank used as clean room for inner instrumentation
  - 2015: electronics production and instrumentation (all external mounting)

- Start of Data Taking: Spring 2016. Operation time: ~2 years

Costs and contributions:

- Detector cost ~few MCHF
- Strong participation from: UK, France, Switzerland + others involved in LAGUNA-LBNO

Technical issues related to detector operation and long drift lenght (6m)

- **Very high purity.** The drift of ionization electrons over a distance of 20 m requires a very clean environment, with impurities at the level of 100 ppt O_2 equivalent for an electron lifetime of 3-10 ms. While this has been achieved on small prototypes, this will be the first test with a large scale non-evacuable prototype and the same tank construction technique foreseen for the far detector.

- **Large field cage.** This is a large structure with demanding requirements on its mechanical precision and capable of sustaining a large potential difference (up to 500 kV).

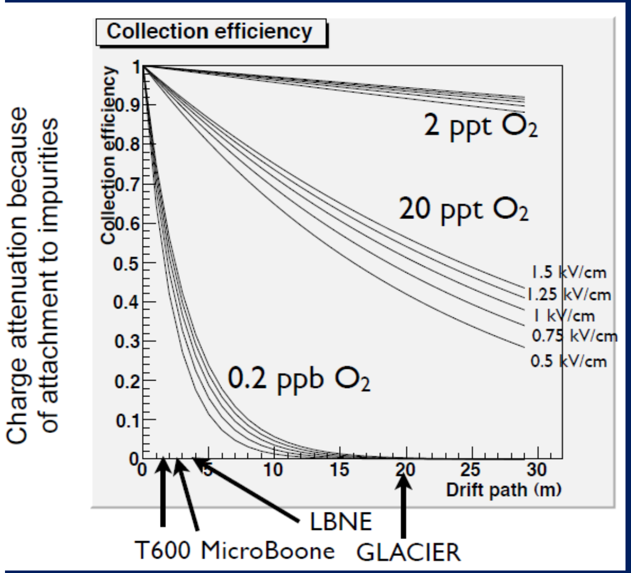
- **Very high voltage generation.** A very low noise and stable power supply able to reach 600 kV to generate an uniform drift field of 1 kV/cm (300 kV power supplies with the required specification are commercially available).

- **Large area micropattern charge readout.** A large 36 m^2 surface will be instrumented with a charge sensitive device providing gas amplification in ultra pure argon vapour.

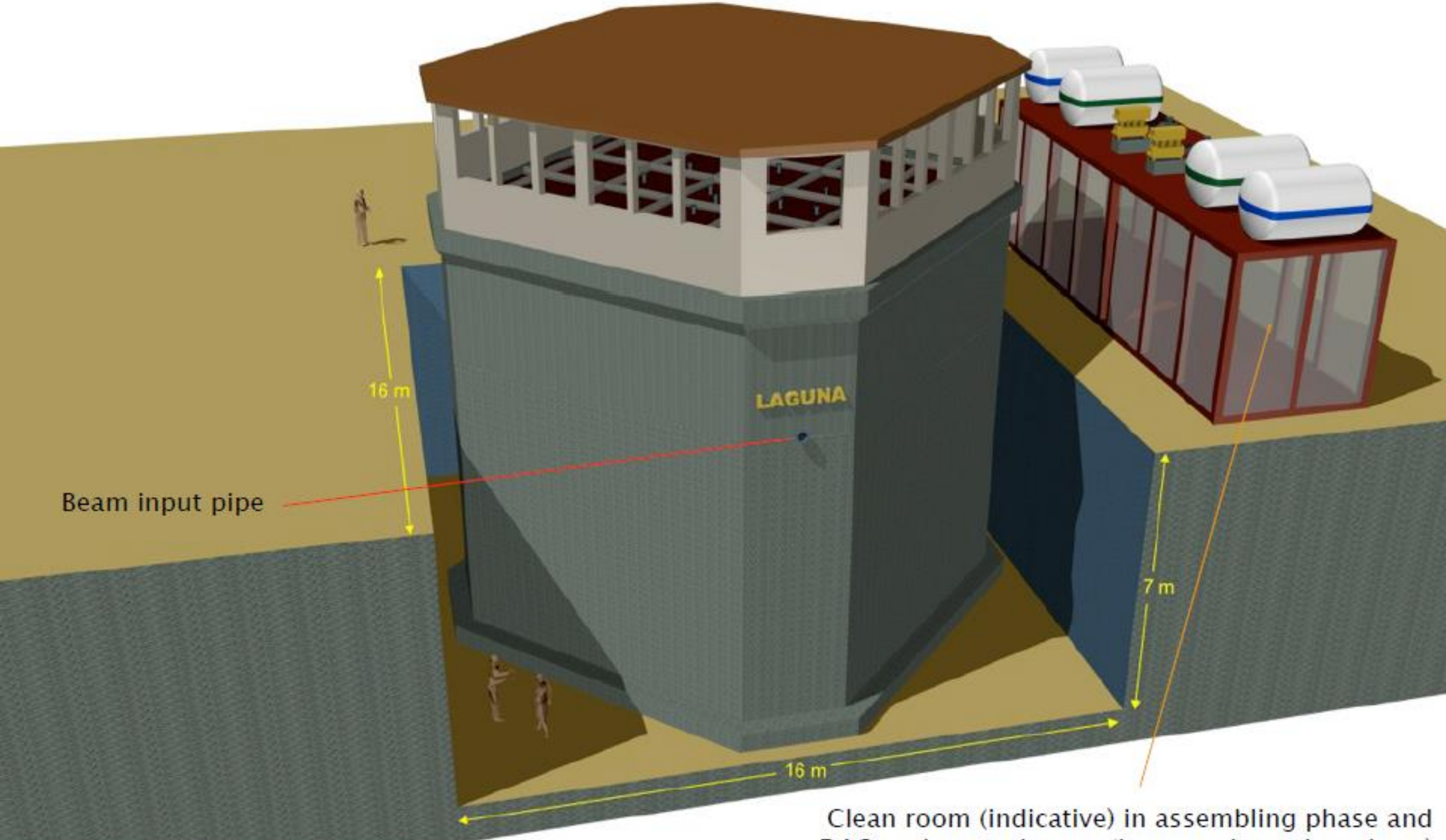
- **Cold front-end charge read-out electronics.** A good S/N is crucial to reach the required physics performances, especially for the low energy neutrino physics. An innovative solution with preamplifiers located as close as possible to the charge-sensitive anode, but yet accessible without opening the inner vessel, will be tested.

- **Long term WLS coating.** A method based on WLS deposition with very long stability (> 10 years) will be implemented and tested.

- **Integrated light readout electronics.** New integrated devices will be developed for the digitisation of argon scintillation light, scalable to very large detectors.



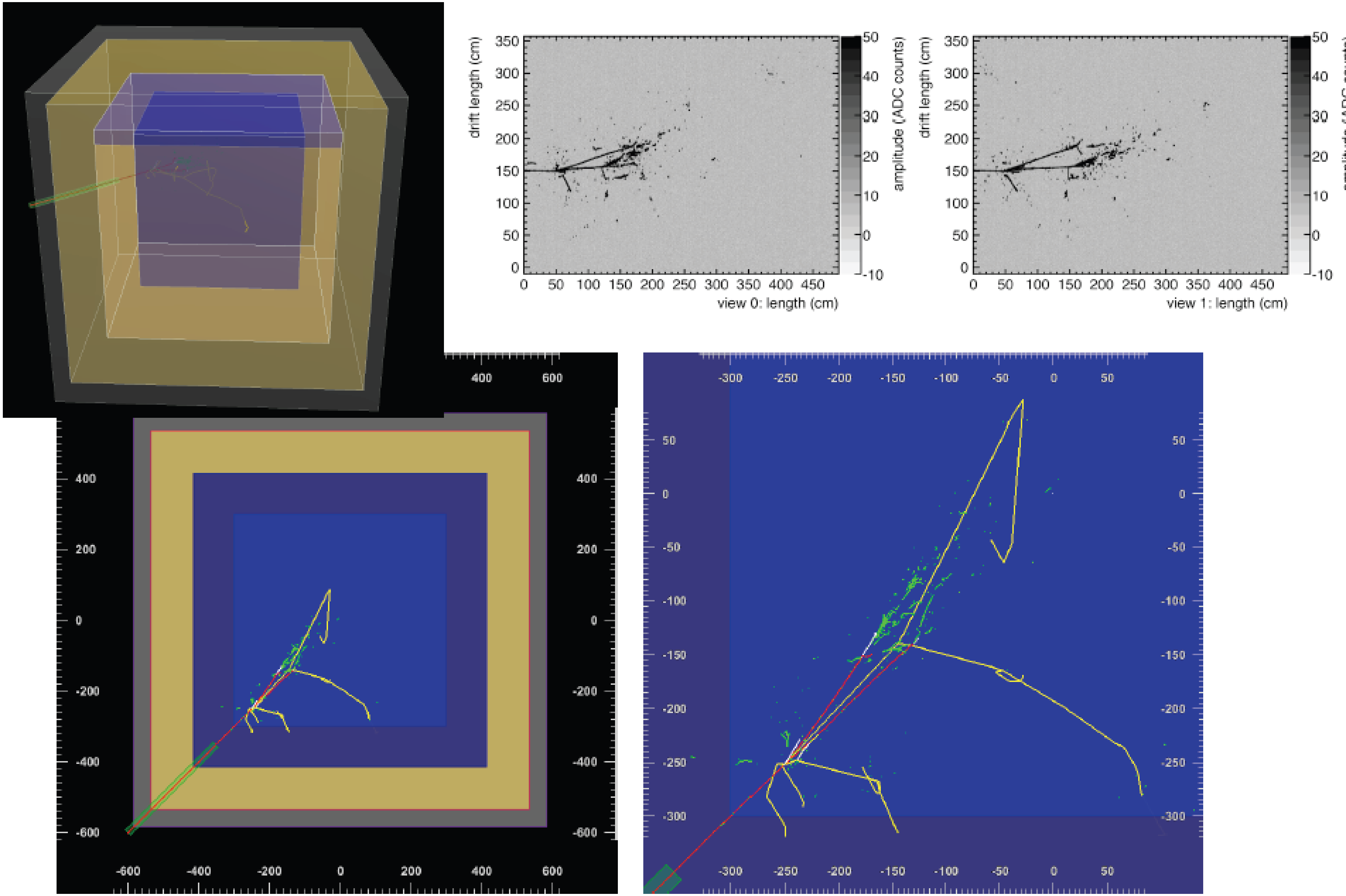
General overview



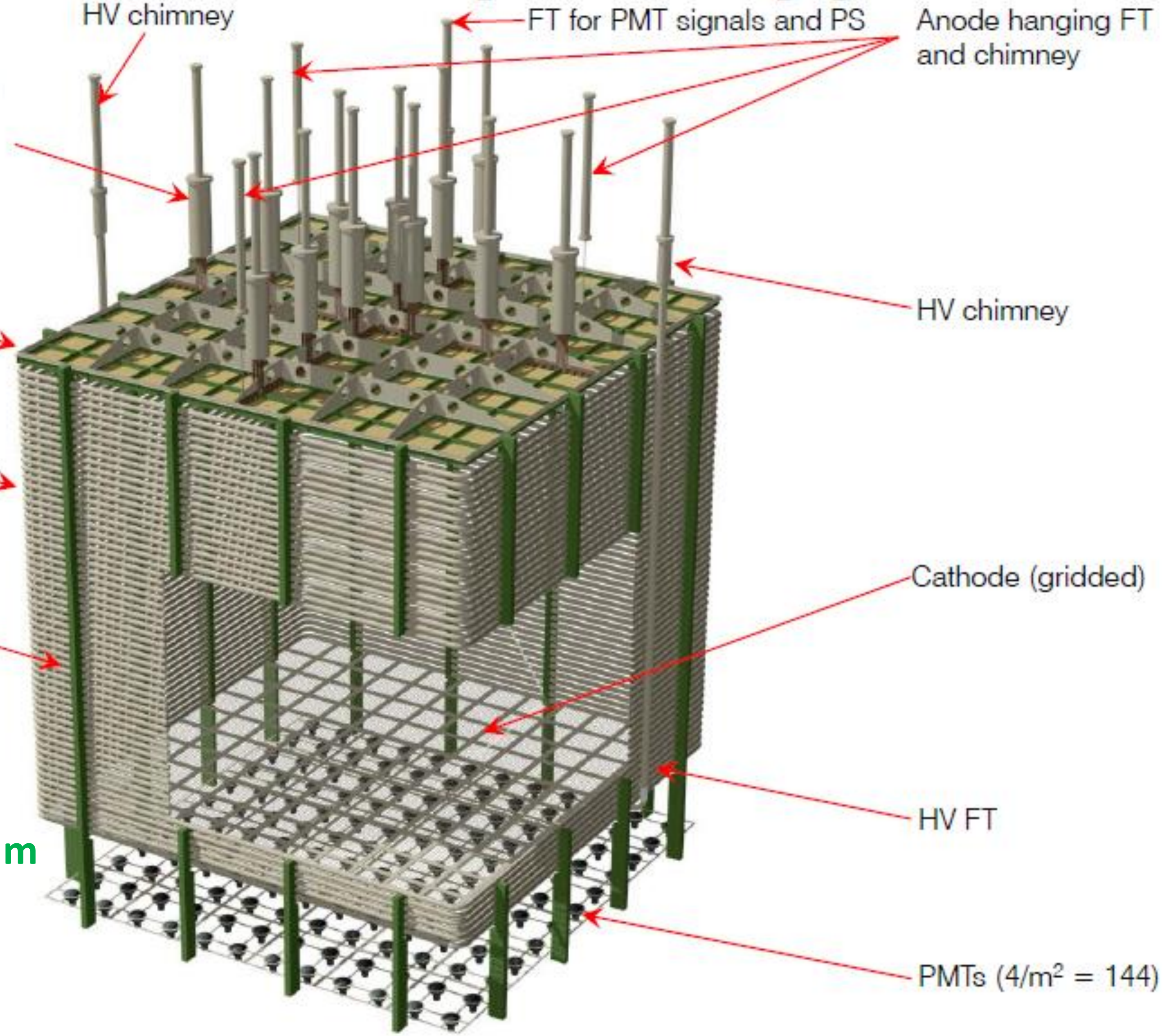
Clean room (indicative) in assembling phase and DAQ and control room (in normal running phase). Eventually used as support for cryocoolers and cryogenic liquid storage vessels

SPSC recommendation:
"validate large scale"

5 GeV π^+ simulation in 6x6x6m^3



LAGUNA LAr prototype



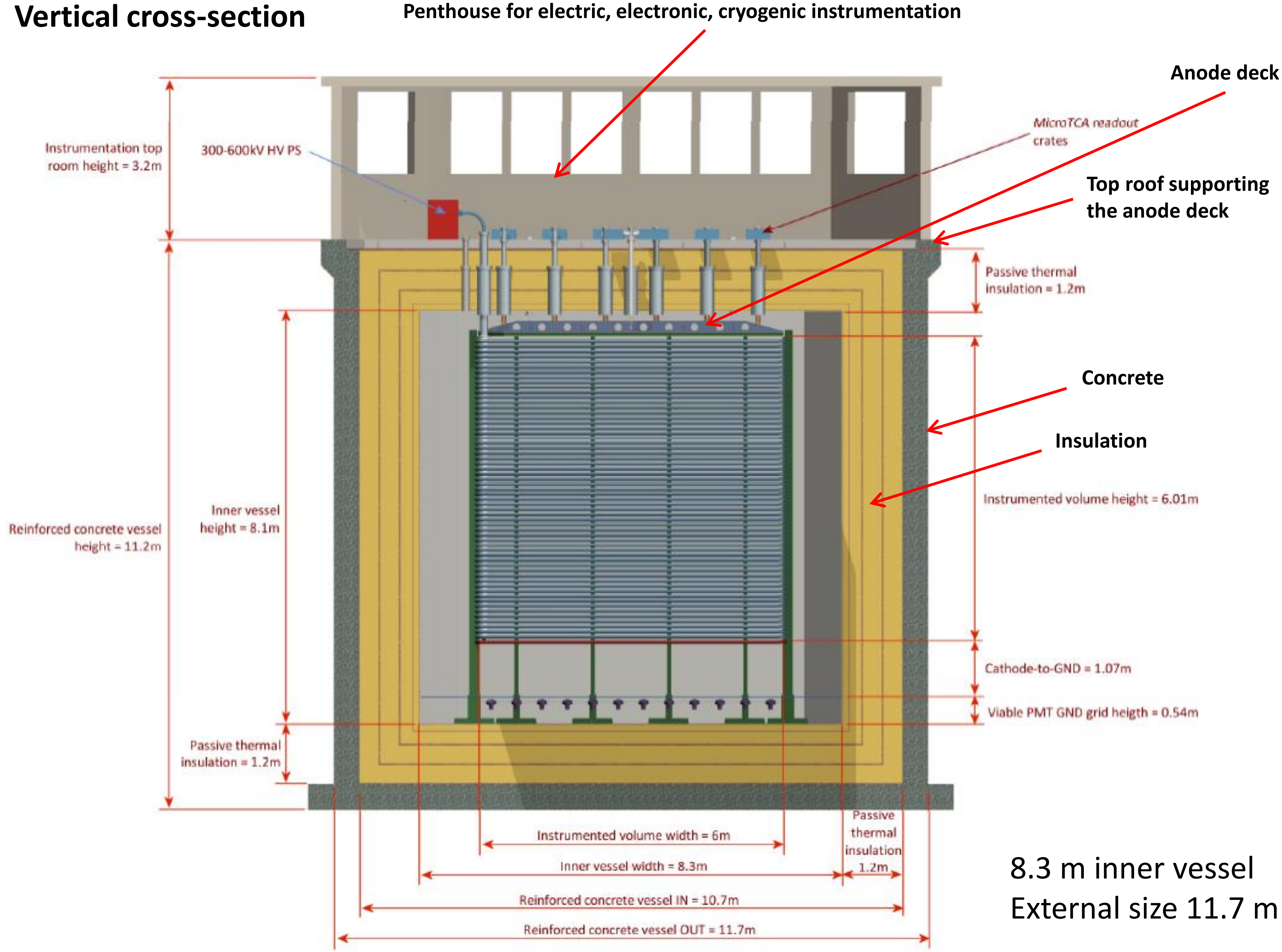
- Total LAr volume size 8.3 m
- Active size 6 m

7680 readout channels, ICARUS T600 for a similar fiducial mass had 27000 channels

Overview of parameters

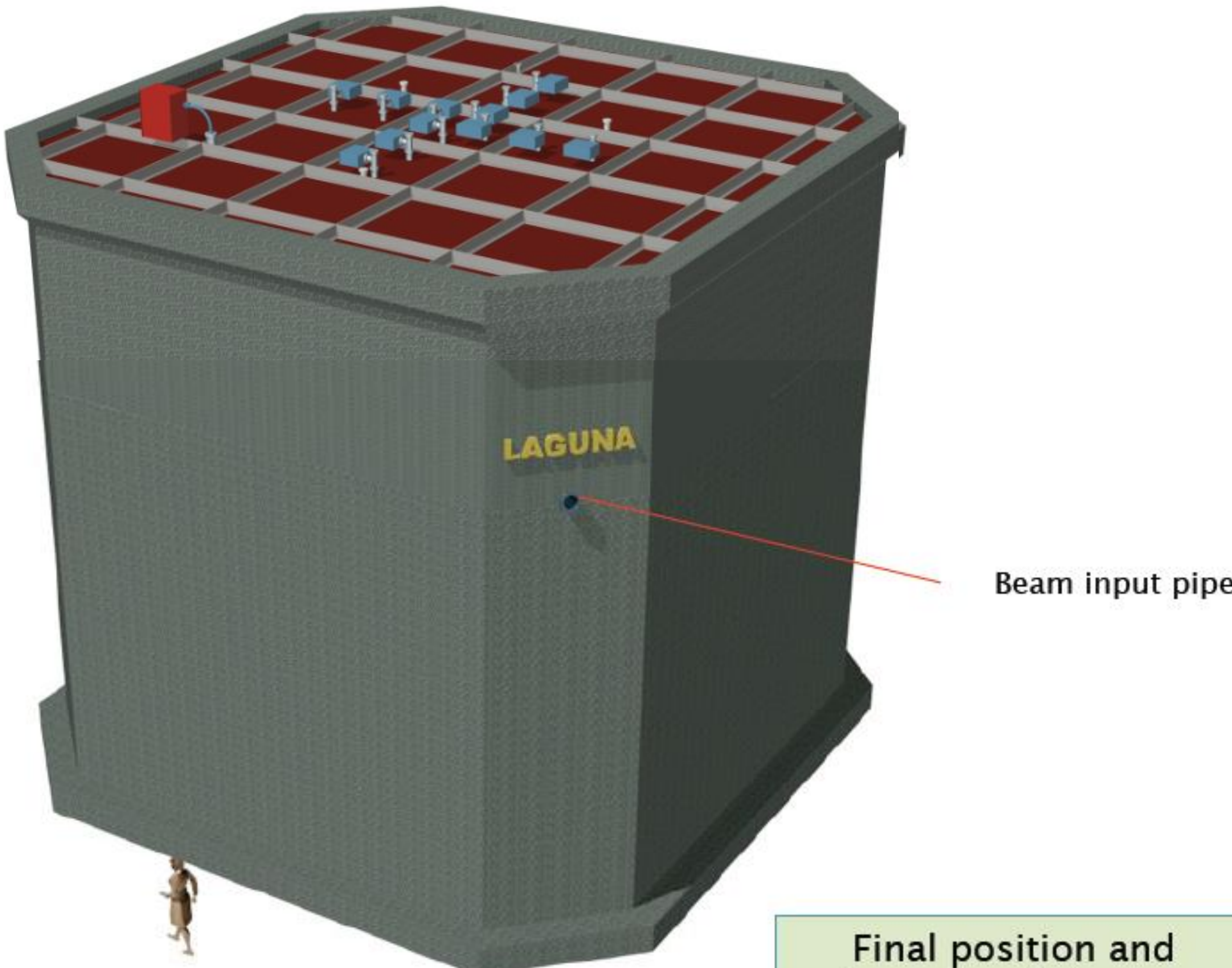
Liquid argon density at 1.2 bar	[T/m^3]	1.38346
Liquid argon volume height	[m]	7.6
Active liquid argon height	[m]	5.992
Pressure on the bottom due to LAr	[T/m^2]	1.05 (≡ 0.1 MPa ≡ 1.031 bar)
Inner vessel size (W x L x H)	[m x m x m]	8.288 x 8.288 x 8.108
Inner vessel base surface	[m^2]	67.6
Total liquid argon volume	[m^3]	509.6
Total liquid argon mass	[T]	705.0
Active LAr area (percentage)	[m^2]	36 (53.3%)
Active (instrumented) mass	[T]	298.2
Charge readout square panels (0.5m×0.5m)		144
Number of signal feedthroughs (640 channels/FT)		12
Number of readout channels		7680
Number of PMT (area for 1 PMT)		144 (0.5m×0.5m)

Vertical cross-section



8.3 m inner vessel
External size 11.7 m

Main detector w/o top deck



Final position and orientation of the beam input pipe still to be defined

Inner vessel thermal insulation

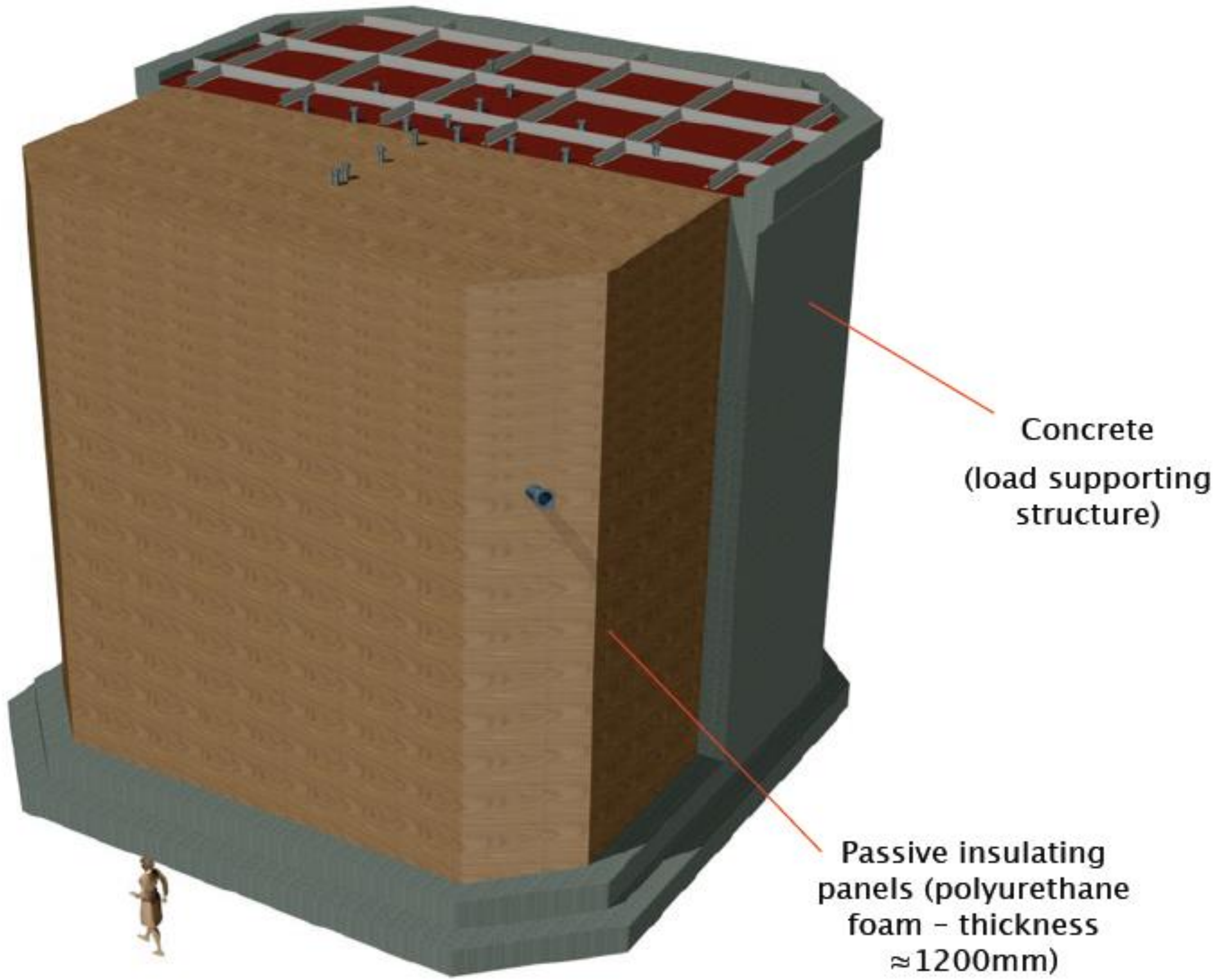
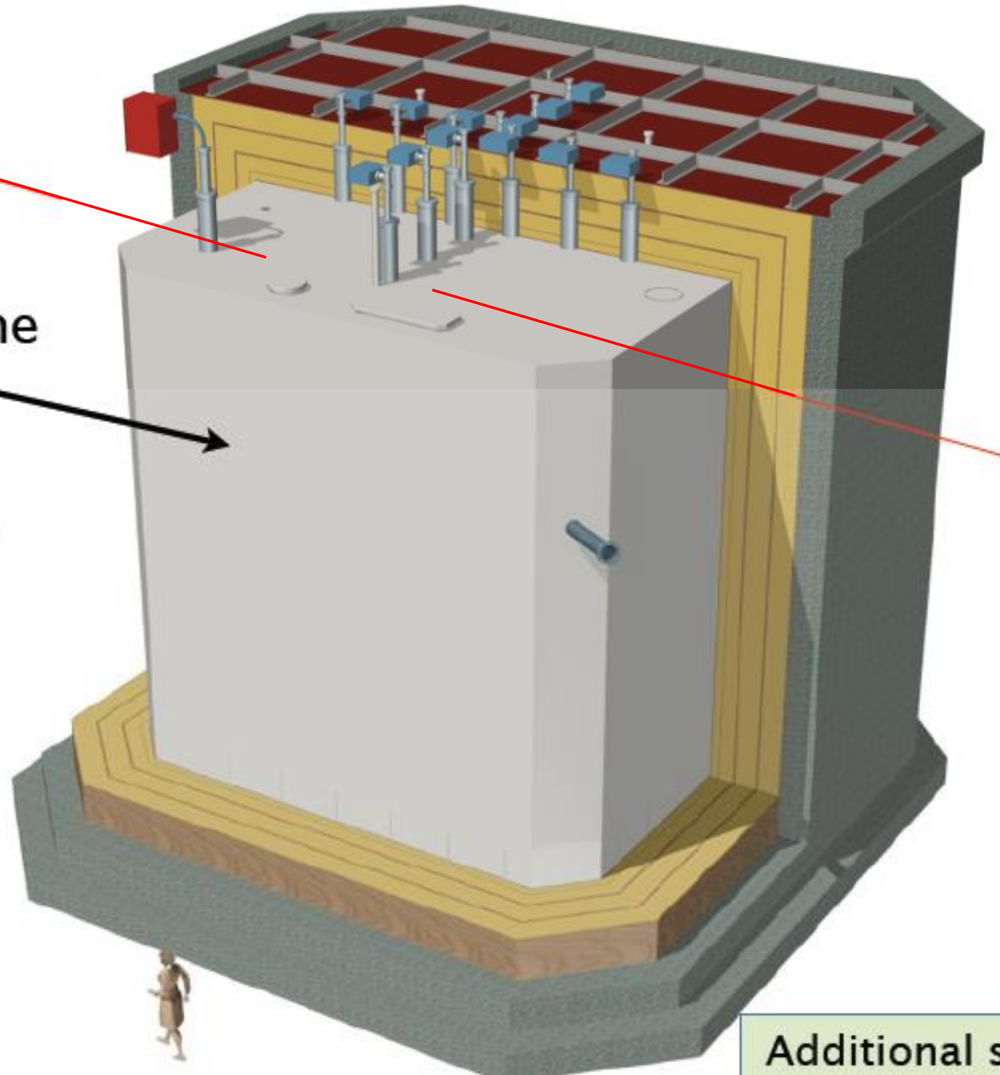
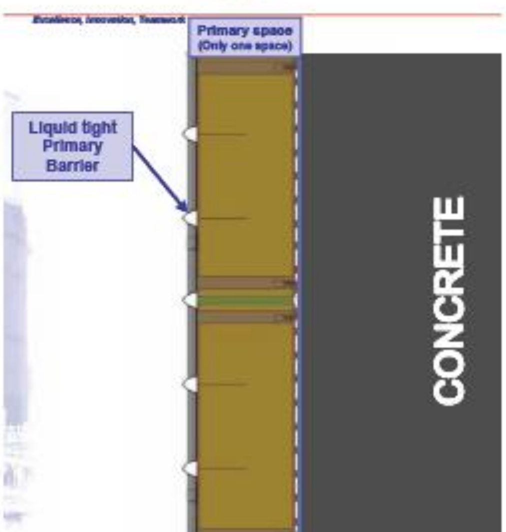


Illustration of inner SS membrane



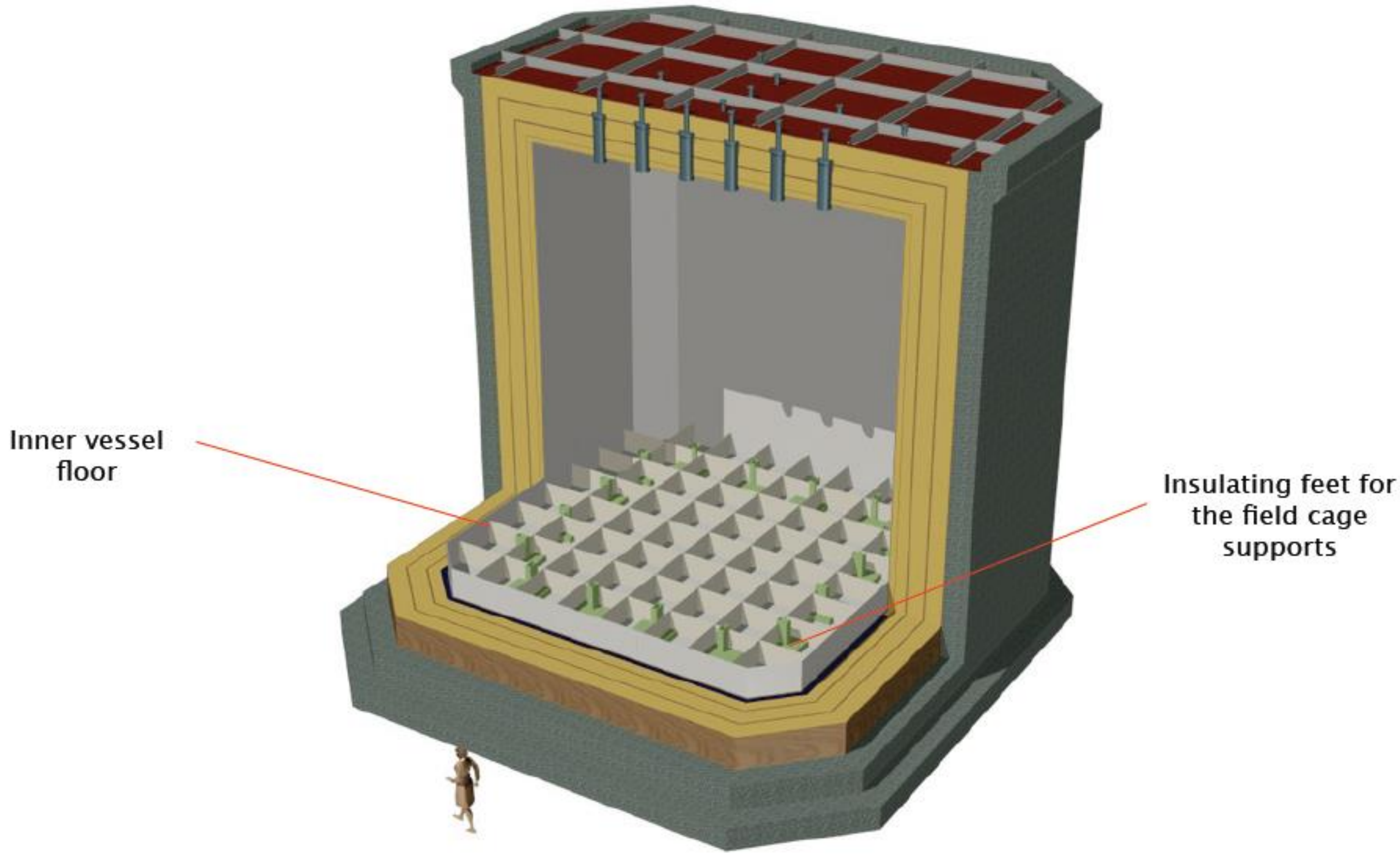
304L SS membrane

Design in partnership with GTT

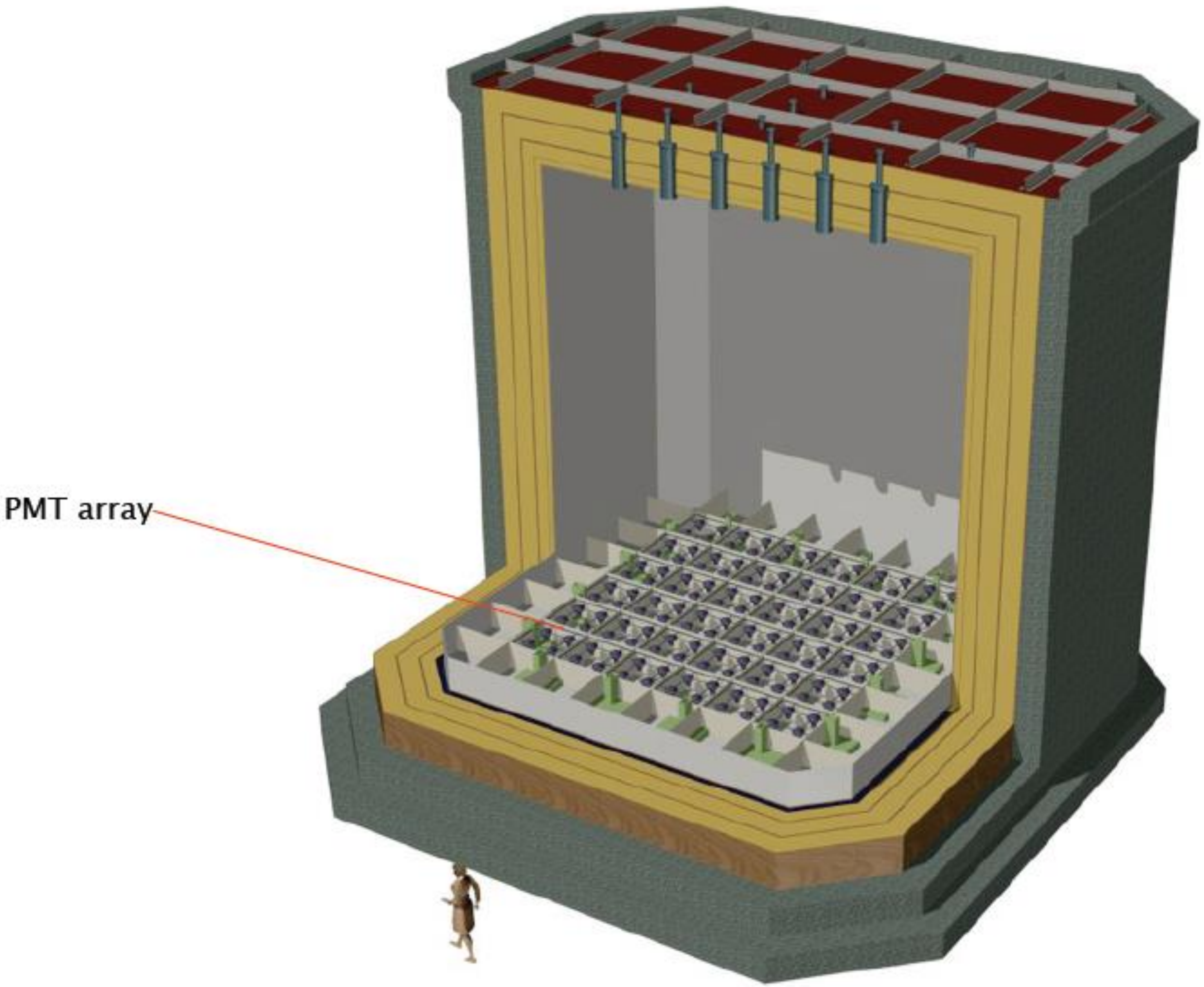


Additional services for gas and liquid handling to be added

Cut view inside main vessel

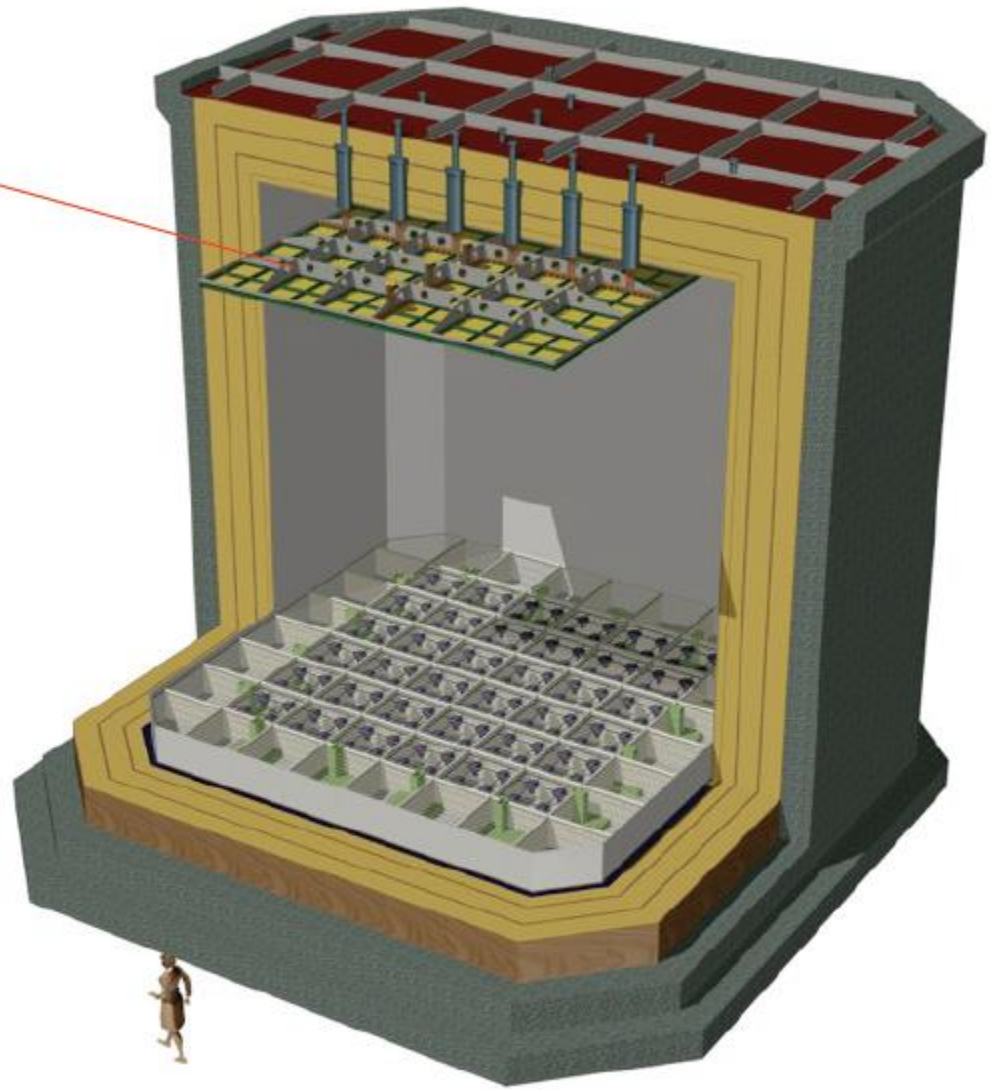


PMT array

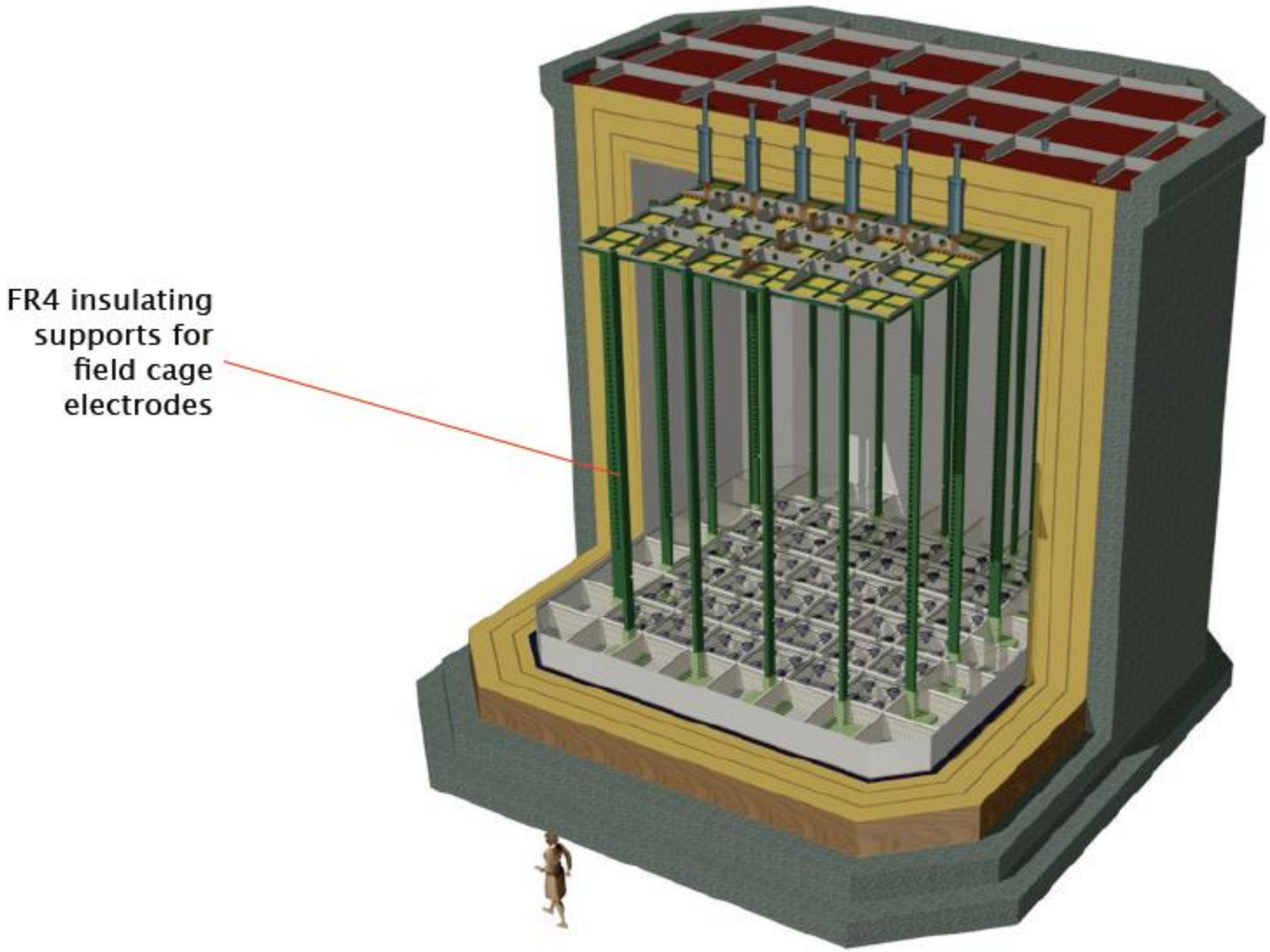


Readout anode deck

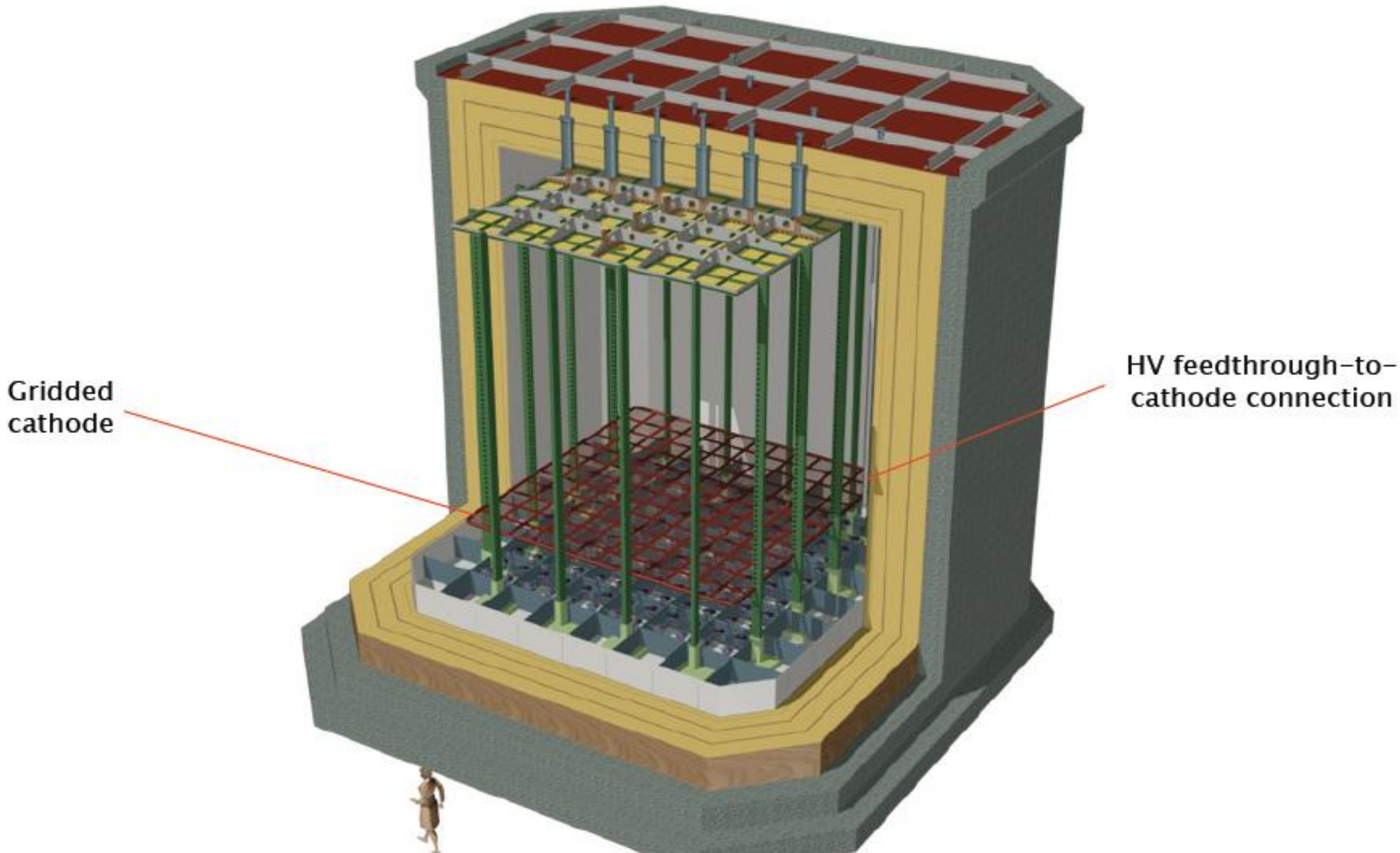
Top anode deck,
including charge
extraction grid, LEM,
2D charge readout
panels



Field cage assembly (I)

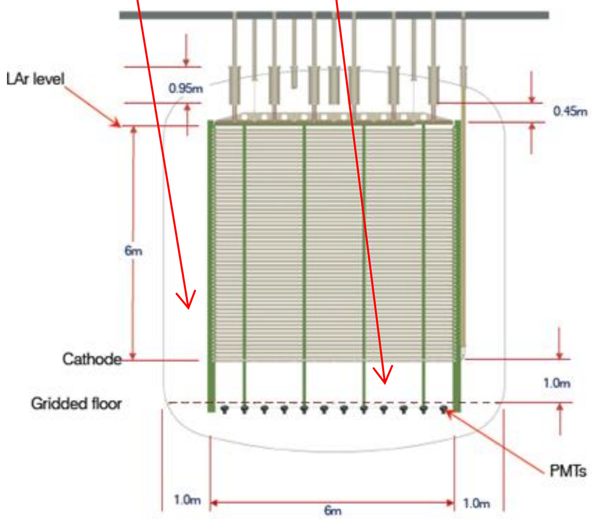


Field cage assembly (II)

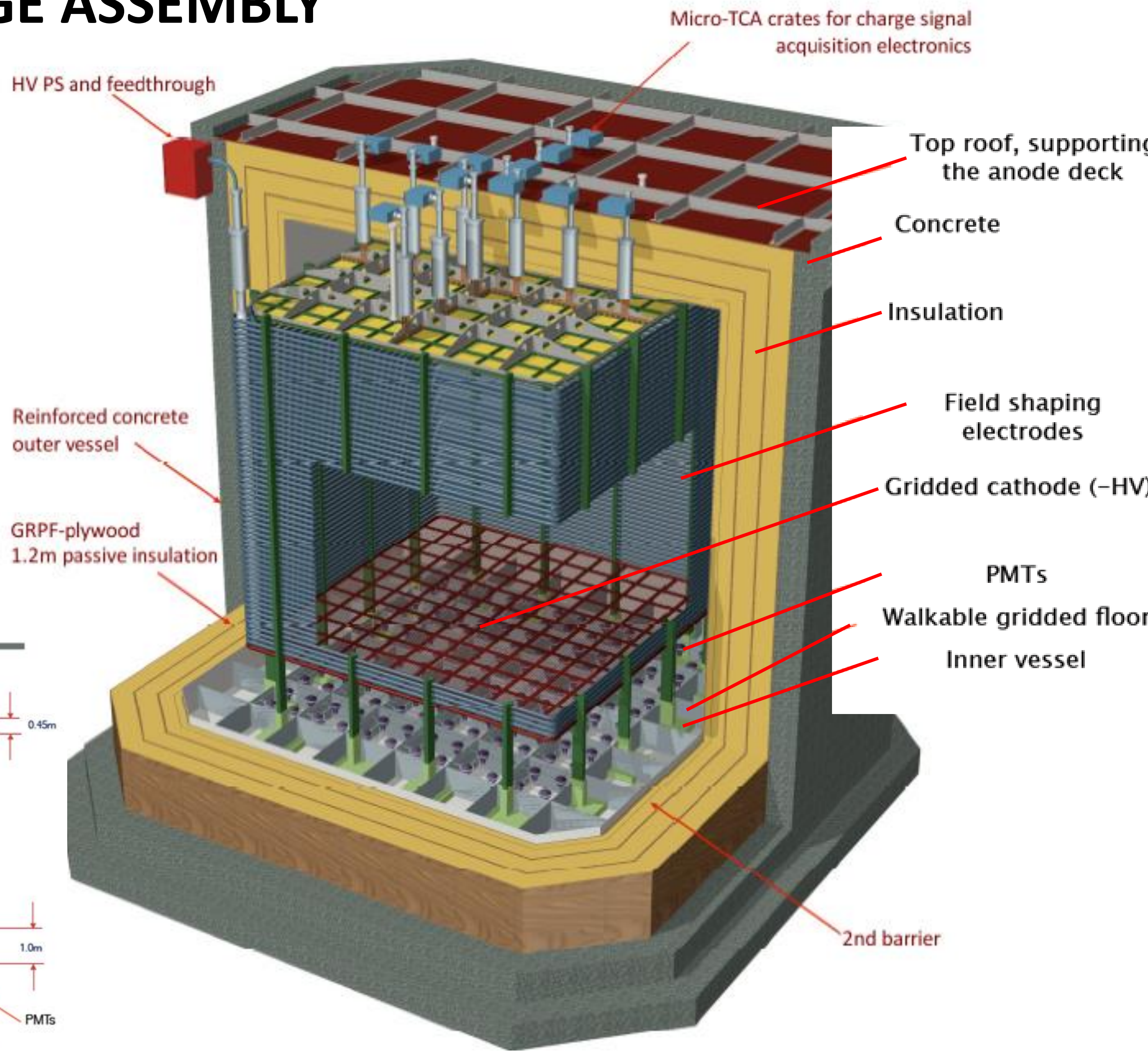


FINAL FIELD CAGE ASSEMBLY

- **1 m distance field cage - walls**
    - **1 m distance cathode-PMTs**

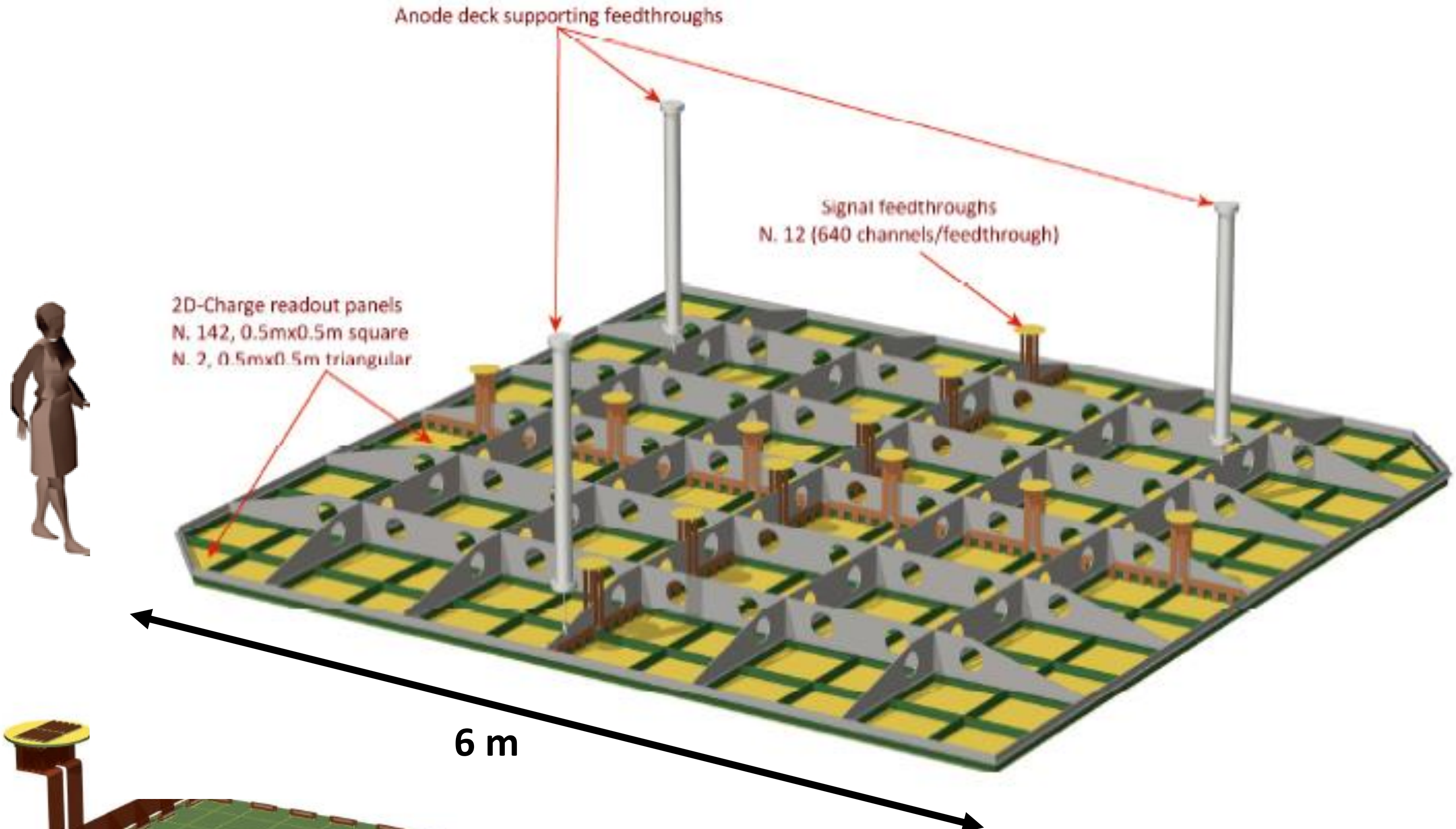


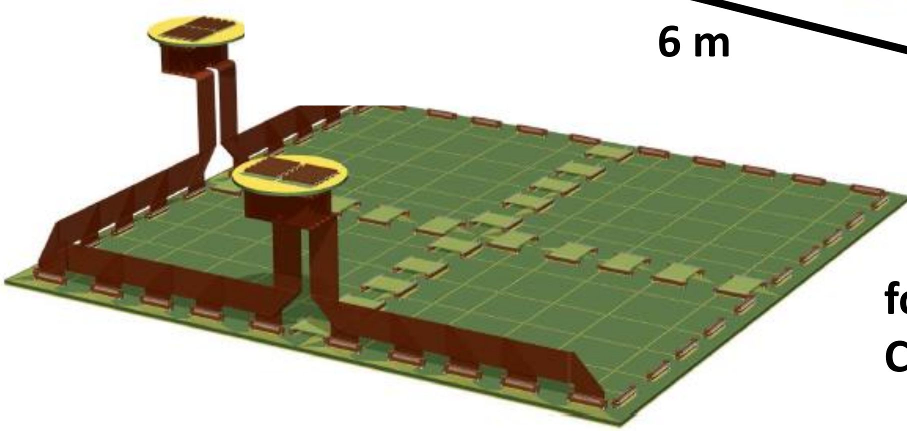
side view



Charge readout anode deck

144 readout modules 0.5x0.5 m2
Two anode coordinates, 3 mm pitch





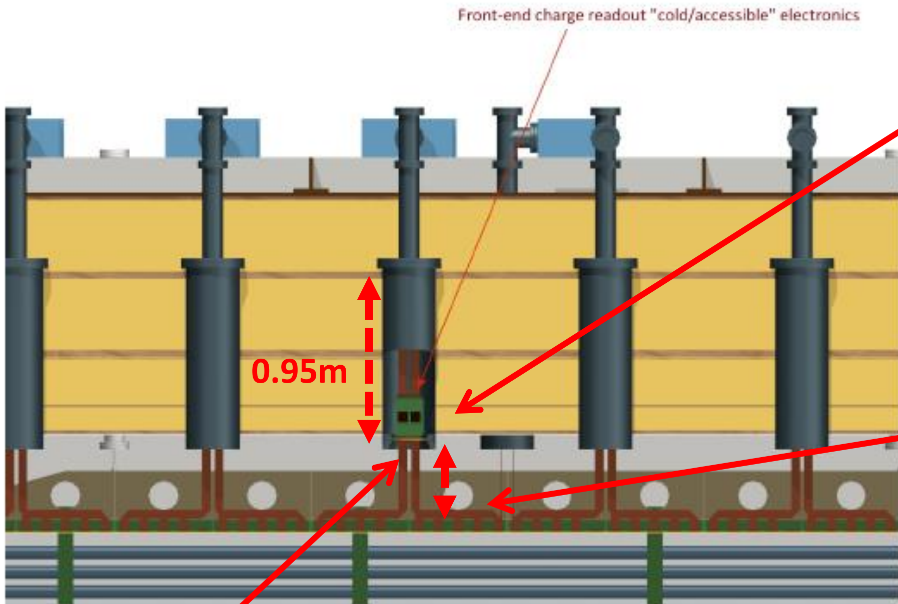
four readout modules assembled in a Charge Readout Plane (CRP) unit

Cold FE hosted at the bottom of the chimney: 640 readout channels

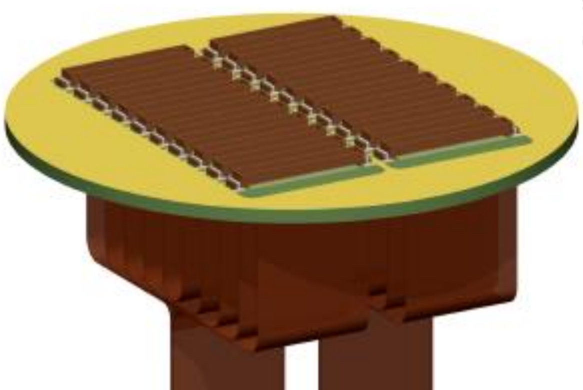
Power dissipation 11.5 w

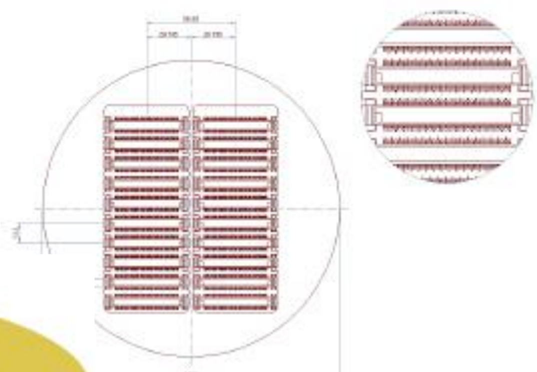
Practically as being in the gas, but: accessibility, possibility for cooling

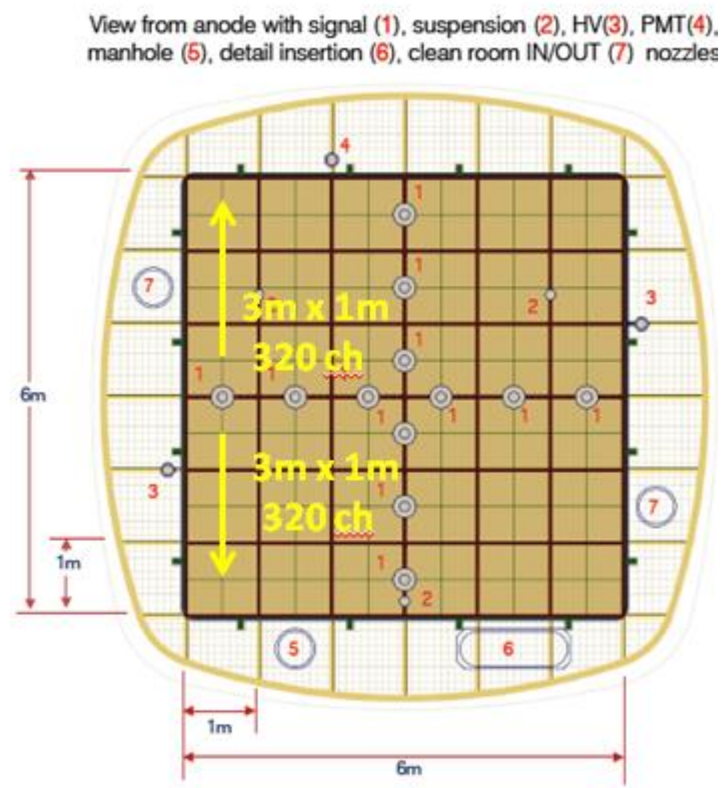
0.45 m distance from readout plane



Flanges CF 250 feedtrhough





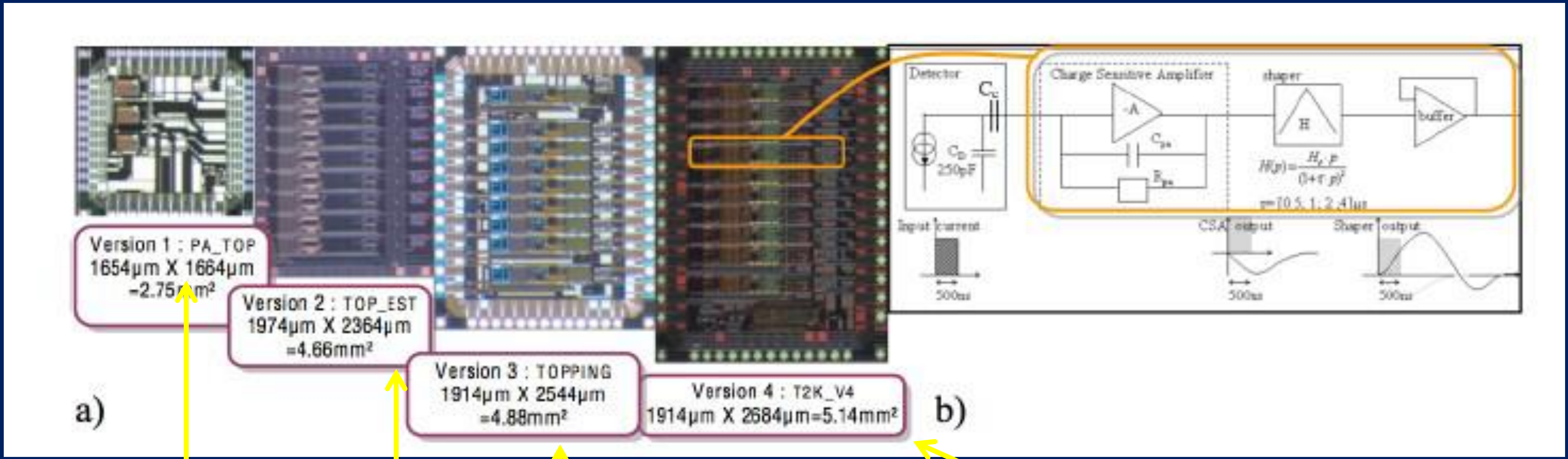


top view

IPNL: 6 versions of the analog ASIC at cold developed so far (~1 iteration/year)

CMOS 0.35 um. (current version V6: 2012, ~1400 e- enc @250 pF)

2007 2008 2009 2010



Amplifier
+ test components

8 channels shaper + buffer, xtalk optimization

8 channels shaper + buffer, selectable configuration

8 channels shaper + buffer
Phase margin optimization

Large scale production costs ~0.3-0.4 eur/channel

R&D on the Gigabit Ethernet readout chain + network time distribution system PTP (IEEE1588)

→ evolution and valorization of OPERA experience:

- Reduce Microprocessors market dependence
- Network stack in hardware to free the CPU
- Performance upgrade -> Gigabit Ethernet
- Simplify synchronization of distributed sensors

- Softcore processors (NIOS II)
- Network offload engine
- Gigabit Ethernet
  - form factor following micro-TCA standard form
- IEEE 1588 for synchronization
  - Improved PTP standard (IEEE 1588)

Also of interest for PTP R&D at ~1ns level,
PTP collaboration with CERN (white rabbit) + others

IPNL:

Digital readout chain based on the evolution of the OPERA DAQ « smart sensors » in uTCA format

V1 available in 2010 for 128 channels

ARIA-GX AMC prototype (2009)

IPMI AMC recognized by the shelf manager
FPGA / NIOS system
Backplane Gigabit link validation
32 ADC channels validation
Software readout scheduling based on RT

32 ADC Mezzanine
LVDS outputs

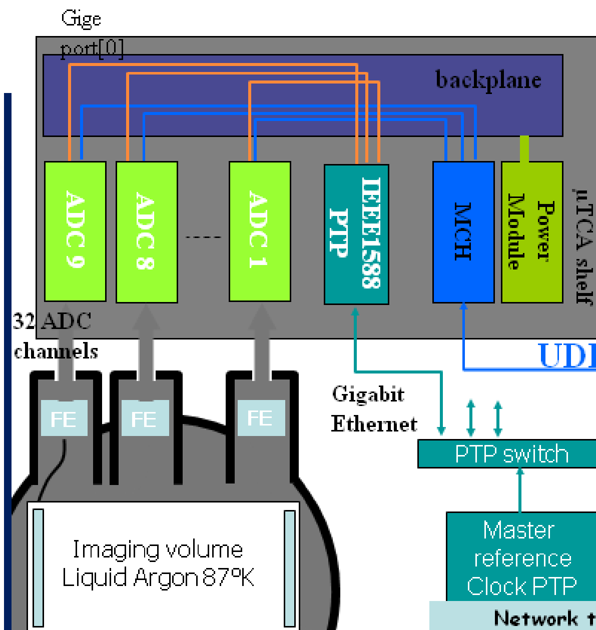
DC/DC
Converter

MMC
VT026
Vadatech

ADC AD9212 8 channels/chip, 40-65 MSPS, 10 bits, LVDS output

μTCA network based DAQ architecture

PTP Switch

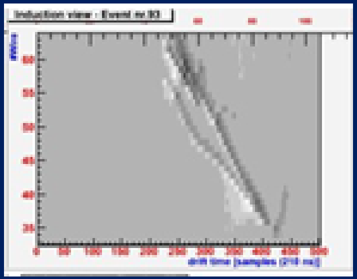


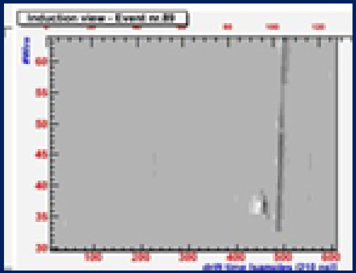
AMC= Advanced Mezzanine Card

MCH=Micro-TCA Carrier Hub (switch+controlle

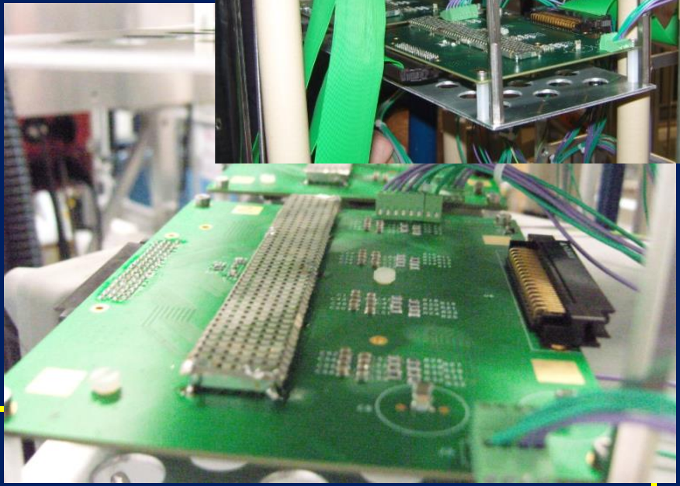
μTCA ⇒

Network topology of the backplane
Modularity given by the AMC concept
High bandwidth potential
Scalability …





Test in Bern in 2010 with the cryogenic ASIC V4 + the microTCA DAQ system



TPC with 192x192 mm sensitive area, 30 cm drift
2 views (induction + collection), wires pitch: 3 mm
64 channels/view in 2 groups of 32 channels

→ 128 channels at cold ~110 K:
4 cards , 4 chips/card, 8 channels/chip + DAQ electronics

ASIC Front End amplifier V6 (2012):

- **8 channels/ASIC, power consumption 18.2 mW/ch**
- **ENC 1400 e- @ Cdet=250 pF**
- **Dynamic range 50 mip (linear regime)**

Also other versions (V1-V5) stable at cold (all tested with LN) , V2 1200 e- ENC

→ Next version (july 2013):

- **Larger number of channels: 16**
- **Noise improvements, shaping optimization vs 1/f noise**
- **Larger dynamics to account for double phase (LEM/micromegas) amplification+drift attenuation (LEM gain 20, Cdet=300 pF, dynamic range 1/6 mip up to 40 mip)**

Next version of DAQ system under development as well for increased integration (form factor) and costs reduction → Detailed costing of the FE+DAQ for LBNO-Proto

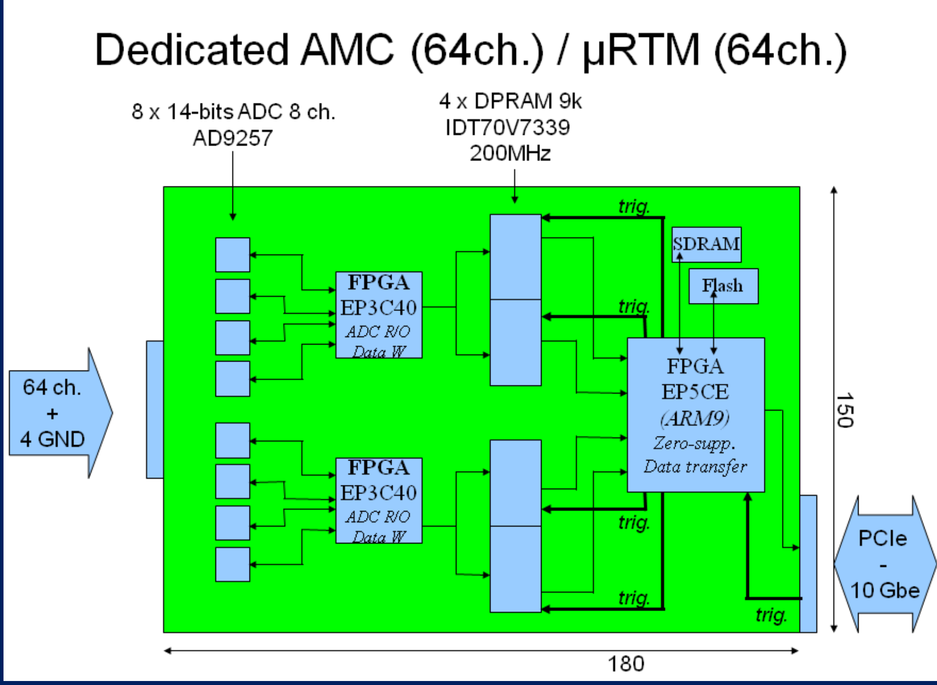
Cost effective and compact evolution of the V1 µTCA DAQ System:

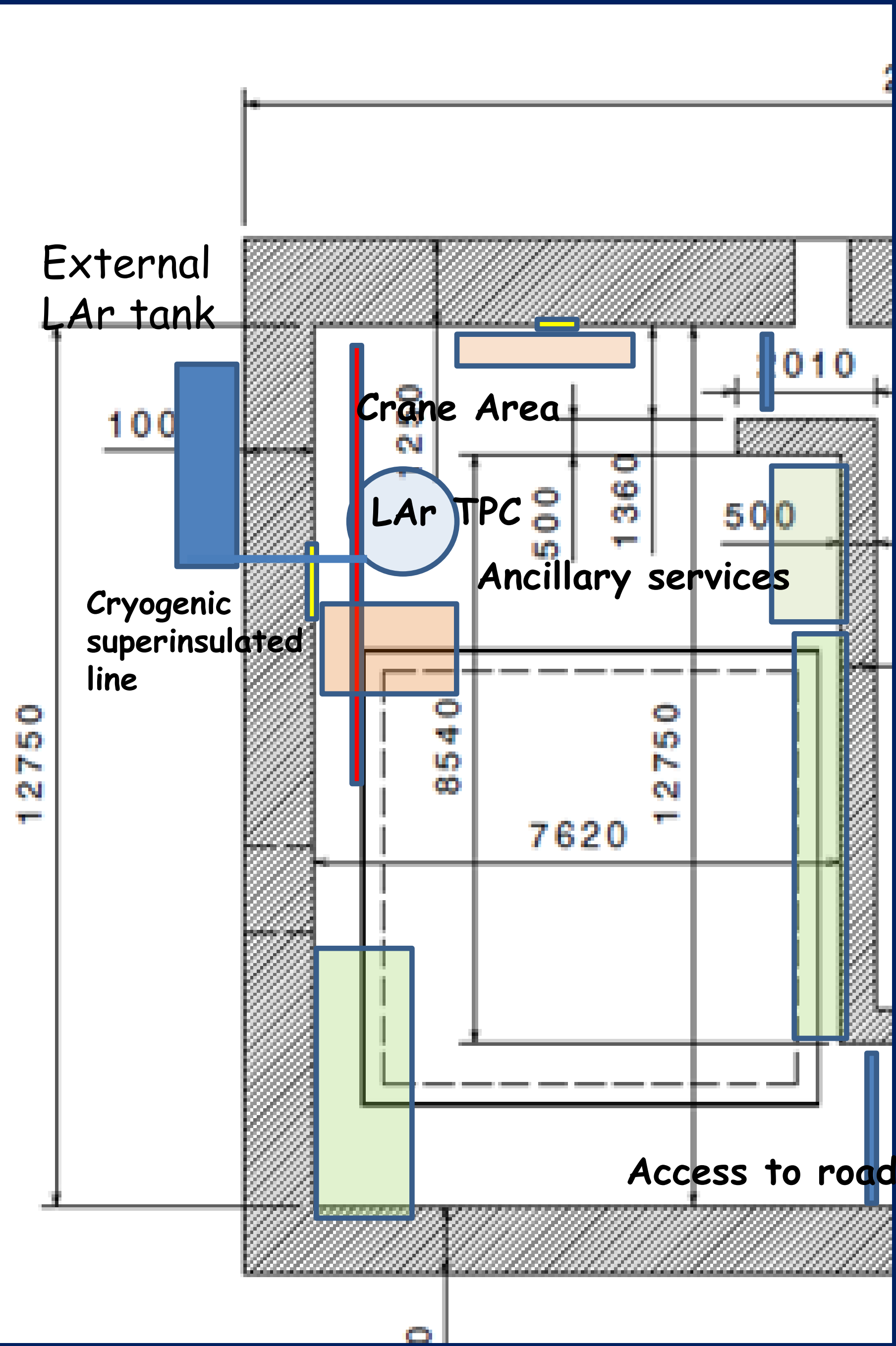
- 19 inches
- 640 channels/crate (or 1280ch/crate in µTCA.4 standard)
- Deterministic data transfer
- all-in-one solution :

- DAQ & data processing (zero suppression)
- Network (10Gbe available in front-panel & backplanes)
- Computing (e.g. AMC with power PC)

DAQ architecture based on µTCA standard
µTCA.1 standard / possible µTCA.4 (µTCA for physics)

- Double-wide (double mid-size) AMC cards
- 12 slots for R/O AMC
- Single MCH
- Dual power modules
- PCIe or 10Gbe on the backplane
- 10 Gbe uplink
- 1 custom MCH or AMC for clock / trigger
(CLK management in µTCA.4 standard)
- 1 standard MCH for uplink and PM management





LIO LABEX LAr project at IPNL:

Support and boost the R&D at IPNL on the charge readout for LAr TPC (activity already ongoing at IPNL since 2006)

→ setting up of a test facility for the electronics with a medium size TPC prototype

→ Support to the LBNO prototype project
Test of FE electronics and DAQ for detector units with wires, LEM and Micromegas

Liquid Argon TPC Laboratory for the LABEX LIO:

- Refurbishing of a 100 m2 area (5m height) in the former Van der Graaf building:

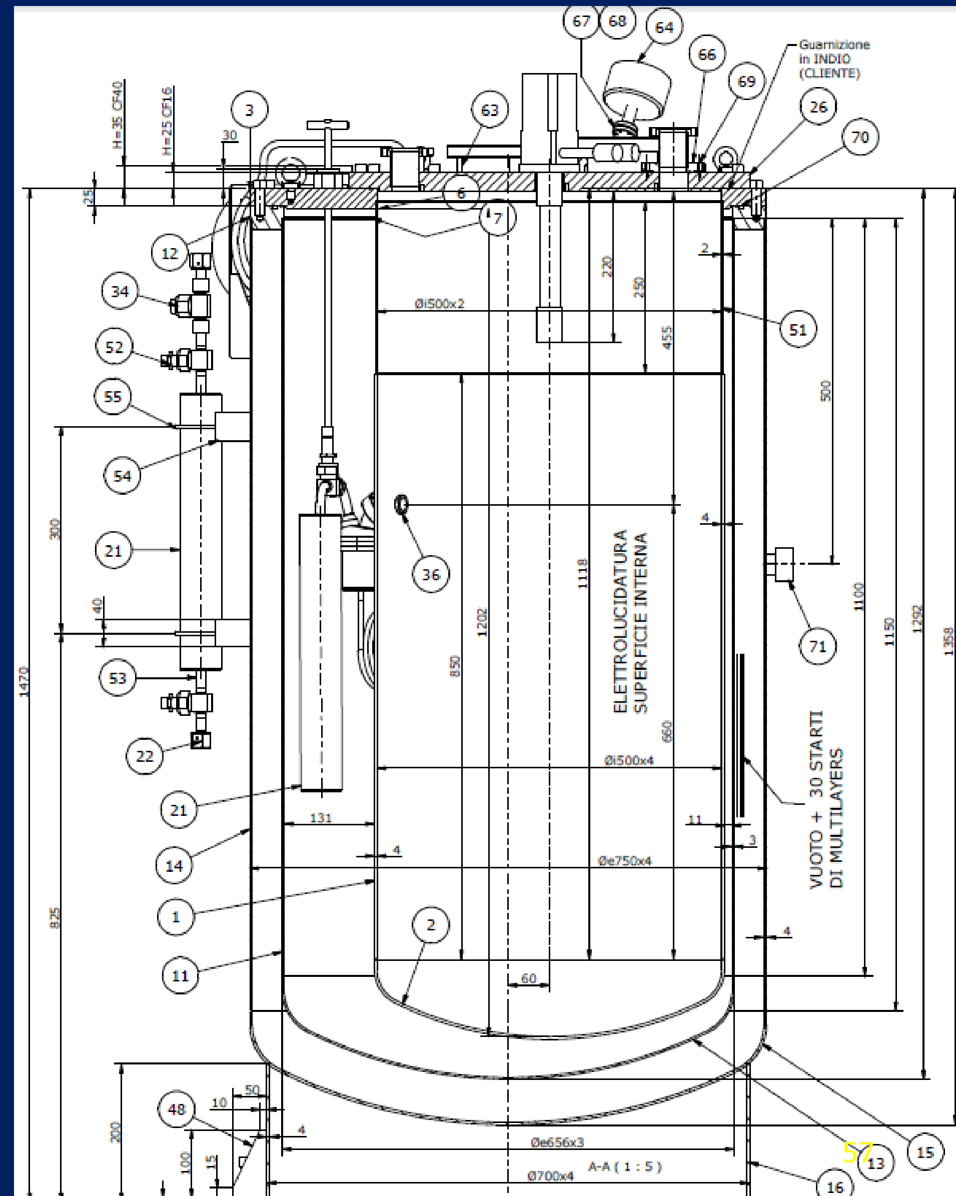
→ Separation wall and doors, cleaning, electrical works, network, crane, exhaust line and ventilation, safety

Laboratory delivered for installation on 18/3/2013


Picture taken on 19/3 after
moving the materials to the
new laboratory

Cryostat, built in collaboration with CRIOTEC Torino

State of the art traditional, vacuum evacuated cryostat



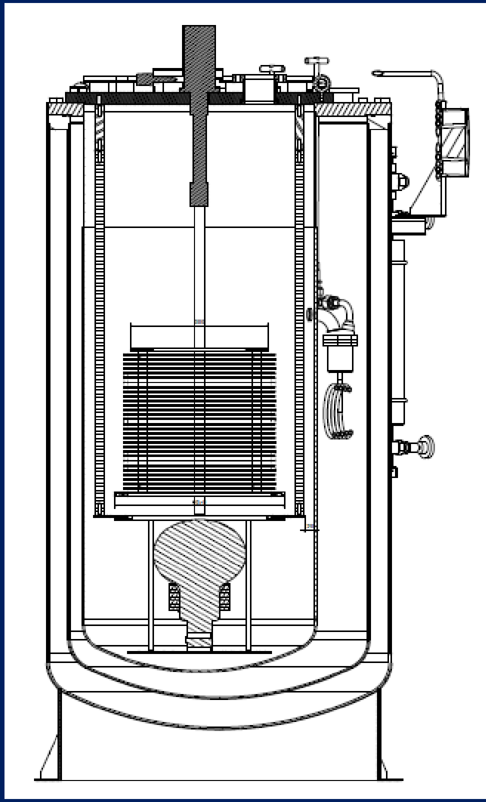
- Double wall superinsulated cryostat 70 cm diameter
- External thermal bath of boiling LAr (366 l) with integrated recirculation purification system of LAr (30 l/m) through trigon cartridge, bellow pump powered by N2 flow. Evaporation rate ~10l/day
- Inner vessel of pure LAr (216 l) , diameter 50 cm, height ~115 cm, LAr input via additional trigon cartridge
- Integrated cryocooler 25W (Cryomech AL25)

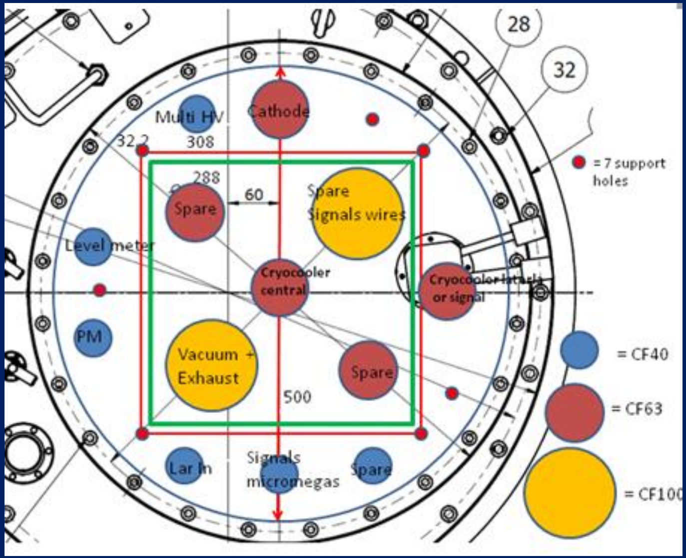
Flexible configuration for double-phase readout tests

→ Keep under control:
- ✓ **Temperature gradient in the gas Ar, electronics dissipation**
- ✓ **Pressure of the gas Ar**
- ✓ **LAr, level, detector parallelism to Lar surface**

Inner instrumentation:

- Light readout with Hamamatsu R5912-mod2
- Wire chamber (under construction) 33 cm diameter field cage, 30 cm drift, 64+64 ch/view, 3 mm pitch
- Double phase tests → profit of control of gas phase (p,T) and electronics temperature with cryocooler:
  - Micromegas tests (in collaboration with IRFU) up to 288 ch, 144/view 2 mm pitch, rectangular field cage, 31 cm side
  - Tests of cold electronics with LEM readout (in collaboration with ETHZ)
- Scintillators hodoscope integrated in DAQ system for selection of horizontal tracks:
  2 planes 1.5x1.5 m2, 2.5 cm pitch





200 liters cryostat, commissioning completed for:

- Vacuum system
- Installation of cryoline by LINDE and related safety system
- Integration of the system
- First complete filling test (external bath and pure LAr), slow controls, operation
- Cryocooler and temperature regulation system (ongoing)

Scintillation light digitization: (APC+OMEGA, LAPP)

144 PMTs, 1PMT/m2, detection of the fast UV component τ~6ns

→ Re-adaptation of the PARISROC ASIC developed by PMm2 for the WC readout

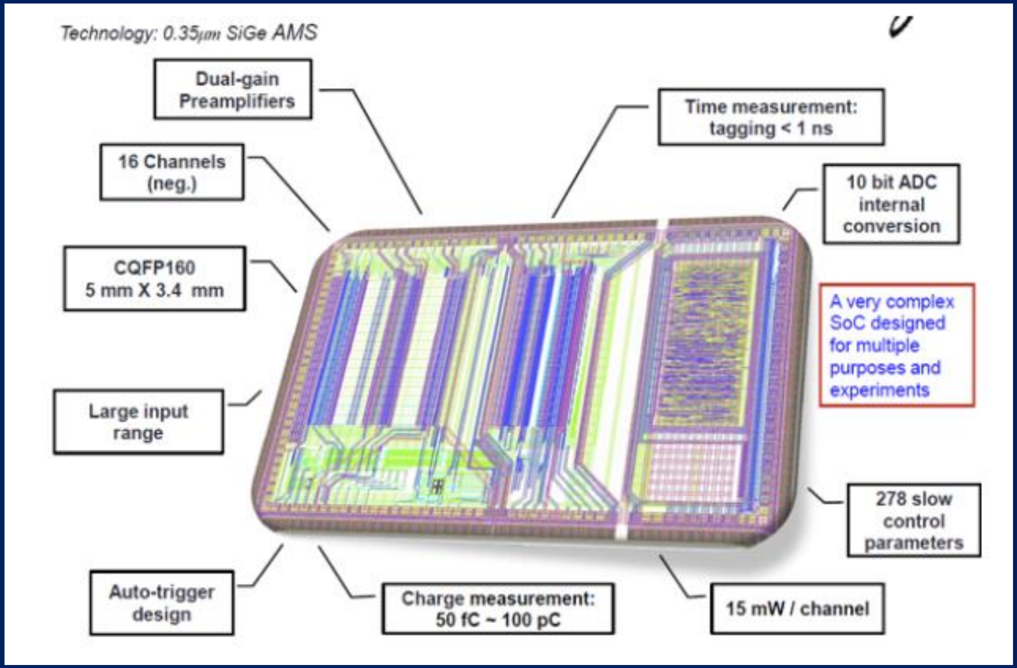
- To be tested in LAr

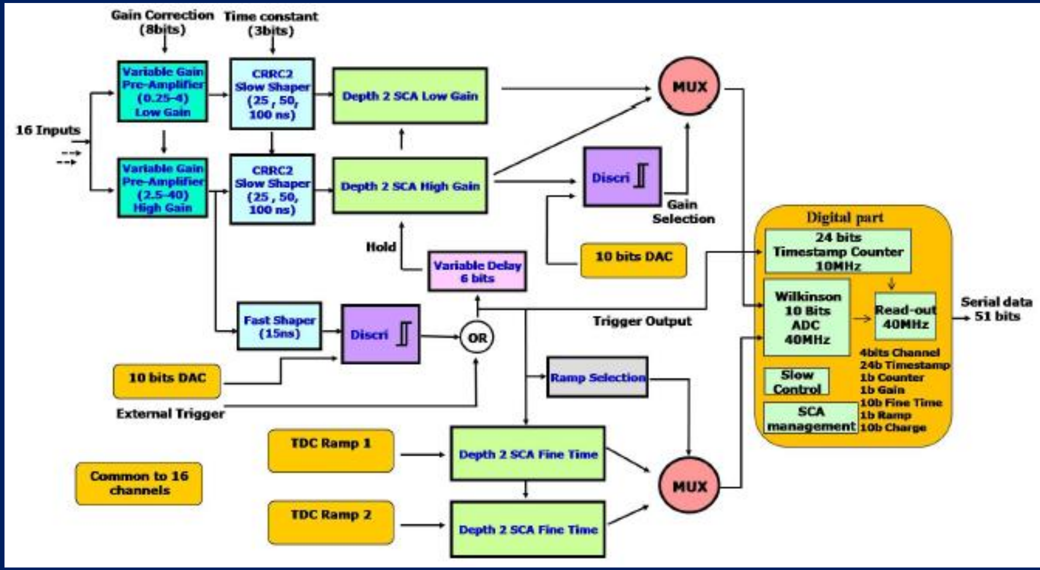
- Cost reduction, large scale integration, simplification of feedthroughs

- 16 channels readout per ASIC
- 15 mW/channel

- Charge measurement 1/3 pe to 600 pe
- Time measurement 600 ps resolution

- Digitized data transmitted on network cable to external data storage (simpler feedthroughs)





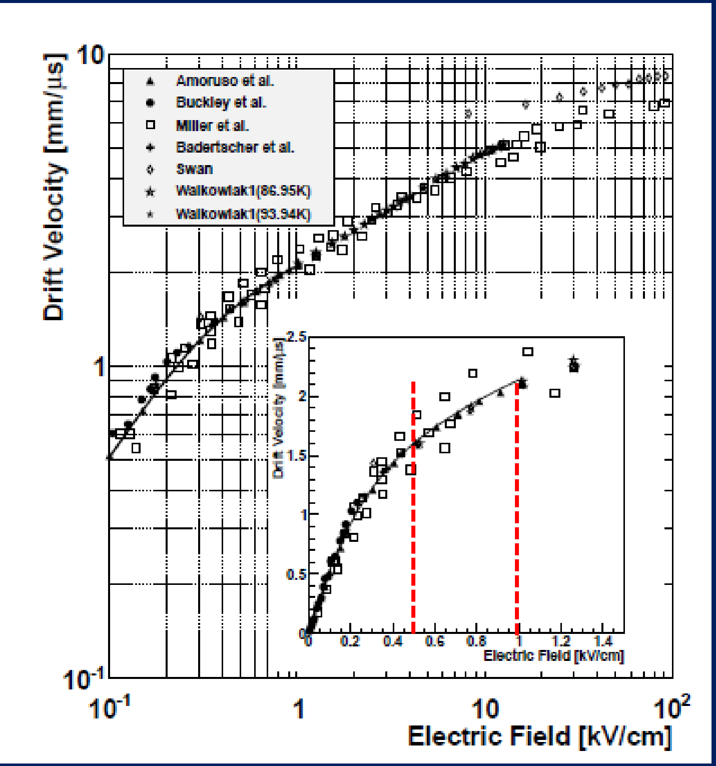
LPNHE: drift high voltage system

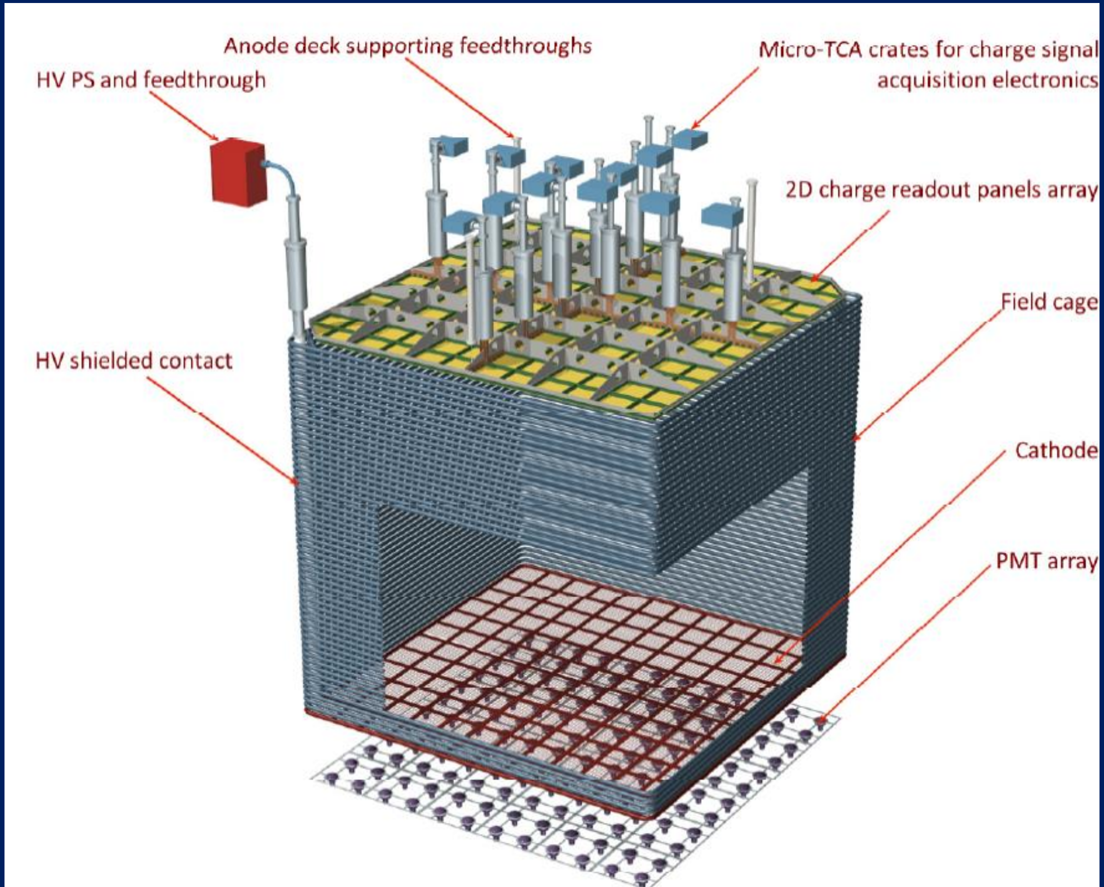
→ Power supply and feedthrough

- First phase 0.5 kV/cm → 300 kV power supply low ripple commercial technique, feedthrough extension of ICARUS

- Second phase: R&D with industrial partners for higher HV

→ Power supply to reach 600 kV, 1 kV/cm drift field, in the next step





Summary of the French groups contributions, related budgets and time profile

Group	Contribution	Hardware cost
APC	Photomultipliers digitization system	48 keur
IPNL	Cryogenic ASICs and DAQ system	265 keur
IRFU	Charge readout detectors	
LAPP	Photomultipliers digitization system Field cage construction and readout plane alignment system under discussion	12 keur **(under evaluation)**
LPNHE	High voltage system and feedthroughts	150 keur
Total		475 keur / 3250 keur (total detector cost)

Table 1: Contributions to the prototype hardware costs by the French groups

- Half 2014: EHN1 ready for installation
- 2014-2015 detector contruction

✓ 9 months for tank contruction
✓ tank inner instrumentation
✓ 2015: electronics production

- Start data-taking: spring 2016

2016-2017: two years of running before CERN LS2

Year	APC				IPNL				LAPP				LPNHE				Total	Year
	FTE	Detector	Missions	Function.	FTE	Detector	Missions	Function.	FTE	Detector	Missions	Function.	FTE	Detector	Missions	Function.		
2014	3,8	15	10	10	6,7	40	20	10	0,8	2	4	0,5	2,5	30	10	5	156,5	2014
2015	3,9	25	15	10	6,7	200	30	10	0,8	8	4	0,5	2,5	100	10	5	417,5	2015
2016	4,9	8	15	10	6,7	25	25	10	0,8	2	4	0,5	2,5	20	10	5	134,5	2016
2017	4	0	10	5	6,7	0	25	10	0,8	0	4	0,5	2,5	0	10	5	69,5	2017
	16,6	48	50	35	26,8	265	100	40	3,2	12	16	2	10	150	40	20	778	Grand total (hardware+Miss.+Func.)
																	475	Hardware total
			85	5,120482			140	5,223881			18	5,625			60	6		
			Mis+Fun	Mis+Fun/FTE			Mis+Fun	Mis+Fun/FTE			Mis+Fun	Mis+Fun/FTE			Mis+Fun	Mis+Fun/FTE		

Budget over 4 years: 2014-2017

- 475 keur hardware costs
- 303 keur missions+ functioning

Timely activity in view of:

1) The construction of the far detector
2) CERN LS2

Conclusions (LBNO-Proto):

- LBNO foresees a breakthrough prototyping activity at CERN: test of a full scale (6x6x6m^3) proof prototype, exposed to charged hadrons beam in the North Area

- This prototype will be constructed with all techniques needed for the far detector and it will represent a milestone for the future long-baseline programs.

- It will also test and calibrate the response to hadronic showers and the reconstruction and, as physics byproduct, improve in general the modeling of hadronic showers

- With this operation CERN will strengthen the European groups which have already an advanced expertise in the field acquired with LAGUNA (as recommended by the ESG)

- There is a strong interest among the French groups (APC, IRFU, IPNL, LAPP, LPNHE) to provide important contributions working on:
  - The detectors for the double phase readout
  - The front-end electronics and the DAQ system for the charge readout
  - The PMTs signals digitization
  - The HV system and feedthrough
  - (The mechanics of the field cage and the alignment system of the readout plane)

This is a small project with a strong added value → It represents the best opportunity for the European/French groups to prepare the next experimental phase, which will bring to fundamental physics results, in optimal conditions on a very advanced detector development

- Include impact of systematic uncertainties in sensitivity computations

Oscillation parameters:

Name	Value	Error (1σ)
L (km)	2300	exact
Δm^2_{21} eV^2	7.60E-05	exact
$\vert\Delta m^2_{32}\vert$ eV^2	2.40E-03	±4%
$\sin^2\theta_{12}$	0.30	exact
$\sin^2 2\theta_{13}$	0.09	±10%
$\sin^2\theta_{23}$	0.50	±10%
<ρ>	3.2 g/cm3	±4%

Oscillation values & errors from http://www.nu-fit.org

$$\chi^2 = \sum_i (N_i - n_i)^2 / \mathrm{N_i} + \sum_j f_j^2/\sigma^2_{f_j}$$

True rate (all sys parameter fixed to default values)

Systematic terms and their priors

$$\mathrm{n} = \left(1 \pm \frac{\mathrm{f}_{\pm}}{2}\right)\left((1+\mathrm{f_{sig}})\mathrm{n_{sig}} + (1+\mathrm{f_{NC}})\mathrm{n_{NC}} + (1+\mathrm{f}_{\nu_e})\mathrm{n}_{\nu_e} + (1+\mathrm{f}_{\nu_\tau})\mathrm{n}_{\nu_\tau}\right)$$

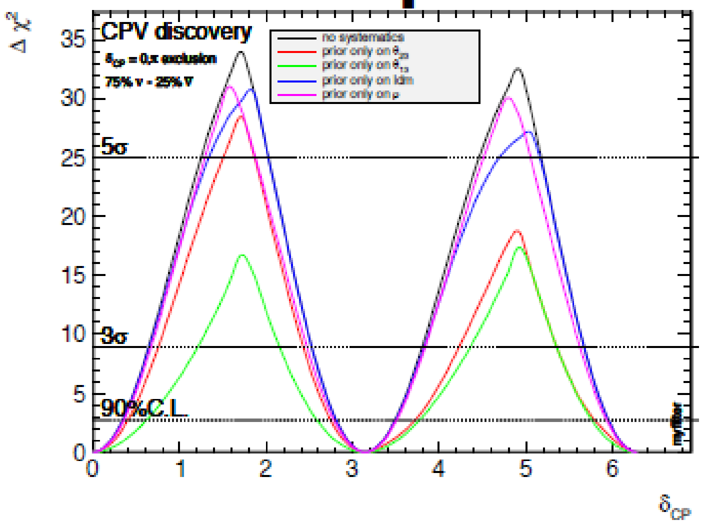
Syst. error on rates in bins of energy

Name	MH determination Error (1σ)	CP determination Error (1σ)
Bin-to-bin correlated:		
Signal normalization (f_{sig})	±5%	±5%
Beam electron contamination normalization ($f_{\nu_e CC}$)	±5%	±5%
Tau normalization ($f_{\nu_\tau CC}$)	±50%	±20%
ν NC and ν_μ CC background ($f_{\nu NC}$)	±10%	±10%
Relative norm. of "+" and "-" horn polarity ($f_{+/-}$)	±5%	±5%
Bin-to-bin uncorrelated	±5%	±5%

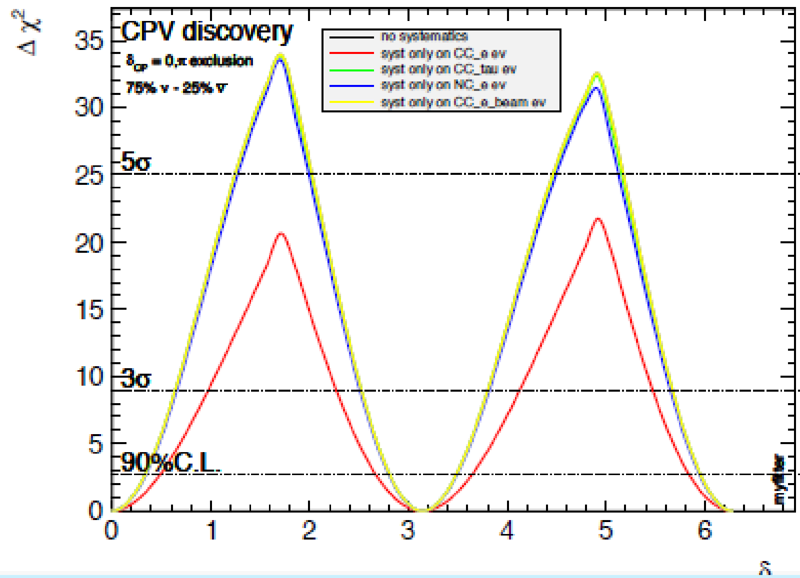
Effect of systematic errors

LBNO L=2300km, 20 kton, 10 years

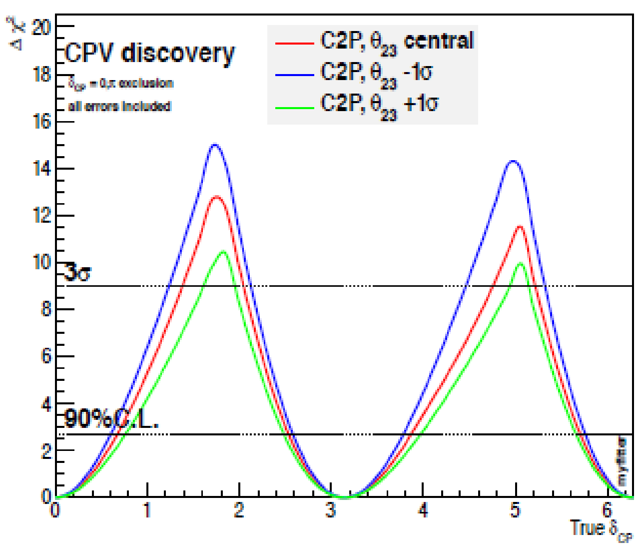
Oscillation parameters



Detector related



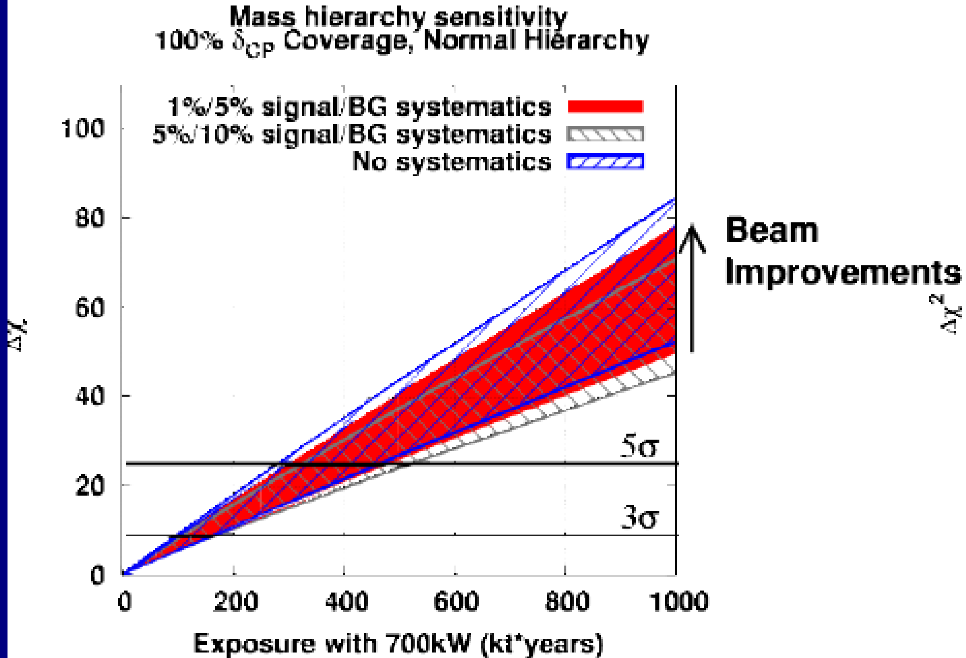
Effect of θ_{23}

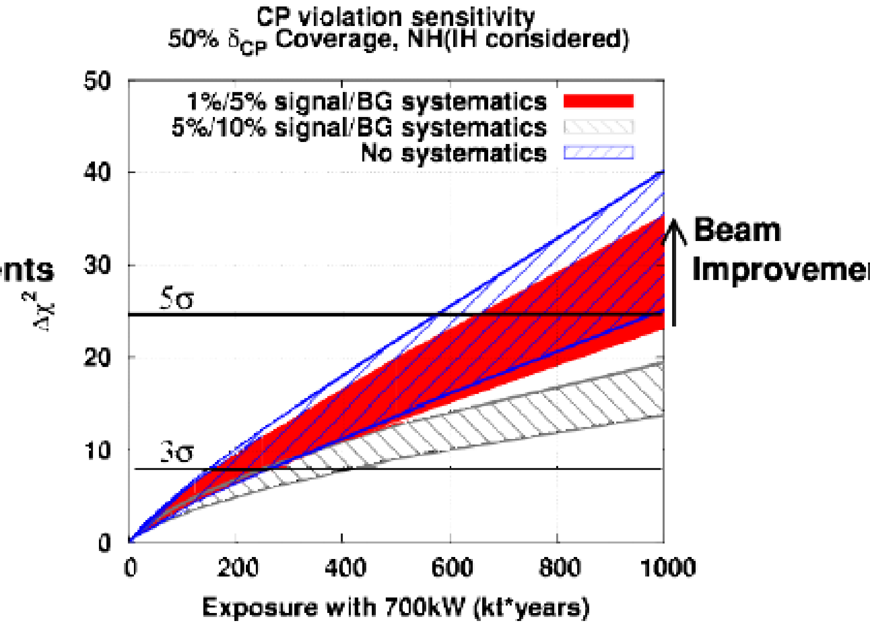


Without systematic errors, the 20 kton would reach 5sigma CPV in 10 years !
The most important oscillation parameters are θ_{23} and θ_{13} and the most important systematics is the knowledge of the absolute rate of ν_e CC events.

LBNE phase-2 sensitivity

34 kton LBNE + Project X





Needs systematic error of 1%/5% to reach 5σ C.L. CPV even in case of phase 2 exposure (1 Mt x year) !

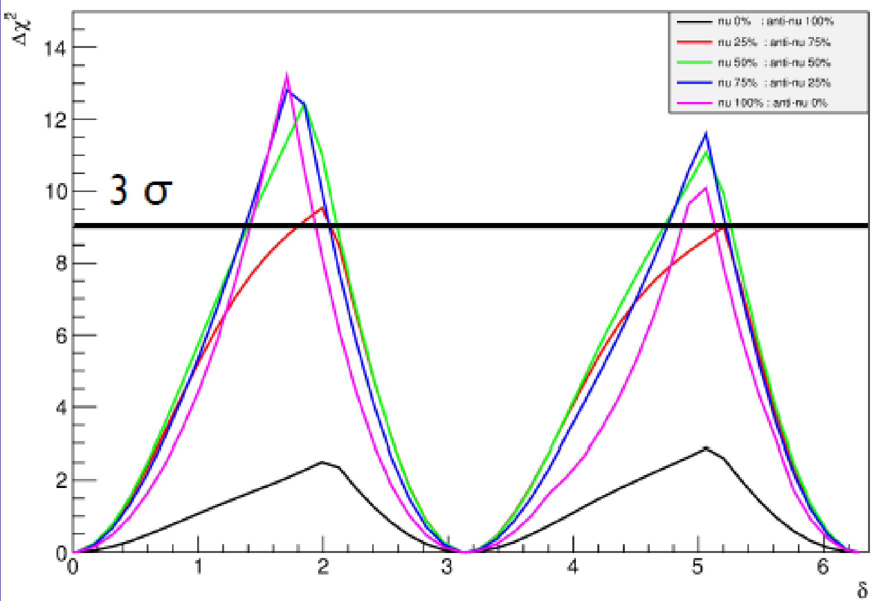
(or go to longer baseline to recover 2nd max sensitivity!)

Sharing between nu vs antinu's

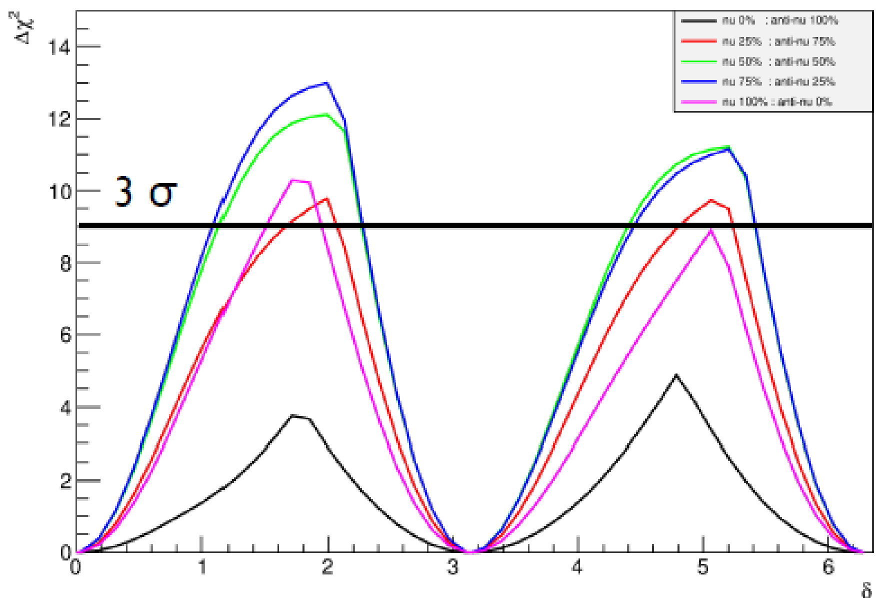
After MH determined in 2 years, run for ≈10 years with optimised sharing of neutrinos / anti-neutrinos to cover the most possible phase space in δ_{CP}

LBNO L=2300km, 20 kton, 10 years

neutrino:anti-neutrino sharing dependence (NH)

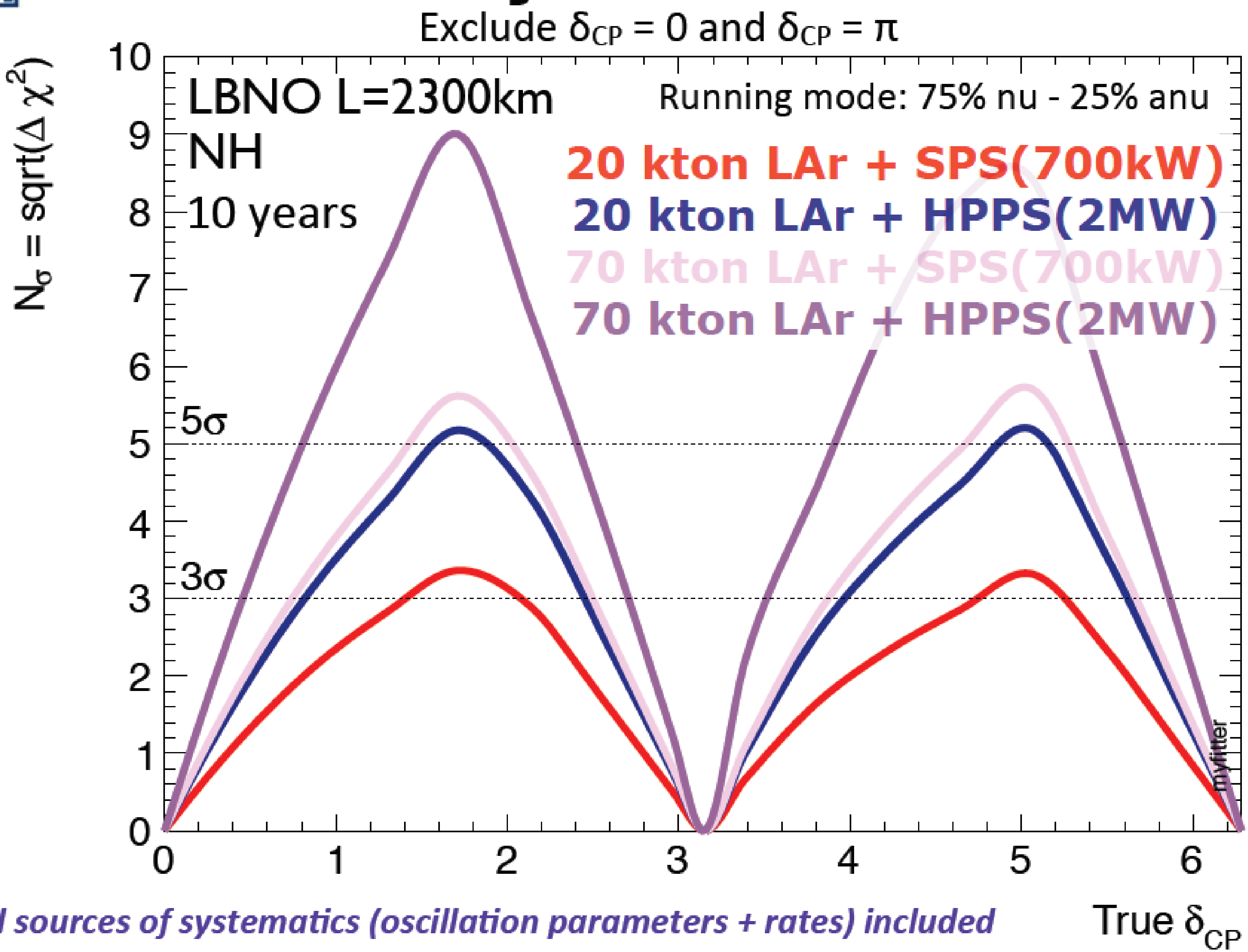


neutrino:anti-neutrino sharing dependence (IH)



Design value: 75 % ν - 25 % anti-ν

Sensitivity to CP violation

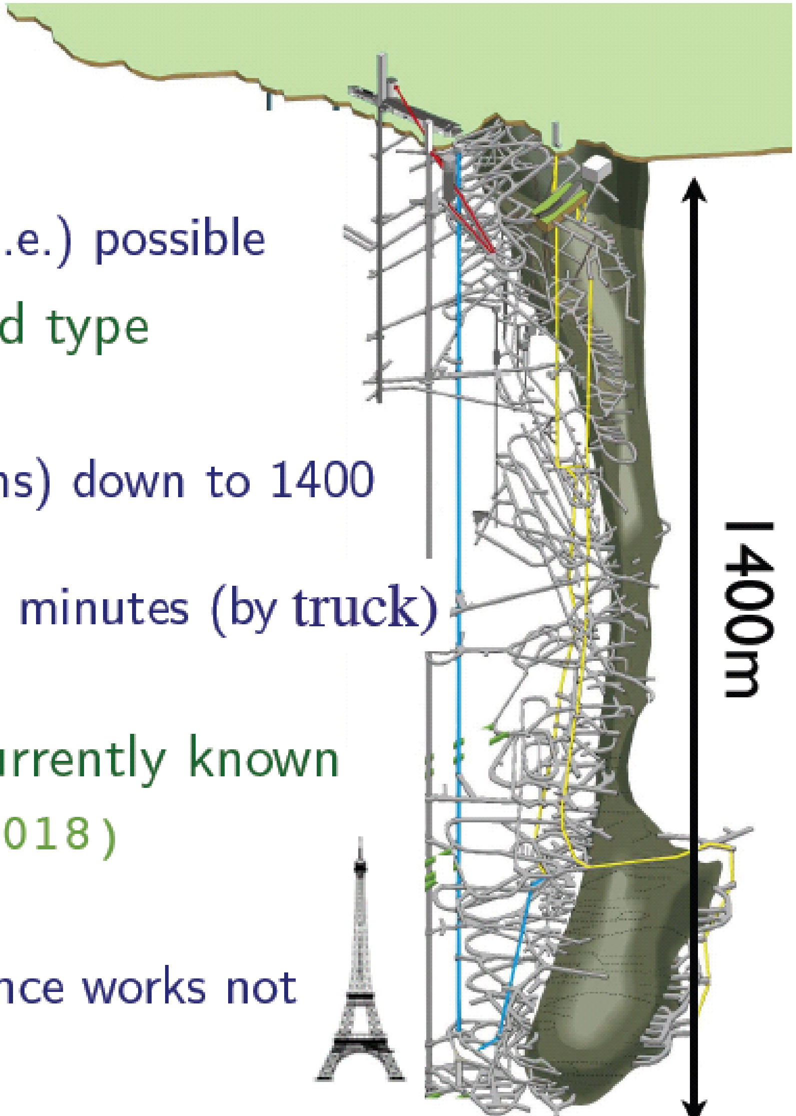


All sources of systematics (oscillation parameters + rates) included

Present state of mine

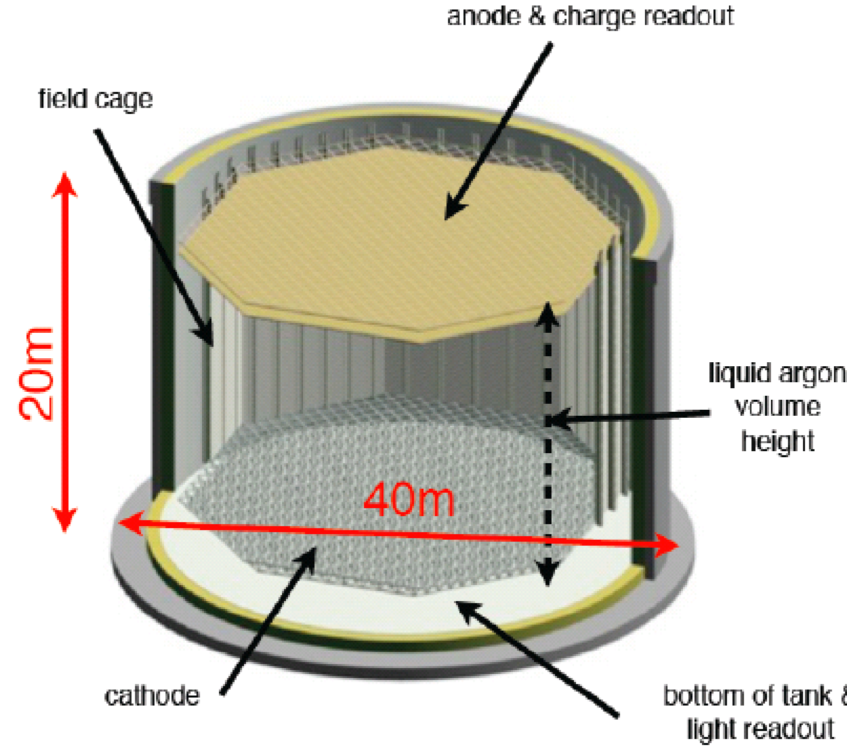
Present: The Pyhäsalmi mine (Inmet Mining Ltd., Canada)

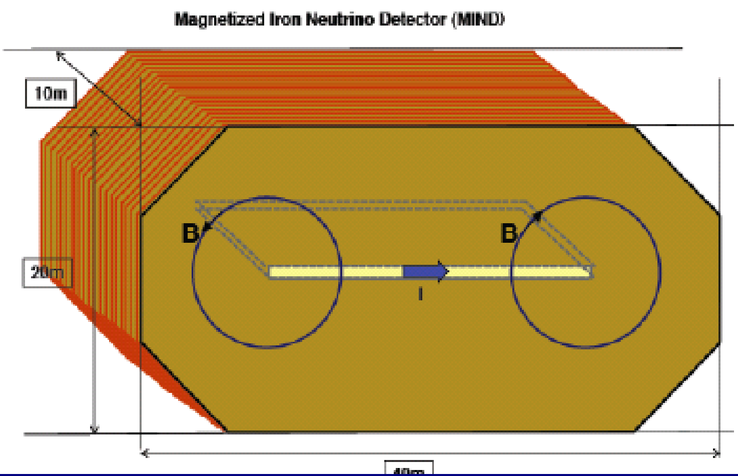
- Produces Cu, Zn, and FeS_2
- The deepest mine in Europe
  - Depths down to 1400 m (4000 m.w.e.) possible
- The most efficient mine of its size and type
- Very modern infrastructure
  - lift (of 21.5 tons of ore or 20 persons) down to 1400 metres takes ∼3 minutes
  - via 11-km long decline it takes ∼40 minutes (by truck)
  - good communication systems
- Operation time still 7–8 years with currently known ore reserves (presumably until 2018)
- Compact mine, small 'foot print'
  - water pumping and other maintenance works not major issues



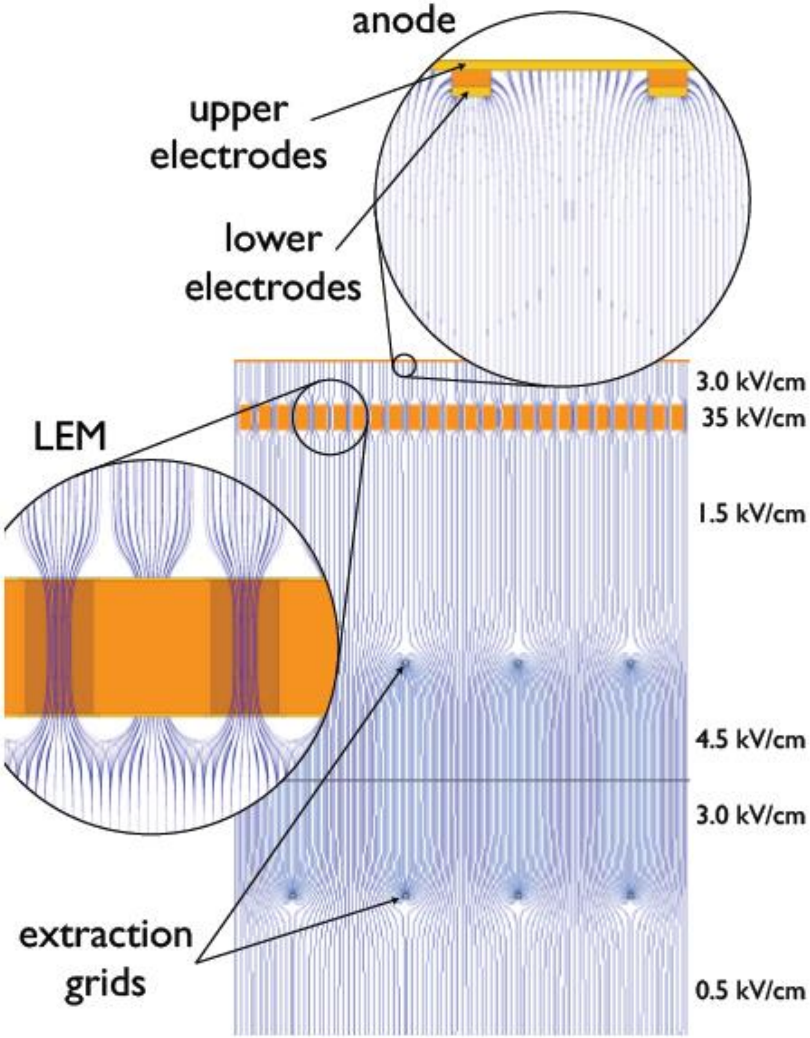
GLACIER + MIND

- **20 kton double phase LAr LEM TPC (GLACIER): best detector for electron appearance measurements with excellent energy resolution and small systematic errors**
  - Very fine grain tracking-calorimeter
  - Exclusive final states, low energy threshold on all particles
  - Excellent ν energy resolution and reconstruction ability from sub GeV to a few GeV, from single prong to high multiplicity
  - Suitable for spectrum measurement with needed wide energy coverage
  - Excellent π^0/electron discrimination
  - Best detector for baselines > 300km
- **35 kton magnetized Muon Detector (MIND): conventional and well-proven detector for muon CC, and NC**
  - muon momentum & charge determination, inclusive total neutrino energy
  - rsμ/wsμ with Neutrino Factory
  - 3cm Fe plates, 1cm scintillator bars, B=1.5-2.5 T

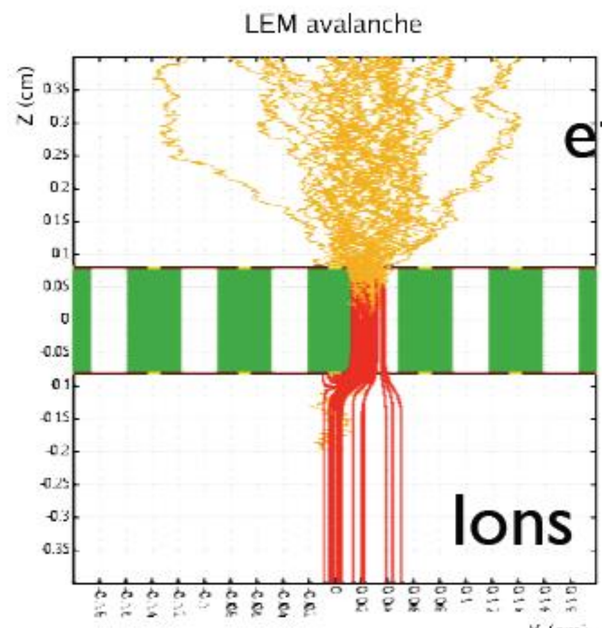




Argon LEM-TPC



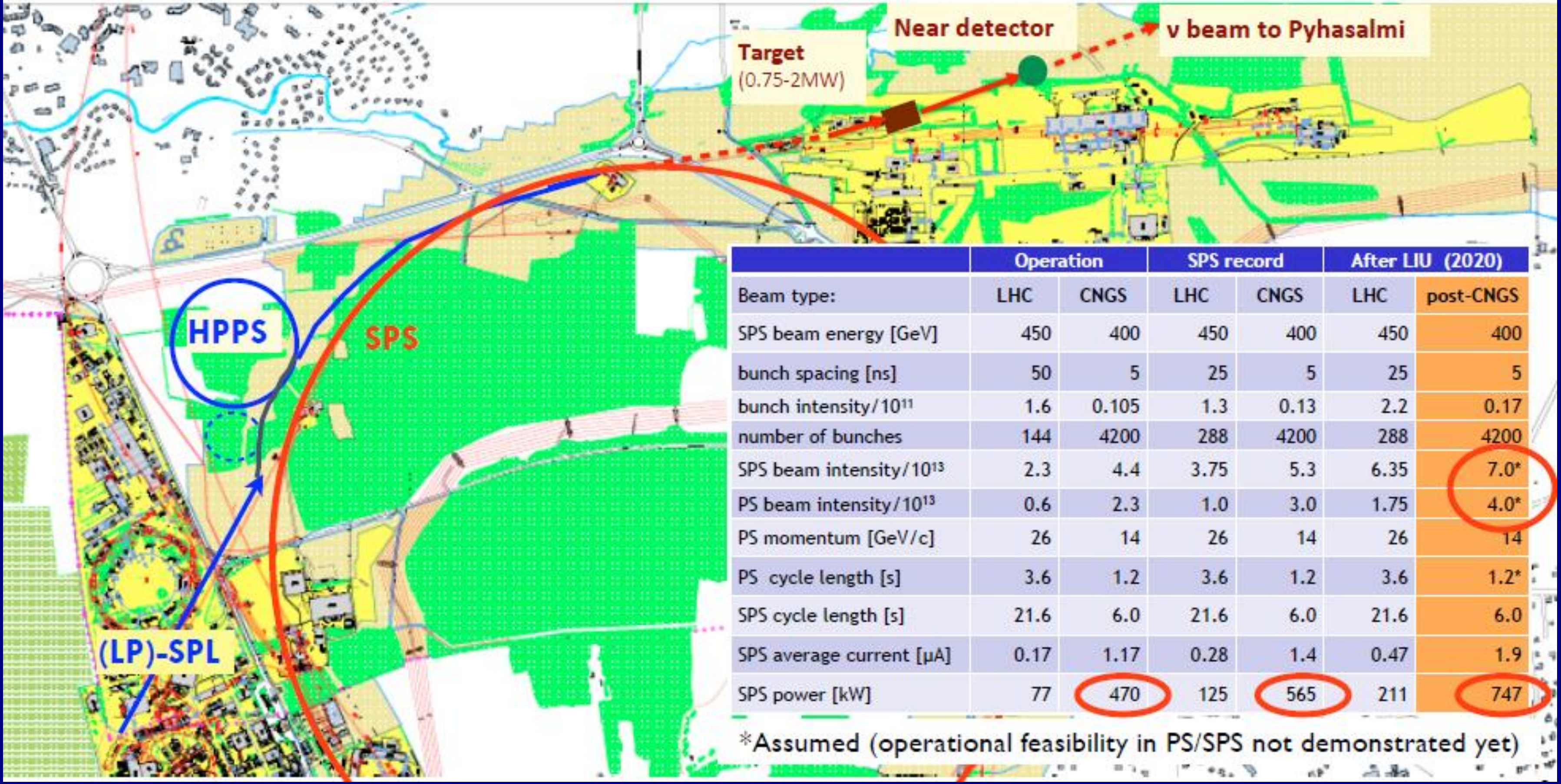
- e⁻ drift up to the liquid argon surface.
- e⁻ are extracted to the vapor phase.
- e⁻ are focused into the LEM holes.
- Townsend avalanche occurs in high electric field region (between two collision e⁻ gain enough energy to ionize argon atoms).



The CN2PY beam

- **Phase 1** : use the proton beam extracted beam from SPS
- **400 GeV**, max 7.0 10^{13} protons every 6 sec, **750 kW** nominal beam power, 10 μs pulse
- Yearly integrated pot = (8–13)e19 pot / yr depending on "sharing" with other fixed target programmes.

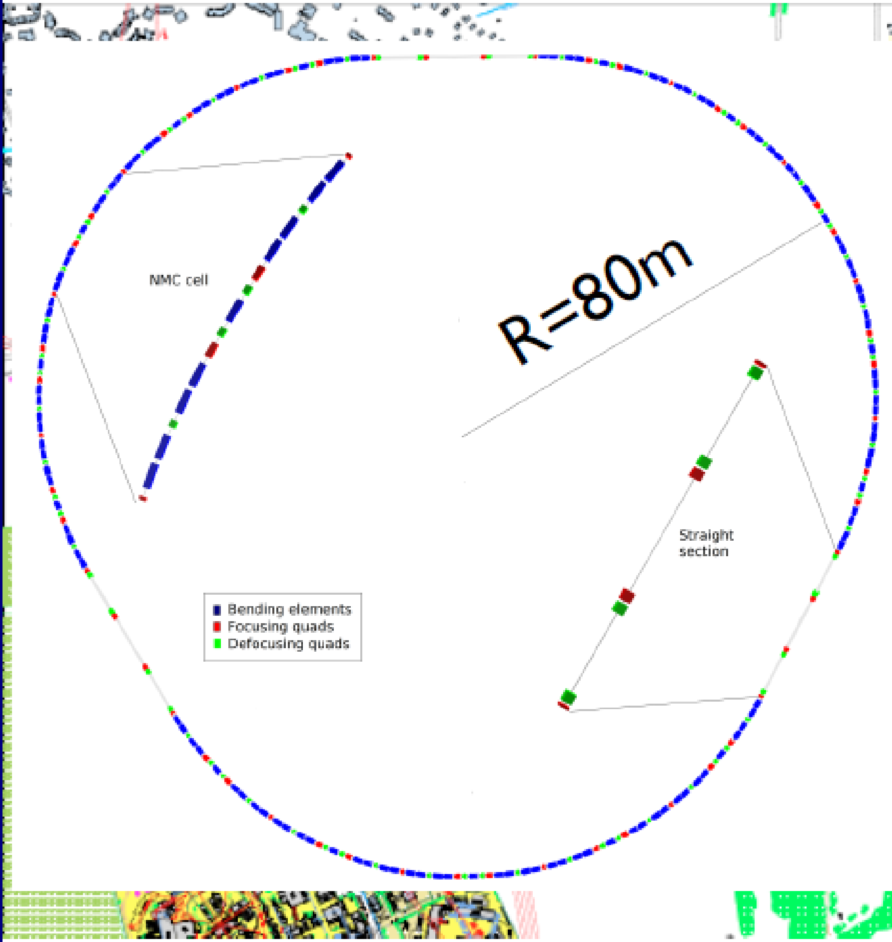
- **Phase 2** : use the proton beam from the new HP-PS
- **50**(70) GeV, 1 Hz, 2.5e14 ppp, **2 MW** nominal beam power, 4 μs pulse



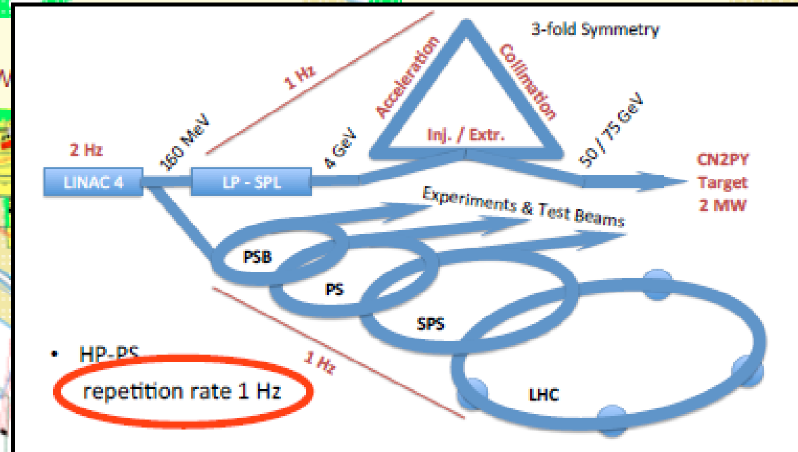
	Operation		SPS record		After LIU (2020)	
Beam type:	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity/10^{11}	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS beam intensity/10^{13}	2.3	4.4	3.75	5.3	6.35	7.0*
PS beam intensity/10^{13}	0.6	2.3	1.0	3.0	1.75	4.0*
PS momentum [GeV/c]	26	14	26	14	26	14
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2*
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	6.0
SPS average current [μA]	0.17	1.17	0.28	1.4	0.47	1.9
SPS power [kW]	77	470	125	565	211	747

*Assumed (operational feasibility in PS/SPS not demonstrated yet)

High power HP-PS study



Target
(0.75-2MW

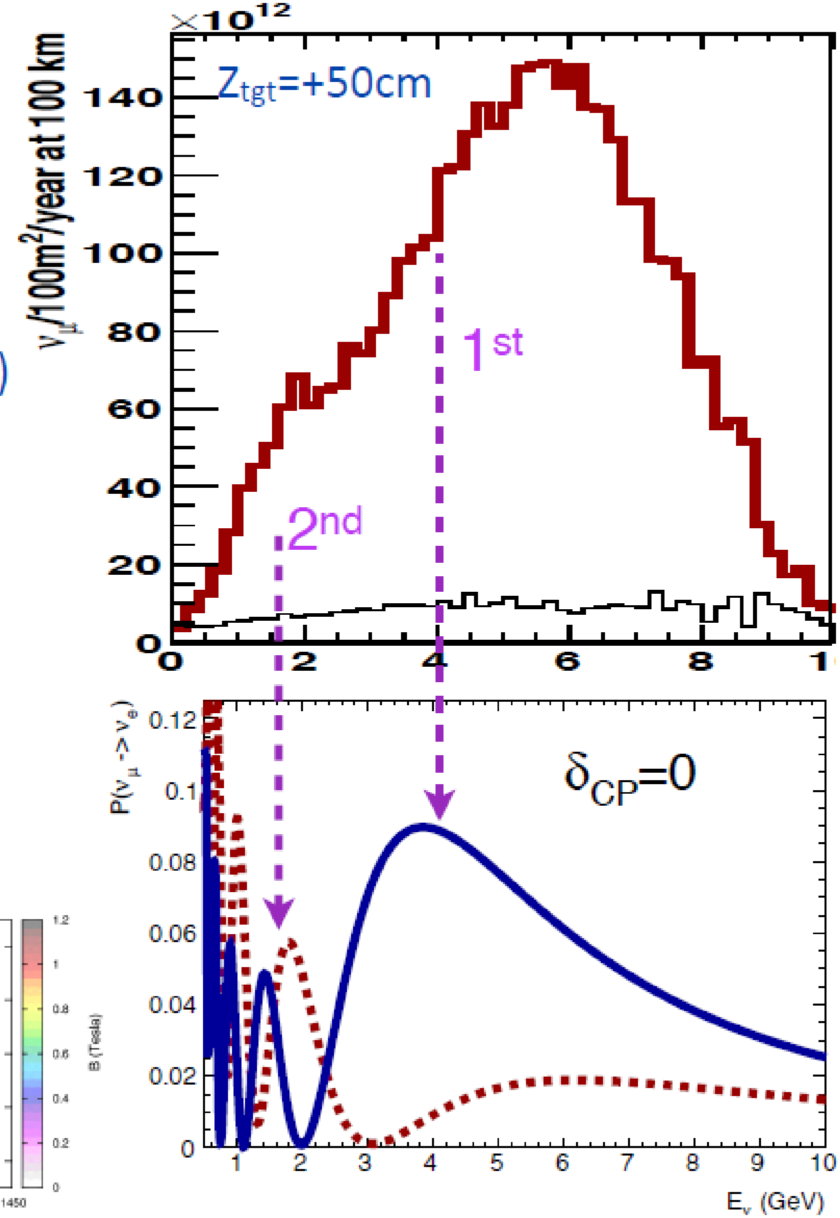


Parameter	50 GeV	75 GeV	Units
Inj. / Extr. Kinetic Energy	4 / 50	4 / 75	[GeV]
Beam power	2		[MW]
Repetition rate	1		[Hz]
f_{rev} / f_{RF} @ inj.	0.248 / 38.97		[MHz]
RF harmonic	157		-
f_{rev} / f_{RF} @ extr.	0.255 / 40.08	0.255 / 40.09	[MHz]
Bunch spacing @ extr.	25		[ns]
Total beam intensity	2.5 x 10^{14}	1.7x10^{14}	-
Number of bunches	147		-
Intensity per bunch	1.7x10^{12}	1.25x10^{12}	-
Main dipole field inj. / extr.	0.17 / 2.1	0.17 / 3.13	[T]
Ramp time	500	500	[ms]
Dipole field rate dB/dt (acc. ramp)	3.9	5.9	[T/s]

- Basic design well underway and main parameters available
- Optics design well advanced
- Injection and extraction concepts are available
- Basic ideas about accelerating RF system
- Basic ideas about collimation
- Consolidate optics and establish set of requirements for different magnet families.
- Design of magnet foreseen.

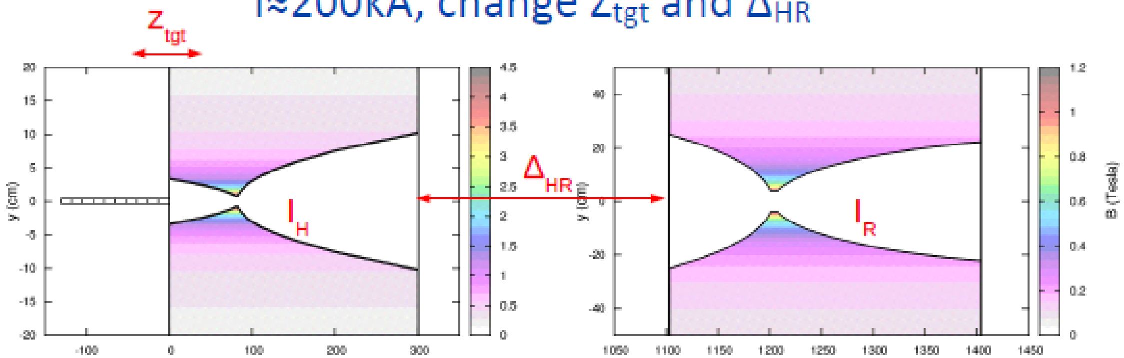
LBNO baseline beam optimisation

- Conventional beam, horn focused
- Medium energy to cover at $E_\nu \approx 4$ GeV (1st max) and $E_\nu \approx 1.5$ GeV (2nd max)
- Wide band covering 1st and 2nd maximum
- Small tail at high energy
- Positive and negative focus (ν and anti-ν modes)
- High beam power (initially 700 kW then 2MW)
- Angle 10deg dip angle (distance = 2300km)
- Muon monitors
- Magnetised near neutrino detector

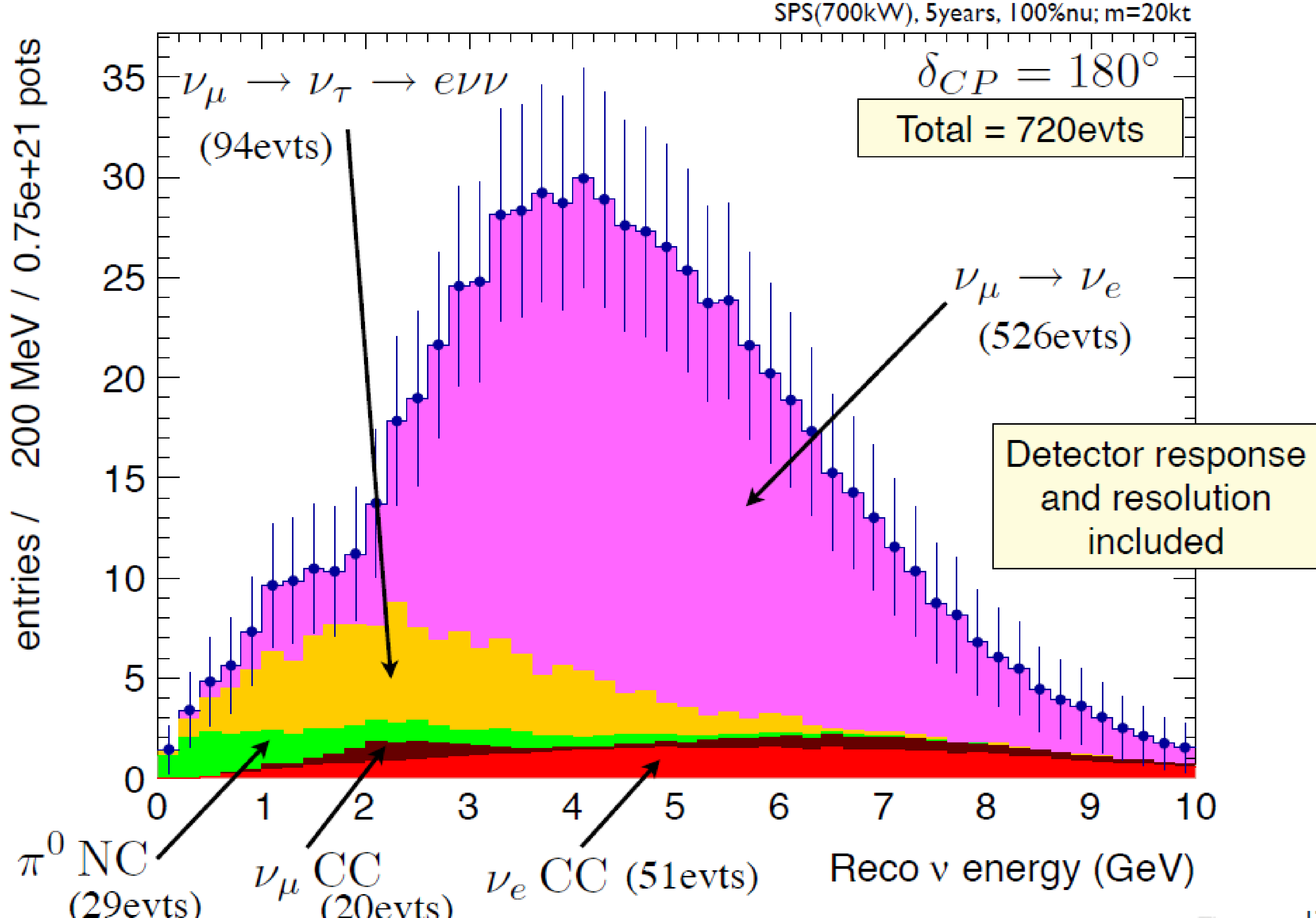


Focusing optimisation (preliminary)

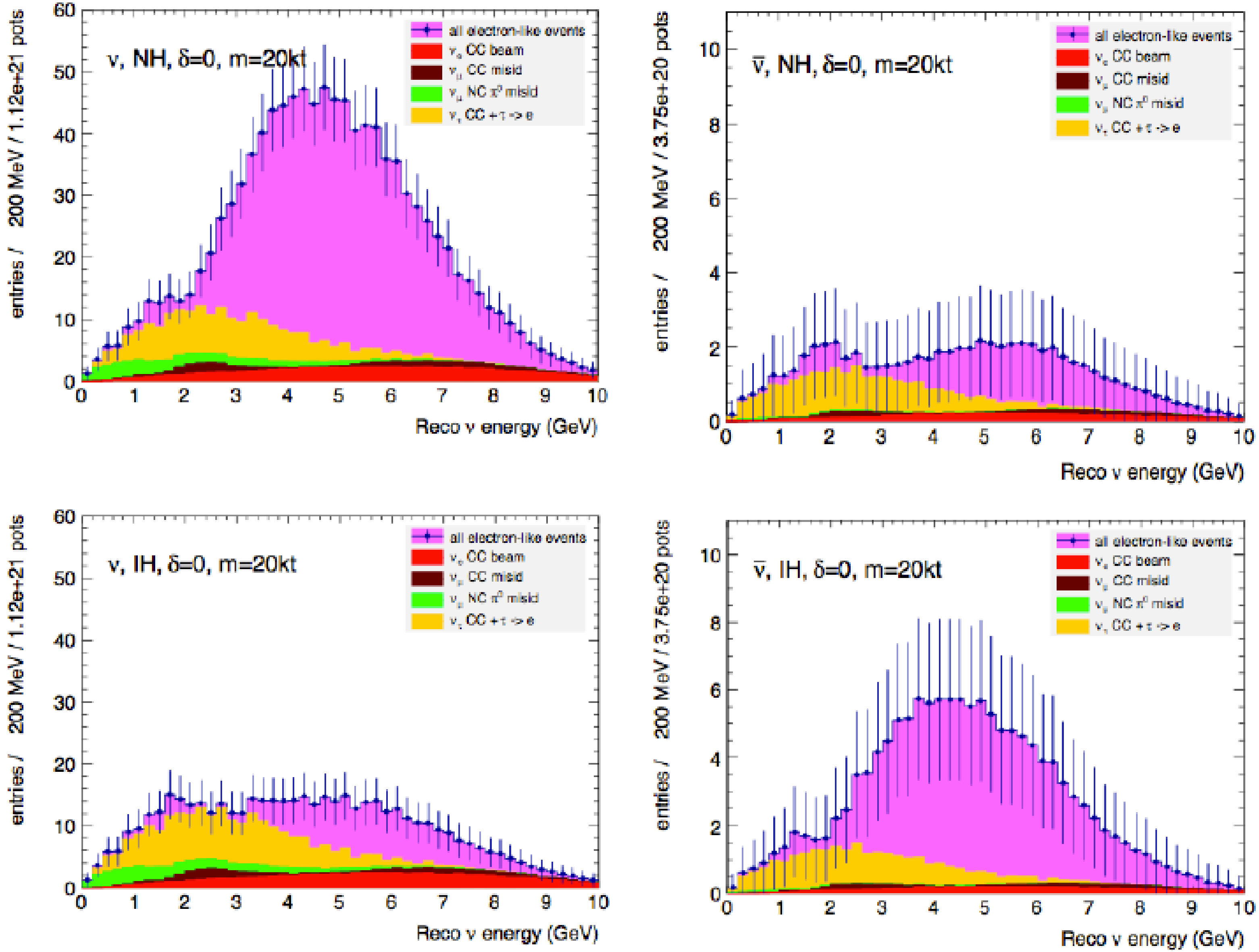
Graphite target (r=4mm), Horn shapes fixed, I≈200kA, change Z_{tgt} and Δ_{HR}

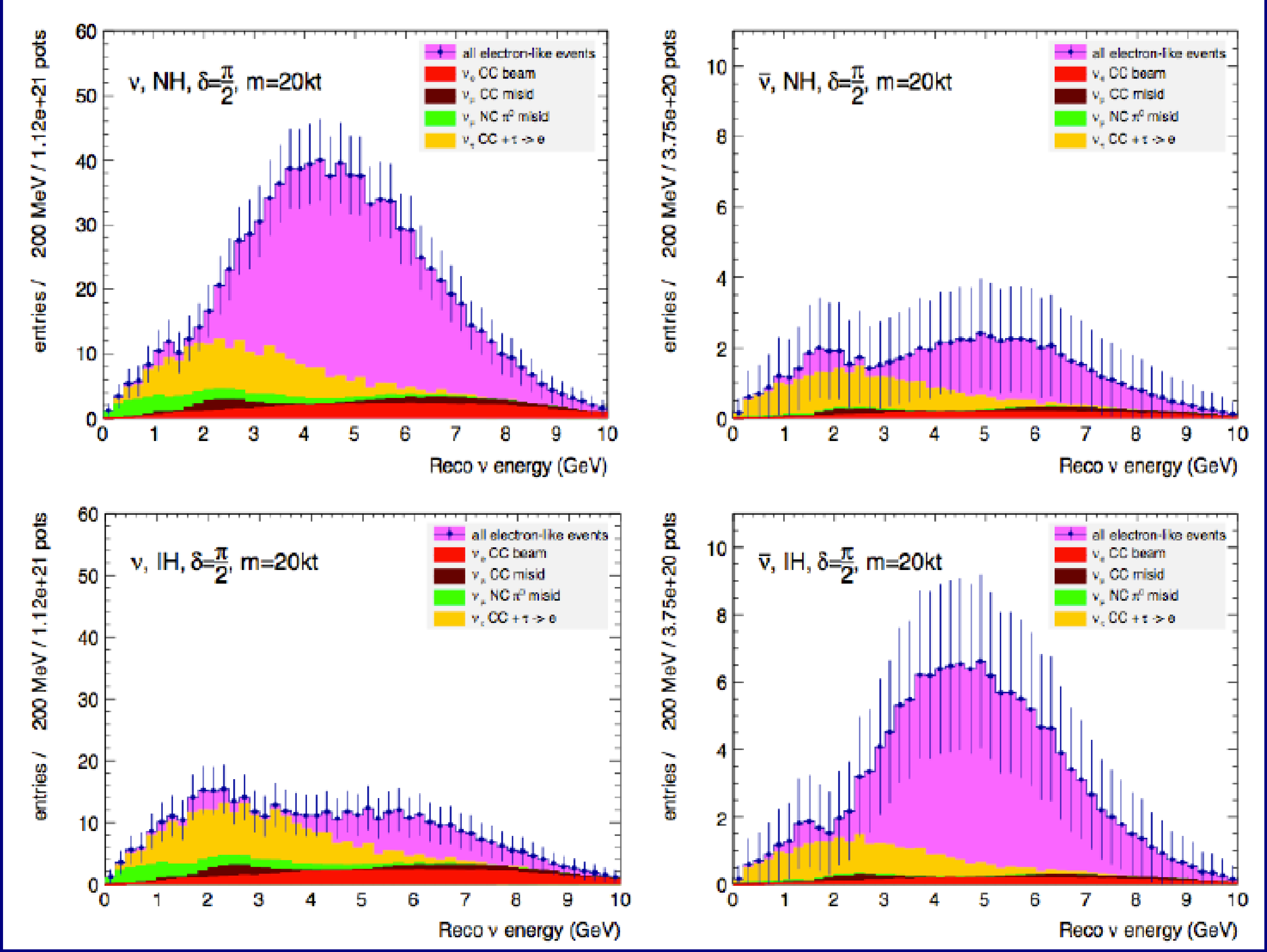


LBNO 20kton LAr: e-like CC sample

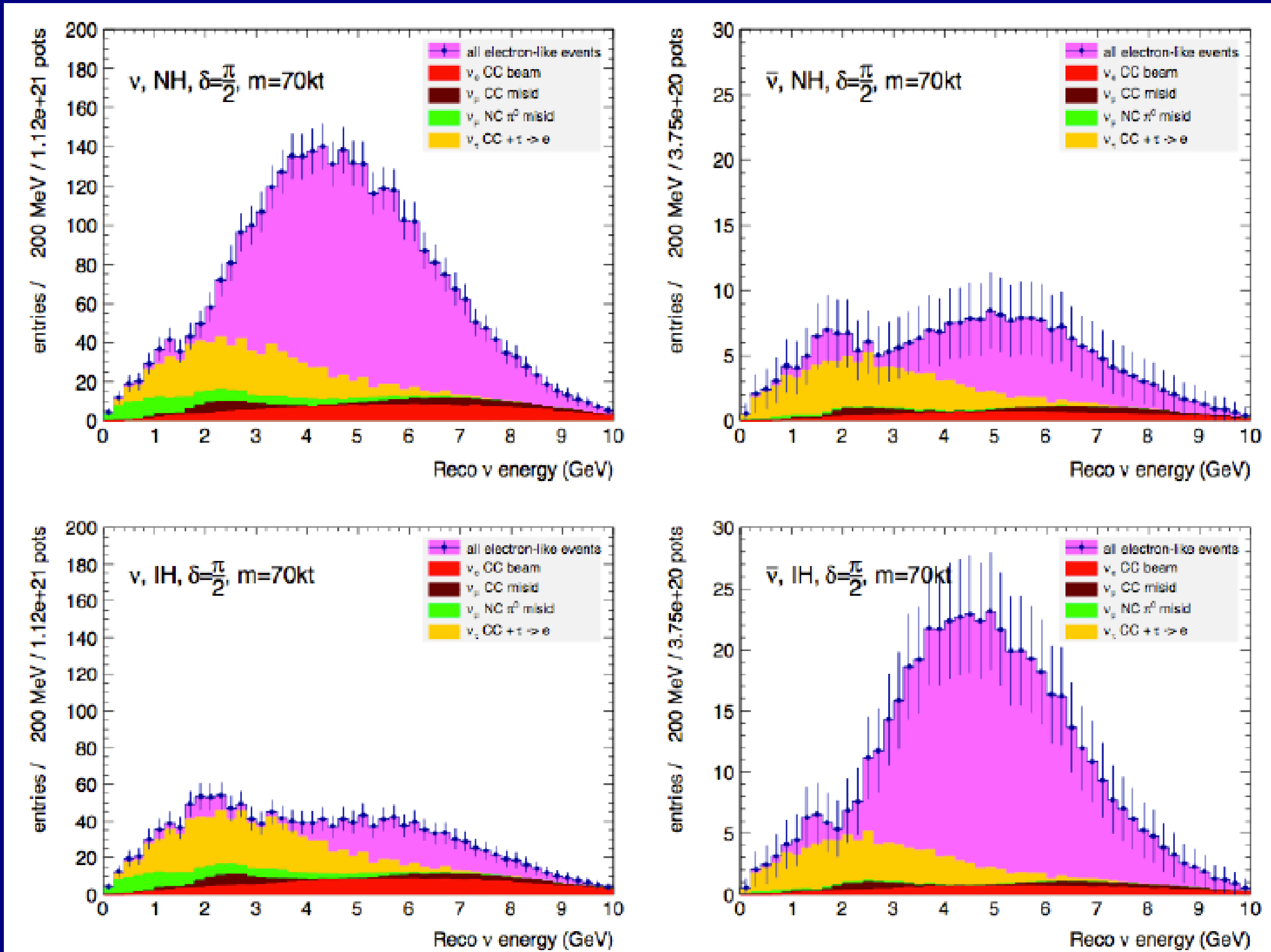


Detector LAr mass = 20 kt:





ν, NH, δ=π/2, m=20kt
ν̄, NH, δ=π/2, m=20kt
ν, IH, δ=π/2, m=20kt
ν̄, IH, δ=π/2, m=20kt
all electron-like events
νe CC beam
νμ CC misid
νμ NC π0 misid
ντ CC + τ -> e
entries / 200 MeV / 1.12e+21 pots
entries / 200 MeV / 3.75e+20 pots
Reco ν energy (GeV)

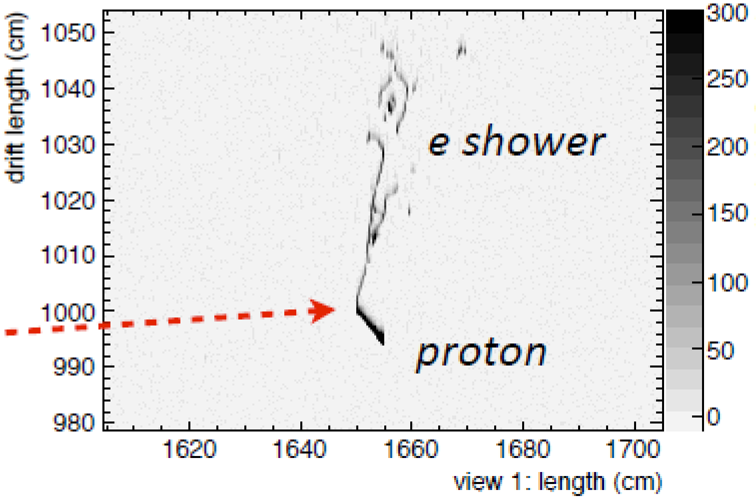


ν, NH, δ=π/2, m=70kt
ν̄, NH, δ=π/2, m=70kt
ν, IH, δ=π/2, m=70kt
ν̄, IH, δ=π/2, m=70kt
all electron-like events
νe CC beam
νμ CC misid
νμ NC π0 misid
ντ CC + τ -> e
entries / 200 MeV / 1.12e+21 pots
entries / 200 MeV / 3.75e+20 pots
Reco ν energy (GeV)

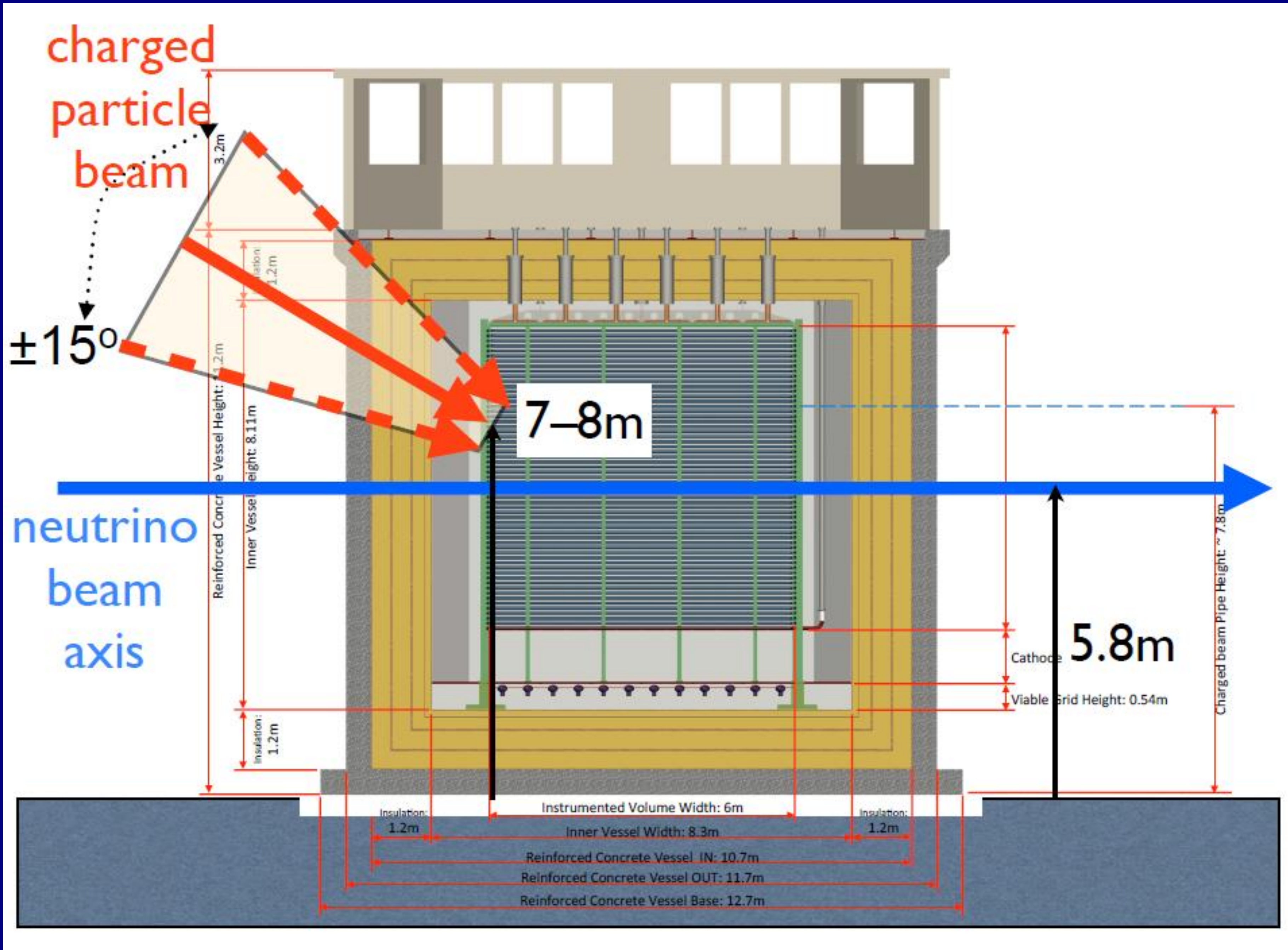
Atmospheric neutrinos

Mode	Events/20kt/yr
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

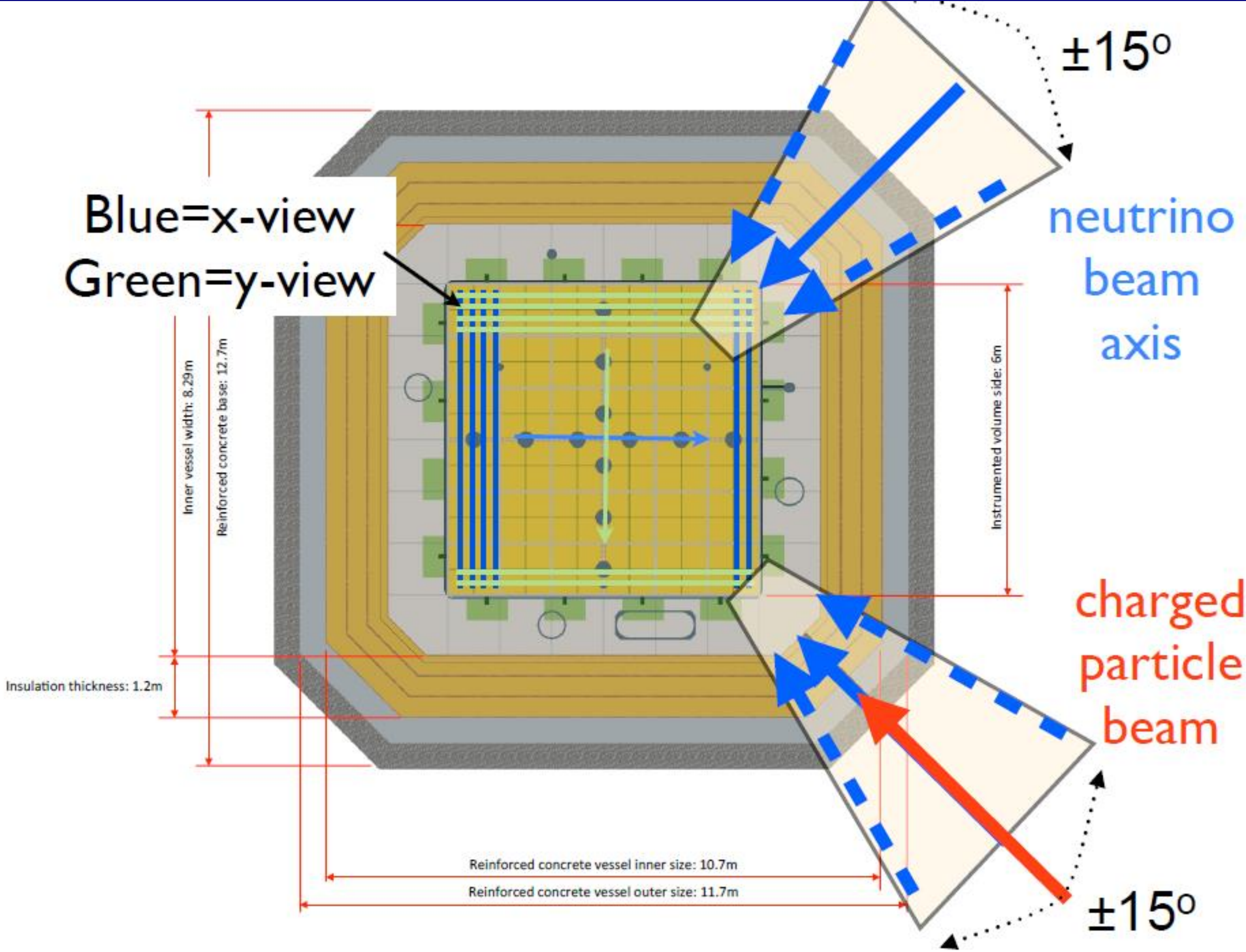
MC: ν_eCC



- **Neutrino oscillation physics complementary to long baseline bear**
- Clean ν_e & ν_μ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 ν_τ CC / year)



charged
particle
beam
±15°
7–8m
neutrino
beam
axis
5.8m
3.2m
Inner Vessel Height: 8.11m
Insulation: 1.2m
Cathode
Viable Grid Height: 0.54m
Charged beam Pipe Height: ~ 7.8m
Instrumented Volume Width: 6m
Inner Vessel Width: 8.3m
Reinforced Concrete Vessel IN: 10.7m
Reinforced Concrete Vessel OUT: 11.7m
Reinforced Concrete Vessel Base: 12.7m


±15°
Blue=x-view
Green=y-view
neutrino
beam
axis
Inner vessel width: 8.29m
Reinforced concrete base: 12.7m
Instrumented volume side: 6m
Insulation thickness: 1.2m
charged
particle
beam
Reinforced concrete vessel inner size: 10.7m
Reinforced concrete vessel outer size: 11.7m
±15°

THE INNER LEM TPC DETECTOR

- The baseline design of the chamber is configured as a 6x6x6 m3 double phase liquid argon LAr LEM-TPC. The ionization charge is drifted and collected in a 2-dimensional readout plane located at the top of the drift volume, providing two independent views of the event. The combination of the two views with the common drift(time) coordinate allows for a three dimensional tracking and calorimetric reconstruction of the events.
- The total fully active volume is ~216 m3. A uniform electric field E ≃ 0.5 kV/cm generated from a bottom cathode plane (6x6 m2) operated at ~300 kV and kept uniform by a stack of field shaping electrodes (round pipes along a square path, with rounded corners) polarized at linearly decreasing voltage from the cathode voltage to ground.
- The possibility to upgrade the electric drift field to 1 kV/cm will be considered, if the parallel development of a MV-class power supply and associated feed-through is successful.
- The cathode plane is transparent to allow the detection of the scintillation light by an array of photomultipliers located below the cathode at a distance of ~1m under it.
- Ionization charge signals are sent to a set of signal feed-throughs, located on the top face of the hosting LAr vessel. Other chimneys/feed-throughs are foreseen for HV, top readout plane suspension and level regulation, PMT high voltage and signal readout, monitoring instrumentation (level, temperature, ...).
- Cathode and field shaping electrodes are kept in their position by a set of insulating supports/spacers resting on the inner vessel floor.
- The readout electronics is located on top of the detector. In a further development, the front-end charge preamplifiers and possibly the digitizers will be located within the thermal insulation and right on top of the signal feed-throughs. This configuration allows for cold electronics while retaining access without opening the main vessel.

CRYOGENIC VESSEL AND THERMAL INSULATION

- The inner vessel has a cubic shape with inner dimensions ~8.3x8.3x8.3m3.
- This volume ensures enough space surrounding the drift cage, acting as electric insulation (~1 m of LAr), for safe operation at HV with up to 300 kV at the cathode.
- This volume shall also be used for access and movement inside the vessel during the construction phase. A manhole and a detail-introduction hole are located at the top face of the vessel.
- During the inner detector assembly, additional chimneys are used to install a controlled air circulation. These additional chimneys are available for the implementation of the liquid argon process during normal operation.
- The cryogenic vessel is built using technologies developed by the petro-chemical industry. This topic has been the subject of several developments between LAGUNA and industry over many years (since 2004). The so-called corrugate membrane panels technique (licensed by GTT/France), has been envisaged as an attractive solution for the LAGUNA LAr prototype.
- The thermal insulation is passive, based on GRPF (glass reinforced polyurethane foam) layers, interspersed with pressure distributing layers of plywood. Its thickness and composition is such to reach a residual heat input of 5 W/m2 in cold operation.
- The total heat input (including the input from the roof and the cables) in cold operation at LAr temperature is ~2 kW.