Path Towards Long Baseline Neutrino Experiments : WA105-DUNE

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Outline :

- Neutrino oscillations
- LBL future projects
- WA105 prototypes

Enigmass General Meeting — December 9th 2016 — Annecy

Neutrino Oscillations

Neutrino mass (i=1,2,3) and flavor (**α**=e,**μ**,**τ**) eigenstates are linked by the PMNS unitary matrix :

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad |\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

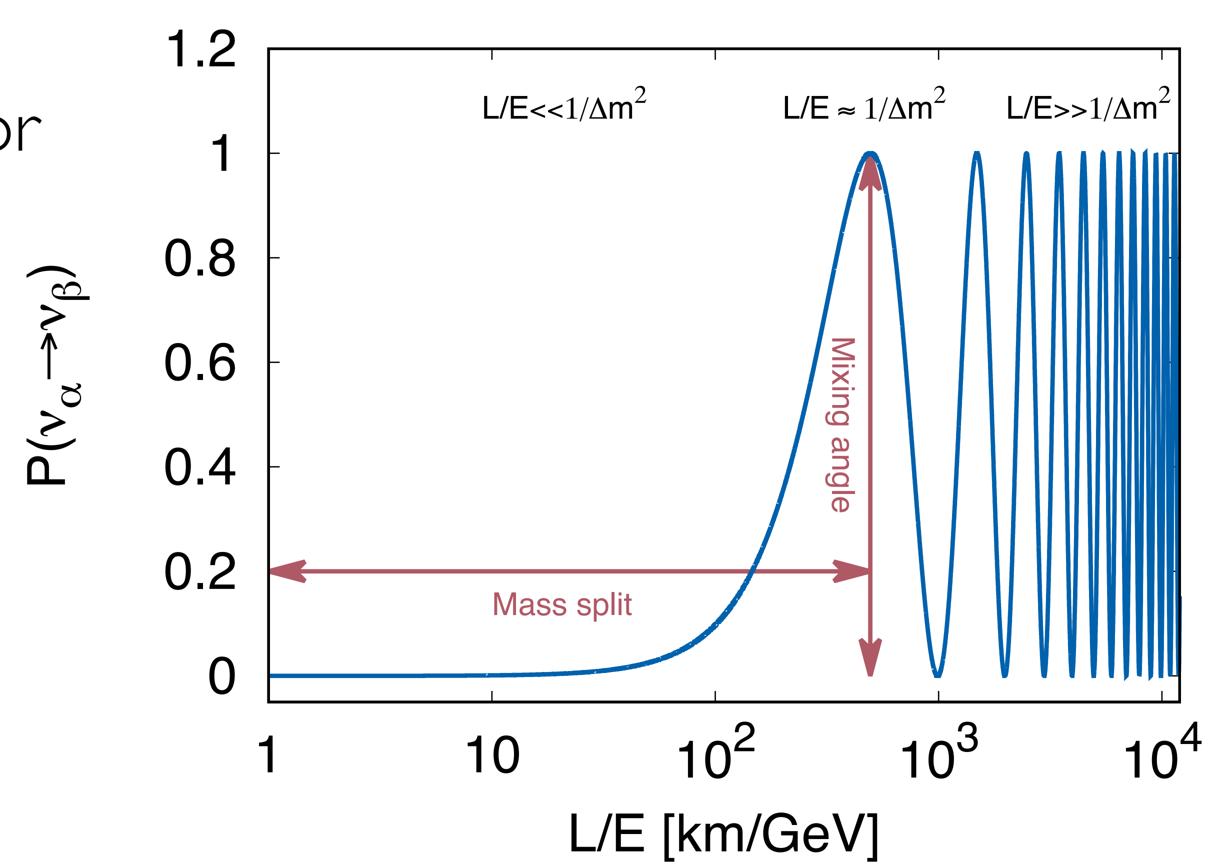
Several consequences :

- Neutrino can oscillate : a produced ν_α at energy E can be detected as a ν_β after travelling a distance L
- Neutrinos are massive
- Can lead to CP violation in the leptonic sector

For 2 **ν** flavors in vacuum, a simplified oscillation probability can be written as :

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 = m_1^2 - m_2^2$$



Neutrino Oscillations - 3 flavors

Atmospheric — Reactor/Accelerator — Solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

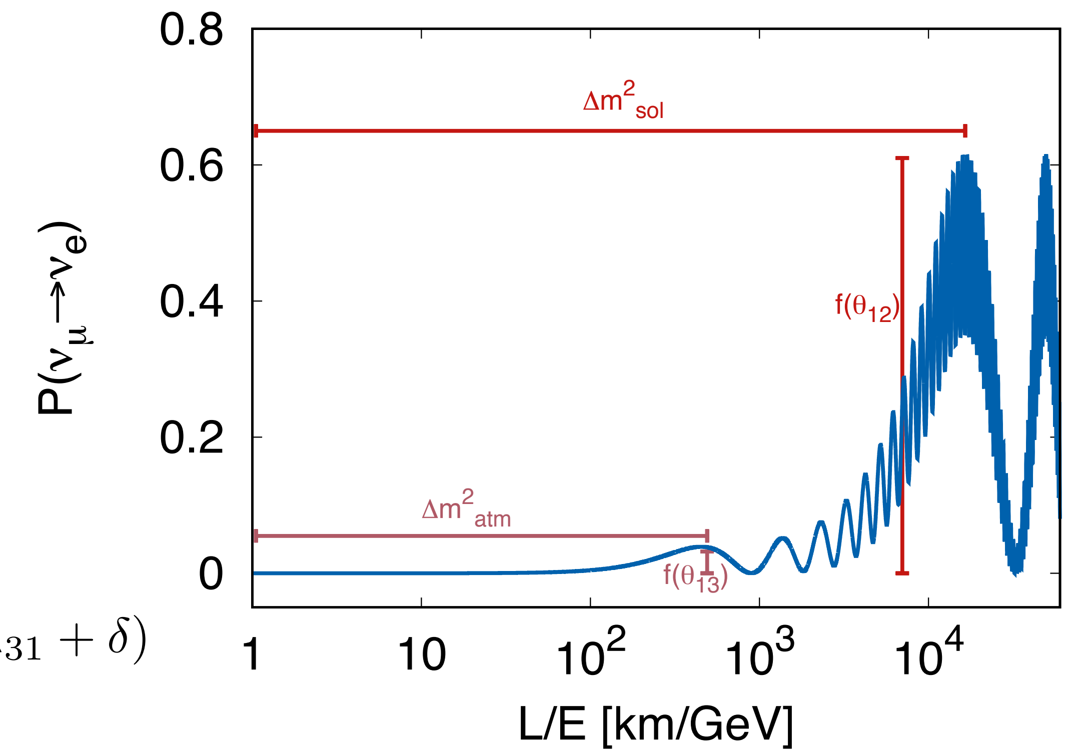
$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

For 3 ν flavors, the oscillation phenomena is parametrized by

- 3 mixing angles θ_{12}, θ_{23}, θ_{13},
- 2 mass splittings Δm^2_{sol}, Δm^2_{atm}
- 1 CP violation phase δ_{cp}
- Oscillation probabilities are modified in matter

ν_e appearance probability from a ν_μ beam in matter :



$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta)$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$a = \frac{G_F \times N_e}{\sqrt{2}}, \quad \Delta_{ij} = \frac{\Delta m^2_{ij}L}{4E}, \quad \Delta m^2_{ij} = m_i^2 - m_j^2$$

Where we are today

[1611.01514, nu-fit.org]

At 1σ level : Normal hierarchy assumed

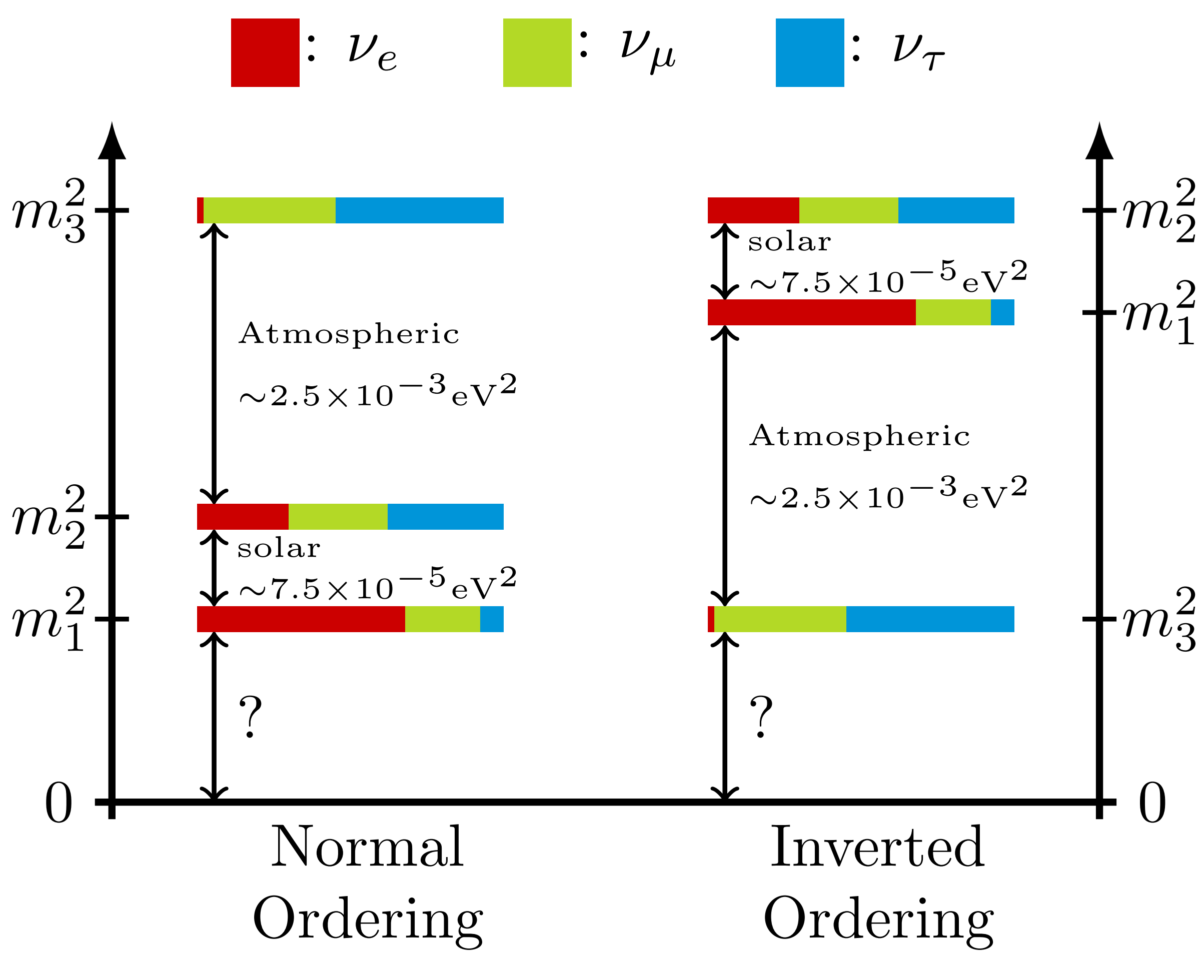
$$\theta_{12} = 33.56^{+0.77}_{-0.75}$$

$$\theta_{23} = 41.6^{+1.5}_{-1.2}$$

$$\theta_{13} = 8.46^{+0.15}_{-0.15}$$

$$\Delta m^2_{21} = \Delta m^2_{sol} = 7.50^{+0.19}_{-0.17} \cdot 10^{-5} \mathrm{eV}^2$$

$$\Delta m^2_{31} = \Delta m^2_{atm} = 2.52^{+0.039}_{-0.040} \cdot 10^{-3} \mathrm{eV}^2$$

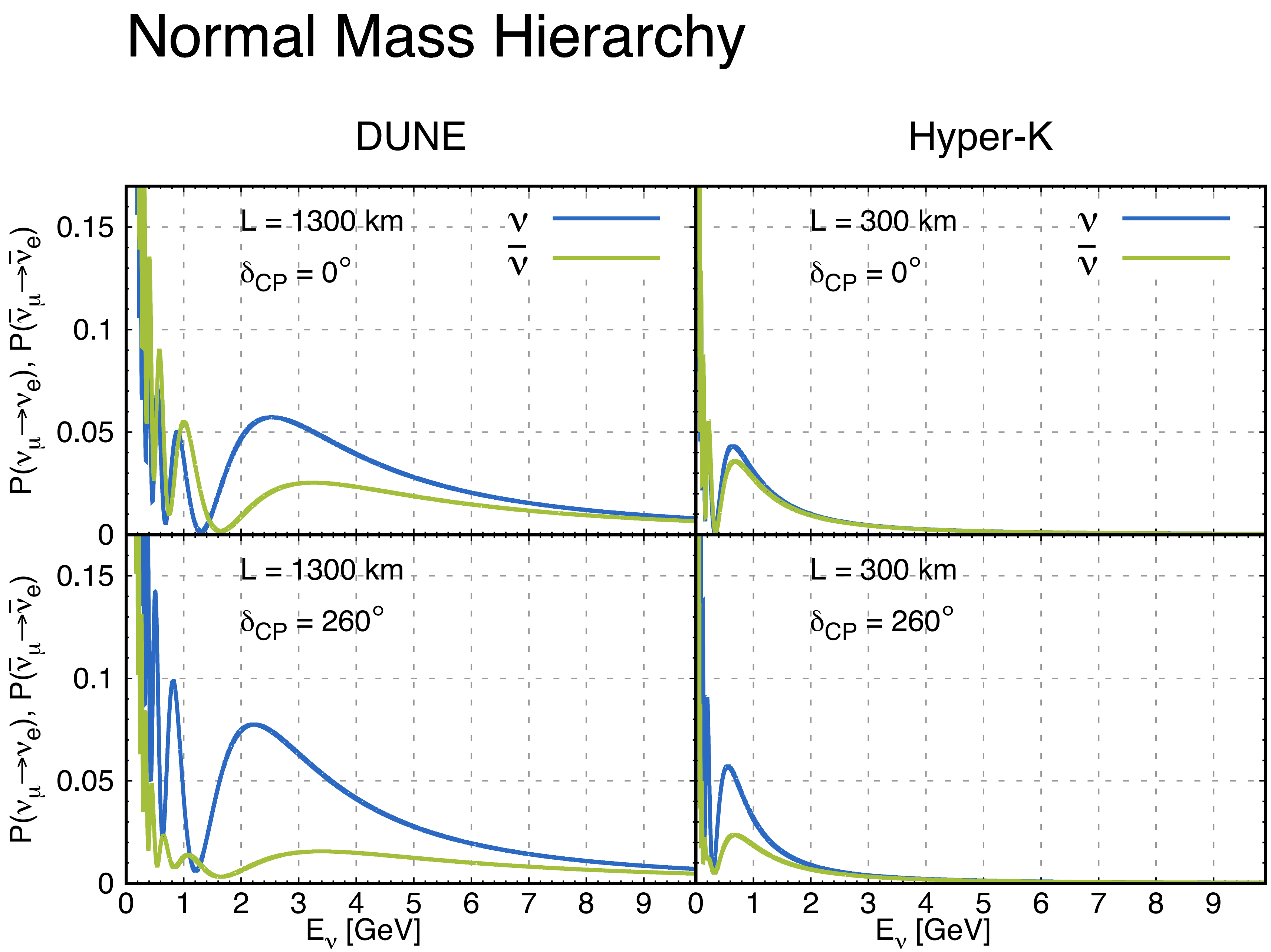


Still unknown :

- Absolute neutrino mass
- Nature of neutrino (Dirac, Majorana)
- Existence of sterile neutrino
- **Mass hierarchy**
- **CP violation**

↳ Can be addressed with long baseline experiments

Oscillation probabilities



$\sin^2\theta_{12} = 0.306$

$\sin^2\theta_{23} = 0.441$

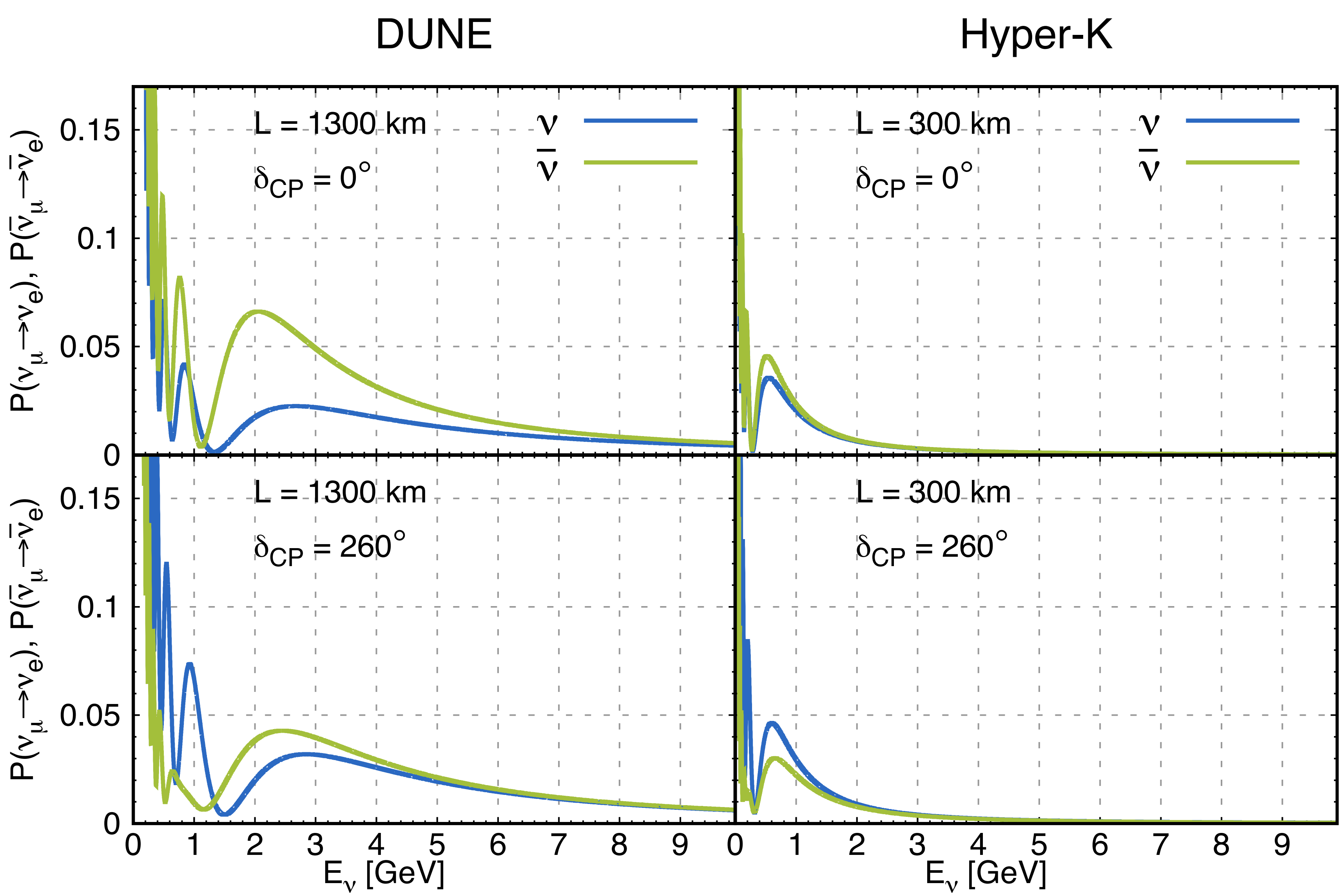
$\sin^2\theta_{13} = 0.022$

$\Delta m^2_{sol} = 7.50\mathrm{x}10^{-5}\ \mathrm{eV}^2$

$\Delta M^2_{atm} = 2.52\mathrm{x}10^{-3}\ \mathrm{eV}^2$

Oscillation probabilities

Inverted Mass Hierarchy



$\sin^2\theta_{12} = 0.306$

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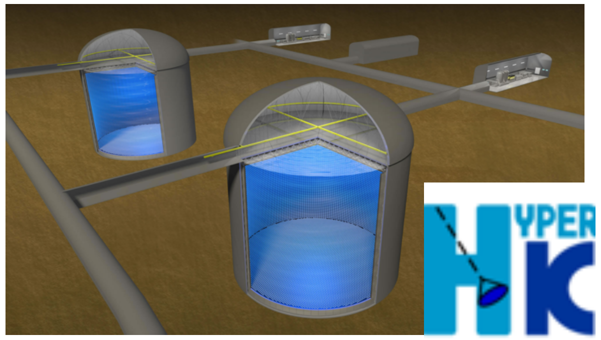
$\Delta m^2_{sol} = 7.50\text{x}10^{-5}\ \text{eV}^2$

$\Delta M^2_{atm} = -2.52\text{x}10^{-3}\ \text{eV}^2$

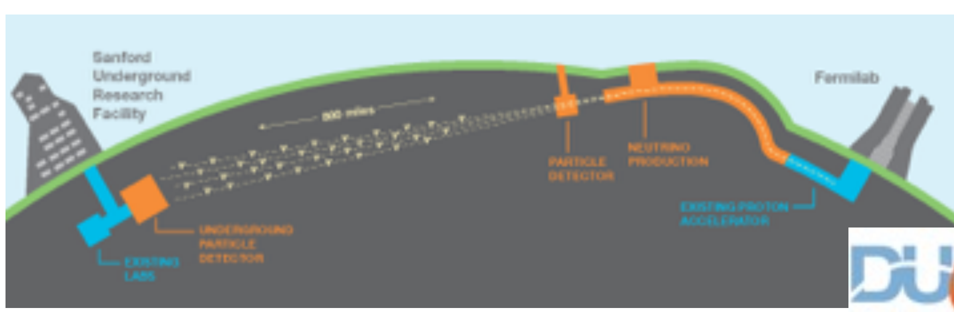
Two projects for future LBL ν experiments



HyperK LoI [1109.3262]

Hyper-Kamiokande [Japan, L~300 km]

- 380 kt water cherenkov detector
- Proven and scalable technology (Kamiokande → Super-Kamiokande)
- Excellent e-μ ring separation
- Little R&D foreseen
- Only low energy beam possible (below 1 GeV)
- Poor energy resolution



DUNE CDR Vol 2 [1512.06148]

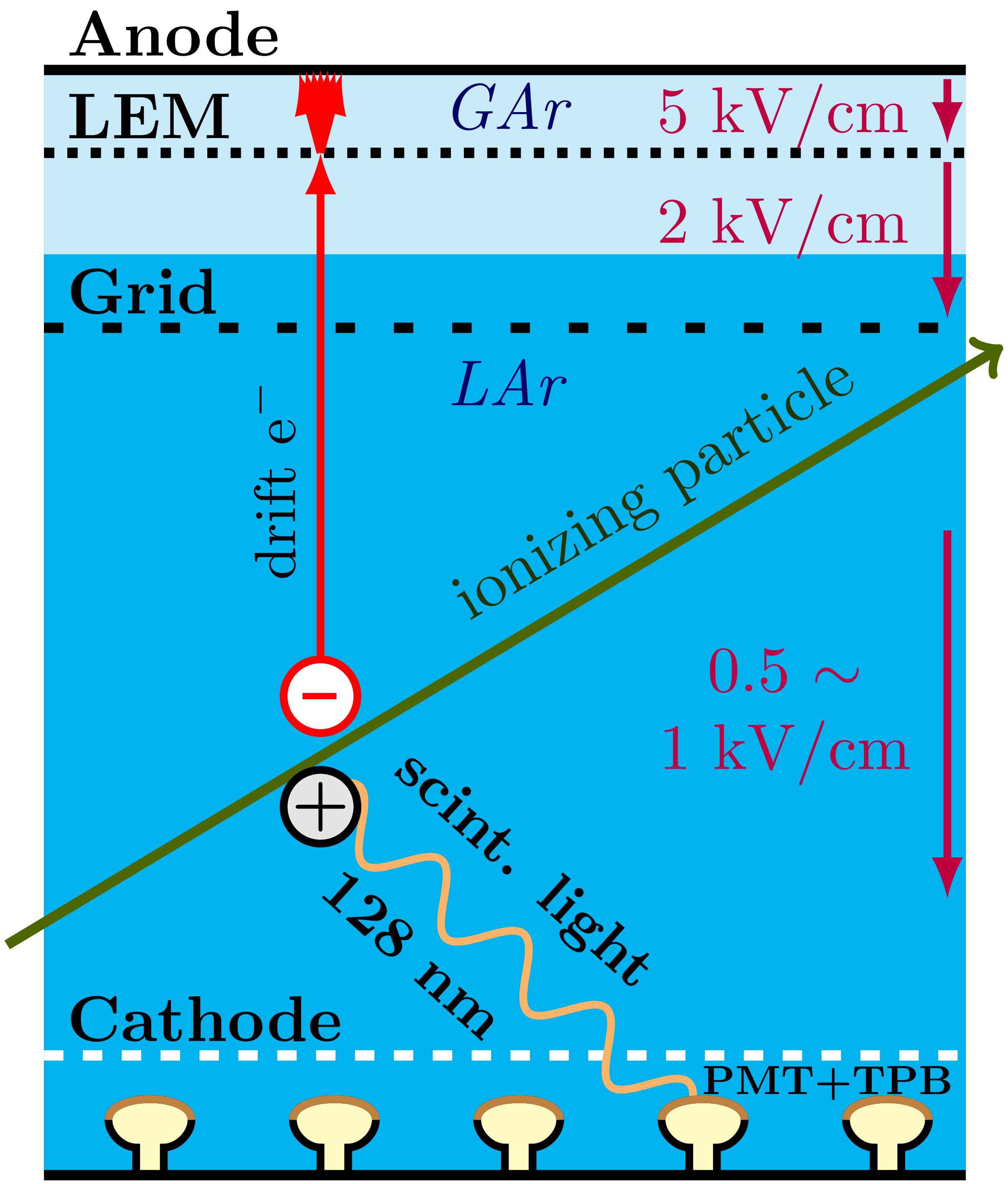
DUNE [USA, L~1300 km]

- 40 kt liquid argon TPC detector
- 3D imaging with high granularity for precise tracking
- Low energy threshold (~10s MeV)

- Important R&D efforts ongoing :
  - Scalability
  - Engineering
  - Purity
  - Physics performance

The two projects are complementary

Liquid Argon TPC principle



- Liquid Argon [T = 87 K] is inert, dense [ρ=1.4 g/mL] and naturally abundant
- Strong electric field applied across the TPC [E ~ 500 V/cm] to collect electrons [v_{drift} ~ 1.6 mm/μs] produced by energy loss [W_i = 23.6 eV/pair]. Electron attachment is low [$\tau_e \simeq 300/\rho(O2\text{ in ppb})$] which allow long drifts.
- Scintillation light [λ = 128 nm] produced [W_s = 19.5 eV/γ] with a fast [τ_f = 6 ns] and a slow [τ_s = 1.6 μs] time constants. Can be used as a trigger and a complementary calorimetry measurement.
- Double phase technology adds a layer of gaseous argon underneath the readout to amplify the signal by a Large Electron Multiplier

The WA105 collaboration

The goal of the experiment is to test the double phase LArTPC technology in real conditions by constructing, operating and analyzing prototypes at CERN.

It is now part of the DUNE project, being referred to as 'ProtoDUNE Dual Phase'
7 countries, 15 institutions, ~100 people involved.

→ 4 french laboratories : APC, IPNL, LAPP, LPNHE and IRFU

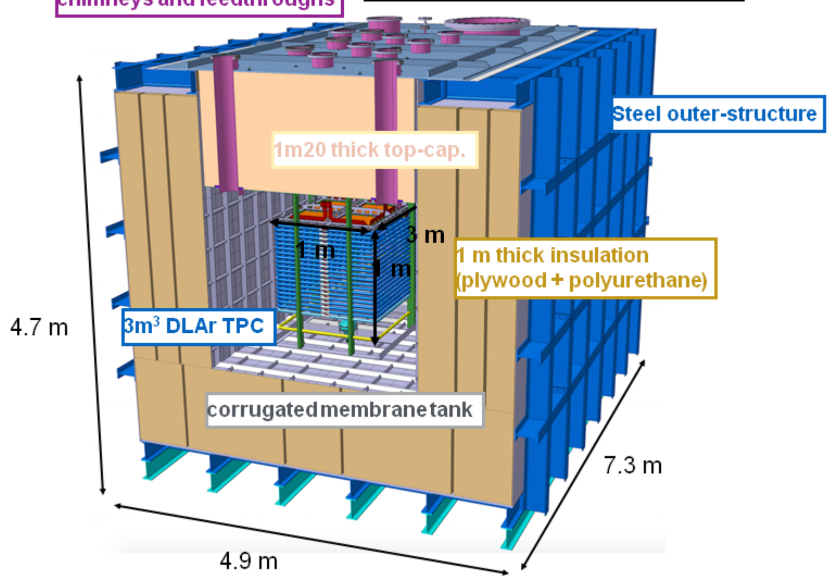
→ LAPP is involved in many aspects (design, construction, operation, simulation, analysis)

<u>Collaboration milestones achieved :</u>
2013: Project started
2014: TDR submitted [CERN-SPSC-2014-013 - SPSC-TDR-004(2014)]
2015: SPSC Annual review [SPSC-SR-158], DUNE CDR, WA105 project MOU signed, WA105 integrated into DUNE
2016: SPSC Annual review [CERN-SPSC-2016-017 SPSC-SR-184], EOI call for institutes

Double phase LArTPC prototypes

3x1x1 m^3 demonstrator

2014 ~ 2017

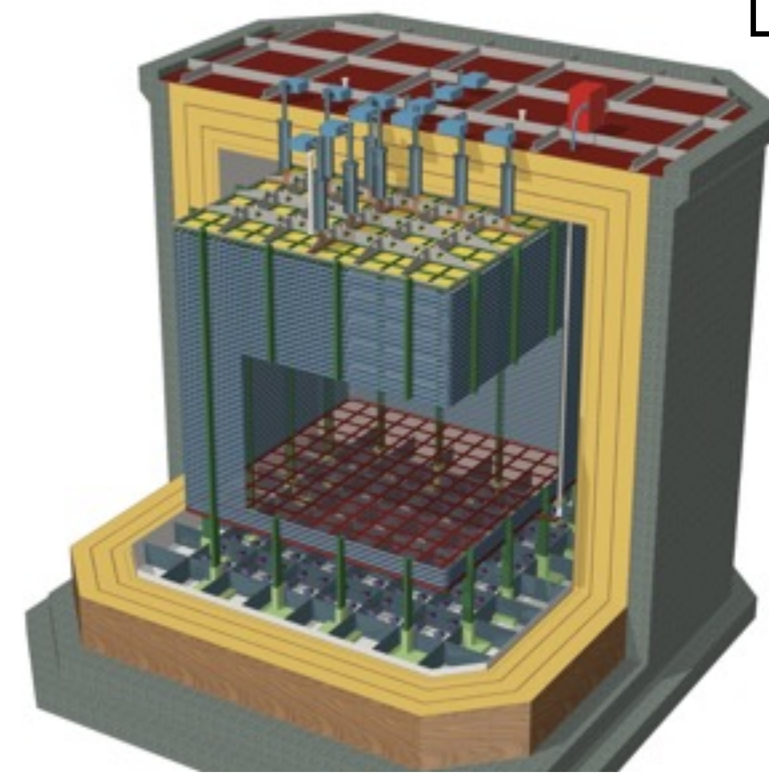


@ CERN BLDG. 182

@ CERN IN NORTH AREA

6x6x6 m^3 prototype

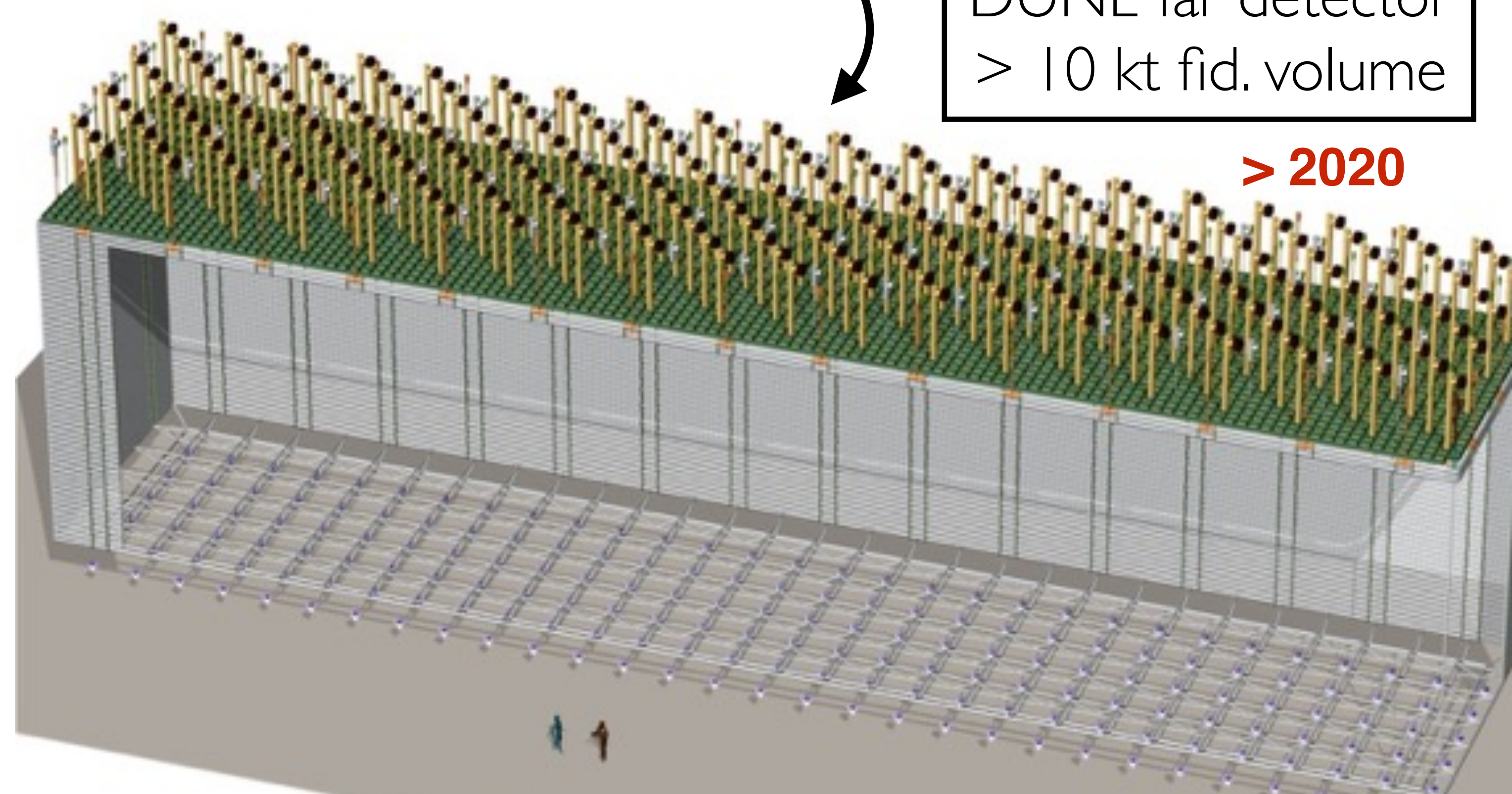
2016 ~ 2019



BEAM

DUNE far detector > 10 kt fid. volume

> 2020



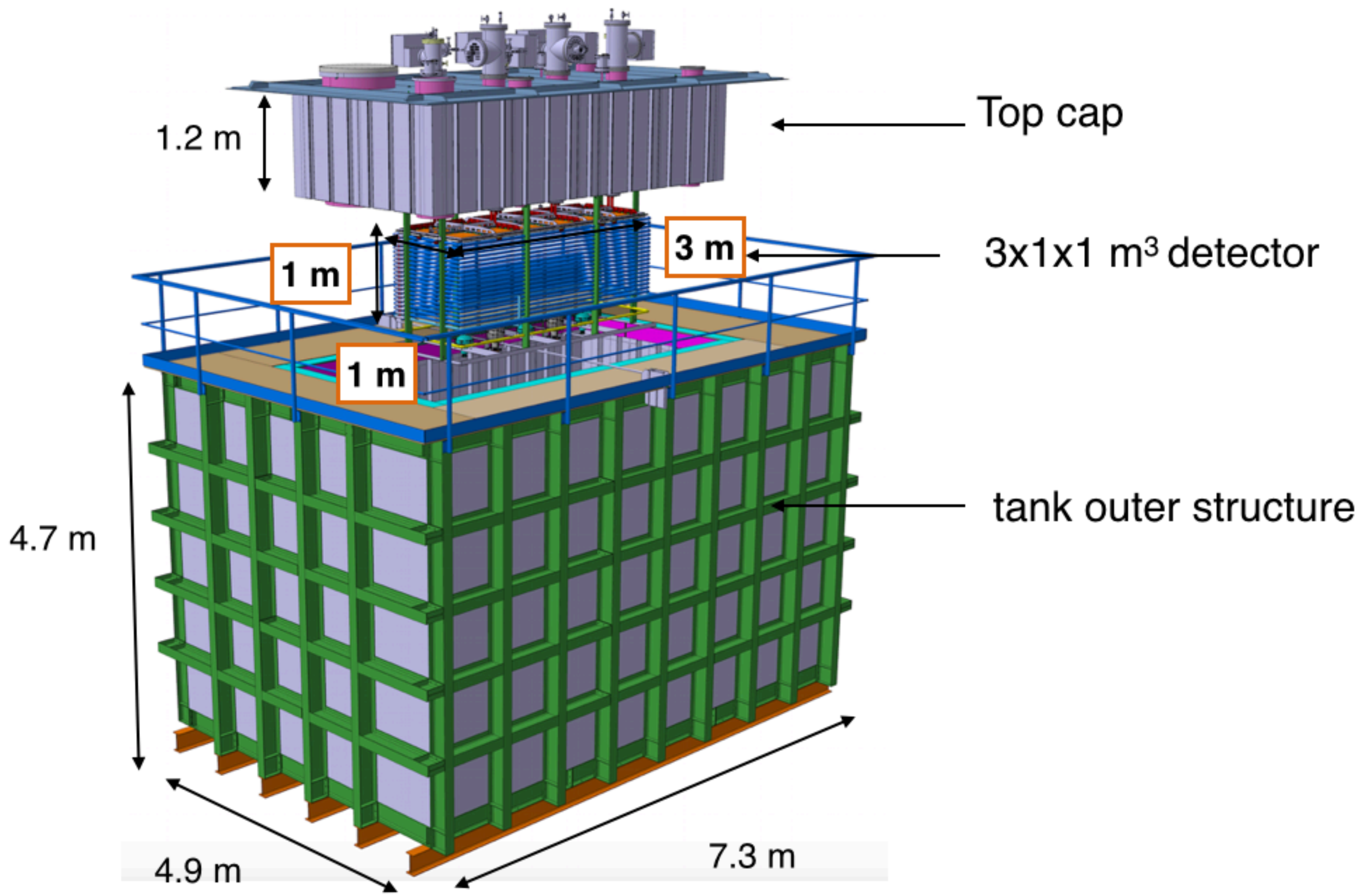
various small TPCs around the world

2010 ~ 2014

WA105 3x1x1 demonstrator at CERN

Built for:

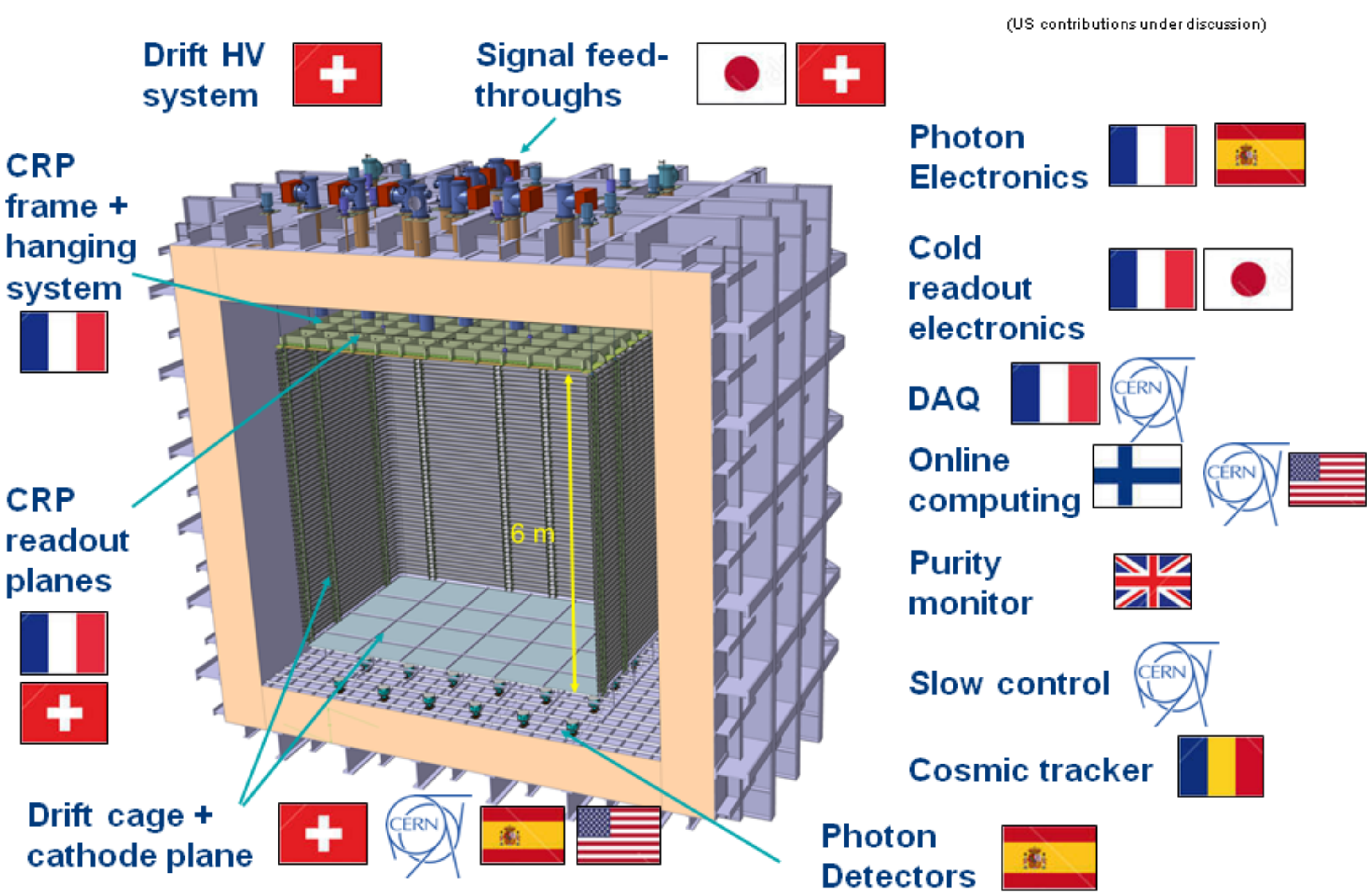
- Establishment of routine procedure for mass production
- Quality assurance and control tests
- Calibration of LEMs
- Cryogenic installation, feedthrough
- Validation of production schedule for the 6x6x6 m^3



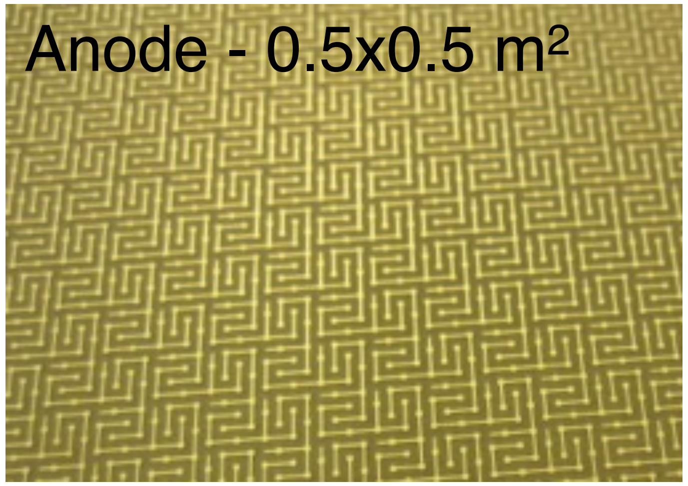
WA105 3x1x1 → 6x6x6 prototype

A bigger prototype of 6x6x6 m^3 will be constructed to assess :

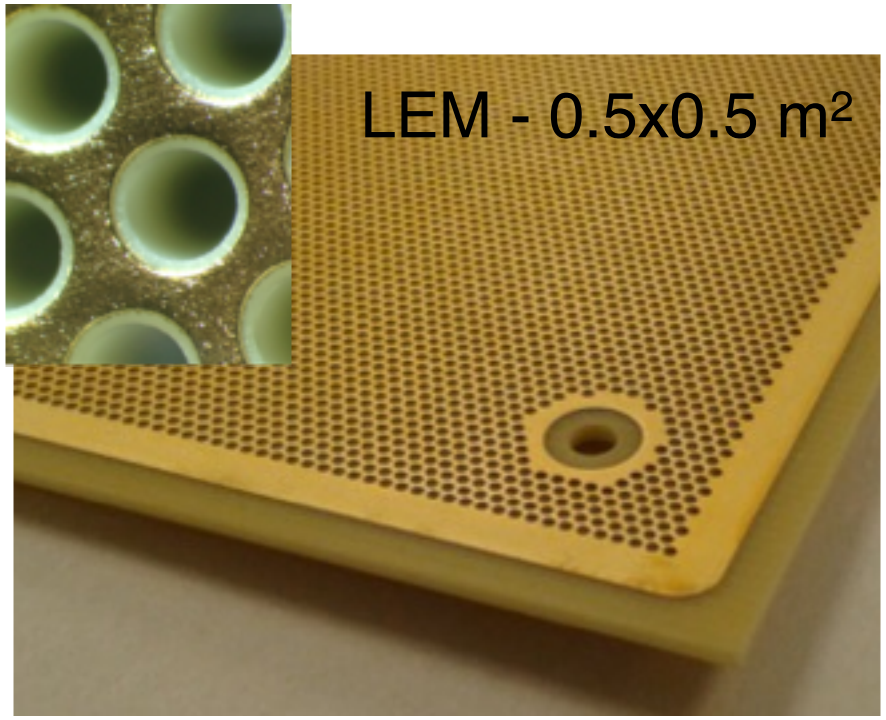
- Large vessel and field cage structure
- Large surface of charge readout
- Very high voltage generation
- Exposure to a charged particle beam
- Long drift
- Design validation towards DUNE



Charge Readout Plane

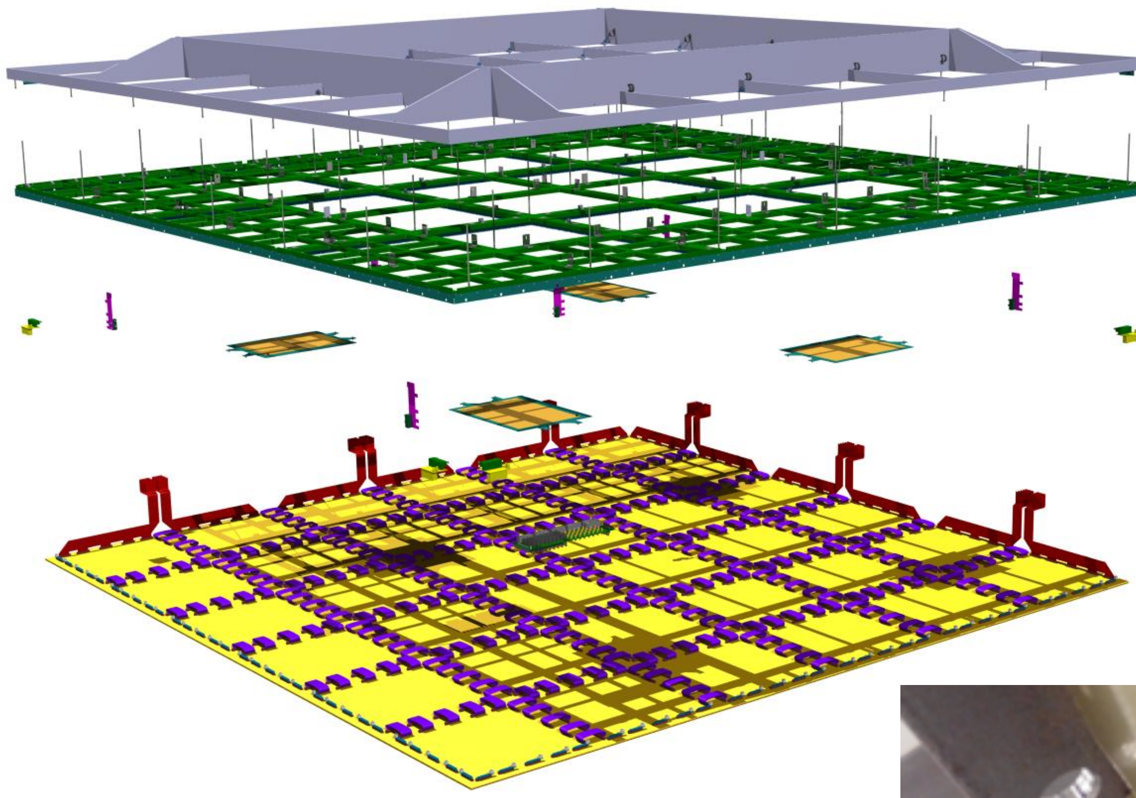


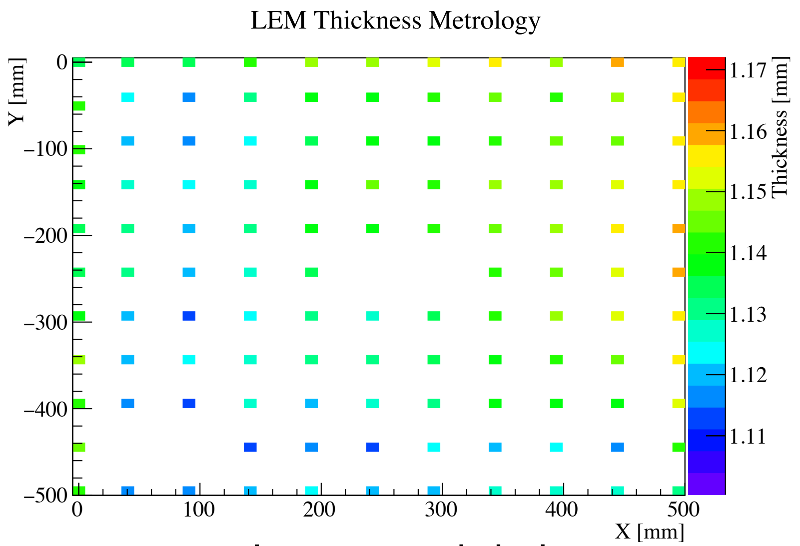
3.125 mm pitch
5x32 ch in X and Y



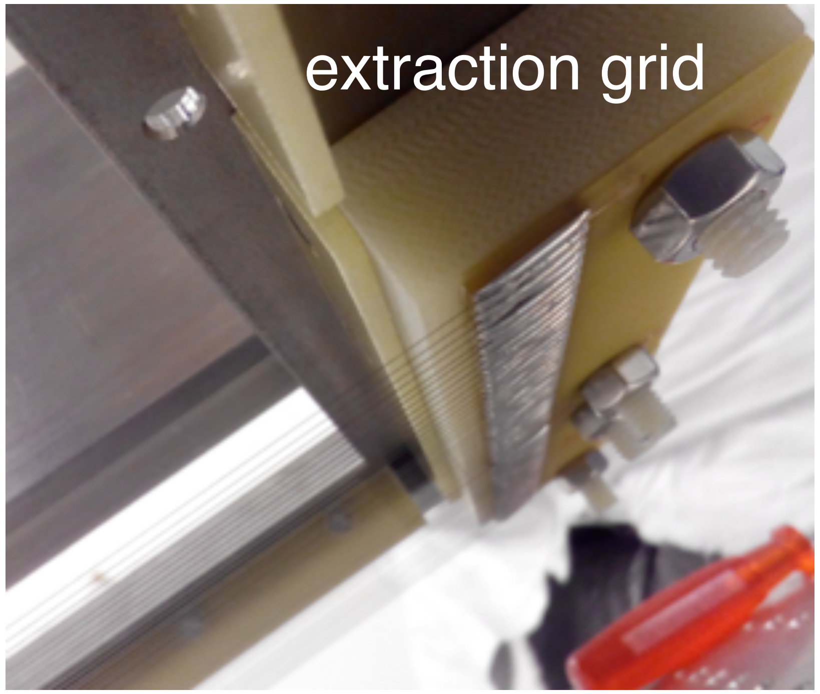
500 000 holes per LEM

CRP structure and suspension designed by LAPP





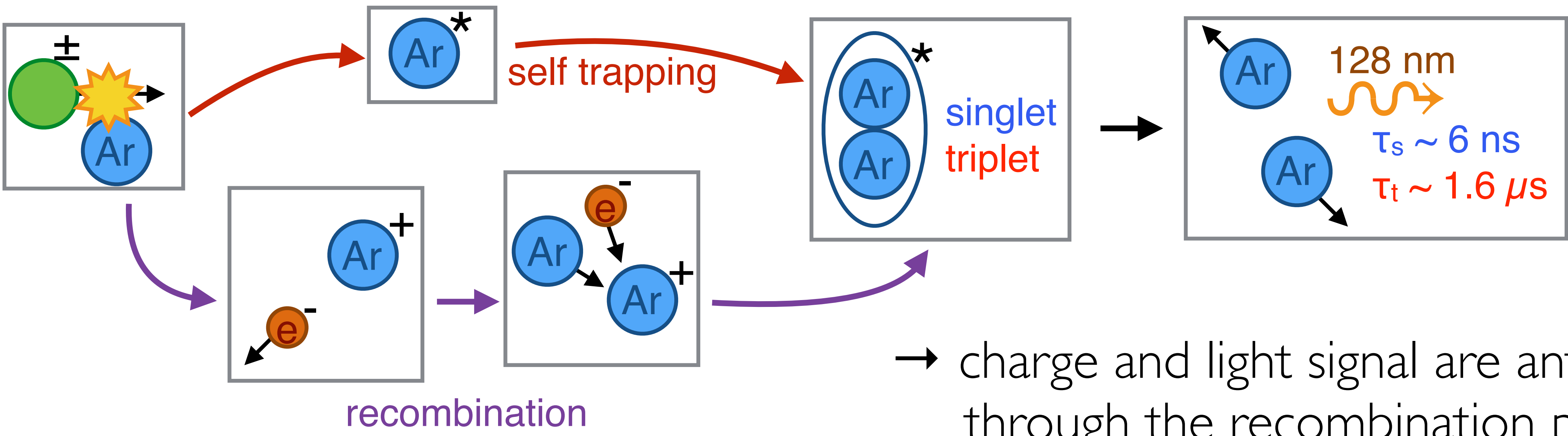
~1 mm thick
RMS ~0.1 mm



wire: SS 100 μm diameter.
3.125 mm spacing

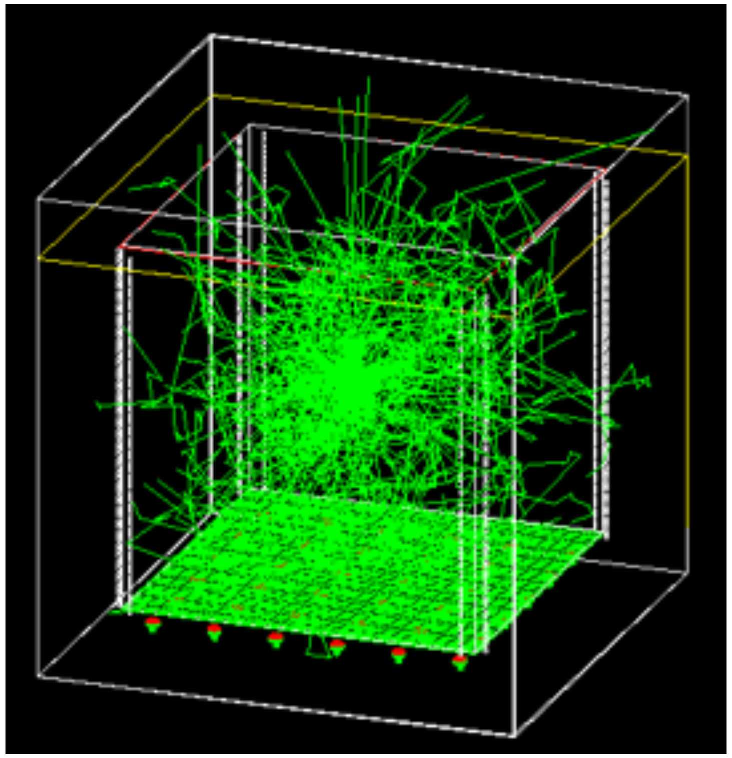
Study of the physics of the scintillation light

Generation of the scintillation light in Argon :



→ charge and light signal are anti-correlated through the recombination process

- About 40 000 γ/MeV produced
- Specific light signal simulation software developed to handle the photon tracking
- Physics behind the light production and propagation in LAr is not well understood → the 6x6x6 prototype will be a good place for detailed studies

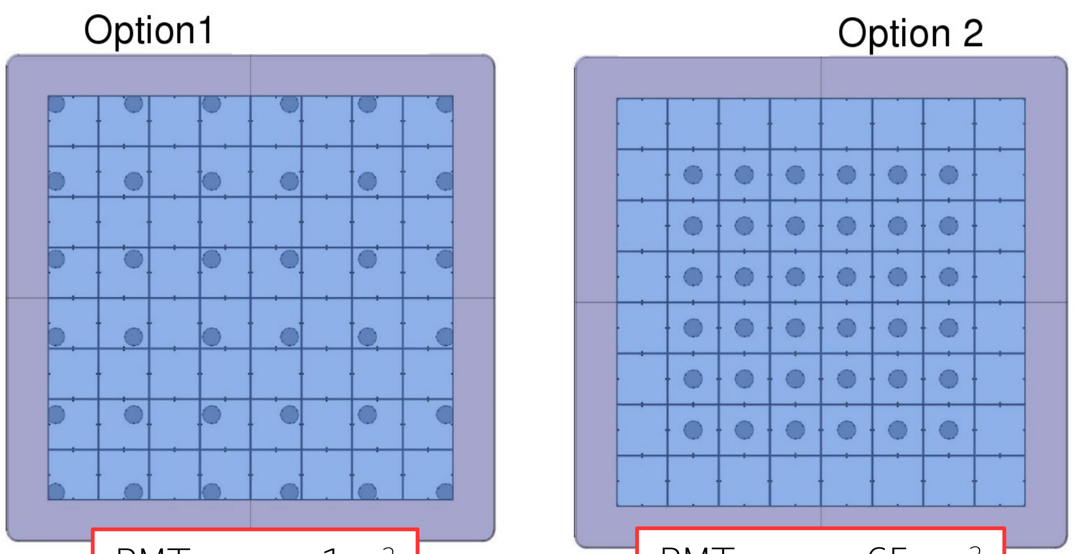


Light simulation efforts lead at LAPP
PhD : A. Chappuis

Design optimization - Light signal

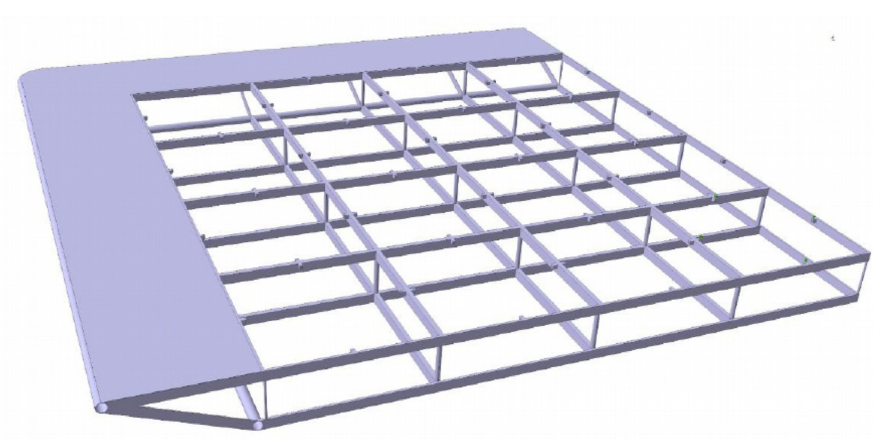
Huge efforts to understand and optimize the light detection for the 6x6x6 prototype

PMT array configuration :

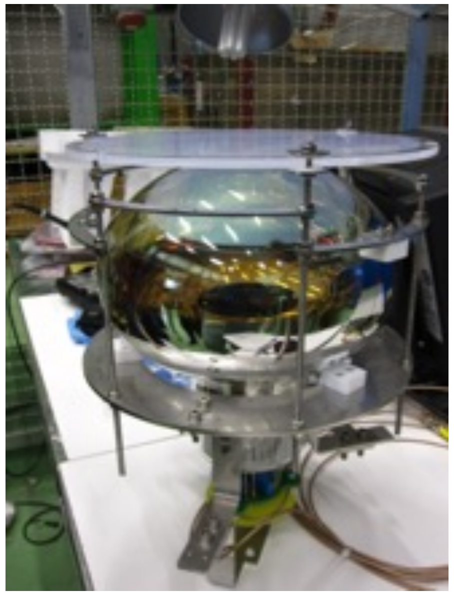


PMTs every 1m²

PMTs every 65cm²



Wavelength shifter position :

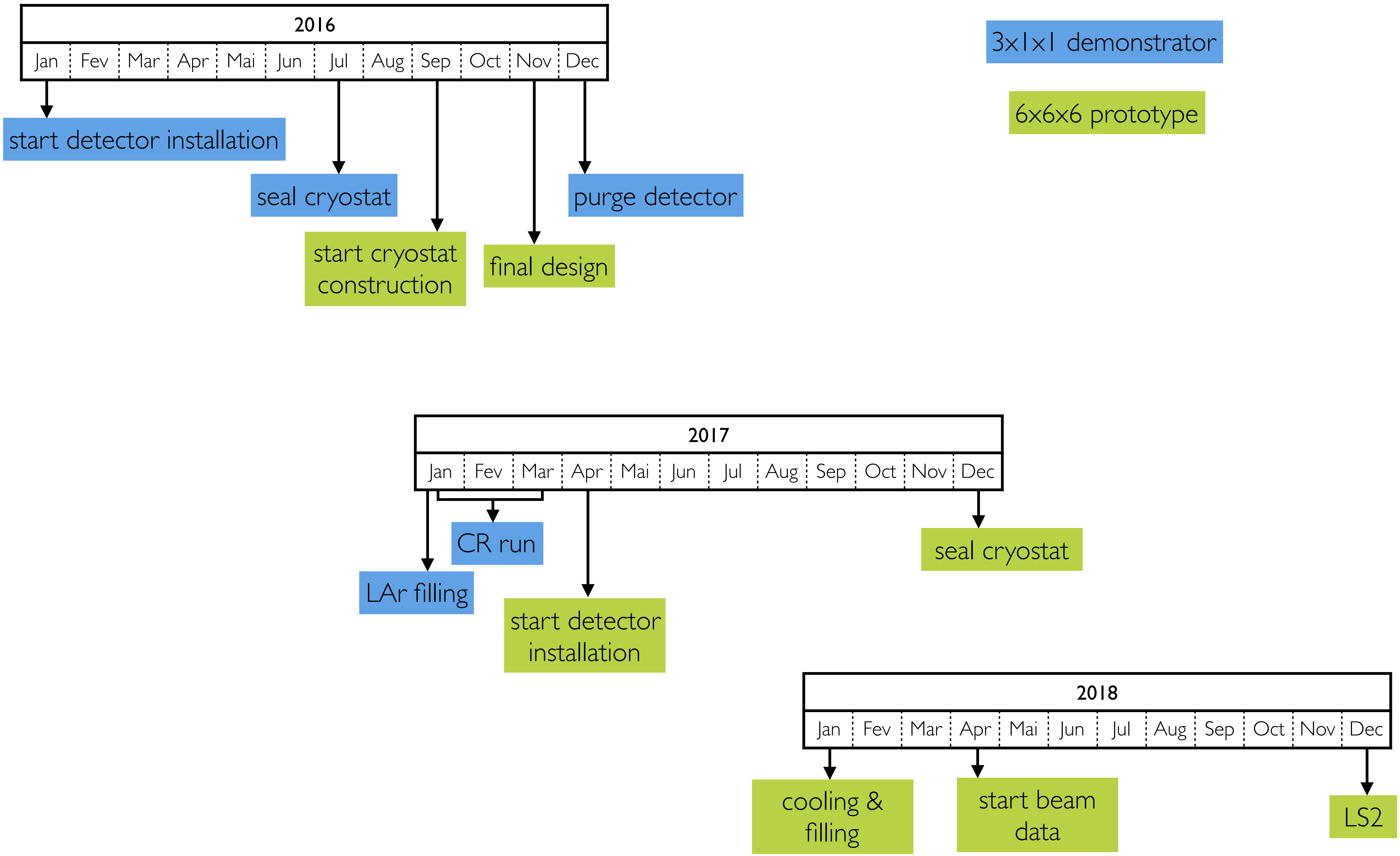


On a PMMA plate above the PMT

On PMT photocathode

Light loss due to the cathode supporting structure above the PMT array

WA105 schedule

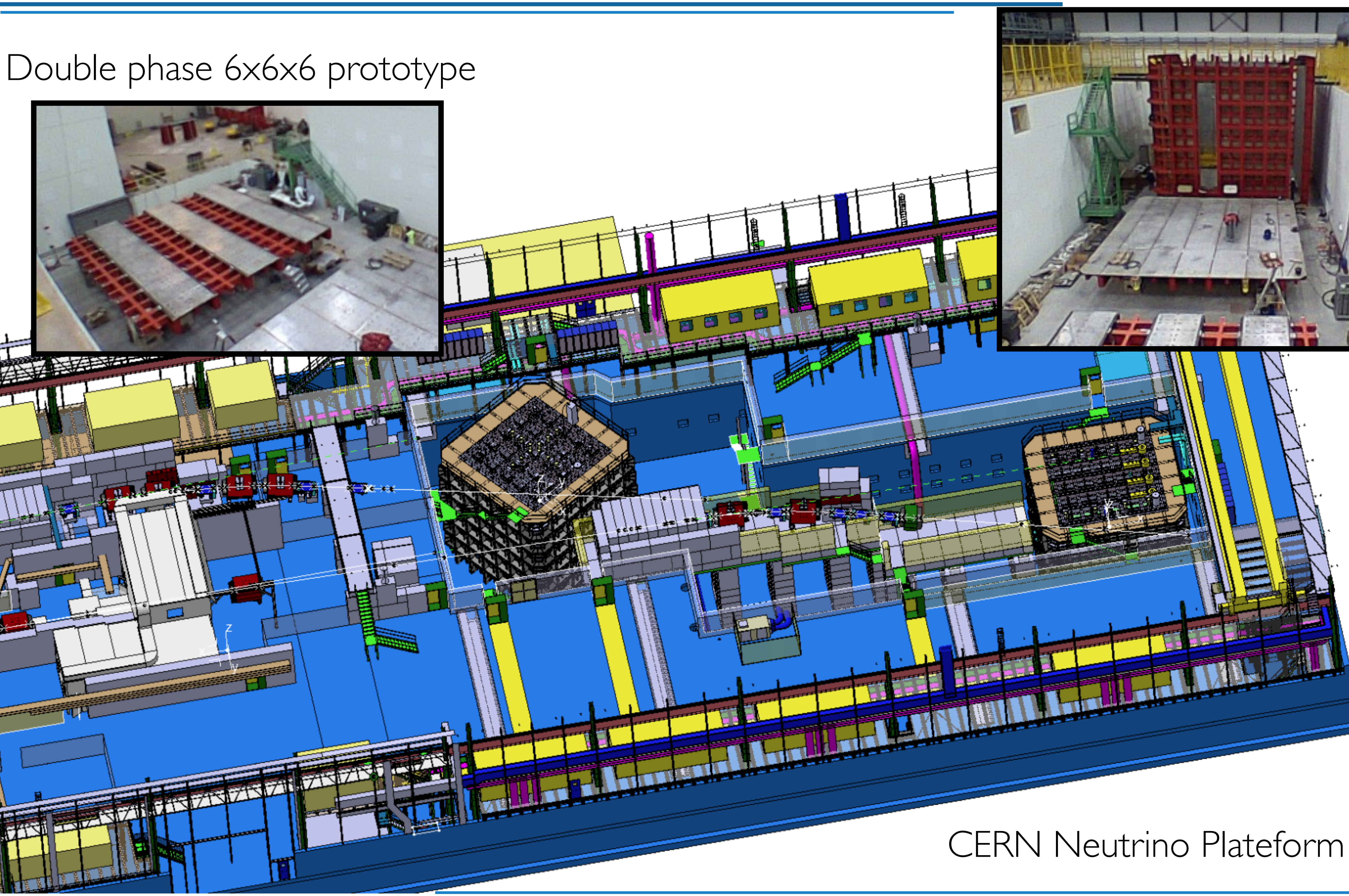


WA105 3x1x1 demonstrator - construction

WA105 at EHN1

Single phase 7x7x6 prototype

Double phase 6x6x6 prototype



CERN Neutrino Plateform

Prospects

- EHN1 proto-DUNEs (single and double phase) are key milestones towards DUNE far detector design
- 2016 has been very challenging and successful with the 3x1x1 construction
- 2017 and 2018 will be very busy and interesting years !