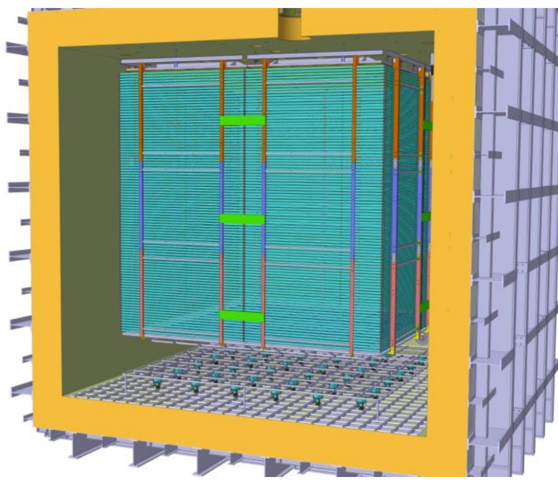
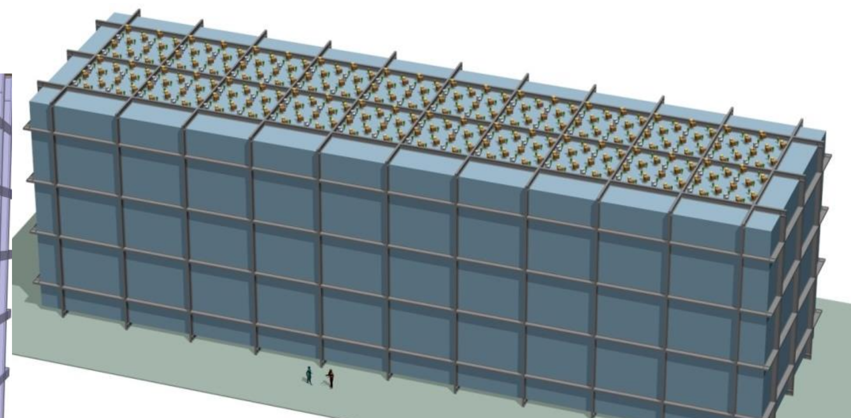
The experimental challenge of next long-baseline neutrino oscillations measurements with the DUNE liquid argon detector

Dario Autiero (IPNL Lyon)

Pisa, December 20, 2016



WA105
Dual-Phase ProtoDUNE



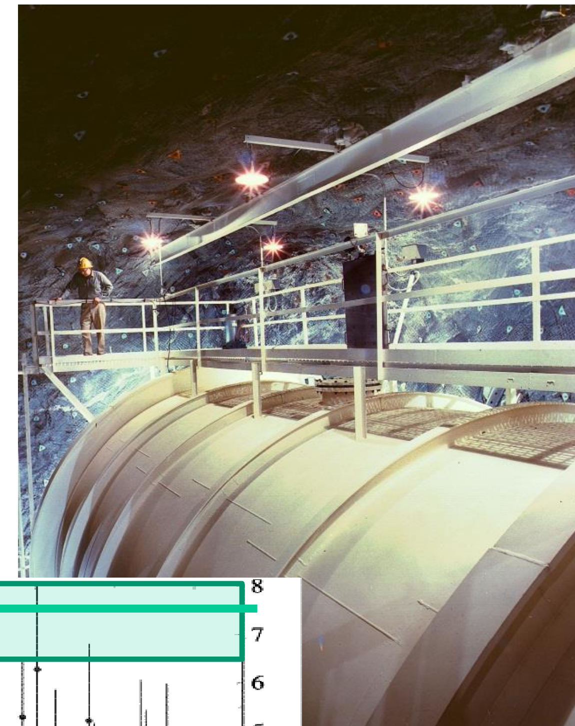
DUNE

First detection of solar neutrinos 1968: Homestake mine experiment (R. Davis)

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (34 days, K-capture) $e^- + {}^{37}Ar \rightarrow \nu_e + {}^{37}Cl$

E(neutrino)> 0.814 MeV

Tank with 390 **m**^{3} of C_2Cl_4
^{37}Cl ~24% of natural Cl

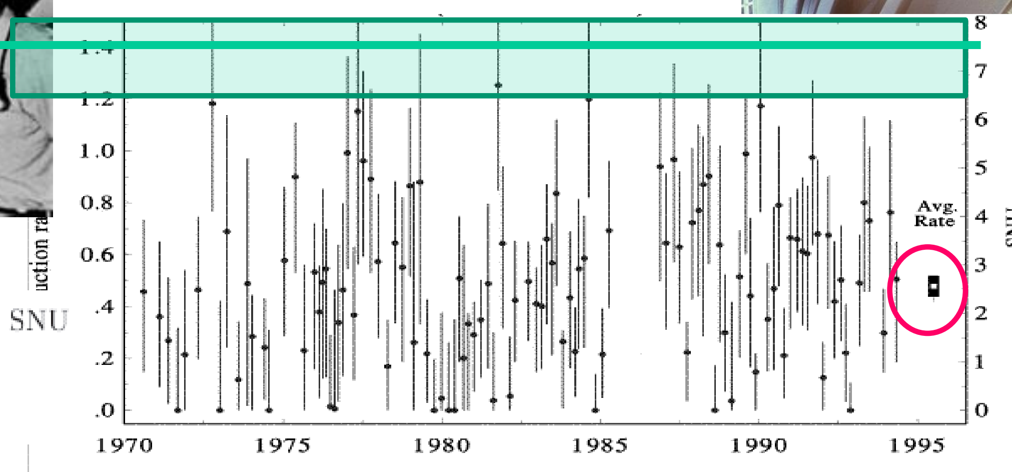


~1.5 Ar atoms/day produced by solar neutrinos
Extracted every 3 months with a flux of N_2

Final state ^{37}Cl excited emitting Augier electrons e/o x rays

Results compared to the neutrino flux predicted by the Standard Solar Model (J. Bahcall)

→ 1/3 of expected rate
Solar neutrinos deficit



$$R({}^{37}Cl) = 2.56 \pm 0.16 \pm 0.16 \text{ SNU}$$
$$R_{SSM} = 7.6^{+1.3}_{-1.1} \text{ SNU}$$
$$R_{Données/SSM} = 0.33 \pm 0.03$$

Interpretations:

> *I [J.N. Bahcall] want to tell you an illustrative story about neutrino research … One of the miners came over to our bench, said : "Hello, Dr. Davis. How is it going ? You don't look too happy." And, Ray replied : "Well, I don't know …I am capturing in my tank many fewer of those neutrinos than this young man says I should be capturing." The miner […] finally said : "Never mind, Dr. Davis, it has been a very cloudy summer here in South Dakota. "*

More seriously debated for long … long time:

The trivial ones:

- The Homestake experiment, which is quite delicate, has some bias in the neutrino detection
- The Standard Solar Model is not correct (neutrino flux depending on T^{25} !)

The fascinating one by Pontecorvo:
the Davis experiment and the SSM are both correct it is new physics: neutrinos change their nature during their trip to the earth

→ Neutrino oscillations
Electronic neutrinos from the sun become muonic neutrinos
The energy of the muonic neutrinos is too low to allow for their charged current interactions → neutrino disappearance

But neutrinos must be massive particles …

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79.   Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31   April 6/10 19 72

April 6, 1972

Prof. J.N.Bahcall

The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

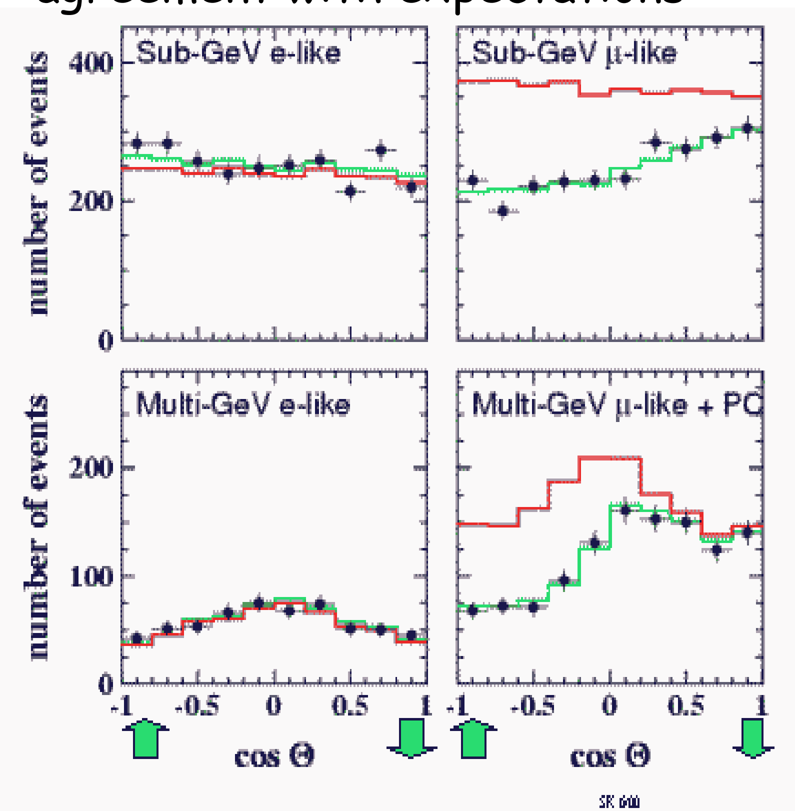
B Pontecorvo

B.Pontecorvo

Pontecorvo was predictive:
It took 30 years for the demonstration !

Neutrino 98 Conference in Takayama (June 1998)

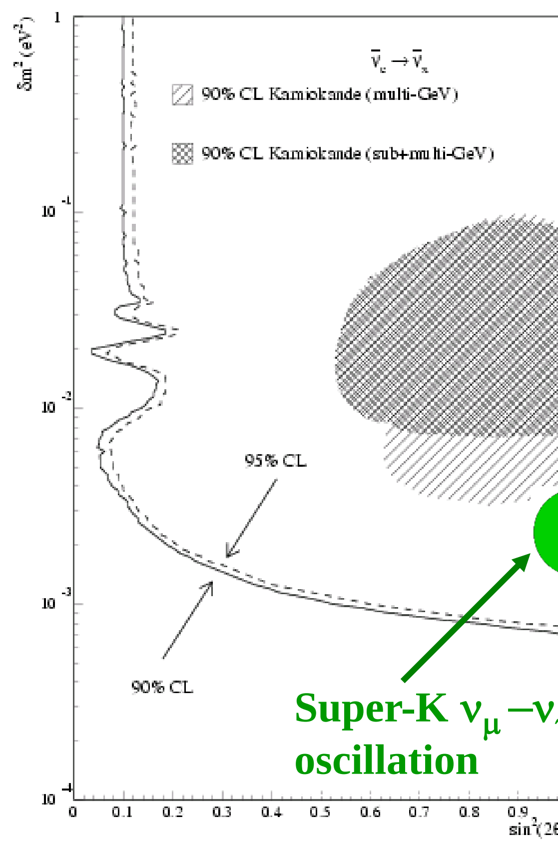
First results from Super-Kamiokande on atmospheric neutrinos, evidence of a zenith angle dependence of ν_μ disappearance, ν_e in agreement with expectations



SK: Atmospheric neutrinos anomaly

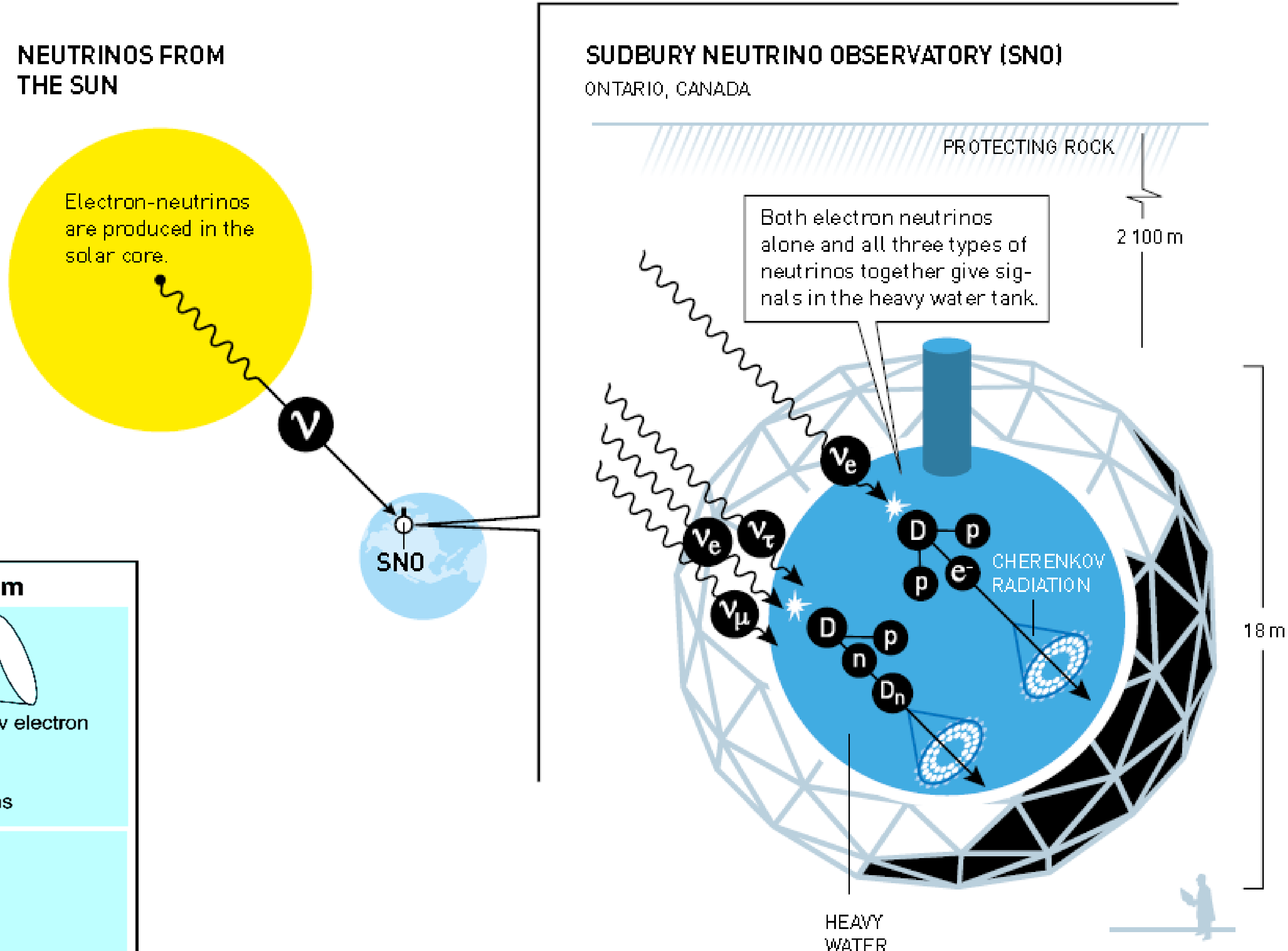
interpretable in terms of $\nu_\mu \rightarrow \nu_\tau$ oscillations with a $\Delta m^2 \sim$ a few 10^{-3} eV^2

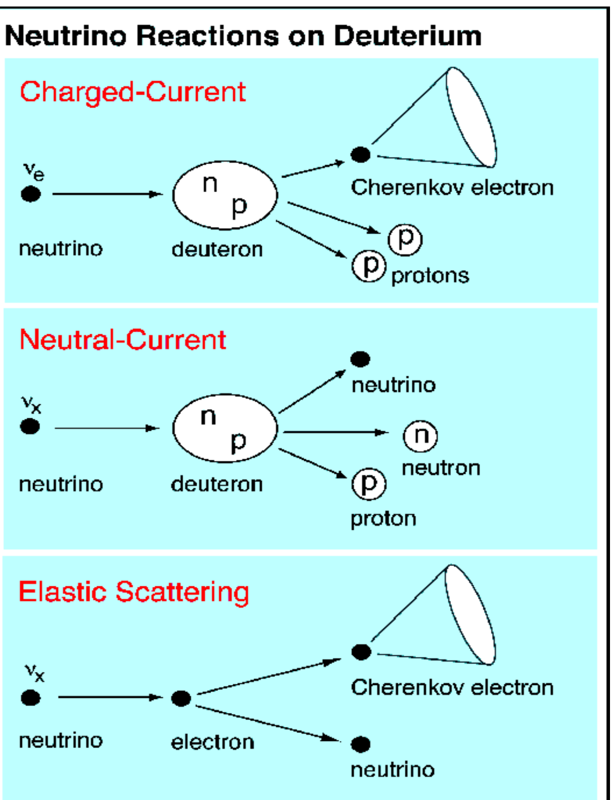
CHOOZ six months before: no $\nu_\mu \rightarrow \nu_e$ oscillations, $\Theta_{13}<11°$



Neutrino oscillations start to be taken seriously as explanation of the atmospheric neutrinos anomaly

→Opens the campaign for long baseline experiments to reproduce the phenomenon with accelerator neutrinos





2001: SNO 1000 tons of heavy water, sensitive to neutral current reactions → measure the total neutrino flux independently from their flavor

The total neutrino flux agrees with the SSM !
→ Electron neutrinos change into other neutrino flavors

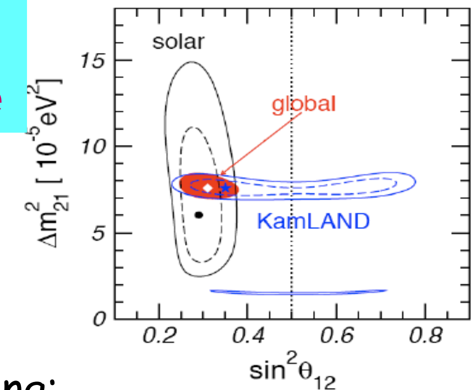
Standard 3 ν framework (ignoring LSND, Miniboone anomaly, Reactors anomaly, Cr source anomaly …)

Two almost independent oscillations describing;

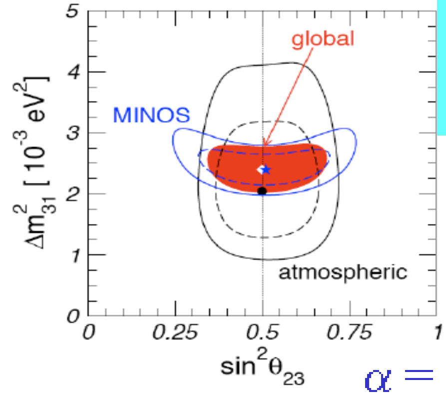
solar neutrinos: Δm^2_{21} $(7.65^{+0.23}_{-0.20})\,10^{-5}\,\text{eV}^2$, $\sin^2\theta_{12}$ $0.304^{+0.022}_{-0.016}$ and atmospheric neutrinos: $|\Delta m^2_{31}|$ $(2.40^{+0.12}_{-0.11})\,10^{-3}\,\text{eV}^2$, $\sin^2\theta_{23}$ $0.50^{+0.07}_{-0.06}$

Solar neutrinos
+ Kamland
ν_e, anti-ν_e disappearance

L/E~15 Km/MeV



L/E~500 Km/GeV



Atmospheric neutrinos
+ accelerators
ν_μ disappearance

3 neutrino flavours mixing:
favorite parametrization of U:
in terms of 3 mixing angles θ_{12} θ_{23} θ_{13} and one Dirac-like CP phase δ :

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

$\alpha = e, \mu, \tau$ (flavor index)
$i = 1, 2, 3$ (mass index)
$U_{\alpha i}$= unitary mixing matrix

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

Atmospheric ν oscillations **Solar ν oscillations**

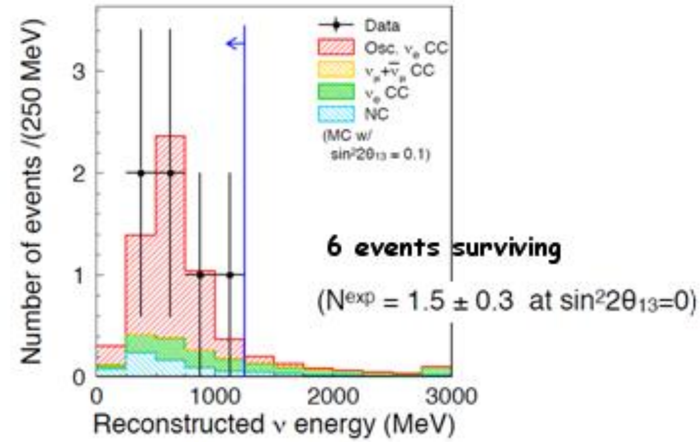
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

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

Bridge
θ_{13},CP violation?

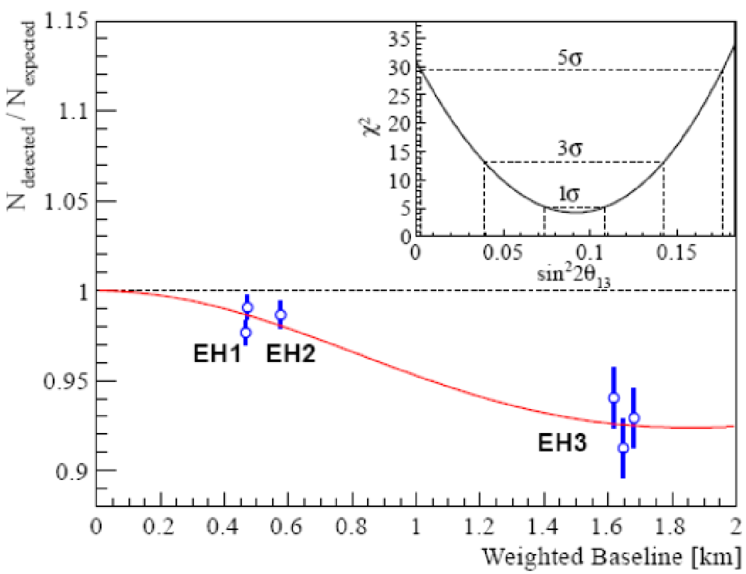
2012: the turning point, $\nu_\mu \rightarrow \nu_e$ oscillations and θ_{13}

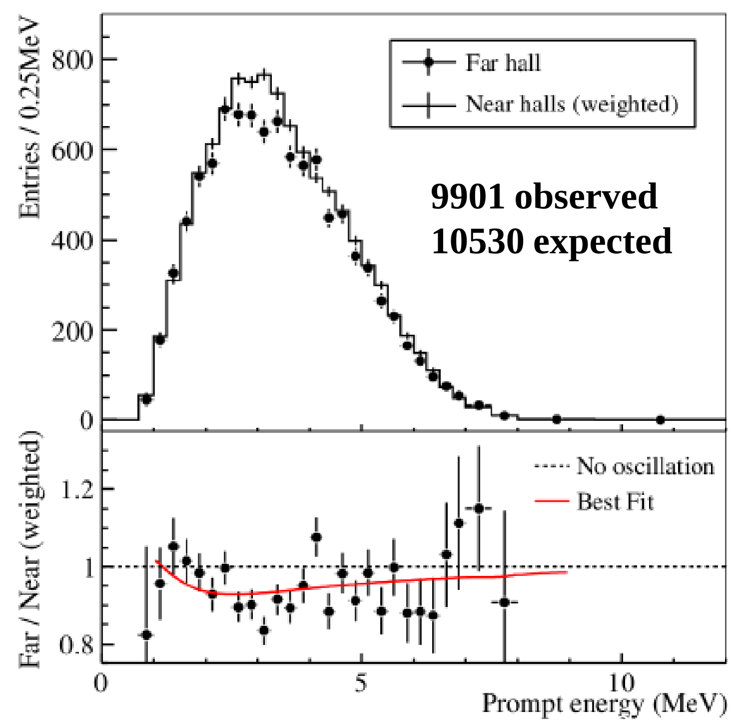
T2K off-axis beam (tuned for osc. max.)
$\nu_\mu \rightarrow \nu_e$ appearance
First result on θ_{13} (June 2011):
6 events observed, 1.5 events bck. → 2.5 σ



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

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



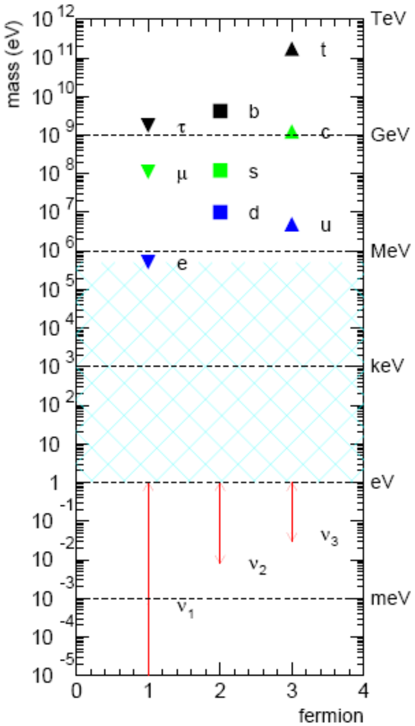


5.2 σ for non-zero θ_{13}

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

Neutrino oscillations are presently in particle physics the only evidence for BSM physics → Neutrinos: a window beyond the S.M. to G.U.T.

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

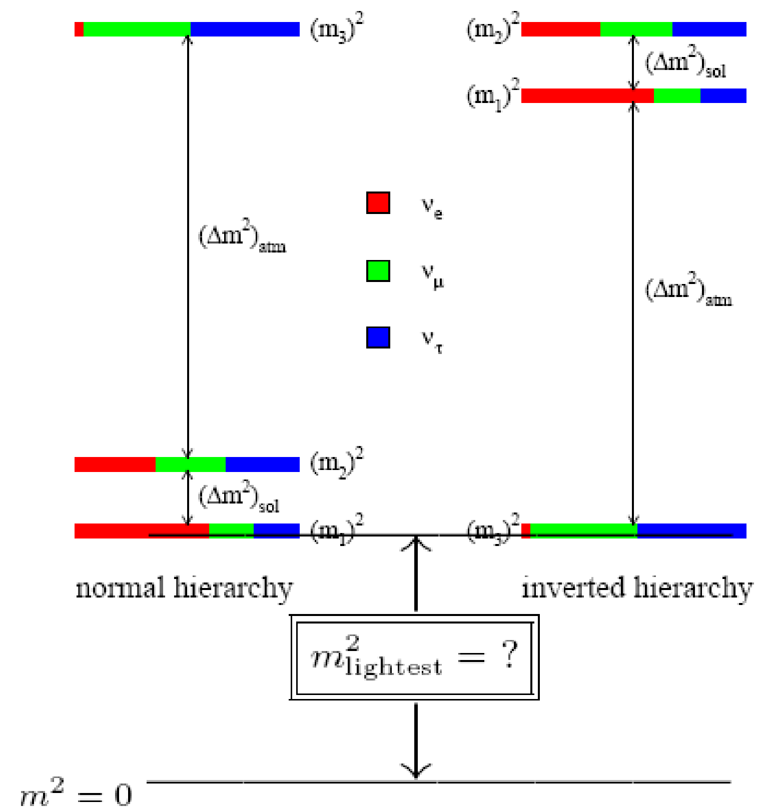


- Why are neutrino masses so small ?
- Why is the mixing matrix so different than the one of the quarks ?

What is this very strange puzzle suggesting us ?

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

- Which is the mass of the lightest state
- Are neutrinos Majorana particles ?
- Which is the hierarchy of the mass eigenstates ?
- Is there CP violation in the neutrino sector ?



CP violation in the neutrino sector can explain the matter/antimatter asymmetry in the universe

An experimental program for the next 30 years (like for CP in quark sector):

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

Direct evidence for CP violation must be searched in with the sub-leading $\nu_\mu \rightarrow \nu_e$ oscillation at the Δm^2 of the atmospheric neutrinos ($\Delta m^2 \sim 10^{-3}$ eV^2)

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

Matter effect

Leading term

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

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

CP-terms

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

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

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

The same oscillation channel provides infos on:

- θ_{13}
- Matter effects and mass hierarchy
- CP violation

Large θ13 → next steps accessible with standard beams !

To study this channel it is crucial to use a detector capable of providing a very good measurement of electrons (electron identification, background rejection) and energy resolution

CP asymmetry as a function of L/E

CP violation can be measured by comparing ν and anti-ν oscillation probabilities in an asymmetry variable

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

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

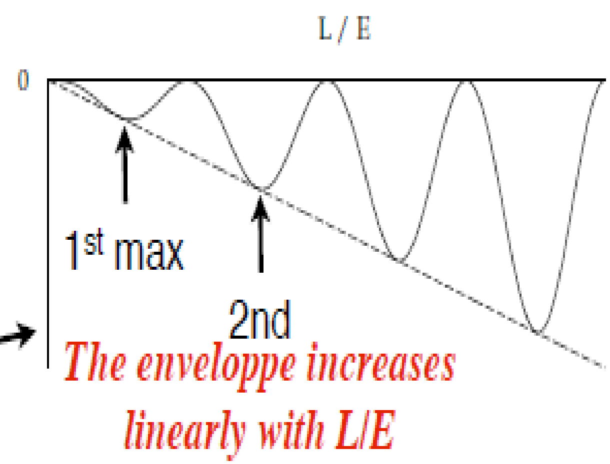
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

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

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

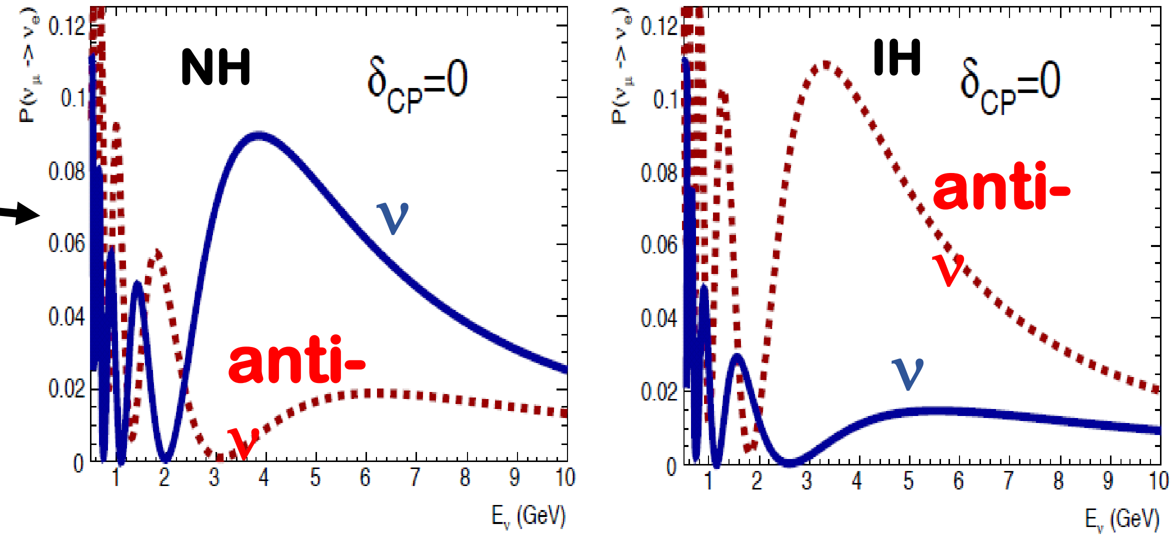


The amplitude of the pure CP term increases with L/E → **this effect is stronger at the** second oscillation maximum**.**

Measurements at the second oscillation maximum are very important and possible only with a detector with very good energy resolution

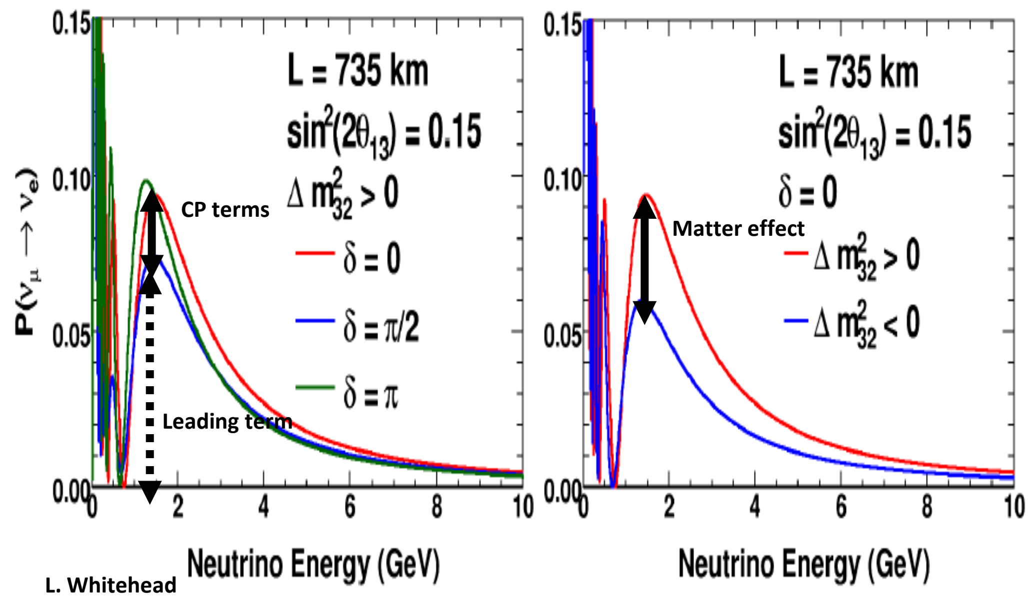
Matter effects and CP violation effects degeneracy

Matter effects on the oscillation probability at L = 2300 km for ν and anti-ν in the case of Normal (NH) or Inverted (IH) hierarchy



Since CP violation is also measured by comparing ν and anti-ν oscillation probabilities matter effects mimic CP violation if the mass hierarchy is not known

- **It is needed to accurately measure and subtract the matter effects in order to look for CP**
- **Matter effects dominate around the first maximum**

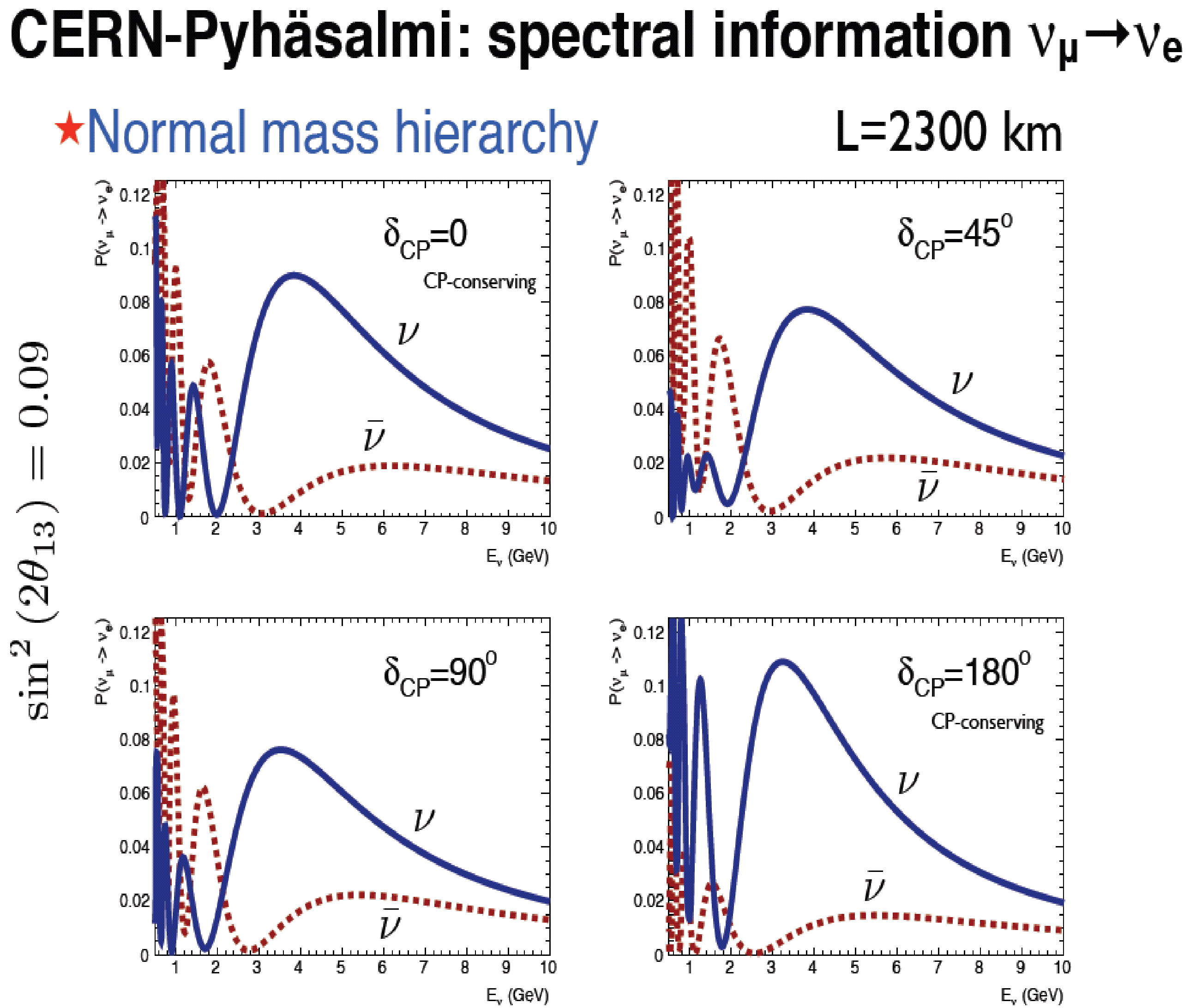


Effects on oscillation probabilities as a function of δ CP

Once the mass hierarchy is determined, it is possible to study the CP-violation and determine the value of d by measuring the ν and anti-ν oscillation probabilities

A lot of information is contained in the shape around the first and second maximum

→Direct measurement of the energy dependence (L/E behavior) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by measurement of events energy spectrum



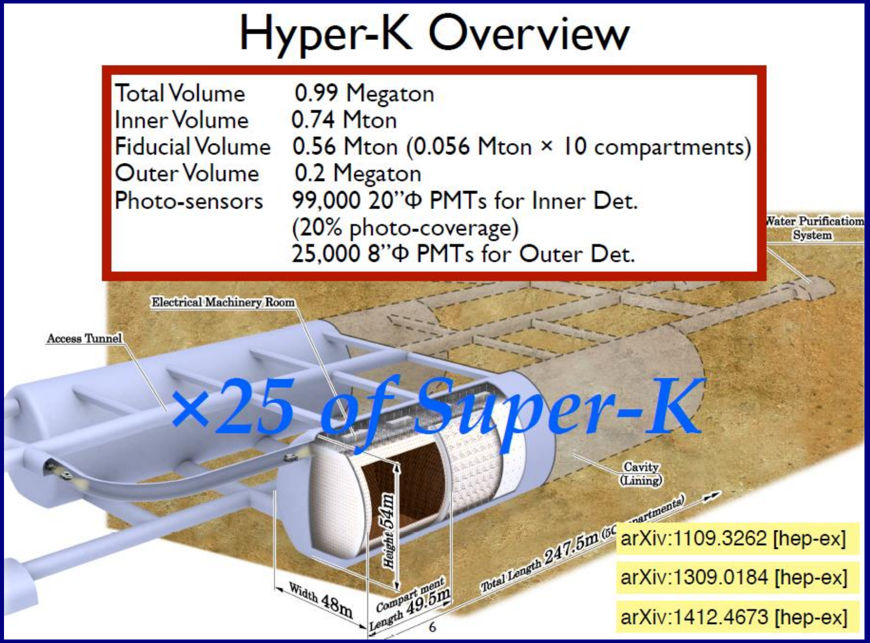
The Water Cerenkov approach (extrapolation ~x25 of SK):

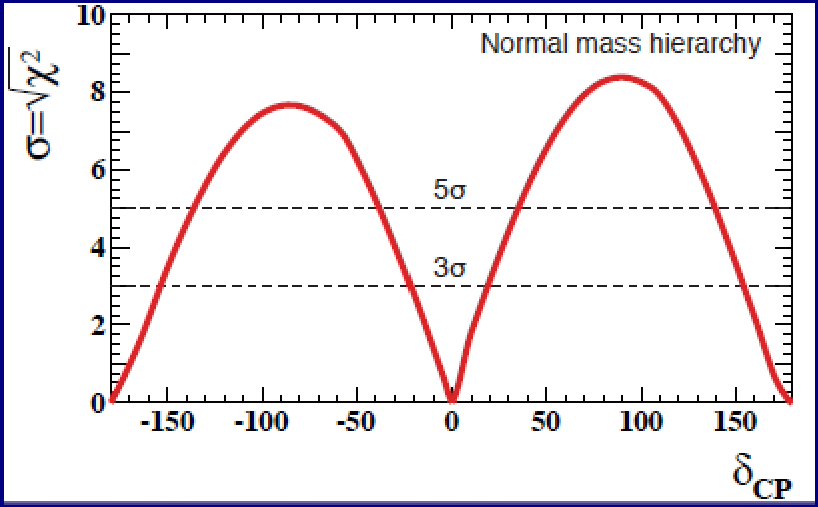
- ✓ Large water Cerenkov detector *O*(0.5 Mton), 140k 12'' PMT
- ✓ Low energy narrow beam (0.1-1 GeV) → just lepton reconstruction in QE events
- ✓ Short baseline (100-300 km) → no mass hierarchy determination (*needs an external input (atm. neutrinos, other experiments)*
- ✓ New beam needed ~*1.2 MW*

→ Counting only experiment on neutrinos-antineutrinos asymmetry

- HyperKamiokande project in Japan

0.56 Mton, 99k PMT 20'', new beam from JPARC (295 km)
Beam neutrinos, Supernovae neutrinos, Search for proton decay
→ Seeking for approval in 2016-2017, with expected start in ~2025

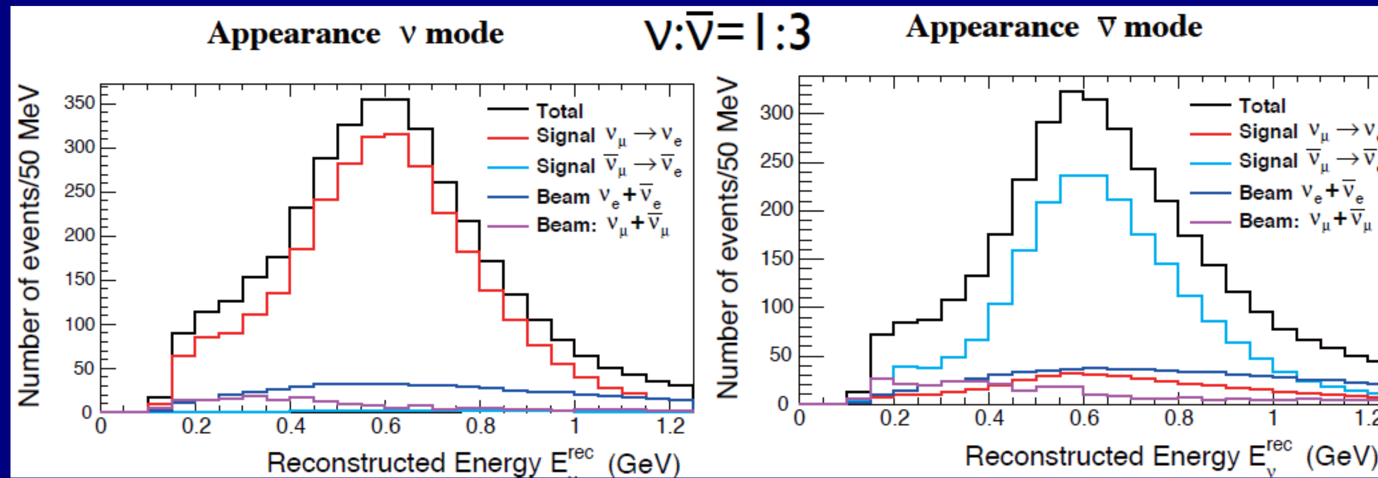




76% (58%) CP coverage 3σ (5σ) if MH know
With 7.5 MW x 10^E7 s exposure

Hyperk:

- Continuation of measurements in sub-GeV region
- Mostly « counting , high statistics experiment »
- MH to be known to avoid a systematic bias



HyperK 10 years at 750 kW

	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν	3,016	28	11	523	172
ν̄	2,110	396	9	618	265

Systematic uncertainties based on:

- ✓ T2K experience
- ✓ WC ND
- ✓ study of atmospheric neutrinos control sample in FD

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
Total	3.3	3.3	6.2	4.5	6.8	7.6

→ total 3.3% uncertainty on nue rate

Fundamental questions to be addressed by the next generation of long-baseline neutrino oscillations experiments:

a) The hierarchy of the mass eigenstates (normal, inverted ?)

b) Is there CP violation in the neutrino sector ?

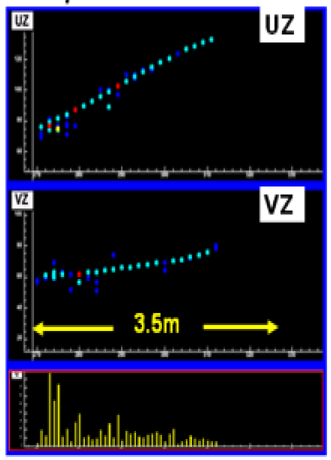
- Both effects will be studied via the sub-leading numu→ nue oscillation in the atmospheric neutrinos sector and its spectral information and by looking at neutrinos vs anti-neutrinos
- Need very long baseline and high intensity neutrino beams (>1000 km) shooting to giant O(few 10kton) fine grained detectors capable of electron identification and good energy resolution
- The determination of the mass hierarchy is needed in a first instance in order to measure CP violation (otherwise its ignorance can severely bias the CP violation measurement via the matter effects)

→ Next neutrino program pursued jointly by Europe and USA are aiming at this goals relying on the detector technology of the liquid argon time projection chamber (LAr TPC)

Typical neutrino interactions events in fine grained detectors

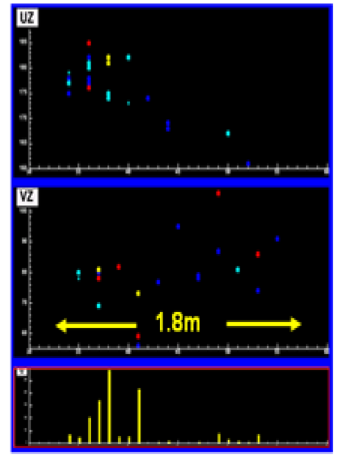
MINOS (sandwich of 2.54 cm magnetized steel and 1 cm scintillator plates)

ν_μ CC Event



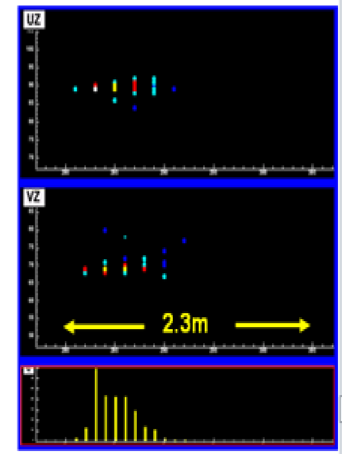
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

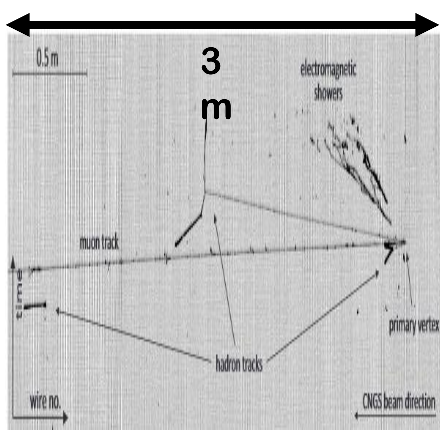
ν_e CC Event



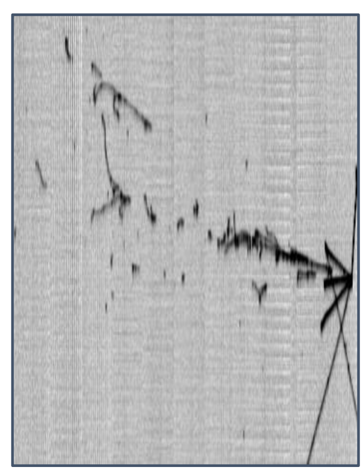
- Short event with typical EM shower profile

ICARUS **LAr TPC neutrino interactions from CNGS beam**

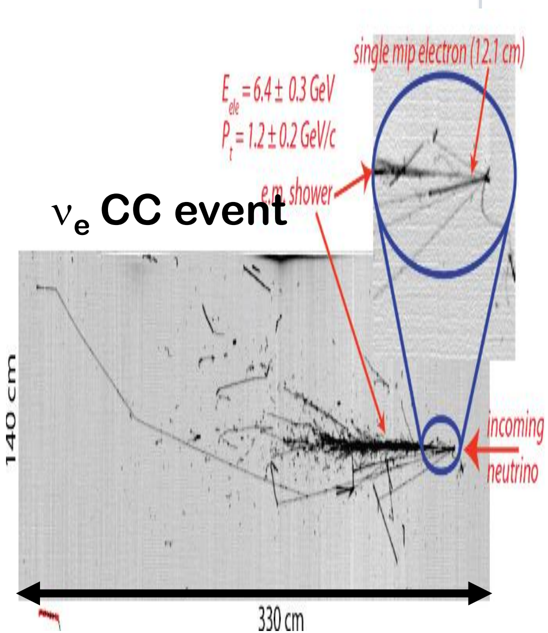
ν_μ CC event with π^0 production



ν_μ NC event with π^0 production

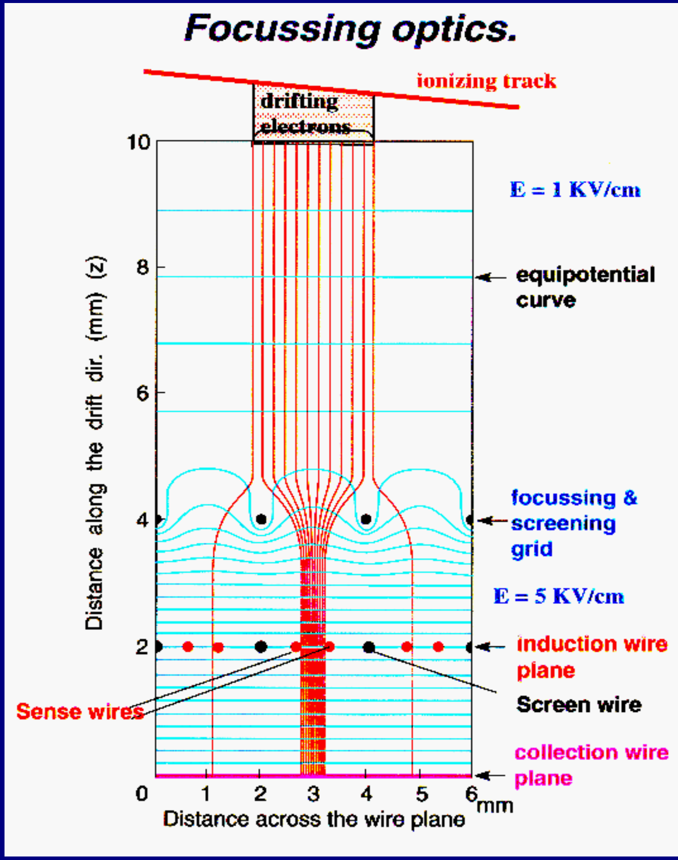


ν_e CC event

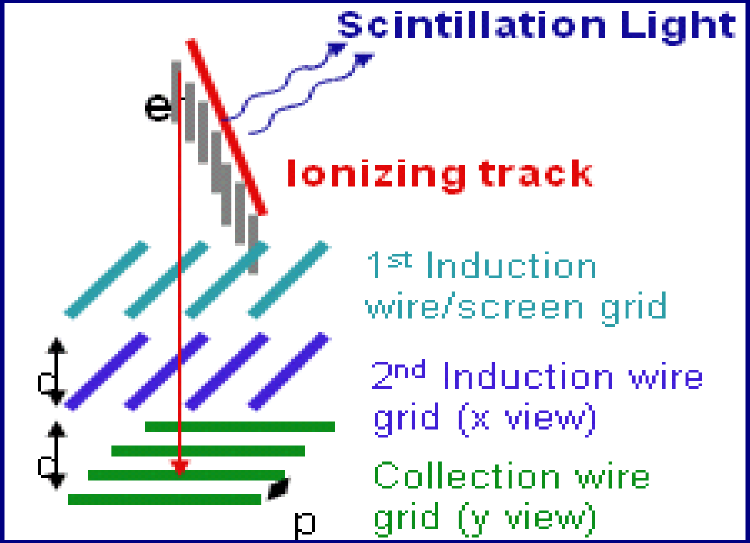


The Liquid Argon Time Projection Chamber (C. Rubbia 1977)

- 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

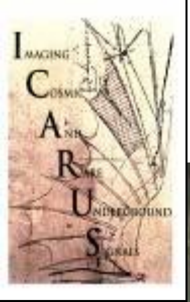


Non-destructive multiple readout with induction planes

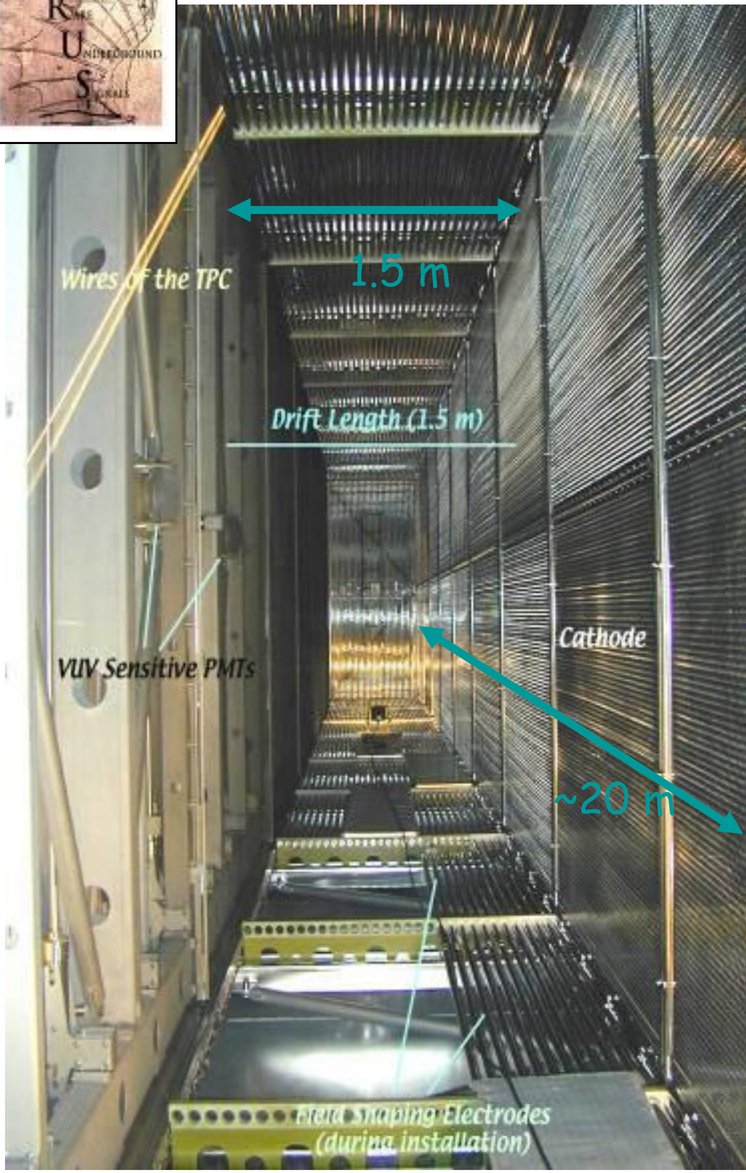
z = drift time

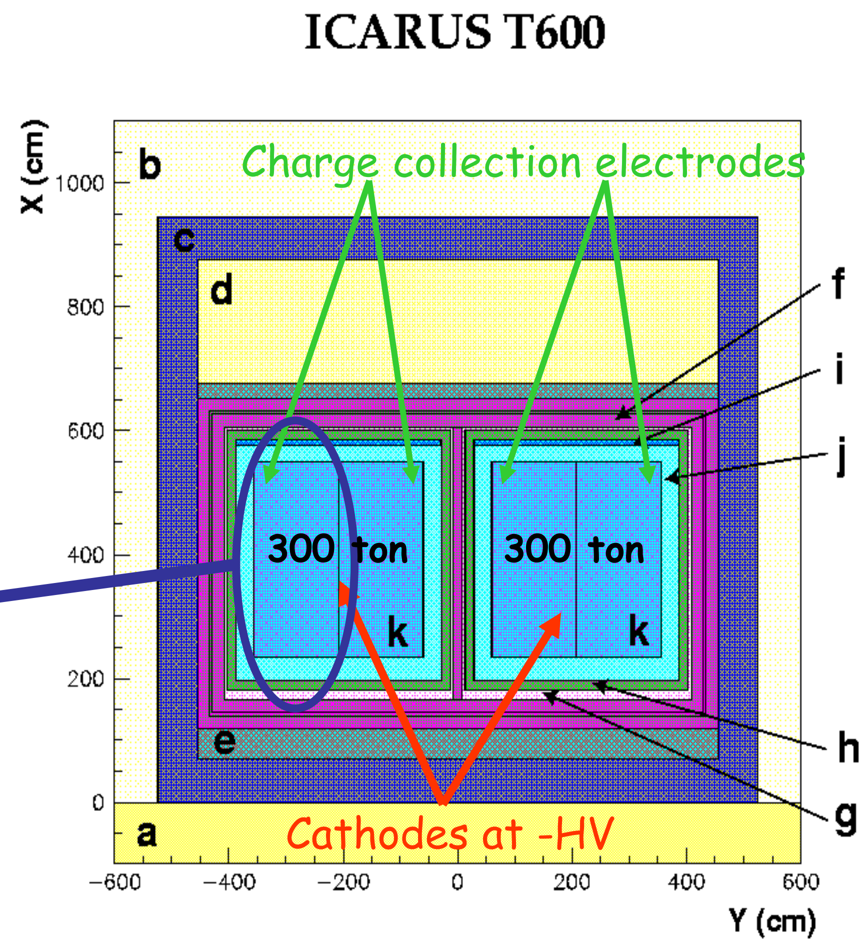
Drift Field: 0.5-1 kV/cm
Drift time:
1.5ms/3m @1 kV/cm

(requiring < 0.1 ppb O_2 equiv. impurities)



The T600 prototype (2001)





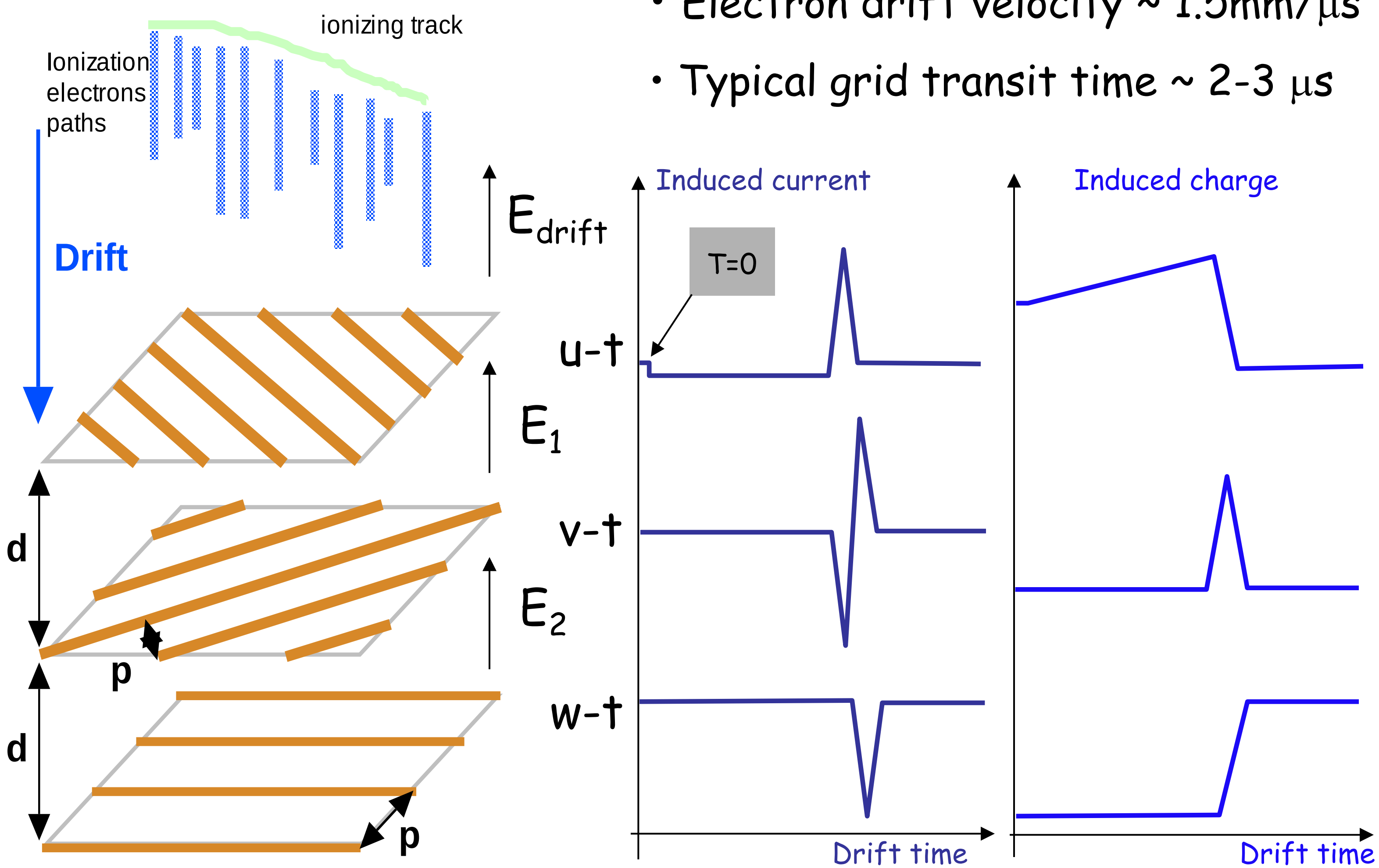
a) rock
b) hall B
c) neutron shield
d) cables-electronics
e) platforms
f) insulation
g) gap
h) container
i) gas phase Ar
j) inactive LAr
k) active LAr

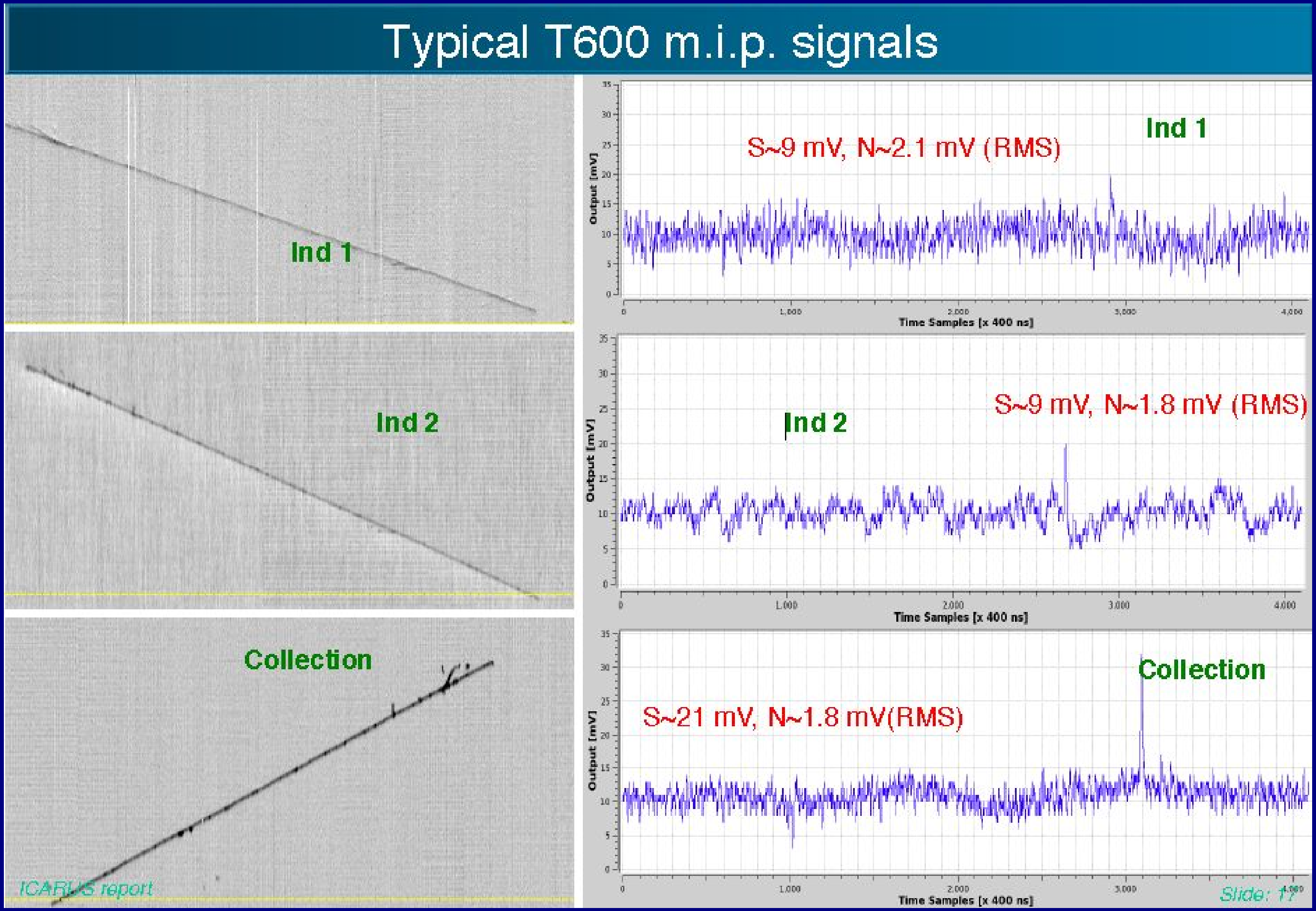
The induction signals

ICARUS: Edrift = 500 V/cm, p = 3mm, d = 3mm, wire radius = 0.1mm

$E_1/E_{drift} = E_2/E_1 > 1.4$ → induction views transparency > 92%

- Electron drift velocity ~ 1.5mm/μs
- Typical grid transit time ~ 2-3 μs





Example of tracks in single phase LAr TPC (ICARUS)

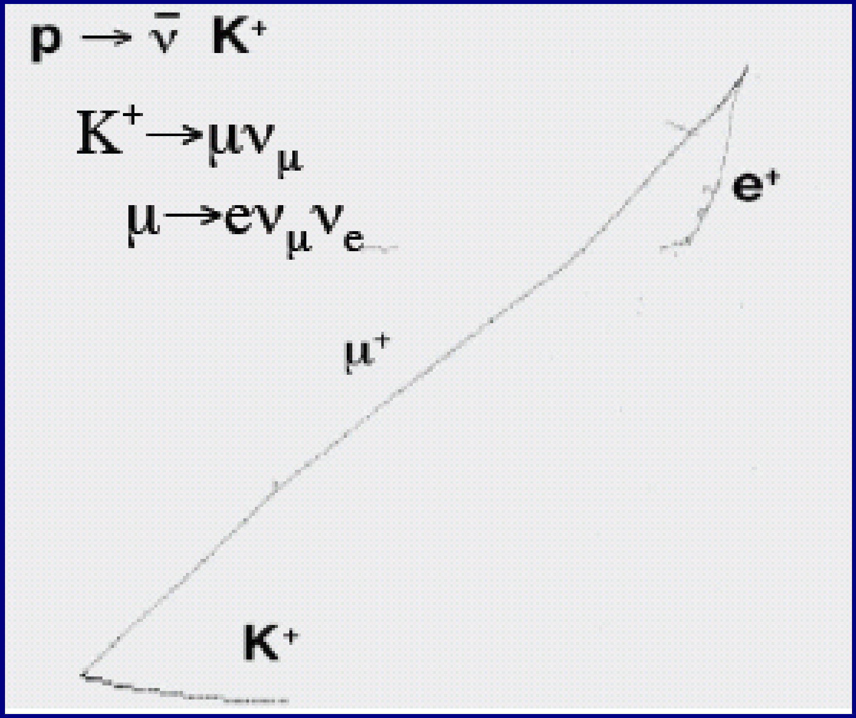
S/N ~ 10 collection view

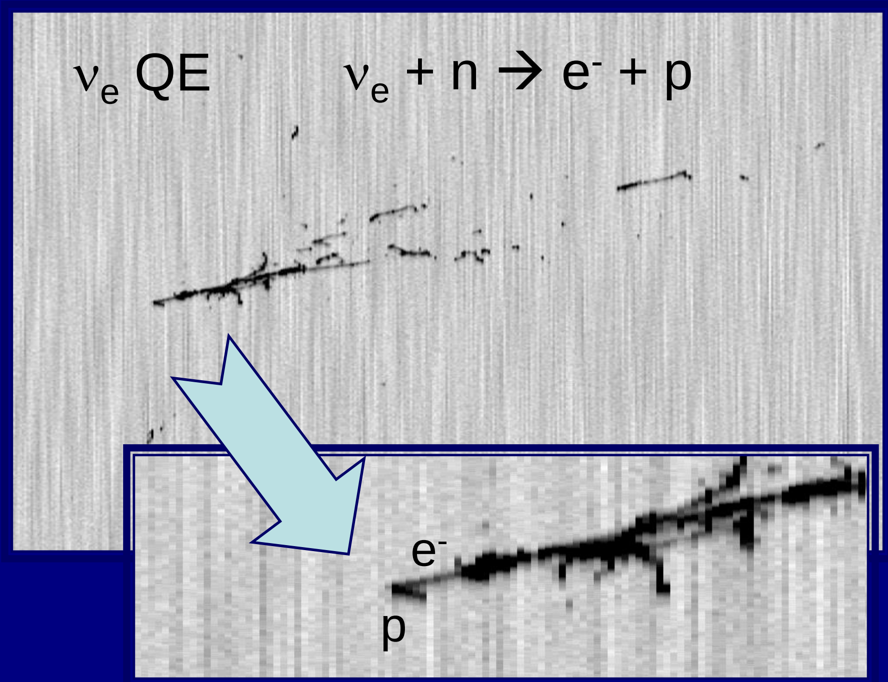
S/N ~ 5 induction views

The liquid argon TPC as an electronic bubble chamber

- Large mass, homogeneous detector, low thresholds, exclusive final states
- Tracking + calorimetry (0.02 X0 sampling)
- **Electron** identification, π^0 rejection, particles **identification with dE/dx**

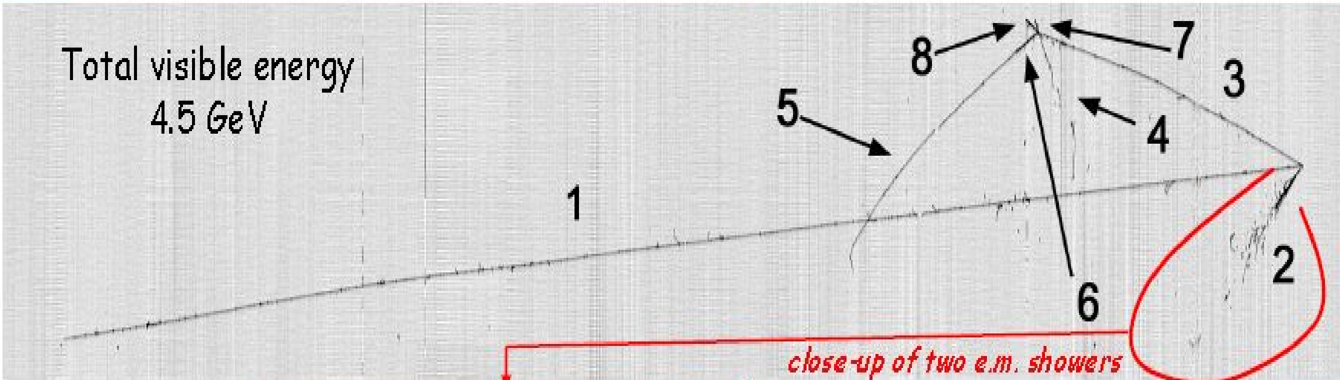
→ Neutrino physics (electron identification, reconstruction of event kinematics, identification of exclusive states, excellent energy resolution from sub GeV to multi GeV)
→ Supernovae neutrinos
→ Proton decay search (large mass, particles id.)





The liquid argon TPC as an electronic bubble chamber

Run 9927 Event 572: ν_μ-CC CNGS event

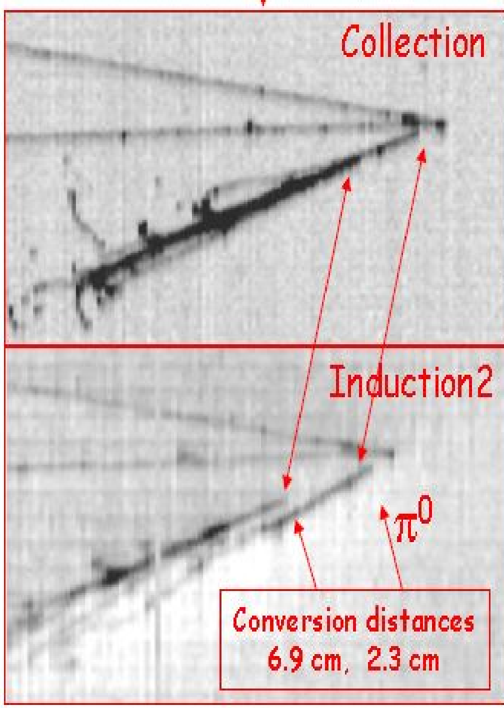


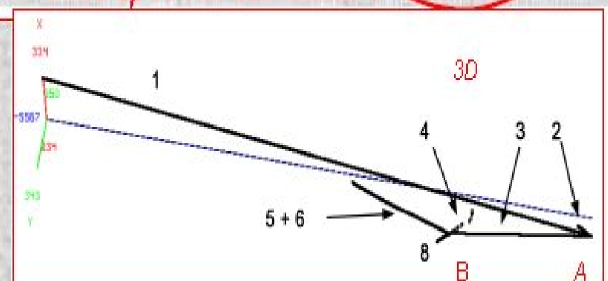
Primary vertex (A):

very long μ (1), e.m.cascades(2), π (3)

Secondary vertex (B):

the longest track (5) is a μ coming from stopping **k** (6). μ decay is observed

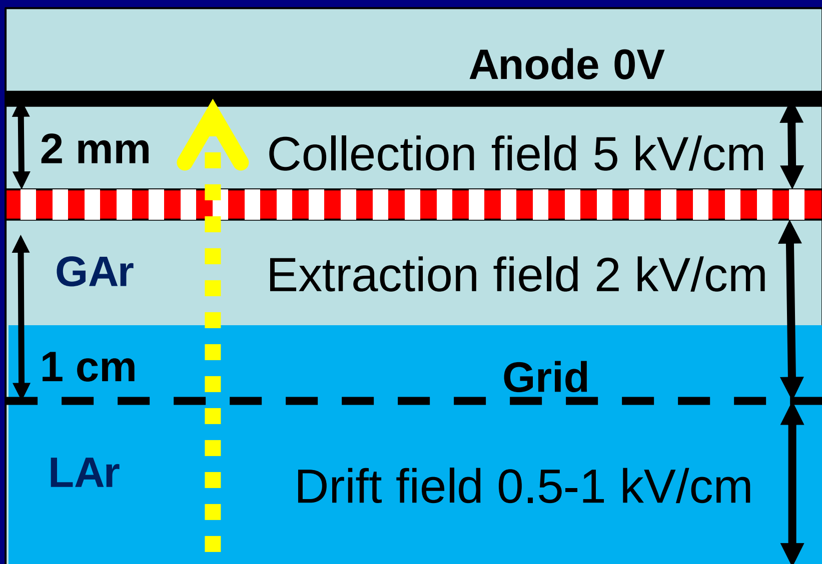




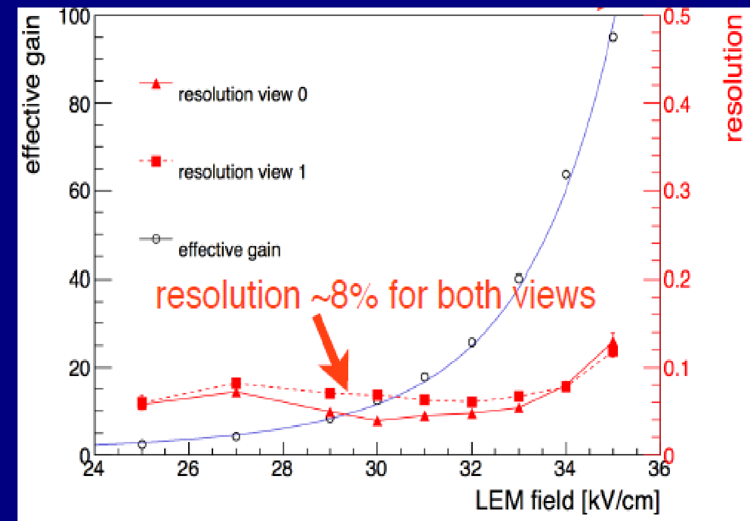
Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

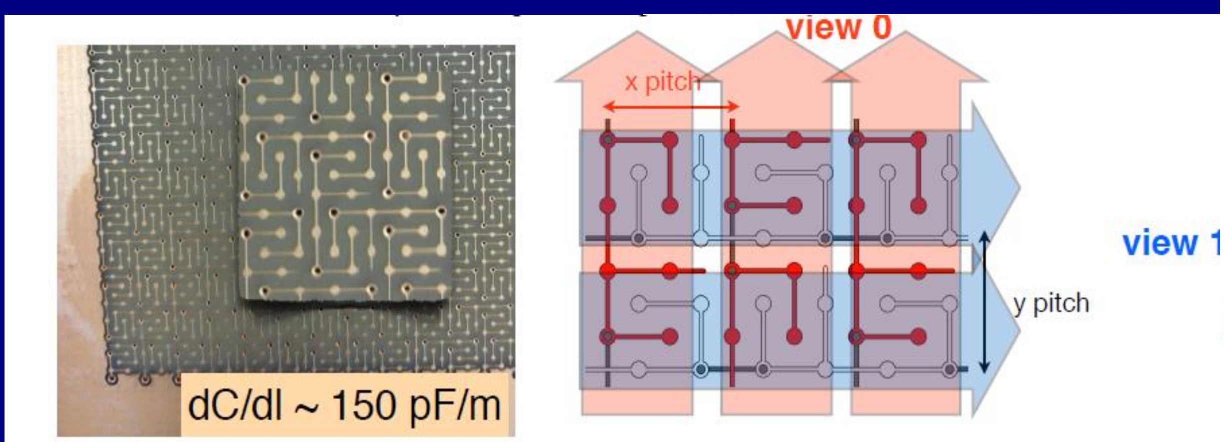
Double-phase readout:

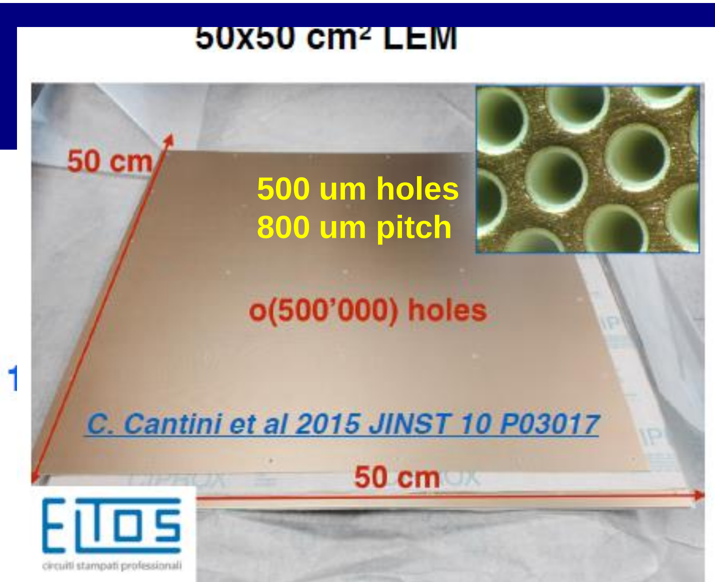
Long drift, high S/N: extraction of electrons from the liquid and multiplication with avalanches in pure argon with micro-pattern detectors like LEM (Large Electron Multipliers)
Tunable gain (~20 minimum), two symmetric collection views, coupling to cold electronics

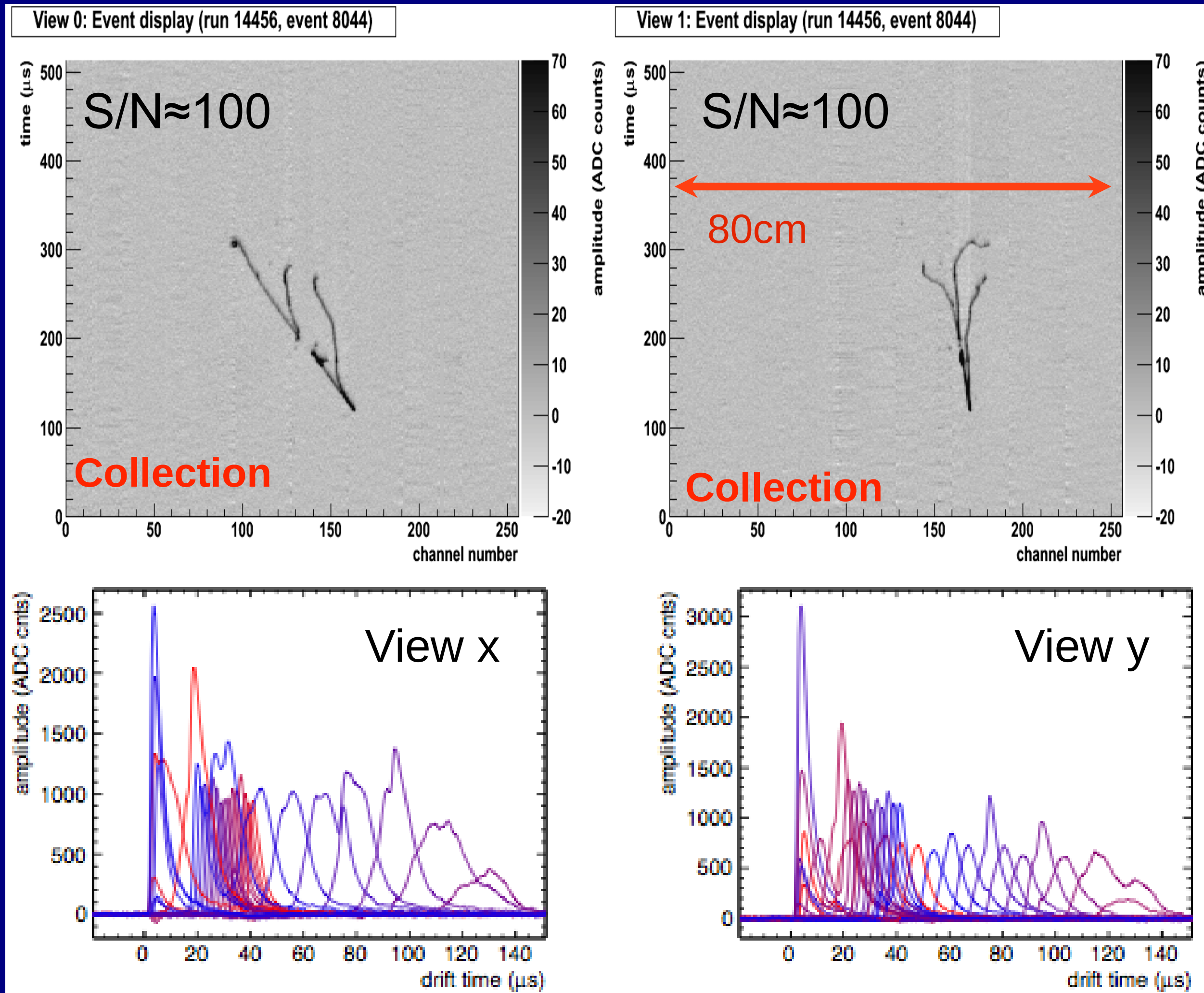


LEM (1mm)
25-35 kV/cm









Double-phase prototypes measuring real data events since 6 years with active volumes from 3 to 250 liters:

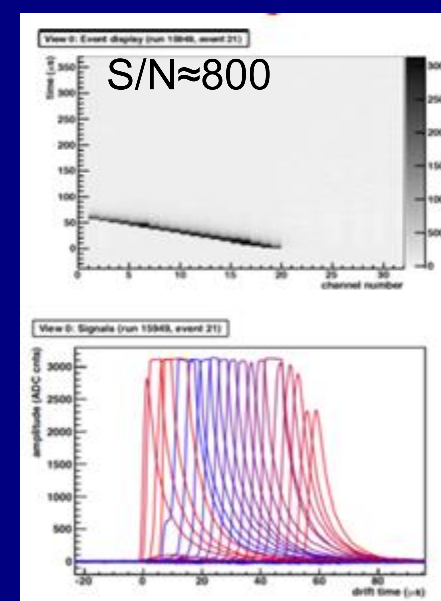
> 15 millions of cosmic events collected in stable conditions S/N~100 for m.i.p. achieved starting from gain ~15

- $3x1x1\ m^3$ setup at CERN
- WA105 $6x6x6\ m^3$ setup will start data taking in 2018

Literature:

NIM A617 (2010) p188-192
NIM A641 (2011) p 48-57
JINST 7 (2012) P08026
JINST 8 (2013) P04012
JINST 9 (2014) P03017
JINST 10 (2015) P03017

Max achieved gain ~200



LAGUNA-LBNO (2008-2014) Design Study

2 EU program, 14 Meur, >200 physicists, 6 years of work

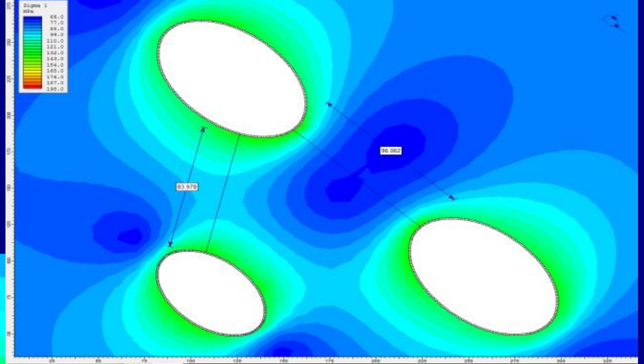
→ Outcome: optimized configuration for a LBL experiment studied in Europe (as recommended by CERN, APPEC) with associated technological developments, innovative solutions and full costing

- Deliverables to the EC, outcome of the design study, documented in >4000 pages (0.5 GB)

- Study performed in collaboration with the EU industrial partners
- Final design study meeting in Helsinki (24-28 August 2014)

→ Design to build an affordable large size underground liquid argon TPC detector

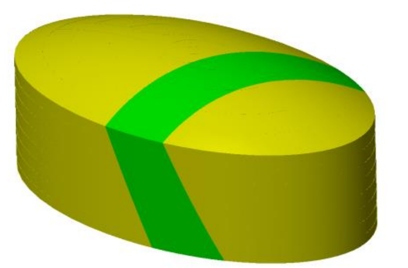
- Precious input to define a joint program EU-USA (ELBNF)

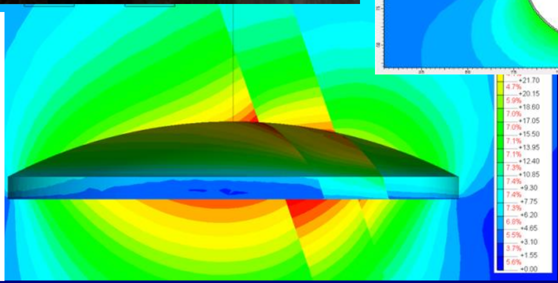


Rock engineering
Caverns:

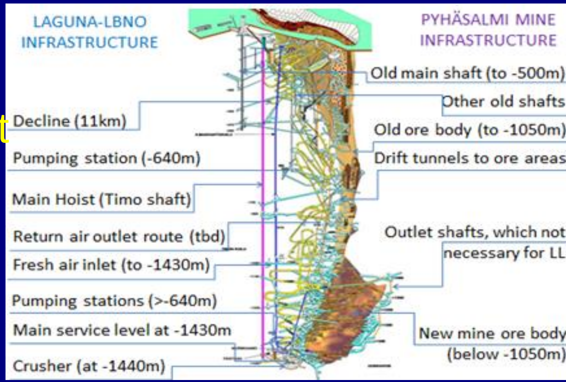
- ✓ 64m span,
- ✓ 100 m length,
- ✓ 38 m height

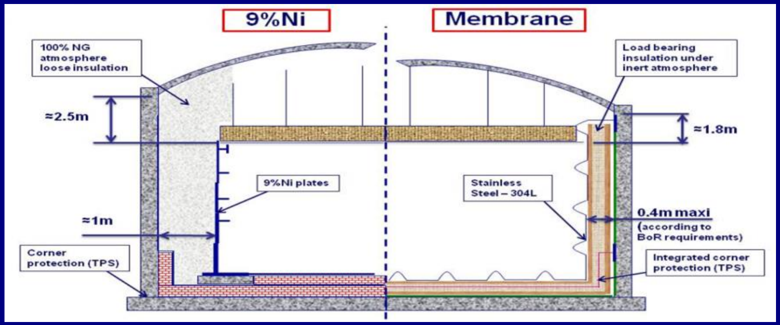
at 1400 m dept.





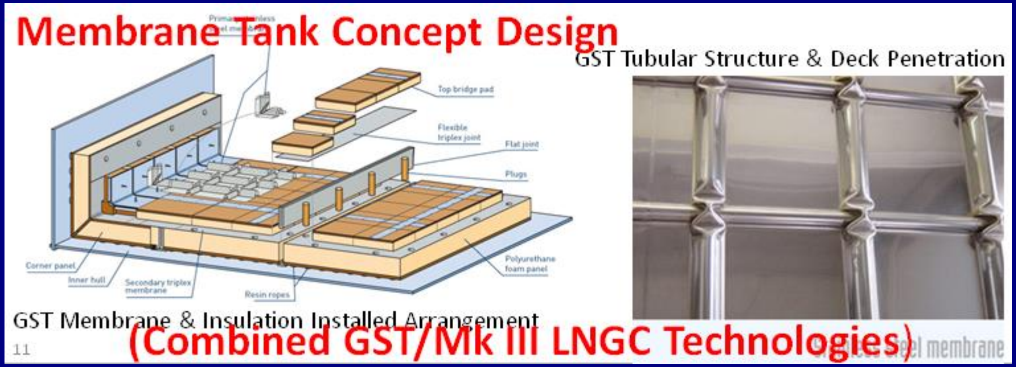
- Infrastructure integration with mine environment
- Concrete production

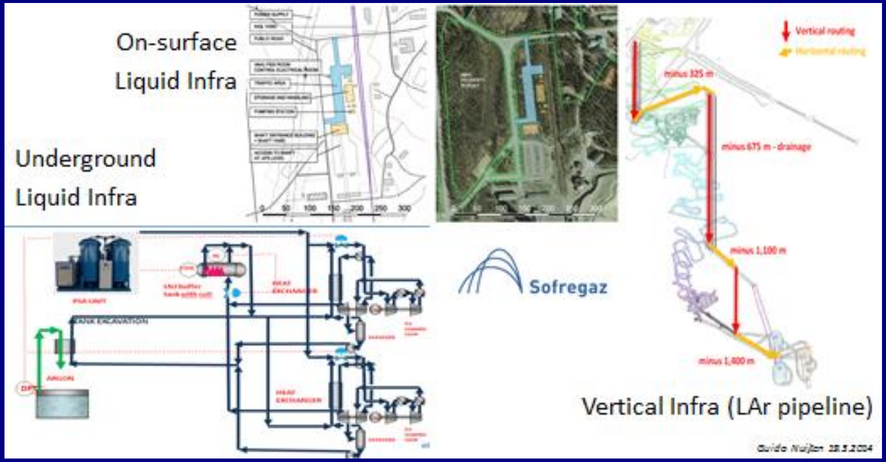




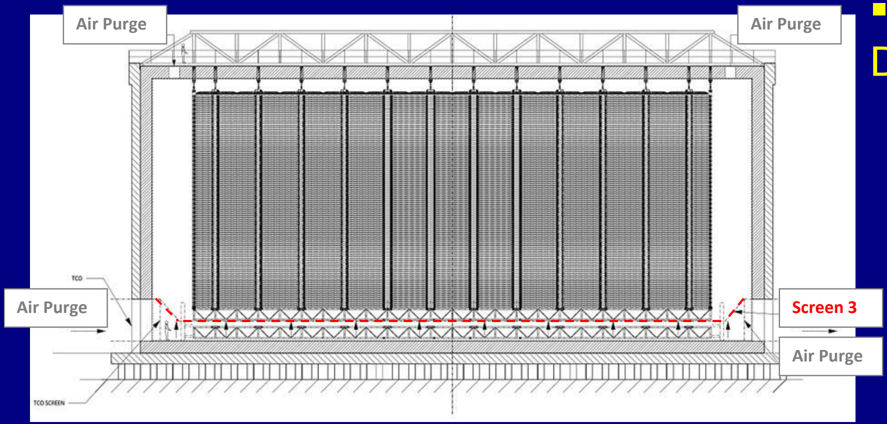
- Study of single/double containment underground

→ Membrane tank double containment



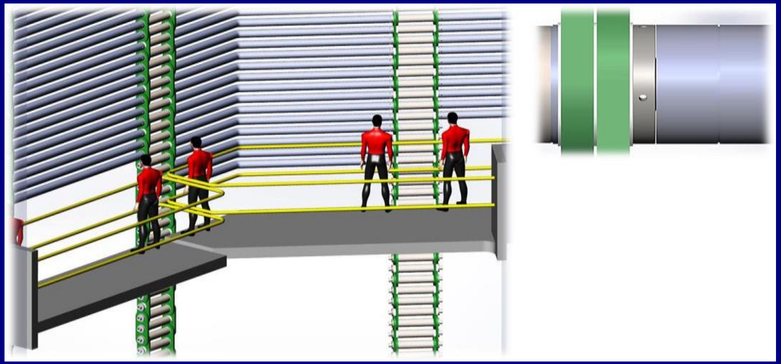


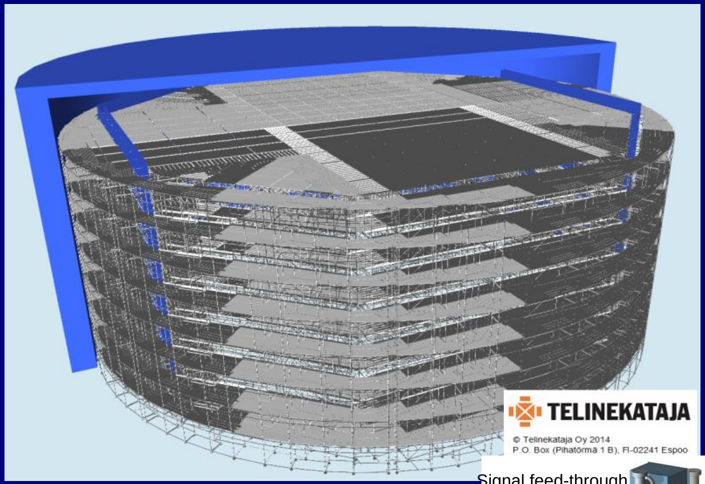
- Design and integration of the liquid handling infrastructure
- Liquid procurement, safety, risk assessment



- Construction/Installation

Design and detailed logistics of the construction steps

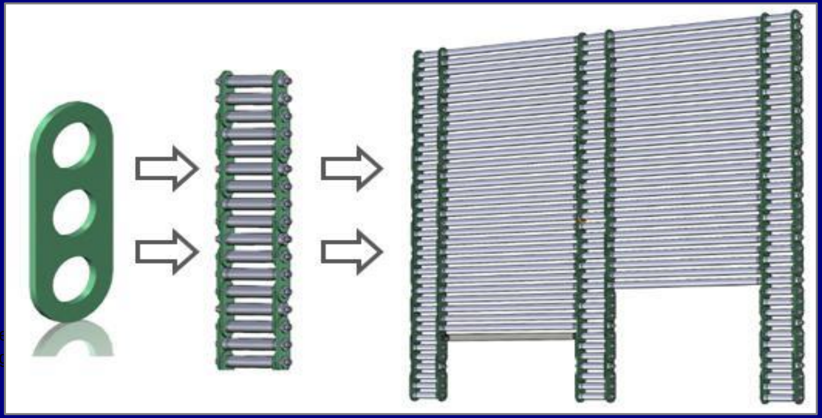




- Special construction materials and demands

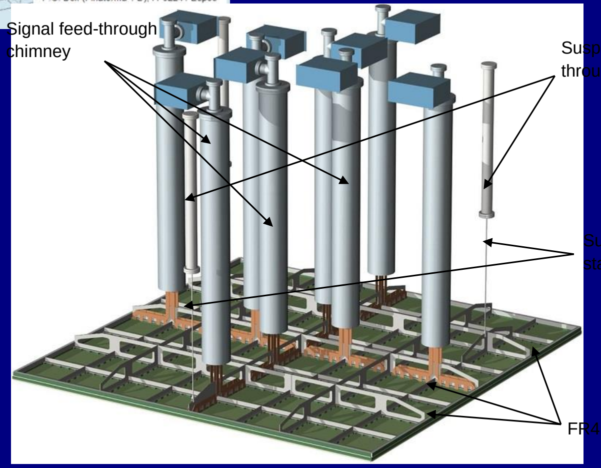
Field cage, cathode, anode deck and feed-throughs

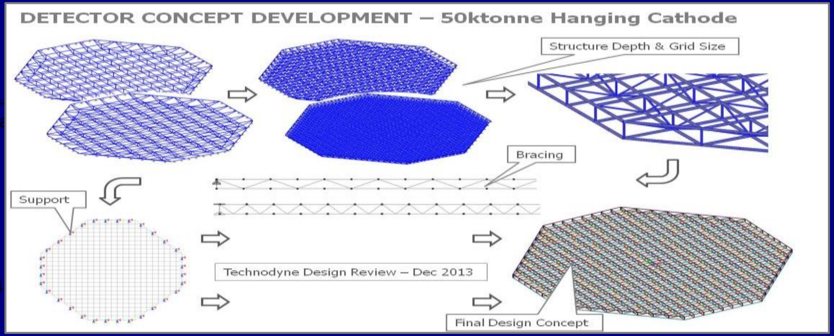
- Scaffolding
- Clean room integration



And last but not least:

- Double phase detectors design and integration
- FE electronics and DAQ
- VHV





LAGUNA-LBNO:

A very long baseline neutrino experiment

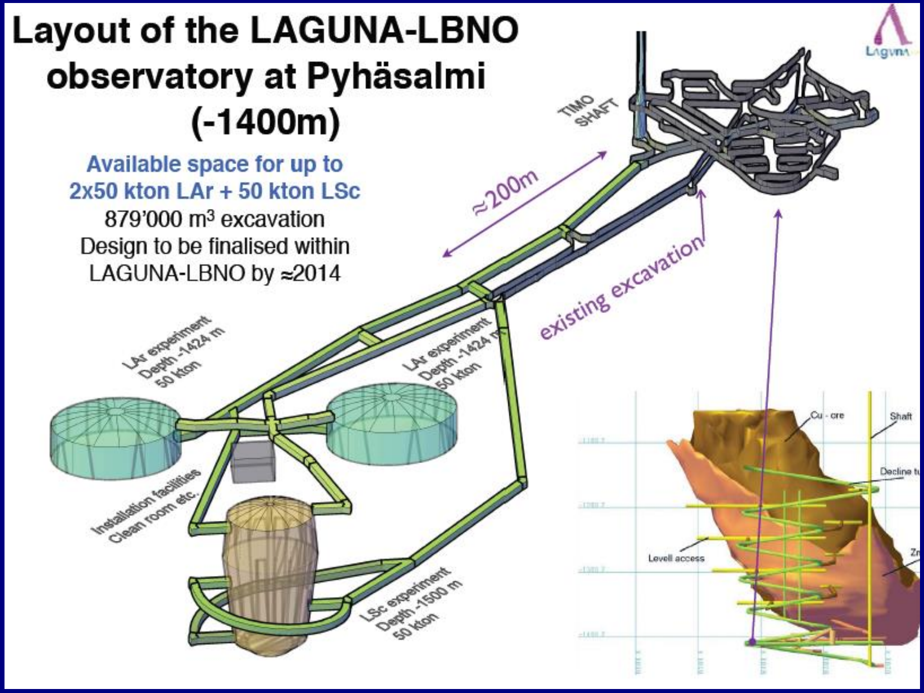
CERN EOI June 2012

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

224 physicists, 52 institutions

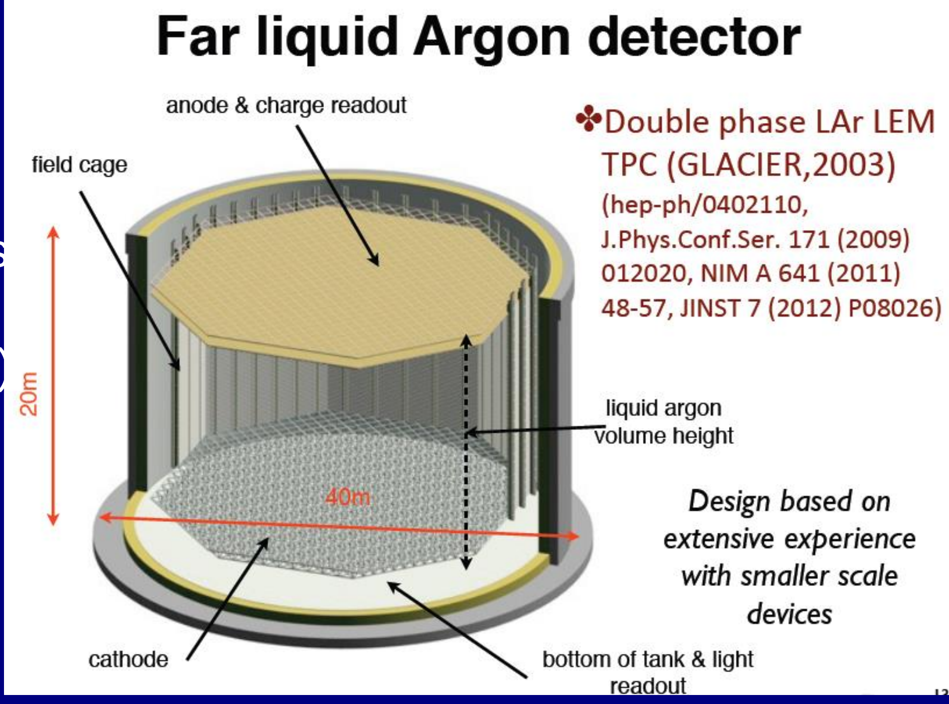
Physics program:

- Determination of neutrino mass hierarchy
- Search for CP violation
- Proton decay
- Atmospheric and supernovae neutrinos



LBNO Phase I: capable of guaranteeing fast unambiguous mass hierarchy determination (>5σ)

20 kton double phase LAr TPC



LBNO physics strategy

- Select a very long baseline (2300km and optimized site for installation) to explore the L/E pattern predicted by the 3 flavor mixing mechanism over the 1st and 2nd max.
- Staged experiment adjusting the beam and detector mass on the bases of the findings of the first phase, most efficient use of resources:

- **Phase I (LBNO20)**
  24 kton DLAR + SPS beam (700 kW, 400 GeV/c), 15E20 pot, 25% antinu
  Guaranteed 5σ MH determination +46% CP coverage at 3σ + proton decay + astroparticle physics

- **Phase II (LBNO70)**
  70 kton DLAR + HPPS beam (2 MW, 50 GeV/c) 30E21 pot, 25% antinu or Protvino beam, 80% (65%) CP coverage at 3σ (5σ) + proton decay + astroparticle physics

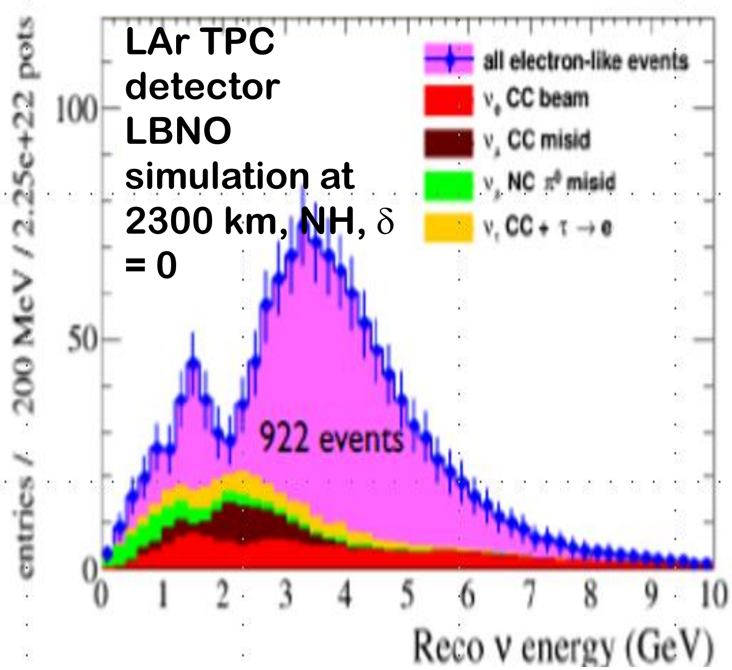
- Complementarity to HyperK (numu vs anti-numu at first max, 300 km) → L/E dependence at 2300 km, 25% antinumu. matter effects

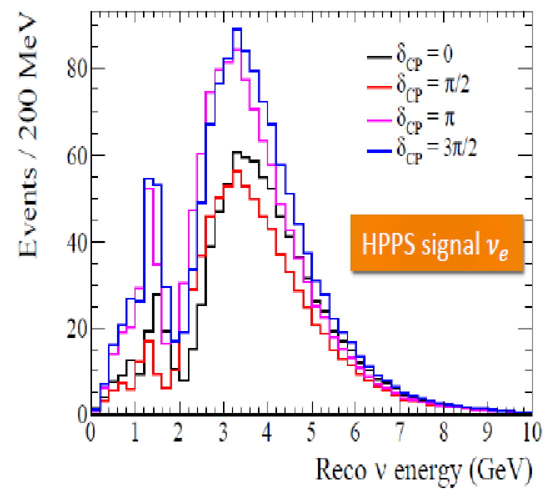
- L/E pattern measurement releases requirements on systematic errors related to the rate normalization at the first maximum

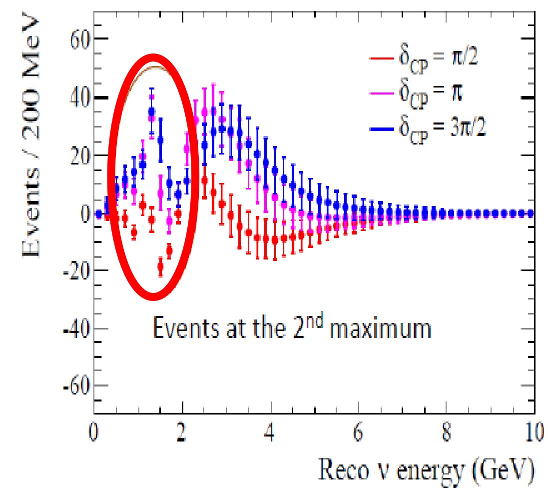
→ Guarantee MH at 5σ and incremental CP coverage satisfying the P5 requirements

What is observed in the detector: relevance of spectral informations

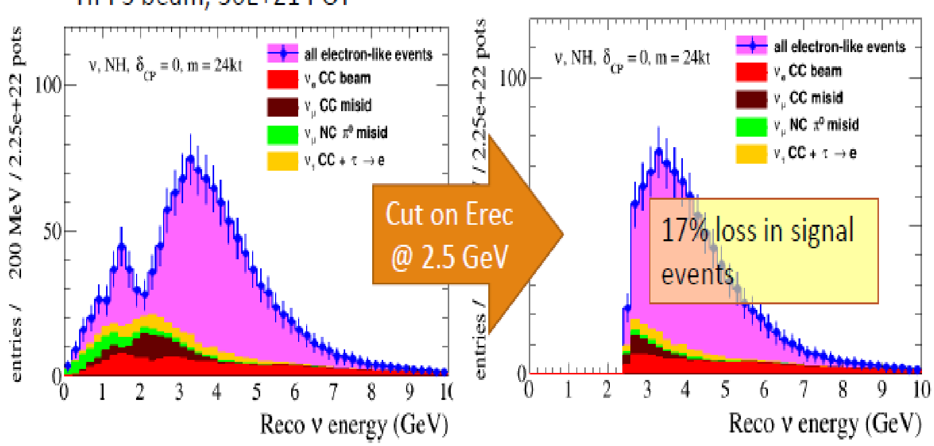
ν_e CC spectrum for neutrino run



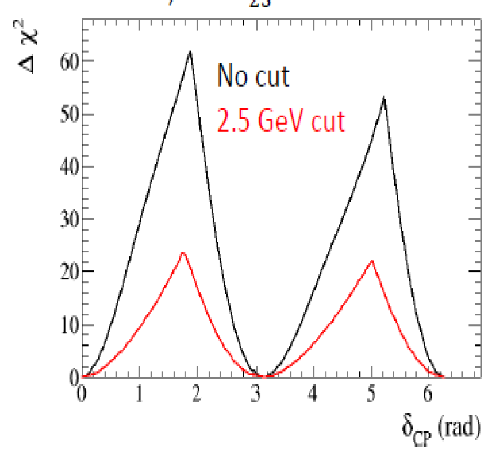




HPPS beam, 30E+21 POT



24 kton, $\sin^2\theta_{23} = 0.45$



Studying CP at only the first oscillation maximum results in a strong loss of sensitivity!

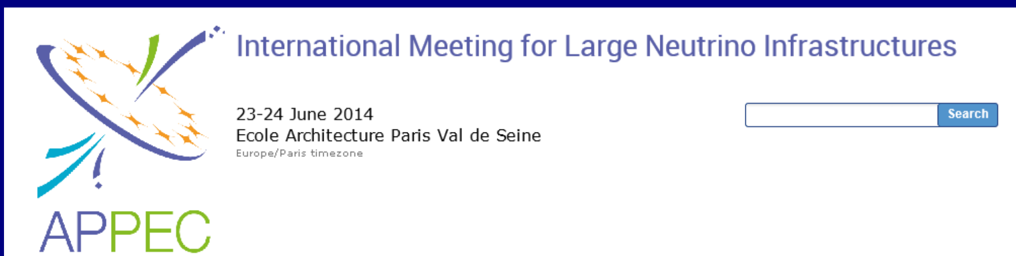
Joint USA-Europe initiative for a common long-baseline experiment based on the liquid argon TPC technology at the LBNF facility

Very quick developments since July 2014:

- **Top priority of the USA P5 committee (HEP strategy in the USA) May 2014**

→ Reformulation of the program

- **APPEC Meeting on Neutrino Infrastructures Paris June 2014**



- **August 2014: creation of an Interim International Executive Board (IIEB) for LBNF chaired by the Fermilab Director N. Lockyer**

- **January 2015: Presentation of the LOI to the FNAL PAC (LBNF (facility) + ELBNF (experiment): 40 kton at Homestake (1300 km from FNAL), 1.2 MW beam upgradable to 2.4 MW, first 10 kton module in 2021**

- **March 2015: Formalization of the collaboration (DUNE), writing of a Conceptual Design Report (CDR) for the DOE "CD-1 refresh" review**
- **July 14-16th 2015: Final CD1 review**

- **September 2016 LBNF CD3a approval → start of funding for the facility preparation**

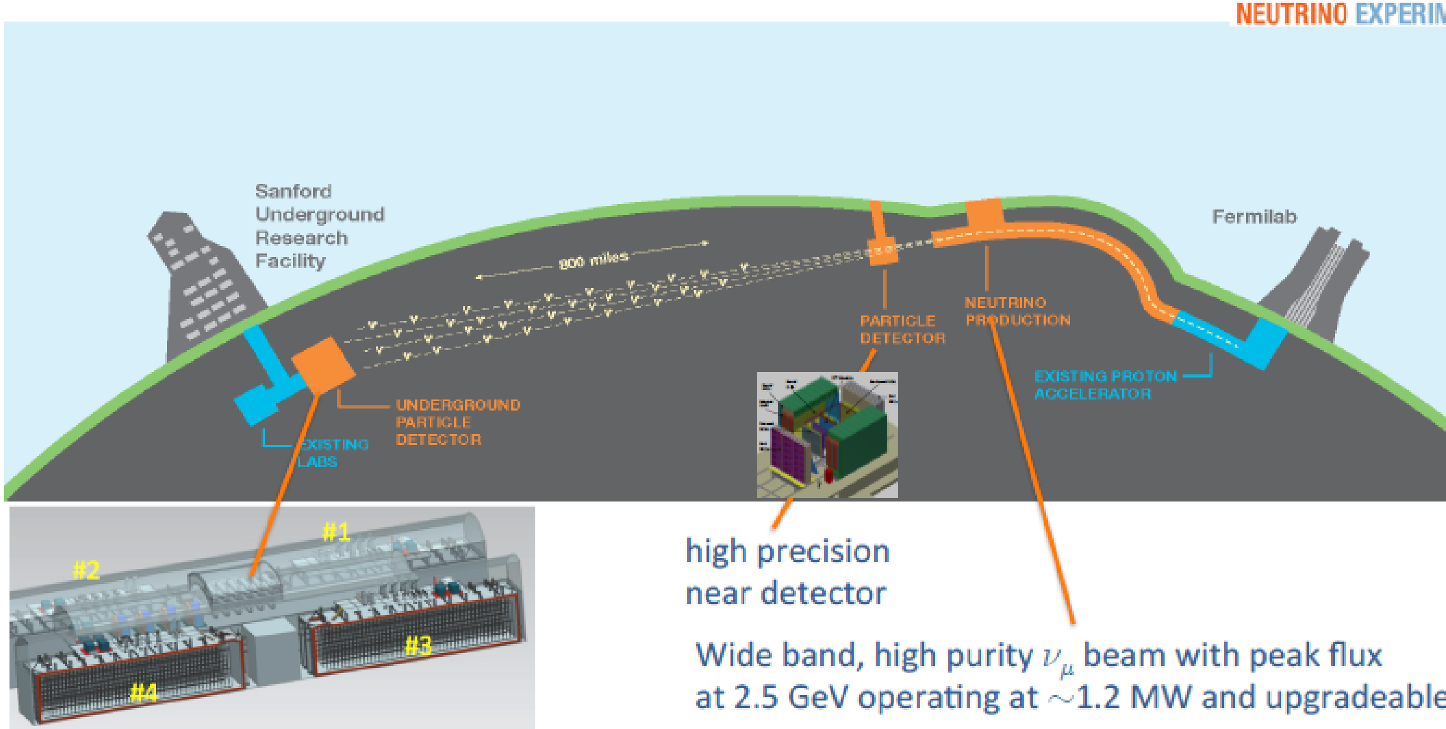
Merging on LBNO and LBNE in an international LBL program hosted in the USA based on the “LHC model”

- **40 kton LAr target at 1300 km from FNAL at the Homestake mine (LBNO experience on double-phase to achieve large mass), high precision near detector**
- **1.2 MW (upgradeable to 2.4 MW) and neutrino beam with second max optimization à la LBNO**

→ Start of beam operations expected in 2026

Overall Experimental Layout

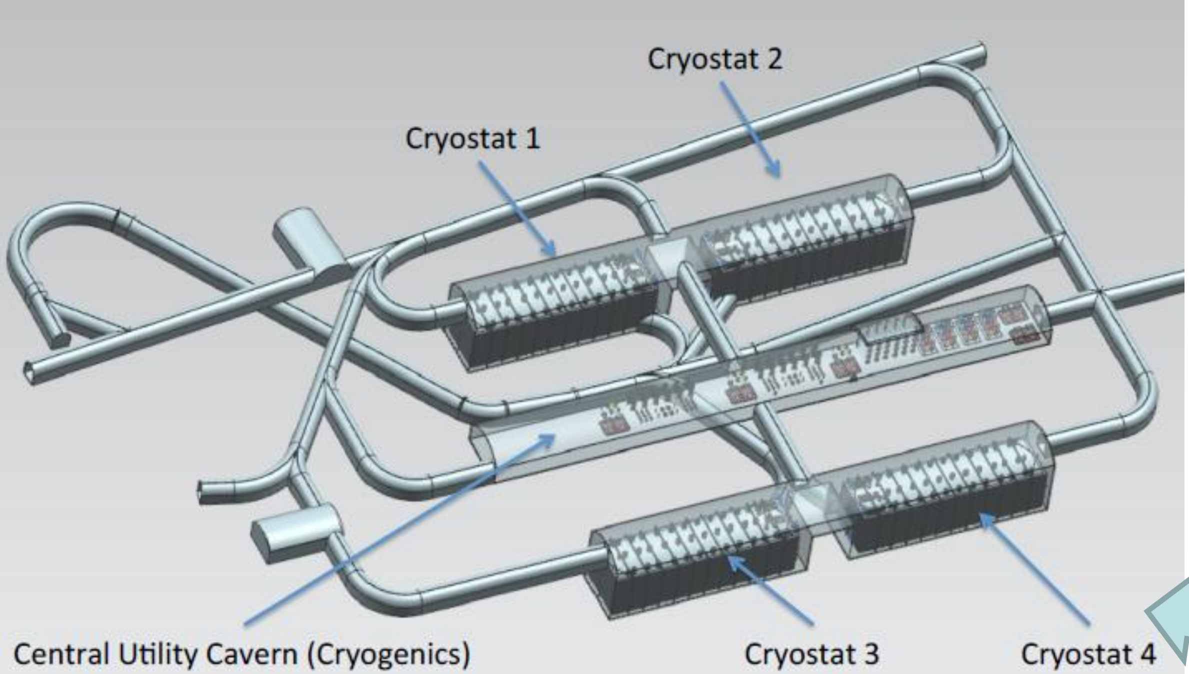
DEEP UNDERGROUND NEUTRINO EXPERIMENT



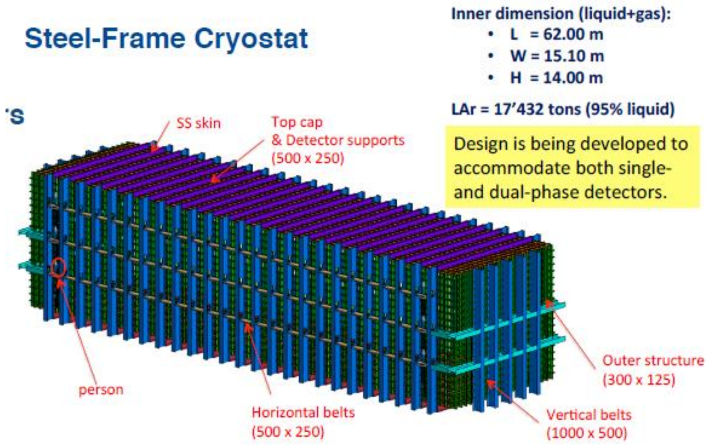
high precision near detector

Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

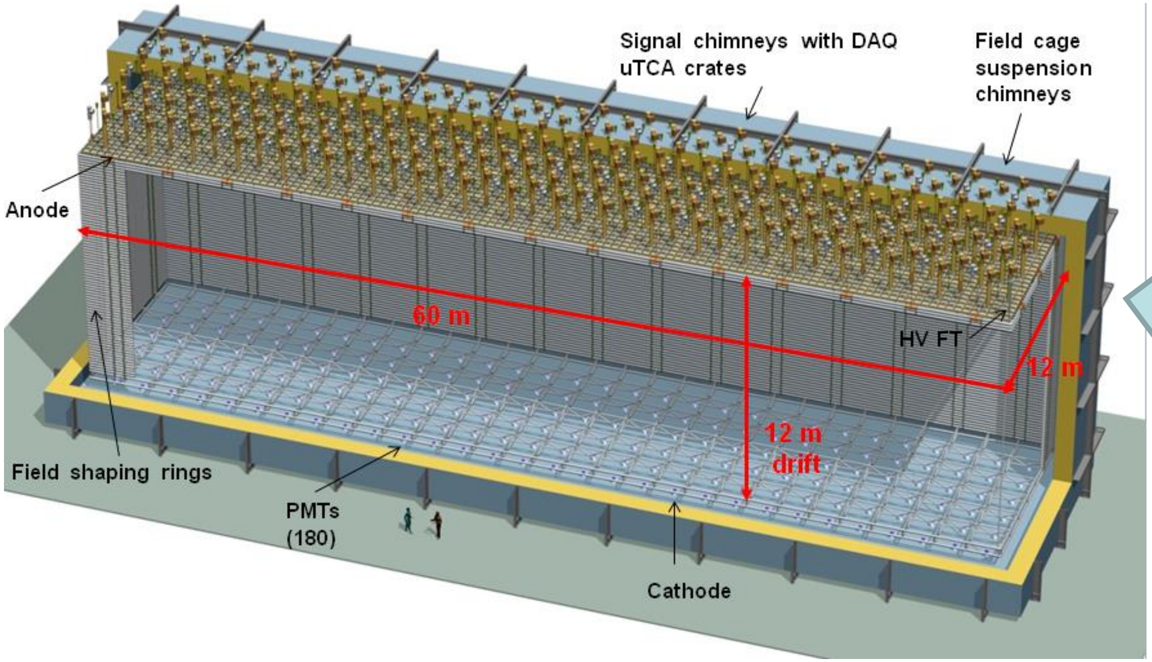
- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration



CERN steel-frame cryostat



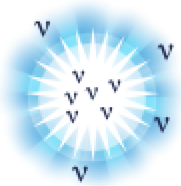
4-caverns, 4-10kton modules layout at SURF (Homestake)



Double-phase 10kton module design (based on LAGUNA-LBNO and WA105) presented in the DUNE Conceptual Design Report submitted for the DOE CD-1 refresh

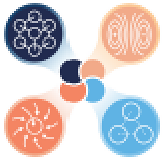
DUNE science program

Focus on fundamental open questions in particle physics and astroparticle physics – <u>aim for discoveries</u>



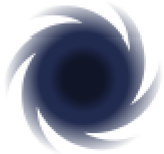
1) Neutrino & Antineutrino Oscillation Physics in Wide-Band Beam – Appearance and Disappearance Signals

- CPV in the leptonic sector
- Neutrino Mass Hierarchy
- Precise Oscillation Parameters
- Testing the 3-flavour paradigm



2) Nucleon Decay Searches with Zero Background

- Predicted by Grand Unified theories



3) Galactic Supernova Burst physics & astrophysics

- Core collapse supernovae still not fully understood and neutrinos are intimately involved

DUNE Oscillation Strategy

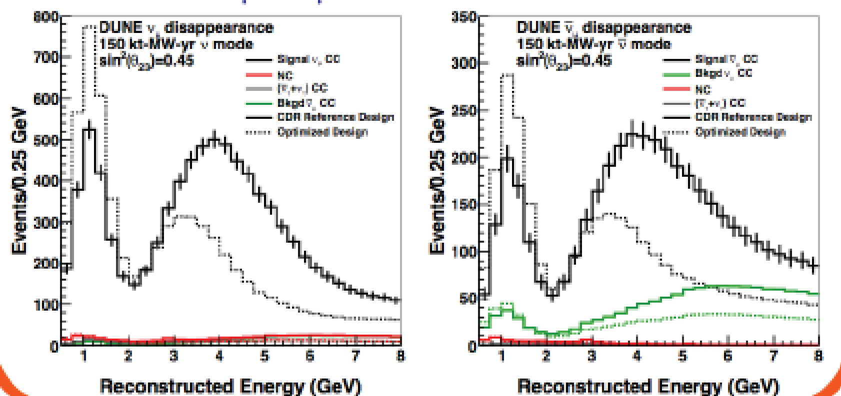
Measure neutrino spectra at 1300 km in a wide-band beam

- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for BSM effects (e.g. NSI) in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

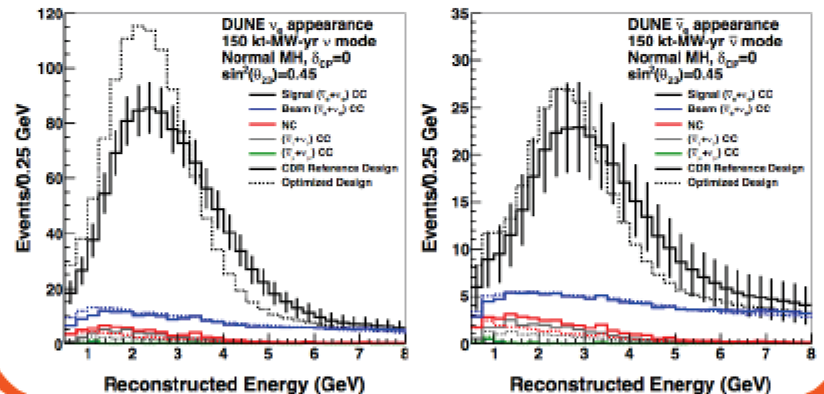
μ

ν_μ / $\bar{\nu}_\mu$ disappearance



e

ν_e / $\bar{\nu}_e$ appearance



Timescales: year zero = 2025

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for Mass Hierarchy :
  - **Reach 5σ MH sensitivity with 20 – 30 kt.MW.year**

Discovery

~2 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 3σ CPV sensitivity with 60 – 70 kt.MW.year**

Strong evidence

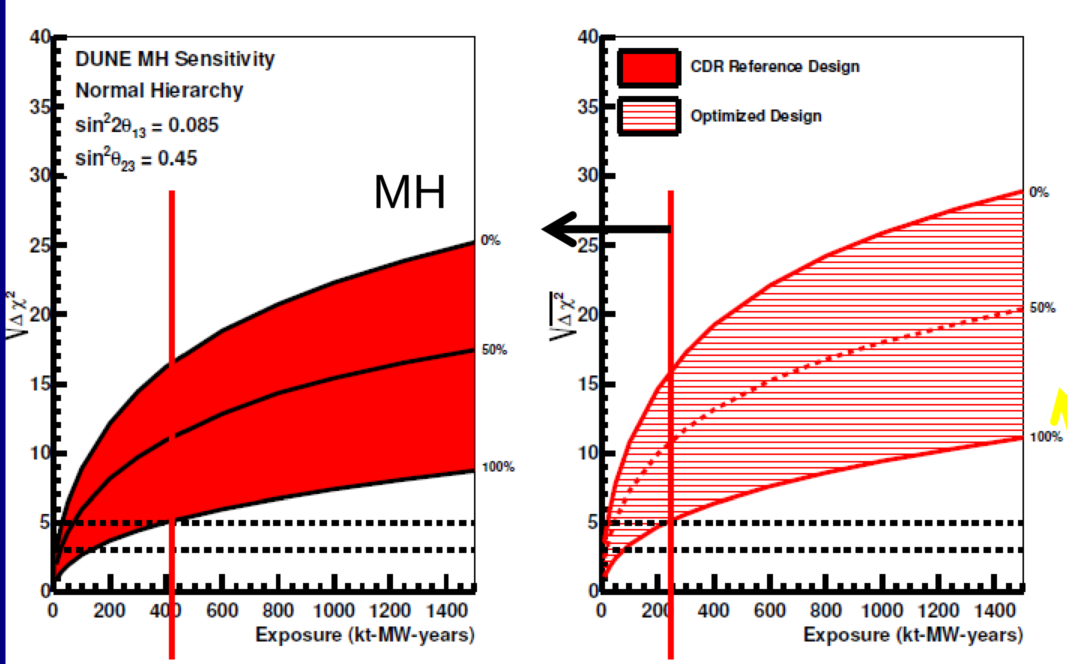
~3-4 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 5σ CPV sensitivity with 210 – 280 kt.MW.year**

Discovery

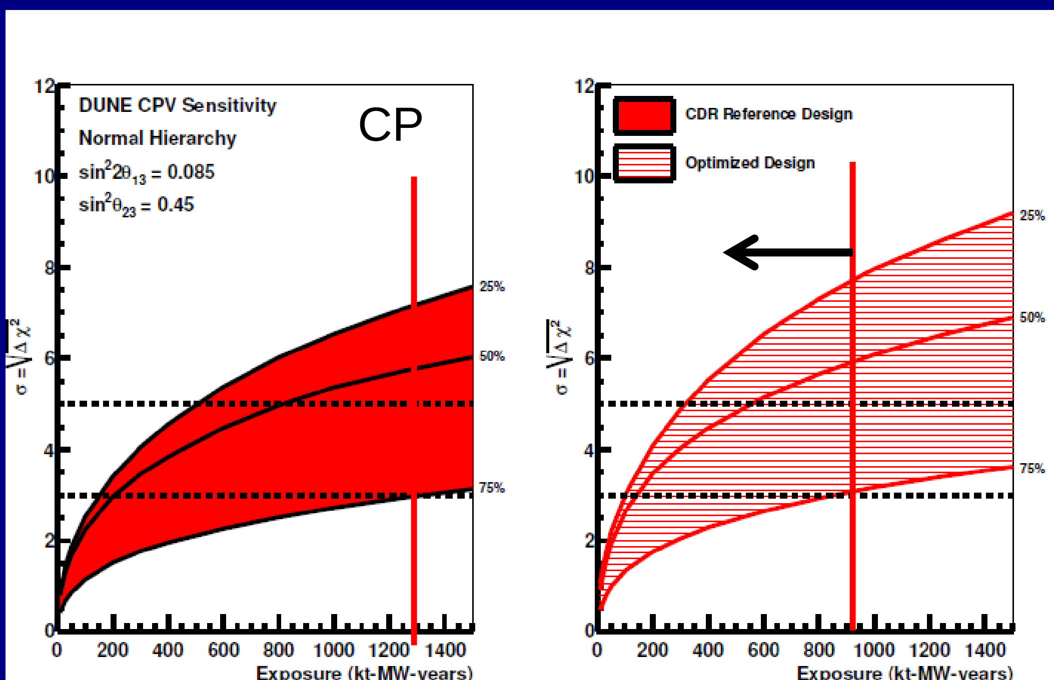
~6-7 years

★ **Genuine potential for early physics discovery**



Reference beam

Optimised beam



Effect of beam optimization: exposure time to reach a certain significance

Sensitivities shown as a function of exposure in kt-MW-yr's.
40-kt x 10 yrs x 1.2 MW ~ 500 kt-MW-yr

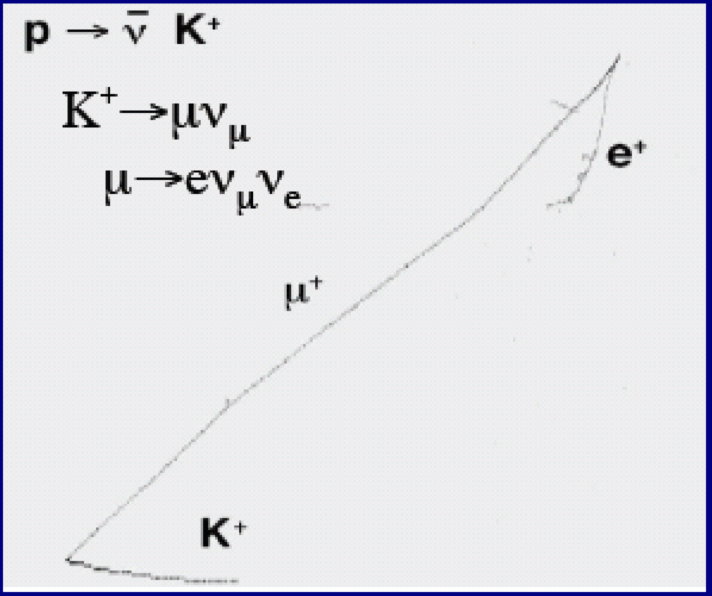
Bands for different values of:

- MH: probability to reach a certain significance
- Fraction of CP coverage

→ Beam optimization process being further pursued in DUNE (Task force 2)

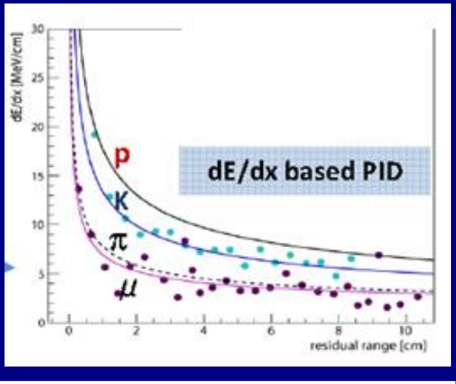
Proton decay

Simulated event



Exclusive channels,
(like p→ K^+ + anti-ν)
Particles ID in final state

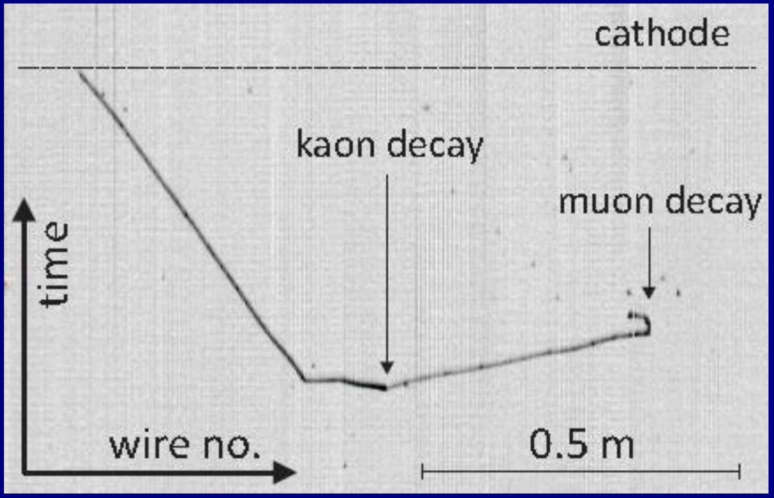
Clean signature, very low backgrounds



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

K decay chain of a K from a neutrino interaction observed in ICARUS



200 kton/year (JHEP 0704 (2007) 041 → x10 sensitivity increase, comparable to HK

Supernova neutrinos

JCAP 0310 (2003) 009
JCAP 0408 (2004) 001

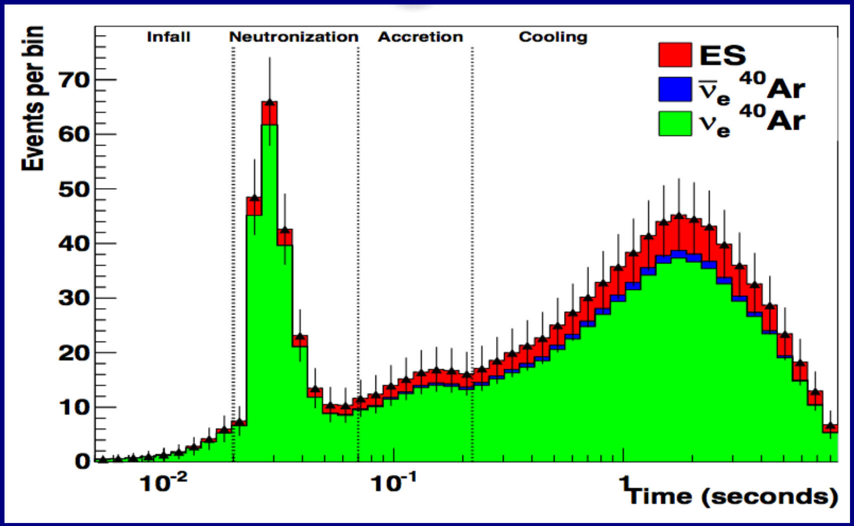
For a SN explosion at the distance of 5 kpc

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

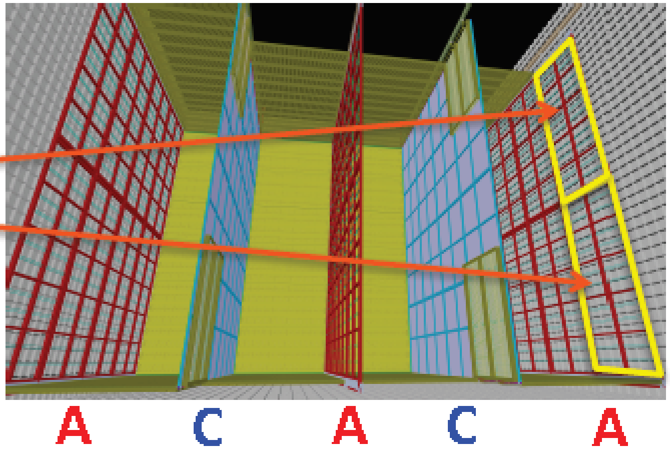
		Events:
$\nu_e\ {}^{40}Ar \rightarrow e^-\ {}^{40}K^*$	(E_ν > 1.5 MeV)	≈23820
$\bar{\nu}_e\ {}^{40}Ar \rightarrow e^+\ {}^{40}Cl^*$	(E_ν > 7.48 MeV)	≈2420
$\nu_x\ {}^{40}Ar \rightarrow \nu_x +\ {}^{40}Ar^*$		≈30440
$\nu_x\ e^- \rightarrow \nu_x\ e^-$		≈1330

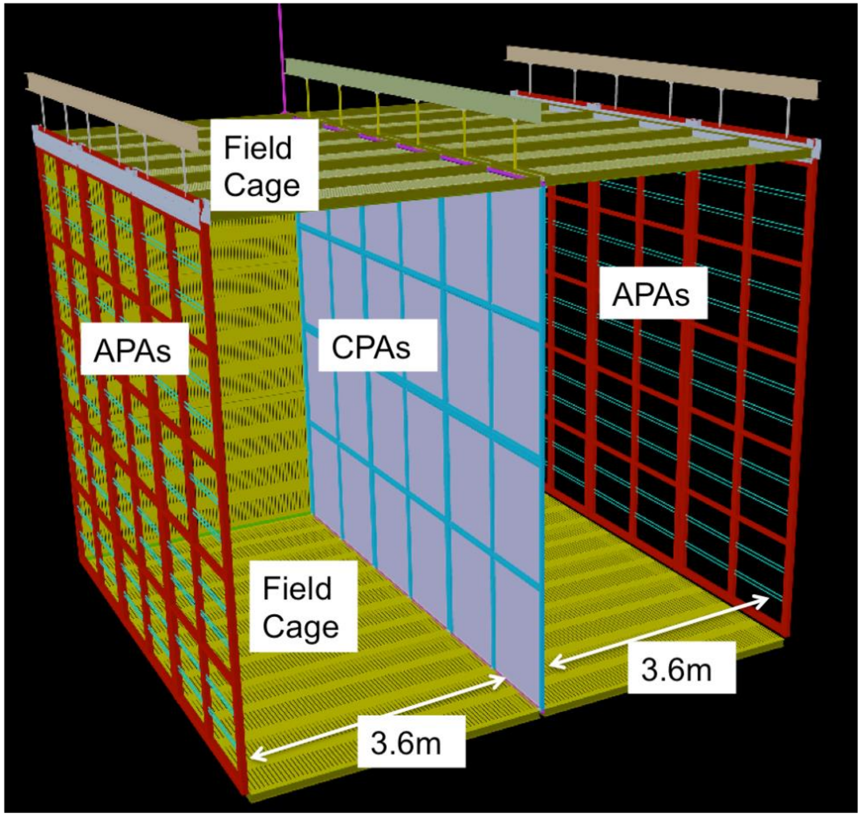
About 10k neutrinos (ν_e + ^{40} Ar interaction) observable in DUNE for a SN explosion in our galaxy in a time window of 10s (detailed observation of emission time profile, neutronization burst, etc ..)

Possibility to distinguish neutrino/anti-neutrinos and NC interactions with dual-phase detectors (de-excitation photons)

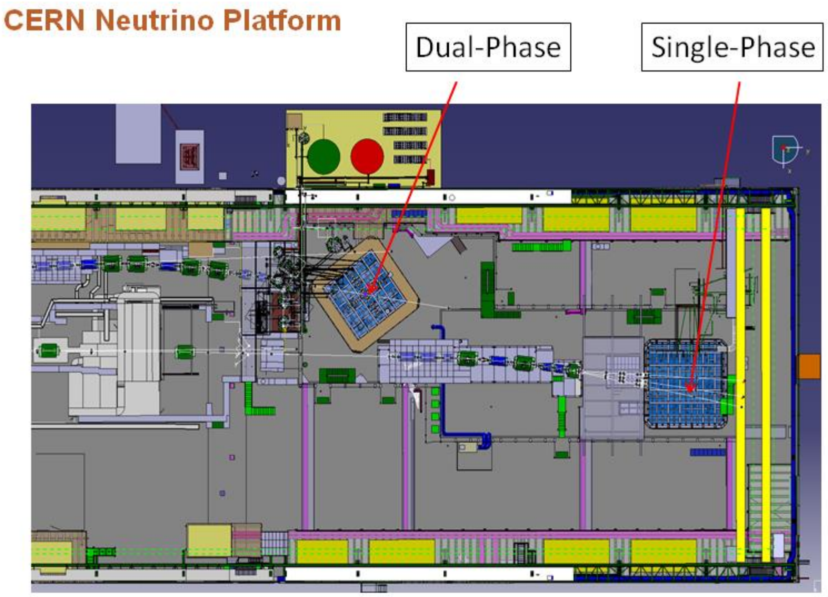


- **Modular** implementation of Single-Phase TPC
  - Active volume: **12m x 14m x 58m**
  - 150 Anode Plane Assemblies (APA)
    - 6m high x 2.3m wide
  - 200 Cathode Plane Assemblies
    - Cathode @ -180 kV for 3.5m drift



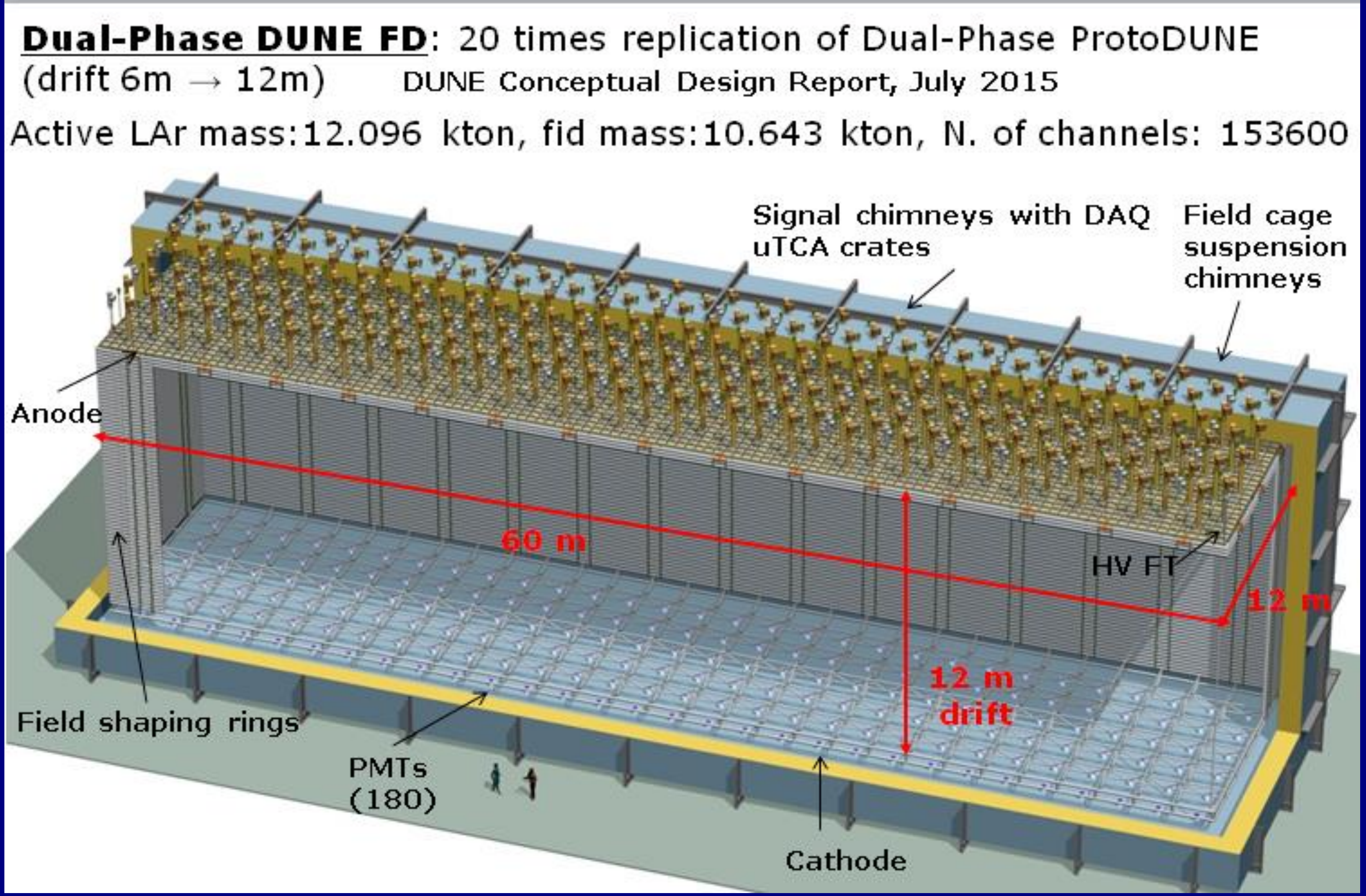


Single-phase proto-DUNE (TDR submitted to CERN SPSC October 2016)



Dual-phase 10 kton FD module

- 80 CRP units
- 60 field shaping rings
- 240 signal FT chimneys
- 240 suspension chimneys
- 180 PMTs
- 153600 readout channels

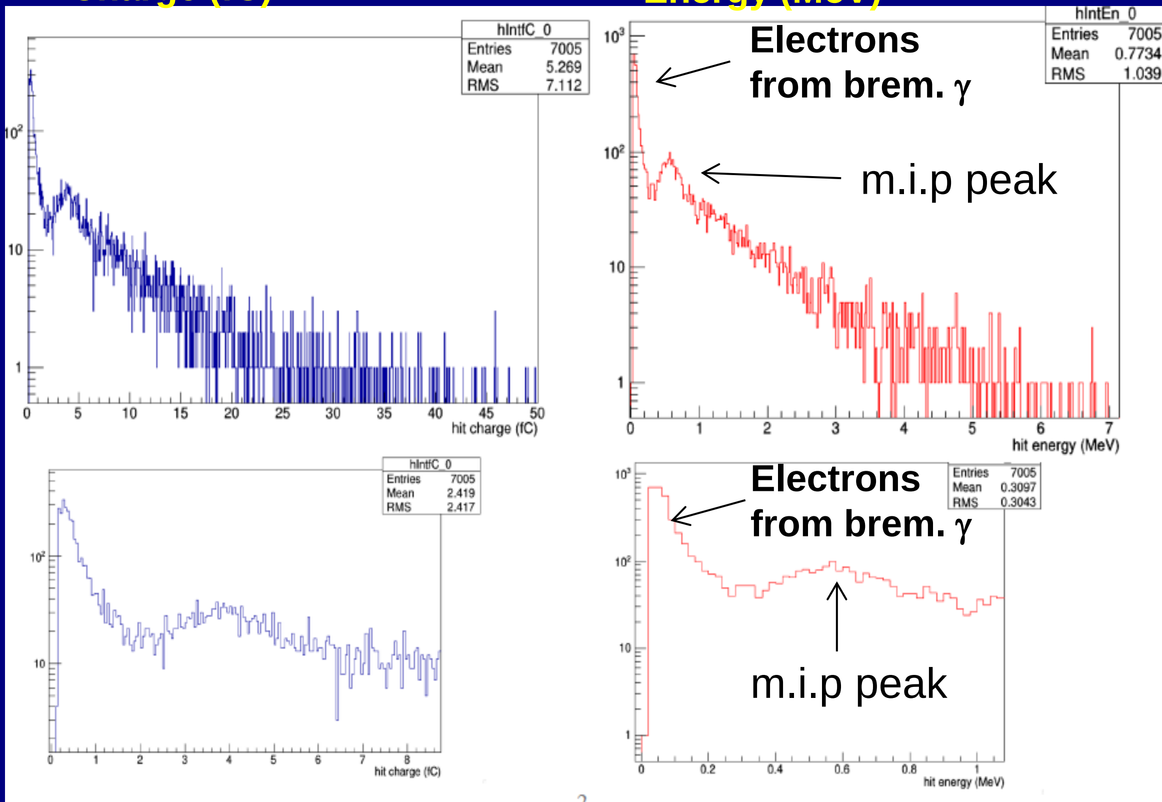


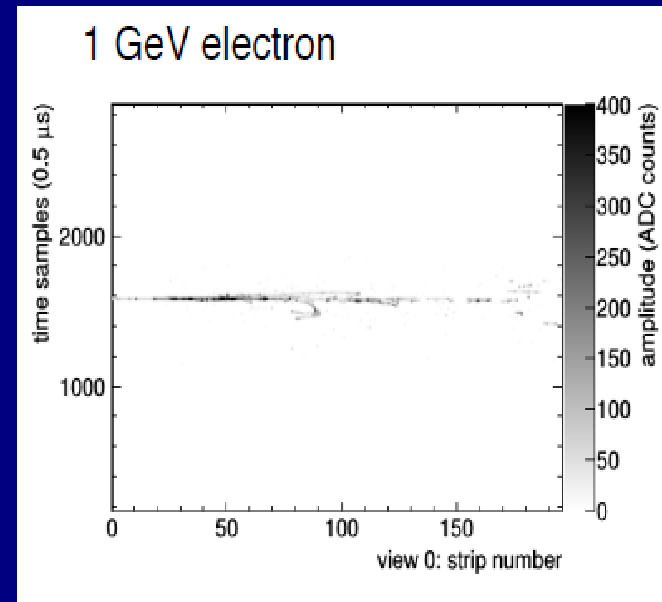
Advantages of double-phase design:

- Anode with 2 collection (X, Y) views (no induction views), no ambiguities
- Strips pitch 3.125 mm, 3 m length
- Tunable gain in gas phase (20-100), high S/N ratio for m.i.p. > 100, <100 KeV threshold, min. purity requirement 3ms → operative margins vs purity, noise
- Long drift projective geometry: reduced number of readout channels
- No materials in the active volume
- Accessible and replaceable cryogenic FE electronics, high bandwidth low cost external uTCA digital electronics

Energy depositions seen at the single wire level for a 1 GeV electron simulated shower (3.125 mm pitch)

Charge (fC) **Energy (MeV)**





→ Many tiny depositions at the single wire level from brem. photons which contribute to the energy reconstruction

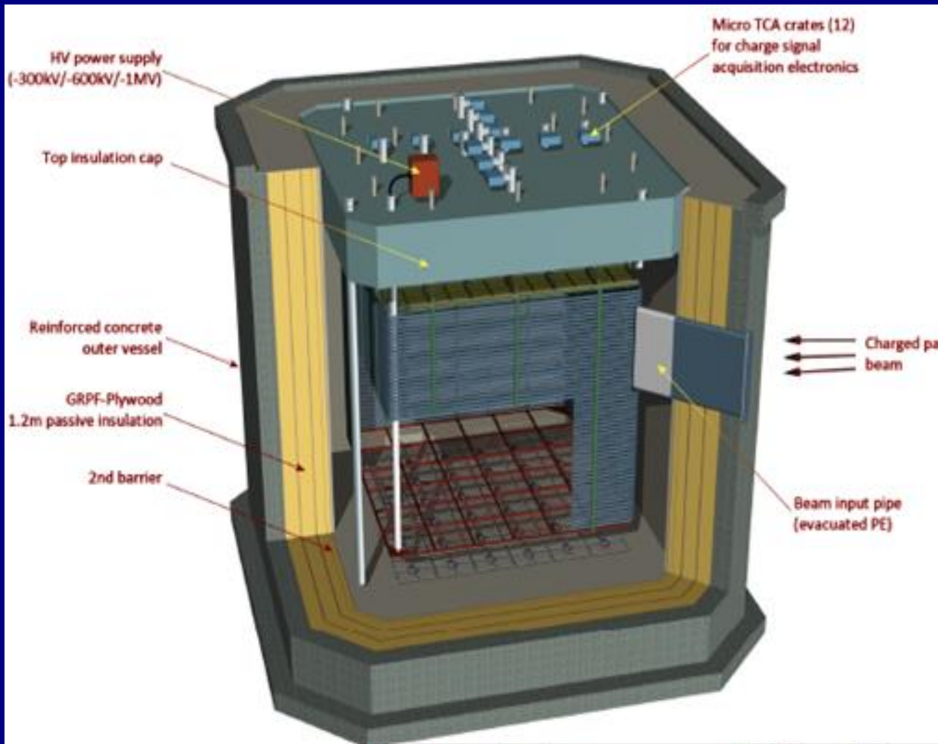
→ Importance of operating at low energy thresholds < 100 keV

→ Do not consider only average value of m.i.p. peak for S/N but also under-fluctuations in Landau width

A 10-20 MeV electron from a SNB event will brem. and be split in little per-wire depositions
For SNB is also very important to detect de-excitation gammas of 40K*(40Cl*) for neutrino(anti) tagging → Also pointing to relevance of reconstructing low energy depositions for SNB

The LBNO-DEMO/WA105 experiment at CERN (approved in 2013)

WA105



Liquid argon density	T/m^3	1.38
Liquid argon volume height	m	7.6
Active liquid argon height	m	5.99
Hydrostatic pressure at the bottom	bar	1.03
Inner vessel size (WxLxH)	m^3	8.3 × 8.3 × 8.1
Inner vessel base surface	m^2	67.6
Total liquid argon volume	m^3	509.6
Total liquid argon mass	t	705
Active LAr area	m^2	36
Charge readout module (0.5 x0.5 m^2)		36
N of signal feedthrough		12
N of readout channels		7680
N of PMT		36

→ 1/20 of 20 kton LBNO detector

6x6x6m^3 active volume, 300 ton , 7680 readout channels, LAr TPC (double phase+2-D collection anode): DLAr
Exposure to charged hadrons, muons and electrons beams (0.5-20(10) GeV/c)

Full-scale demonstrator of all innovative LAGUNA-LBNO technologies for a large LAr detector:

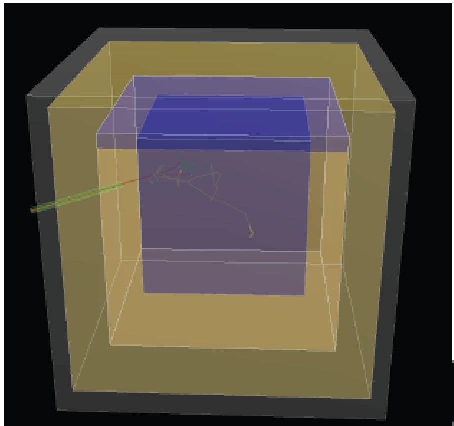
- **LNG tank construction technique (with non evacuated vessel)**
- **Purification system**
- **Long drift**
- **HV system 300-600 KV, large hanging field cage**
- **Large area double-phase charge readout**
- **Accessible FE and cheap readout electronics**
- **Long term stability of UV light readout**

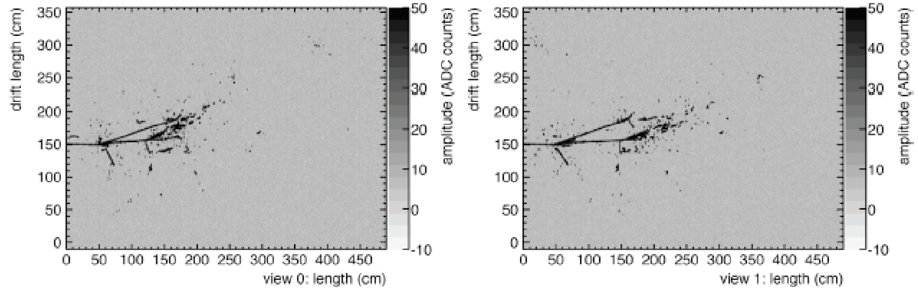
Assess performance in reconstructing hadronic showers (most demanding task in neutrino interactions):

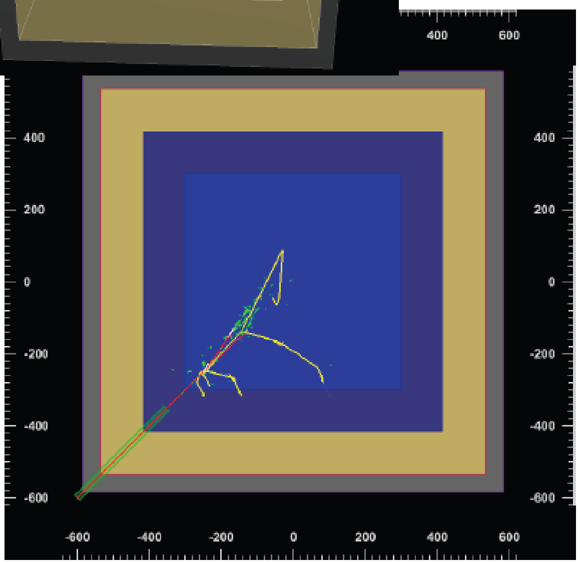
- **Measurements in hadronic and electromagnetic calorimetry and PID performance**
- **Full-scale software development, simulation and reconstruction to be validated and improved**

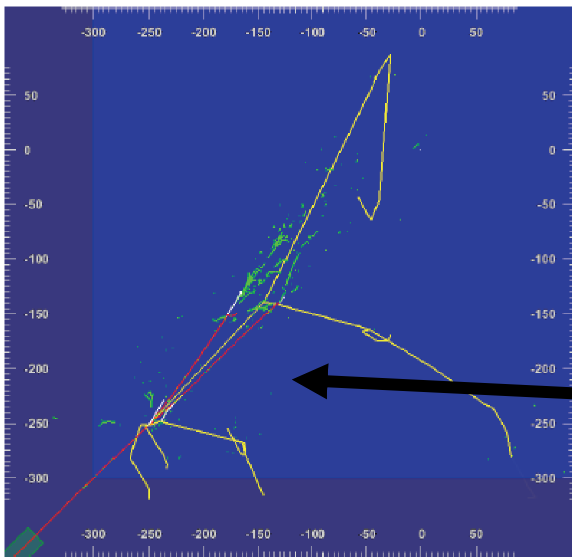
Installation in the CERN NA EHN1 extension, data taking in 2018
→ Fundamental step for the construction of a large LAr detector

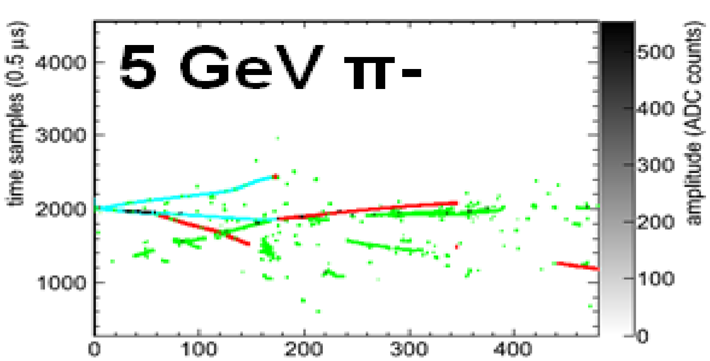
5 GeV π+ simulation in 6x6x6m³

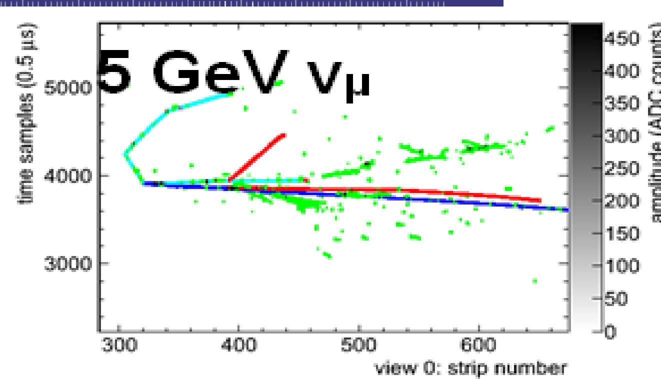












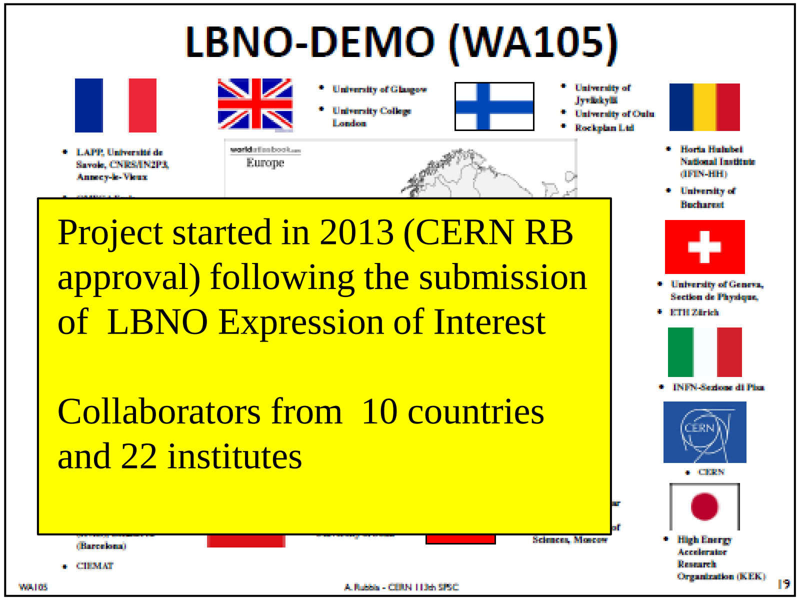
Physics program already outlined in the TDR:

- Em/hadronic calorimetry
- Cross section measurements
- π0 rejection at secondary vertices
- Systematics for far detector

Hadronic showers fully contained in WA105

Reconstructed pion and neutrino interactions in DLAr

History of Dual-Phase ProtoDUNE / WA105



Project started in 2013 (CERN RB approval) following the submission of LBNO Expression of Interest

Collaborators from 10 countries and 22 institutes

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

March 31st, 2014
CERN-SPSC-2014-013
SPSC-TDR-004

Technical Design Report
for large-scale neutrino detectors prototyping
and phased performance assessment
in view of a long-baseline oscillation experiment

...boration

TDR
submitted on 31st March 2014
CERN-SPSC-2014-013
SPSC-TDR-004(2014)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-...
March...

CERN-SPSC-2015-013 / SPSC-SR-158
31/03/2015

Progress report on LBNO-DEMO/WA105 (2015)

The WA105 Collaboration

G. Balik, L. Brunetti, I. De Bonis, P. Del Amo Sanchez, G. Deleglise,
C. Drancourt, D. Duchesneau, N. Geffroy, Y. Karyotakis, and H. Pessard
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Faculty of Physics, University of Bucharest, Bucharest, Romania

P. Bourgeois, F. Duval, I. Efthymiopoulos, U. Kose, G. Maire, D. Mladenov, M. Nessi, and F. Noto
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R. Bayes and F.J.P. Soler
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G.A. Nuijten
Rockplan Ltd., Helsinki, Finland

2015 Annual SPSC progress report 31st March 2015
SPSC-SR-158

DUNE CDR, July 2015:
WA105 and Dual-phase
10 kton design

WA105 project MOU fully signed, December 2015

Integration in DUNE project as DP-ProtoDUNE December 2015; EOI call for ProtoDUNEs, January 2016

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Yearly progress report on WA105/ProtoDUNE dual...

G. Balik, L. Brunetti, A. Chappuis, I. De Bonis, G. Deleglise, C. D...
D. Duchesneau, N. Geffroy, Y. Karyotakis, H. Pessard, and L. Z...
LAPP, Université de Savoie, CNRS/IN2P3, Annecy-le-Vieux...

B. Bourguille, S. Bordoni, T. Lux, and F. Sanchez
Institut de Fisica d'Altes Energies (IFAE), Bellaterra (Barcelona), Spain

M. C...
Fac...

N. Bourgeois, F. Duval, I. Efthymiopoulos, U. Kose, G. Maire, D. Mladenov, M. Nessi, and F. Noto
CERN, Geneva, Switzerland

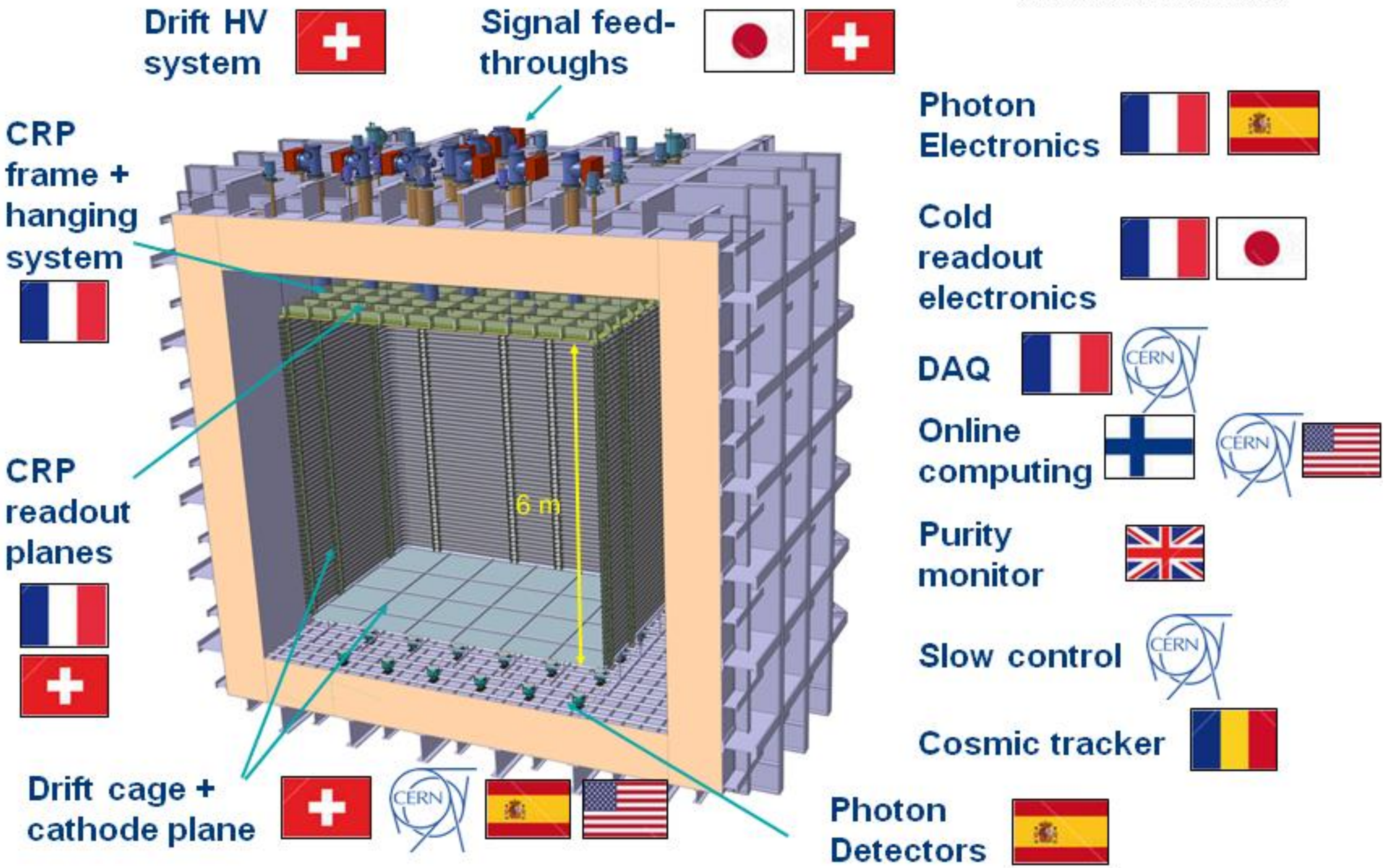
K. Loo, J. Maalampi, W.H. Trzaska, and S. Vihonen
Department of Physics, University of Jyväskylä, Finland

2016 Annual SPSC progress report, 7th April 2016
CERN-SPSC-2016-017
SPSC-SR-184

LBNC review June 2016

Dual phase protoDUNE - WA105 6x6x6m^3

(US contributions under discussion)

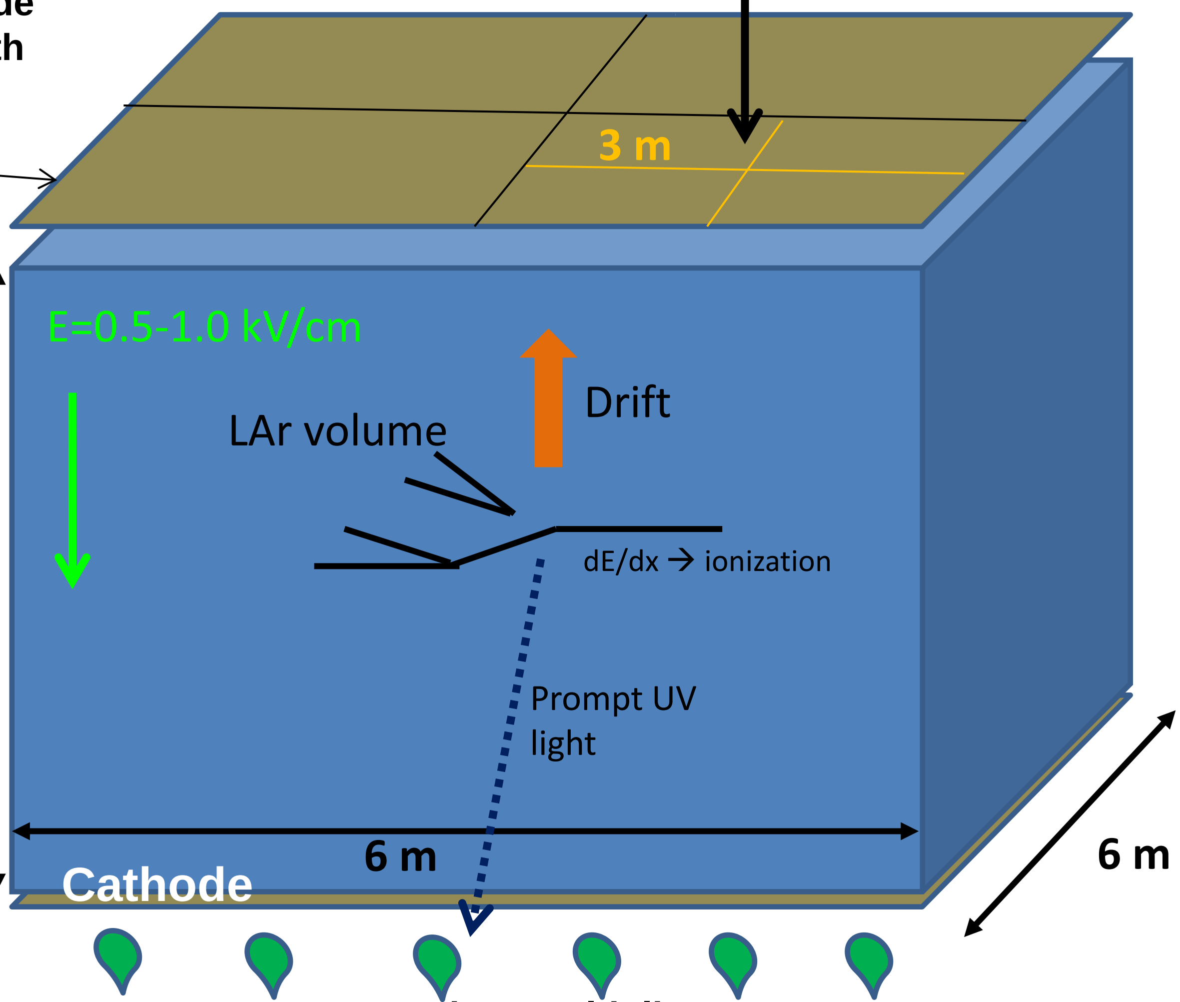


Dual phase liquid argon TPC
6x6x6 m^3 active volume

→ **Event size: drift window of 7680 channels x 10000 samples ⇒ 146.8 MB**

X and Y charge collection strips
3.125 mm pitch, 3 m long →7680 readout channels

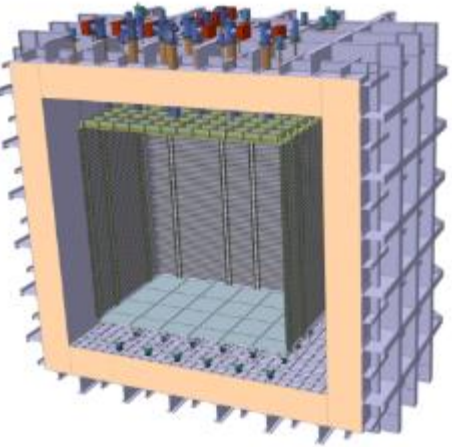
Segmented anode in gas phase with dual phase amplification

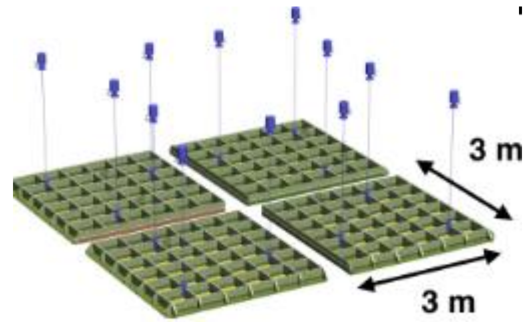


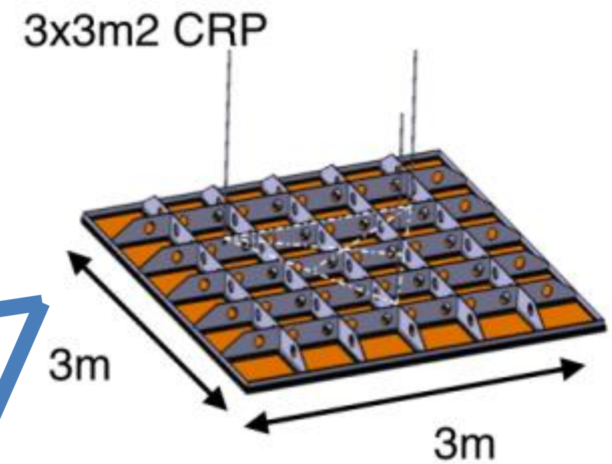
Drift coordinate
6 m = 4 ms
sampling 2.5 MHz (400 ns), 12 bits

→ 10000 samples per drift window

The Dual-Phase ProtoDUNE/WA105 6x6x6 m^3 detector is built out of the same **3x3m² Charge Readout Plane units (CRP)** foreseen for the 10 kton Dual-Phase DUNE Far Detector (same QA/QC and installation chains)



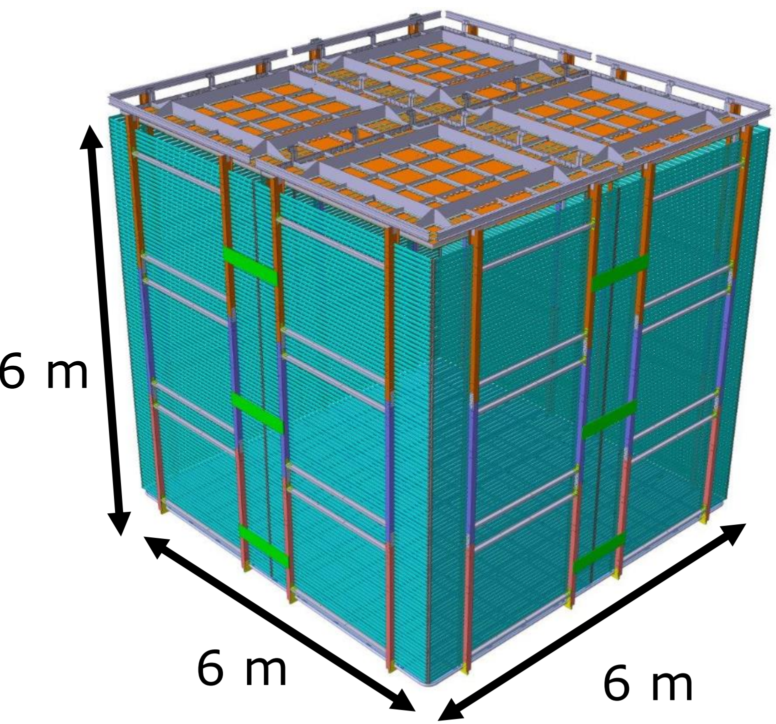


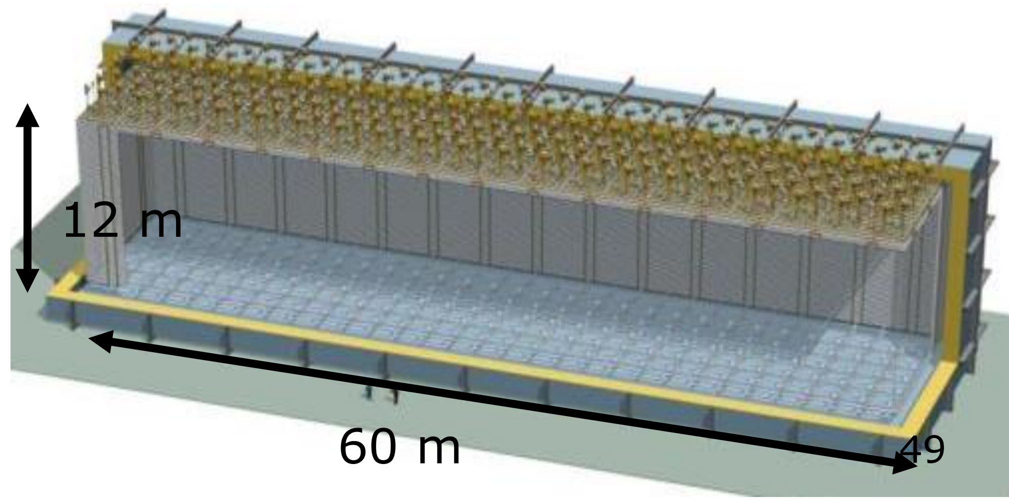


1920 channels/CRP
Accessible cold electronics in chimney

WA105: 4 CRP

10 kton: 80 CRP





WA105 Accessible cold front-end electronics and uTCA DAQ system 7680 ch

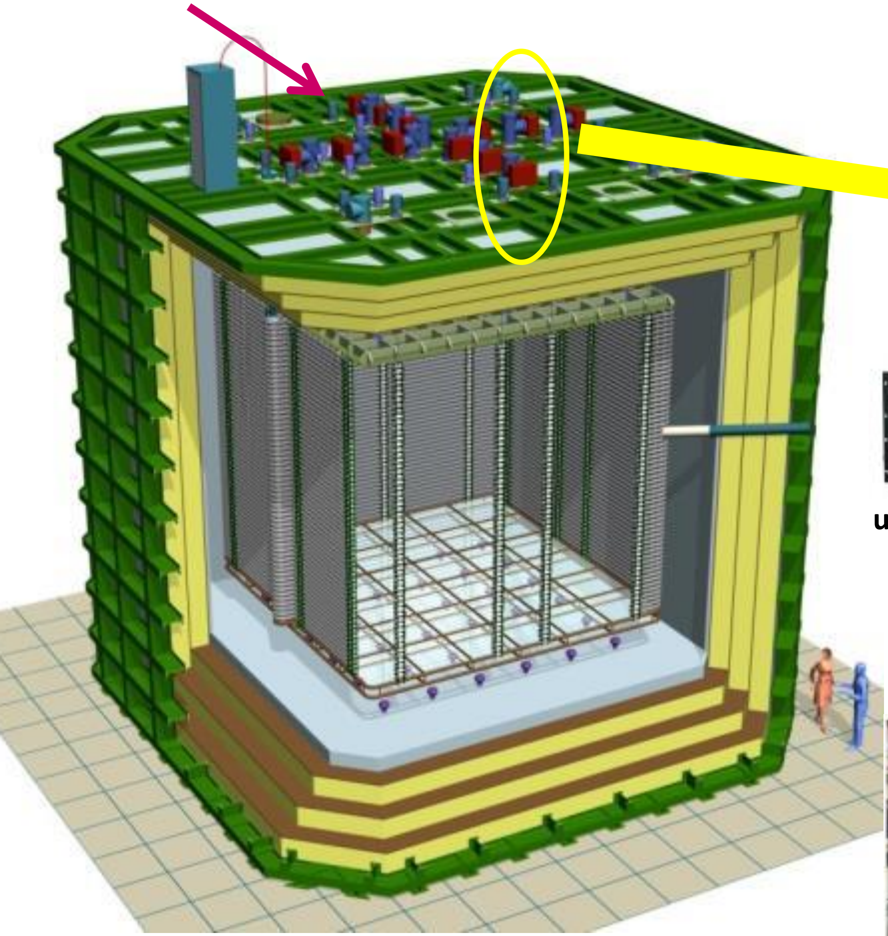
Full accessibility provided by the double-phase charge readout at the top of the detector

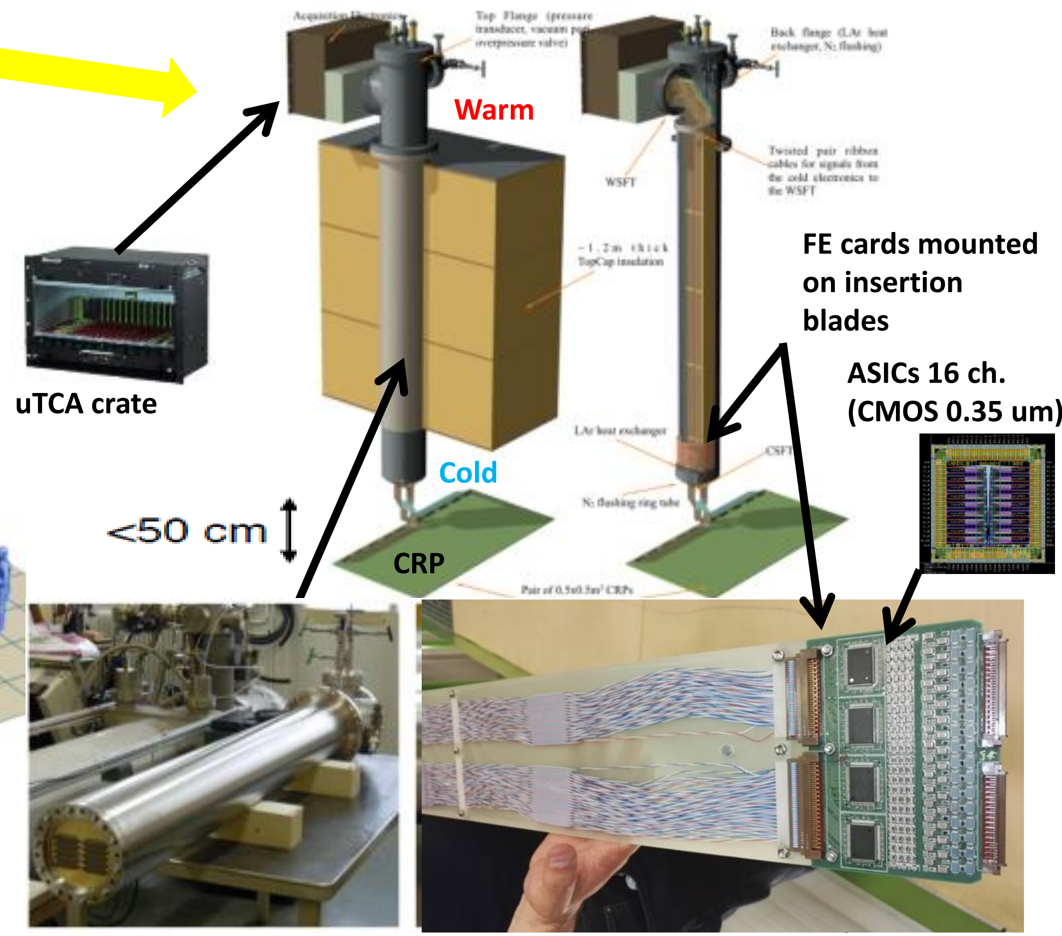
- **Digital electronics at warm on the tank deck:**
  - Architecture based on uTCA standard
  - 1 crate/signal chimney, 640 channels/crate

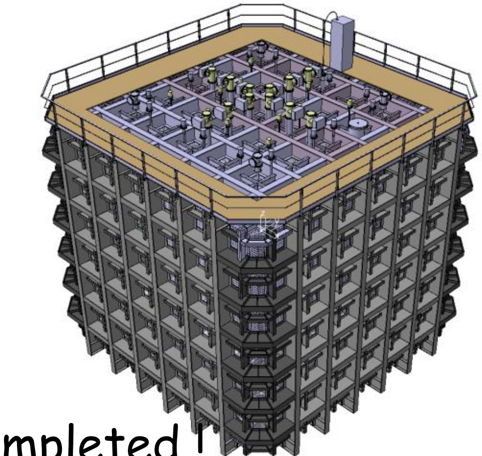
→ 12 uTCA crates, 10 AMC cards/crate, 64 ch/card

- **Cryogenic ASIC amplifiers (CMOS 0.35um) 16ch externally accessible:**
  - Working at 110K at the bottom of the signal chimneys
  - Cards fixed to a plug accessible from outside

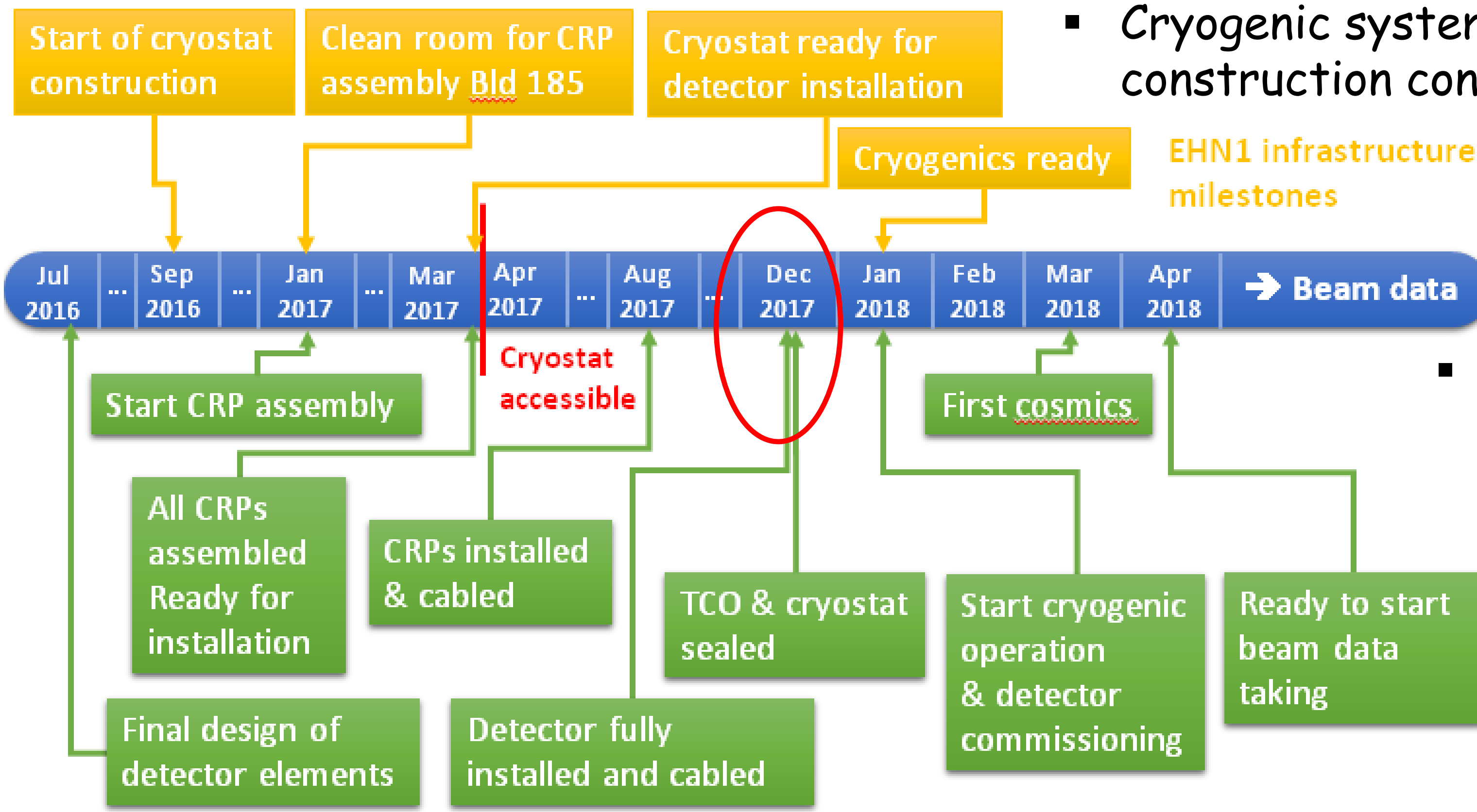
→Short cables capacitance, low noise at low T







- Extension of North Area completed !
- Cryostat construction started → Available for WA105 installation in April 2015
- Cryogenic system designed and construction contract assigned



- Detector installation expected to be completed by Dec 2017

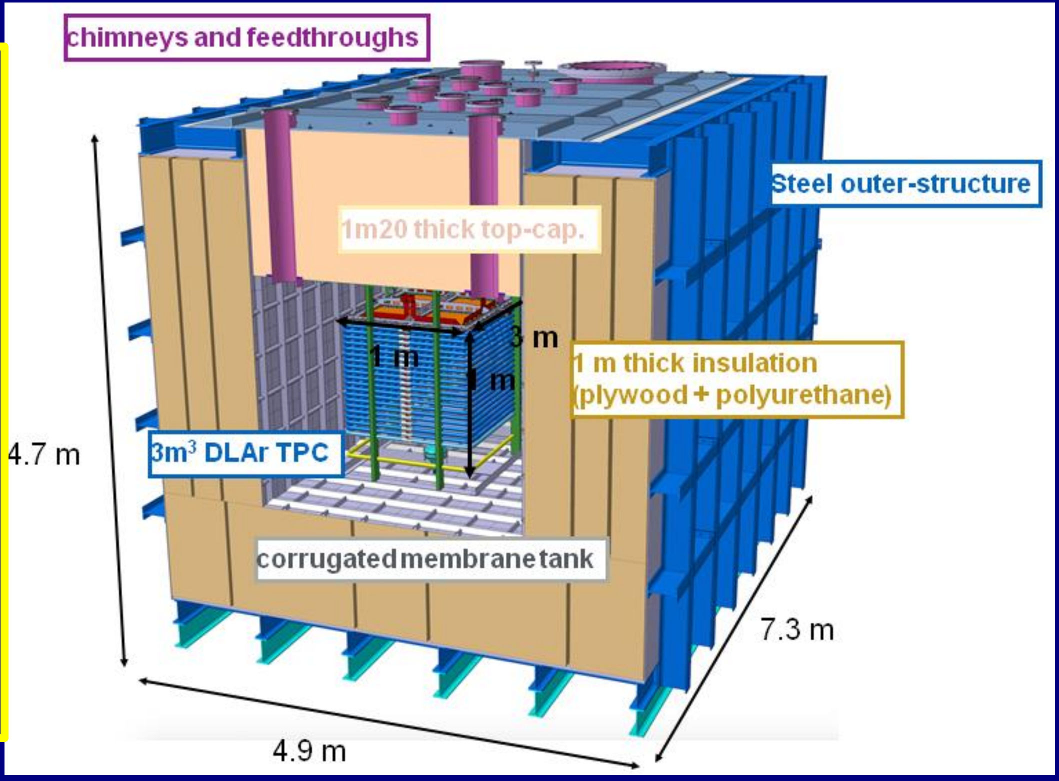
3x1x1 catalyzing progress on 6x6x6 m^3:

- Membrane vessel design and procurement
- Cryogenics
- Charge Readout Plane (CRP) detectors
- CRP structure and hanging system
- Feedthroughs
- HV and field cage
- Charge readout FE electronics + digital electronics
- Light readout system + electronics
- DAQ and online processing
- Slow Control

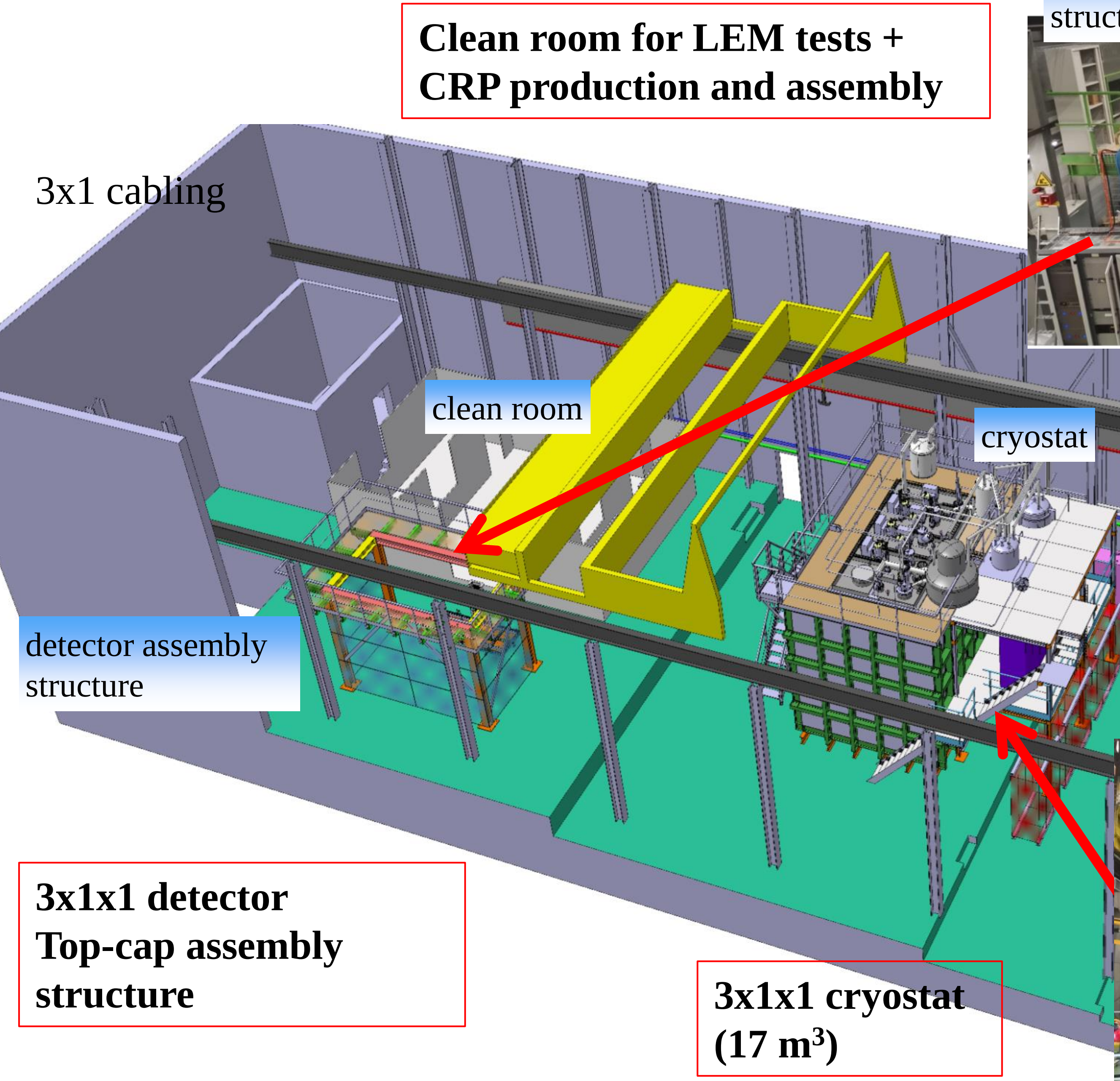
Advanced state of design, prototyping and production preparation

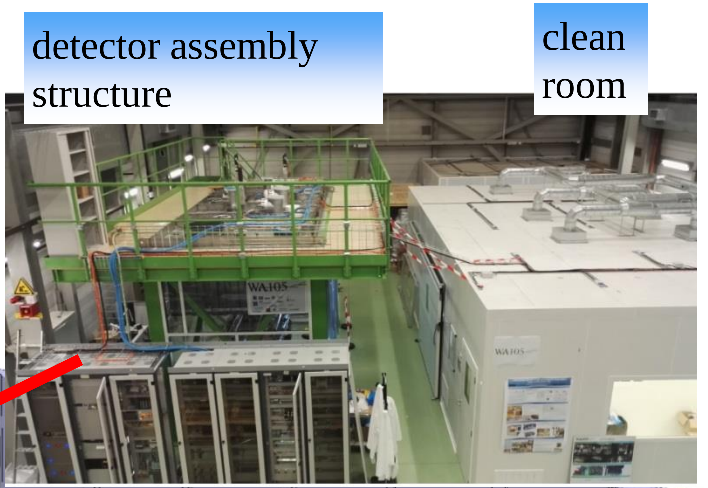
For many items huge benefit from immediate application of a smaller 3x1 prototype LAr-proto (minimal size of RO unit in 6x6x6)

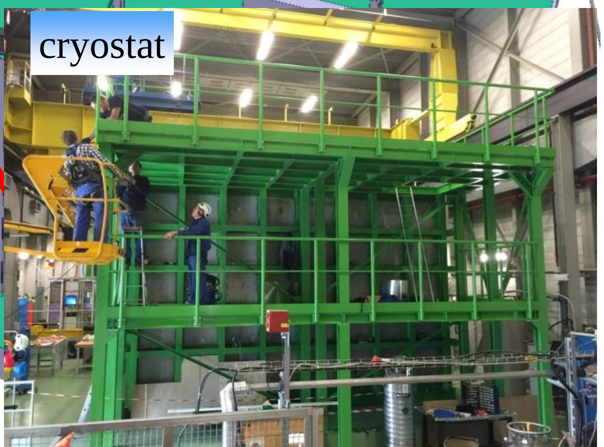
- ✓ **Fully engineered versions of many detector components** with pre-production and direct implementation (installation details and ancillary services)
- ✓ First overview of the complete system integration: **set up full chains** for QA, construction, installation, commissioning
- ✓ **Anticipate legal and practical aspects** related to procurement, **costs and schedule verification**
- ✓ Dedicated weekly meeting to follow up construction progress



WA105 tests infrastructure in Building 182

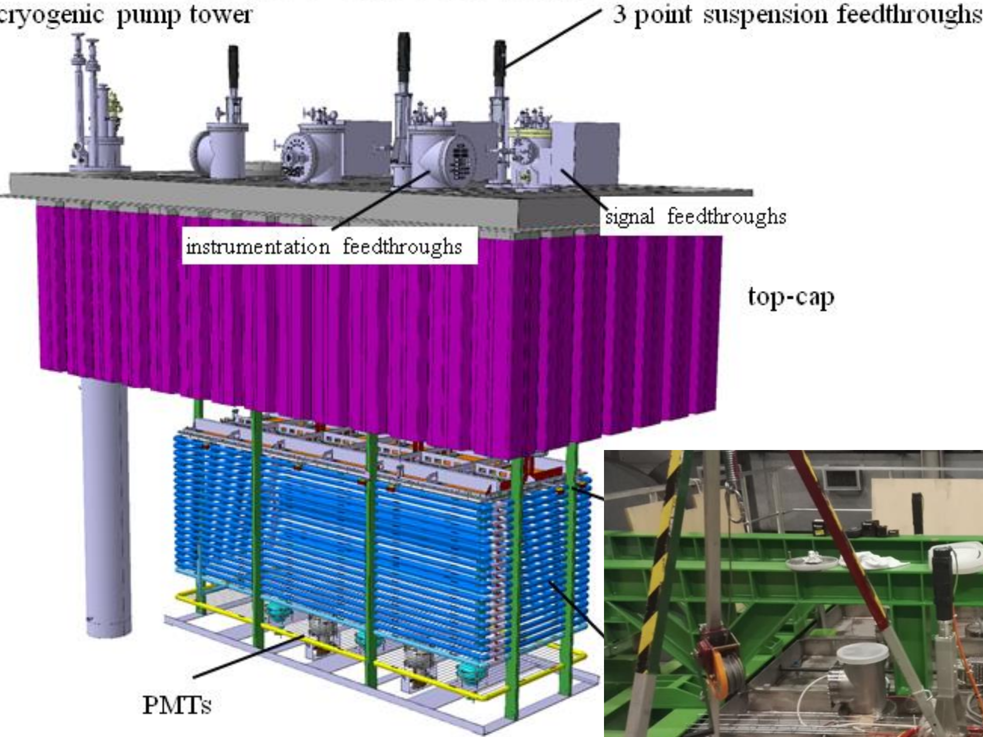


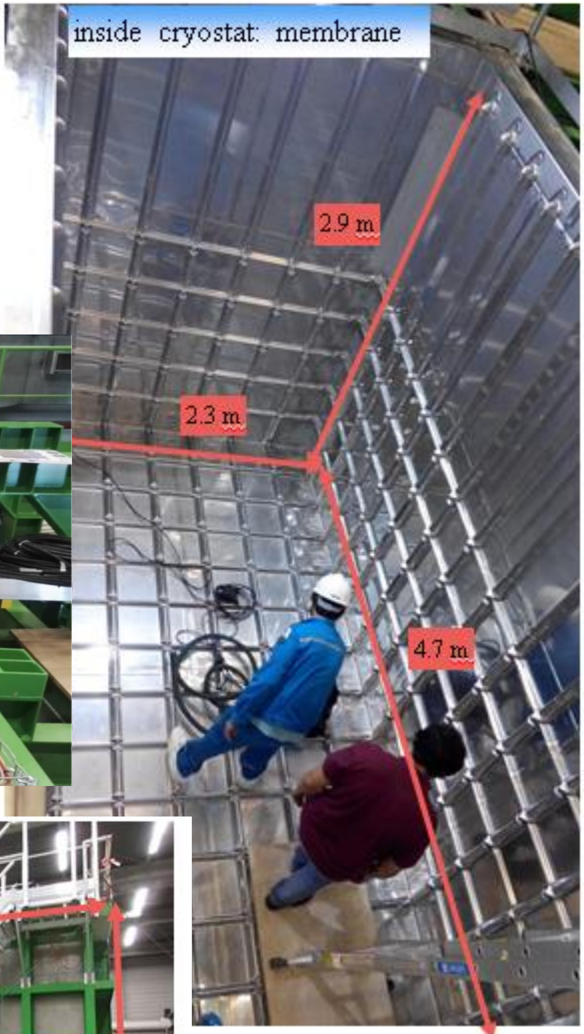


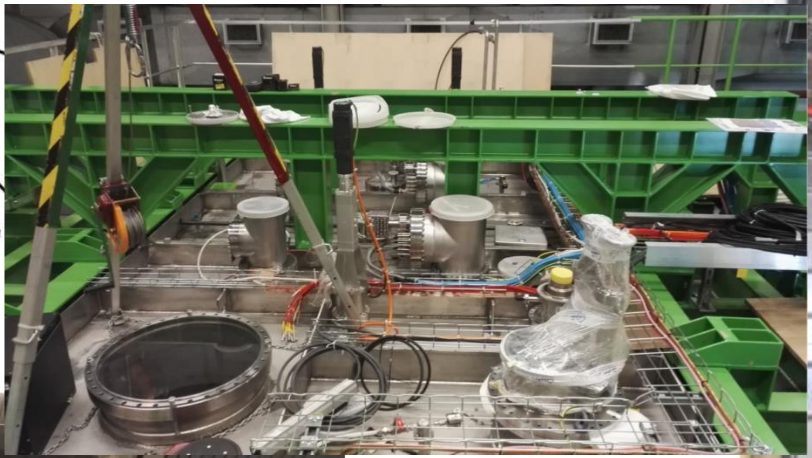


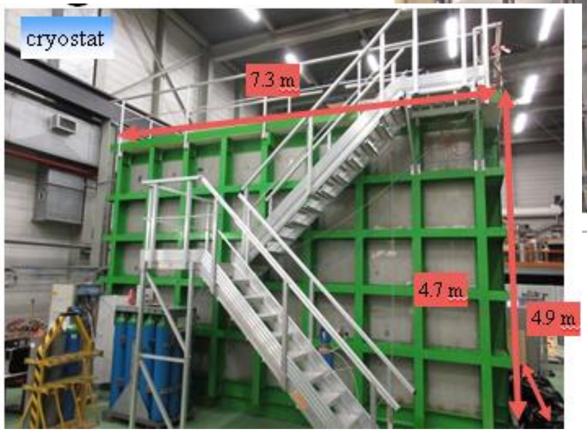
Pilot detector: $3x1x1m^3$

Detector construction completed !
Recent completion of cryogenic and warm gas system

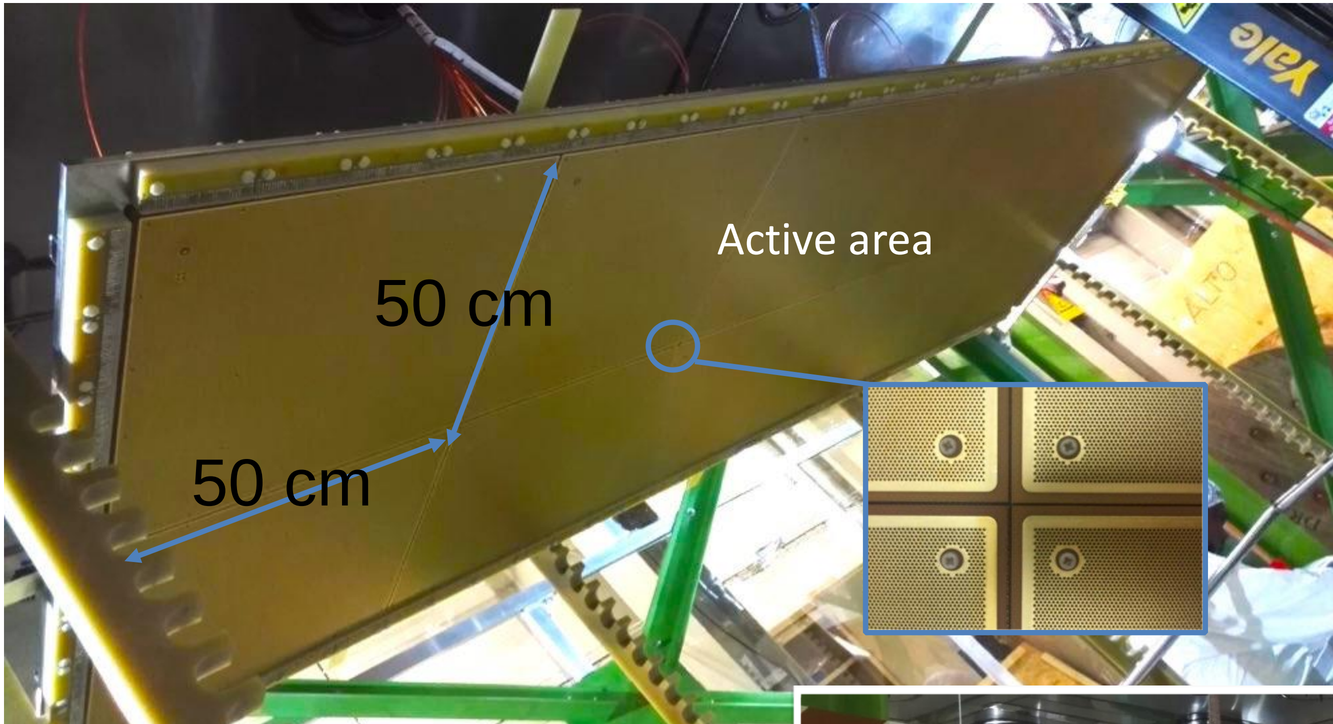


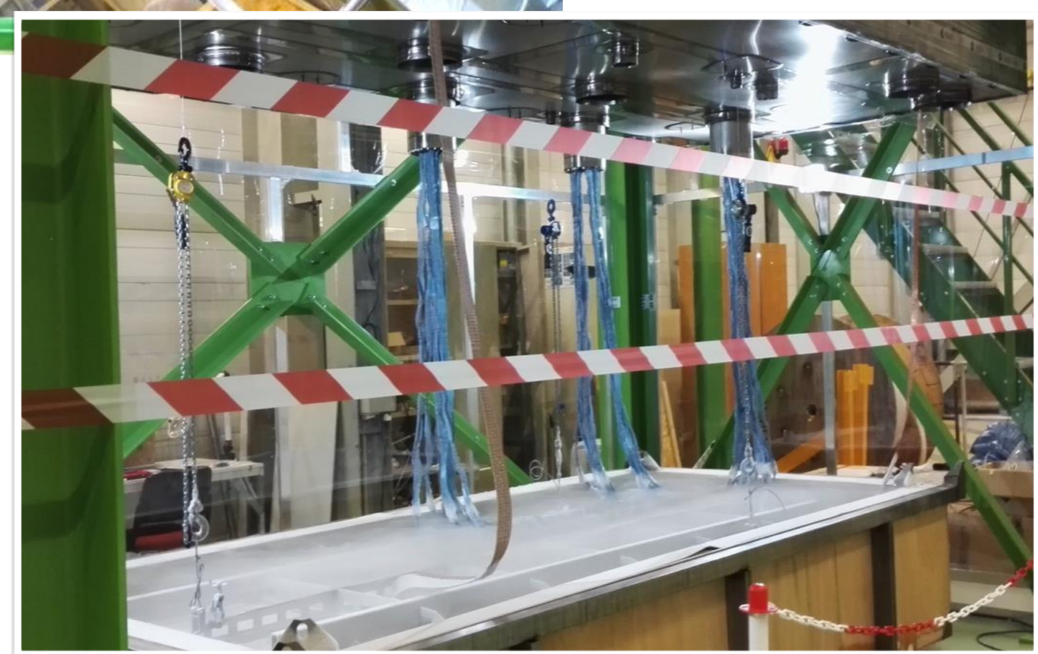


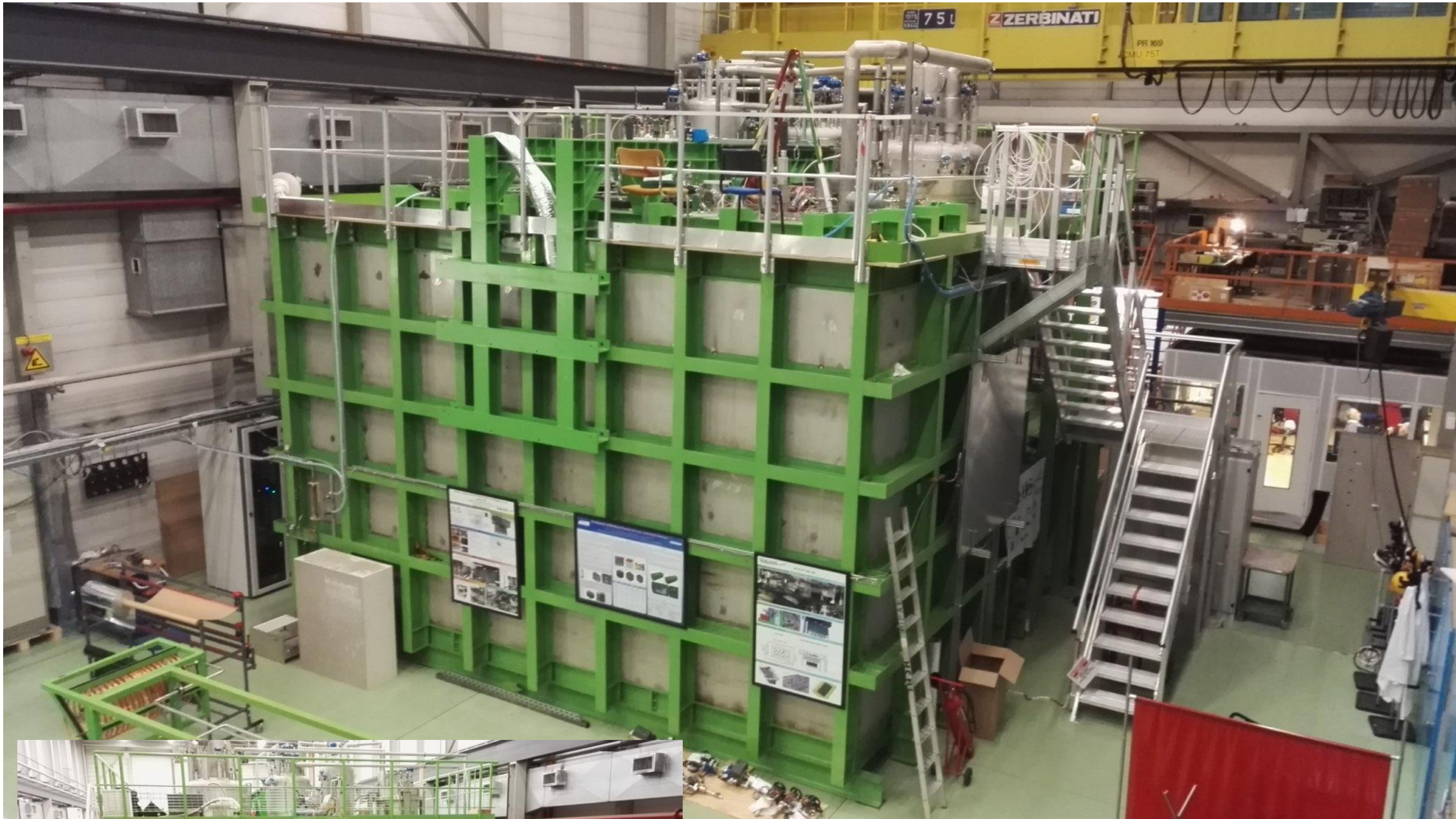




May-June 2016 CRP assembly and cold bath test with photogrammetry:





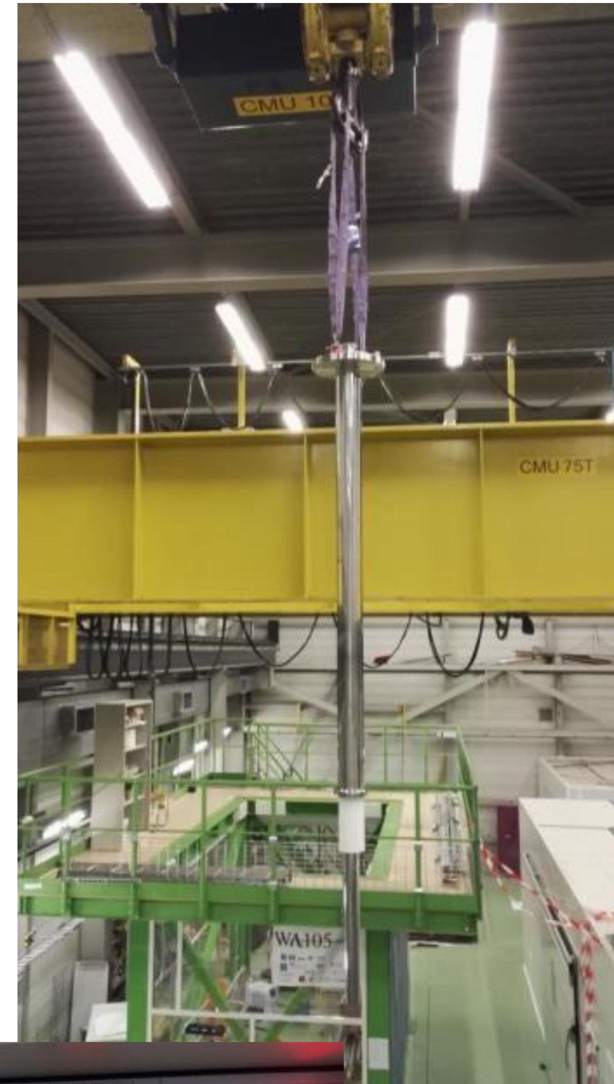


- Cryogenic and warm gas installation just completed, system commissioning starting
- Detector filling in January

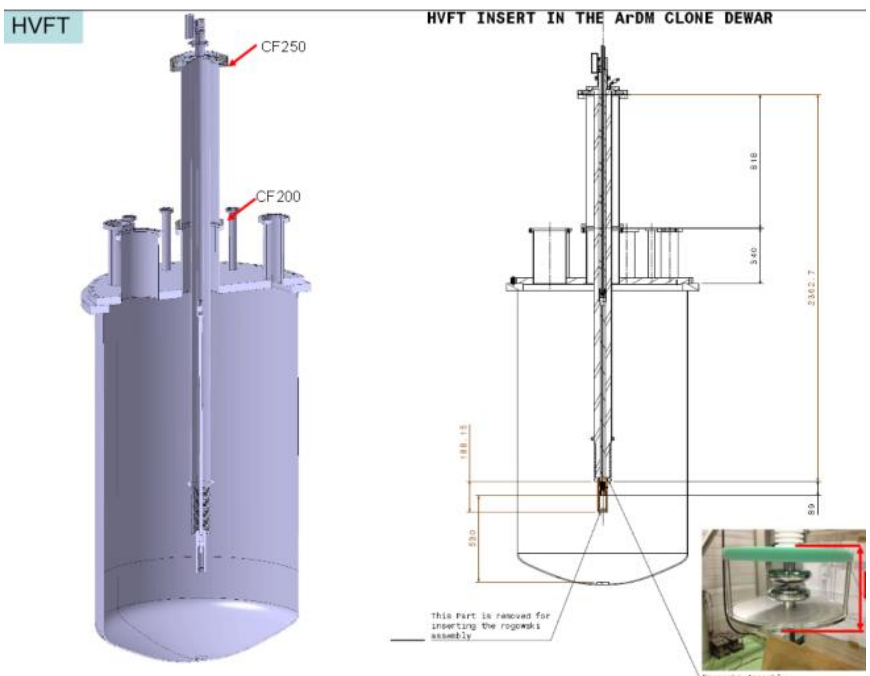
High voltage system for the drift field:

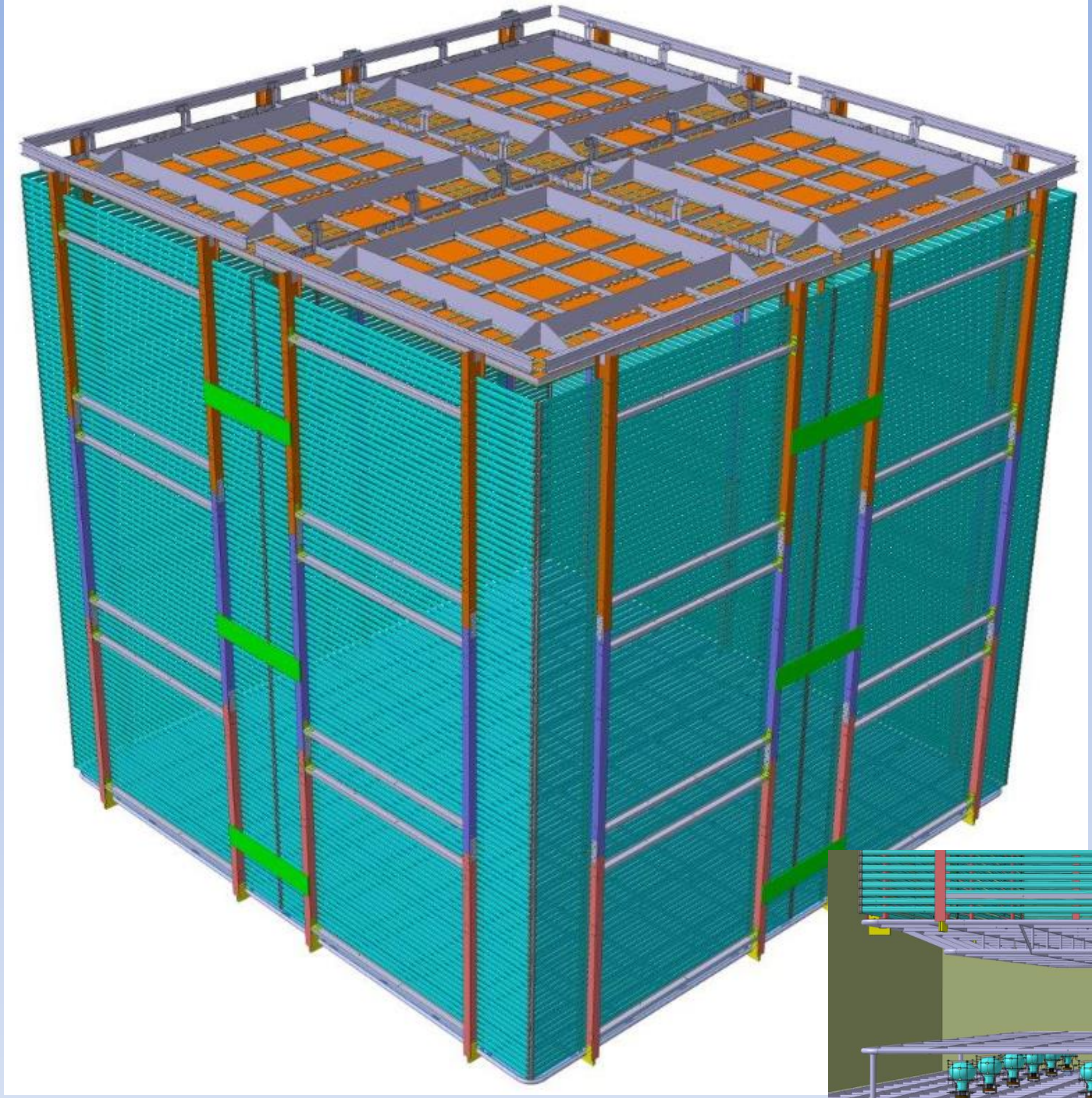
- 300 KV HV power supply already available
- HV feedthrough already built and tested (nominal field of 6x6x6) at 300 kV in a dedicated LAr cryostat and deployed on 3x1x1 detector where it will operate at lower field
- The achievement of 300 kV is an important milestone and world record.

300 kV HV feedthrough→



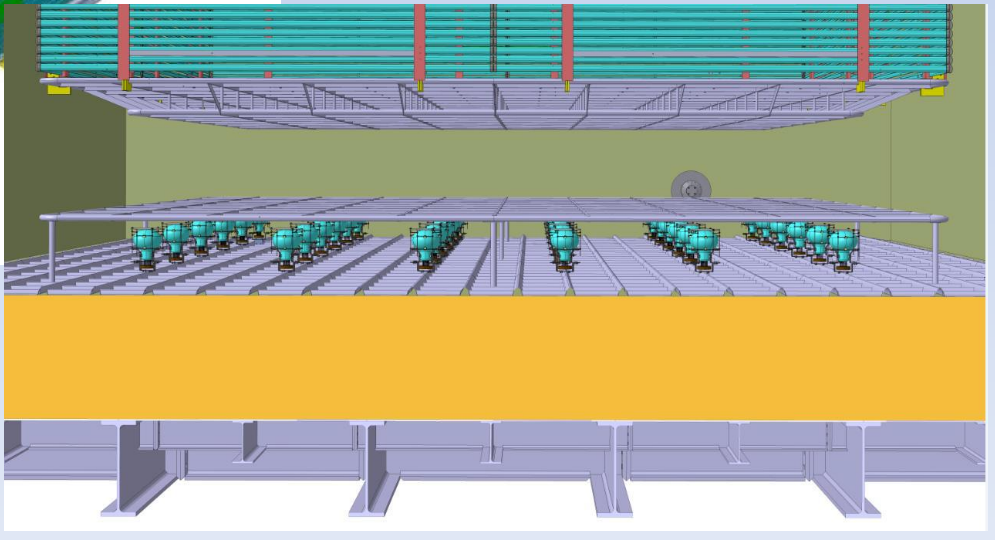
Test setup of HV feedthrough





6x6x6 integrated designs of :

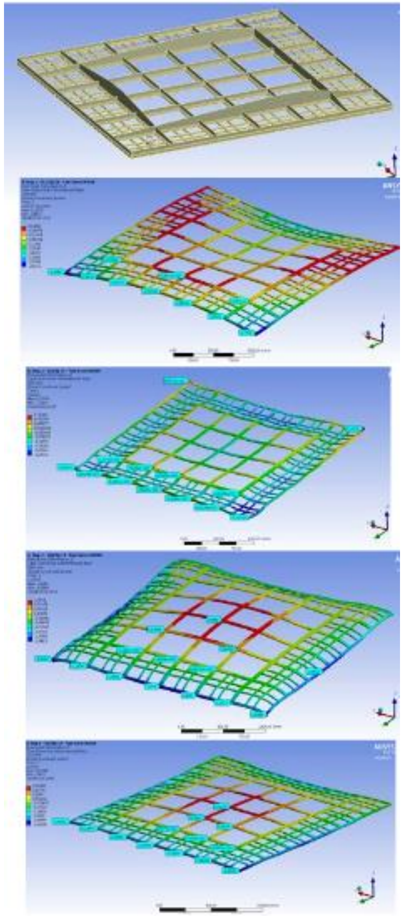
- CRPs
- Field cage
- Cathode

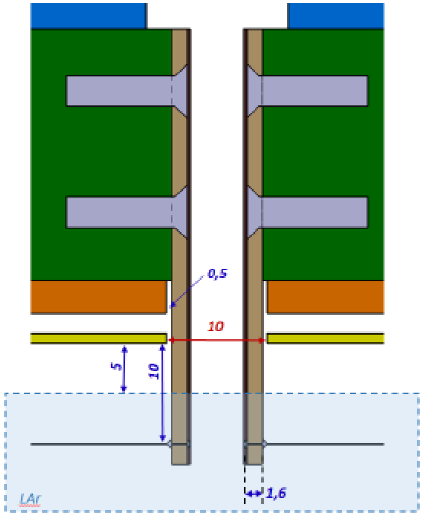


Design of the 3x3 m2 supporting frame of the LEM-anode sandwiches (50x50 cm2) + feedthroughs for the 6x6x6

→Invar frame + decoupling mechanisms in assembly in order to ensure planarity conditions (gravity, temperature gradient) over the 3x3 surface which incorporate composite materials and ensure minimal dead space in between CRPs

Executive design completed by November 2016





Integration of the grid of submerged extraction wires in the frame minimizing dead space in between CRPs. Tests for the wires system design

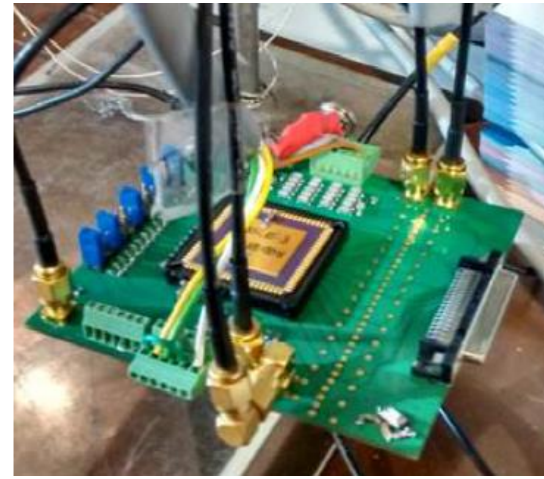
CRP mechanical structure design:
Campaign of cold bath tests + photogrammetry on differential effects in thermal contraction, design of decoupling mechanism

Cryogenic FE electronics (R&D started in 2006):

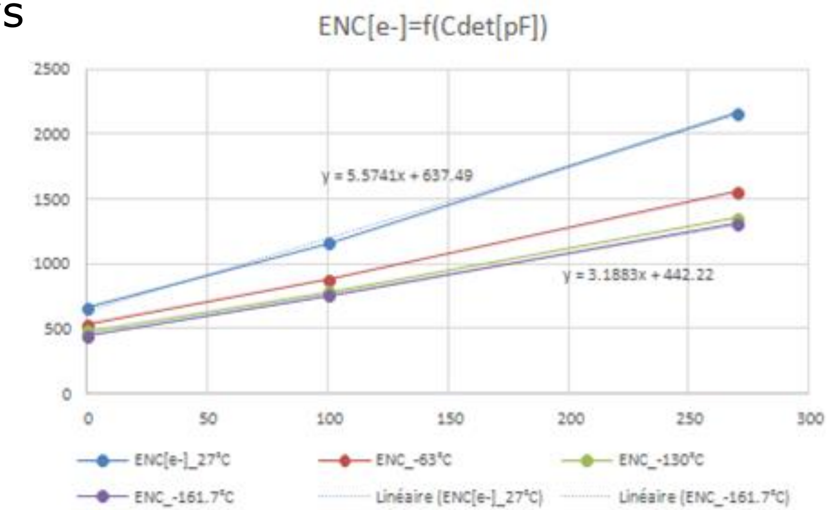
Dual-slope ASICs final version

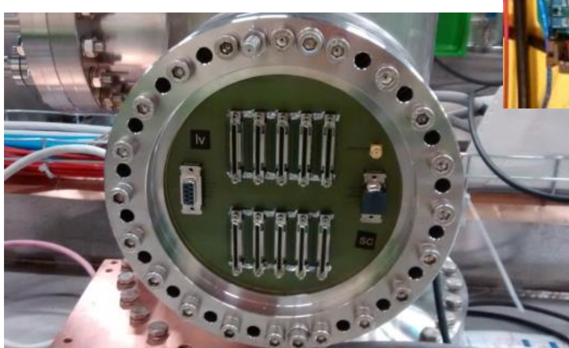
- 16 channels
- Double slope gain with “kink” at 400 fC
- 1200 fC dynamic range

(batch of 25 circuits) tested in January 2016, fully satisfactory. Full production for 6x6x6 produced and purchased (700 chips).



FE-cards designed in 2016 together with chimneys warm flanges PCBs





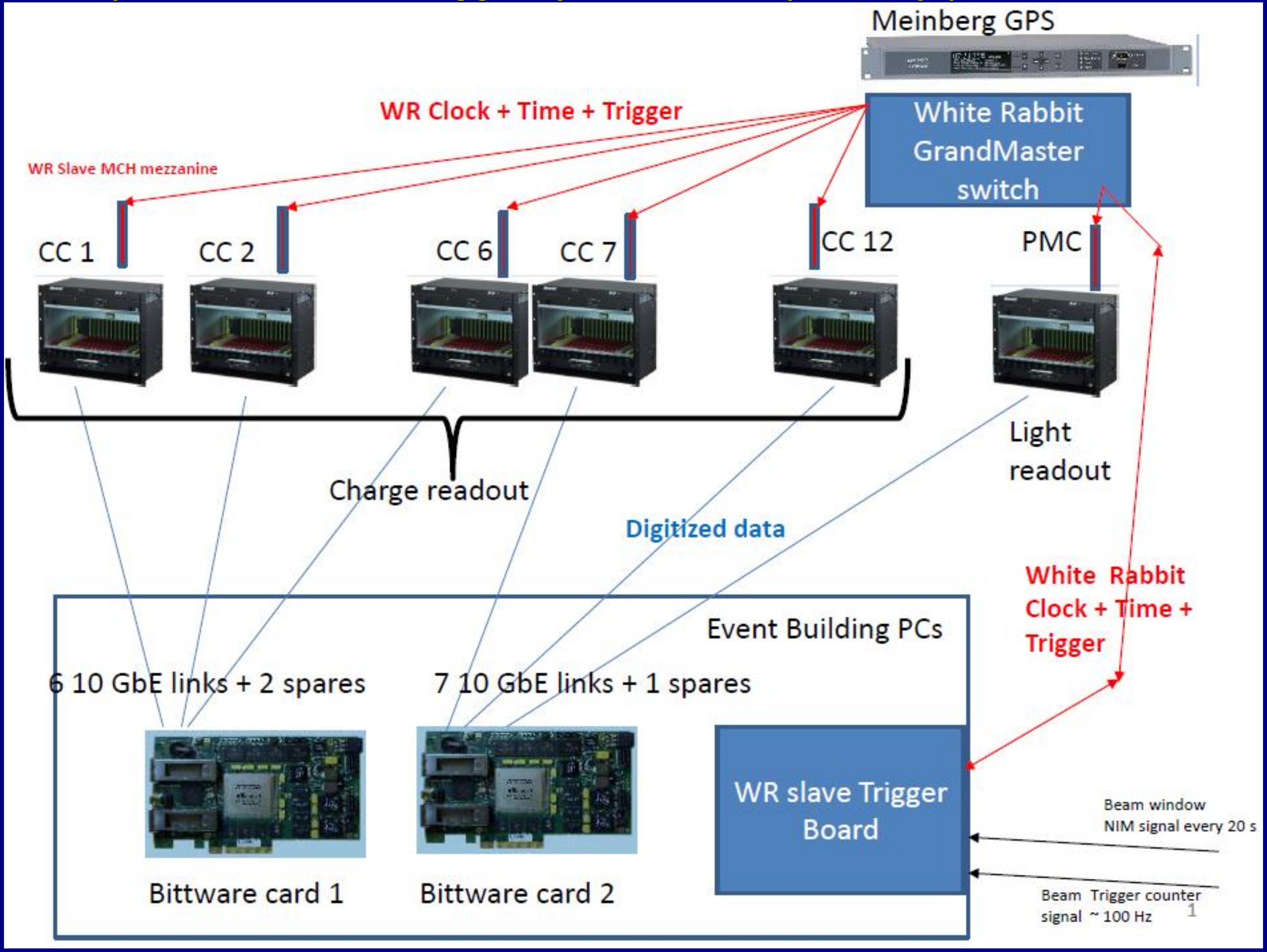
20 FE cards (1280 channels) produced and installed on 3x1x1 pilot detector at CERN

Global uTCA DAQ architecture

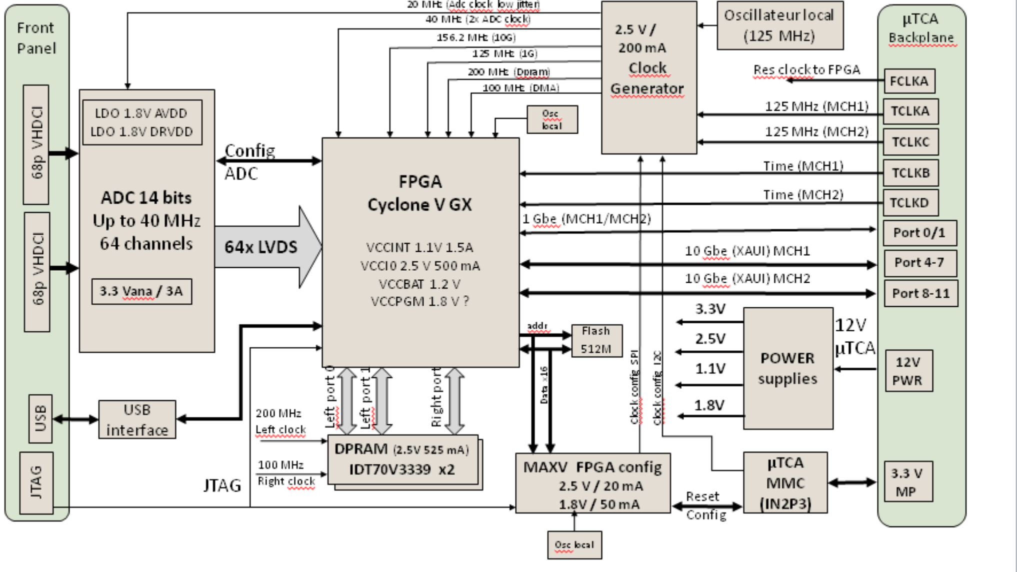
integrated with « White Rabbit » (WR) Time and Trigger distribution network

+ White Rabbit slaves nodes in uTCA crates

WR system (time source, GM, trigger system, slaves) already produced for the 6x6x6)



uTCA DAQ system:
(R&D started in 2006)



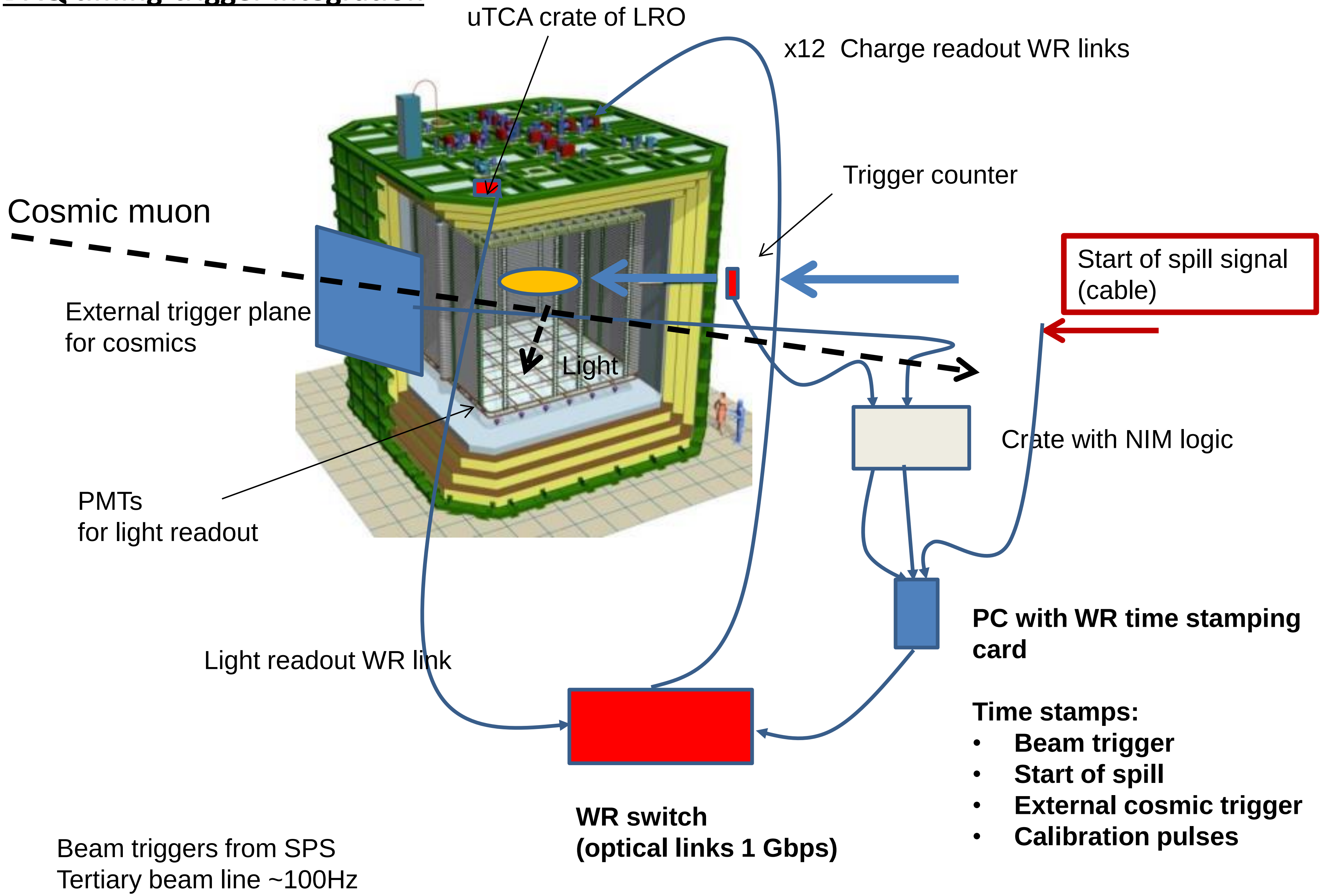
64 channels AMC digitization cards (2.5-25 MHz, 12 bits, 10 GbE output

- Demonstrator card with 64 ADC channels built and tested in 2015 for the definition of the final card
- Purchase of main components of the final cards by end of 2015 to equip the entire 6x6x6
- Final design of digitization AMCs: May 2016
- 20 cards produced by September 2016 to equip the 3x1x1
- Production of remaining 100 FE and uTCA cards for 6x6x6 under completion

Time sync / trigger

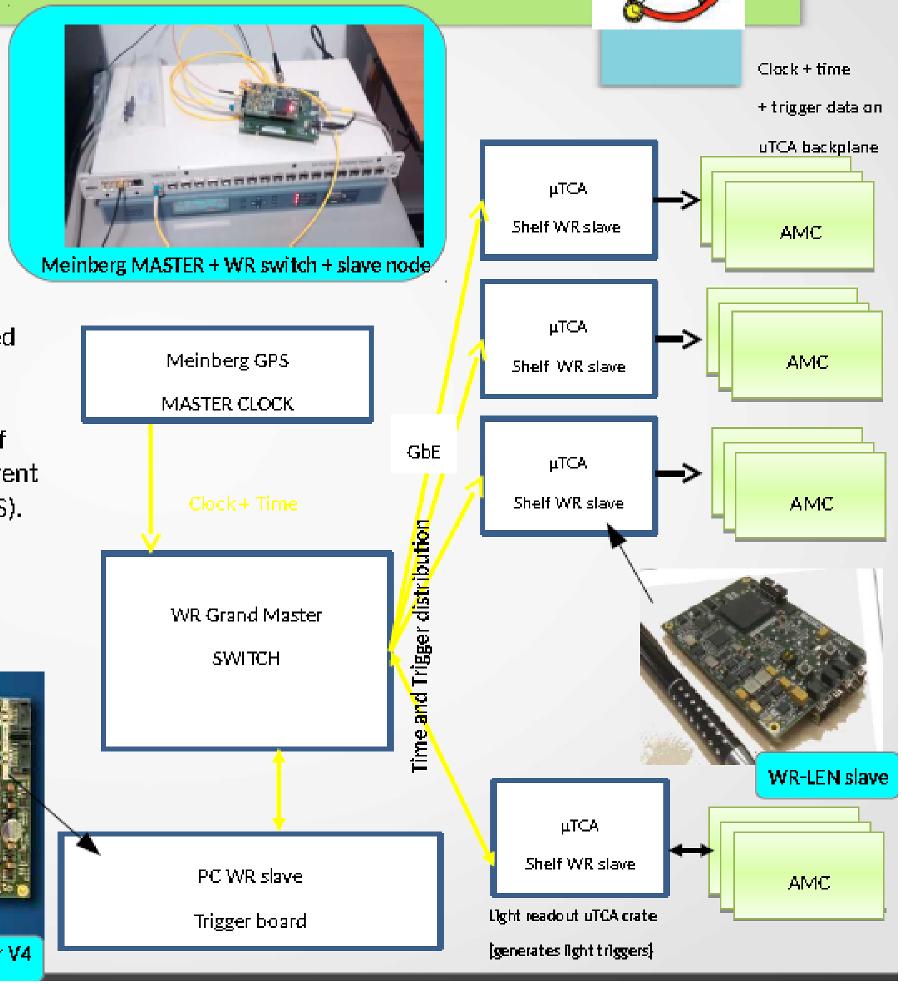
10 Gbit/s data link

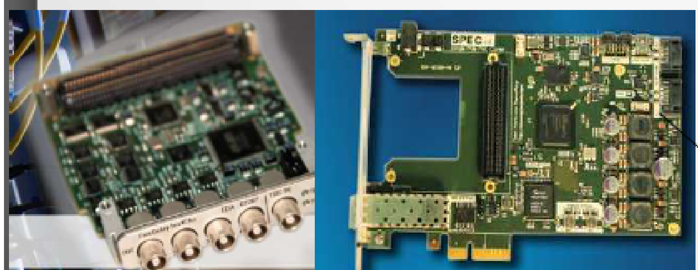
DAQ timing-trigger integration



White Rabbit scheme

- WR is an evolution of the synchronization scheme based on **synchronous Ethernet + PTP** which was previously developed at IPNL in 2008: http://arxiv.org/abs/0906.2325
- WR is accurate at sub-ns level, enough to align the 400ns samples
- At the level of the charge readout DAQ is distributed the beam trigger timestamp.
- Trigger time info starts and closes the acquisition of the samples belonging to the drift window of an event in each AMC (important when operating without ZS).
- The beam trigger can be time-stamped on the PC trigger board and be broadcasted to the microTCA crates via the WR time distribution network





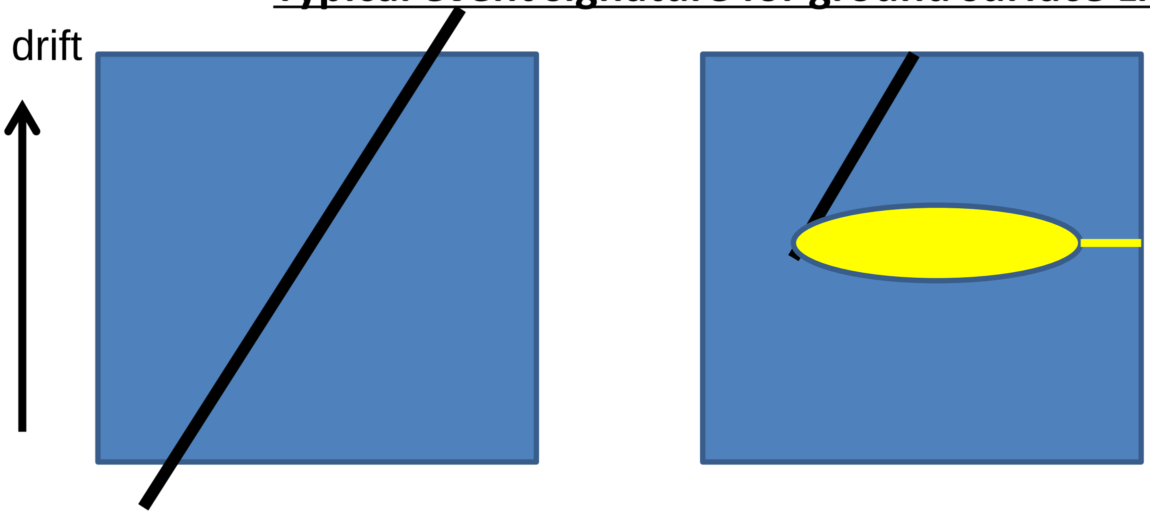
FMC Fine Delay 1 ns 4 channels

SPEC FMC PCIe carrier V4

White Rabbit uTCA slave node developed and produced for 6x6x6 (13 units)

Other parts of the chain (GPS receiver, WR grandmaster, trigger time tagging card and PC) available as commercial components

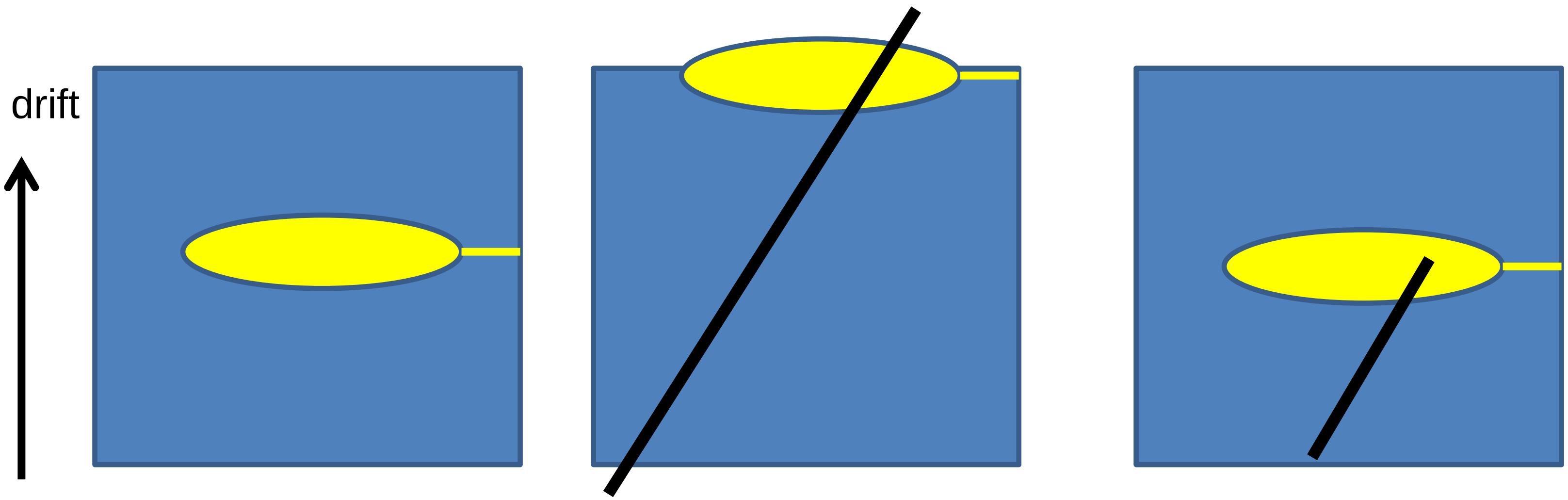
Typical event signature for ground surface Liquid Ar TPC operation



The « belt conveyor » effect
+- 4 ms around the beam
trigger time

t=beam trigger - 2 ms

t=beam trigger → reconstructed event



t=beam trigger

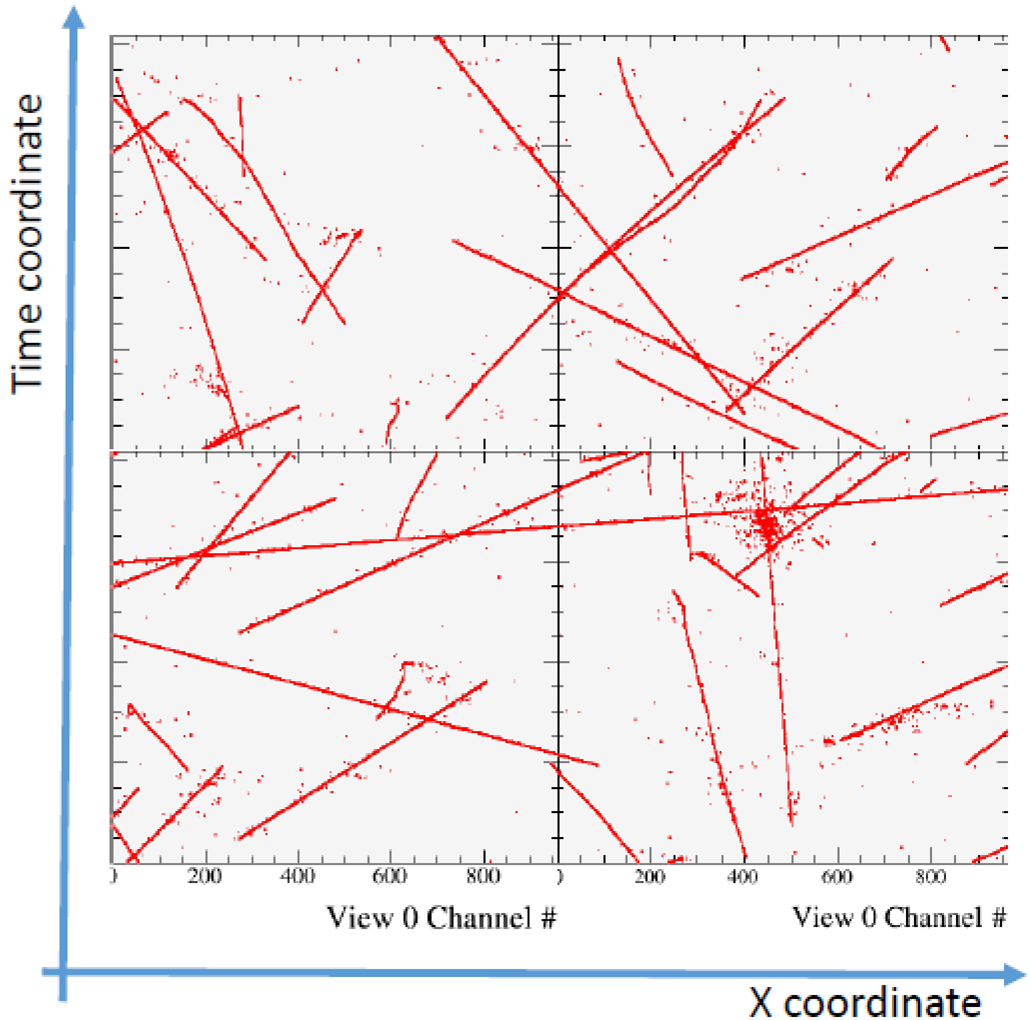
t=beam trigger + 2 ms

reconstructed event

Typical event signature for ground surface Liquid Ar TPC operation

For each beam trigger we can have on average 70 cosmics overlapped on the drift window after the trigger (these cosmics may have interacted with the detector in the 4 ms before the trigger and in the 4 ms after the trigger → chopped tracks, “belt conveyor” effect

In-spill cosmics in charge data



Example of cosmics only event (in one of the views)

- Red points are reconstructed hits
- TPC is readout in 4 3x3m^2 modules
- After track reconstruction:
  - Attempt to correlate found tracks with light data
  - Remove CR background from beam event
  - Select a subsample of long tracks for calibration purposes

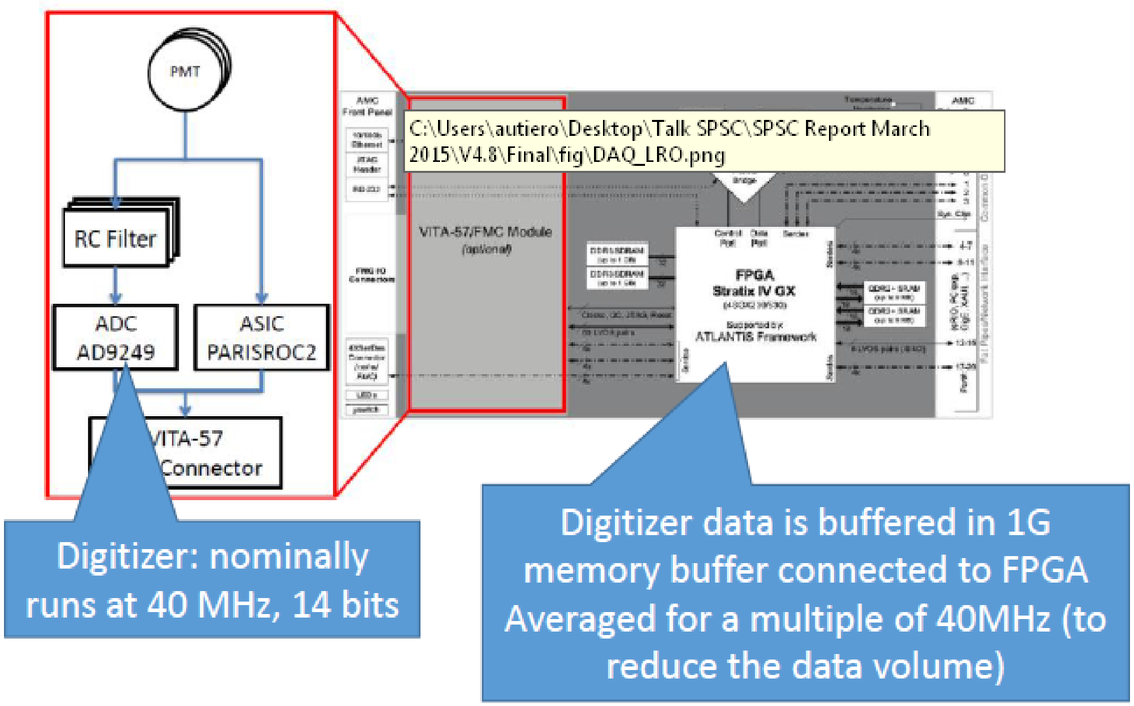
→ During spills it is needed a continuous digitization of the light in the +-4 ms around the trigger time (the light signal is instantaneous and keeps memory of the real arrival time of the cosmics)

→ Sampling can be coarse up to 400 ns just to correlate to charge readout

Light readout electronics

Two modes of acquisition:

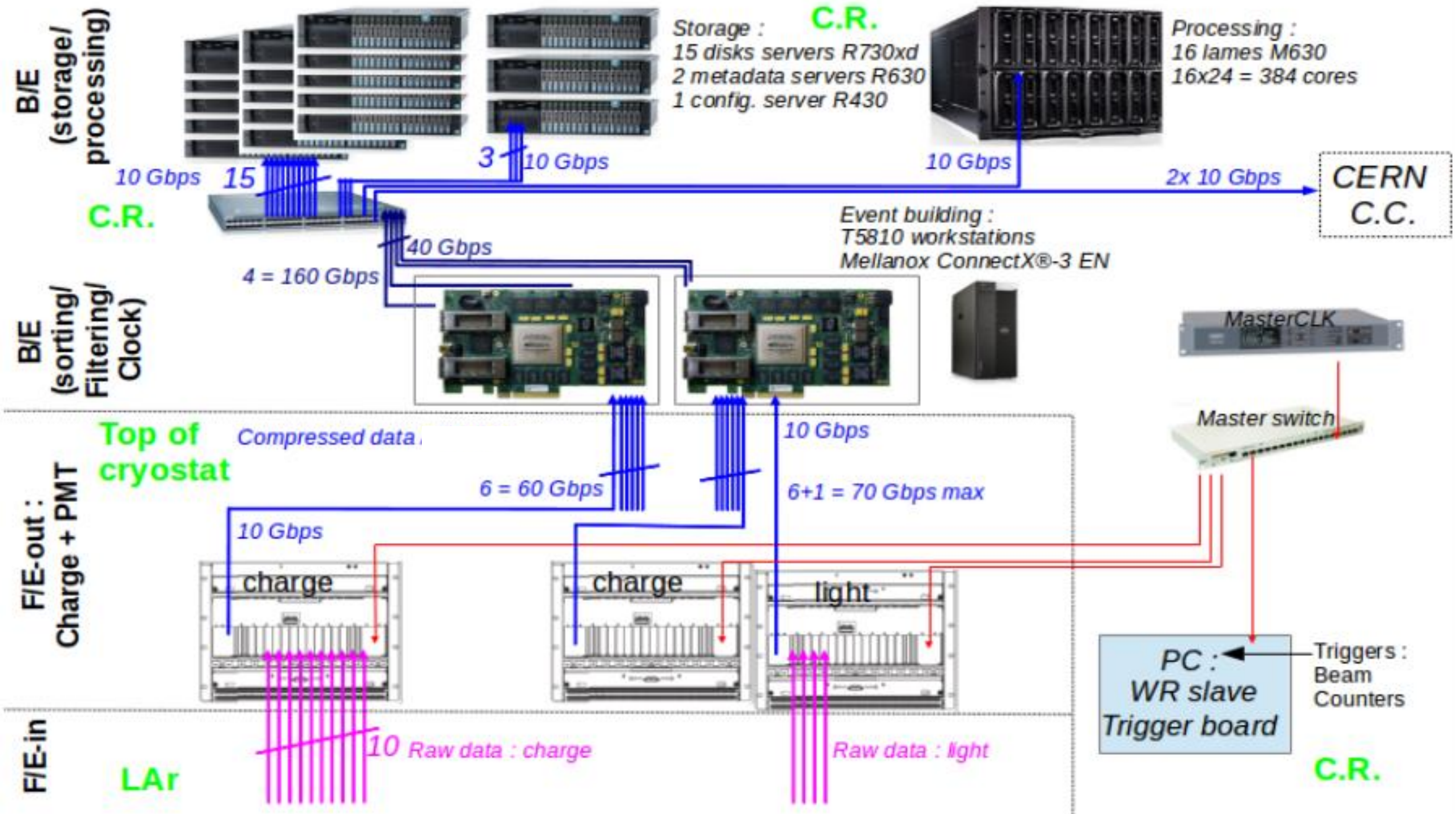
- External beam trigger to acquire ±4ms around the spill
- Internal trigger from PARISROC2 ASIC to acquire short time segments



→ Sum 16 samples at 40MHz to get an effective 2.5 MHz sampling like for the charge readout

The LRO card has to know spill/out of spill
Out of spill it can define self-triggering light triggers when “n” PMTs are over a certain threshold and transmit its time-stamp over the WR

Online processing and storage facility: internal bandwidth 20 GB/s, 1 PB storage, 384 cores: key element for online analysis (removal of cosmics, purity, gain, events filtering)



C.R. stands for Counting Room

▪Design of online storage/processing DAQ back-end farm completed in 2016 (1PB, 300 cores, 20Gb/s data flow),

DELL-based solution : configuration

storage servers :
* 15 R730XD (storage servers) including :
* 16 disks 6To
* 32Go RAM
* 2 disks system RAID 1, 300 Go 10k
* 1 network card Intel X540 double port 10 GB
* 4 years extended guarantee (D+1 intervention)
* 2 processors Intel Xeon E5-2609 v3
* raid H730P
* Rails with management arm
* double power supply

metadata servers (MDS) :
* 2 R630 (metadata servers), including :
* 2 disks 200 Go SSD SAS Mix Use MLC 12Gb/s
* 2 processors Intel Xeon E5-2630 v3
* 32Go DDR4
* RAID H730p
* network : Intel X540 2 ports 10 Gb
* 4 years extended guarantee (D+1 intervention)
* Rails with management arm
* double power supply

configuration server :
* 1 R430 (configuration server)
* 1 processor E5-2603 v3
* RAID H730
* 2 hard disks 500 Go Nearline SAS 6 Gbps 7,2k
* 16 Go DDR4
* Rails with management arm
* double power supply

Offline computing farm: 16*24 = 384 cores
* 1 blade center PowerEdge M1000e with 16 lames M630, each including :
  * 128Go DDR4
  * 2 processors Intel Xeon E5-2670 v3
  * 4 years extended guarantee (D+1 intervention)
  * 2 hard disks 500 Go SATA 7200 Tpm
  * netwok Intel X540 10 Gb

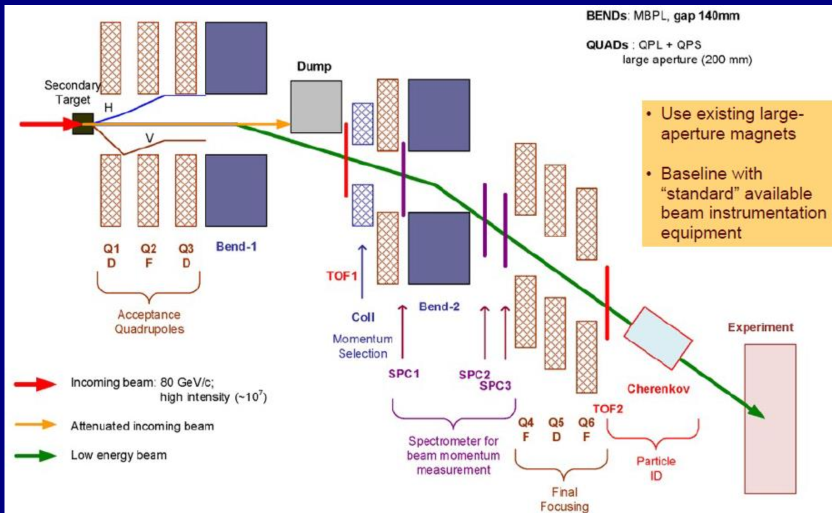
Switch Force10, S4820T (see next slide) :
* 48 x 10GbaseT ports
* 4 x 40G QSFP+ ports
* 1 x AC PSU
* 2 fans

▪Prototype already installed and operative for 3x1x1
Tests to finalise the architecture of final farm
Thanks to CERN/IT support for the procurement of the hardware

▪ 5 Storage servers 240 TB
▪ 3 QUAD CPU units → 300 cores

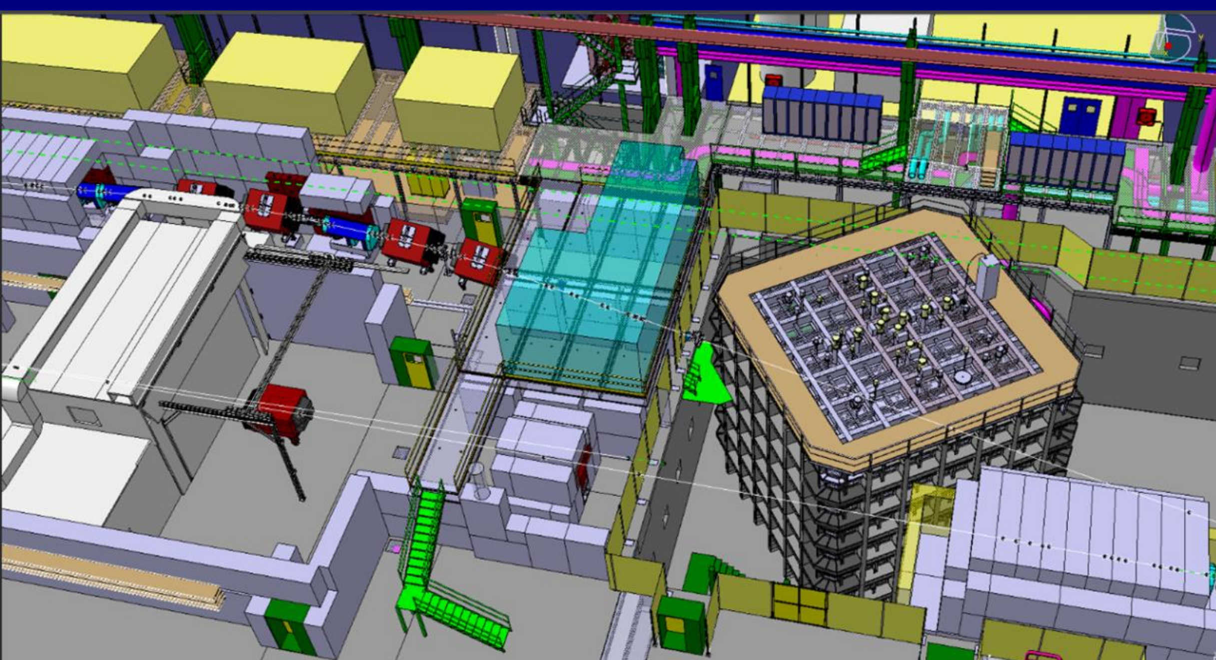
H2-VLE beamline

Tertiary beam on H2 beamline:
1-12 GeV/c, momentum bite 5% (can be reduced to 1% with integrated spectrometer measurements)



- **Mixed hadrons beam 1-12 GeV/c: pions, kaons, protons + electrons contamination at low energies**
- **Pure electron beams**
- **Parasitic muon halo**

→ O(100 M) beam triggers to be acquired in 2018 at 100 Hz over 120 days



Definition of beam line instrumentation (TOF, triggers, beam profile and spectrometer, Cerenkov → common work also with single-phase group to define and procure the missing hardware.

Integration of beam-line DAQ with WA105 White-Rabbit time distribution system

Synergy with SP in definition of beam window/beam plug in non active LAr volume

Conclusions:

- The study of neutrinos provides fundamental information in particle physics, astrophysics and cosmology. They are a window on the physics beyond the SM.

- Neutrinos are difficult particles to be studied and require to overcome strong experimental challenges. The giant liquid-argon TPC technology which is envisaged by the joint US-EU efforts provides also the capability for interesting observations of supernova neutrinos and proton decay. The preparation of this next generation long-baseline experiment if a long term process which has already more than 20 years of efforts behind and a solid intermediate working plan supported by CERN

- The LAr TPC is a very interesting detector with a reach physics output. The dual-phase design provides many appealing aspects in improving the detector performance and reducing its construction costs. Long standing efforts have been spent in this direction during the last 10 years and are now culminating in a large scale implementation with the 6x6x6 detector operation in the CERN North Area.

- The design of remaining aspects of the 6x6x6 has been completed. Some parts (electronics, PMTs, HV) are already in production phase. The 300 kV milestone has been reached. Full installation planning, driven by the EHN1 infrastructure, has been developed for data taking in April 2018. Beam requests have been submitted for 100M beam triggers obtainable over a period of several months.

- The DP ProtoDUNE advanced state largely benefited of the preparation activities with the 3x1x1 pilot detector. We are looking forward to the DP ProtoDUNE detector exploitation with the beamline in 2018 !

- A last « anthropic-like » personal consideration from the last 25 years ;-)

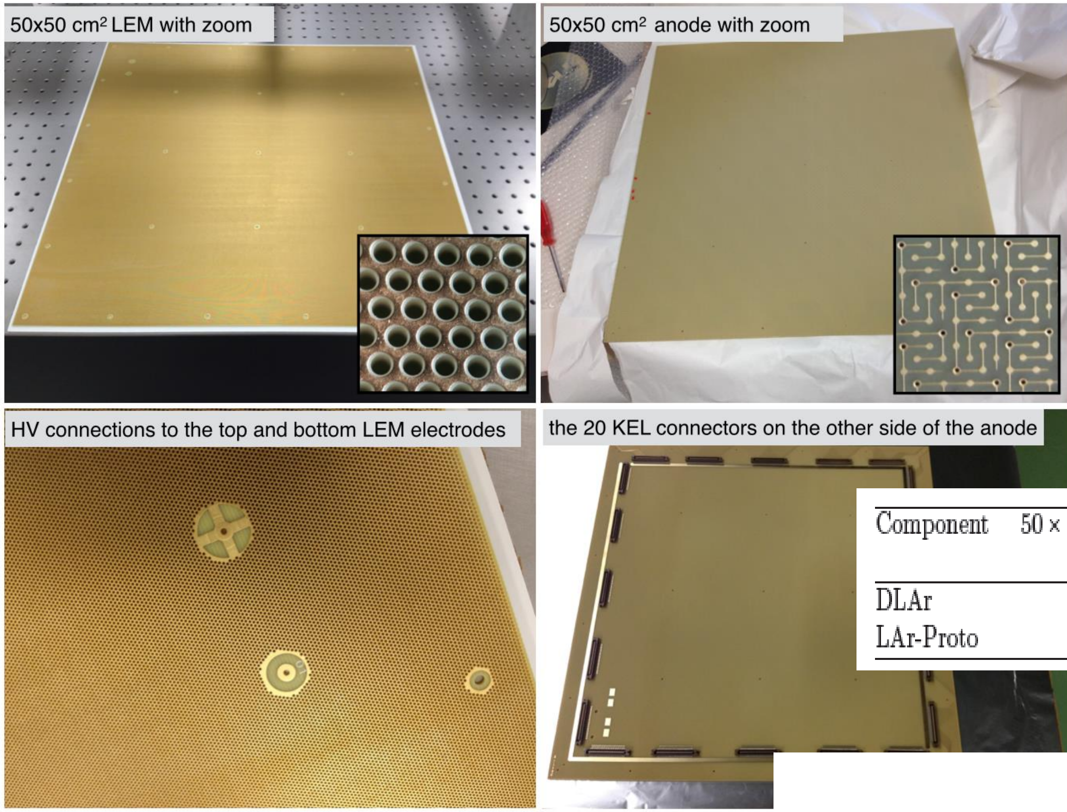
Despite the fact that neutrinos are difficult particles to be studied, nature has been kind to us so far:

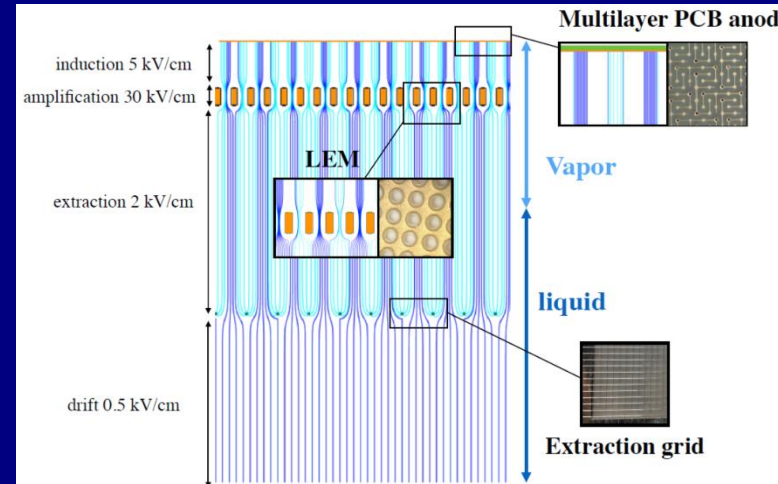
- Somehow we have been lucky that the Δm^2 among the 3 mass states are such that the related solar and atmospheric oscillations are accessible with experimental means on earth !

- We have been lucky that the large mixing angle MSW solution is the one valid for solar neutrinos and again that θ_{13} is large and just below the CHOOZ limit.

Probably CP violation and the mass hierarchy will be the next steps demonstrated by DUNE on a reasonable time scale ….

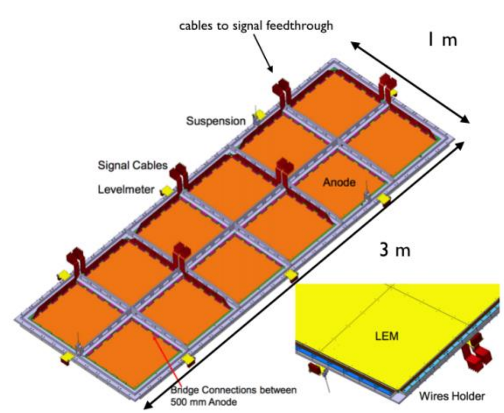
Charge Readout Plane (CRP) 50x50 cm² LEM-Anode Sandwich (LAS)

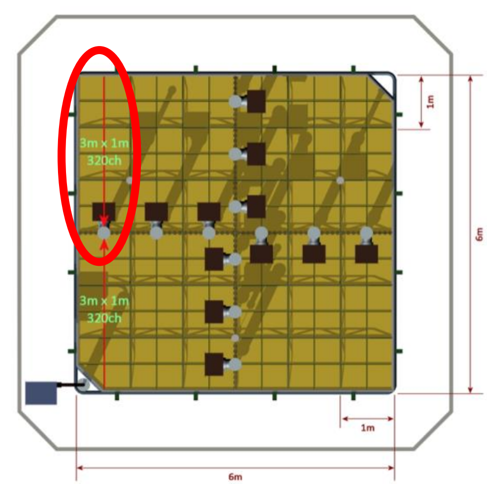




Component	50 × 50 cm² Anode panels	50 × 50 cm² LEM panels	Signal feddthrough	Suspension feddthrough	readout strip length (m)
DLAr	144	144	12	3	3
LAr-Proto	12	12	6	3	1 or 3

3m readout units in 6x6

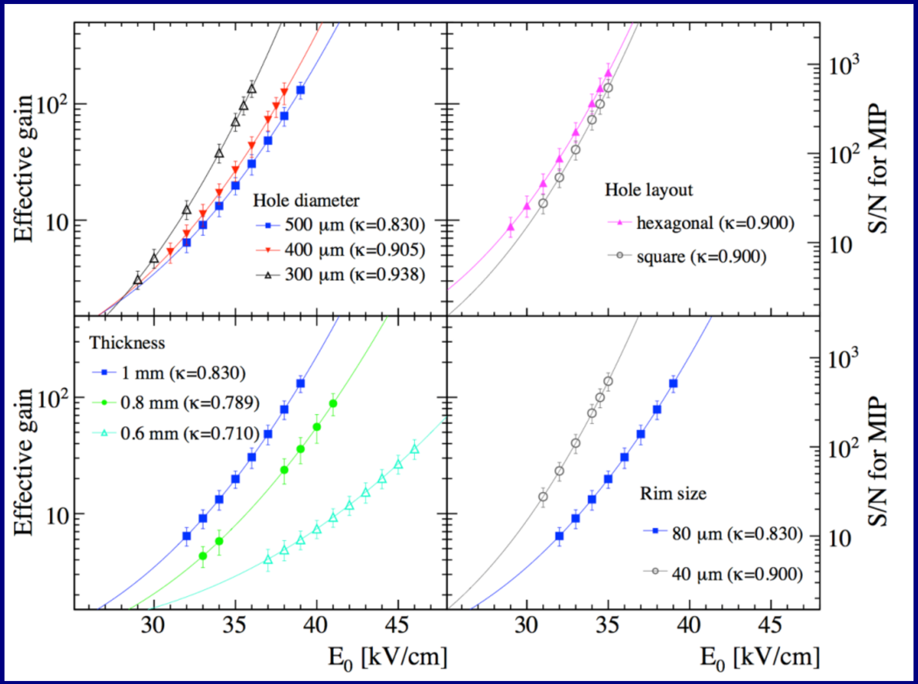




LEM and anodes produced by ELTOS

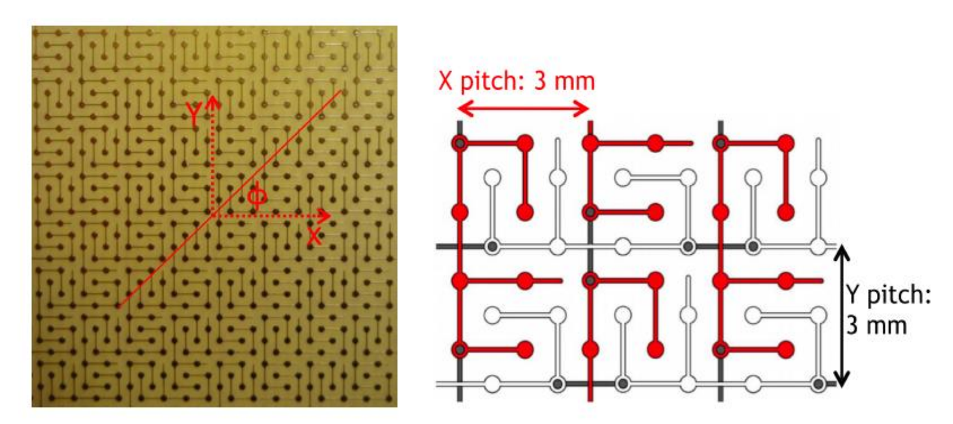
- **LEM: 500 um holes spaced by 800 um, 40 um rim**
- **Anodes: 2D collection views, 3.125 mm pitch, 150 pF/m**

LEM geometry optimization (JINST 10 P03017):

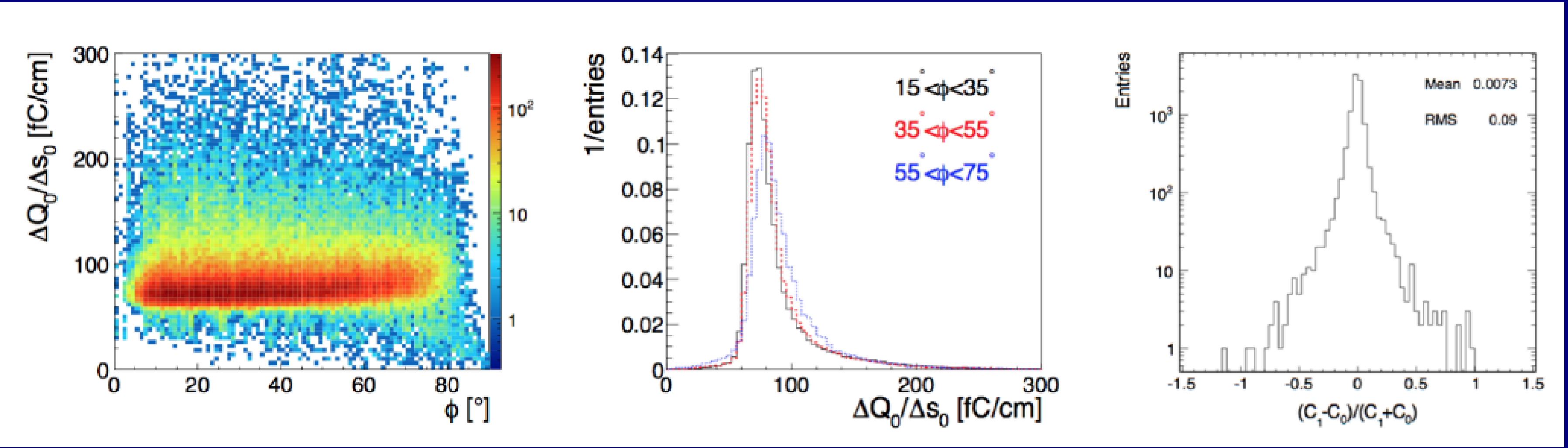


→ Tunable gain by adjusting the LEM HV (up to 200 achieved)

Anode geometry optimization JINST 9 P03017



Anode geometry optimization; 2 collection views, 3.125 mm pitch, 150 pF/m
→ Equal charge sharing among the two views, independency on track azimuthal angle



Clean room buffer design