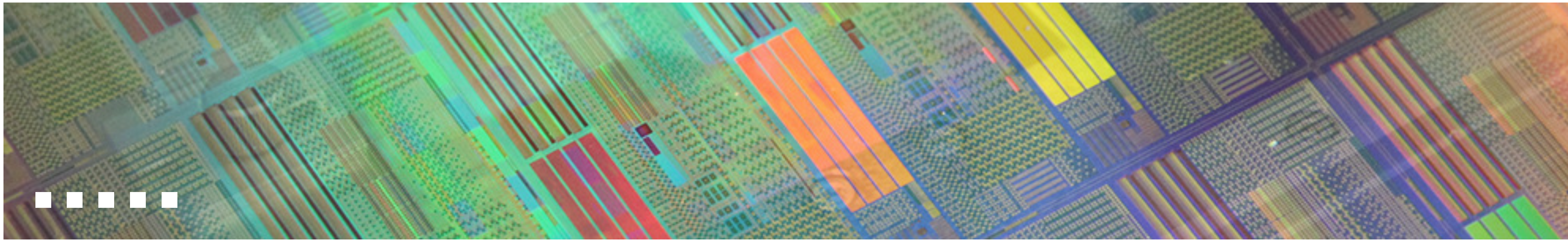
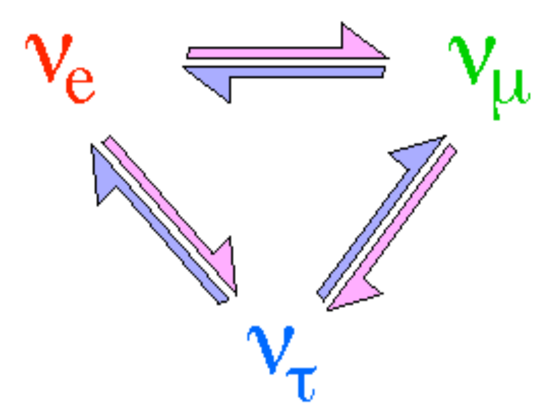
Nikhef Nationaal instituut voor subatomaire fysica



Prospects for a next-generation international long-baseline experiment

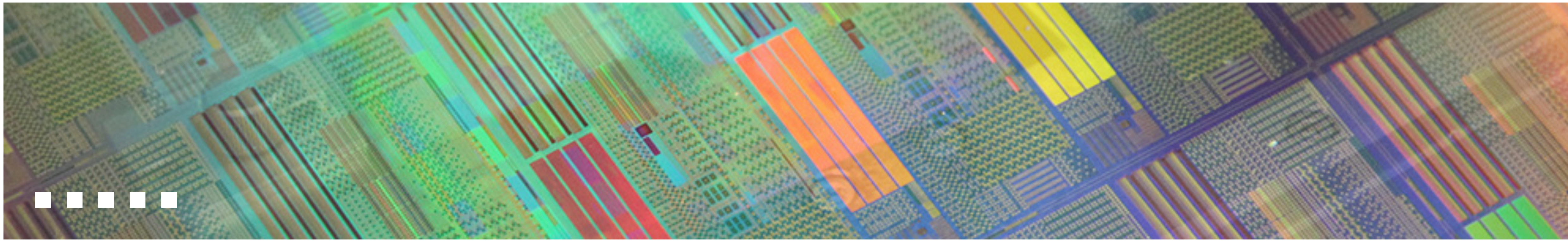
André Rubbia (ETH Zürich)



ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

NIKHEF Colloquium, Amsterdam, January 2015

v2



Colloquium Andre Rubbia

16-01-2015

Friday 16 January, 11:00h, at Nikhef in H331

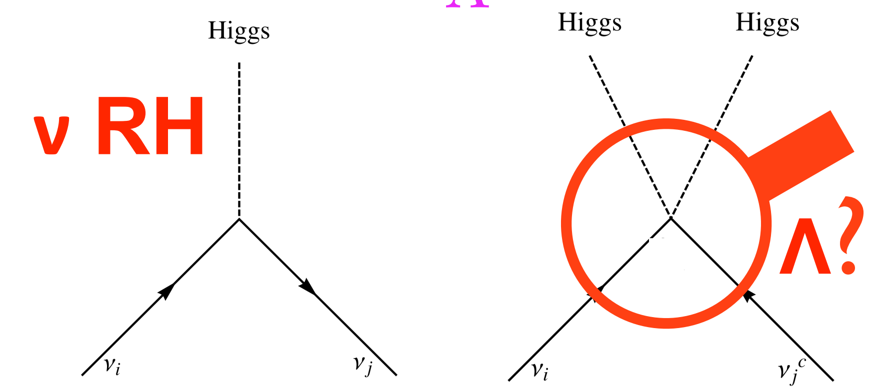
Speaker: Andre Rubbia (ETH Zurich)

Title: "Prospects for a next-generation international long-baseline experiment"

Abstract:
A next generation very large-scale neutrino observatory must be capable of addressing key open questions and complete our knowledge in neutrino oscillations. Is there CP violation (CPV) in the leptonic sector ? are matter effects in long-baseline oscillations understood and what is the neutrino mass hierarchy (MH) ? The recent measurement of the theta_13 angle of the PMNS mixing matrix has now promoted these open questions as the next milestones, with exciting implications on our understanding of the matter-antimatter asymmetry in the Universe. These challenging physics goals can be uniquely addressed by a new very large underground detector coupled to a long-baseline neutrino beam. Such a new facility will also be an ideal observatory for solar, atmospheric and supernovae neutrinos, as well as for high sensitivity nucleon decay searches. The European neutrino community has early on recognised the importance of this sector and has been strongly supported to prepare the new experiment with the LAGUNA and LAGUNA-LBNO design studies. This consortium is now active in the construction of a large (300t) demonstrator at CERN (WA105). Following the European Strategy Recommendation and the P5 report in the USA, neutrino physics "entered the global era" and the European neutrino community is now exploring the possibility to participate in the ELBNF hosted by Fermilab.

Neutrinos at the frontier

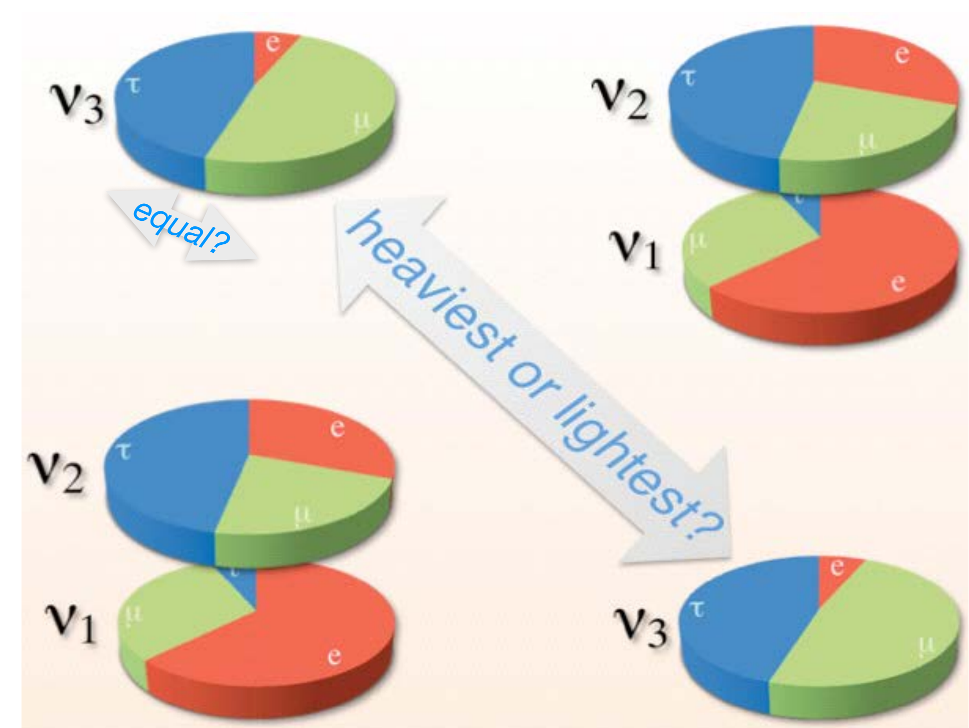
$$\underbrace{Y^{ij}\Psi_L^i\Psi_R^j\phi}_{-\mathcal{L}_{\text{Dirac}}} + \underbrace{\frac{g^{ij}}{\Lambda}\Psi_L^i\Psi_L^{T,j}\phi\phi^T}_{-\mathcal{L}_{\text{Majorana}}}$$



- **Neutrinos play a fundamental and special role in particle physics, astrophysics and cosmology**
- **Neutrino masses** → presently the only evidence of new physics beyond the SM – additional d.o.f. must exist: either **ν RH** and/or **new scale Λ** (>> TeV ?)
- **A window to 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 quarks? What does this picture suggest ?**
  - **How is the hierarchy of the ν mass eigenstates ?**
  - Which is the absolute mass of the lightest state ?
  - Are neutrinos Majorana particles ?
  - **P, CP, CPT are fundamental symmetries. "P is maximally violated by neutrinos but CP is saved" (W. Pauli). Is CP violated by neutrinos as well or is it a special feature of quarks ?**
  - Are there sterile neutrino states and is there mixing … ?

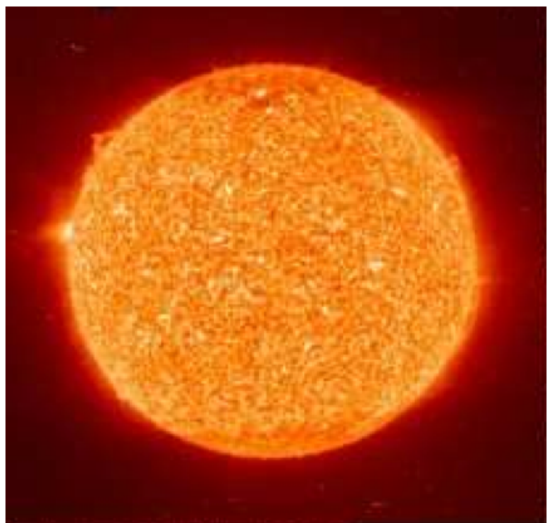
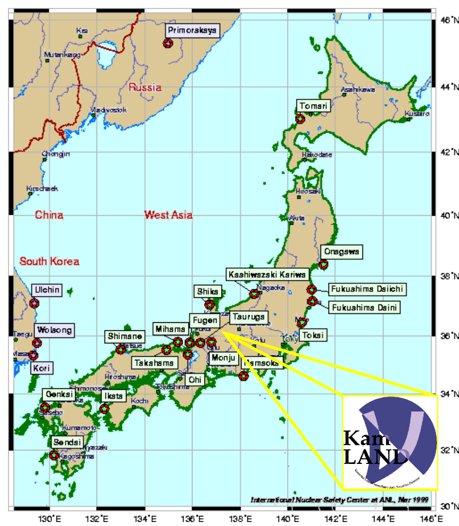
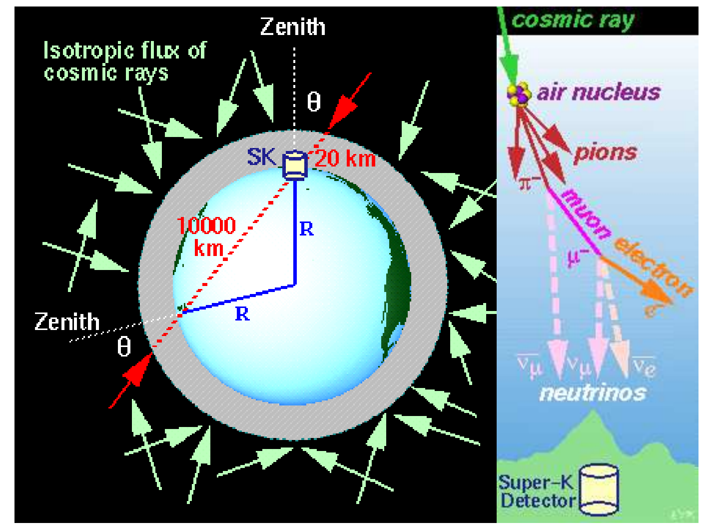
NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$



Global data on neutrino oscillations

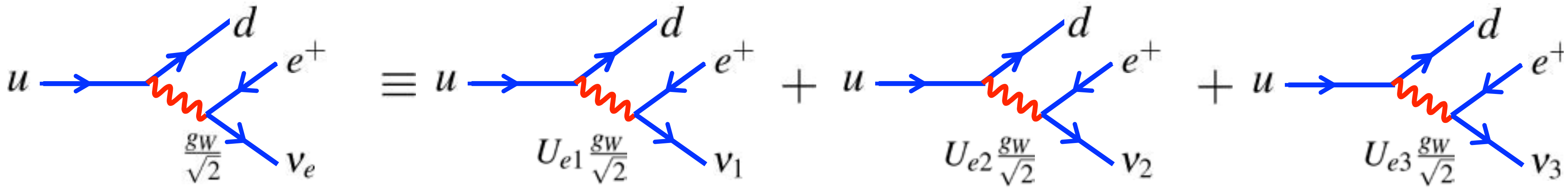
from various neutrino sources and
vastly different energy and distance scales:

sun	reactors	atmosphere	accelerators
			
Homestake,SAGE,GALLEX SuperK, SNO, Borexino	KamLAND, CHOOZ Daya-Bay, Double Chooz, RENO	SuperKamiokande + MINOS	K2K, MINOS, T2K CNGS, NOvA

- global data fits nicely with the 3 neutrinos from the SM
- a few “anomalies” at 2-3 σ: LSND, MiniBooNE, reactor anomaly,
  - *Sterile* states would imply PMNS matrix non-unitary

The 3νSM paradigm: where we are today

- Weak eigenstates are coherent superposition of the fundamental mass eigenstates:



★ **The 3x3 Unitary matrix U is known as the Pontecorvo-Maki-Nakagawa-Sakata matrix, usually abbreviated PMNS**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Dominates: "Atmospheric" — "subleading" — "Solar"

2014)

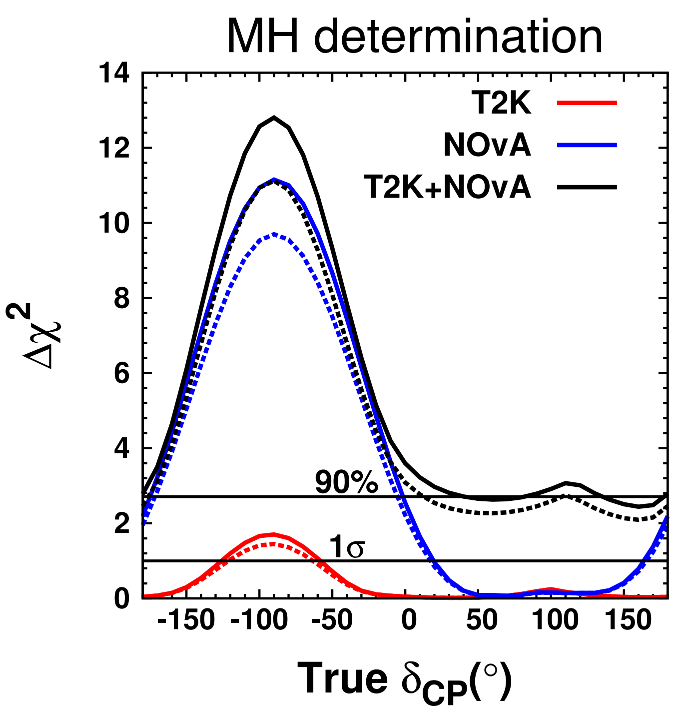
http://www.nu-fit.org

JHEP 11 (2014) 052

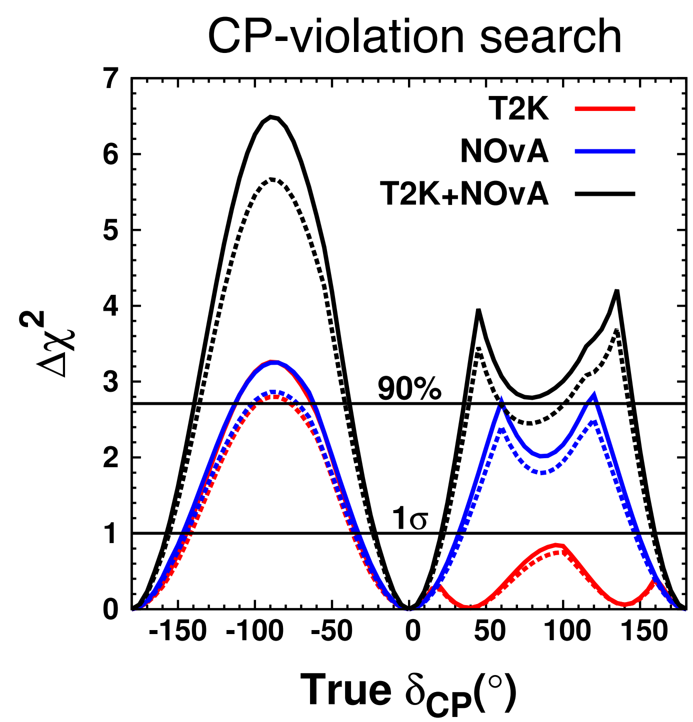
	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

- **Post-NOW2014 precision on parameters:** $\delta(\theta_{12}) \approx 2\%$, $\delta(\theta_{23}) \approx 7\%$, $\delta(\theta_{13}) \approx 2\%$, $\delta(\Delta m^2_{21}) \approx 3\%$, $\delta(\Delta m^2_{31}) \approx 2\%$
- **All values of CP-phase δ are allowed at 3σ C.L.**
- **No hints for correct neutrino mass hierarchy (MH)**
- Caveat: Global fits deliver the best adjustment to the existing data, but cannot prove the models. They cannot replace new direct experimental tests.

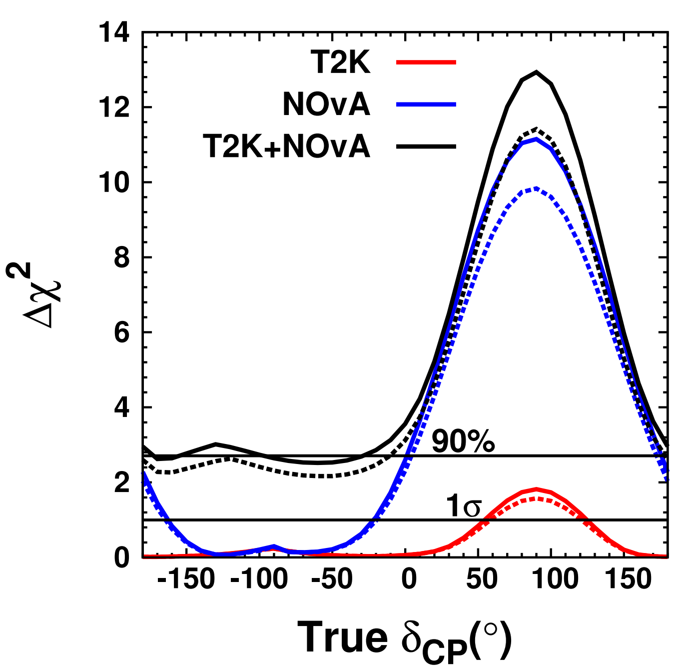
T2K and NOvA: the future until ≈2020



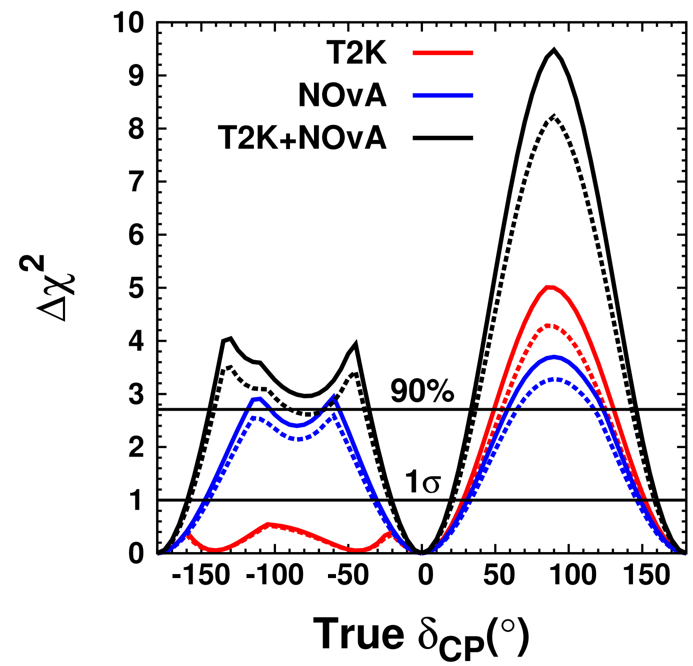
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH



(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH

Mass hierarchy determination:

- combined fit NOvA (6 years of nominal running) + T2K pot projection
- exploiting bigger matter effect (≈30%) at 830km(NOvA) comparing to 295km(T2K)
- strongly depends on true value of δ_{CP} and on true hierarchy (NH/IH)
- **>50% phase-space unreachable**

CP-violation discovery:

- combined fit NOvA (6 years of nominal running) + T2K pot projection
- **in the best case a 2.5σ(NH) hint**
- **>50% phase-space unreachable**

⇒New experiments needed beyond 2020 !

In Europe: LAGUNA, LAGUNA-LBNO, LBNO...

The European neutrino community has early on recognised the importance of this sector and has been strongly supported to prepare the new experiment with the LAGUNA and LAGUNA-LBNO design studies.

GLACIER (Giant Liquid Argon Charge Imaging ExpeRiment, **2003**)

- New concept of Double Phase Liquid Argon TPC for CP-violation and future deep underground detector, up to 100 kton mass (hep-ph/0402110)

LAGUNA DS (FP7 Design Study **2008-2011**)

- ~100 members; 10 countries
- 3 detector technologies $\otimes$ 7 sites, different baselines (130 → 2300km)

LAGUNA-LBNO DS (FP7 DS Long Baseline Neutrino Oscillations, **2011-2014**)

- ~300 members; 14 countries + CERN
- Fully engineered detector designs for 20/50 kt DLAr, 50 kt LSc, 540 kt WCD
- Infrastructure design, construction scheme and full costing

LBNO (CERN SPSC EoI for a very long baseline neutrino oscillation experiment, **June 2012**)

- An incremental approach with high level physics starting from phase 1 (MH + LCPV + Astro)
- ~230 authors; 51 institutions

CERN-SPSC-2012-021, SPSC-EOI-007

- Design study is **concluded** and the deliverables soon on the Archive

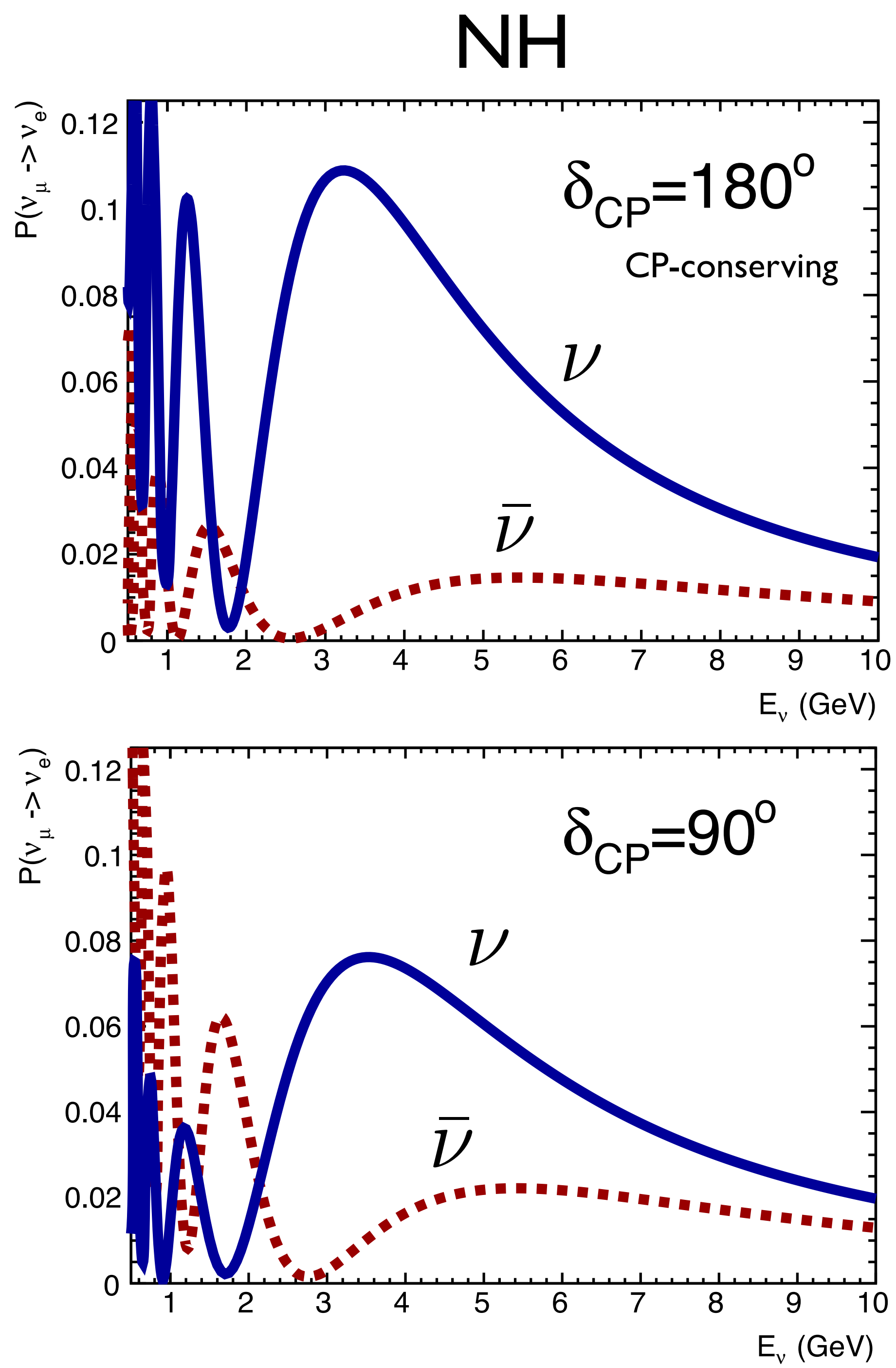
LBNO-DEMO WA105 (@CERN first Collaboration meeting 16-17 **October 2014**)

- kt-scale demonstrator for LBNO @ CERN: engineering and charged particle calibration

CERN-SPSC-2014-013, SPSC-TDR-004

LBNO physics goals

- **Long baseline neutrino oscillations**
  - $\nu\mu \rightarrow \nu e$ & $\nu\mu \rightarrow \nu\tau$ & $\nu\mu \rightarrow \nu\mu$ & νNC
  - Direct measurement of the energy dependence (L/E behaviour) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by direct measurement of event spectrum, in particular covering 1st and 2nd oscillation maxima
  - Mass hierarchy determination at >5σ C.L. in first two years of running
  - CP-phase measurement and CPV "discovery" ($\Rightarrow$ 5σ C.L.)
  - Test of three generation mixing paradigm



- **A full astrophysics programme**
  - Nucleon decays (direct GUT evidence)
  - Atmospheric neutrino detection with complementary oscillation measurements and Earth spectroscopy
  - Astrophysical neutrino detection and searches for new sources of neutrinos

How to test CPV in neutrino sector?

- If PMNS matrix is complex, then neutrino and antineutrinos will behave differently in their flavour oscillations. CP and T will be violated (CPT conserved). This excludes disappearance channels (e.g. $\nu_e \rightarrow \nu_e$).

→ **Main channel of investigation: the appearance channel $\nu\mu \rightarrow \nu e$**

- **Neutrino/antineutrino difference:**

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

➡ Sensitive to any origin (in principle not only induced by δ_{CP})

- **Energy dependence of oscillation probability, independently for neutrinos and antineutrinos:**

$$\begin{aligned} P(\nu_\mu \to \nu_\mathrm{e}; L) \simeq\ & 4c_{13}^2 s_{13}^2 s_{23}^2 \left\{1 + \frac{a}{\delta m_{31}^2} \cdot 2(1 - 2s_{13}^2)\right\} \sin^2 \frac{\delta m_{31}^2 L}{4E} \\ & + c_{13}^2 s_{13} s_{23} \left\{-\frac{aL}{E} s_{13} s_{23} (1 - 2s_{13}^2) + \frac{\delta m_{21}^2 L}{E} s_{12} (-s_{13} s_{23} s_{12} + c_\delta c_{23} c_{12})\right\} \sin \frac{\delta m_{31}^2 L}{2E} \\ & - 4 \frac{\delta m_{21}^2 L}{2E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12} \sin^2 \frac{\delta m_{31}^2 L}{4E} \end{aligned}$$

$$a \equiv 2\sqrt{2} G_\mathrm{F} n_\mathrm{e} E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm^{-3}}} \frac{E}{\mathrm{GeV}}$$

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

Matter terms$\sim a$

CP-even

L/E dependence

CP-odd$\sim \sin\delta_{CP}$

$$a \equiv 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm^{-3}}} \frac{E}{\mathrm{GeV}}$$

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

Matter terms~a

CP-even

L/E dependence

CP-odd~sinδ_{CP}

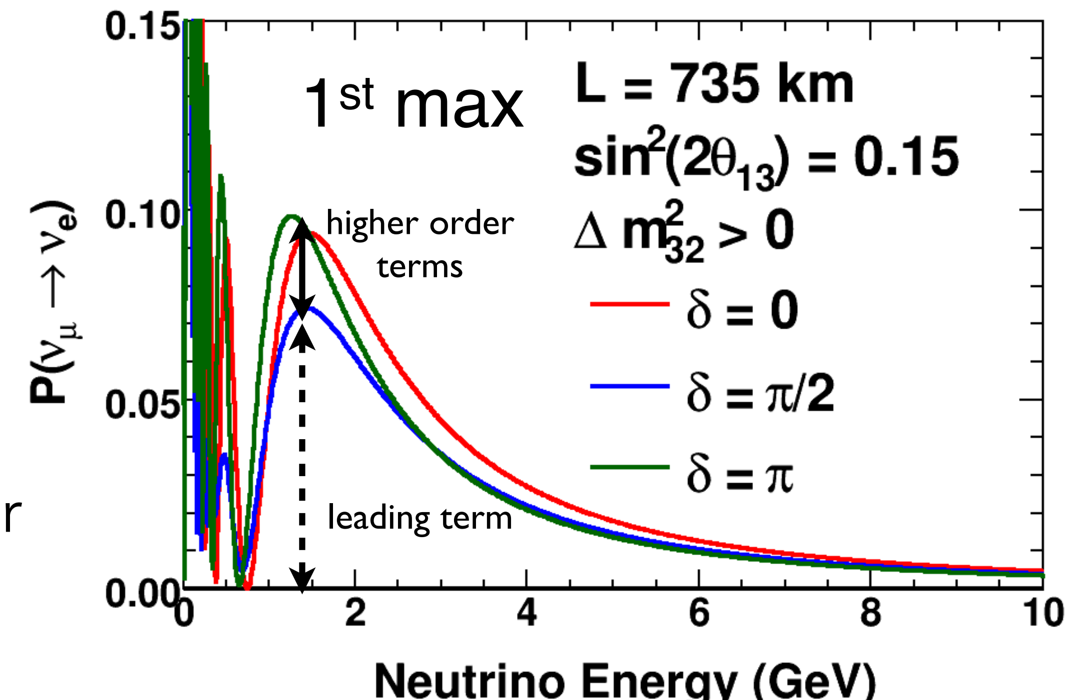
$$a \equiv 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm^{-3}}} \frac{E}{\mathrm{GeV}}$$

➡ Direct test of δ_{CP} origin of CPV and of matter terms

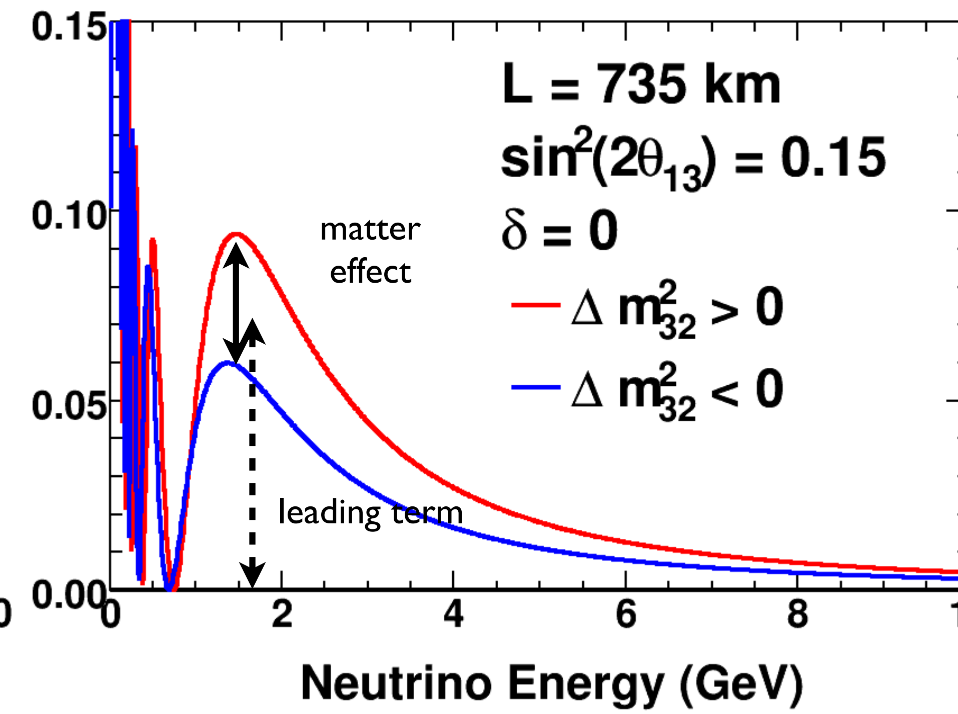
Matter effects and CPV degeneracy

Matter effects in Earth mimic CP violation as they affect neutrinos and antineutrinos differently
→ They have to be accurately measured and subtracted in order to look for CP

δ dependence



mass hierarchy dependence



Courtesy: L. Whitehead

Example: 295 km baseline such as T2K and foreseen for T2HK

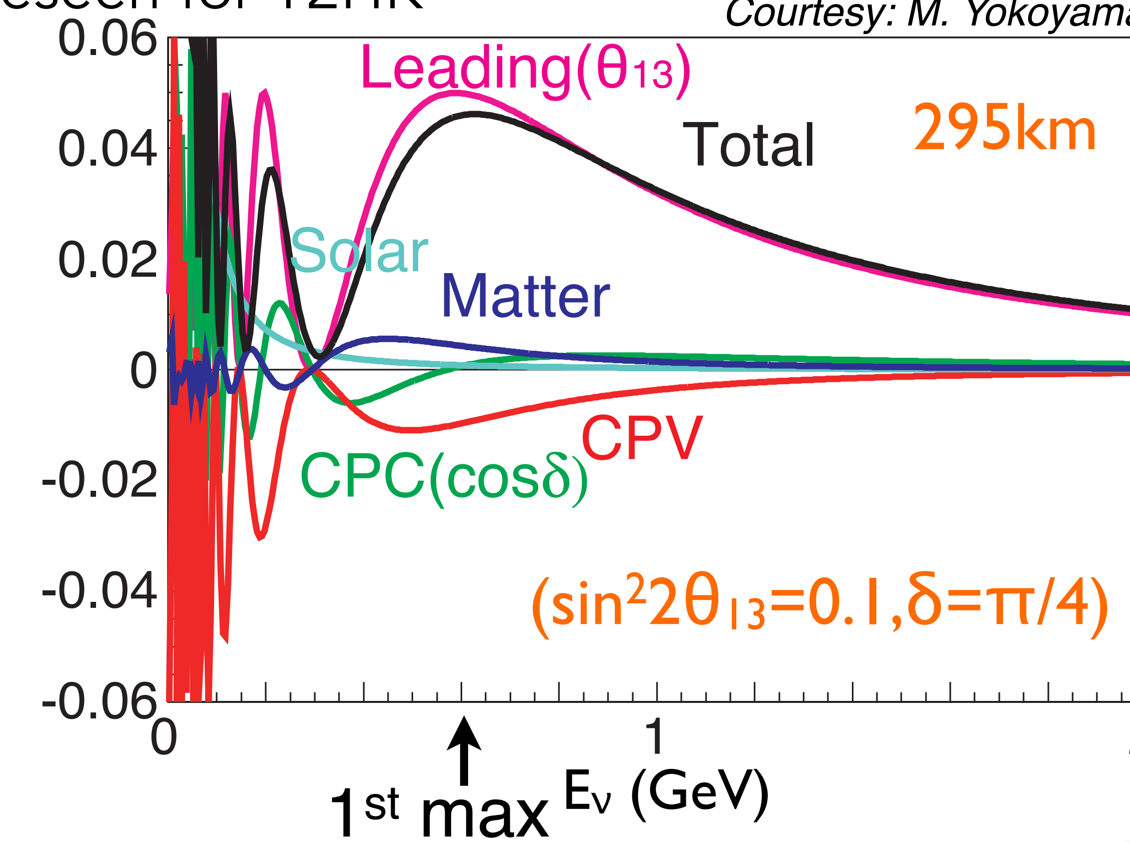
Leading term $\propto \sin^2 2\theta_{13}$

CPV term $\propto \sin 2\theta_{13}$

Matter effect $\propto \sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$
signal ↑, CP asymmetry ↓
matter/CP ↑

Courtesy: M. Yokoyama



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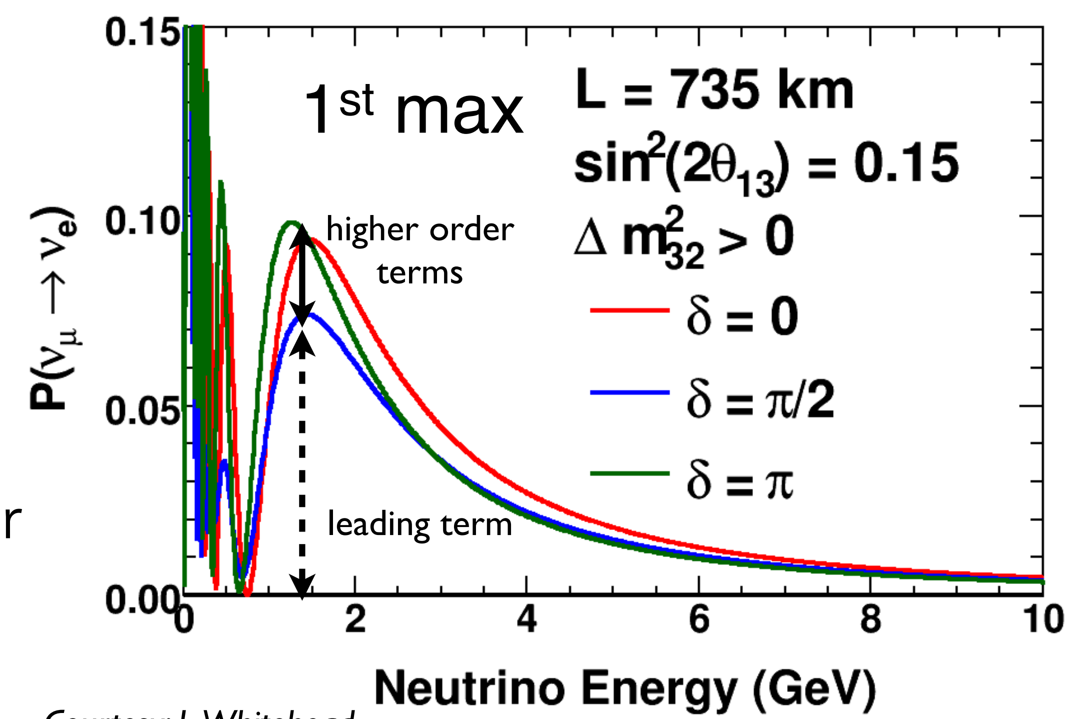
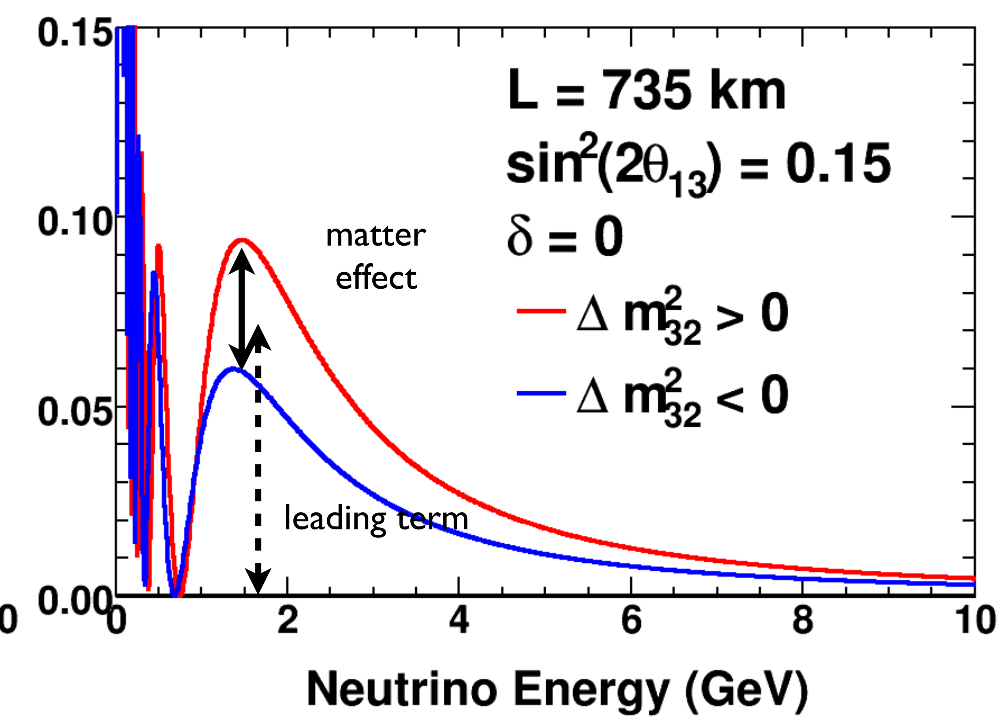


Courtesy: L.Whitehead

mass hierarchy dependence



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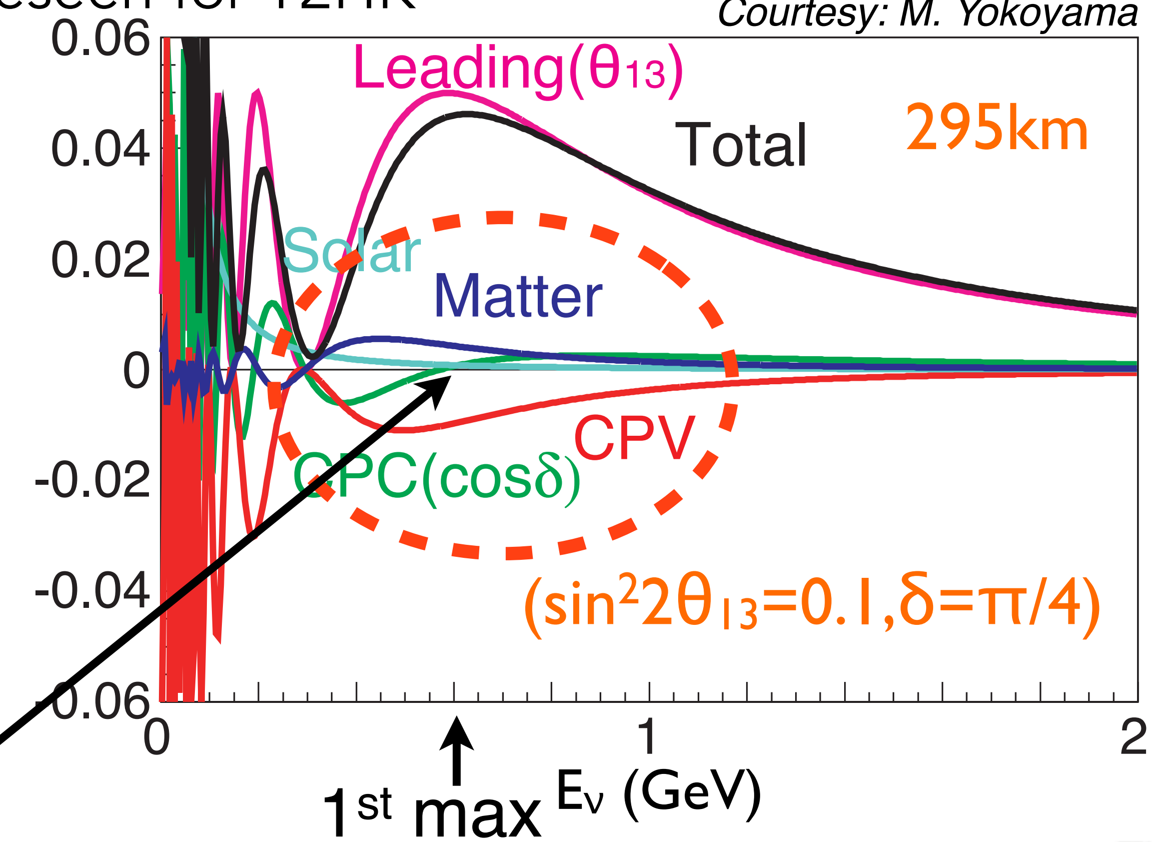
CPV term $\propto \sin 2\theta_{13}$
Matter effect $\propto \sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$
signal ↑, CP asymmetry ↓
matter/CP ↑

Matter effects and CPV asymmetries are of the same order !

Courtesy: M. Yokoyama



Enhanced CP effect at 2nd maximum

- **Matter- and pure CP-terms are disentangled by their different L/E dependence and by the growing CP effect with L/E:**

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

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

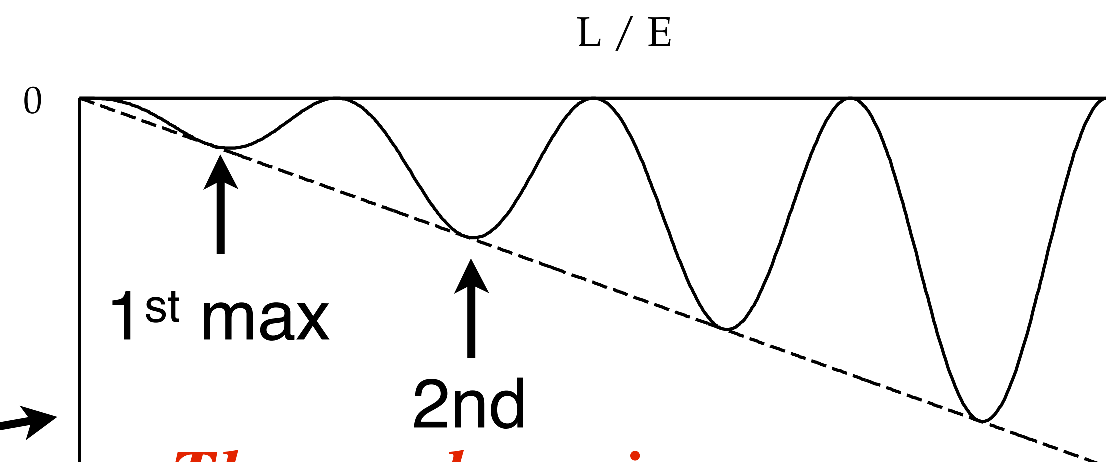
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

Matter terms

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

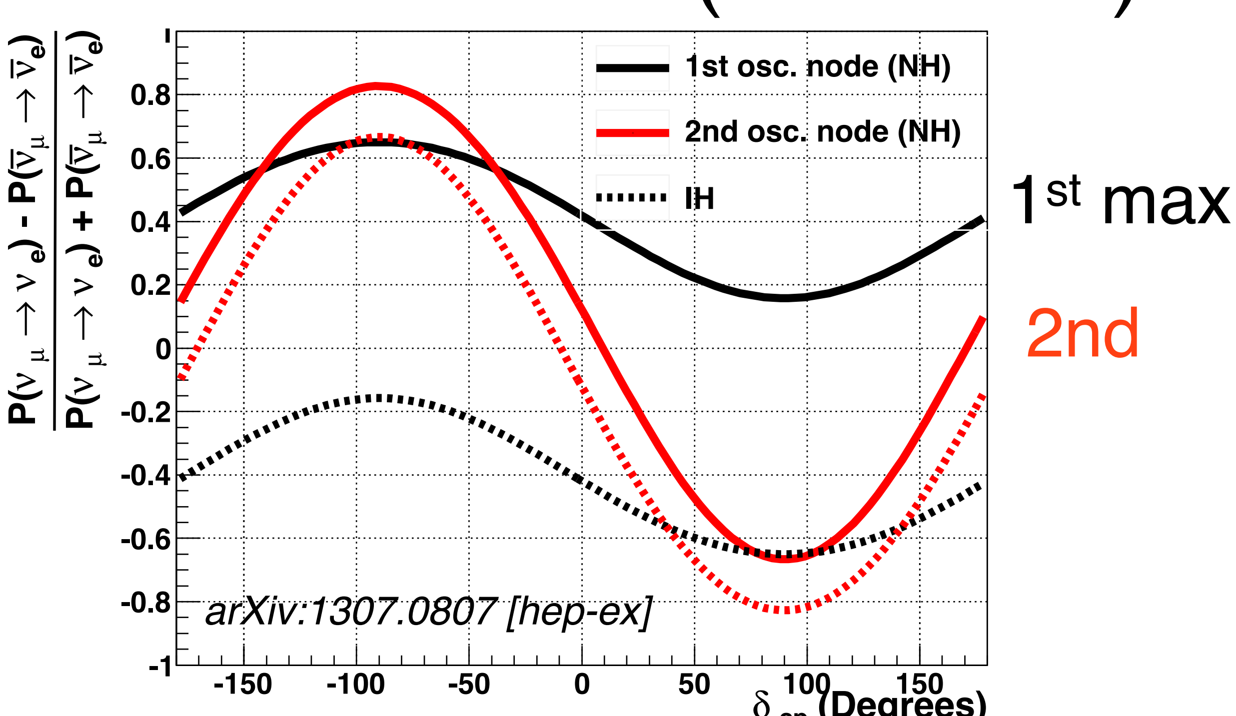
Pure CP-term

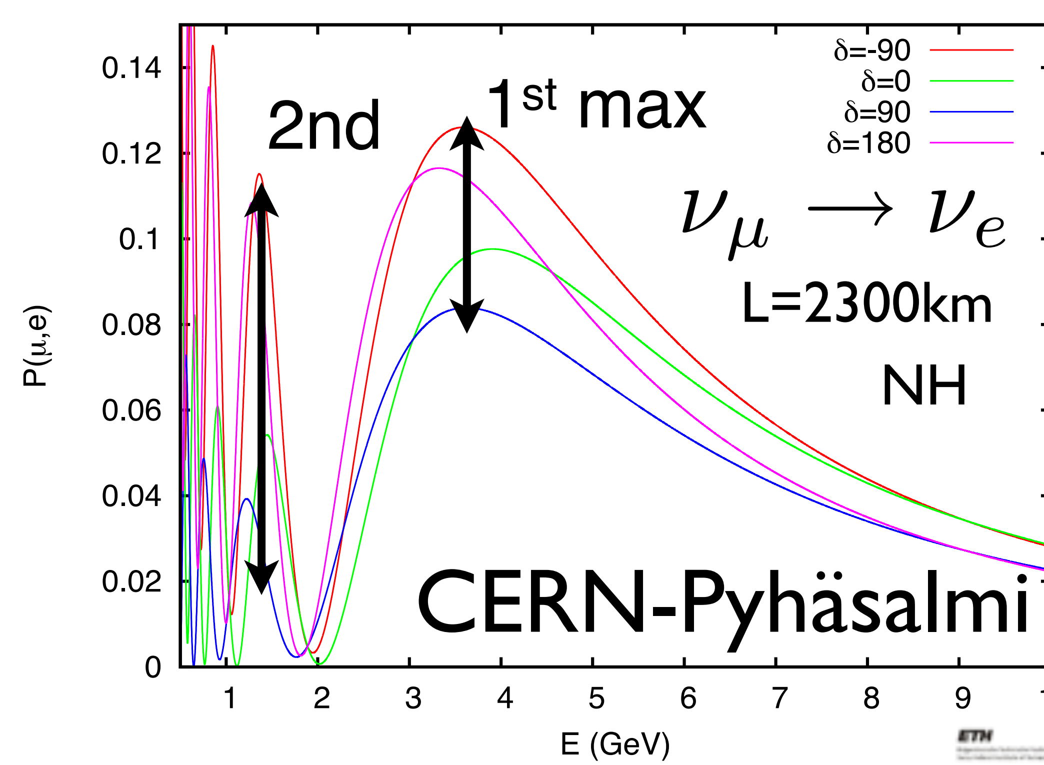
$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}$$



The enveloppe increases linearly with L/E

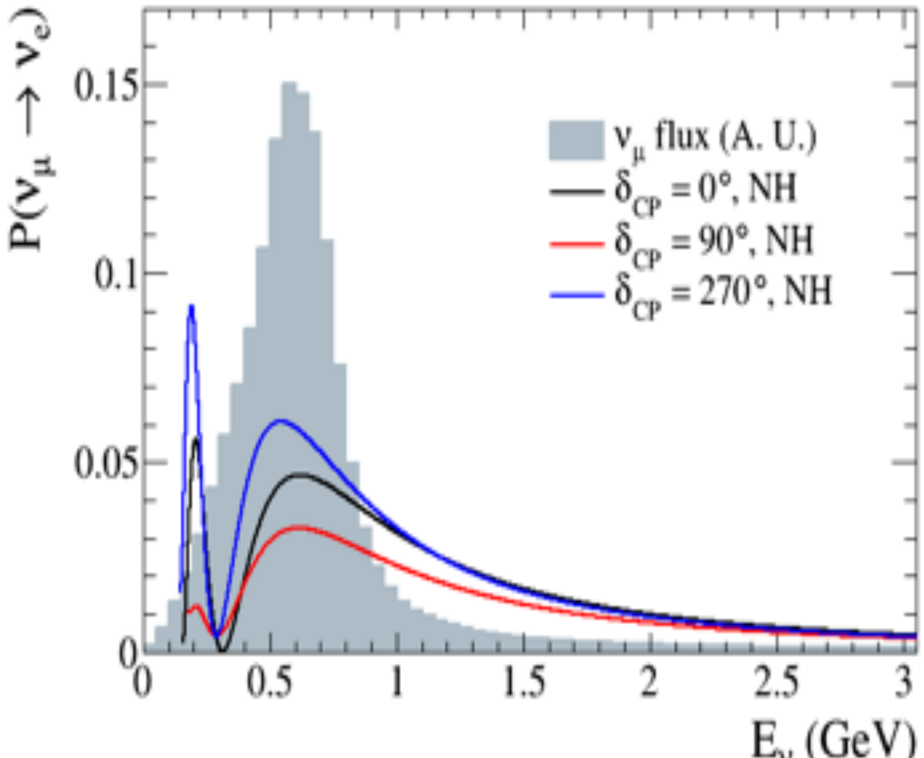
FNAL-Homestake (L=1300km)



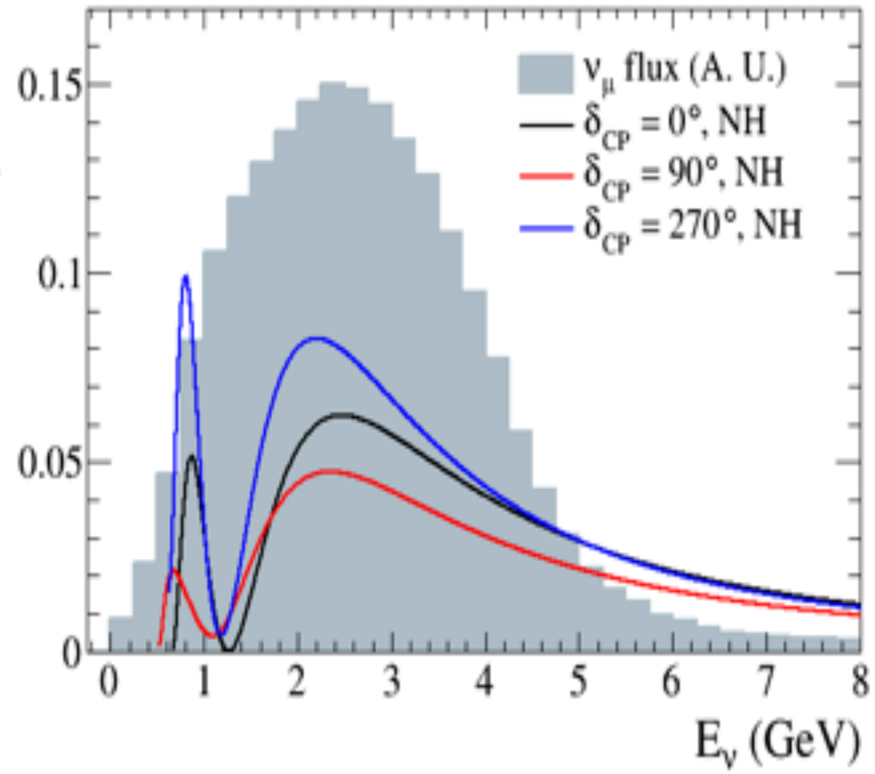


Baseline optimisation

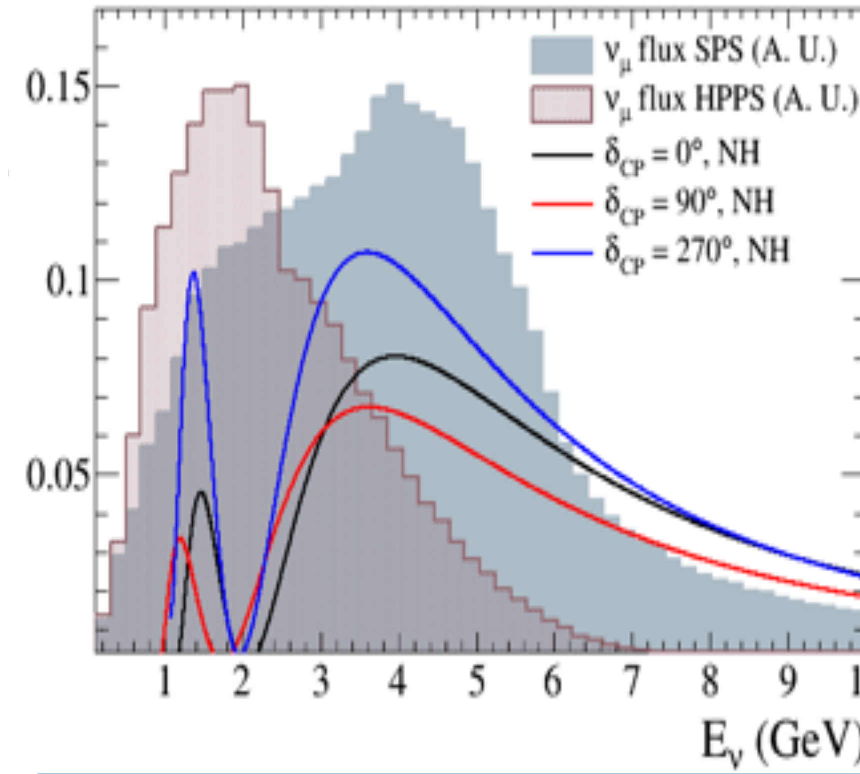
T2HK: L = 295 km



LBNE: L = 1300 km



LBNO: L = 2300 km



Off-axis narrow band sub-GeV beam:

- OA = 2.5 deg & $\langle E_\nu \rangle$ = 0.6 GeV
- 30 GeV primary p beam
- Exposure 16E+21POT total

Covers 1st oscillation maximum

Short baseline → small matter effects → No MH from beam

Wide-band neutrino beam

- 80 GeV primary p beam
- 1.2 MW, 9E+21POT total

Covers mostly 1st oscillation max

→ 2nd max is challenging (low flux x low cross section)

Significant matter effects → MH

Wide-band neutrino beam

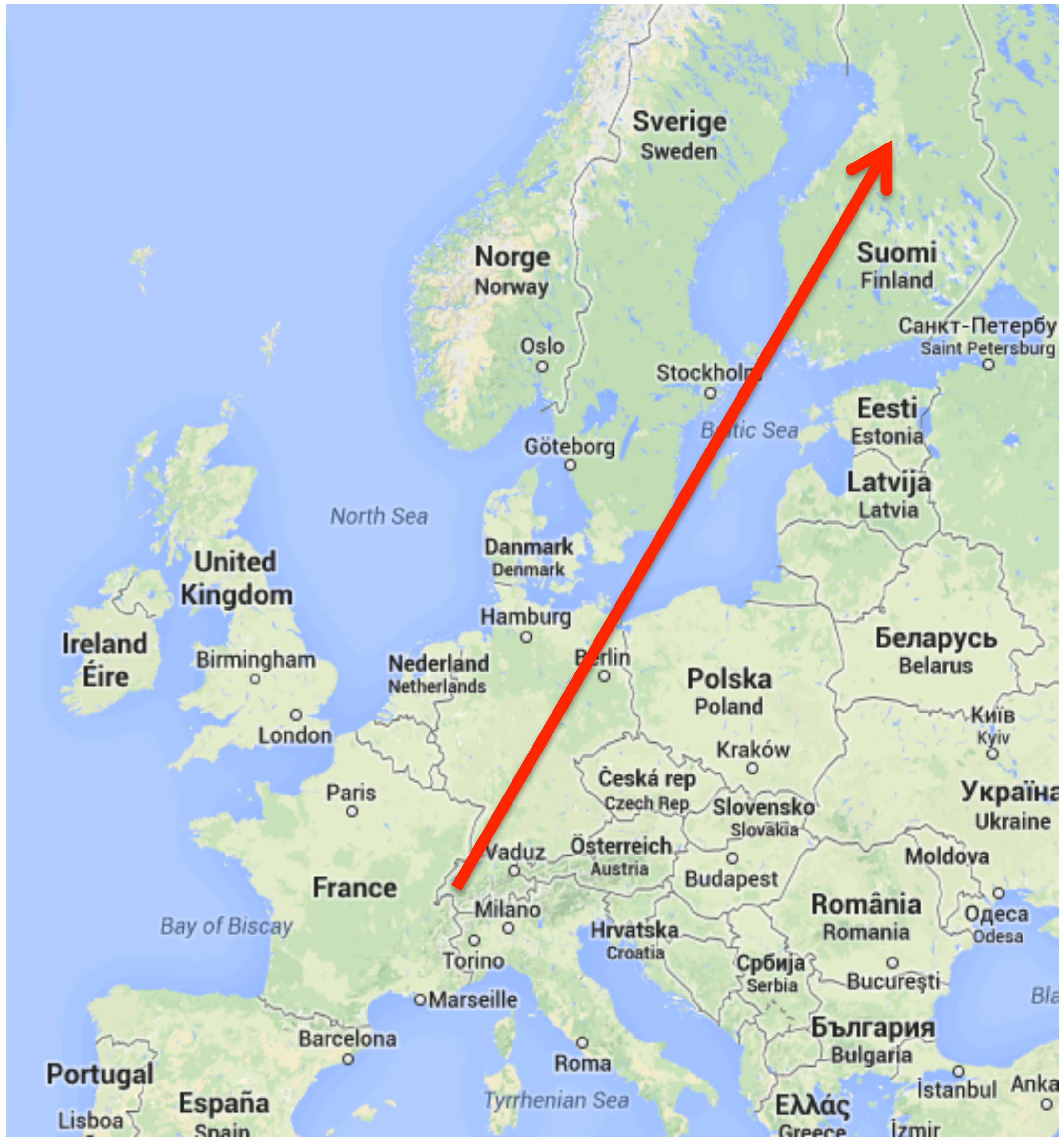
Two optimizations:

- 400 GeV p beam (Phase I): 750 kW, 1.5E+21POT total
- 50 GeV p beam (Phase II): 2 MW, 30E+21POT total

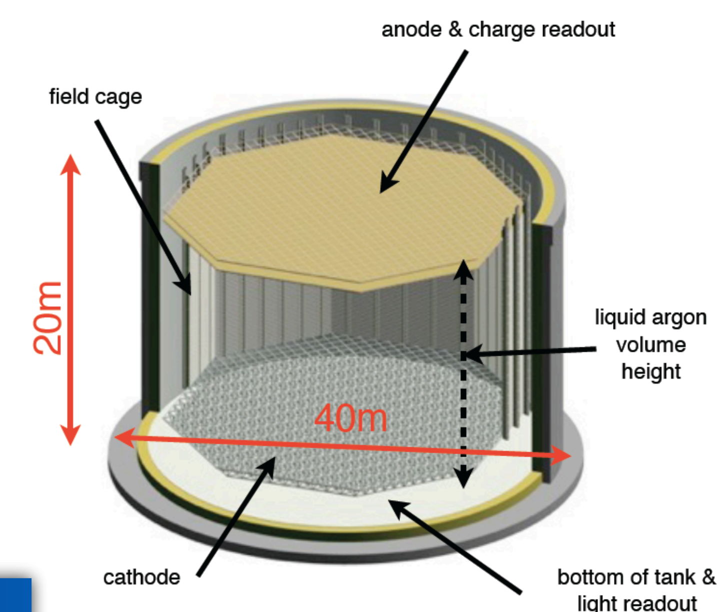
Can cover both 1st and 2nd max

Huge matter effects → quick MH

LBNO scenarios



- 2300 km baseline from CERN (CN2PY)
- SPS 400 GeV protons – 750 kW beam
- HPPS 50 GeV protons – 2 MW beam
- Liquid Argon double phase TPC detector GLACIER : 20 kt (LBNO20) up to 70 kt (LBNO70)



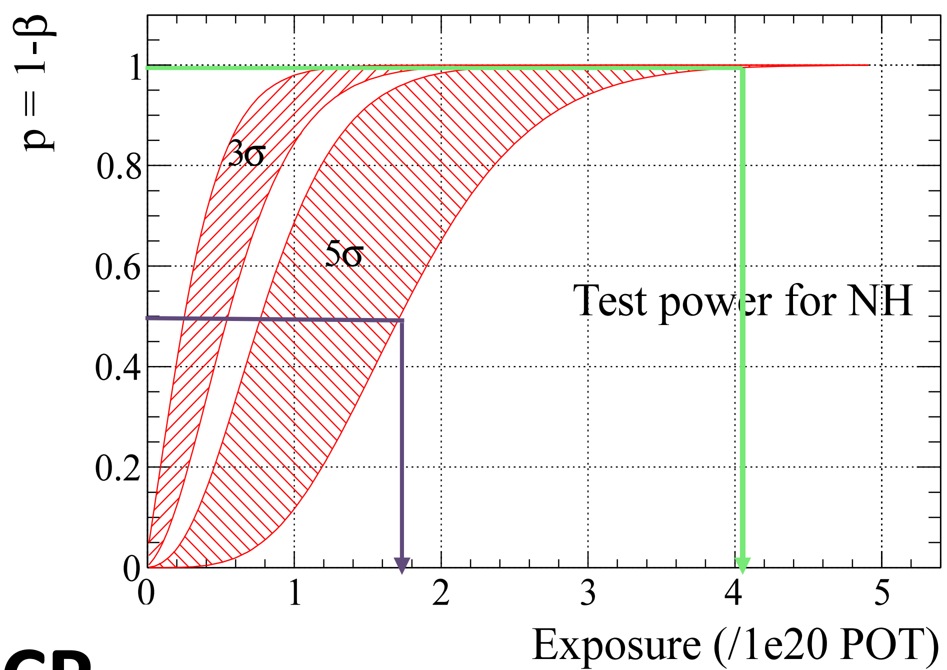
- Phase I (LBNO20):
  24kt DLAr detector + beam from CERN SPS (750kW,Ep=400GeV)
  - ❑ Guaranteed 5 σ MH determination + 46 % δ_{CP} coverage at 3 σ
  - ❑ *p-decay sensitivity from p->Kv improved by 1 order of magnitude w.r.t. current limit*
- Phase II (LBNO70):
  70 kt DLAr detector + HPPS beam (2 MW, Ep = 50 GeV) or Protvino beam
  - ❑ δ_{CP} coverage at 5 σ
  - ❑ *sensitivity to MH effect on SuperNovae neutronization burst*

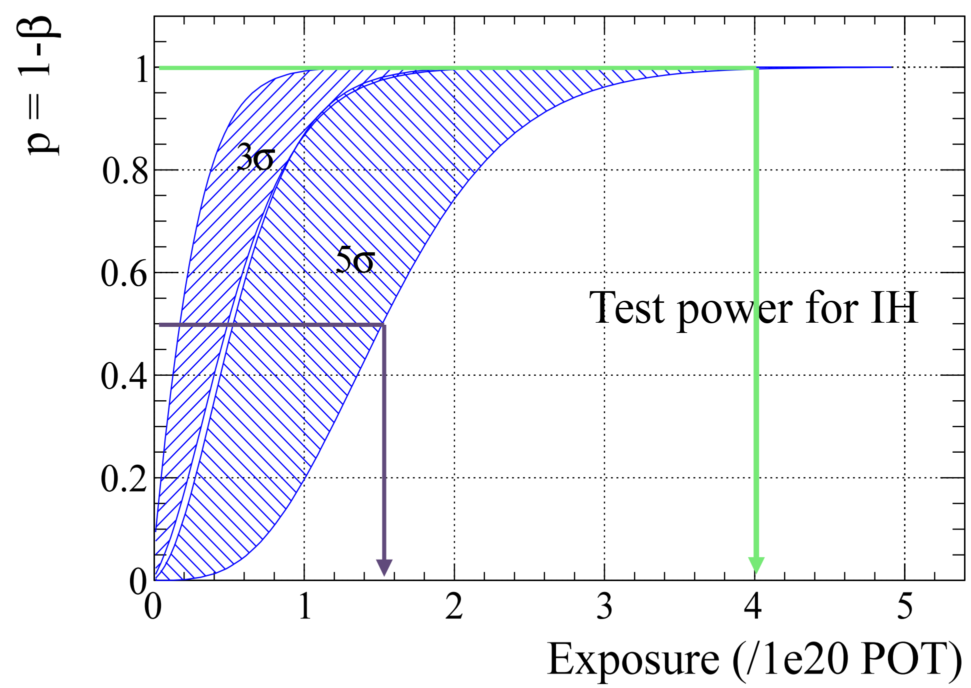
Incremental approach

Mass Hierarchy and CPV

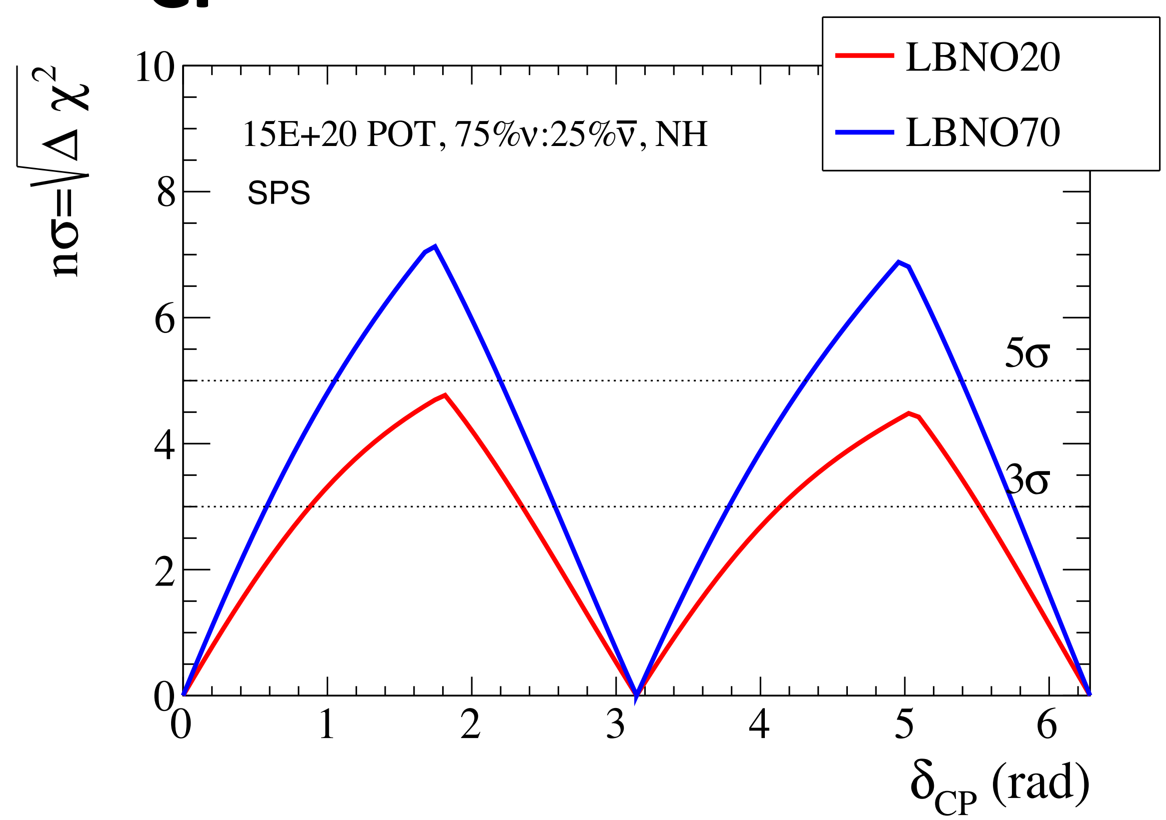
MH Power vs exposure for all values of δ_{CP} (shaded bands) LBNO20 + SPS

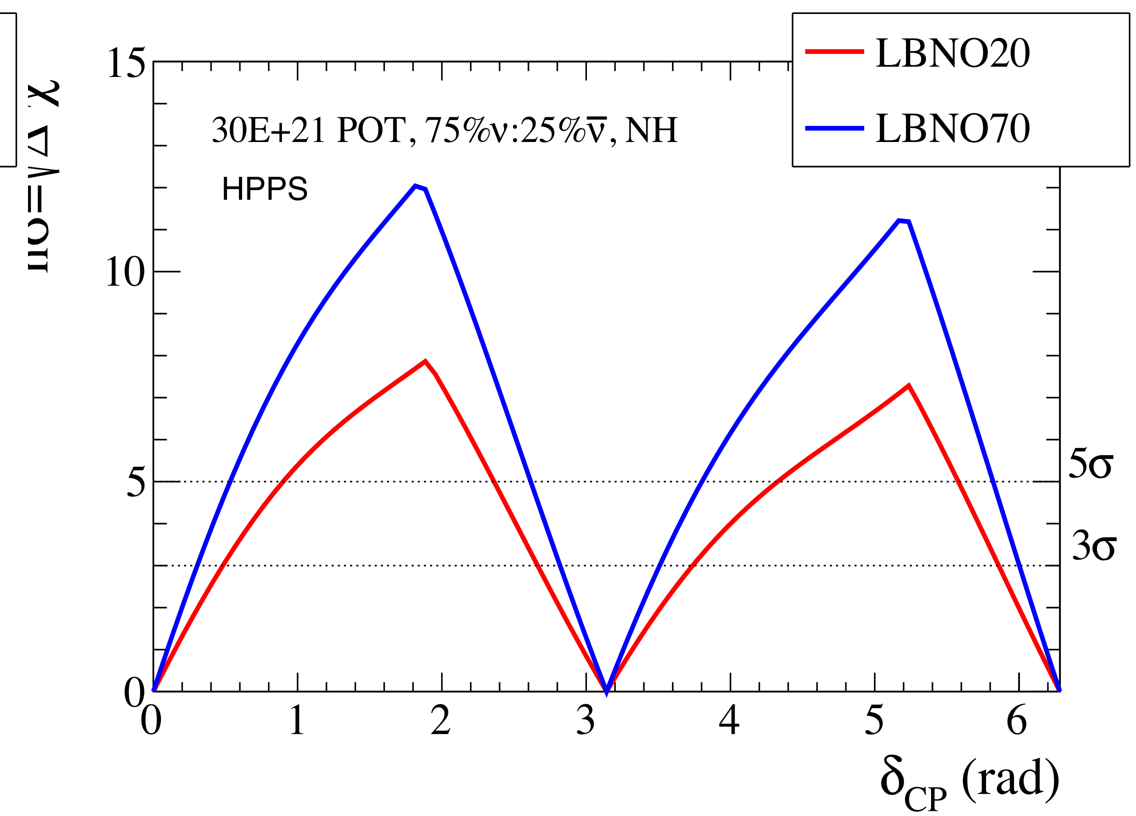
JHEP05(2014)094





CP

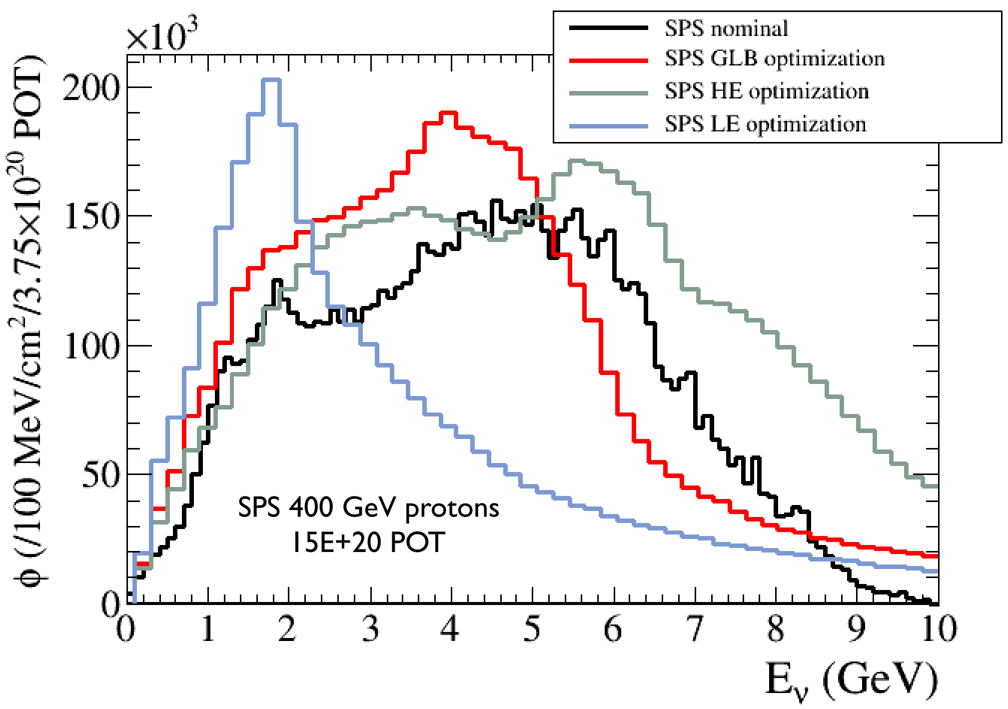




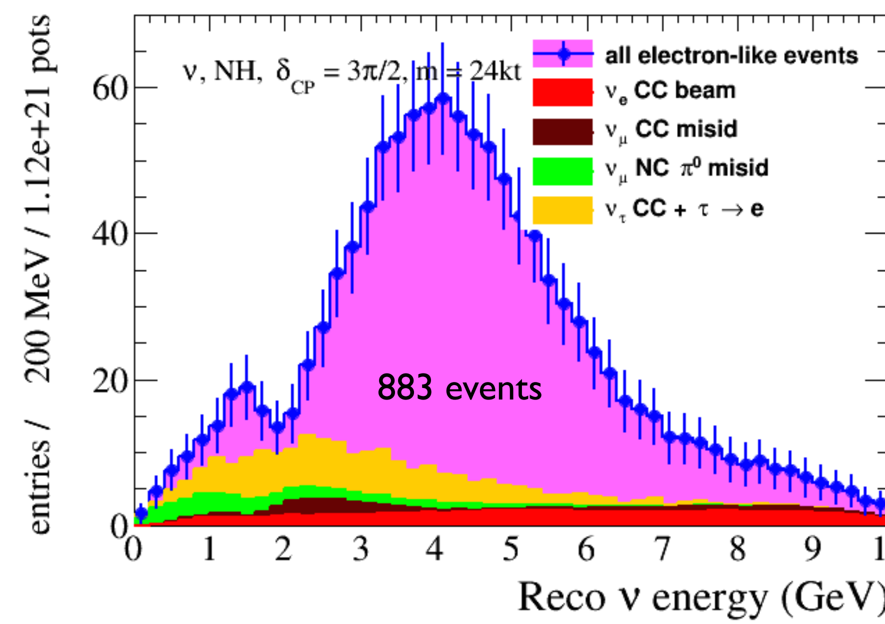
arXiv:1412.0593v1

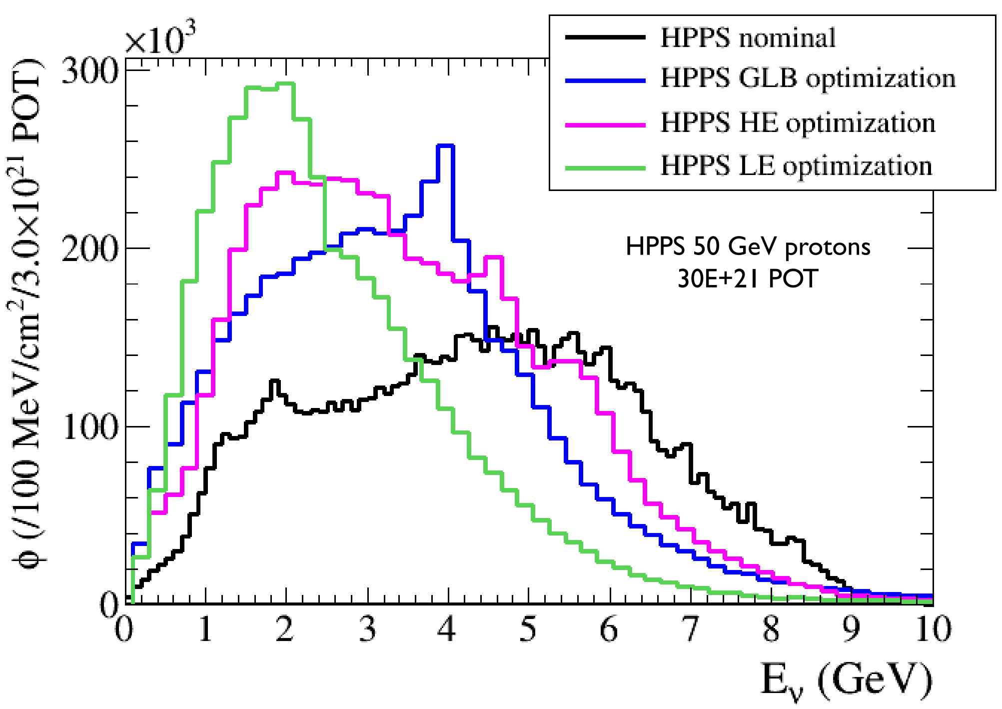
LBNO-CN2PY beam optimisation

Continuous effort to optimise the beam to enhance the CPV coverage of the experiment:

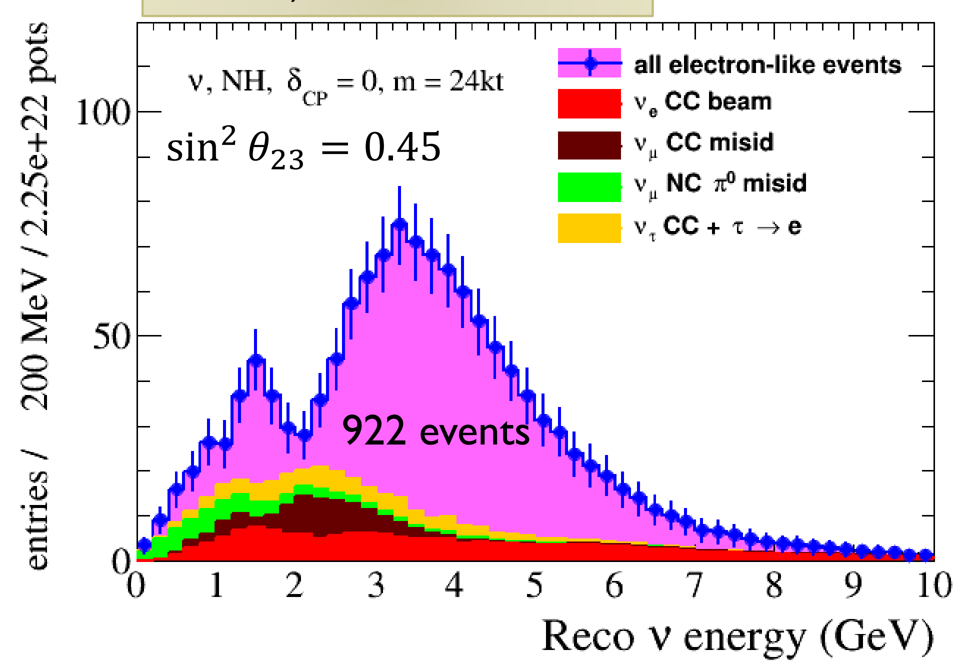


ν beam, 0.75 x 15E+20 POT





ν beam, 0.75 x 30E+21 POT



Best CPV coverage is obtained for "SPS GLB" and "HPPS LEOPT"

LBNO sensitivity to CPV

Assumed values and errors for oscillation parameters and systematics

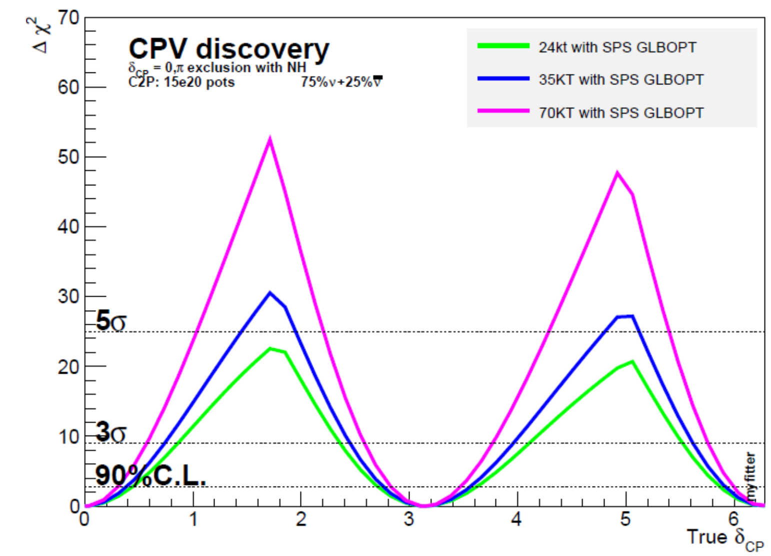
Parameter	Value	Error
L	2300 km	exact
Δm^2_{21}	7.45×10^{-5} eV^2	fixed
Δm^2_{31}	2.42×10^{-3} eV^2	2 %
$\sin^2\theta_{12}$	0.306	fixed
$\sin^2\theta_{23}$	0.446	5 %
$\sin^2\theta_{13}$	0.09	3 %
ρ	3.20 g/cm^3	4 %

www.nu-fit.org

After TAUP 2013

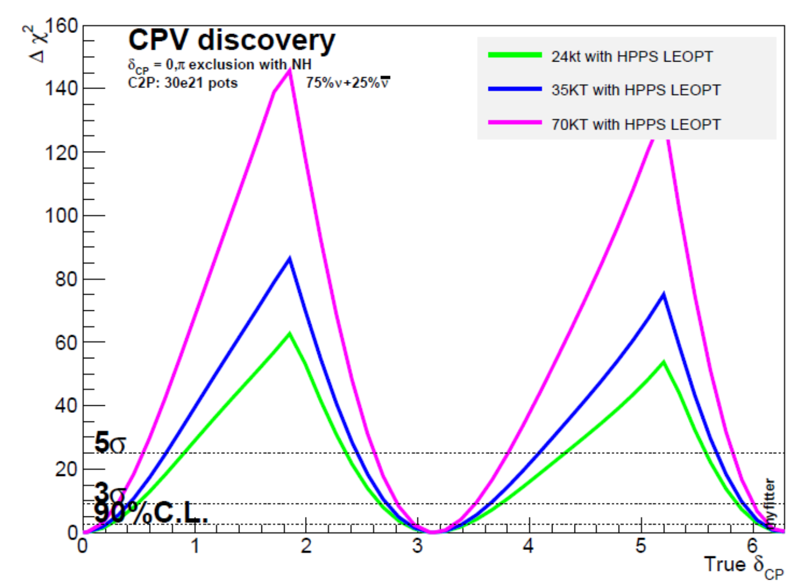
Parameter	Value	Error
Signal normalization (f_{sig})	1	3 %
Beam electron contamination normalization ($f_{\upsilon e}$)	1	5 %
Tau normalization ($f_{\upsilon \tau}$)	1	20 %
υ NC and $\upsilon\mu$ CC background (f_{NC})	1	10 %

LBNO Phase I (24 kt) with Optimized SPS beam: Covers 47 % CPV space at 3σ



Remark: Similar results are obtained with LBNO @ Garpenberg

LBNO Phase II (70kt) with Optimized HPPS beam: Covers 80 % CPV space at 3σ

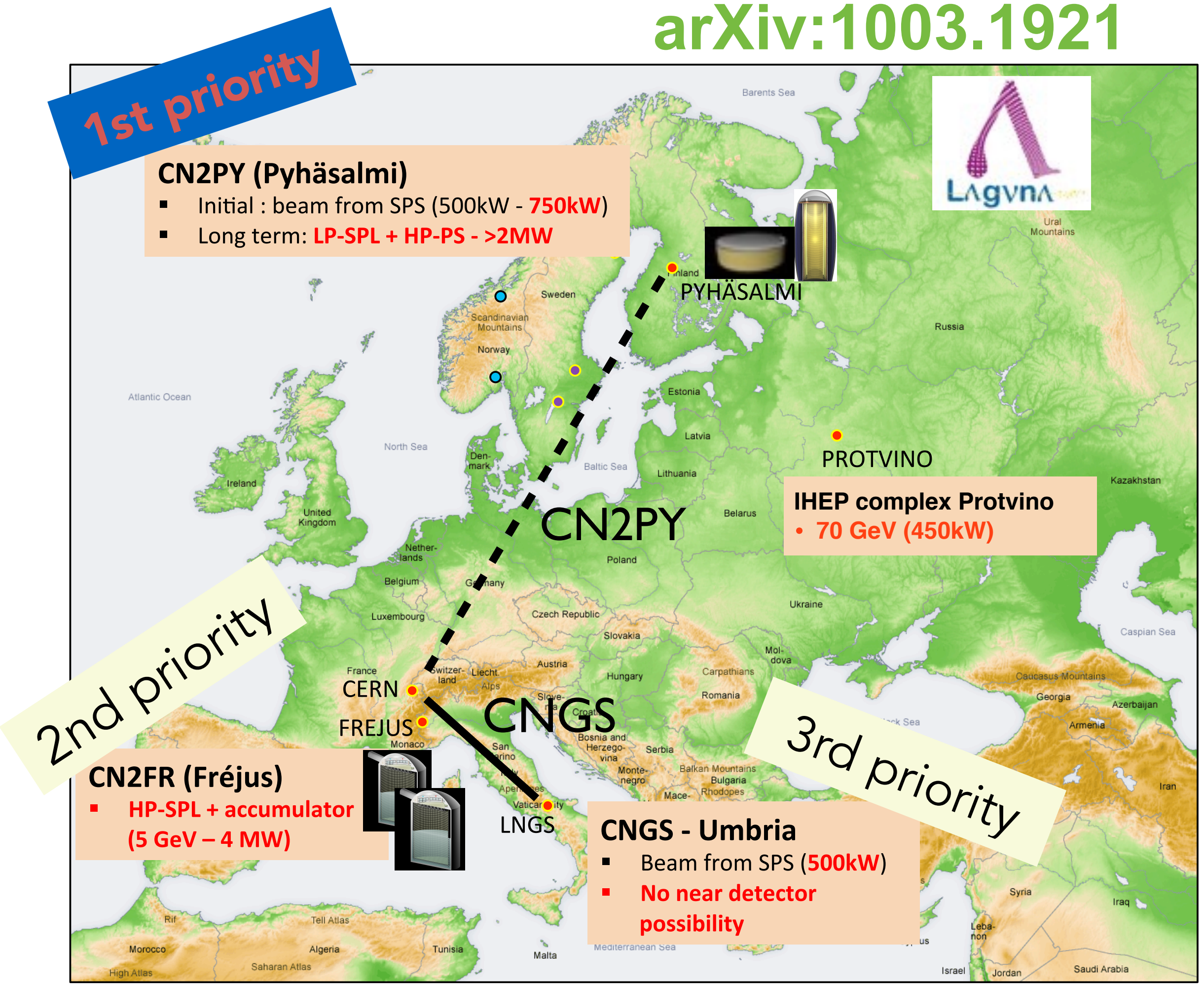


Remark: Alternatively an additional beam from Protvino instead of HPPS

LBNO Conceptual Design

6 years of comprehensive design study for the feasibility of large underground NNN detectors in Europe (7 sites, 3 technologies LAr, LSc, WCD) strongly supported by FP7 EC, CERN and ApPEC

arXiv:1003.1921



Total budget (2008-2014): 17 M€

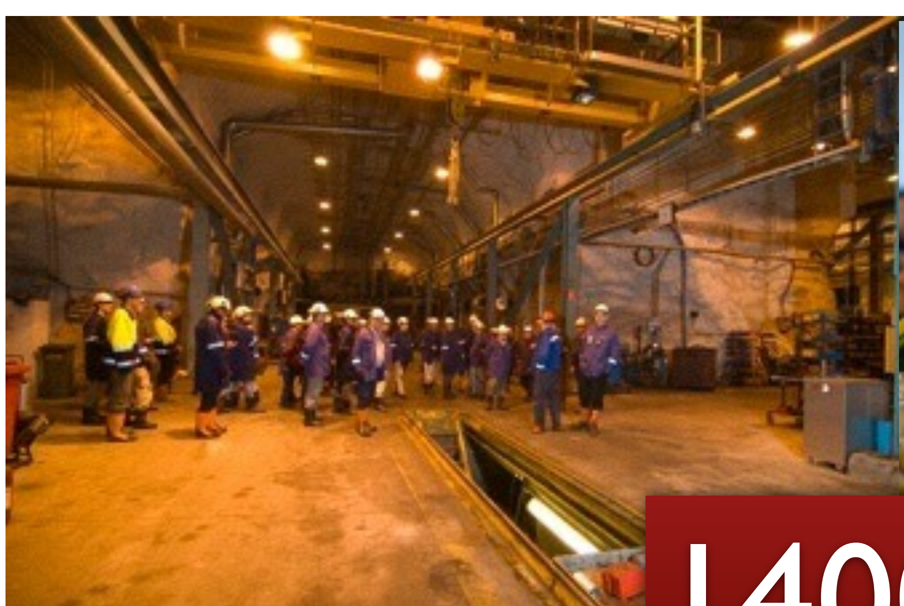
LAGUNA-LBNO collaboration meeting Hanasaari Aug 2014

Main task : develop a conceptual design for a deep underground neutrino observatory that is cost optimised.

LAGUNA at work…

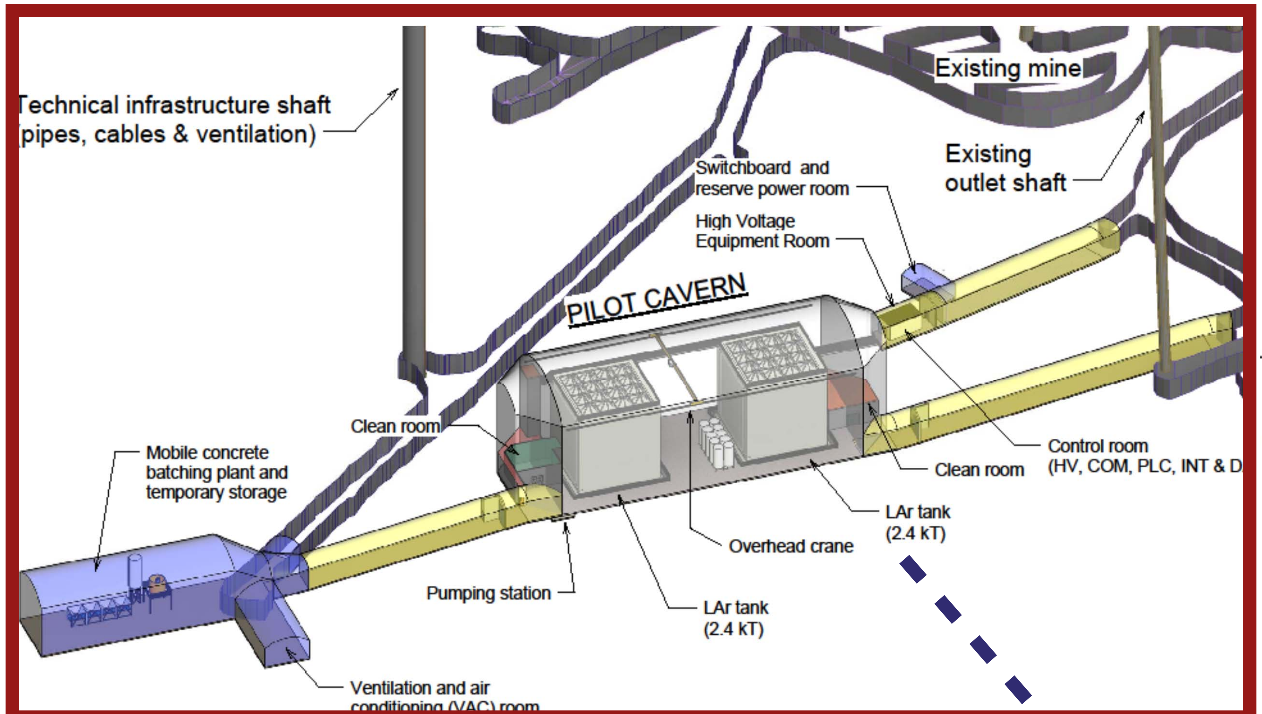
Organised in Work Packages
Site visits and meetings, brainstorm
Several questions addressed:

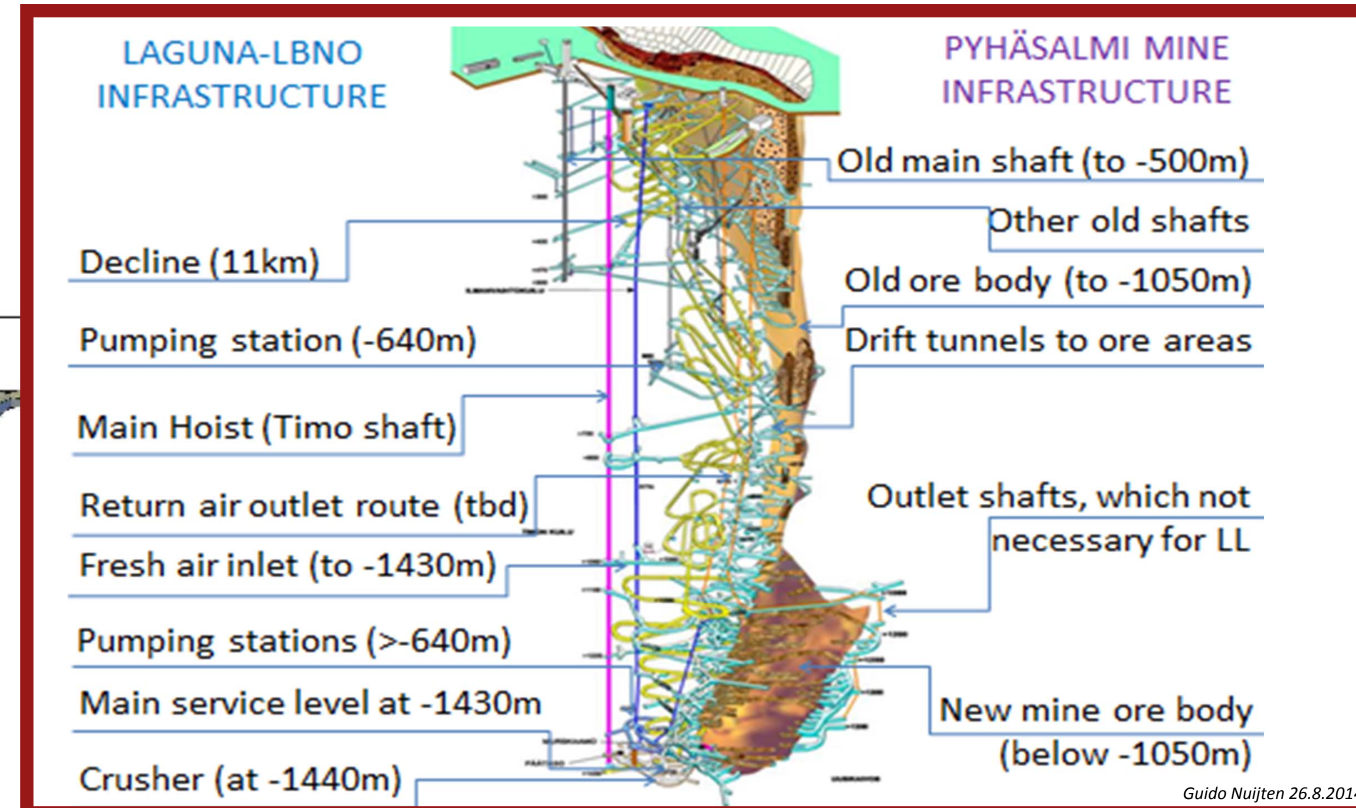
- Physics performance assessment and optimisation
- Assessment of strengths and weaknesses
- Rock mechanics, geology, …
- Design of tanks and instrumentation, …
- Underground construction and assembly phases
- Transport, handling, purification of liquids
- Underground access (tunnel and mine)
- Environmental impact and safety
- Cost models
- High intensity neutrino beams
- etc…



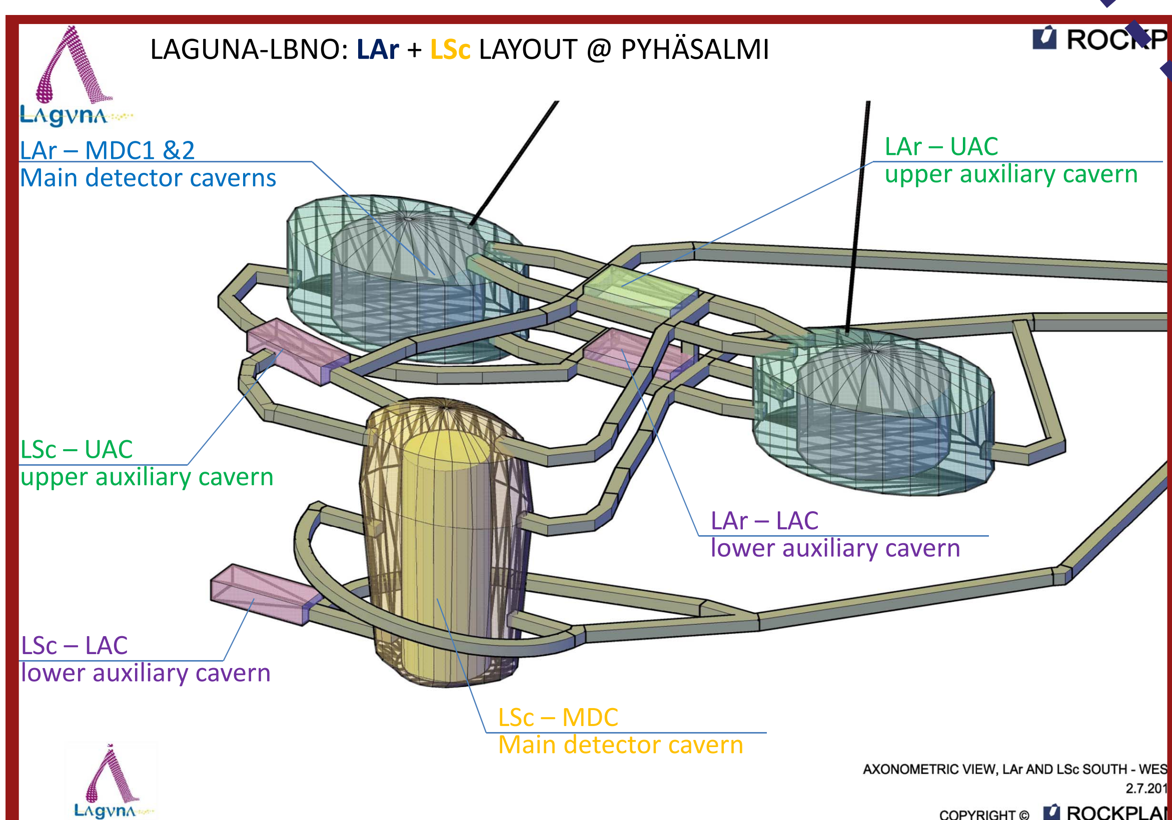
1400 person * month

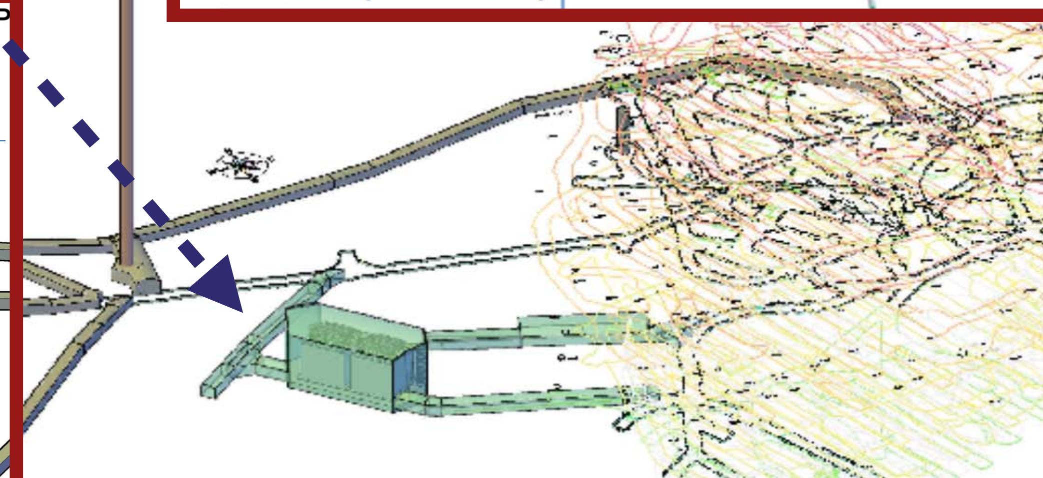
The top site: Pyhäsalmi





LAGUNA-LBNO 20+50kton LAr and 50 kton LSc options:

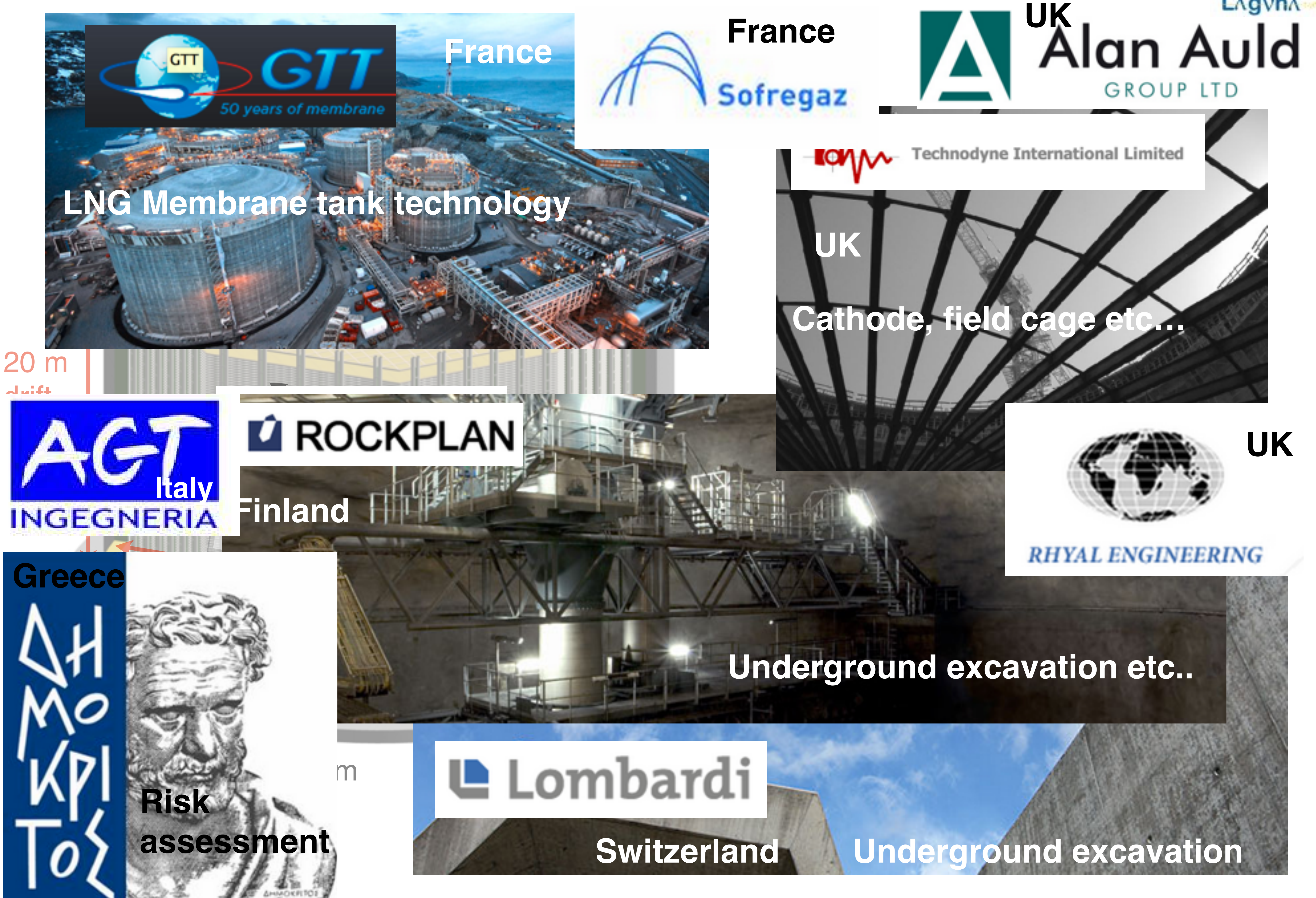




<u>Top site</u> -> Pyhäsalmi

- Very large caverns possible, ease of access (decline), cost effective approach
- Baselines from CERN 2300km, Protvino 1160km

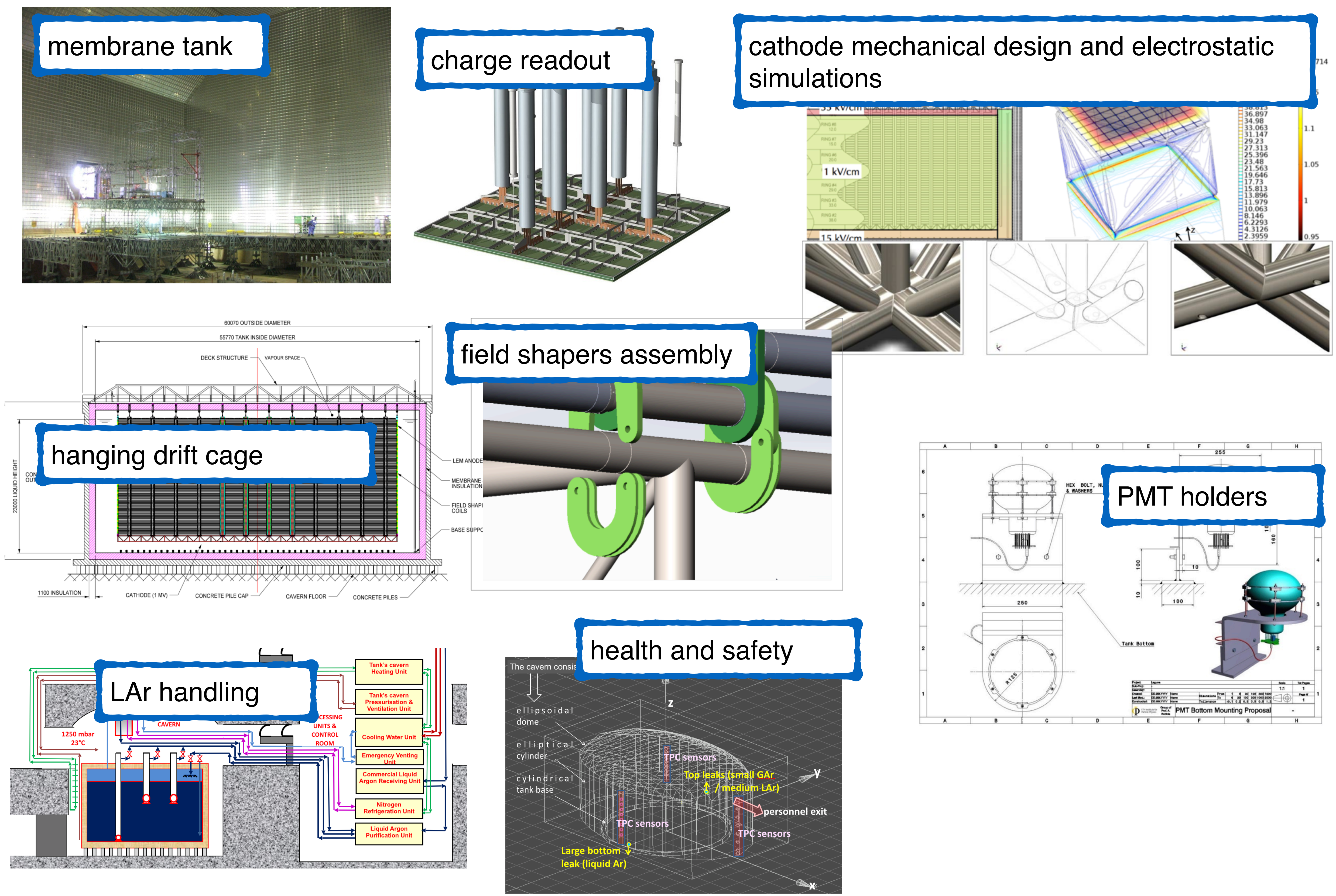
All this has been done in tight industrial partnerships:



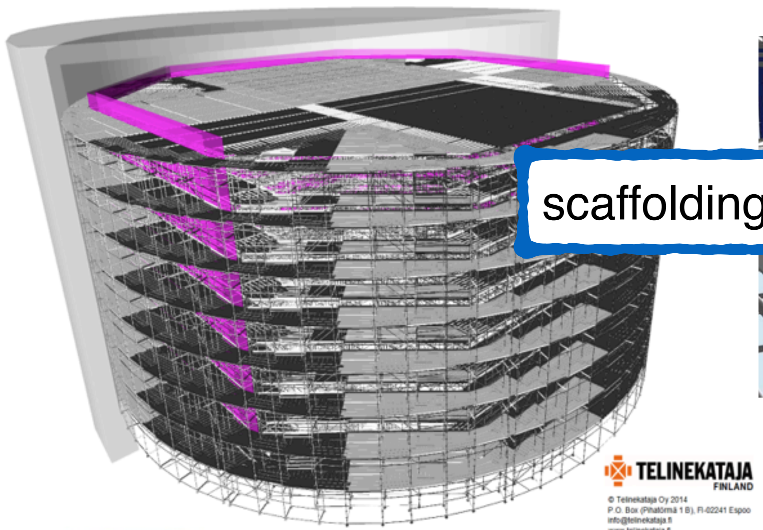
The conceptual design phase is complete

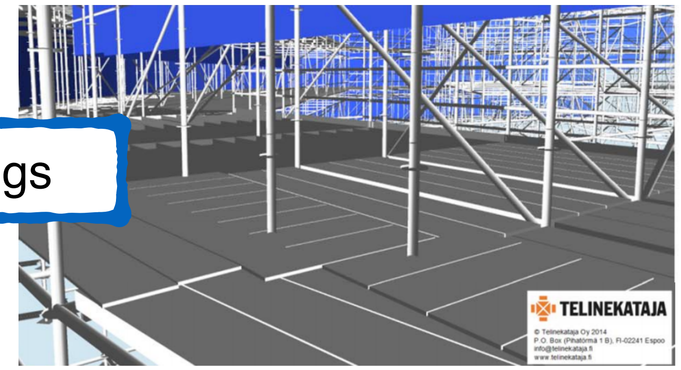
- The LAGUNA Consortium has addressed all aspects necessary for a complete realisation of the project in a **global & coherent way**:
  - **Science case**
  - **Underground infrastructure & facility**
  - **Detector construction sequences and programmes**
  - **Liquid handling**
  - **Detailed costs model**
  - **Extensive evaluation and quantification of risks**
- CERN has developed the **Conceptual Design of a new high-power accelerator neutrino beam directed towards Pyhäsalmi.**
- **The goals of the FP7 LAGUNA-LBNO Design Study have been met.** The large amount of work performed and extensive material generated is a solid base and an important source of information for future developments worldwide.

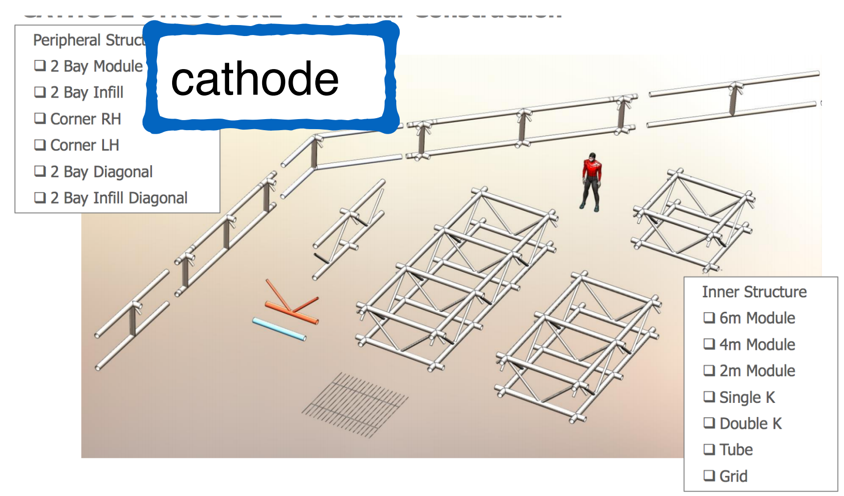
The designs are fully engineered:

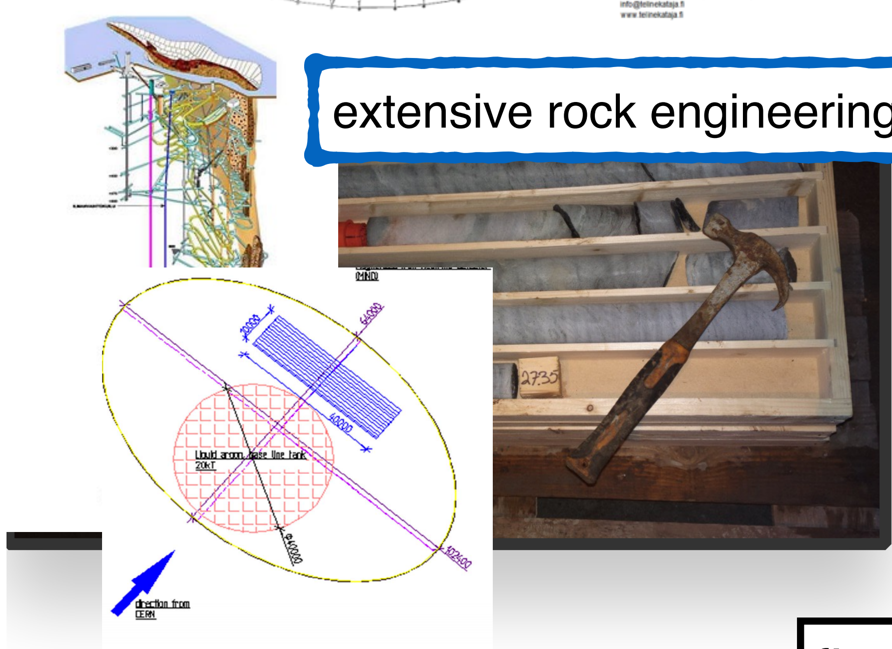


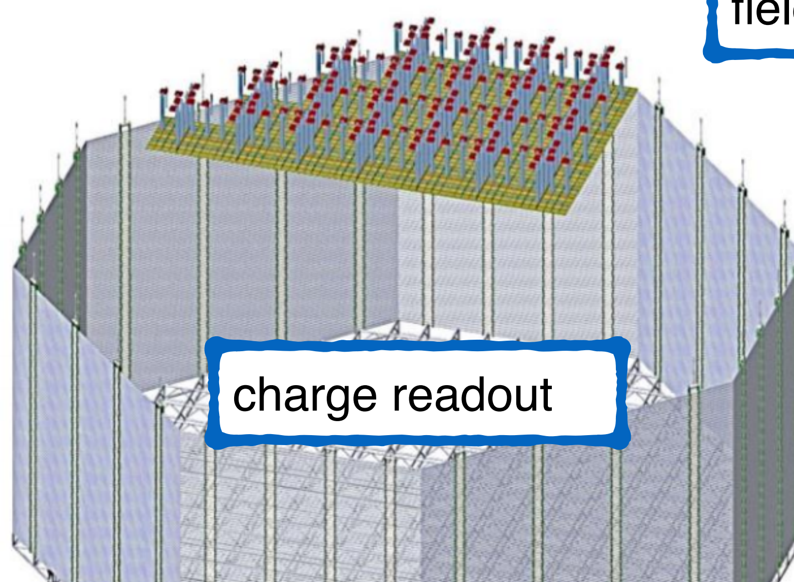
Underground construction sequence defined

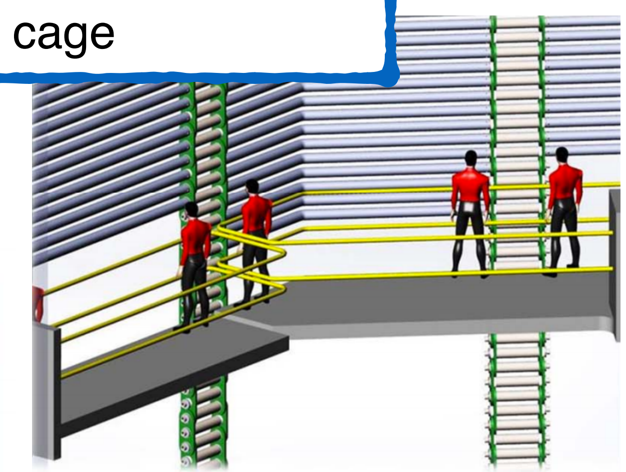










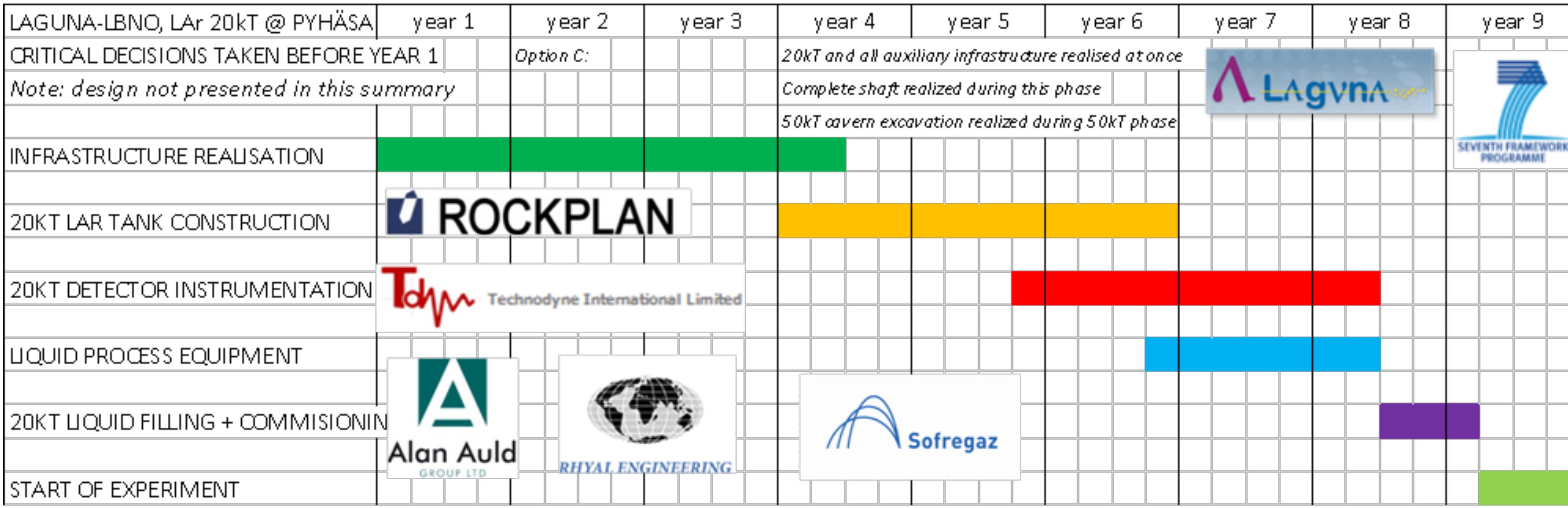


first time a membrane tank will be installed below ground!

One of the most challenging part of the Detector Installation was addressing the logistics and Installation sequences in the underground confined space taking into account the demands set especially on cleanliness, tolerances and overall fit inside the tank.

Phases of construction

20 kton LAr @ Pyhäsalmi



(a) infrastructure realisation (b) liquid argon tank construction (c) tank instrumentation (d) liquid argon process equipment (e) liquid filling and commissioning (f) start of experiment

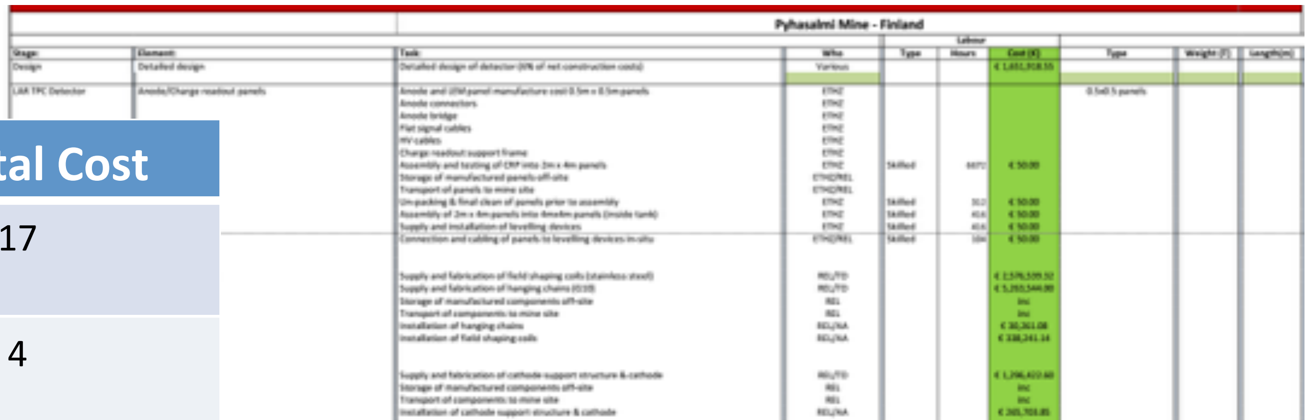
Information on other options are available in the written LAGUNA-LBNO reports.

Detailed full costing

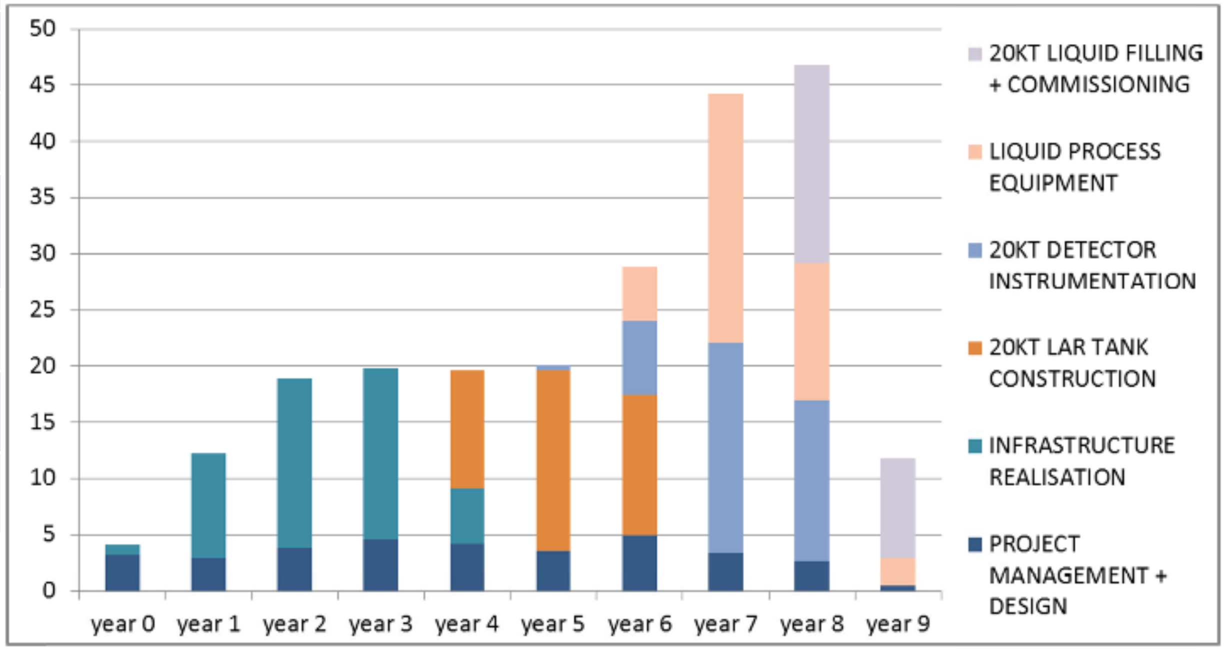
Example: LBNO20 double phase LAr detector

Detailed cost breakdown: every detector part is listed

For the past 3 years, the the LAGUNA-LBNO technical board have been generating, collating and checking construction costs generated from within the group of Industrial Partners and the Scientific Community.


Pyhasalmi Mine - Finland

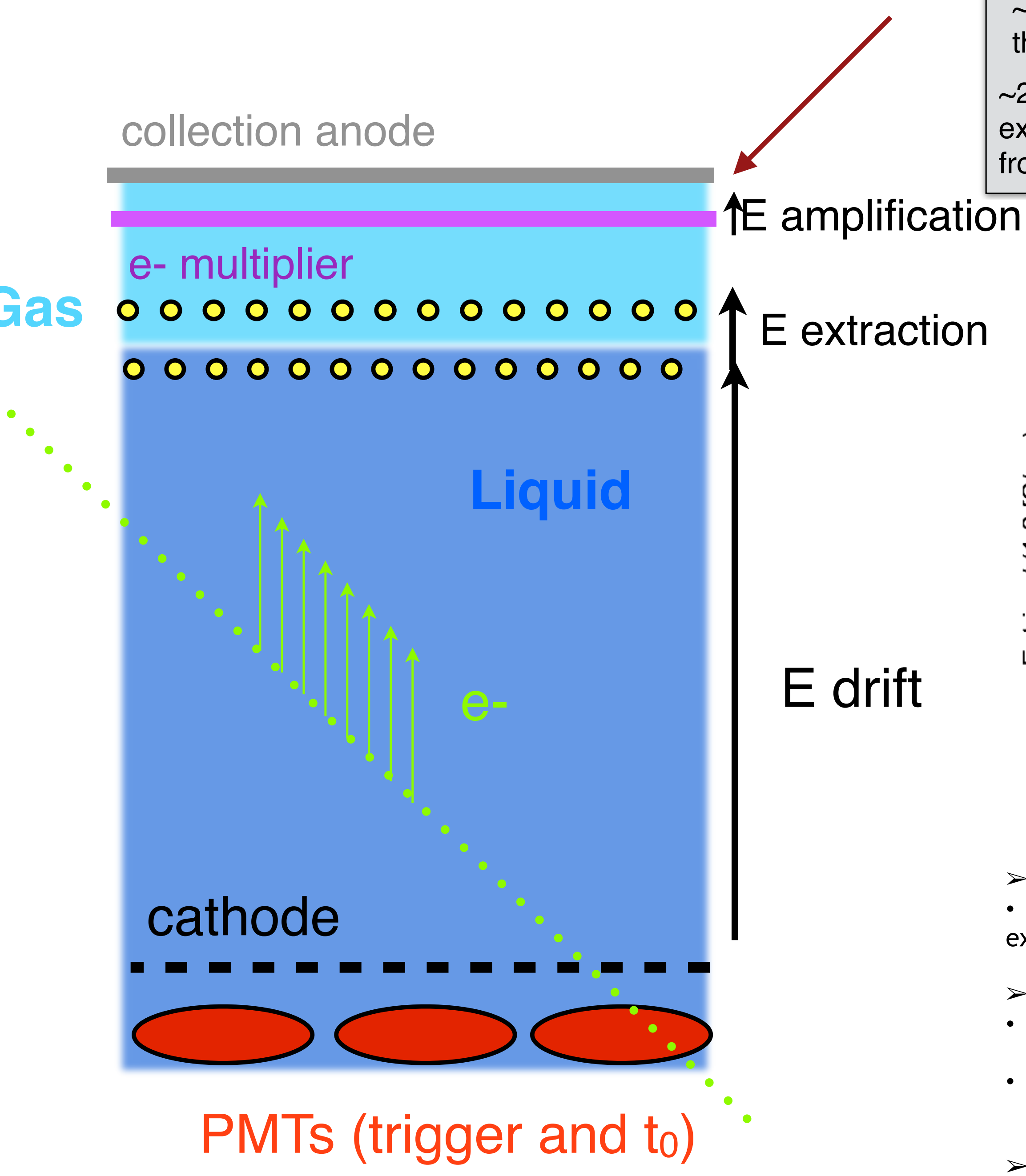
Element	Cost (€m)	% of Total Cost
Excavation Work (Tunnels and Caverns)	€38,700.00	17
Civil Works & Underground Infrastructure	€9,400.00	4
20kT Membrane Tank	€45,400.00	20
Detector	€41,500.00	18
Liquid Infrastructure Equipment	€40,400.00	18
Liquid Argon (LAr)	€26,300.00	12
Contingency (Risks)	€24,700.00	11
TOTAL	**€226,400.00**	**100**

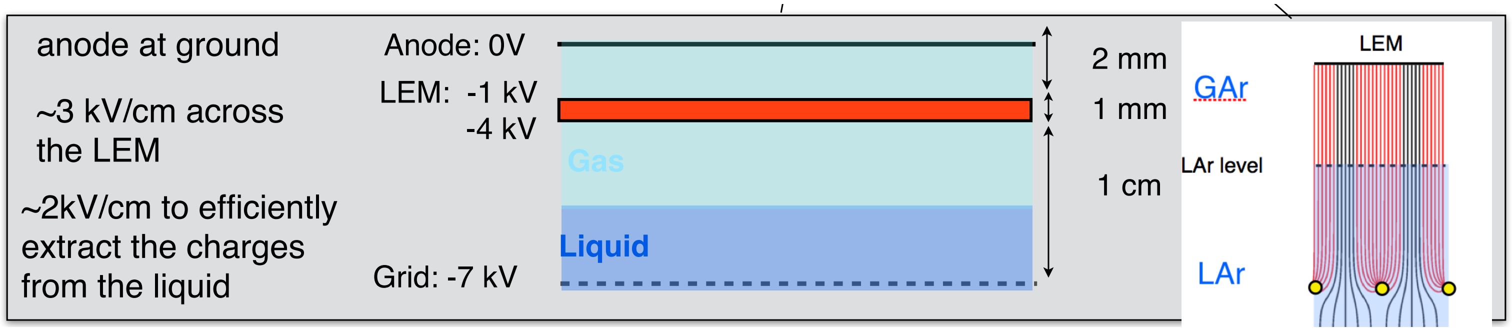


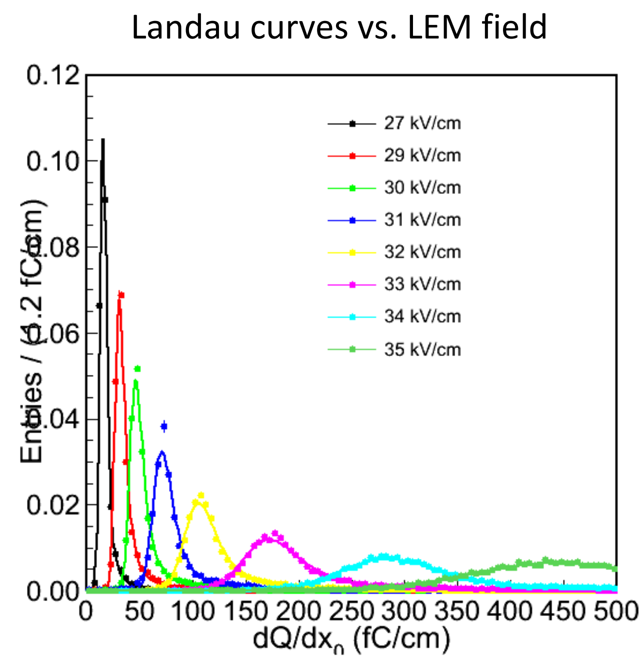
TOTAL COSTS; for full scale 20kT LAr experiment 226 M€

Detailed comparison with LBNE @ SURF started

Far detector: double Phase LAr TPC







- Tuneable charge amplification
- Threshold < 100 keV on single channel
- S/N>100 for m.i.p.
- Symmetric collection views
- Very long drift (>5m)
- Cheaper electronics

For MIPs:
- 10 fC/cm — ~10 k e- for each strip (3 mm pitch,2 views) — SNR of 10 (noise of 1000 e-)
- SNR of 100 — gain of 20 is needed

➢ **2003: the GLACIER concept**
- A. Rubbia, Experiments for CP-violation: A giant liquid argon scintillation, Cherenkov and Charge imaging experiment? arXiv:hep-ph/0402110

➢ **Proof of principle with 10x10 cm² double phase LAr LEM-TPC prototype:**
- A. Badertscher et al., "Operation of a double-phase pure argon Large Electron Multiplier Time Projection Chamber: Comparison of single and double phase operation "NIM A617 (2010) p.188-192
- A. Badertscher et al., "First operation of a double phase LAr Large Electron Multiplier Time Projection Chamber with a two-dimensional projective readout anode" NIM A641 (2011) p.48-57

➢ **First successful operation of a 40x76 cm² device in November 2011:**
- A. Badertscher et al., "First operation and drift field performance of a large area double phase LAr Electron Multiplier Time Projection Chamber with an immersed Greinacher high-voltage multiplier " JINST 7 (2012) P08026
- A. Badertscher et al., "First operation and performance of a 200 lt double phase LAr LEM-TPC with a 40x76 cm² readout", JINST 8 (2013)P04012

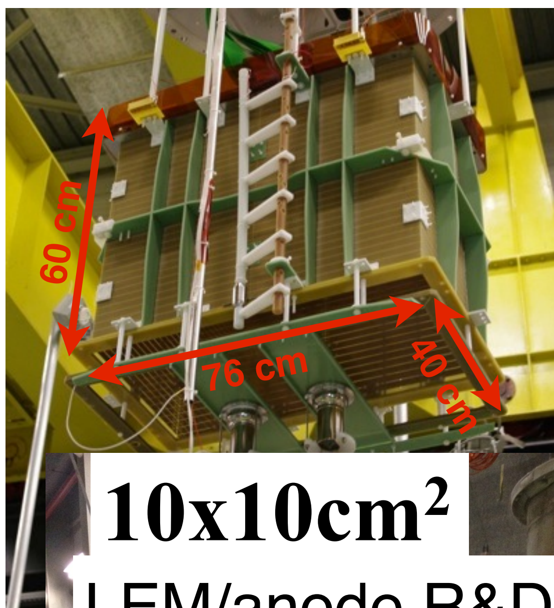
➢ **10x10 cm² double phase LAr LEM-TPC prototype: further R&D towards final, simplified charge readout for GLACIER:**
- Long-term operation of a double phase LAr LEM Time Projection Chamber with a simplified anode and extraction-grid design, JINST 9 P03017
- Performance study of the effective gain of Large Electron Multipliers in LAr-LEM TPCs, paper on arXiv soon

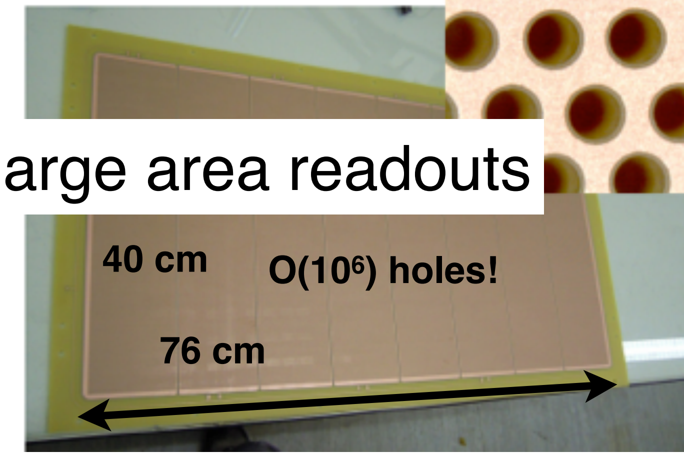
Result of many years of R&D

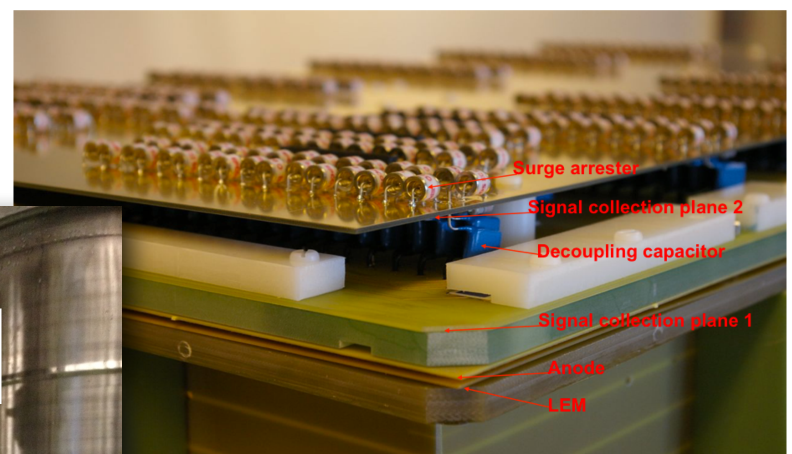
Continuation of the supporting R&D activities on smaller prototypes

40x80cm²

stable operation of large area readouts

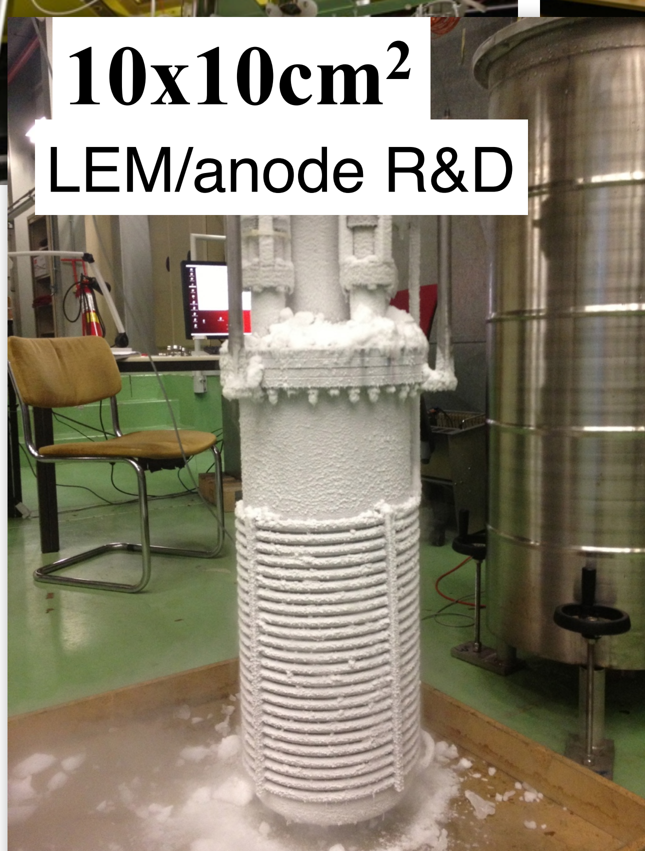


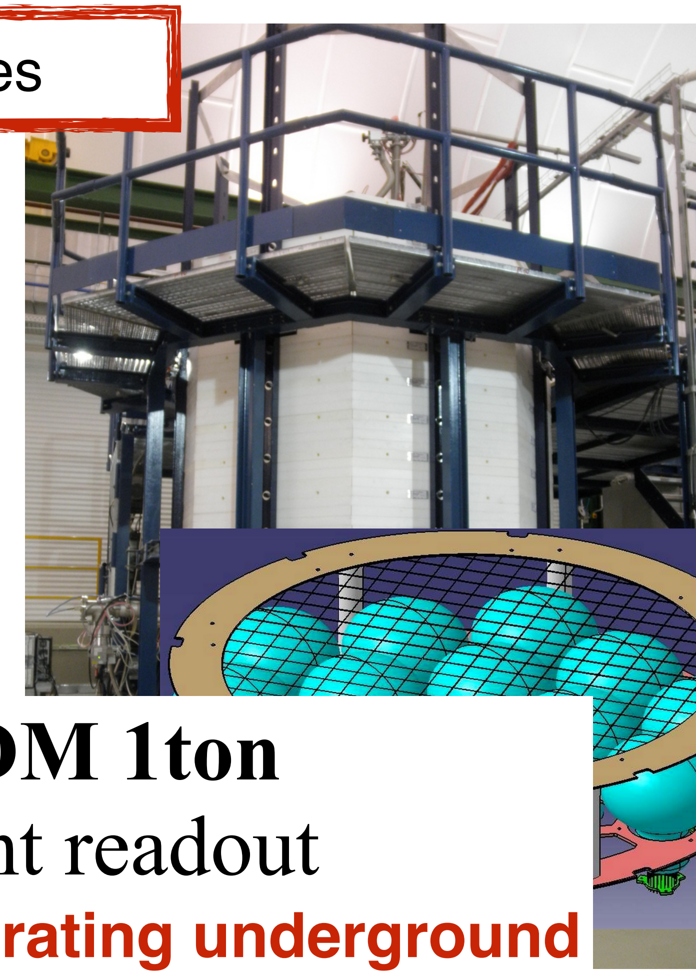




10x10cm²

LEM/anode R&D

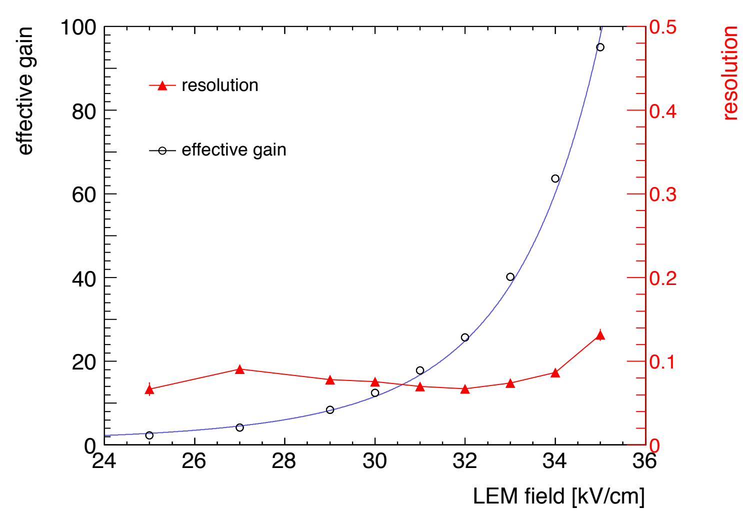


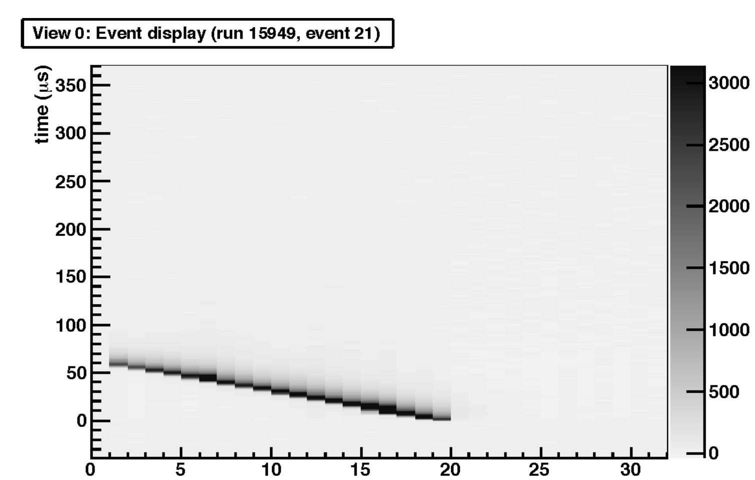


ArDM 1ton

-light readout

-**Operating underground**

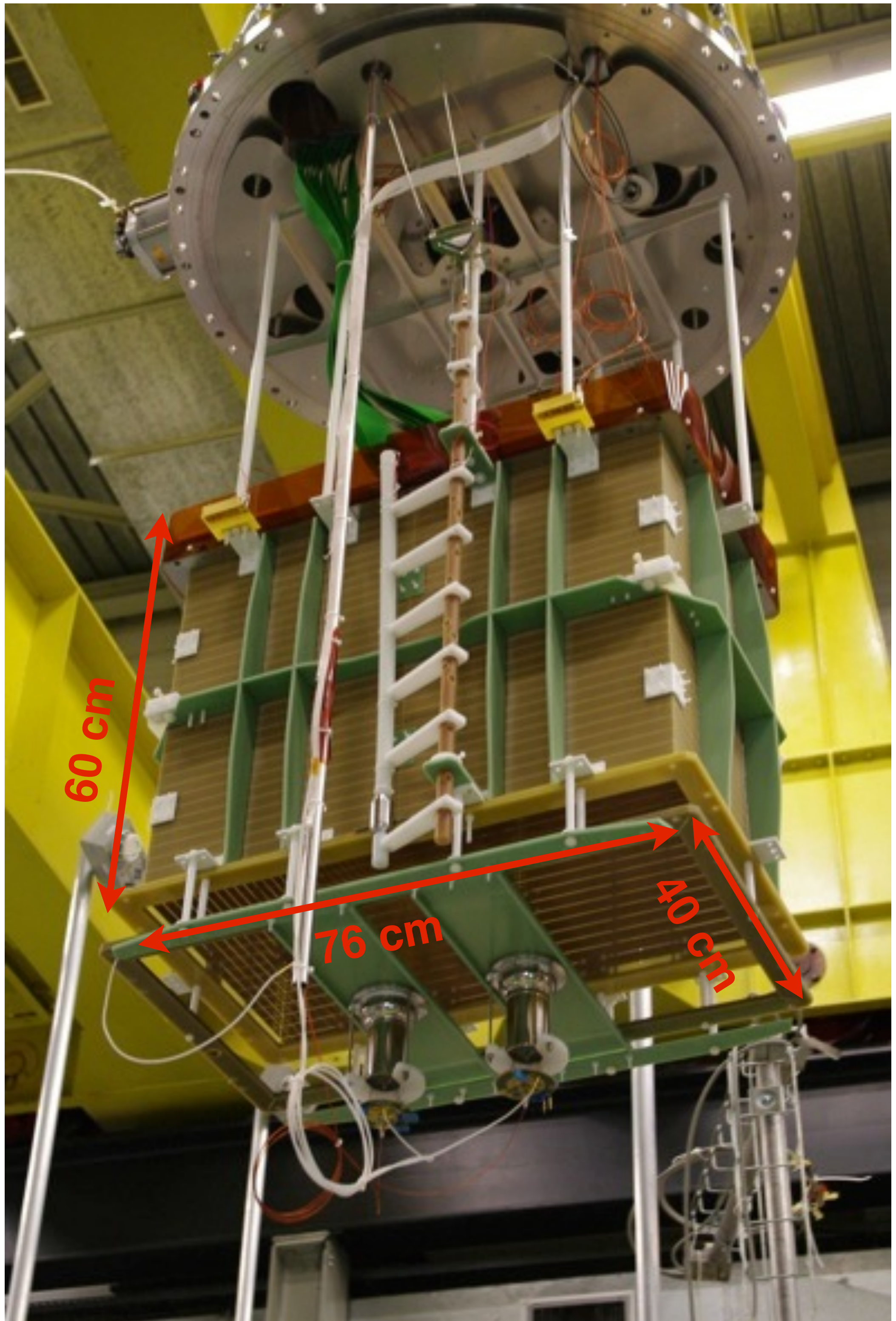




200 lt DLAr TPC prototype

A. Badertscher et al. JINST 8 (2013)P04012,

detector fully assembled

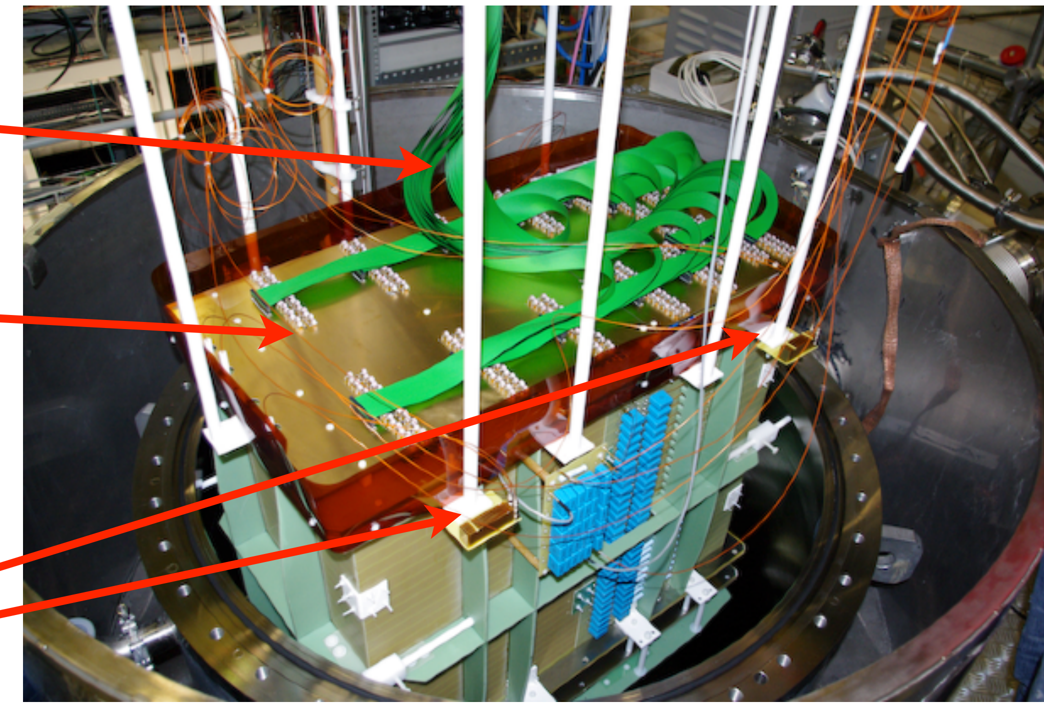


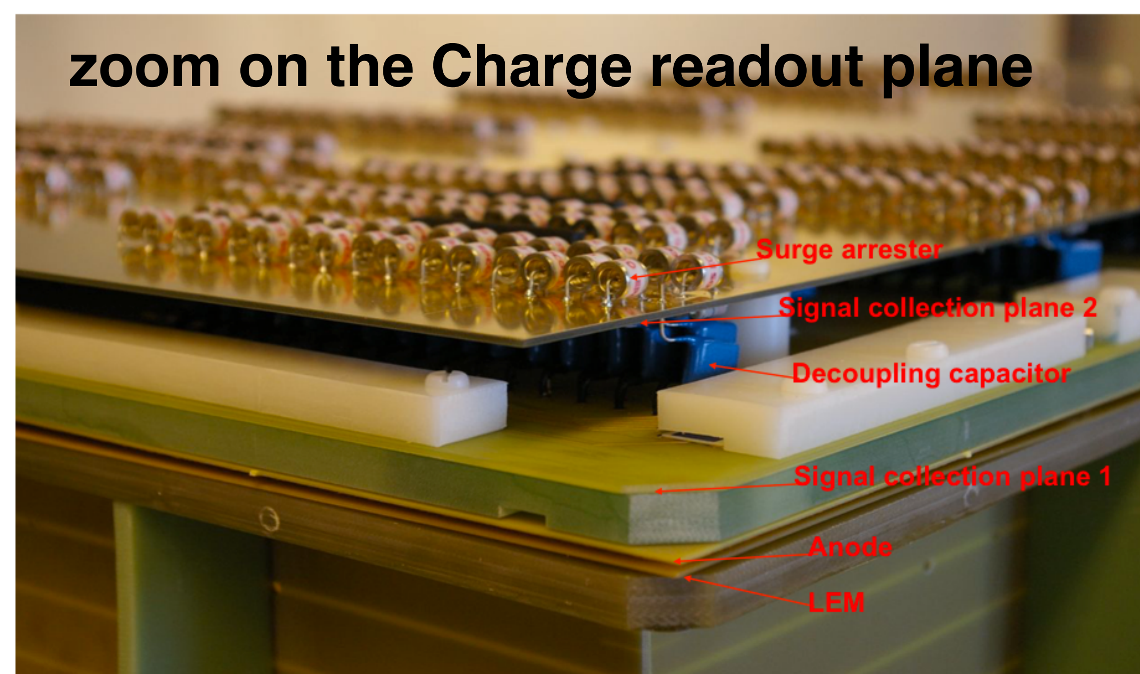
going into the ArDM cryostat

16 signal cables

charge readout plane

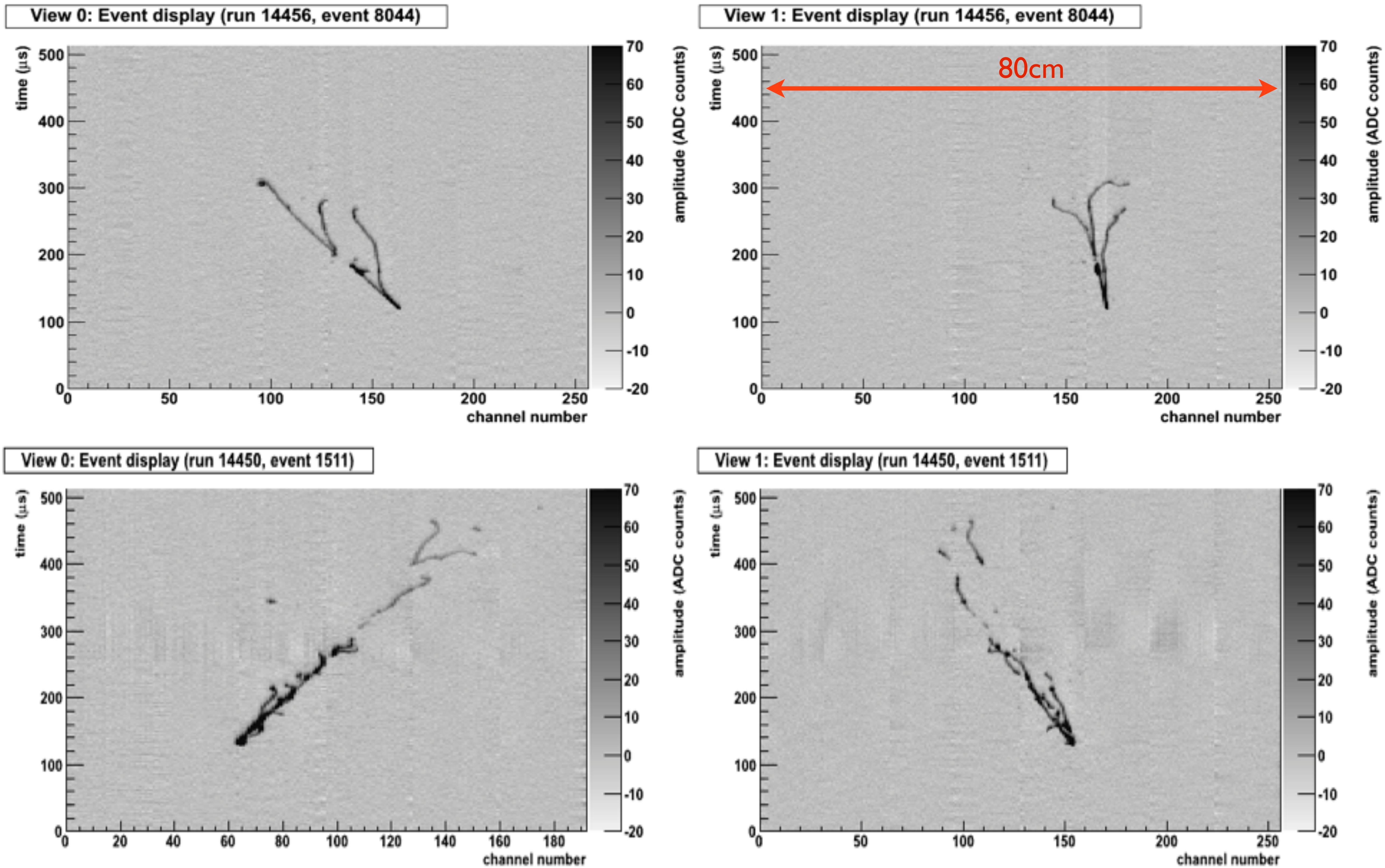
4 capacitive level meters





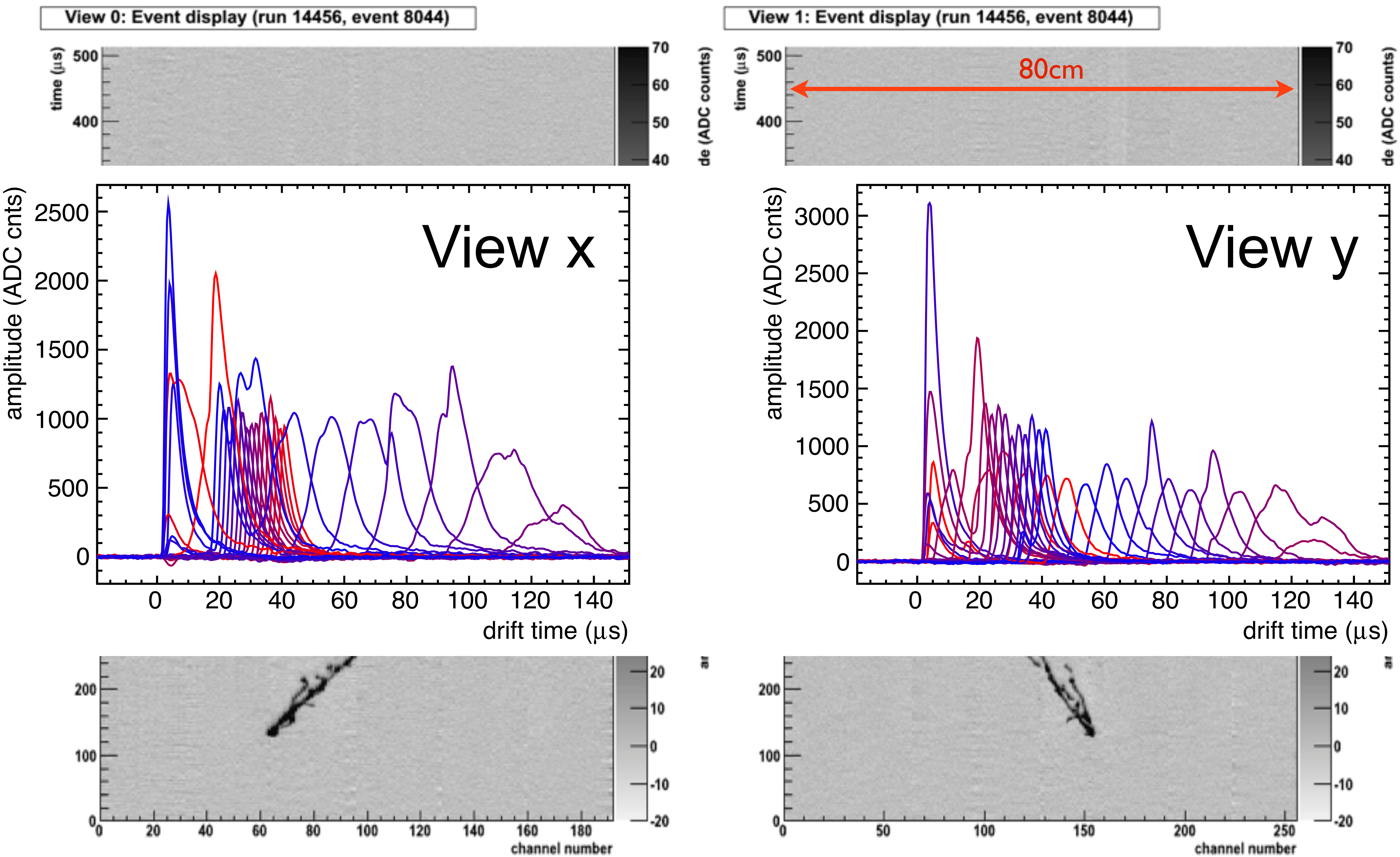
Cosmic data from 200 lt DLAr TPC

Gain ≈ 10



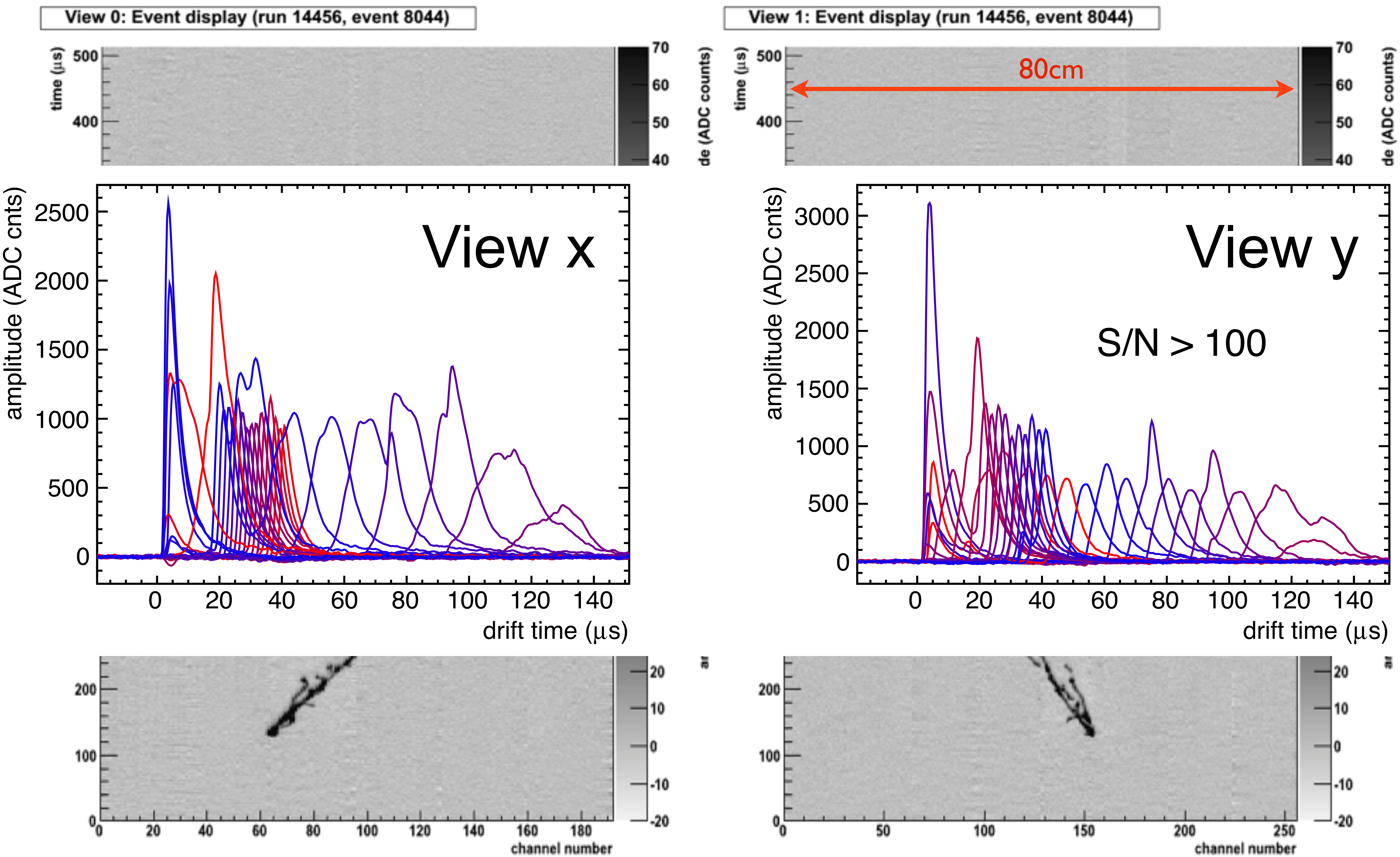
Cosmic data from 200 lt DLAr TPC

Gain ≈ 10



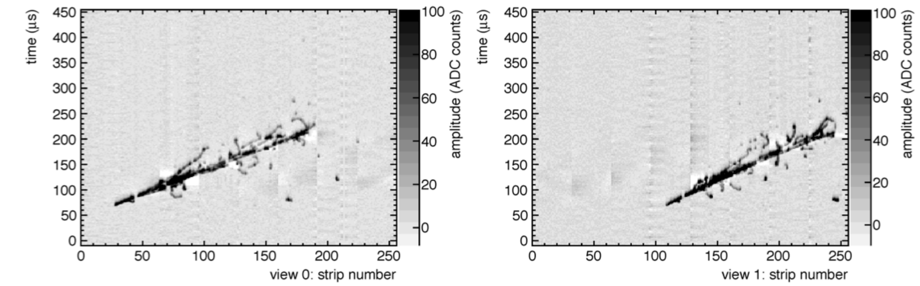
Cosmic data from 200 lt DLAr TPC

Gain ≈ 10



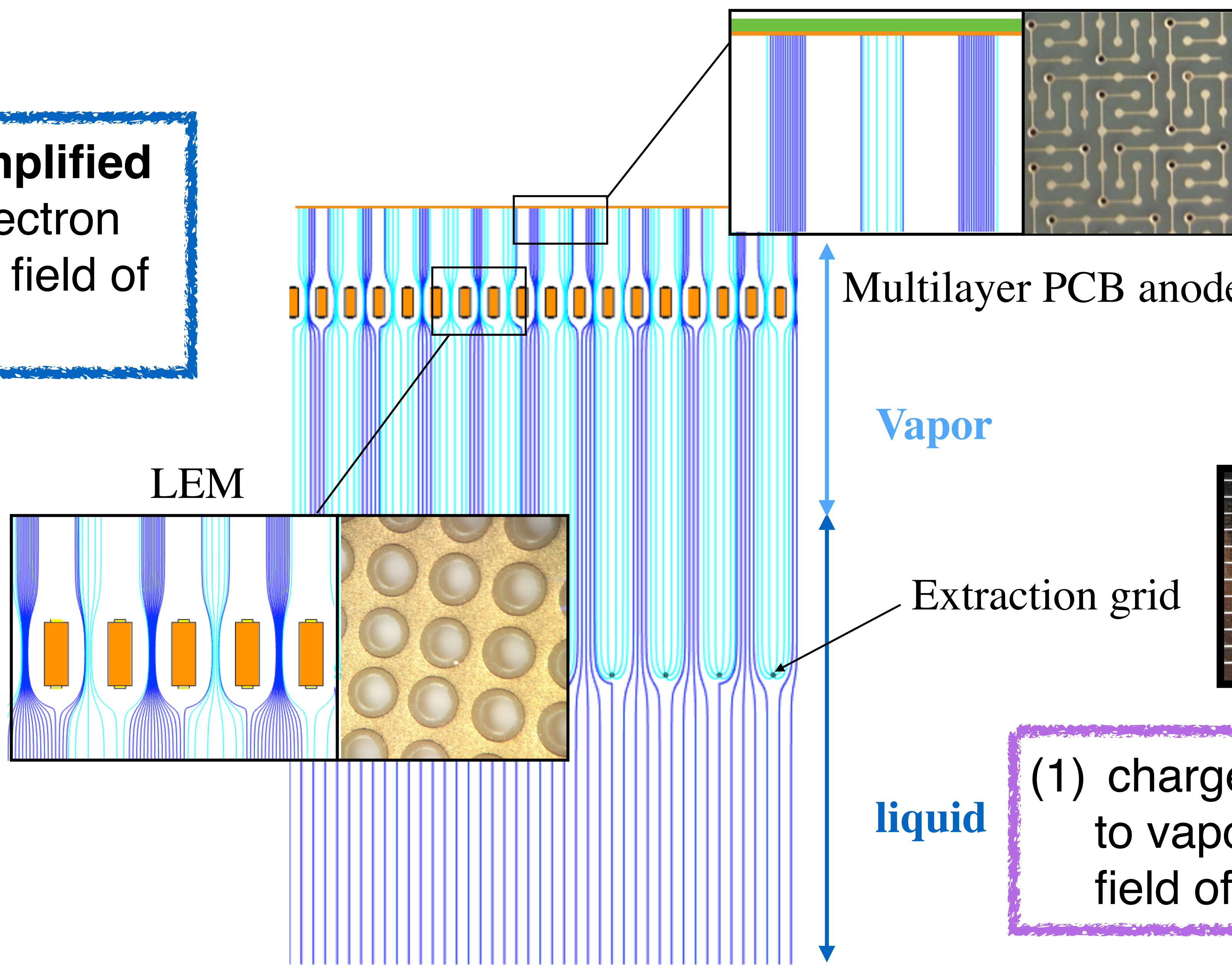
Double phase readout: detail

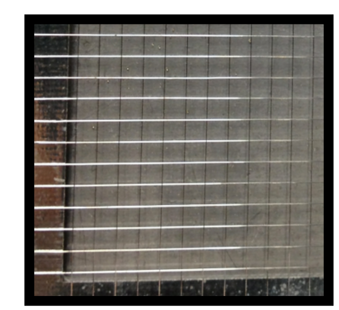
data collected on a 40x80 cm^2 DLAr TPC at CERN

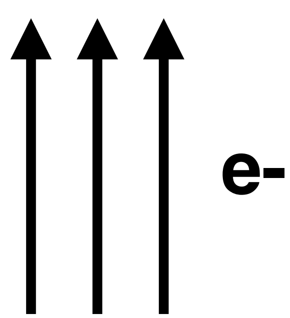


(3) charges **collected** on specially designed two view anode. Both views see the same amount of charge and have **identical signals**

(2) charges **amplified** in Large Electron Multiplier E field of ~30 kV/cm





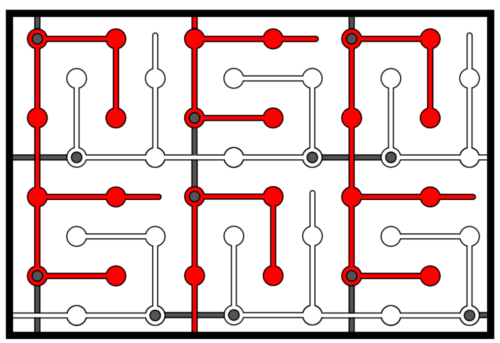


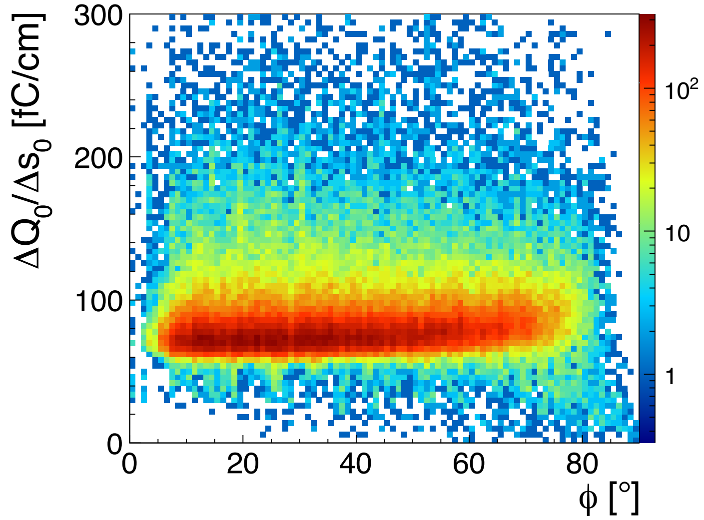
(1) charges **extracted** to vapor phase E field of ~2 kV/cm

Optimisation of anode

anode: compromise between resolution on charge measurement and capacitance

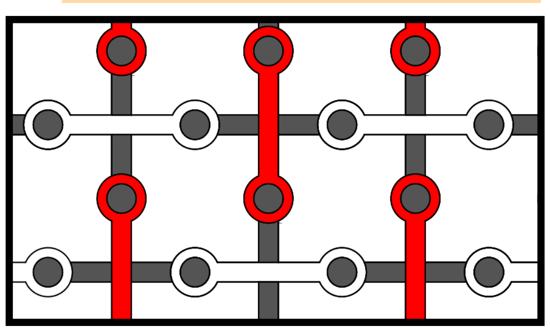
dC/dl ~ 150 pF/m

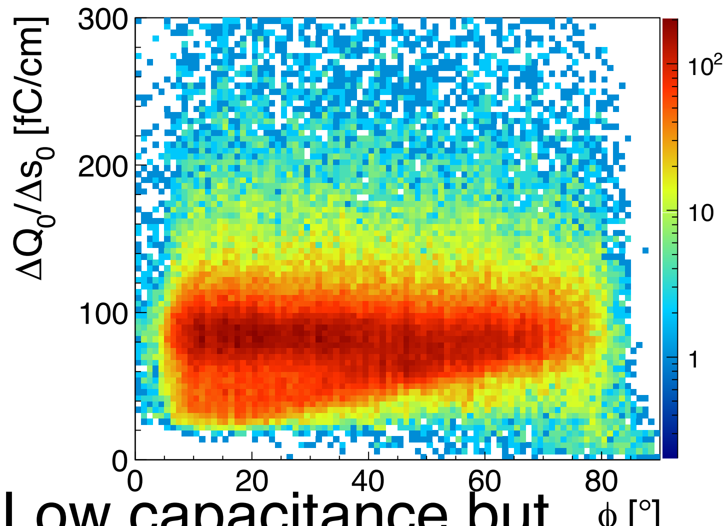




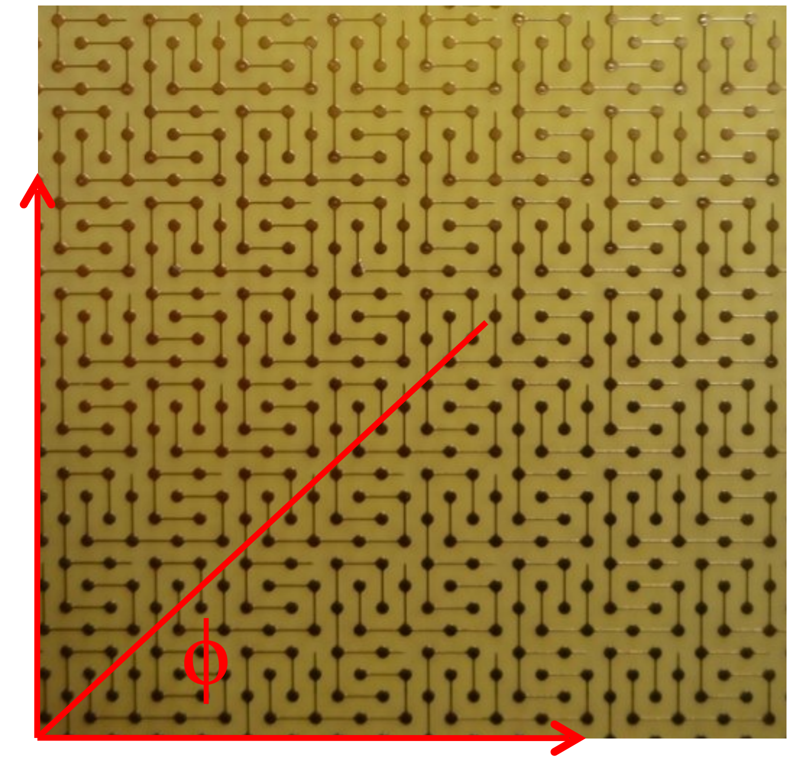
C Cantini et al 2014 JINST 9 P03017

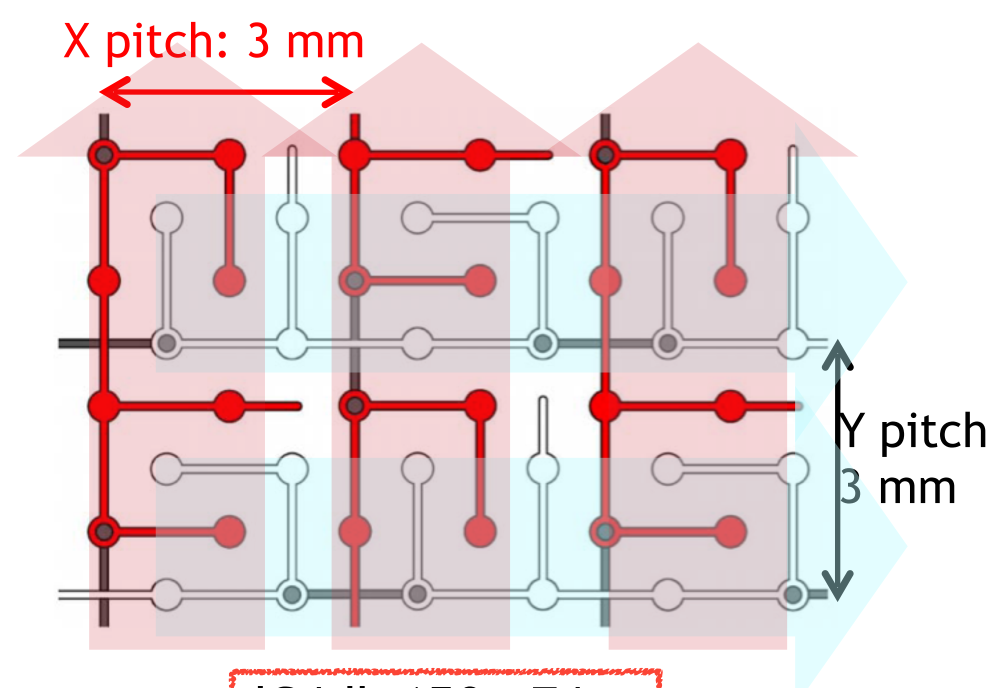
dC/dl ~ 100 pF/m





anode pattern too corse. Low capacitance but charge collection not uniform



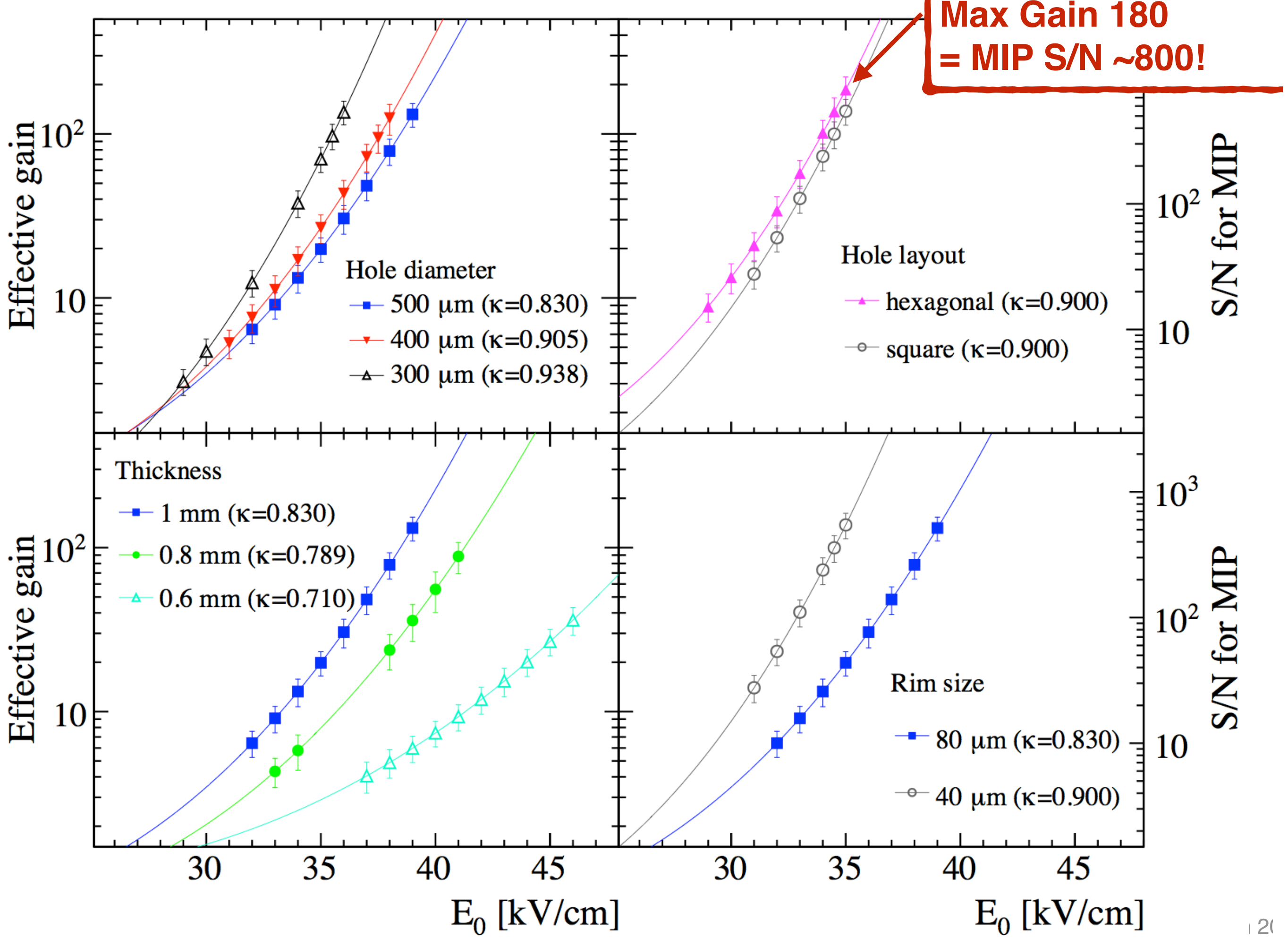


dC/dl~150 pF/m

Best solution to optimize capacitance and resolution

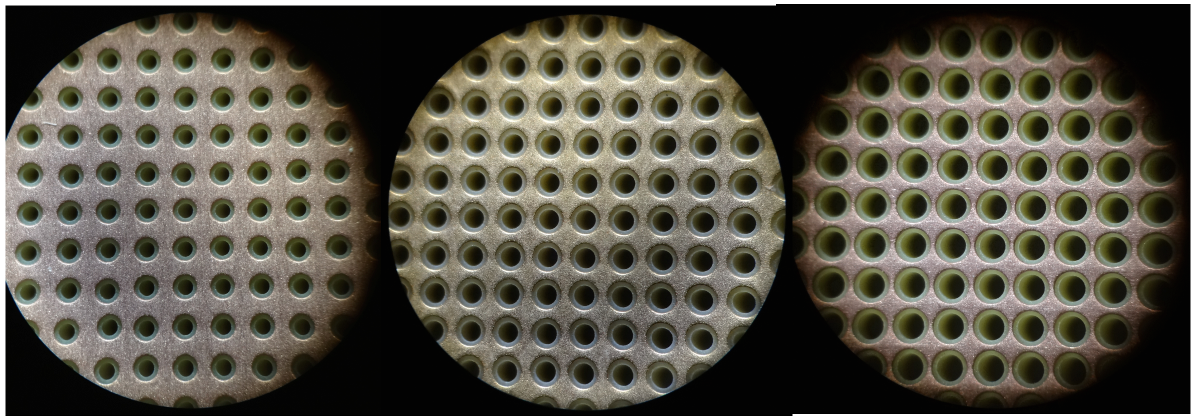
LEM performance study

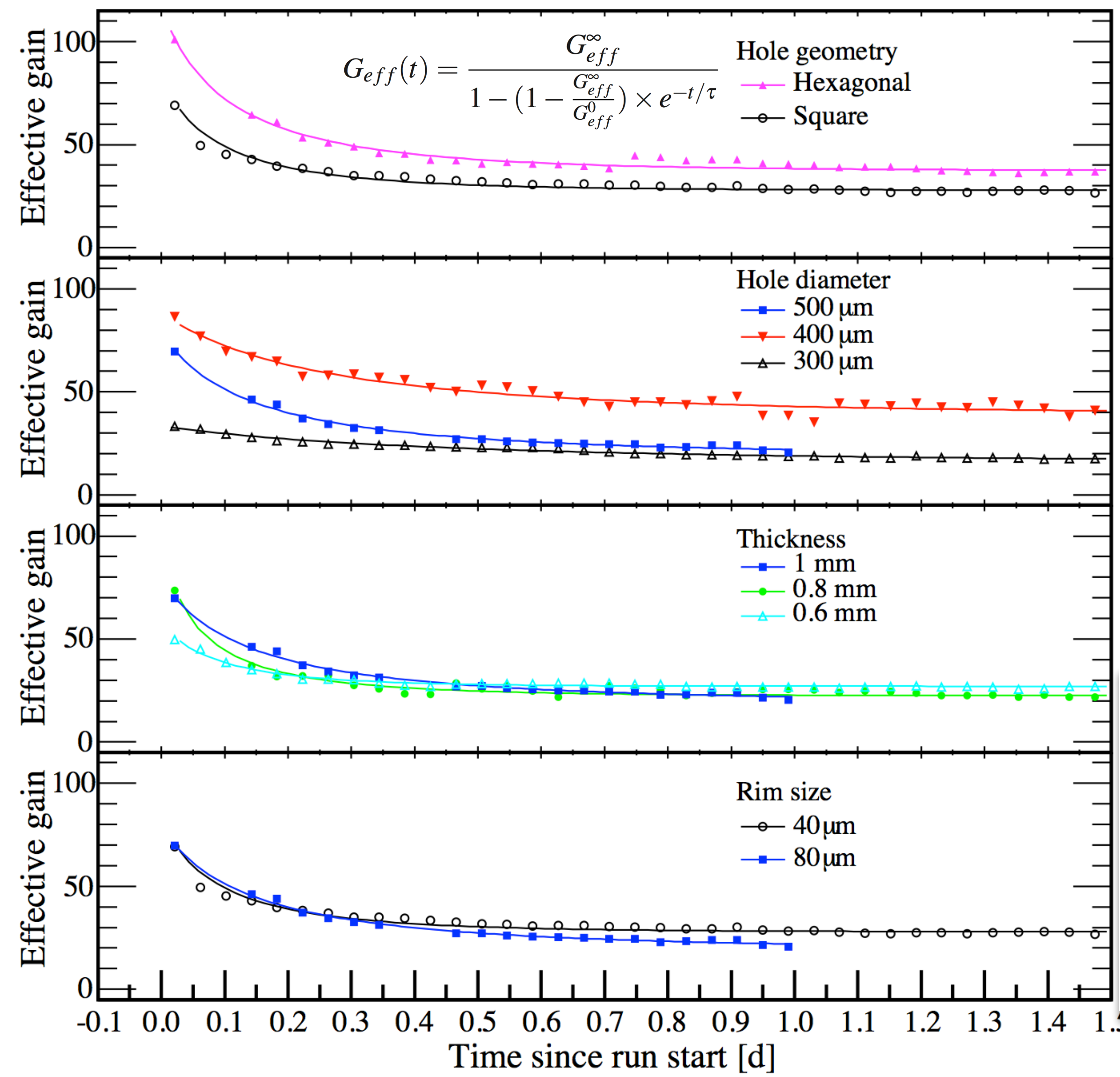
Fitting function: $G_{eff}(E,\rho,t) \equiv \mathscr{T} e^{\alpha(\rho,E)x} \times \mathscr{C}(t) \quad \alpha(\rho,E) = A\rho e^{-B\rho/E}$

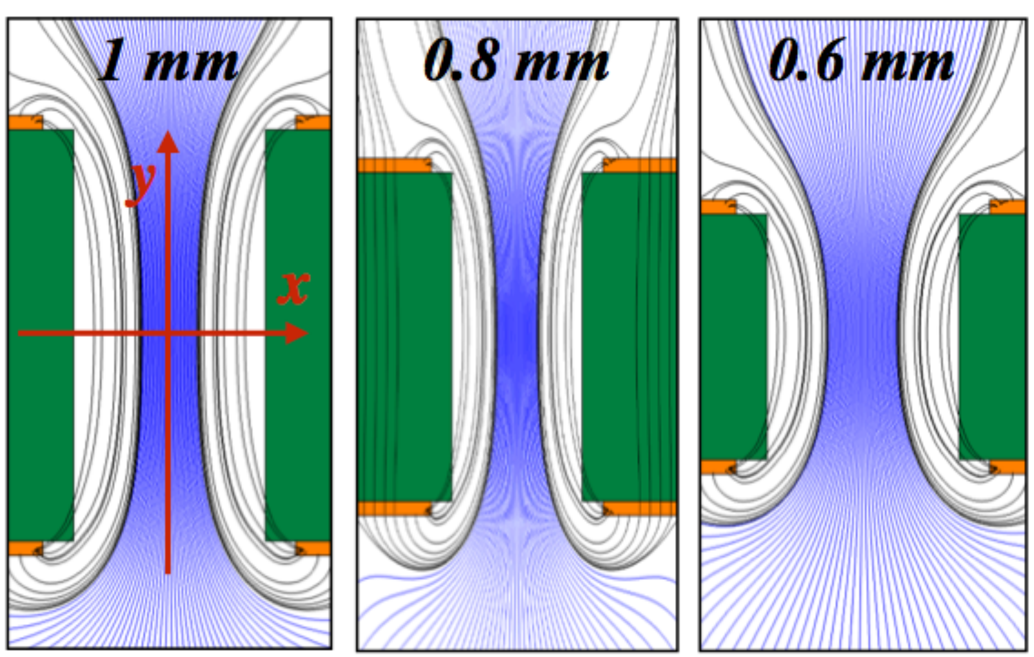


Hole diameter:

300 µm 400 µm 500 µm

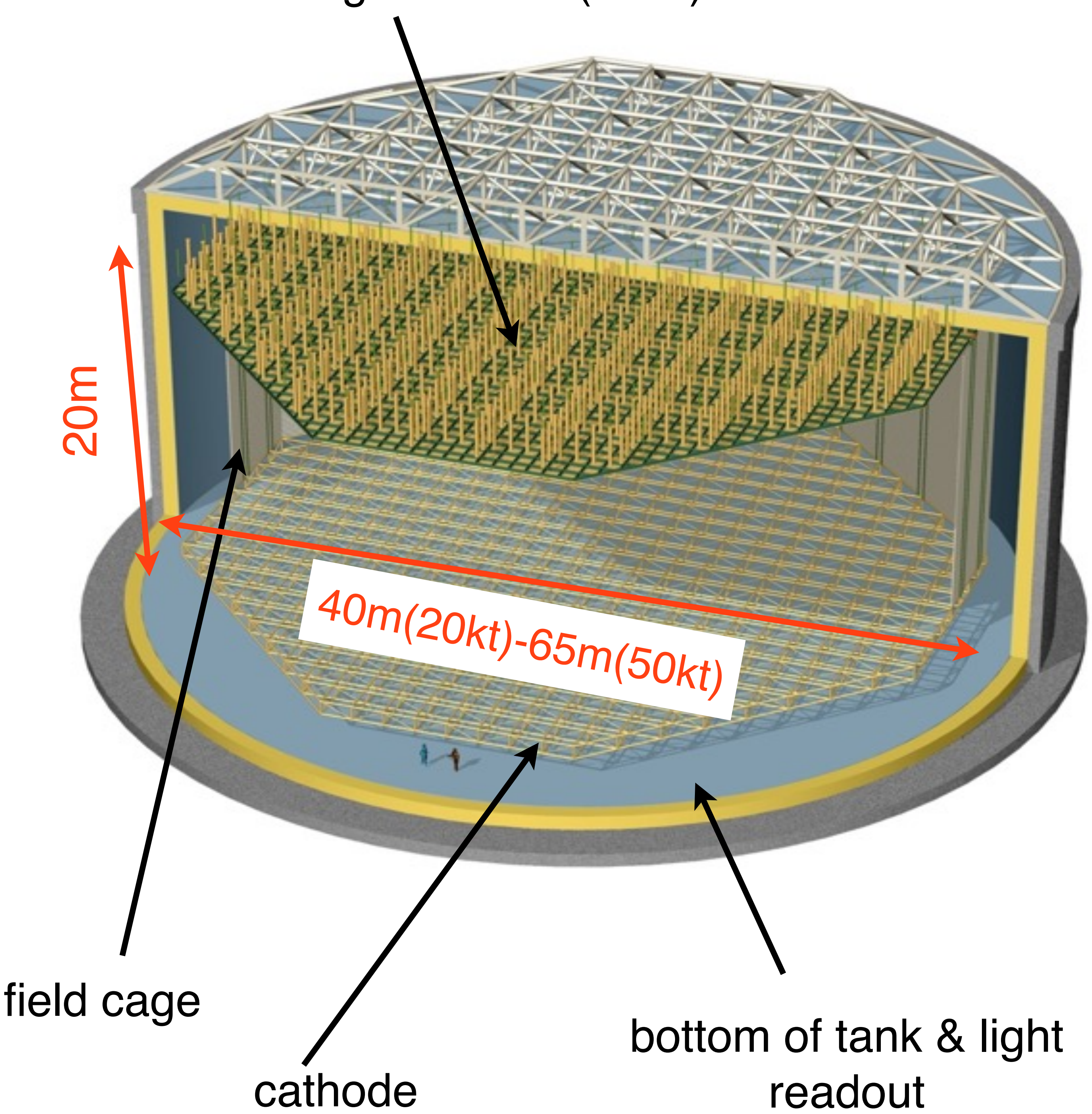






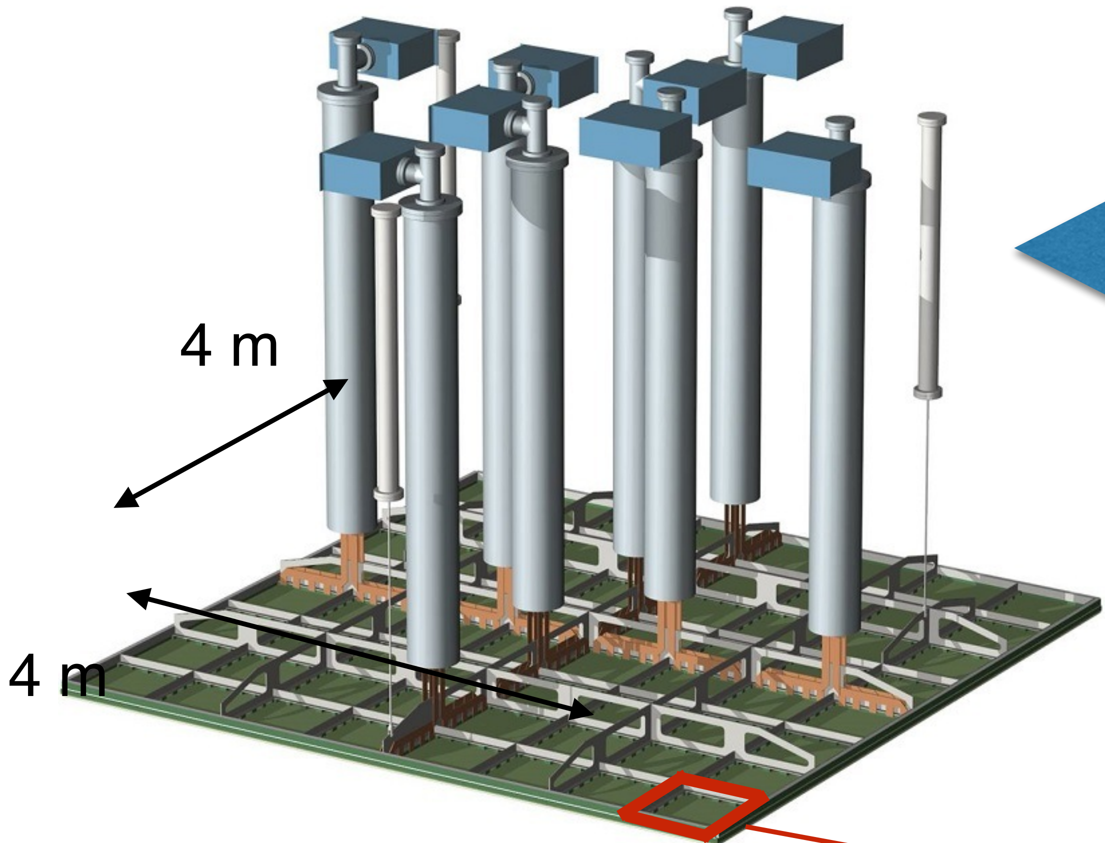
LBNO far liquid Argon detector

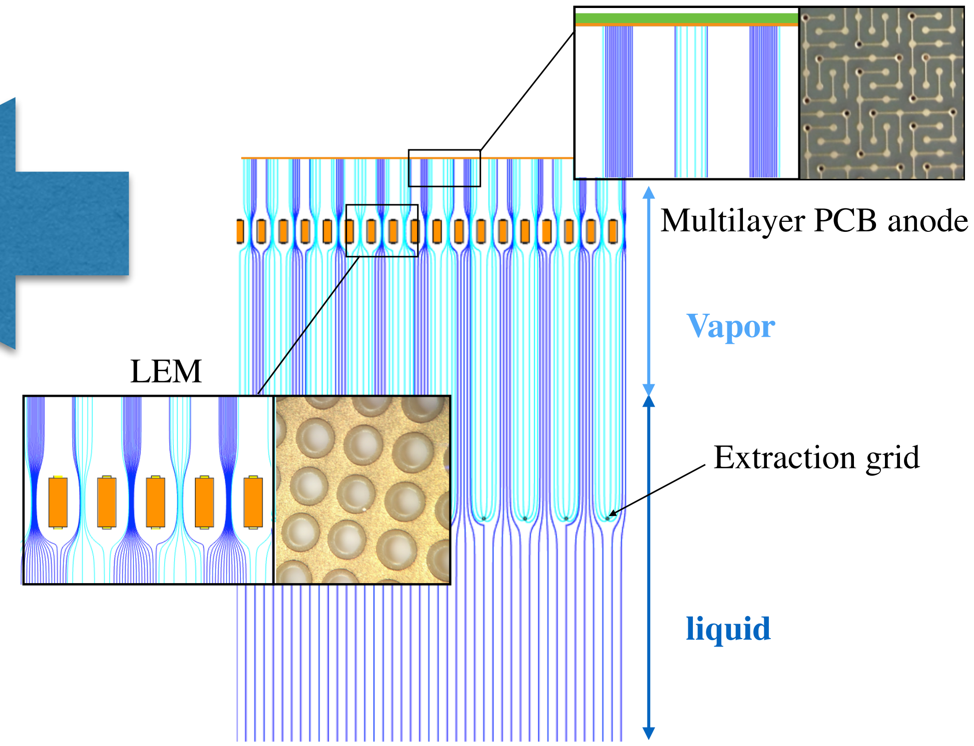
✤Design for an affordable detector



		20 KT	50 KT	100 KT
Liquid argon density at 1.2 bar	[T/m³]	1.38346		
Liquid argon volume height	[m]	22		
Active liquid argon height	[m]	20		
Pressure on the bottom due to LAr	[T/m²]	30.4 (≡ 0.3 MPa ≡ 3 bar)		
Inner vessel diameter	[m]	37	55	76
Inner vessel base surface	[m²]	1075.2	2375.8	4536.5
Liquid argon volume	[m³]	23654.6	52268.2	99802.1
Total liquid argon mass	[T]	32525.6	71869.8	137229.9
Active LAr area (percentage)	[m²]	824 (76.6%)	1854 (78%)	3634 (80.1%)
Active (instrumented) mass	**[KT]**	**22.799**	**51.299**	**100.550**
Charge readout square panels (1m×1m)		804	1824	3596
Charge readout triangular panels (1m×1m)		40	60	72
Number of signal feedthroughs (666 channels/FT)		416	1028	1872
Number of readout channels		277056	660672	1246752
Number of PMT (area for 1 PMT)		804 (1m×1m)	1288 (1.2m×1.2m)	909 (2m×2m)
Number of field shaping electrode supports (with suspension SS ropes linked to the outer deck)		44	64	92

Individual charge readout plane

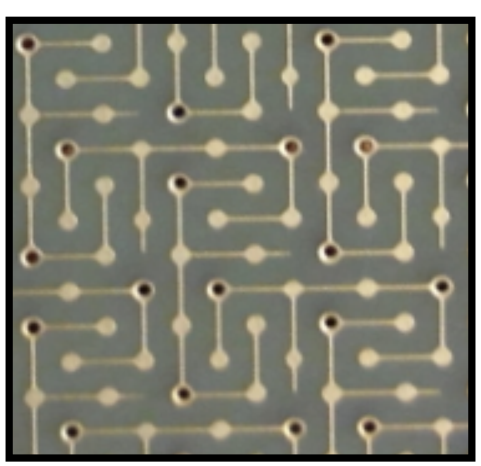




Modules of 50x50 cm²

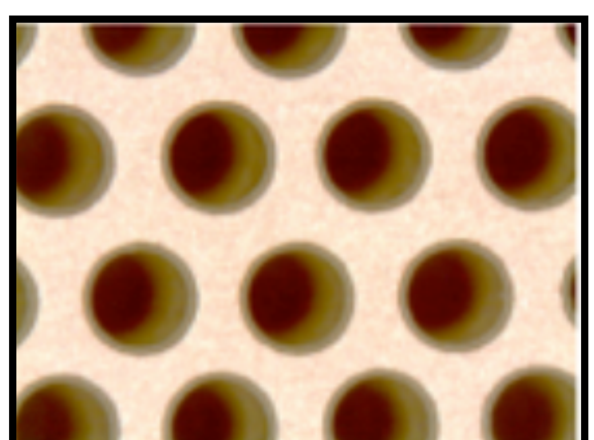
multilayer PCB anode

- 3.125 mm readout pitch
- 3.4 mm thick



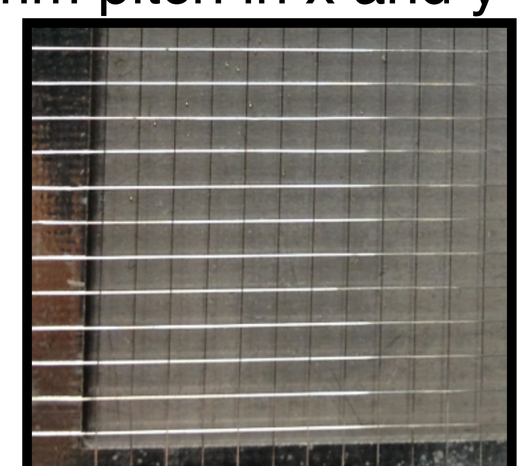
LEM

- 500 µm holes, 800 µm pitch
- 1 mm thick FR4



Extraction grid

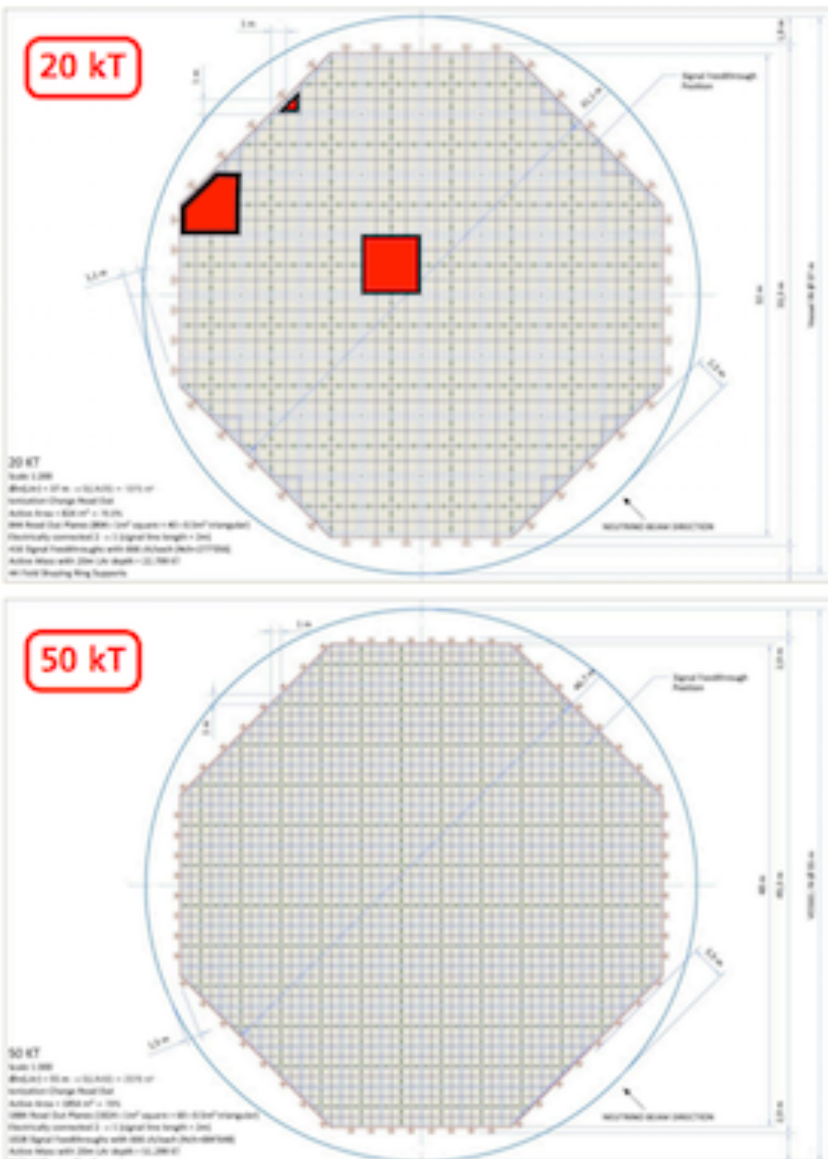
- 100 µm stainless wires
- 3mm pitch in x and y



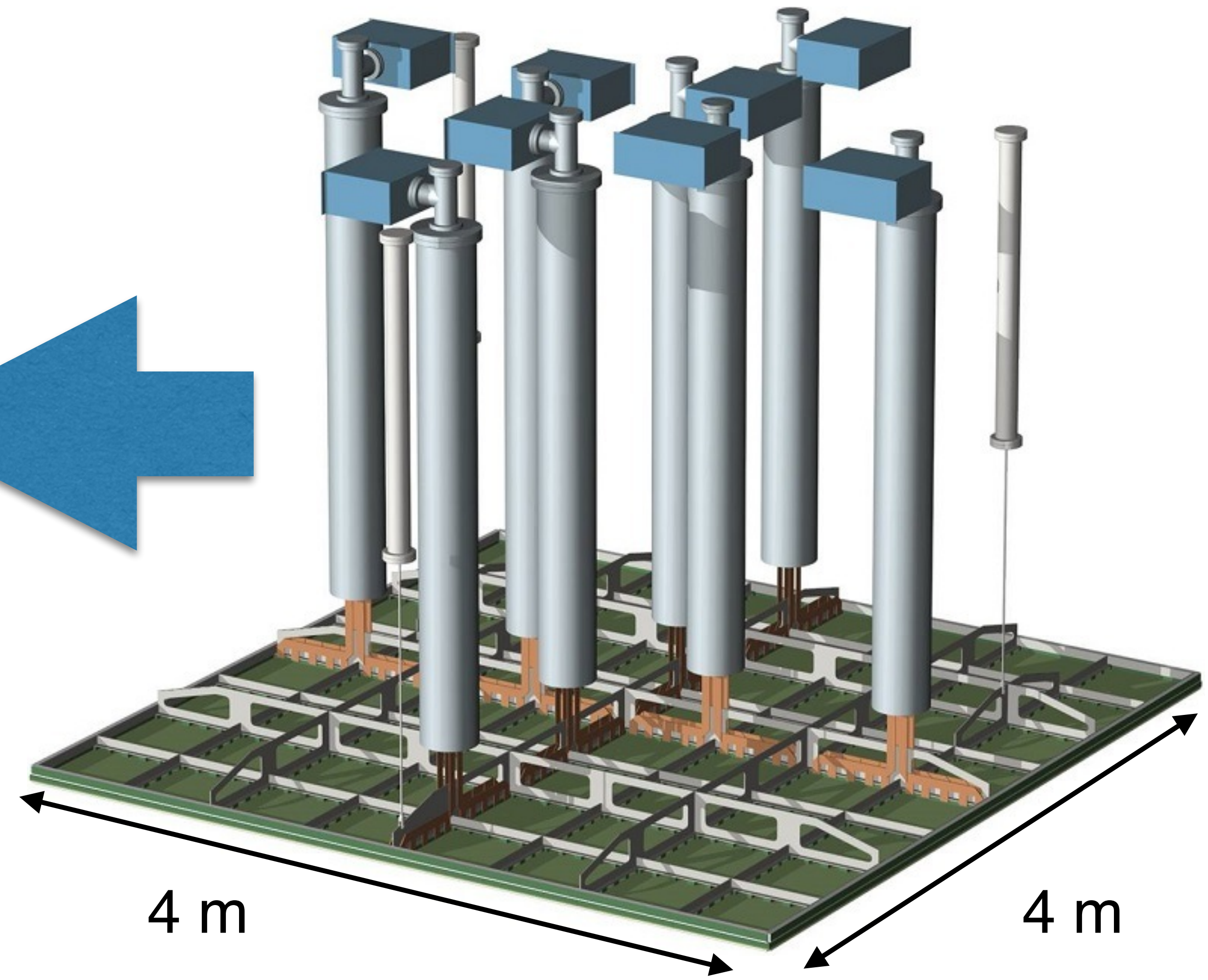
Modular design within single cryogenic system

GLACIER 20kt, 50kt: 4x4 m^2 modules

Each Charge Readout Plane is an independent detector



different geometries but all with the same functionality and identical construction sequence.



- Each CRP has its own signal and HV feed throughs
- Adjustable to LAr level
- The LBNO demonstrator will have an enlarged 4x4 m^2 => 6x6m^2

WA105/LBNO-DEMO

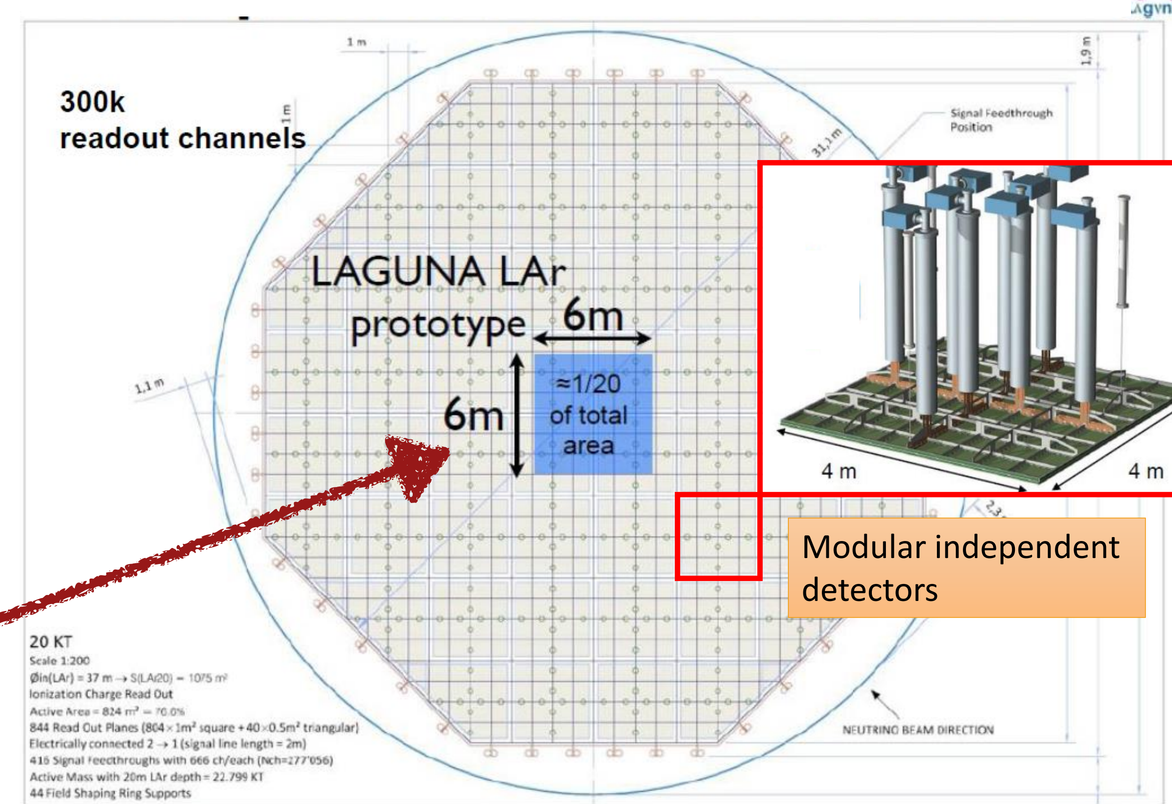
WA105

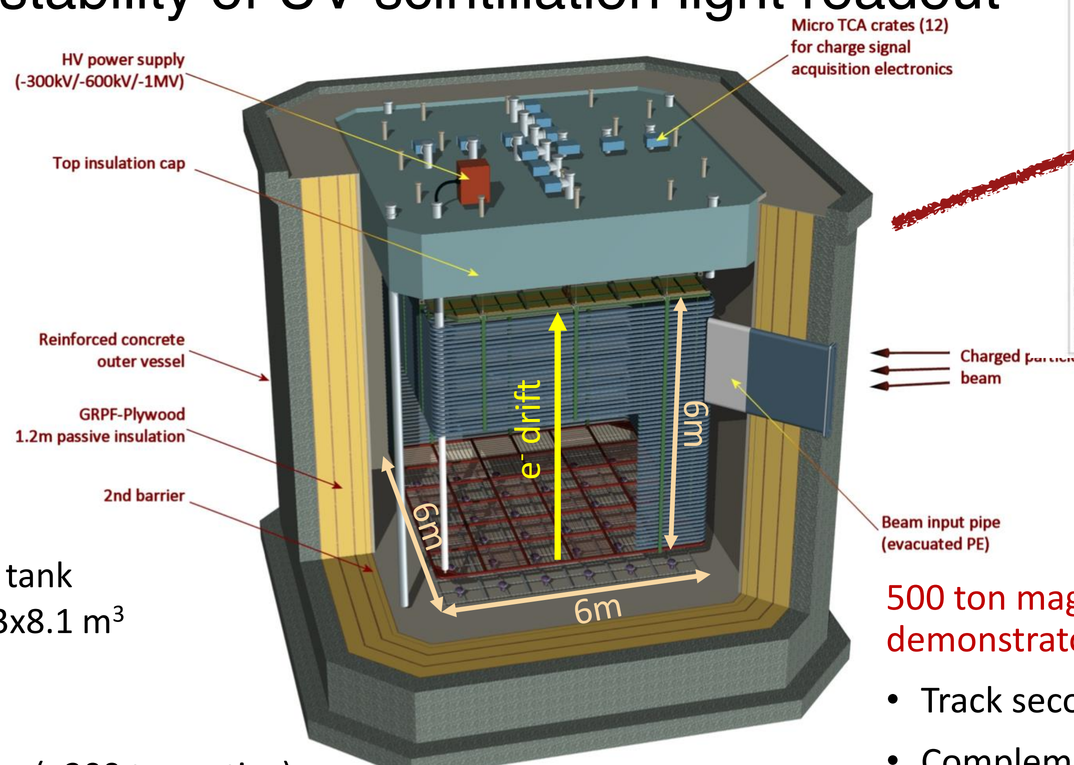
Build and operate a large scale prototype (LBNO-Demo) to demonstrate the feasibility of LAGUNA/LBNO DLAr TPC design for O(10) kton detectors

CERN-SPSC-2014-013 ; SPSC-TDR-004 (April 2014)

- A 1:20-scale "demonstrator" & industrial solutions
- Technical proof-of-principle:
  - Purity in non-evacuated tank
  - Large hanging field cage structure
  - Very high voltage generation
  - Large area charge readout
  - Accessible cold front-end electronics
  - Long term stability of UV scintillation light readout

Compared to LAGUNA/LBNO 20 kton DLAr



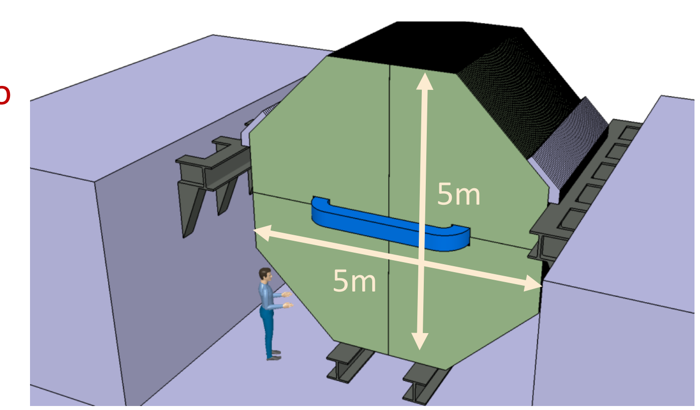


Some detector parameters:

- Insulated membrane tank
  → inner volume 8.3x8.3x8.1 m^3
- Active area 36 m^2
- Drift length 6 m
- Total LAr mass 705 ton (~300 ton active)
- Hanging field cage & readout plane
- # of signal channels: 7680 in 12 signal FT
- # of PMTs: 36

500 ton magnetized iron detector demonstrator installed after LBNO-Demo

- Track secondaries escaping from DLAr
- Complement momentum reconstruction of high energy muons
- Study reconstruction for charge ID of low energy muons (<1 GeV)



The collaboration (formed in Oct 2014)

WA105

22 institutes, 130 physicists

UNIVERSITY of OULU

UCL

CERN

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Ciemat
Centro de Investigaciones
Energéticas, Medioambientale
gicas

ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
РОССИЙСКОЙ АКАДЕМИИ НАУК
INSTITUTE FOR NUCLEAR RESEARCH
OF RUSSIAN ACADEMY OF SCIENCES

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

UNIVERSITY OF JYVÄSKYLÄ

Institut de Física
d'Altes Energies
IFAE

LPNHE
PARIS

lapp

University of Glasgow

UNIVERSITÉ DE GENÈVE

cea
SACLAY

ipnl

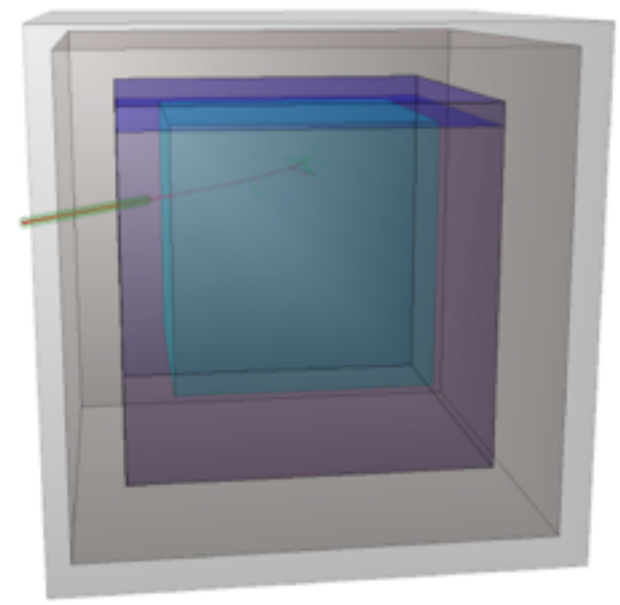
APC

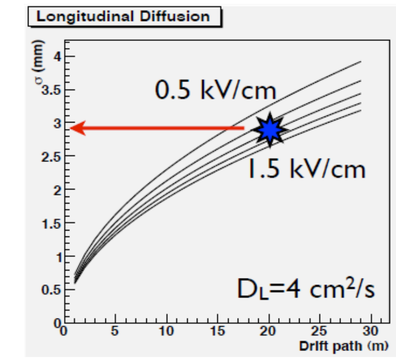
IN2P3
INSTITUT NATIONAL DE PHYSIQUE NUCLÉAIRE ET DE PHYSIQUE DES PARTICULES

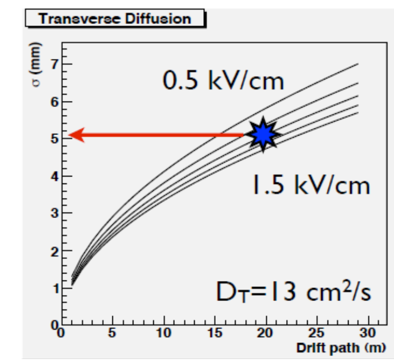
WA105 measurement goals

- LAr TPC provide a fully active homogeneous medium
- High granularity 3x3 mm^2 ← two orders of magnitude better than most granular calorimeters
  - e.g., CALICE AHCAL prototype has 3x3 cm^2
- Additional handle from dE/dx

Opportunity to provide unprecedented measurements of hadronic shower development to HEP community



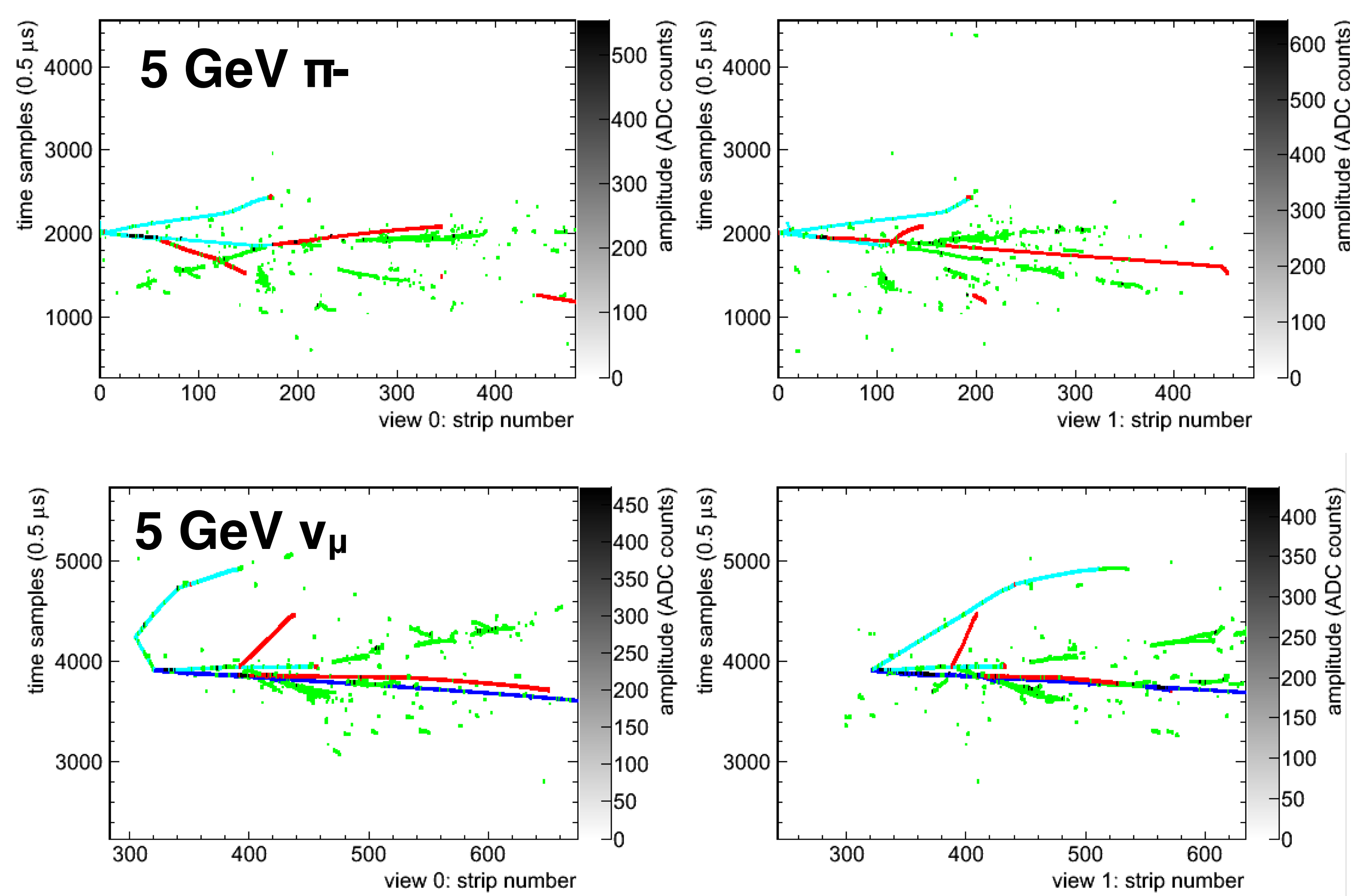




Some goals

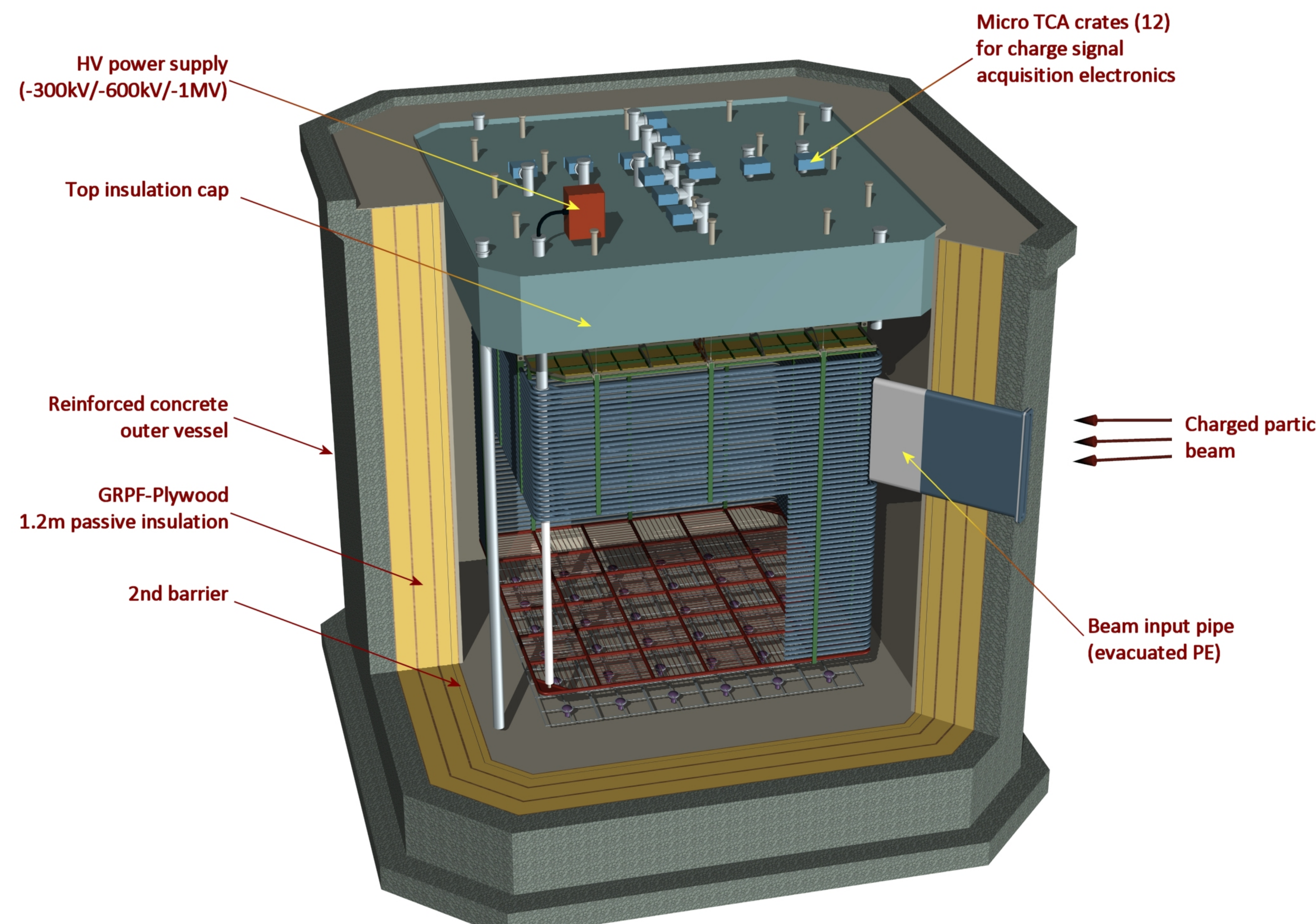
- Development of automatic event **reconstruction**
- **test NC background rejection** algorithms on "ν_e free" events
- Charged **pions** and proton **cross-section** on Argon nuclei. Rate of pion production is important!
- What is the achievable **energy resolution?**
- **Development** and proof-check of industrial solutions

pions, electrons/positrons, protons, muons



WA105 DLAr

- Membrane GTT® tank with passive insulation
- Top deck with chimneys and insulation
- **6x6m² anode large readout area**, **6m long drift length** (3ms max drift time @ 1kV/cm)
- Charged particle beam window
- 300 ton LAr instrumented: 7680 charge readout channels, 36 PMTs (baseline layout)

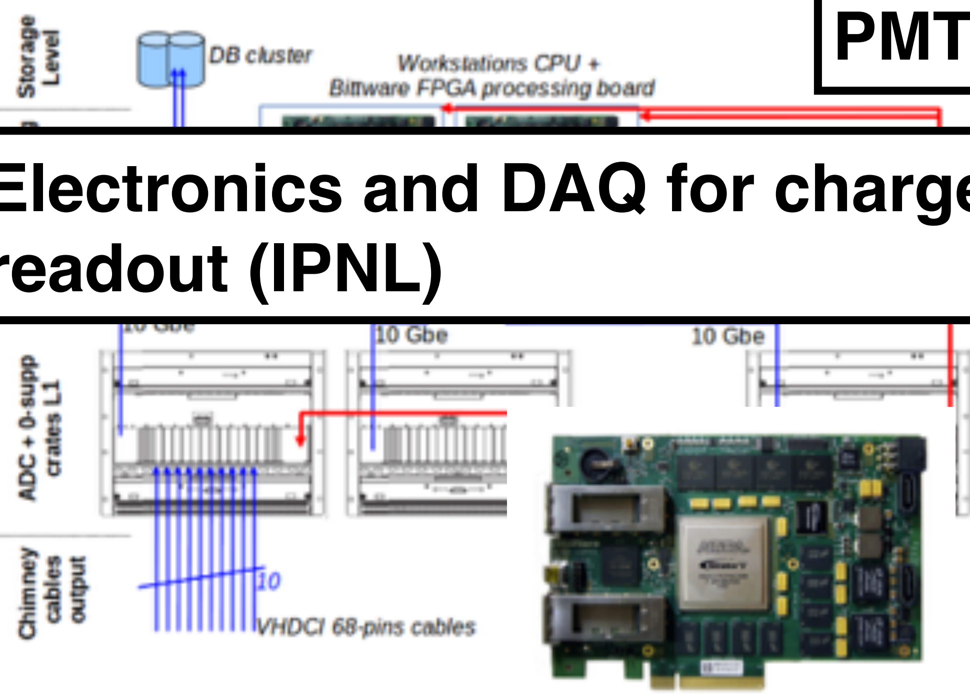


Liquid argon density	T/m^3	1.38
Liquid argon volume height	m	7.6
Active liquid argon height	m	5.99
Hydrostatic pressure at the bottom	bar	1.03
Inner vessel size (WxLxH)	m^3	8.3 × 8.3 × 8.1
Inner vessel base surface	m^2	67.6
Total liquid argon volume	m^3	509.6
Total liquid argon mass	t	705
Active LAr 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

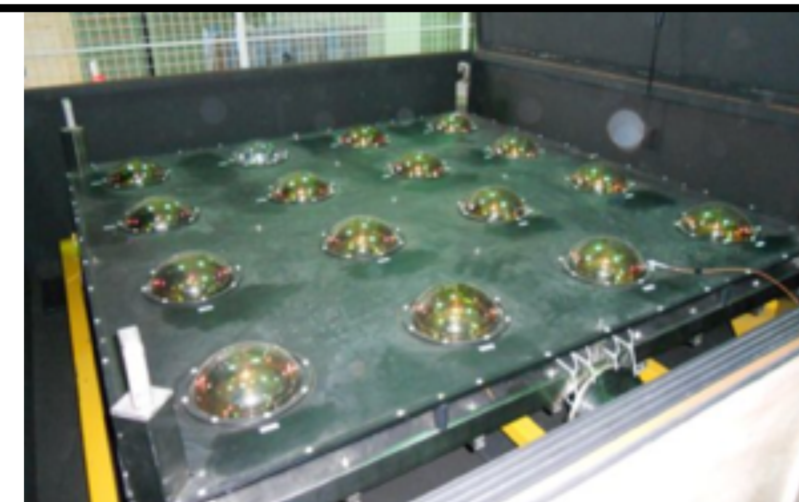
DLAr design work in progress

WA105

Electronics and DAQ for charge readout (IPNL)



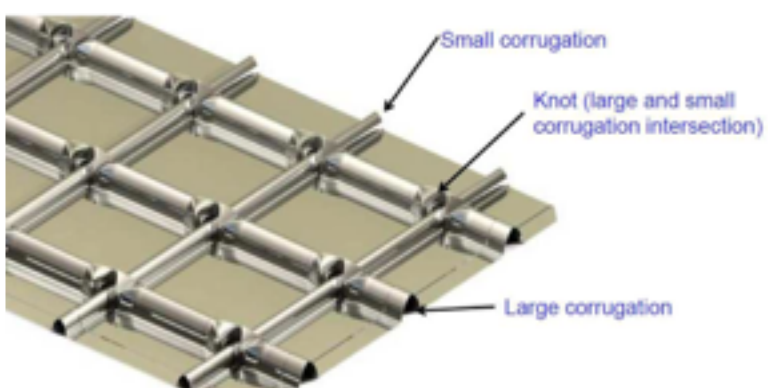
PMT light readout (APC, Barcelona, CIEMAT, KEK,LAPP)



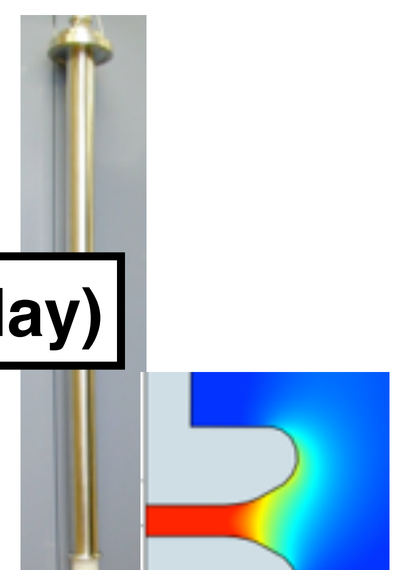
SiPM light readout (INR+Genève)

Field cage (CEA, Romania)

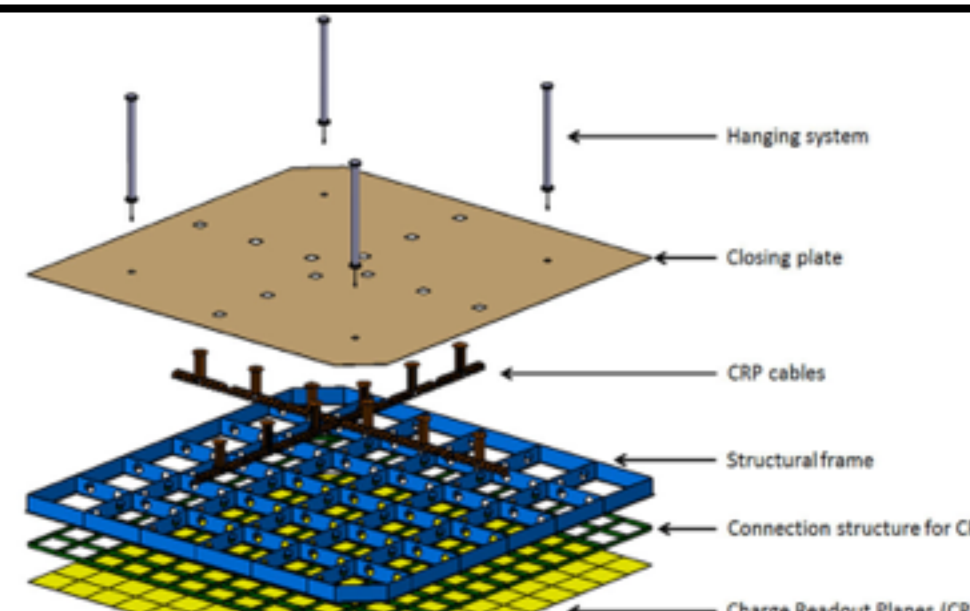
membrane tank (ETHZ, CERN)



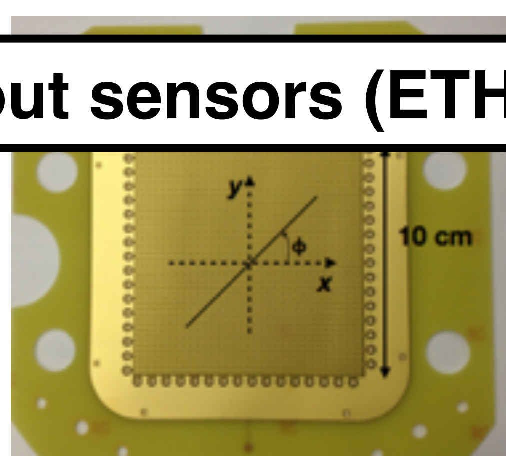
HV (LPNHE, ETHZ)



Anode deck suspension (LAPP)



charge readout sensors (ETHZ, Saclay)

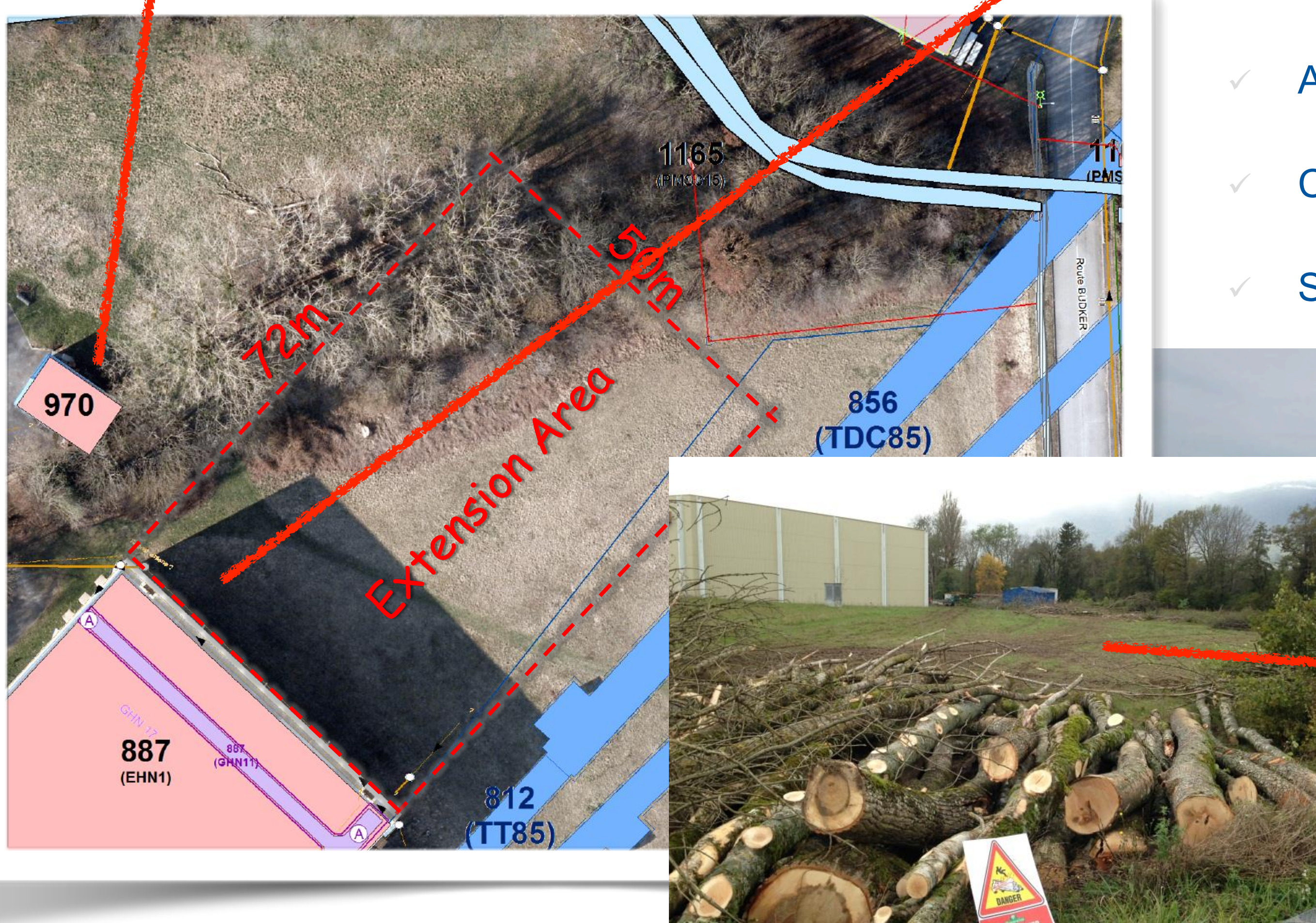


all groups involved in software and data analysis

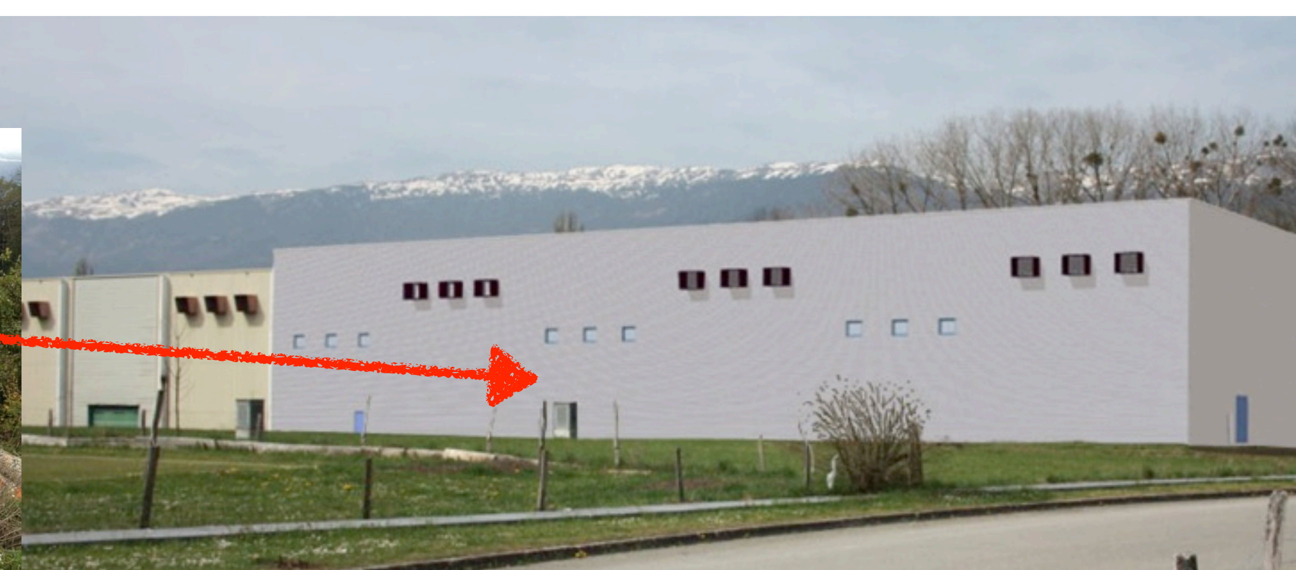
North Area Extension (EHN1-X)

Photo taken on October 29th, 2014

Extension area: 72m x 50m



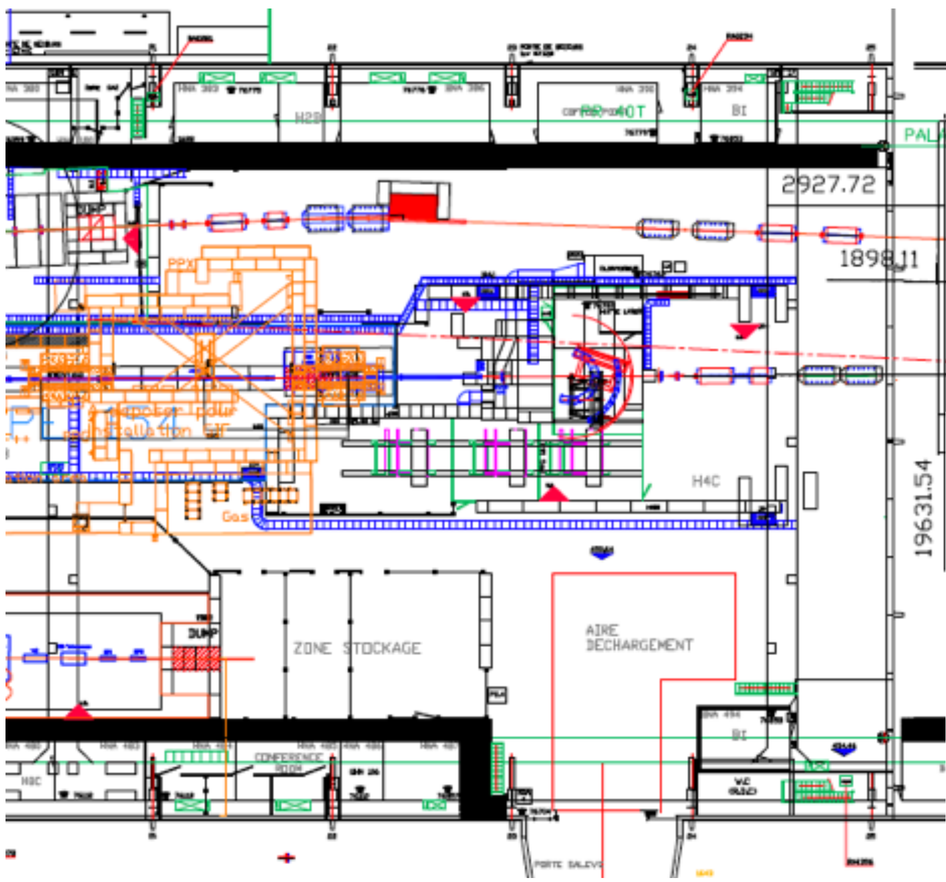
- Construction Design Phase (**ONGOING, completion by end-November**)
- Adjudication foreseen in December 2014 FC
- Contract signature
- Start of the works officially in January 2015 (anticipation, if possible)

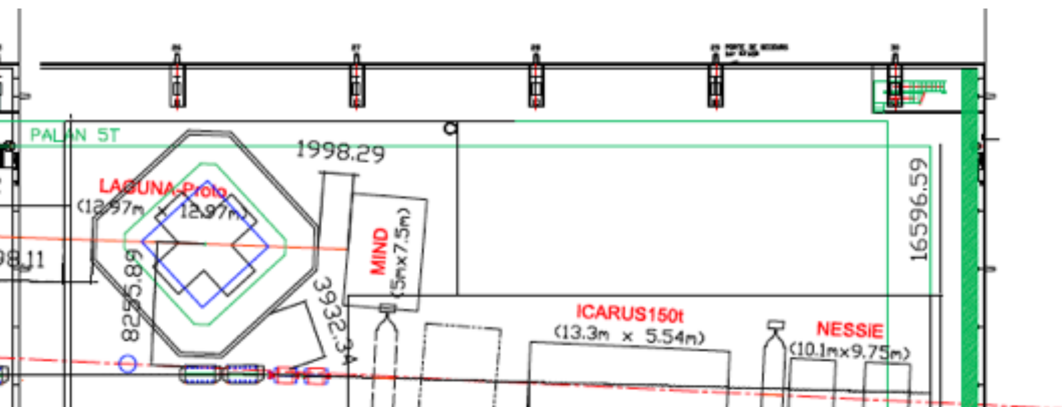


EHN1-X: charged beams

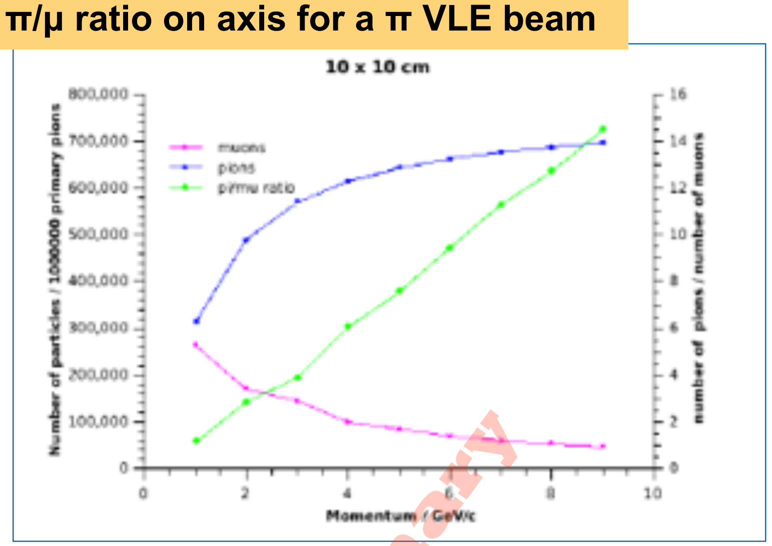
- VLE tertiary beams for the ν detectors
  - H2 extension: **1-20 GeV/c**, hadrons (π±, μ±, p - mixed beam), electrons(e±)
  - H4 extension: **1-5(7) GeV/c**, hadrons (π±, μ±, p - mixed beam), electrons(e±)
    - interest to go lower, down to 0.2 GeV beams for LBN TPC test

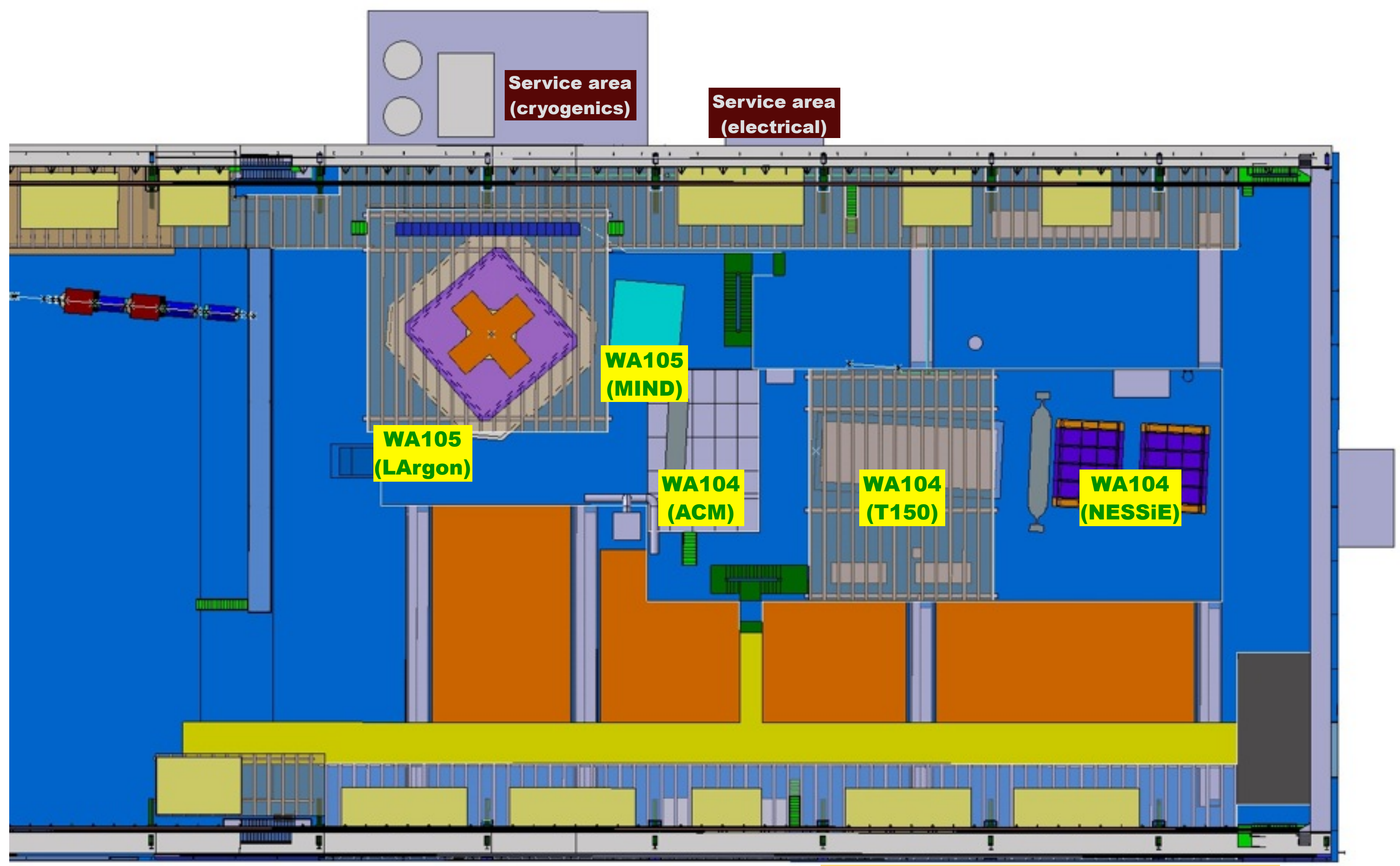
Courtesy I. Efthymiopoulos





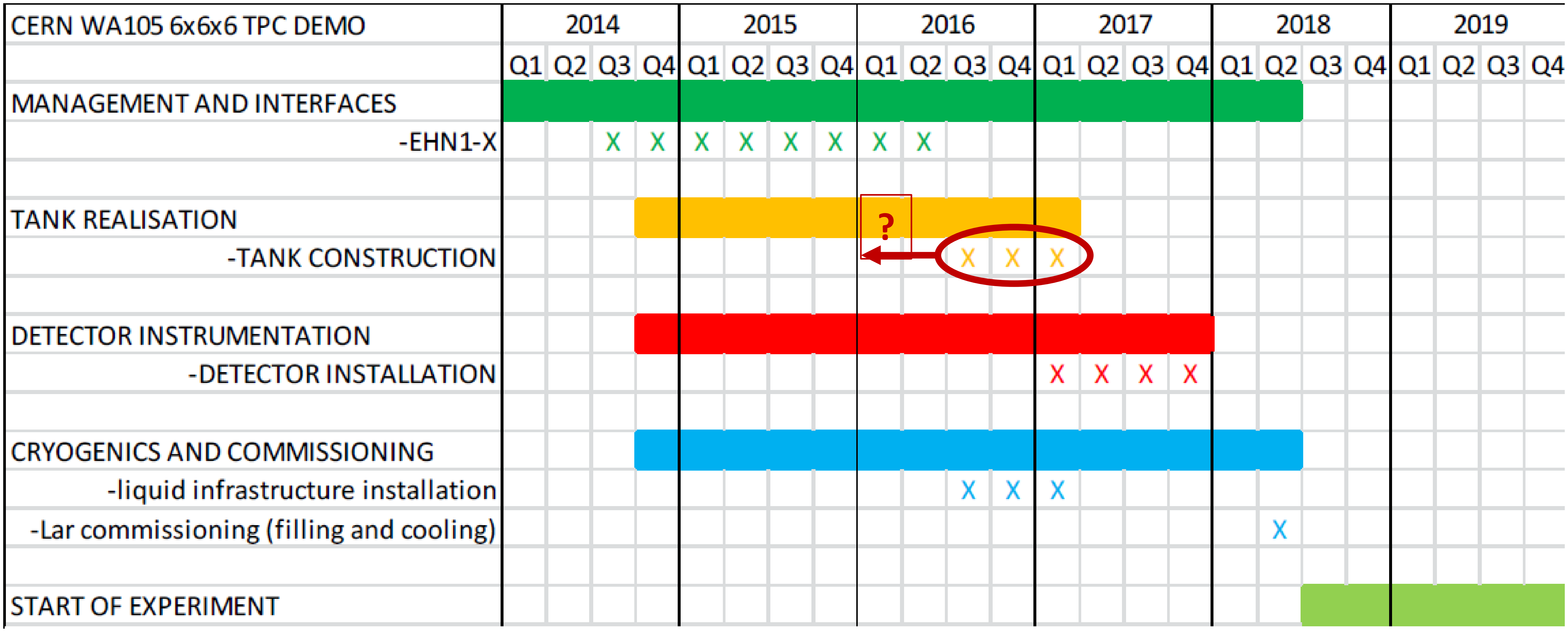
- π/μ ratio on axis for a π VLE beam





Integration designs: V. Clerc EN/MEF

WA105 timescale



Construction of EHN1 extension on the critical path

Optimization of construction schedule

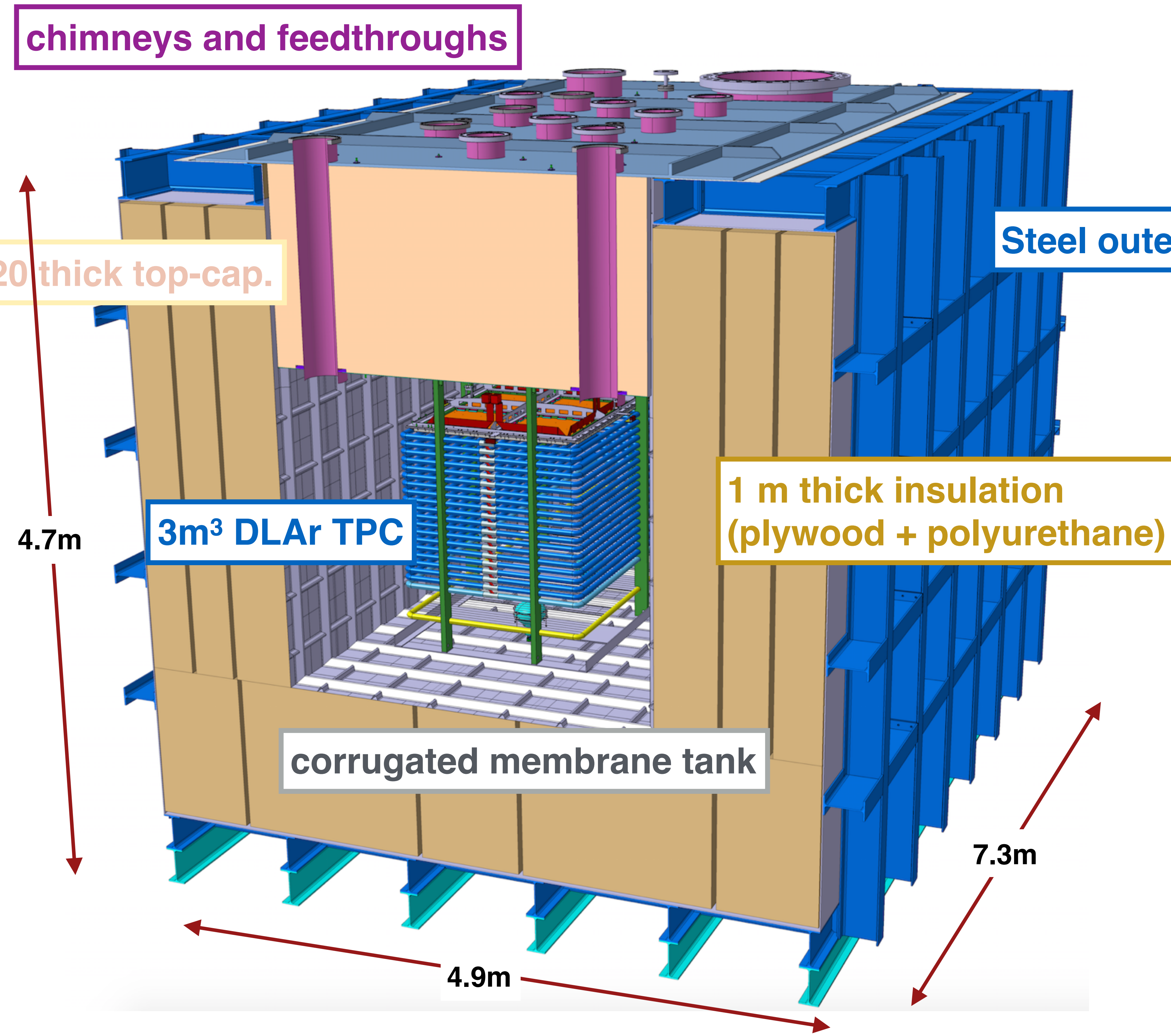
Currently aim to start data taking by mid 2018

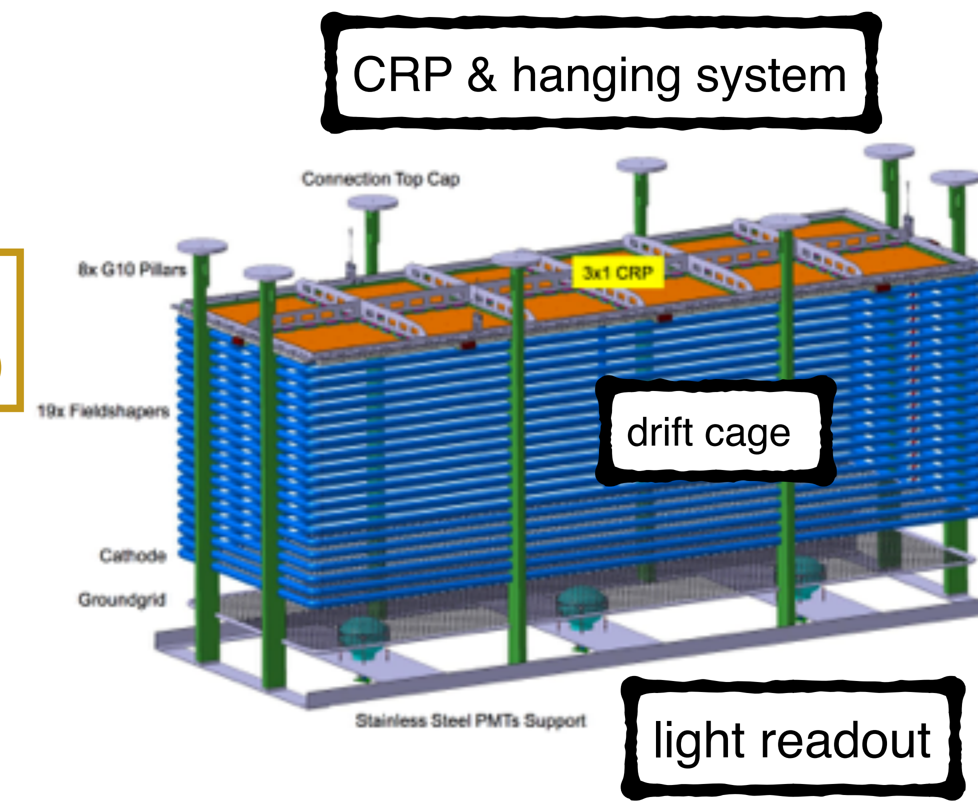
WA105/3x1x1m3 proto

WA105

20 ton prototype to be exposed to cosmic rays

Timescale: 2014-2016



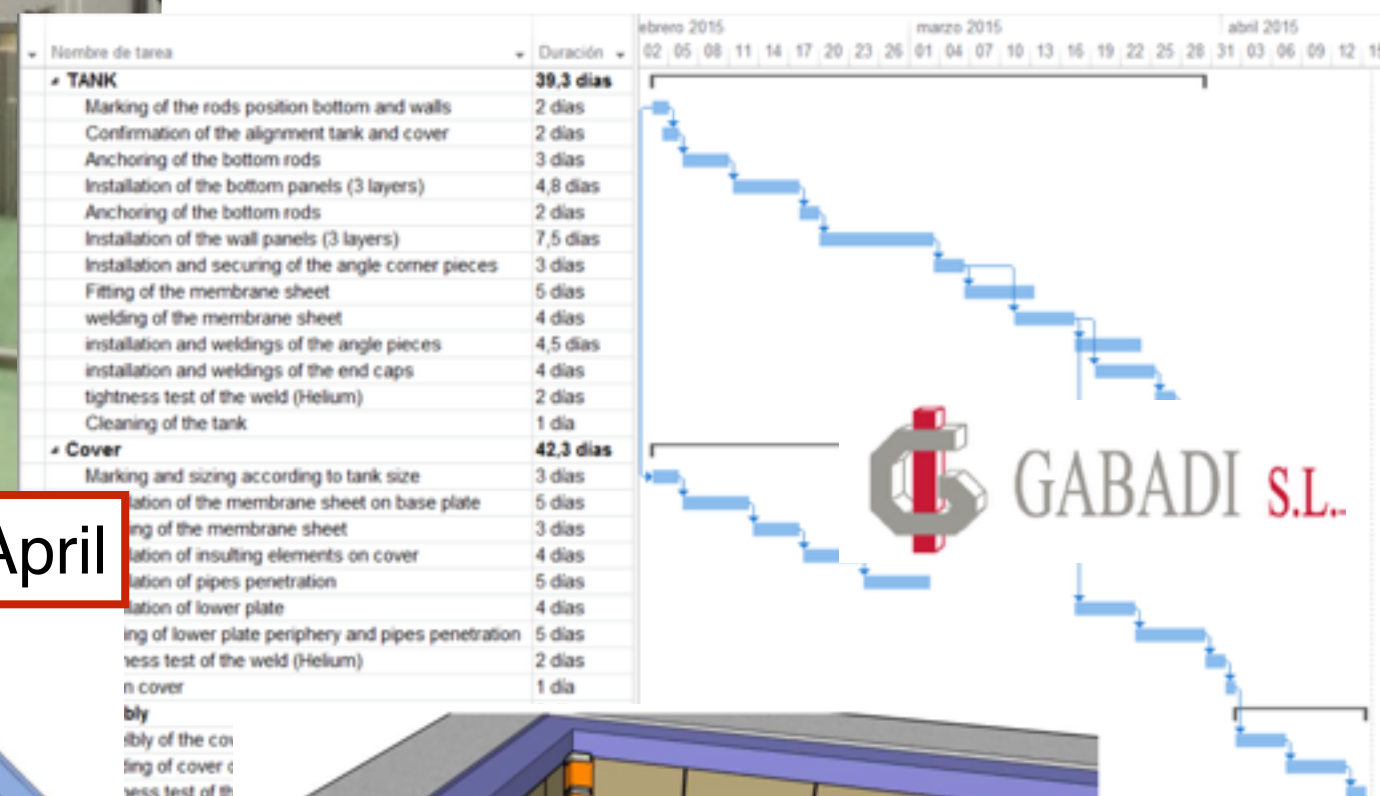


3x1x1m3 DLAr TPC
(5 ton active)
1280 r/o channels

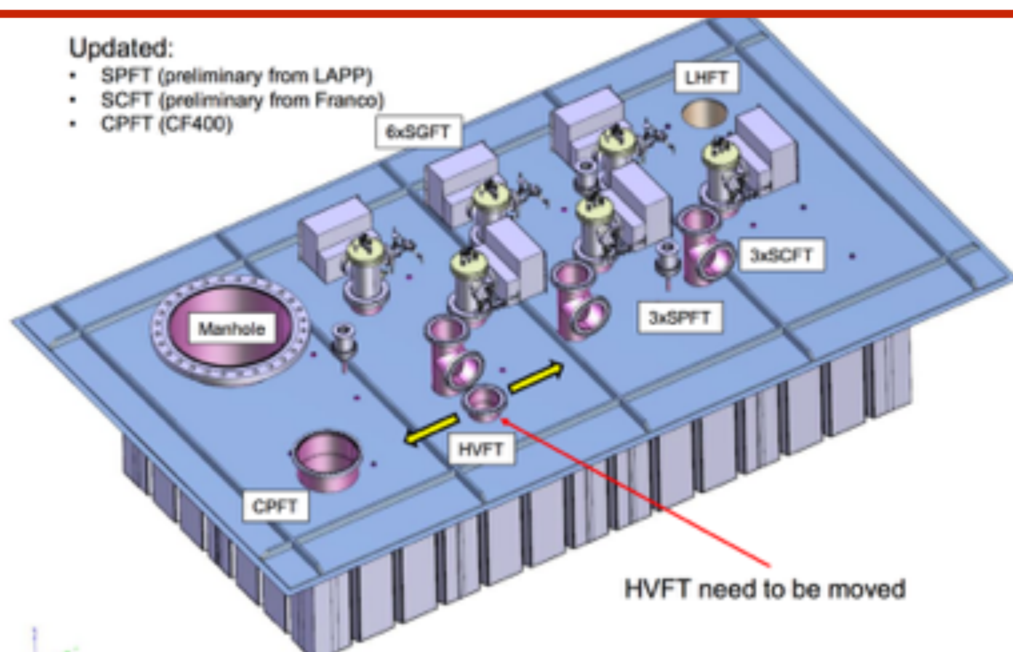
Cryostat + top cap

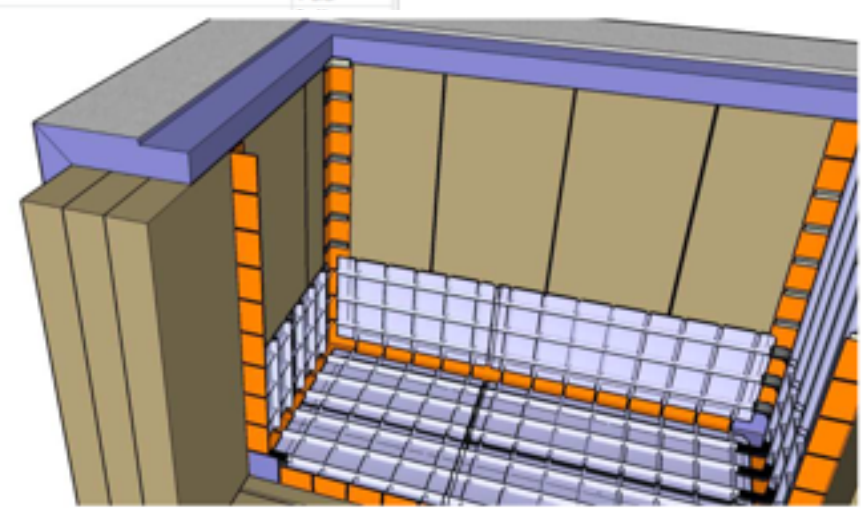
Outer structure was installed before christmas

click here to download movie:
[outer-structure-construction-time-lapse]



and insulation + membrane + top-cap by April

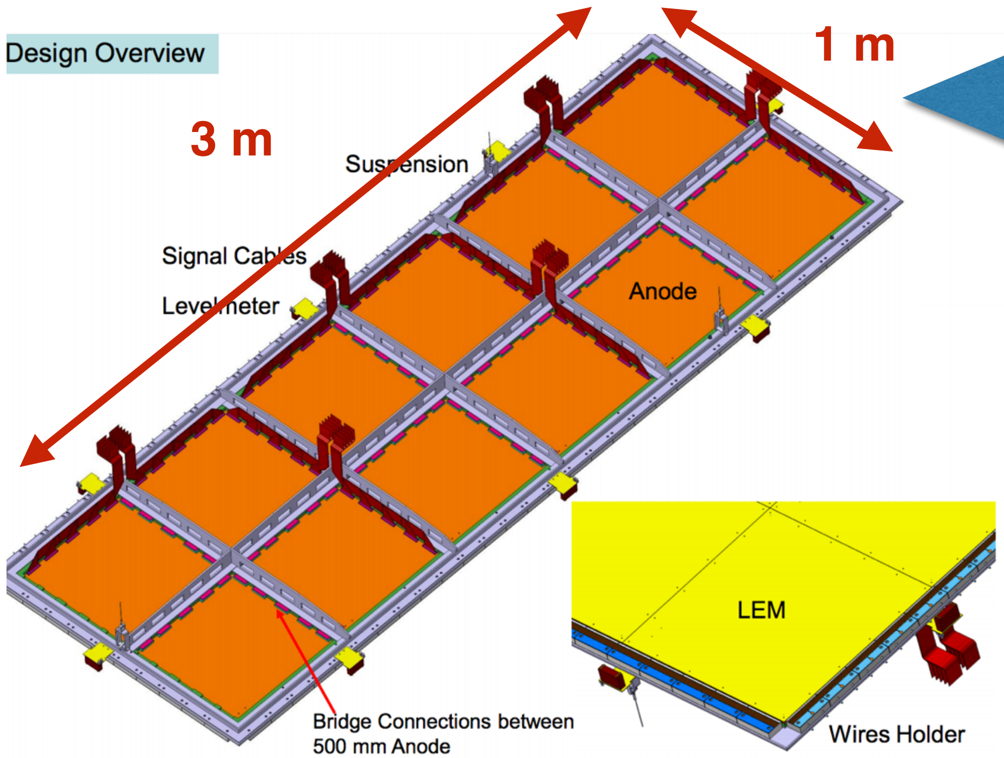


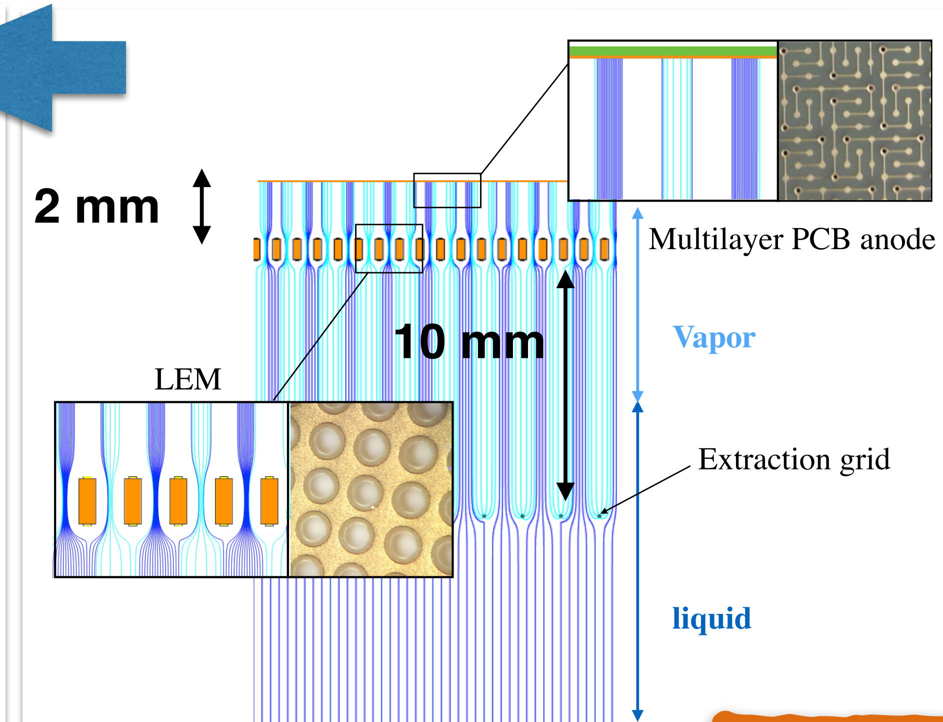


Charge Readout Plane (CRP)

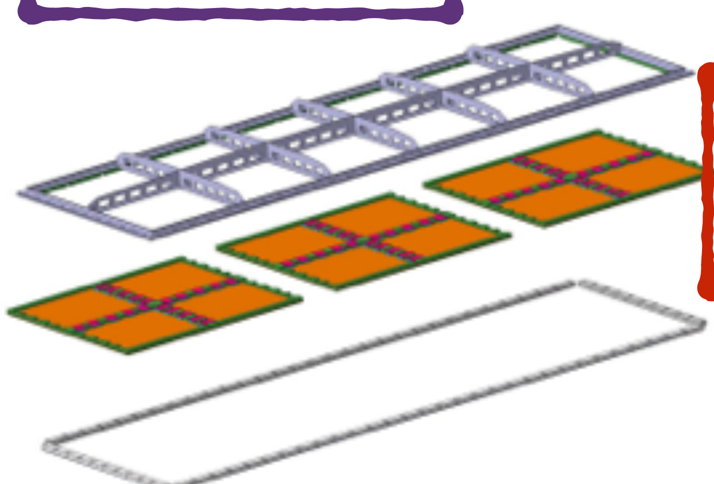
extraction grid-LEM and anode all in one single module

50x50 cm² LEM+anodes mounted in readout modules of 1m² on a 1x3 m² frame



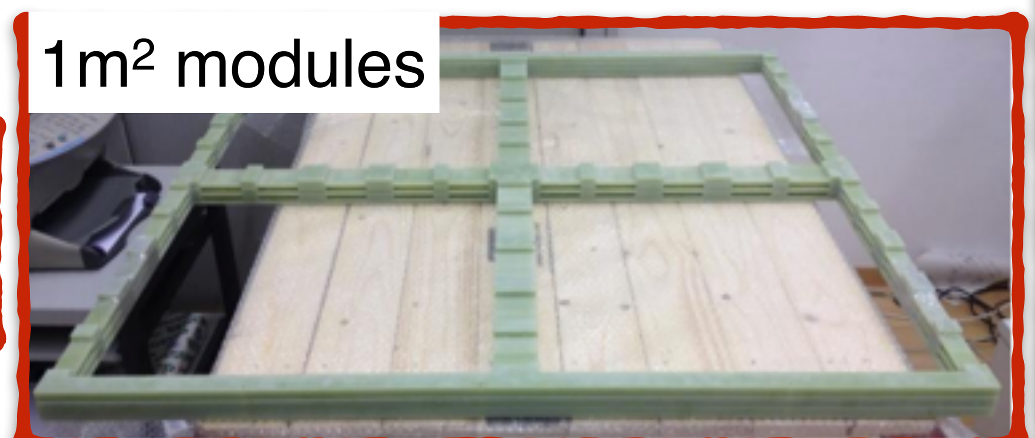


Aluminium frame

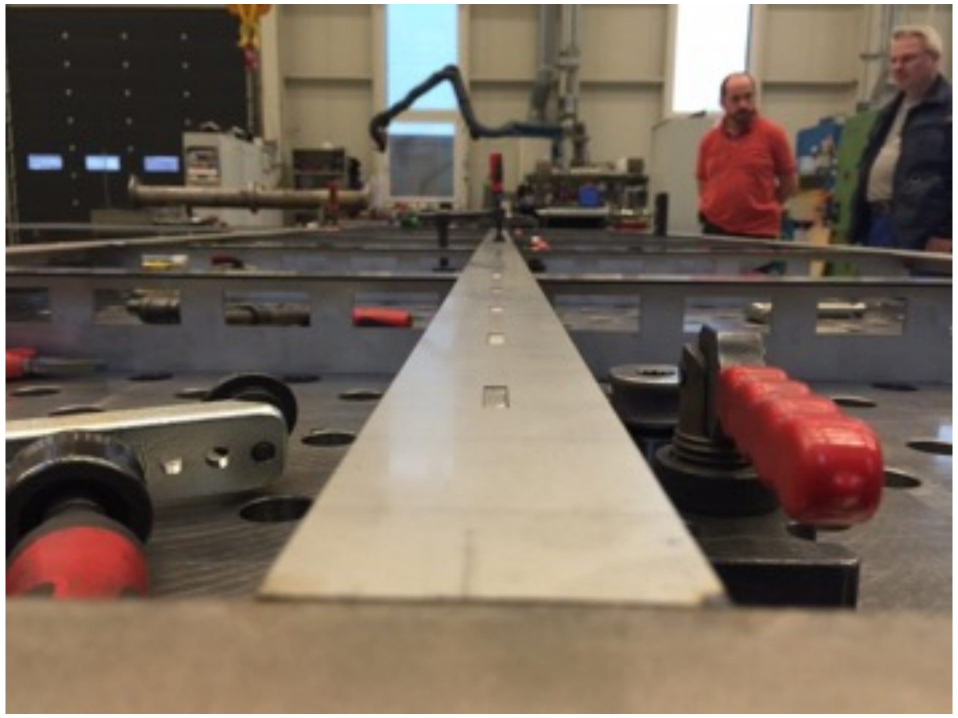


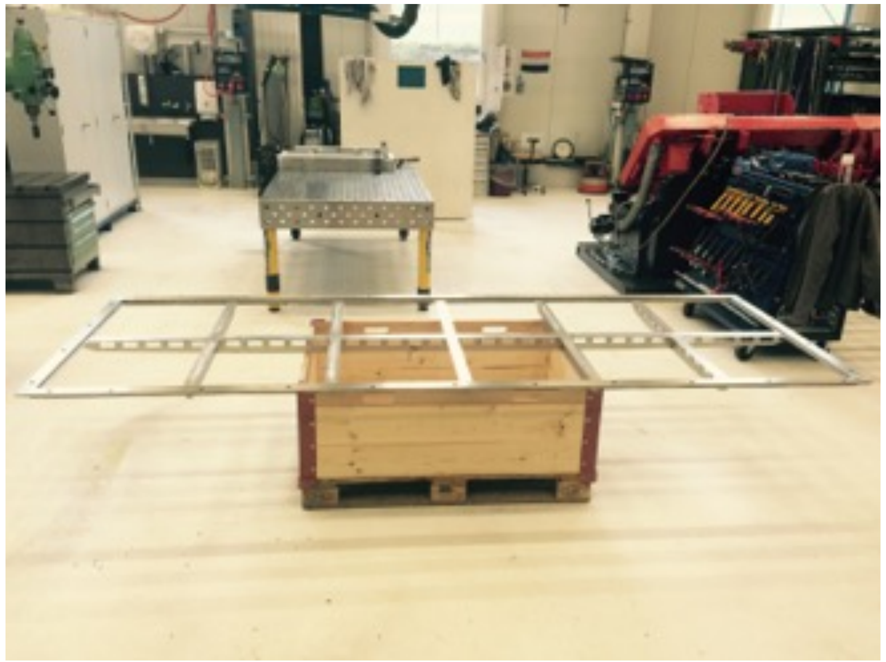
3 individual 1m² modules for anode+LEM

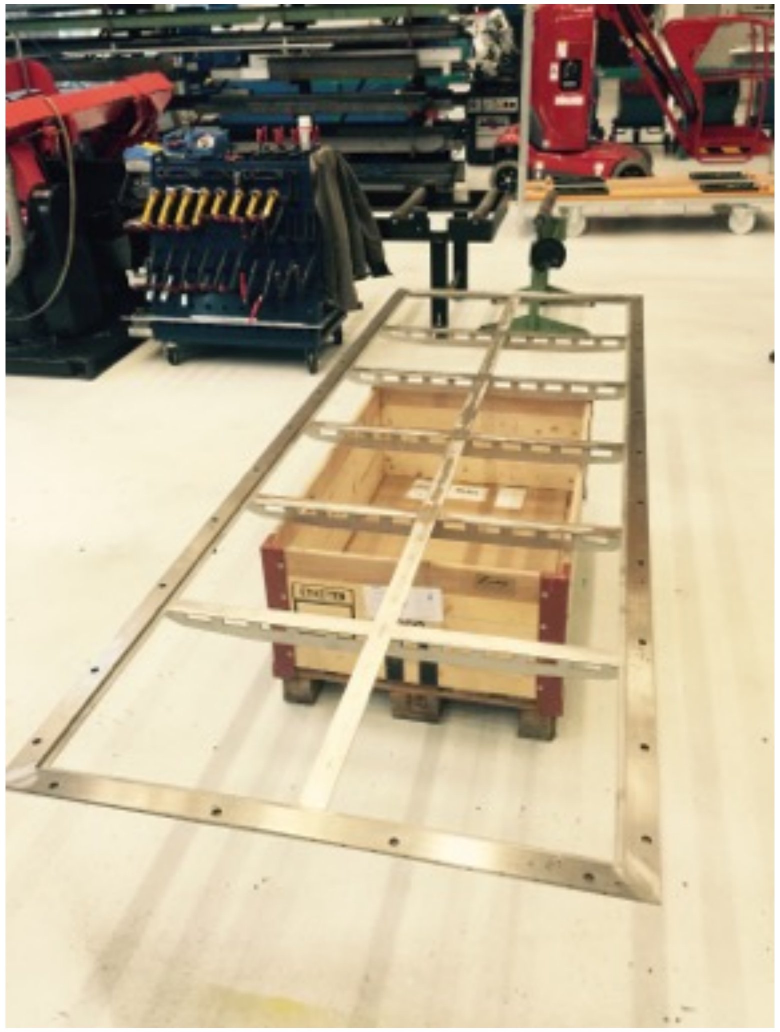
wire holders for extraction grid



The CRP mechanical structure

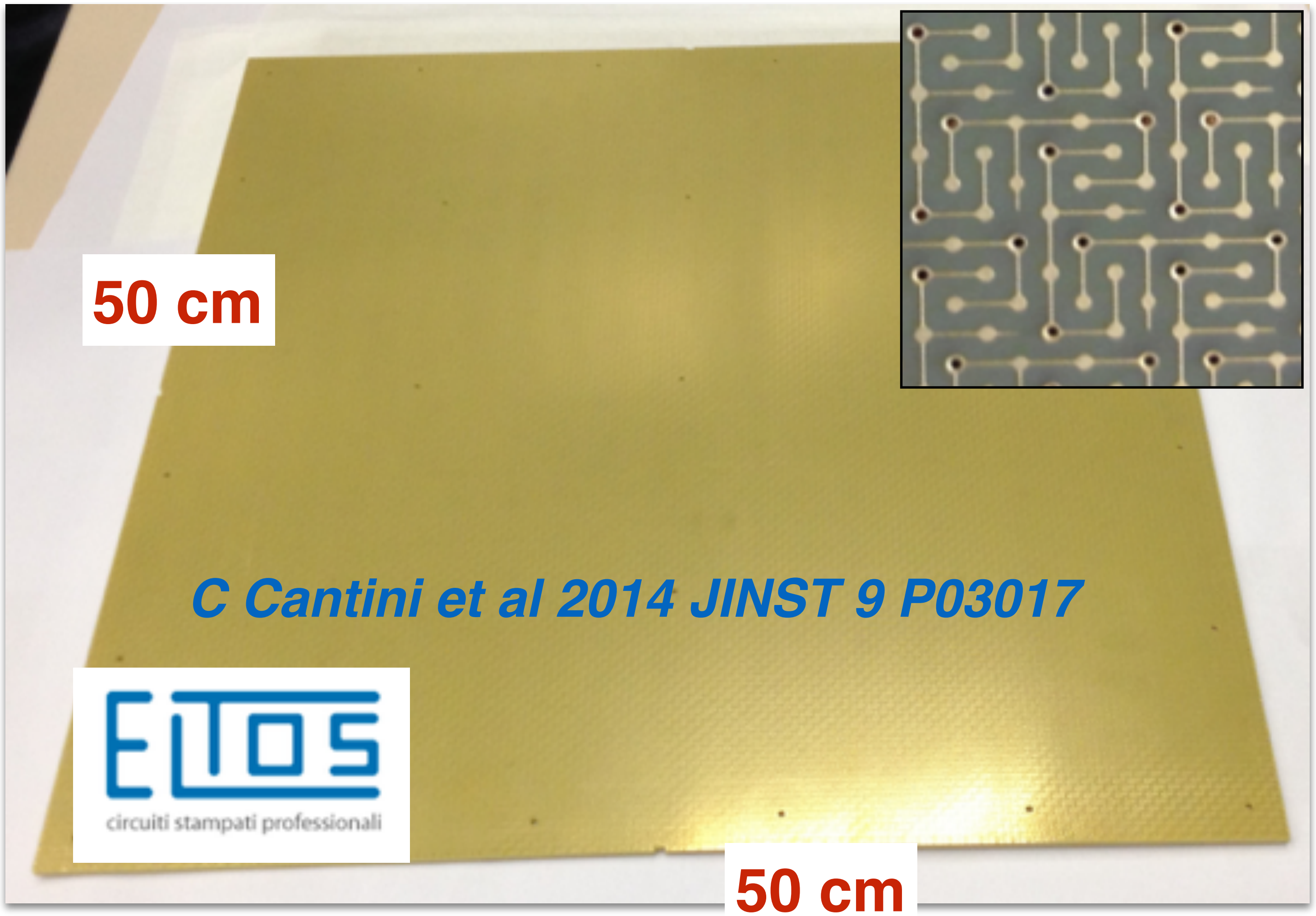


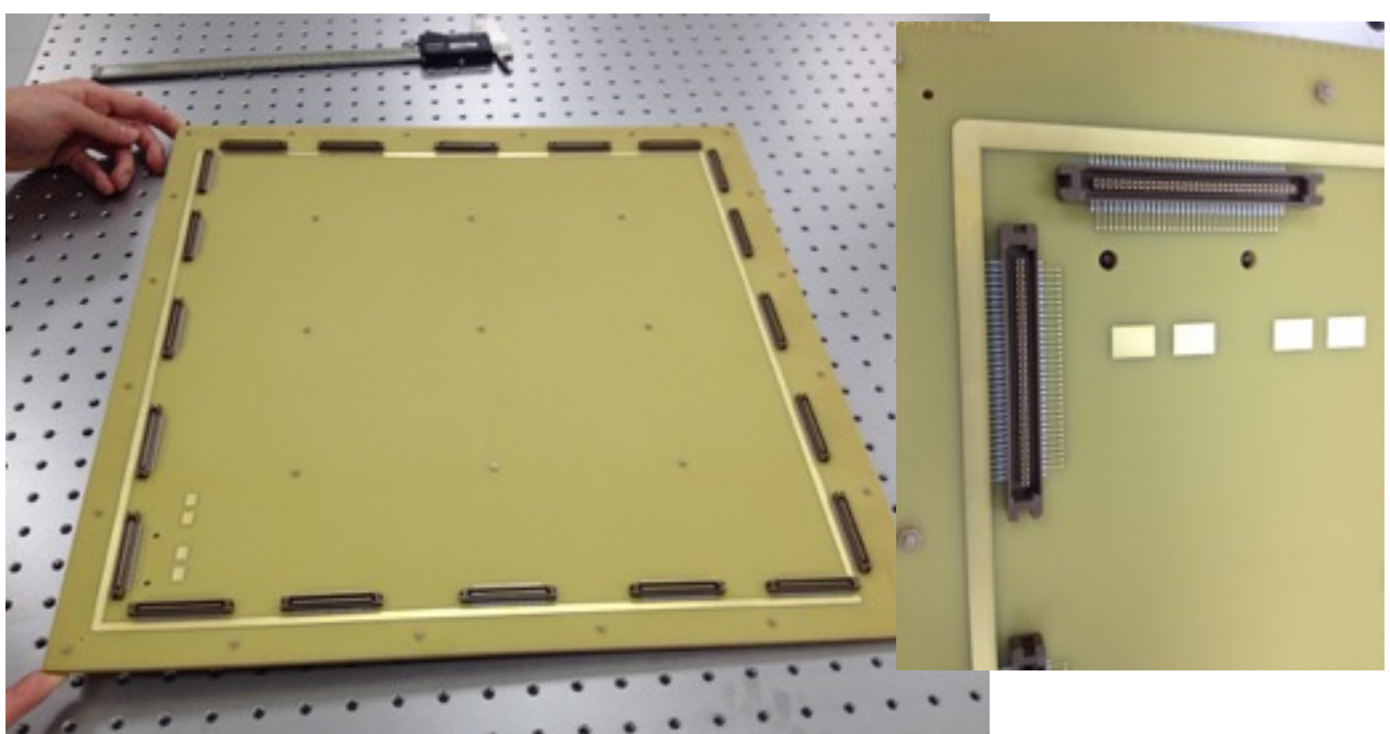




±1mm planarity over the 3m[2].

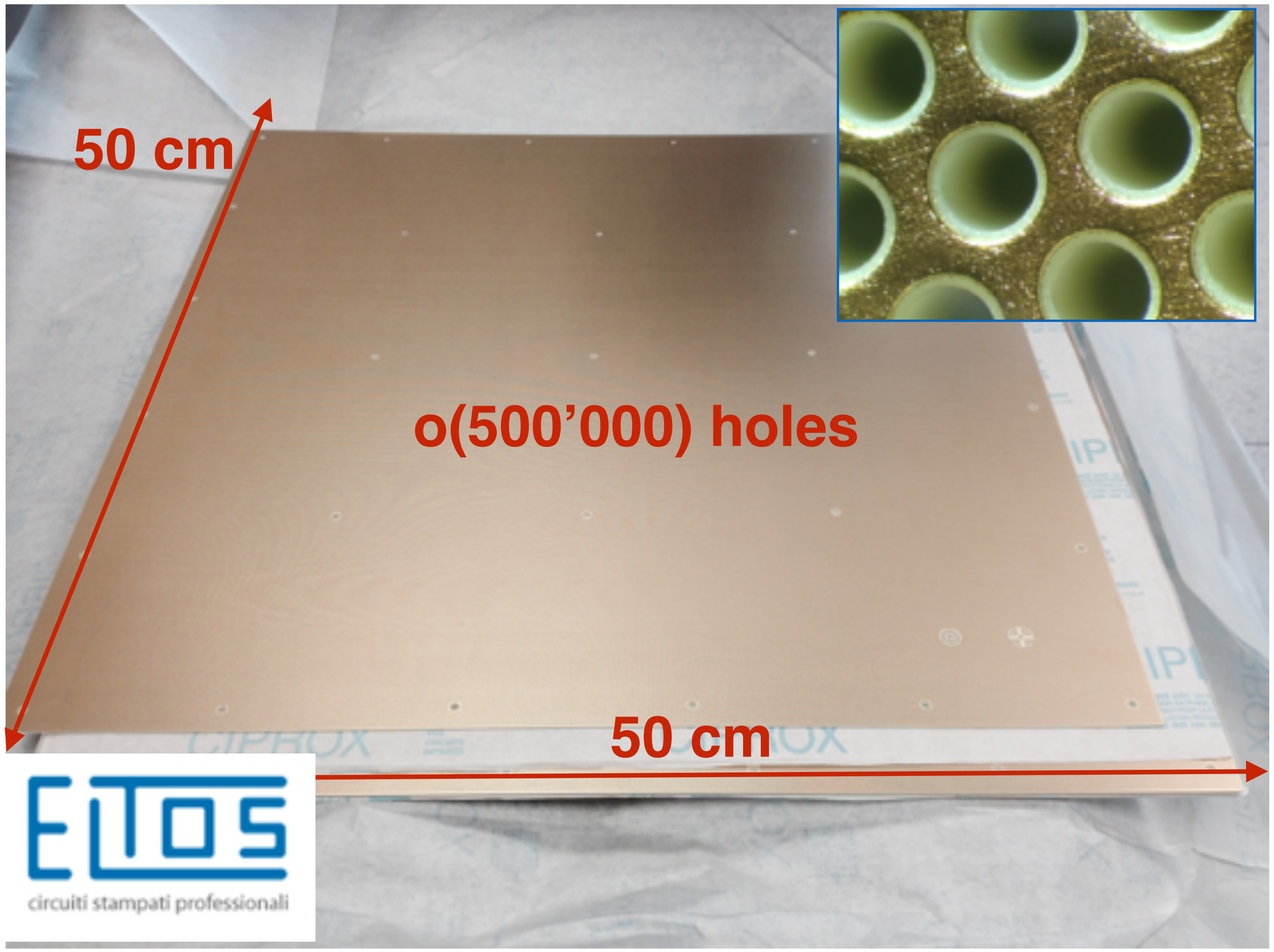
The anodes

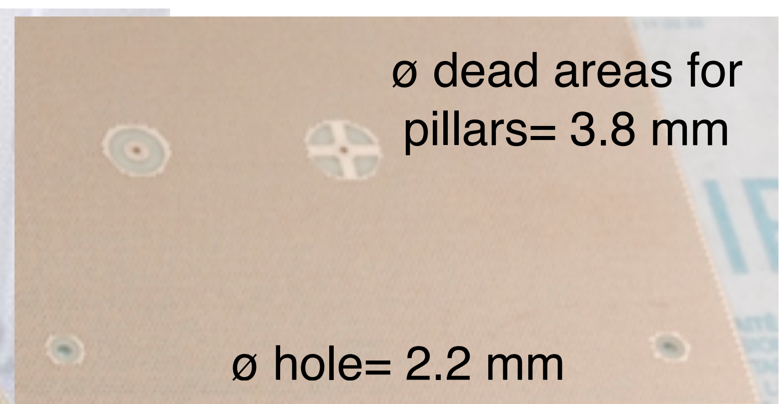




- ✓ “simple” multilayer PCB. 3.4 mm thick.
- ✓ 3 mm readout pitch
- ✓ Equal charge sharing on both collection views.
- ✓ low capacitance per unit length (~150 pF/m)
- ✓ design is a result of ~1 year R&D.
- ✓ relatively easy, cheap and fast to produce. All channels electrically tested by the company.
- ✓ soldering of the 20 KEL connectors at SMD CERN workshop. Takes about 2hrs for one board.

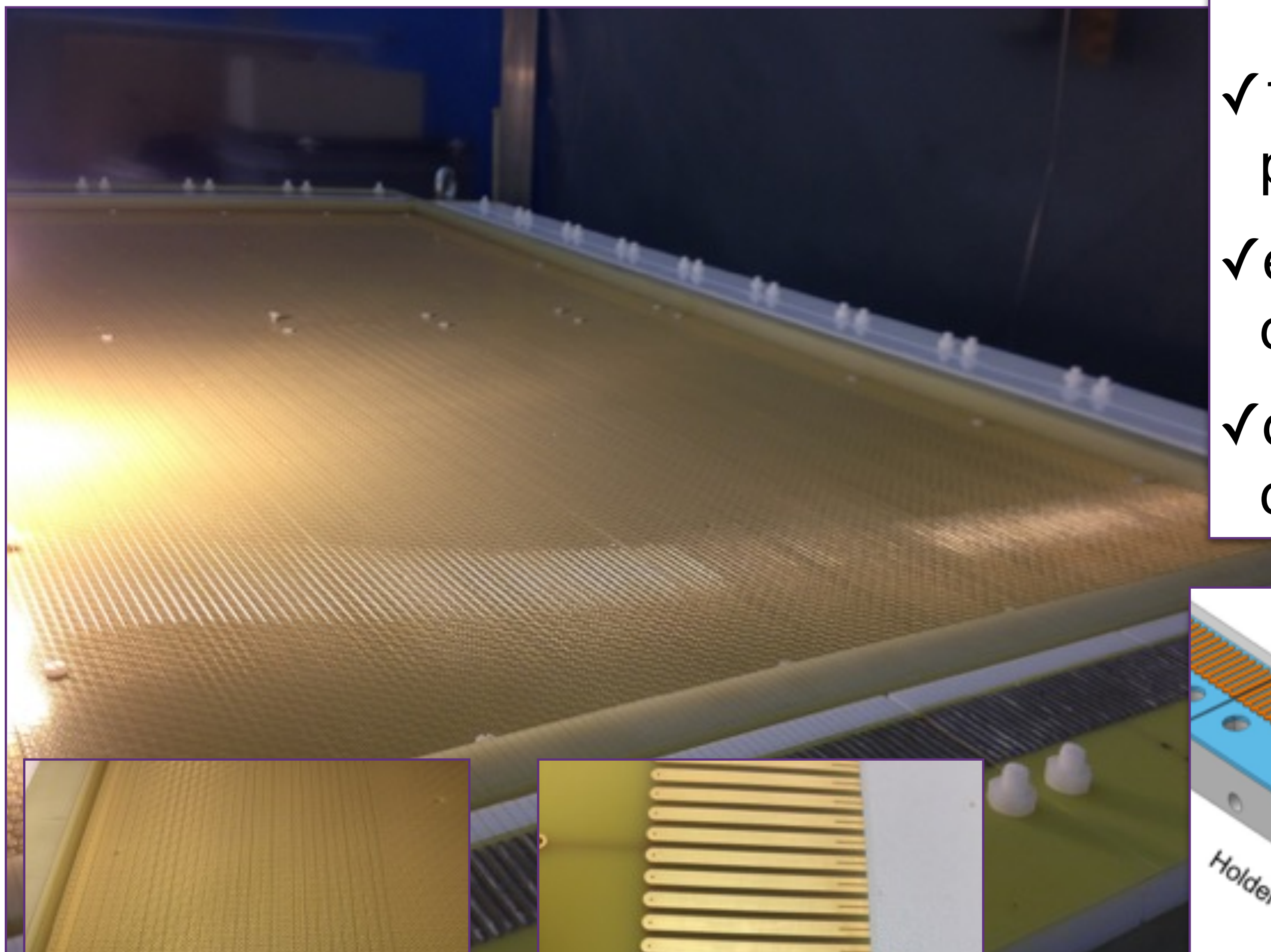
The LEMs

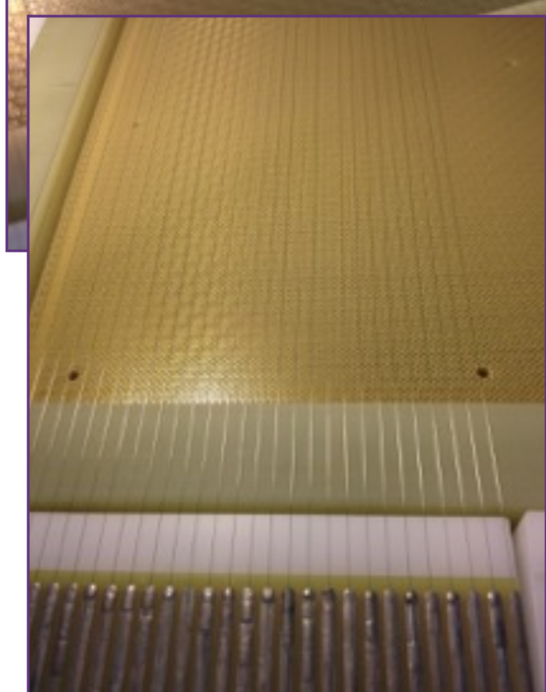


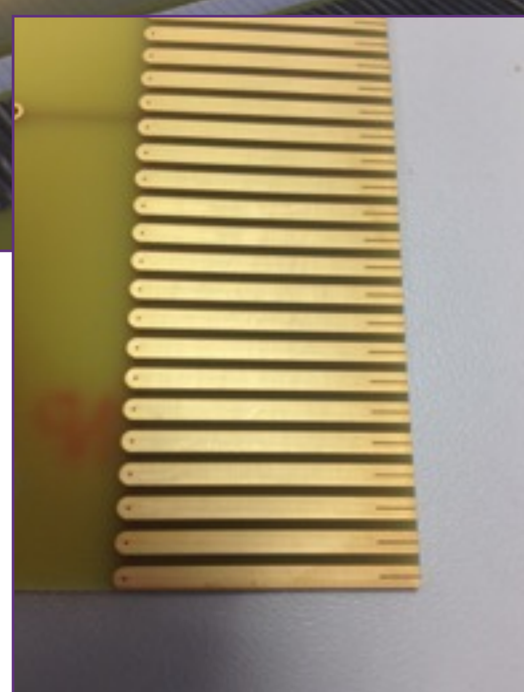


- ✓ PCB CNC drilled with o(150) holes per cm^2. 1 mm thick.
- ✓ 500 um hole diameter 800 um pitch.
- ✓ 40 um dielectric rim around the holes to avoid edge-induced discharges
- ✓ powered at around 30 kV/cm
- ✓ design is the result of many years of R&D on smaller scale prototypes.
- ✓ Latest paper on hole/rim size optimisation for stable gain in LAr:
  arxiv 1412.4402 Dec. 2014 (submitted to JINST)

The extraction grid

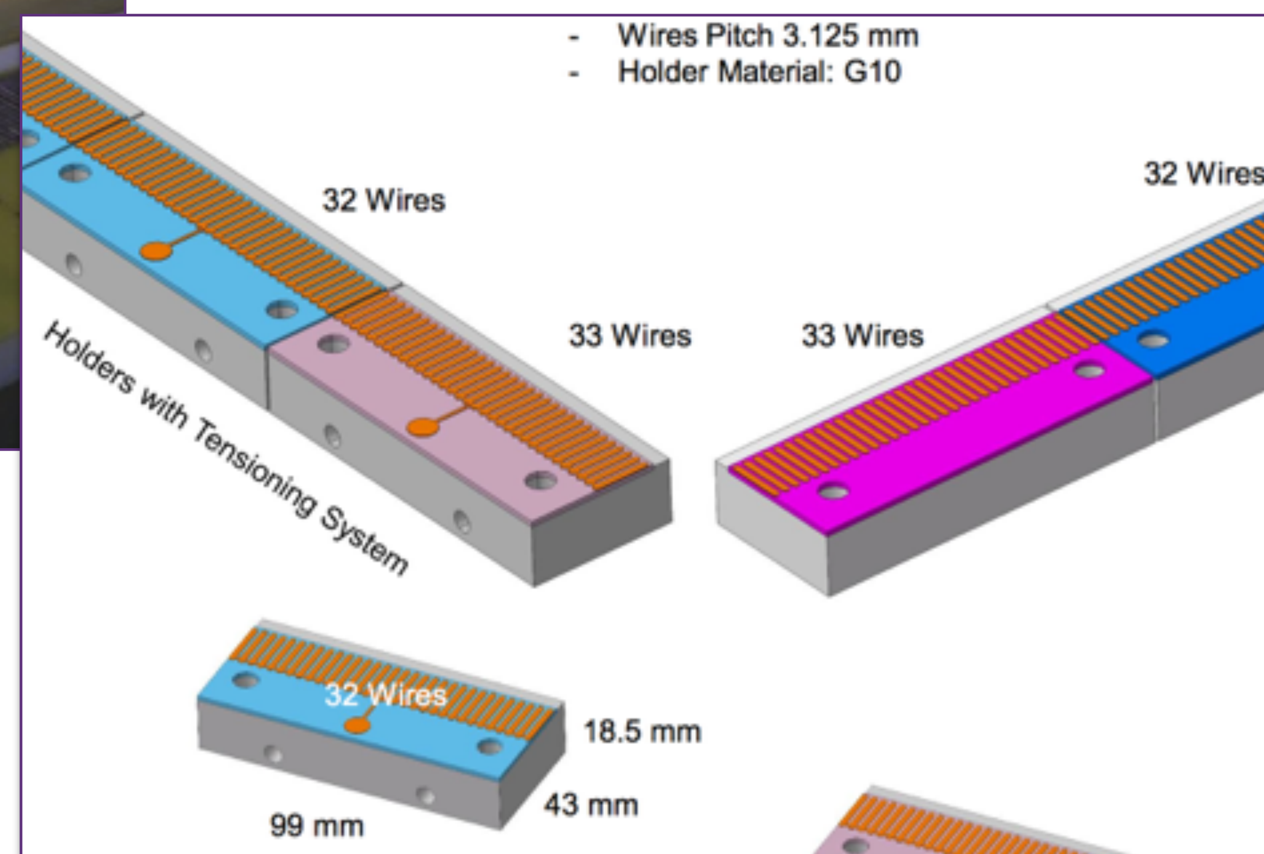




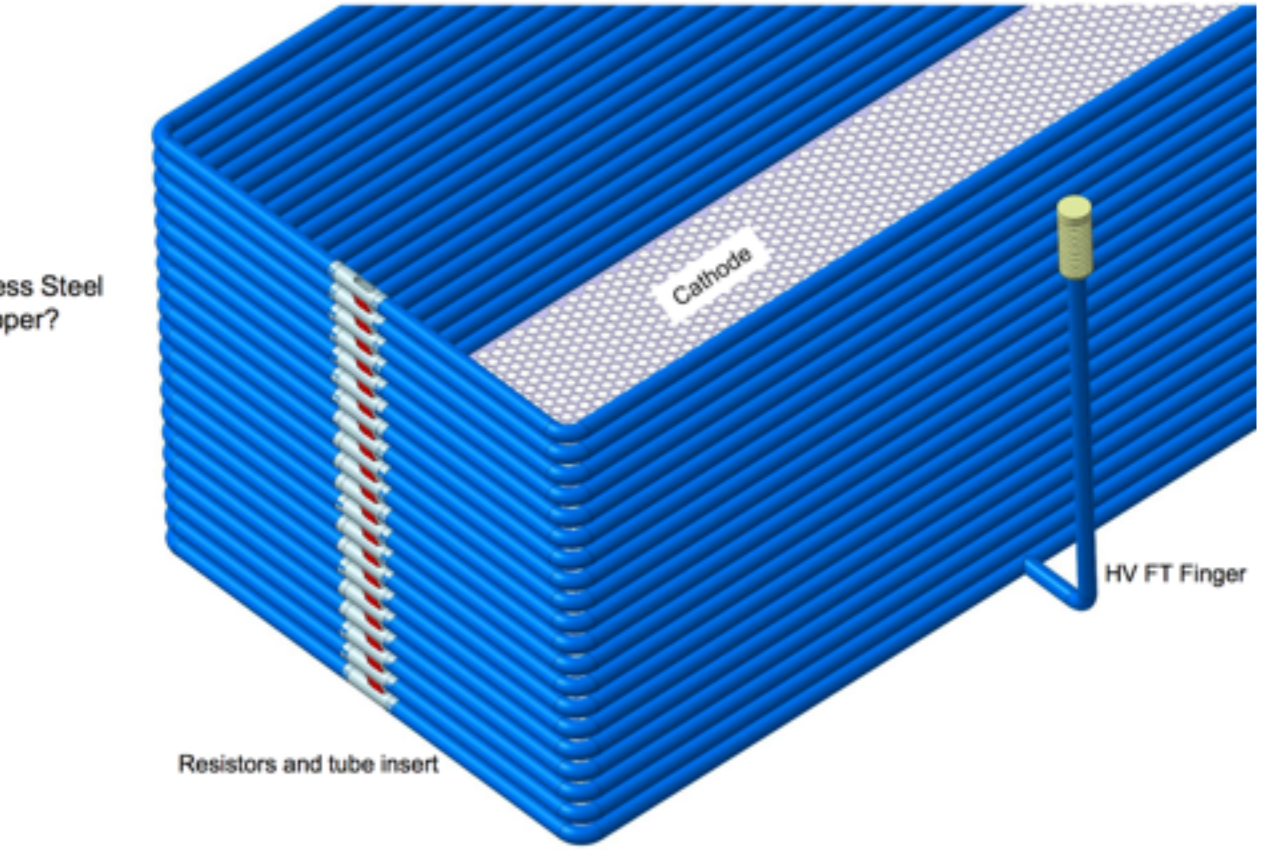


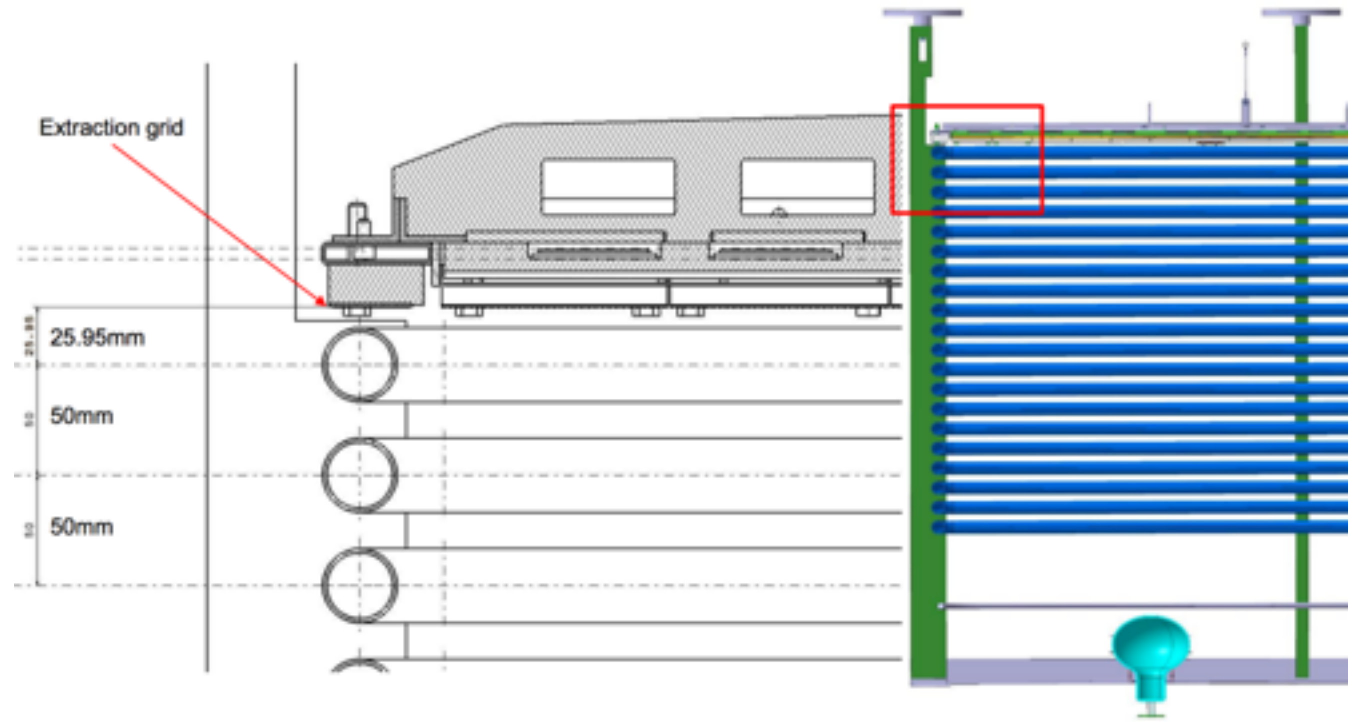
Extraction grid

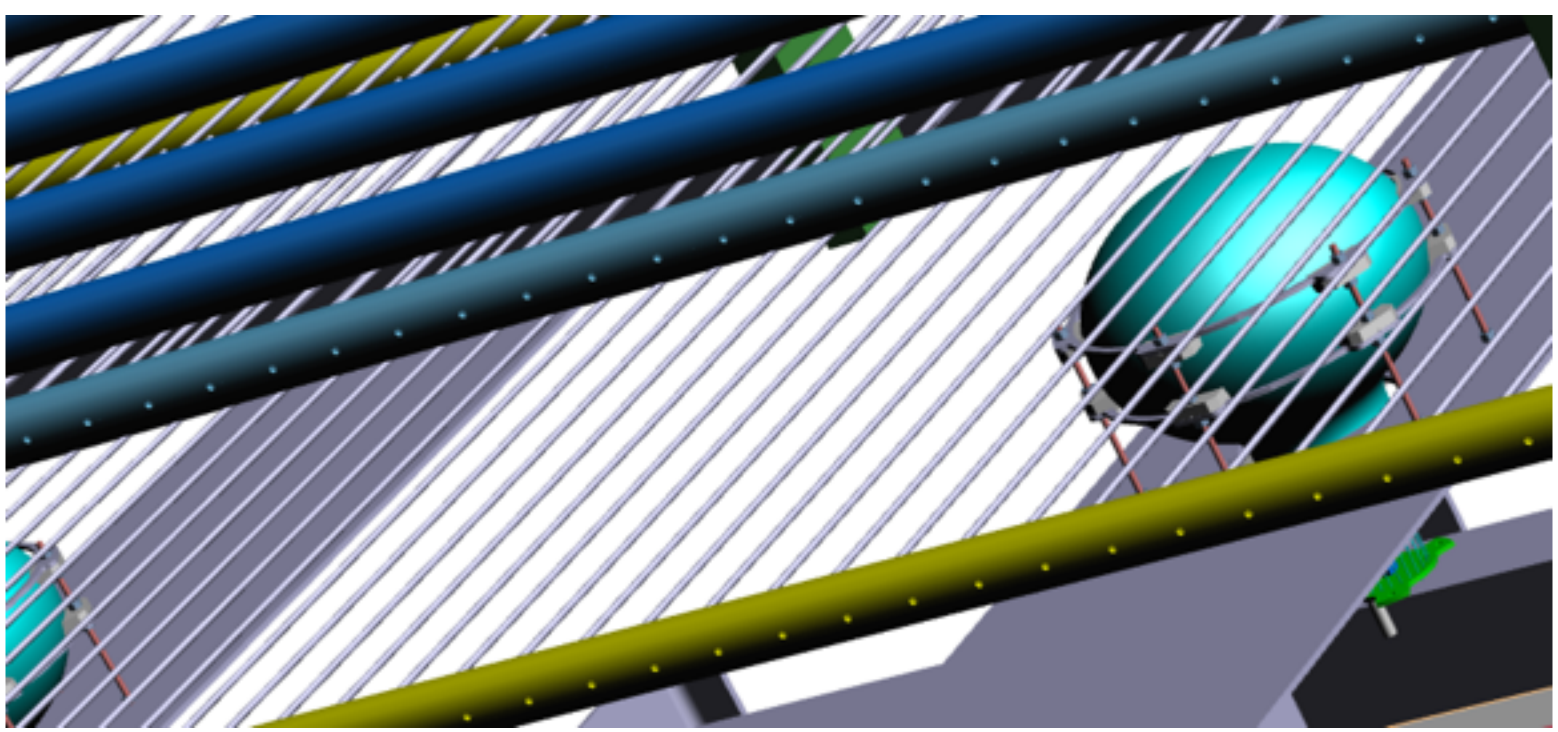
- ✓100 micron stainless wire with 3 mm pitch in x and y directions
- ✓effect on gain uniformity tested in LAr on 10x10 cm² readout
- ✓design has been extensively tested on a 1 m² prototype.

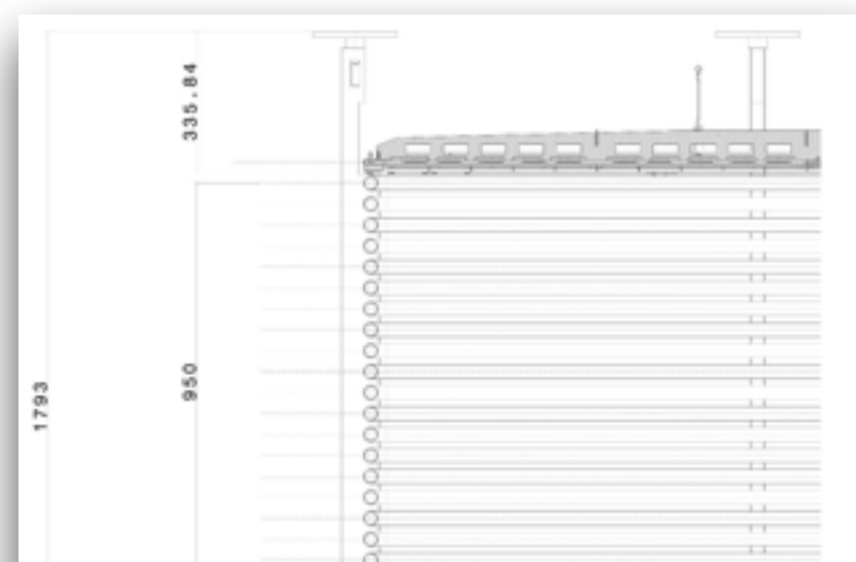


The drift cage







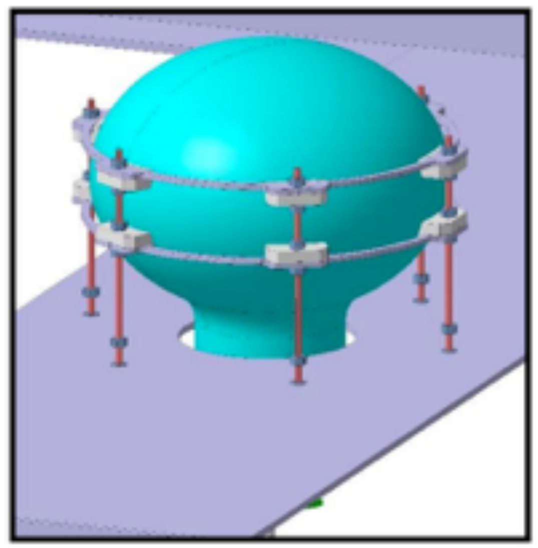


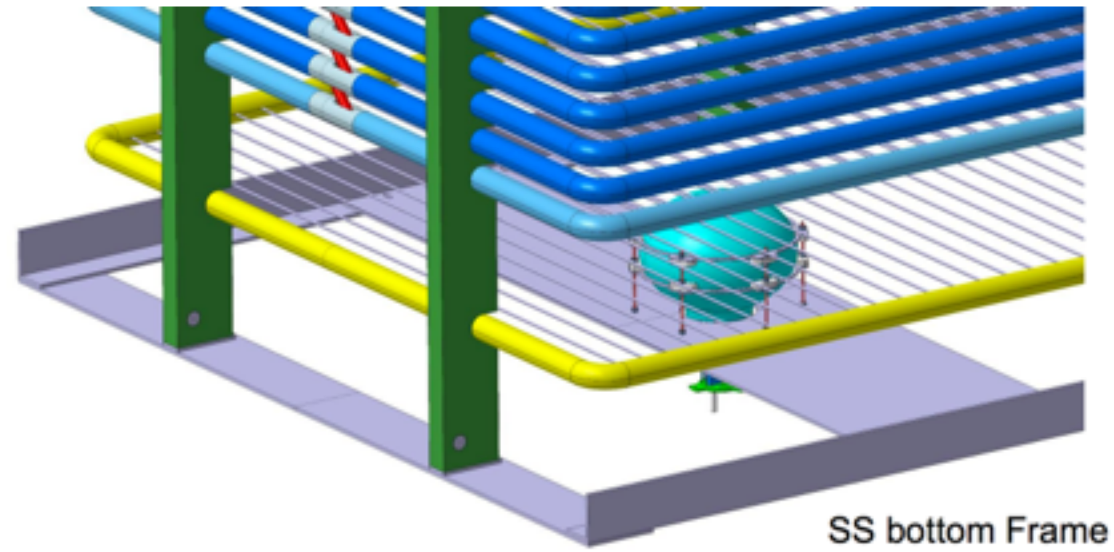
✓Following similar design to ArDM's drift-cage.
✓Assembled off-site and delivered to CERN.

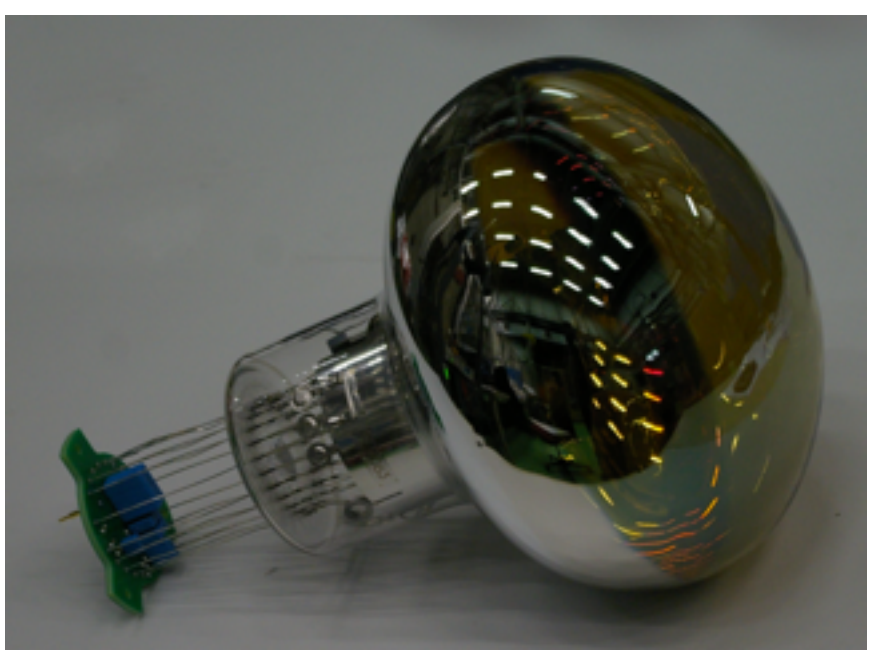
The light readout

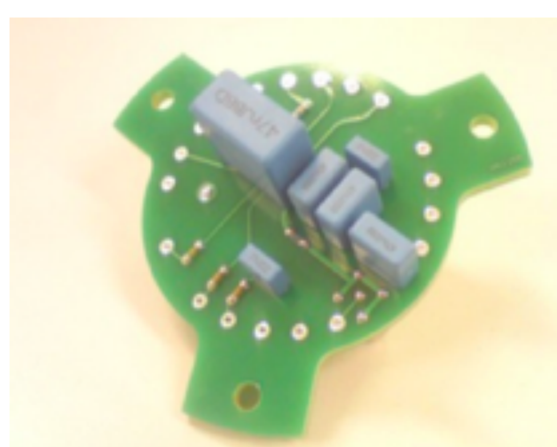
Baseline design: 3 Hamamatsu 8” R5912 PMTs. Same installation as ArDM.

R5912-02MOD









✓PMT ordered and bases are fabricated at KEK following design from ArDM.
✓WLS coating and testing at CERN planned in April.

Entering the "global" era

- **CERN European Strategy:**
  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 long-baseline neutrino projects in the US and Japan.

- **US P5 report:**
  Recommendation 12 : In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

Beyond LAGUNA-LBNO...

A threefold strategy was adopted by the Consortium:

1. Following the Update of CERN European Strategy and coherent with the US P5 vision, **explore the North American and Asian options, and best exploit the LAGUNA-LBNO studies to help foster a major European contribution to the LBNF facility being developed in USA.**

2. **Construct and operate the LBNO-DEMO demonstrator at CERN (WA105 project)** implementing all the techniques developed in LAGUNA-LBNO and in the context of the neutrino R&D & charged particle beam platform.

3. **Develop the plans for an underground PILOT project**, to test all the aspects of the underground installation and operation and provide an early physics programme.

LBNE-LBNO geotech meeting

- Joint meeting on rock mechanics and LAr cryostat design in October 2014 at SURF, South Dakota + underground site visit
- Working towards a common understanding of cryostat design within the SURF facility
- Goal: develop a unified design for cavern, cryostat and cryogenics → **towards common conventional facilities design for single- and dual-phase detectors**
- Outcome: urgent joint & focused effort needed at quickly resolving pending issues with implementation at SURF (shaft limited access, cavern size, self-supporting tank, construction, safety, risk analysis, etc.)

Sanford Underground Research Facility

October 20, 2014

Professor André Rubbia
ETH Zurich, Coordinator of the International FP7 LAGUNA Design Study
CERN
CH-1211, MO4010
Geneva 23, Switzerland

Dear André,

On behalf of the South Dakota Science and Technology Authority (SDSTA) team, I'd like to thank you for participating in the recent long-baseline neutrino discussions at the Sanford Underground Research Facility (SURF) in Lead, SD. Like you, we felt the discussions were very productive and are already helping to establish a strong working relationship between the Long-Baseline Neutrino Experiment (LBNE) and the Long Baseline Neutrino Oscillations (LBNO) teams as the LBNE Collaboration is reformulated.

The SDSTA is proud to be a part of this project and excited to work with the collective LBNE – LBNO team to field an operational experiment as soon as possible. If there is anything that my staff or I can do to assist, please let us know. Again, thank you for visiting us, and we hope you enjoy the enclosed group picture from the SURF 4850L.

Warm regards,

Mike Headley
Executive Director

LBNE-LBNO geotech meeting

Side-by-side comparison of Homestake and Pyhäsalmi sites

ROCKPLAN

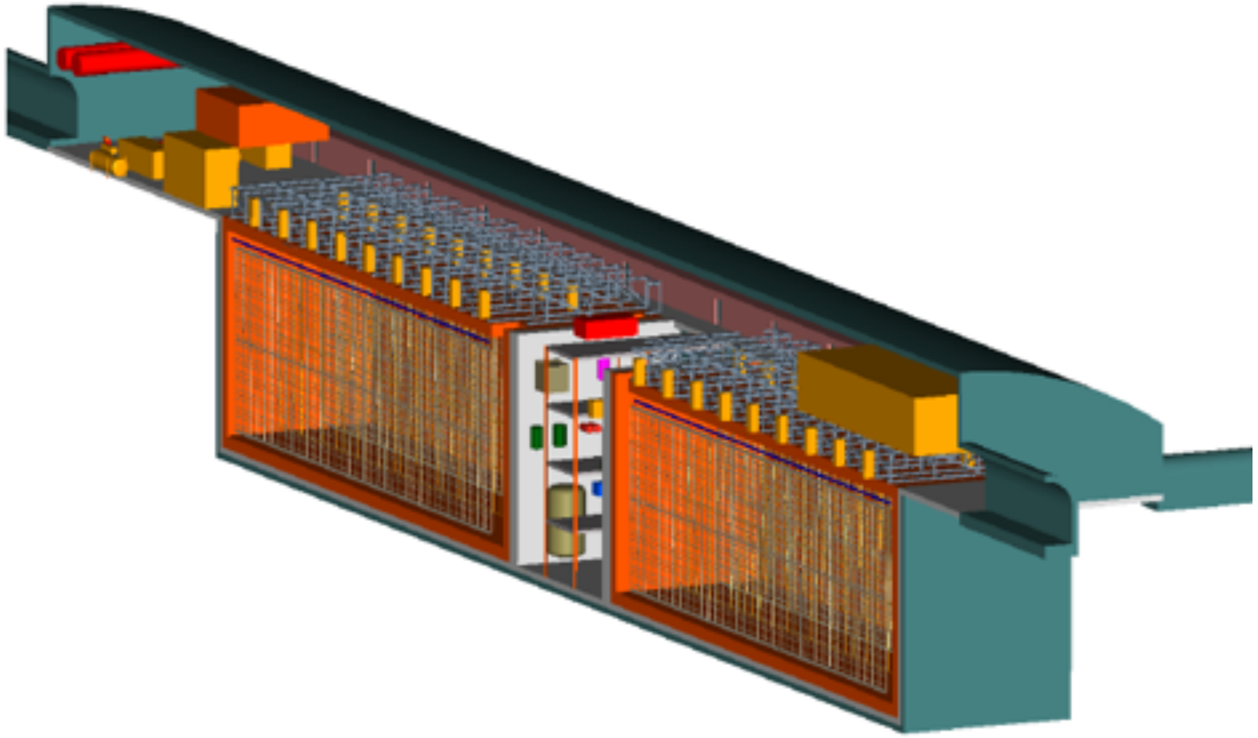
PYHÄSALMI + HOMESTAKE
TABLE OF CONTENT

2

Guido Nuijten

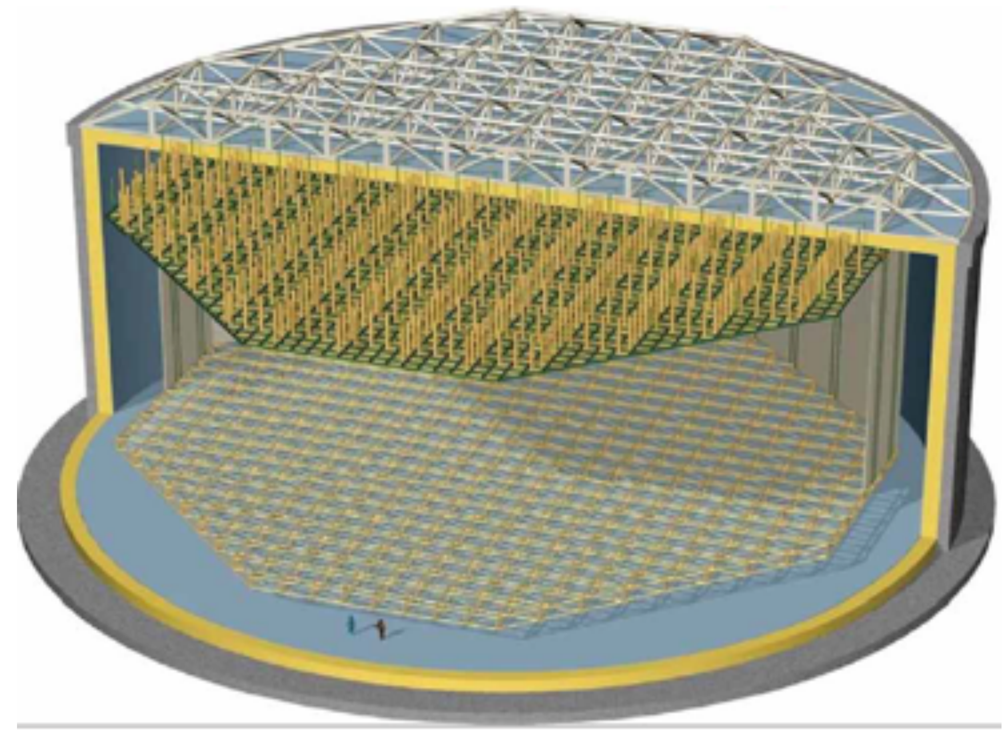
Rectangular vs. Cylindrical Cryostat

LBNE Design:
Rectangular, rock-supported cryostat



- Current reference design for LBNF
- Rectangular geometry makes maximum use of excavated volume
- Rectangular geometry requires rock support

LBNO Design:
Cylindrical, free-standing cryostat



3D Tank & Detector Model Screen Shot (courtesy ETH Zürich)

- Follows industry standard design and construction methods
- Requires larger span cavern, similar to LBNE WCD design

Joint LBNE – LBNO – FNAL – CERN evaluation launched

ELBNF international project

LOI submitted to Fermilab PAC in December 2014
Signed by ≈500 authors, 142 institutions, 23 countries

- An on-going **process to merge all previous efforts and any other interested parties** to build, operate, exploit
  - a (staged) 40 kt LAr detector, at the SURF site, 1300 km from FNAL
  - a high granularity/high precision near detector
  - exposed to a 1.2 MW, tunable ν beam (1st and 2nd max.) produced by the PIP-II upgrade at FNAL by 2024.
- Fermilab to work with international and U.S. partners, **with a model derived from the CERN LHC**, which clearly separates the ownership of the experiment (International Collaboration) from the ownership of the facility (Host Lab)
- **The process of setting up a large international collaboration is in motion. On Jan 22-23 first ELBNF proto-collaboration meeting.**
- The goal is to enable the operation of an initial 10 kt far detector in ~2021 and provide a clear path to the full ELBNF experiment soon thereafter.
- **A strong R&D program has started and is needed to provide the necessary input to the definition of ELBNF.**

Summary and Conclusions (I)

- **A next-generation very large-scale neutrino observatory must be capable of addressing key open questions and complete our knowledge in neutrino oscillations:**
  - Is there CP violation (CPV) in the leptonic sector ?
  - Are matter effects in long-baseline oscillations understood and what is the neutrino mass hierarchy (MH) ?

- **The recent measurements of the PMNS mixing matrix has now promoted these open questions as the next milestones, with exciting implications on our understanding of the matter-antimatter asymmetry in the Universe.**

- These challenging physics goals can be uniquely addressed by a new very large underground detector coupled to a long-baseline neutrino beam. **Such a new facility will also be an ideal observatory for solar, atmospheric and supernovae neutrinos, as well as for high sensitivity nucleon decay searches.**

- **The European neutrino community has early on recognised the importance of this sector and has been strongly supported to prepare the new experiment with the LAGUNA and LAGUNA-LBNO design studies.**

- **Following the European Strategy Recommendation and the P5 report in the USA, neutrino physics "entered the global era" and the European neutrino community is now exploring the international merger – ELBNF – to be hosted by Fermilab.**

Summary and Conclusions (II)

- Since the completion of the DS, the LAGUNA-LBNO consortium is active in the construction of a large (300t) demonstrator (CERN WA105) using the techniques developed during the conceptual design phase.

- **WA105 is now an approved CERN experiment, which will provide vital input for ELBNF.** We have a set of **well defined technical and physics goals** to deliver which will have implications for the long baseline neutrino programs being developed.

- WA105 although an a priori independent effort, was strongly supported by the LBNE management, the Fermilab management and is **included in the ELBNF LOI submitted to PAC in Dec 2014, as part of the necessary path towards the definition of the far detector modules.**

- **The success of the WA105 R&D will allow to expand the physics capabilities of ELBNF by permitting the addition of cost-effective modules to help reach the design value of 40 kt.**

- **WA105 is open to all new collaborators.**

Thank you !

Expected event rates for 20 kton

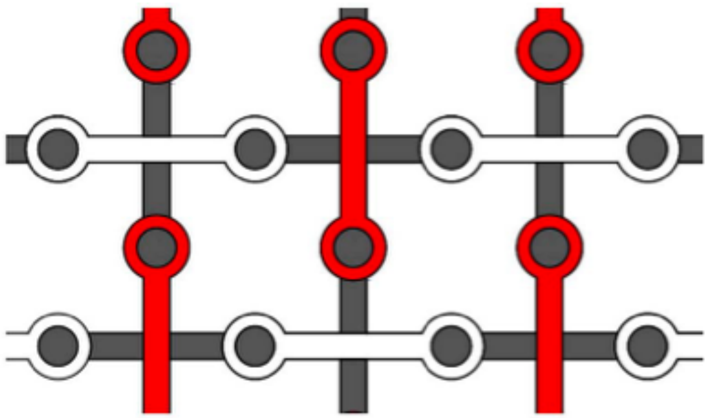
POT normalisation
(corresponds events/1 year):

Protvino: 4e20 pot @ 70 GeV
CERN: SPS 1.5e20 pot @ 400GeV and HP-PS 3.5e21 pot @ 50 GeV

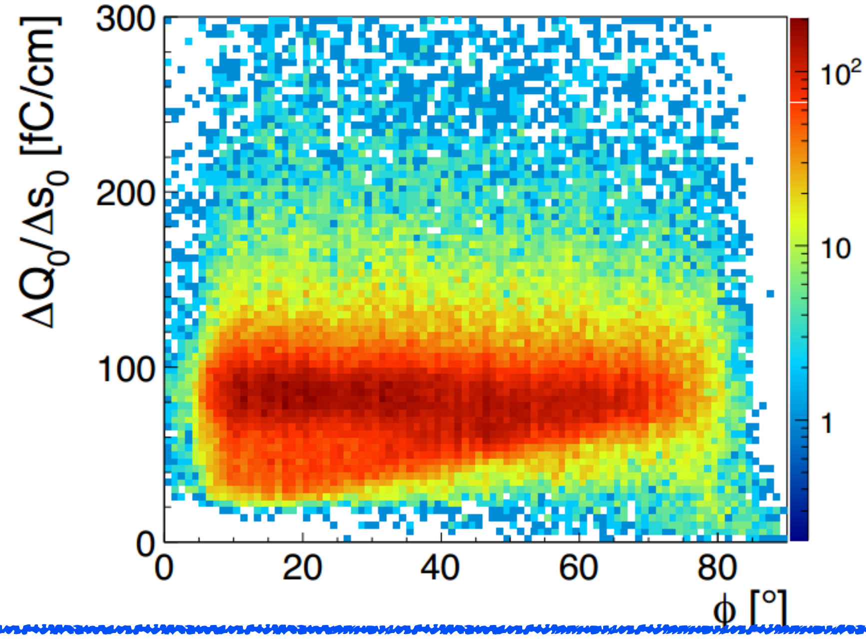
Nu beam	CERN SPS 700kW		CERN HP-PS 2MW		Protvino 450kW	
	ν_μ CC	$\nu_e+\bar{\nu}_e$ CC	ν_μ CC	$\nu_e+\bar{\nu}_e$ CC	ν_μ CC	$\nu_e+\bar{\nu}_e$ CC
NEUT					2056	21
GENIE	**1428**	10	**4007**	26	**1805**	18
GLOBES	1426	10	3975	26	1756	18

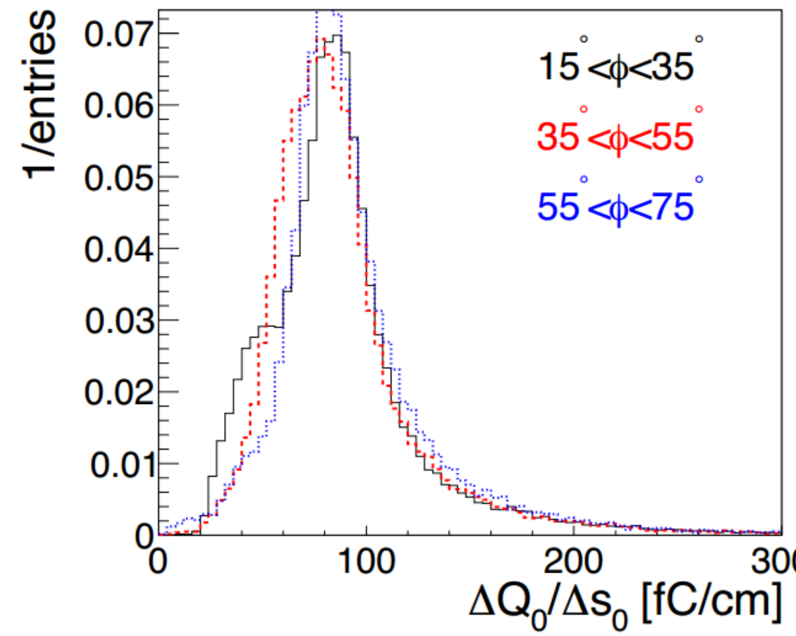
Anti-nu beam	CERN SPS 700kW		CERN HP-PS 2MW		Protvino 450kW	
	$\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	$\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	$\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC
NEUT					561	6
GENIE	**559**	5	**1438**	26	**525**	6
GLOBES	680	6	1741	26	629	6

Other anodes tested



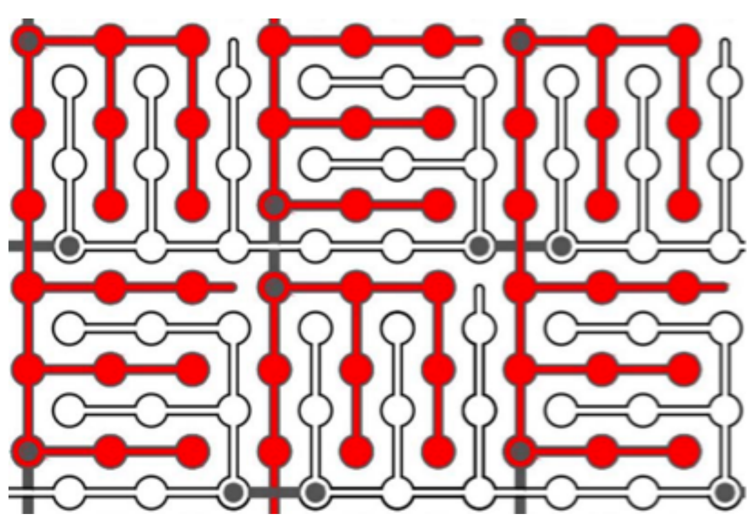
dC/dl~100 pF/m



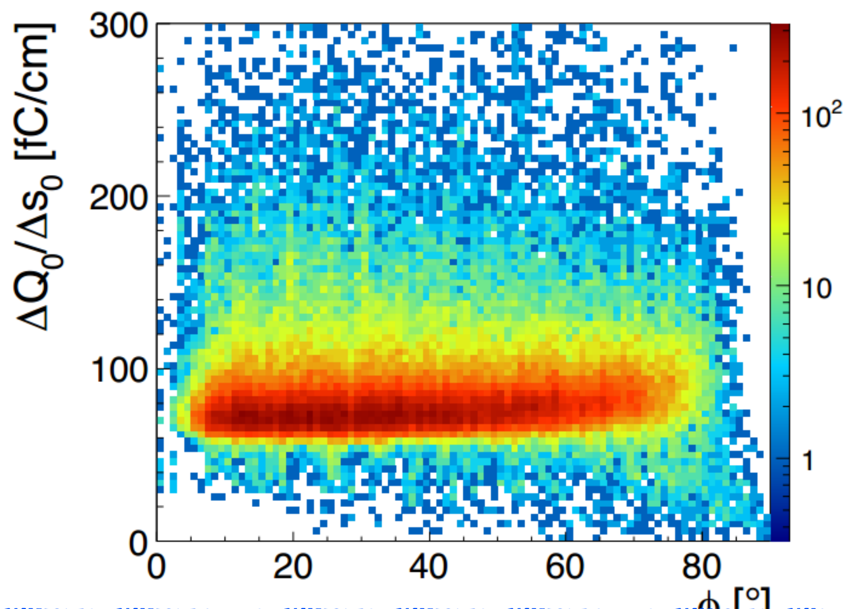


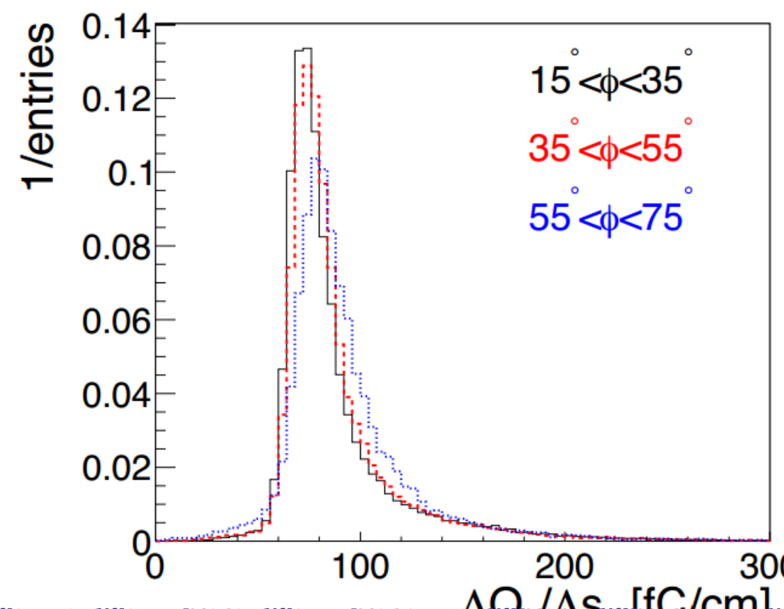
Pattern too loose, non uniform charge collection between strips

JINST 9 P03017



dC/dl~250 pF/m





Compatible performance as 150 pF/m anode, but has higher capacitance