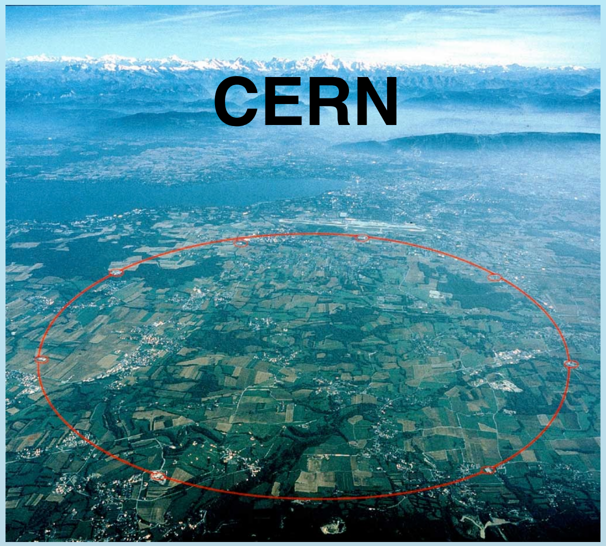
Liquid Argon developments in Europe and Japan

Sebastien Murphy ETH Zürich

on behalf of the Laguna/LBNO collaboration

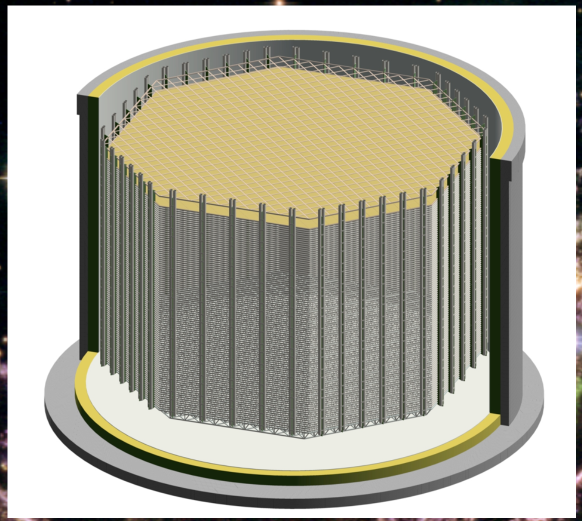
Motivation for Laguna-LBNO

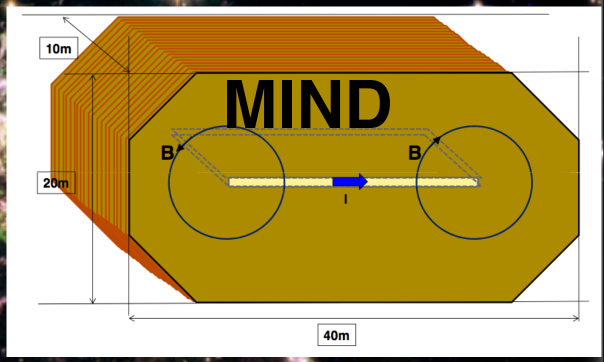


2300 km

GLACIER 20kt,50 kt

deep underground





neutrino beam + near detector

- ✳wide band ν_μ beam ~1-10 GeV => covers 2 oscillation maximums
- ✳SPS protons @ 400 GeV
- ✳New 50 GeV HP-PS 2MW
- ✳Near detector:
  HpAr TPC + magnetised iron detector (MIND)

Deep underground neutrino observatory

- ✳Giant double-phase LAr TPC+ magnetized iron detector (MIND)
- ✳Neutrinos from MeV to 10's GeV (accelerator based, supernovae, reactors,solar, atmospheric..)
- ✳Address questions of particle and astroparticle physics
- ✳Proton decay

A new massive deep underground neutrino observatory for long baseline neutrino studies, capable of proton decay searches, atmospheric and astrophysical neutrino detection

ETH

Laguna-LBNO: an incremental approach

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Expression of Interest

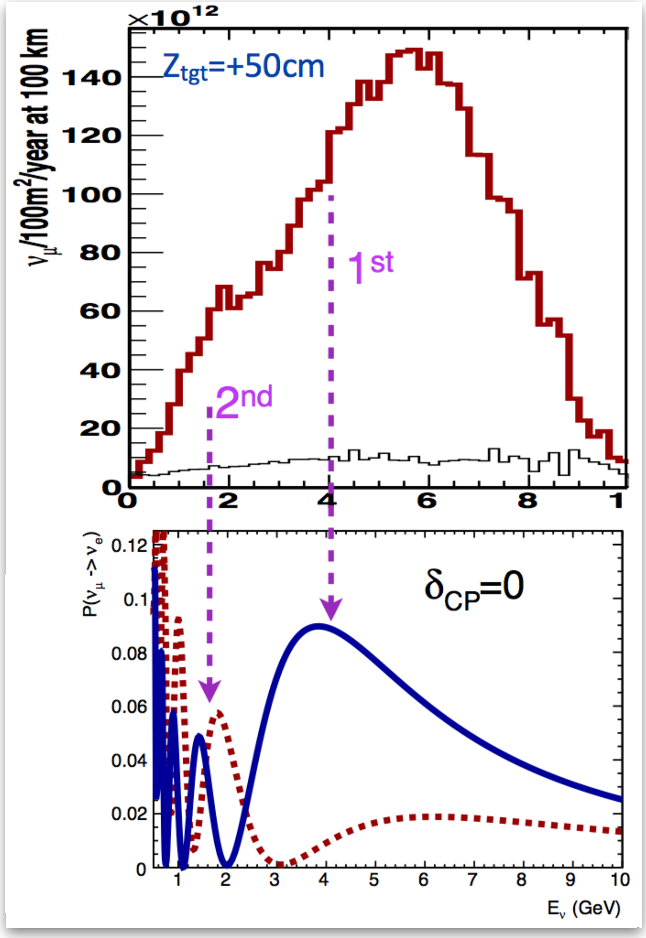
for a very long baseline neutrino oscillation experiment

(LBNO)

LAGUNA-LBNO Expression of interest (~300 members; 14 countries + CERN):

- **phase 1**: SPS 700 kW + 20 kton LAr + 35 kt iron/scintillator
  - ➡ Mass hierarchy 5σ + CP exploration
- **phase 2**: add 50 kton: 70 kton LAr and/or 2 MW from HP-PS
  - ➡ Full CP discovery (5σ)
- **phase 3**: Nufact+ ?
  - ➡ precision measurements

Laguna-LBNO: a rich and wide range of (new) physics

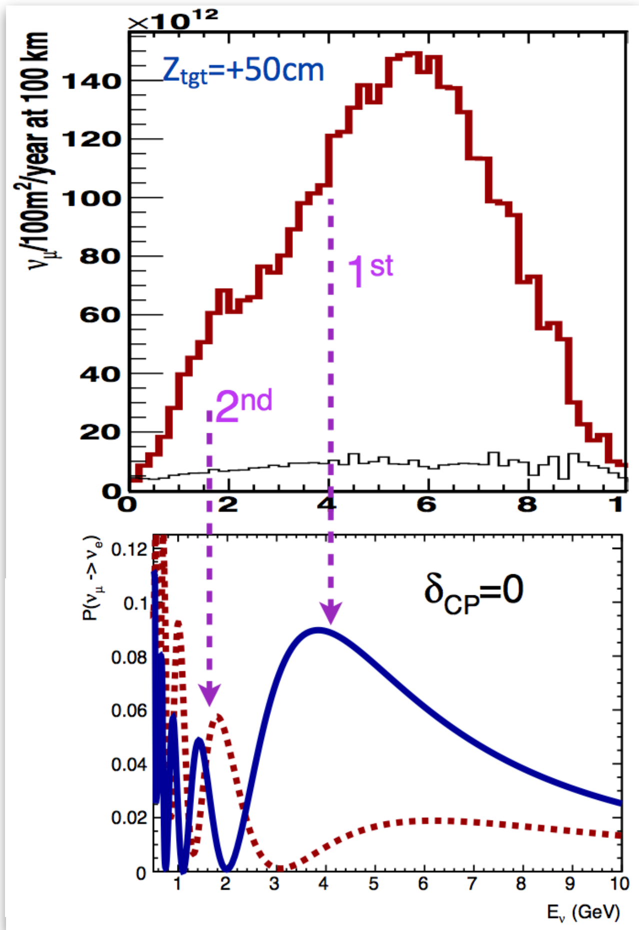


1. Accelerator based neutrino physics:
study the L/E feature of the oscillation induced by matter effects and CP-phase terms. **Cover 2 oscillation peaks.**
Mass Hierarchy determination @ 3σ C.L in 2.5 years (5σ in 6.5 years). CP-phase measurement 1st phase 60% coverage @90%C.L. CPV @ 5σ C.L with upgrades

2. Non Accelerator based:
Significantly extended sensitivity to nucleon decay in many channels e.g: $p \to \nu K > 2*10^{34}$ y, $n \to e^- K^+ > 2x10^{34}$ y (90%C.L.). 20 kton 10 years.

3. Neutrino Astronomy:
Supernova neutrinos >10000's events @ SN@10kpc (20kton)
Diffuse Supernova Neutrinos (DSN)
Neutrinos from DM annihilation
Atmospheric Neutrinos (5600 events/y, 20 kton)

Laguna-LBNO: a rich and wide range of (new) physics



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2. Non Accelerator b
Signific

x10³⁴ y

Far detector with **Large mass**, low energy detection threshold **excellent energy resolution** and tracking performance over a **wide energy range** to "see" the shape of the oscillated spectra

3. Neutrino Astronomy:
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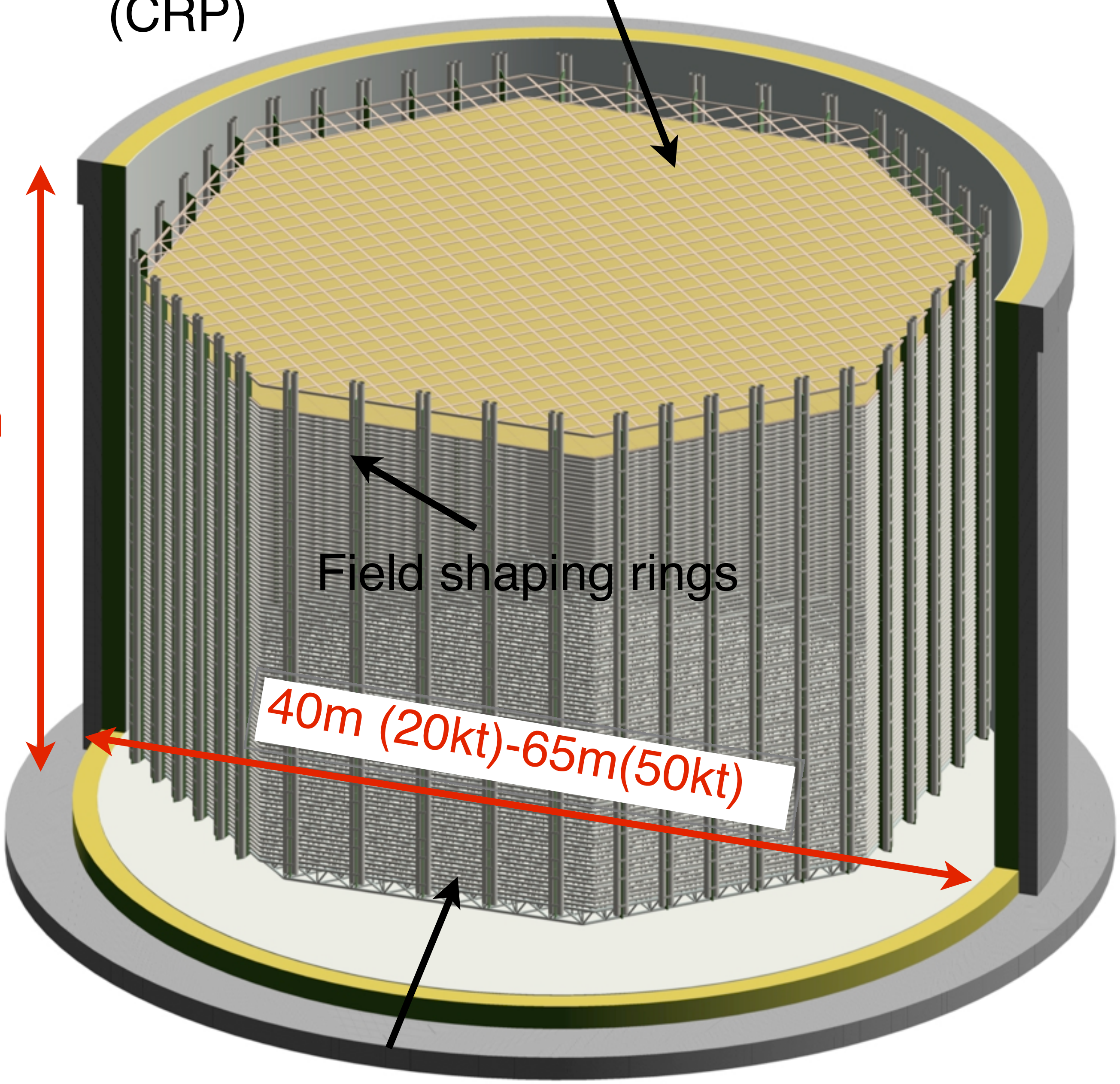
Neutrinos from DM annihilation
Atmospheric Neutrinos (5600 events/y, 20 kton)

Giant Liquid Argon Charge Imaging expERiment

focus on two designs: GLACIER 20kt, 50kt



modular, developing both designs

	20KT	50KT
Liquid argon density at 1.2 bar [T/m3]	1.38346	
Full LAr height [m]	22	
Instrumented LAr height [m]	20	
Pressure on the bottom due to LAr [T/m2]	30.4 (≡ 0.3 MPa ≡ 3 bar)	
Vessel diameter [m]	37	55 76
Vessel base surface [m2]	1'075.2	2'375.8 4'536.5
Instrumented LAr area (percentage) [m2]	824 (77%) (76.6%)	1'845 (78%) 3'634 (80.1%)
Liquid argon volume [m3]	23'654.6	52'268.2 99'802.1
Instrumented LAr mass [KT]	22.799	51.299 100.550
Charge readout square panels (1m×1m option)	804	1'824 14'456
Charge readout triangular panels (0.5m2)	40	60
Charge readout square panels (4m×4m option)	40	104
Charge readout triangular panels (2m2)	20	16
Number of signal feed-throughs (666 ch/FT)	416	1'028 1'872
Number of PMTs (1m × 1m option)	~800	~1'850 909
Number of PMTs (1.2m × 1.2m option)		~1'288
Number of PMTs (2m × 2m option)	~200	~450
Number of field shaping rings	100	
Vertical spacing (heart to heart distance) of field shaping rings [mm]	200	

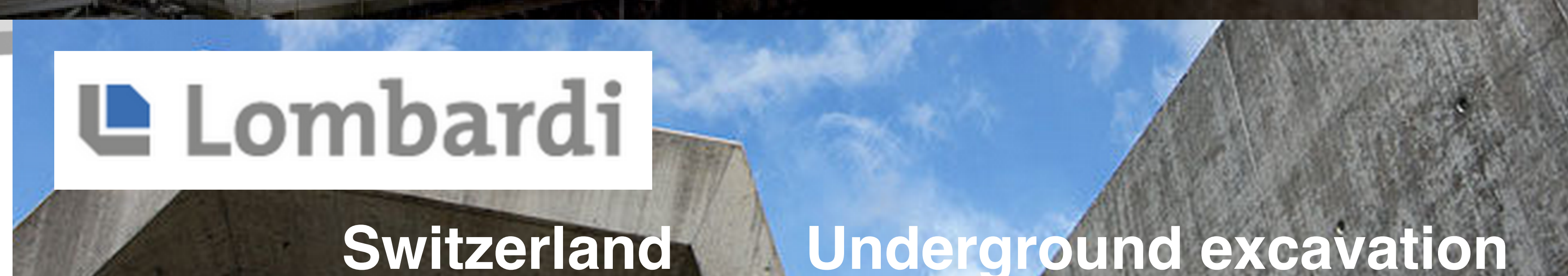
Large industrial partnerships

France
Sofregaz

UK
Alan Auld
GROUP LTD

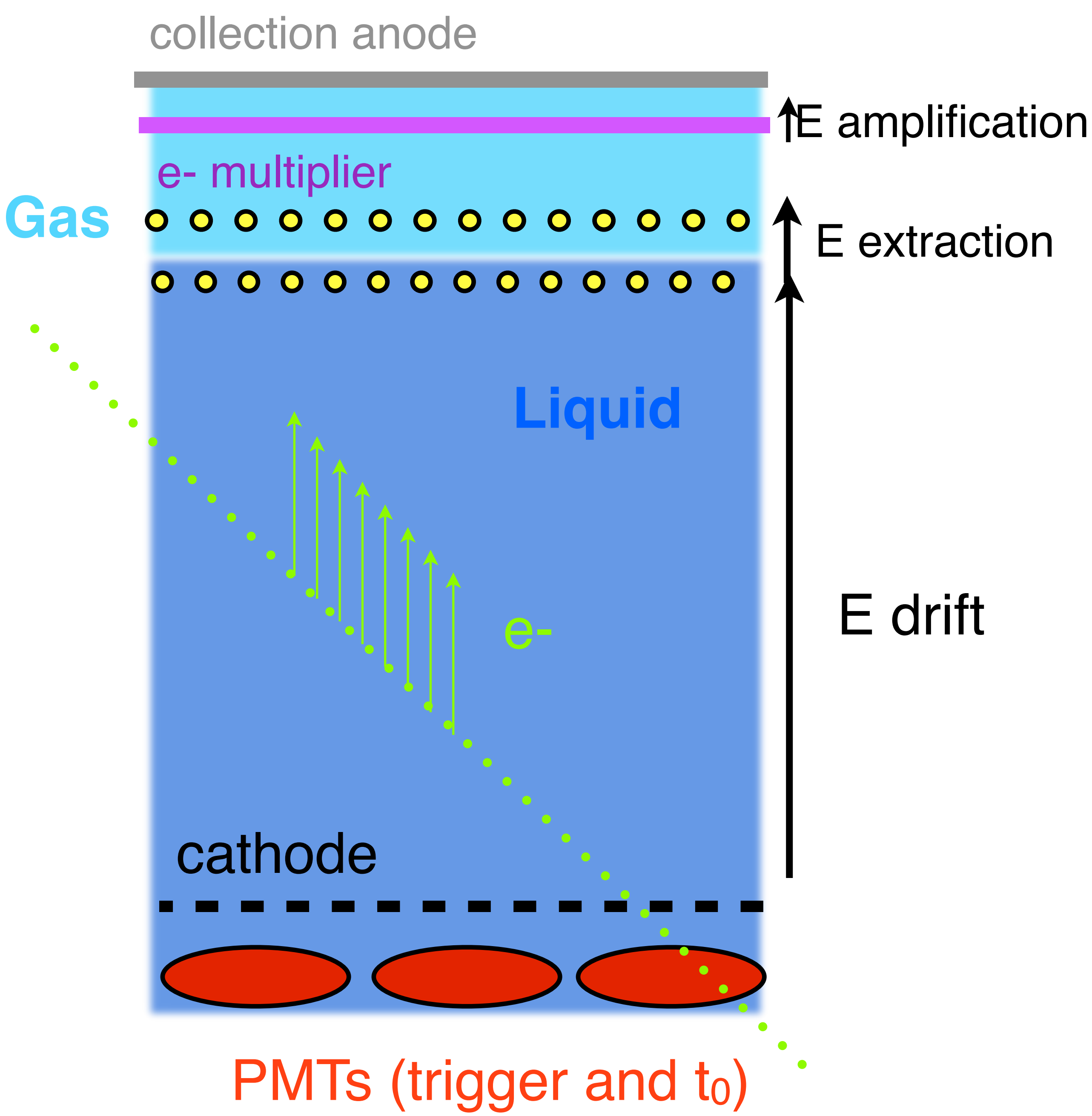
UK
RHYAL ENGINEERING

20 m
drift



Double phase LAr-TPC

signal readout on 2 view collection anode
Signal amplified in the gas



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

2008-2011: Proof of principle with 10x10 cm^2 double phase LAr LEM-TPC prototype:
- A. Badertscher *et al.*, Construction and operation of a Double Phase LAr Large Electron Multiplier Time Projection Chamber arXiv:0811.3384
- 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

2011: First successful operation of a 40x80 cm^2 device
- 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
- First operation and performance of a 200 lt double phase LAr LEM-TPC with a 40x76 cm^2 readout, JINST 8 (2013) P04012

2012-2013: further R&D towards final, simplified charge readout for GLACIER:
- first results presented TPC-symposium, Paris Dec. 2011

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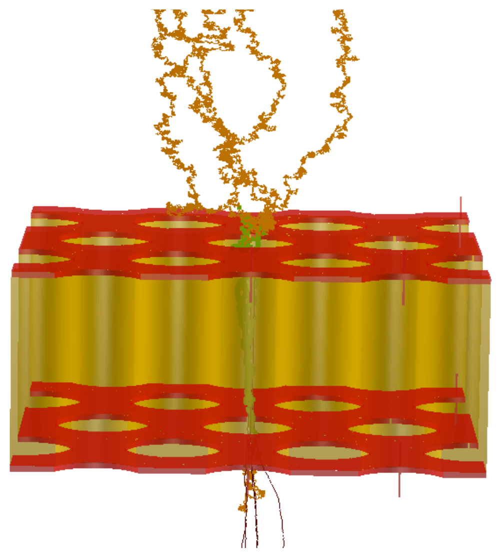
The Double phase concept

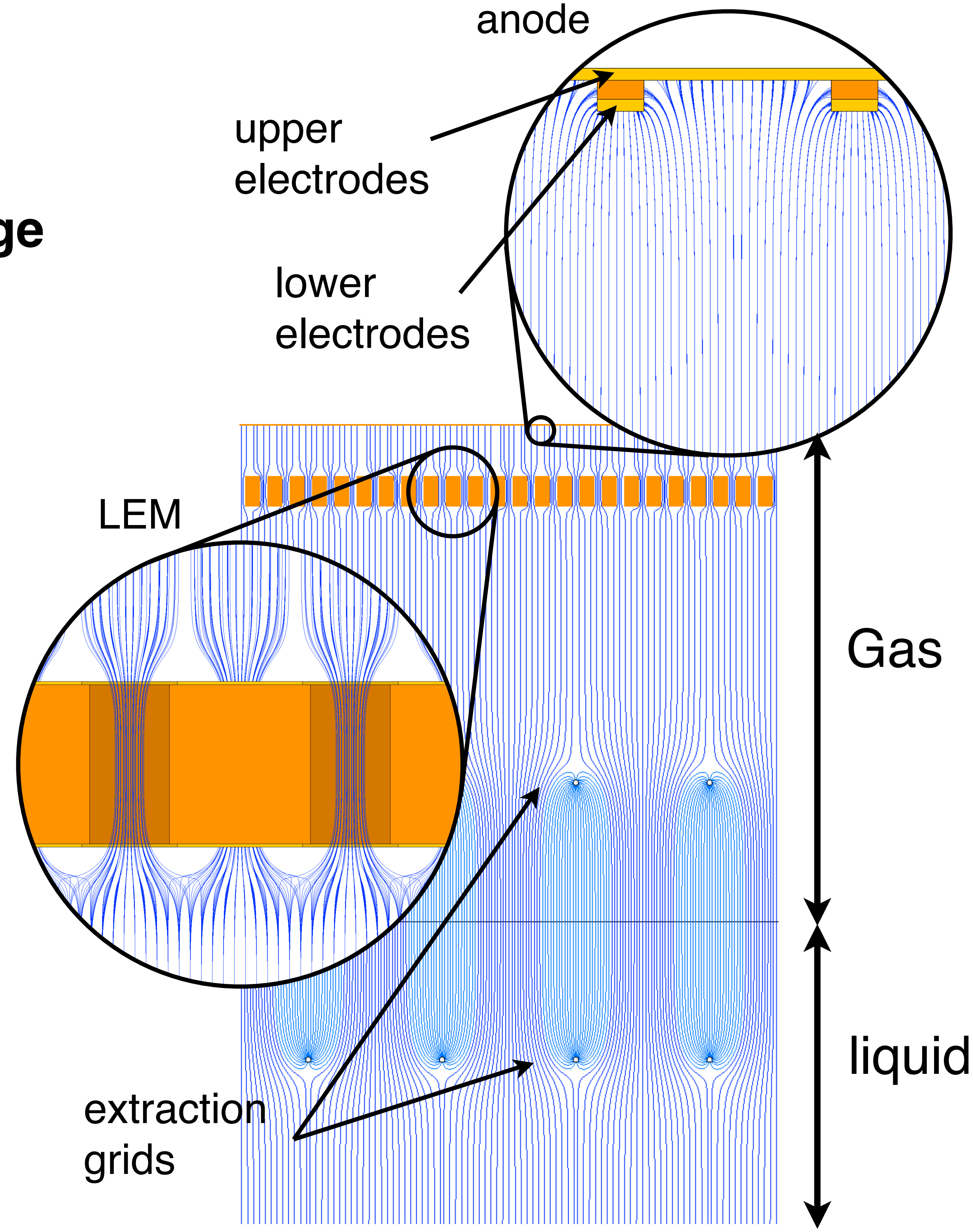
4.) Charge **collection** on a **2D anode readout** (symmetric unipolar signals with two orthogonal views)

3.) Charge multiplication in the holes of the **Large Electron Multiplier (LEM)**



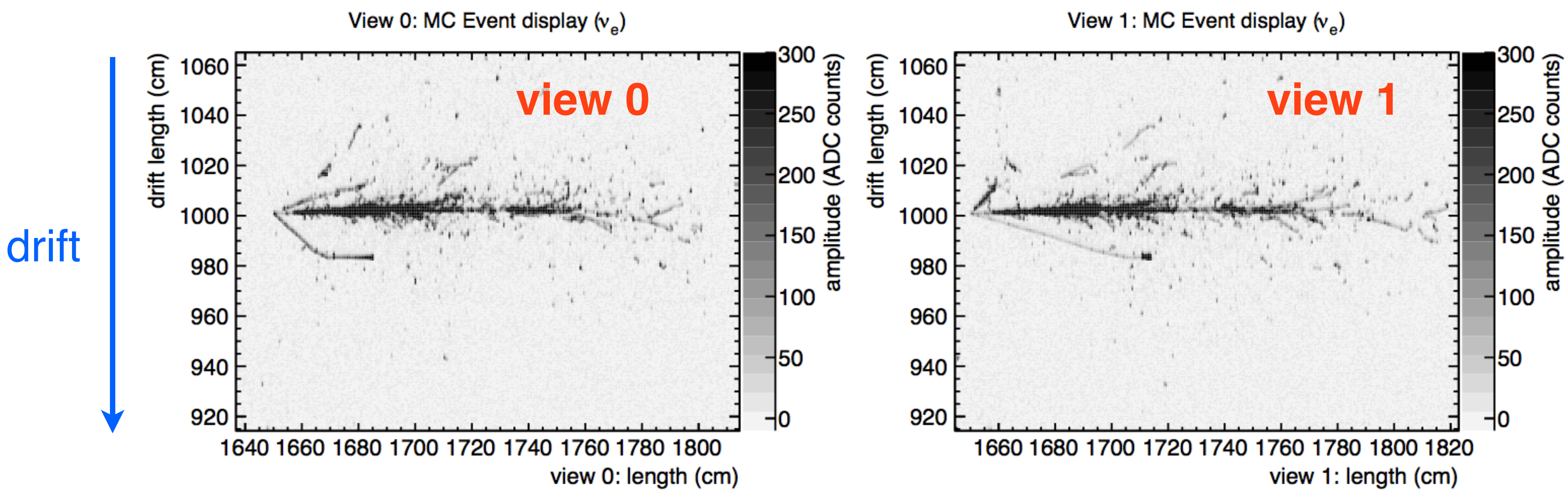
2.) Drift electrons are efficiently emitted into the gas phase

1.) Ionization electrons drift towards the liquid argon surface



Benefits of the double phase LAr TPC

ve CC event in CLACIER



✓Excellent energy resolution and tracking performance. Efficient background rejection (e.g NCπ0 from CCv$_e$)

✓High granularity: ~0.05 cm in drift direction, 3mm in transverse direction

✓Very high signal-to-noise (>100) thanks to amplification in gas. => build large detectors with longer drifts (~20m) and larger readout capacitances.

✓Adjustable energy threshold=>sensitivity from sub-GeV to multi-GeV

R&D towards GLACIER

Double phase is the state of the art technology to extrapolate to very large liquid argon volumes.

Key to LBNO: The LAr far detector.
Demonstrate the operation of large double phase LAr detectors.

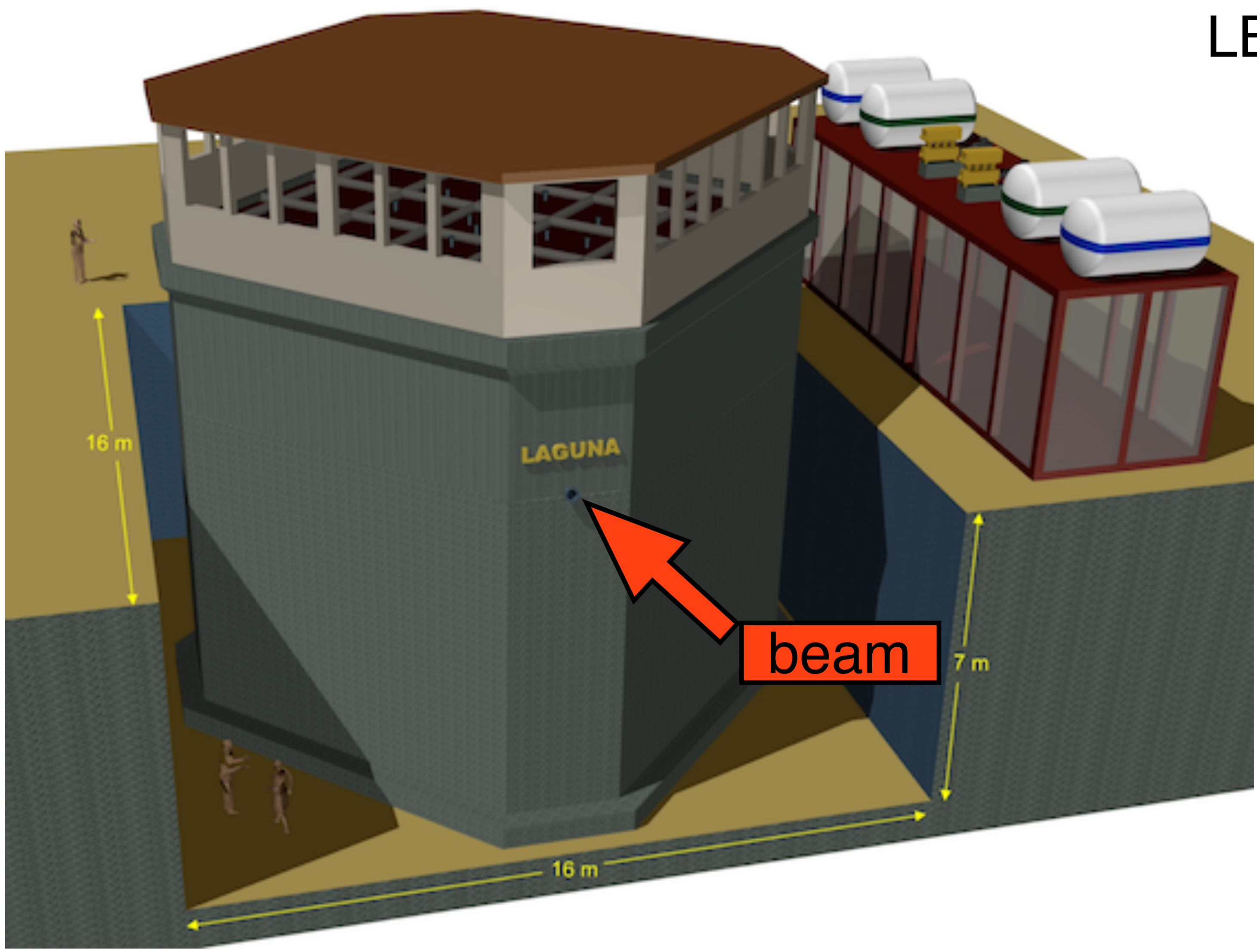
Some of the components we have to test and extrapolate to large areas:

- ✳Charge readout
- ✳Long distance drift (up to 20m) + diffusion
- ✳HV up to the MV scale
- ✳purity in non evacuated membrane tank
- ✳cost effective cold front-end electronics and DAQ
- ✳UV scintillation light readout with long term stability

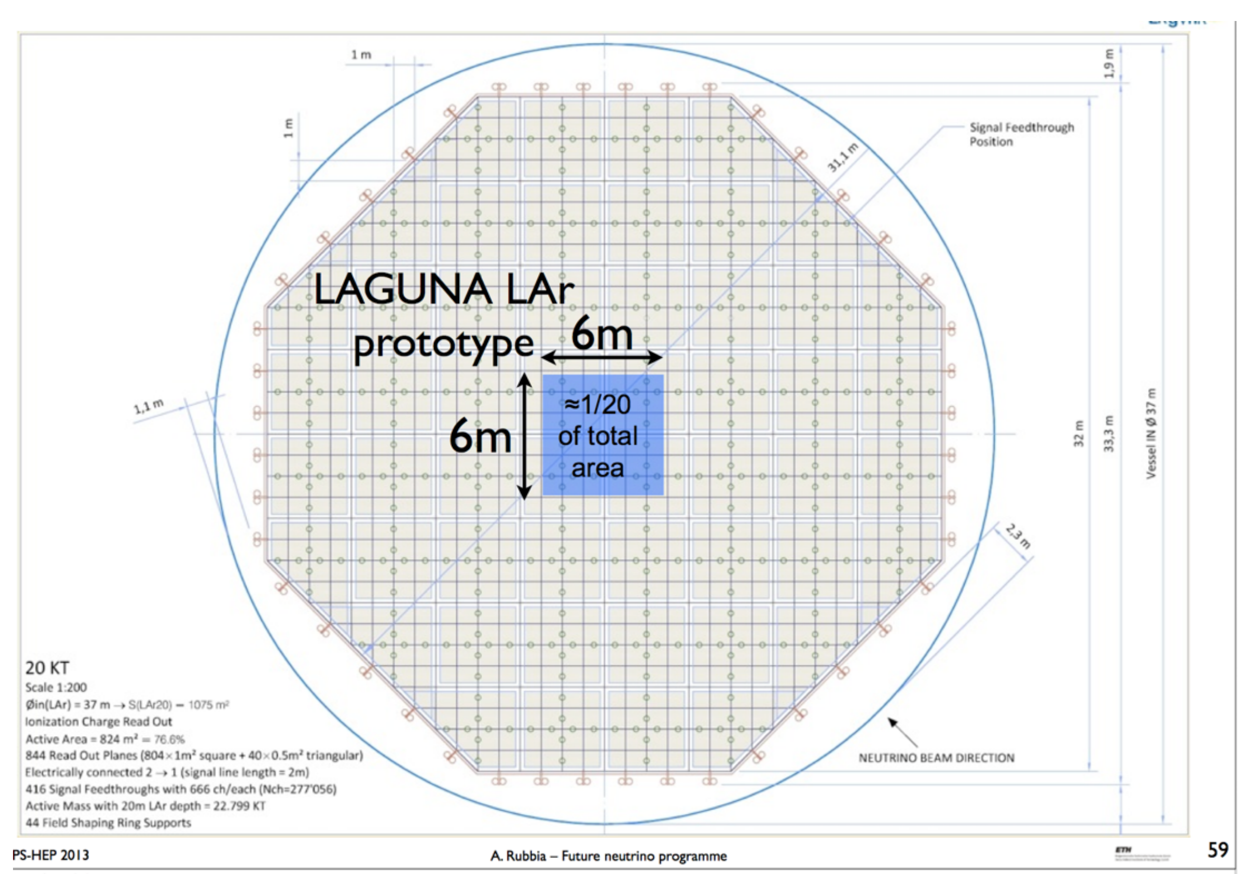
All this will be tested in a double phase LAr TPC at the a relevant scale of 300 ton @ CERN (WA 105)

LBNO prototype

LBNO prototype WA105 to be built at CERN: 6x6x6 m³ (~300 ton) double phase LAr demonstrator in charged-particle test beam.

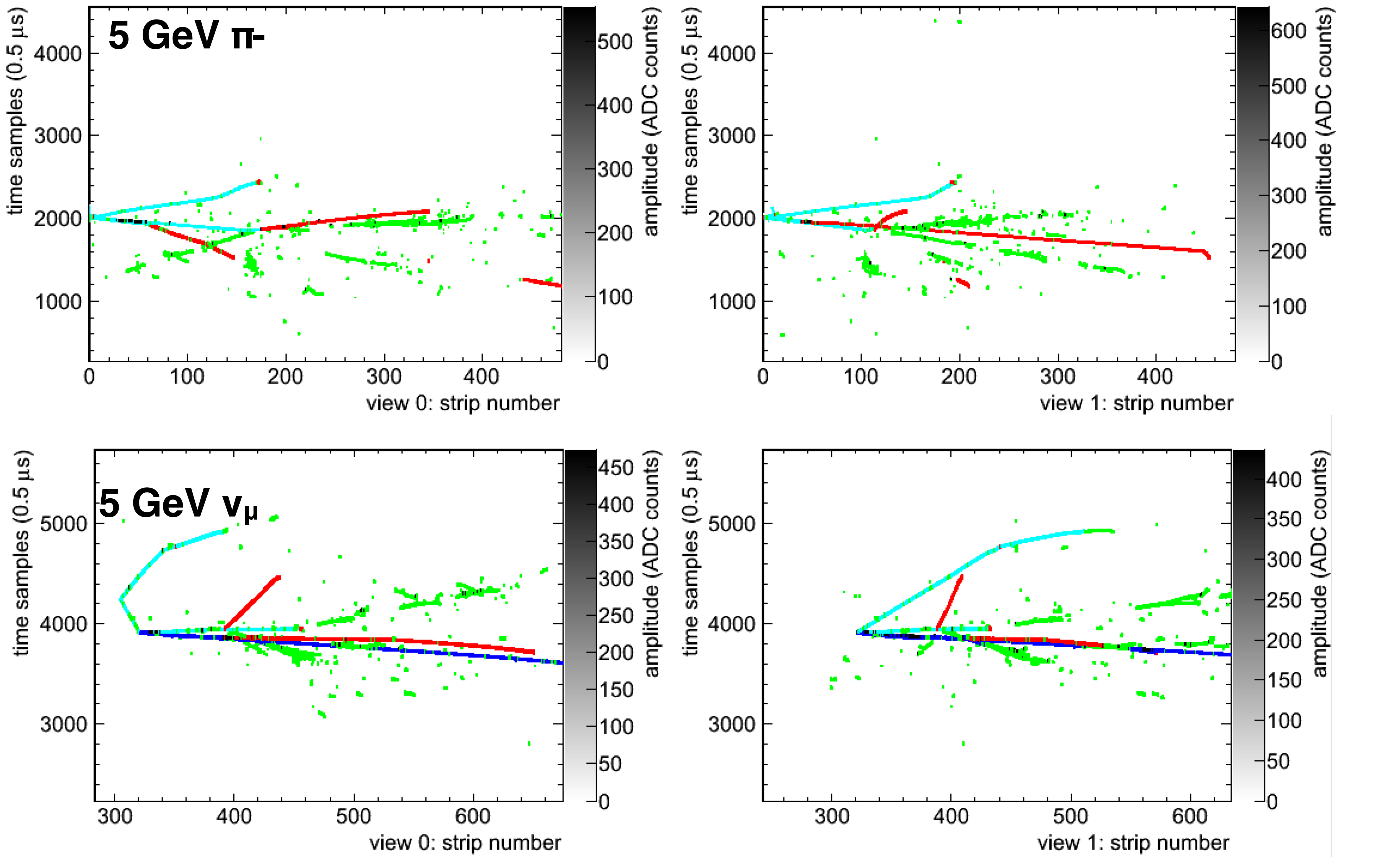


LBNO-proto compared to GLACIER 20 kt



simulated events in LBNO-prototype

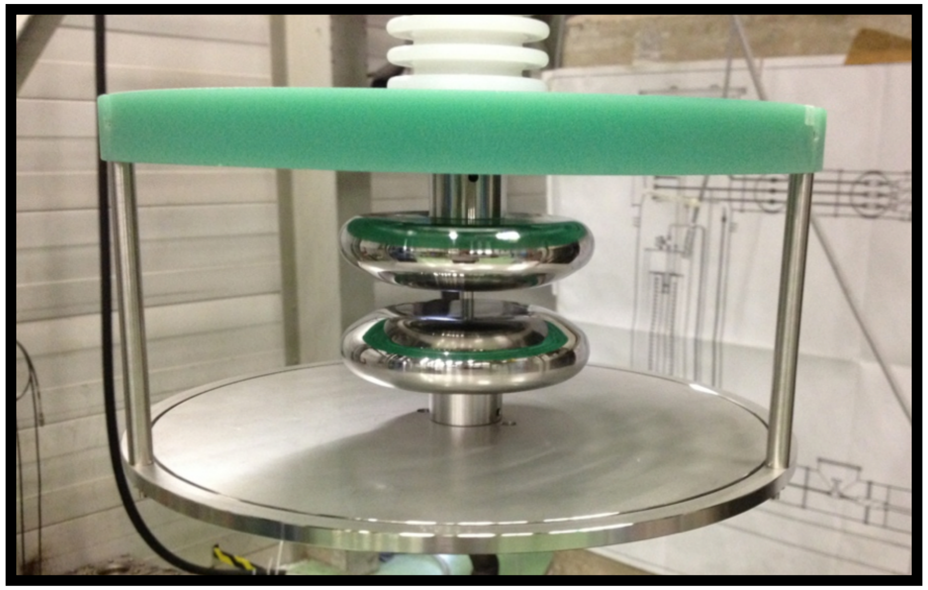
test reconstruction on data from charged particle beam (well defined primary particles and energies)



pions, electrons/positrons, protons, muons

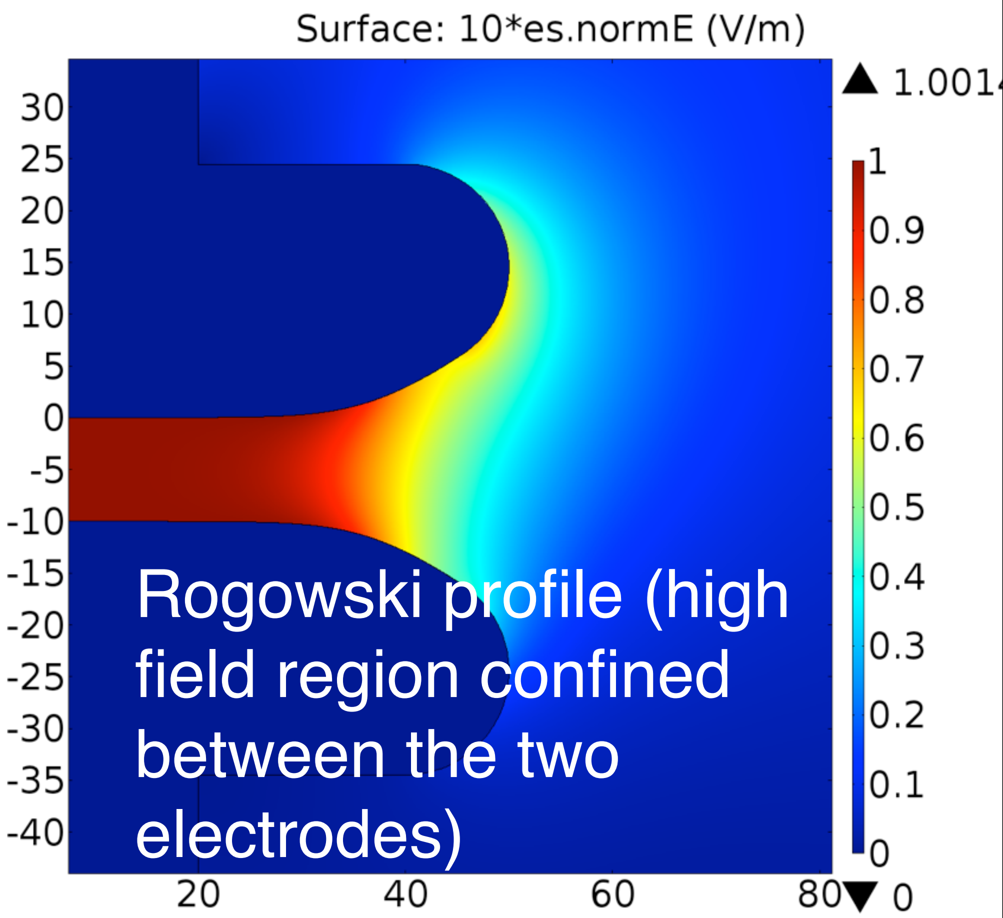
High voltage R&D

to get 0.5 or 1 kV/cm drift field=> proto will test up to 600 kV at the cathode with the LBNO proto



Significant ongoing R&D efforts for the HV system of the drift field:

- Custom development of feedthroughs based on previous experience
- LAr dielectric rigidity versus distance between electrodes
- Bubble and LAr purity effects on discharges
- Argon ionisation and space charge effects
- effect of material
- …



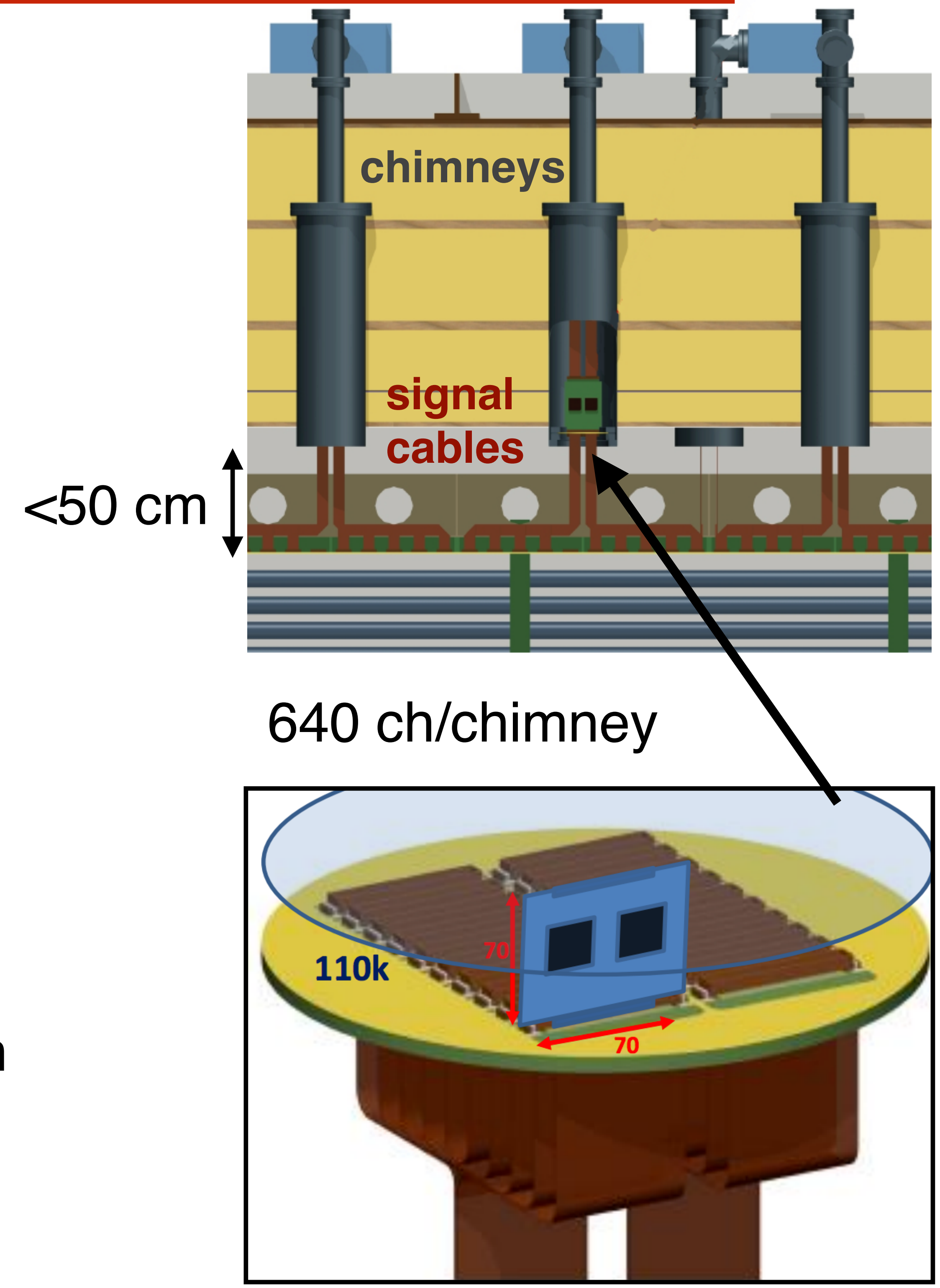
Heinzinger 300 kV DC PS

Cost effective cold front end electronics and DAQ R&D

Remove long cables and their capacitance, exploit intrinsic noise reduction at low T

Front-end electronics inside chimney. All cards are fixed to a "plug" that is accessible from the outside

- distance cards-CRP: 50 cm
- dynamic range 40 MIPS
- Power consumption 18 mW/ch
- ASICs at ~110 K in order to profit from the minimal noise condition



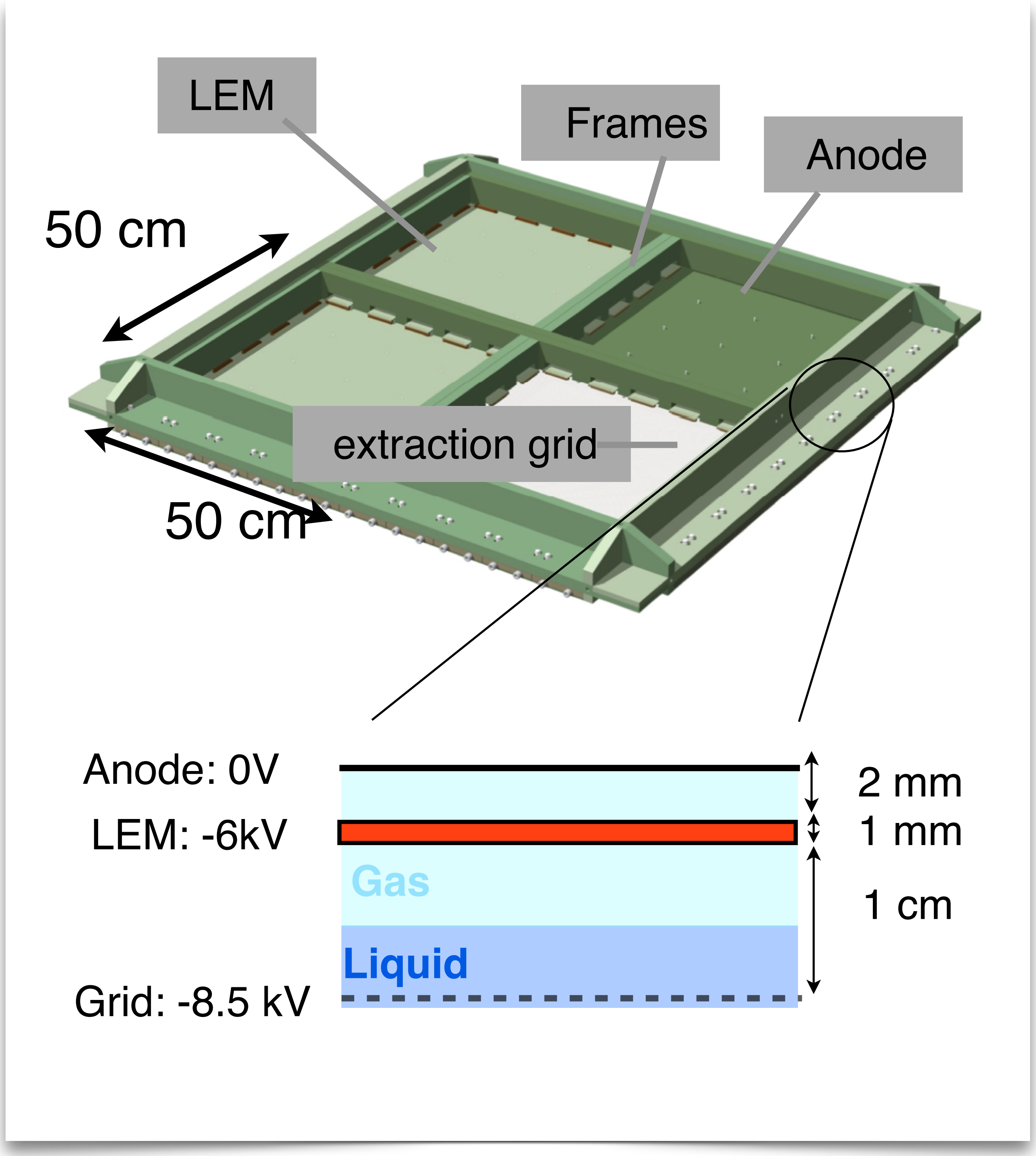
DAQ architecture based on μTCA standard

Digitisation and interface to DAQ in warm zone on deck of tank large

Charge readout R&D

Each Charge Readout Plane is an independent detector

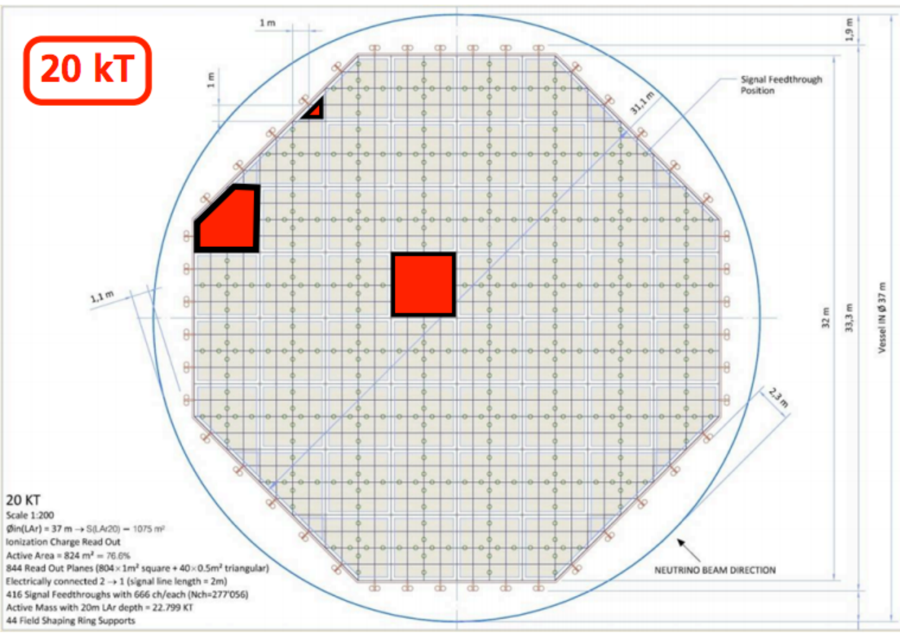
- ✳Has its own signal and HV feed throughs
- ✳Adjustable to LAr level
- ✳Extraction grid, LEM (large electron multiplier) and anode all constructed as **single compact readout module of one square meter. that can fit the prototype but also GLACIER 20kt, 50kt**

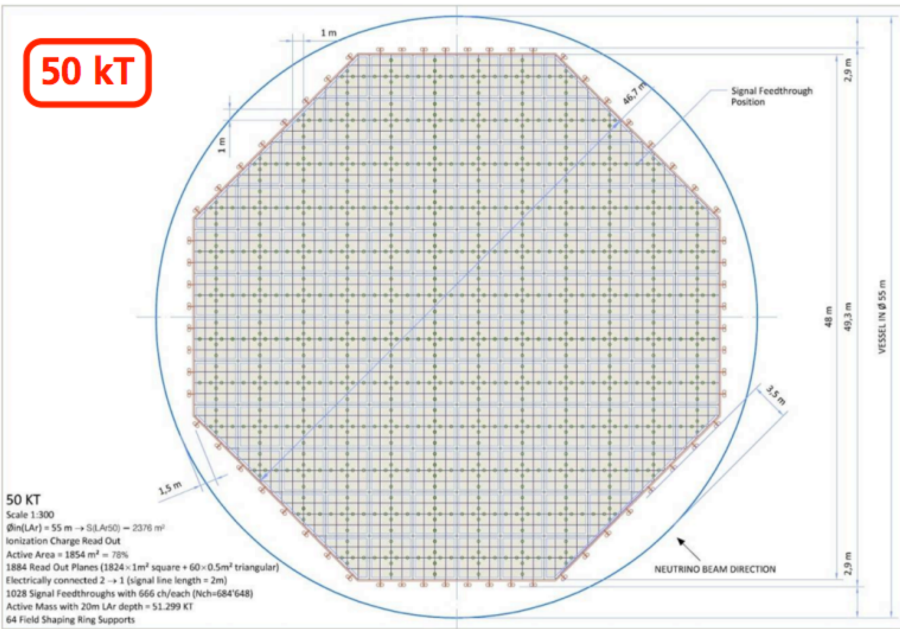


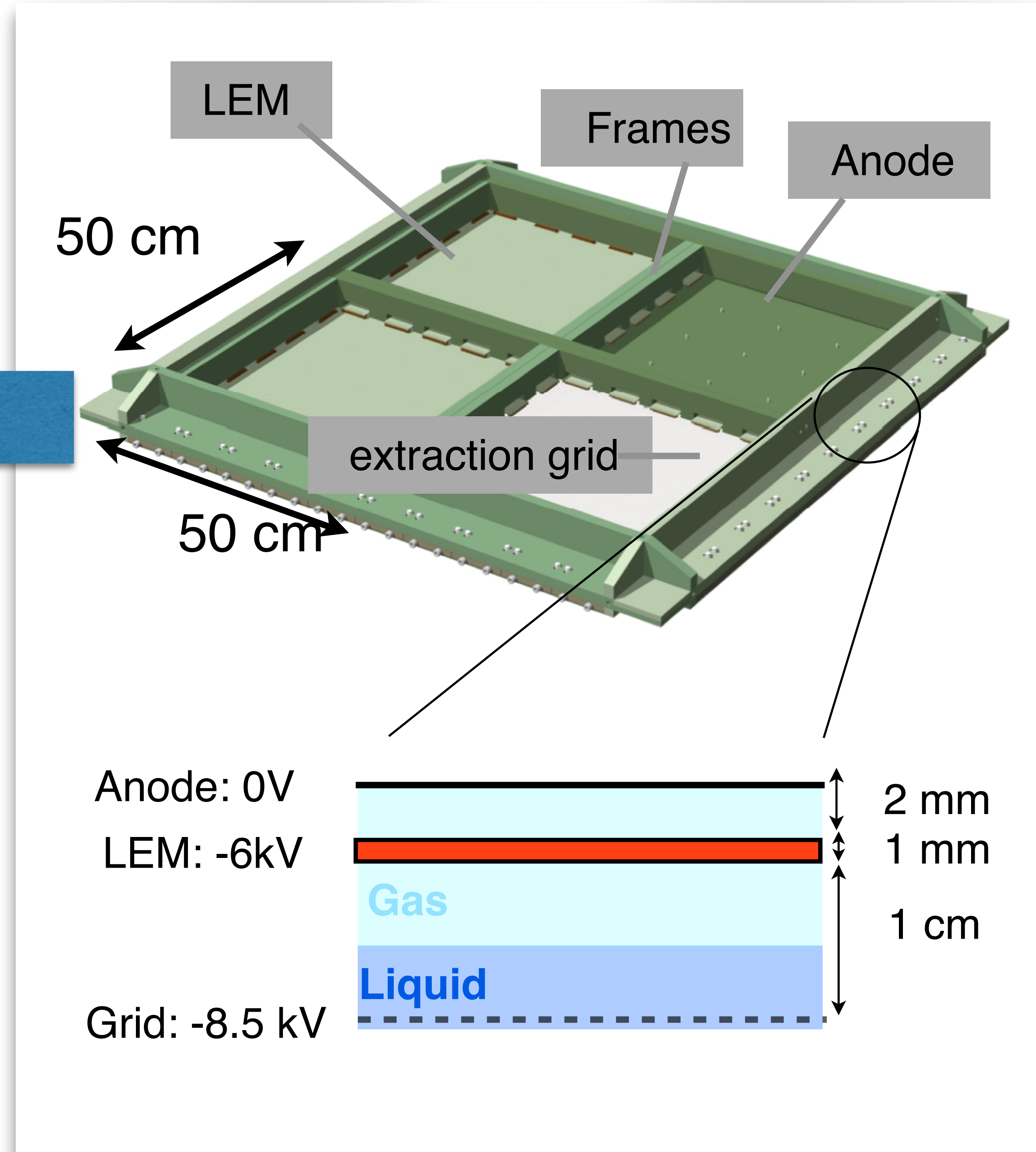
Charge readout R&D

Each Charge Readout Plane is an independent detector

Same design as for GLACIER 20kt, 50kt





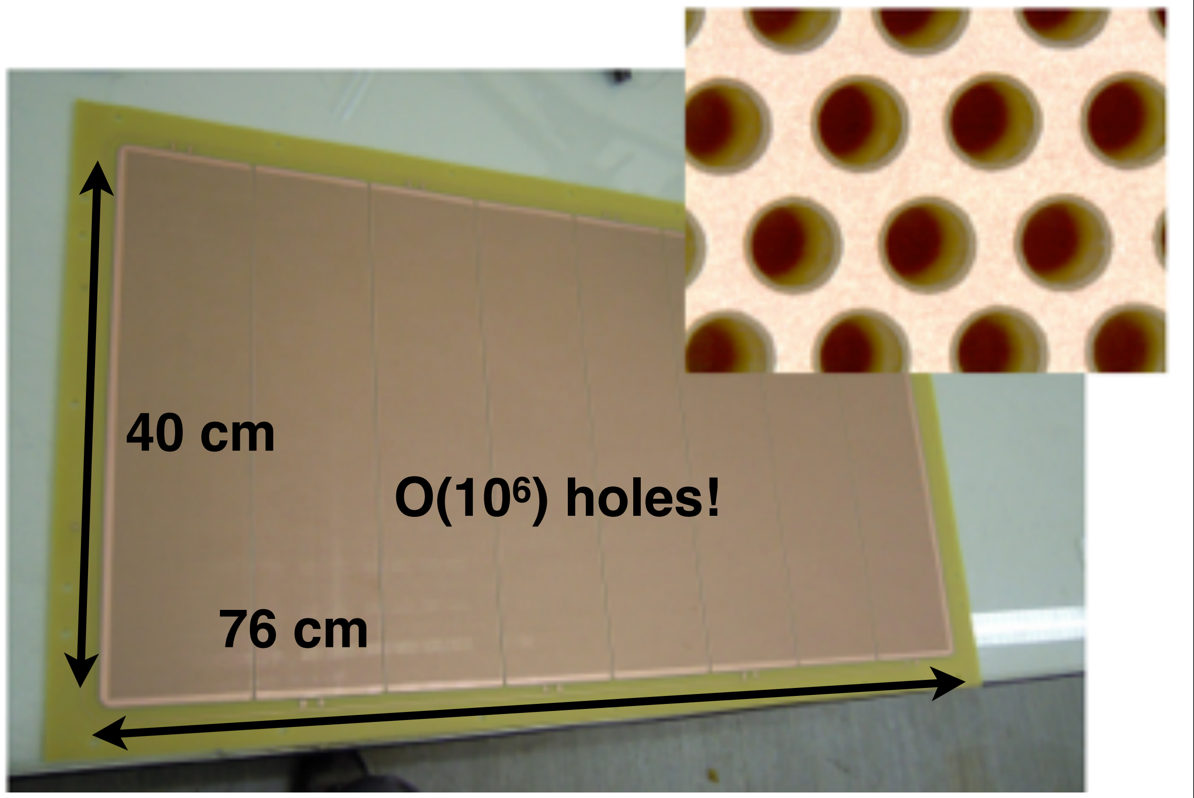


different geometries but all with the same functionality and identical construction sequence.

Towards a large area readout: the 40x76 cm^2 prototype

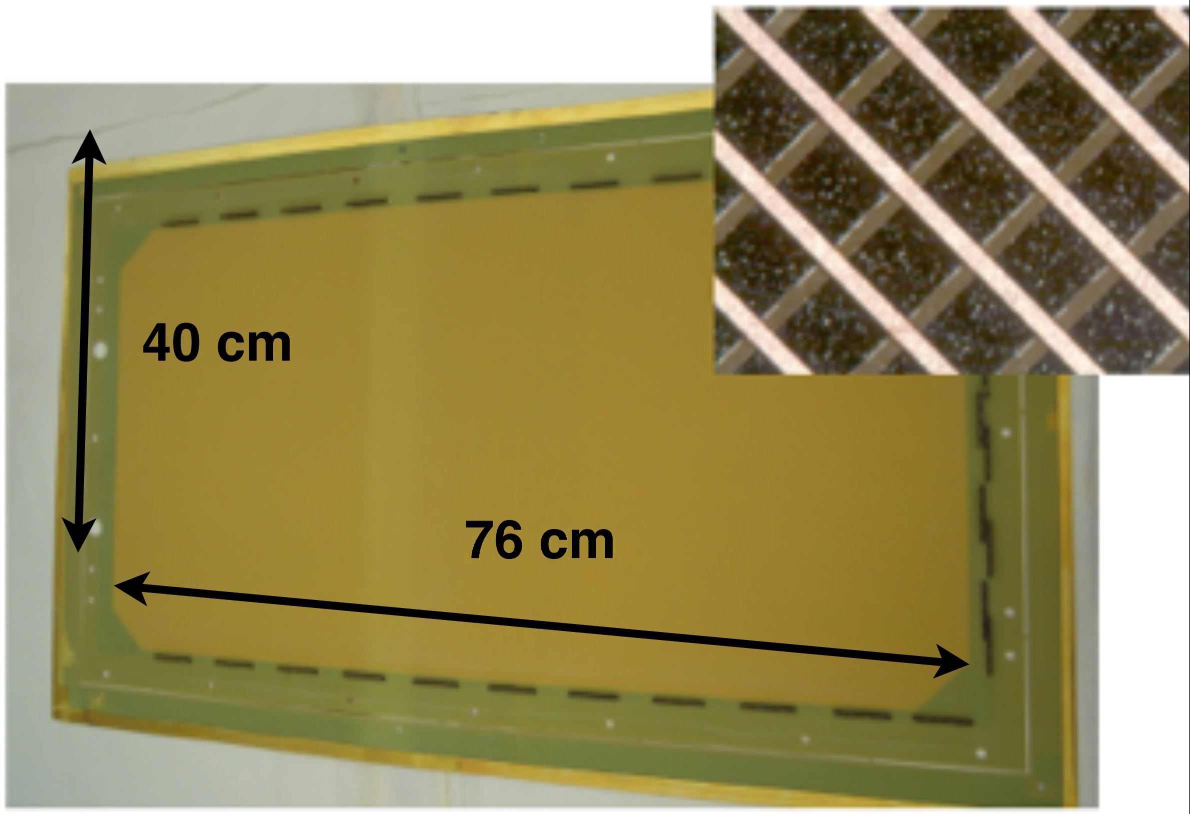
Large Electron Multiplier (LEM)

- ✳Macroscopic Gas hole multiplier
- ✳more robust than GEMs (cryogenic temperatures, discharge resistant)
- ✳manufactured with standard PCB techniques
- ✳Large area coverable by 50x50 cm^2 modules
- ✳Light quenching within the holes



2D projective anode readout

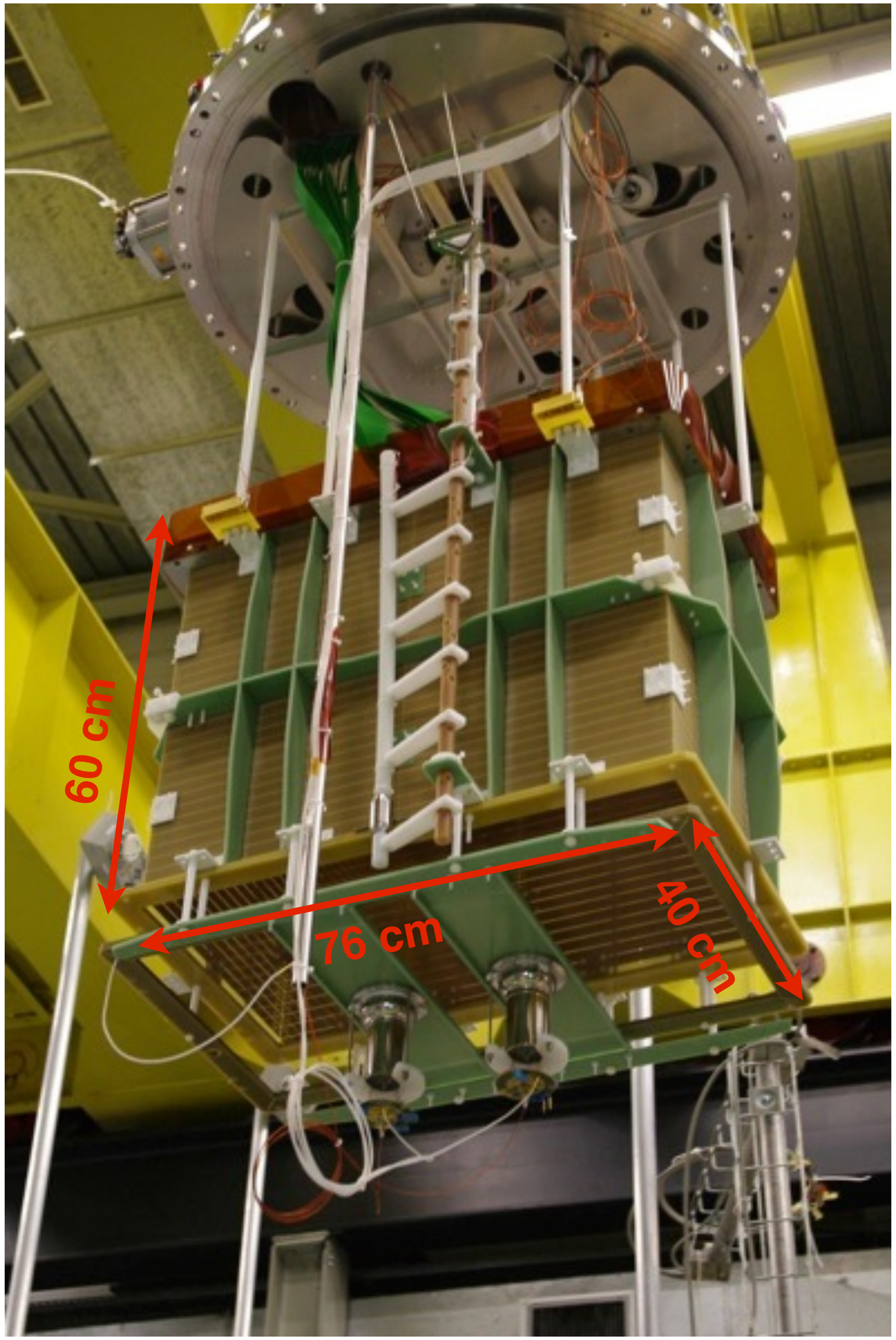
- ✳Charge equally collected on two sets of strips (views)
- ✳Readout independent of multiplication
- ✳Signals have the same shape for both views:
  - -two collection views (unipolar signals)
  - -no induction view (bipolar signals) as in the case of a LAr-TPC with induction wires



So far largest area LEM/2D anode produced!

Large area readout: the 40x76 cm^2 prototype @ CERN

detector fully assembled



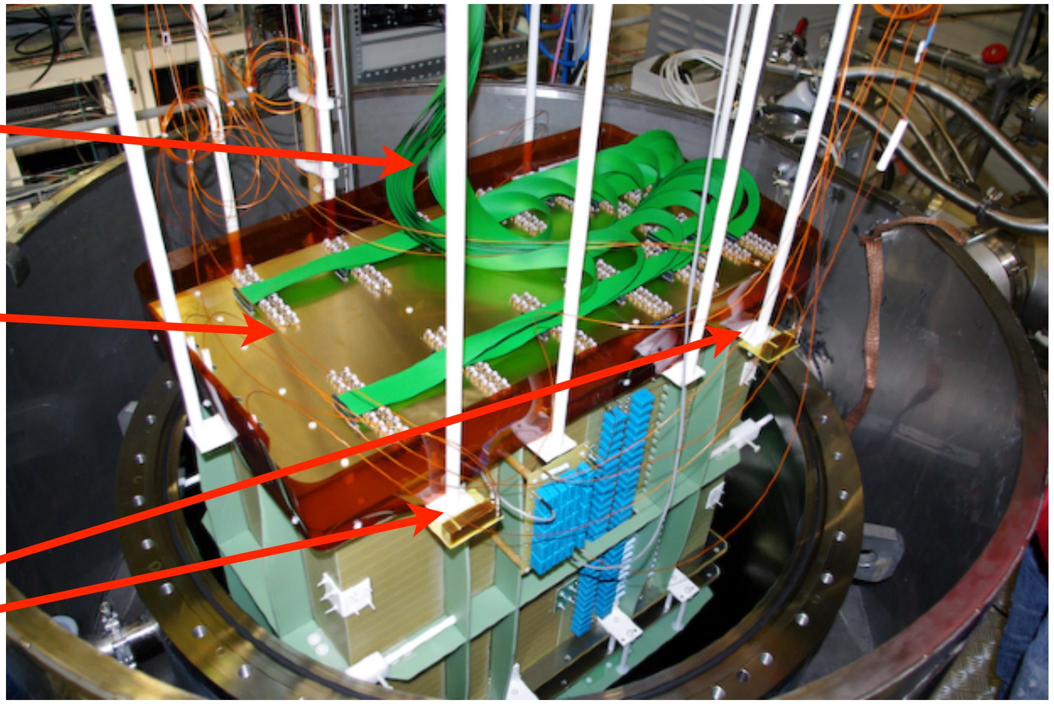
A. Badertscher et al. JINST 8 (2013)P04012,

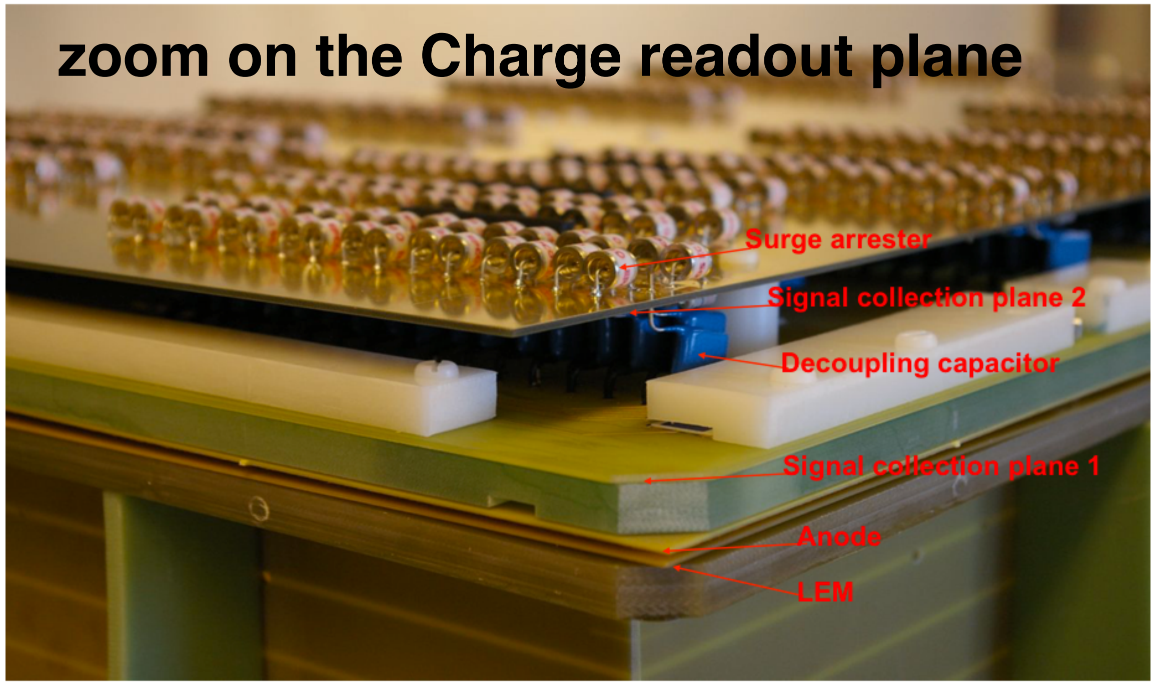
going into the ArDM cryostat

16 signal cables

charge readout plane

4 capacitive level meters



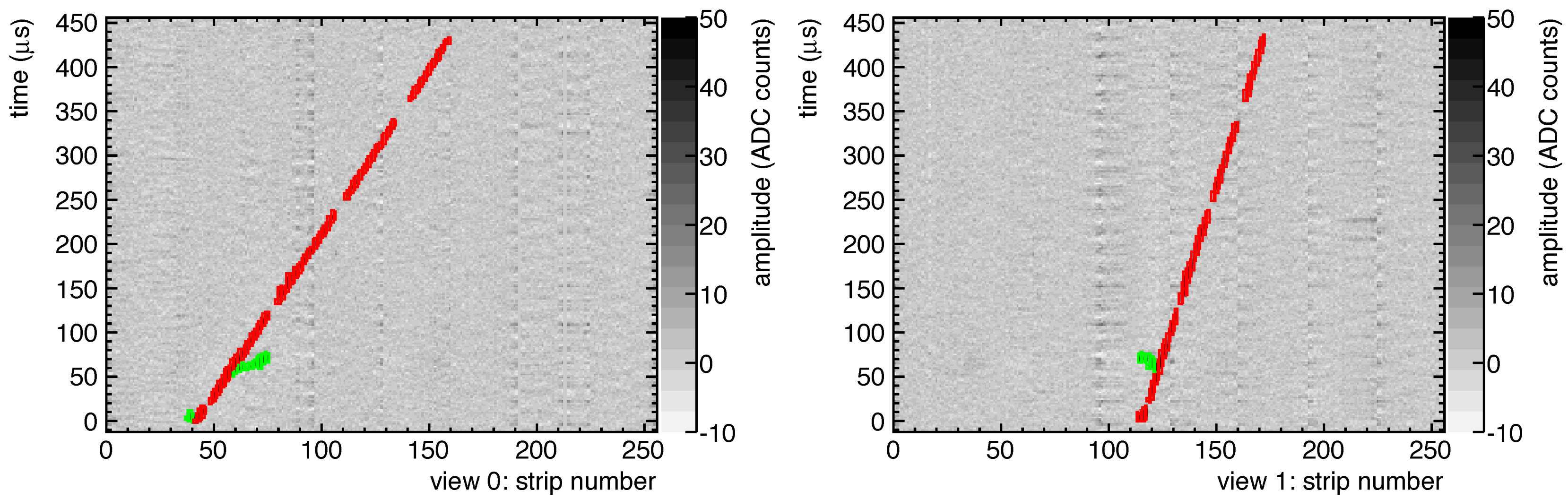


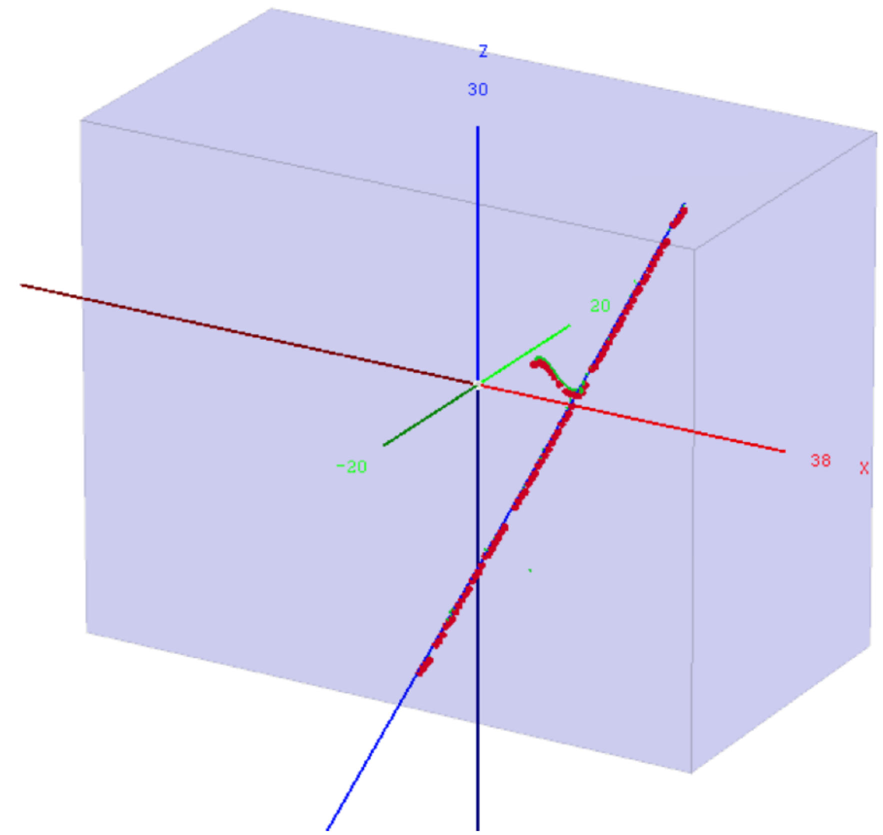
Results from the 40x76 cm^2 prototype

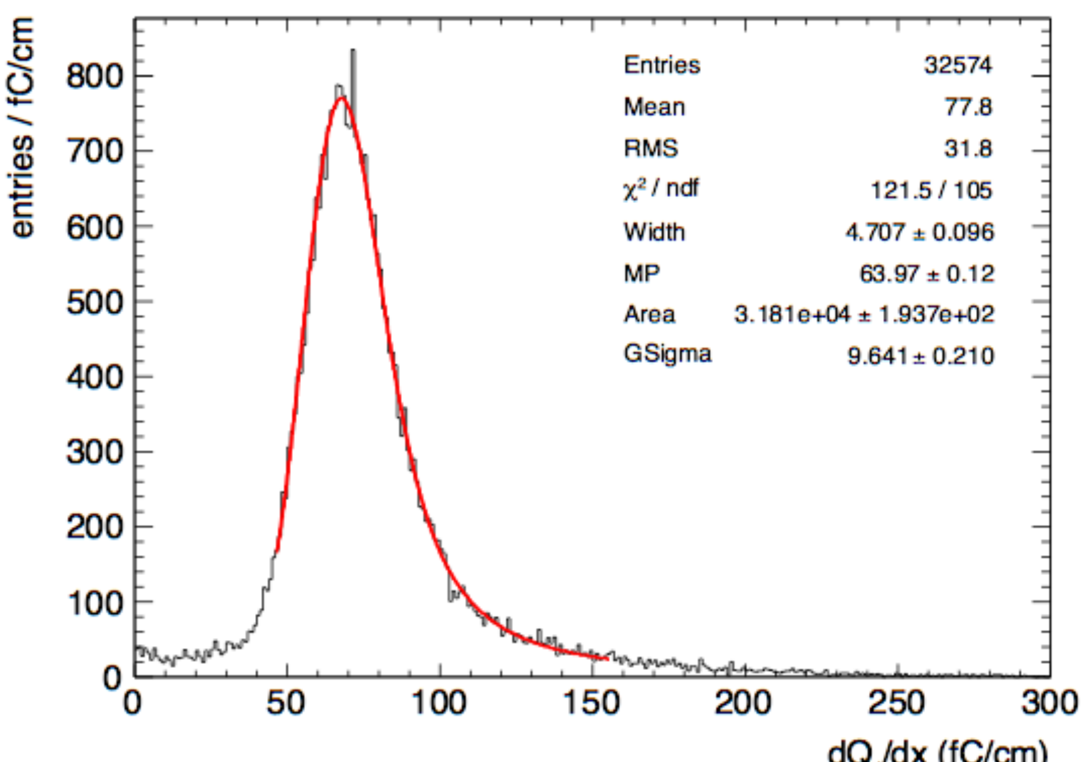
We have operated the detector for the first time in October 2011 during more than 1 month.

Operated under controlled pressure: 1023±1 mbar A. Badertscher et al. JINST 8 (2013)P04012,

delta ray identified and reconstructed in 3D!







Effective gain:

$(dQ/dx_{view0} + dQ/dx_{view1})/dQ/dx_{MIP}$ (≈10fC/cm)

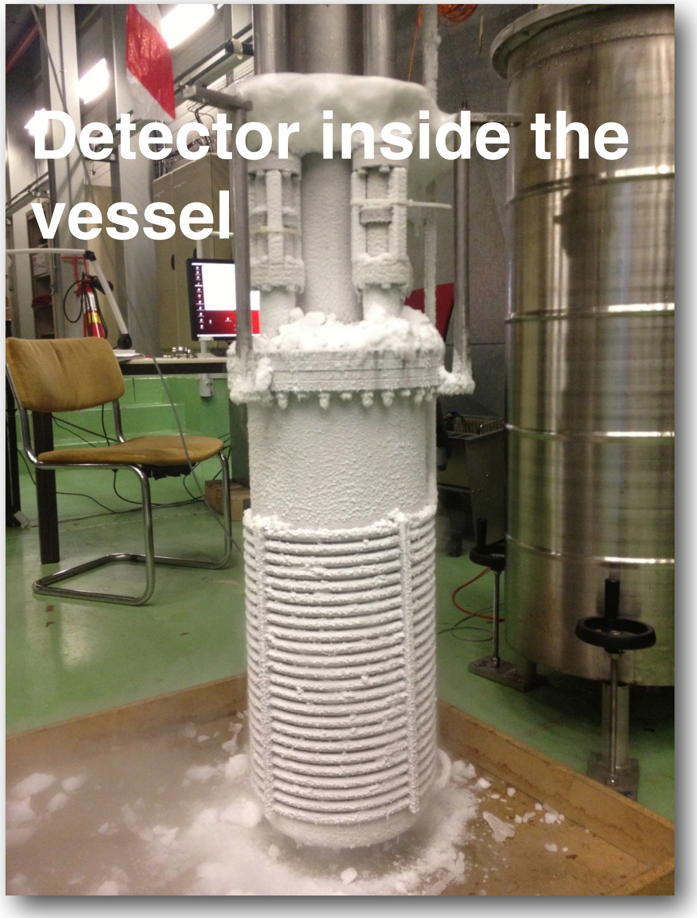
$<dQ/dx>$=146 fC/cm

➡effective gain≈14.6, (S/N≈30)

charge sharing between the two collection views:

$(Q_1-Q_0)/(Q_1+Q_0)$≈8%

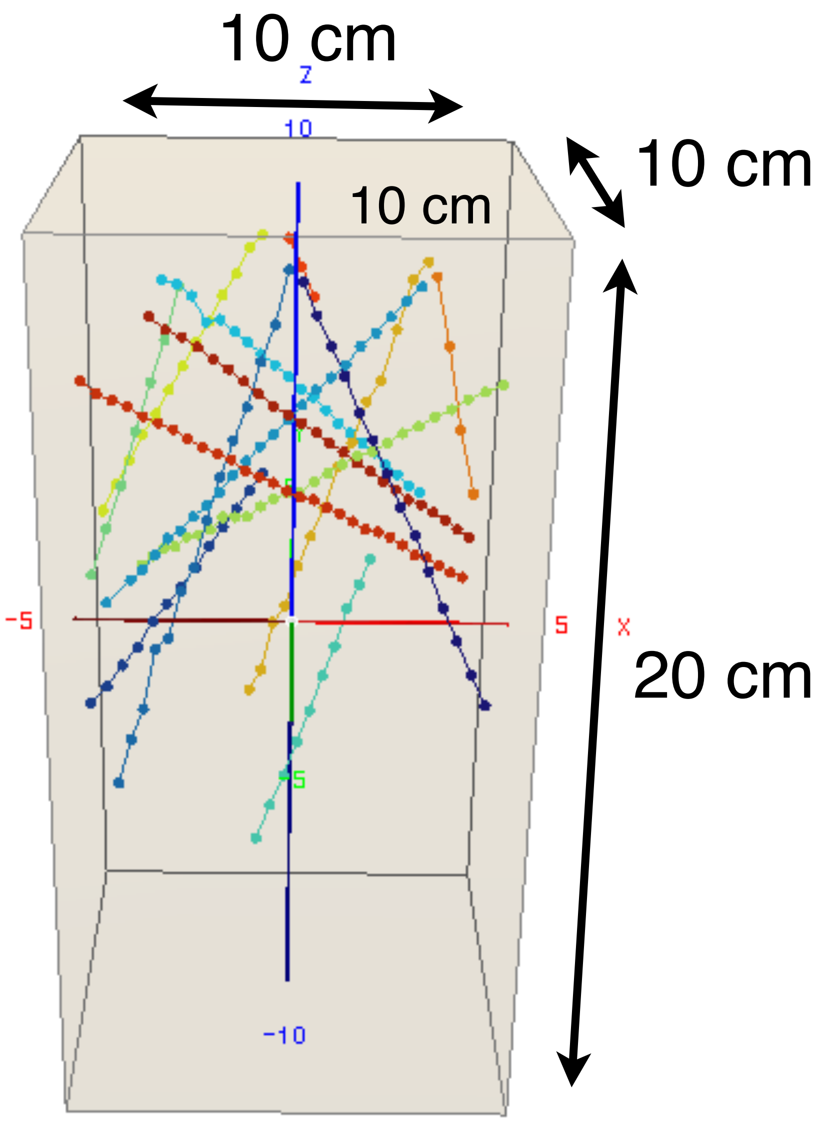
What we also tested : 10x10 cm^2 prototype



With this small chamber, we can collect in a short amount of time a high quality and **large data-sets of cosmic muon**

Some of the things we tested:

- ✳**Uniformity** of the charge sharing between both views
- ✳**Stability** of the gain and signal-to-noise-ratio for extended running periods.
- ✳**Discharges** across the LEM (how frequent? do they affect the gain?..)
- ✳How can we further **Simplify** the readout?



3D reconstructed muons

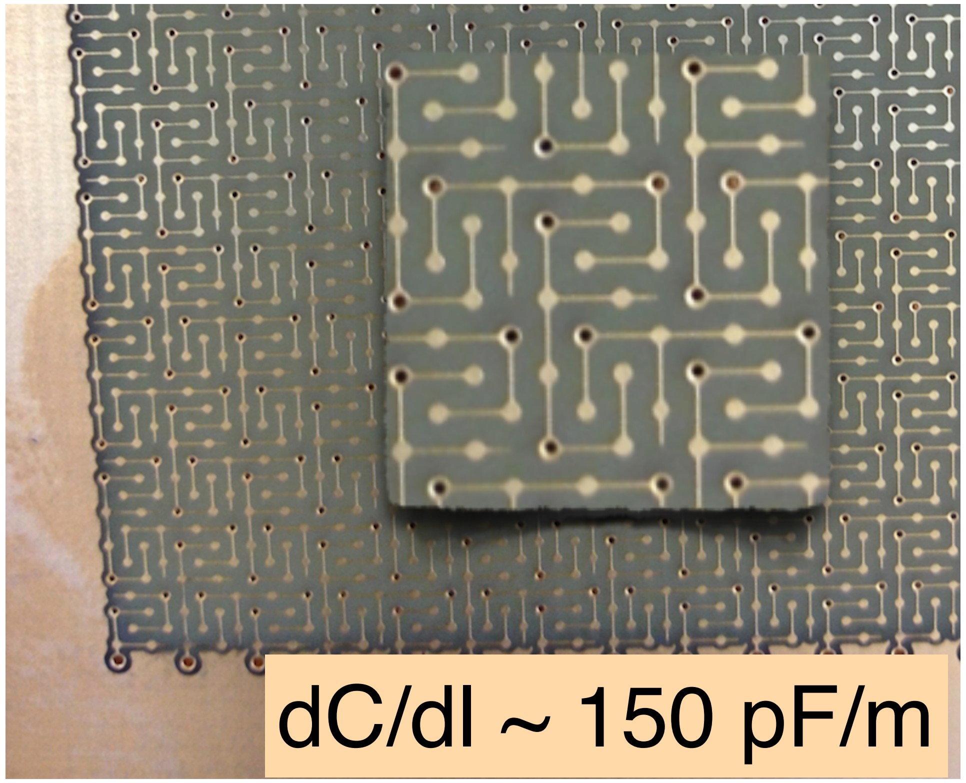
Towards large area readout - anode considerations

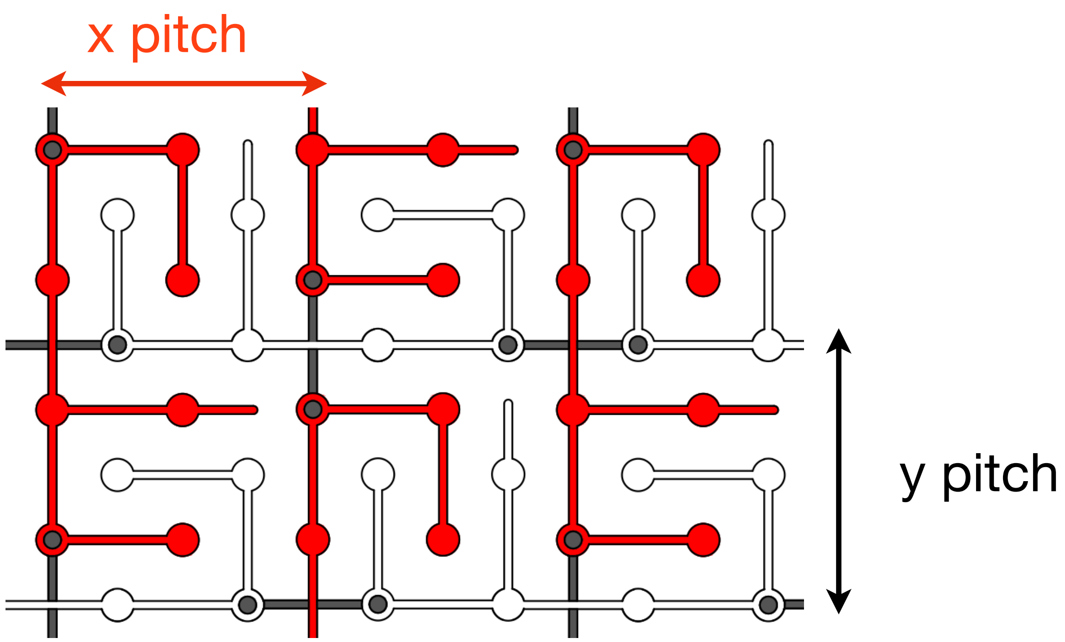
Goal: readout of at least 0.5x0.5 m²

need low capacitance readouts to go large dimensions
previous anodes (copper strips + Kapton insulator) dC/dl ~600 pF/m

the anode should:

i) be easy to manufacture on large scale
ii) have low capacitance to have long readout strips while keeping the noise to minimum.
iii) have equal charge sharing between both views





Multi-layer PCB anode designed to be completely x-y symmetric.

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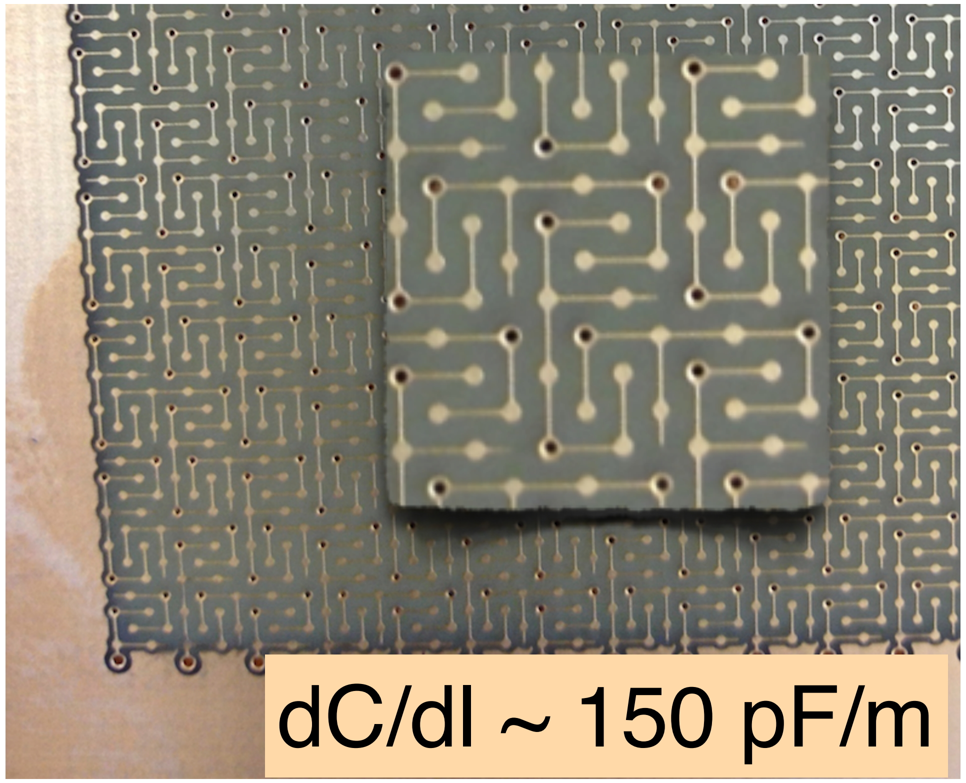
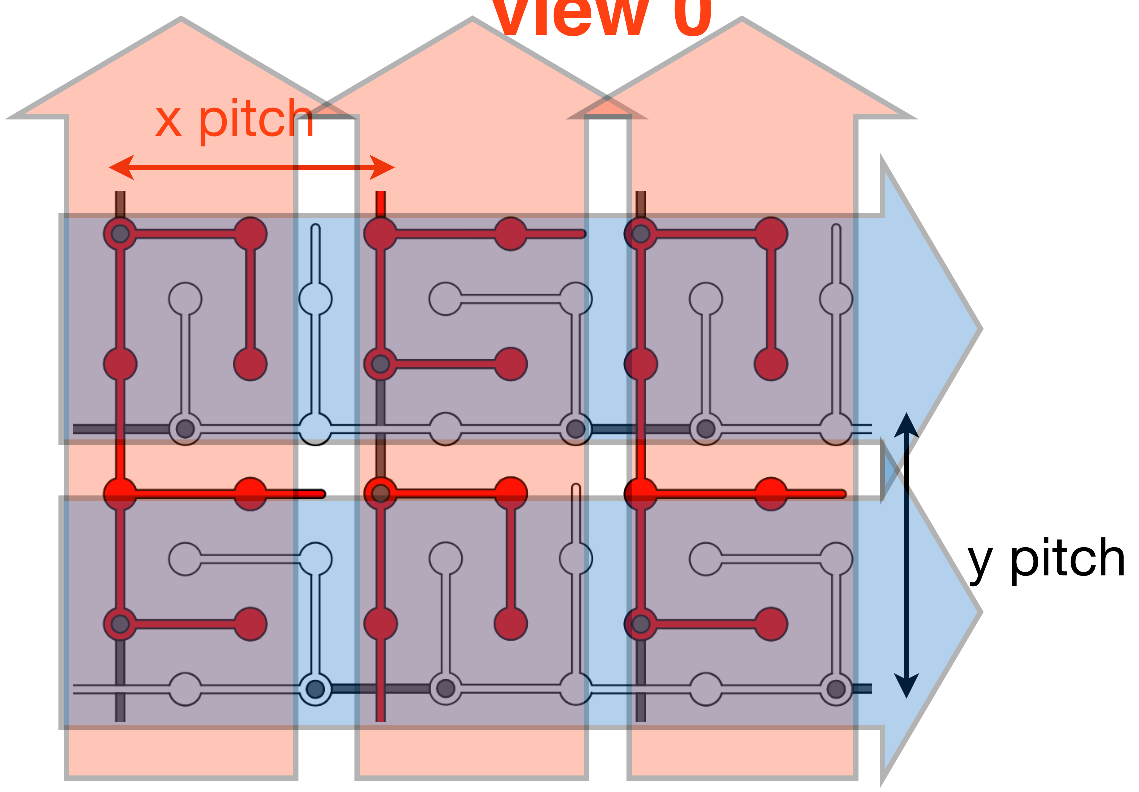
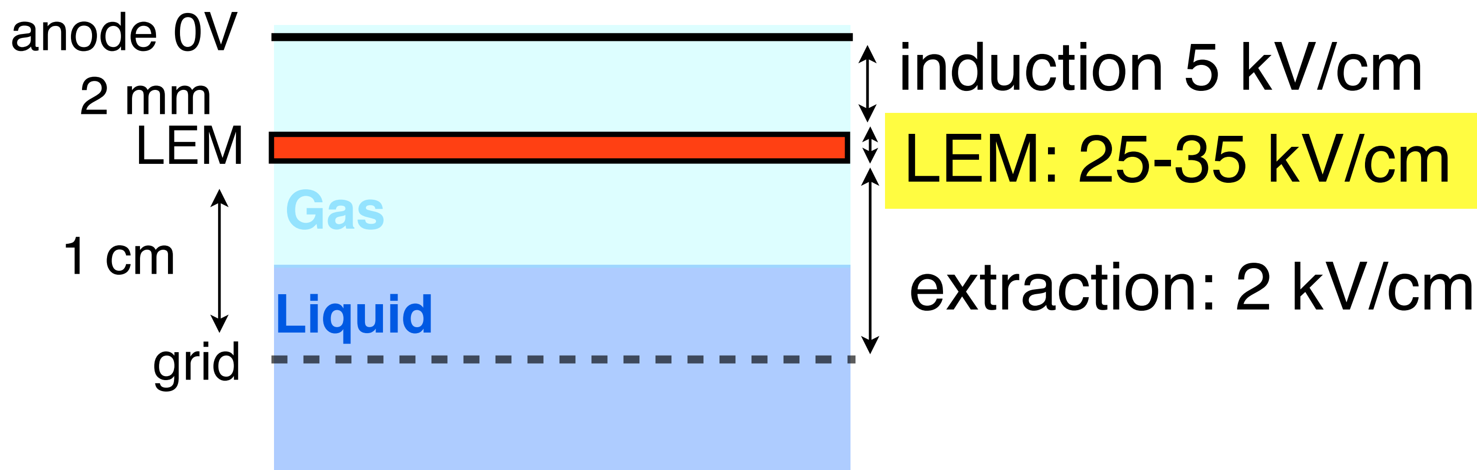




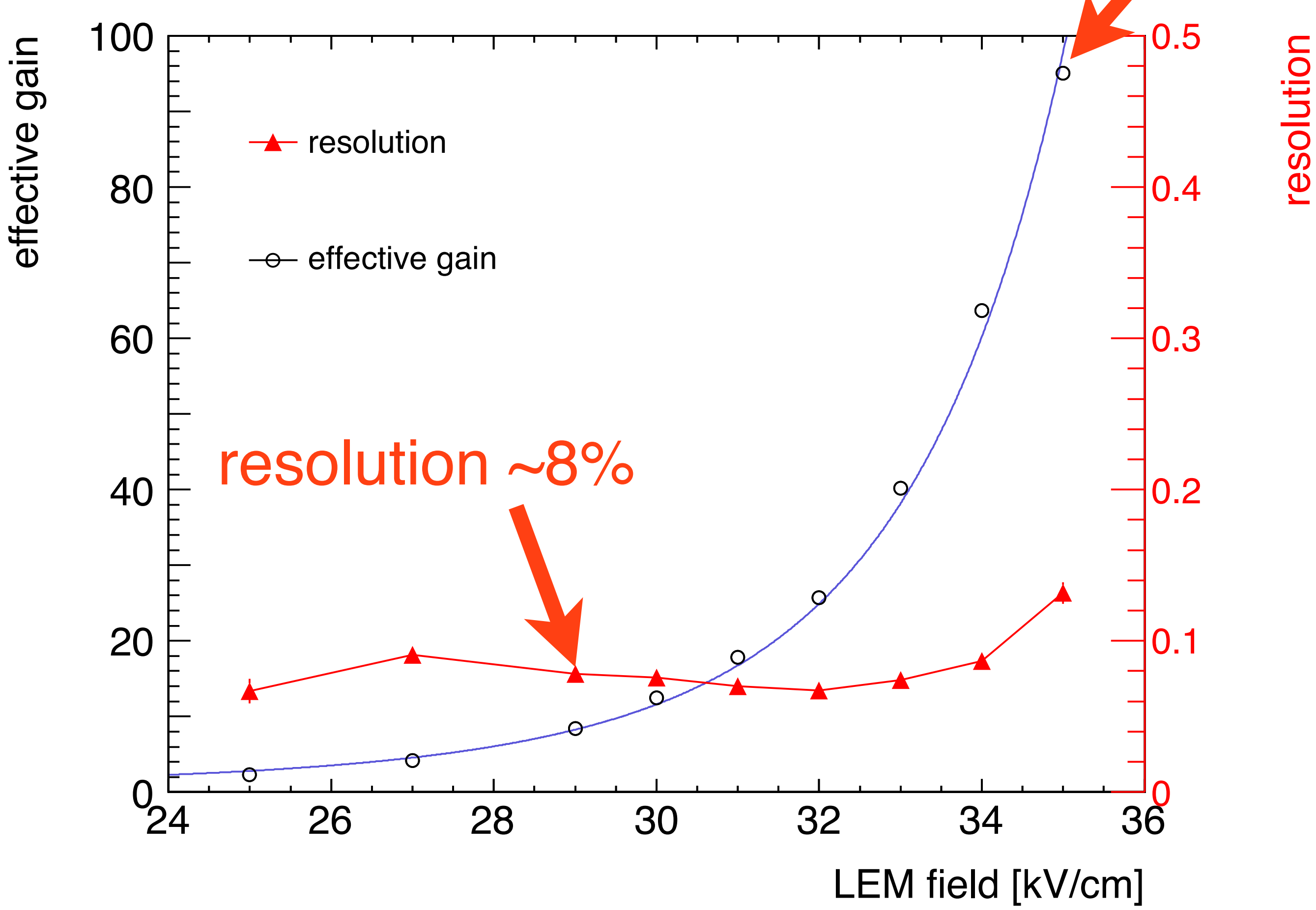
Multi-layer PCB anode designed to be completely x-y symmetric.

LEM field scan up to gain 90!

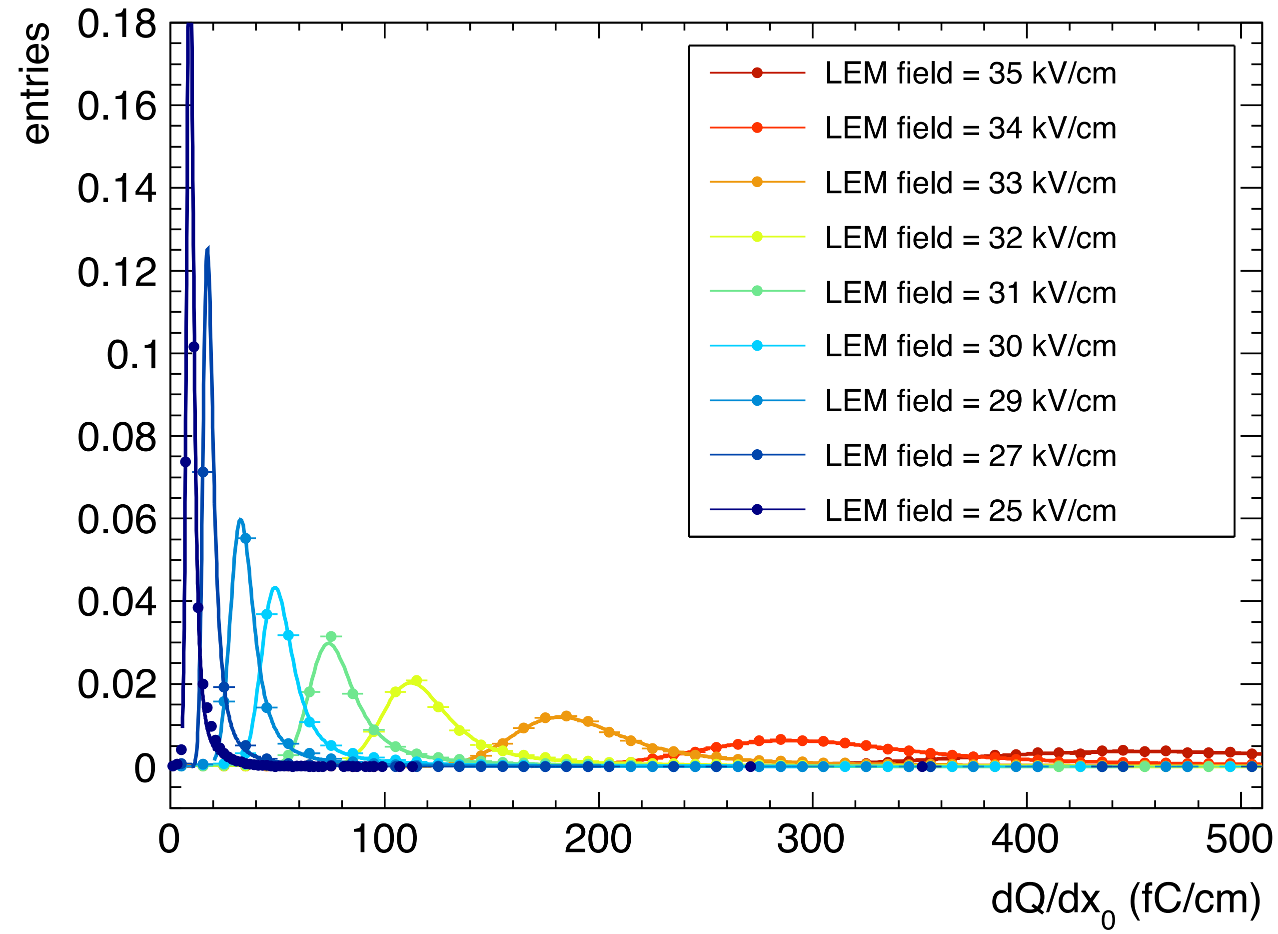


onset of discharges @ gain > 90!

gain and resolution for diff. LEM fields

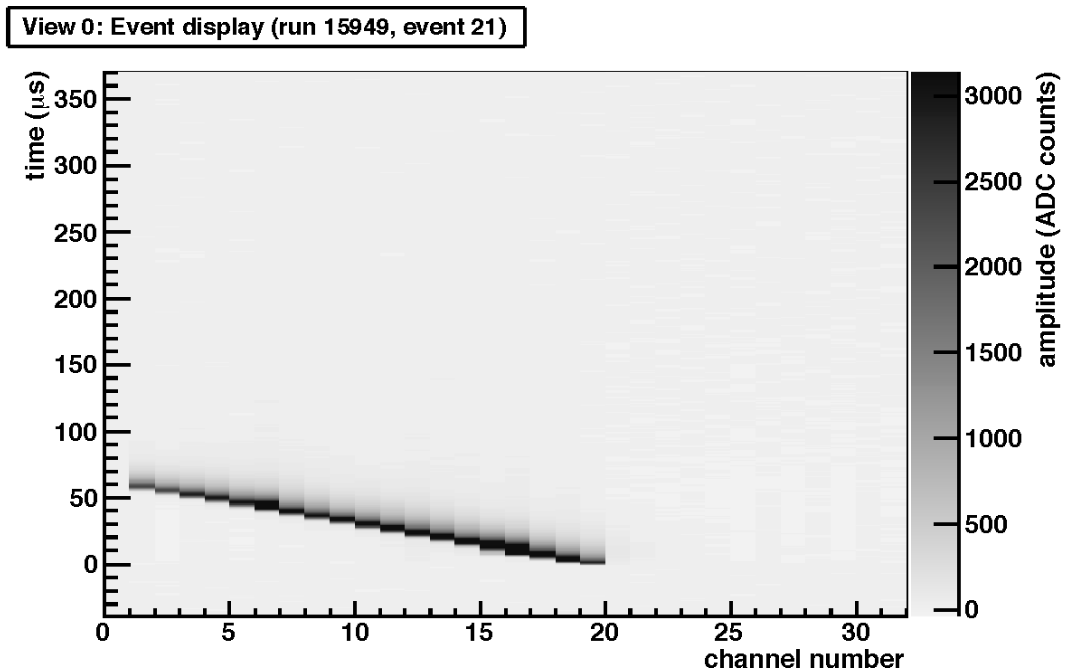


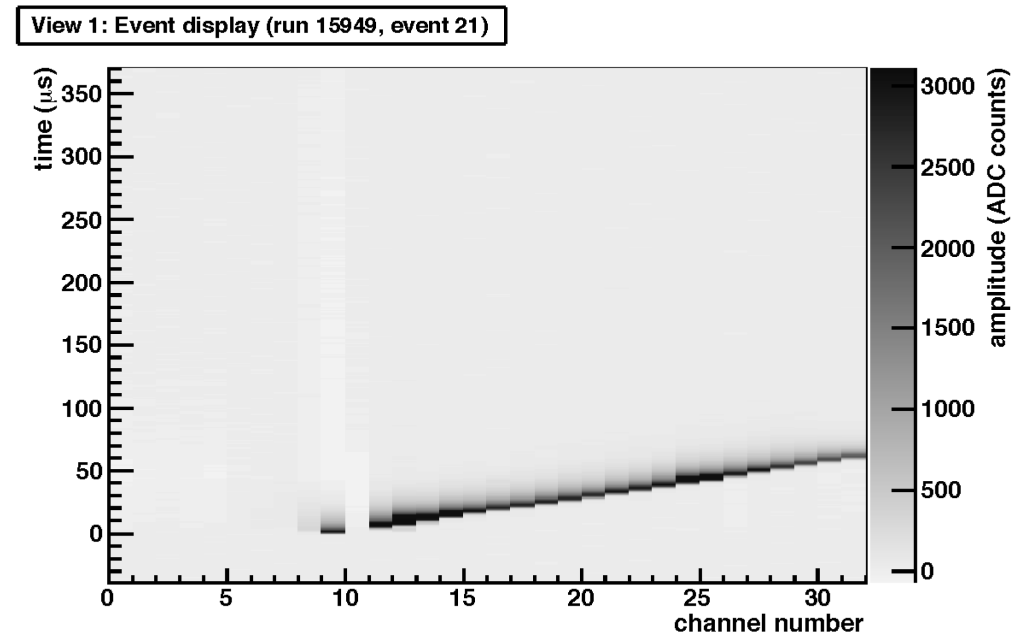
Landau distributions for diff. LEM fields

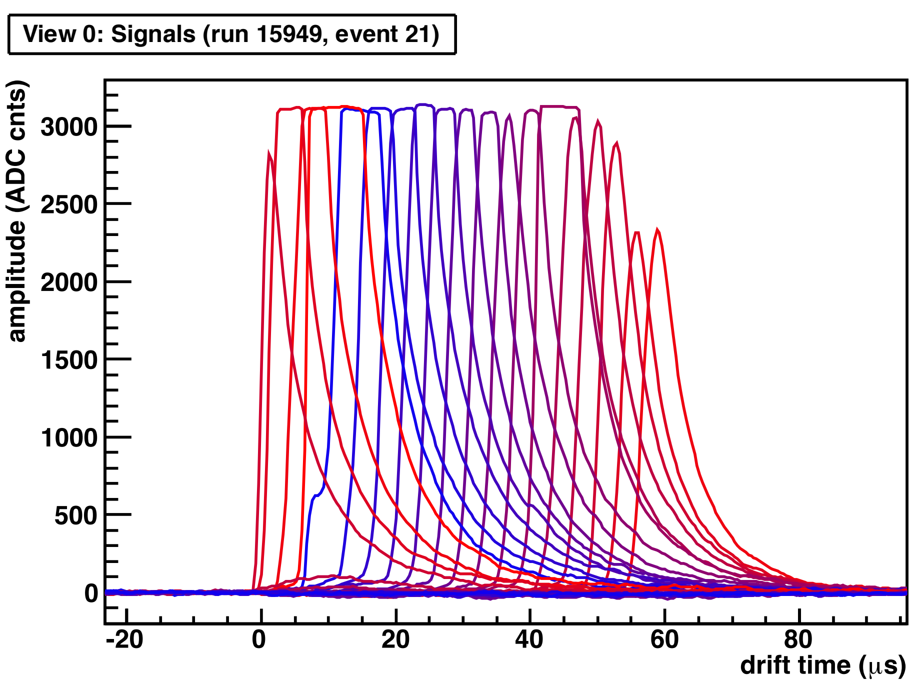


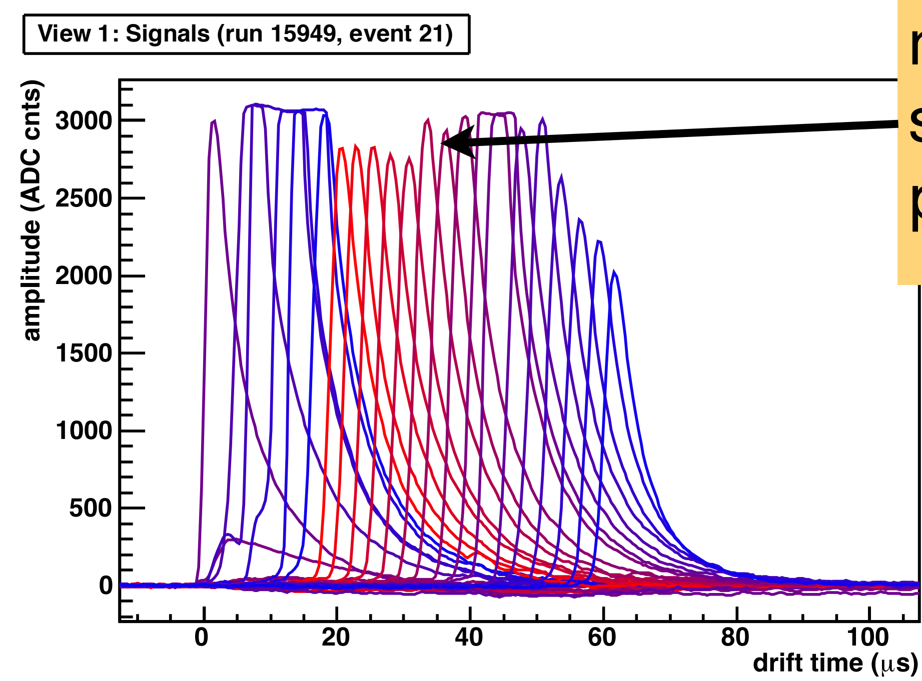
LEM operated at highest gain >90!

LEM: 35 kV/cm, induction: 5 kV/cm, extraction: 2 kV/cm, drift: 0.5 kV/cm







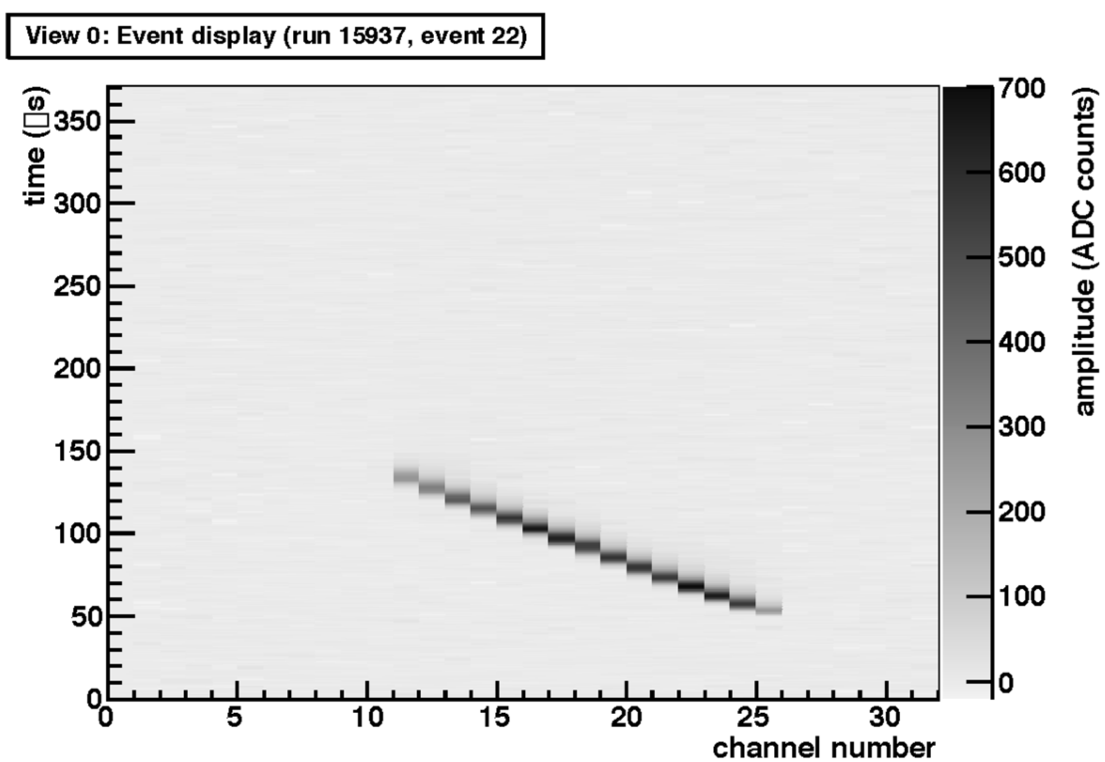


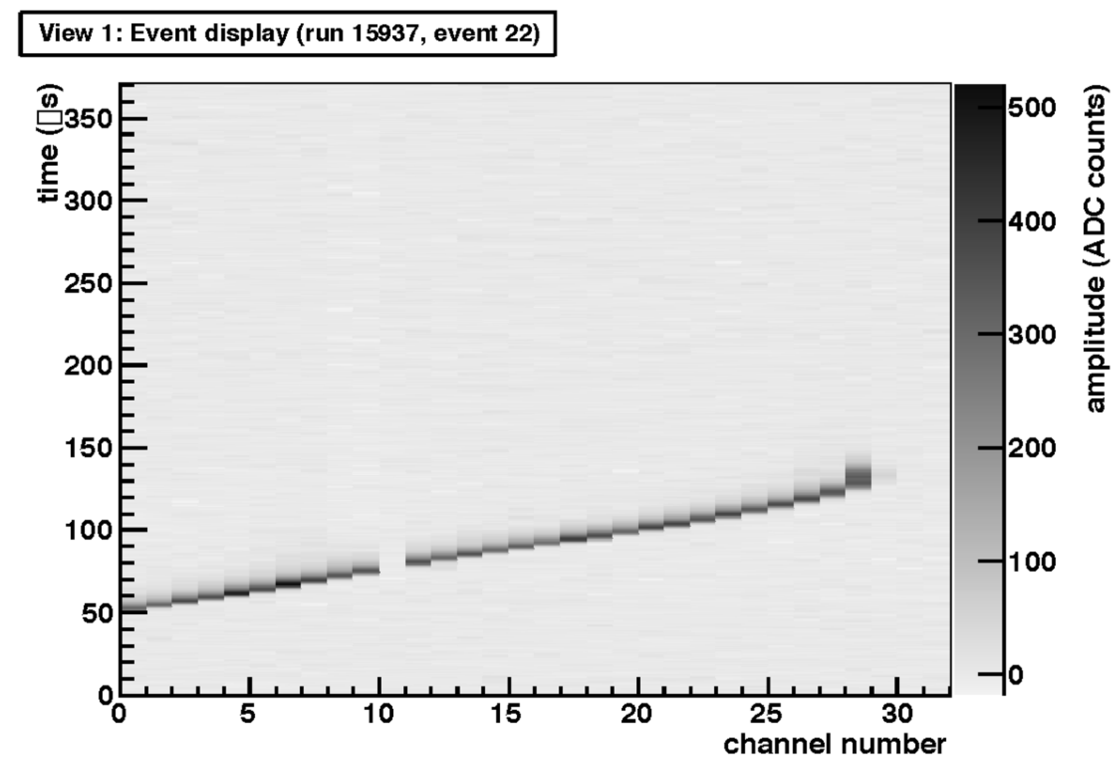
mip signals saturate preamplifier!

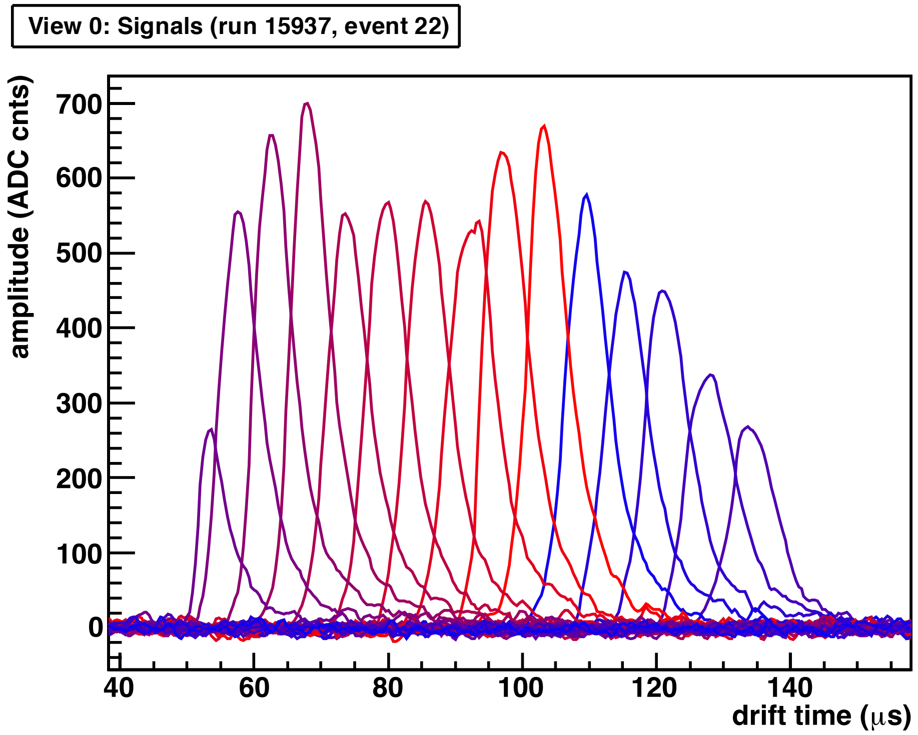
In future versions dynamic range of the preamp will be adapted to the gain.
non-linear behaviour to adapt to a wide dynamic range

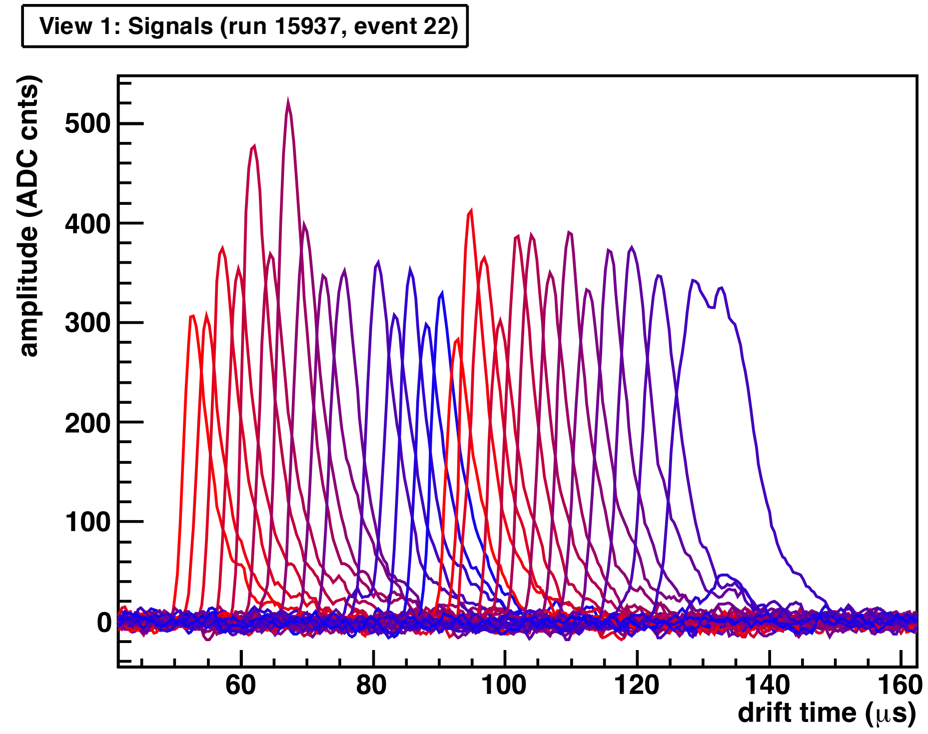
Event at effective gain ~ 20

LEM: 31 kV/cm, induction: 5 kV/cm, extraction: 2 kV/cm, drift: 0.5 kV/cm







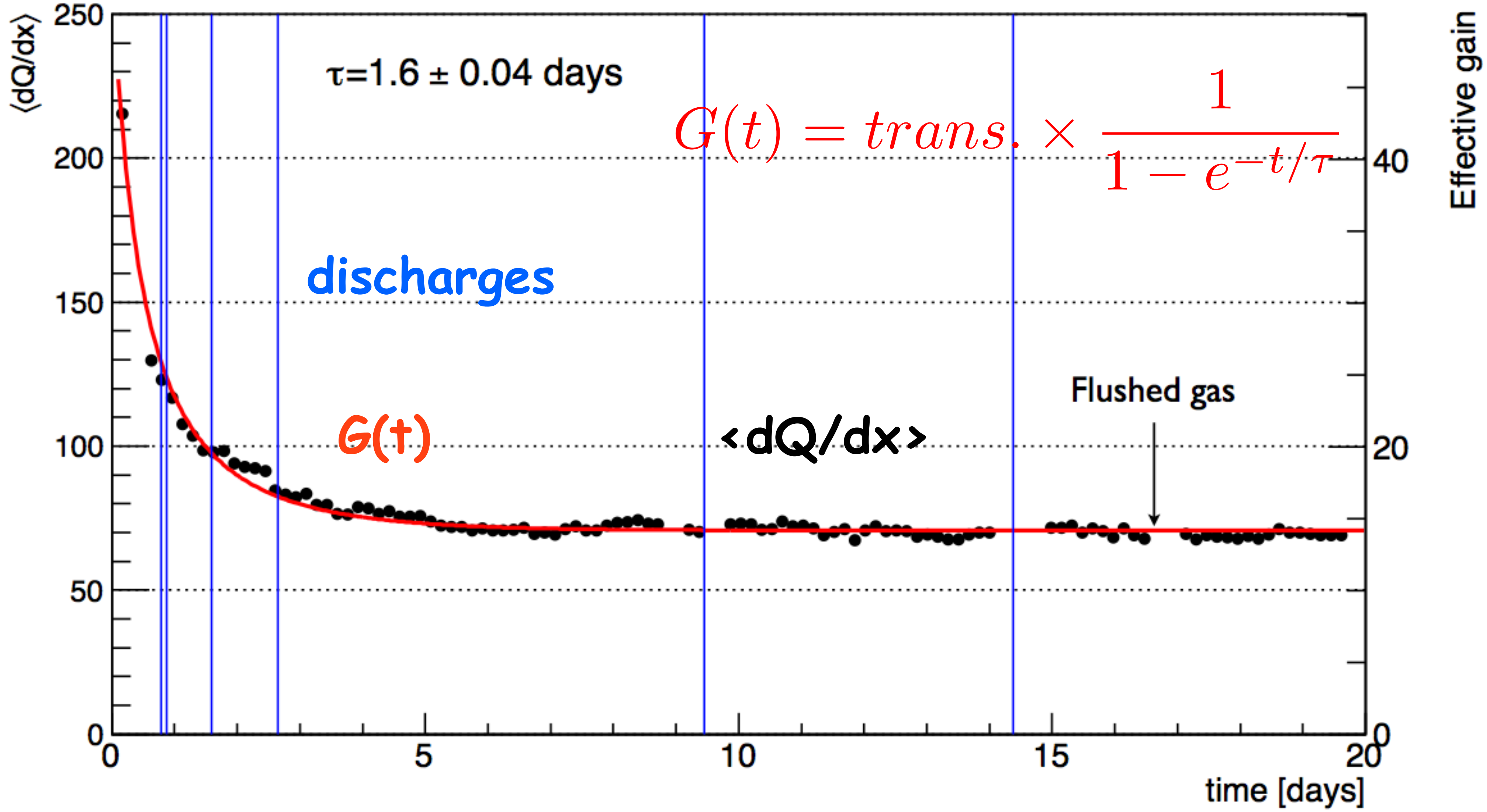


Gain stability

Evolution of <dQ/dx> corrected for variations of the pressure

✳Gain is stable over a period of ~15 days once the LEM has charged up (w/ time constant tau~1.5 days)

✳The discharges do not lead to a change of overall gain

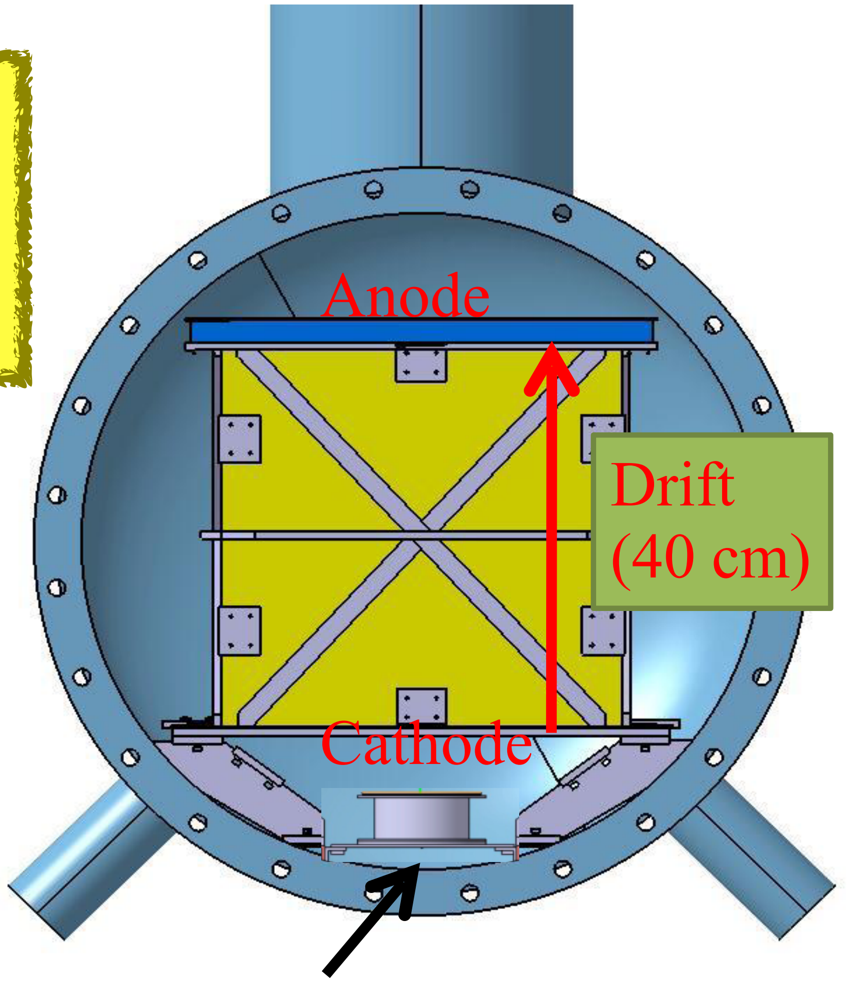


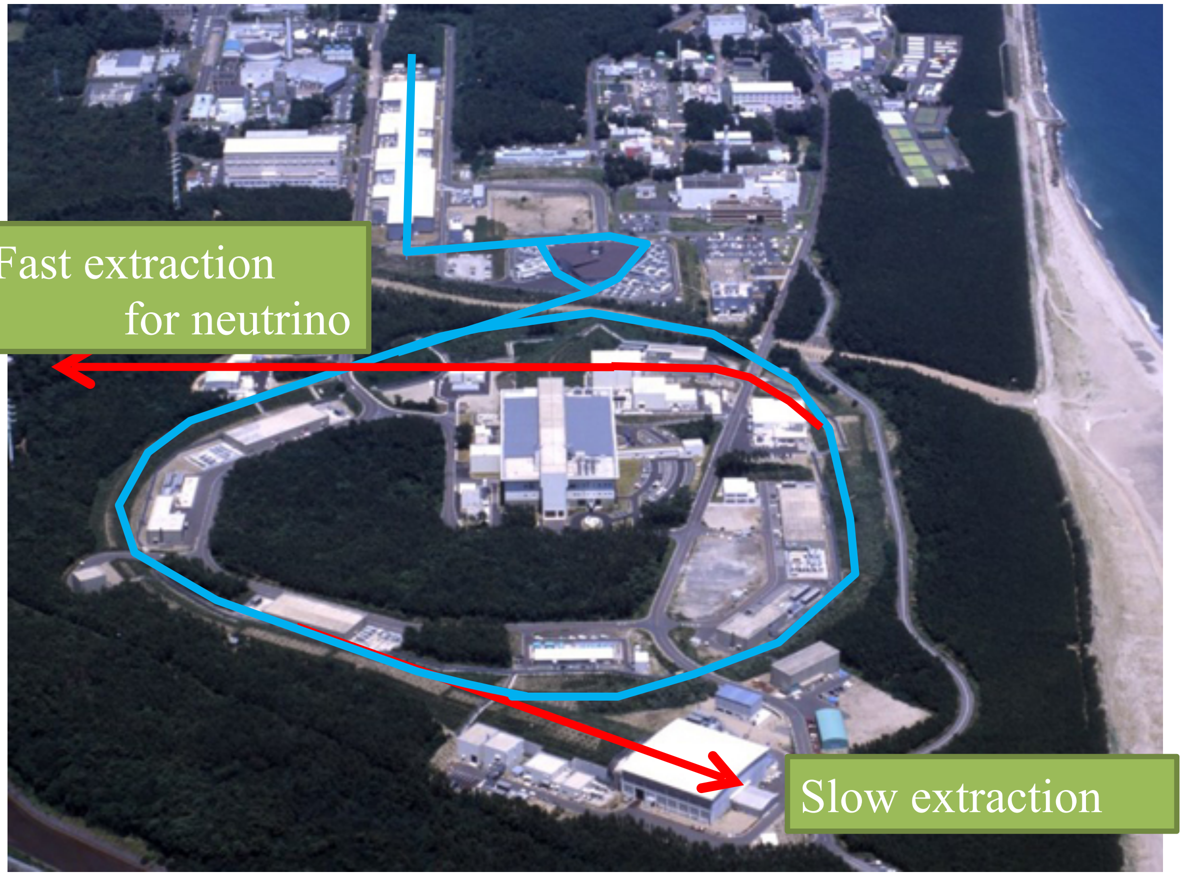
~15 days operation under stable gain of ~15

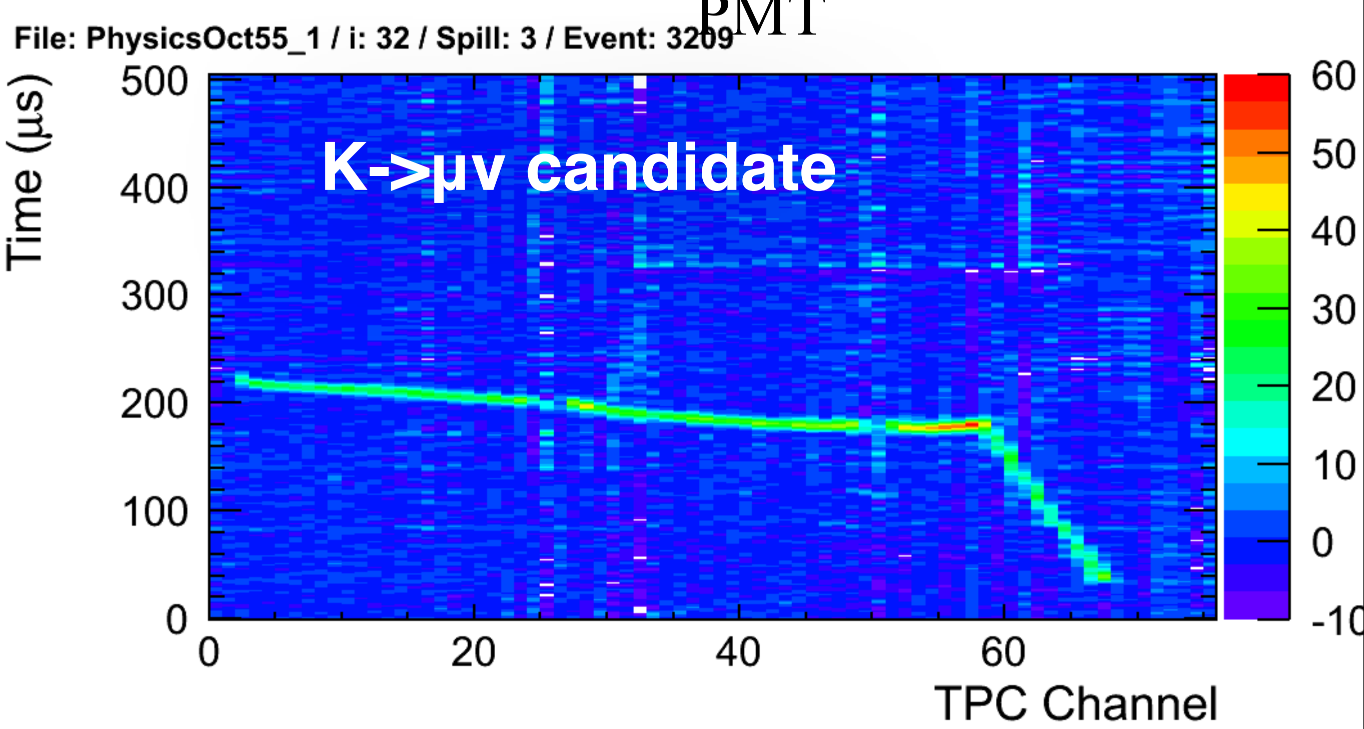
LAr TPC exposed to a charged particle beam @ JPARC

Essential to asses the detector performance from exposure to charged particle beams, providing particles of known mass, momentum and direction.

- Vessel dimension: 70cm Φ× 100cm evacuable, vacuum insulated
- 40 × 40 × 80 cm^3 TPC inside (130 l)
- Drift distance: 40 cm
- **first data autumn 2010**

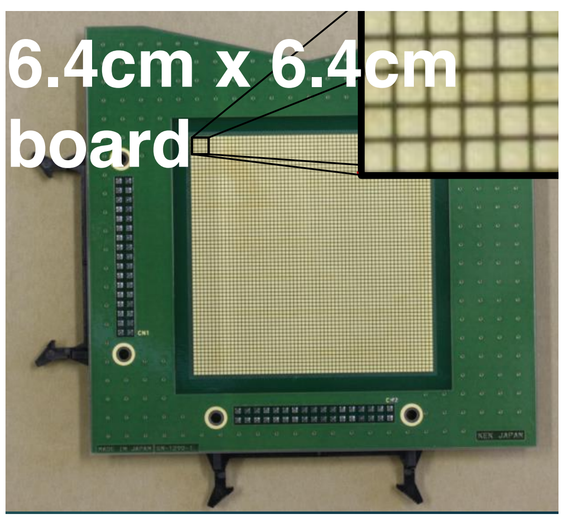


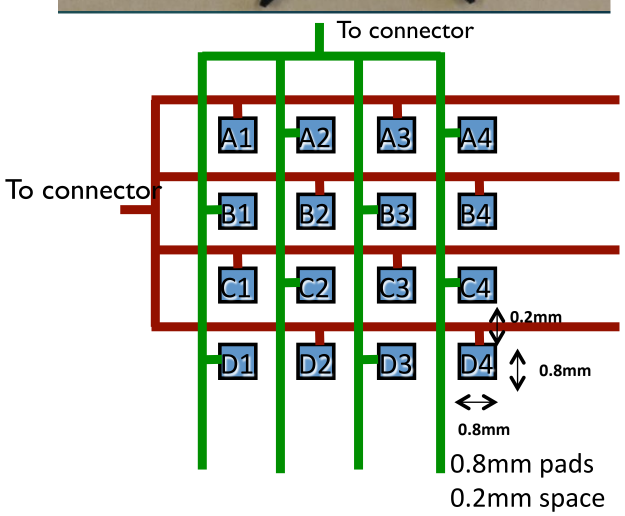




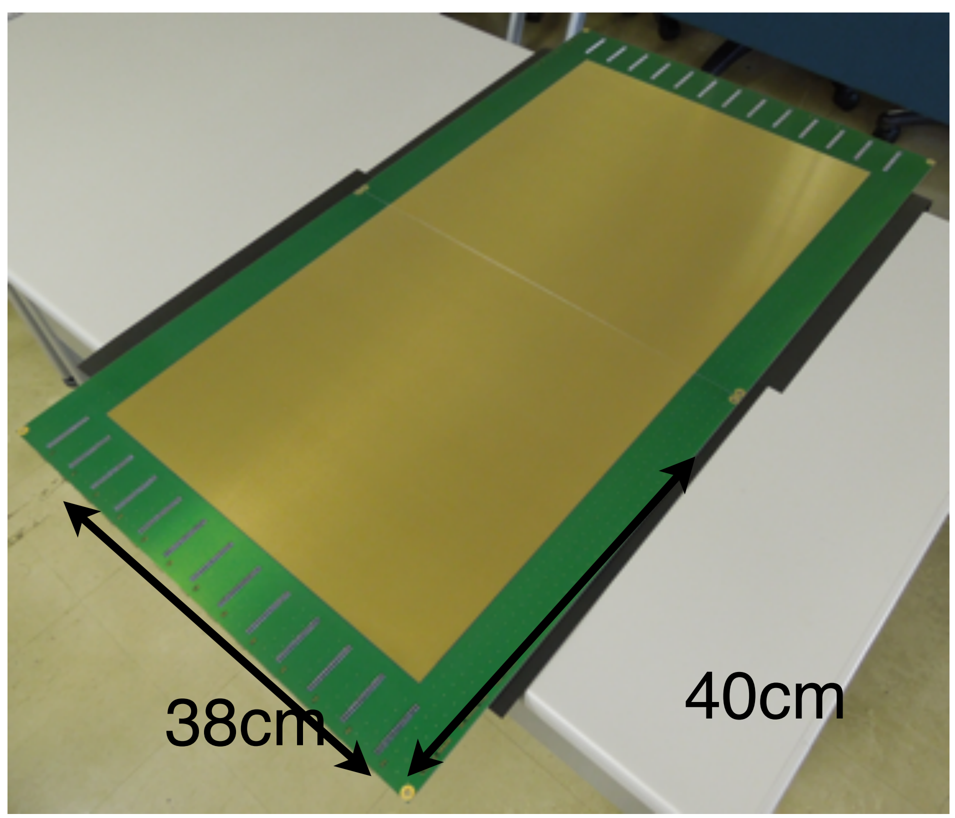
Test of 2D readout anode and FE electronics

- ✳developing a 4mm pitch 2D PDB readout anode board
- ✳6.4cm x 6.4cm and 40cm x 38cm prototype were tested
- ✳readout the signal in a single phase LAr
- ✳performance (Q sharing, noise) is under study
- ✳low noise high gain ASIC electronics

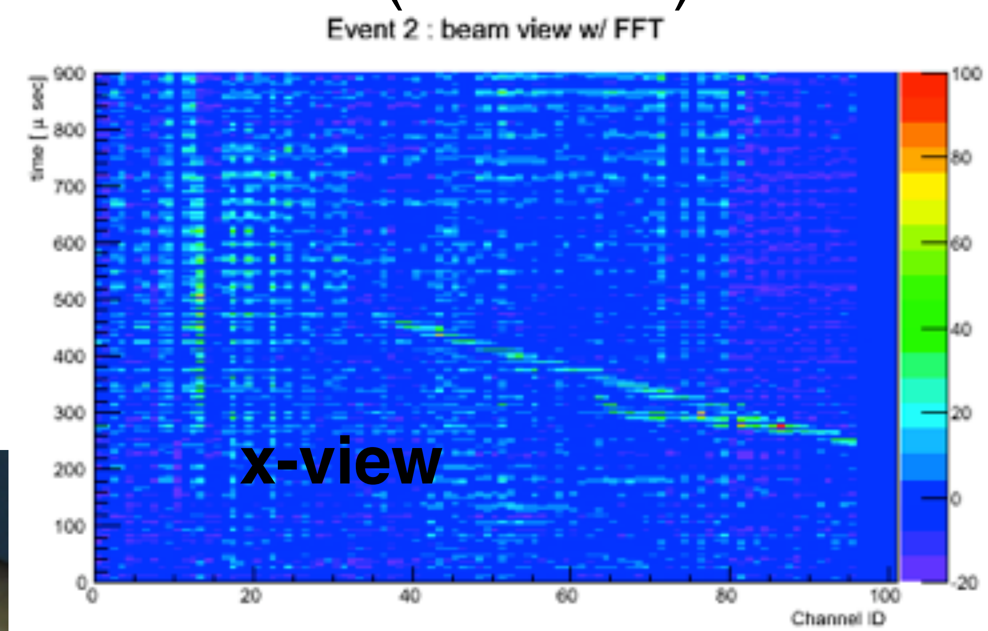


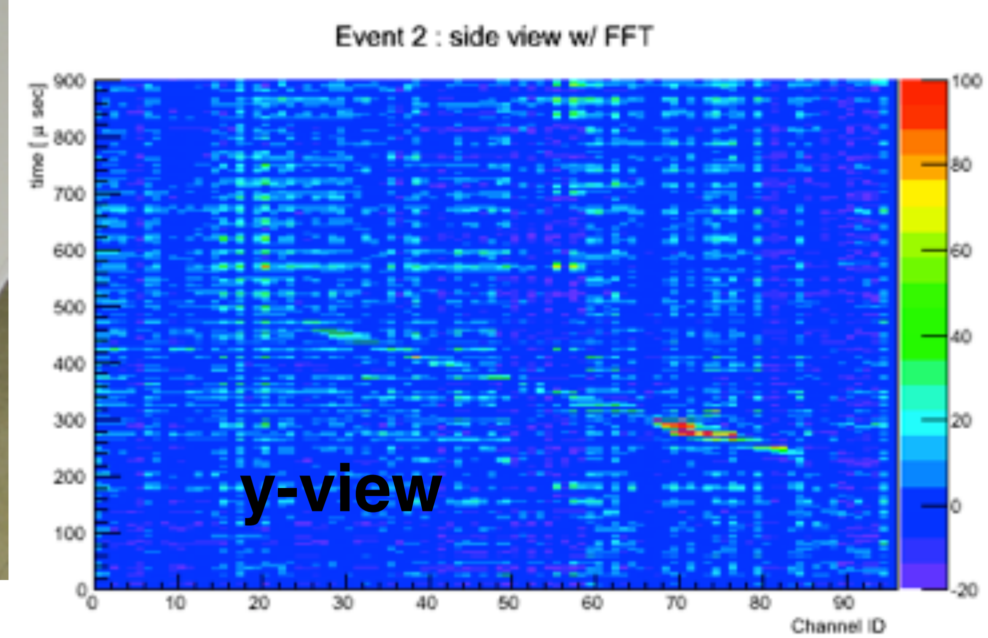


2*(40cm x 38cm) boards



cosmic ray event display obtained by 40cm x 38cm board (250L LAr)





Summary and outlook

- LBNO has been put forward to CERN with **unique physics potentials**, including astro-particle physics and proton decay search.

- **Significant R&D efforts** and results towards large Double LAr detectors:
  - optimisation of the charge readout: large gains (>90) reached and chosen operating gain (~15) stable over a period of several weeks.
  - Results from High voltage tests expected soon.
  - Development of analog front-end ASIC working at cryogenic temperatures.
  - **Large industrial support.** Final report + costing by summer 2014

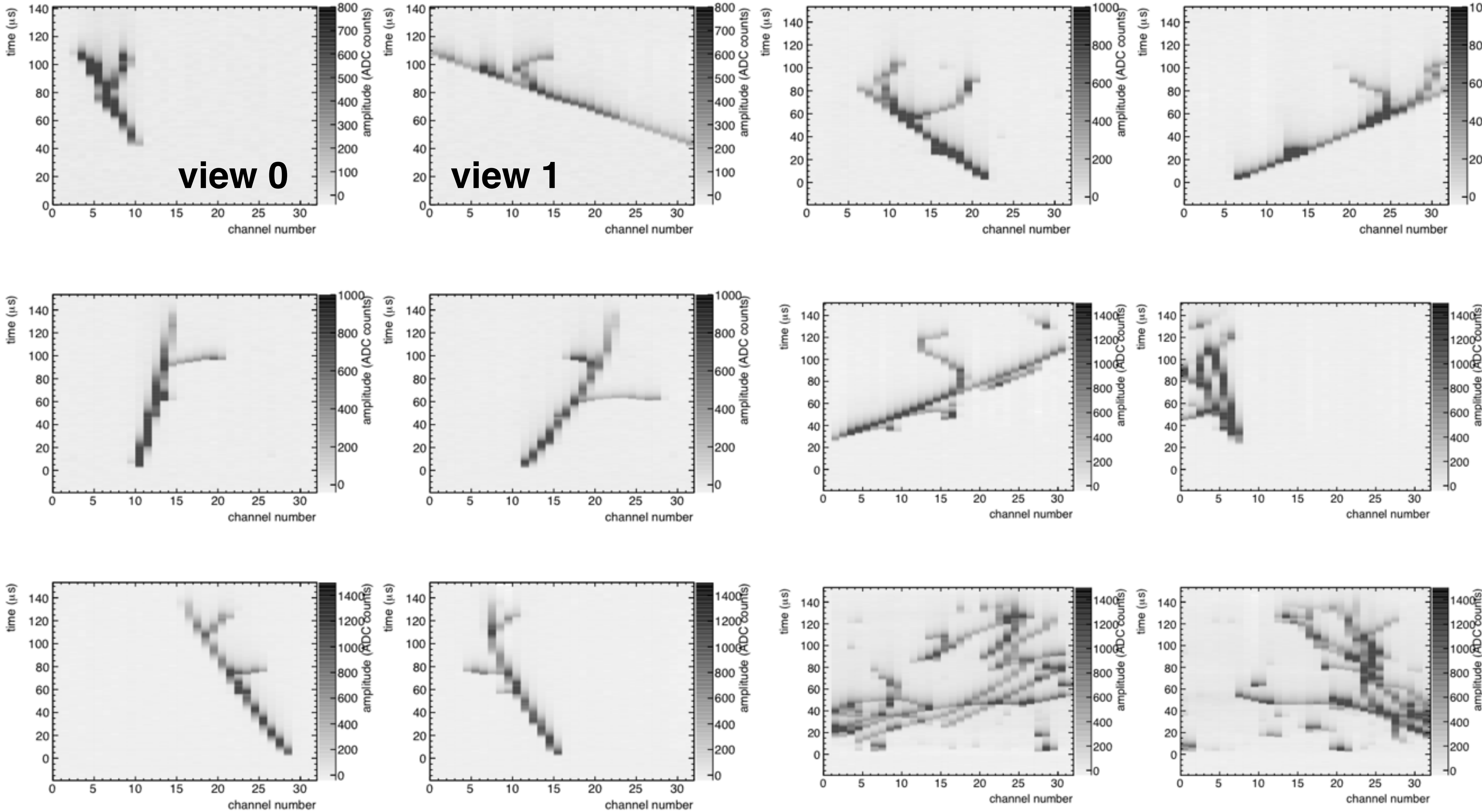
CERN WA105 experiment has been approved to continue the necessary R&D towards LBNO.

The TDR for the 6x6x6m3 prototype will be submitted by April 2014.

backup

More events

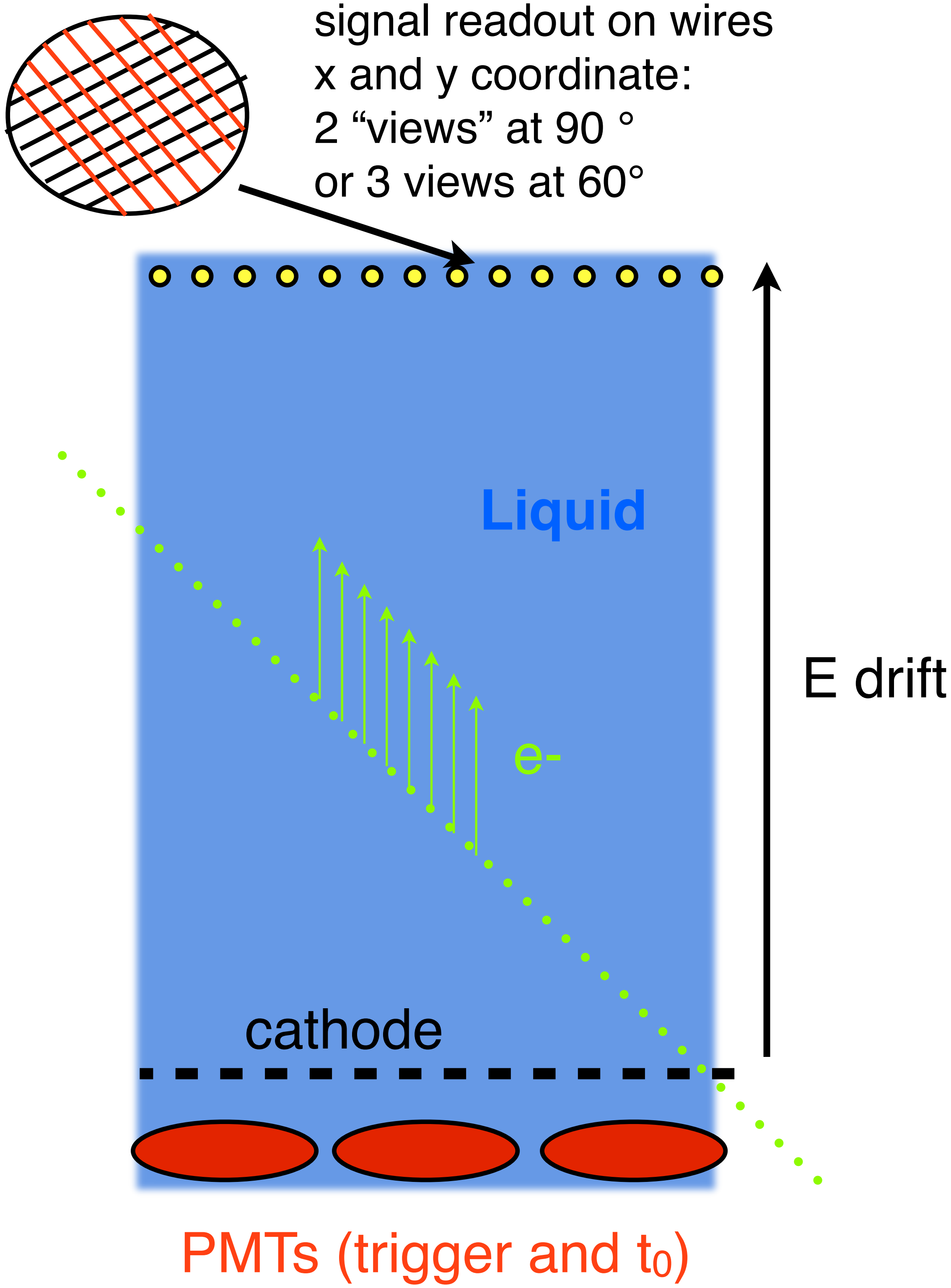
gain ~30



LAr-TPC single vs double phase

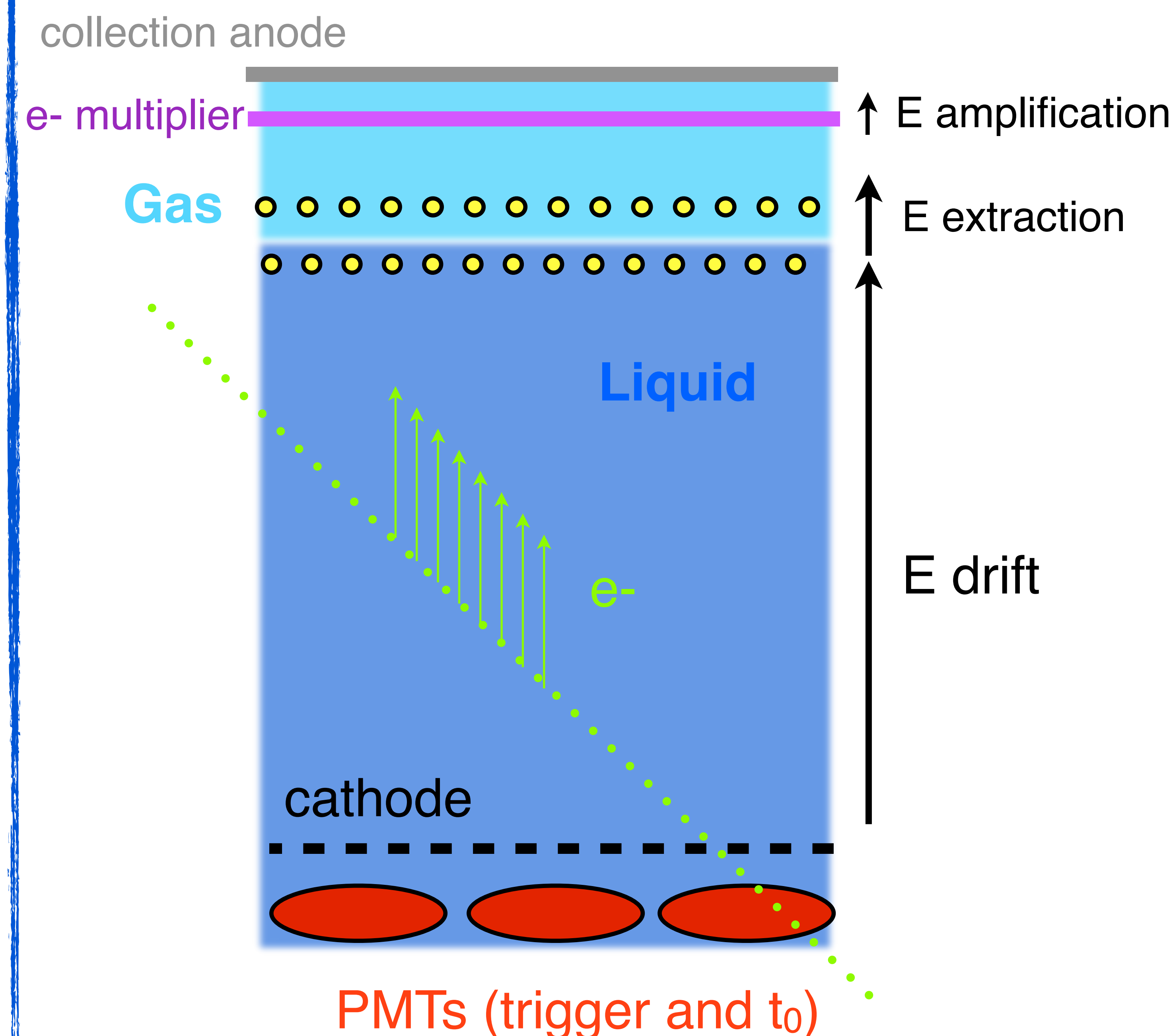
Single phase

signal readout on wires
x and y coordinate:
2 “views” at 90 °
or 3 views at 60°

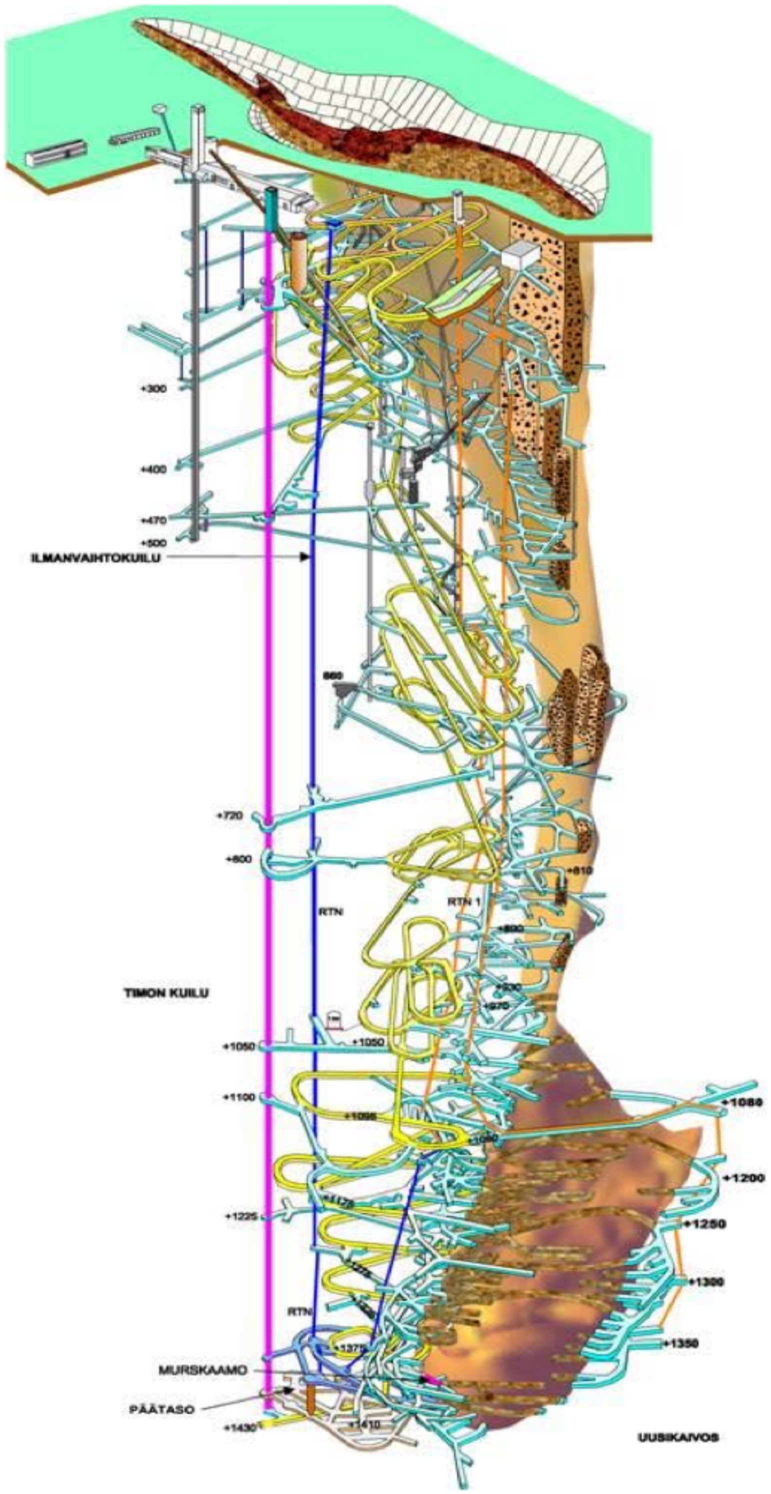


Double phase

signal readout on 2 view collection anode
Signal amplified in the gas



The Pyhäsalmi far site



Extremely convenient site:
- Deepest mine in Europe: ~1400 m, 4000 m.w.e
- Baseline from CERN 2300 km
- lowest reactor neutrino background in Europe
- efficient infrastructures and excavation aspects
- Interesting distance from other potential neutrino sources
  DESY(1500km), Protvino(1160km), RAL(2300km)

Discussions will continue with Finland in order to define it real contribution. Other sites in Scandinivia are also being looked into.

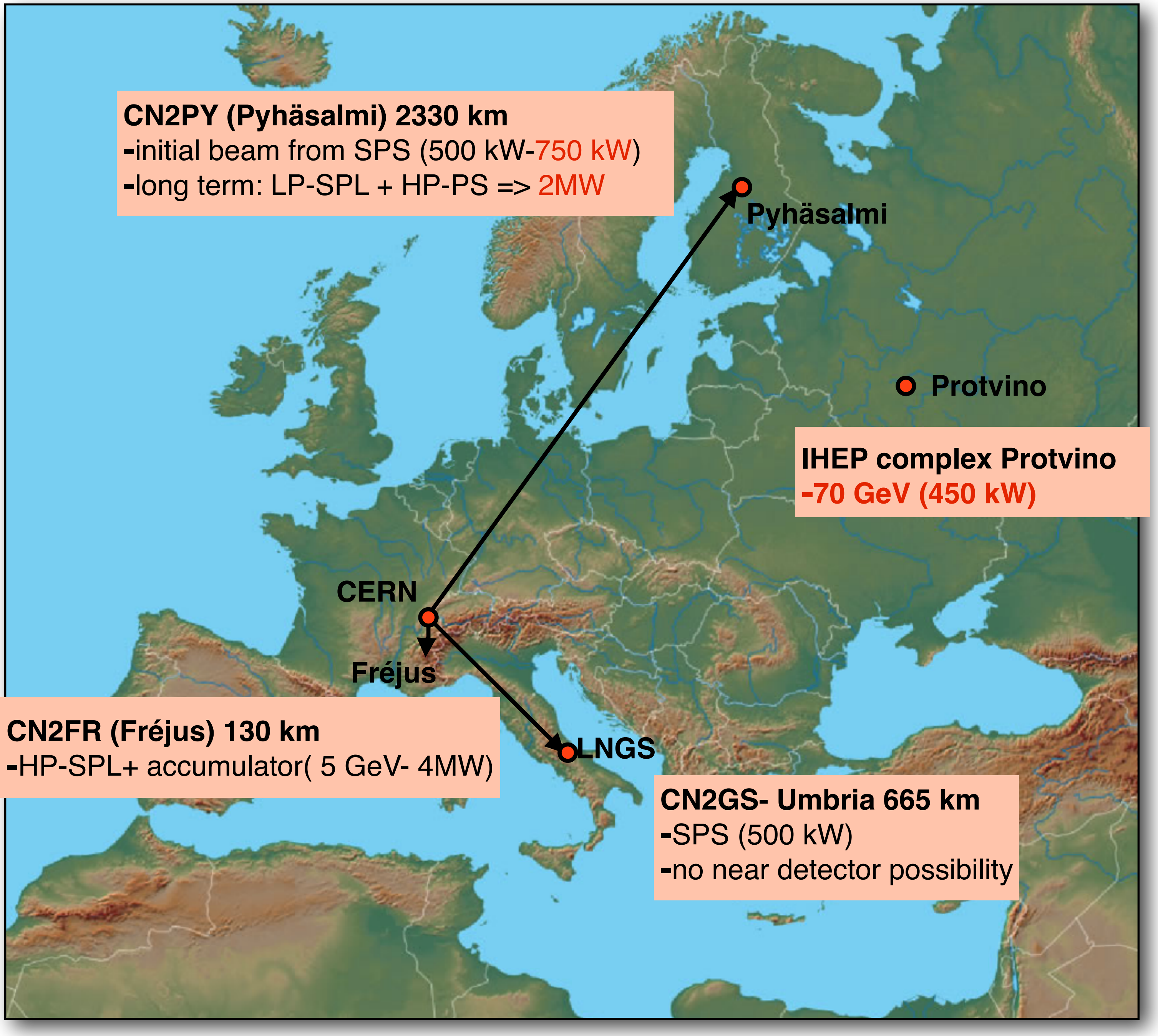
Sites Overview

✳Option 1: Pyhäsalmi mine, privately owned, 4000 m.w.e overburden, excellent infrastructure for deep underground access.

✳Option 2: Frejus, nearby road tunnel, 4800 m.w.e overburden, horizontal access. no MH, counting only experiment on ν ν_bar assymetry

✳Option 3: Umbria (LNGS extension), 2000 m.w.e overburden, horizontal access. CNGS off-axis beam

✳Beams
-Design of new CERN conventional neutrino beam to Finland (CN2PY) Baseline = 2300 km
-Upgrades of CERN SPS to 700kW
New CERN HP-PS (2MW@50 GeV) -
Recently: assessment of a new conventional beam coupled to accelerator upgrade at Protvino, Russia (OMEGA project) – Baseline = 1160 km



A new massive deep underground neutrino observatory for long baseline neutrino studies, capable of proton decay searches, atmospheric and astrophysical neutrino detection

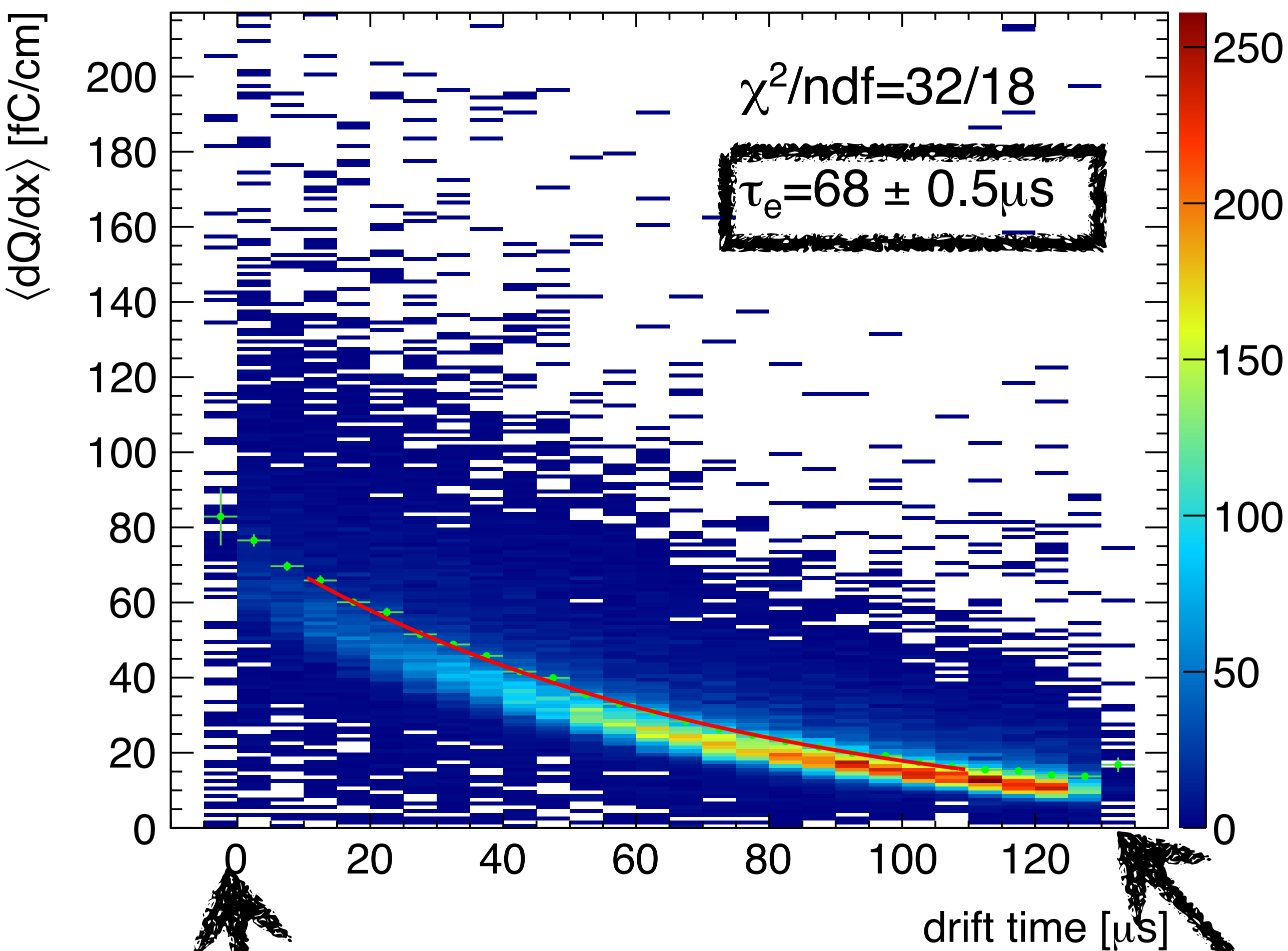
ETH

Calibration: drift attenuation

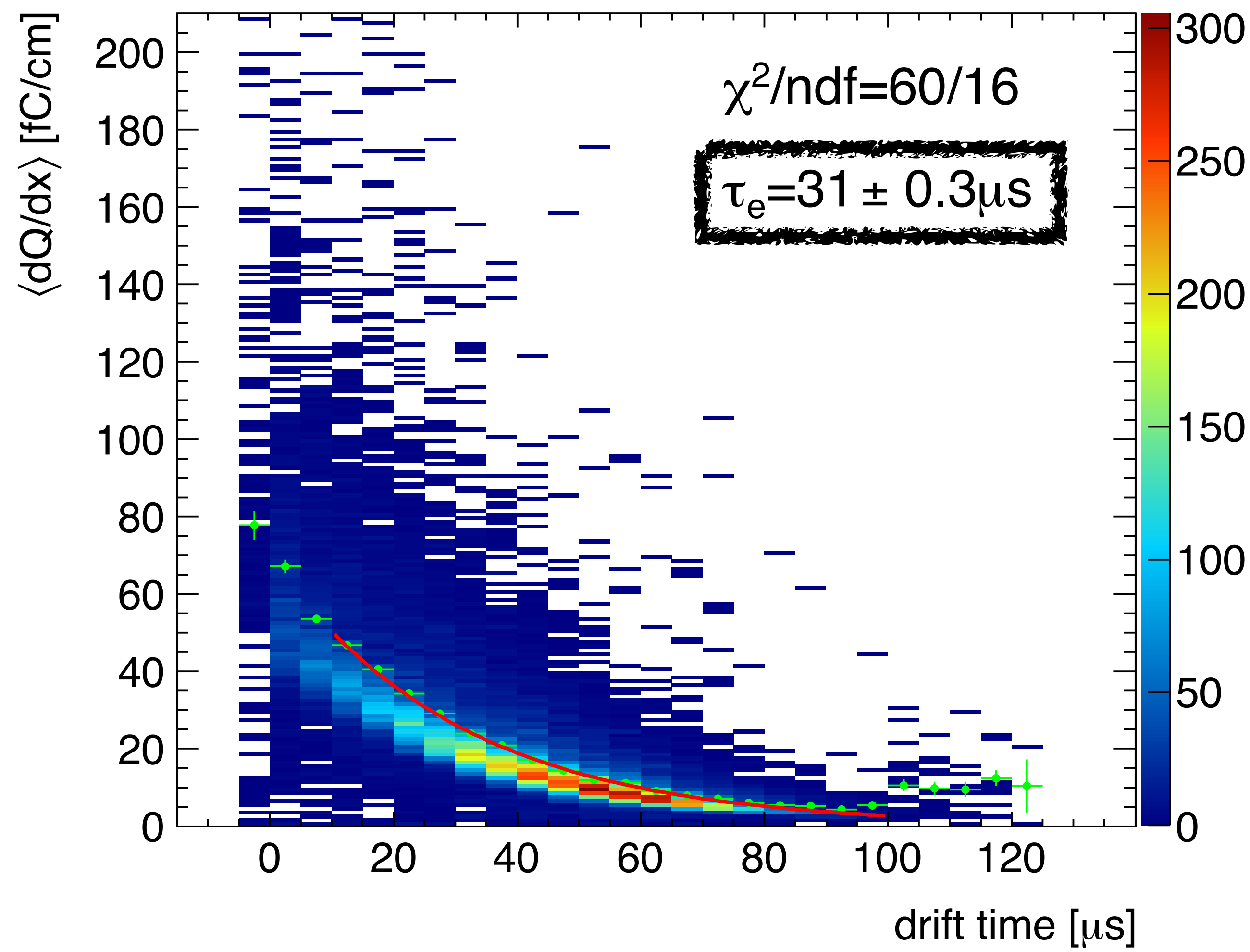
drifting electrons are trapped by impurities in LAr:

$$dQ/dx \propto \exp(-t_{drift}/\tau_e)$$

towards the beginning of a run



towards the end of a run

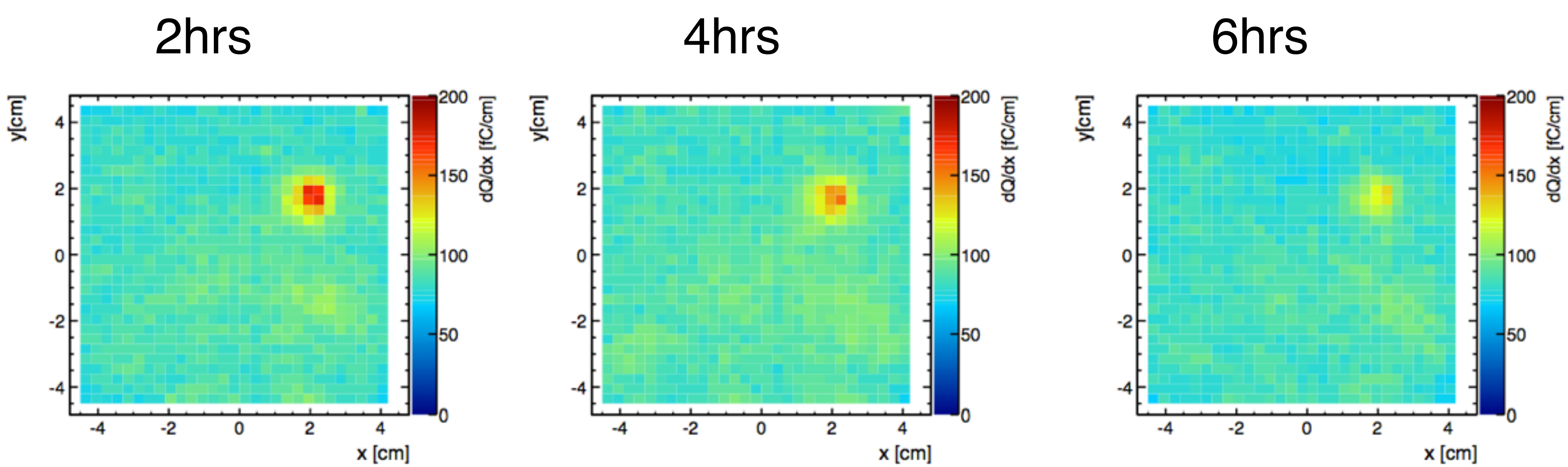


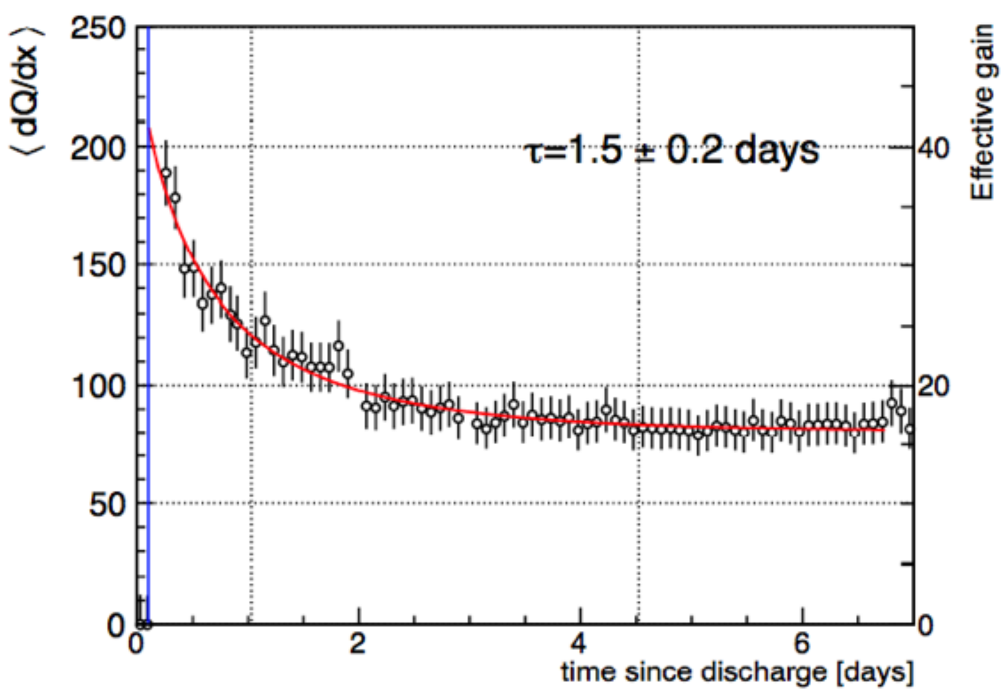
top of the chamber

bottom of the chamber

Local vs global gain evolution

time after discharge

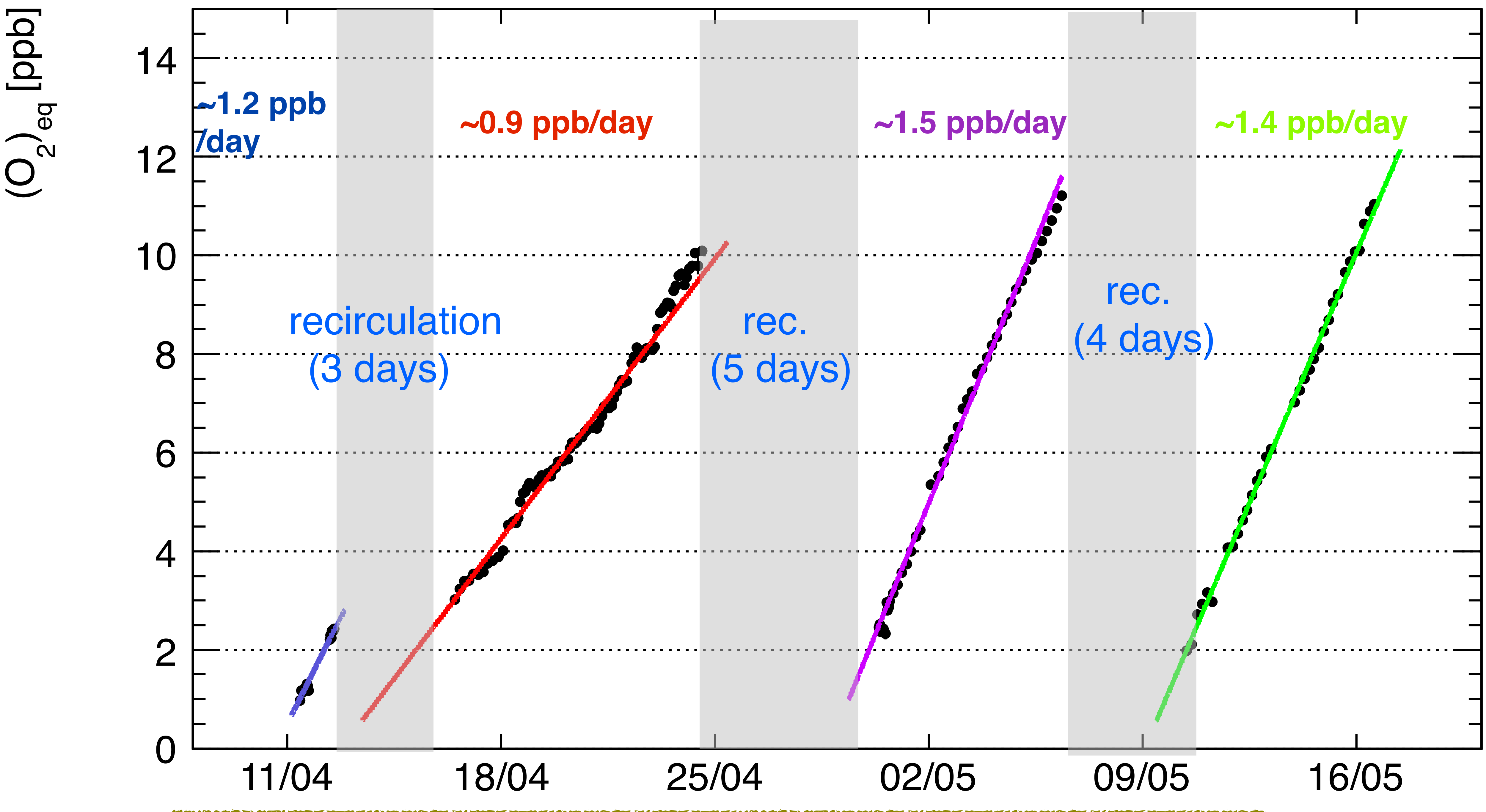




Evolution of the free electron lifetime

Impurities in the liquid: $[O2]_{eq} \approx 300\ \mu s / \tau_e$

4 runs. few days of gas recirculation between each run.



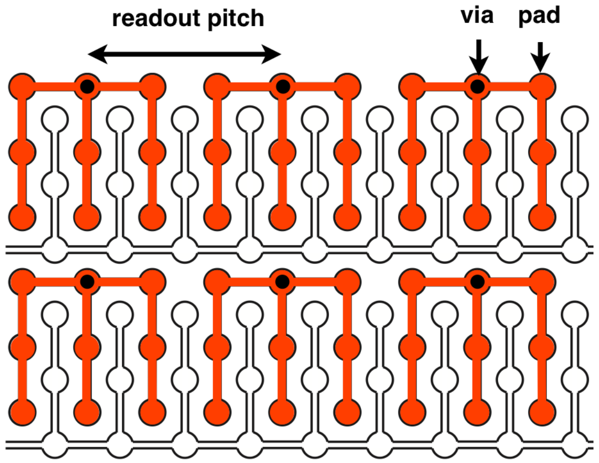
more than 1 month of continuous operation!

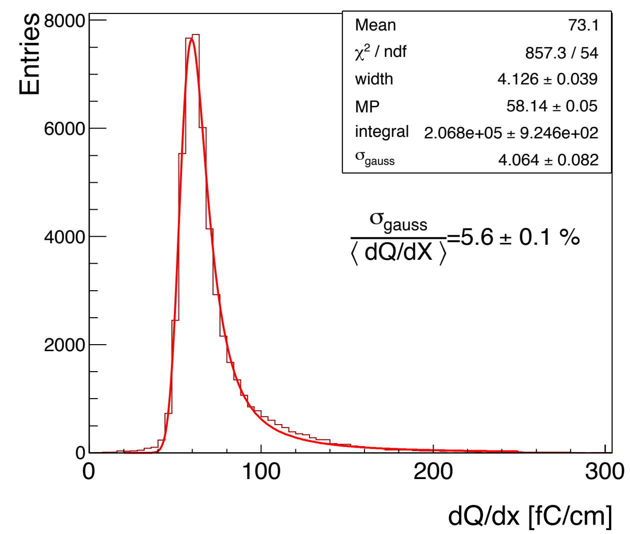
Various anode designs were tested

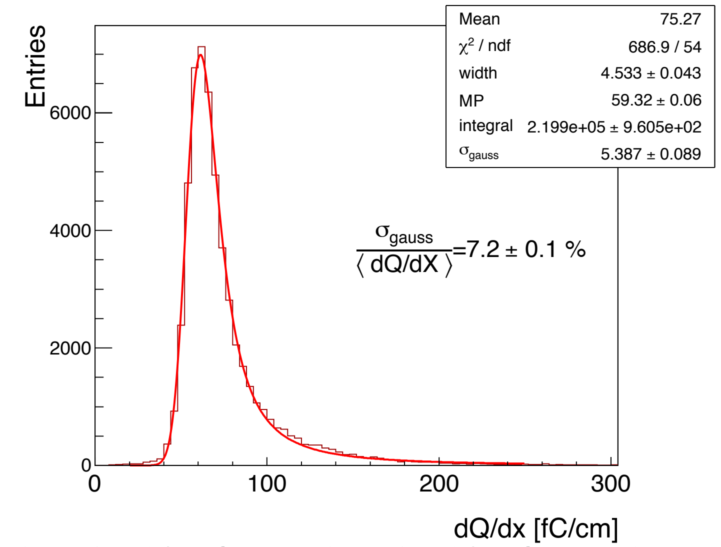
view 0 (red) | view 1 (white)

anode A

~200 pF/m

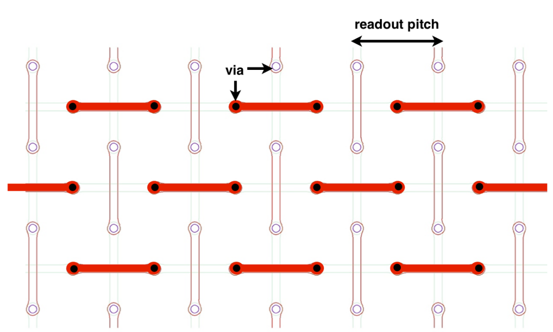


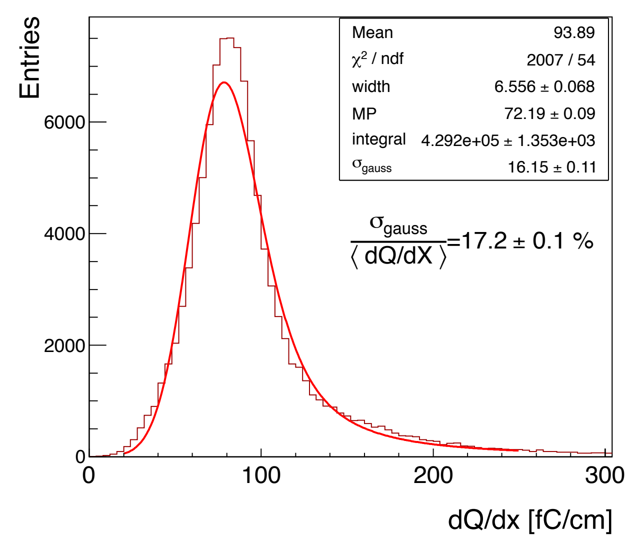


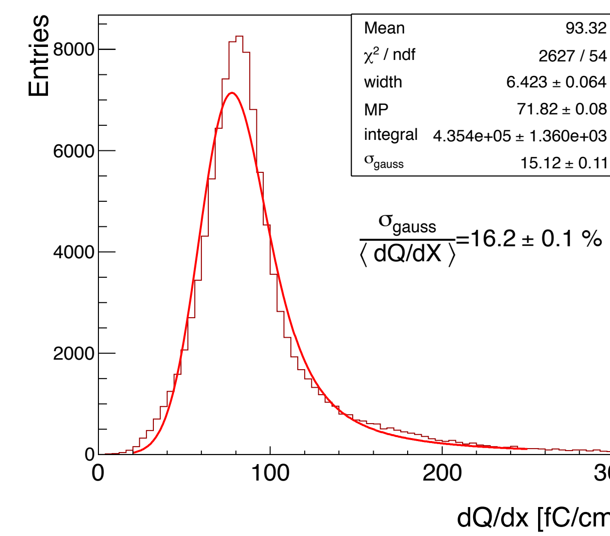


anode B

~100 pF/m

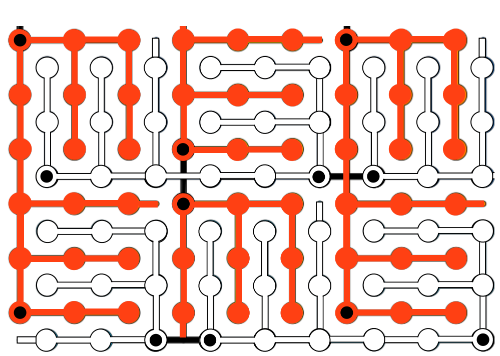


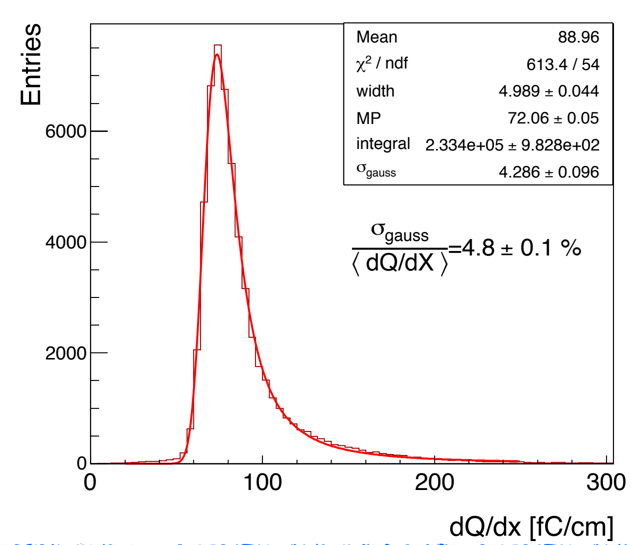


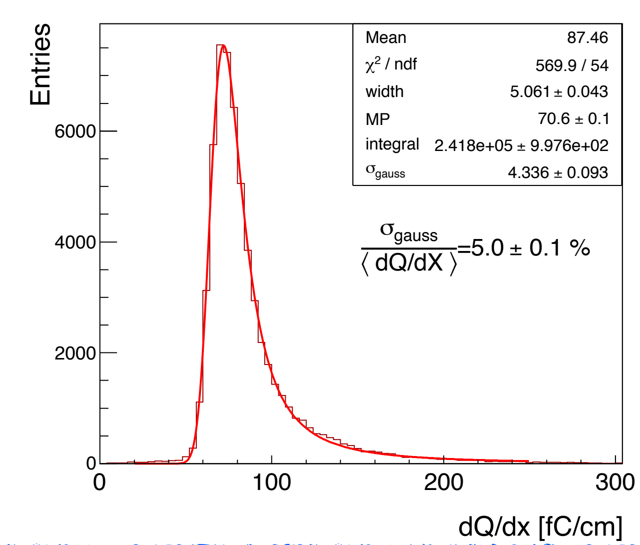


anode C

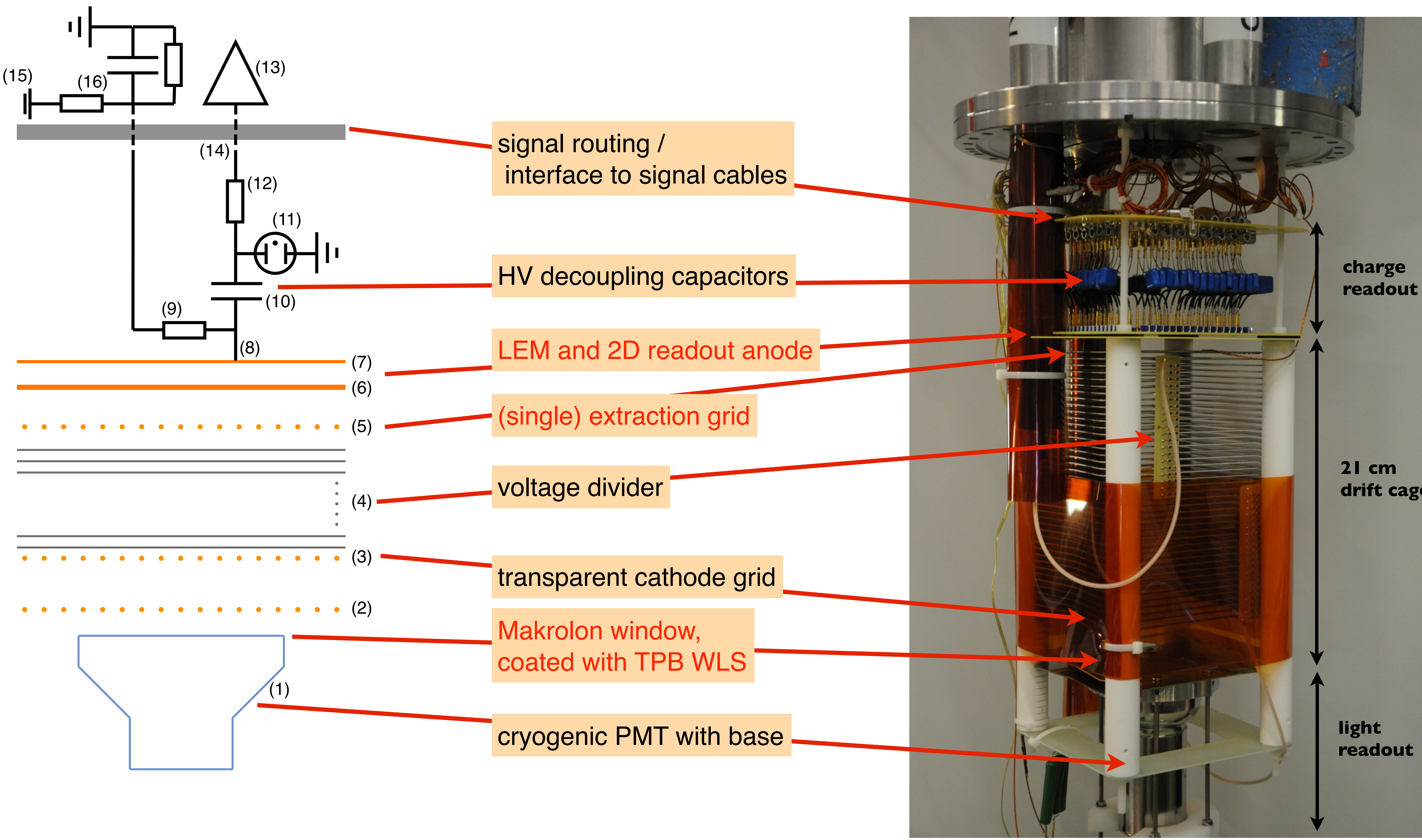
~200 pF/m





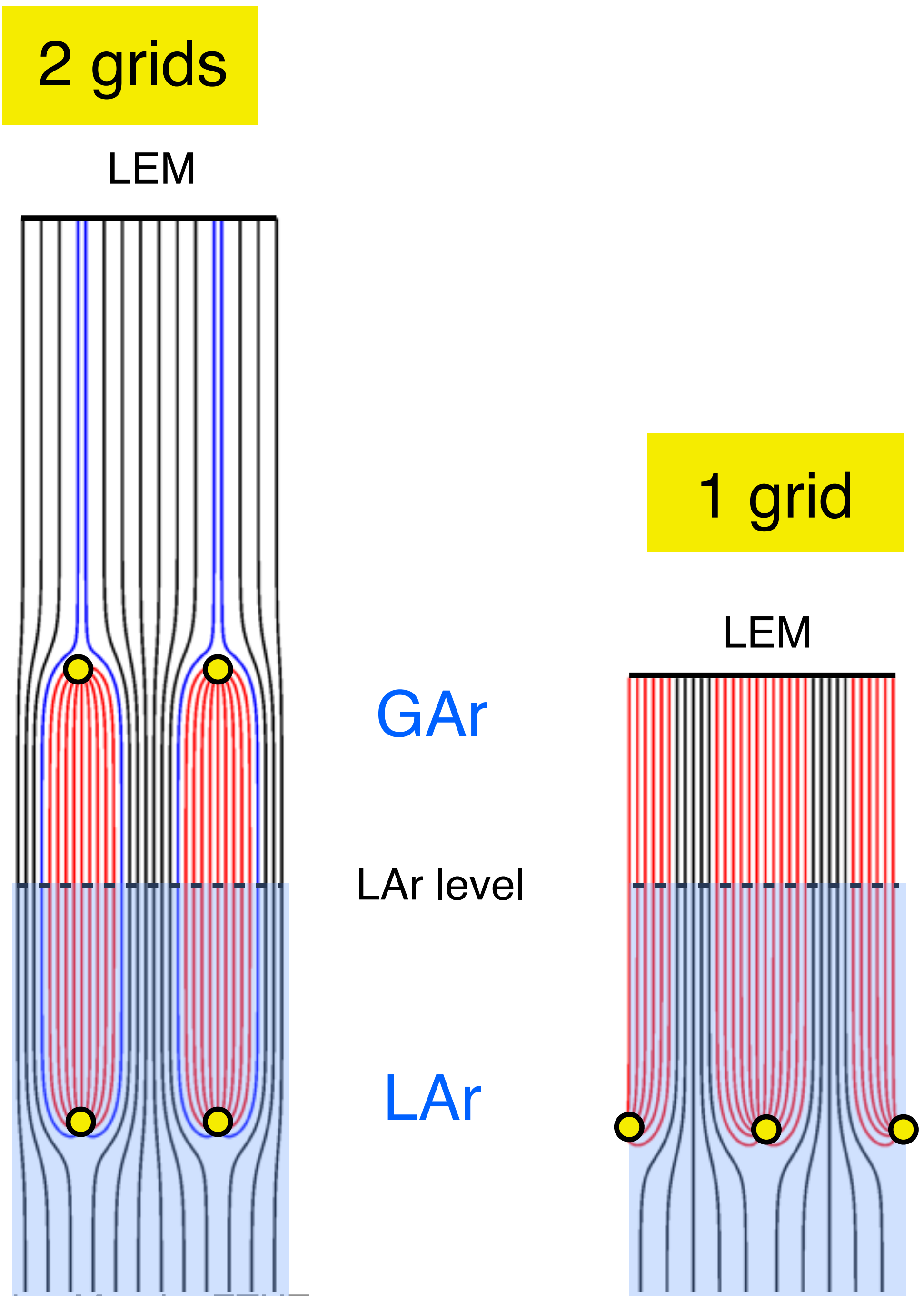


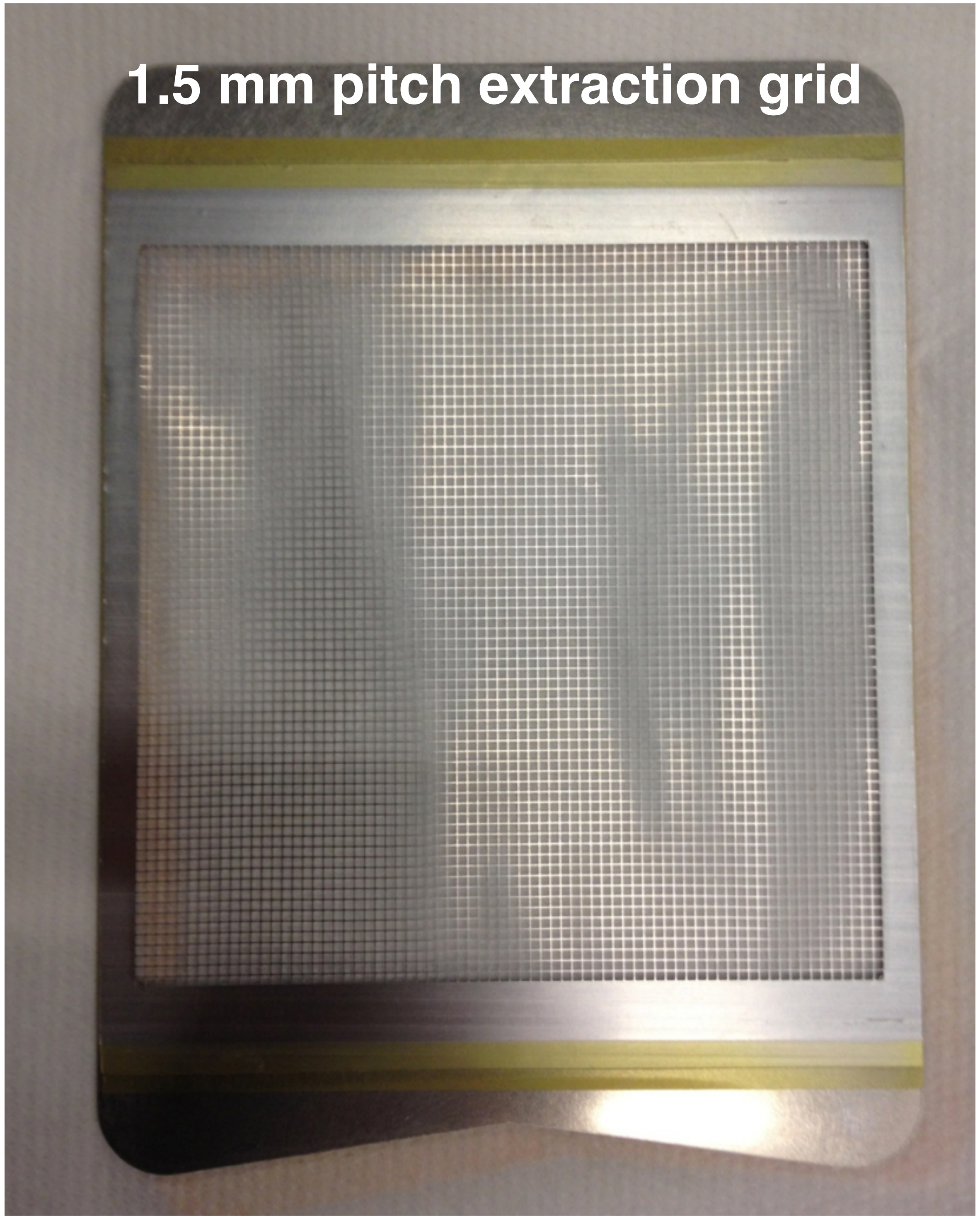
10x10x20 cm3 prototype: overview



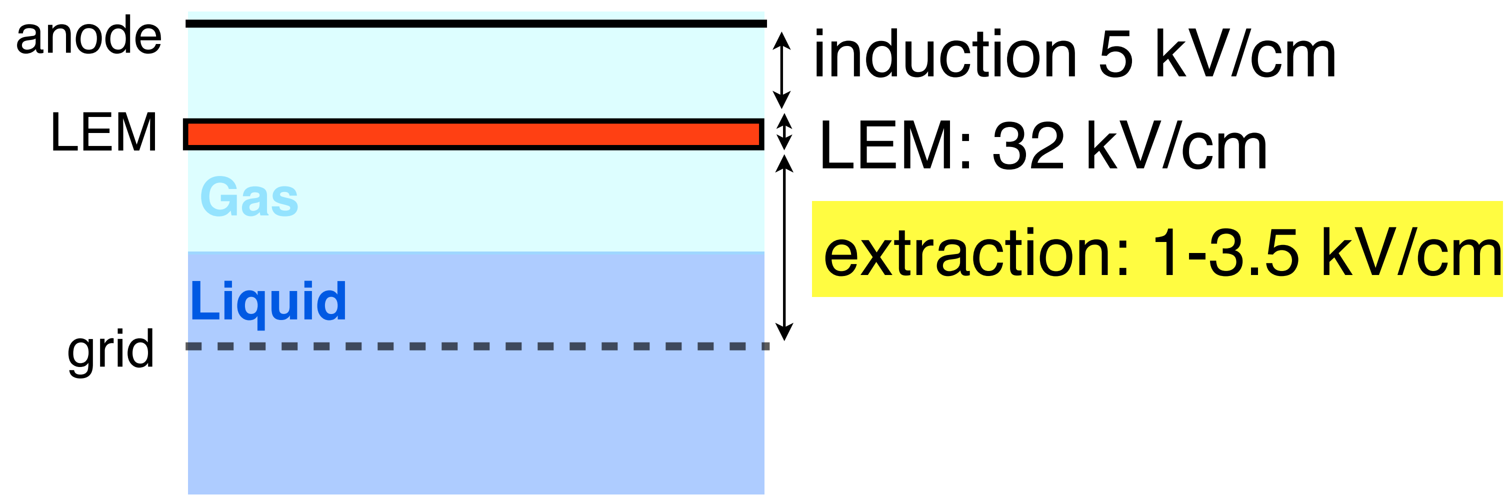
Simplifying the design- single extraction grid

- Simplified scheme
- Higher transparency possible (no alignment of grids needed)
- Less absolute voltage

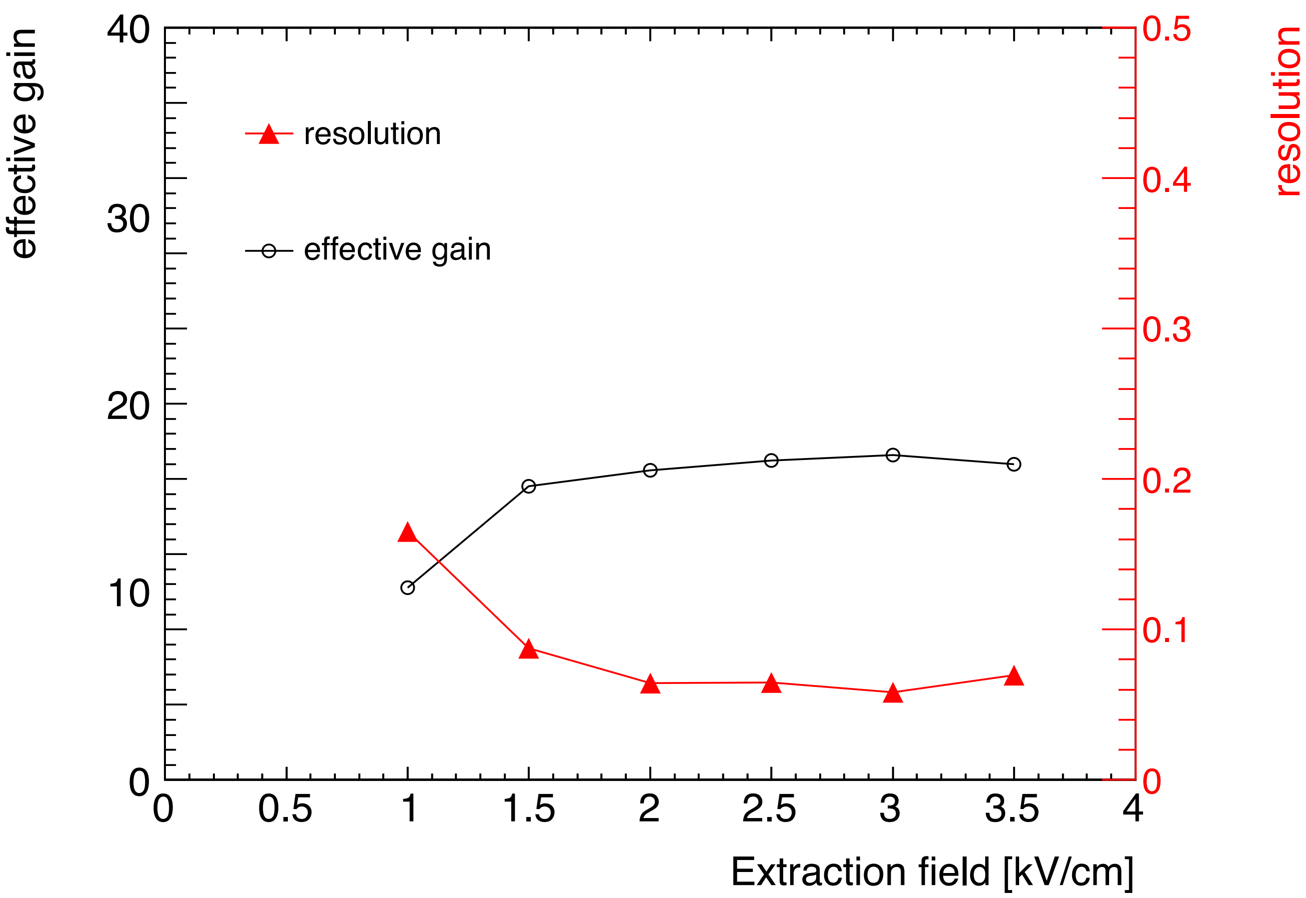




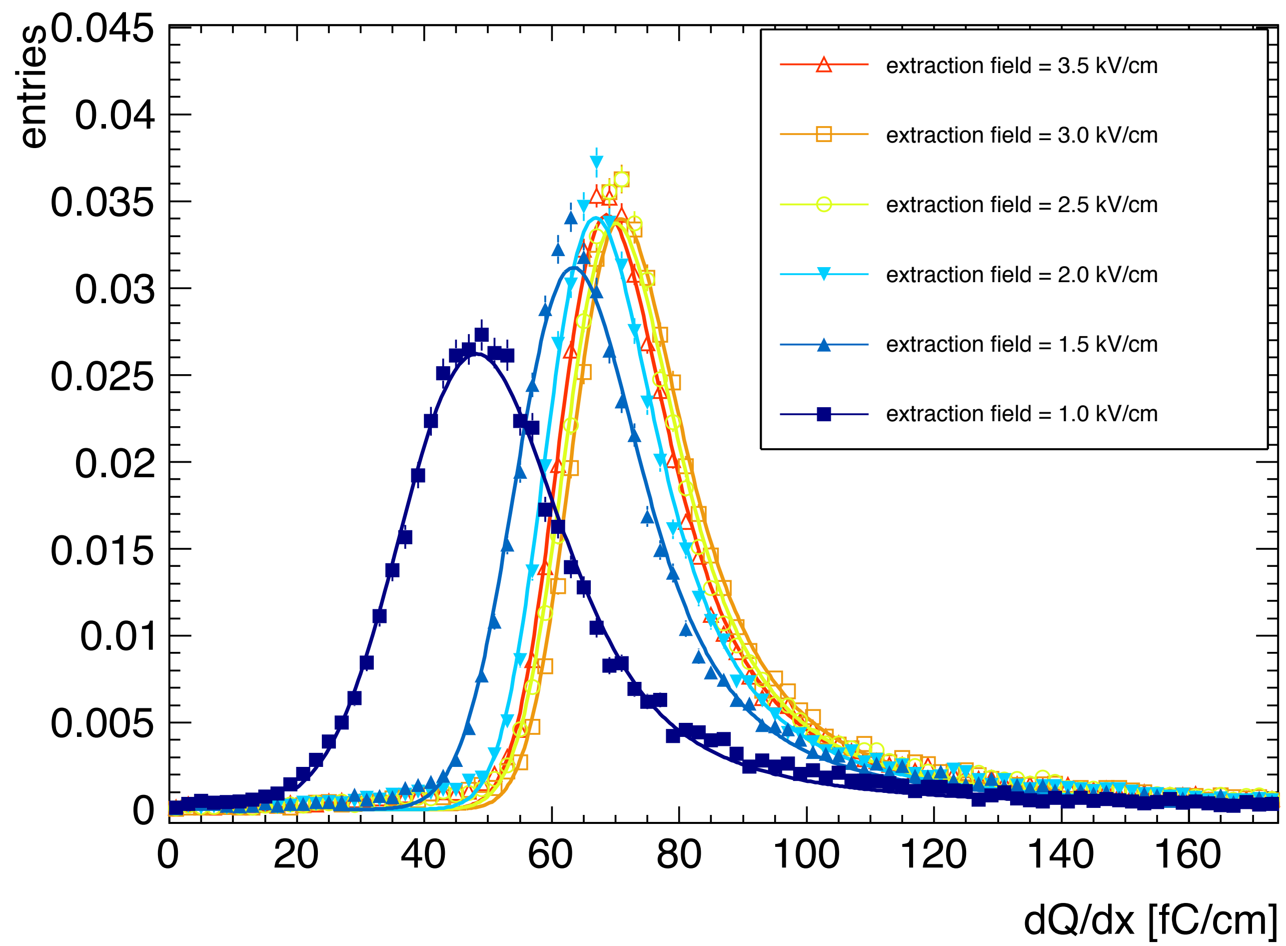
Extraction field scan



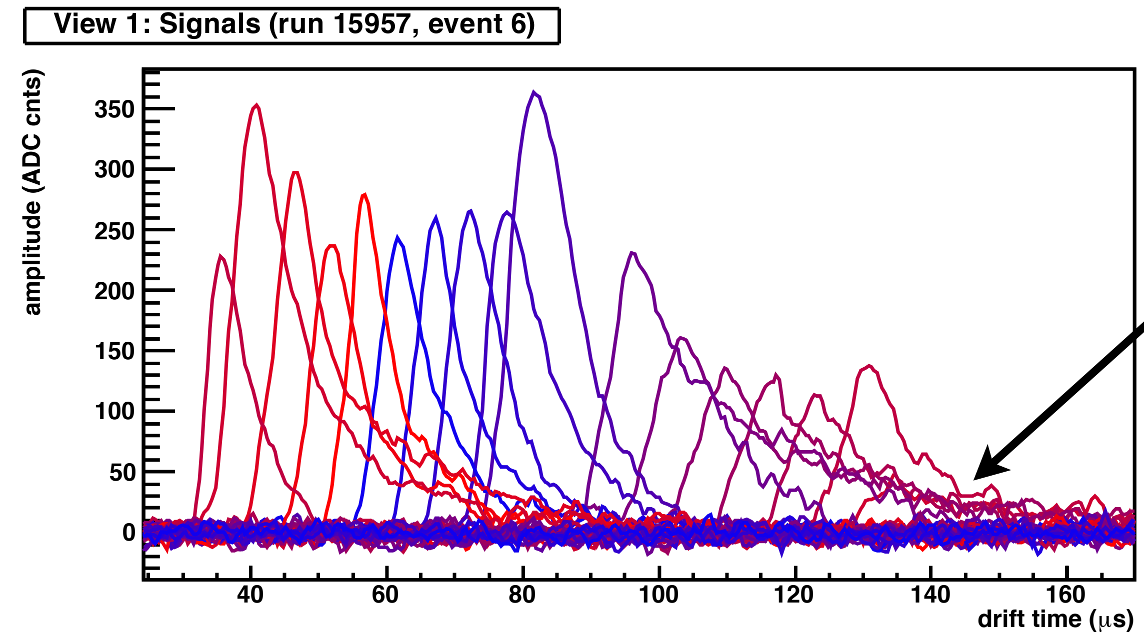
gain and resolution for diff. extr. fields



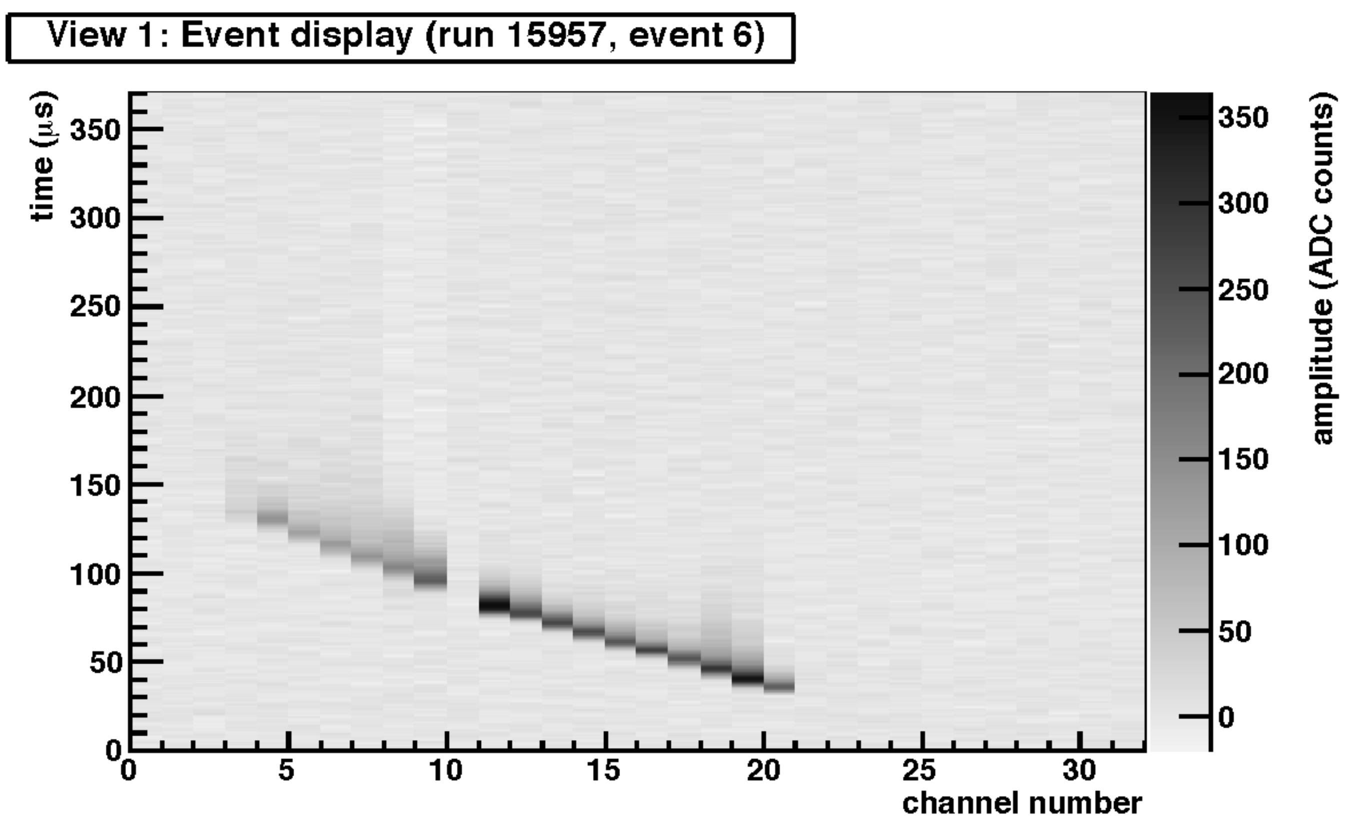
Landau distributions for diff. extr. fields



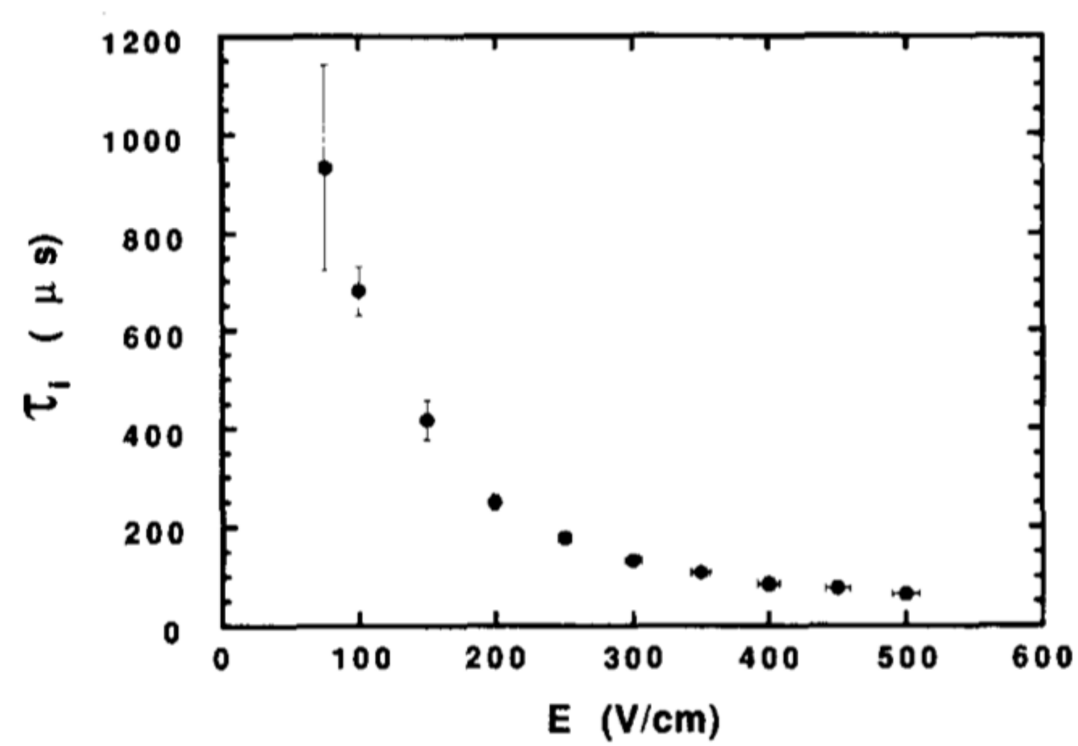
What happens at low extraction fields?



tails, due to slow electron emission at low fields (here: 1.5 kV/cm)



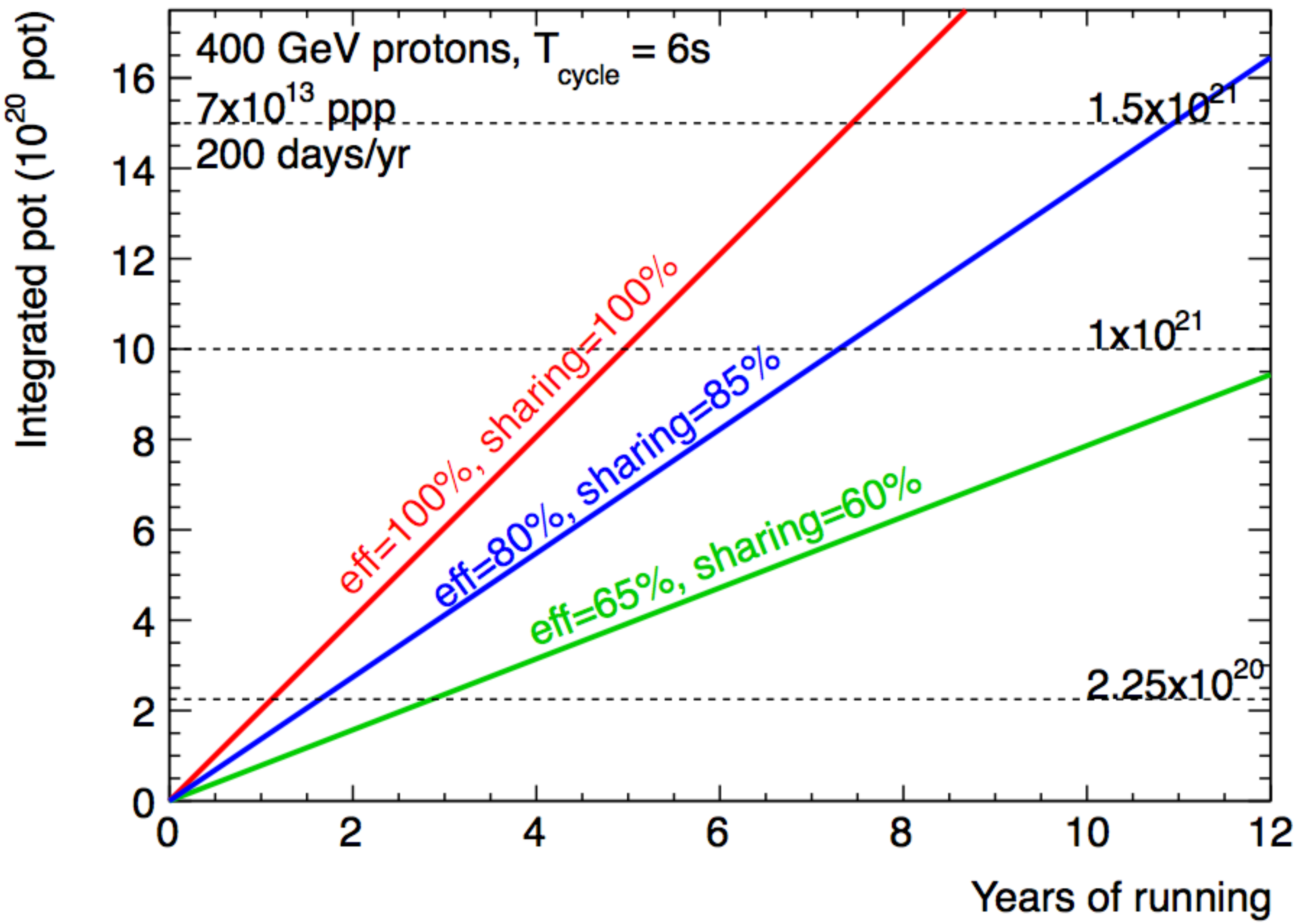
Literature:



Borghesani et al., “Electron transmission through the Ar liquid-vapor interface”, Phys. Lett. A149 (9)

protons availability

CNGS: 4.5e19 protons/year (w/o sharing 7.6e19 protons/year)
LBNO: assume 1.5 e21 pot in 12 year => ~1.5 e20 protons/year from improved SPS intensity (7e13 ppp instead of 4e13 presently) and operation sharing



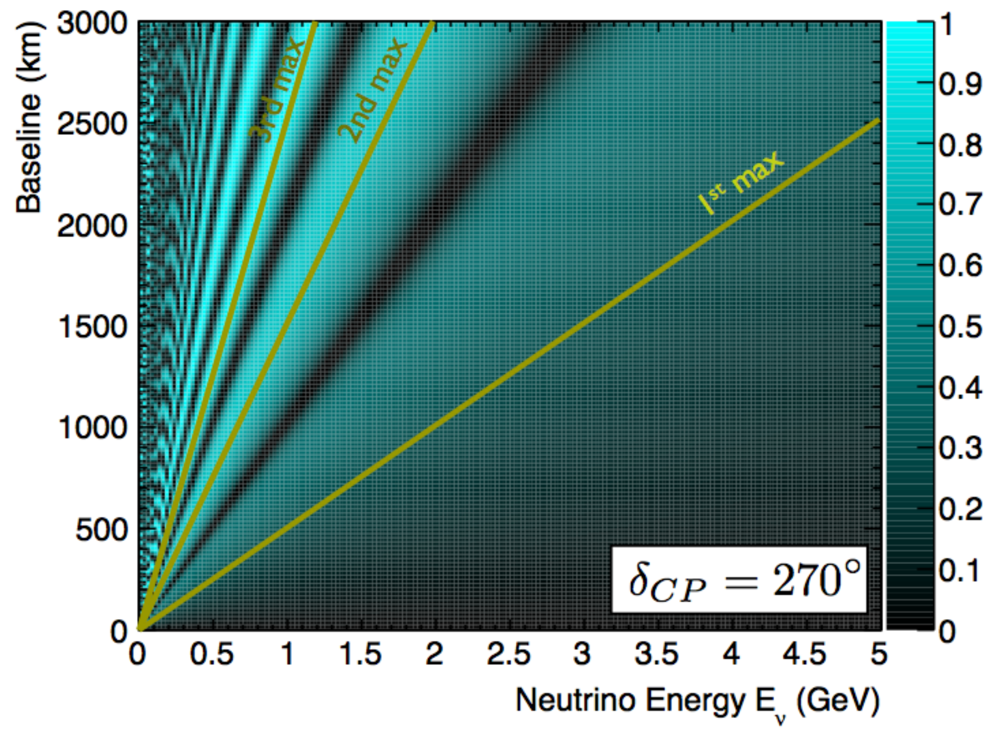
✓5 sigma CPV

✓5 sigma MH

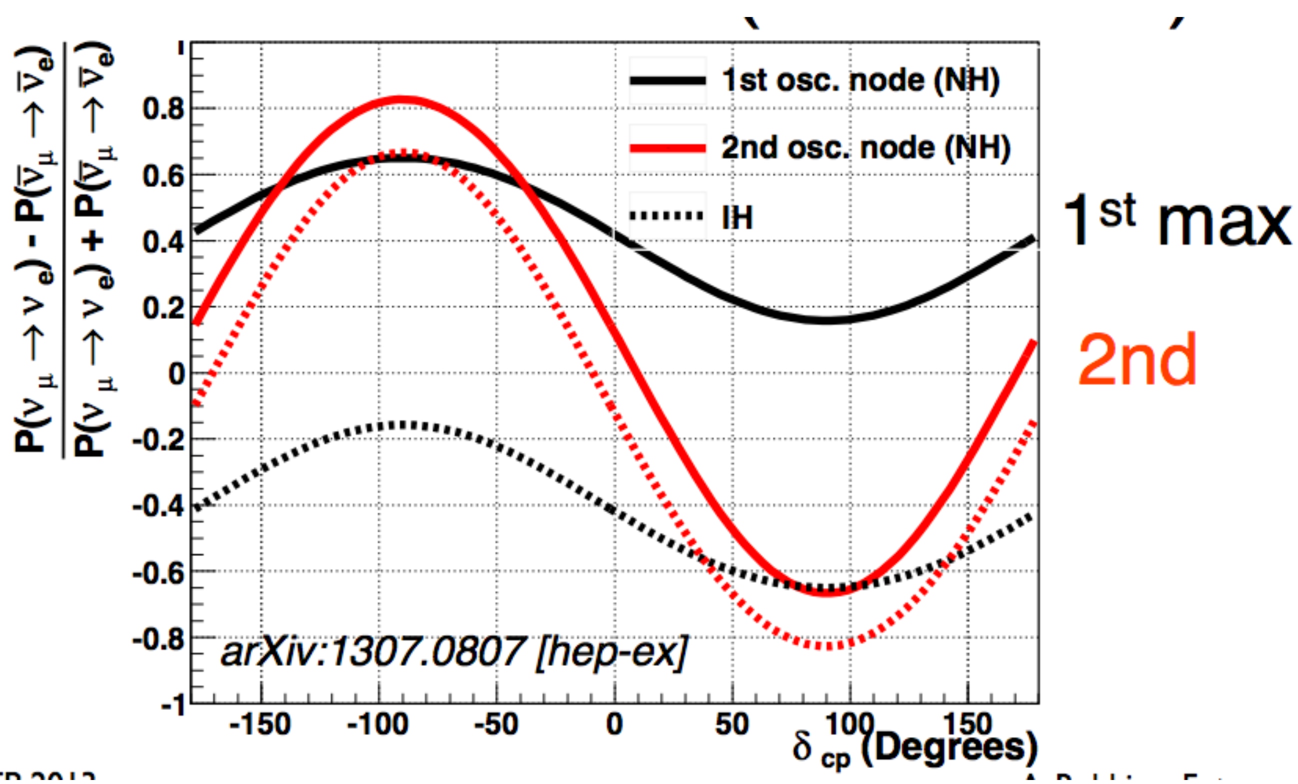
Long baseline

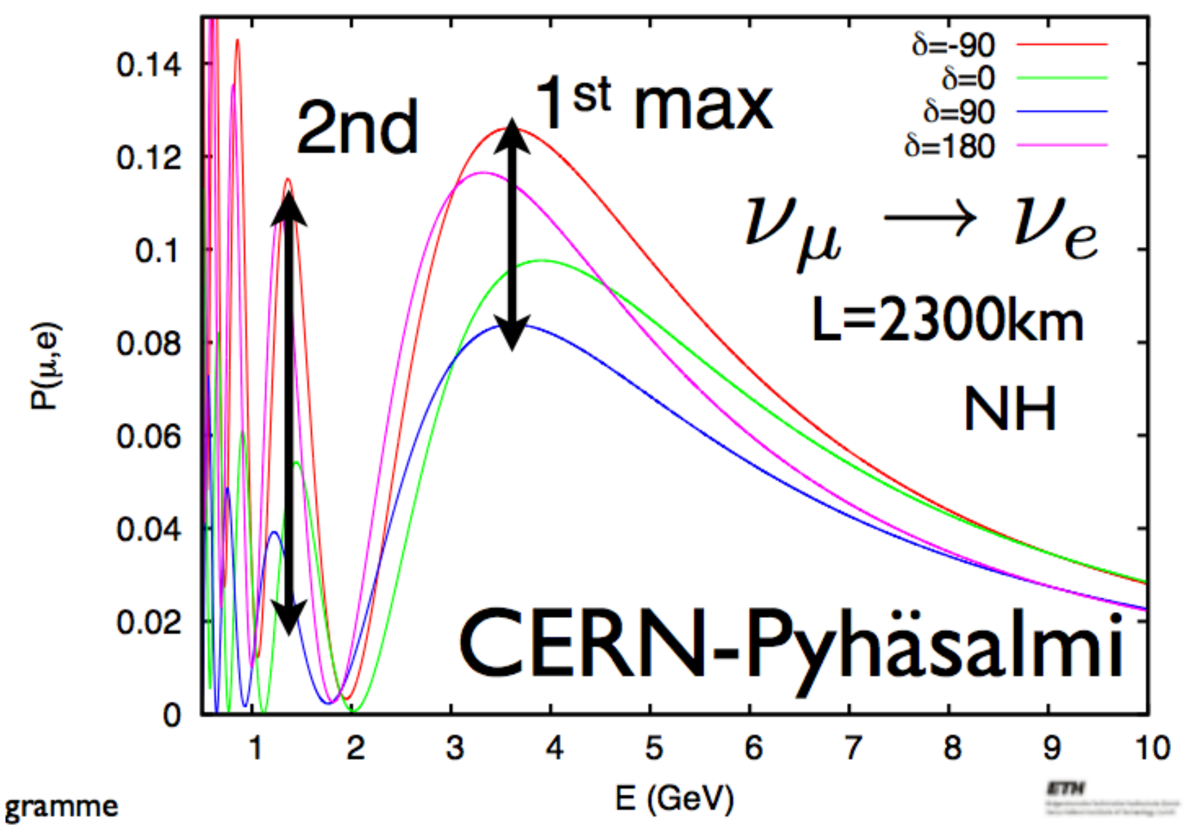
$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2 s_\delta c_{12} s_{12}}{s_{13}} \cot\theta_{23} \frac{\delta m^2_{21} L}{2E}$$

Growing CP effect with L/E=>CP asymmetries larger for 2nd, 3rd .. maxima
Long baseline (>1000 km) needed



FNAL->homestake (1300 km)



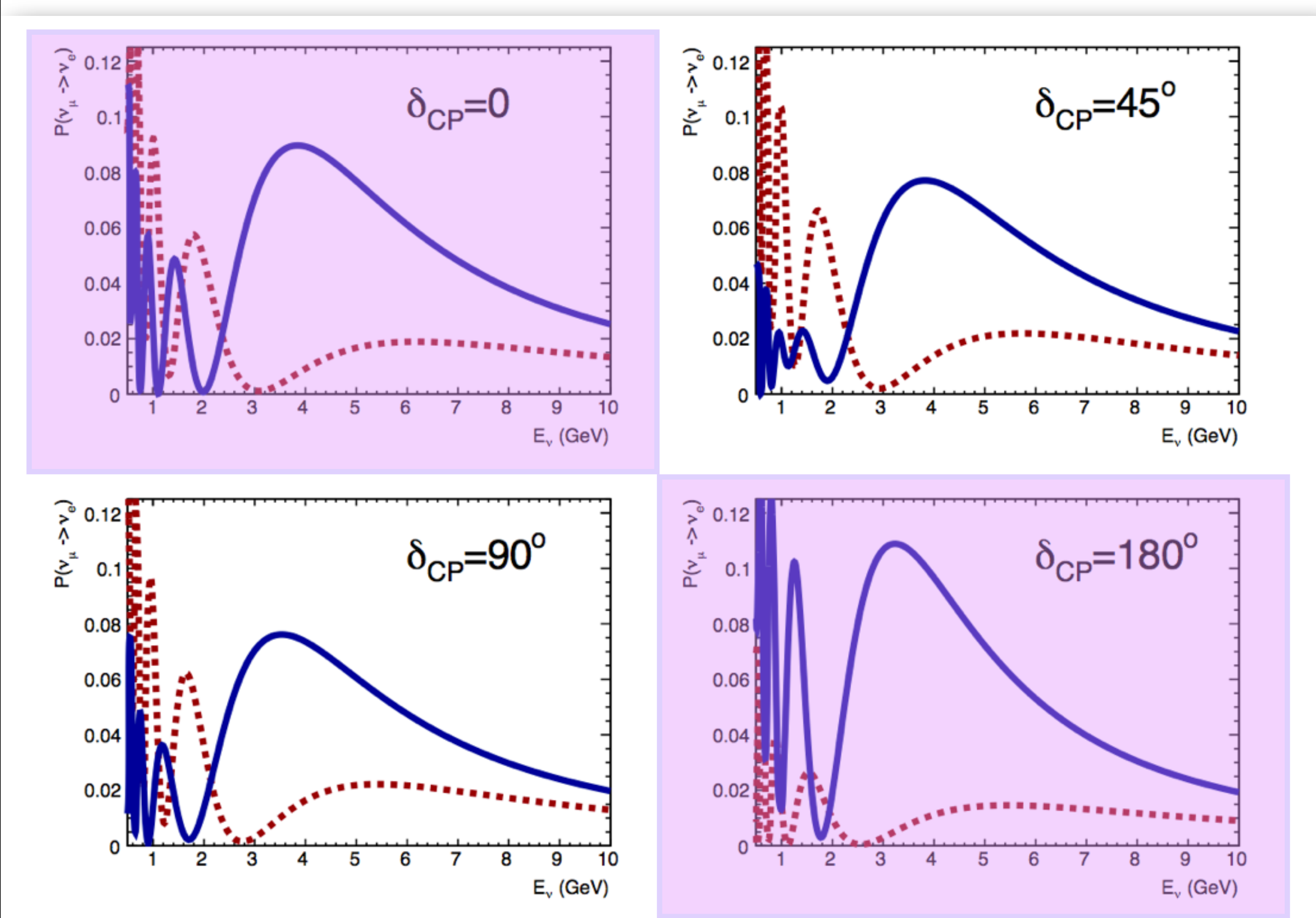


gramme

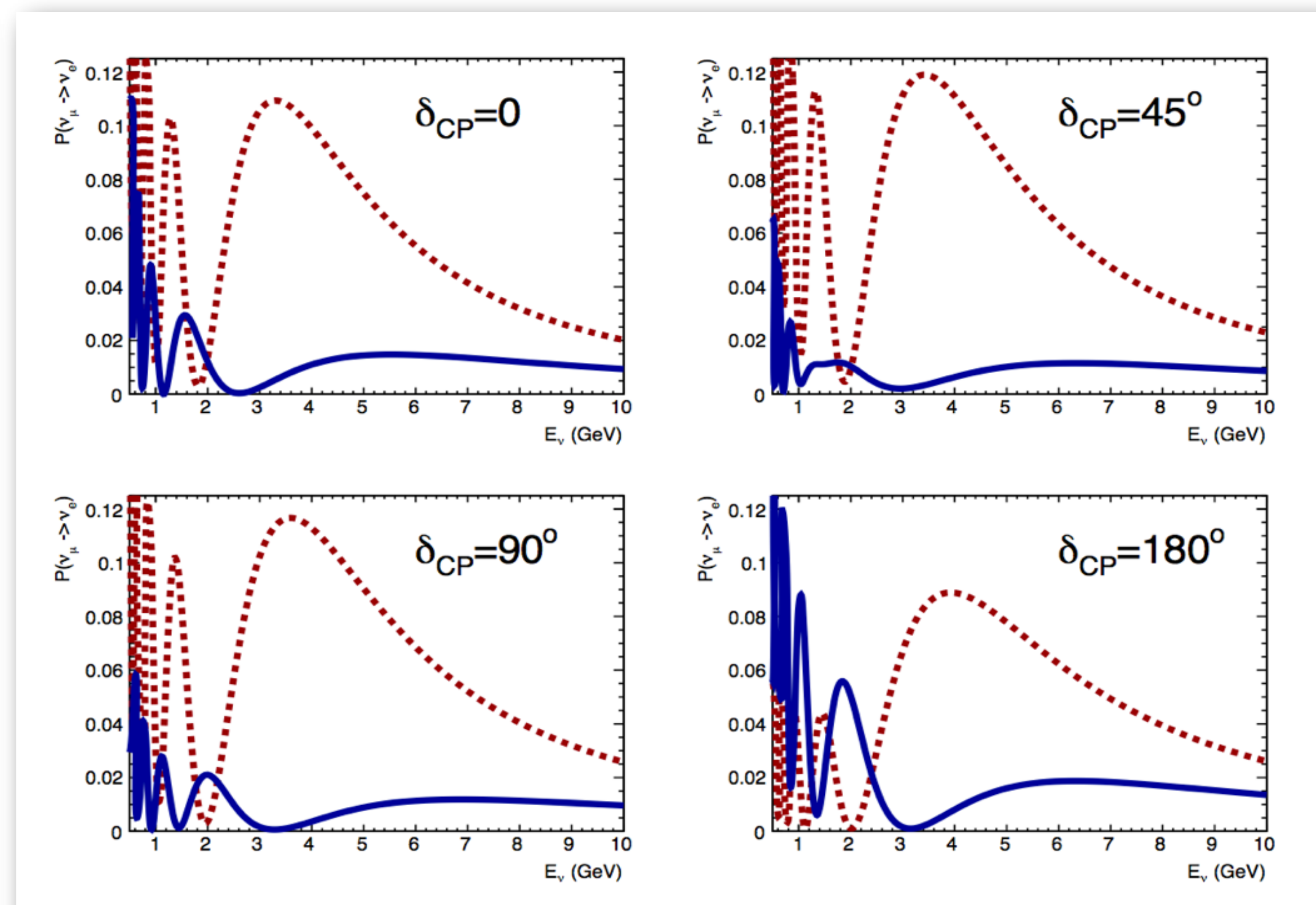
Long baseline

-Long baseline=>complete swap between neutrinos and and antineutrinos
-spectral information provides unambiguous determination of osc para and allows to distinguish the two CP conserving scenarios

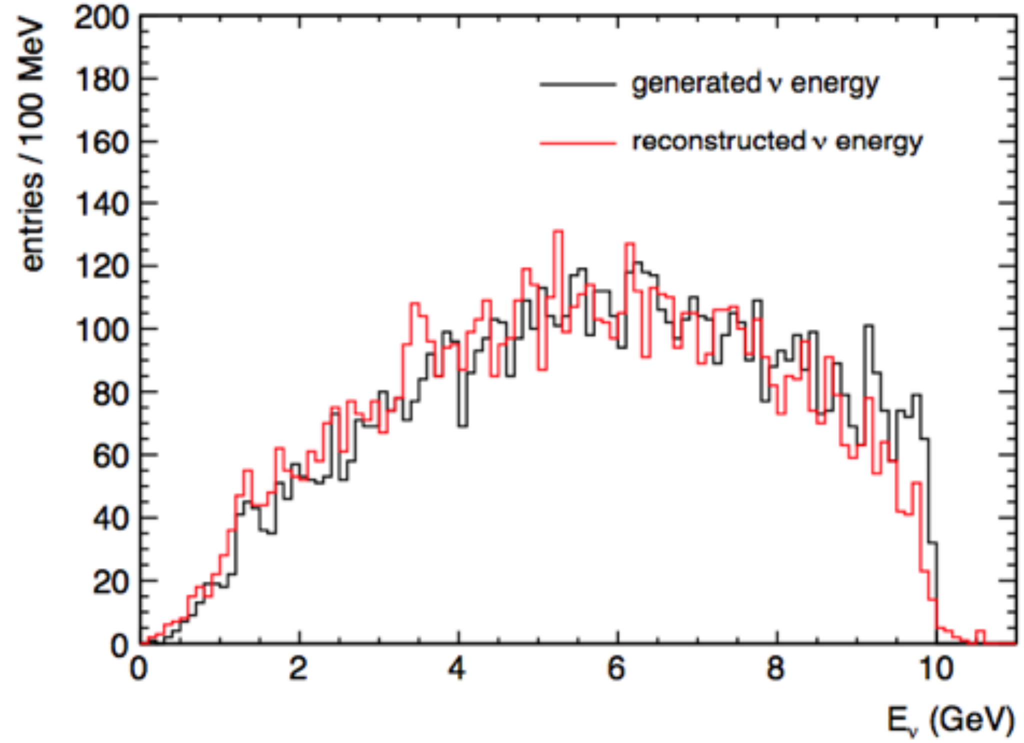
NH

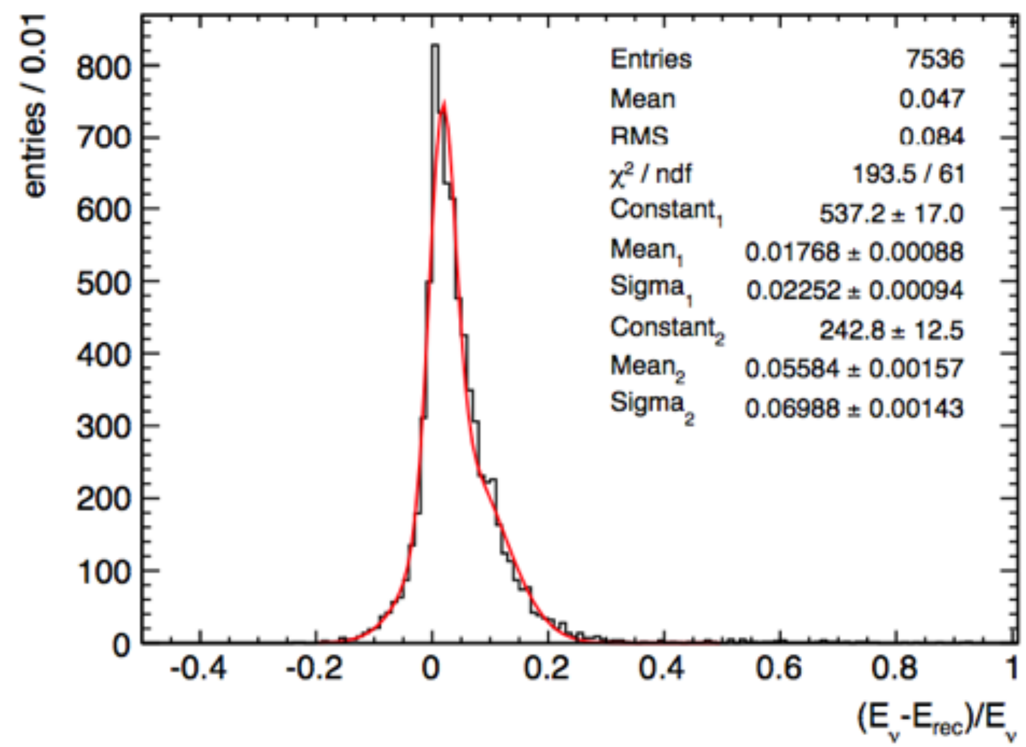


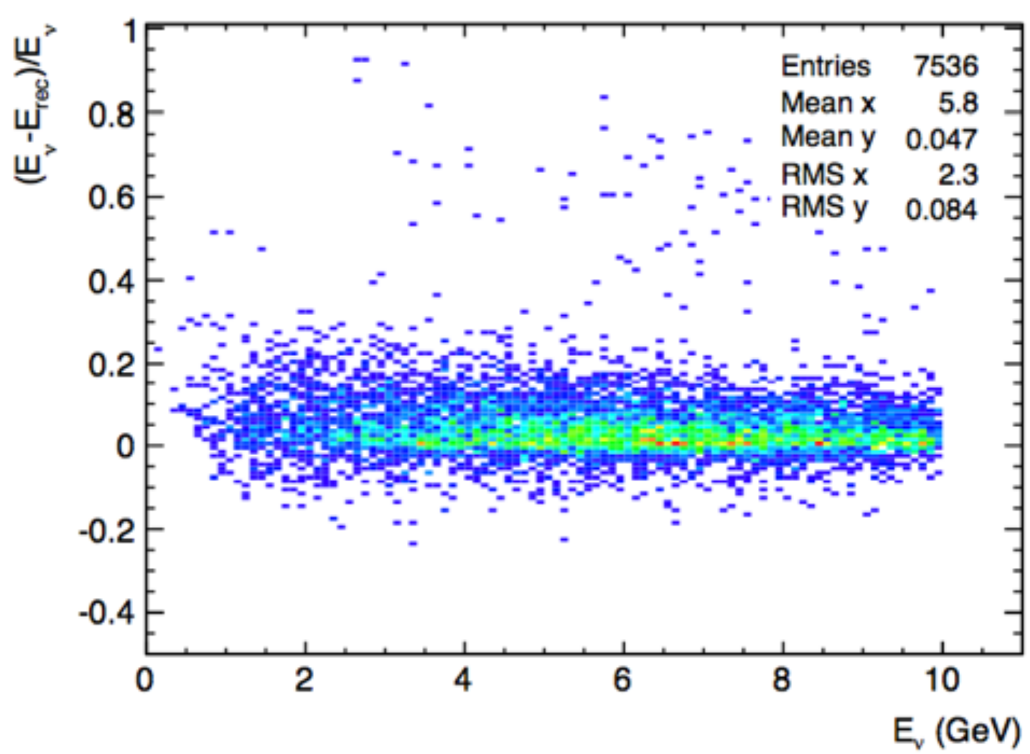
IH



CC nue resolution







- tracking done with GEANT4, including electron ion recombination
- event vertex placed in the center of the detector (all events are fully contained!)

***$(E_\nu-E_{rec})/E_\nu$* RMS=8.4%**