Giant double phase liquid argon TPCs: from R&D to LBNO

Sebastien Murphy ETH Zürich

Lawrence Berkeley National Laboratory
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The future of neutrino oscillation

In just over a decade, we have learned a lot about neutrino oscillations - measured 2 mass splittings and 3 mixing angles.

Future questions to answer about oscillations:

- ✳Why are neutrino masses so small ?
- ✳Which is the absolute mass of the lightest state?
- ✳Are there more neutrinos than the 3 active flavors?
- ✳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 ?**
- ✳**How is the hierarchy of the neutrino mass eigenstates?**
- ✳Are neutrinos Majorana particles?
- ✳is θ_{23} maximal?

The past and present

✳A rich and varied experimental neutrino oscillation program

A decade of revolutionary experiments have unraveled a new flavor sector

✳Equally as important but not discussed here:

-Experiments at end-point of single beta decays aimed at measuring the absolute neutrino mass (KATRIN) and new searches for neutrino-less double beta decays to test Majorana nature of neutrinos (CUORE, EXO, GERDA, Kamland-Zen, Majorana, NEMO, NEXT, SNO+, ...)

-Cosmological observations

Discovery of θ_{13}: a turning point

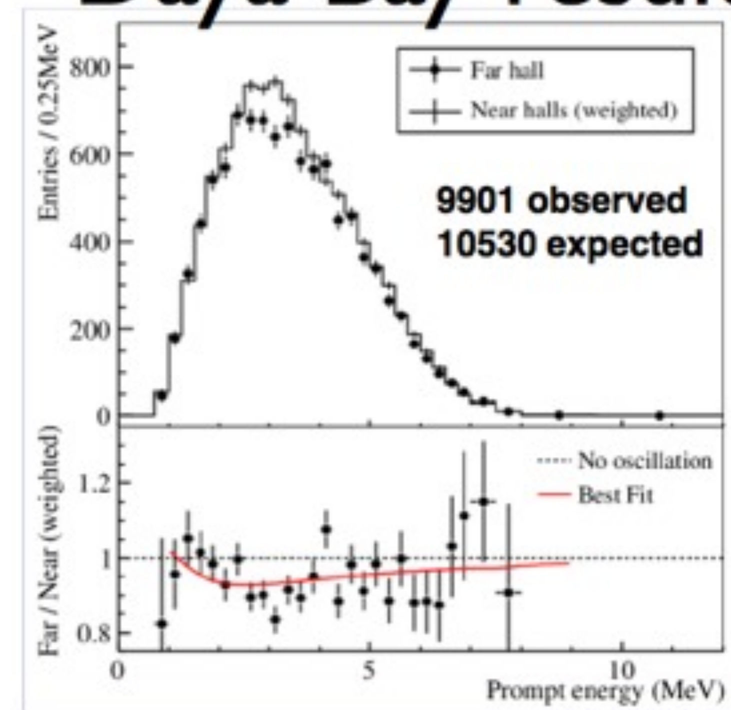
✳June 2011: First result from T2K off-axis beam experiment ($\nu_\mu \rightarrow \nu_e$ appearance)
6 events observed, 1.5 events background → 2.5σ for non-zero θ_{13}

✳March 2012: Daya Bay reactor anti-neutrinos $\nu_e \rightarrow \nu_x$ (ν_e disappearance) → 5.2σ exclusion of no oscillation hypothesis. Also Double Chooz and RENO.

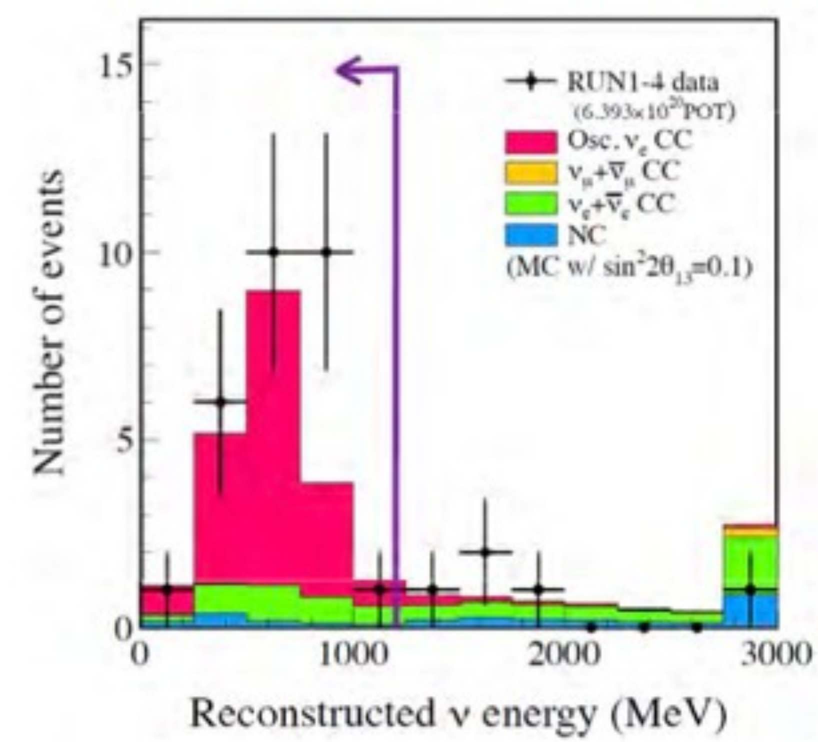
✳July 2013: T2K reports 28 candidate events for electron appearance with 4.64±0.53 events background → 7.5σ discovery of appearance of new flavor in neutrino oscillation

✳Aug 2013: Daya Bay 217 days 6 detectors rate +shape analysis $\sin^2 2\theta_{13} = 0.09^{+0.008}_{-0.009}$

Daya Bay result



T2K 2013 result



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With large θ_{13} the next steps are accessible with conventional neutrino beams. Mass hierarchy and CP-violation become the new goals!

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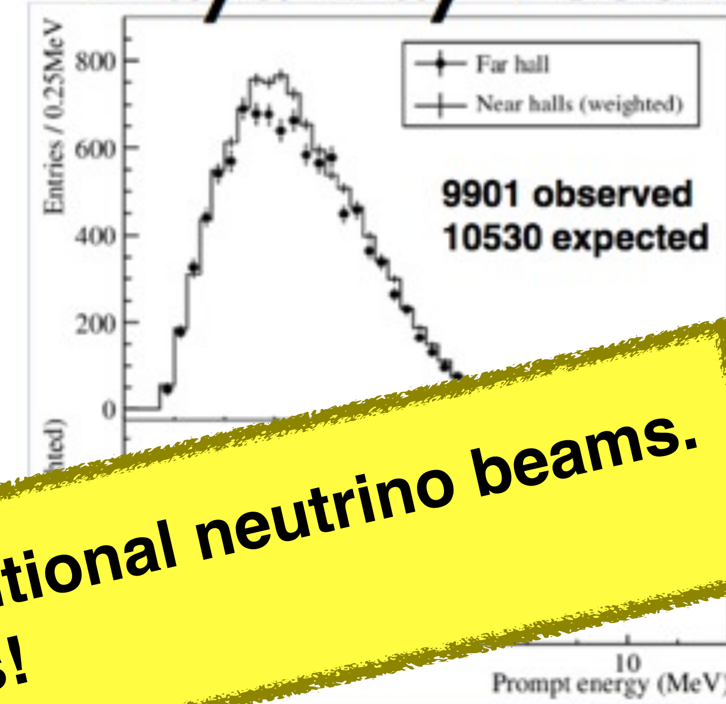
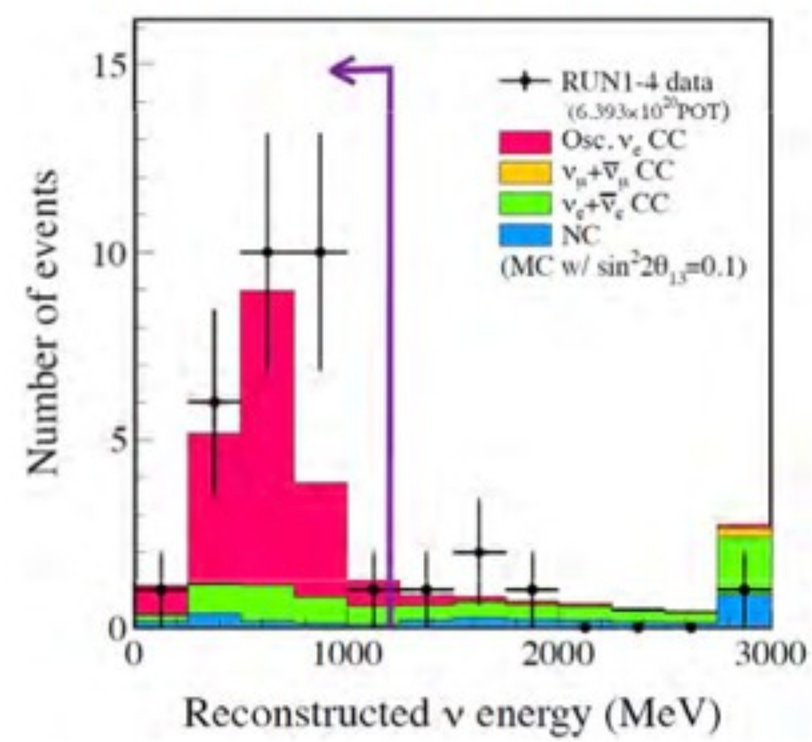
Daya Bay result



T2K 2013 result



Testing CP-violation in the neutrino sector

If PMNS matrix is complex, then neutrino and antineutrinos will behave differently in their flavour oscillations.

Main channel of investigation: the appearance channel $\nu_\mu \rightarrow \nu_e$

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

look for neutrino/anti-neutrino difference: $P(\nu_\mu \rightarrow \nu_e; E) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e; E)$

Energy dependence of oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e; L) \simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \left\{1 + \frac{a}{\delta m_{31}^2} \cdot 2(1 - 2s_{13}^2)\right\} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$
$$+ c_{13}^2 s_{13} s_{23} \left\{-\frac{aL}{E} s_{13} s_{23}(1 - 2s_{13}^2) + \frac{\delta m_{21}^2 L}{E} s_{12}(-s_{13} s_{23} s_{12} + c_\delta c_{23} c_{12})\right\} \sin \frac{\delta m_{31}^2 L}{2E}$$
$$- 4\frac{\delta m_{21}^2 L}{2E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$

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

Testing CP-violation in the neutrino sector

If PMNS matrix is complex, then neutrino and antineutrinos will behave differently in their flavour oscillations.

Main channel of investigation: the appearance channel νμ→νe

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look for neutrino/anti-neutrino difference: $P(\nu_\mu \to \nu_e; E) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e; E)$

Energy dependence of oscillation probability:

matter terms ~a

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CP even

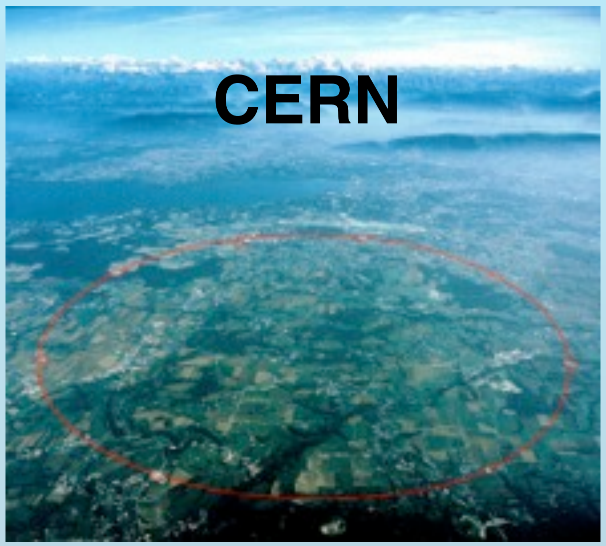
L/E dependance

CP odd ~sinδ

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

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

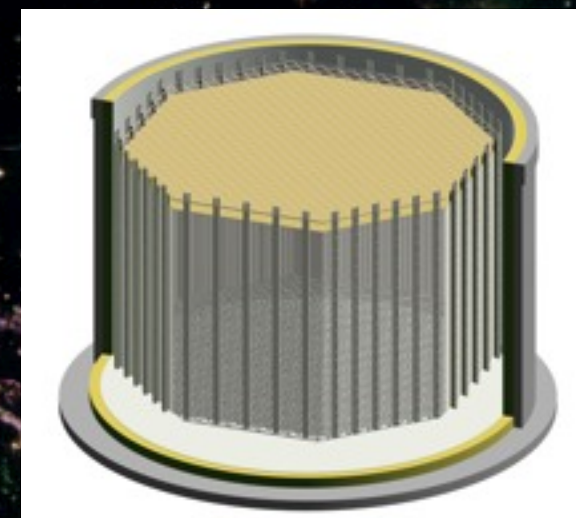
Laguna-LBNO: overview

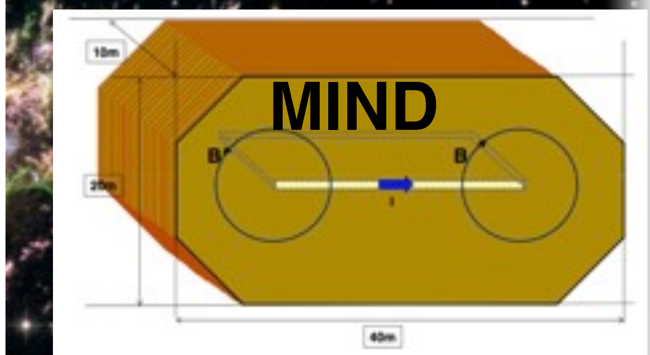


2300 km

GLACIER 20kt,50 kt

deep underground





neutrino beam + near detector

- **wide band ν_μ beam ~1-10 GeV => covers 2 oscillation maximums ~4 and ~1.5 GeV**
- SPS protons @ 400 GeV
- SPS upgrade 800 GeV 2 MW
- Near detector:
  HpAr TPC + magnetized iron detector (MIND)

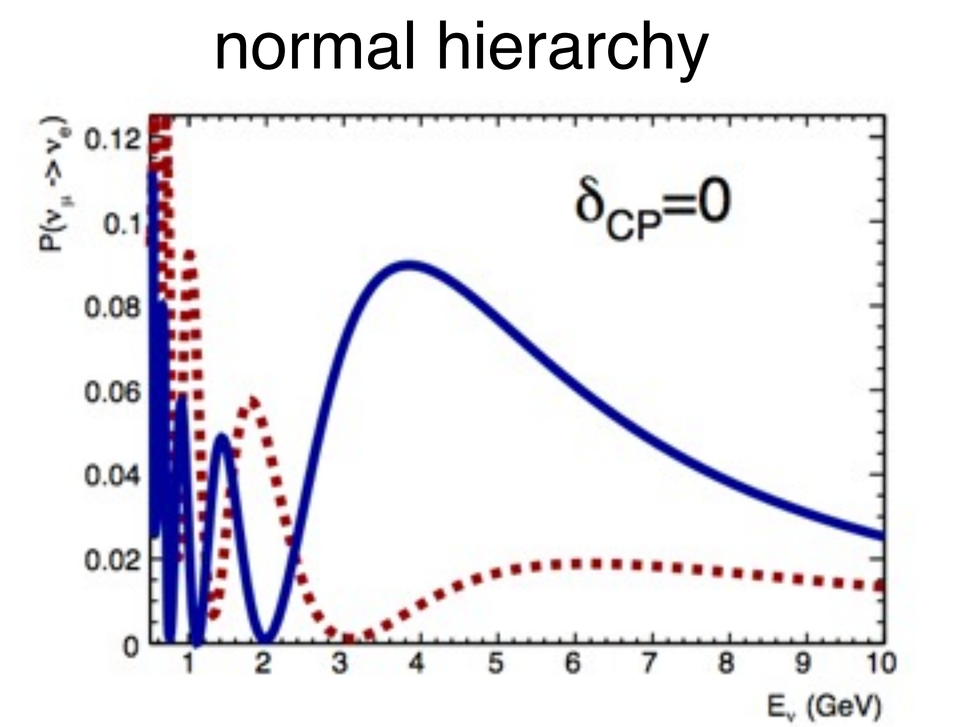
LAGUNA
Deep underground neutrino observatory

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

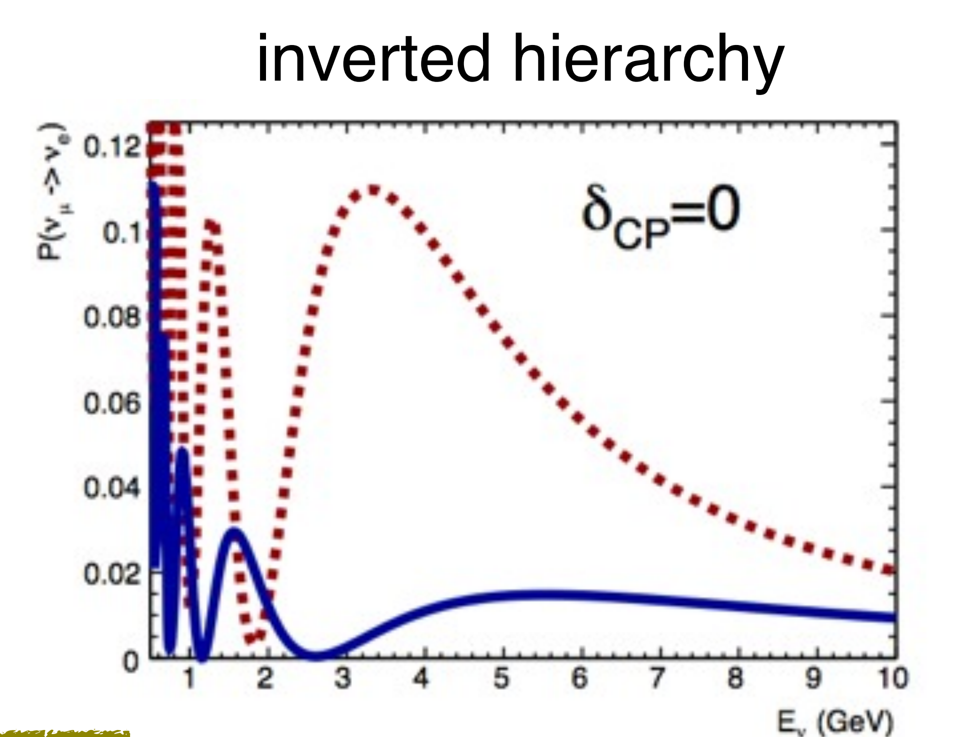
LBNO: Neutrino oscillations → MH, CPV, precision measurements

Reaching very long baselines

✳"Zoom effect": The L/E dependence can be observed in an "expanded" scale at large L
➠ Measure the full spectral information for unambiguous sensitivity and a direct proof of the observed phenomenon.



✳Decoupling of MH and CPV: A guaranteed & conclusive sensitivity to MH with existing beam power and initial mass requires a very long baseline.
➠ After MH fixed, optimise the running for CP (this depends on NH/IH)!



now is the time to move to very long baselines !!

LBNO strategy: Mass Hierarchy and CP

✳To measure **MH on the > 5σ level** one need to go to very long baselines, ~ 1000 km doesn't give enough matter effects to measure the full phase space.

✳Global fits of many experiments can guide and help the research but cannot replace the measurement of a dedicated experiment.

✳**LBNO aims at exploring and resolve the mass hierarchy and the CP-phase problem by observing clear signatures and determining their L/E dependence =>Very Long Baseline**

✳ LBNO incremental approach:

1st phase: initial LAr mass of 20 kton =>

1. MH determination in 2 years!
2. Investigation of CPV

2nd phase: LAr mass 70 kton: Determination of CPV.

LBNO: unambiguous Mass hierarchy measurement

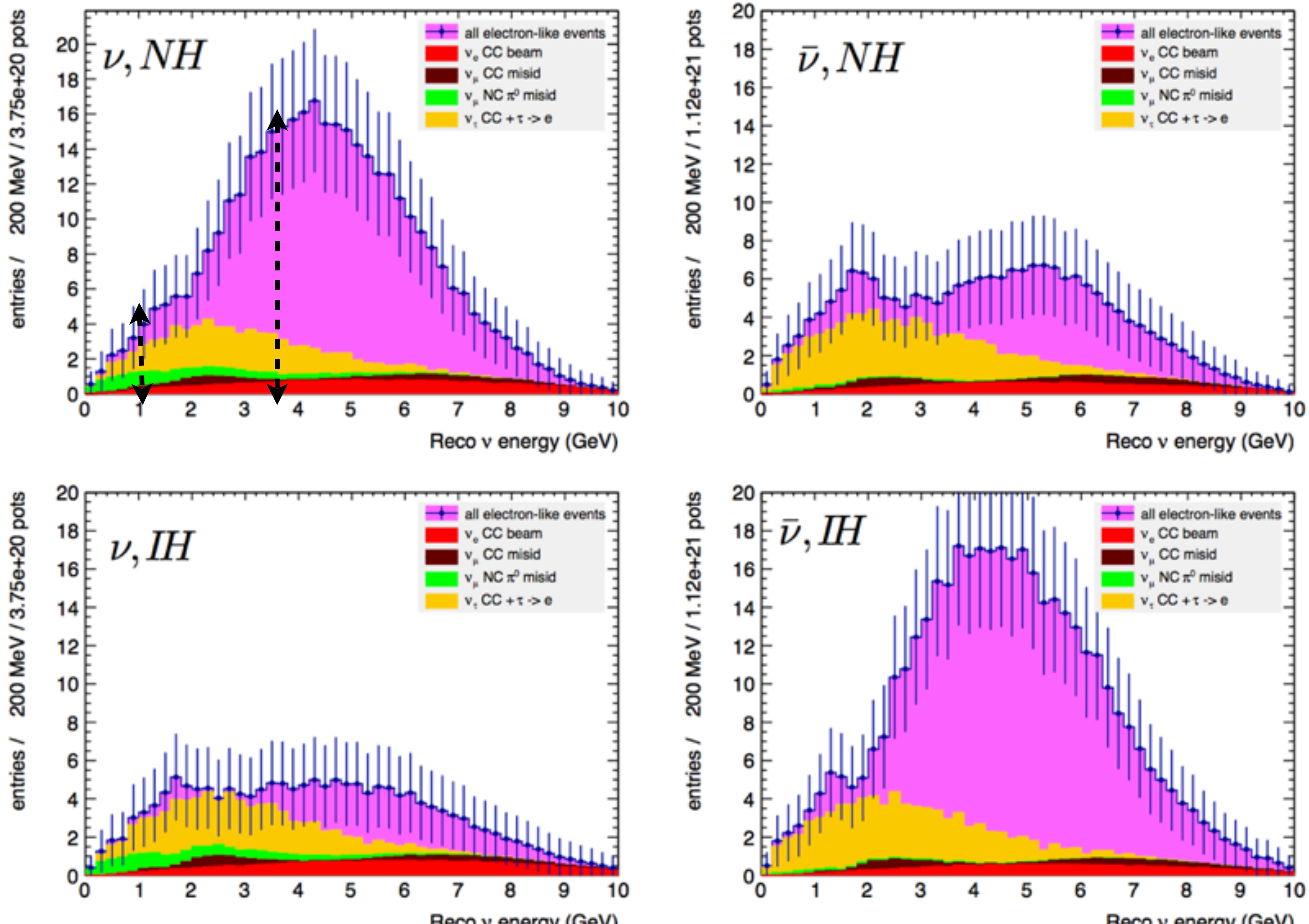
SPS(700kW), 10y, 75%nu-25%antinu; m=20 kt δ_{CP}=0
Detector response and resolution included

ν + anti-ν running to distinguish NH from IH

neutrinos | anti-neutrinos

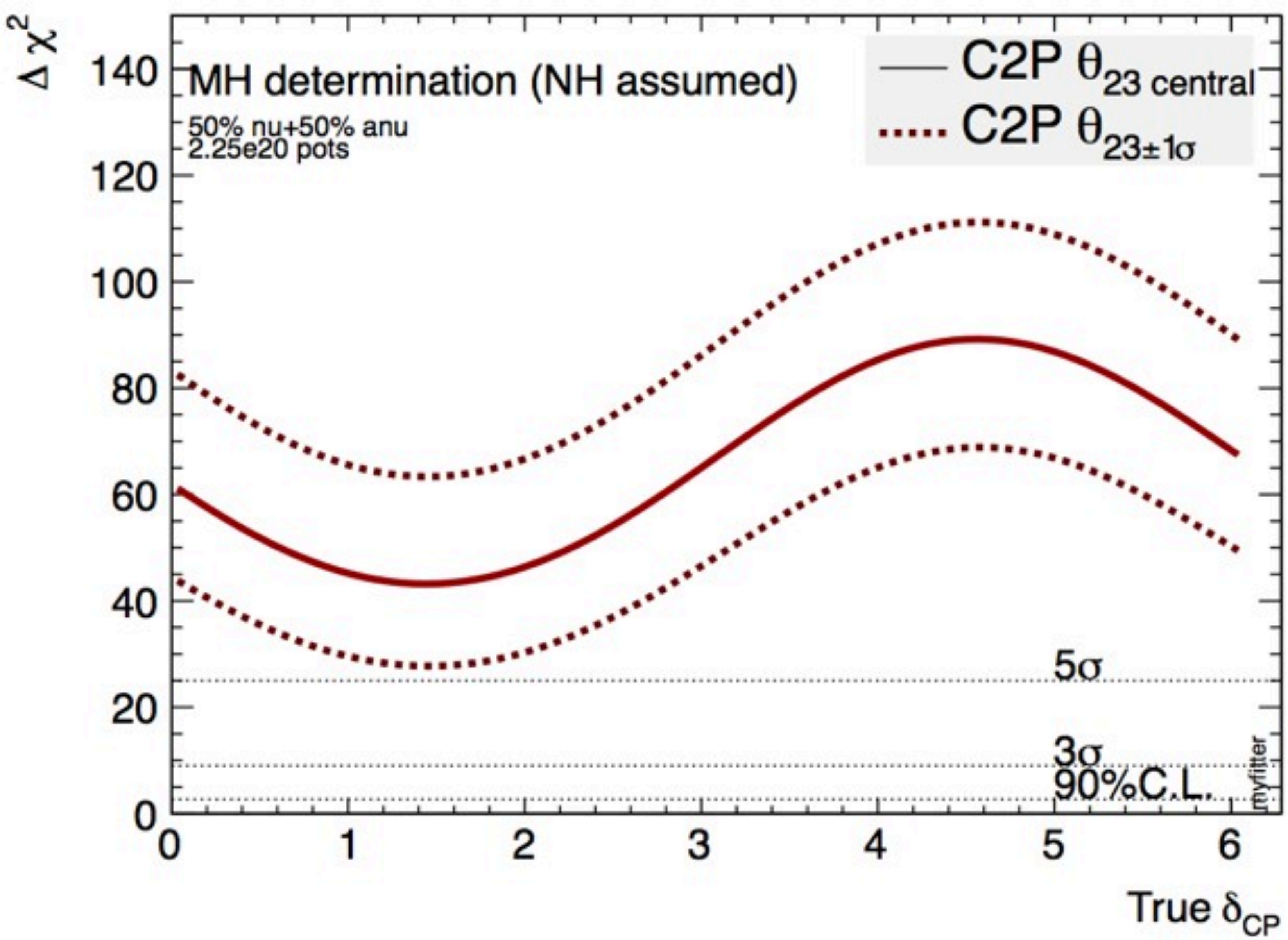
NH

IH



LBNO unambiguous Mass hierarchy measurement

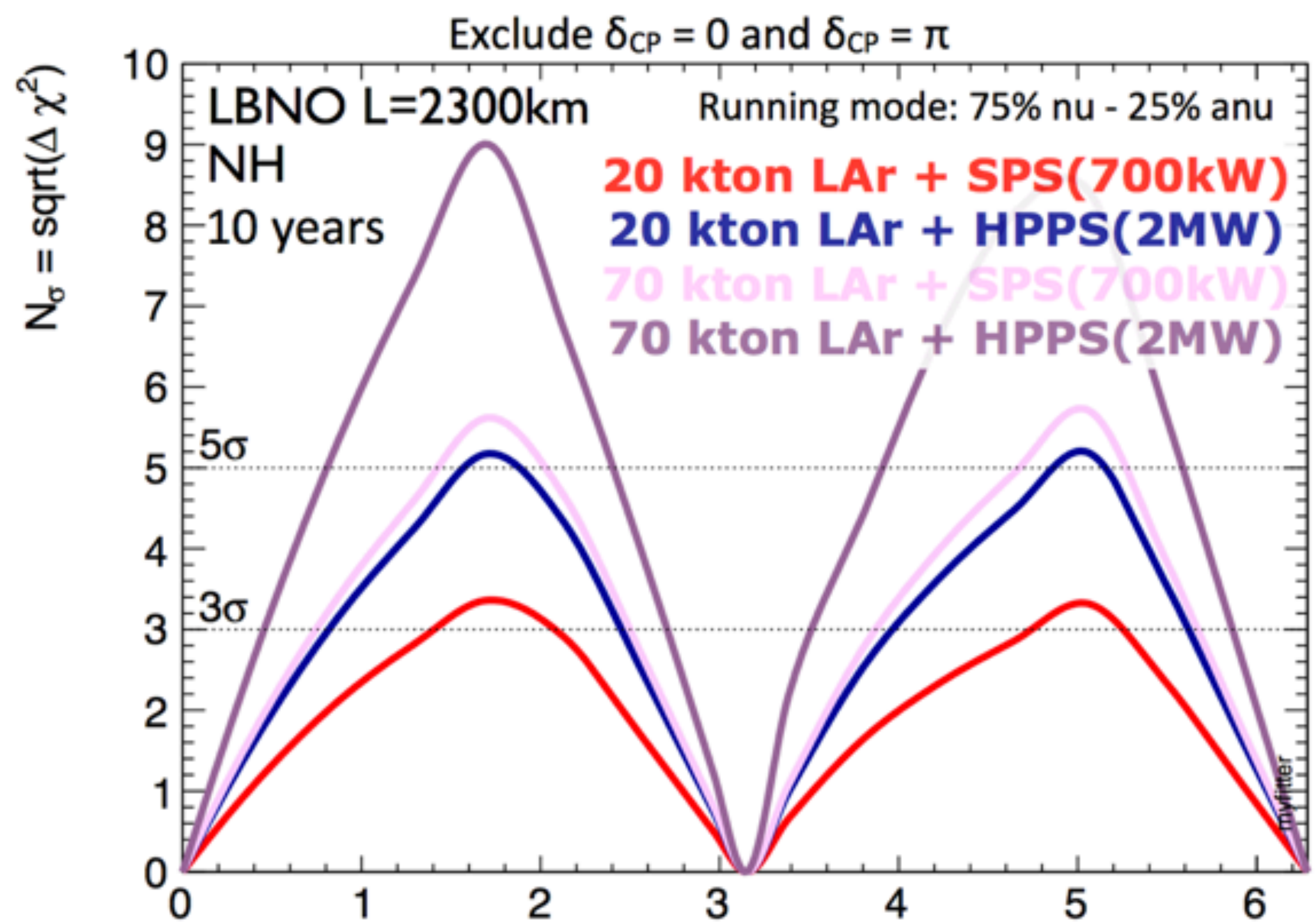
Provide a >5σ direct determination of MH independent of the values of θ_{23} & δ_{CP} in ≈2 years of running



Unique setup in the world to test matter effects in neutrino propagation!
L/E shape + nu/nubar by changing horn polarity

LBNO sensitivity to CP violation

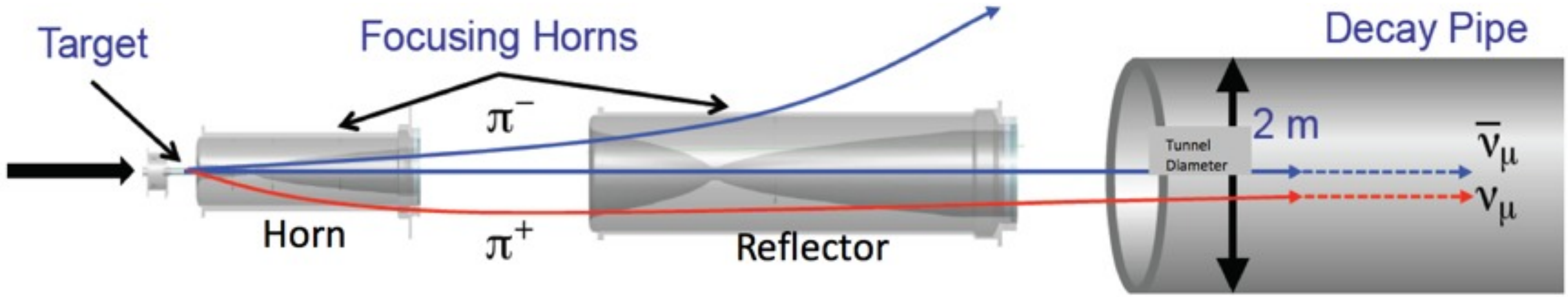
CPV 60% coverage 90% C.L. end evidence for maximal CP (π/2, 3/2π) in 10 years



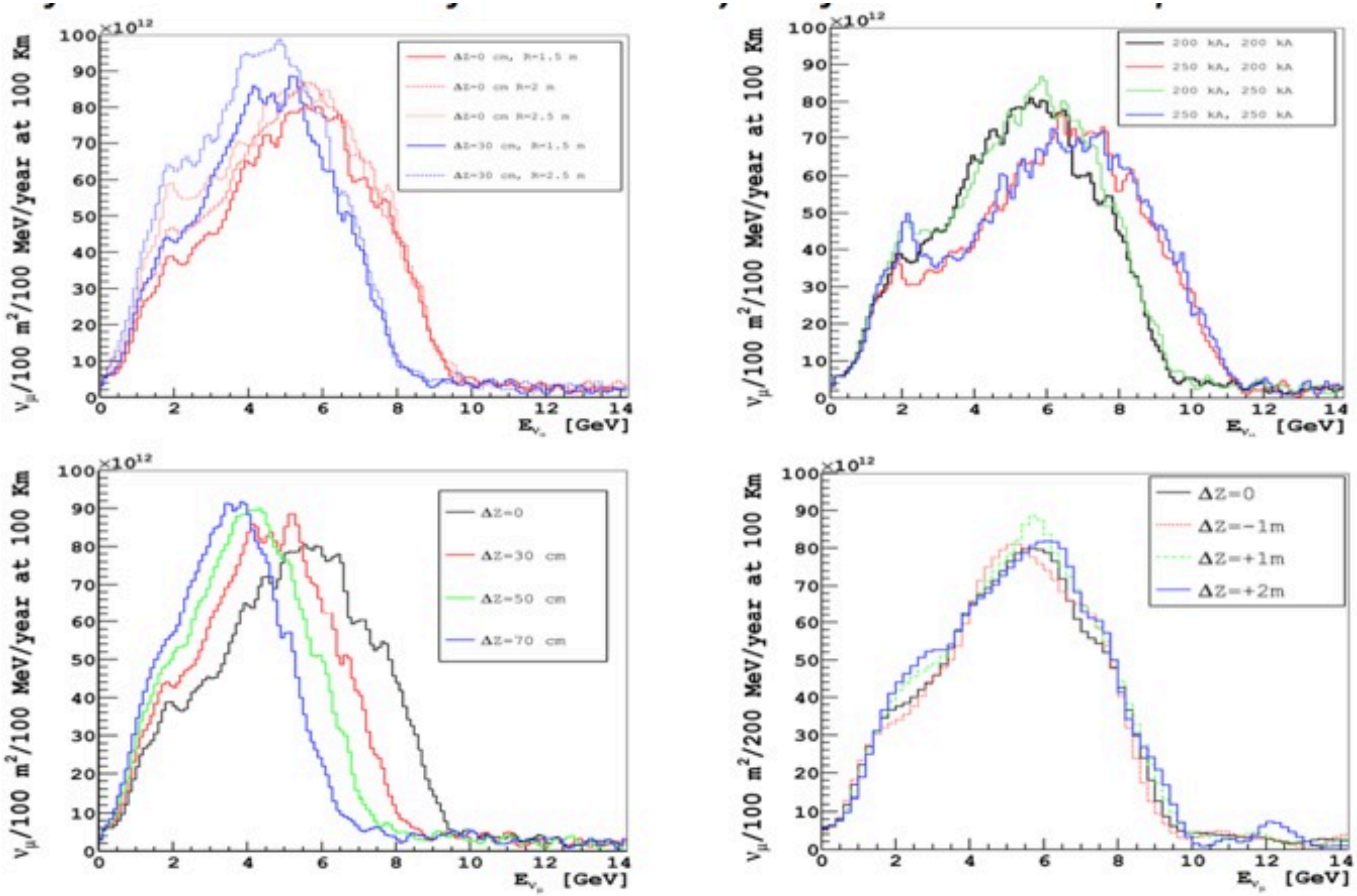
Name	Value	Error (1σ)
L (km)	2300	exact
Δm^2_{21} eV²	7.60E-05	exact
$\vert\Delta m^2_{32}\vert$ eV²	2.40E-03	±4%
$\sin^2\theta_{12}$	0.30	exact
$\sin^2 2\theta_{13}$	0.09	±10%
$\sin^2\theta_{23}$	0.50	±10%
<ρ>	3.2 g/cm3	±4%

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

CN2PY (CERN to Pyhäsalmi) beam



Beam line parameter varied in order to find the configuration which maximize the information extracted from the analysis of the oscillation spectra

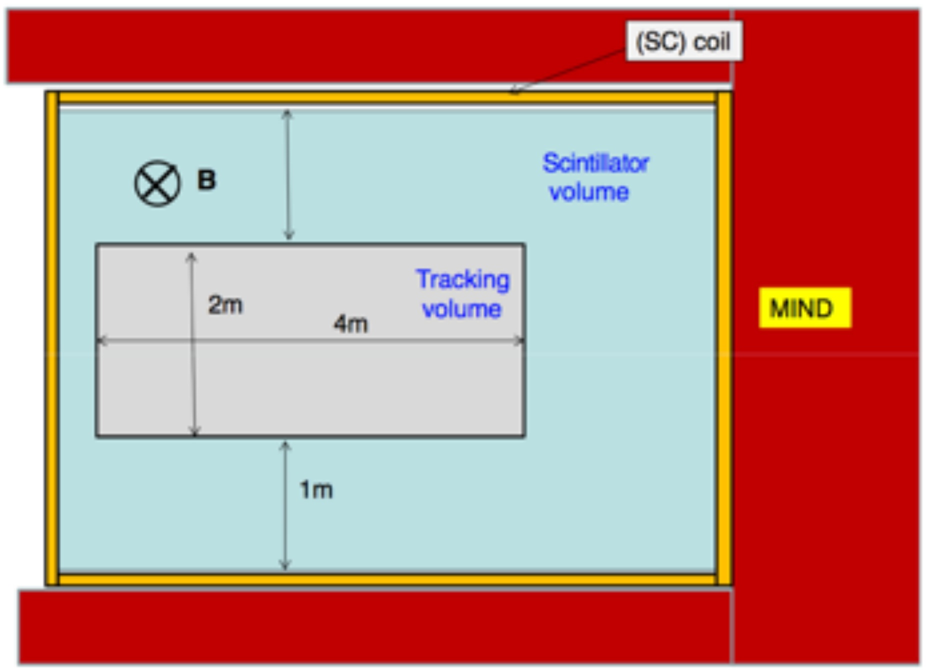


Decay Tunnel dimensions
Target-Horn position
Horn-Reflector Position
Horn(Reflector) shape
Horn(Reflector) current
...

Near detector and hadro-production experiment

Goal: <5% Systematic error on the signal and background in the Far detector

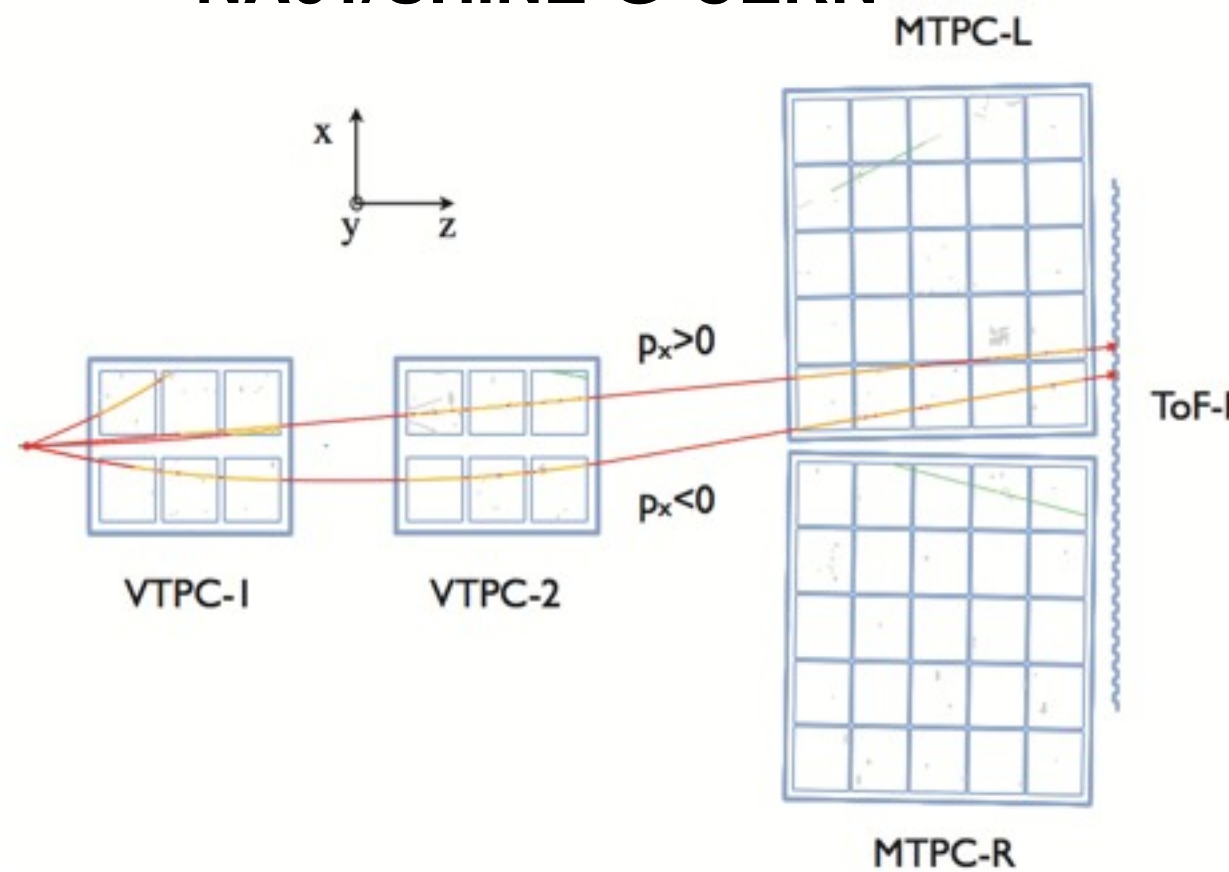
Near detector



Same materials as in far detectors

- ✓Argon TPC (10 bar)
- ✓Scintillator bar tracker
- ✓Magnetic field 0.5 T
- ✓0.2 events/spill @ 700 kW

NA61/SHINE @ CERN



✓best experiment in the world for hadro-production measurements @ SPS energies
✓$\pi^{\pm}$,K^{+},p production @30 GeV data significantly contributed to reduce T2K flux systematics *Phys. Rev. **C 85** (Mar, 2012) 035210.*

✓has required acceptance to study hadro-production @ 400 GeV

Far sites Overview

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

✳Option 2: **Fréjus**, nearby road tunnel, 4800 m.w.e overburden, horizontal access. no MH, counting only experiment on v v_bar assymetry

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

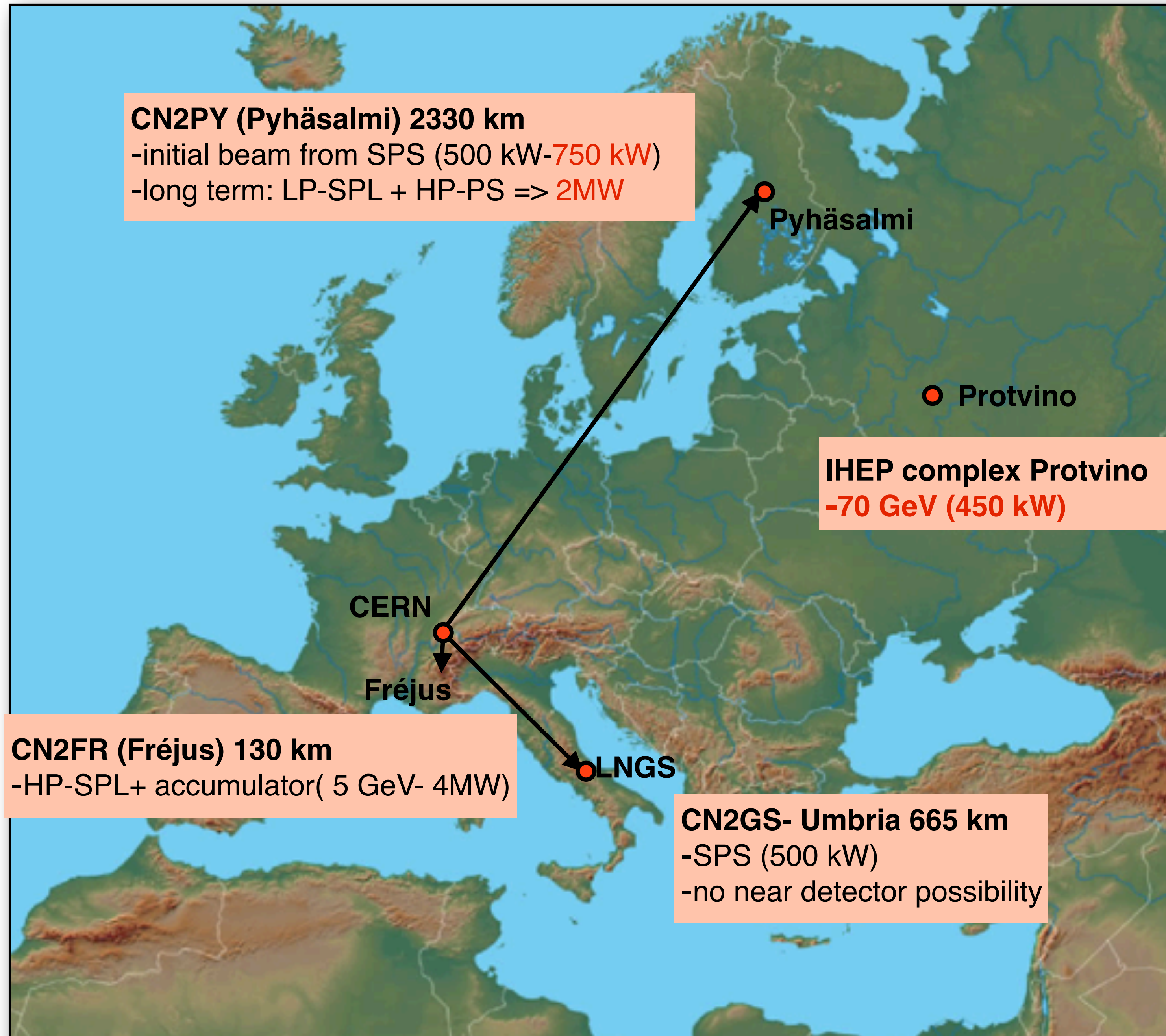
✳Beams

-Design of new CERN conventional neutrino beam to Finland (CN2PY) Baseline = 2300 km

-Upgrades of CERN SPS to 700kW

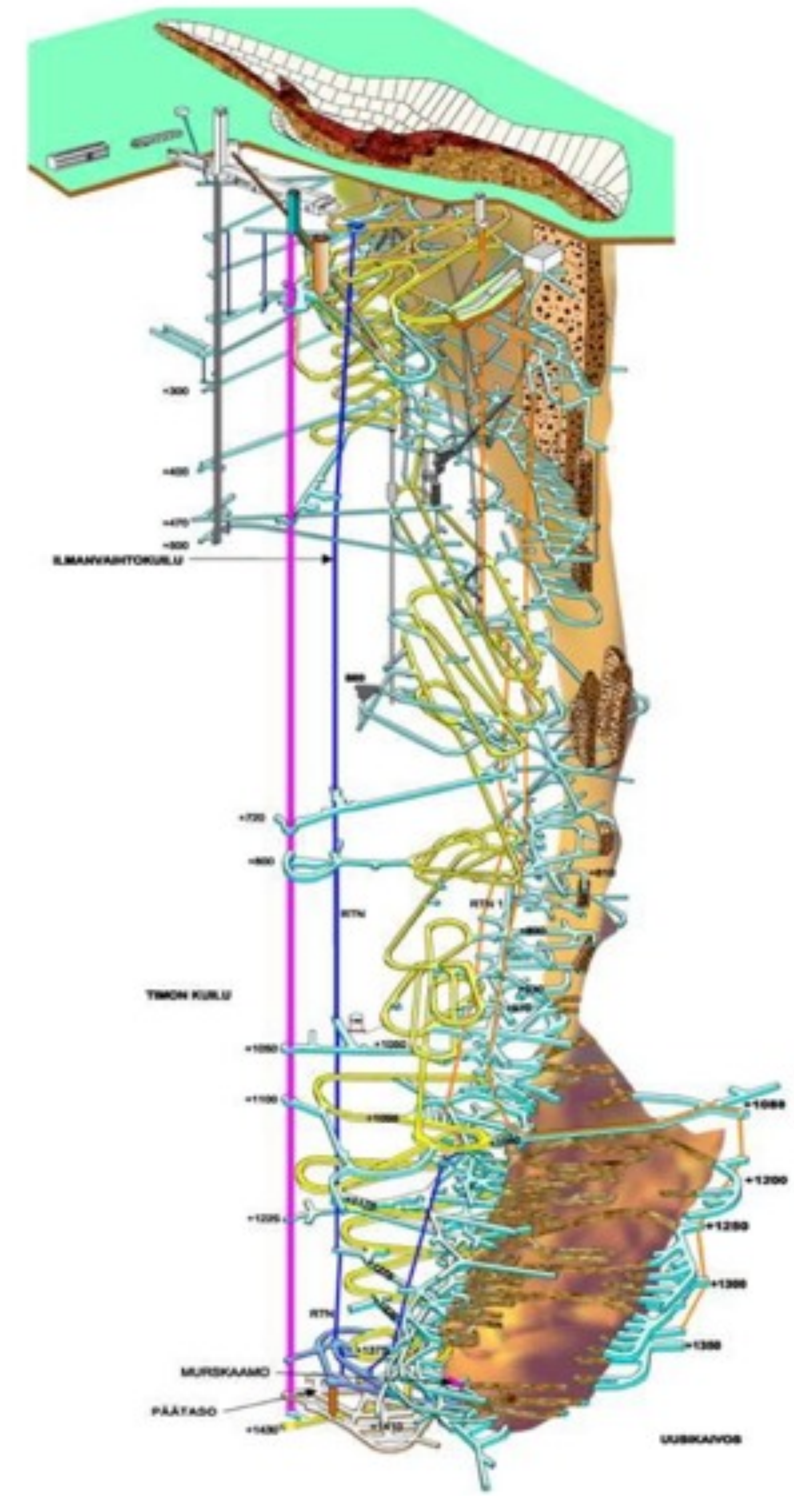
New CERN HP-PS (2MW@50 GeV) -

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

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)

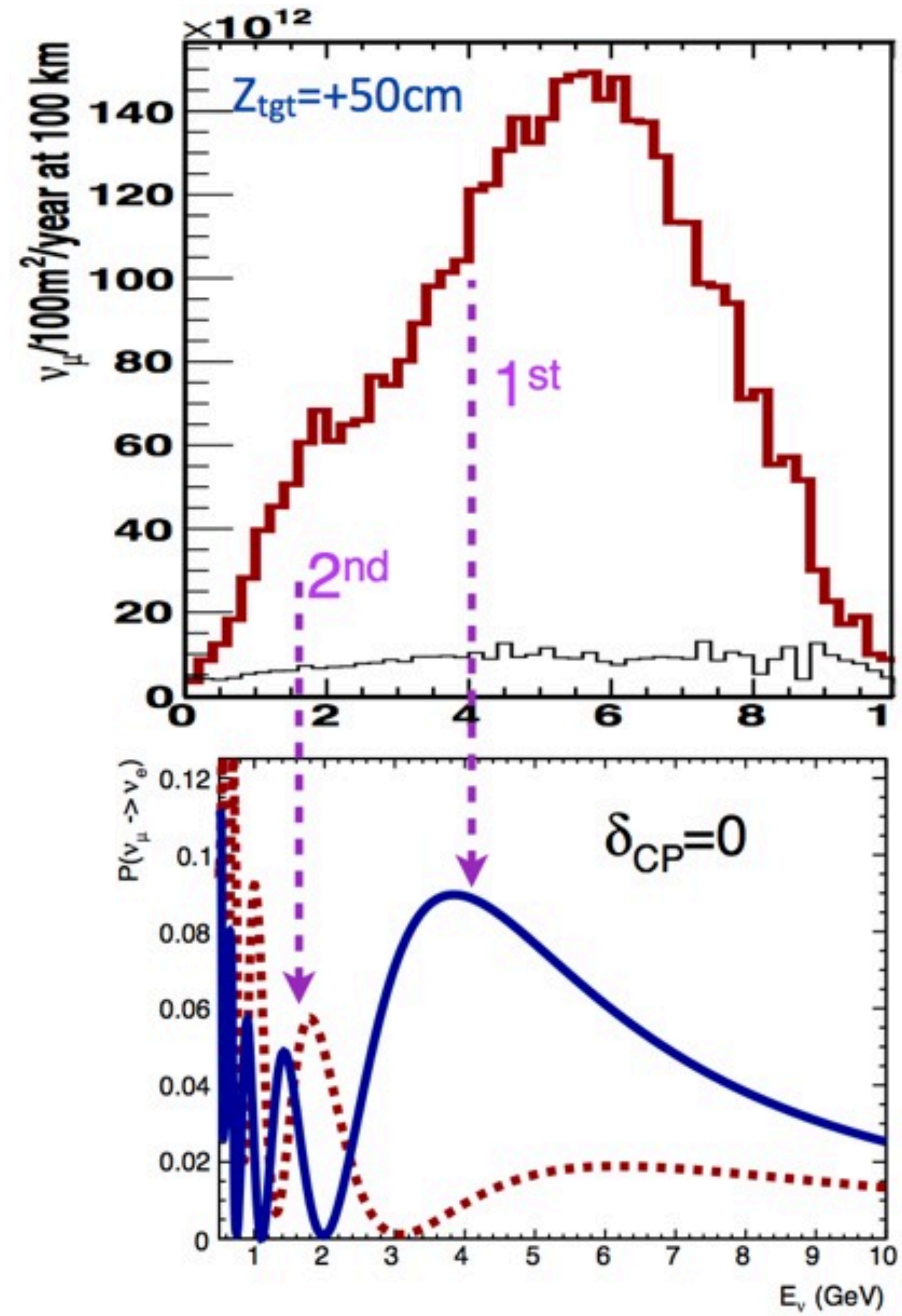
Discussions will continue with Finland in order to define it real contribution. Other sites in Scandinivia are also being looked into.

LBNO: reaching the physics goals

Long baseline program

- $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_\mu$ & νNC

- study the L/E feature of the oscillation induced by matter effects and CP-phase terms, independently for ν and anti-ν, by direct measurement of event spectrum which covers the **first and second oscillation maxima thanks to the long baseline**



Astrophysics program

- extended nucleon decay search: probe BSM physics up to GUT scale

- Astrophysical and atmospheric neutrino detection

LBNO: reaching the physics goals

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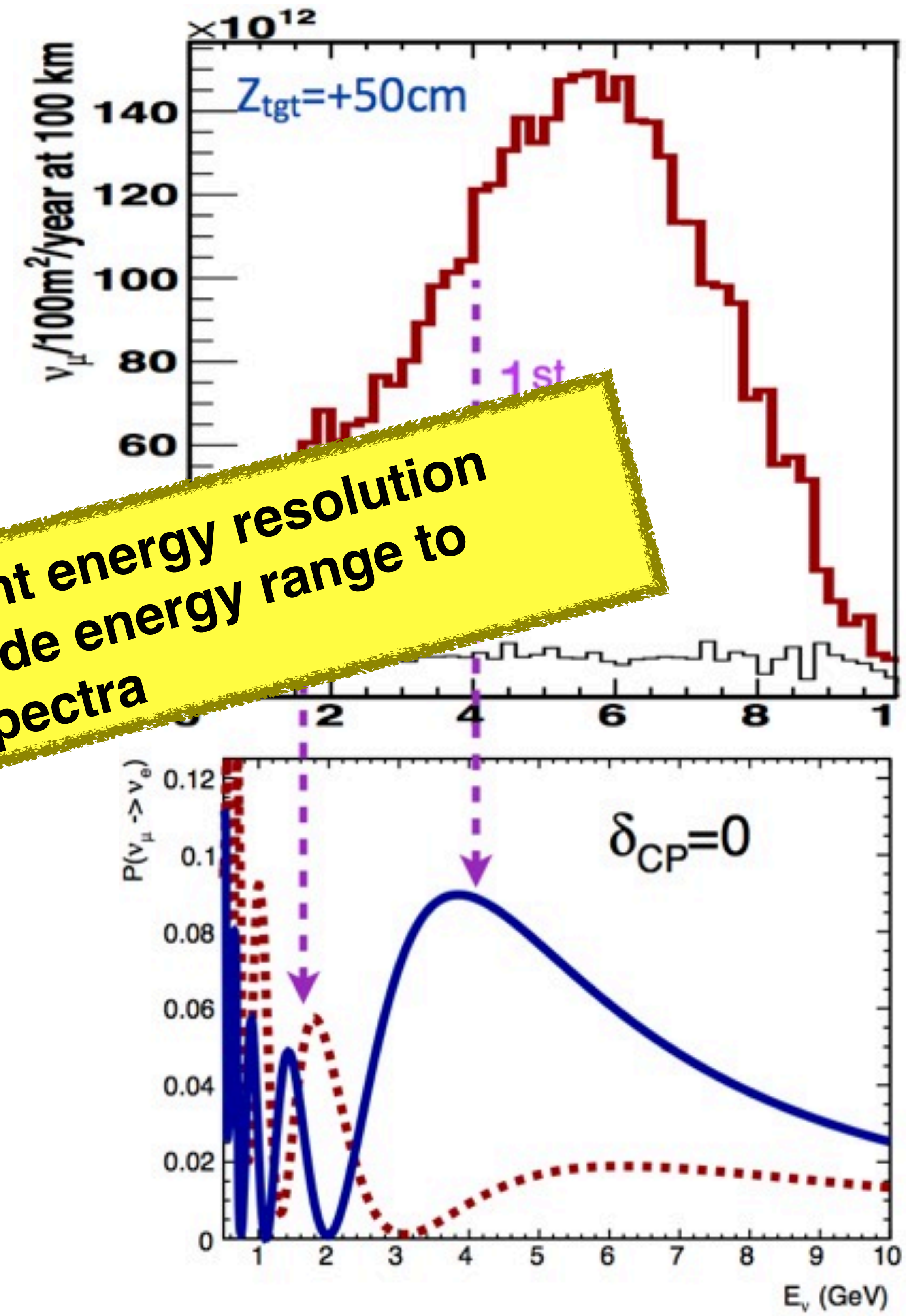
- ✳ study the L/E feature of the oscillation induced by matter effects and CP-phase terms, independently for ν and anti-ν, by direct measurement of event spectrum which covers the **first and second oscillation maxima thanks to th**… **baseline**

A detector with large mass, excellent energy resolution and tracking performance over a wide energy range to "see" the shape of the oscillated spectra

Astrophy…

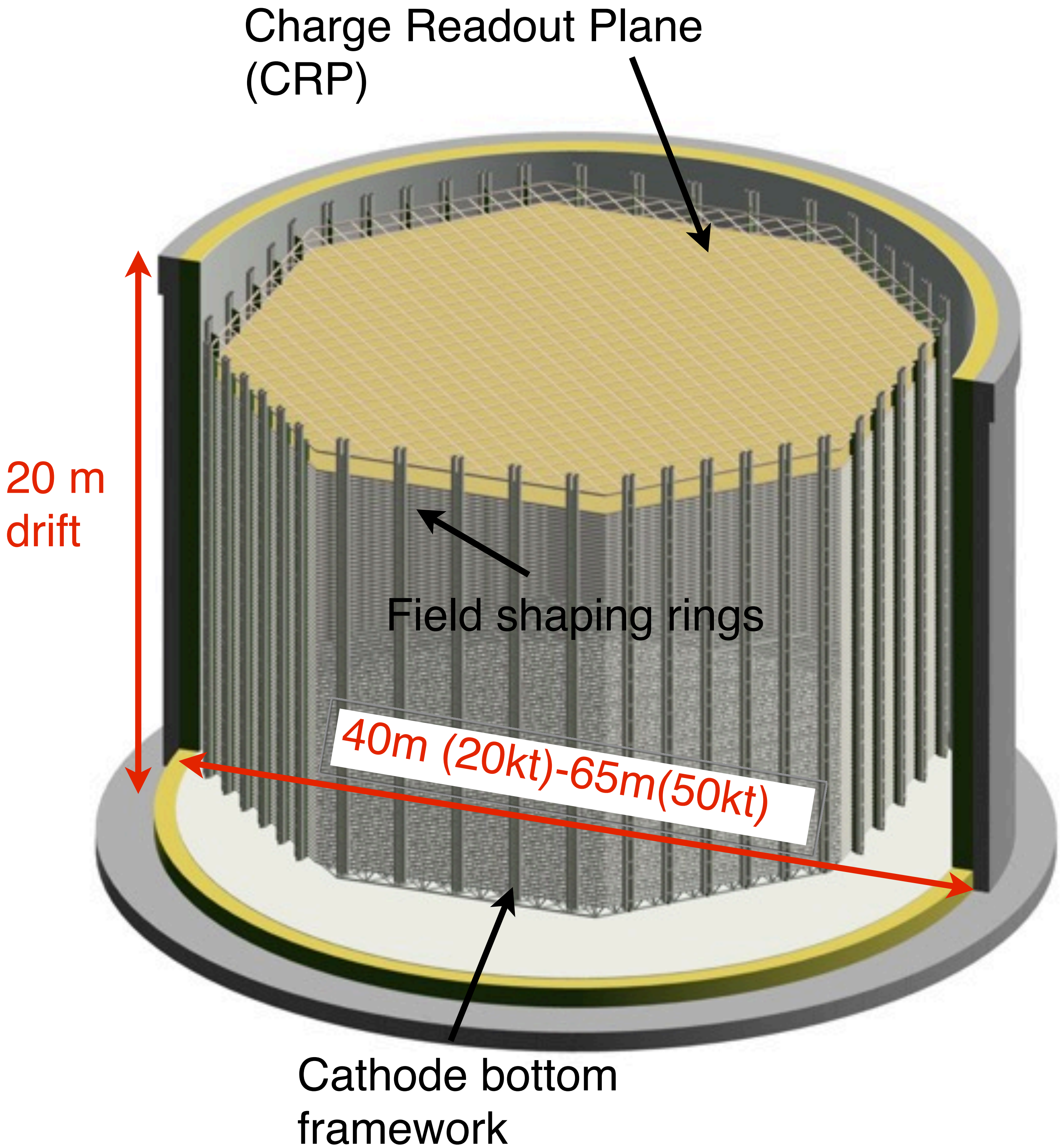
- ✳ extende… …cleon decay search: probe BSM physics up to GUT scale

- ✳ Astrophysical and atmospheric neutrino detection



Giant Liquid Argon Charge Imaging expERiment

GLACIER 20kt, 50kt Giant double phase LAr TPC

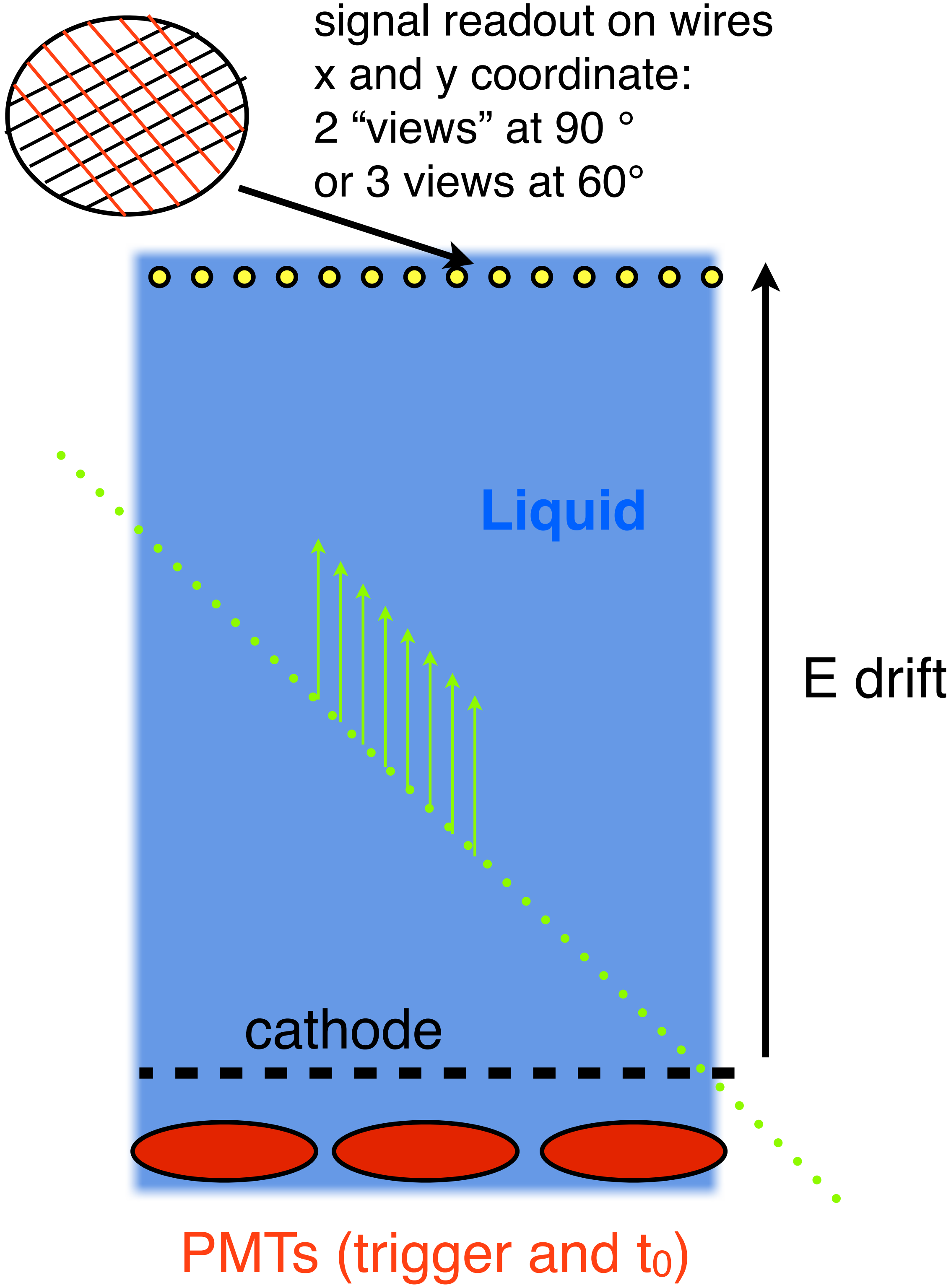


	20KT	50KT
Liquid argon density at 1.2 bar [T/m3]	1.38346	
Full LAr height [m]	22	
Instrumented LAr height [m]	20	
Pressure on the bottom due to LAr [T/m2]	30.4 (≡ 0.3 MPa ≡ 3 bar)	
Vessel diameter [m]	37	55 76
Vessel base surface [m2]	1'075.2	2'375.8 4'536.5
Instrumented LAr area (percentage) [m2]	824 (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	

LAr-TPC single vs double phase

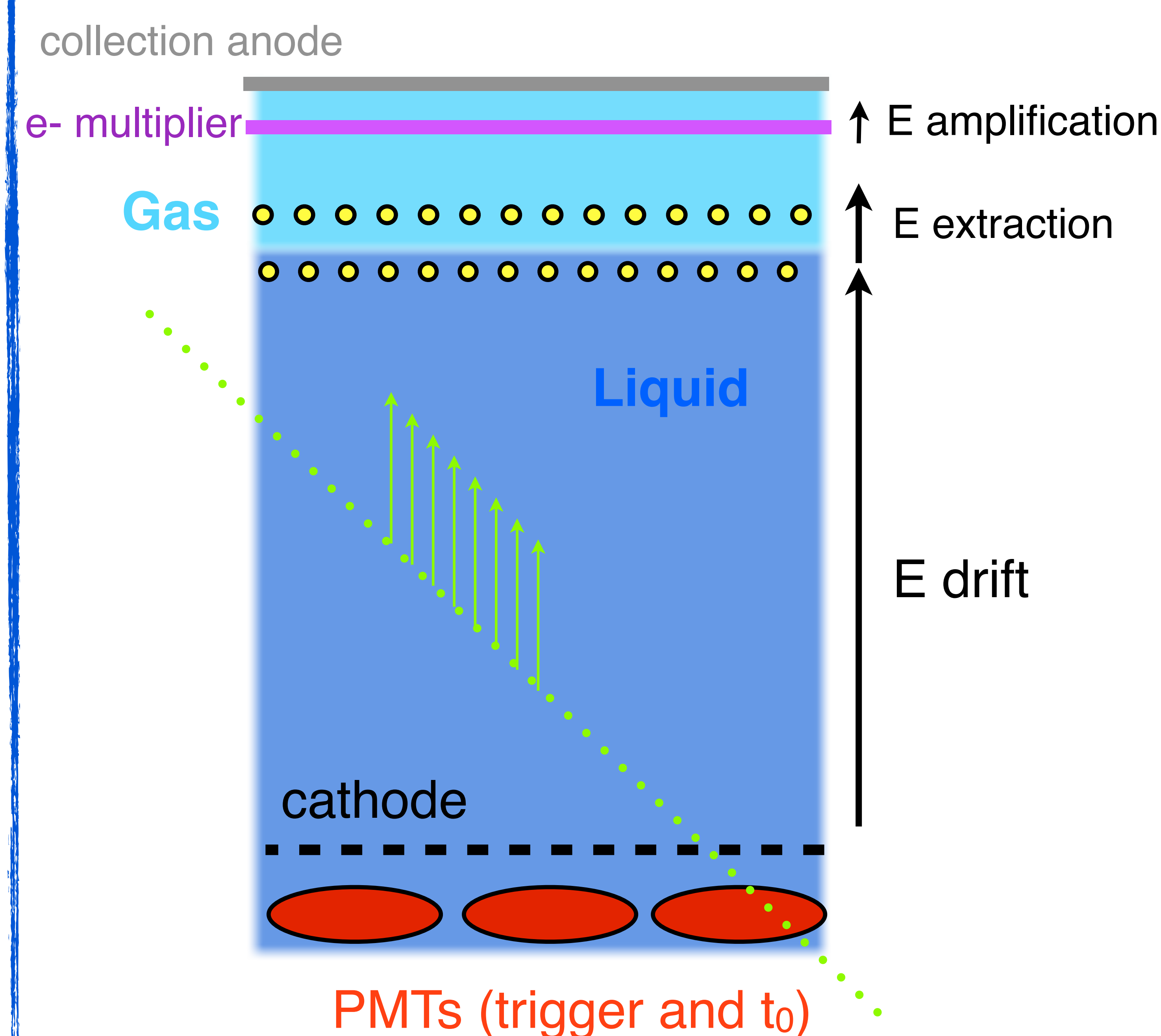
Single phase

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



Double phase

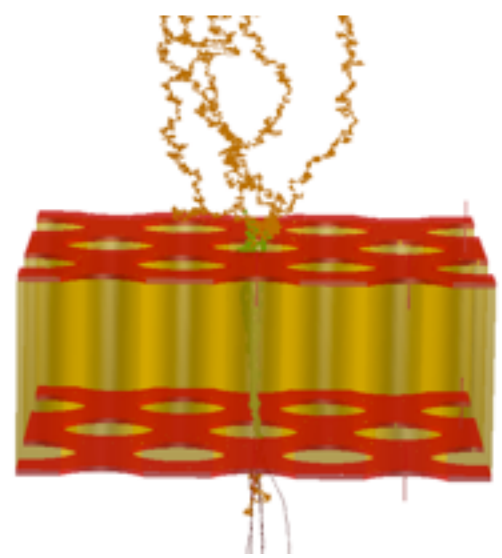
signal readout on 2 view collection anode
Signal amplified in the gas

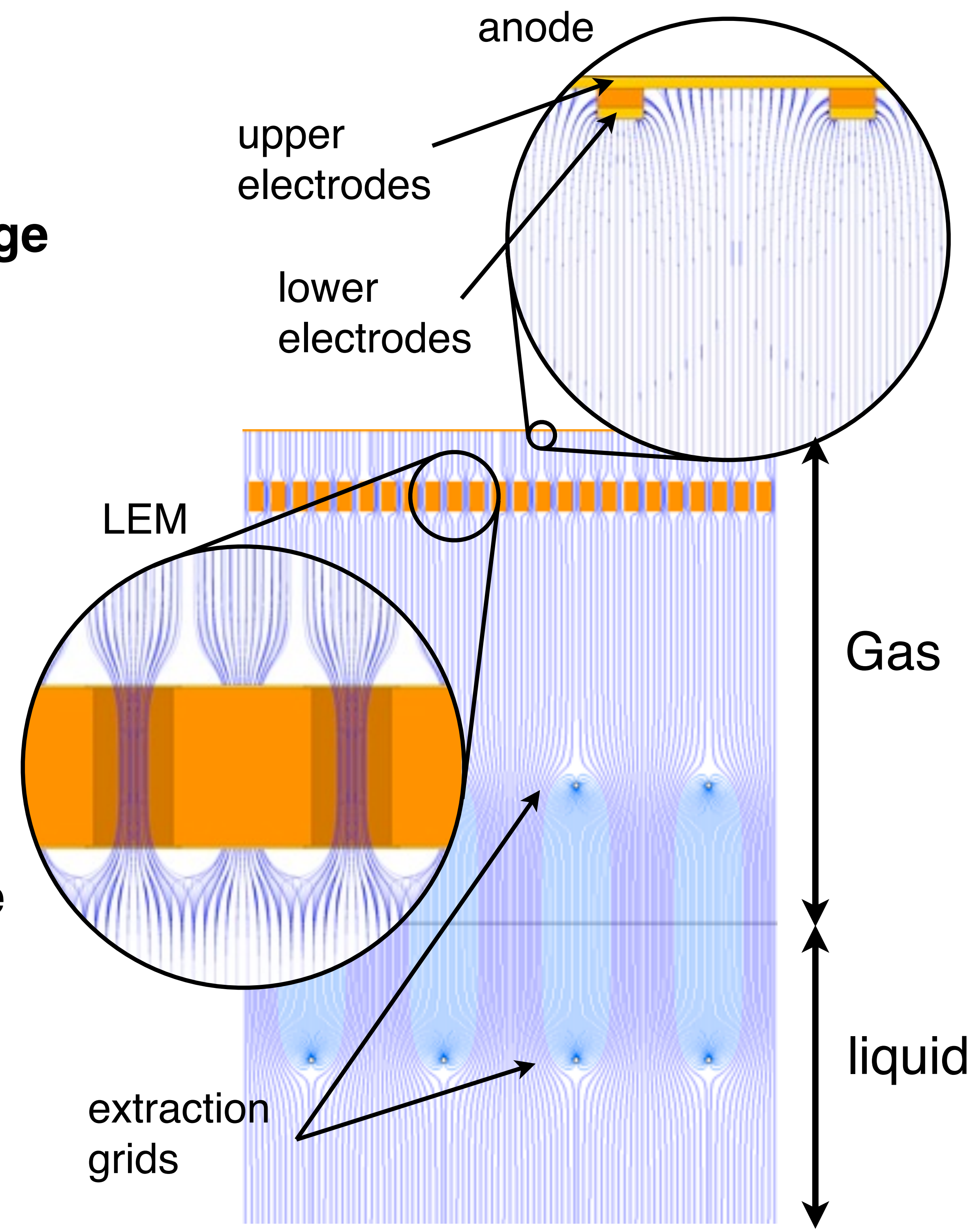


The Double phase concept

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)**



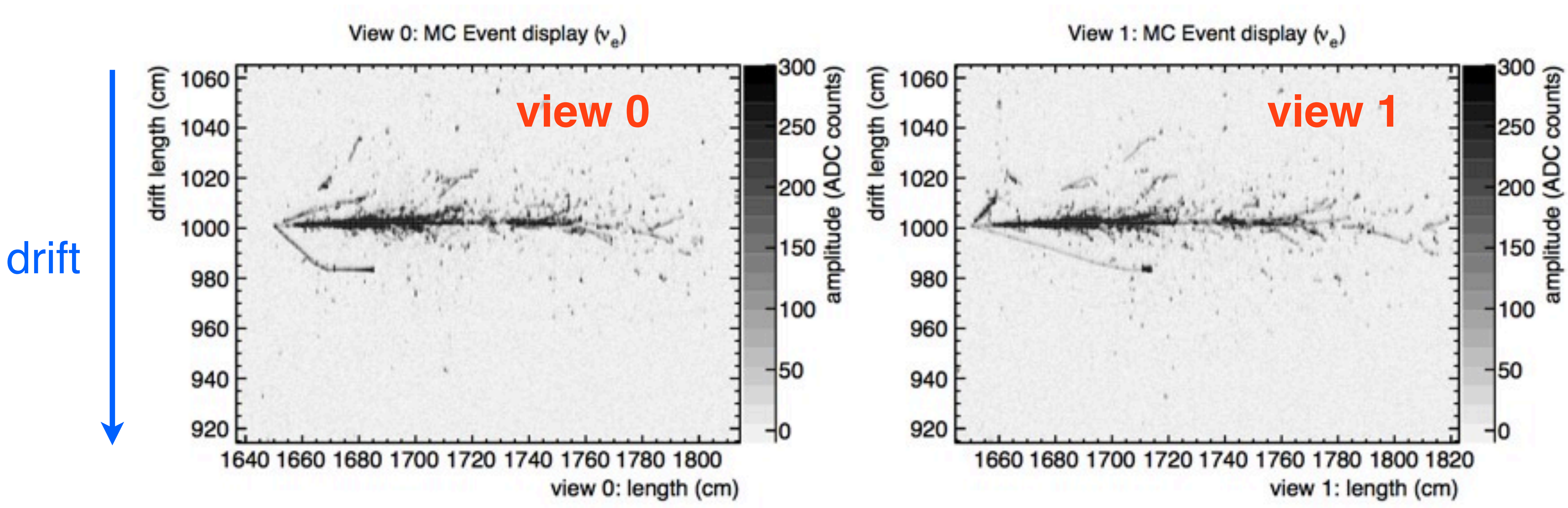


2.) Drift electrons are efficiently emitted into the gas phase

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 over a wide energy range. Efficient background rejection (e.g NCπ0 from CCν_e)

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

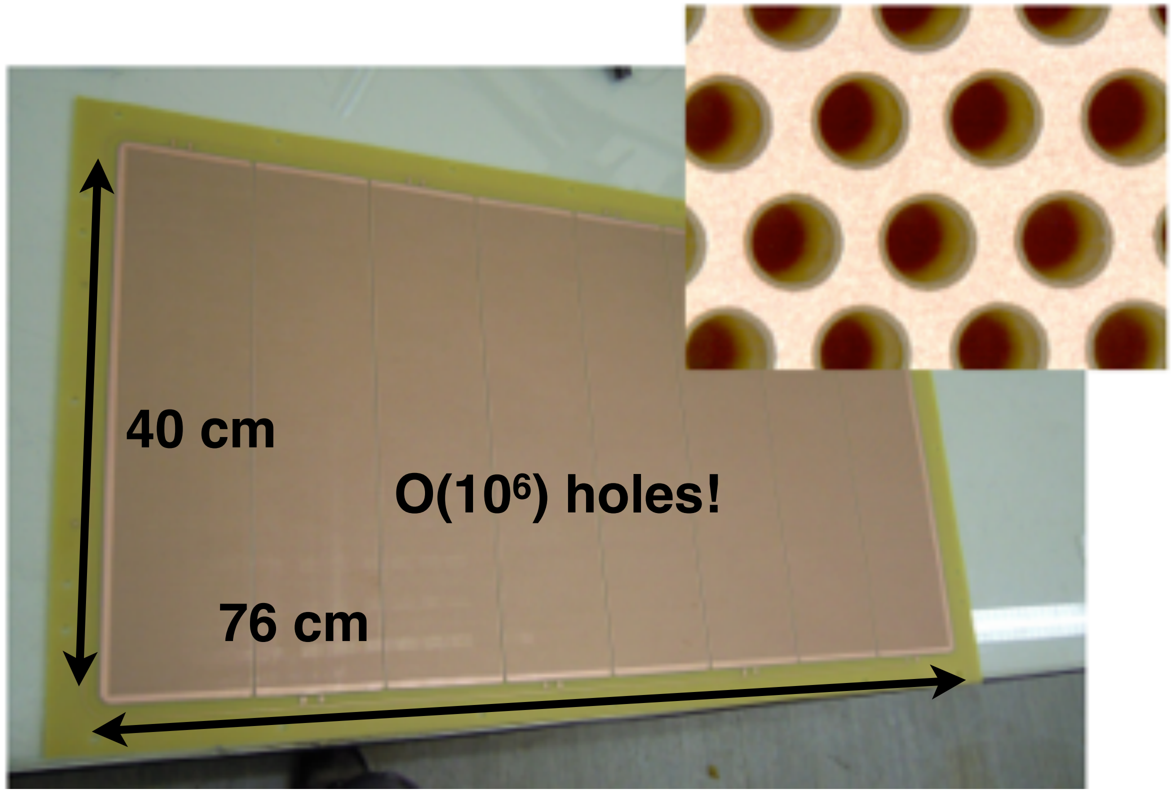
✓Very high signal-to-noise (>100) thanks to amplification in gas. => build large detectors with longer drifts (~20m) and larger readout capacitances.

✓Adjustable Energy threshold=>sensitive down to very low energies (~100 keV).

Towards a large area readout: the 40x76 cm² prototype

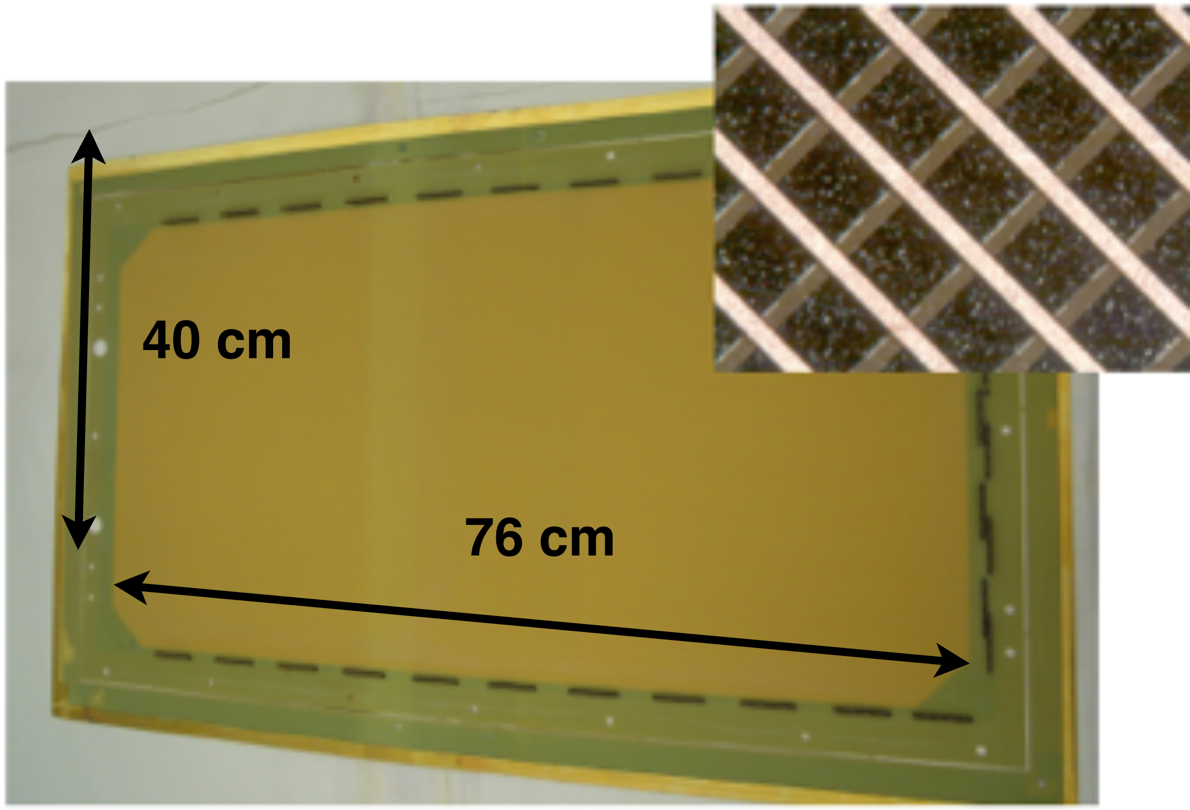
Large Electron Multiplier (LEM)

- Macroscopic Gas hole multiplier
- more robust than GEMs (cryogenic temperatures, discharge resistant)
- manufactured with standard PCB techniques
- Large area coverable by 50x50 cm² modules
- Light quenching within the holes



2D projective anode readout

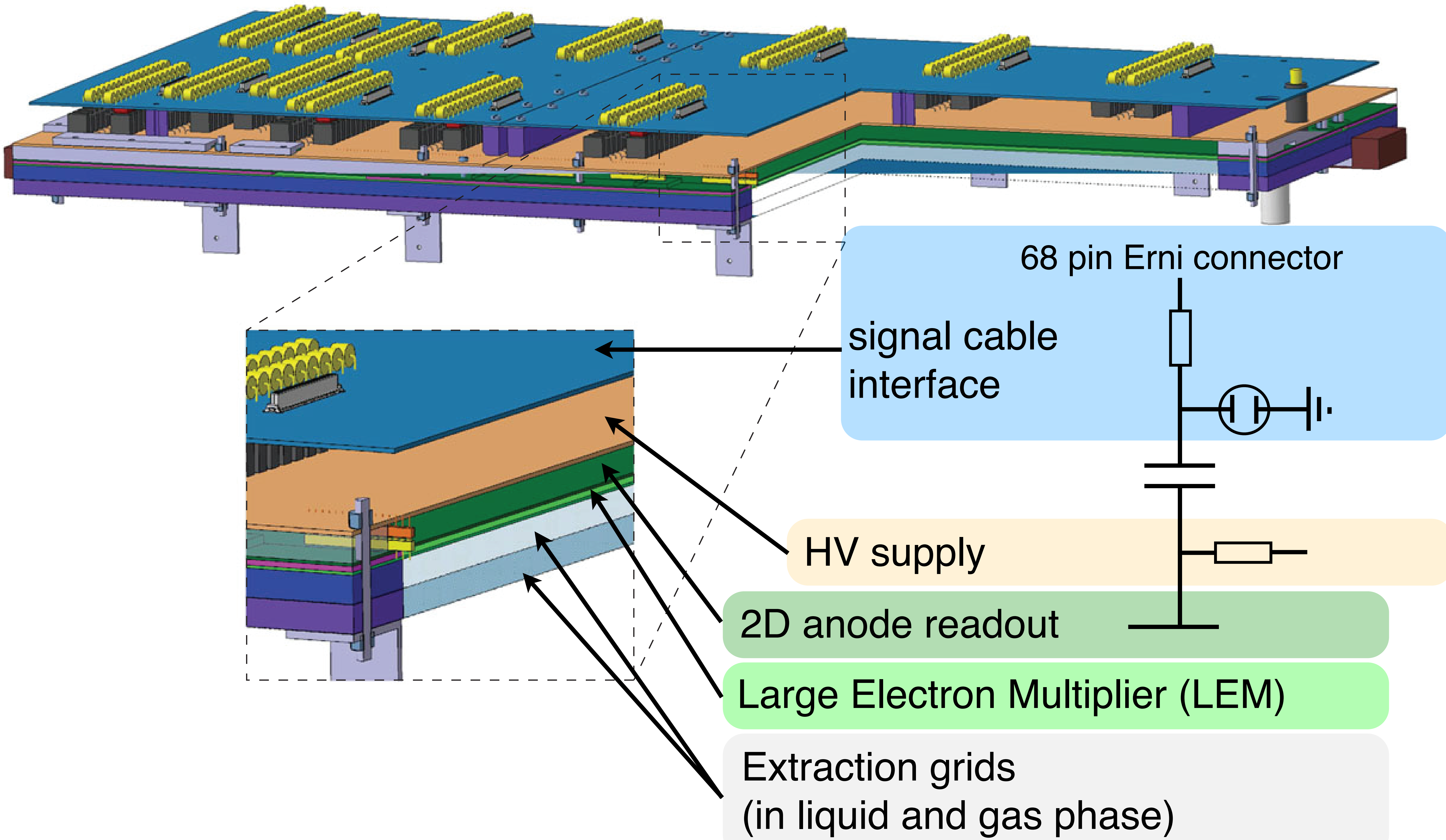
- Charge equally collected on two sets of strips (views)
- Readout independent of multiplication
- Signals have the same shape for both views:
  - -two collection views (unipolar signals)
  - -no induction view (bipolar signals) as in the case of a LAr-TPC with induction wires



So far largest area LEM/2D anode produced!

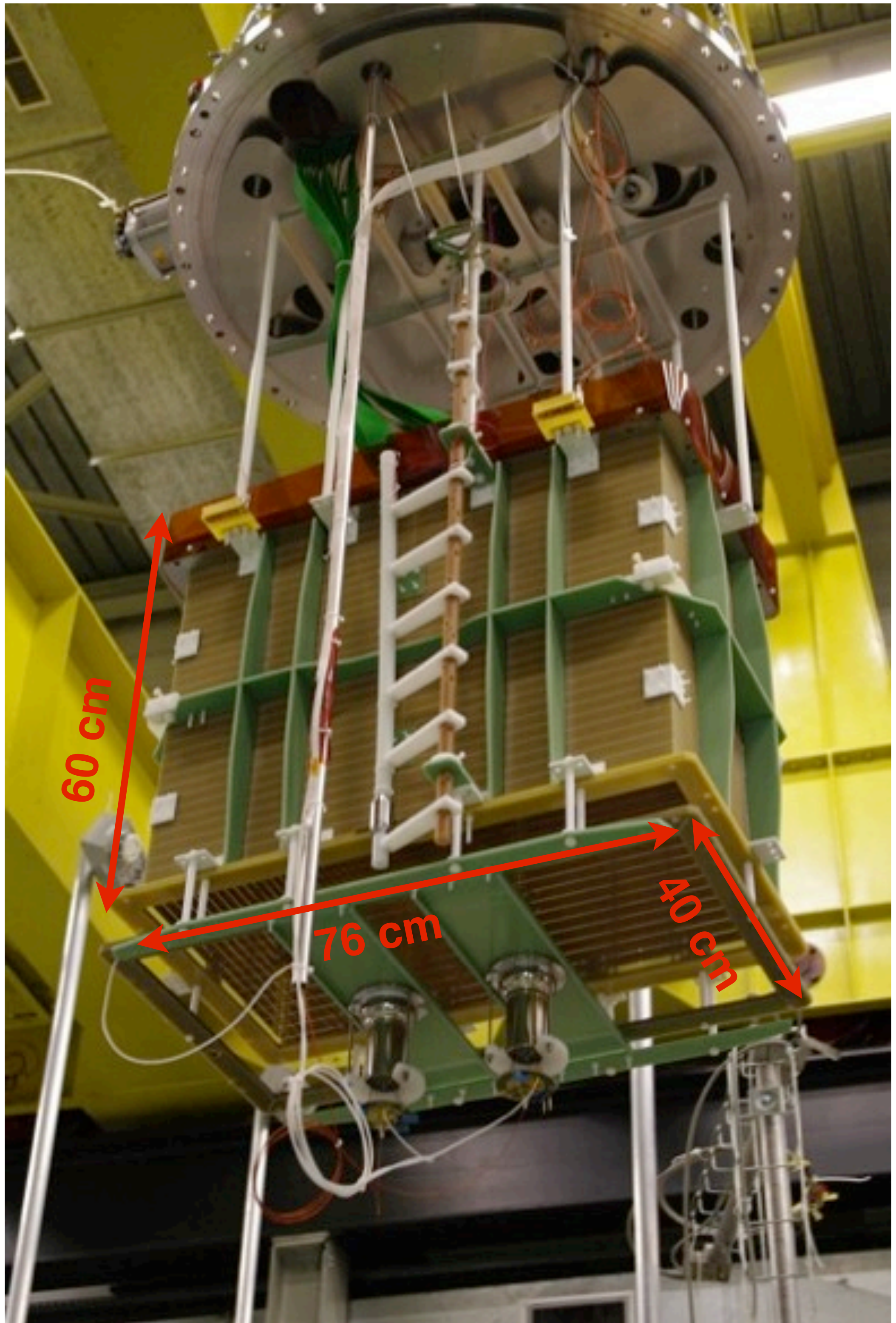
Compact Charge Readout Design (CRP)

Single Compact readout module of square meter doing extraction, amplification and readout



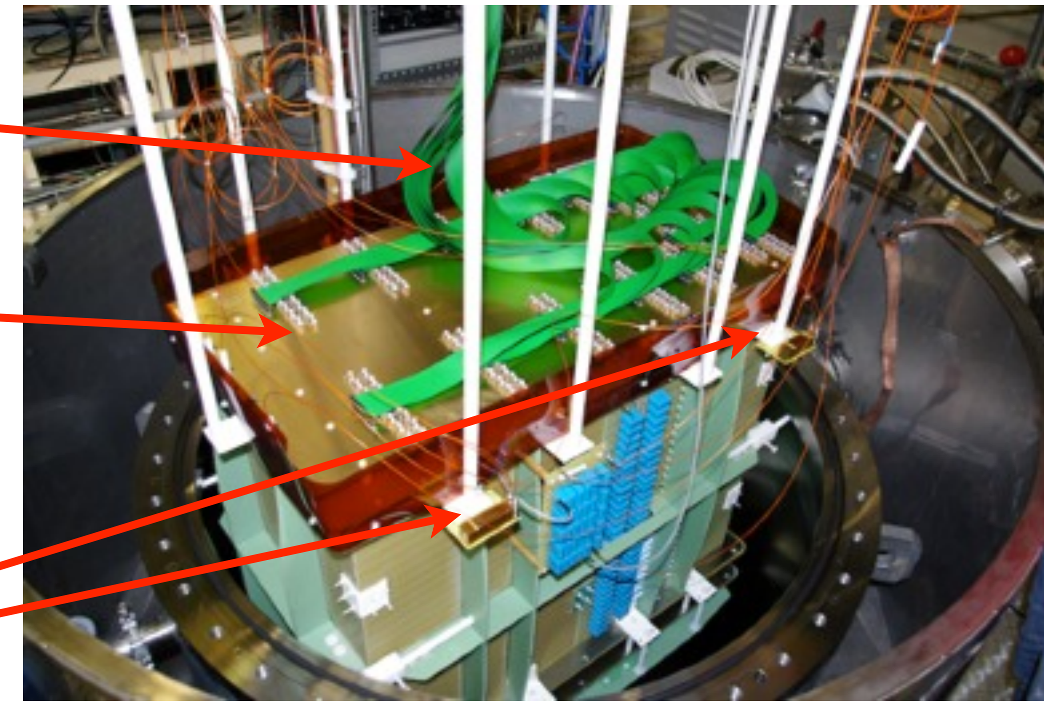
Large area readout: the 40x76 cm^2 prototype

detector fully assembled



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

going into the ArDM cryostat

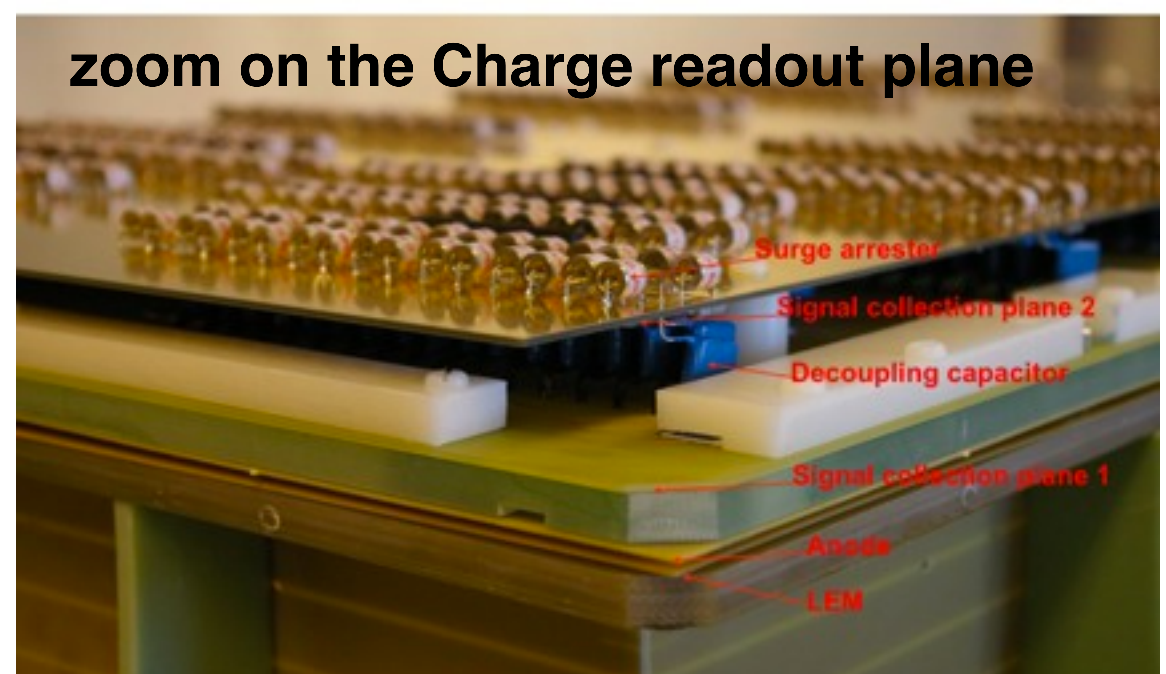


16 signal cables

charge readout plane

4 capacitive level meters

zoom on the Charge readout plane

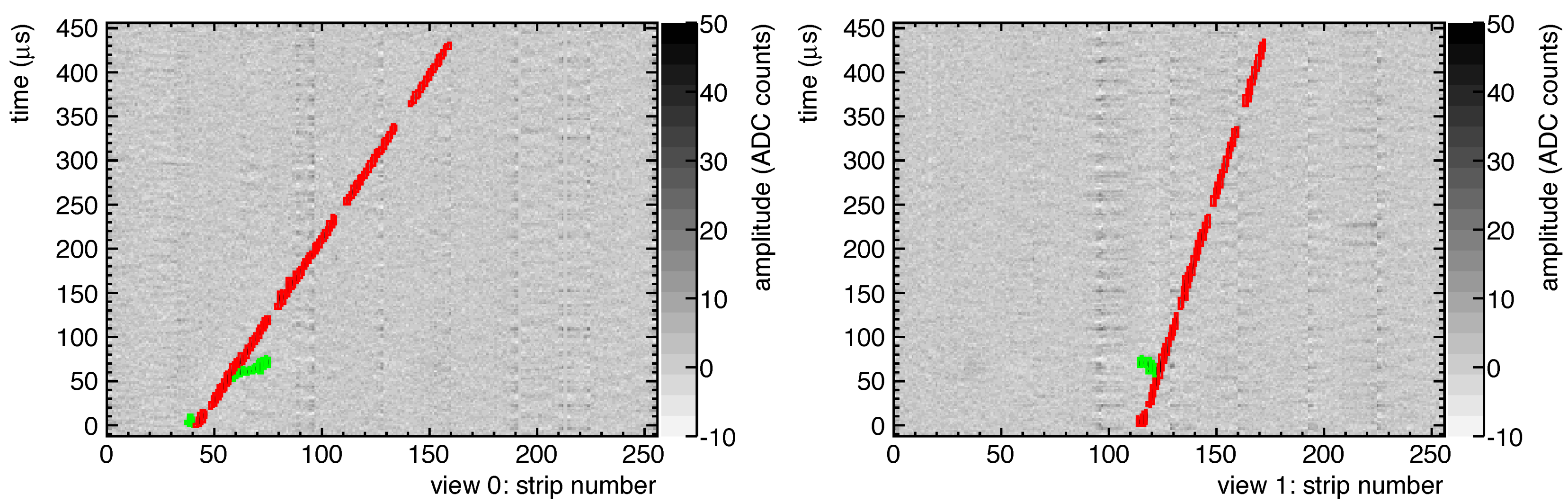


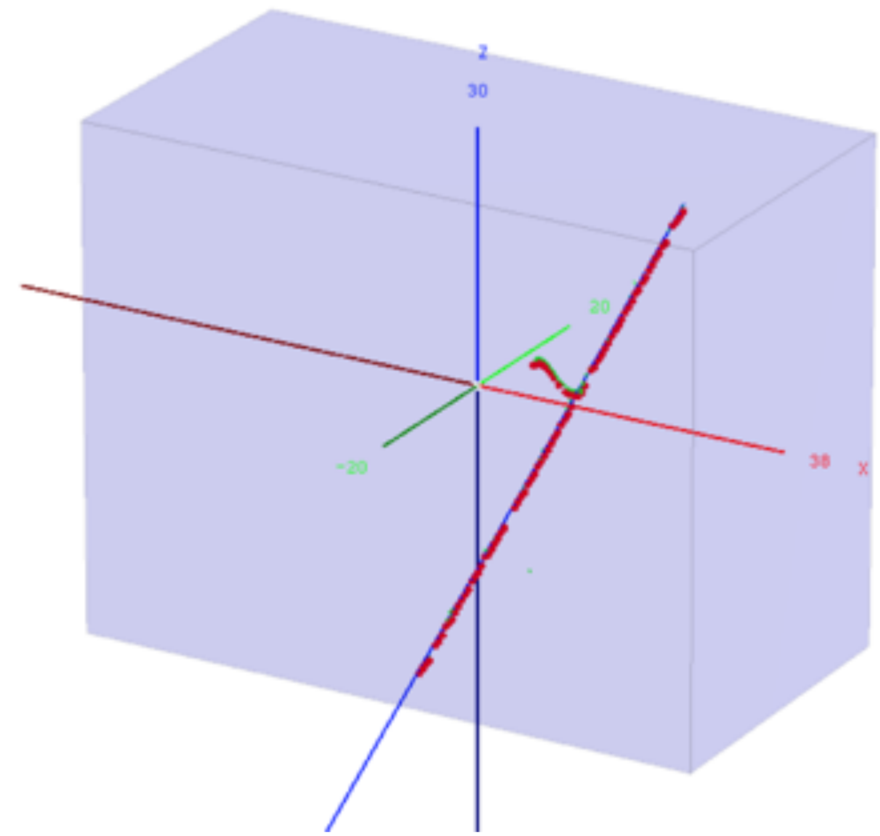
Results from the 40x76 cm^2 prototype

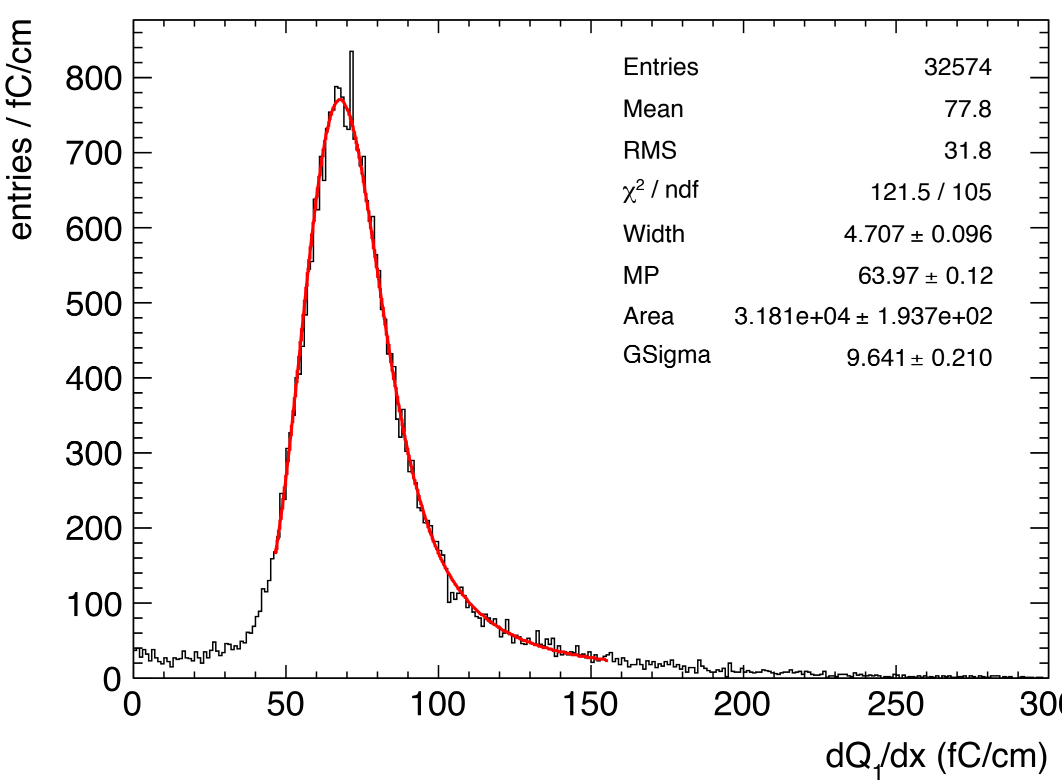
We have operated the detector for the first time in October 2011 during more than 1 month.

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)

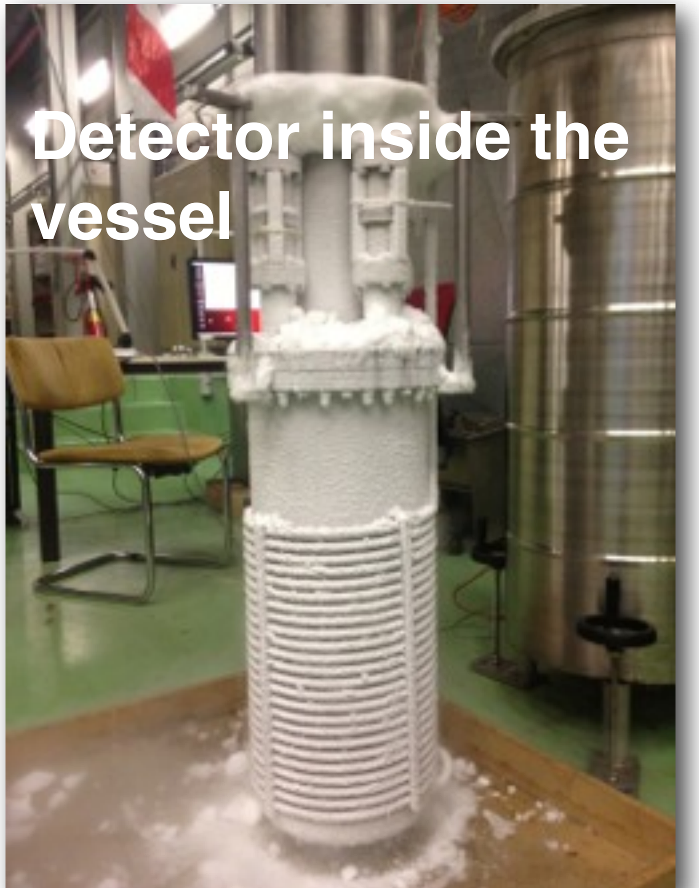
<dQ/dx>=146 fC/cm

➡effective gain≈14.6, (S/N≈30)

charge sharing between the two collection views:

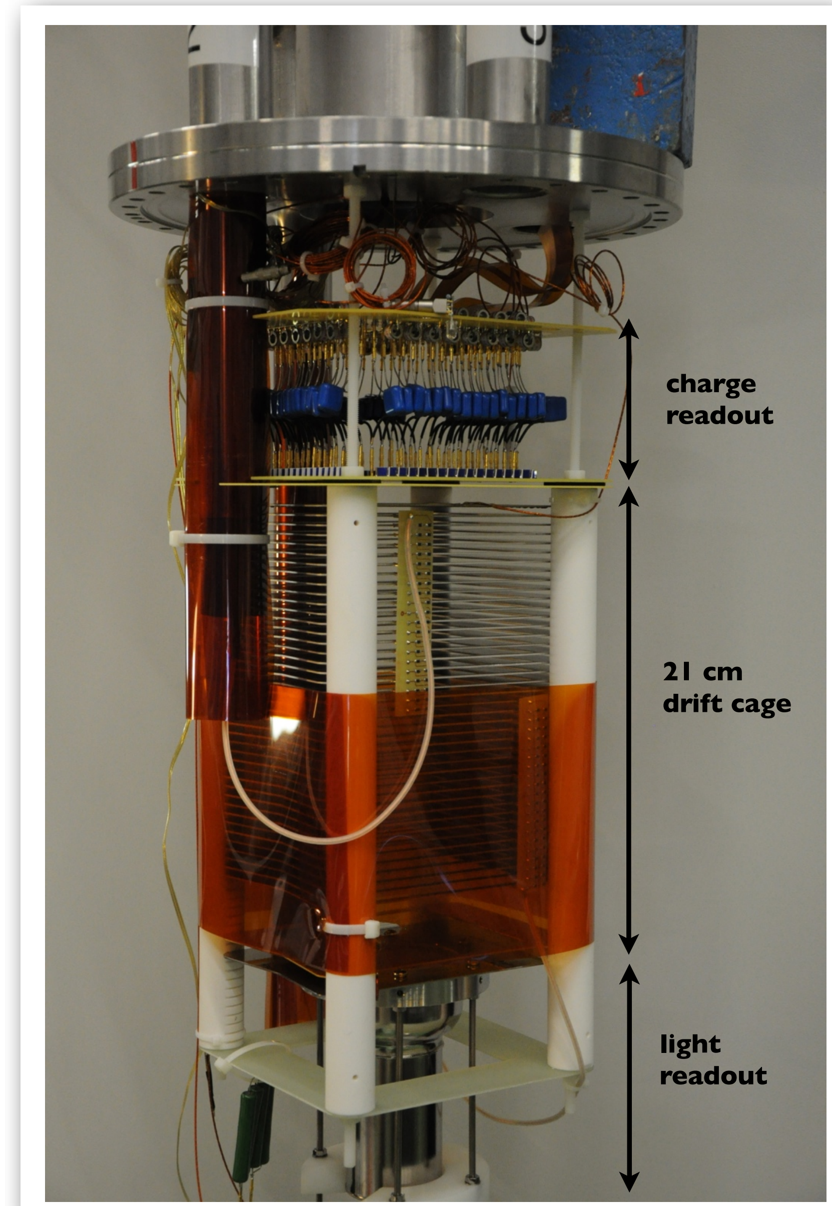
$(Q_1-Q_0)/(Q_1+Q_0)$≈8%

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 gain.
- **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?

Towards large area readout - anode considerations

Goal: readout of at least 0.5x0.5 m^2

need low capacitance readouts to go large dimensions

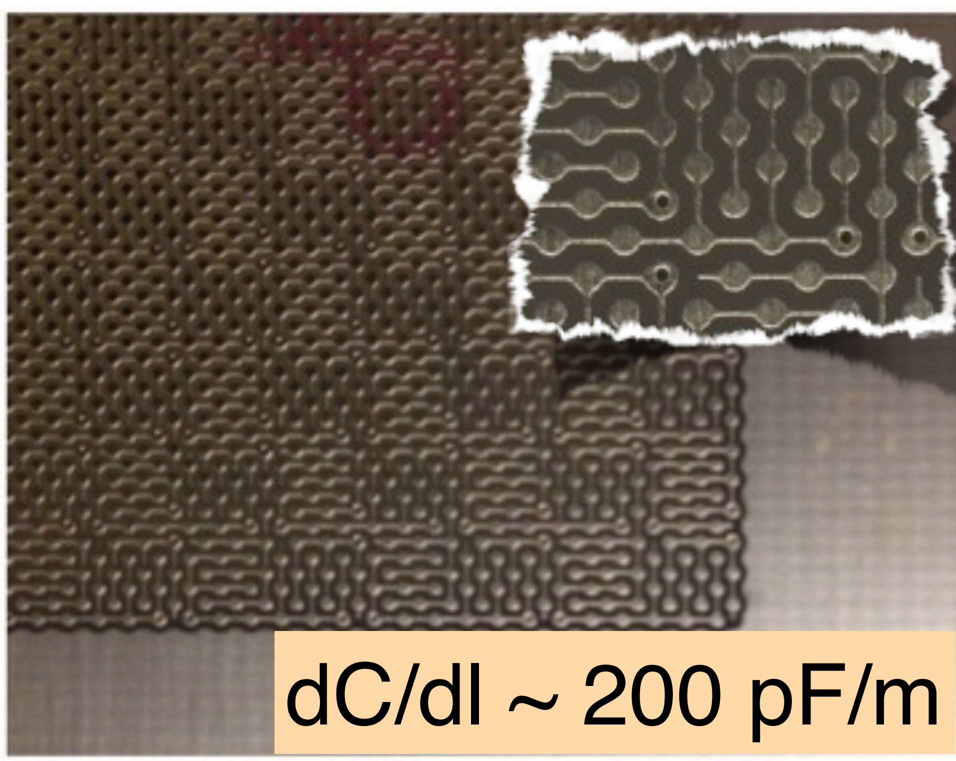
previous Kapton type anode dC/dl ~600 pF/m

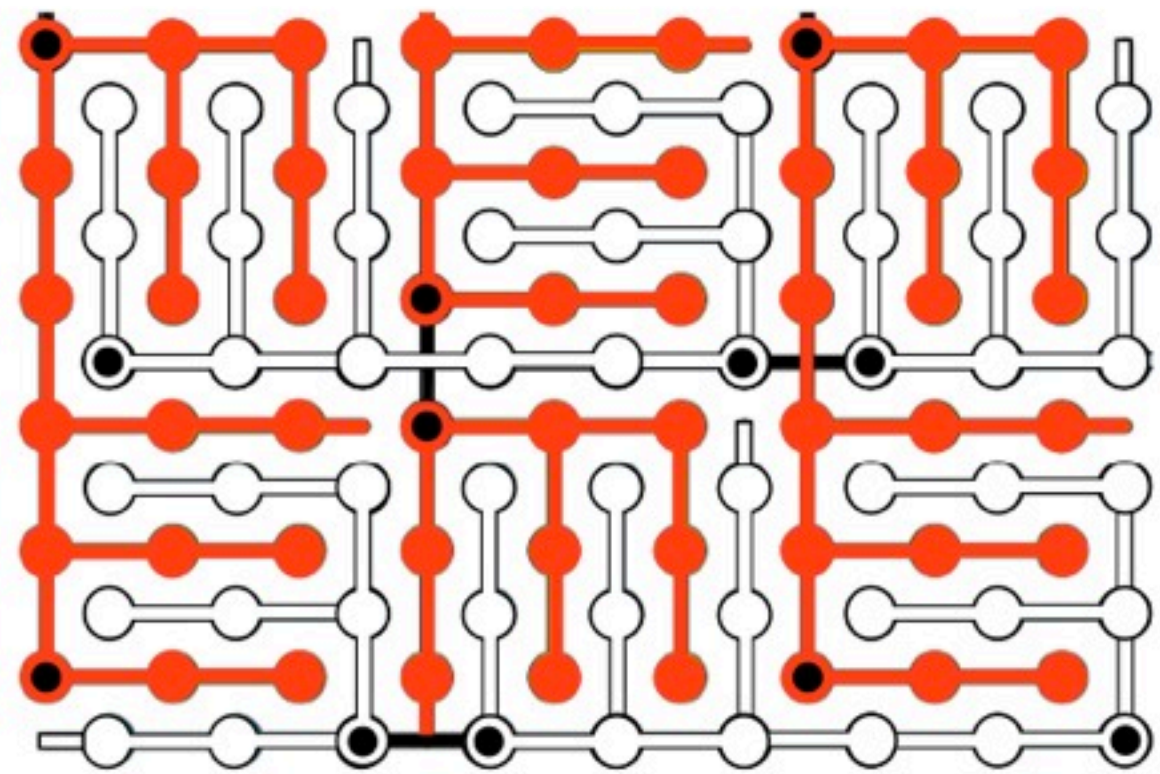
the anode should:

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.

Towards large area readout - anode considerations

Goal: readout of at least 0.5x0.5 m²

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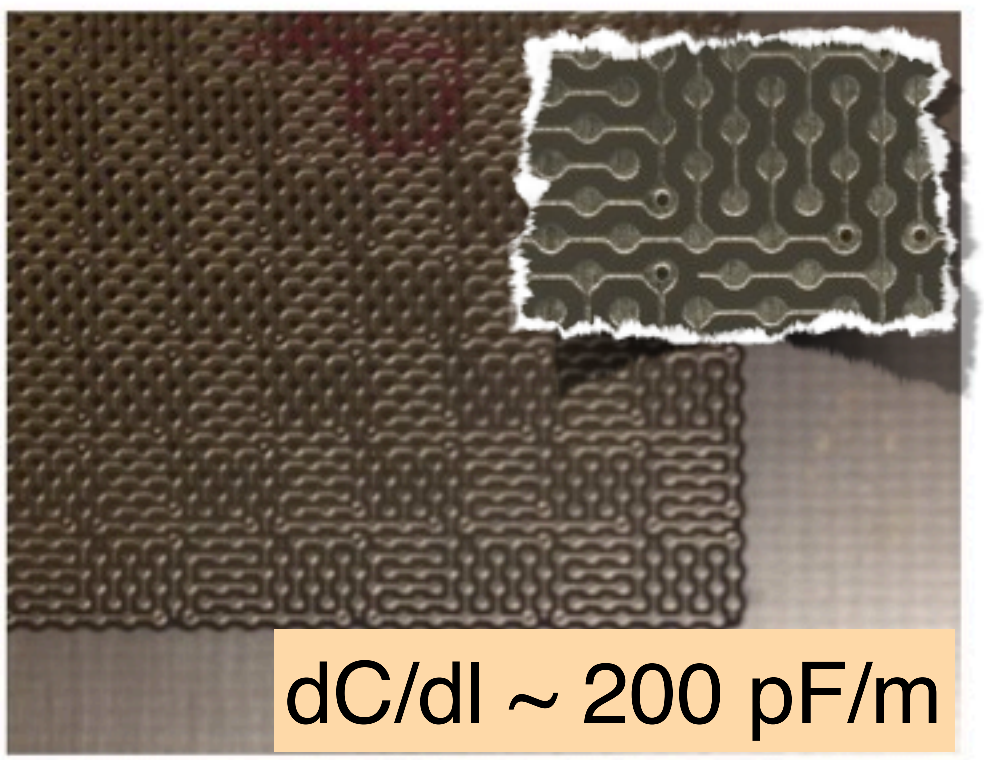
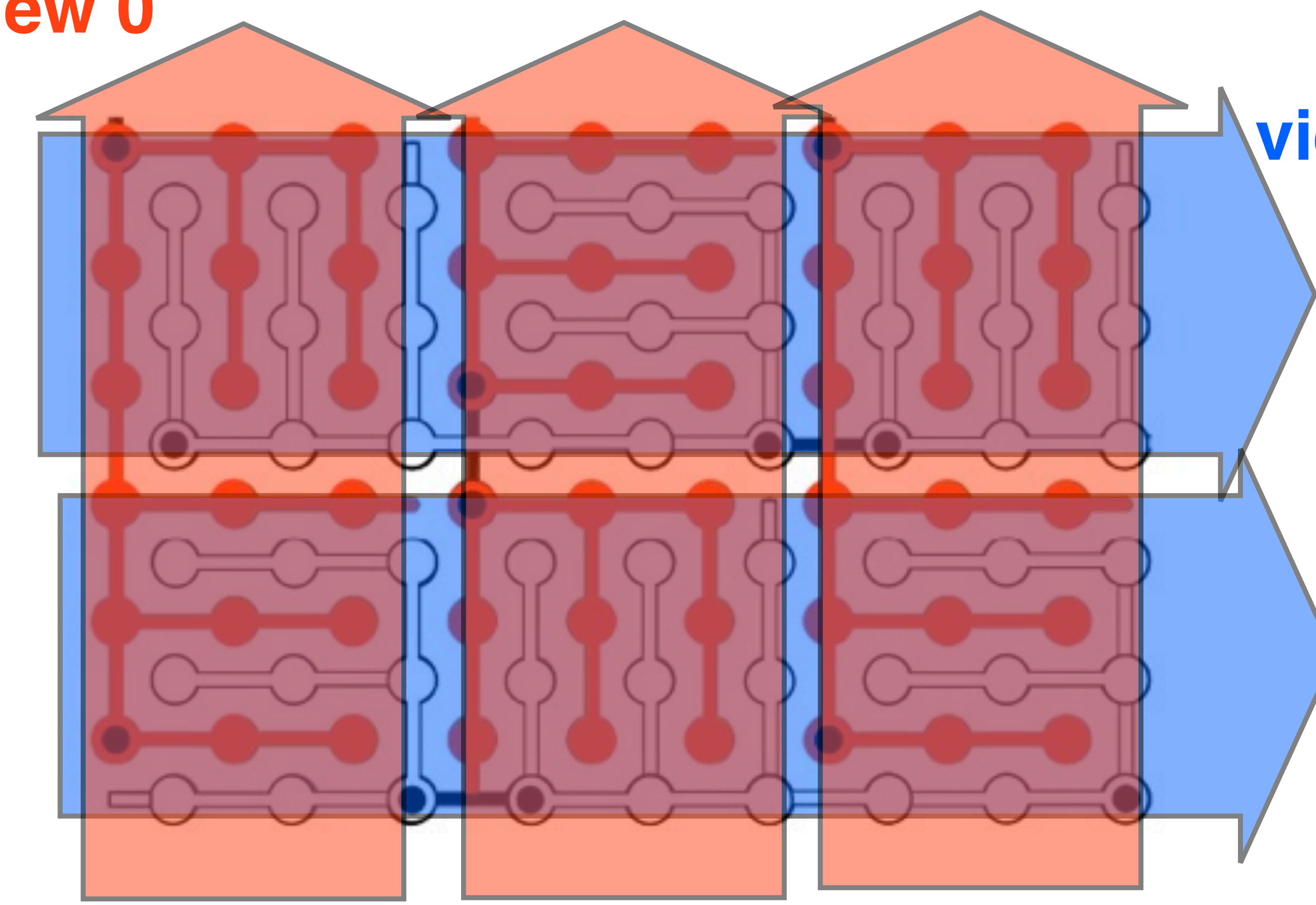


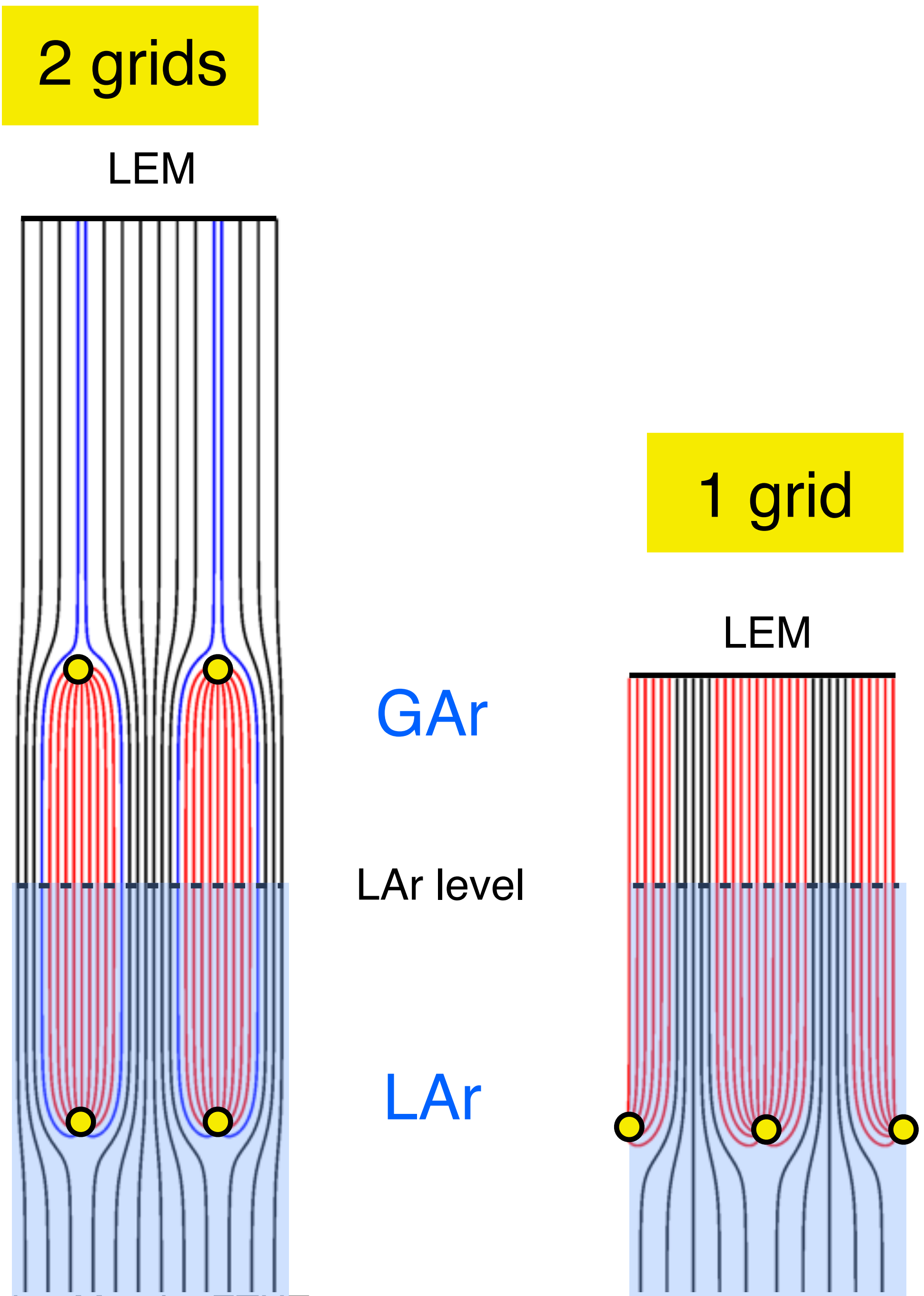


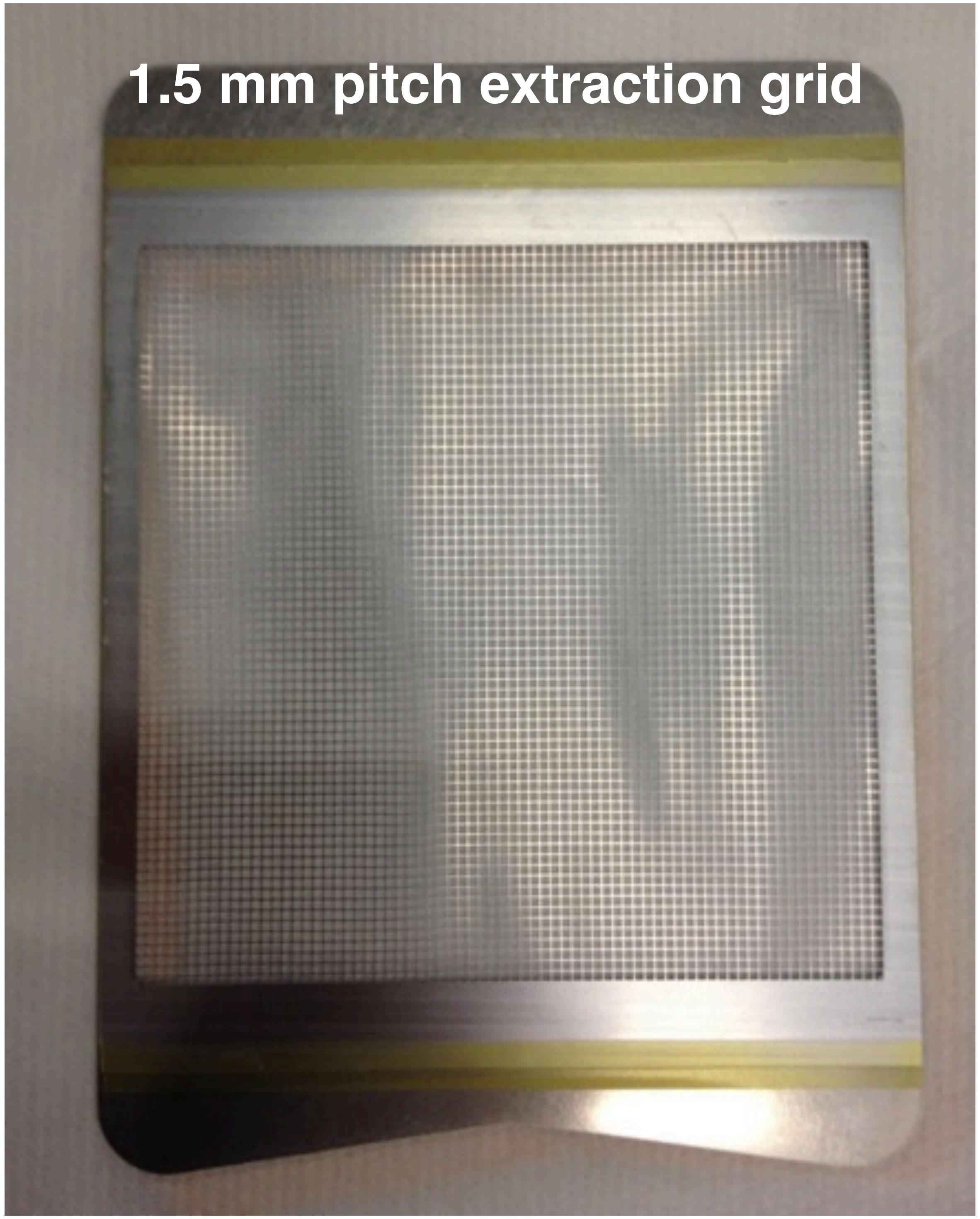
previous Kapton type anode dC/dl ~600 pF/m

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

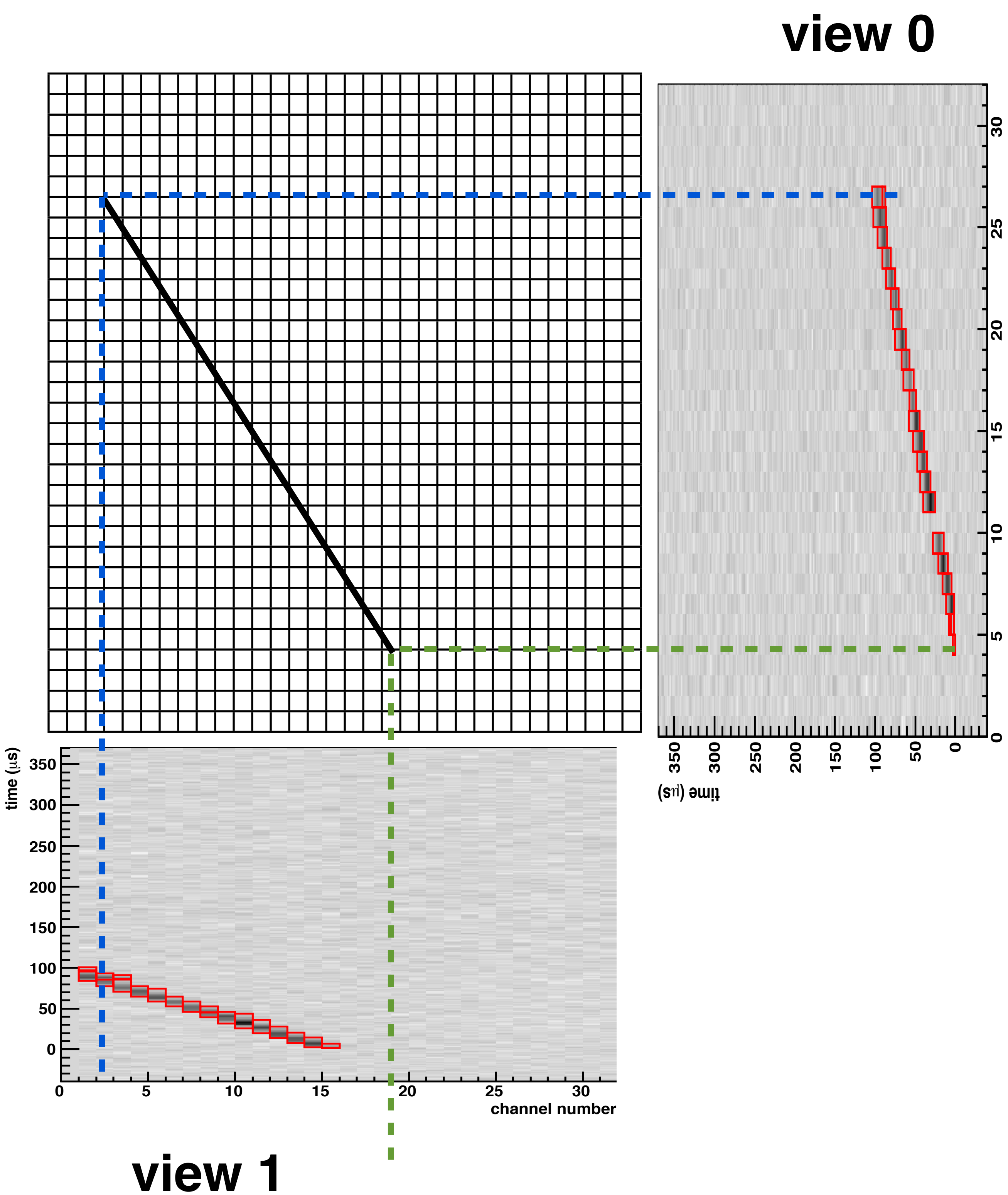
Simplifying the design- single extraction grid

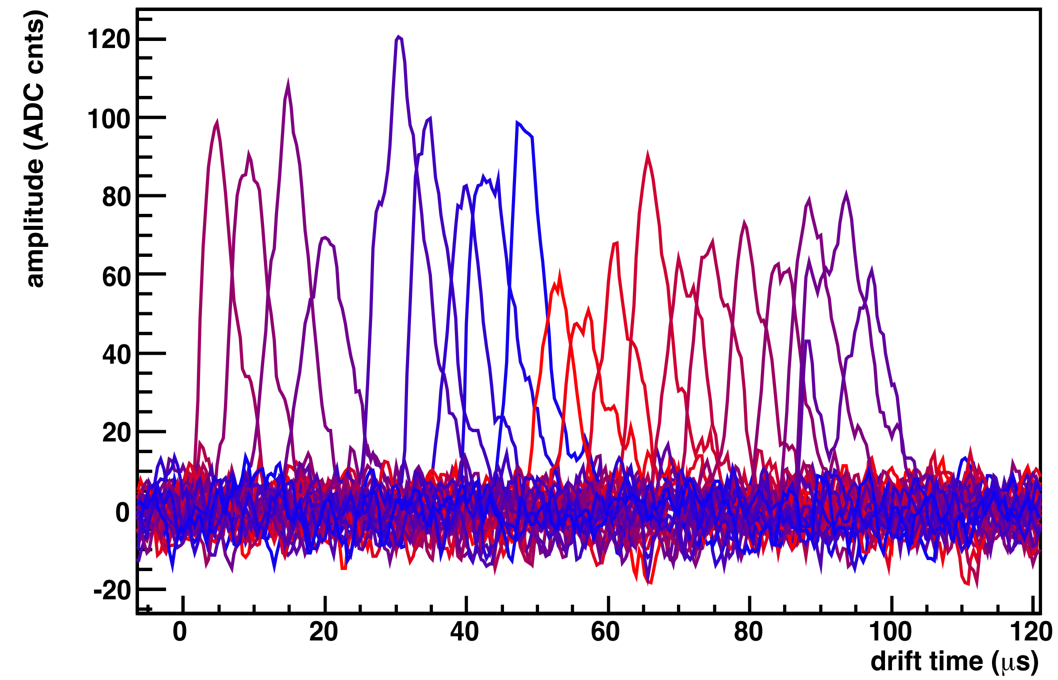
- Simplified scheme
- Higher transparency possible (no alignment of grids needed)
- Less absolute voltage





Track reconstruction



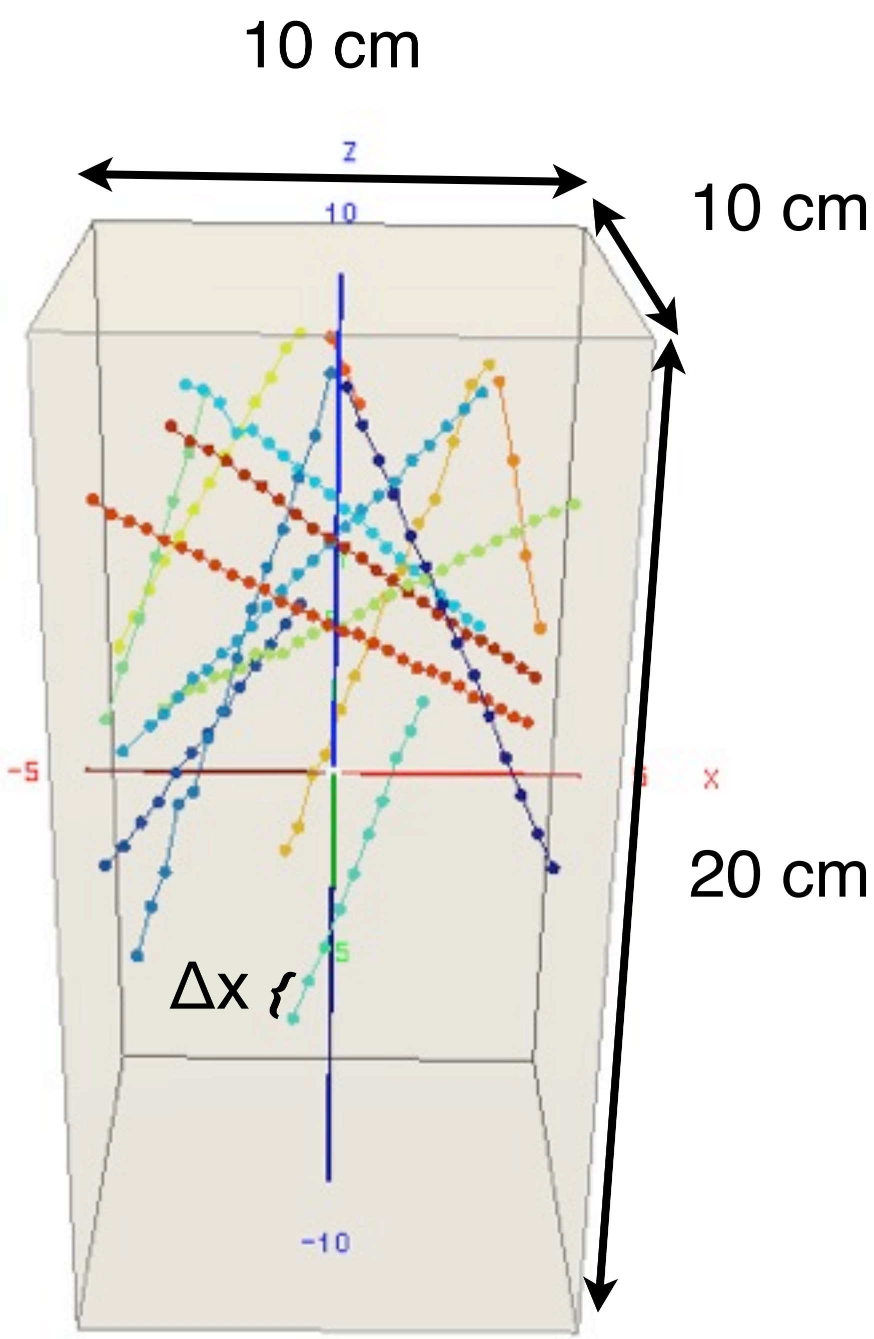


2 orthogonal projections (=views) are recorded

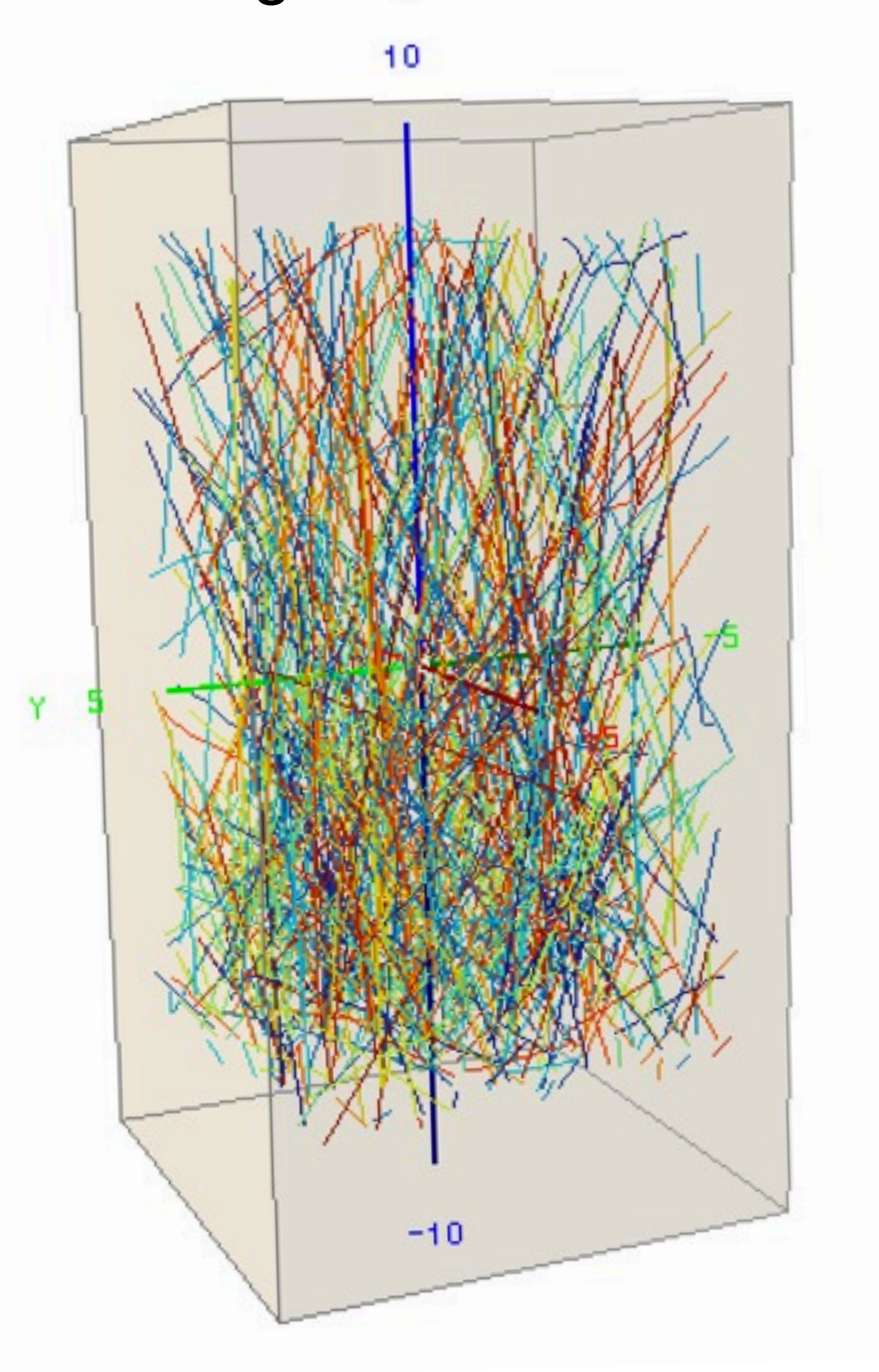
1. subtract noise, find signals (=hits, red boxes)
2. find straight tracks in each view
3. reconstruct 3D coordinates by matching coincident hits

3D Track reconstruction

➡ ΔQ and Δx (3 dimensional track segment!) for each view, literature: ΔQ/Δx=10 fC/cm (mip)



large statistics!

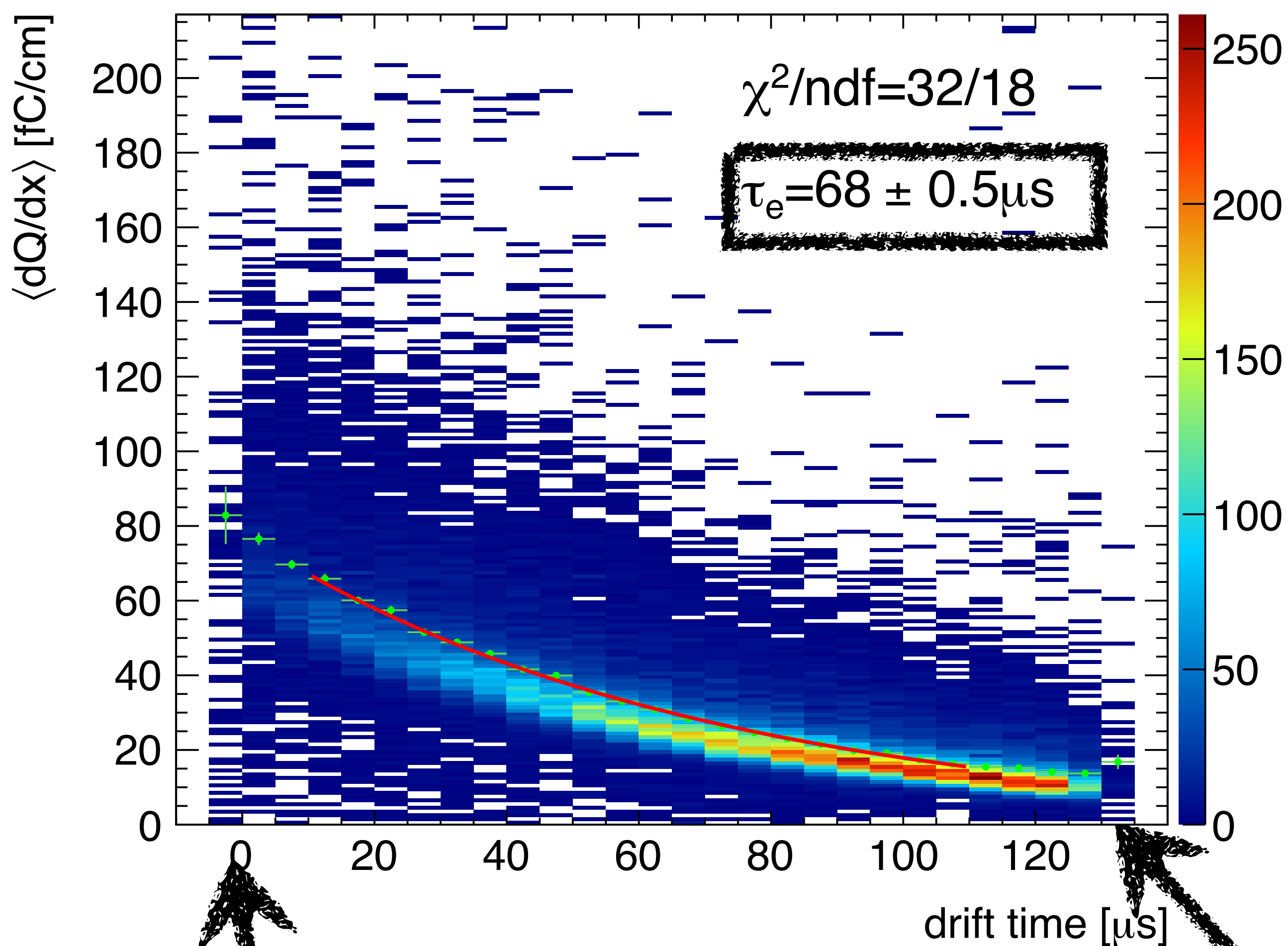


Calibration: drift attenuation

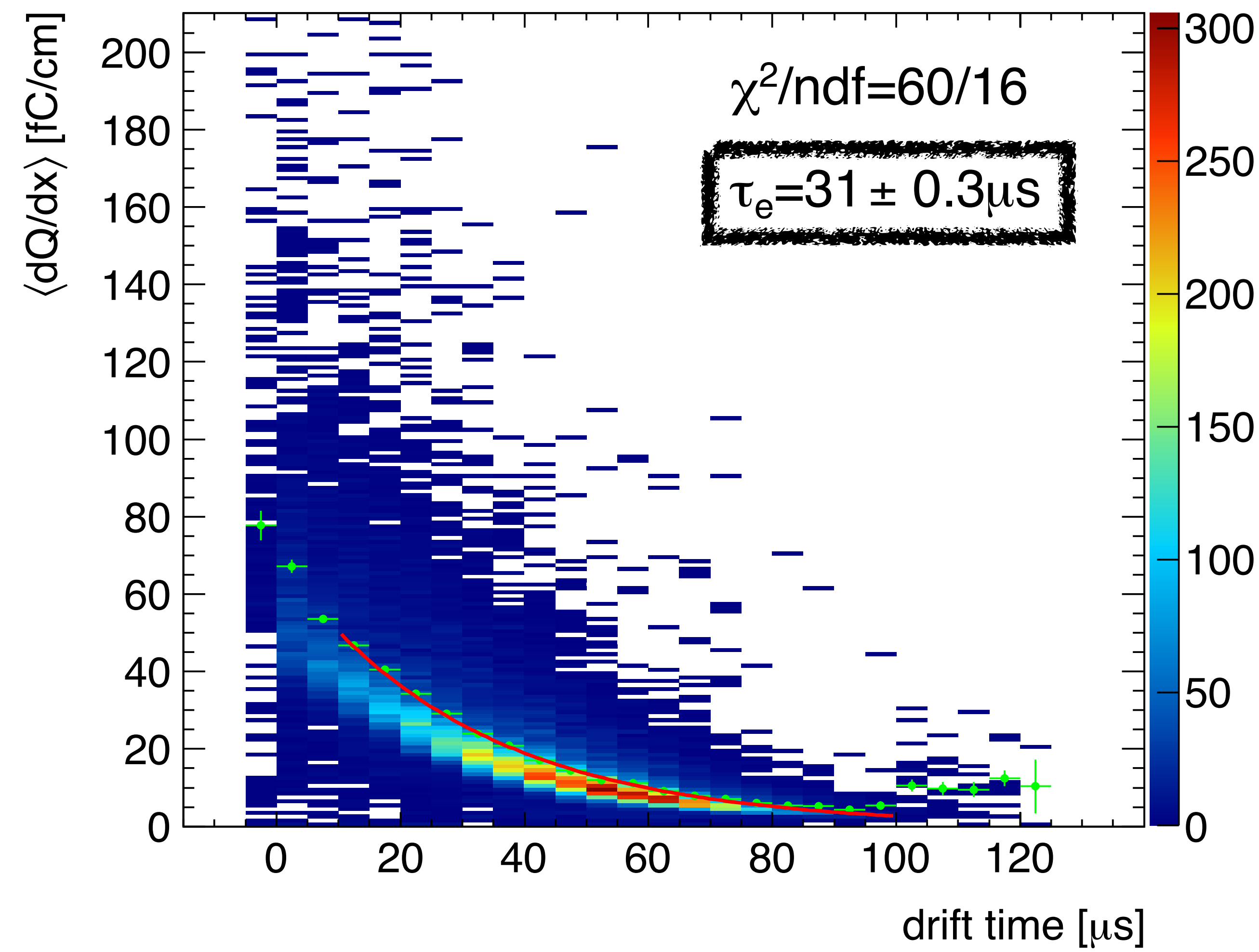
drifting electrons are trapped by impurities in LAr:

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

towards the beginning of a run



towards the end of a run



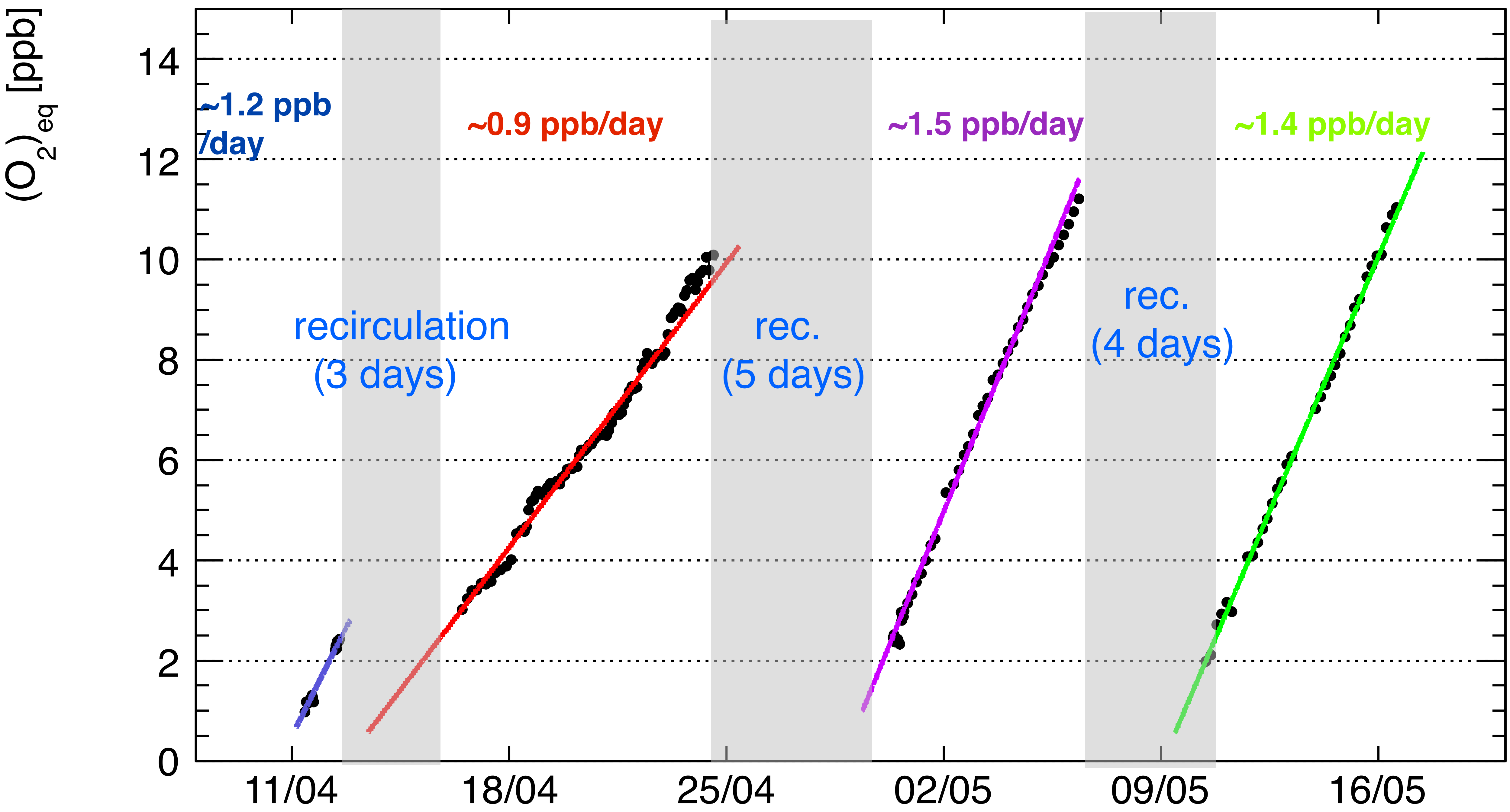
top of the chamber

bottom of the chamber

Evolution of the free electron lifetime

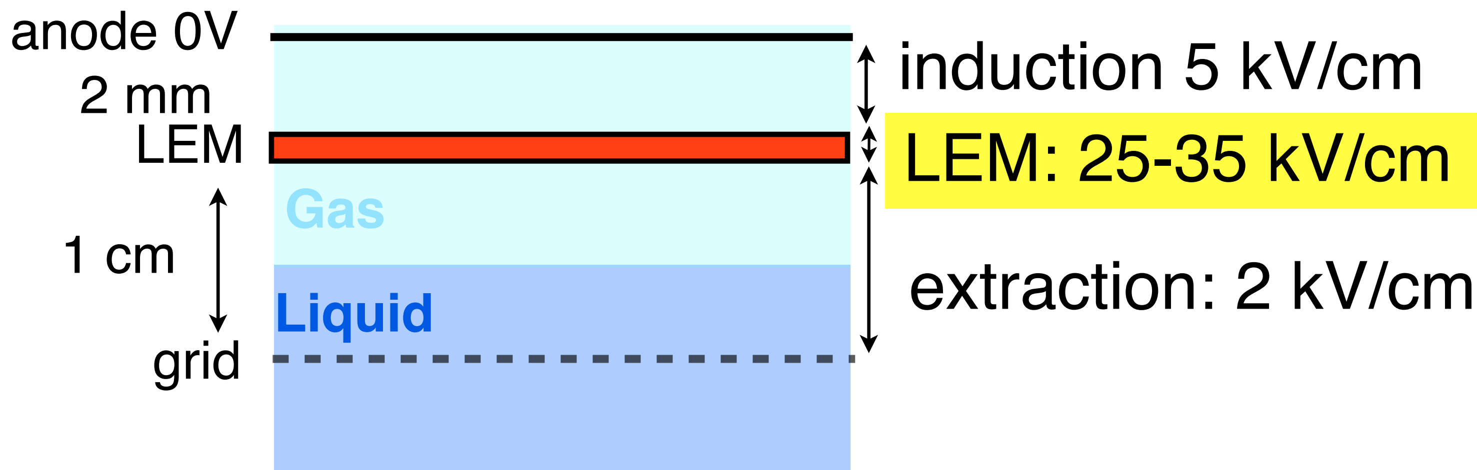
Impurities in the liquid: $[O2]_{eq} \approx 300\ \mu s\ /\ \tau_e$

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



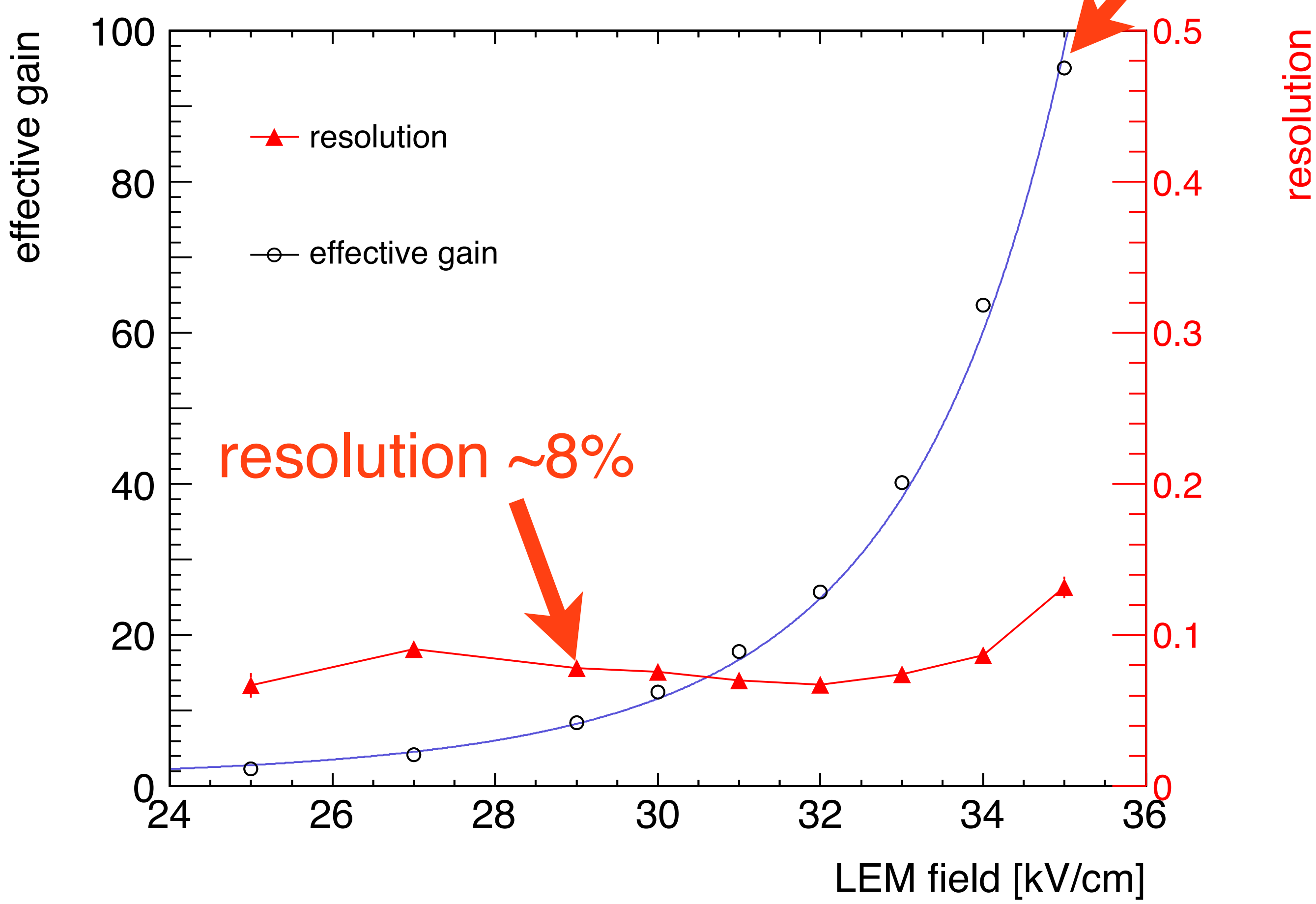
more than 1 month of continuous operation!

LEM field scan up to gain 90!

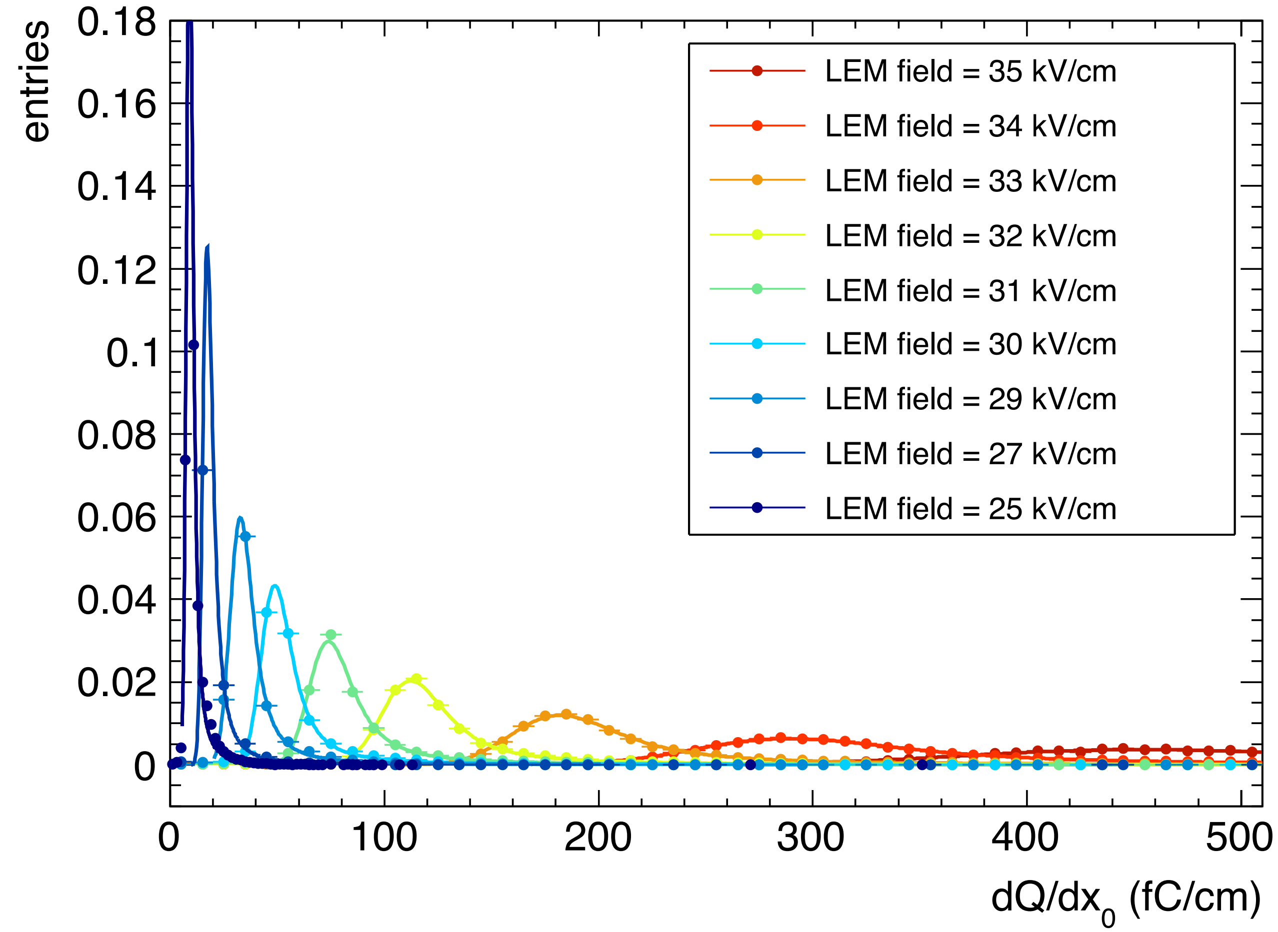


onset of discharges @ gain > 90!

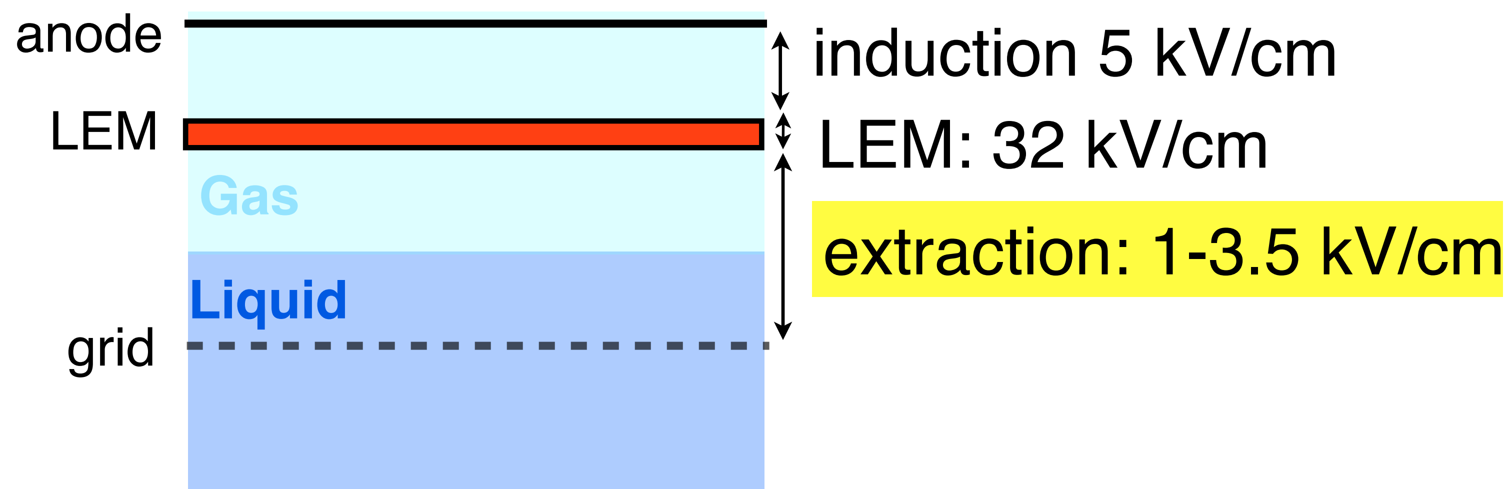
gain and resolution for diff. LEM fields



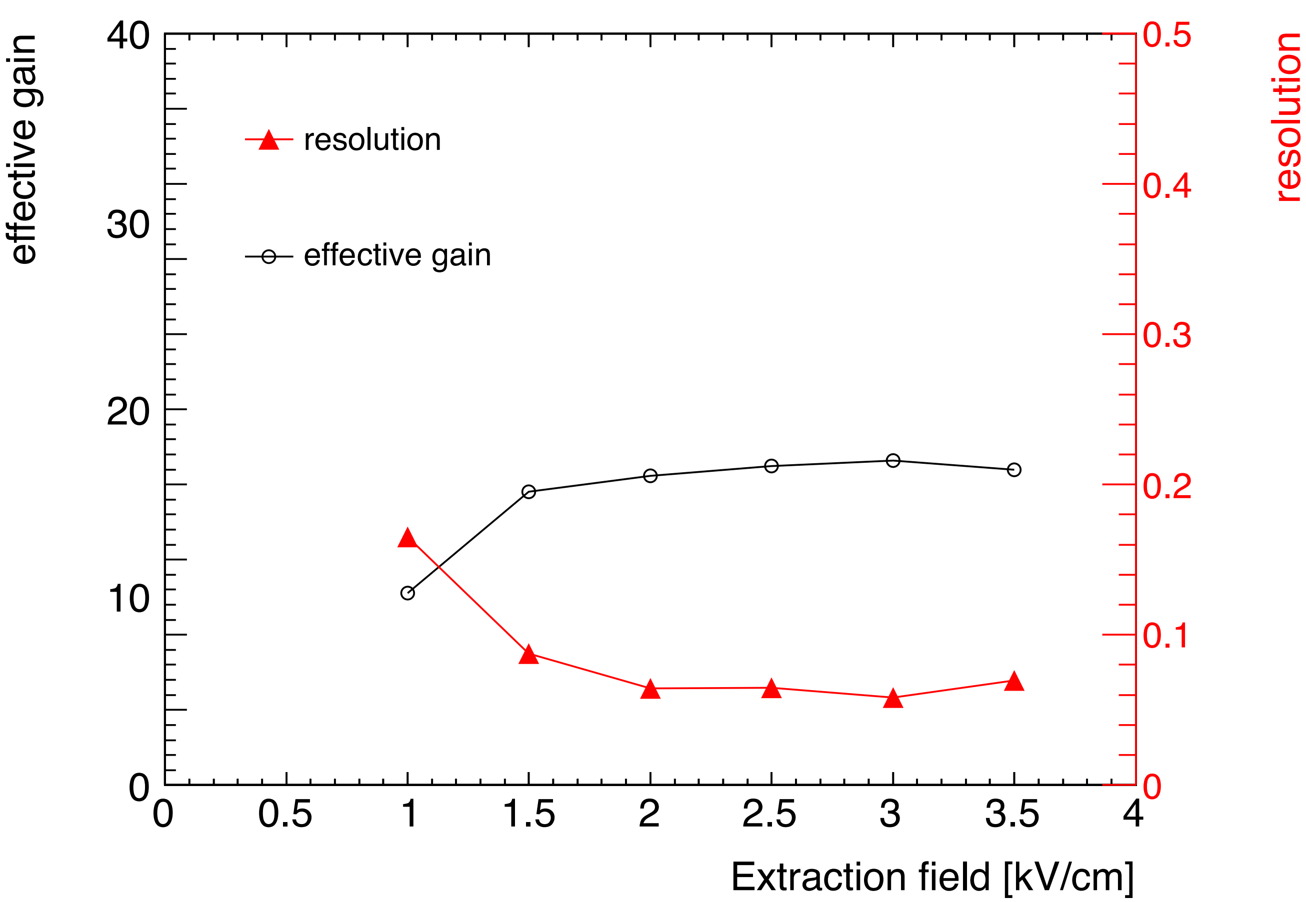
Landau distributions for diff. LEM fields



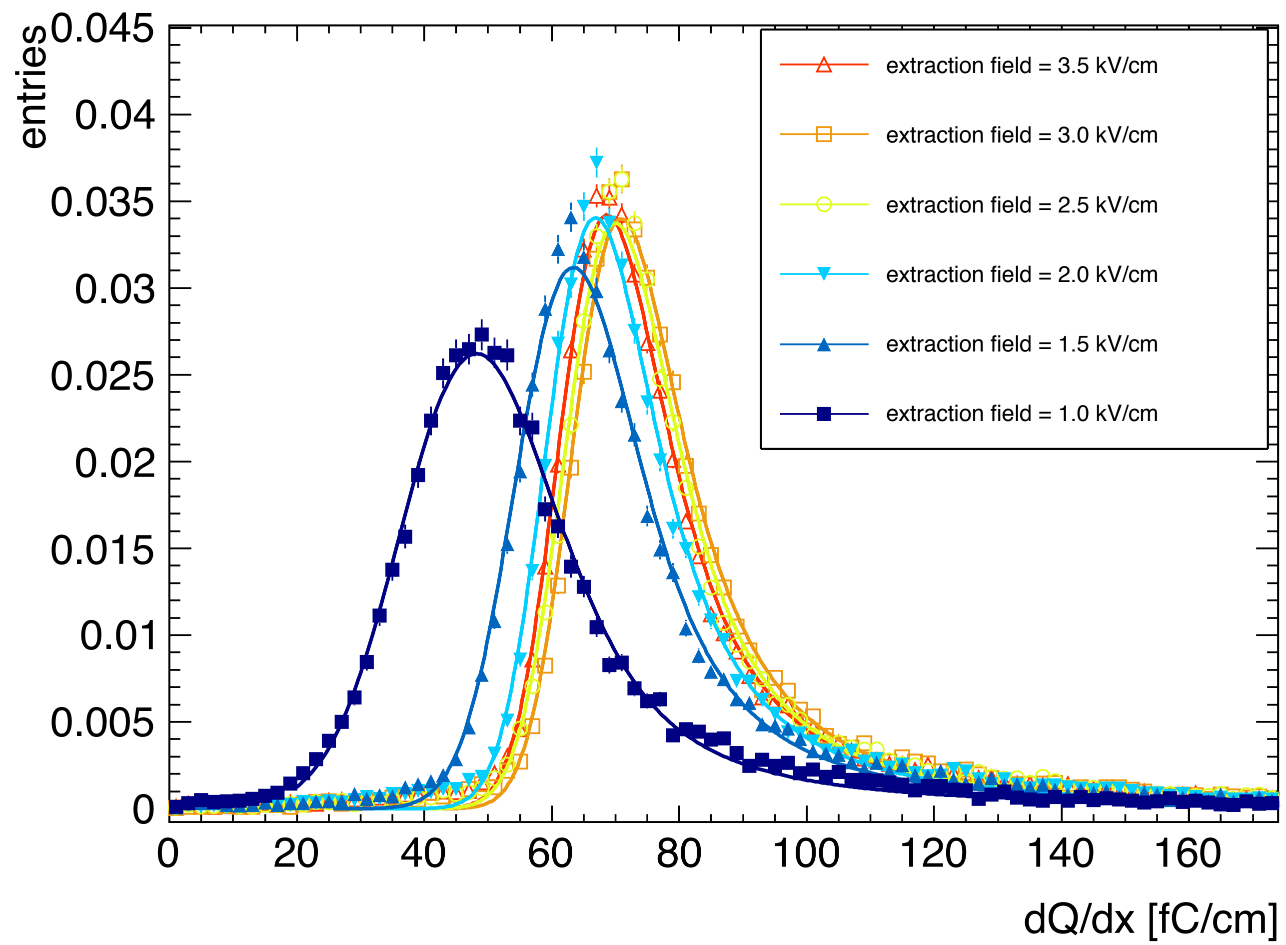
Extraction field scan



gain and resolution for diff. extr. fields

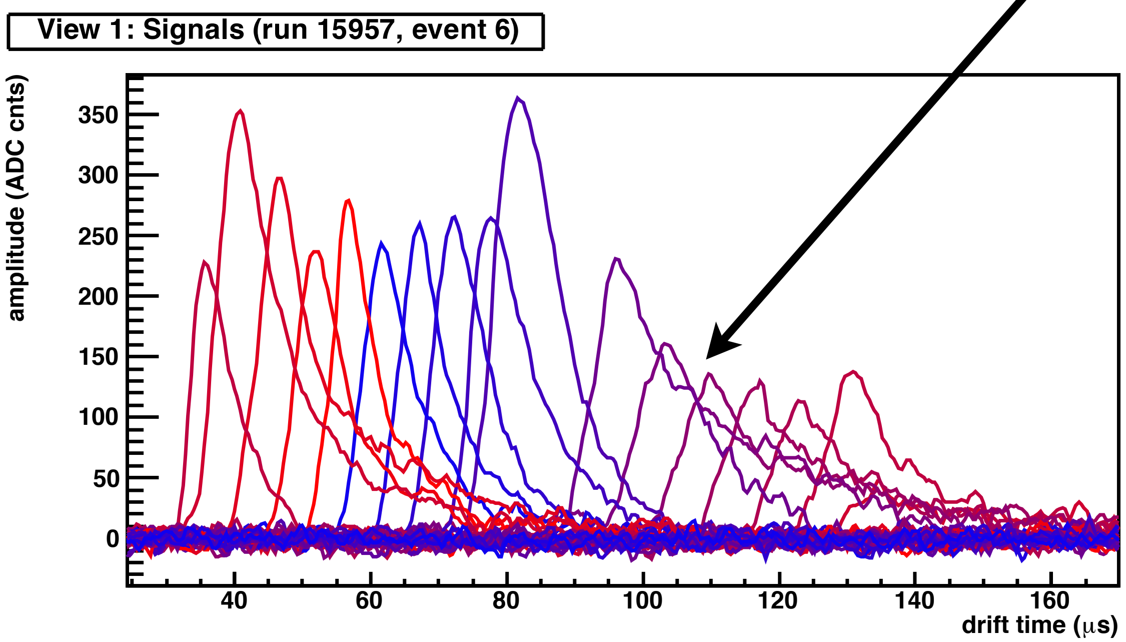


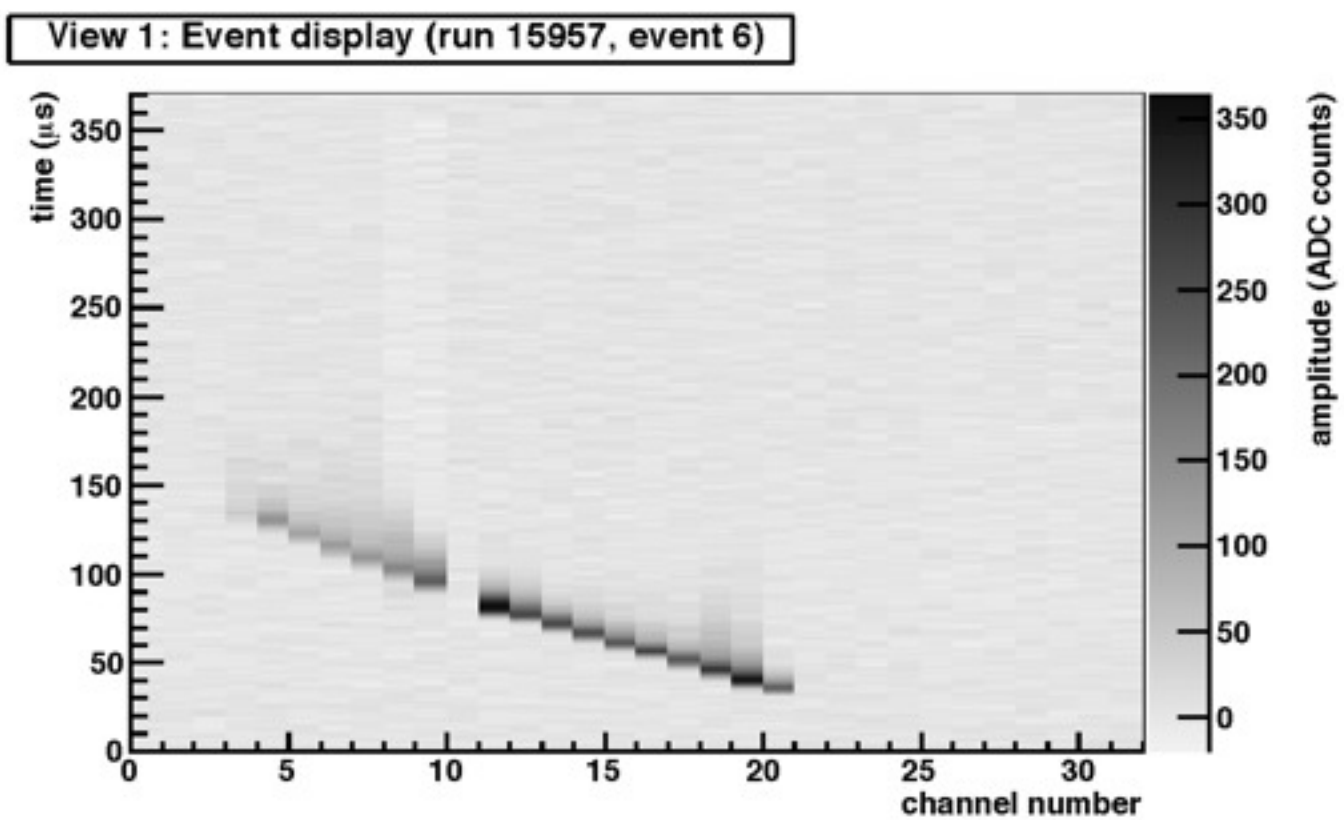
Landau distributions for diff. extr. fields



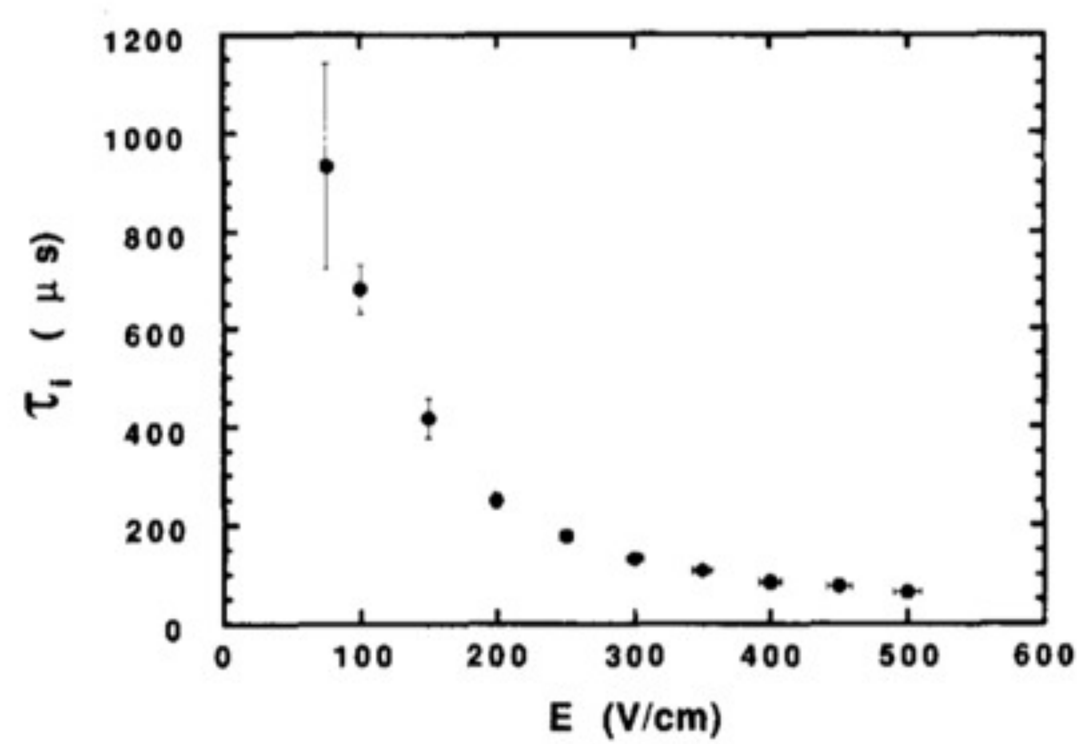
What happens at low extraction fields?

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





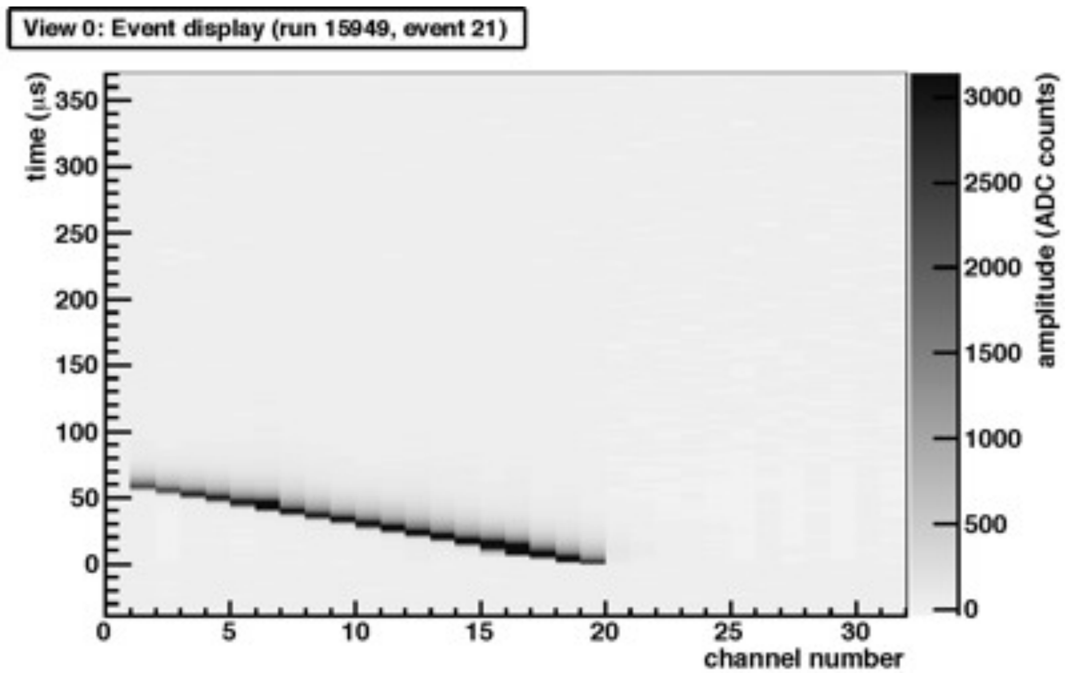
Literature:

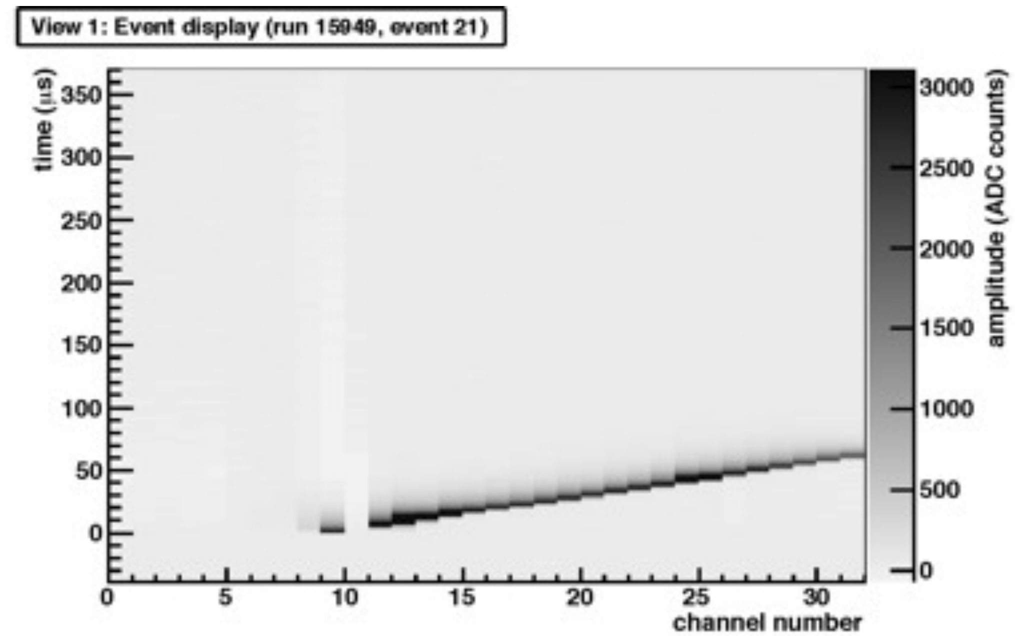


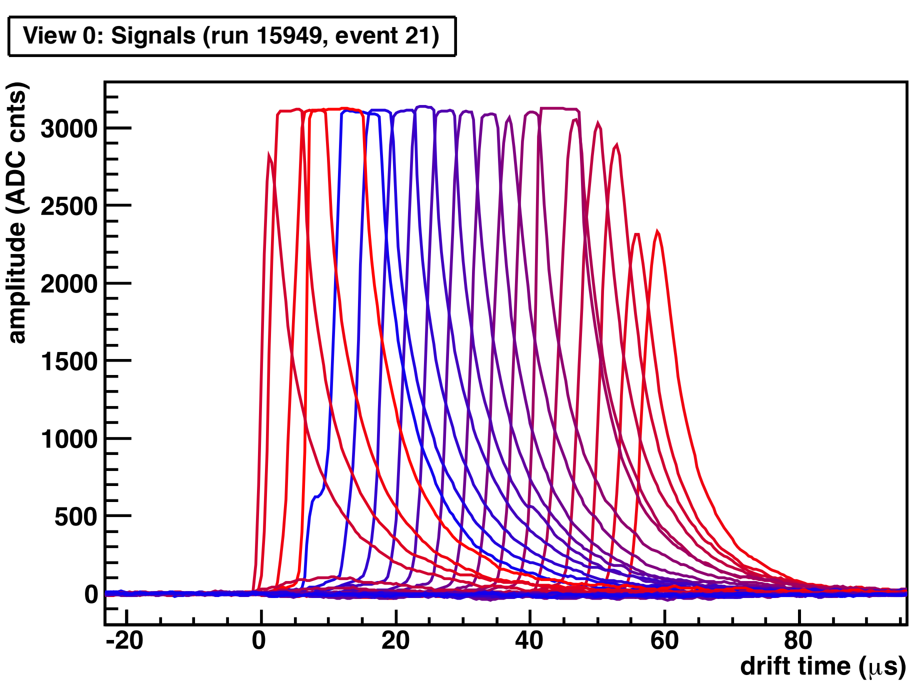
Borghesani et al., "Electron transmission through the Ar liquid-vapor interface", Phys. Lett. A149 (9)

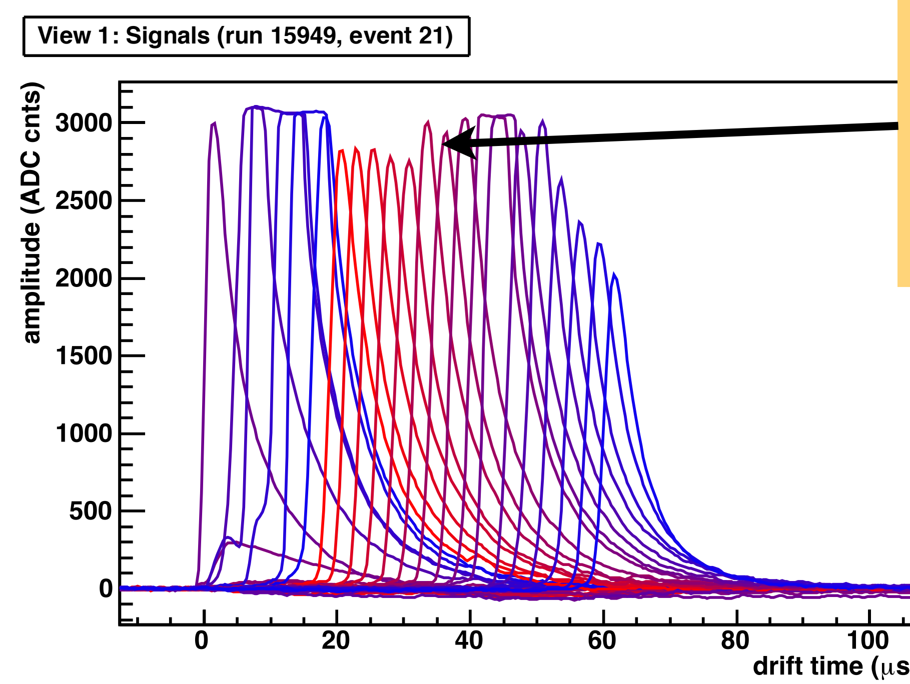
LEM operated at highest gain >90!

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







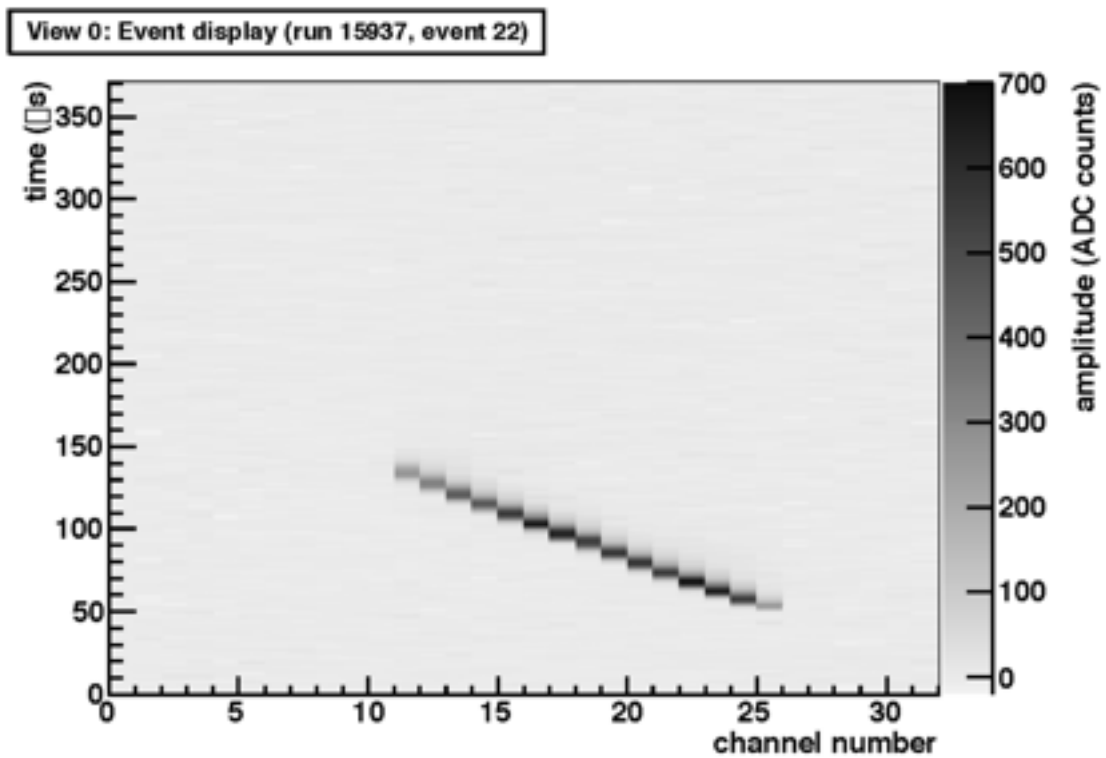


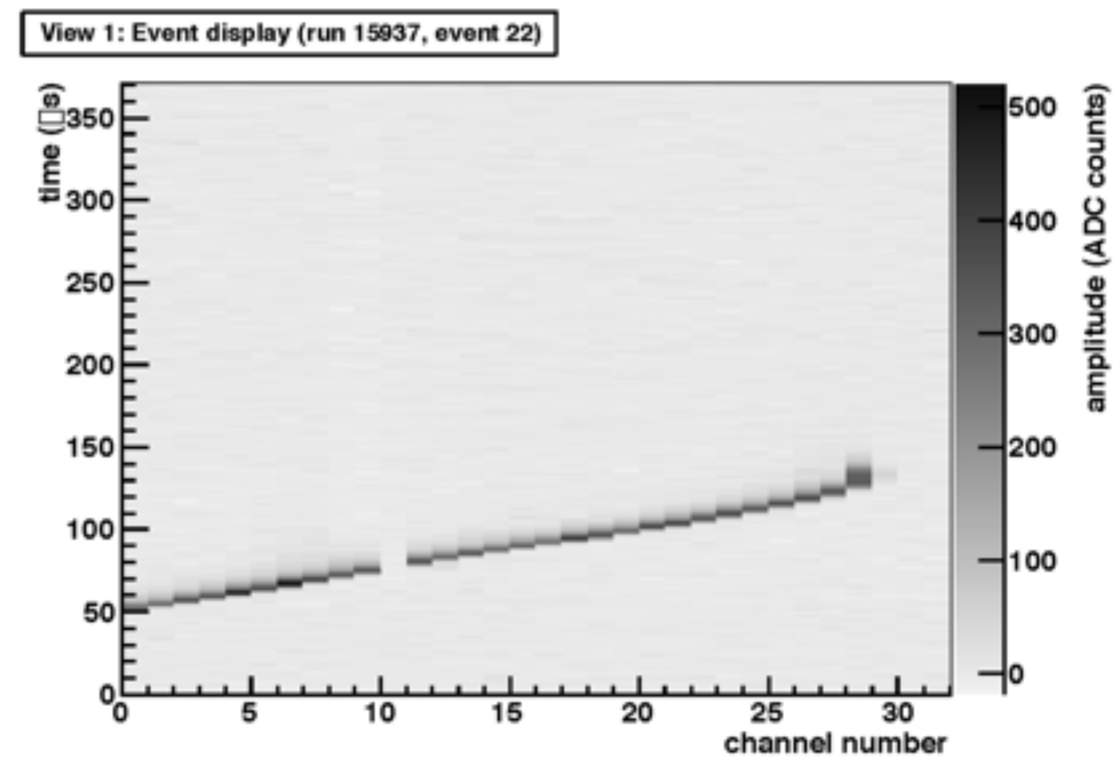
mip signals saturate preamplifier!

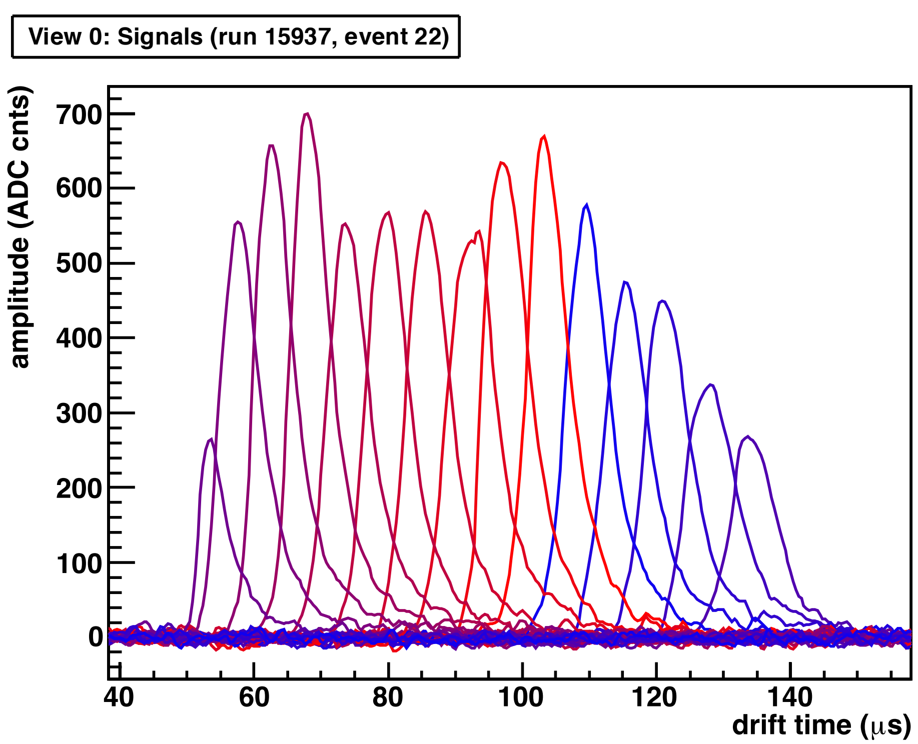
In future versions dynamic range of the preamp will be adapted to the gain.
non-linear behaviour to adapt to a wide dynamic range

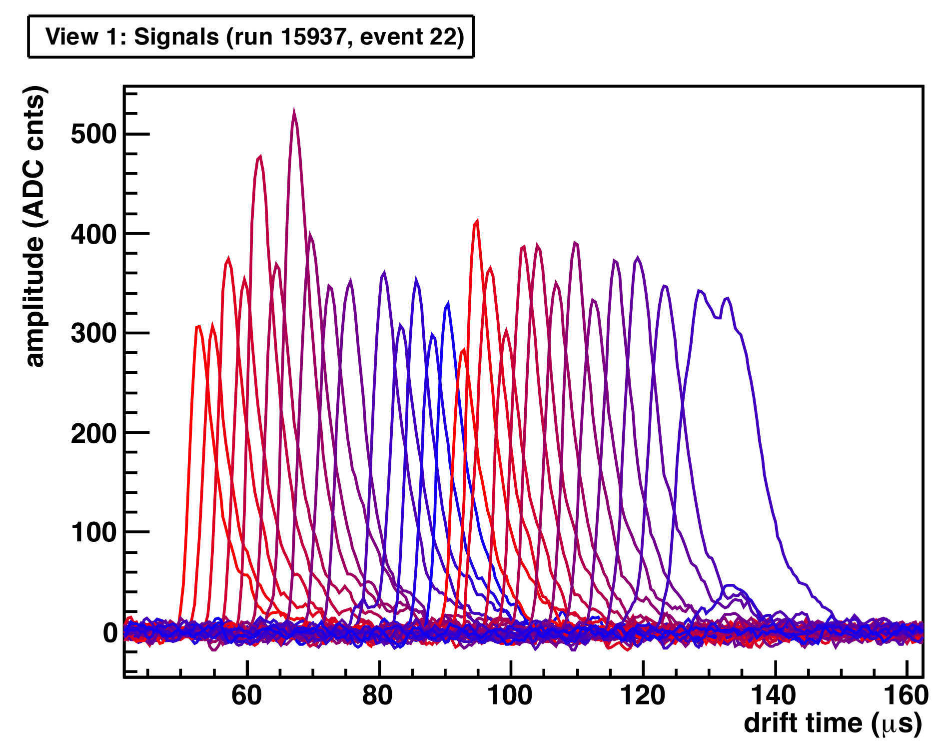
Event at effective gain ~ 20

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



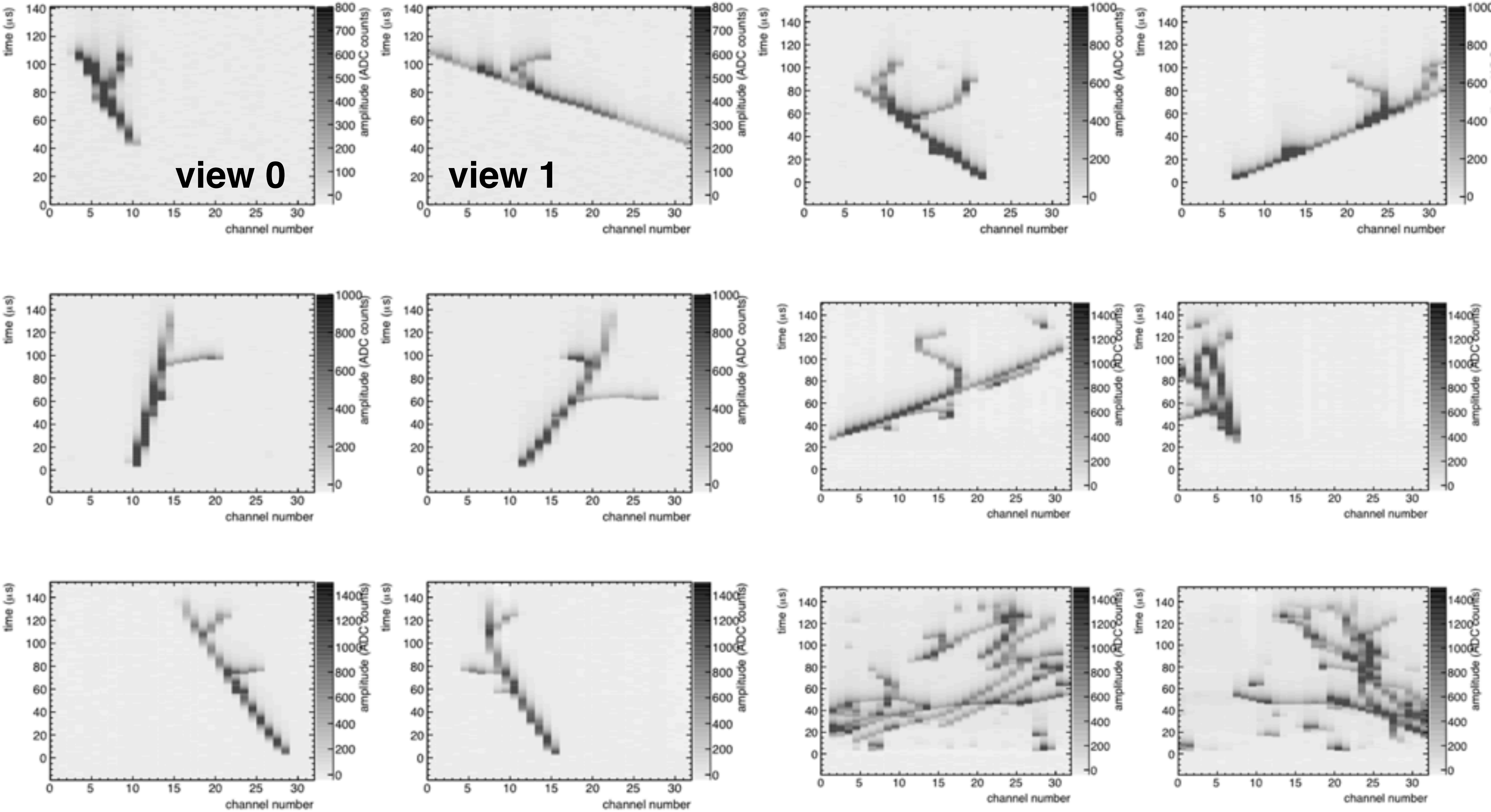






More events

gain ~30

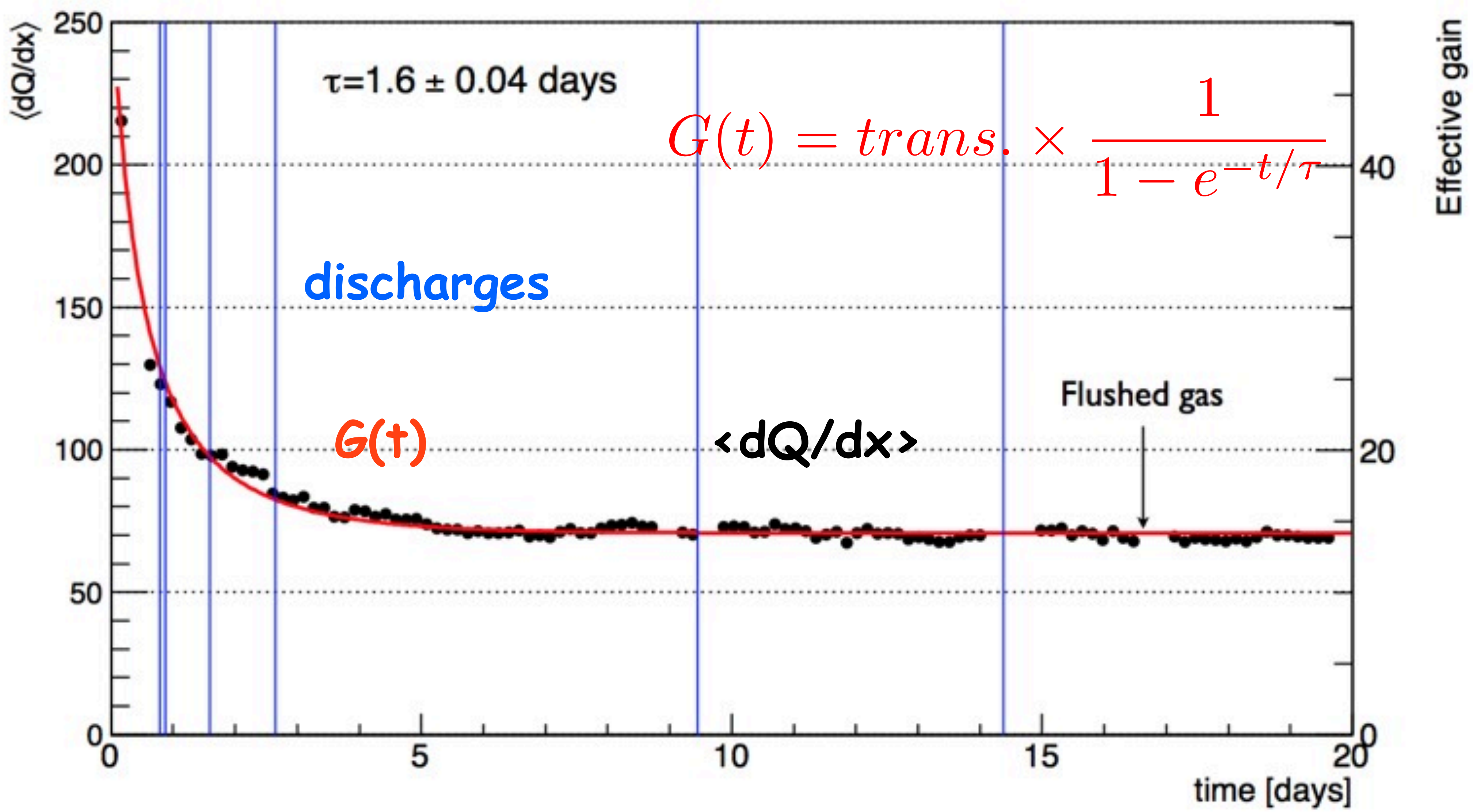


Gain stability

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)

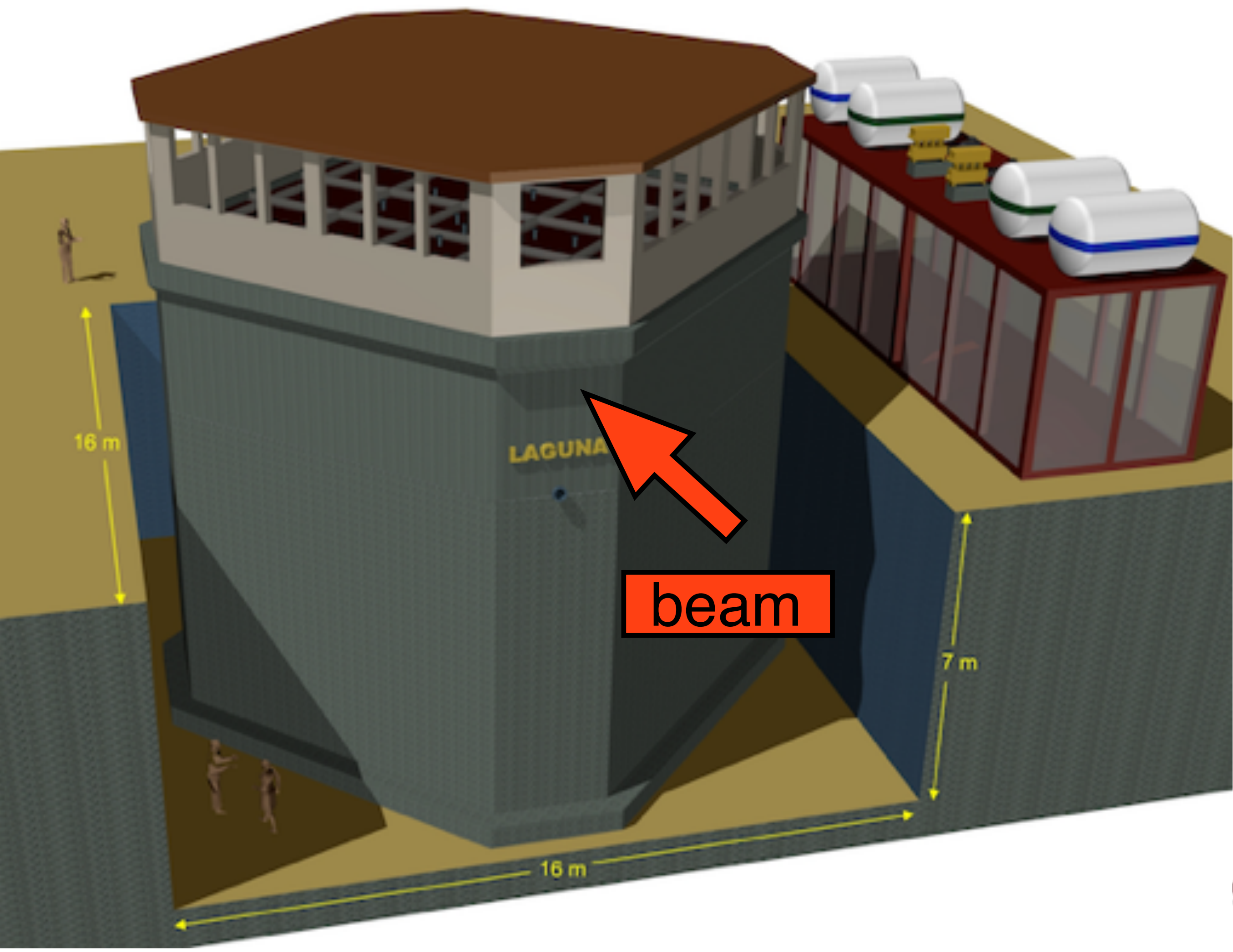
✳The discharges do not lead to a change of overall gain



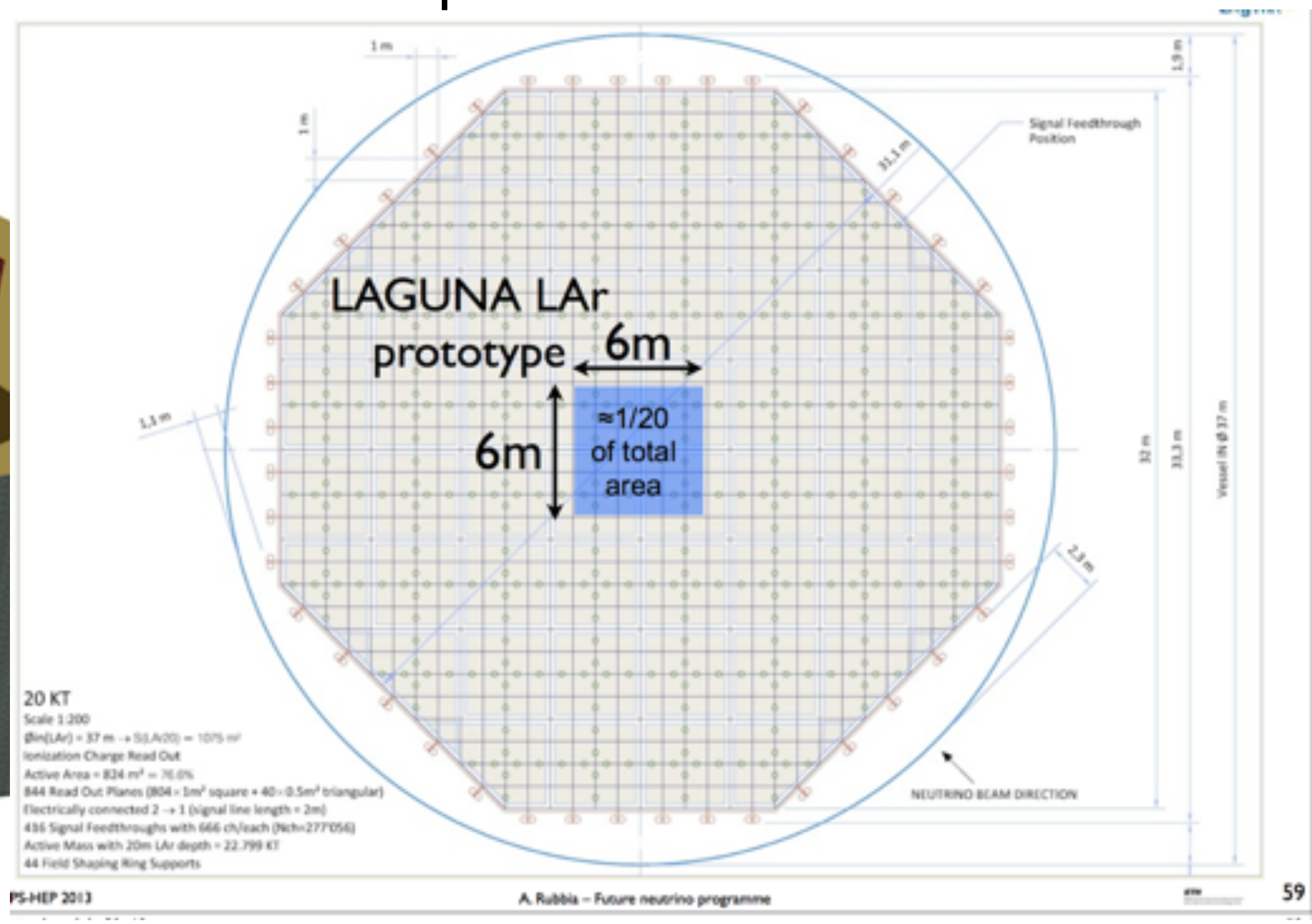
~15 days operation under stable gain of ~15

Next milestone: $6x6x6m^3$ prototype

Next milestone: Large-scale LBNO detectors prototyping at CERN, with priority emphasis on a large double-phase LAr demonstrator, using charged-particle test beams (2014-2017). TDR submitted to SPS Committee in June.



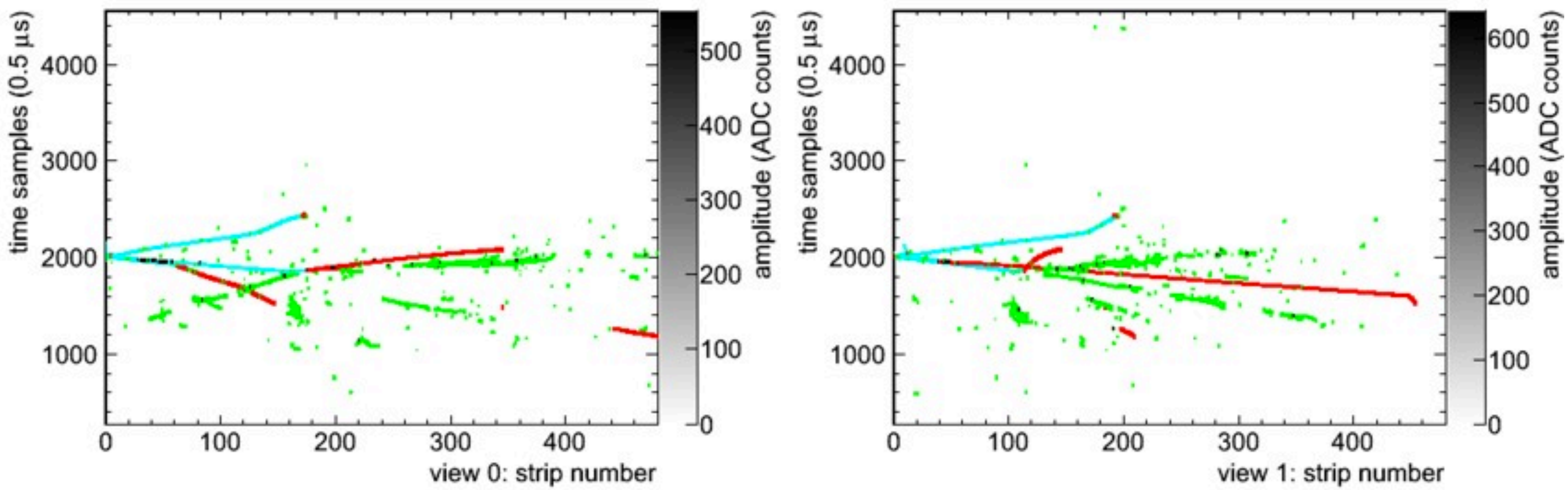
6x6x6m3 compared to GLACIER 20 kt



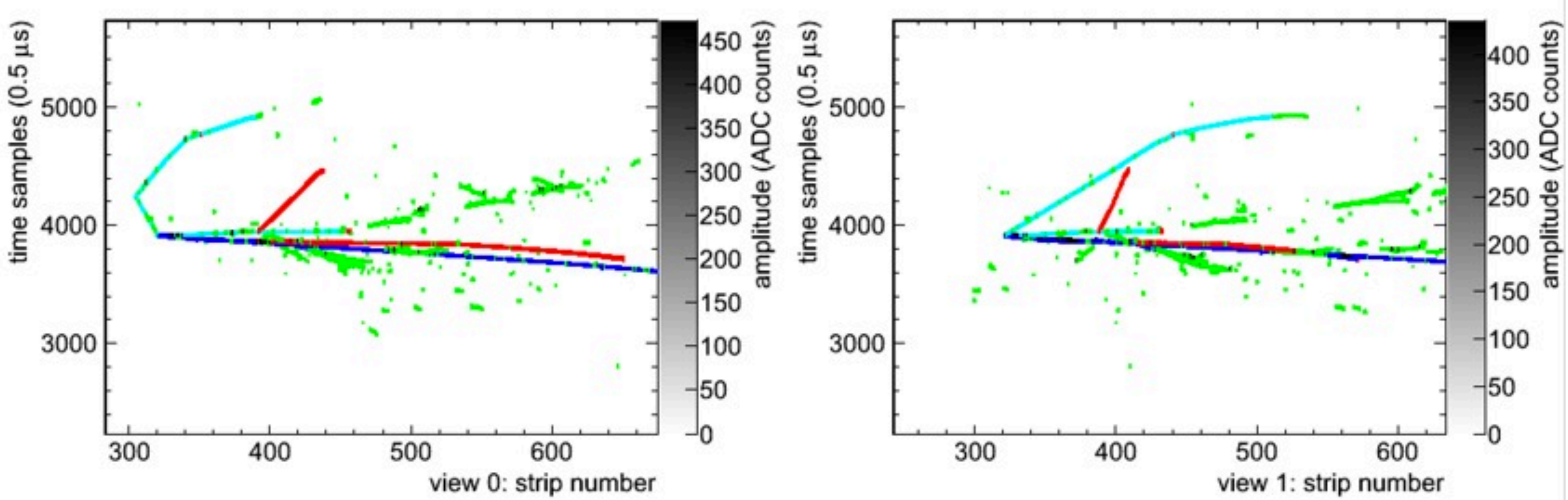
Simulated events in the 6x6x6m^3 prototype

5 GeV pi-

pions, electrons/positrons, protons, muons



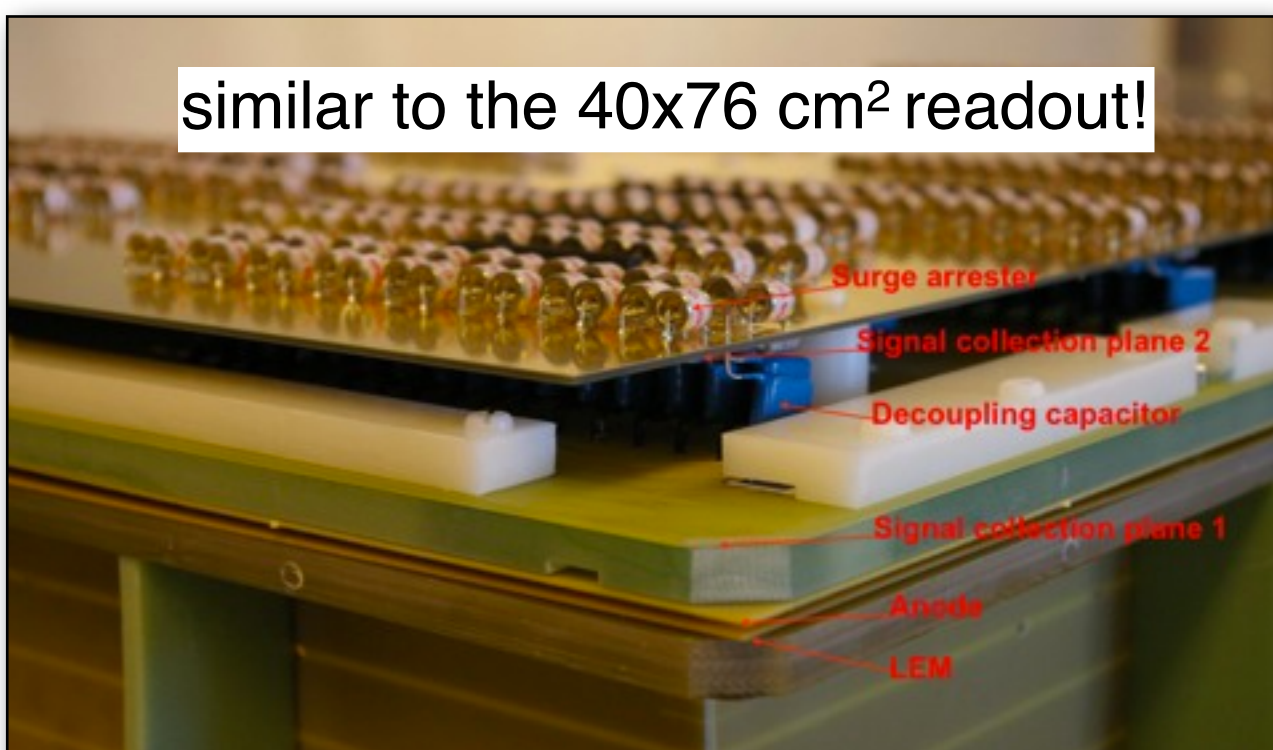
5 GeV nu_mu

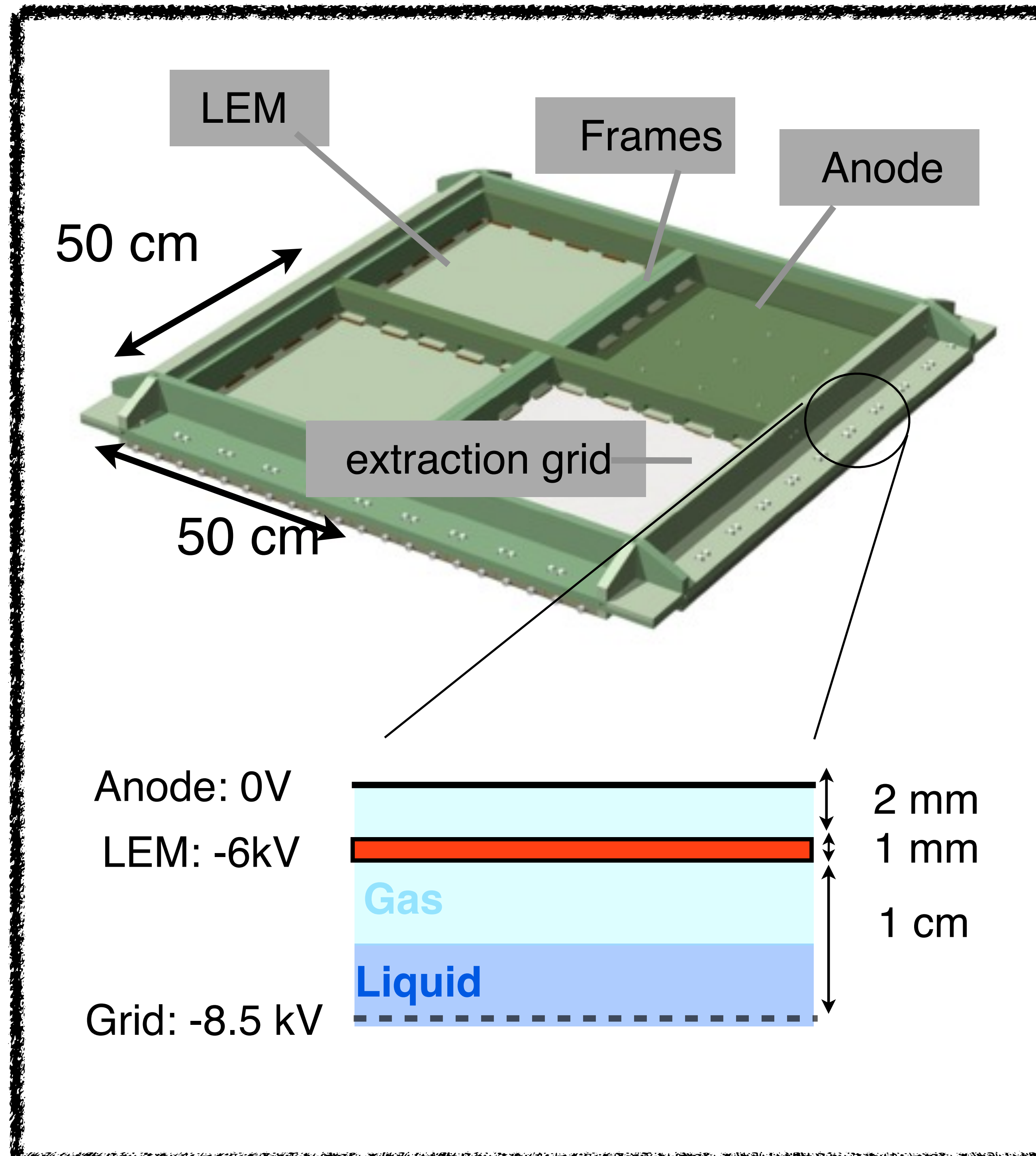


test reconstruction algorithms on data from charged particle beam

Design of 6x6x6m^3 charge readout

- Independent modules of 50x50 cm^2.
- Single extraction grid.
- LEM 1mm thick 500 um holes 800 um pitch.
- Anode with ~200 pF/m
- Front end readout electronics
- Overall Mechanical structure





Summary

✳ LAGUNA/LBNO is a project with a very rich and interesting physics program with **fundamental discovery potential.**

✳The LAGUNA-LBNO collaboration decided to propose stage I of 20kt LAr + 700 kW SPS at 2300km of baseline

✳Outstanding Physics Potential:

1. Accelerator based:
    - Mass Hierarchy > 5 σ all phase space in 2y • δCP
    - MSNP precision --> 3 ν or 3+n ?
2. Non Accelerator based:
    - Proton decay:Significantly extended sensitivity to nucleon decay in many channels.

    Br(p → anti-ν K) > 2 × 1034y (90%C.L.) Br(n → e K+) > 2 × 1034y (90%C.L.)
3. Neutrino Astronomy:
    - Supernova neutrinos >10000's events @ SN explosion@10kpc
    - Diffuse Supernova Neutrinos (DSN)
    - Neutrinos from DM annihilation
    - Atmospheric Neutrinos (5600 events/y)

R&D outlook

- significant R&D efforts and results towards large Double LAr detectors:
  - optimization of the charge readout.
  - Good performance of low capacitance PCB anode.
  - reached gains higher than 90.
  - Chosen working point with gain about 15 is stable over a period of several weeks.
- We are now proposing a demonstrator for the double phase LAr technology at a relevant scale 6x6x6m^3 (216m^3).
  - TDR submitted to CERN in June.
  - In the process of completing the design of a 1 square meter Charge Readout Plane

Towards a real experiment: letter of intent

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Expression of Interest

for a very long baseline neutrino oscillation experiment

(LBNO)

A. Stahl,[1] C. Wiebusch,[1] A. M. Guler,[2] M. Kamiscioglu,[2] R. Sever,[2] A.U. Yilmazer,[3] C. Gunes,[3] D. Yilmaz,[3] P. Del Amo Sanchez,[4] D. Duchesneau,[4] H. Pessard,[4] E. Marcoulaki,[5] I. A. Papazoglou,[5] V. Berardi,[6] F. Cafagna,[6] M.G. Catanesi,[6] L. Magaletti,[6] A. Mercadante,[6] M. Quinto,[6] E. Radicioni,[6] A. Ereditato,[7] I. Kreslo,[7] C. Pistillo,[7] M. Weber,[7] A. Ariga,[7] T. Ariga,[7] T. Strauss,[7] M. Hierholzer,[7] J. Kawada,[7] C. Hsu,[7] S. Haug,[7] A. Jipa,[8] I. Lazanu,[8] A. Cardini,[9] A. Lai,[9] R. Oldeman,[10] M. Thomson,[11] A. Blake,[11] M. Prest,[12] A. Auld,[13] J. Elliot,[13] J. Lumbard,[13] C. Thompson,[13] Y.A. Gornushkin,[14] S. Pascoli,[15] R. Collins,[16] M. Haworth,[16] J. Thompson,[16] A. Longhin,[17] A. Blondel,[18] A. Bravar,[18] F. Dufour,[18] Y. Karadzhov,[18] A. Korzenev,[18] E. Noah,[18] M. Ravonel,[18] M. Rayner,[18] R. Asfandiyarov,[18] A. Haesler,[18] C. Martin,[18] E. Scantamburlo,[18] F. Cadoux,[18] R. Bayes,[19] F.J.P. Soler,[19] L. Aalto-Setälä,[20] K. Enqvist,[20] K. Huitu,[20] K. Rummukainen,[20] G. Nuijten,[21] M. Manninen,[22] J. Maalampi,[22] K.J. Eskola,[22] K. Kainulainen,[22] T. Kalliokoski,[22] J. Kumpulainen,[22] K. Loo,[22] I. Moore,[22] J. Suhonen,[22] W.H. Trzaska,[22] K. Tuominen,[22] A. Vrtanen,[22] I. Bertram,[23] A. Finch,[23] N. Grant,[23] L.L. Kormos,[23] P. Ratoff,[23] G. Christodoulou,[24] J. Coleman,[24] C. Touramanis,[24] K. Mavrokoridis,[24] M. Murdoch,[24] N. McCauley,[24] D. Payne,[24] P. Jonsson,[25] A. Kaboth,[25] K. Long,[25] M. Malek,[25] M. Scott,[25] Y. Uchida,[25] M.O. Wascko,[25] F. Di Lodovico,[26] J.R. Wilson,[26] B. Still,[26] R. Sacco,[26] R. Terri,[26] M. Campanelli,[27] R. Nichol,[27] J. Thomas,[27] A. Izmaylov,[28] M. Khabibullin,[28] A. Khotjantsev,[28] Y. Kudenko,[28] V. Matveev,[28] O. Mineev,[28] N. Yershov,[28] V. Palladino,[29] J. Evans,[30] M. Bonesini,[31] T. Pihlajaniemi,[32] M. Weckström,[32] K. Mursula,[32] T. Enqvist,[32] P. Kuusiniemi,[32] T. Räihä,[32] J. Sarkamo,[32] M. Slupecki,[32] J. Hissa,[32] E. Kokko,[32] M. Aittola,[32] G. Barr,[33] M.D. Haigh,[33] J. de Jong,[33] H. O'Keeffe,[33] A. Vacheret,[33] A. Weber,[33,34] G. Galvanin,[35] M. Temussi,[35] O. Caretta,[34] T. Davenne,[34] C. Densham,[34] J. Ilic,[34] P. Loveridge,[34] J. Odell,[34] D. Wark,[34] A. Robert,[36] B. Andrieu,[36] B. Popov,[36,14] C. Giganti,[36] J.-M. Levy,[36] J. Dumarchez,[36] M. Buizza-Avanzini,[37] A. Cabrera,[37] J. Dawson,[37] D. Franco,[37] D. Kryn,[37] M. Obolensky,[37] T. Patzak,[37] A. Tonazzo,[37] F. Vanucci,[37] D. Orestano,[38] B. Di Micco,[38] L. Tortora,[39] O. Bésida,[40] A. Delbart,[40] S. Emery,[40] V. Galymov,[40] E. Mazzucato,[40] G. Vasseur,[40] M. Zito,[40] V. Kudryavtsev,[41] L. Thompson,[41] R. Tsenov,[42] D. Kolev,[42] I. Rusinov,[42] M. Bogomilov,[42] G. Vankova,[42] R. Matev,[42] A. Vorobyev,[43] Yu. Novikov,[43] S. Kosyanenko,[43] V. Suvorov,[43] G. Gavrilov,[43] E. Baussan,[44] M. Dracos,[44] C. Jollet,[44] A. Meregaglia,[44] E. Vallazza,[45] S.K. Agarwalla,[46] T. Li,[46] D. Autiero,[47] L. Chaussard,[47] Y. Déclais,[47] J. Marteau,[47] E. Pennacchio,[47] E. Rondio,[48] J. Lagoda,[48] J. Zalipska,[48] P. Przewlocki,[48] K. Grzelak,[49] G. J. Barker,[50] S. Boyd,[50] R.P. Litchfield,[50] Y. Ramachers,[50] A. Badertscher,[51] A. Curioni,[51] U. Degunda,[51] L. Epprecht,[51] A. Gendotti,[51] L. Knecht,[51] S. DiLuise,[51] S. Horikawa,[51] D. Lussi,[51] S. Murphy,[51] G. Natterer,[51] F. Petrolo,[51] L. Periale,[51] A. Rubbia,[51,*] F. Sergiampietri,[51] and T. Viant[51]

[1]III. Physikalisches Institut, RWTH Aachen, Aachen, Germany
[2]Middle East Technical University (METU), Ankara, Turkey
[3]Ankara University, Ankara, Turkey
[4]LAPP, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
[5]Institute of Nuclear Technology-Radiation Protection, National Centre for Scientific Research "Demokritos", Athens, Greece
[6]INFN and Dipartimento interateneo di Fisica di Bari, Bari, Italy
[7]University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics (LHEP), Bern, Switzerland
[8]Faculty of Physics, University of Bucharest, Bucharest, Romania
[9]INFN Sezione di Cagliari, Cagliari, Italy
[10]INFN Sezione di Cagliari and Università di Cagliari, Cagliari, Italy
[11]University of Cambridge, Cambridge, United Kingdom
[12]Universita' dell'Insubria, sede di Como/ INFN Milano Bicocca, Como, Italy
[13]Alan Auld Engineering, Doncaster, United Kingdom
[14]Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
[15]Institute for Particle Physics Phenomenology, Durham University, United Kingdom
[16]Technodyne International Limited, Eastleigh, Hampshire, United Kingdom
[17]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[18]University of Geneva, Section de Physique, DPNC, Geneva, Switzerland
[19]University of Glasgow, Glasgow, United Kingdom
[20]University of Helsinki, Helsinki, Finland
[21]Rockplan Ltd., Helsinki, Finland
[22]Department of Physics, University of Jyväskylä, Finland
[23]Physics Department, Lancaster University, Lancaster, United Kingdom
[24]University of Liverpool, Department of Physics, Liverpool, United Kingdom
[25]Imperial College, London, United Kingdom
[26]Queen Mary University of London, School of Physics, London, United Kingdom
[27]Dept. of Physics and Astronomy, University College London, London, United Kingdom
[28]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia


Thank you!

backup

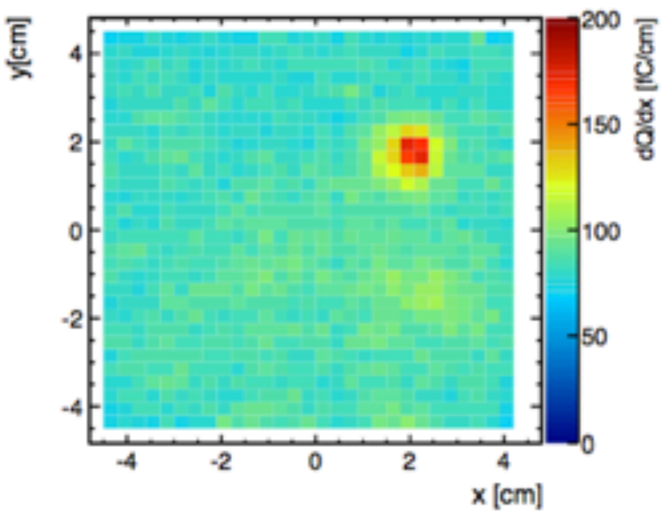
Timeline

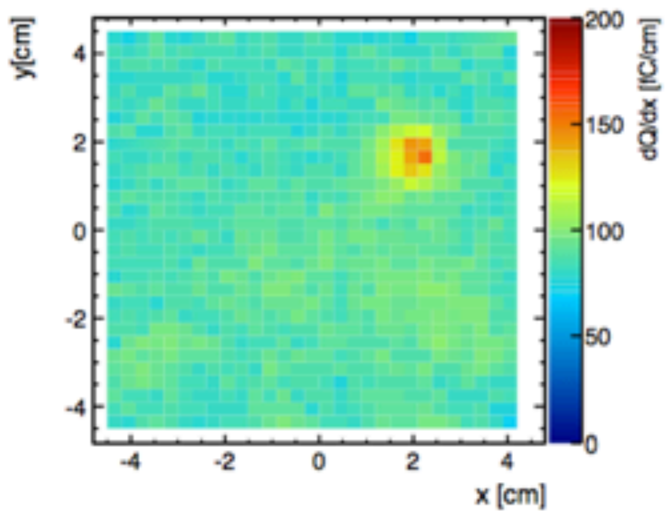
LAGUNA Design Study funded for site studies:	**2008-2011**
Categorize the sites and down-select:	**Sept. 2010**
Start of LAGUNA-LBNO	**2011**
Submission of LBNO EoI to CERN	**2012**
End of LAGUNA-LBNO DS: technical designs, layouts, liquids handling&storage, safety, ...	**2014**
Critical decision	**2015 ?**
Excavation-construction (incremental):	**2016-2021 ?**
Phase 1 LBL physics start:	**2023 ?**
Phase 2 incremental step implementation:	**>2025 ?**

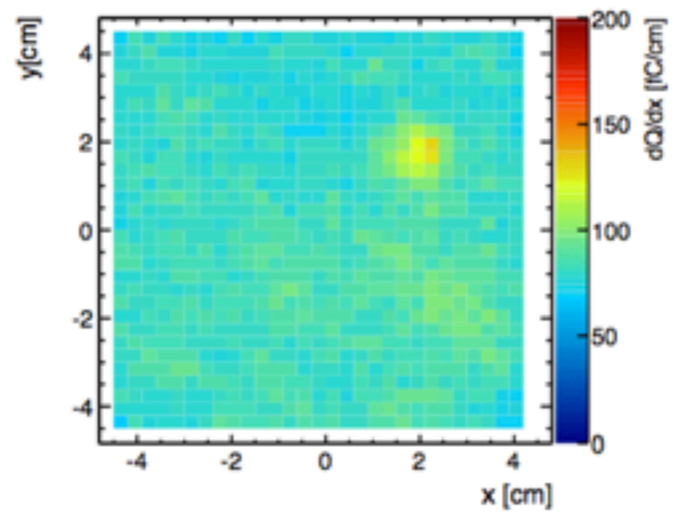
Local vs global gain evolution

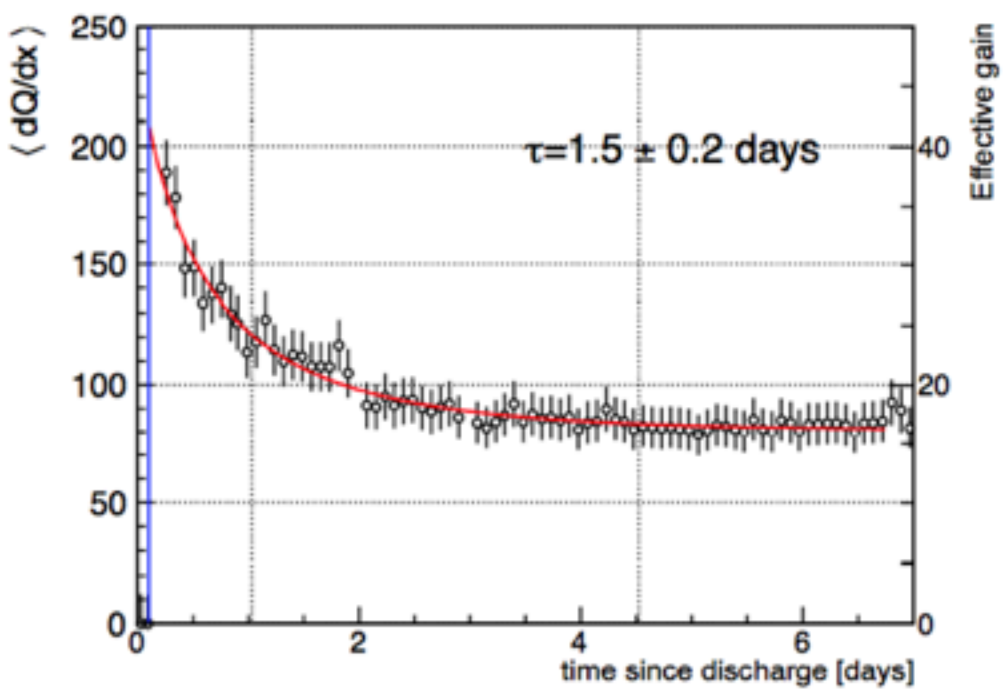
time after discharge

2hrs	4hrs	6hrs

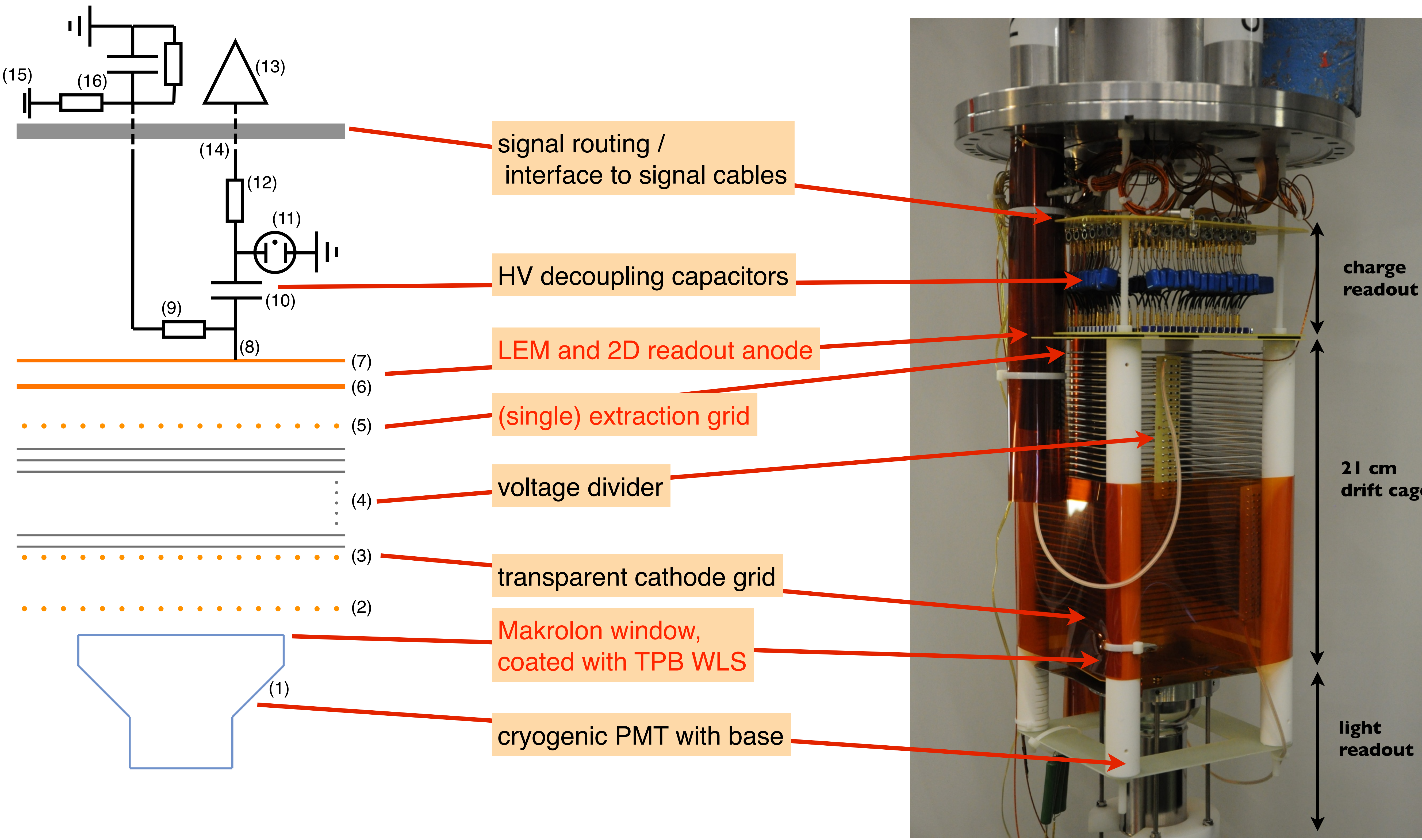








10x10x20 cm3 prototype: overview



Where we stand

✳**Proof of principle with 10x10 cm2 double phase Ar 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 40x80 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, available at http://dx.doi.org/10.1088/1748-0221/8/04/P04012

✳**10x10 cm2 double phase Ar LEM-TPC prototype: further R&D towards final, simplified charge readout for GLACIER:**

first results presented TPC-symposium, Paris Dec. 2011

✳**Future:**

1x1x3 m^3 prototype to test feasibility of large area readouts.

6x6x6 m^3 prototype to be operated at CERN NA in a charged particle beam.

Final goal:

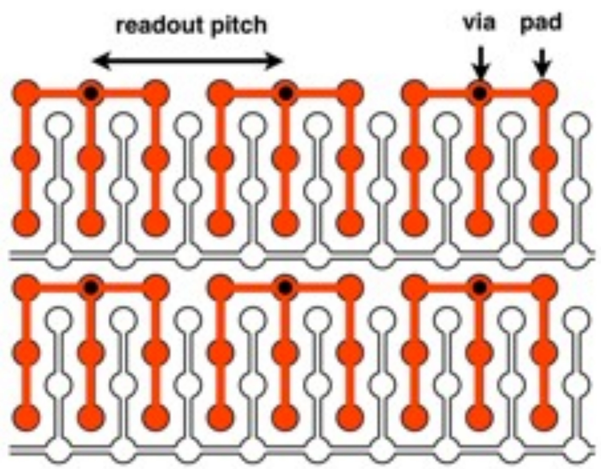
Giant LAr LEM TPC as far detector for a Long Baseline Neutrino Oscillation (LBNO) experiment (SPSC-EOI-007)

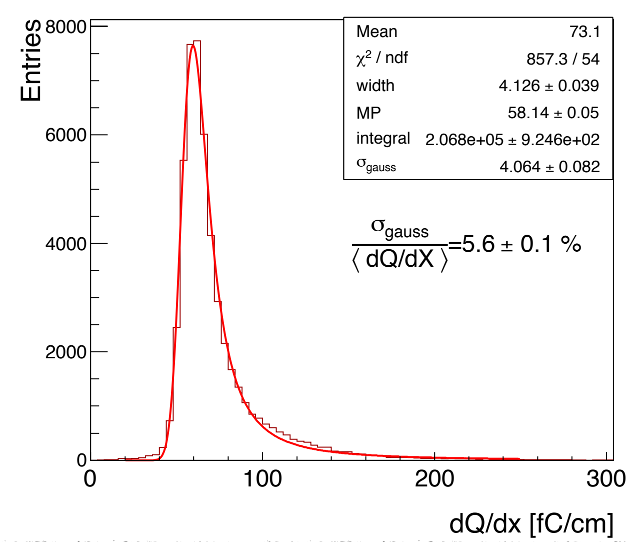
Various anode designs were tested

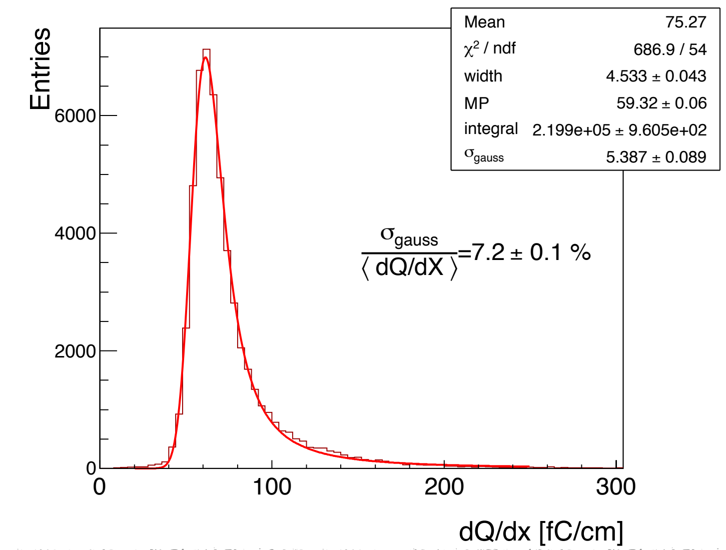
view 0 (red) | view 1 (white)

anode A

~200 pF/m

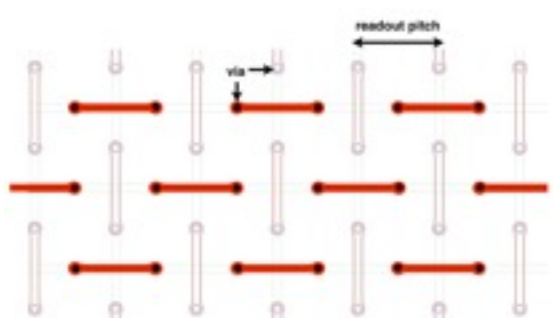


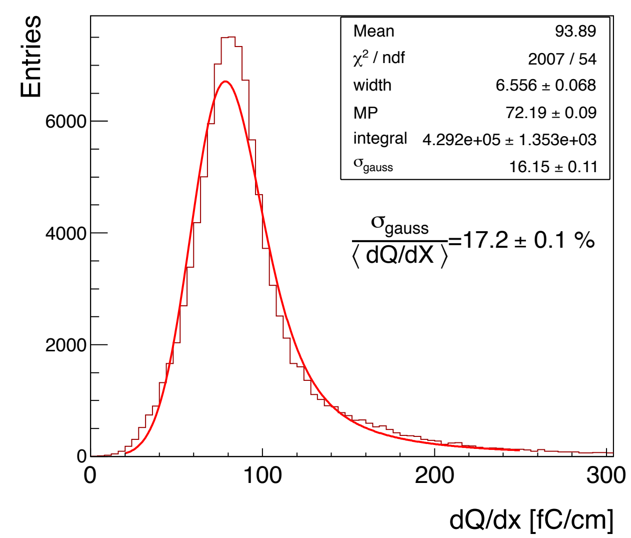


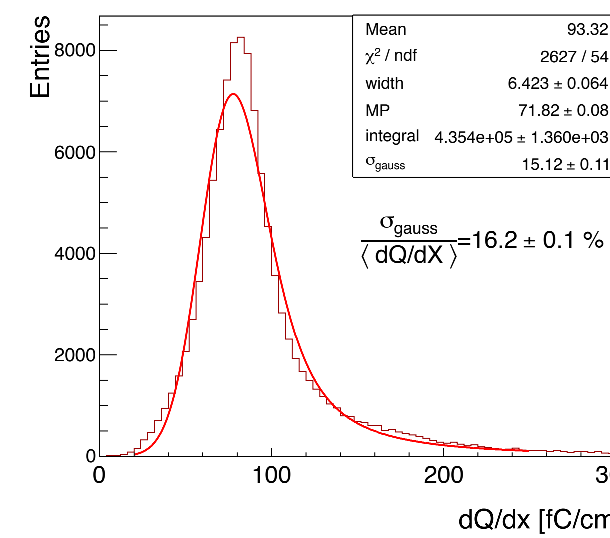


anode B

~100 pF/m

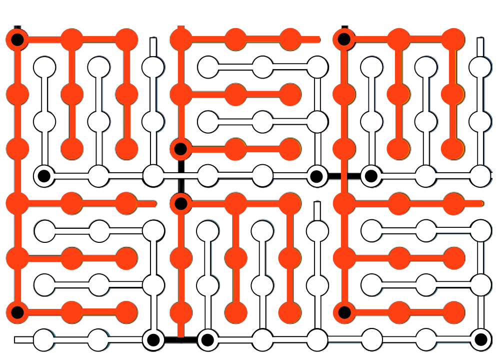


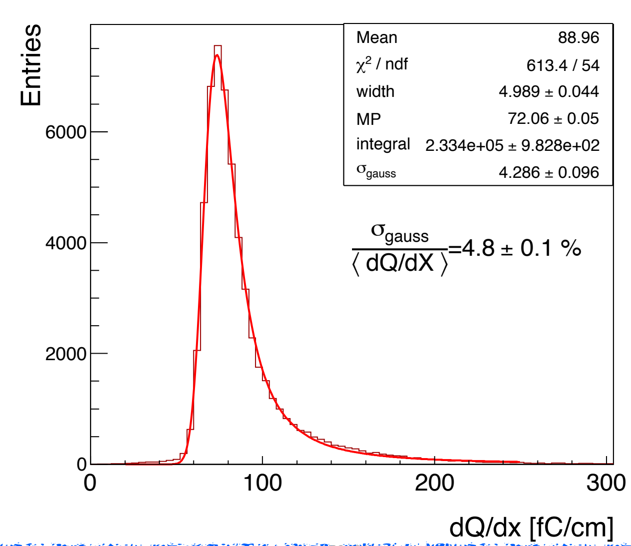


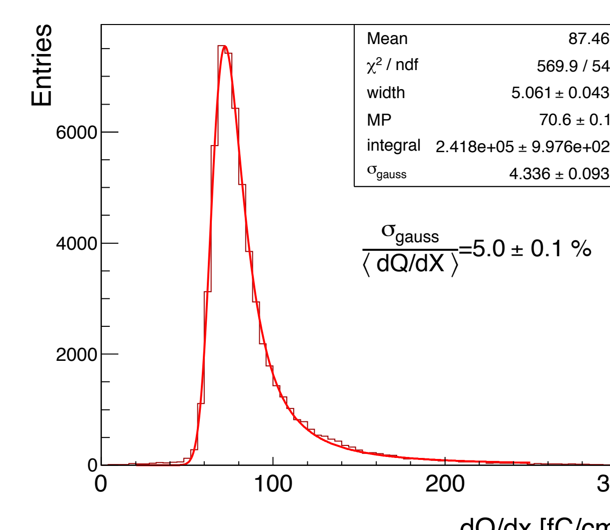


anode C

~200 pF/m

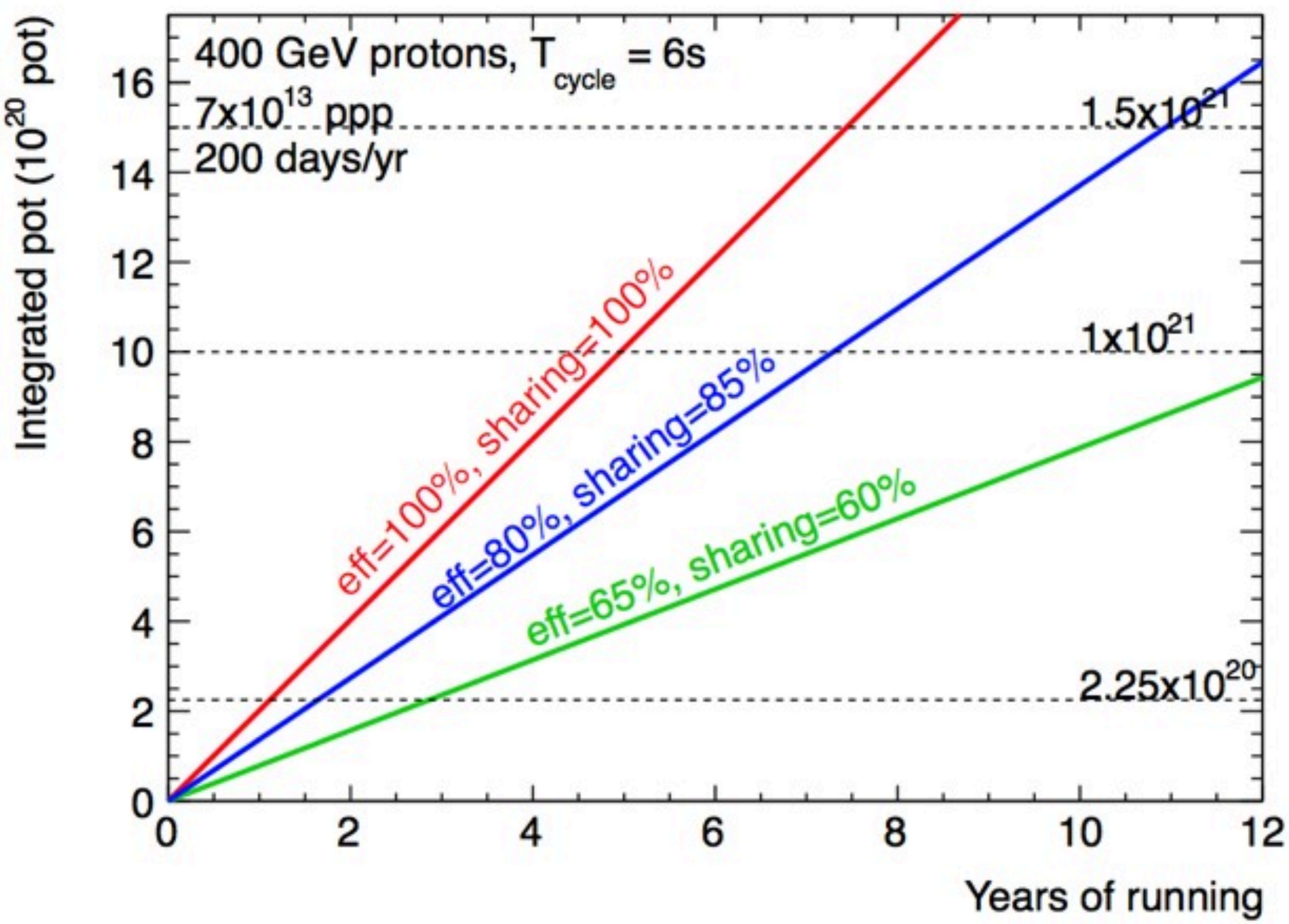






protons availability

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

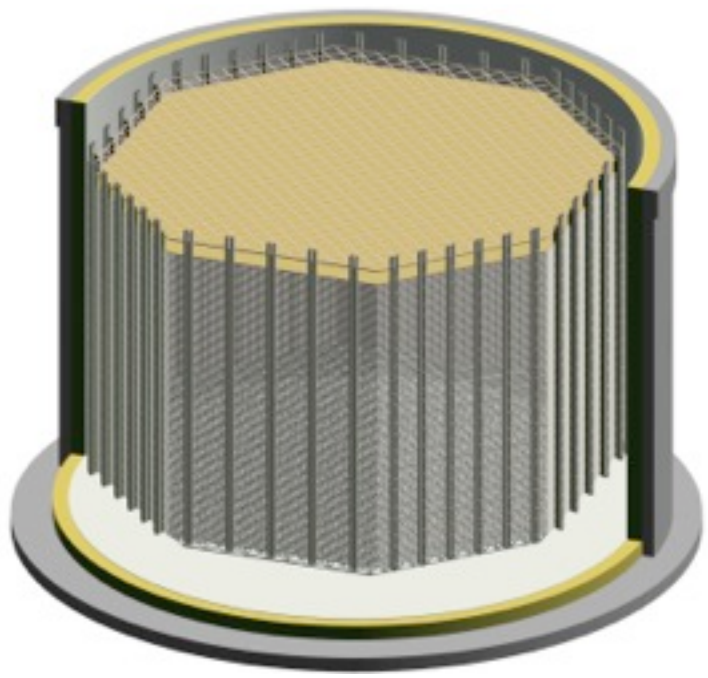


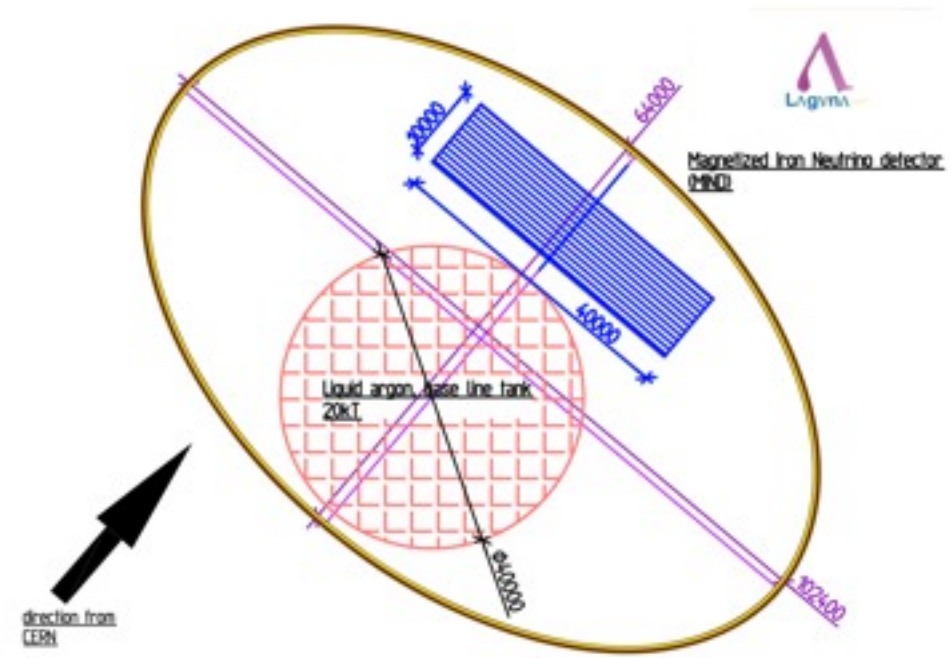
✓60% coverage
CP@90% C.L. maximal
CP @ 3 sigma

✓5 sigma MH

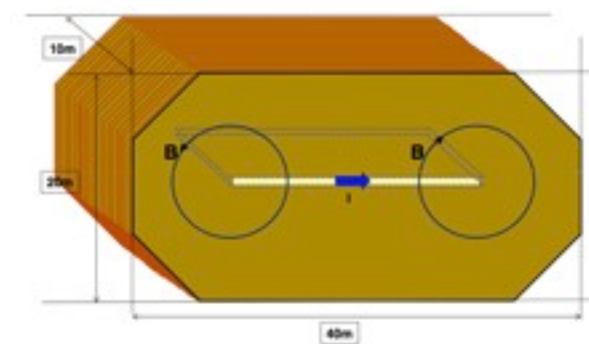
The Far underground detectors

GLACIER





MIND



20,50 kt Double Phase LAr LEM TPC

- Low energy threshold: exclusive final states
- Low systematic error
- Excellent energy resolution on a wide energy range
- Excellent π^0/e separation: necessary to suppress NC background

35 kt Magnetized Muon Detector

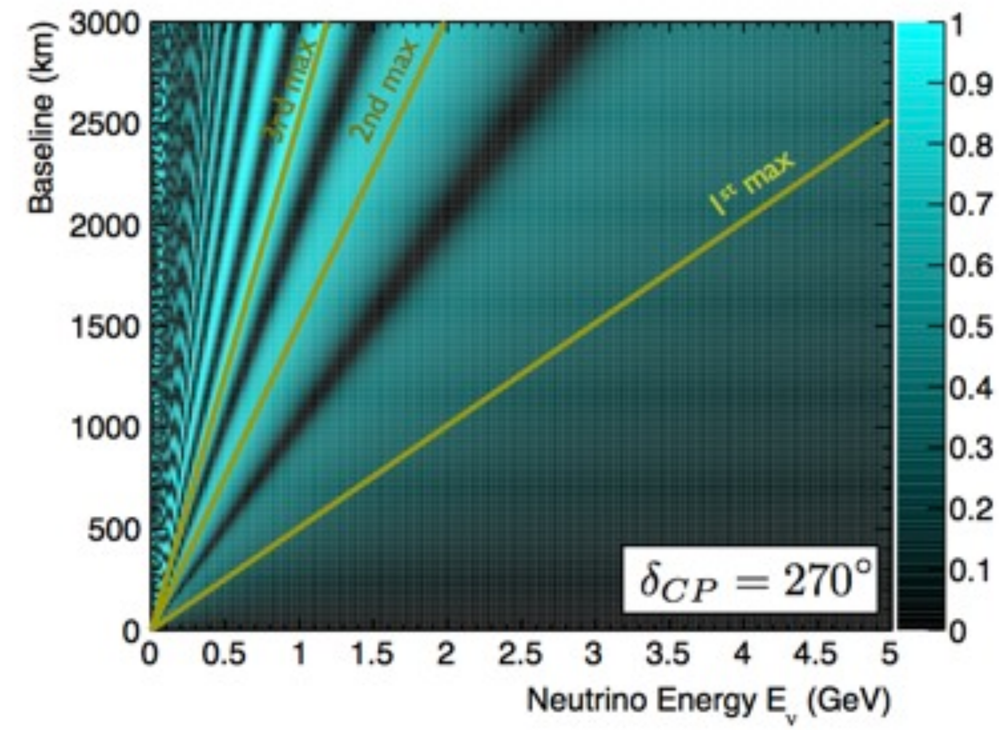
(3 cm Fe, 1 cm scint. bars, 1.5-2.5 T)

- Muon momentum and charge
- inclusive neutrino energy rec.

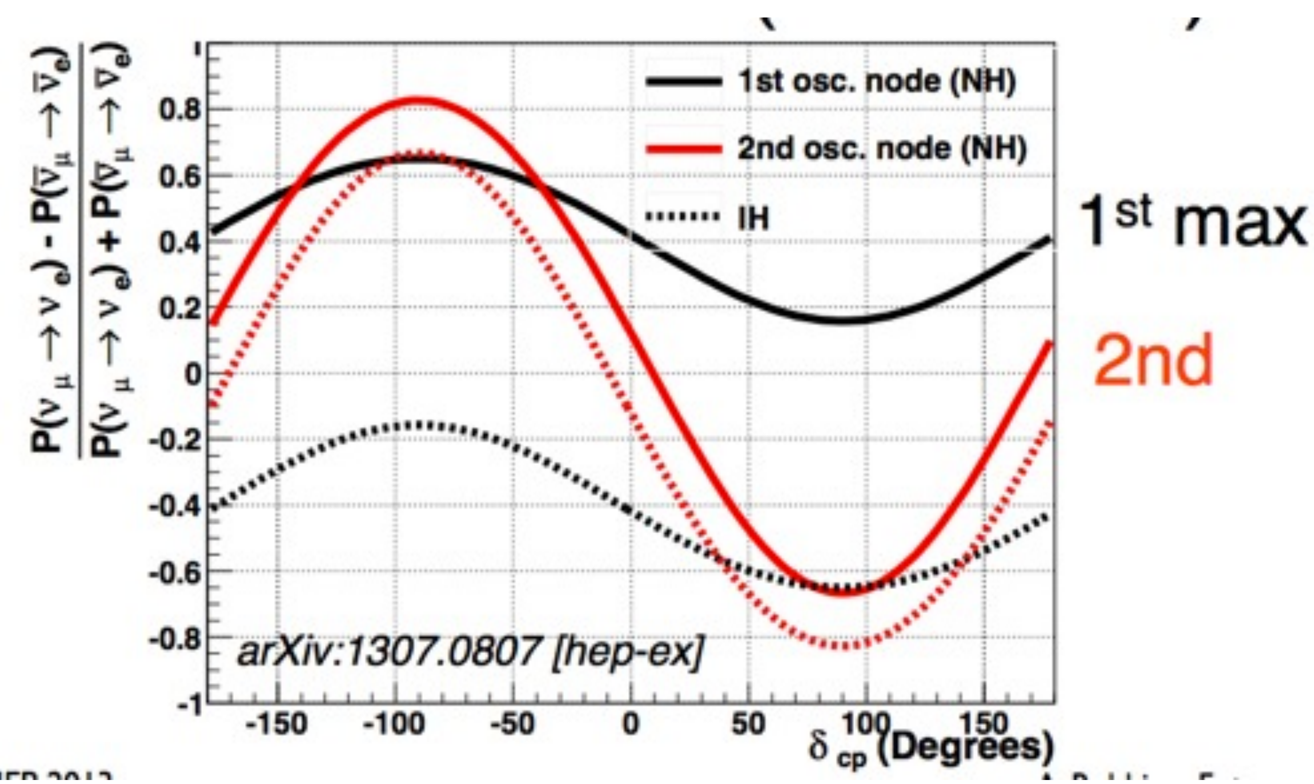
Long baseline

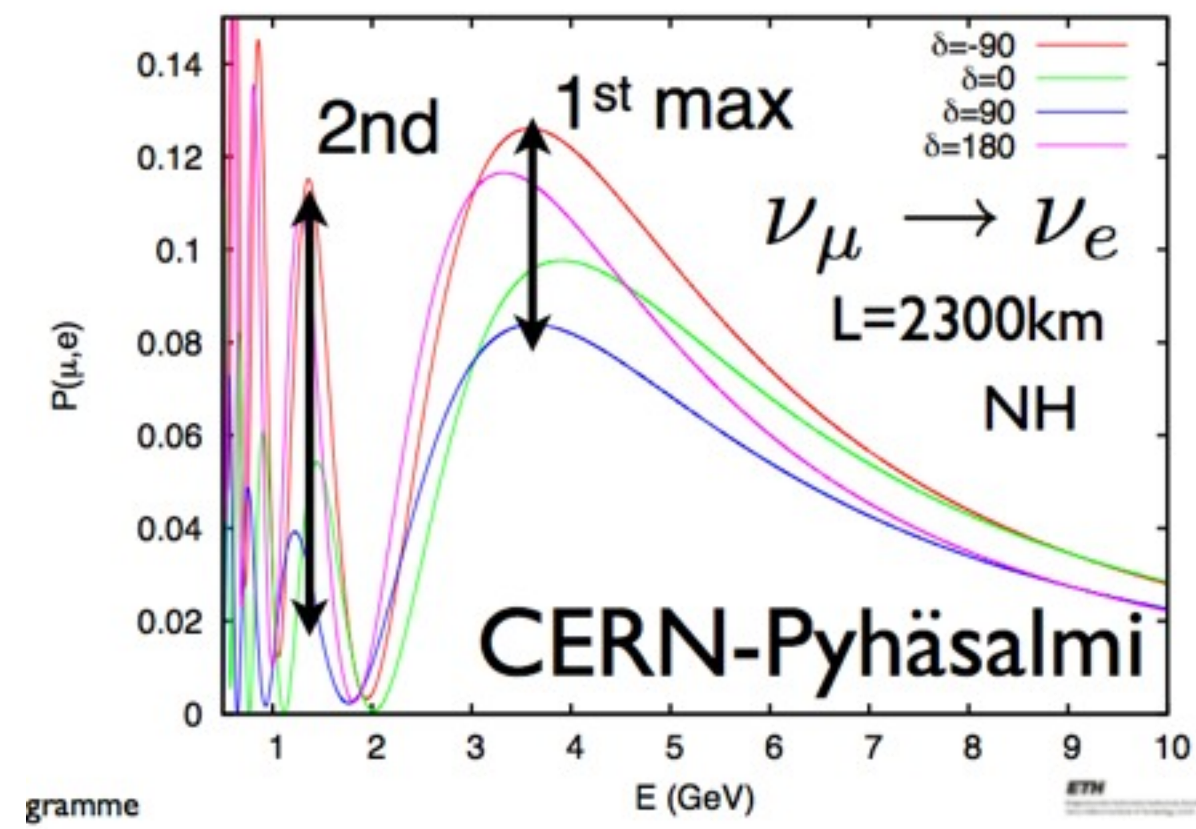
$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2 s_{\delta} c_{12} s_{12}}{s_{13}} \cot\theta_{23} \frac{\delta m^2_{21} L}{2E}$$

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



FNAL->homestake (1300 km)





ETH

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:

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

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

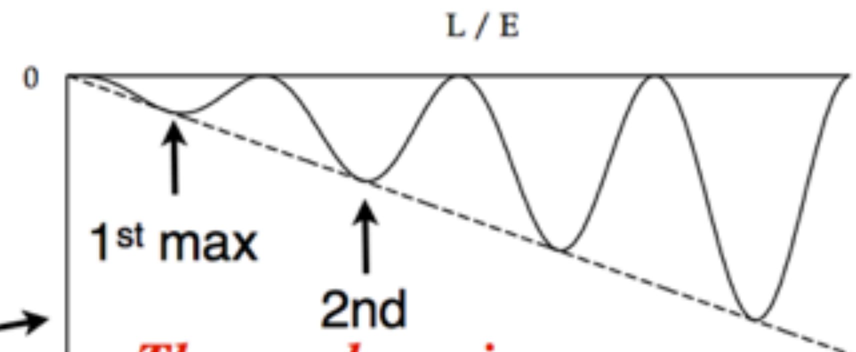
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

Matter terms

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

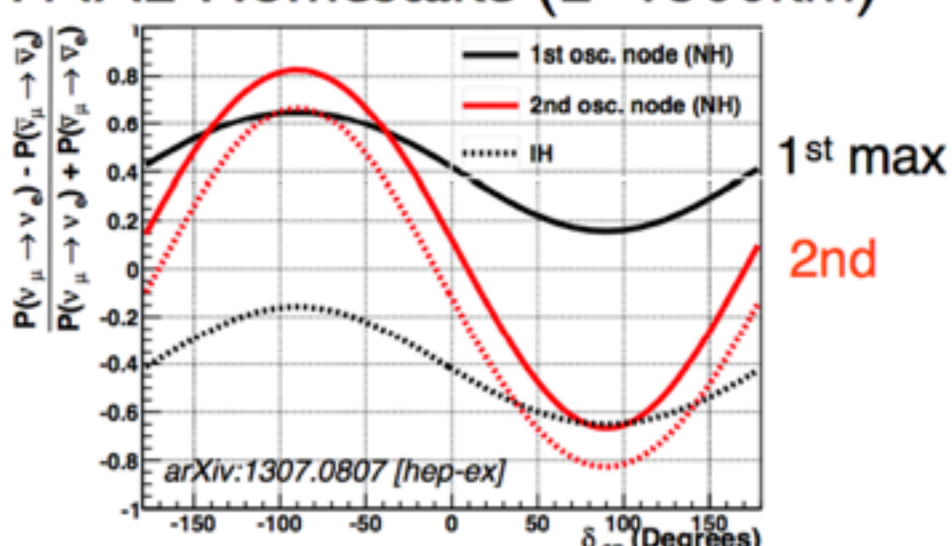
Pure CP-term

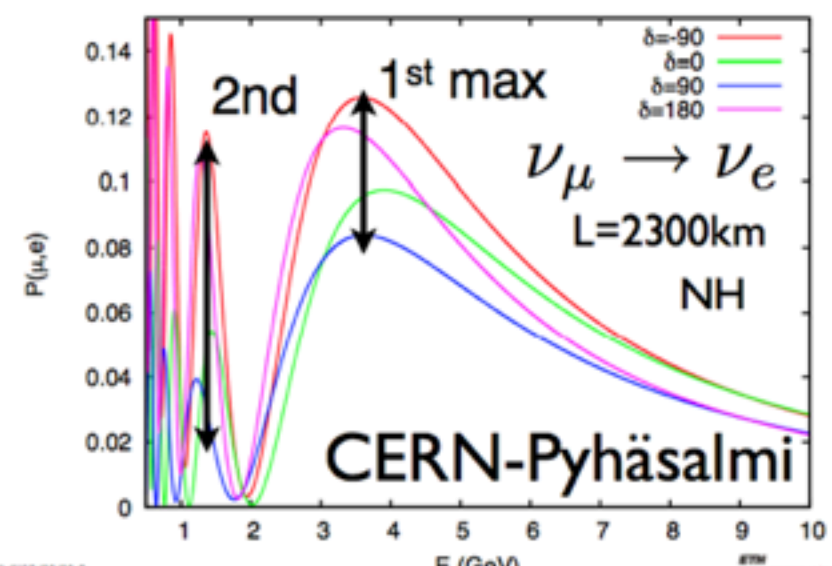
$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}$$



The envelope increases linearly with L/E

FNAL-Homestake (L=1300km)



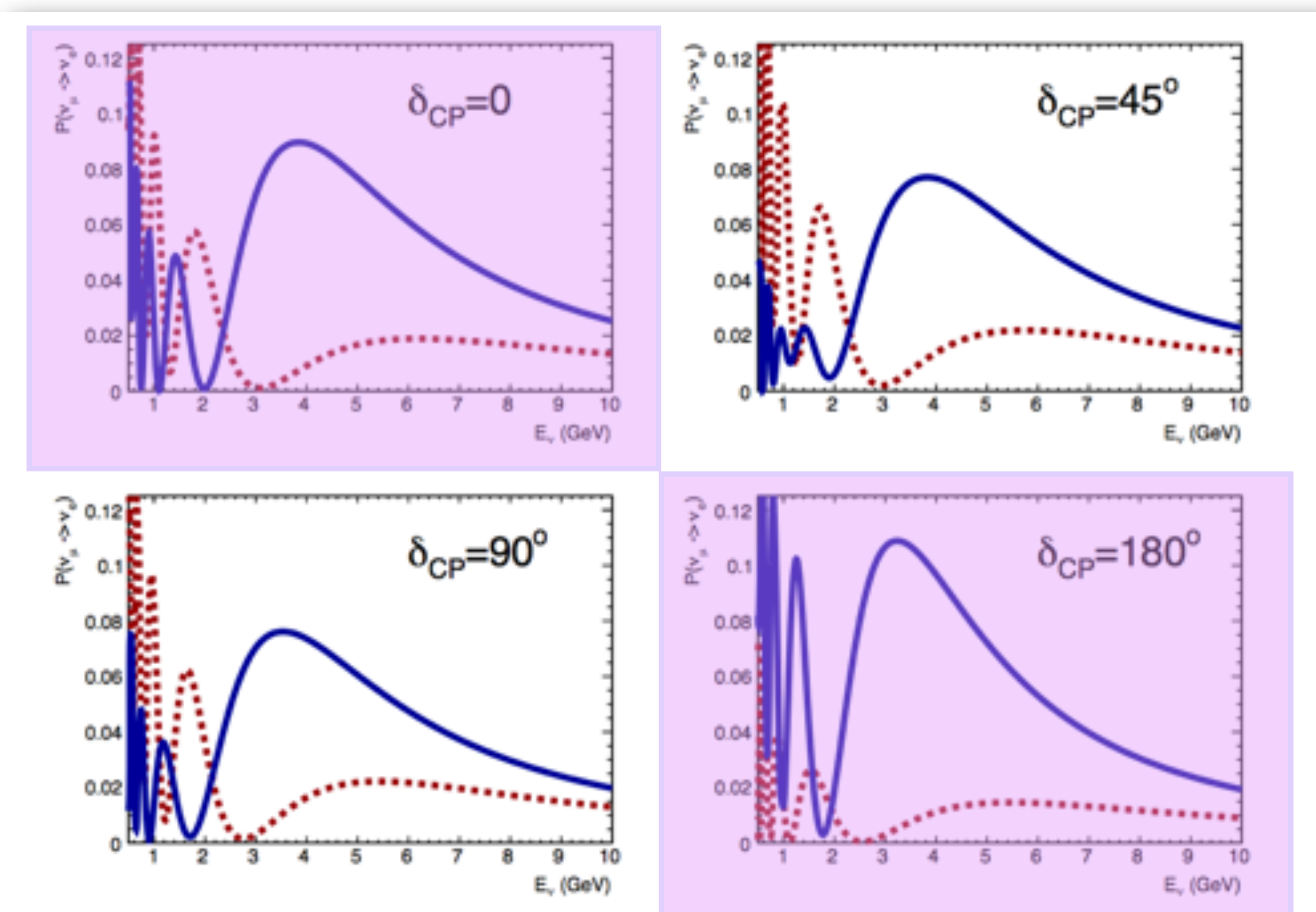


EPS-HEP 2013 A. Rubbia – Future neutrino programme

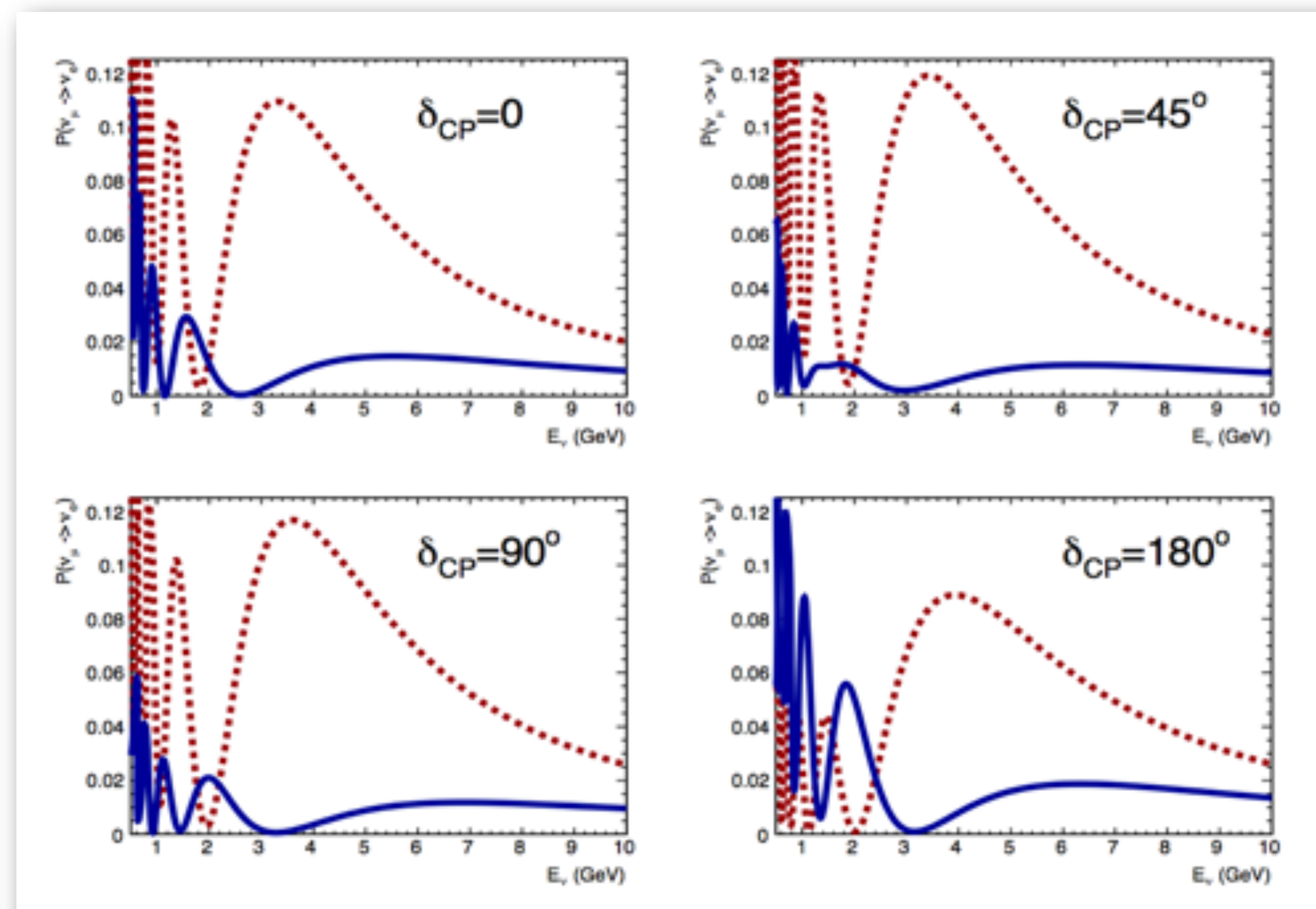
Long baseline

-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

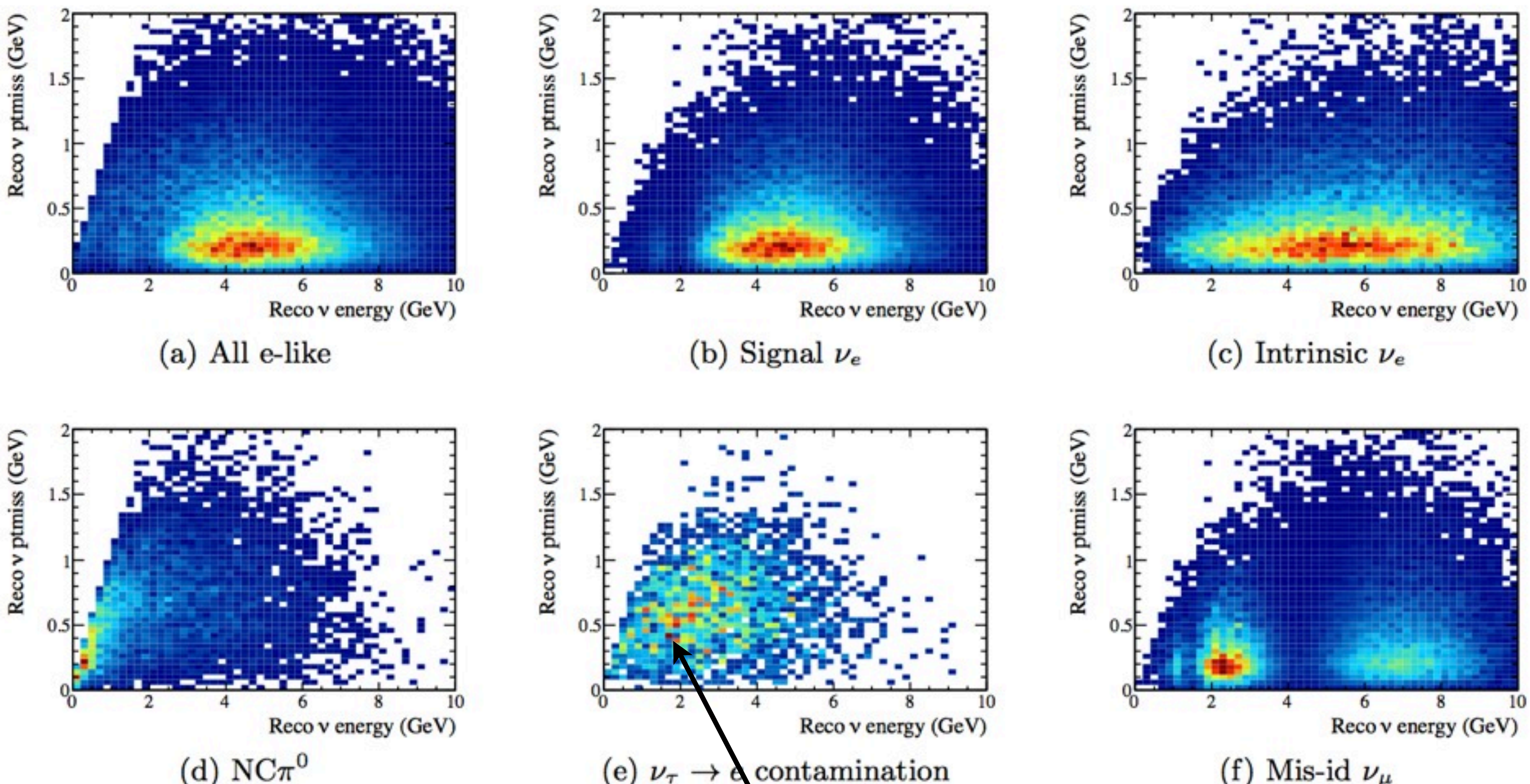


Rates

Beam	ν_μ unosc. CC	ν_μ osc. CC	ν_e beam CC	ν_μ NC	$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_e$ CC $\delta_{CP} = -\pi/2$,	0,	$\pi/2$
LBNO: 2300 km, NH 400 GeV, 750 kW 1.5×10^{20} POT/year								
50kt years ν	4128	1086	26	1416	258	295	241	194
50kt years $\bar{\nu}$	1538	396	6	650	117	21	32	35
LBNO: 2300 km, IH 400 GeV, 750 kW 1.5×10^{20} POT/year								
50kt years ν	4128	1022	26	1416	286	85	52	38
50kt years $\bar{\nu}$	1538	396	6	650	119	74	92	107
LBNO: 2300, NH km 50 GeV, 2 MW 3.0×10^{21} POT/year								
50kt years ν	10317	2713	65	3538	646	737	602	486
50kt years $\bar{\nu}$	3981	991	15	1628	298	53	78	87
LBNO: 2300 km, IH 50 GeV, 2 MW 3.0×10^{21} POT/year								
50kt years ν	10317	2553	65	3538	714	212	131	95
50kt years $\bar{\nu}$	3981	991	15	1628	298	185	230	268
LBNE low energy beam 80 GeV, 700 kW 9×10^{20} POT/year								
50 kt-years ν	7421	2531	63	1953	91	353	280	204
50 kt-years $\bar{\nu}$	2478	812	20	876	28	30	50	62

e-like events and backgrounds

dCP=0, NH



(a) All e-like (b) Signal ν_e (c) Intrinsic ν_e

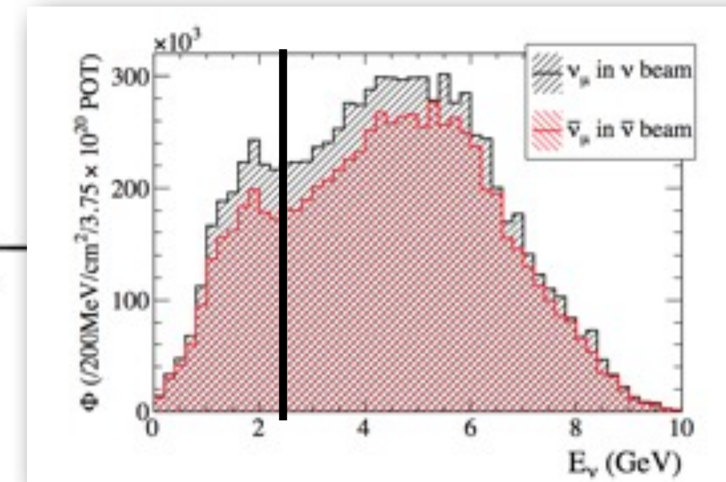
(d) NCπ^0 (e) $\nu_\tau \to e$ contamination (f) Mis-id ν_μ

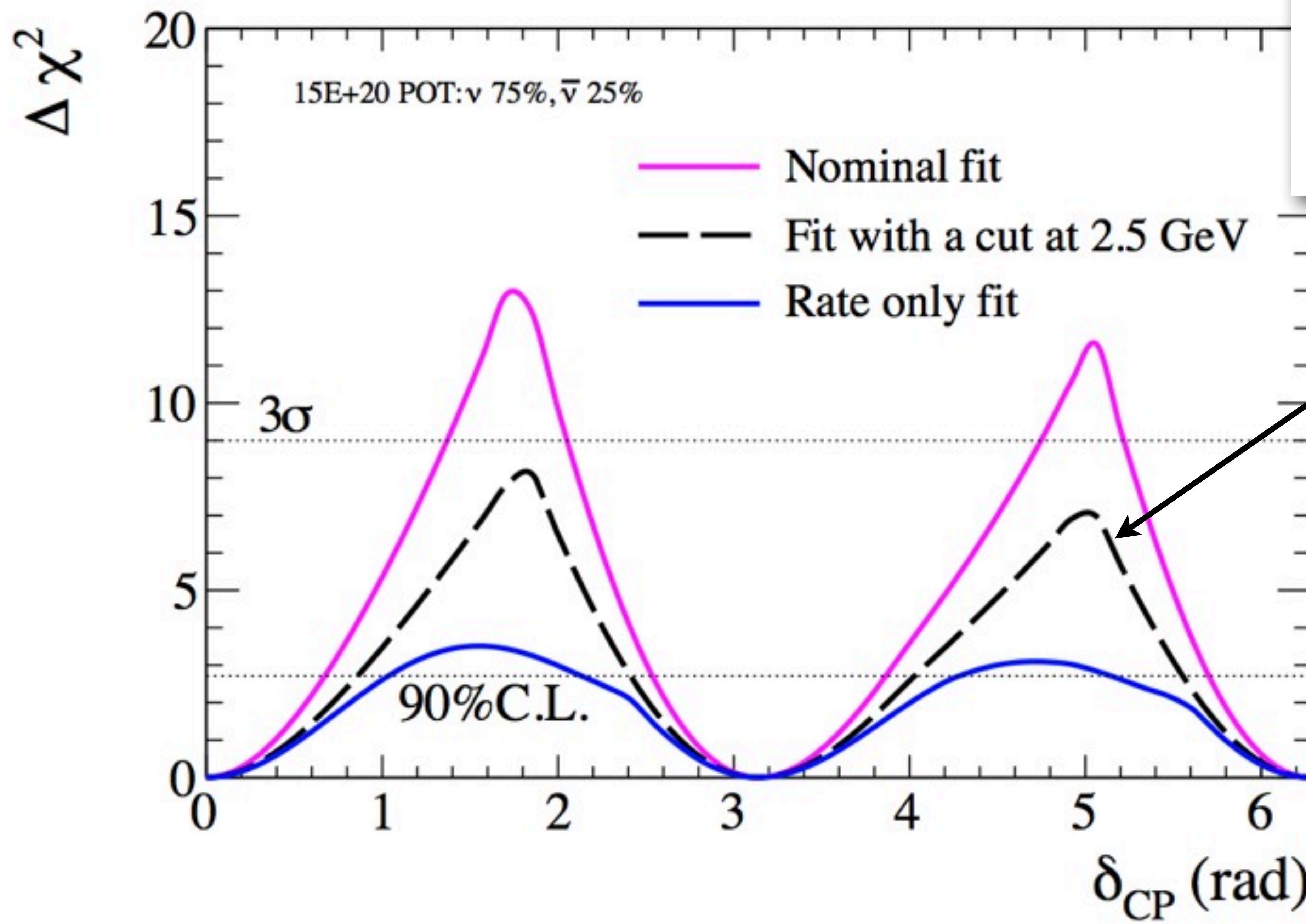
larger pt_miss because fo two v in final state

importance of second maximum

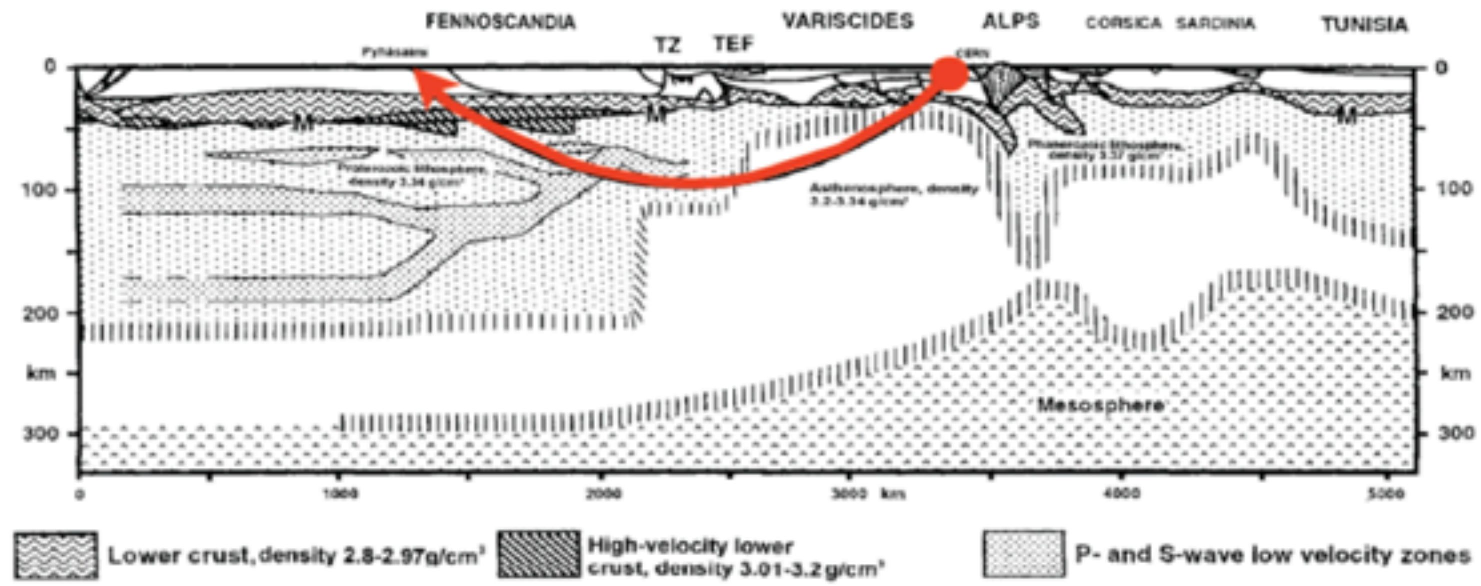
Use all spectral information: Rate & Shape for energy range 1st - 2nd max

w/ 2nd maximum

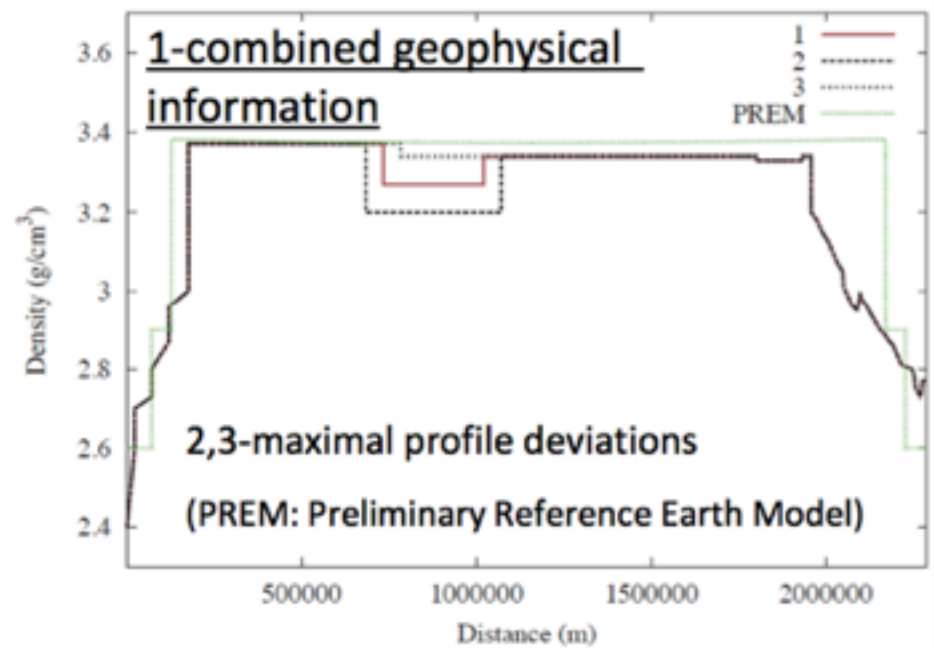




ETH



Earth Density Profile
Measured by several Geophysical projects
2.4<ρ<3.4 g/cm³

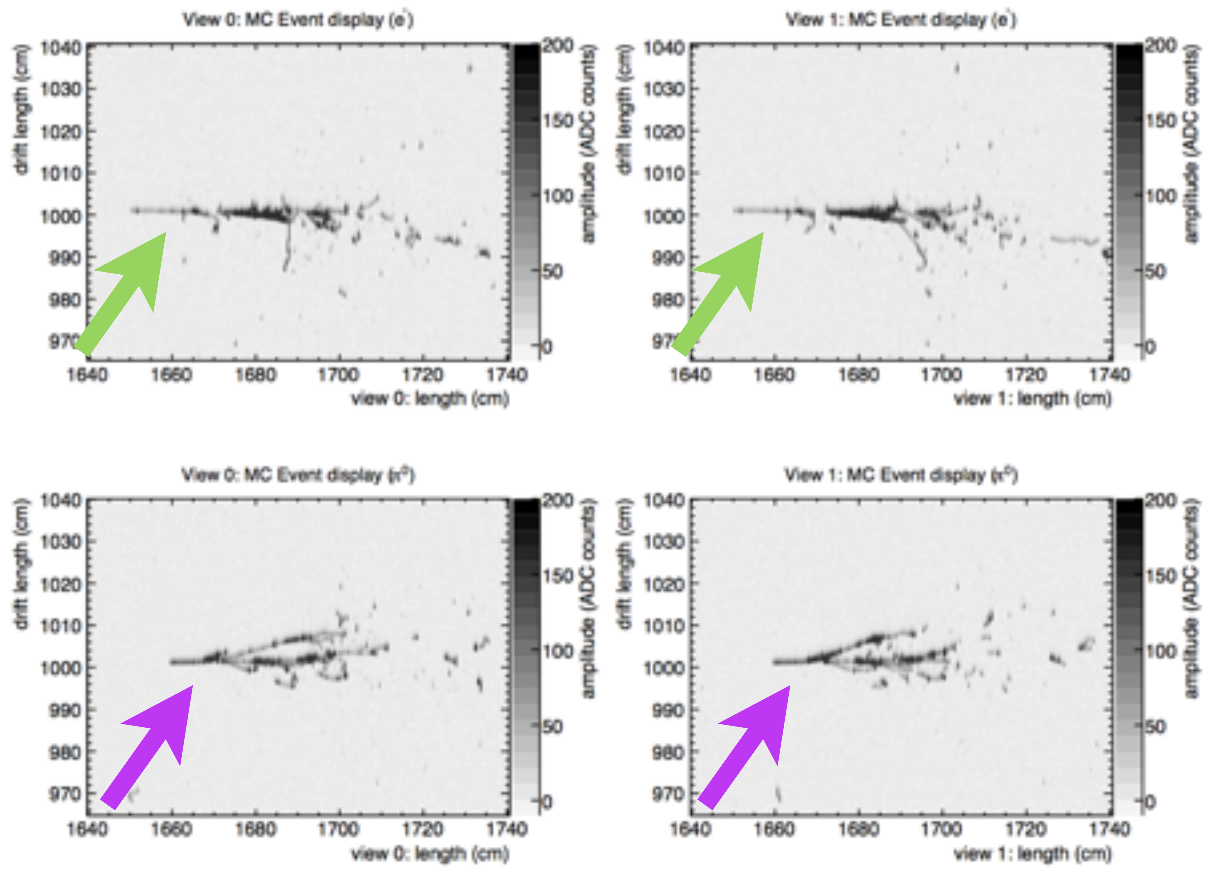


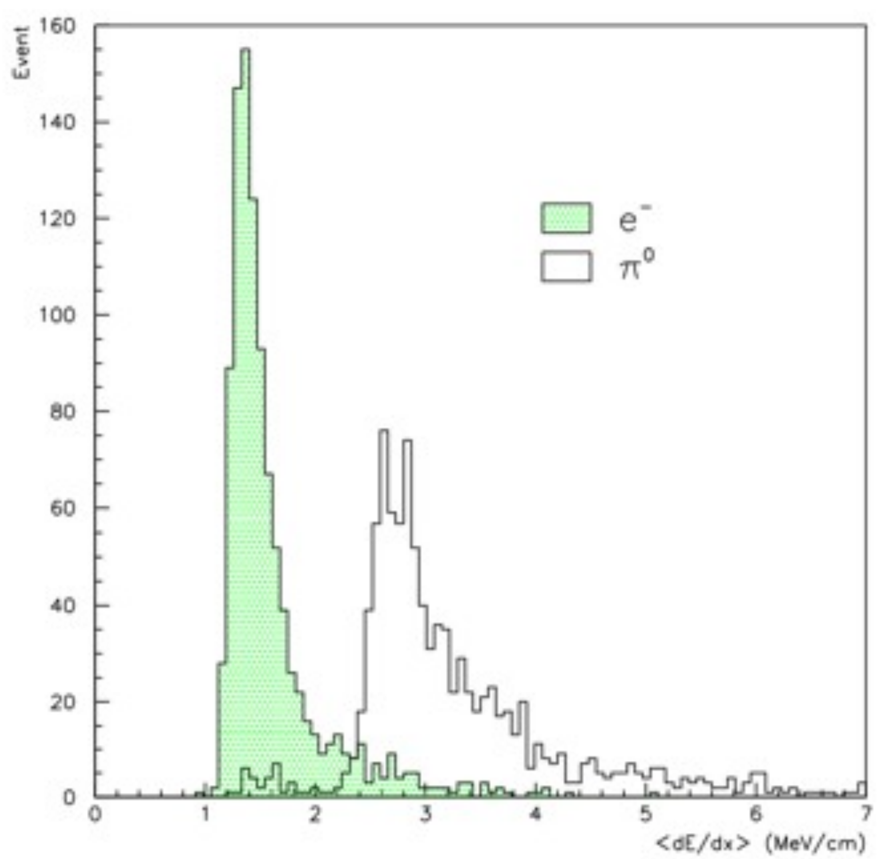
- ❑ The ν line of flight is comprised in a geological section extensively studied in the past
  - ➢ mean density variations known with high accuracy
- ❑ Local density variations are estimated to be of about 5%
  - ➢ total effect on oscillation probability averages out
  - ➢ conservative approach is to assume ±4% syst. error (global mean shift)

NC π0 from CCve

e-

π0

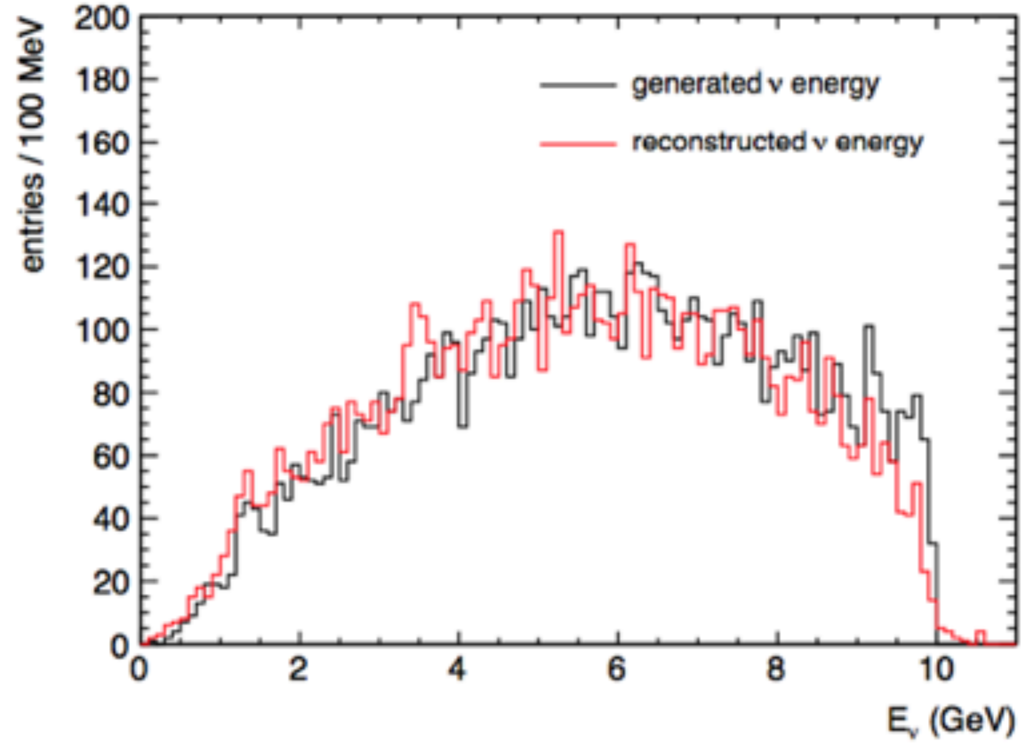


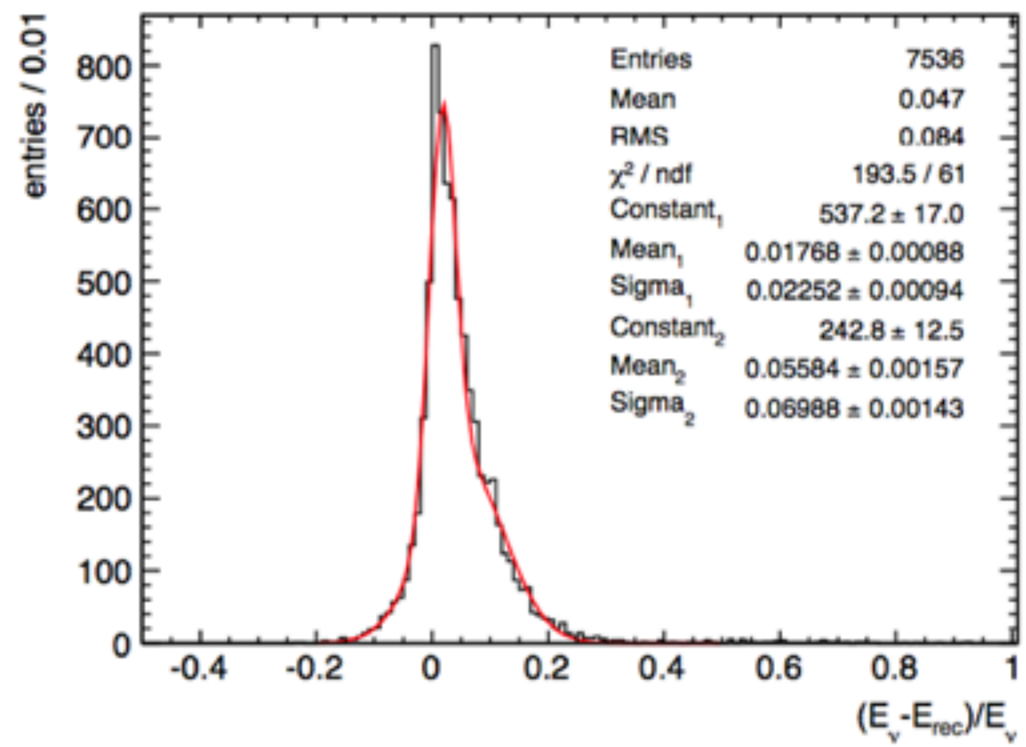


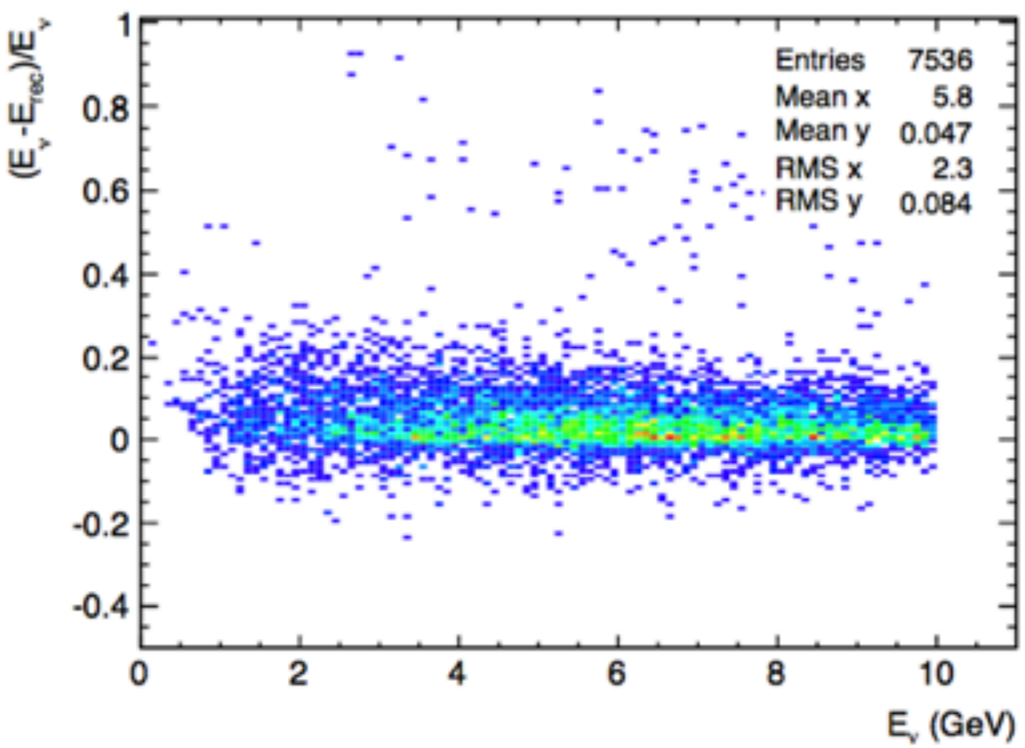
dE/dx of first 30 reconstructed hits

Energy (GeV)	π^0 contamination (%)	$< dE/dx >_{cut}$ (MeV/cm)
0.25	6.5	2.13
0.5	5.5	2.19
1	3.7	2.21
2	2.7	2.10

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%**

Stability of the gain

Gain in the LEM depends on:

- density of the gas (=pressure, temperature)
- the electric field across the LEM

Well described by the function:

$$G(t) = trans. \times e^{x \cdot \alpha(p,T,E)} \times \frac{1}{1 - e^{-t/\tau}}$$

with $\alpha(p,T,E) = \frac{Ap}{T} e^{-\frac{Bp}{E}}$