NEW TECHNOLOGIES FOR DISCOVERY

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

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University Center - 300 W. First Street Arlington, TX 76019

Liquid Argon TPC

André Rubbia (ETH Zürich)

Parallel Session: Noble Liquids

A tool for discoveries

- The **Liquid Argon Time Projection Chamber** is the successful marriage between the "gaseous TPC" and "the liquid argon calorimeter" to obtain a dense and very fine grained 3D tracking device (mm-scale resolution) with local dE/dx information and a homogenous full sampling calorimeter (e.g. $\approx 2\% X_0$ sampling rate for 3mm pitch). It can be operated in trigger-less mode, hence is continuously active.
- After many decades of pioneering R&D, the technology has matured into a **fundamental and necessary technique to address the particle physics challenges of the 21st century.** It has the potential to be the tool to discover new phenomena, such as:
  - **the convincing case for the existence of sterile neutrinos;**
  - **the discovery of CP-violation in the lepton sector;**
  - **the unambiguous observation of nucleon decay;**
  - **the direct detection of Dark Matter WIMPs-induced recoils or of the "neutrino floor";**
  - **the possible observation of unpredicted rare events.**

A tool for discoveries

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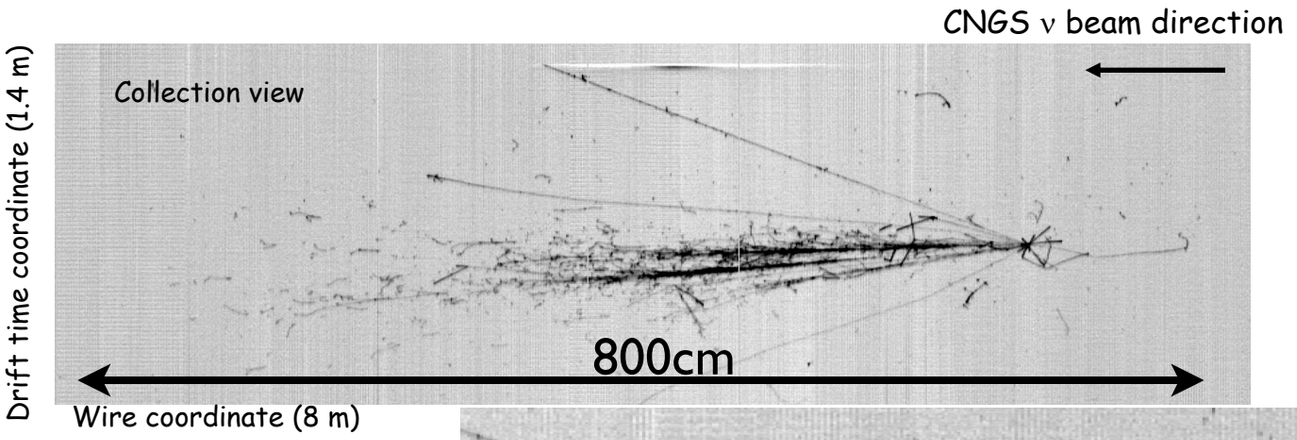
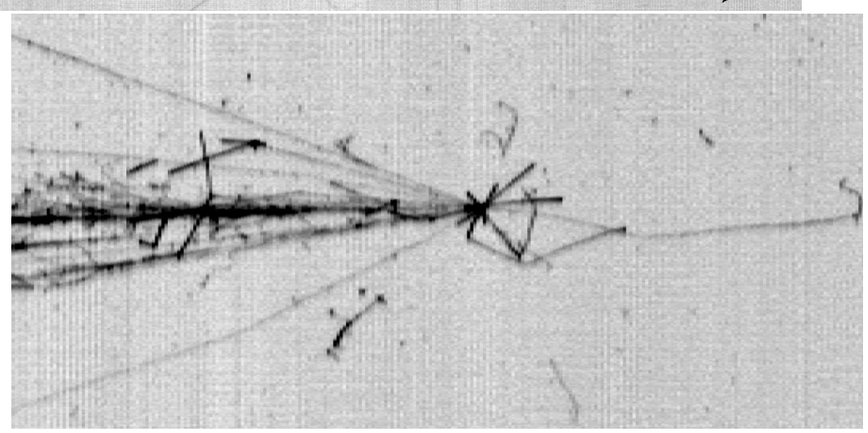
  - **possible observation of unpredicted rare events.**

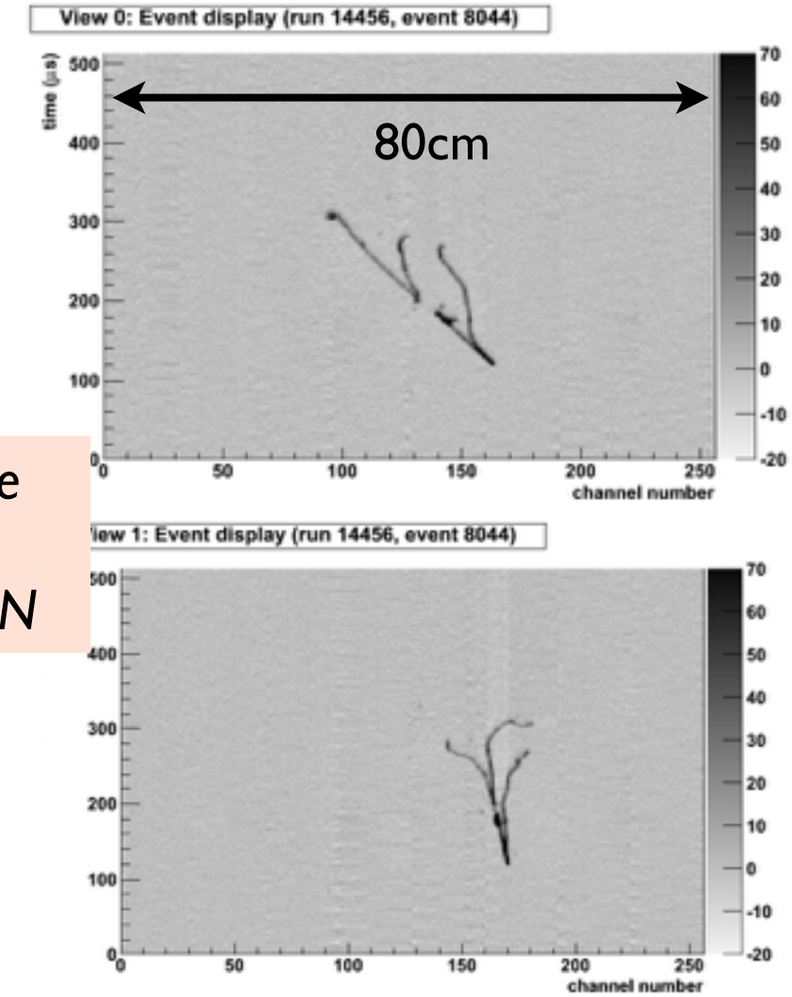
Any one of these would be a major discovery !!!!

The “electronic bubble chamber”

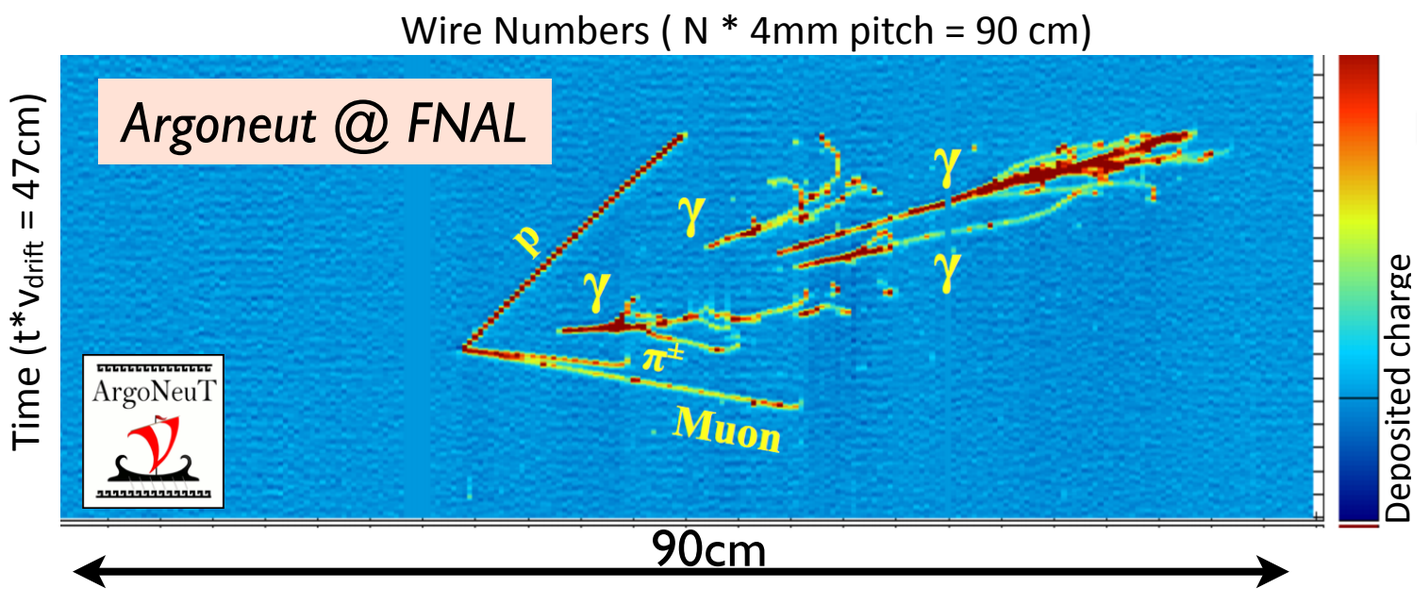




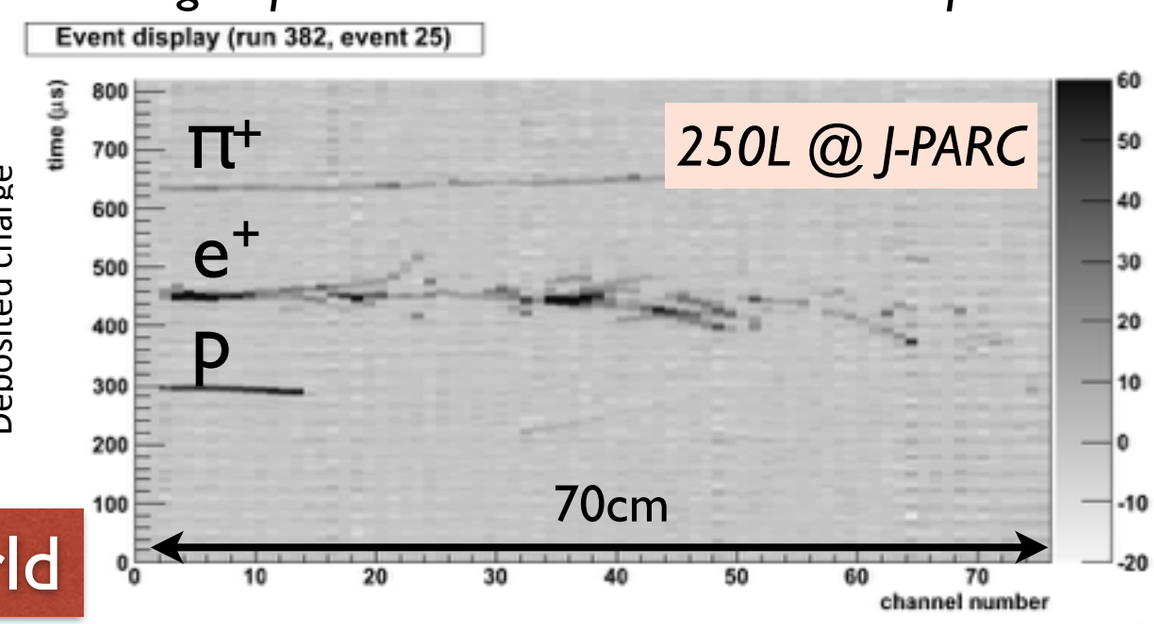
ICARUS T600 @ LNGS



Dual phase 250L @ ETHZ/CERN



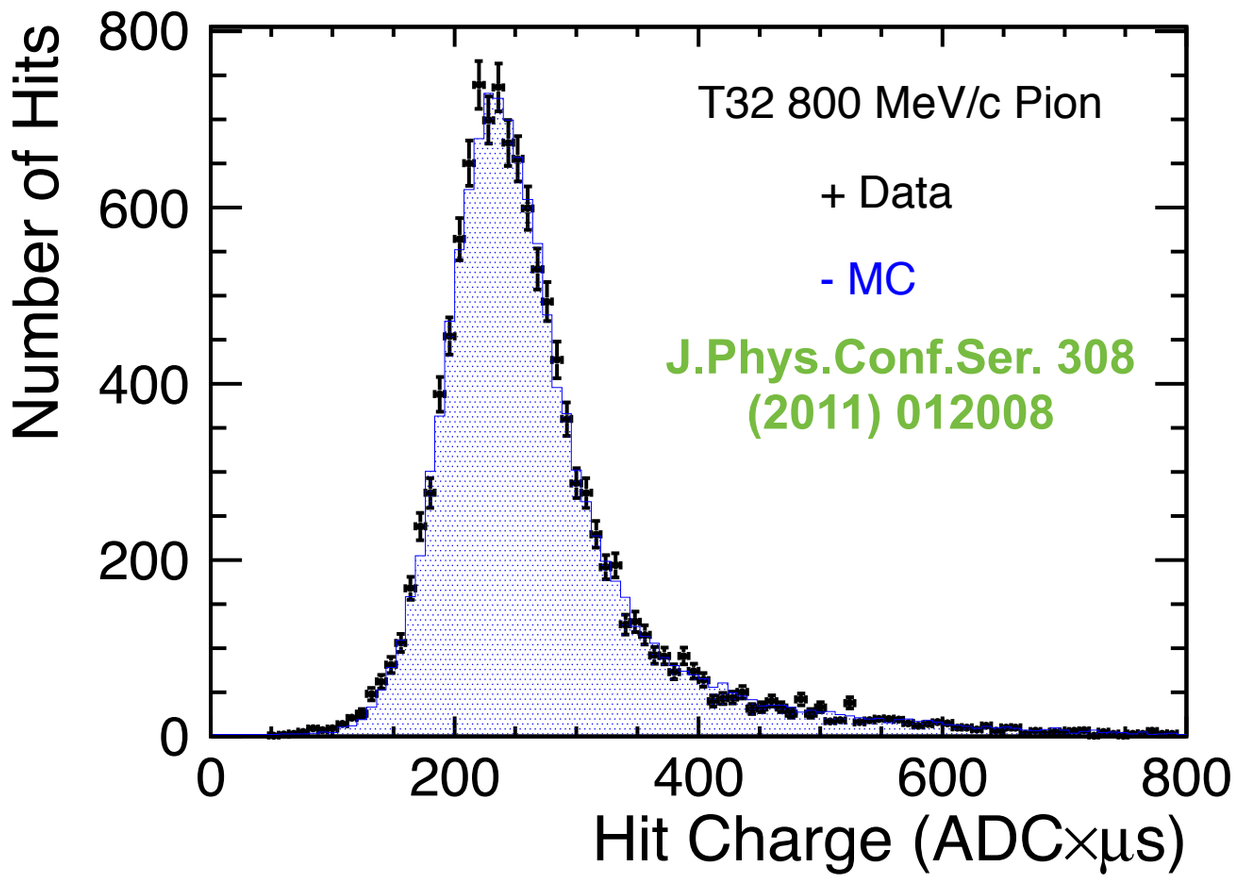
Charged particle beam ≈800 MeV/c exposure



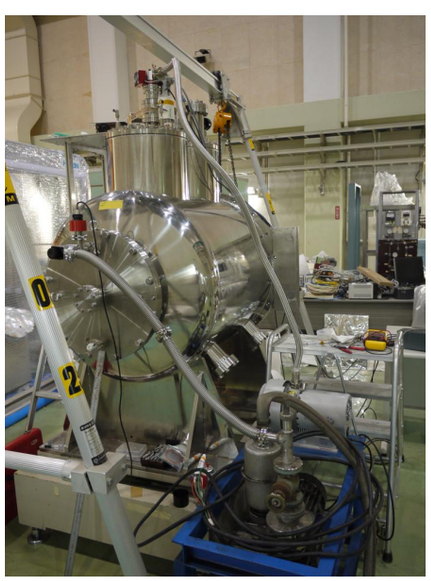
Basic features reproducible around the world

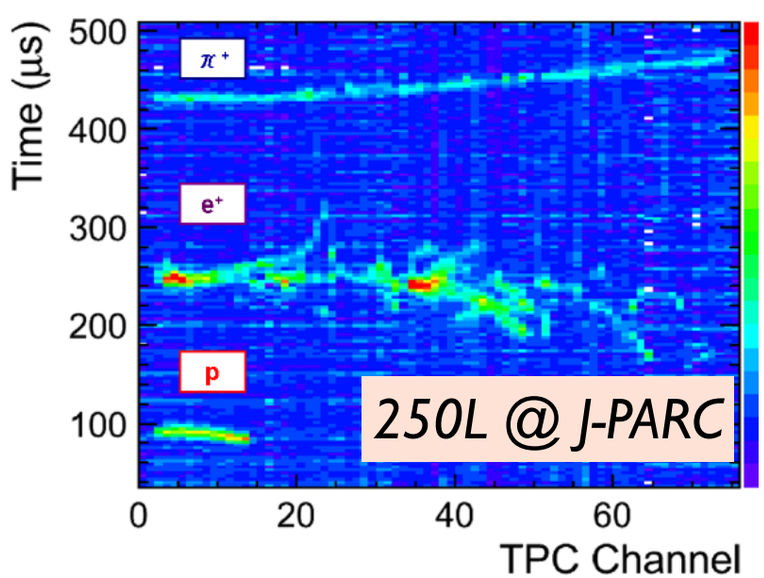
Tracking performance

JPARC T32 exposed to K1.1BR tagged beam



J-PARC T32 chamber (ETHZ-KEK-Iwate-Waseda)





Charge recombination

Data well described by:

Birks Law

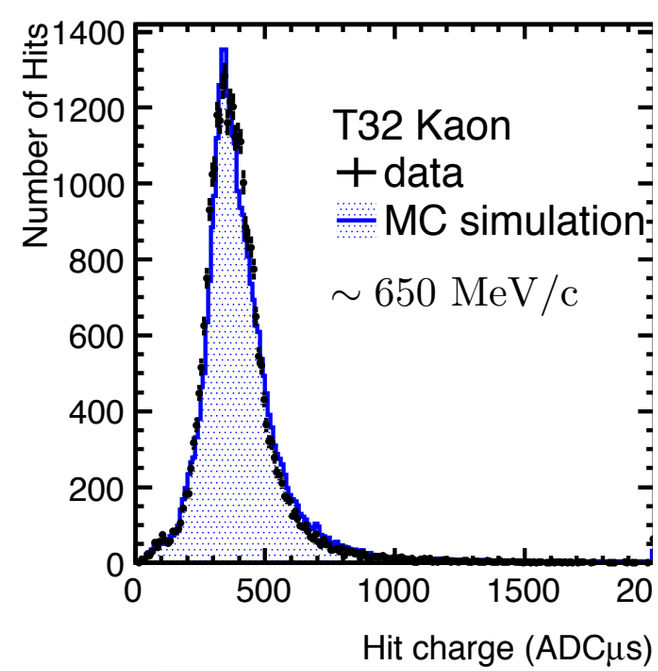
$$Q = A \frac{Q_0}{1+(k/\varepsilon)\times(dE/dx)\times(1/\rho)}$$

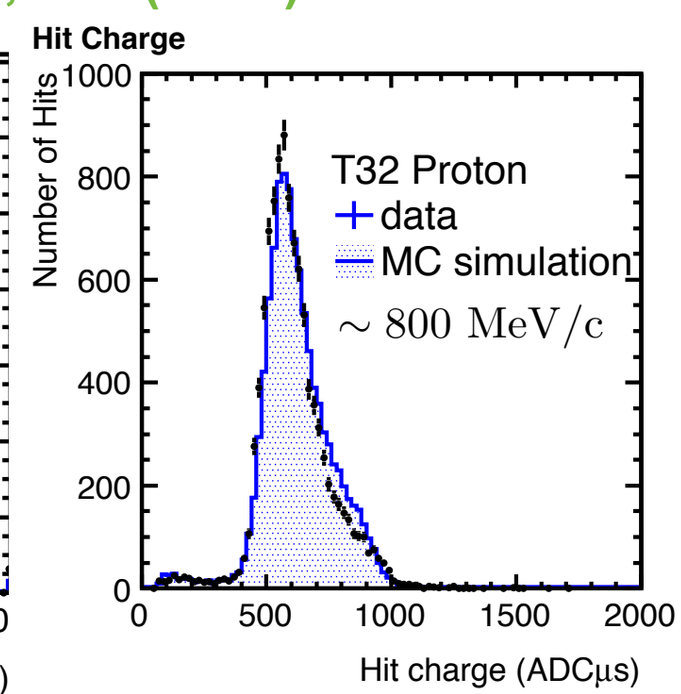
Raw charge (Q_0); Observable charge (Q)

$$A = 0.8$$

$$k = 0.0486\ \mathrm{kV/cm}\,\frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

NIM A 523, 275 (2004)



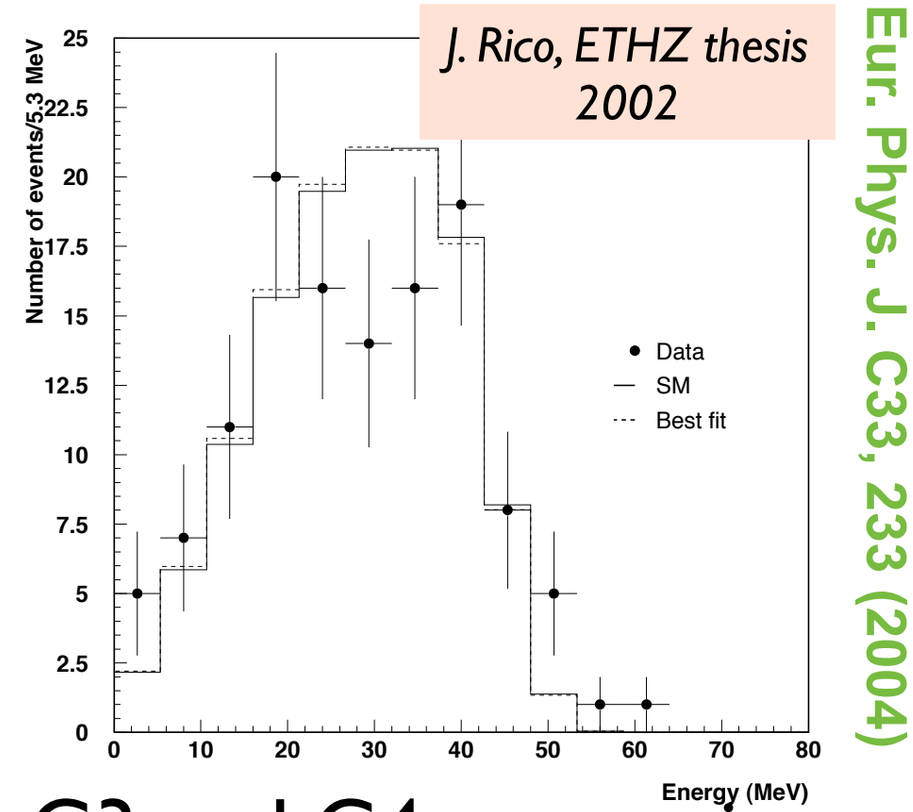


Good understanding of tracking

Calorimetric performance

Michel electrons form stopping muon decay sample

$$\frac{\sigma_e}{E} \simeq \frac{11\%}{\sqrt{E(\mathrm{MeV})}} \oplus 4\%$$



Eur. Phys. J. C33, 233 (2004)

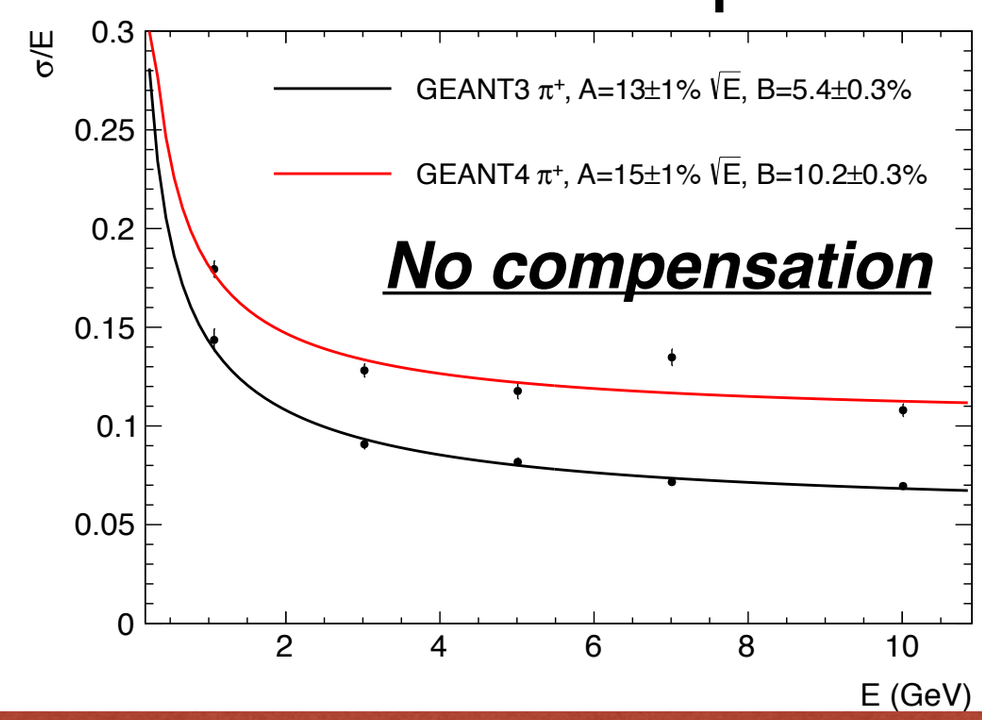
MC simulations at higher energies:

$$\frac{\sigma_{em}^{MC}}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus 1\%$$

$$\frac{\sigma_{had}^{MC}}{E} \simeq \frac{15\%}{\sqrt{E}} \oplus 10\%$$

needs to be confirmed by experimental data

G3 and G4 comparison

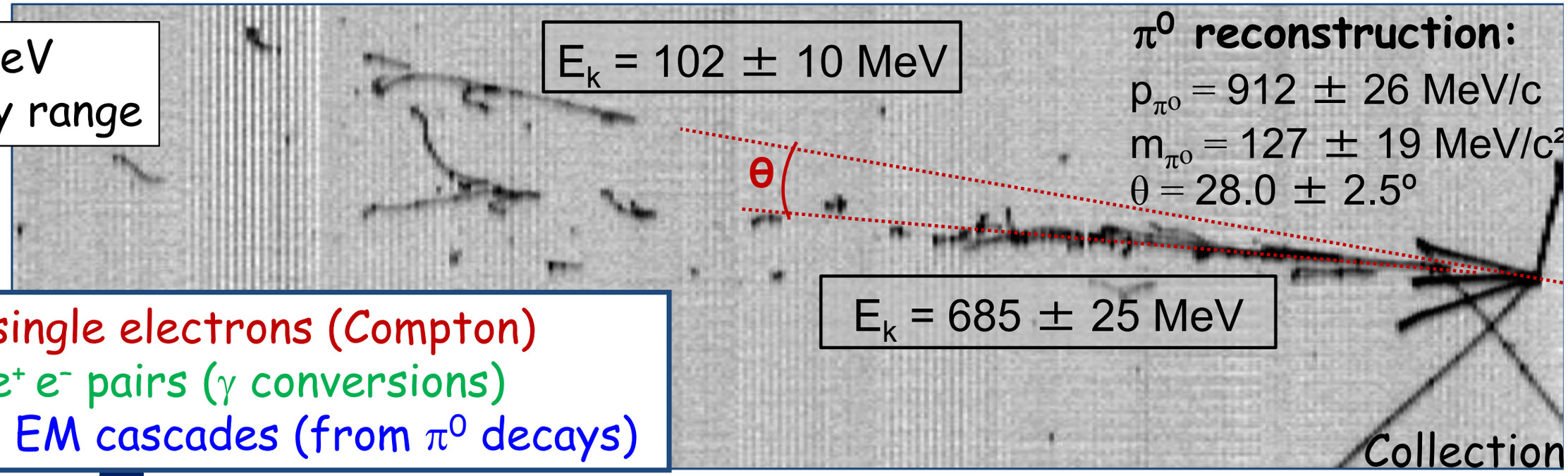


Calorimetry with LAr TPC is less well known

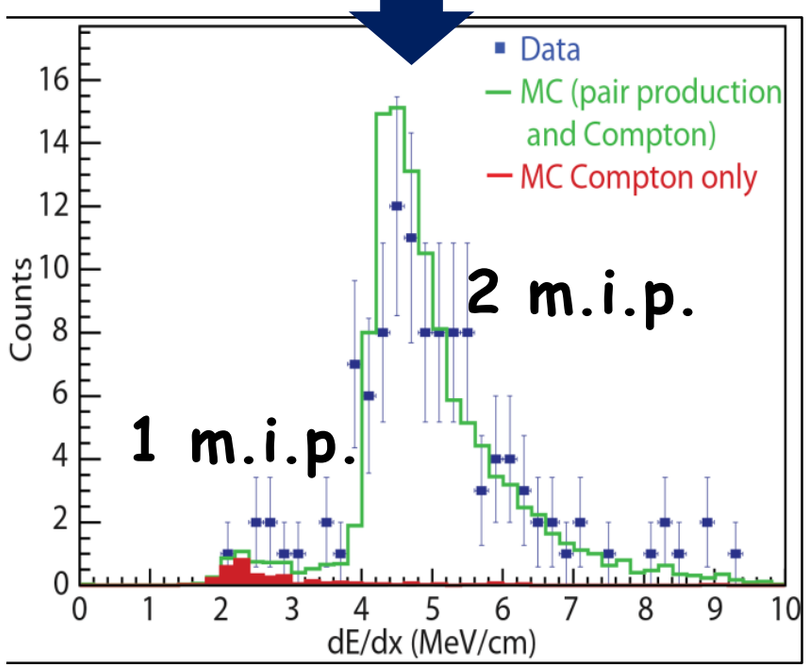
e/gamma separation

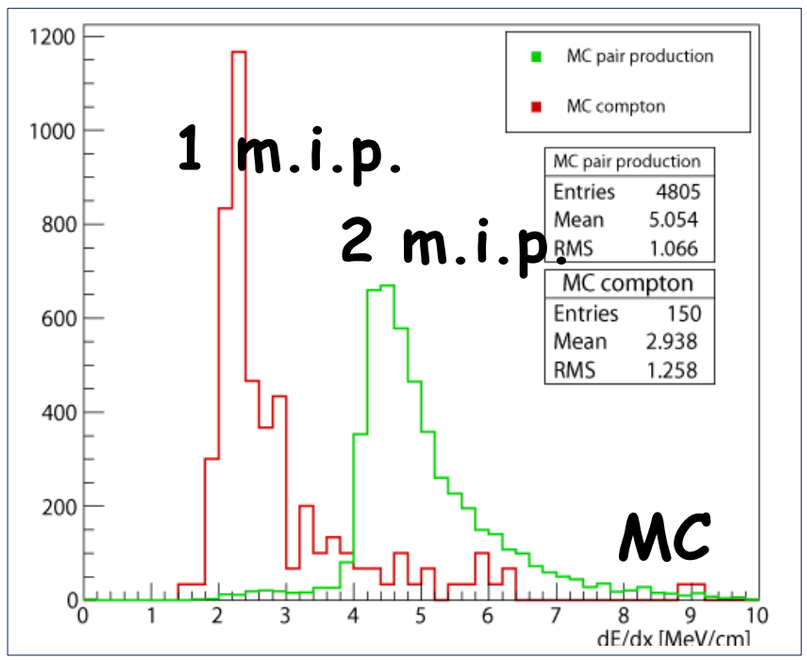
ICARUS T600
@ LNGS

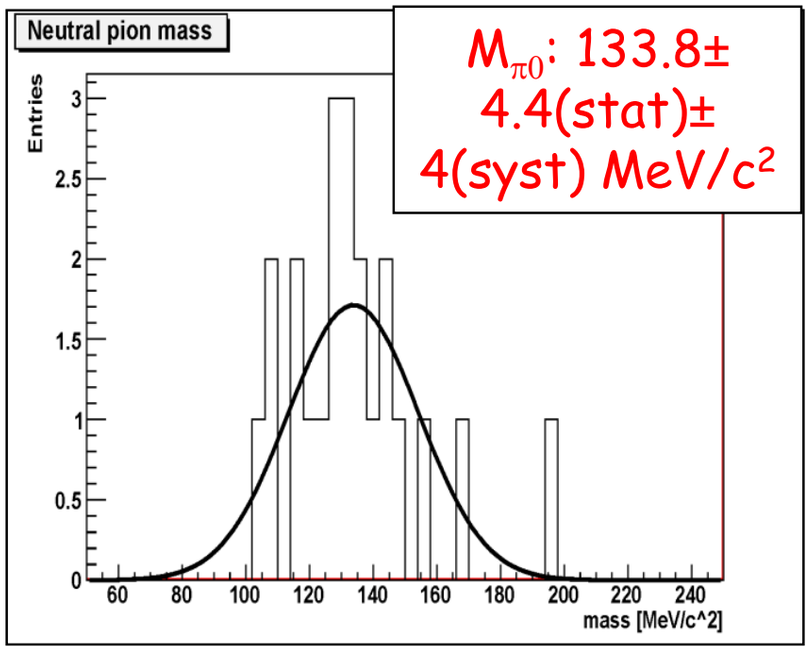
Sub-GeV
Energy range



- MC: single electrons (Compton)
- MC: $e^+ e^-$ pairs (γ conversions)
- data: EM cascades (from π^0 decays)







LAr unique features allow e/γ separation and π^0 reconstruction

Performance is promising - to be further tested in ongoing programs (see later)

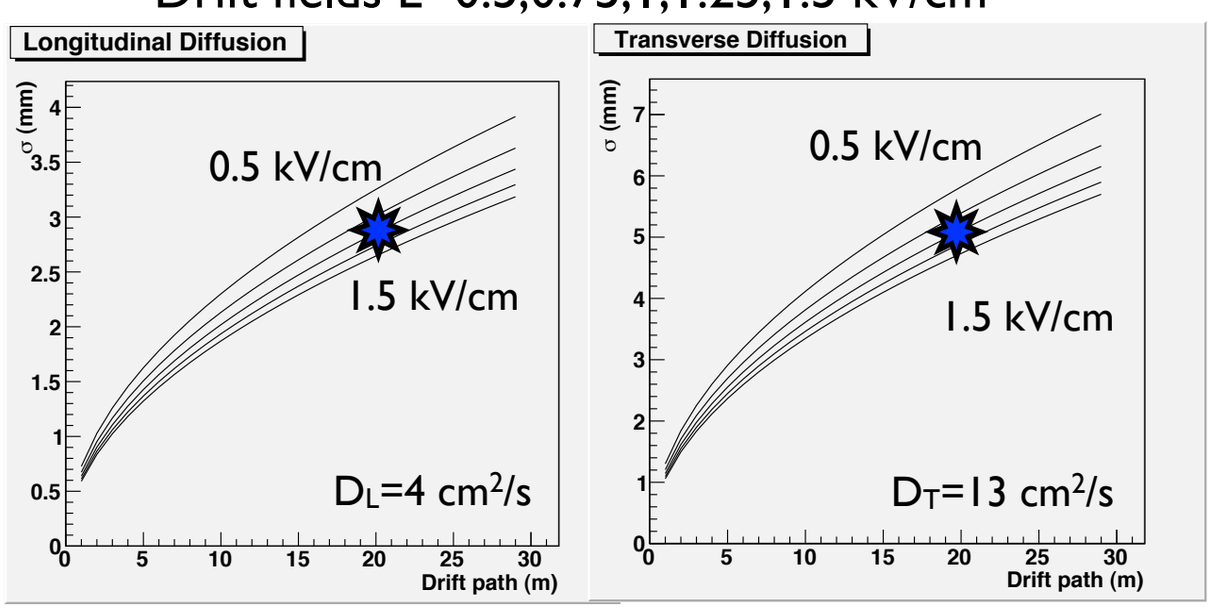
Liquid Argon properties

Property	Liquid Argon
Density (g/cm3)	1.4
Radiation length (cm)	14
Interaction length (cm)	83.6
dE/dx mip (MeV/cm)	2.1
We (eV) @ E=∞	23.6
Wγ (eV) @ E=0	20
Refractive index (visible)	1.24
Cerenkov angle	36°
Cerenkov $d^2N/dEdx$ (β=1)	≈ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold	140 MeV/c
Boiling point @ 1 bar	87 K

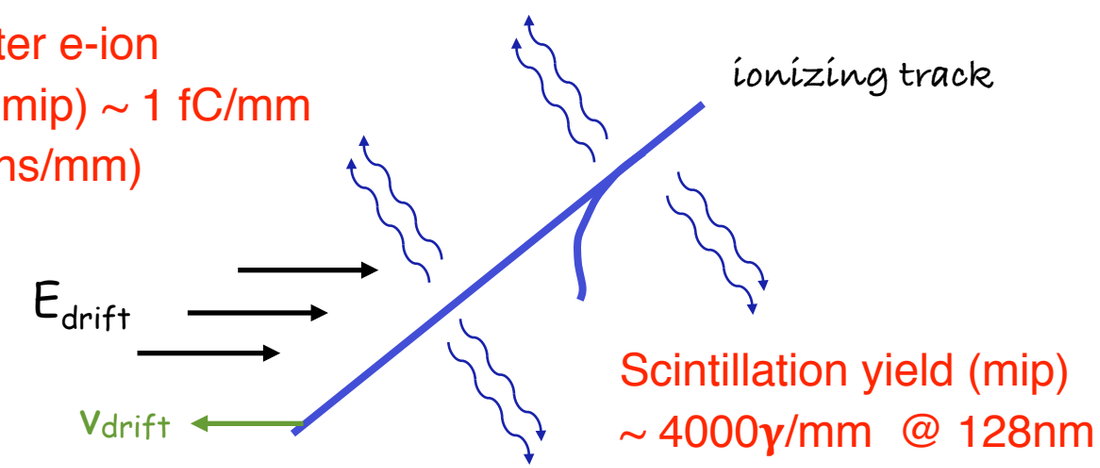
Noble liquid

Liquid Argon:
+ High density, cheap medium
+ Quasi free electrons from ionizing tracks are drifted by E_{drift}.
+ Electron drift velocity ≈ 2mm/μs @ 1 kV/cm
+ Electron cloud diffusion is small
($\sigma \approx \sqrt{2Dx/v_{drift}}$ ≈ mm after several meters of drift)
+ High scintillation yield (@ 128 nm) can be used for T_0, trigger, ...

Drift fields E=0.5,0.75,1,1.25,1.5 kV/cm



Charge yield after e-ion recombination (mip) ~ 1 fC/mm (~ 6000 electrons/mm)

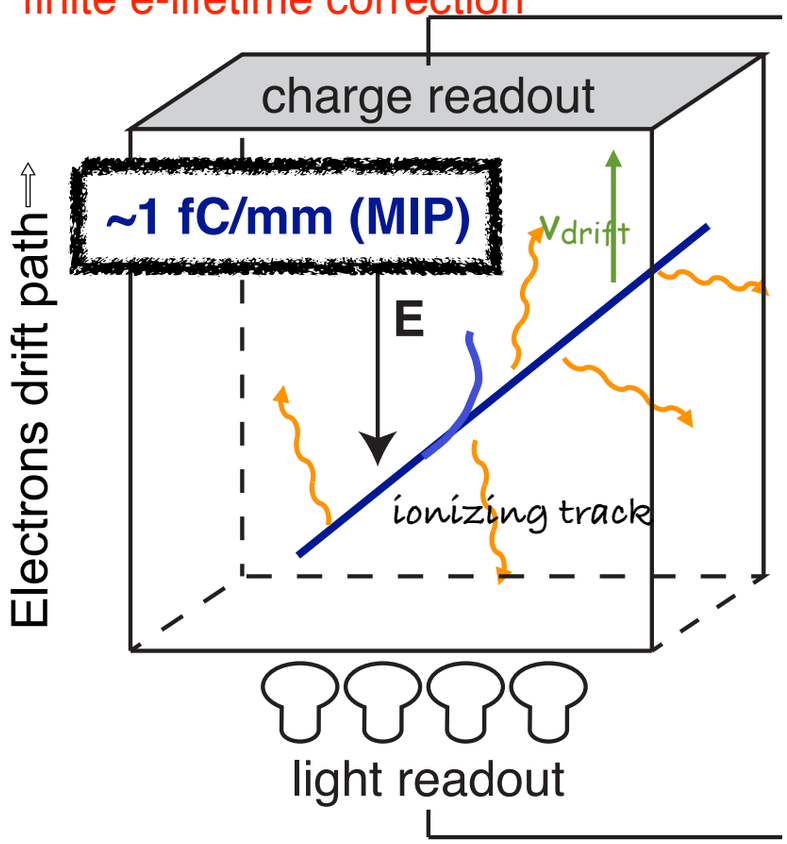


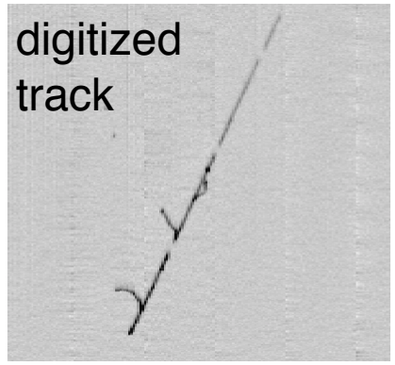
(Electron-ion recombination ≈ 30% for m.i.p. @ 1 kV/cm)

Principle of the LAr TPC

Basic technique established

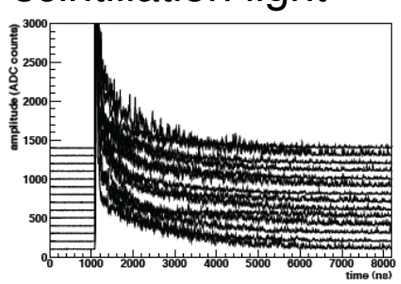
Charge yield after e-ion recombination (mip) ~ 1 fC/mm (~ 6000 electrons/mm) before finite e-lifetime correction





Scintillation yield (mip) ~ 4000γ/mm @ 128nm

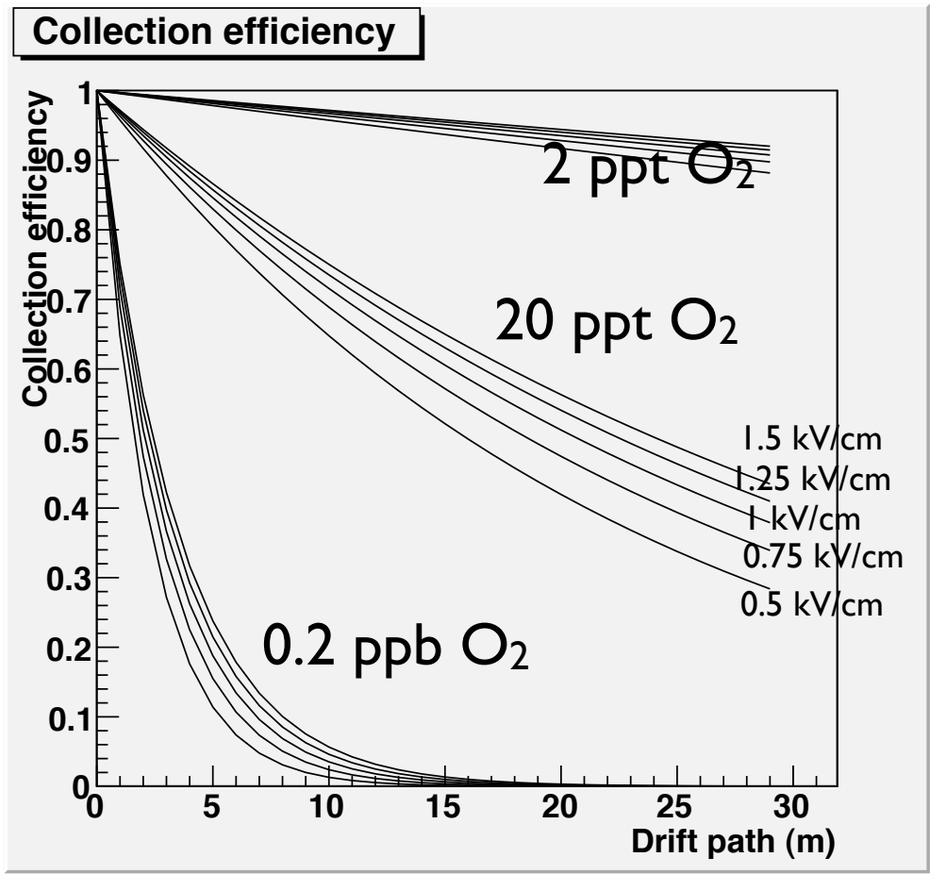
scintillation light

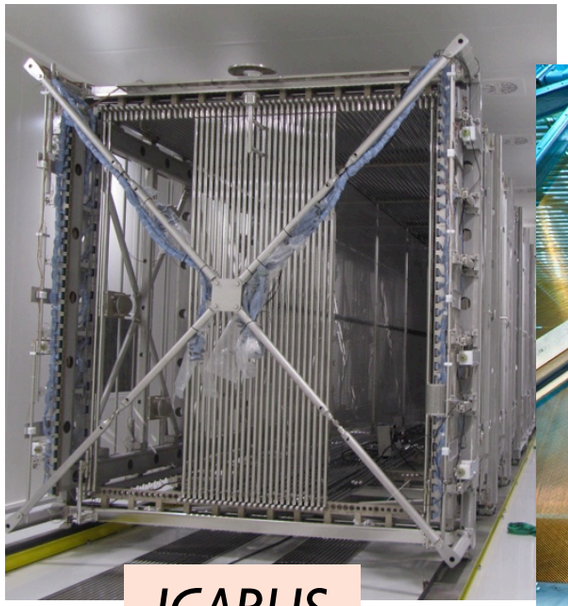


Technical challenges:

– Long drift requires ultra high purity
  * free of electro-negative molecules (O_2, H_2O, ...)
    Goal << 100 ppt O_2 equivalent !!
  * Drift field implies high voltage on the cathode
– Large readout chambers at cryogenic T
– No charge amplification in single phase: fC-level charge sensitive preamplifiers
– Large #readout channels
– Large cryogenic systems

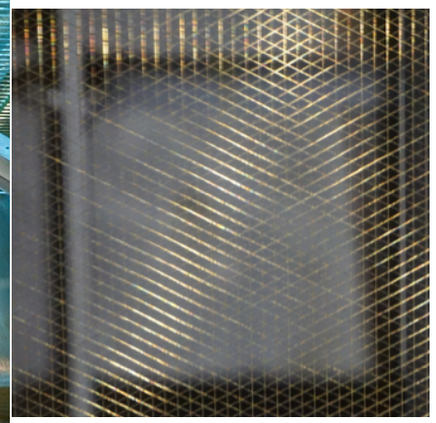
Charge attenuation because of attachment to impurities





ICARUS

MicroBoone



3mm wire pitch

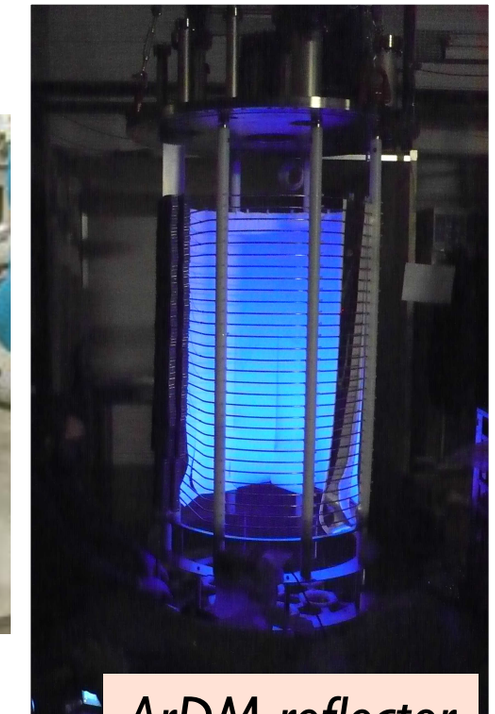
Scintillation light detection

- Liquid Ar is an excellent scintillator
  - 1 MeV dE/dx → ~24,000 photons (at 500 V/cm field)
  - ¼ of the photons are prompt (6ns) around 128nm
  - Rayleigh/Absorption length ~66/>200 cm

1. Direct detection with WLS-coated PMTs + reflectors

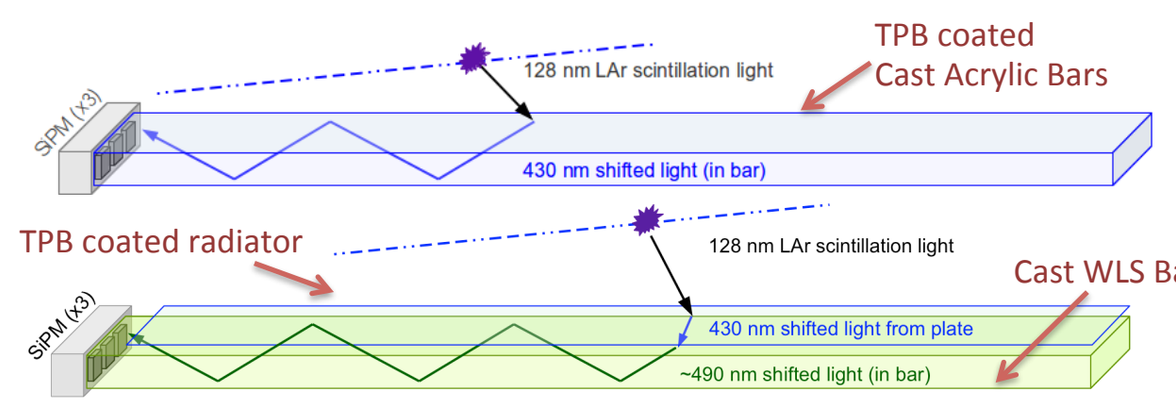
Hamamatsu R5912MOD02

ArDM 8" coated PMT



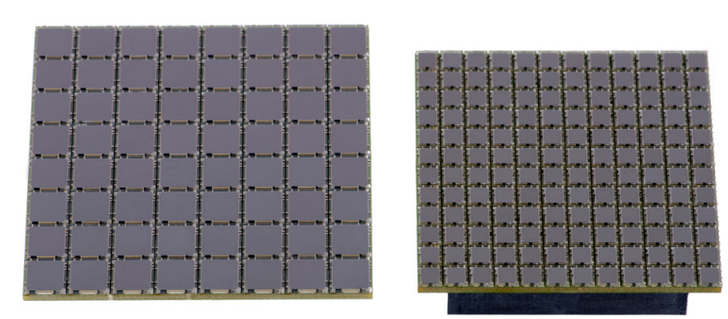
ArDM reflector

2. Hybrid light guide collection + SiPMs



3. Direct detection with SiPMs with WLS

Is it competitive with PMT? yes for very low background application (e.g. DM)

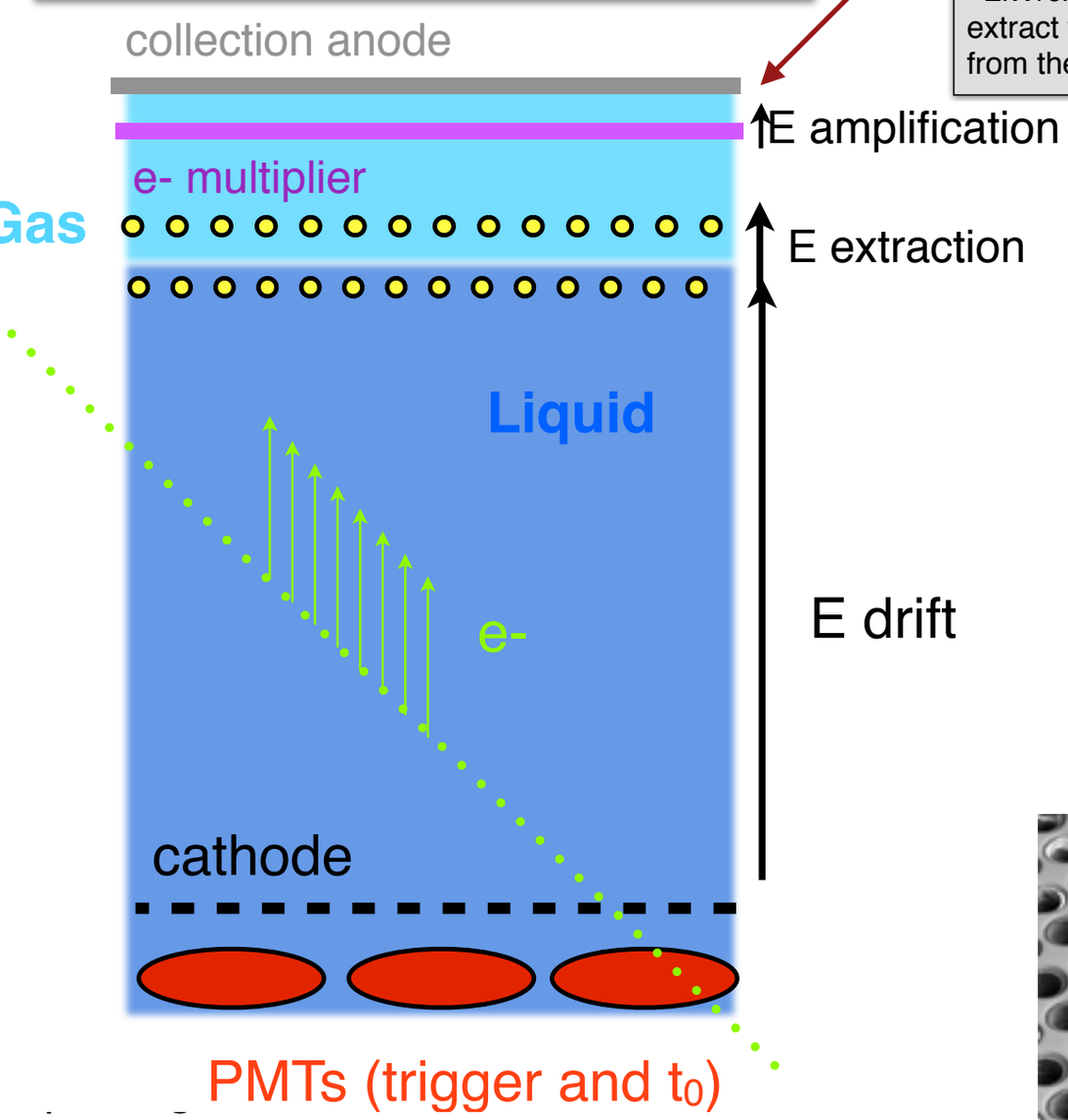


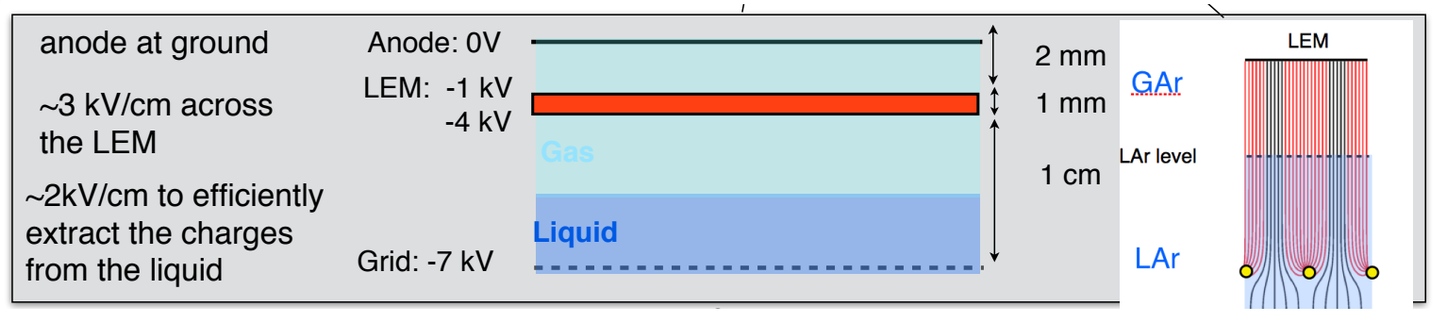
SensL

Many ongoing R&D efforts: large area, high LY, robust, cheap, SiPMs at cryo T,…

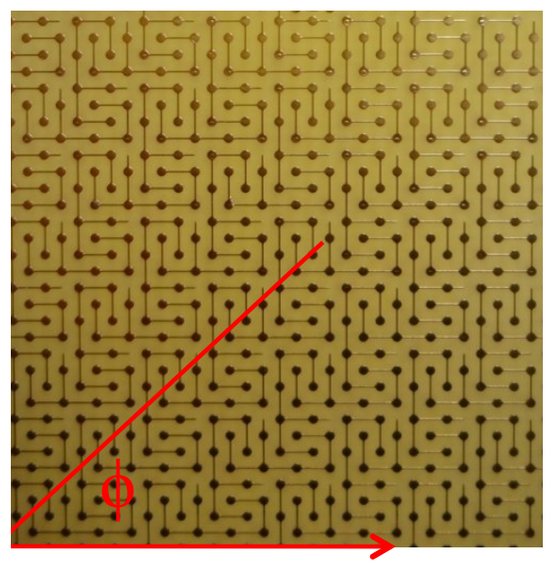
Dual phase LAr TPC

Basic technique OK – R&D towards large scale

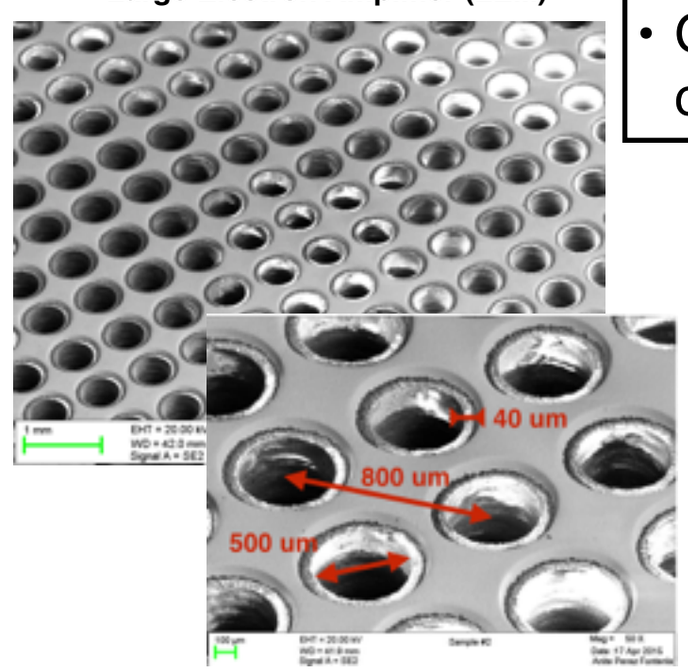




Anode

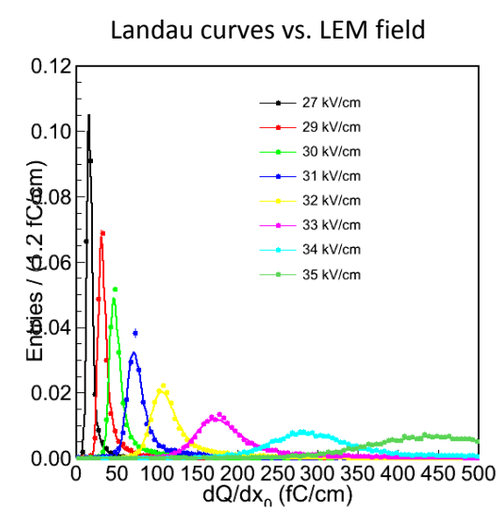


Large Electron Amplifier (LEM)



- Longer drift path with less #chan's
- Finer readout pitch
- More robust S/N ratio with tuneable gain
- Lower detection energy threshold
- Better pattern reconstruction of events
- Only charge collection views (no induction)
- Gain demonstrated up to 90
- Optimal gain for neutrino physics operation ≈ 10 - 20

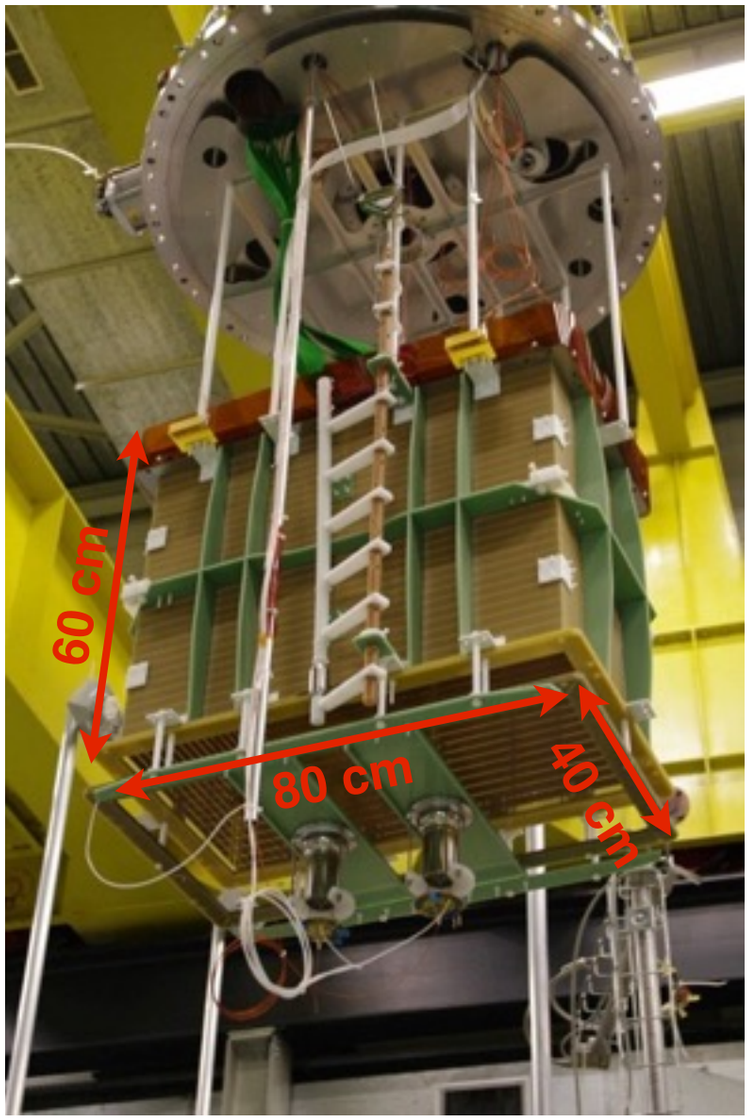
For MIPs:
- 10 fC/cm — ~10 k e^- for each strip (3 mm pitch,2 views) — SNR of 10 (noise of 1000 e^-)
- SNR of 100 — gain of 20 is needed



A. Badertscher et al. NIM A641 (2011) 48-57

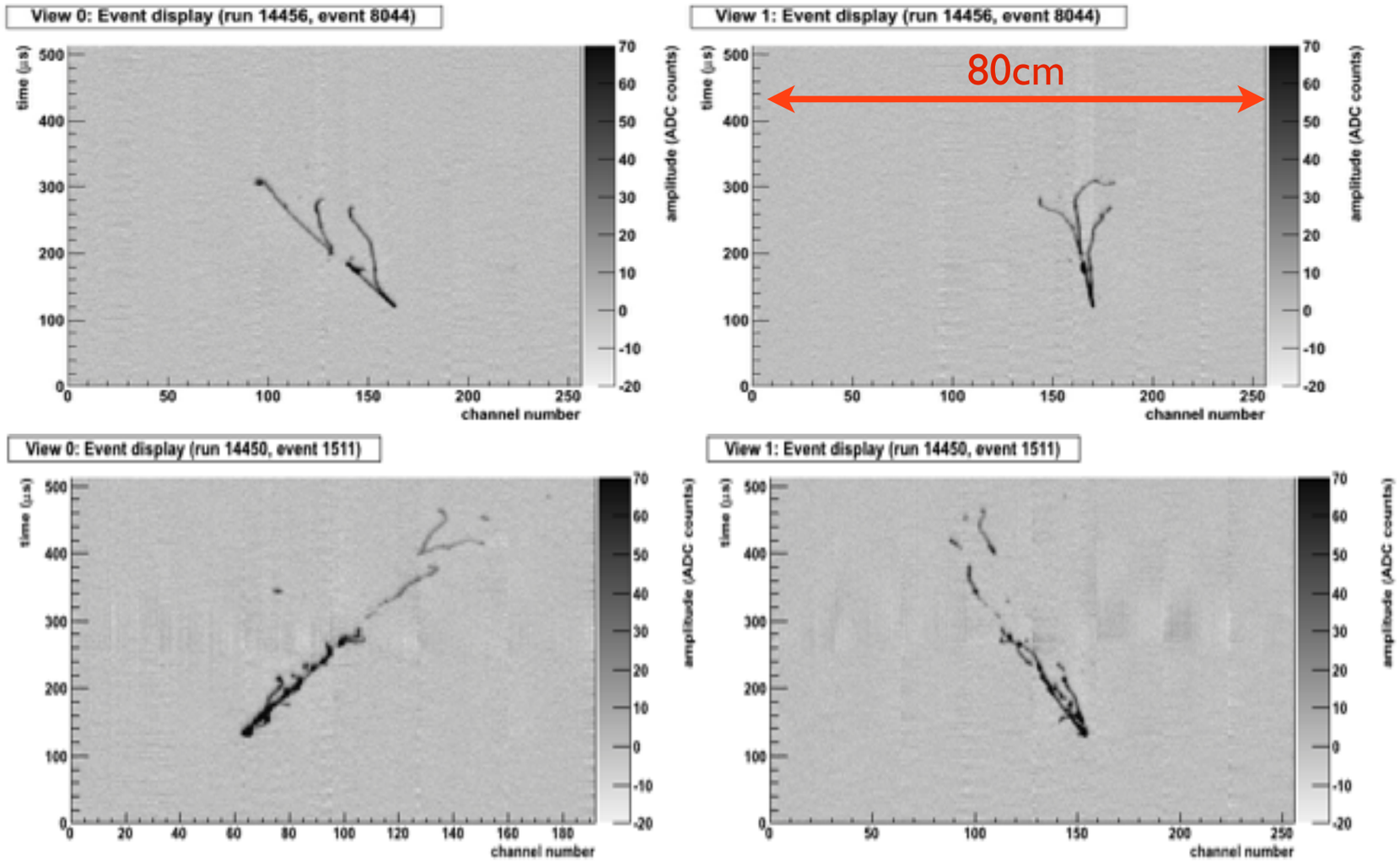
CR events in dual-phase 250L proto

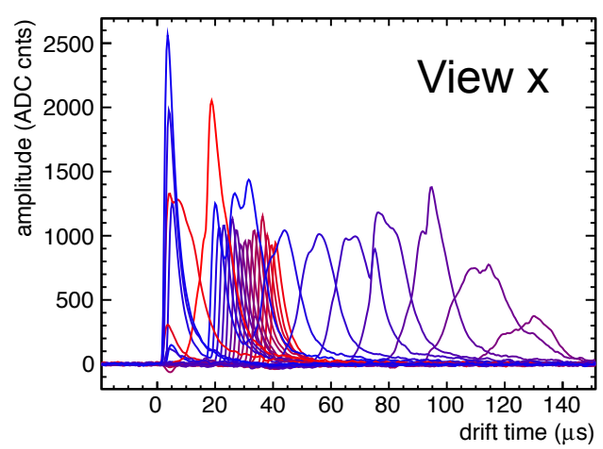
Dual phase demonstrated with a detector of the size of ArgoNEUT/LArIAT → Allows finer readout pitch, lower energy thresholds and better pattern recognition

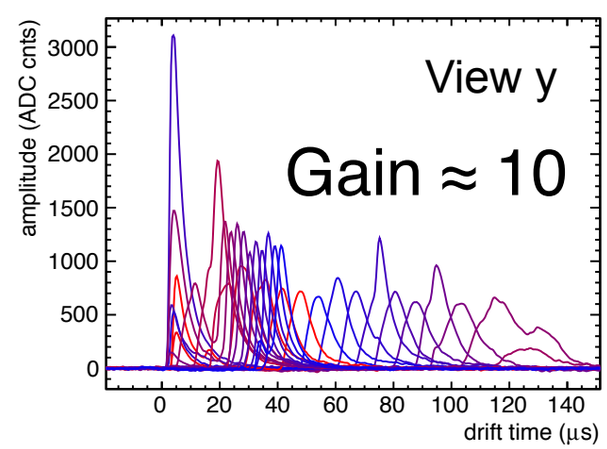


Dual phase 250L chamber @ ETHZ/CERN

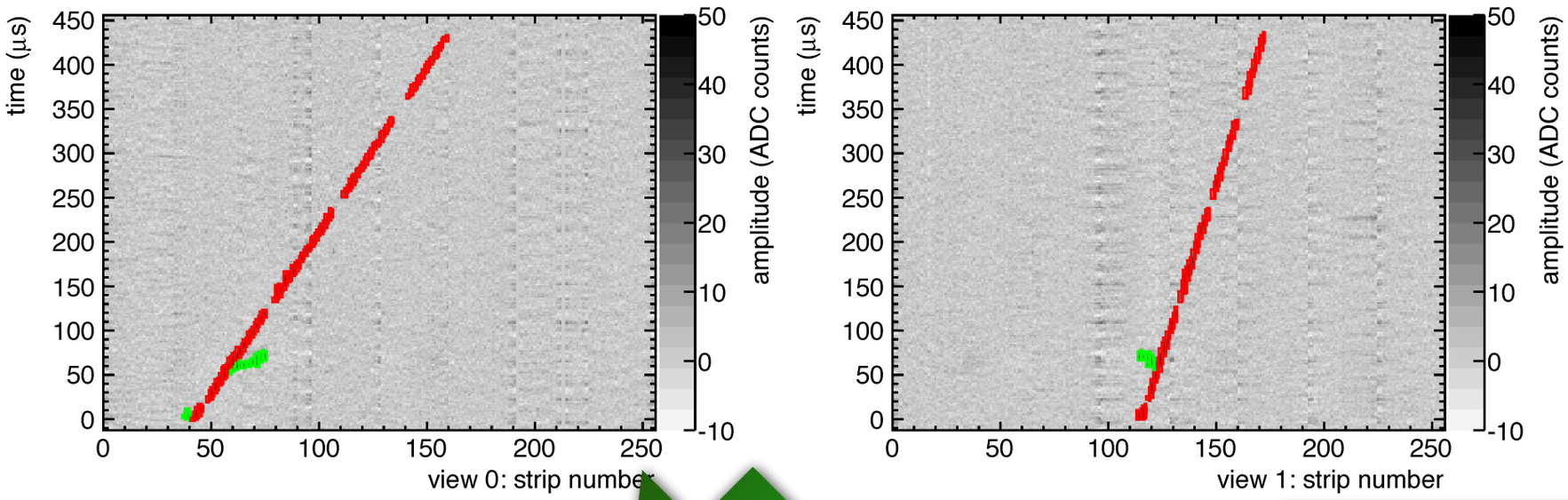
A. Badertscher et al. JINST 8 (2013)P04012





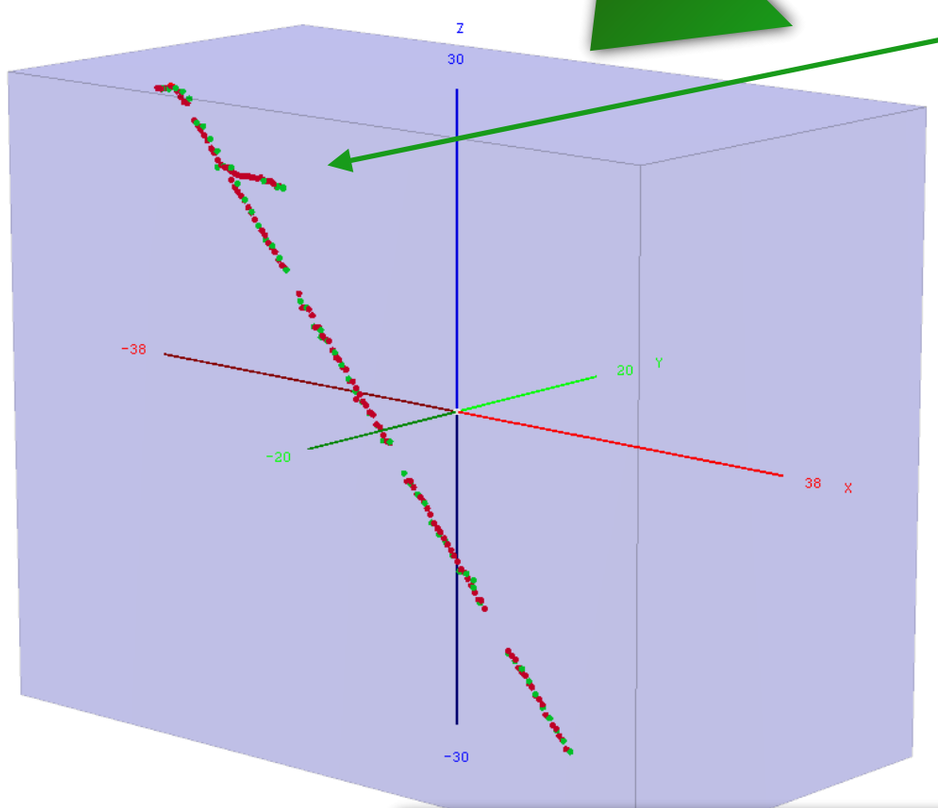


Delta-rays 250L prototype



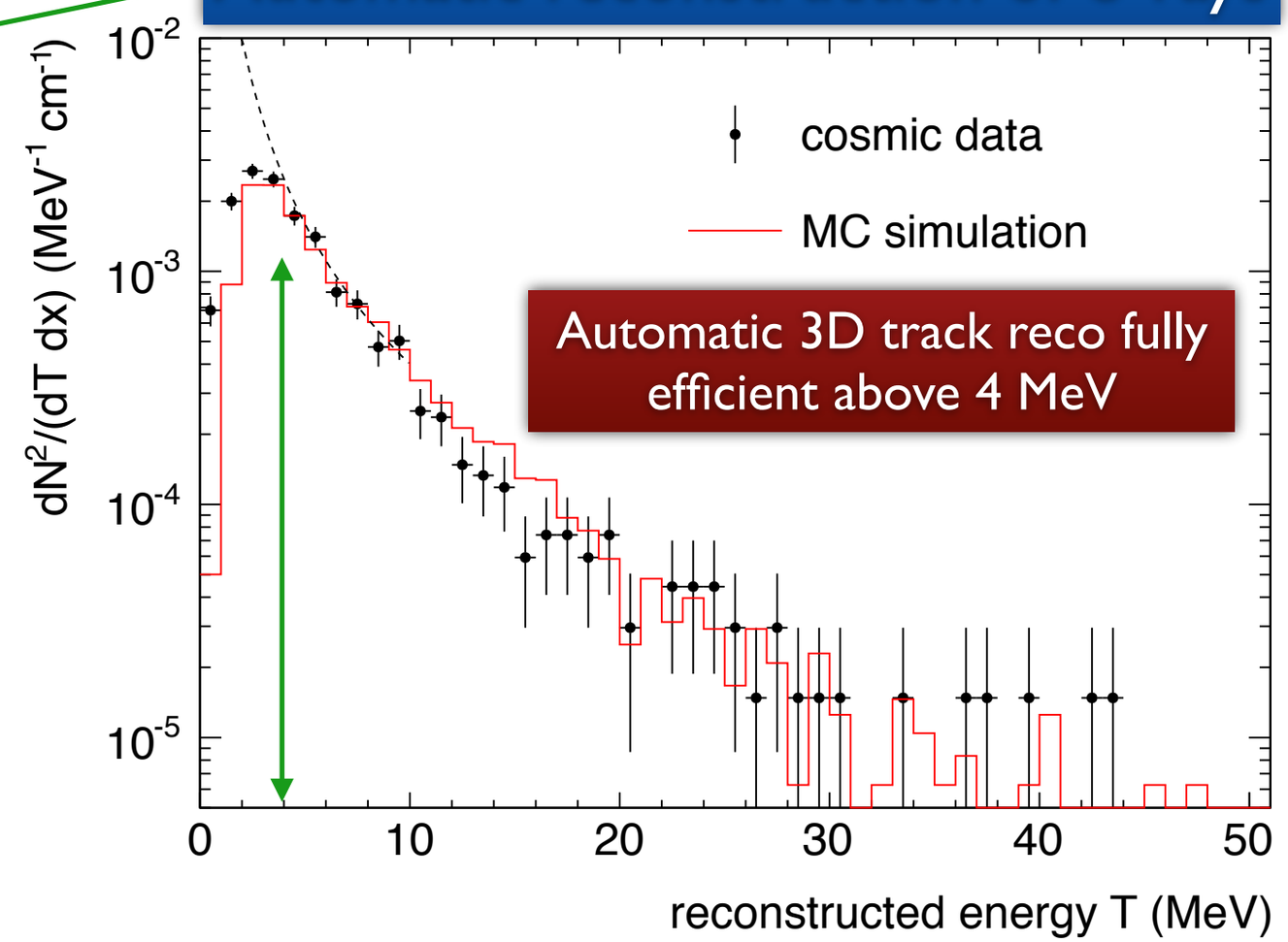
JINST 8 (2013) P04012

Event recorded in 200L double phase chamber exposed to cosmic rays



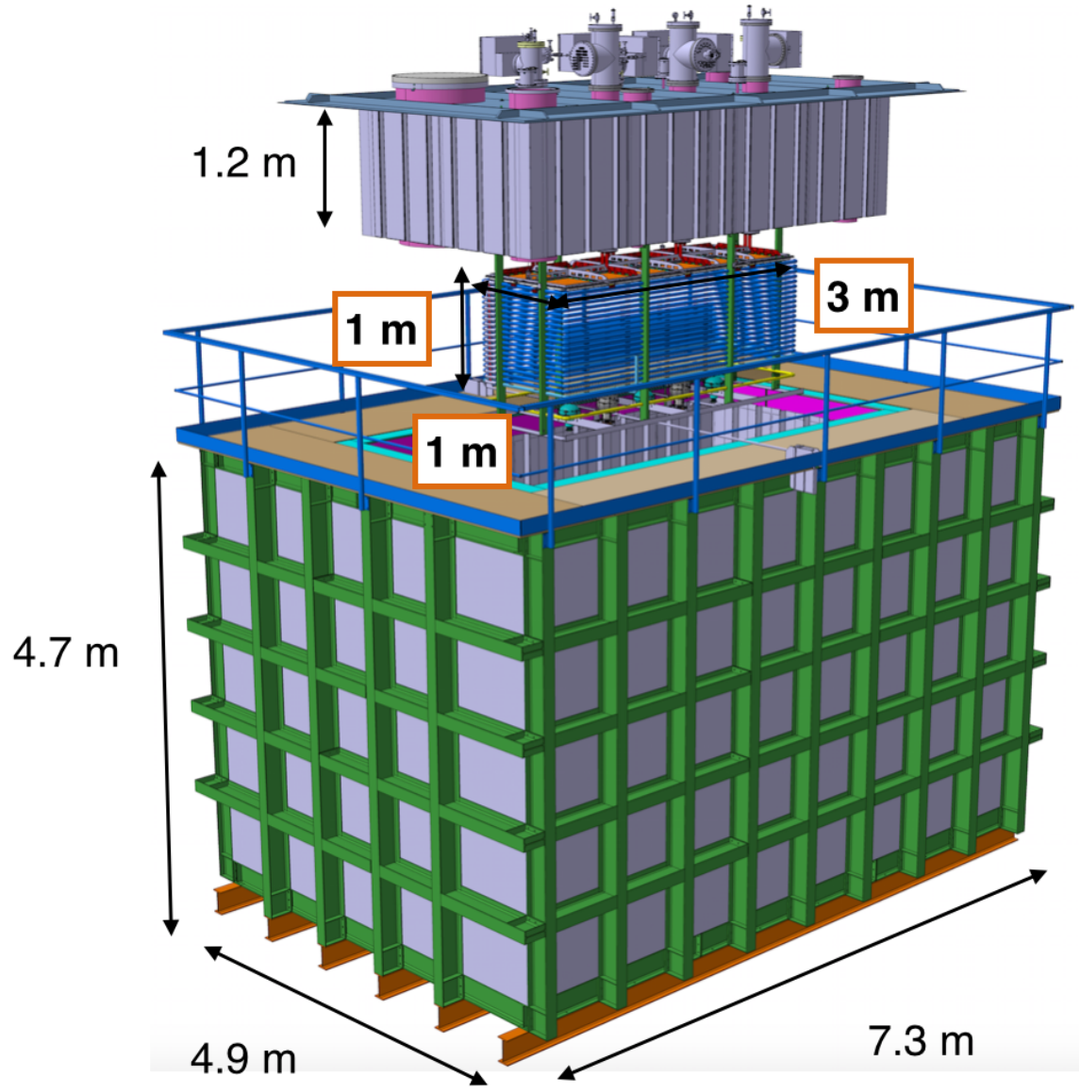
3D reconstruction

Automatic reconstruction of δ-rays



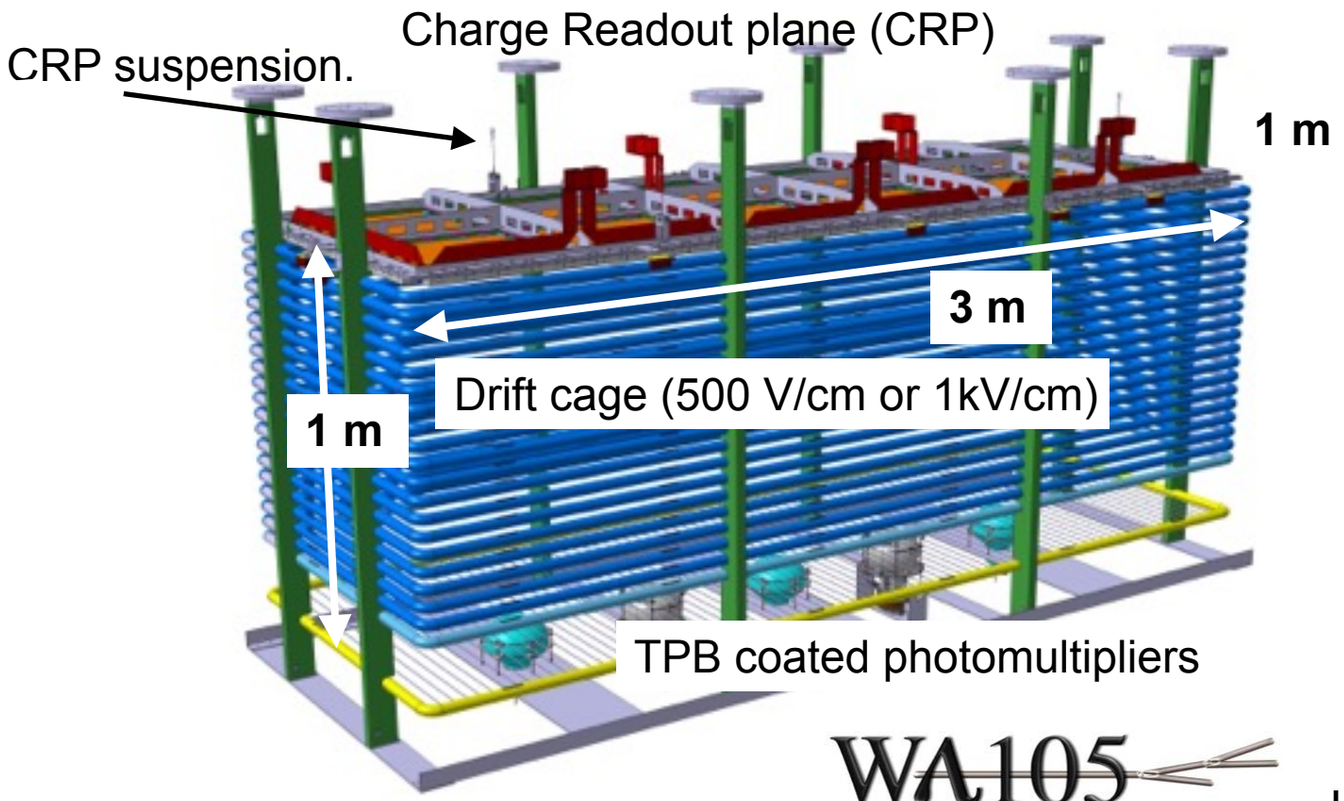
Automatic 3D track reco fully efficient above 4 MeV

WA105 3x1x1m3: A 24 ton dual phase TPC



Leak check Membrane:

i. GABADI & CEGELEC→ sensitive to 1e-5 (mbar l/s)
ii. CERN is improving the test in order to reach 1e-9 (mbar l/s)

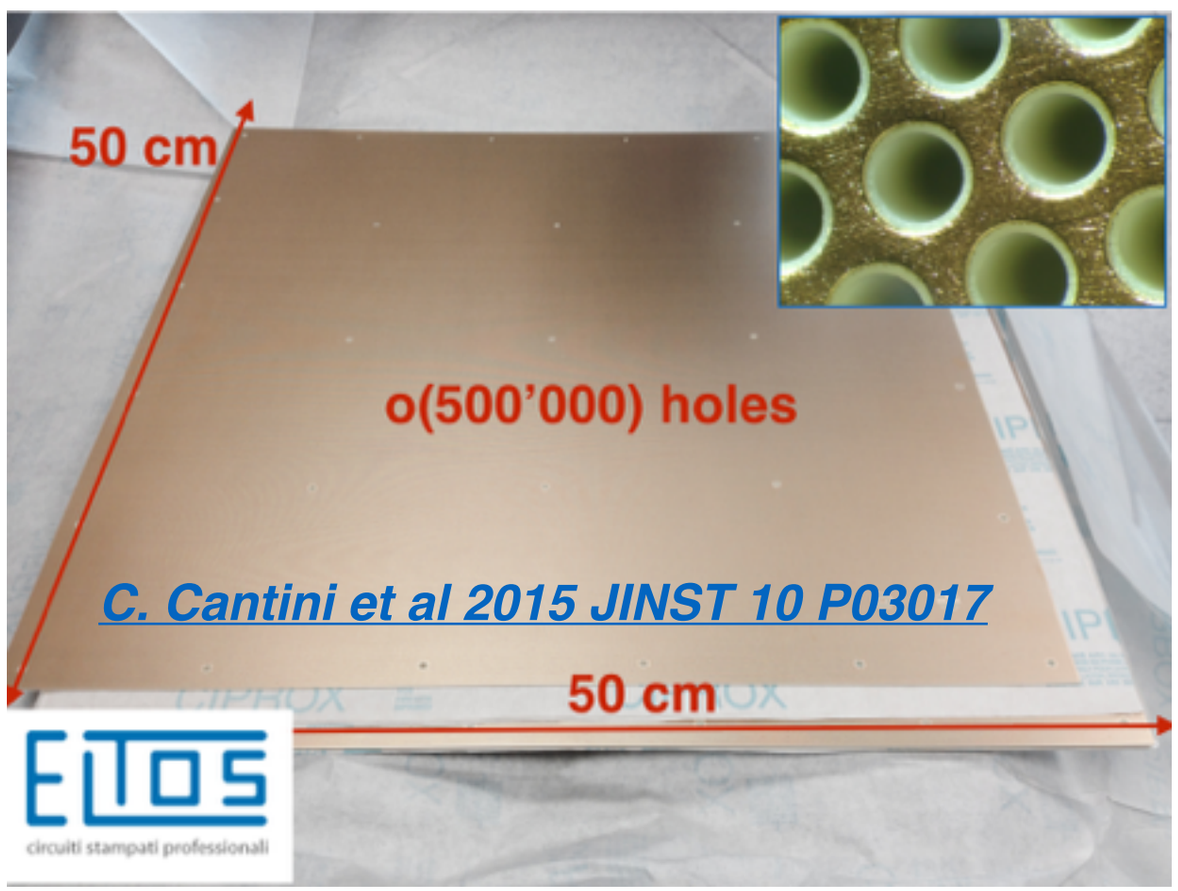


- First large scale of dual phase TPC
  - 25 ton total LAr mass
  - Active mass 4.2 tons
  - 3 mm readout pitch
  - 2 views
  - 1920 readout channels
  - (3+2) 8” PMTs

50x50 cm² LEMs & anodes

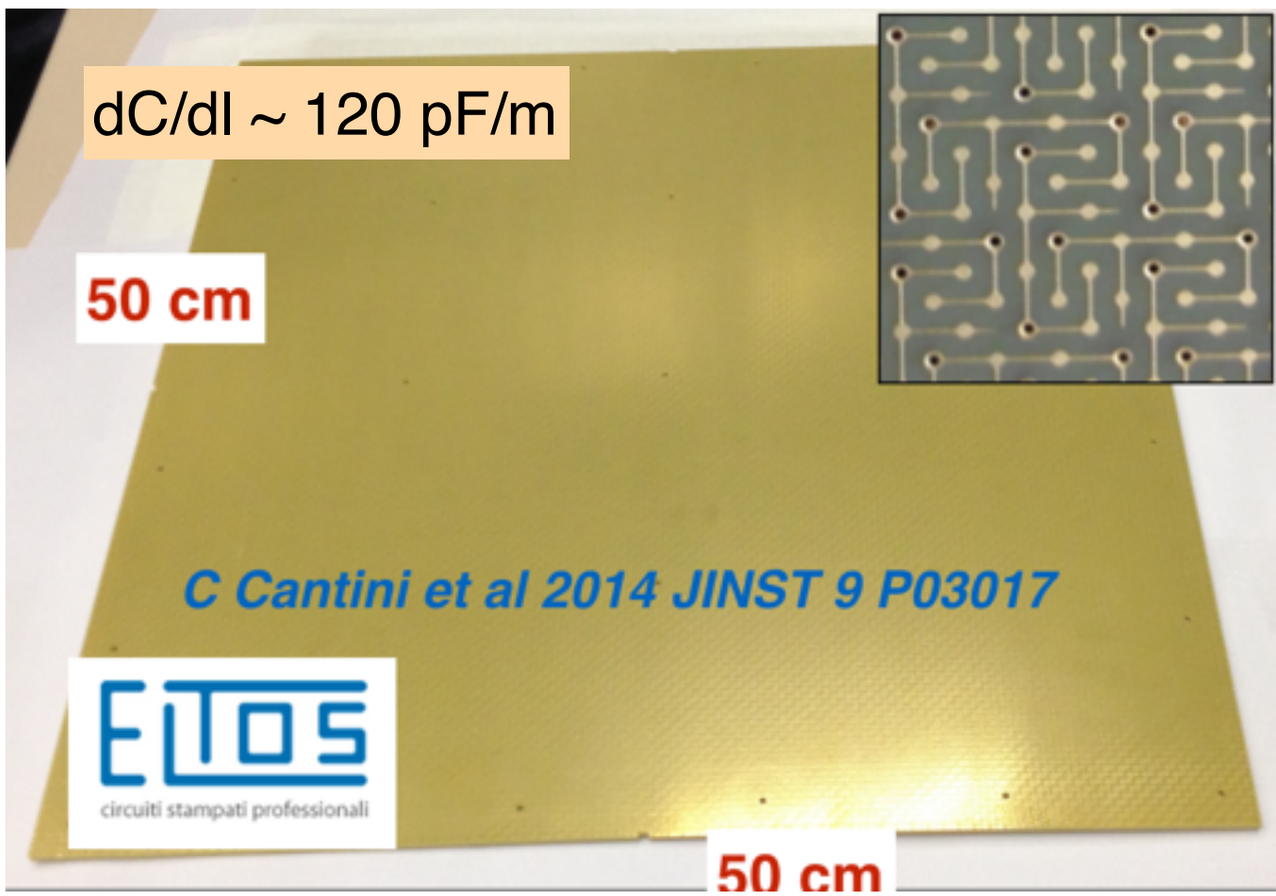
- ✓ PCB CNC drilled with o(150) holes per cm². 1 mm thick.
- ✓ 500 um hole diameter 800 um pitch.
- ✓ 40 μm dielectric rim around the holes to avoid edge-induced discharges
- ✓ powered at around 30 kV/cm
- ✓ design is the result of many years of R&D on smaller scale prototypes.
- ✓ See JINST 10 (2015) 03, P03017 for hole/rim size optimisation

50x50 cm² LEM

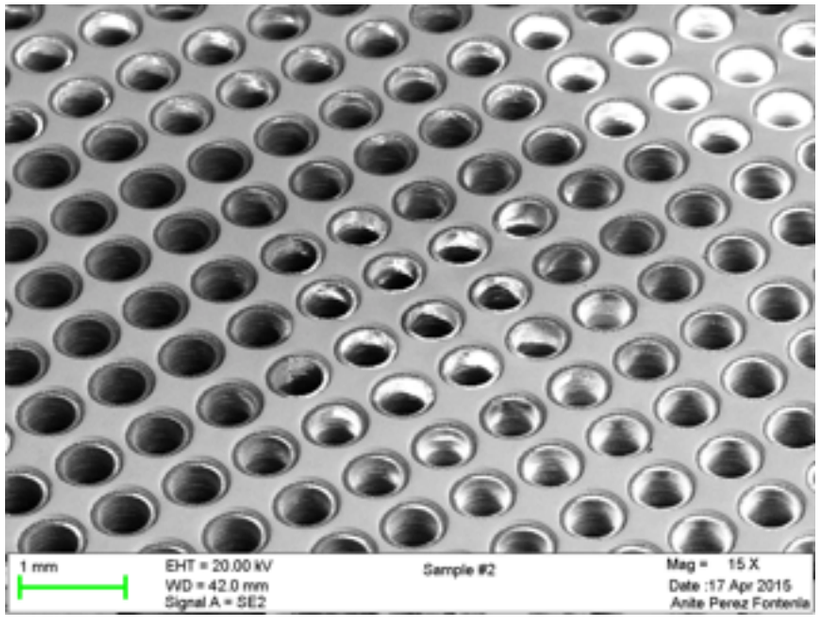


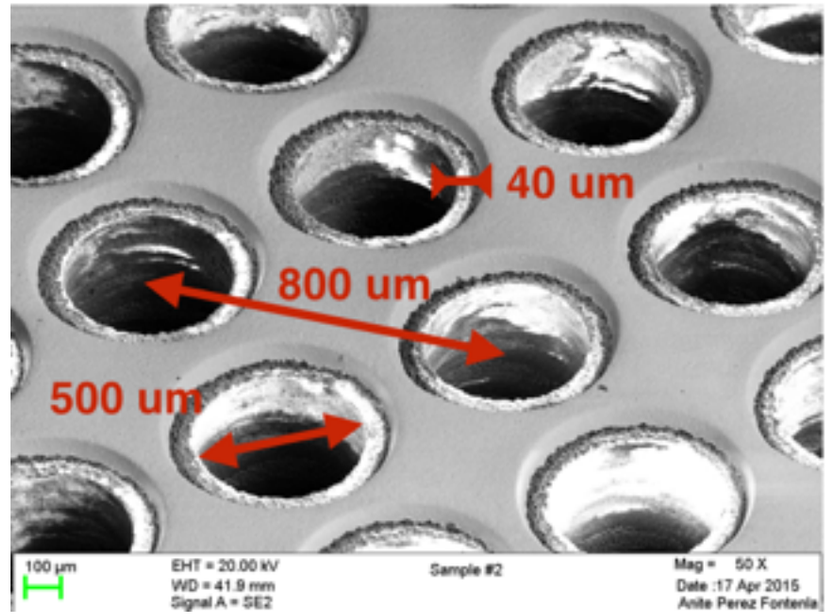
- ✓ "simple" multilayer PCB. 3.4 mm thick.
- ✓ 3 mm readout pitch
- ✓ Equal charge sharing on both collection views.
- ✓ low capacitance per unit length (~150 pF/m)
- ✓ design is a result of ~1 year R&D.
- ✓ relatively easy, cheap and fast to produce. All channels electrically tested by the company.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

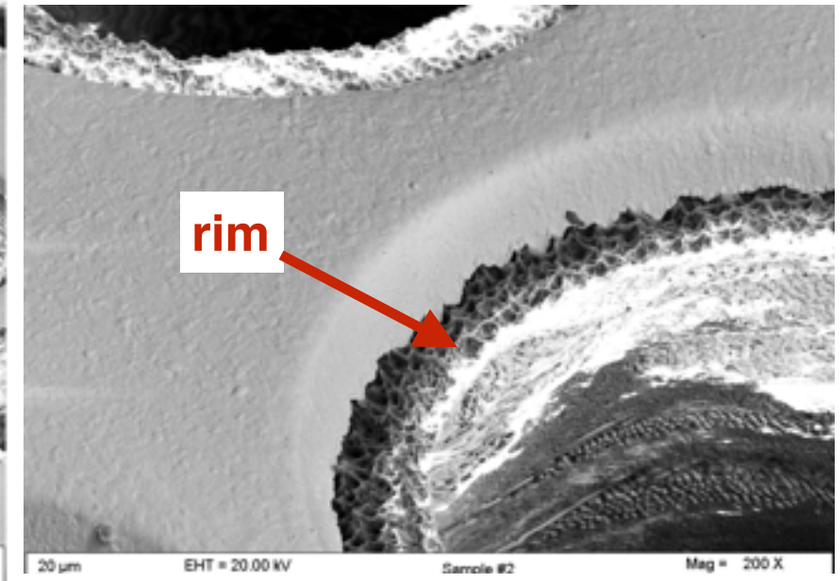
50x50 cm² Anode



LEM characterisation





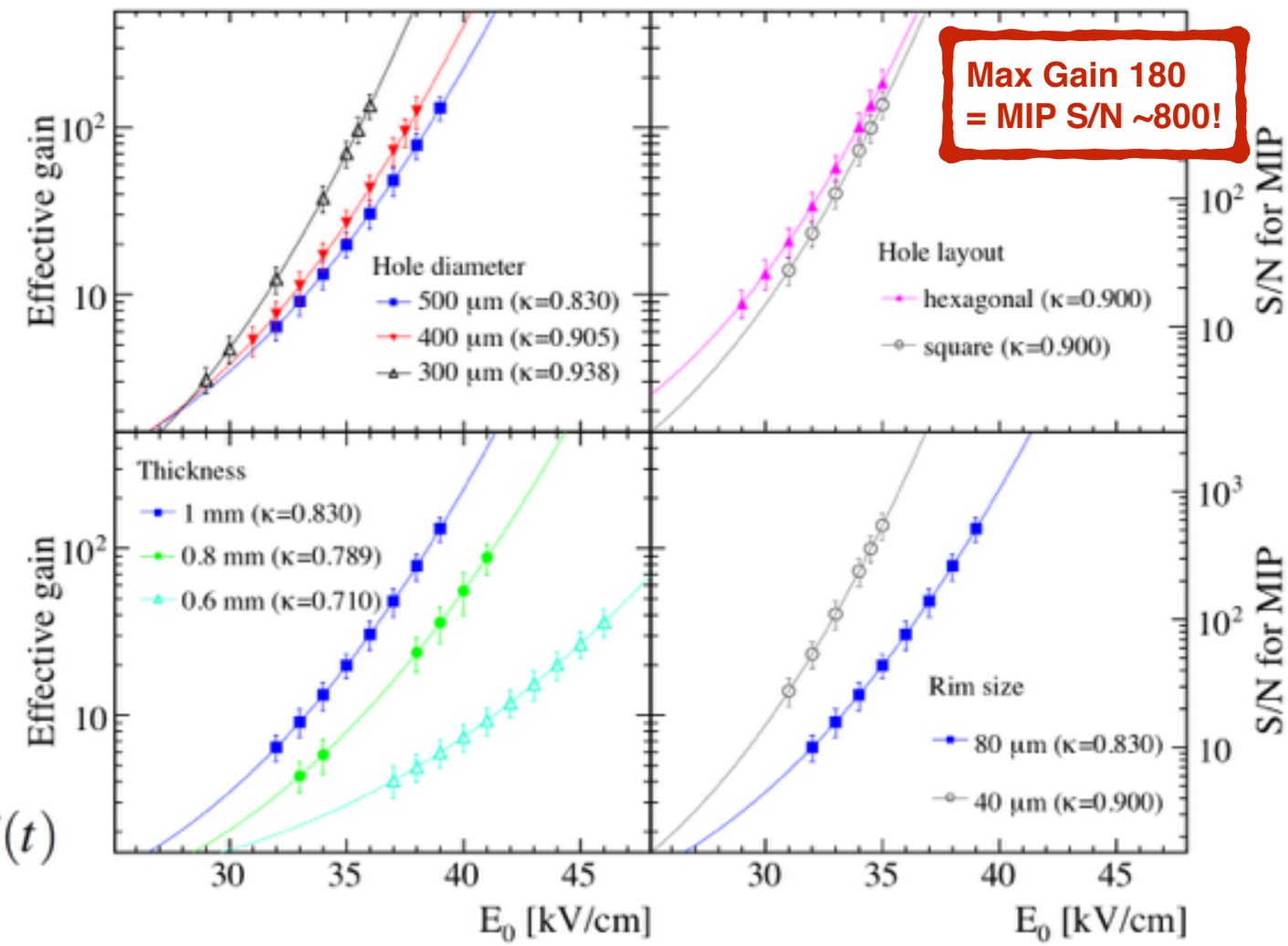


Optimisation from 10x10 cm² LEMs in dual phase operation

C. Cantini et al 2015 JINST 10 P03017

effect of

- rim size
- hole diameter
- hole layout
- PCB thickness

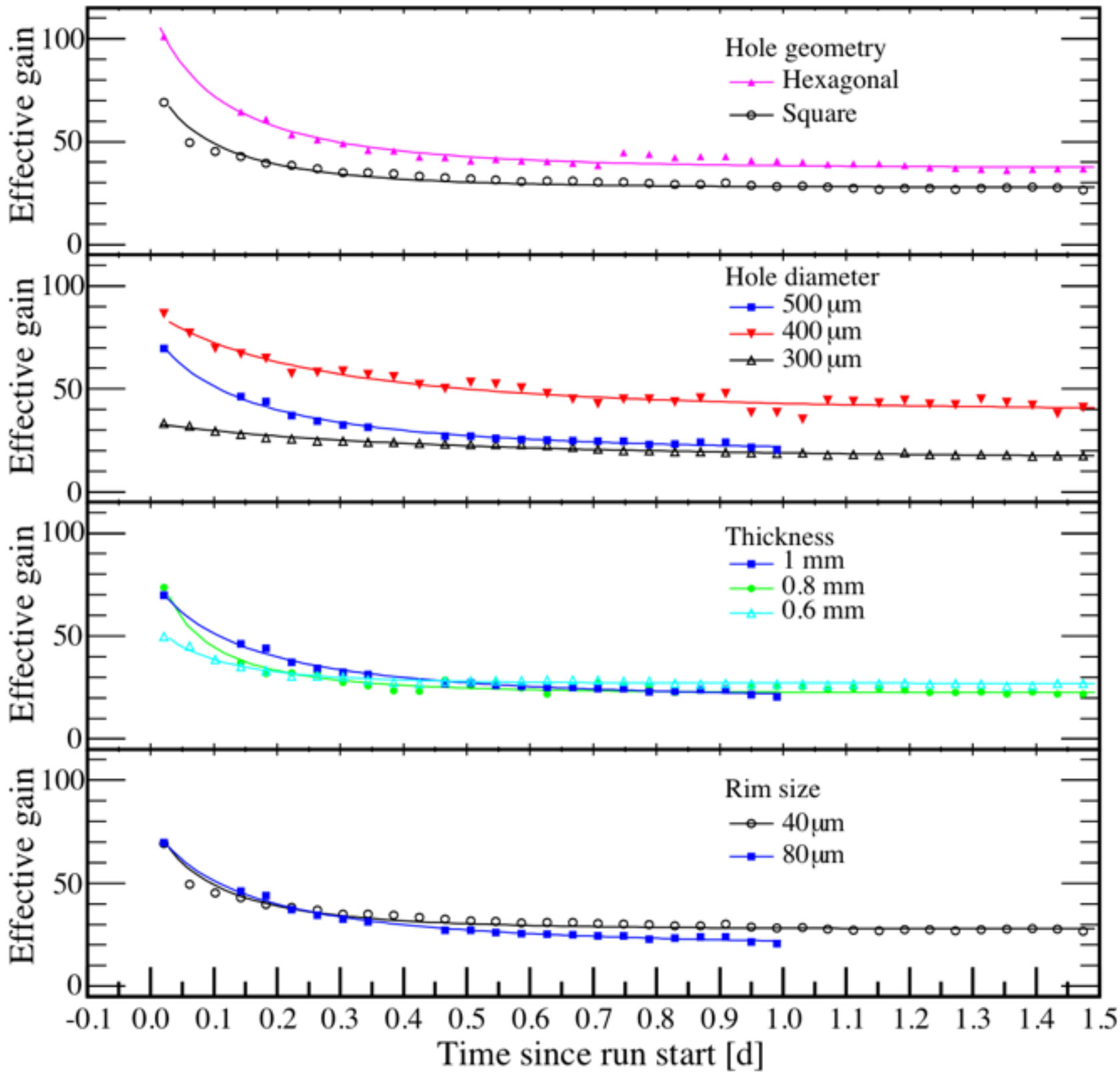


Fitting function:

$$G_{eff}(E,\rho,t) \equiv \mathscr{T} e^{\alpha(\rho,E)x} \times \mathscr{C}(t)$$

$$\alpha(\rho,E) = A\rho e^{-B\rho/E}$$

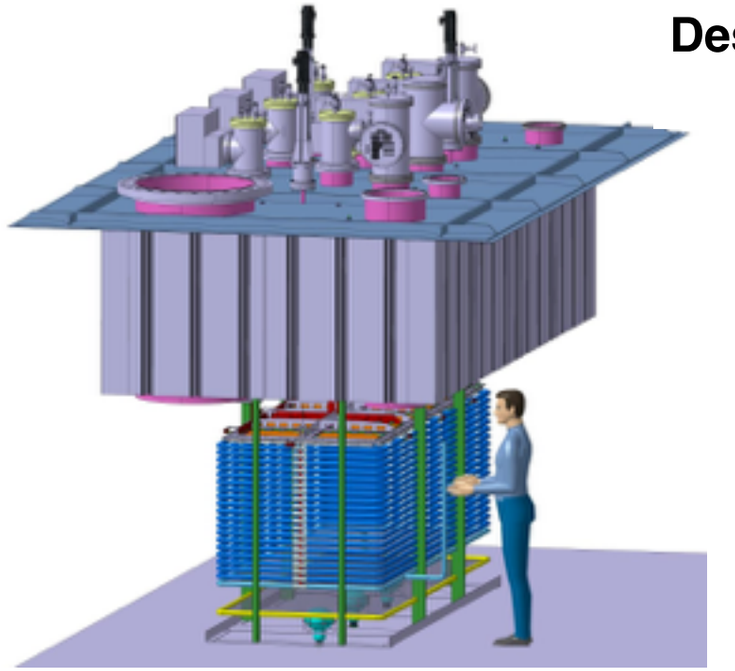
Gain stability



C. Cantini et al 2015 JINST 10 P03017

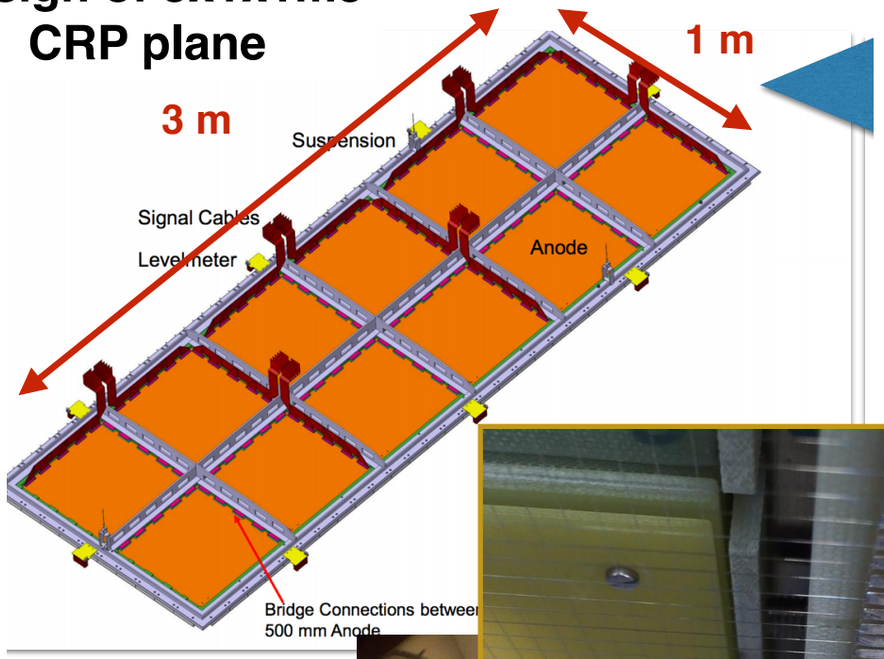
The LEMs had slightly different charging up characteristics but all could be **operated stably at gains of at least 20**.

3x1x1m3 assembly (CRP+field cage) WA105

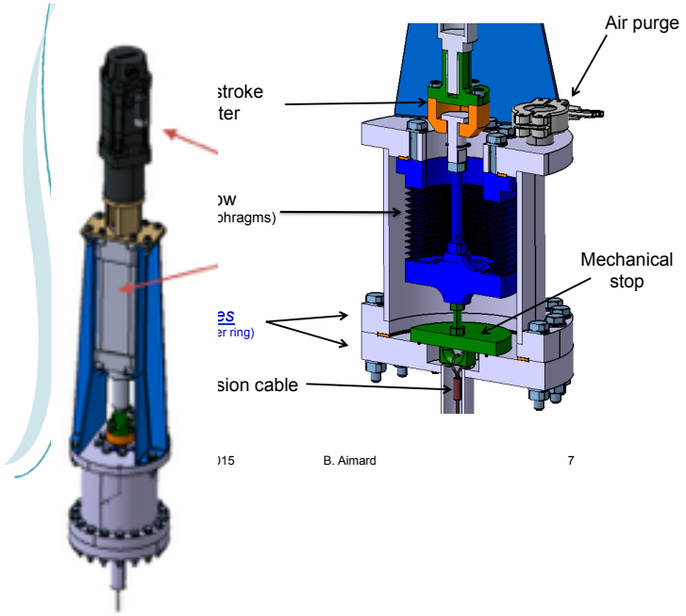


Suspended and adjustable to LAr level

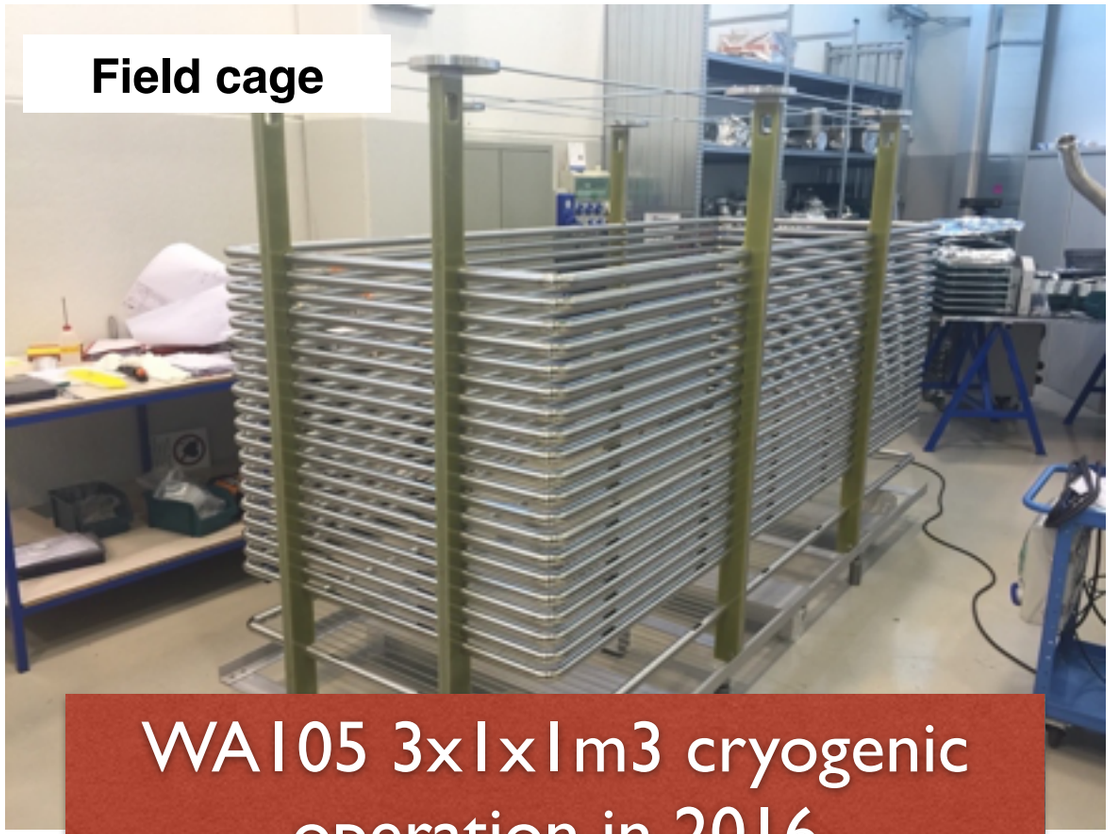
Design of 3x1x1m3 CRP plane



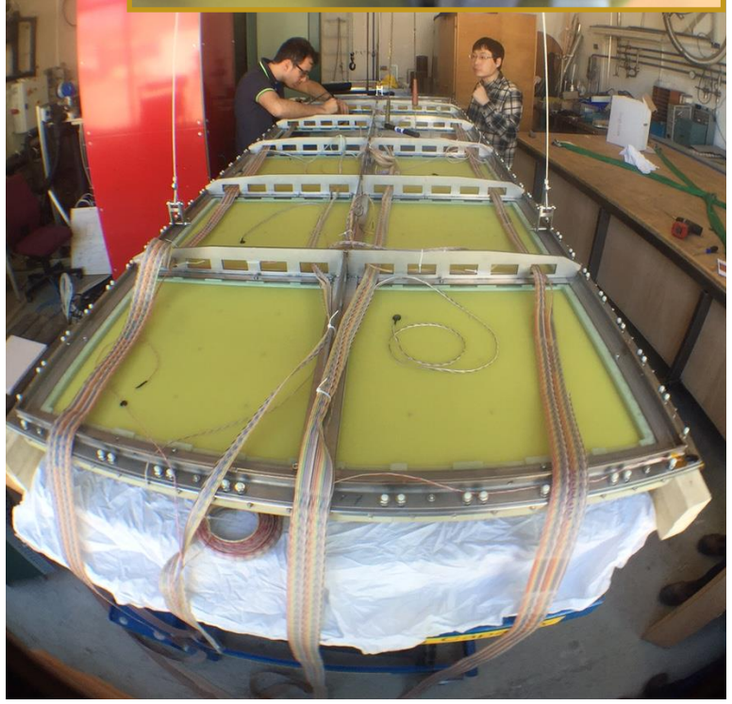
CRP suspension feedthrough



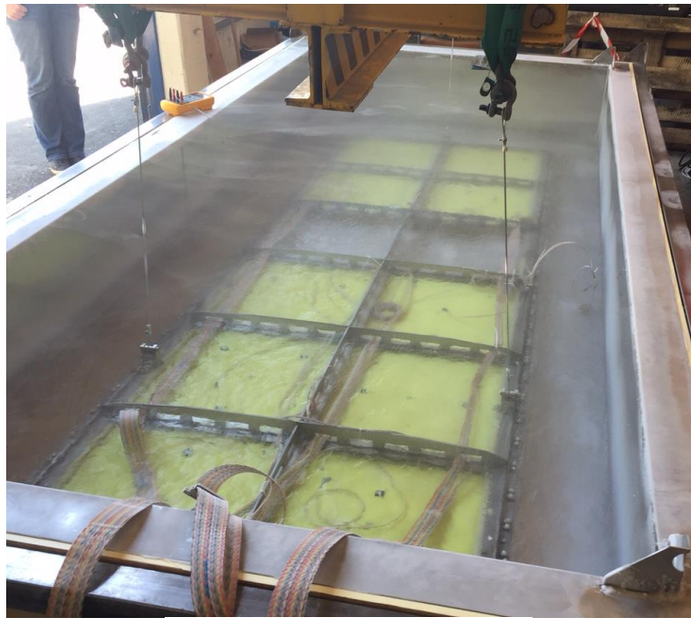
Field cage



WA105 3x1x1m3 cryogenic operation in 2016



CRP cold test



Immersed in LN2 to measure deformation

LAr TPC detectors: overview

Project	LAr mass (tons)	Goal	Baseline (km)	Where	Status
ArgoNEUT	0.25	Neutrino detection	n/a	FNAL	Took data
LArIAT	0.25	Test beam	n/a	FNAL	Took data
CAPTAIN	5	Neutrino detection	n/a	Los Alamos	Construction
MicroBOONE	89	short baseline	0.47	FNAL BNB	Taking data
SBND	112	2nd detector for short baseline	≈0.7	FNAL BNB	Planned 2018
ICARUS	478	3rd detector for short baseline	1.6	FNAL BNB	Took data
DUNE 35T	35	R&D single phase	n/a	FNAL	Construction
WA105 3x1x1m3	25	R&D dual phase	n/a	CERN	Construction
ProtoDUNE	300	Test beam single phase	n/a	CERN	Planned 2018
WA105 6x6x6m3	300	Test beam dual phase	n/a	CERN	Planned 2018
DUNE	4x10000	LBL and astrophysics, nucleon decay	1300	SURF	Planned 2024

LArIAT: Liquid ARgon TPC In A Testbeam

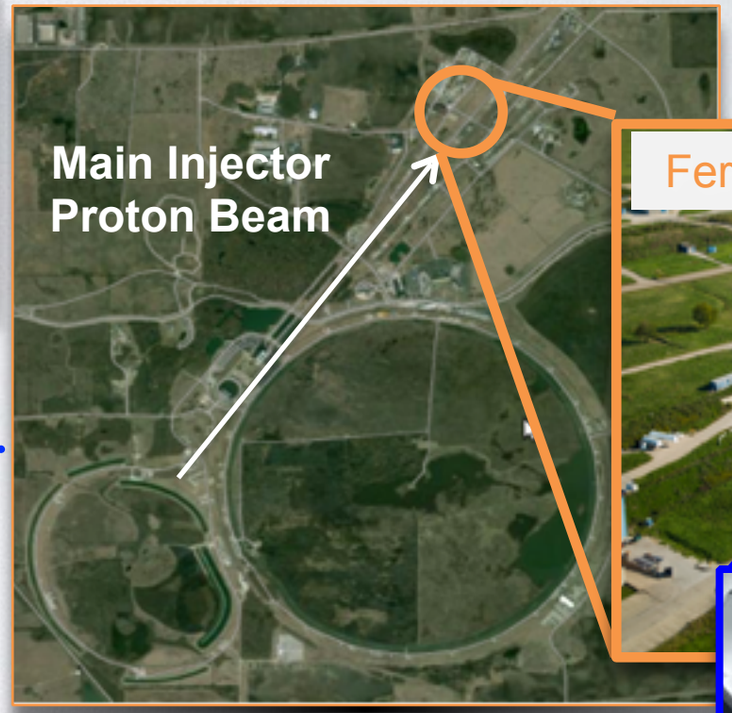
Status:

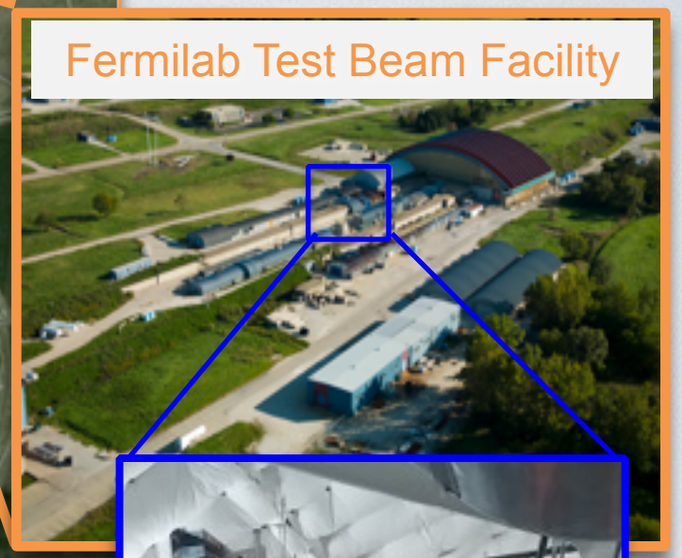
Physics Run 1 completed

- Data collected from April 30 to July 8,'15.
- Analysis ongoing (first results expected by end 2015)

Physics Run 2

- Start Run Feb. 2016





MCenter Tertiary Beam (looking upstream)

Goal:

Characterize LArTPC performance in the range of energies relevant to upcoming short- and long-baseline experiments for neutrino physics and for proton decay searches.

Physics

- Charged pion interaction cross section measurements (total & exclusive channels)
- Optimize pion and kaon ID
- Experimentally measure e-γ separation capabilities
- Develop criteria for muon charge sign determination w/out magnetic field
- Improve Energy Resolution and Particle Identification by combining information from scintillation light and ionization charge signals

R&D

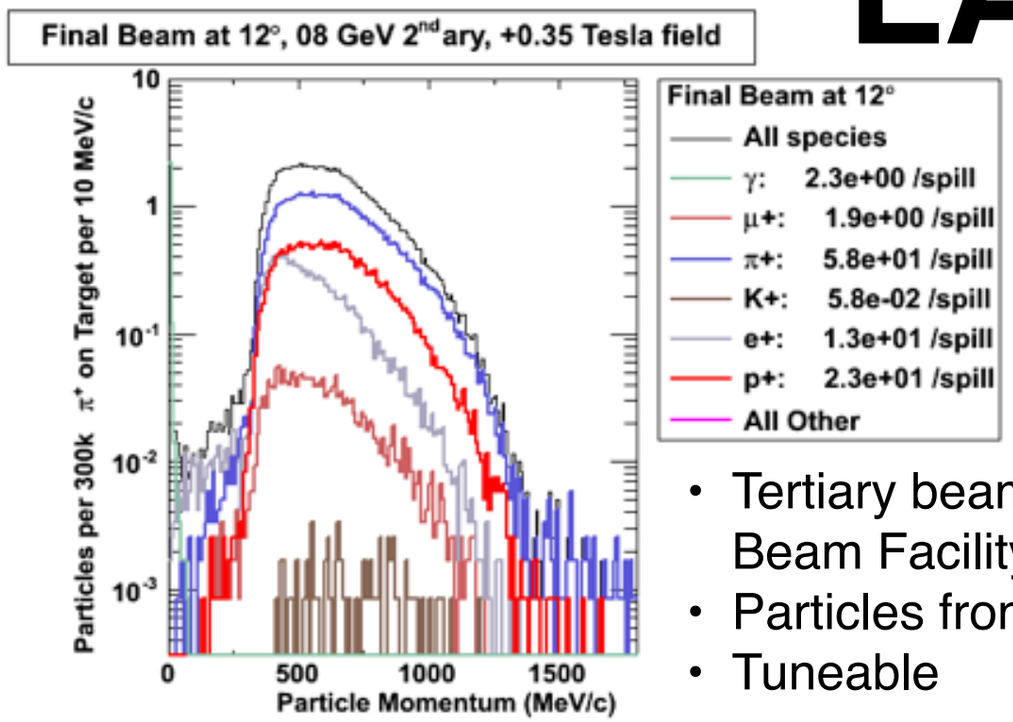
- Development of innovative Scintillation Light detection Systems for Liquid Argon Neutrino Detectors *with enhanced collection efficiency & uniformity*

LArIAT TPC

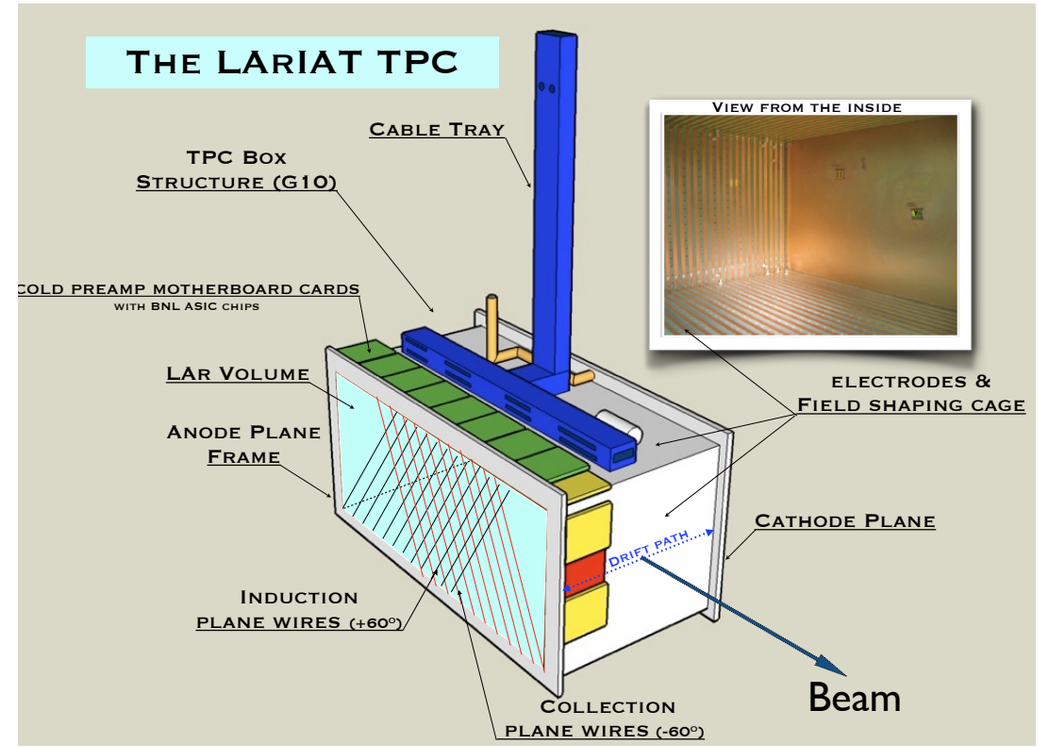
refurbished ArgoNeuT LArTPC

Events from Run 1

LArIAT



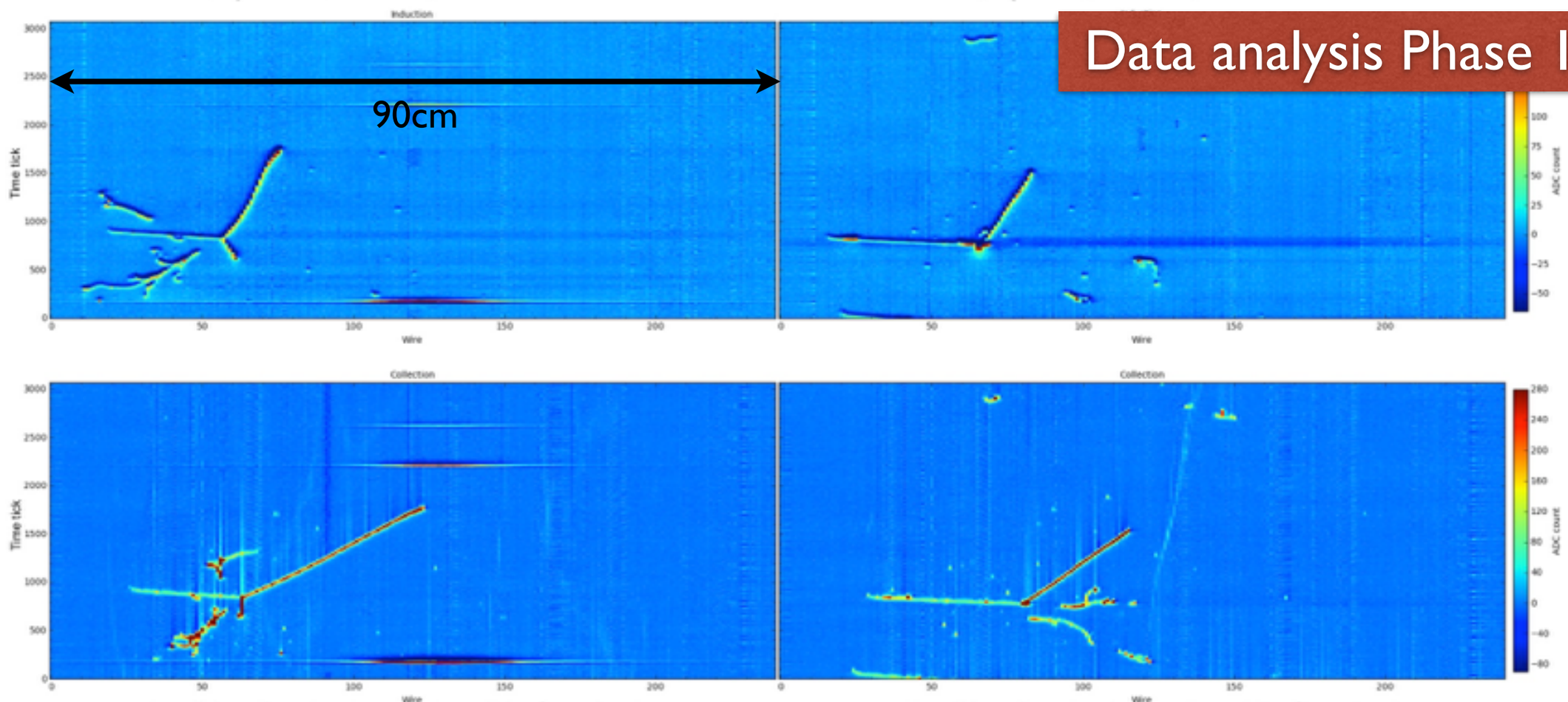
- Tertiary beam at FNAL Test Beam Facility (FTBF)
- Particles from 0.2 to 2 GeV
- Tuneable



Run 5979; Spill 136; Event 0; 2015-05-29 02:08:05

Run 6056; Spill 42; Event 0; 2015-06-05 18:49:53

Data analysis Phase I run



Candidate for pion interaction with π^0 production

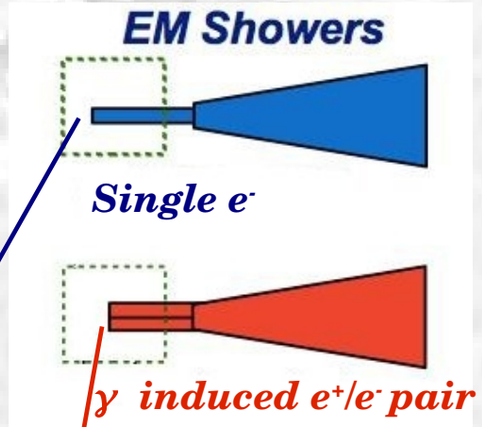
Candidate for pion interaction with π^0 production

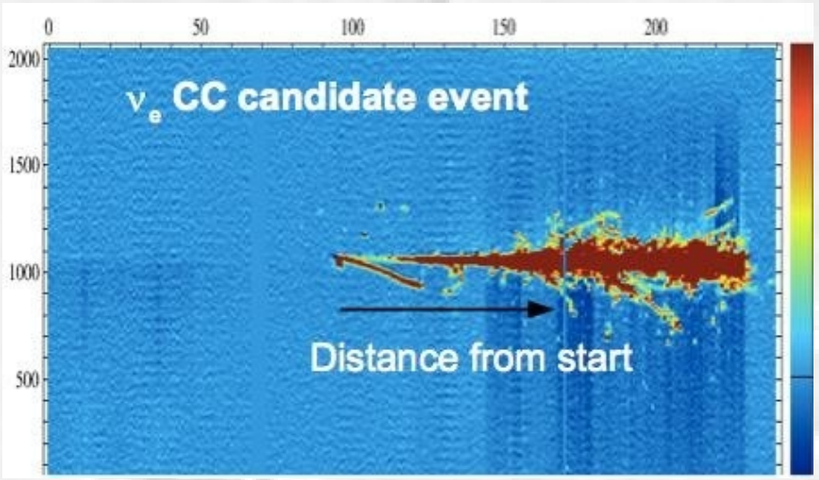
Electron/gamma separation

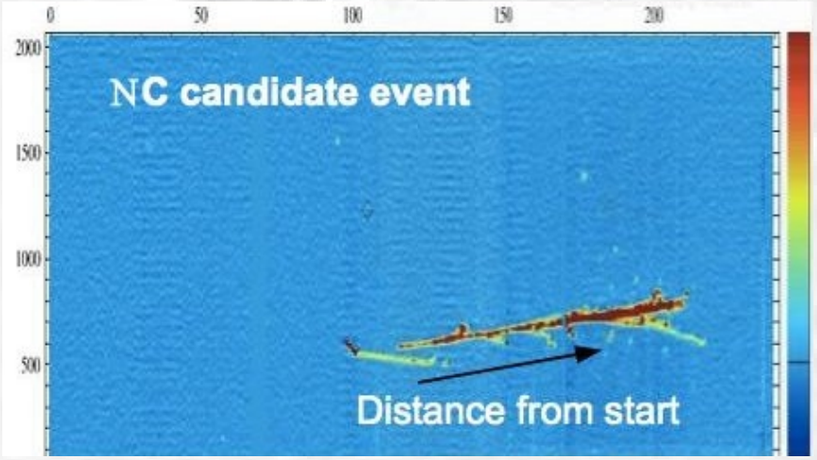
Important to discriminate ν_e CC signal from π_0 background coming from NC interactions

✔ Gammas defined as EM showers detached from visible vertex

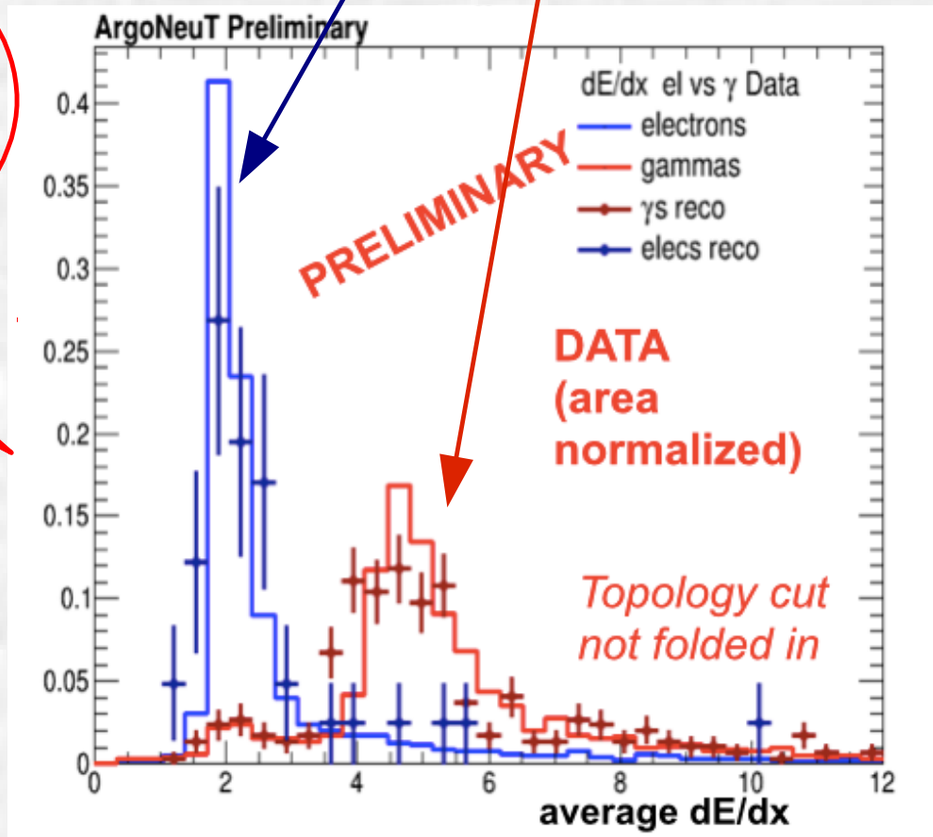
✔ Electrons defined as EM showers with visible vertex activity and no gap







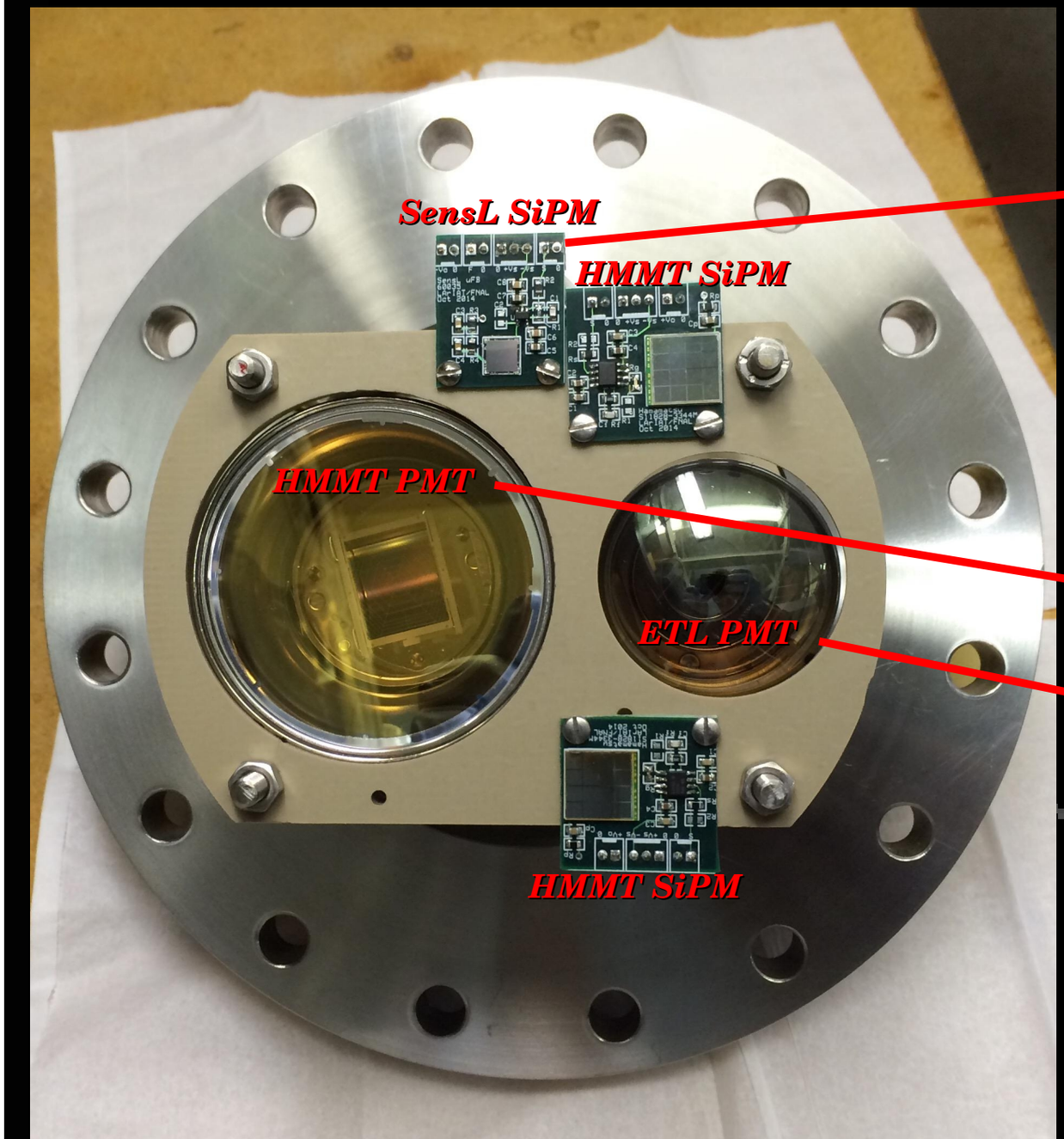
Additional discrimination tool given by the dE/dx of the first two centimeter of the track

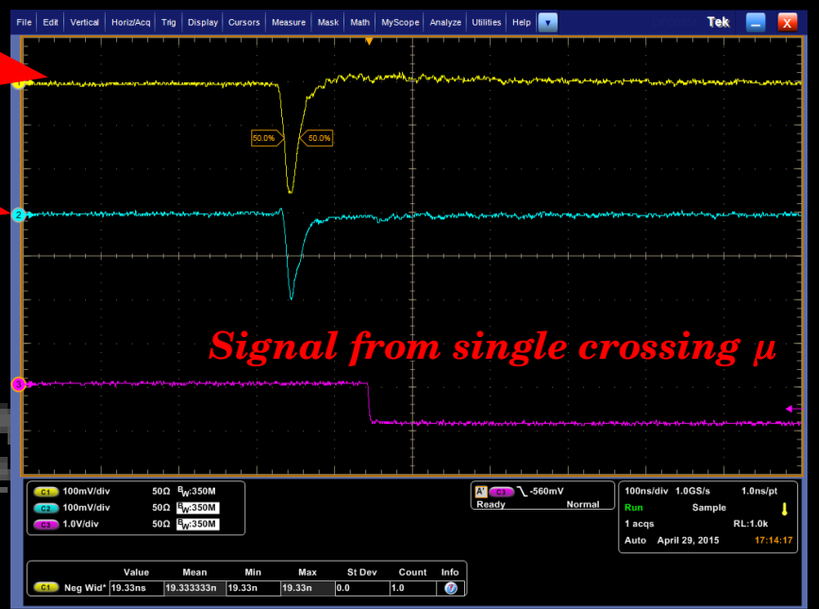


Paper under review

Light Collection System

2 PMTs and 3 SiPMs viewing the active volume through the wire planes





MicroBooNE

MicroBooNE TPC has been installed in the cryostat

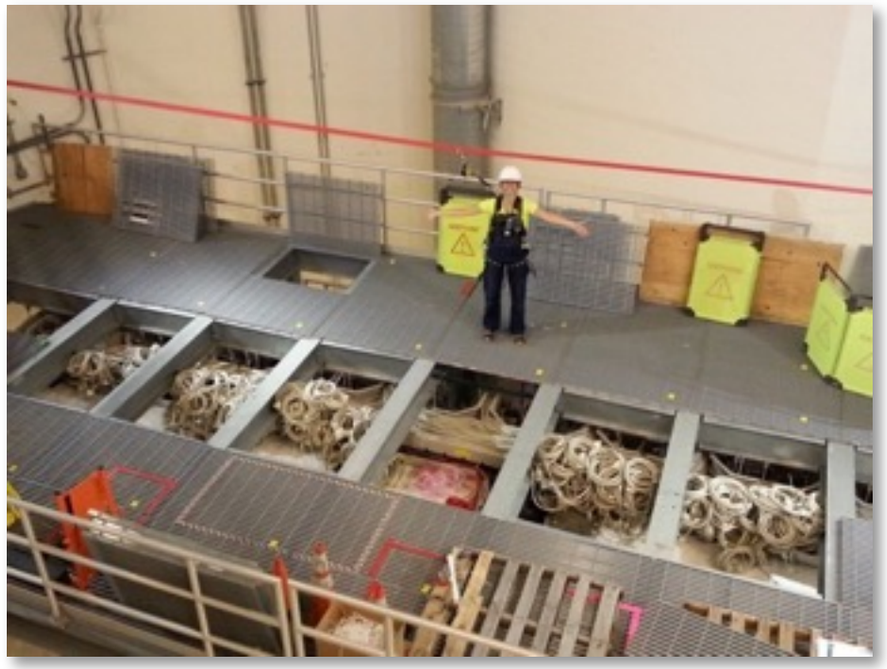
Purified argon is circulating and the foam saddles are installed → Building is ready to receive the detector!

- **170 ton (total) Liquid Argon Time Projection Chamber will be the largest LAr TPC in the U.S.**
- **Important step towards large scale LAr TPCs for long-baseline n physics**
- **Physics goals:**
  - *address MiniBooNE low energy excess*
  - *measure n cross sections on argon*
- **R&D goals:**
  - *argon fill without evacuation*
  - *cold front-end electronics*
  - *long drift (2.5m)*
  - *near surface operation*
  - *automated event reconstruction*

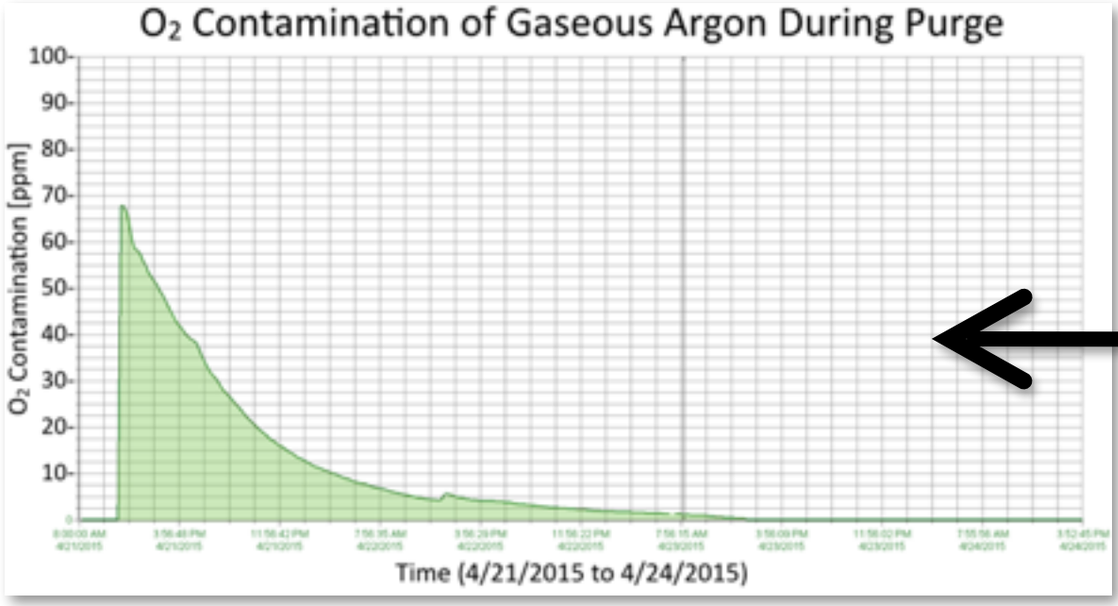
- Electron efficiency ~2x better than MiniBooNE
- e/γ differentiation removes νμ induced single photon backgrounds
- good efficiency for low energy (down to MeV)

MicroBooNE Highlights

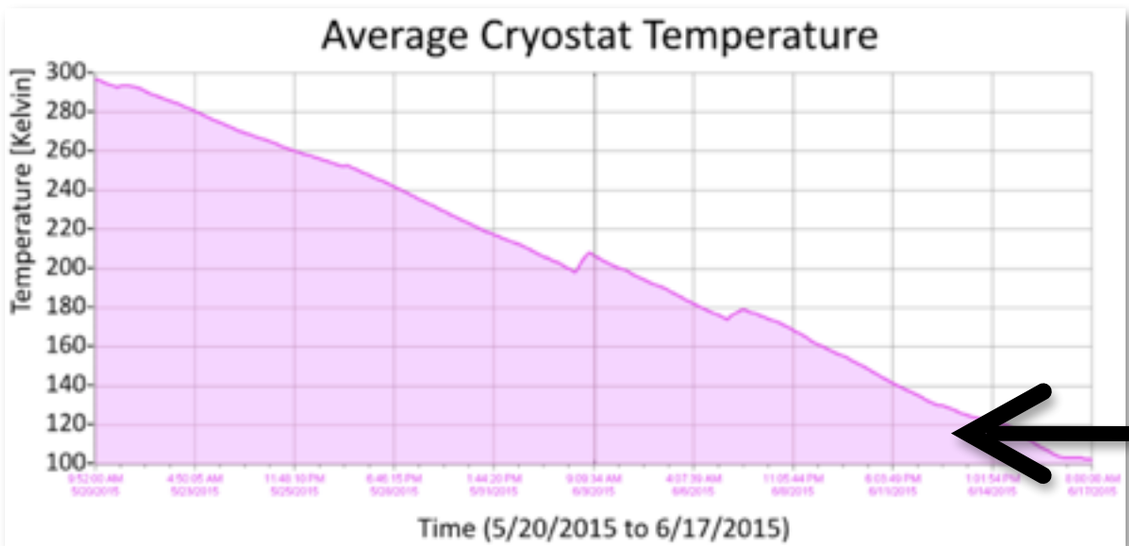
- winter 2013: TPC installed in cryostat
- summer 2014: detector moved to Booster ν beamline
- 2014-2015: installation and commissioning



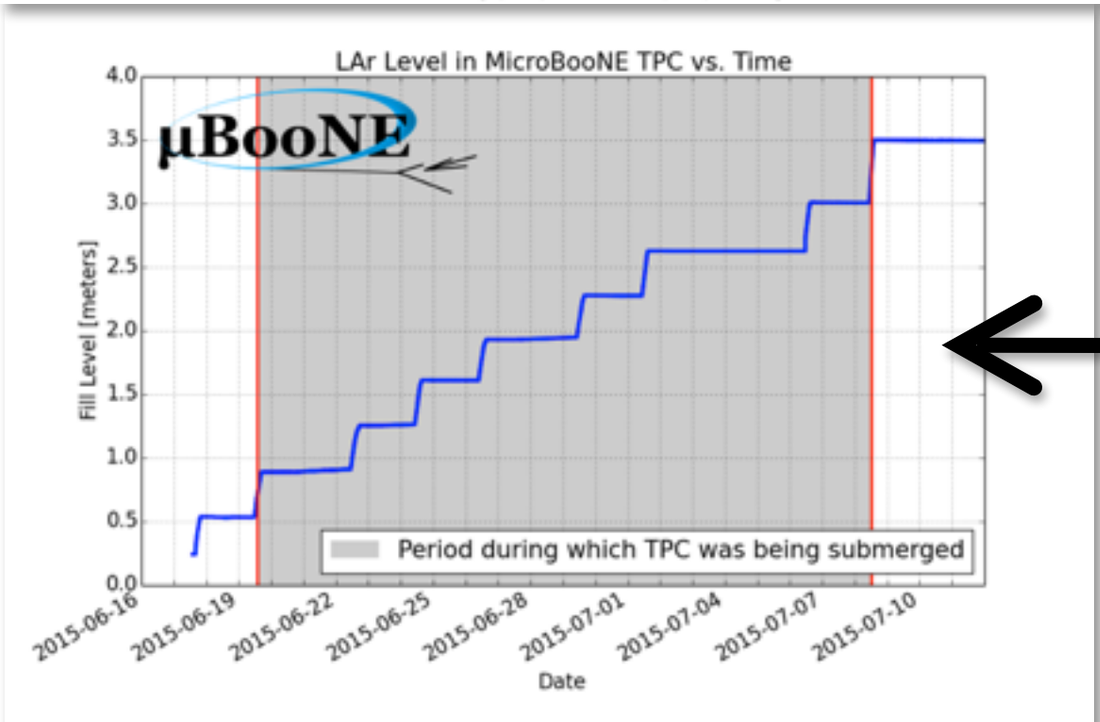
Successful Purge, Cooldown, and Fill



- <u>step 1</u>: purge with gaseous argon
  - *O_2 contamination reduced by 2 orders of magnitude in 10 volume exchanges*
  - *first demonstration of this technique in a fully instrumented physics experiment*
    - → *vessel evacuation not necessary*



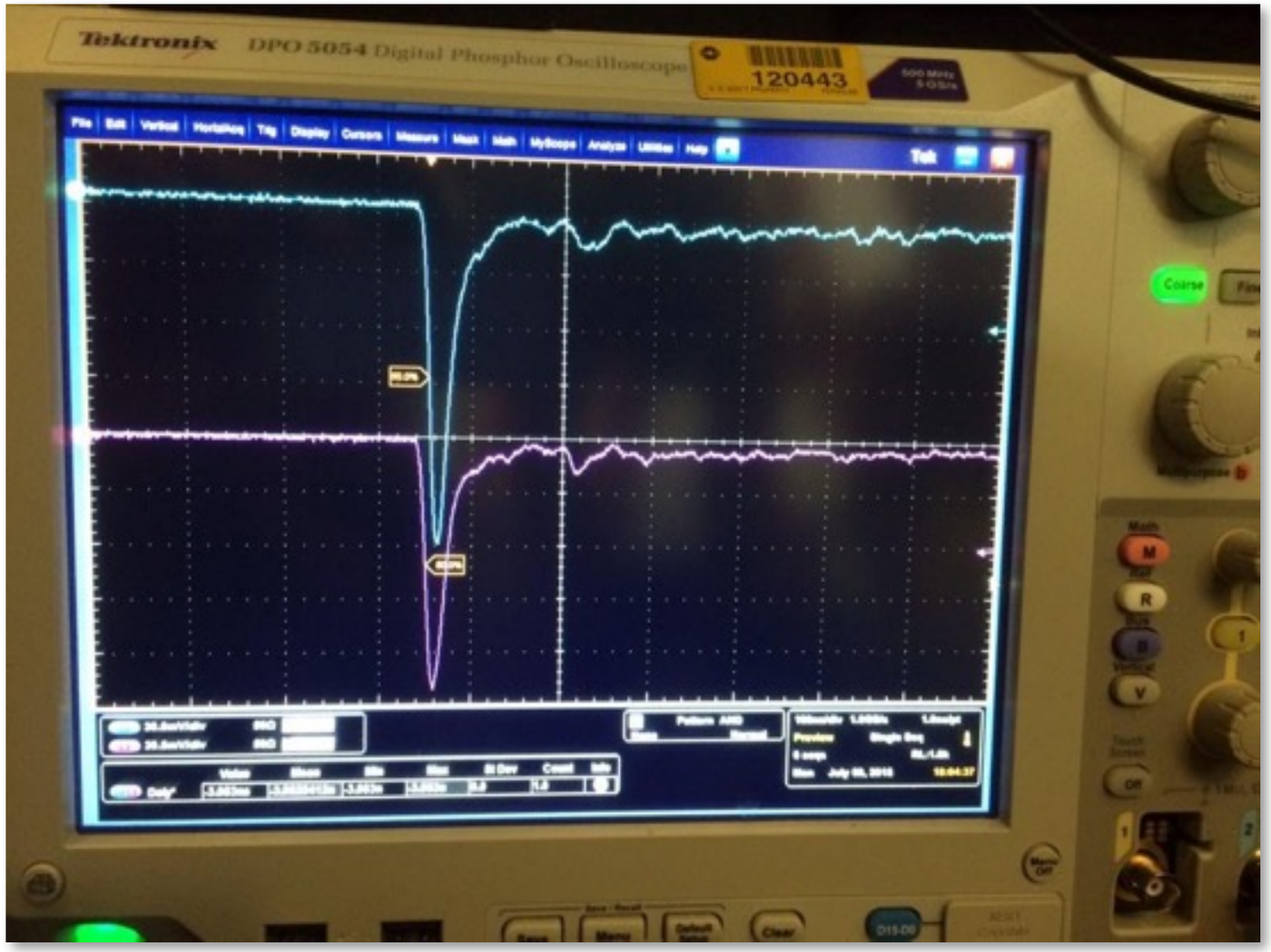
- <u>step 2</u>: cool to LAr temperatures
  - *slowly cooled down from 300 → 100 K over the course of 28 days*



- <u>step 3</u>: fill with liquid argon
  - *it took 9 tanker trucks to fill the vessel*
  - *detector is now filled with 34,000 gallons (170 tons) of high purity LAr*

Day After Fill

PMT system turned on

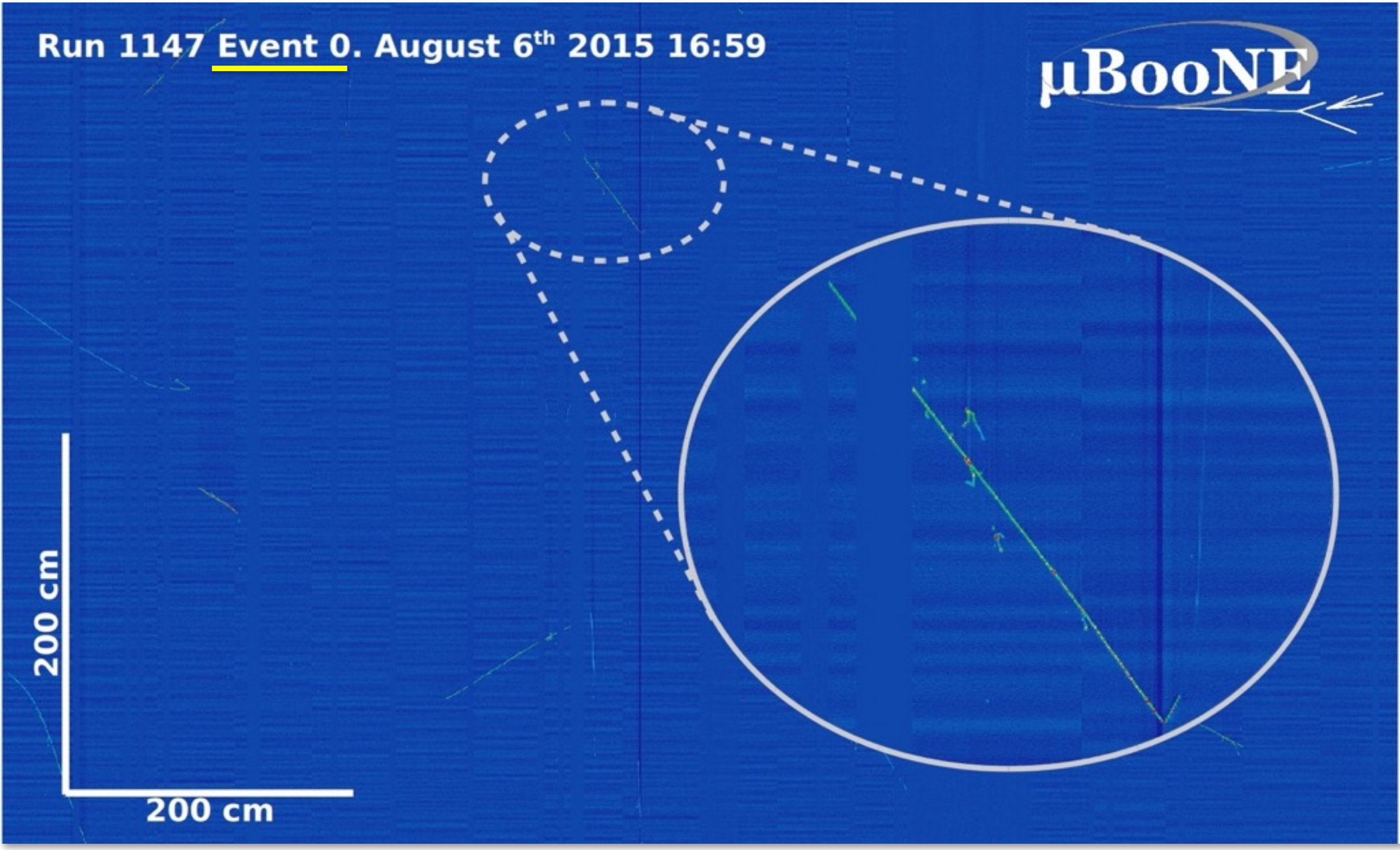


coincident pulses seen on adjacent PMTs

→ cosmic muon candidate!

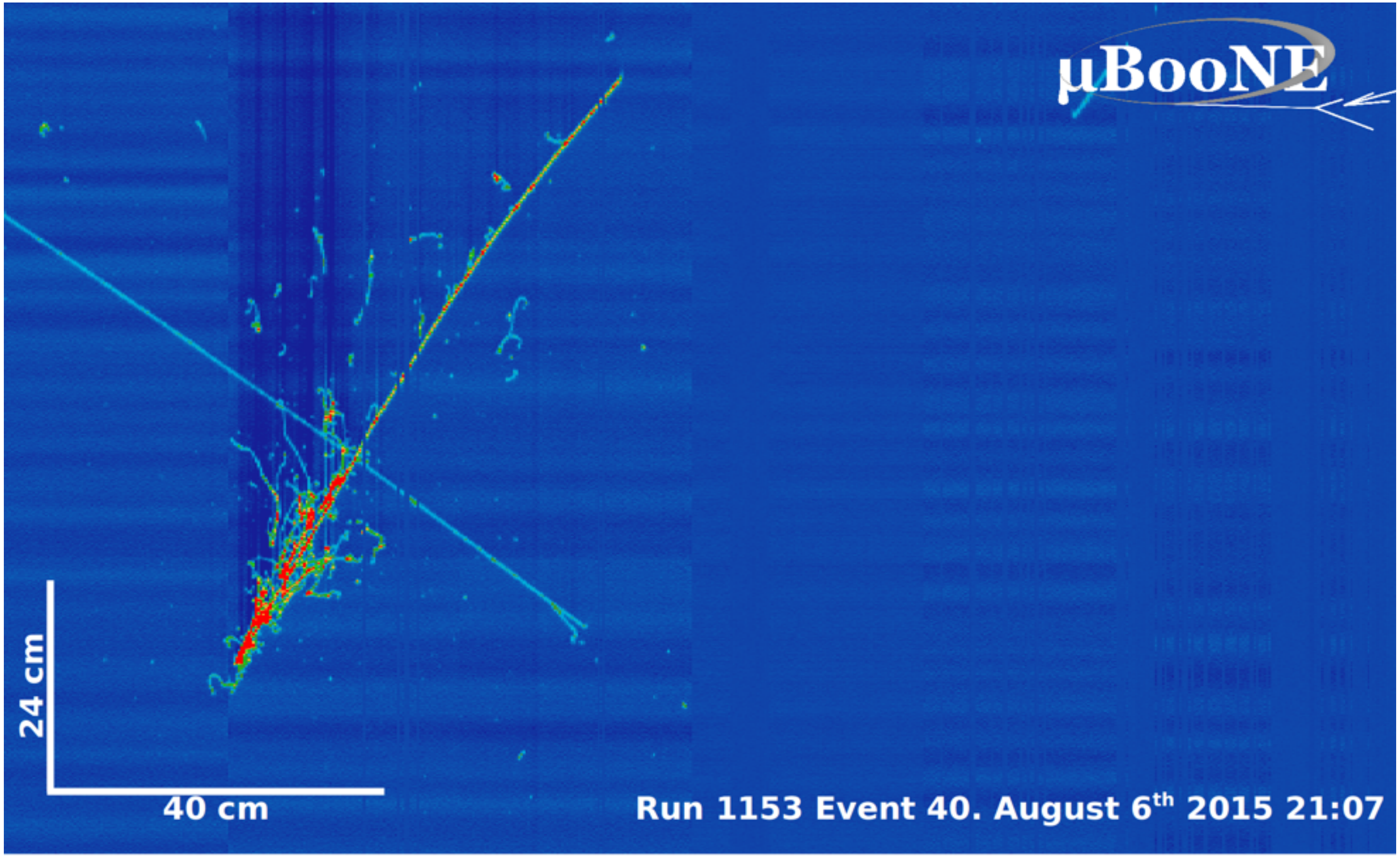
First Ramp of Drift High Voltage on August 6, 2015

First cosmic tracks!



raw cosmic ray data, drift HV at -58 kV

First shower



MicroBooNE summary

- MicroBooNE assembly and installation complete
- Detector filled with ultrapure LAr and running at 70kV
  - running at lower voltage is safer for the detector
  - excellent purity and minimal space charge effects allow us to make this conservative choice for now
  - Final commissioning underway
- First neutrino physics beam expected the week of October 12th
- Actively preparing tools and analyses for first physics!

MicroBOONE @ FNAL

- ★ Present MicroBooNE plan: Neutrino running, 6.6E20 POT
- ➡ first large statistics fully contained neutrino exclusive final states and cross-section measurements with a LAr TPC. One regret: no muon spectrometer, for cross-sections.

Expected event rates for 6.6 x 10^{20} POT

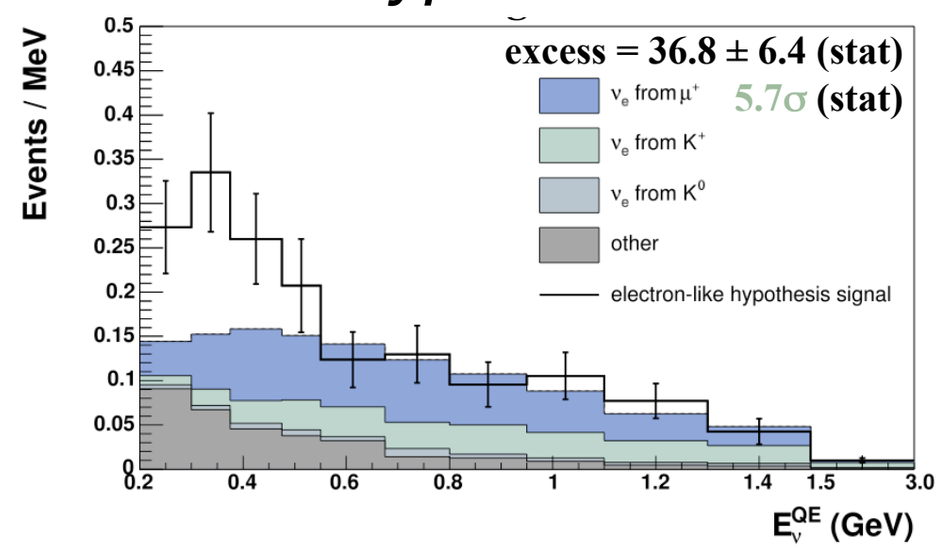
production mode	# events
CC QE ($\nu_\mu n \to \mu^- p$)	60,161
NC elastic ($\nu_\mu N \to \nu_\mu N$)	19,409
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	25,149
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	6,994
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	7,388
NC resonant $\pi^\pm$ ($\nu_\mu N \to \nu_\mu N' \pi^\pm$)	4,796
CC DIS ($\nu_\mu N \to \mu^- X$, $W > 2$ GeV)	1,229
NC DIS ($\nu_\mu N \to \nu_\mu X$, $W > 2$ GeV)	456
NC coherent π^0 ($\nu_\mu A \to \nu_\mu A \pi^0$)	1,694
CC coherent π^+ ($\nu_\mu A \to \mu^- A \pi^+$)	2,626
NC kaon ($\nu_\mu N \to \nu_\mu K X$)	39
CC kaon ($\nu_\mu N \to \mu^- K X$)	117
other ν_μ	3,678
total ν_μ CC	98,849
total ν_μ NC+CC	133,580
ν_e QE	326
ν_e CC	657

Exclusive neutrino cross-sections on Ar

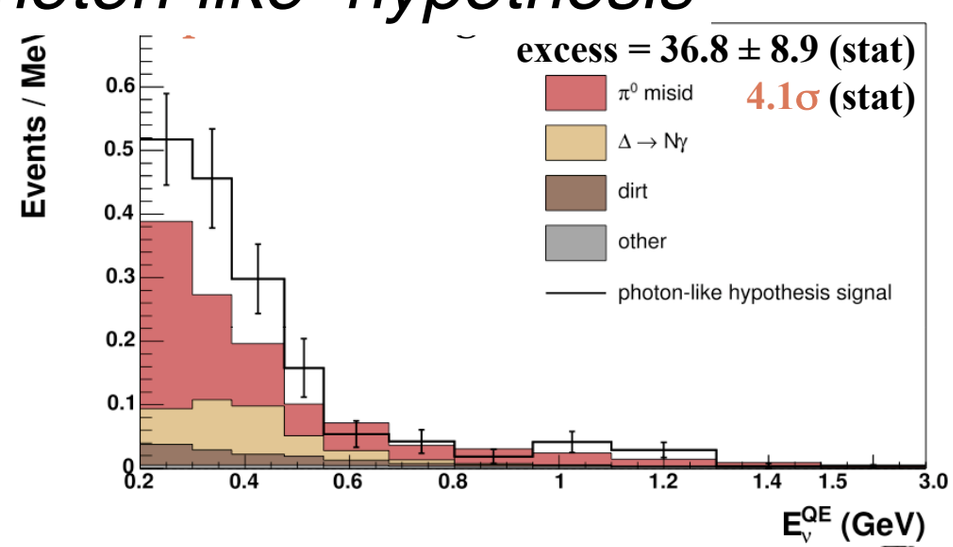
MiniBoone low energy:

e or γ?

Electron-like hypothesis



Photon-like hypothesis



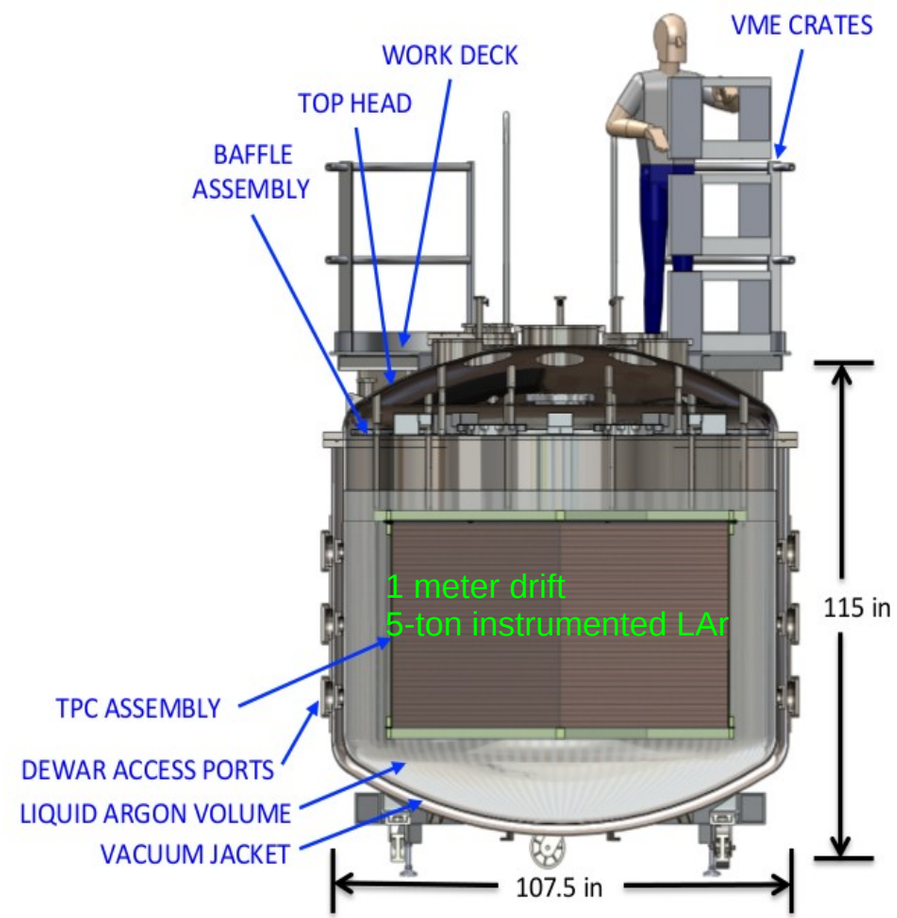
CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

Aim at unique measurements of **neutron-argon (at the Weapons Neutron Research (WNR) Facility at Los Alamos)** and **neutrino-argon** interactions relevant to DUNE

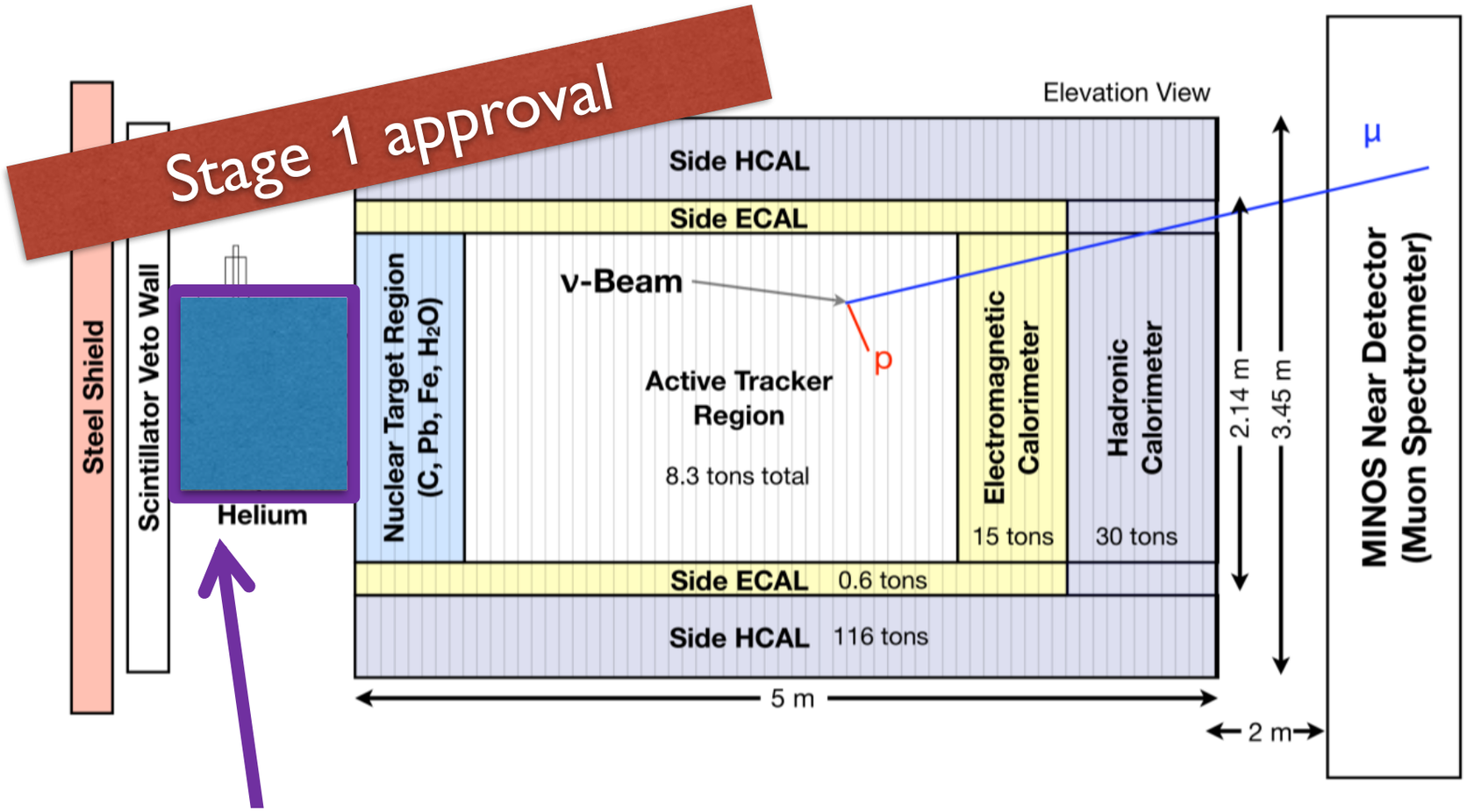
Measurement of DAR neutrinos on LAr at FNAL BNB beam (off-axis) – direct relevance to DUNE for detection of supernova neutrino burst.

Prototype (MiniCAPTAIN) under construction

- Fun… Research and …tutional collaboration
- …scale TPC and a prototype
- 7700 L cryostat (**Portable and evacuable**)
- 500 V/cm drift field and 1.6 mm/μs drift velocity
- 2001 channels (667/plane), 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system (Hamamatsu R8520-500 PMTs)
- MicroBooNE cold electronics
- Purification system design based on MicroBooNE and LAPD



CAPTAIN-MiNERvA @ NUMI



MINERvA will be used as a hadronic calorimeter for events where final state particles exit CAPTAIN.

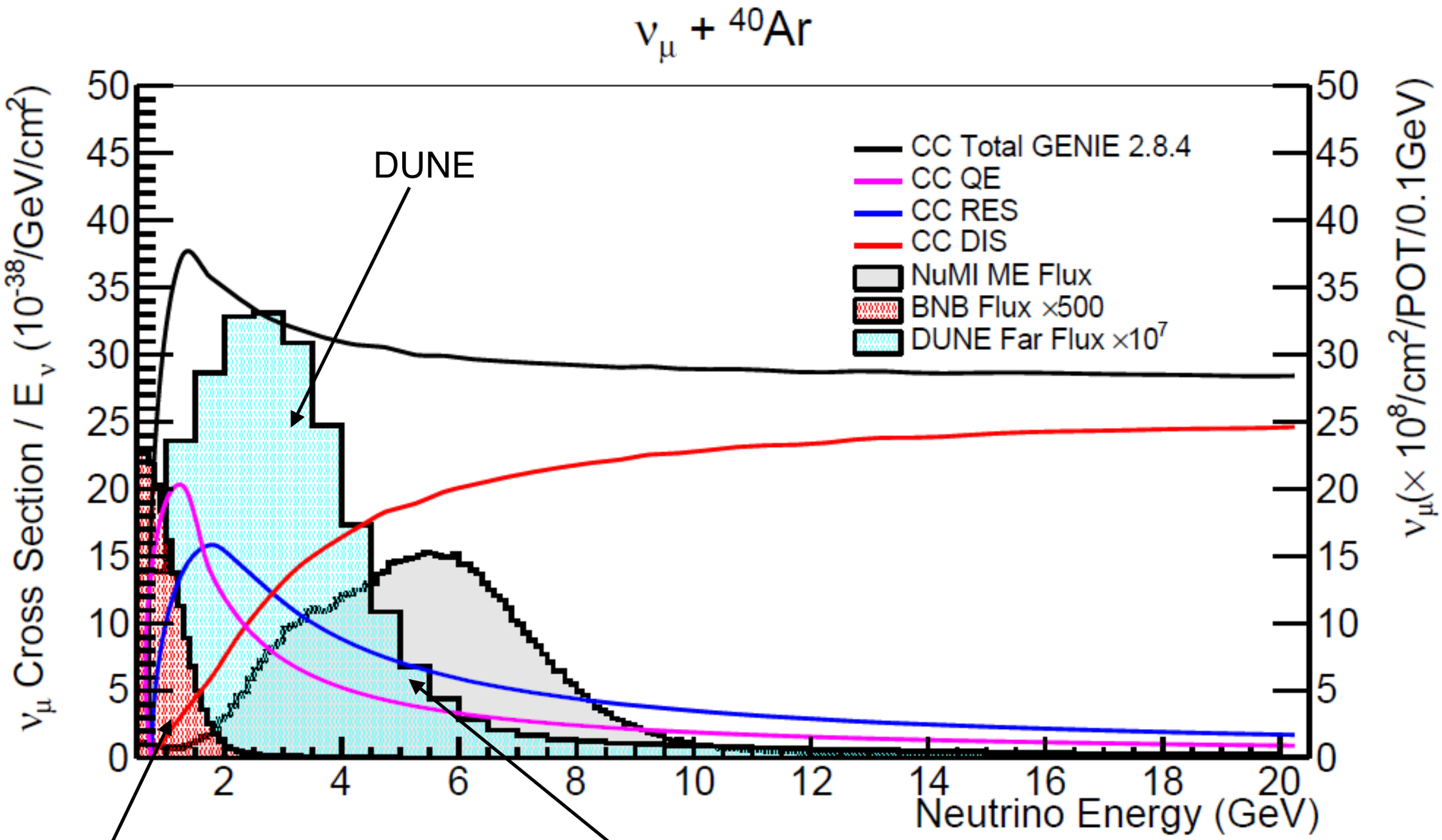
MINOS as a magnetized Muon Catcher.

~10-15% of CC interactions will have the hadronic energy contained in CAPTAIN and have a muon reconstructed by MINOS or MINERvA.

	CC events with muon reconstructed (MINOS or MINERvA)	CC events with muon reconstructed by MINOS
6×10^{20} POT Neutrino mode	Events w/ reco μ	Events w/ reco μ and charge
CCQE-like	916k	784k
$CC1\pi^{\pm}$	1953k	966k
$CC1\pi^{0}$	1553k	597k

- Presented LOI to the Fermilab PAC in January 2015
- Presented proposal to Fermilab PAC in June 2015
- Received Stage 1 approval from Fermilab Director in July 2015
- Submitted proposal for funding from DOE's Intermediate Neutrino Research Program ~1 month ago
- The CAPTAIN detector will be commissioned at a surface location at Fermilab beginning in ~2017, with preparations beginning in 2016
- Neutrino data with CAPTAIN-MINERvA beginning in ~2018
- One year (6×10^{20} POT) in neutrino mode + one year in antineutrino mode (contingent on NuMI schedule)

Covering the energy range for DUNE



ArgoNEUT, MicroBOONE, SBND, ICAR-US

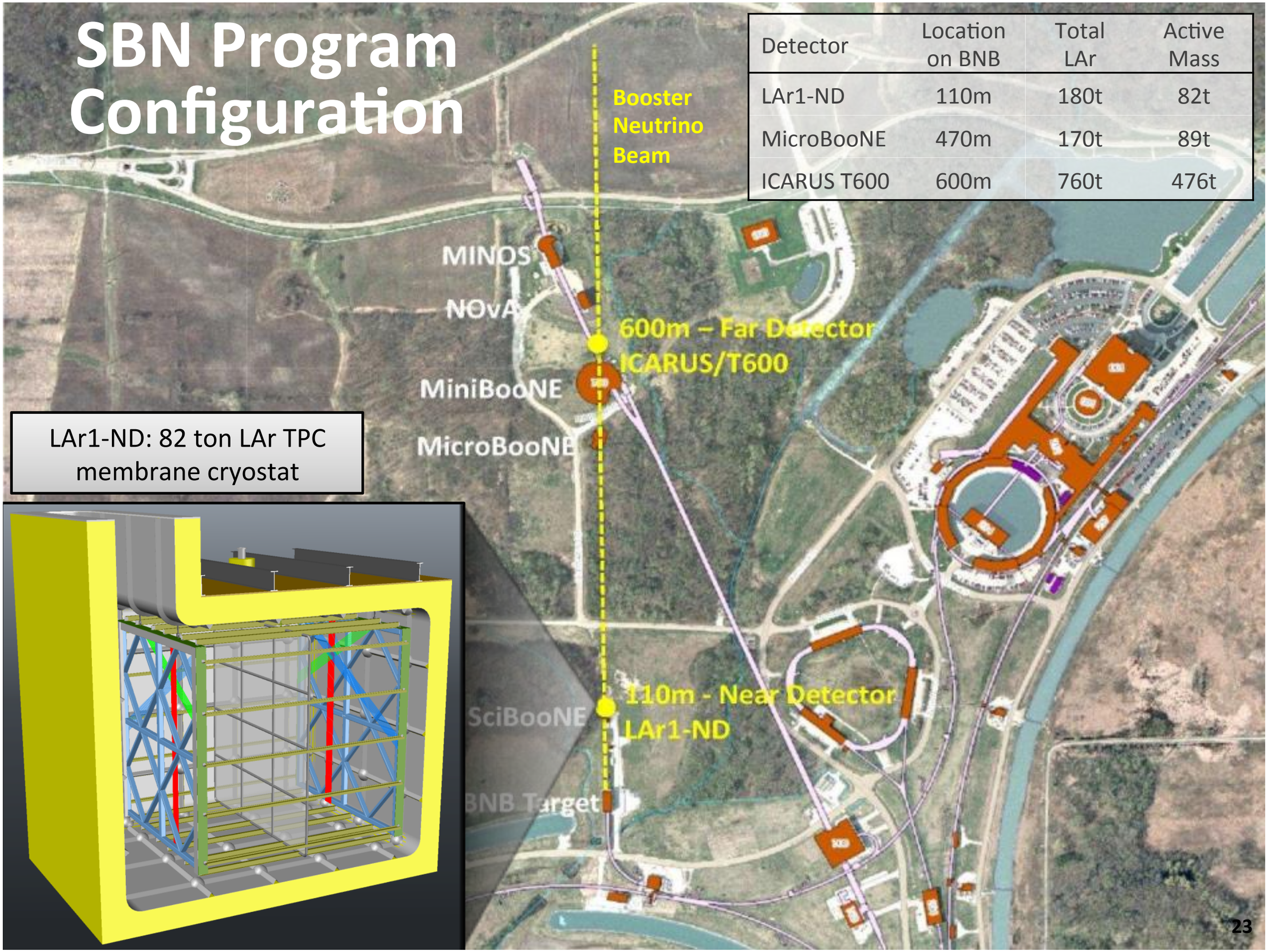
CAPTAIN-MINERvA

Mostly relevant for DUNE atmospheric & proton decay searches

BNB+NUMI : relevant energy neutrino range for DUNE
Need also antineutrinos!

SBN Program Configuration

Detector	Location on BNB	Total LAr	Active Mass
LAr1-ND	110m	180t	82t
MicroBooNE	470m	170t	89t
ICARUS T600	600m	760t	476t

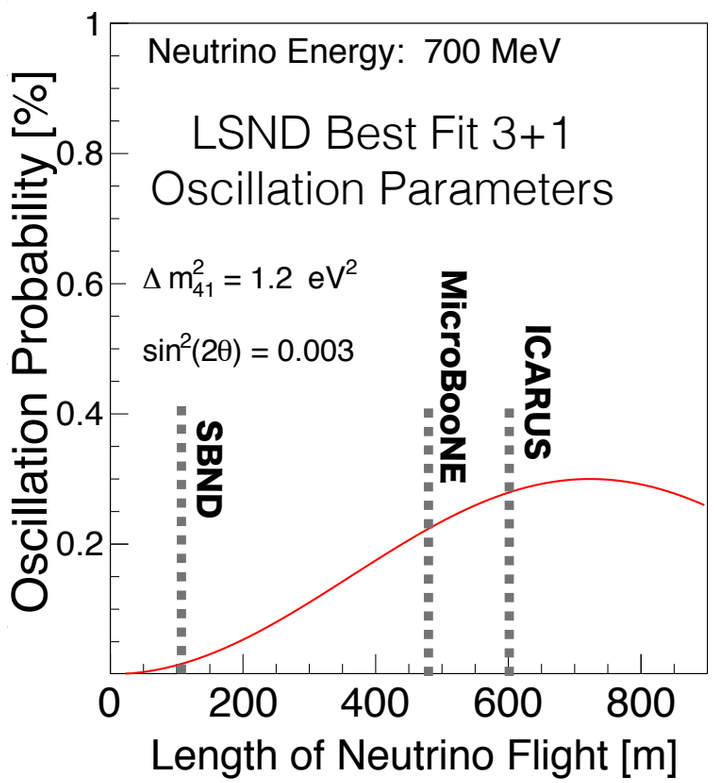


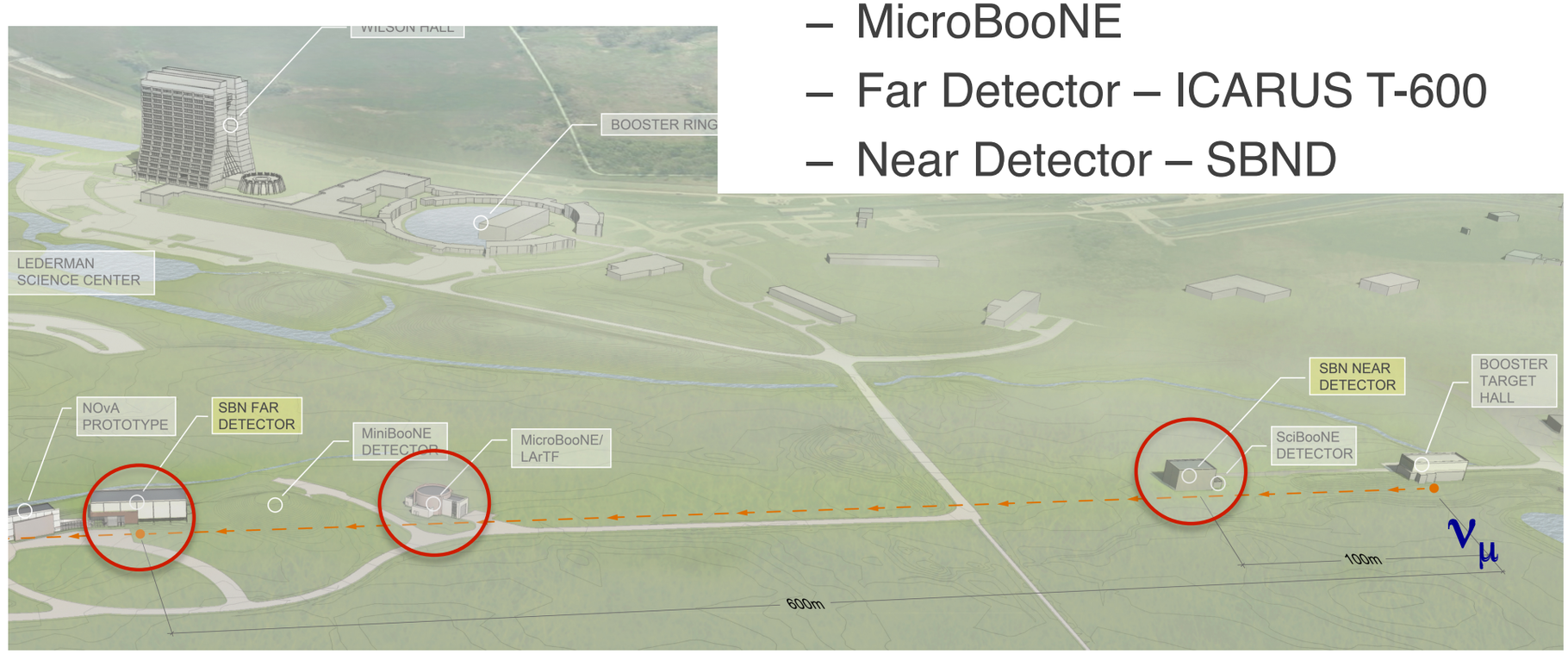
LAr1-ND: 82 ton LAr TPC membrane cryostat

Short Baseline Neutrino @ FNAL

- Booster Neutrino Beam :
  - 8 GeV Booster protons produce ~1 GeV neutrino beam
  - Max. rep. rate : 5 Hz; typical : 2 Hz (when NuMI operating)
  - 5×10^{12} POT/spill; ~2 – 3 $\times 10^{20}$ POT/yr with current configuration

- Three detector physics program :
  - MicroBooNE
  - Far Detector – ICARUS T-600
  - Near Detector – SBND





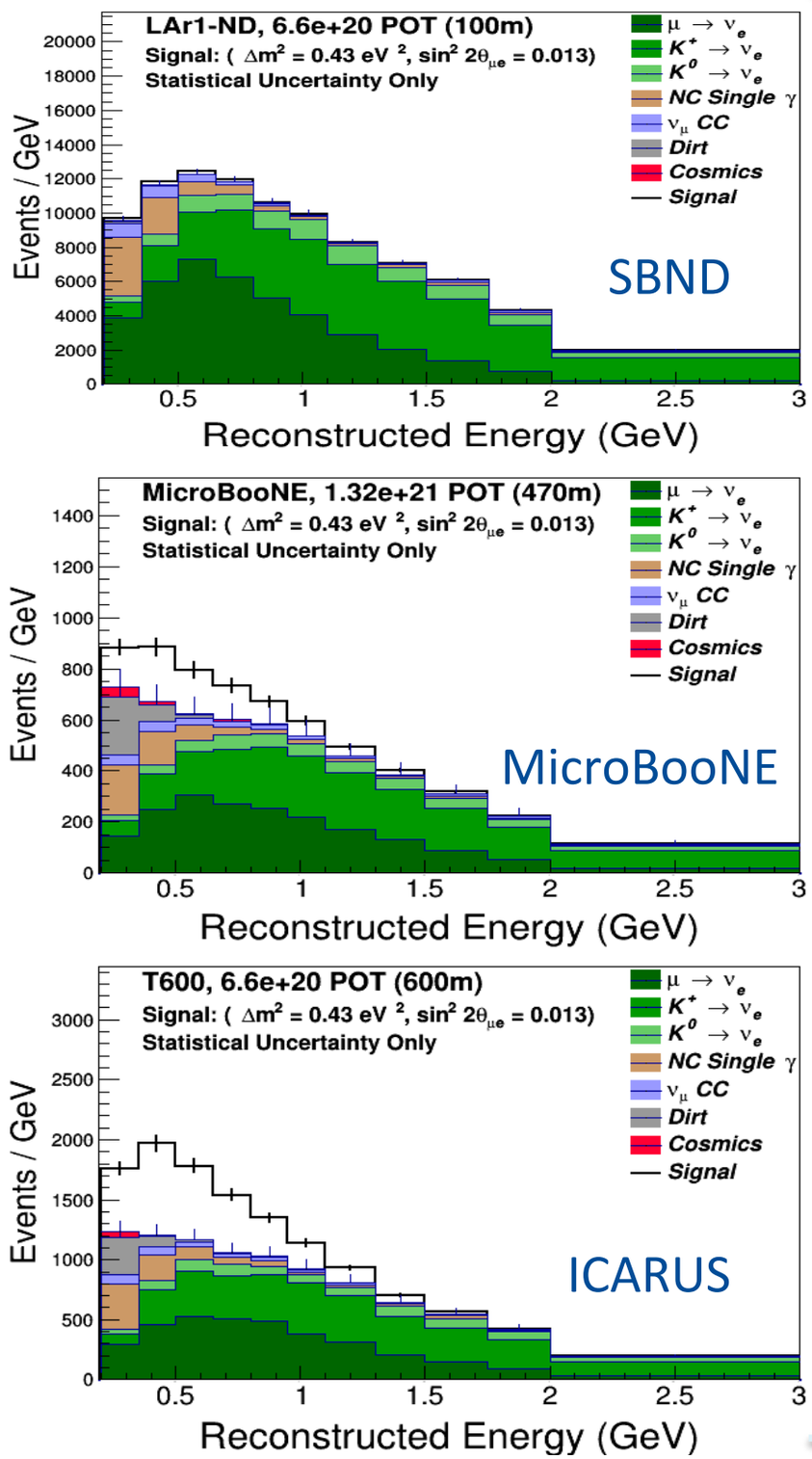
	ICARUS	MicroBooNE	SBND	Produce
ν_μ Disappearance	Fewer ν_μ ?	Fewer ν_μ ?	ν_μ	ν_μ
ν_e Appearance	More ν_e?	More ν_e?	~1% ν_e	~1% ν_e

110m

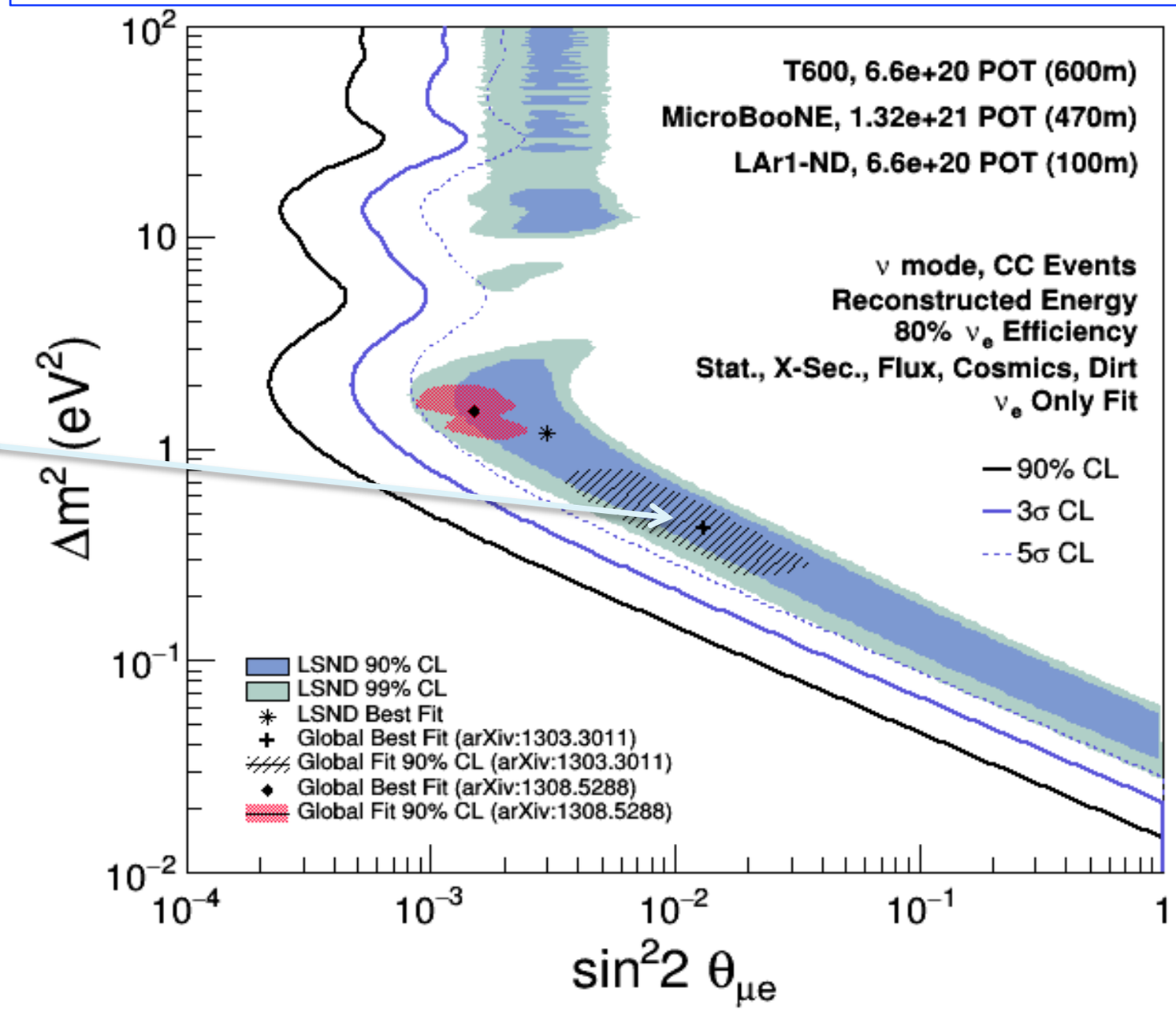
470m

600m

SBN electron appearance sensitivity

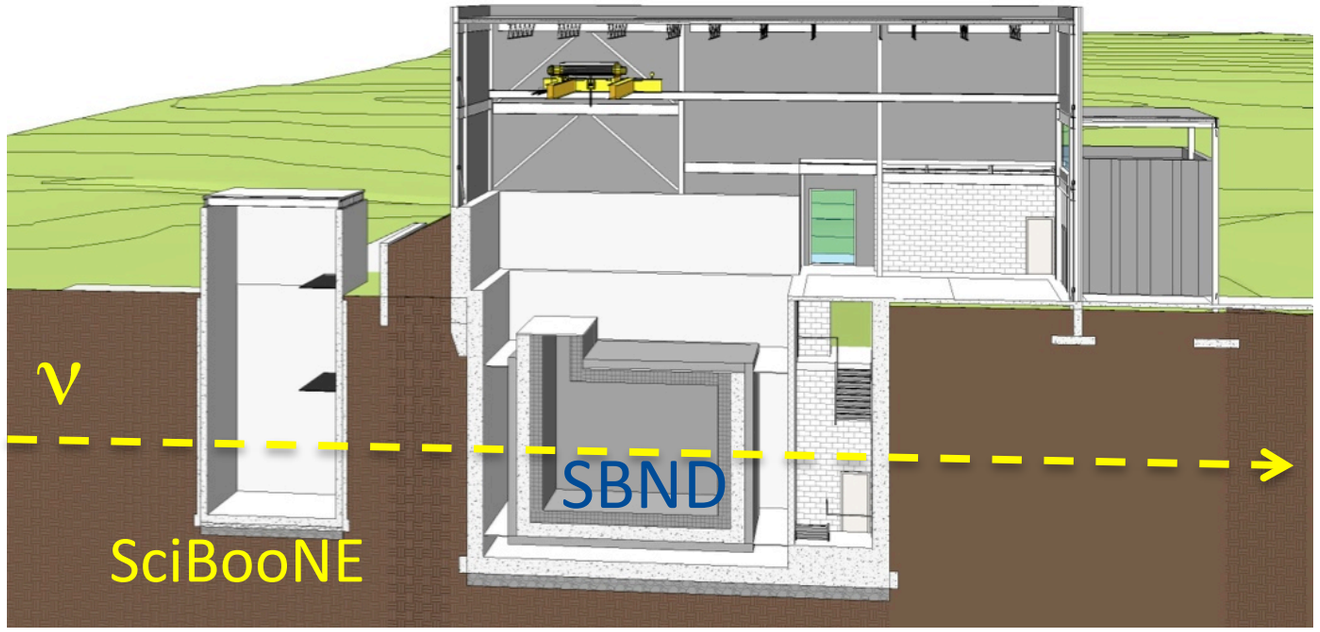


~5σ coverage of LSND 99% CL Region for 6.6×10^{20} P.O.T. ~ 3 years (13.2×10^{20} for MicroBooNE)



SBND: status

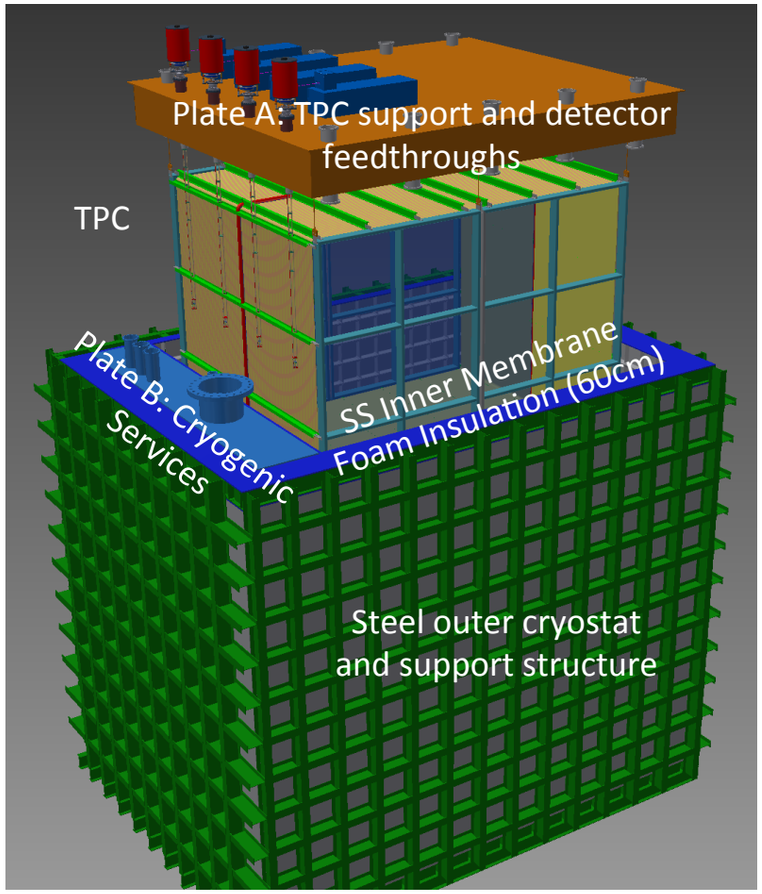
- The near detector building is finalizing its design with construction scheduled to begin October 2015



- The designs for the cryostat and TPC are maturing quickly

Prototyping effort: APA wire chambers, cold electronics, PDS, etc.

Synergies with DUNE/LBNF



https://indico.fnal.gov/conferenceDisplay.py?confId=10271

SBND - ν Event rates

Process		No. Events	Events/ ton	Stat. Uncert.
	ν_μ Events (By Final State Topology)			
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	· $\nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	· $\nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	· $\nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	· $\nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924	2,330	0.20%
NC $>2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ > 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443	3,200	0.17%
	ν_e Events			
CC Inclusive		36798	329	0.52%
NC Inclusive		14351	128	0.83%
Total ν_μ and ν_e Events		7,251,948	64,750	
	ν_μ Events (By Physical Process)			
CC QE	$\nu_\mu n \to \mu^- p$	3,122,600	27,880	
CC RES	$\nu_\mu N \to \mu^- \pi N$	1,450,410	12,950	
CC DIS	$\nu_\mu N \to \mu^- X$	542,516	4,844	
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	18,881	169	

ν_μ-Ar
(7 Million in 3 years)

ν_e-Ar
(50,000 in 3 years)

Estimated event rates (GENIE) in the SBND active volume (112 ton) for a 6.6 10^{20} POT exposure

A fundamental source of information for LBL – need antineutrinos as well

Timescale of SBN program

EPOC	EXPT	2015	2016	2017	2018	2019	2020		
NOW	MINOS+	RUN							
NOW	MicroBooNE		RUN 1			RUN - SBN			
NEXT	SBND		BUILD + INSTALL *			RUN - SBN			
NEXT	ICARUS		REFURBISH+INSTALL*			RUN - SBN			
NEXT+	?							decide	????

PROGRESS

MINOS+ → $\sin^2 2\theta_{24}$ sensitivity ~ 0.02 (90%CL) for Δm^2 ~ 0.5 eV^2

MicroBooNE → MiniBooNE anomaly e or γ determination at 4-5 σ

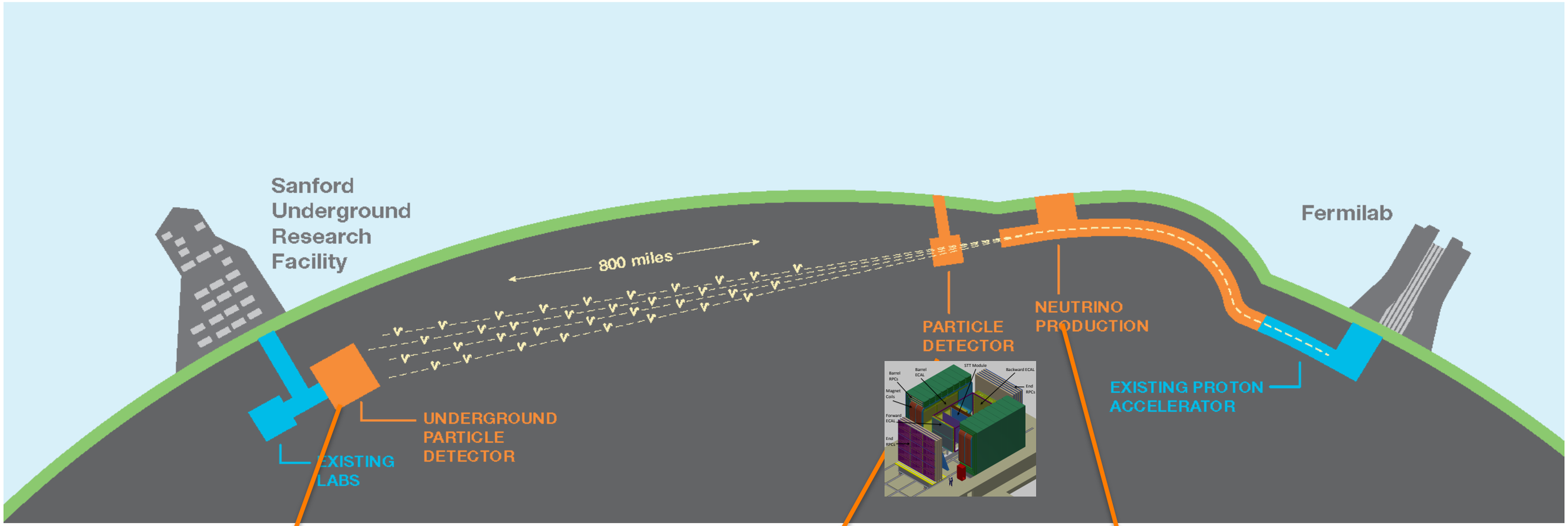
SBN → Increasing sensitivity to LSND anomaly

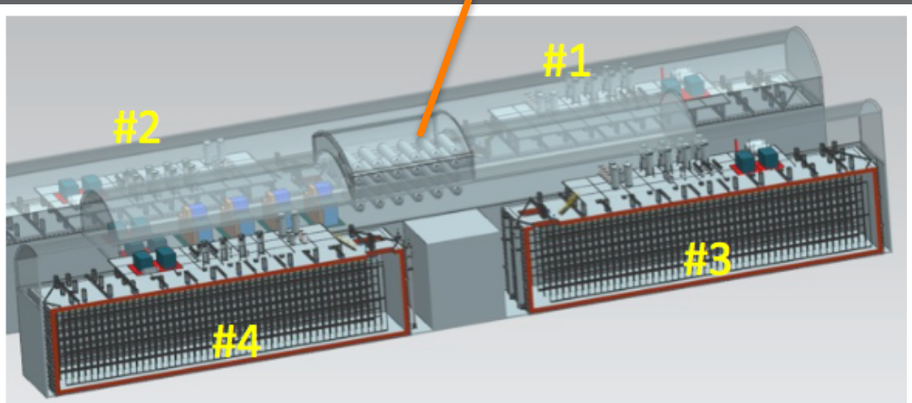
5σ

* Important contributions from CERN Neutrino Platform and European funding agencies (INFN, STFC, SNSF)

DUNE long baseline experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT





high precision
near detector

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

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

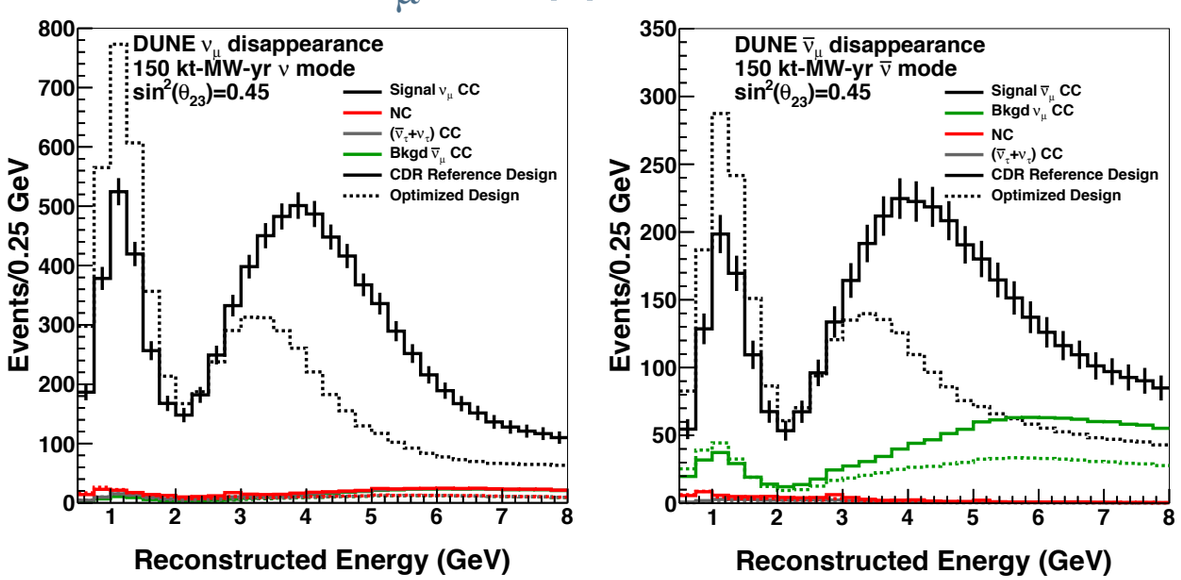
DUNE LBL oscillation strategy

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

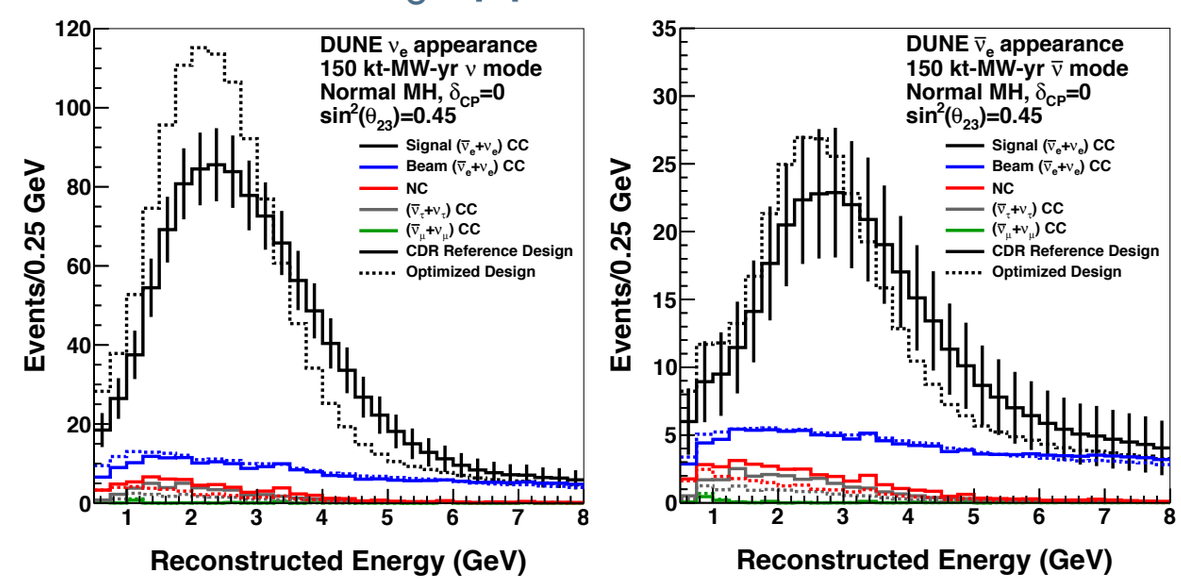
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Study $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) and $\nu_\mu \to \nu_x$ ($\bar{\nu}_\mu \to \bar{\nu}_x$) over range of energies
    - MH & CPV effects are separable

Systematic errors to be negligible compared to statistical power reached over lifetime of experiment

ν_μ disappearance

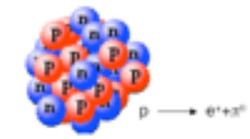


ν_e appearance



Precisely compare neutrinos <u>and</u> antineutrinos samples

Nucleon decay ↔ GUT theories



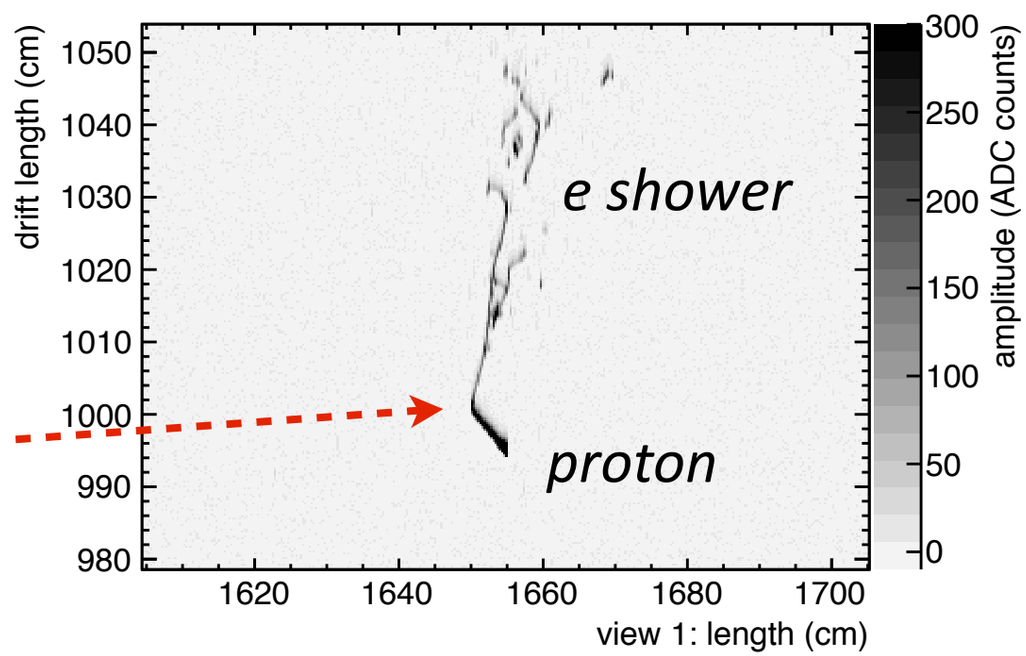
Generational advance in detection method:
Exploit tracking and calorimetry for unbiased, exclusive final state reconstruction of decay products with precise kinematics

Atmospheric neutrinos: the most abundant sample of events in DUNE in the GeV range (≈4000 events/year)!

For a 20kton exposure of 10 years (200 kton×year)

JHEP 0704 (2007) 041

Atm MC: $\nu_e \mathrm{CC}$

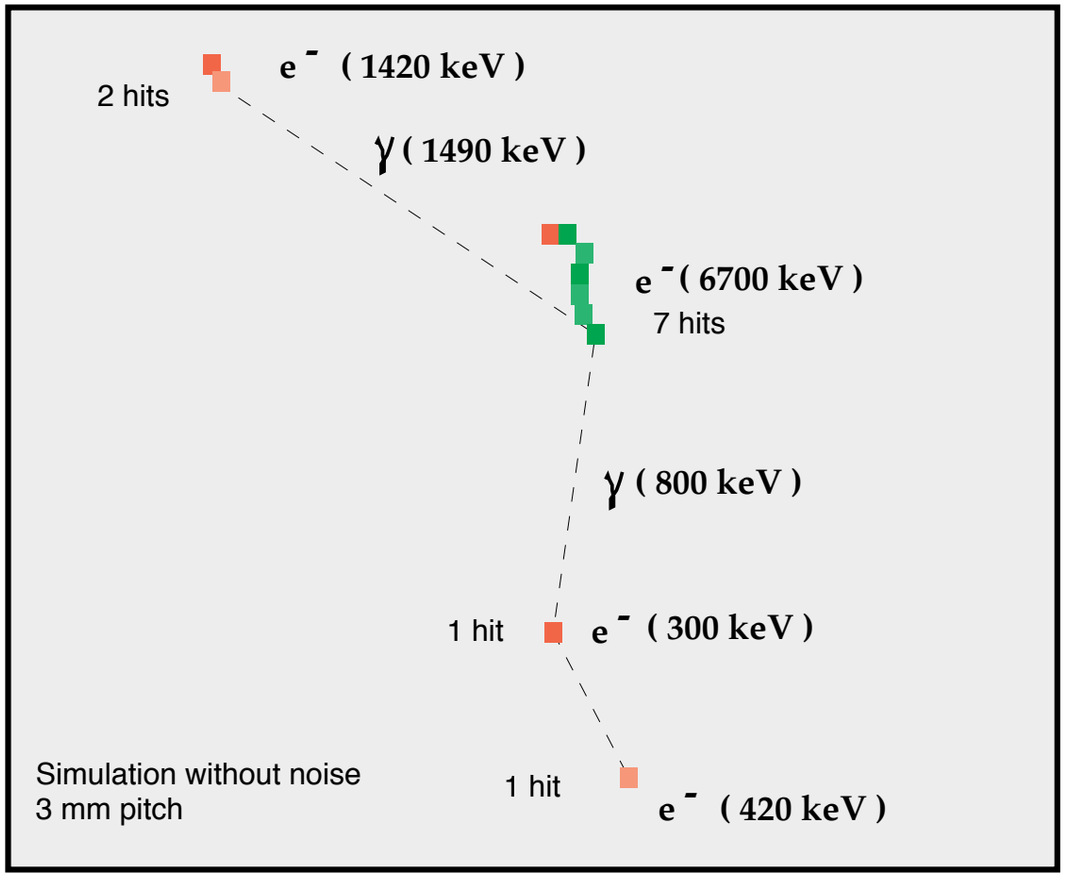


Mode	Lifetime (90%C.L.)
$p \to \nu K^+$	$>3\times10^{34}$ yrs
$p \to e^+\gamma$, $p \to \mu^+\gamma$	$>3\times10^{34}$ yrs
$p \to \mu^-\pi^+K^+$	$>3\times10^{34}$ yrs
$n \to e^-K^+$	$>3\times10^{34}$ yrs
$p \to \mu^+K^0$, $p \to e^+K^0$	$>1\times10^{34}$ yrs
$p \to e^+\pi^0$	$>1\times10^{34}$ yrs
$p \to \mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n \to e^+\pi^-$	$>0.8\times10^{34}$ yrs

Expect ≈linear sensitivity improvement with exposure until 1000 kton×year

Supernova neutrino burst detection

An example of beautiful event at low energy: e.g. supernovae, solar neutrinos



Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Not much information in literature

Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Can use for pointing

Track length !

$E_{\text{primary electron track}}$ = 6700 keV

Associated Compton energy= 2140 KeV

Multiplicity of secondary tracks= 3

Requires very low detection threshold on single readout channel

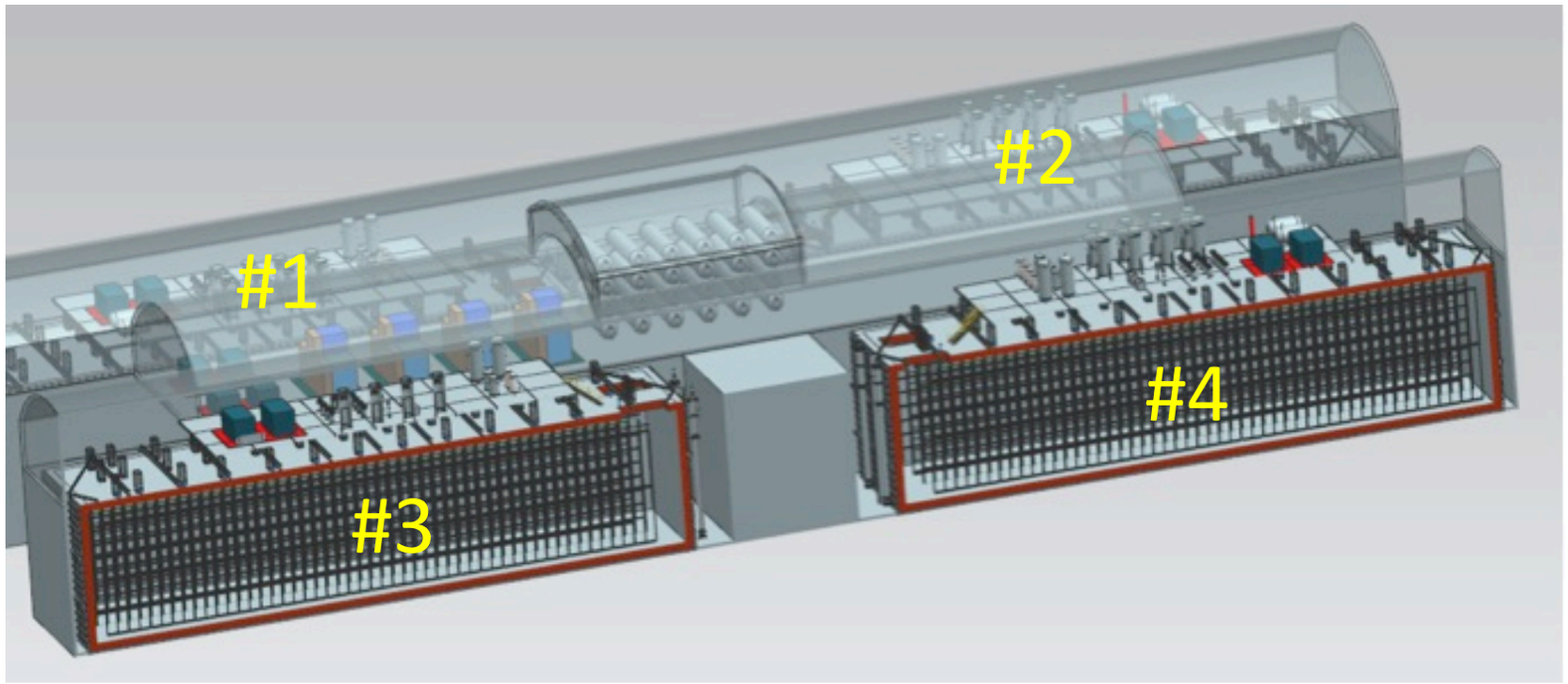
Staged approach to Far Detector

Cavern Layout at the Sanford Underground Research Facility (SURF) fixed in January 2015

Decision based on: strategic + technical input

⇨ four caverns hosting **four independent 10-kt FD modules**

- Allows for staged construction of the full 40-kt far detector
- Gives flexibility for **evolution** of LArTPC technology
  - Assume four identical cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m3
  - Assume the four 10-kt modules will be similar but not identical

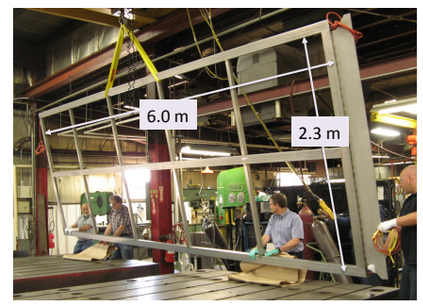


Detector development path

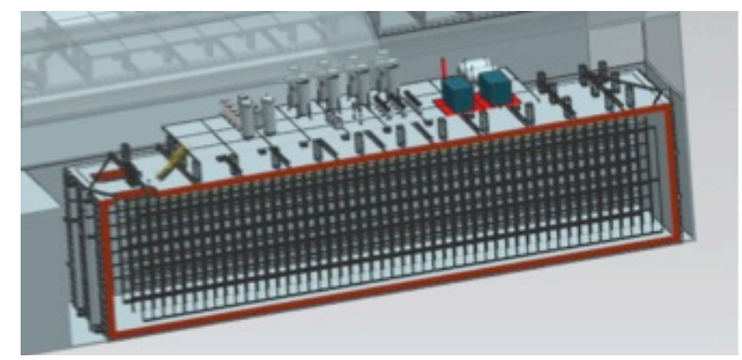
Fermilab SBN and CERN Neutrino Platform provide a strong LArTPC development and prototyping program

35-t prototype

ProtoDUNE@CERN

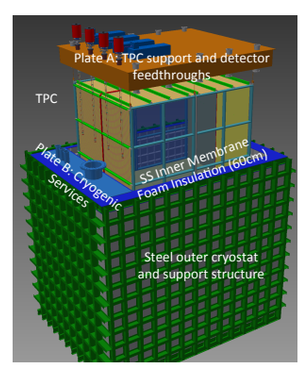


DUNE reference design

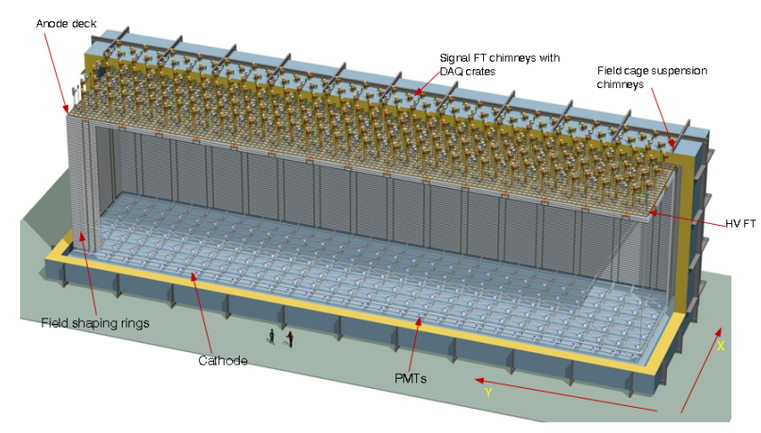


MicroBooNE

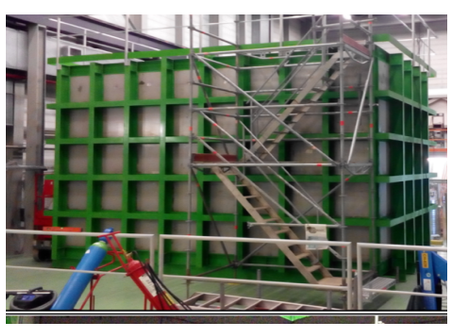
SBND@FNAL



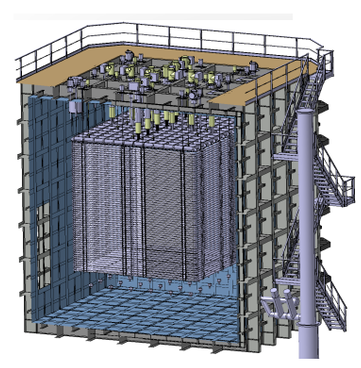
DUNE alternate design



WA105 3x1x1@CERN



WA105 6x6x6@CERN

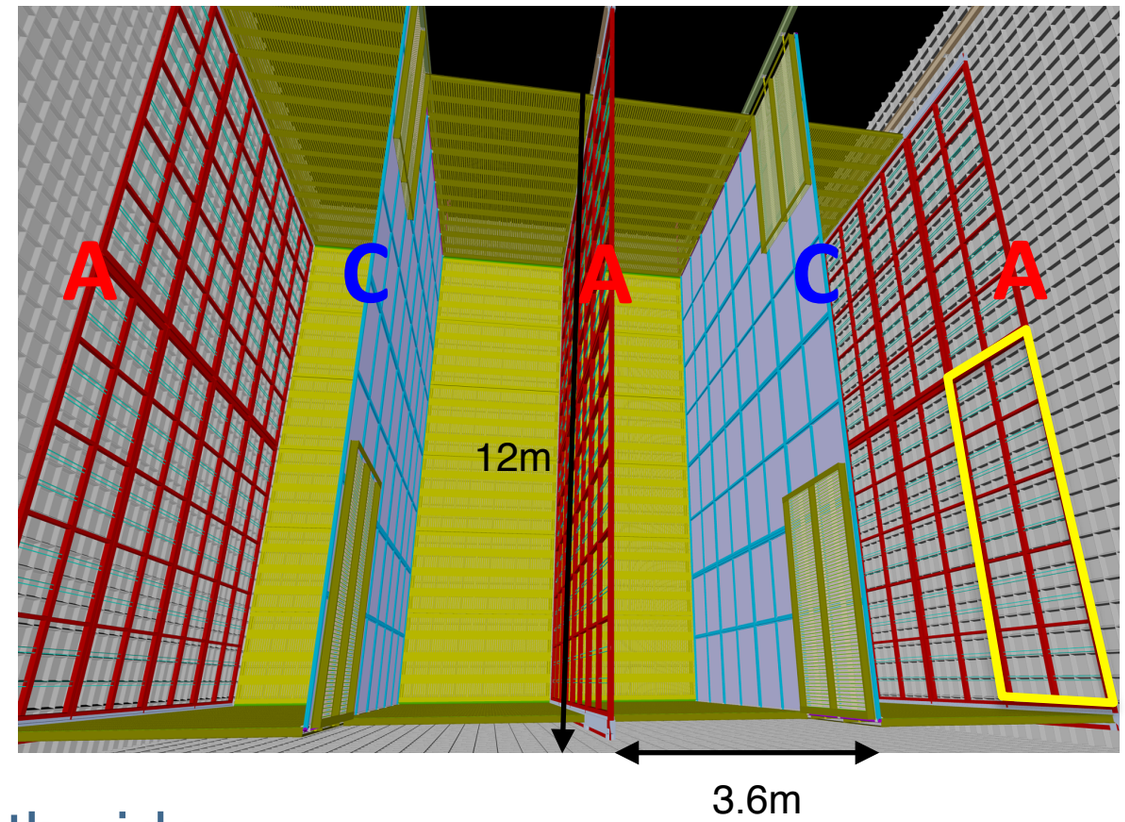


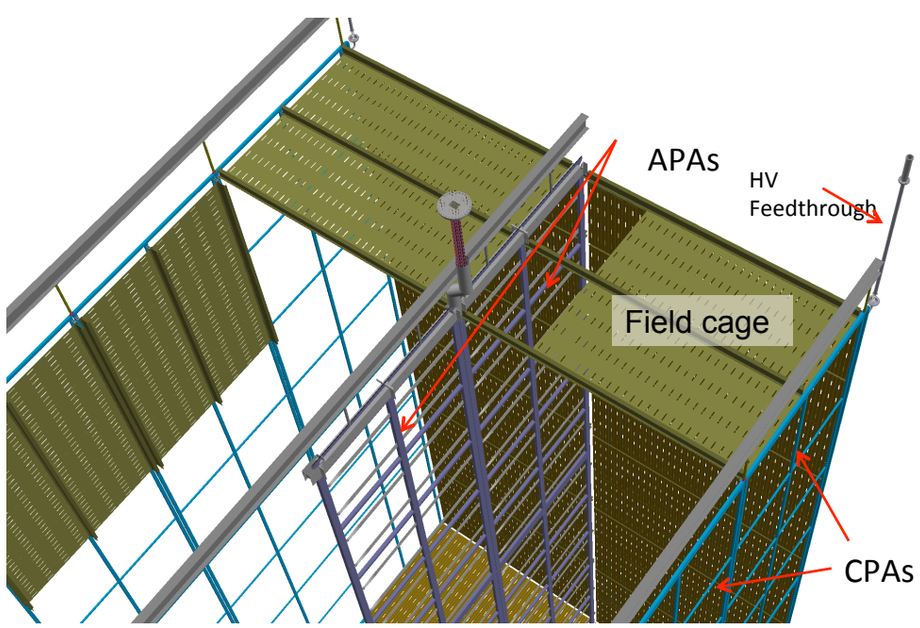
DUNE FD Reference design

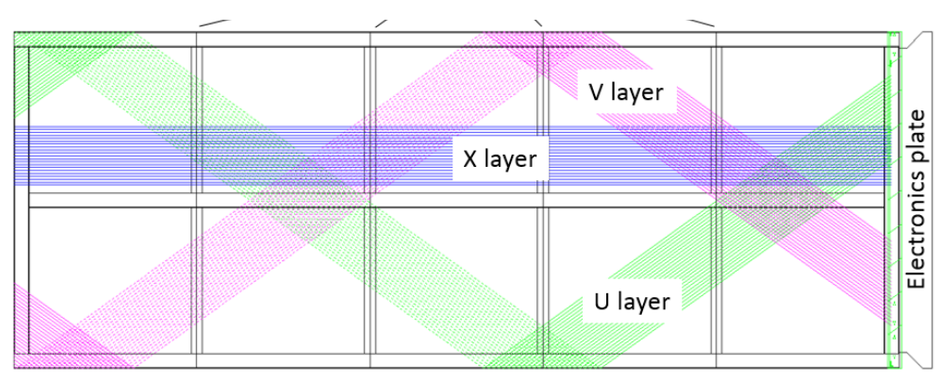
Modular implementation of a single phase TPC

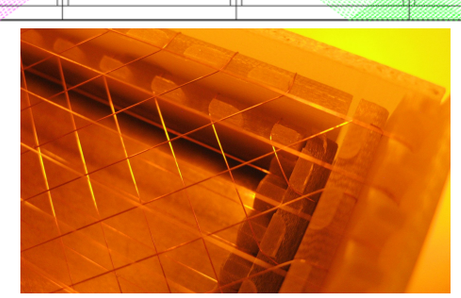
One 10 kt FD module:

- Active volume: **12m x 14m x 58m**
- 150 Anode Plane Assemblies
  - 6.3m high x 2.3m wide
- 200 Cathode Plane Assemblies
  - 3m high x 2.3m wide
- A:C:A:C:A arrangement
- Cathodes at -180 kV for 3.6m drift
- APAs have wrapped wires – read out both sides
- Each side has one collection wire plane & two induction planes

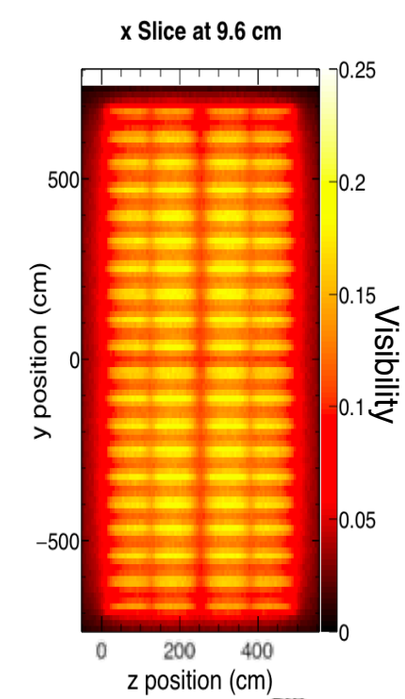






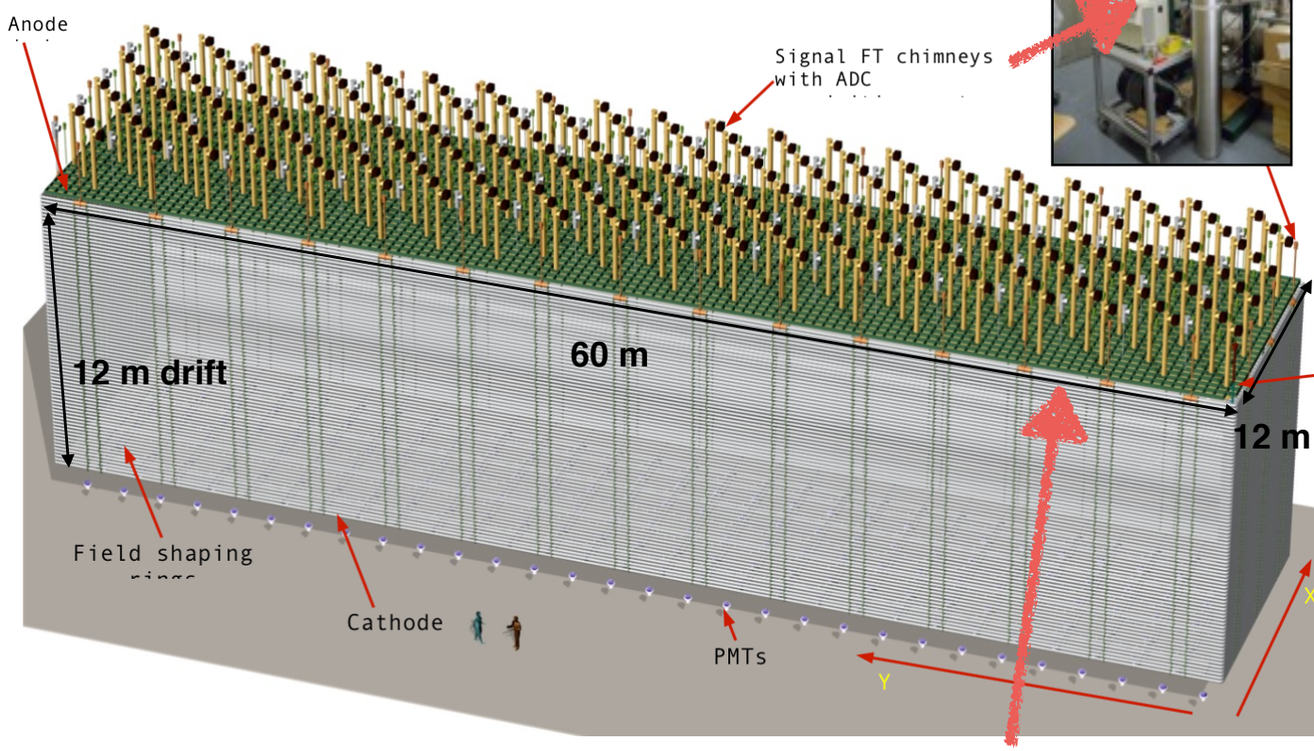


3520 wires/APA
Cold electronics on one end
Embedded photon detectors



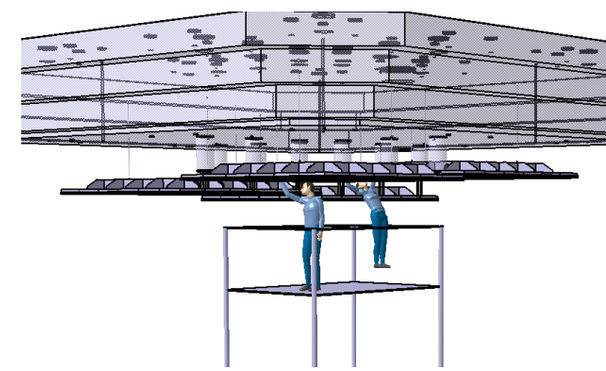
DUNE FD Alternate design

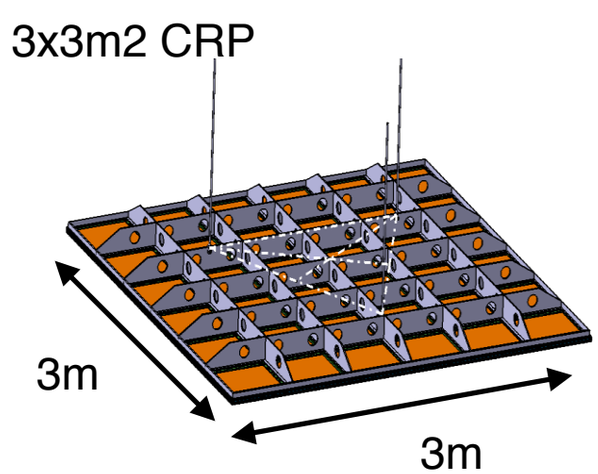
Modular implementation of a dual phase TPC



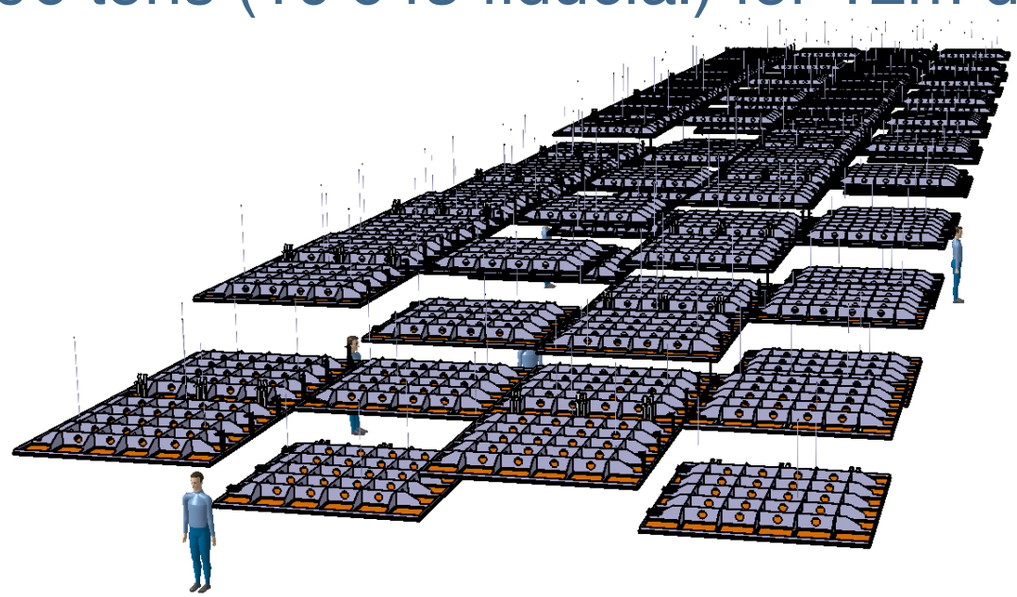
One 10 kt FD module:

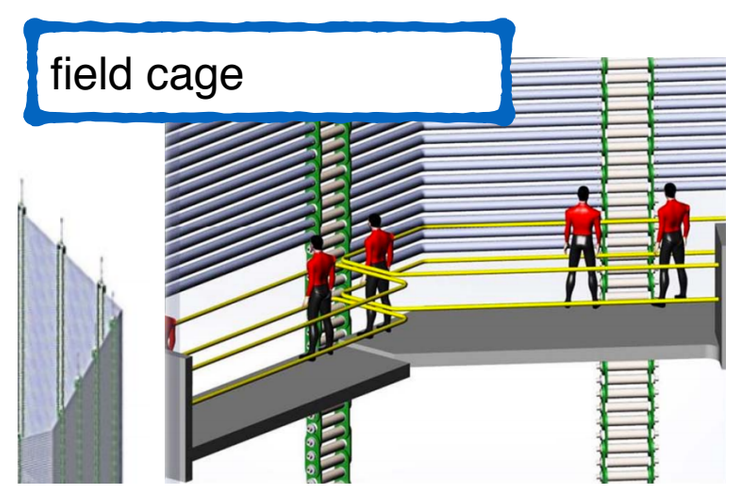
- 3x3m2 CRP modules placed at the gas-liquid interface
- 2 perpendicular "collection" views, 3mm readout pitch
- 80 CRPs / 10 kton
- 153,600 ionisation readout channels
- Accessible cold electronics
- Hanging field cage and cathode@600 kV for 0.5 kV/cm
- Decoupled PD system (w/ no. 720 8" PMT)
- Active mass 12'096 tons (10'643 fiducial) for 12m drift





1920 channels/CRP
Accessible cold electronics in chimney

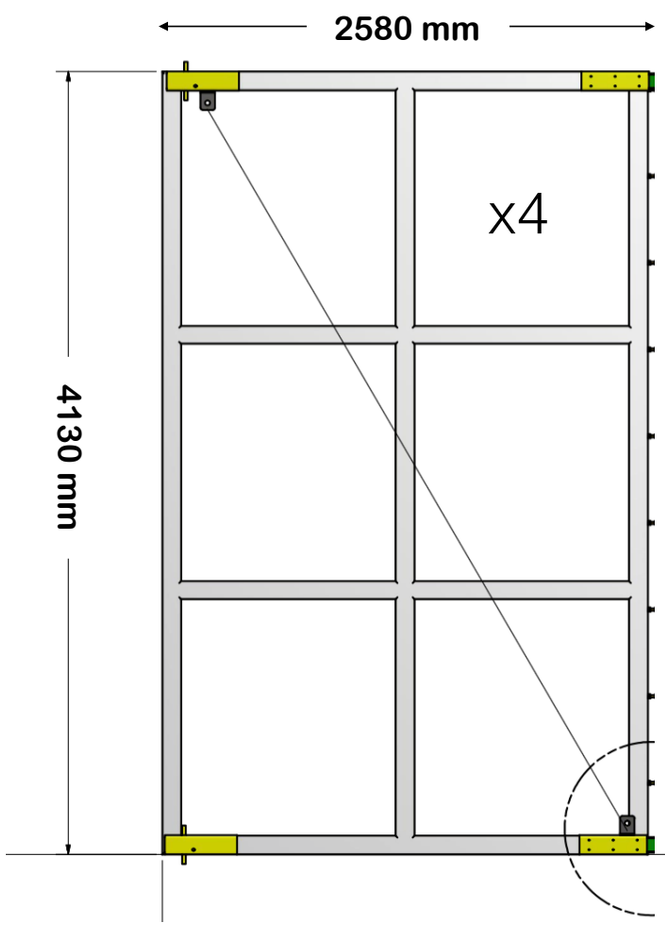




Engineering prototypes of actual building block

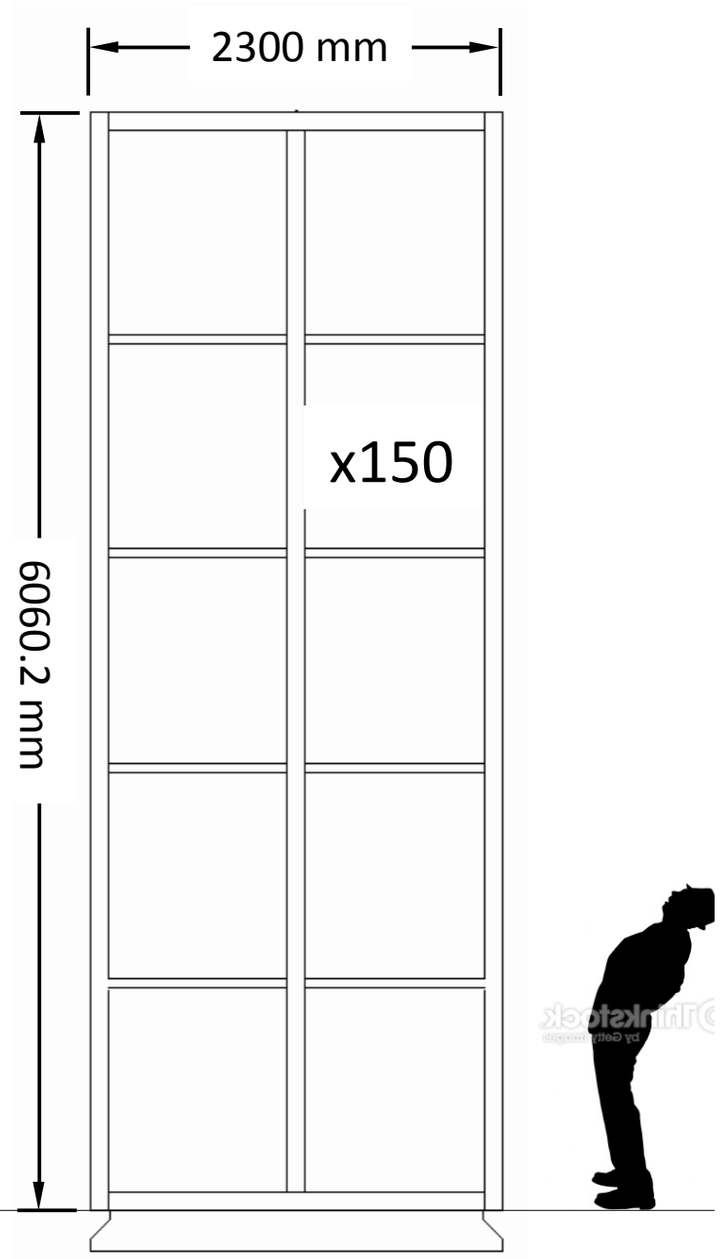
Sets the scale (dimensions) of the "building blocks"

SBND APA



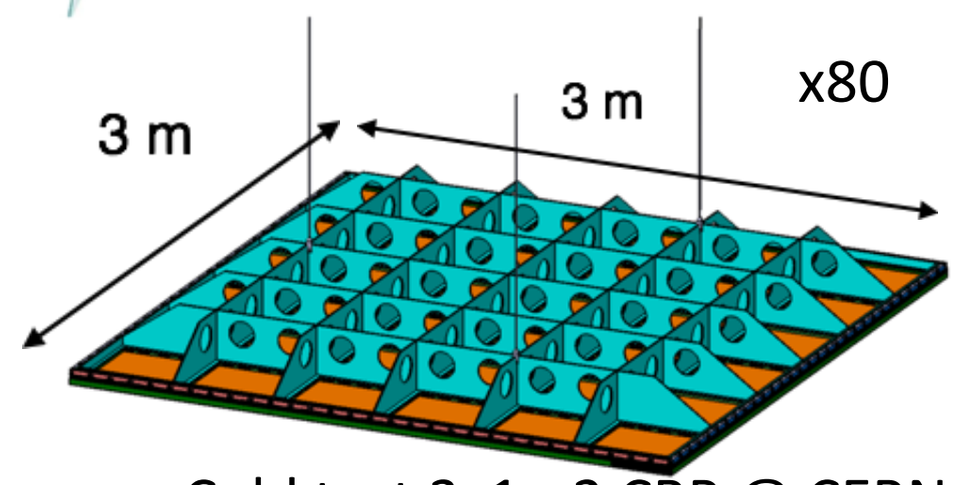
vertical

DUNE APA



vertical

WA105 CRP

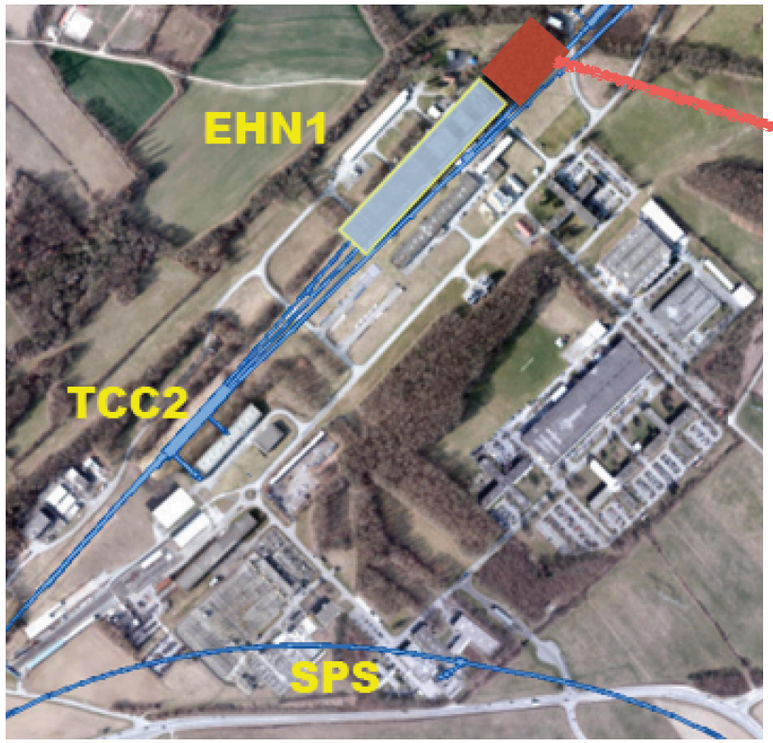


Cold test 3x1m2 CRP @ CERN

horizontal

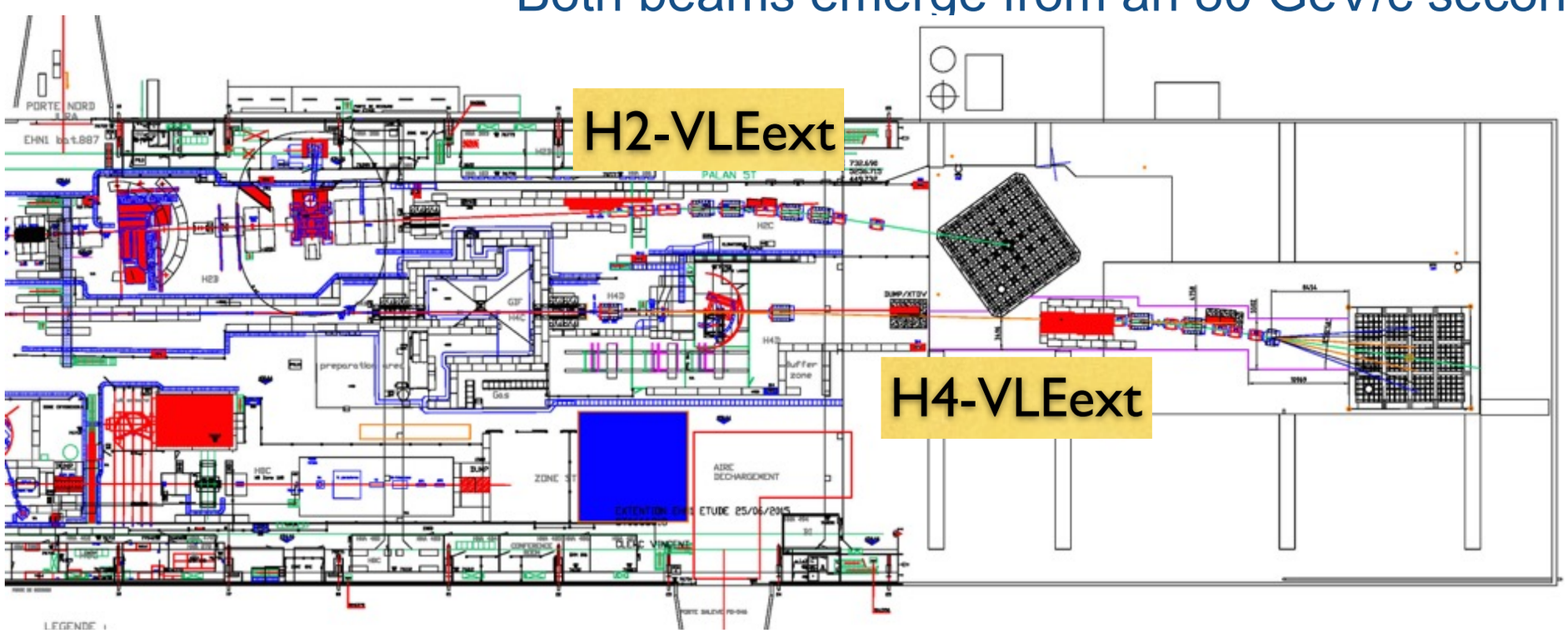
CERN test beam area extension

- Extension of the North Area (EHN1) in the context of the CERN Neutrino Platform



H2-VLEext : energy range 0.4 - 12 GeV/c
H4-VLEext : energy range 0.4 - 7 GeV/c

Both beams emerge from an 80 GeV/c secondary beam



DUNE FD prototyping effort @ CERN

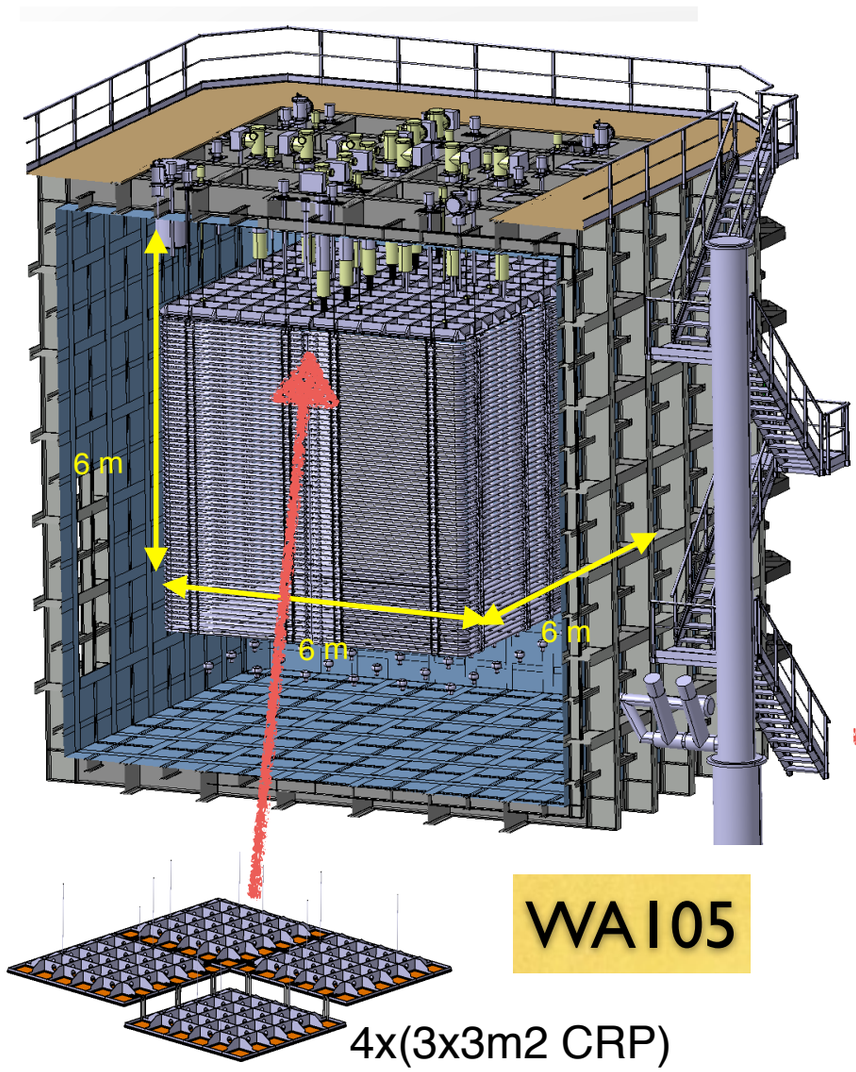
- ProtoDUNE and WA105 are the prototypes of the single-phase and dual-phase DUNE far detector designs.

Engineering Prototype Run

- Measure and benchmark detector performance using full-scale detector components
- Develop manufacturing capabilities at multiple sites
- Test installation procedures and operation

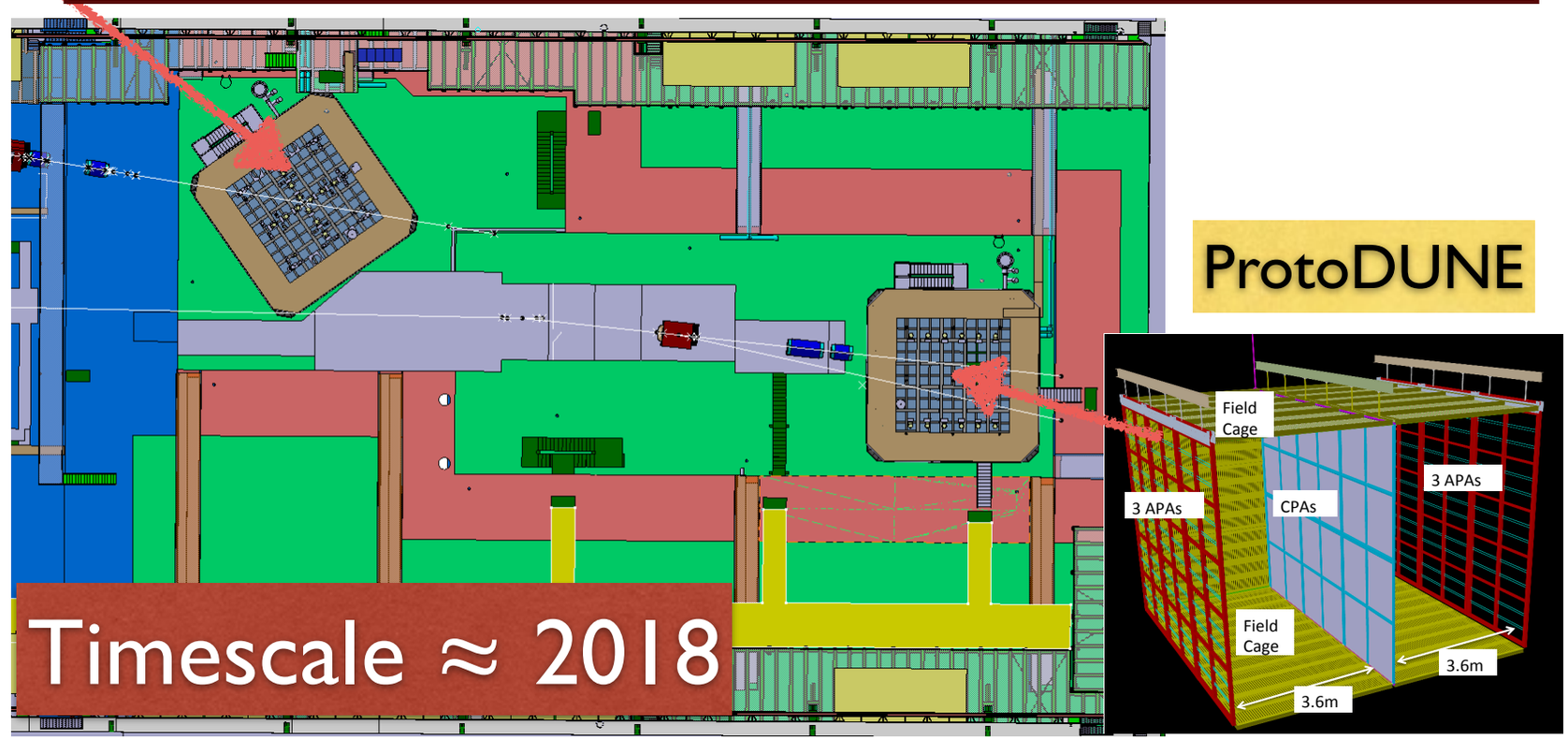
Test Beam Run

- Assess detector systematic uncertainties
- Validate and tune MC simulation to data
- Test reconstruction tools and particle ID algorithms
- Study particle interactions



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



Conclusions

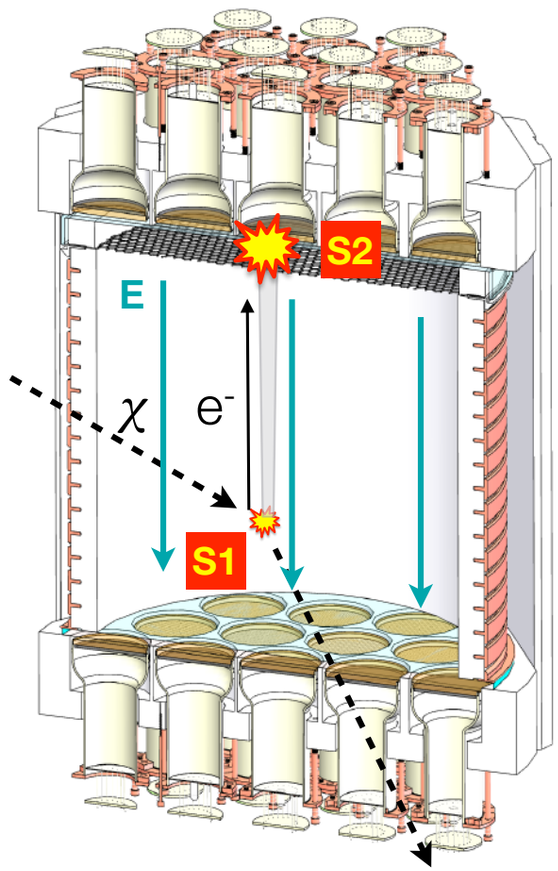
- ★ The LAr TPC is truly **a new instrument for discoveries**. In recent years, the technology has developed into a very mature technique for running or planned experiments at Fermilab and CERN.
- ★ The LAr TPC offers truly **unique** "bubble-chamber-like" **tracking performance**, as well as **excellent calorimetry** – these features will be **fully exploited to reach the science goals** of next generation experiments, such as MicroBooNE, SBN and DUNE.
- ★ The foreseen **test beam campaigns** and **neutrino beam measurements** with very large statistics will provide the data to **accurately understand the response** of the LAr TPCs to single particles and neutrinos, opening the path to **neutrino precision measurements with LAr TPCs**. Exclusive neutrino interaction processes on Argon will be studied with very high precision, providing an **environment to study aspects of nuclear physics with weak interactions**.
- ★ Thanks to worldwide efforts and supported by the big science projects, significant R&D continues to be performed. In this context, **there is now a unique and timely opportunity to further develop the noble liquids, and in particular liquid Argon TPCs**.
- ★ [In particular, the possibility of a magnetised LAr TPC should be pursued.]

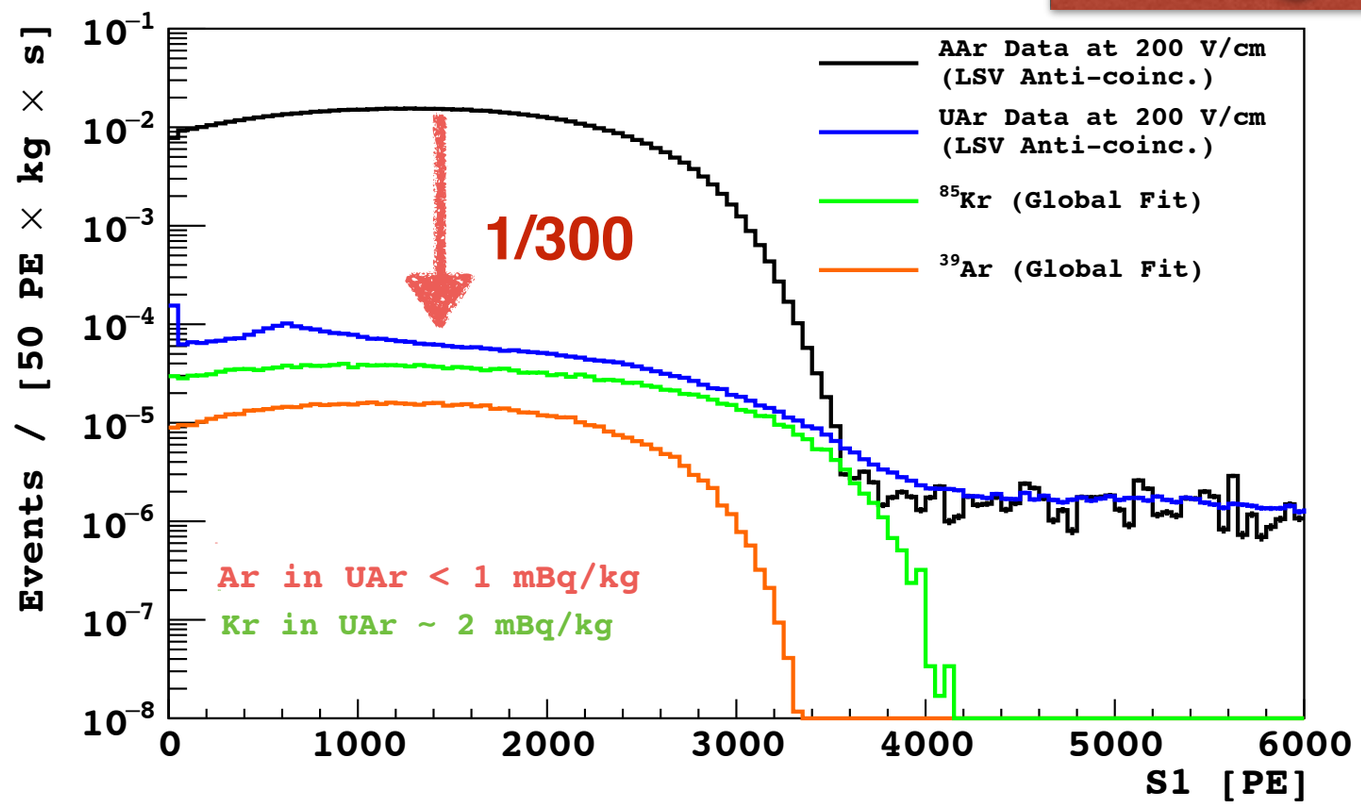
Backup slides

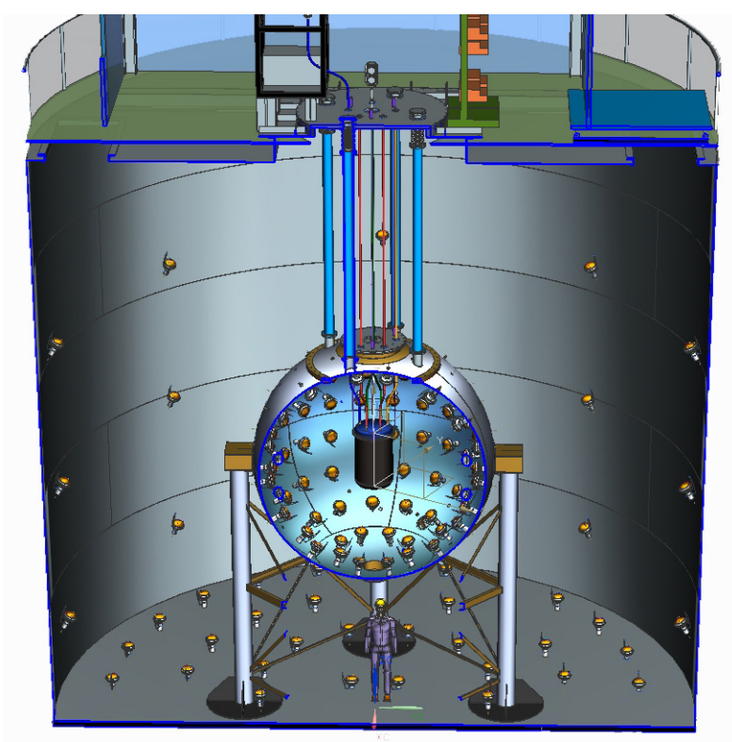
Courtesy PvZ

DarkSide-50 @ LNGS

Taking data







Radon-free Assembly

Clean Room

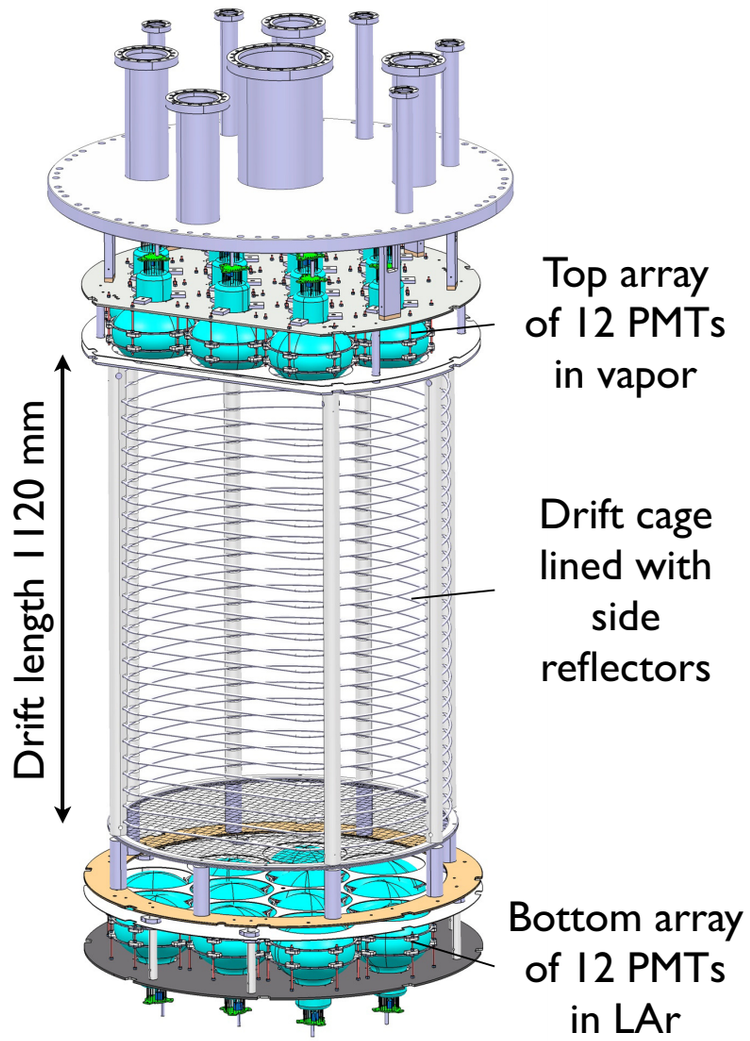
1,000-tonne Water-based Cherenkov Cosmic Ray Veto

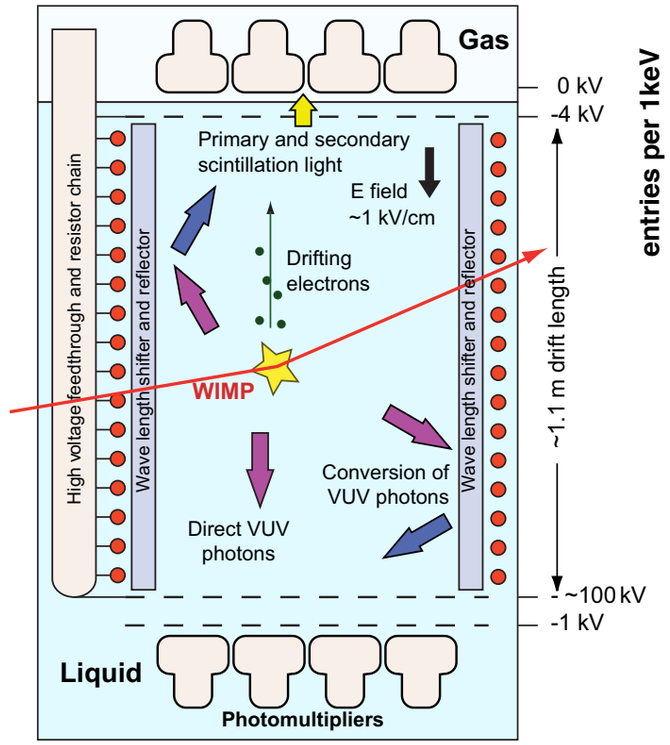
30-tonne Liquid Scintillator

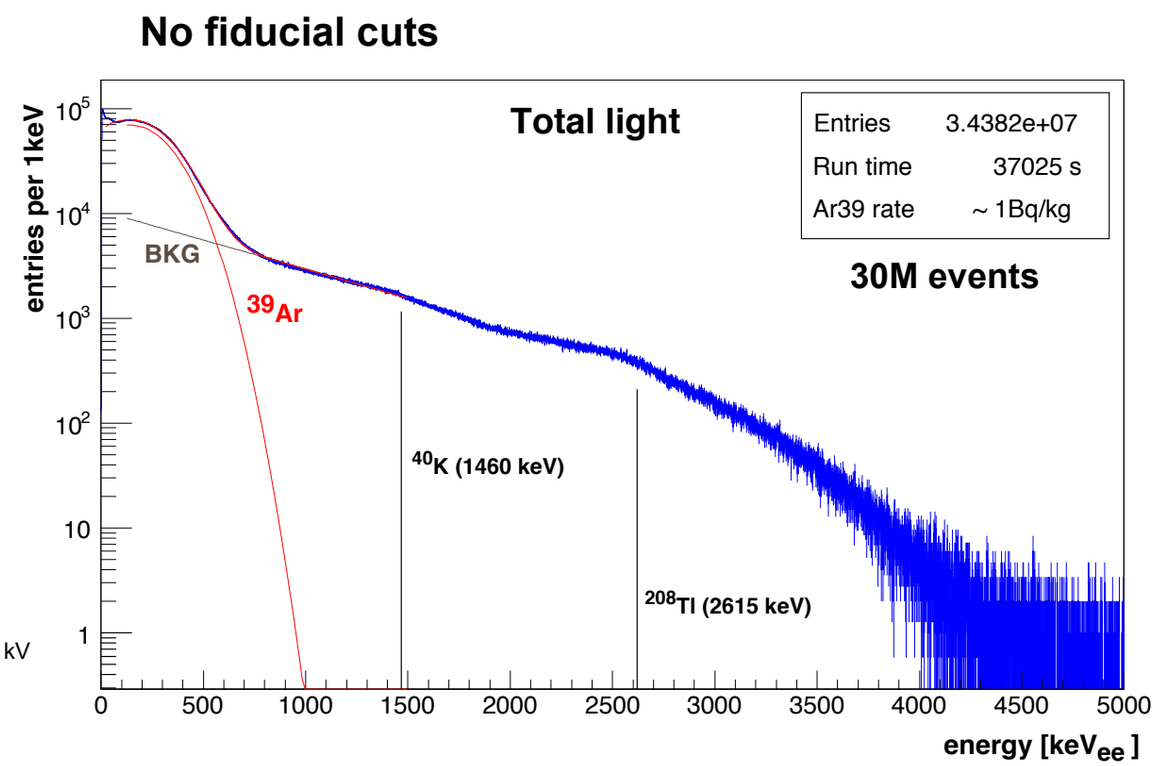
Neutron and γ's Veto Inner detector TPC

ArDM-1t @ LSC

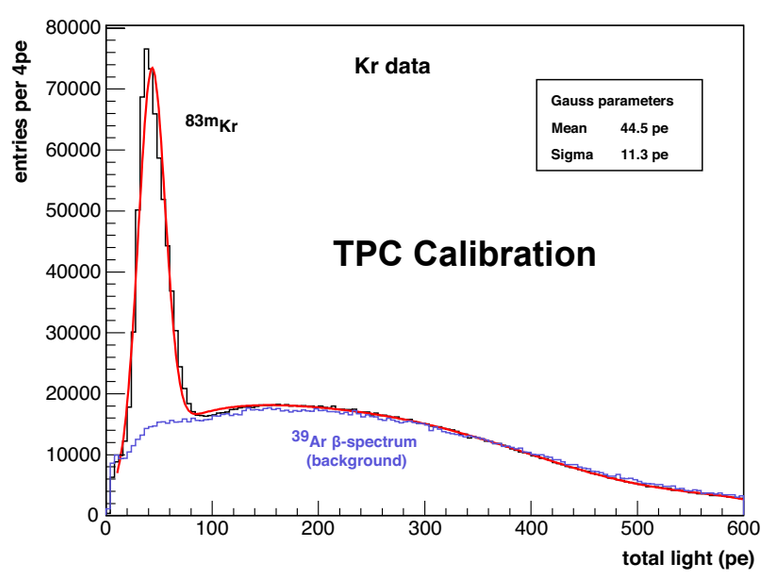
Taking data

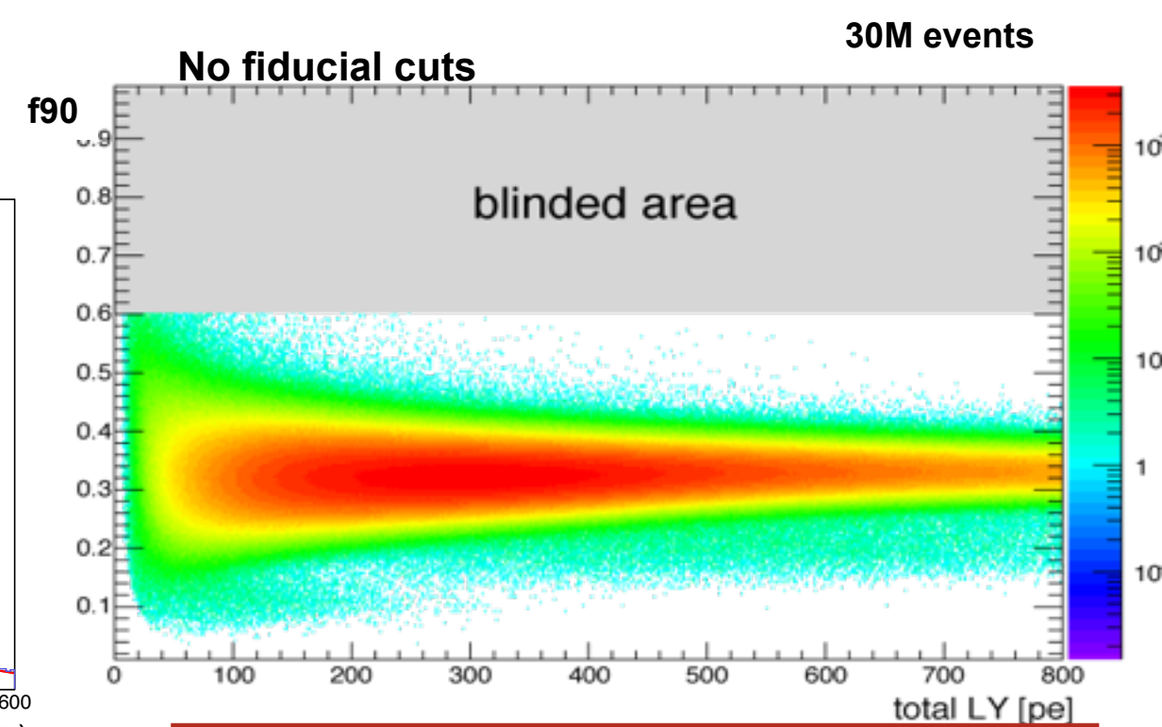






- First operating ton-scale LAr DM detector
- Now in single phase physics mode
- Dual phase in 2016





Background separation by PSD only - very promising

Underground Ar (depleted)

Plant at Colorado

1. Extraction at Colorado (CO_2 Well)
Extract a crude argon gas mixture (Ar, N_2, and He)

2. Purification at Fermilab
Separate Ar from He and N_2

Distillation Column at Fermilab

UAr bottles at LNGS

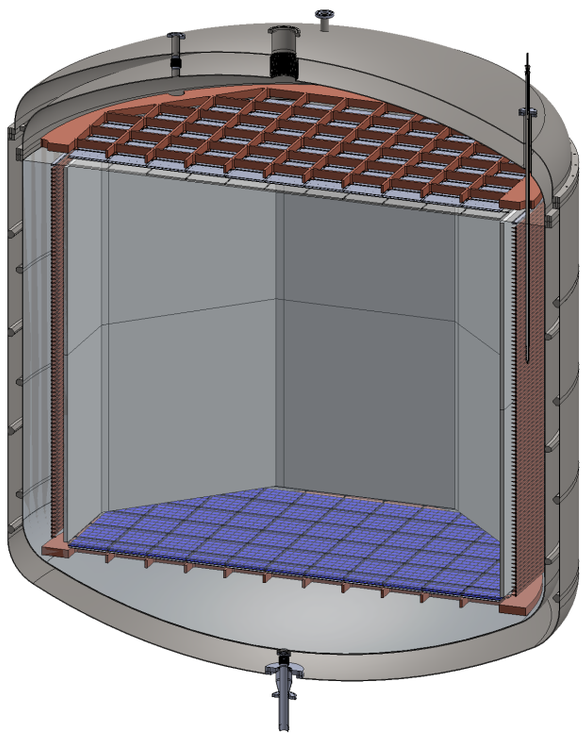
3. Arrived at LNGS
Ready to fill into DS-50

Urania: Replacement of the Ar extraction plant in Colorado → capacity of 100 kg/day

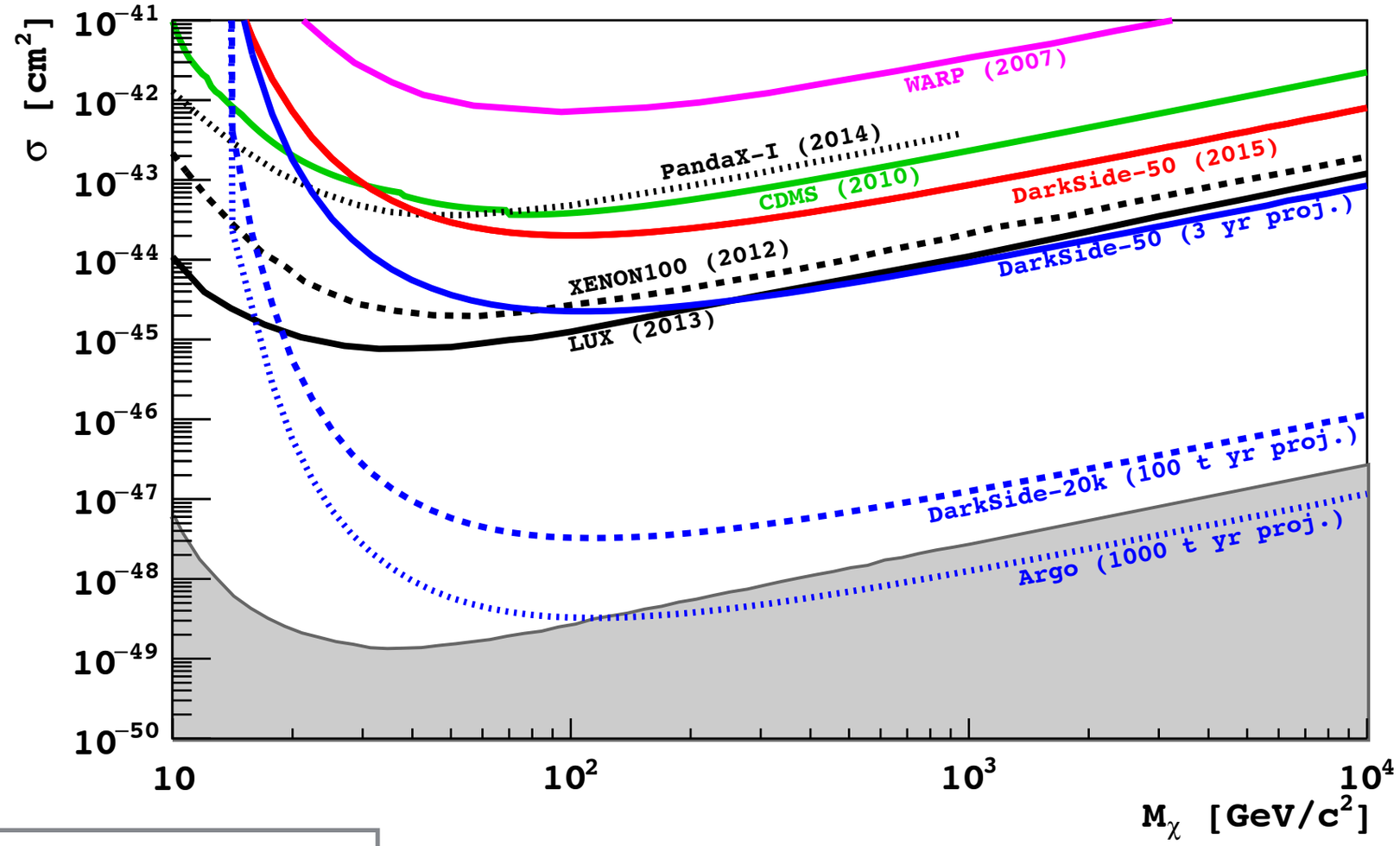
Aria: 350 m tall distillation column in the Seruci mine in Sardinia, Italy Chemical and isotopic purification of Underground Argon

Exploits finite vapour pressure difference between $^{39}Ar/^{40}Ar$

DarkSide-20k @ LNGS



DS-20k



Present design parameters:

15 m² of SiPM's reduced radioactivity
improved photon detection yield
→ intense R&D

Low-radioactivity titanium cryostat

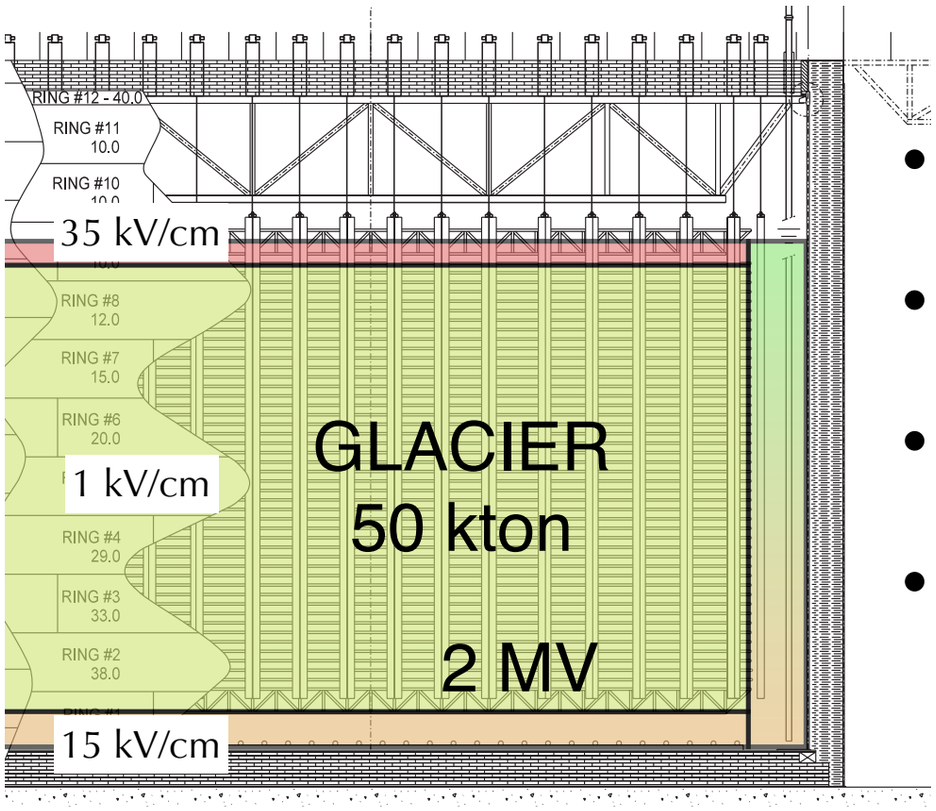
30 tons of depleted UAr

Proposal in preparation

Timescale ≈ 2020

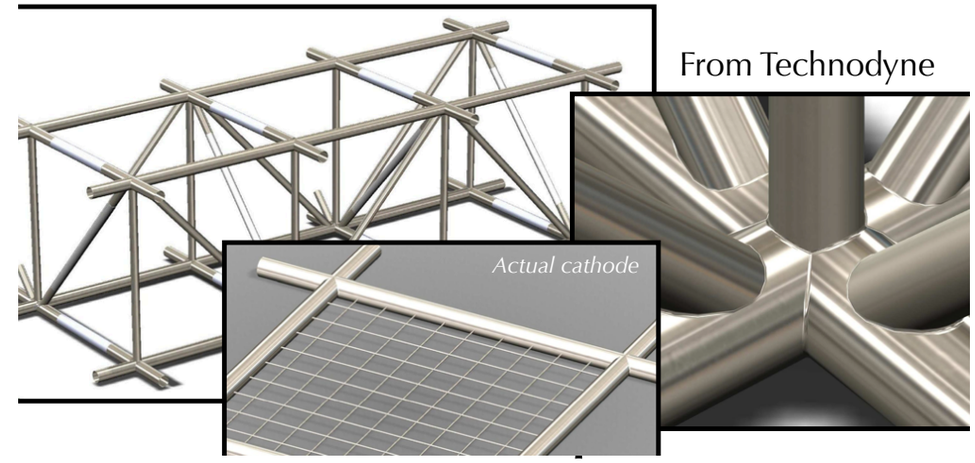
Beyond DS20k → Argo: aim at reaching the neutrino floor

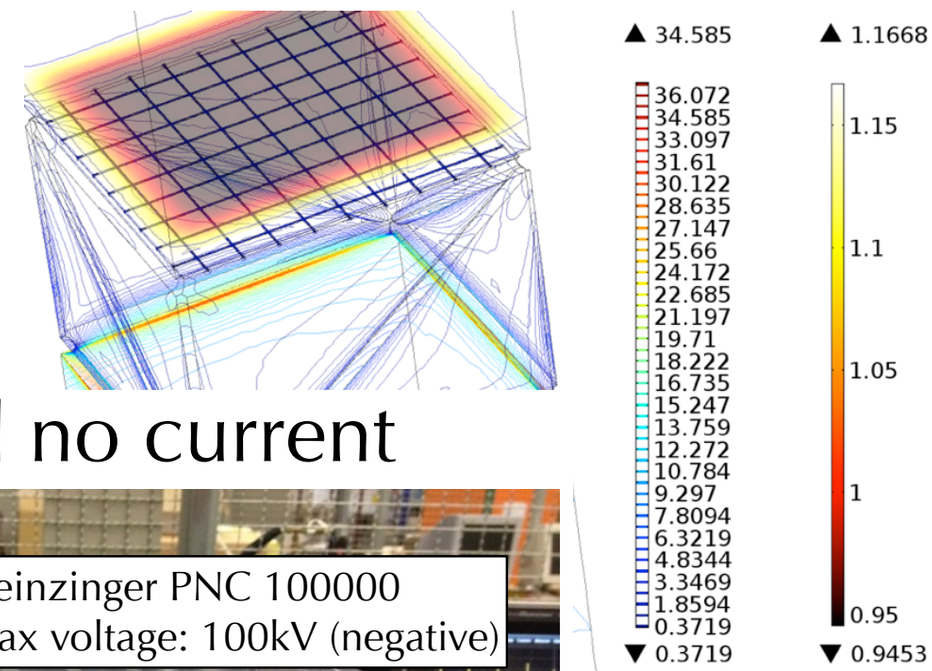
High E-fields in liquid argon medium



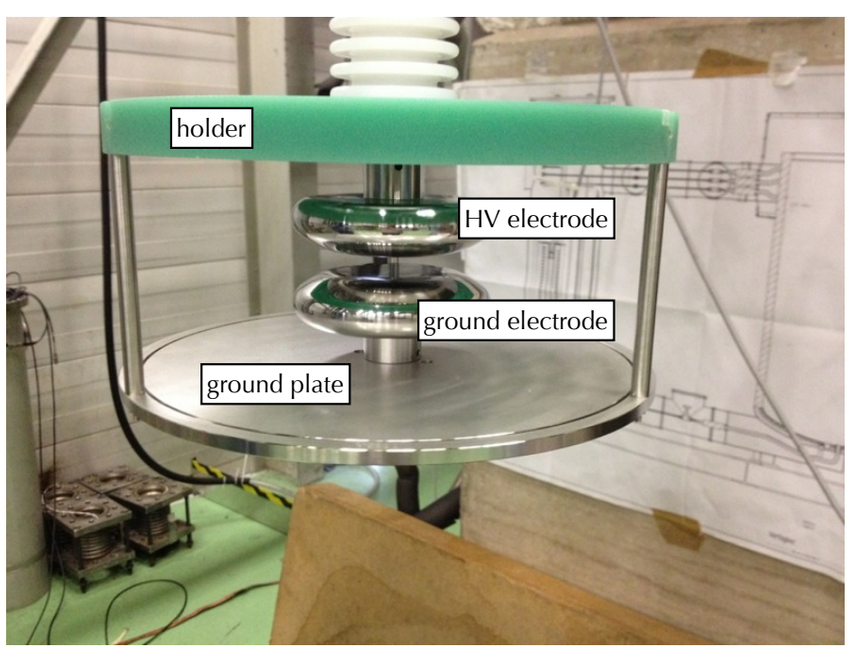
arXiv:1401.2777

- The maximum average electric field is in vapor!
- Largest average electric field in liquid ~15kV/cm
- Sharp edges imply large electric field
- Caution designing the electrodes

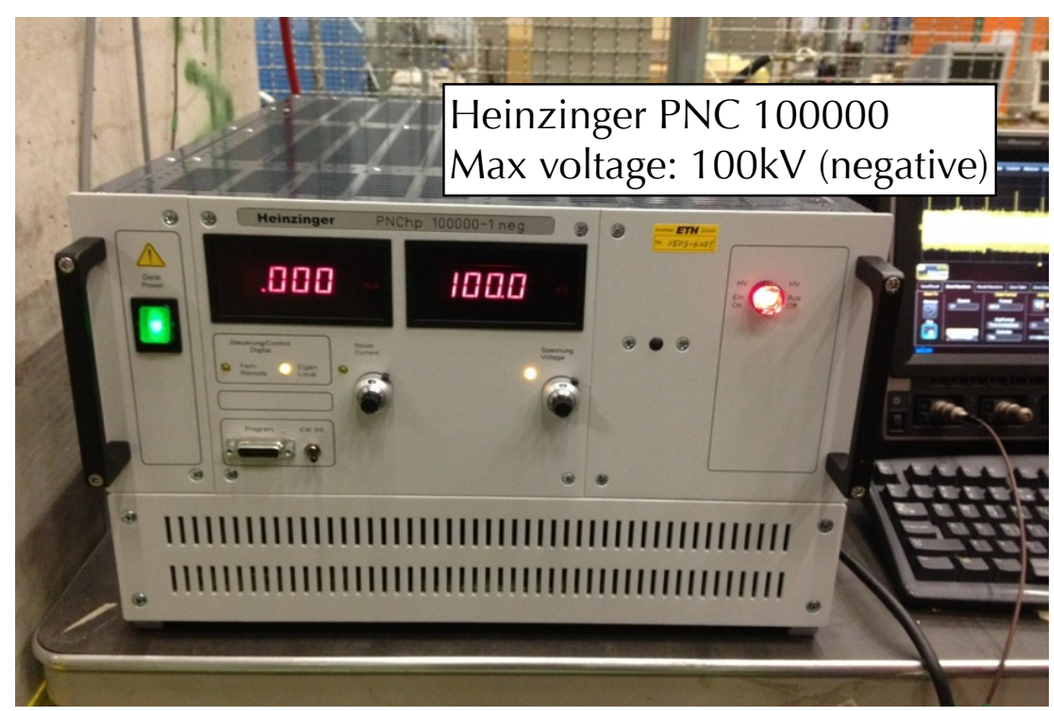




The chamber



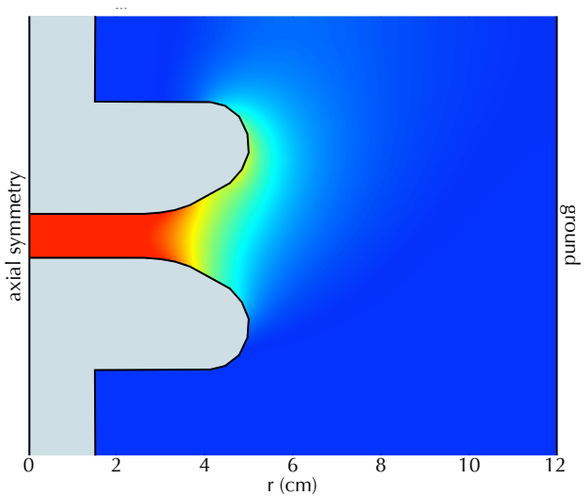
100kV/cm and no current



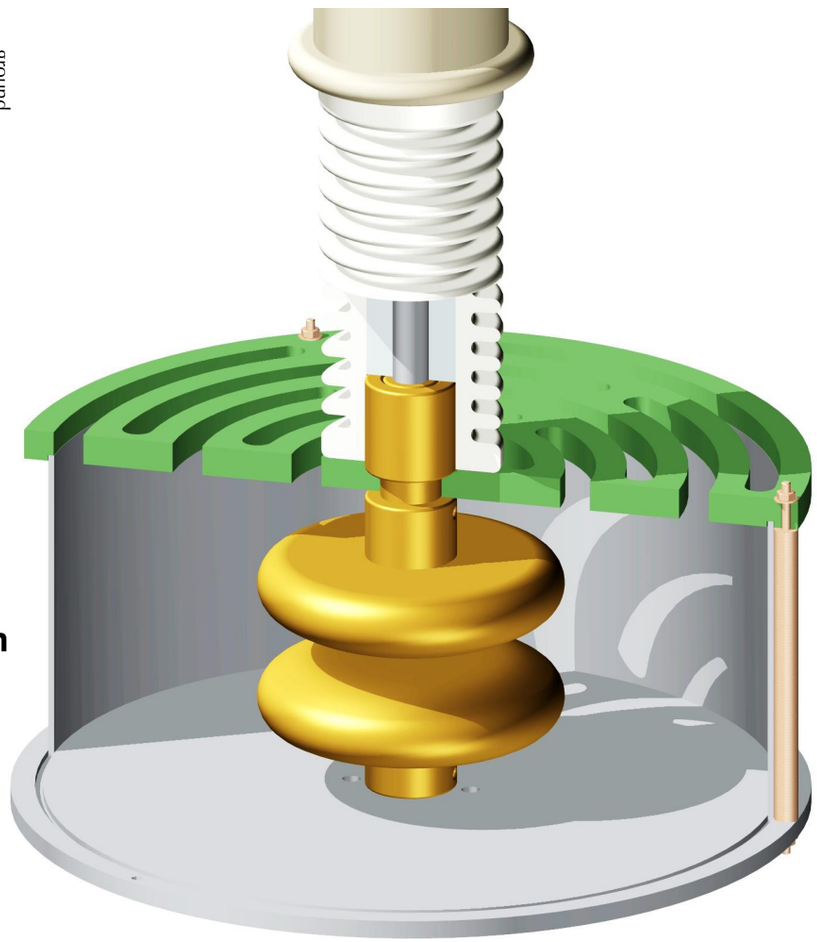
High voltage feedthrough

WA105

LAr electrical rigidity tests at 100kV



W. Rogowski, Arch. Electrotech., 12(1923), 1



Evidence of electric breakdown induced by bubbles in liquid argon

F. Bay, C. Cantini, S. Murphy, F. Resnati, A. Rubbia, F. Sergiampietri, S. Wu
http://arxiv.org/abs/1401.2777

NEXT STEPS: Adapt the present HVFT to the 300kV cable and test in the range 100-300kV

Build a new HVFT suitable for the 6x6x6m^3 and adapt it for the 3x1x1m^3

300 kV test under preparation

-300kV High Voltage Power Supply
(from HEINZINGER)

Residual ripple: ≤0.001% U_{NOM} ± 50mV
Residual Ripple at -300kV ≤3V ± 50mV

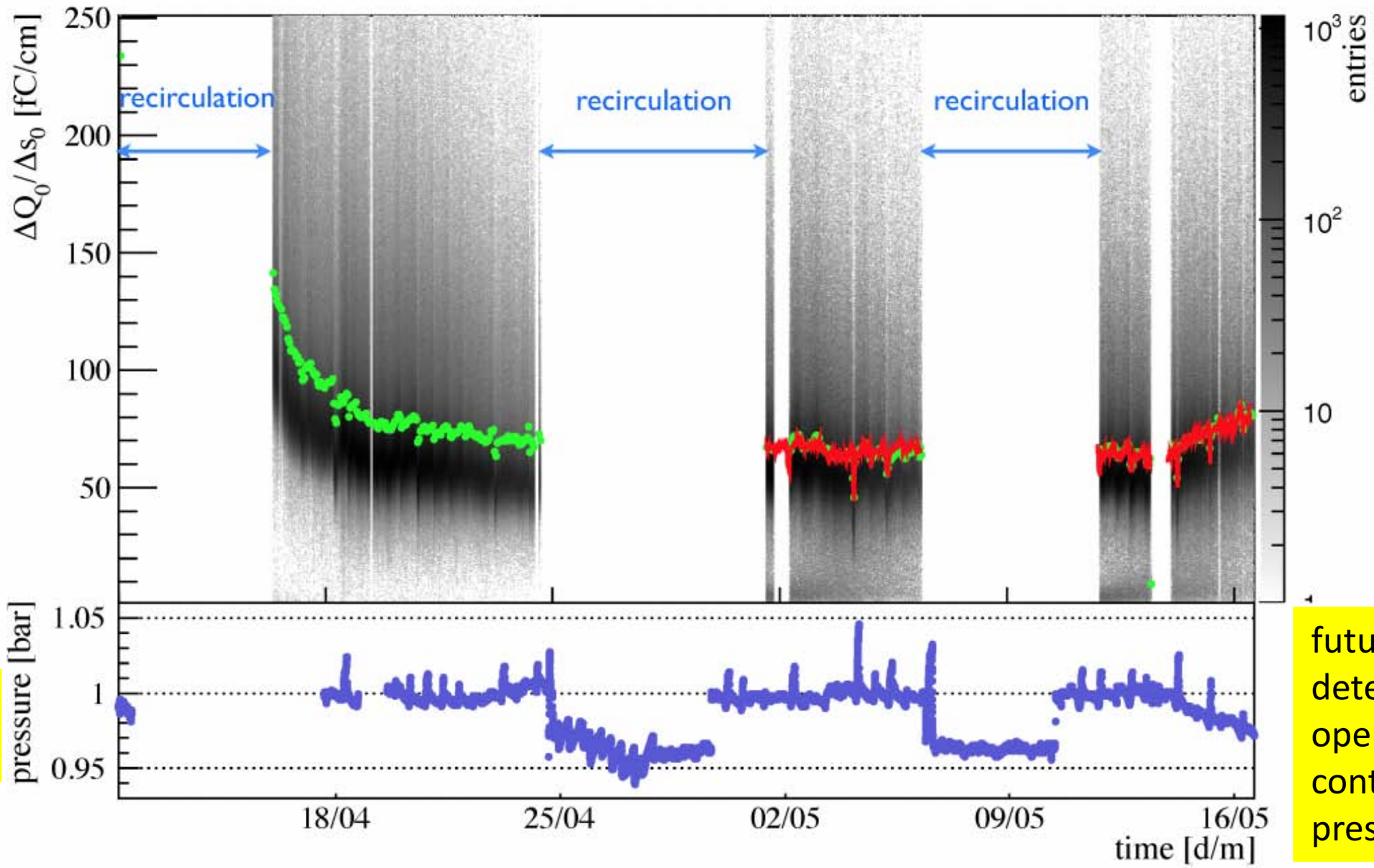
Can be reduced by the RC filter in the load:
with a fieldcage-to-GND capacitance of 5.5nF and a switchi
frequency of 34kHz, a series resistor of ~1kΩ is required.

Stability of the gain

Gain of LEM depends on: 1. gas property (pressure, temperature, mixture…)
2. electric field across the LEM - E
3. effective length across the LEM – x

Described by function: $G_\infty = trans \times e^{x \cdot \alpha(p,T,E)}$ where $\alpha(p,T,E) = \frac{Bp}{T} e^{-\frac{cp}{ET}}$

arXiv:1312.6487



Pressure inside:

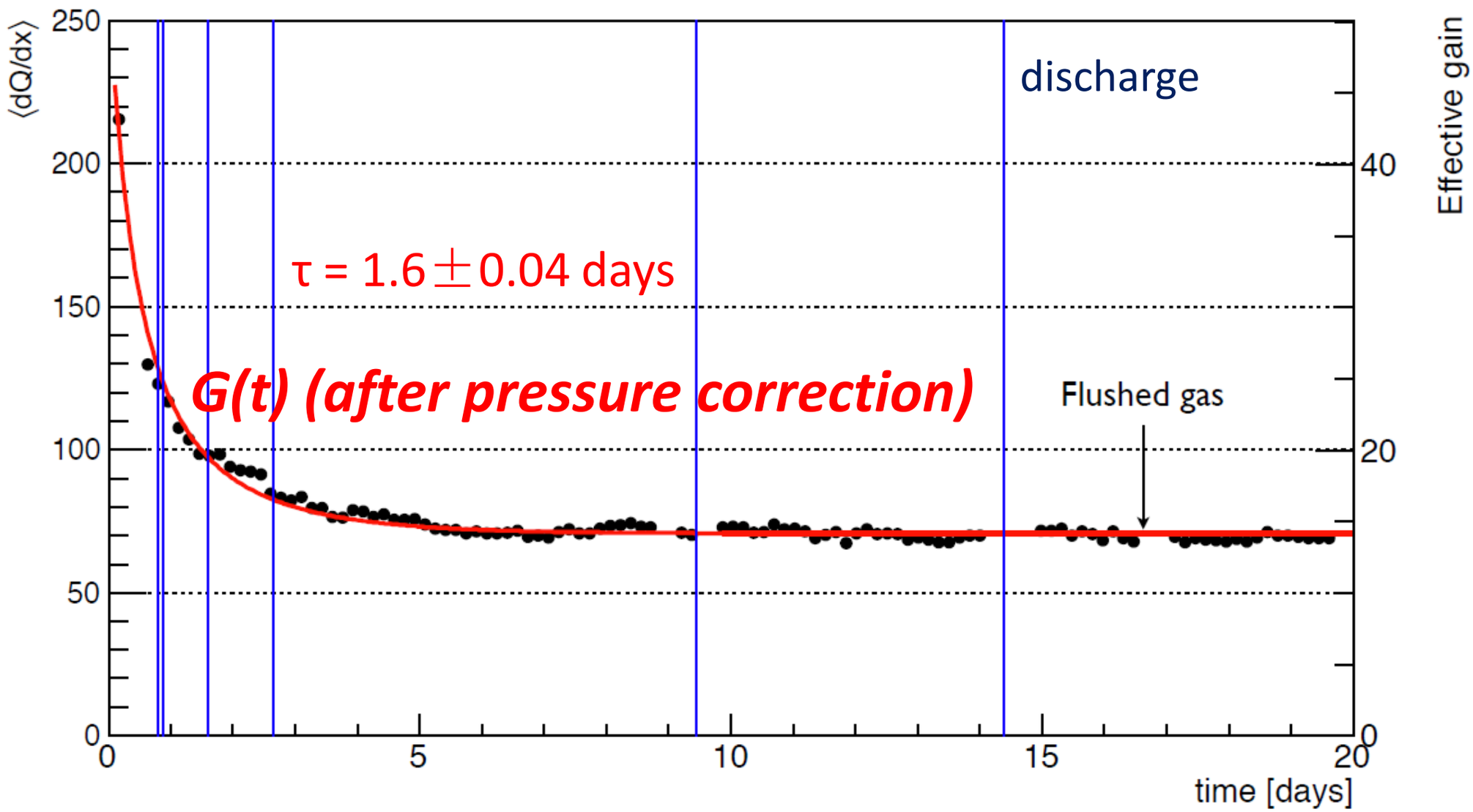
future detectors will operate under controlled pressure!

Stability of the gain

To describe the initial decrease: $G(t) = G_\infty \times \frac{1}{1 - e^{-(t-t_0)/\tau}}$

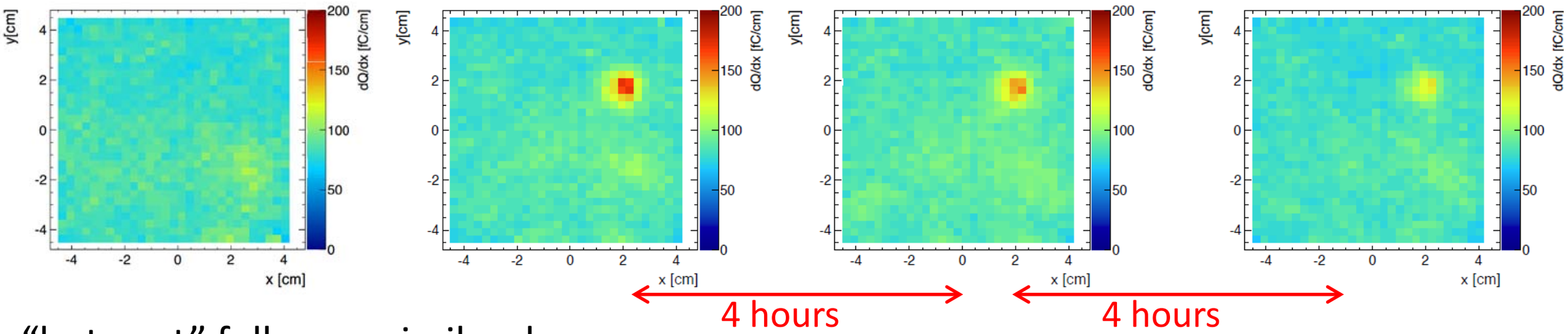
- ✓ Gain stabilizes at ~15 (at LEM field of 33 kV/cm) after an initial decrease with τ ~ 1.6 days
- ✓ Discharge does not affect the overall gain

arXiv:1312.6487

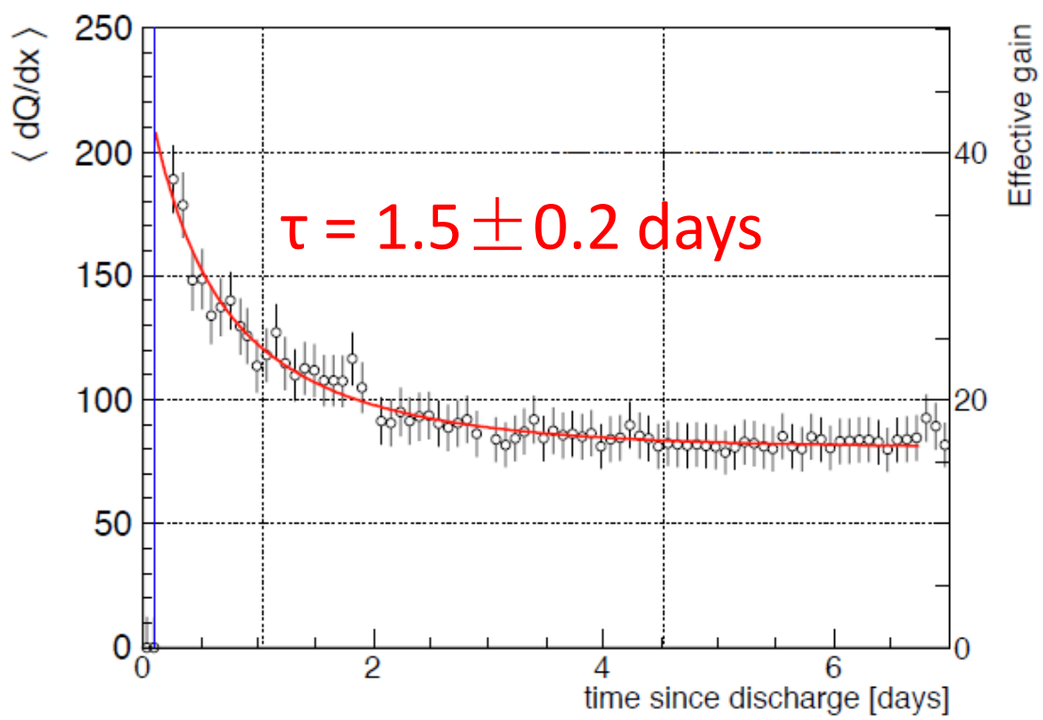


What happens locally when discharging?

before discharge: when discharging: after discharge:



"hot spot" follows a similar decay:



arXiv:1312.6487

Summary of number of discharges:

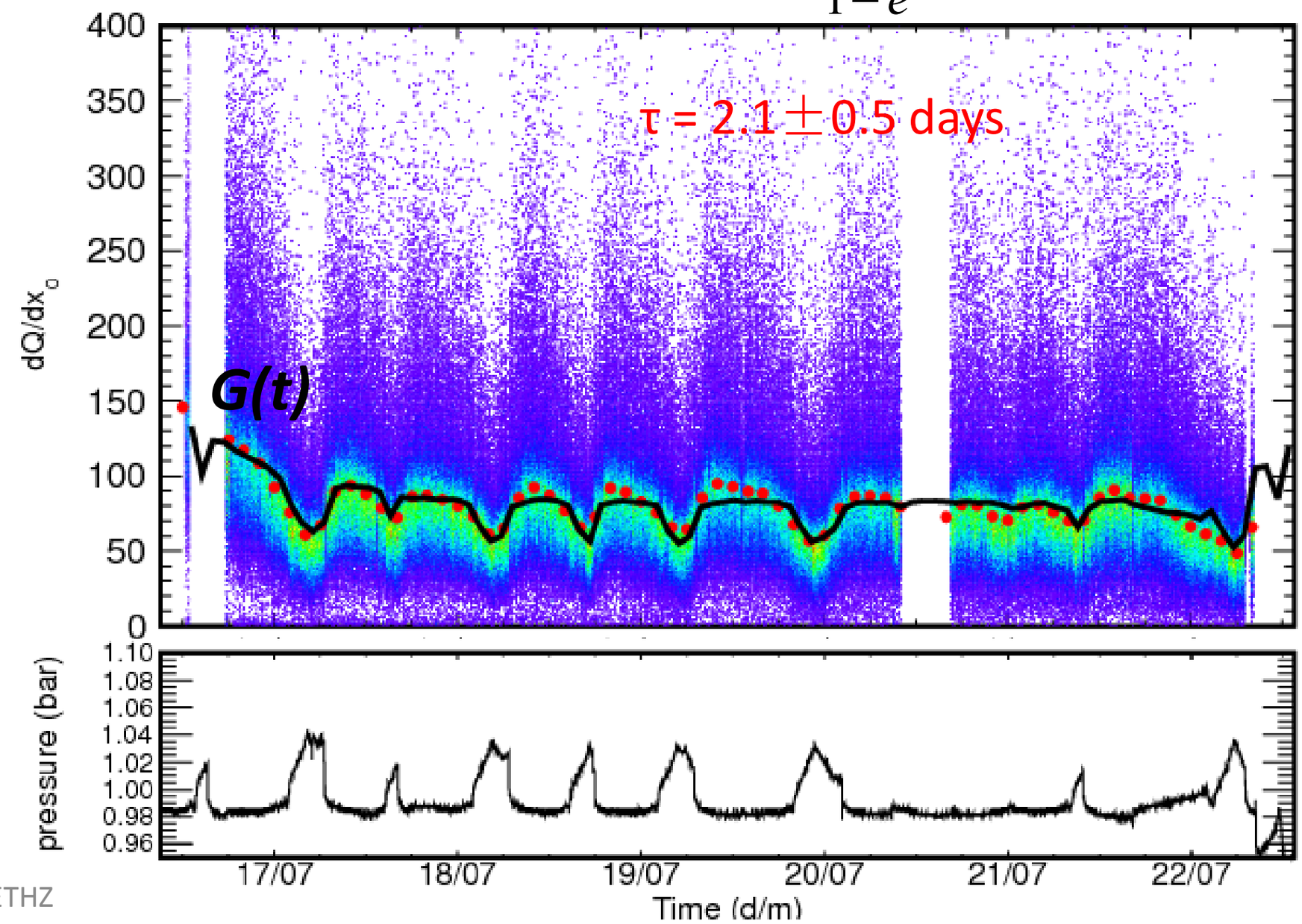
LEM field	Run Time	$N_{discharge}$
33 kV/cm	46 days	8
34 kV/cm	7 days	0
35 kV/cm	7 days	1

Stability of the gain

Gain of LEM depends on: 1. gas property (pressure, temperature, mixture…)
2. electric field across the LEM - E
3. effective length across the LEM – x

Described by function: $G = A \times e^{x \cdot \alpha(p,T,E)}$ where $\alpha(p,T,E) = \frac{Bp}{T} e^{-\frac{cp}{E}}$

To describe the initial decrease: $G(t) = G_\infty \times \frac{1}{1 - e^{-(t-t_0)/\tau}}$



July run: test Anode B

Pressure inside

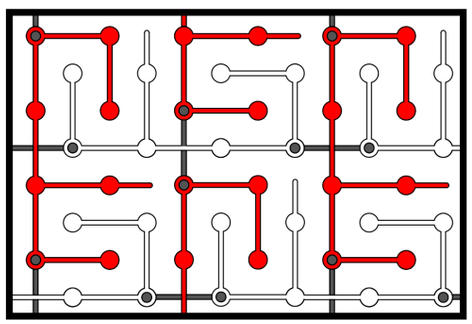
future detectors'll operate under controlled pressure

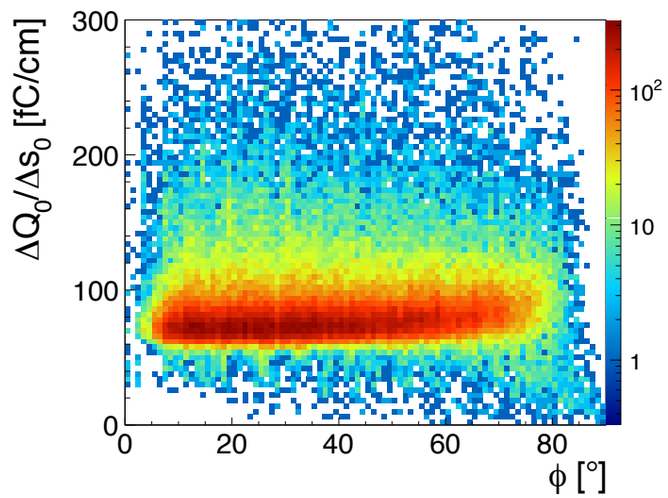
A. Rubbia - CERN 113th SPSC

Optimisation of anode

anode: compromise between resolution on charge measurement and capacitance

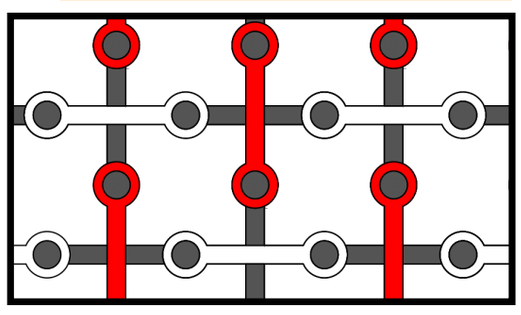
dC/dl ~ 150 pF/m

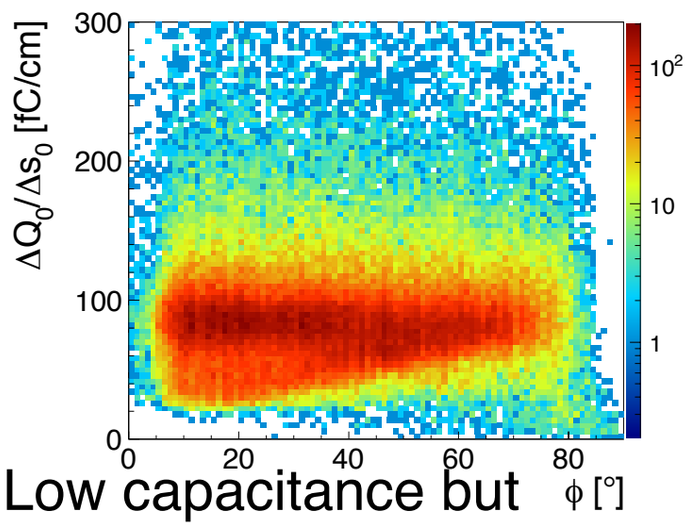




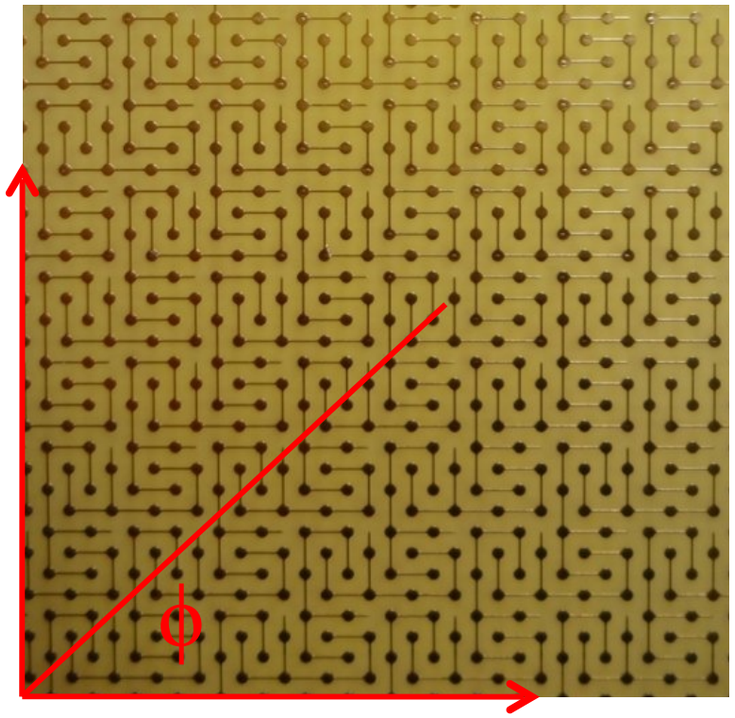
C Cantini et al 2014 JINST 9 P03017

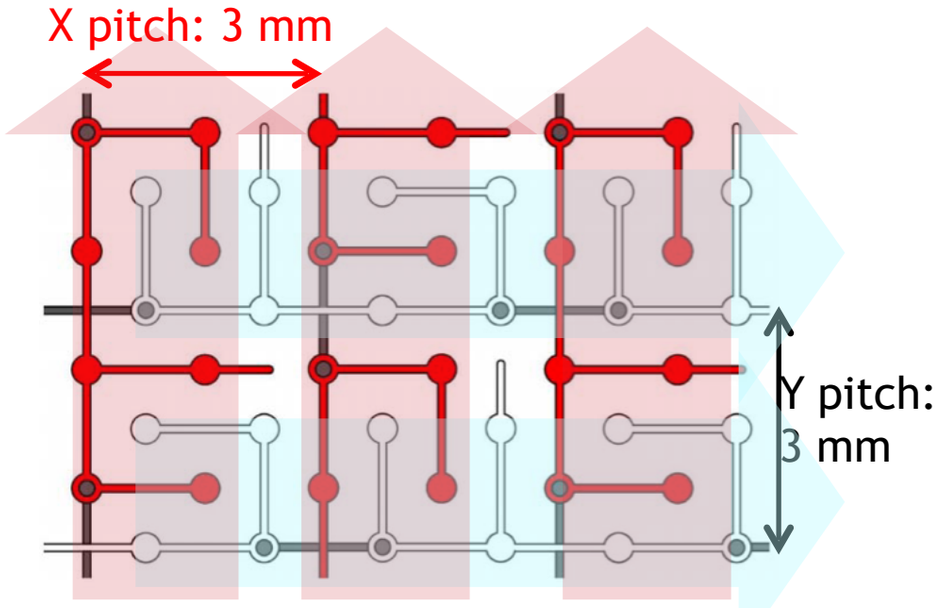
dC/dl ~ 100 pF/m





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





dC/dl~150 pF/m

Best solution to optimize capacitance and resolution