LAr Detectors for Neutrino Physics

Gary Barker

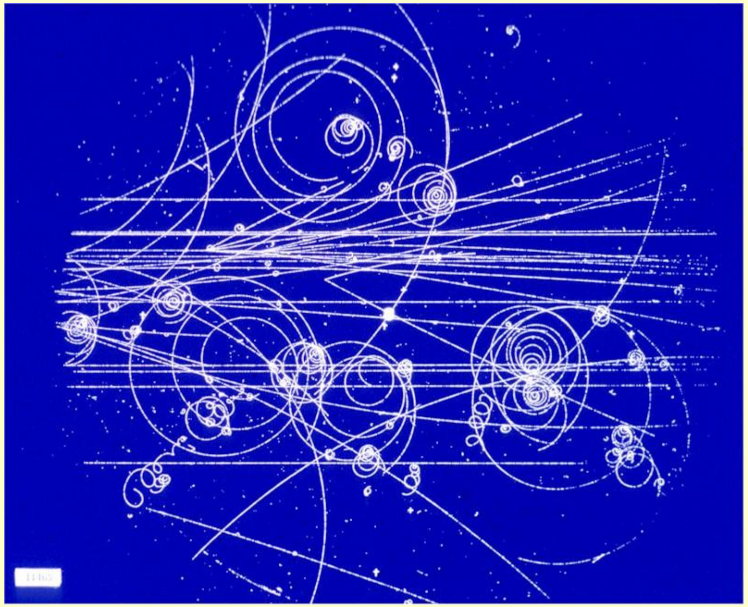
University of Warwick

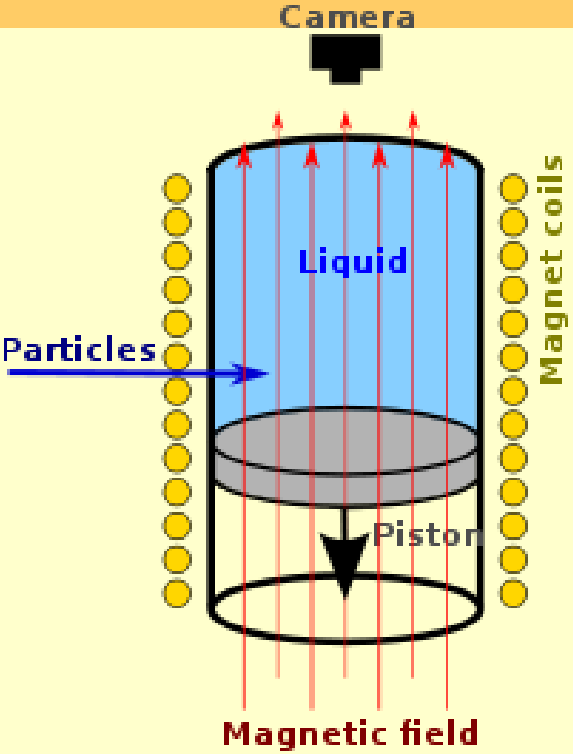
Birmingham, 18/05/11

Outline

- Liquid argon time projection chamber
- Neutrino physics programme
- Detector requirements/options
- LArTPC R&D/ challenges
- Current status
- Outlook and conclusion

Bubble Chambers

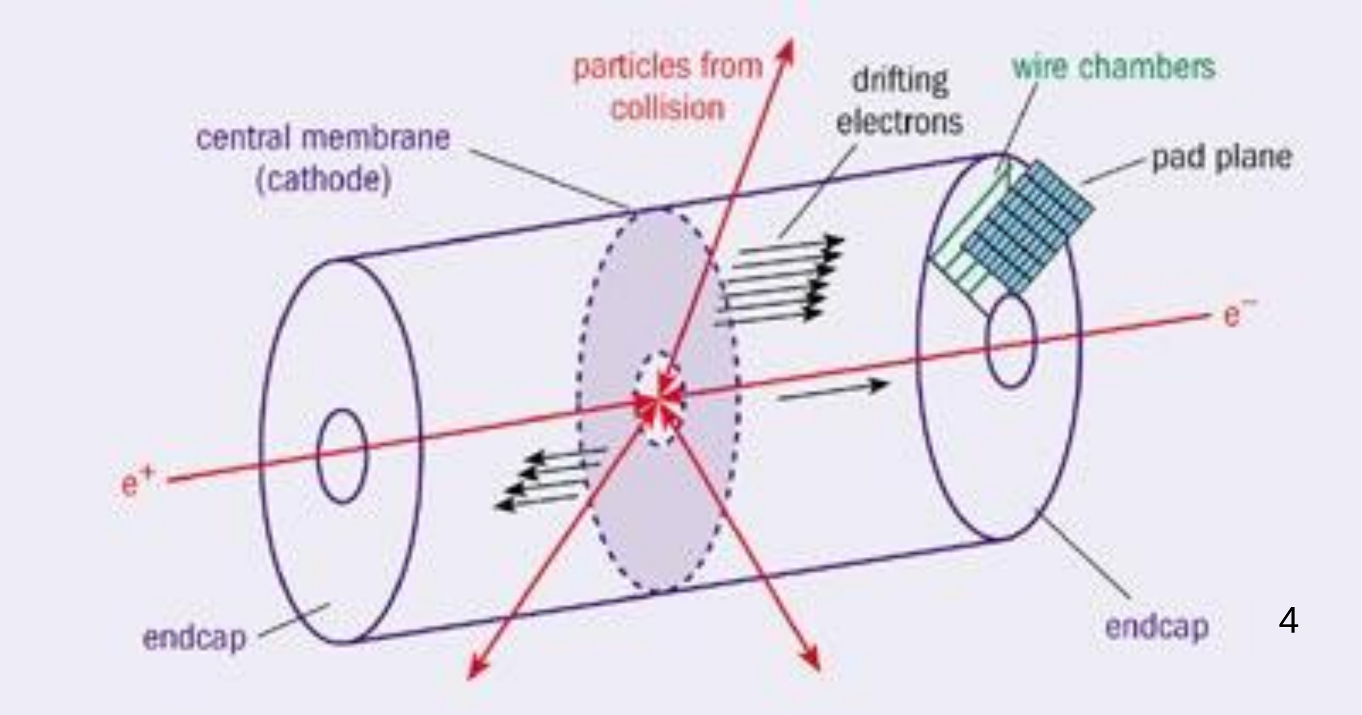




- How to keep topology information of the bubble chamber in a (high mass) neutrino detector?

Time Projection Chamber

- Charpak(1969), Nygren(1974) introduce TPC
- Drift electron-charge image of event to (x,y) electrode array to give (x,y,z) image with drift time



Liquid Argon TPC (LArTPC)

- (1977) Carlo Rubbia proposes a TPC based on LAr as both ν-target and detection medium. Advantages:

  1. Reasonably dense (1.4 g/cm^3)
  2. Does not attach electrons (much) => long drift times
  3. High electron mobility (500 m^2/Vs)
  4. Easy to obtain, cheap (liquefaction from air)
  5. Inert and can be liquefied by liquid nitrogen
  6. Charge, scintillation light and Cherenkov light readout possible

LAr Properties

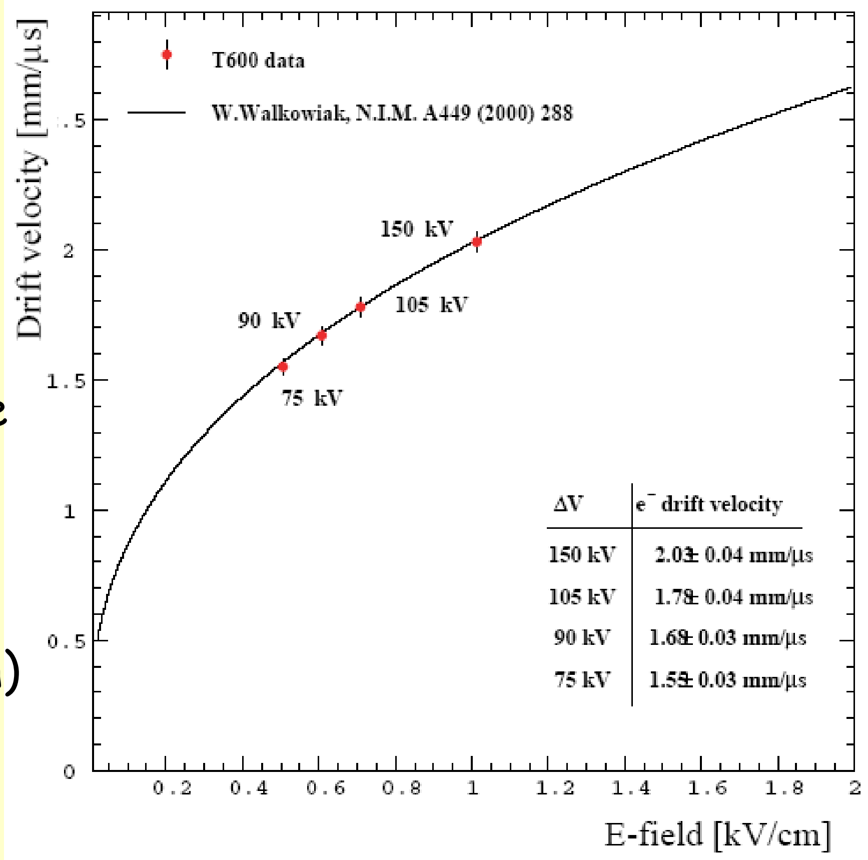
- LAr has many similar properties to freon CF_3Br used in Gargamelle bubble chambers:

	Argon	CF_3Br
Nuclear collision length	53.2 cm	49.5 cm
Absorption length	80.9 cm	73.5 cm
dE/dx, minimum	2.11 MeV/cm	2.3 MeV/cm
Radiation length	14 cm	11 cm
Density	1.40 g/cm^3	1.50 g/cm^3

⇨ Can expect event-development in LAr/bubble chamber is very similar

Ionisation Charge

- LAr ionisation: W_e=23.6 ±0.5 eV ⇨low detection thresholds and ~6k ionisation electrons/mm/m.i.p.
- Some electrons will recombine – suppressed by E_{drift} (absent for mip's at $E_{drift} \geq$ 10 KV/cm)
- Drift velocity parametrised, $V_{drift}(E,T)$, and measured in LArTPC's



V_{drift}~2 mm/μs @ E_{drift}=1 KV/cm

- Oxygen (nitrogen) impurities capture free electrons:

τ_e [μs] ~300/ρ [ppb]

(τ is electron lifetime, ρ is O_2 concentration)

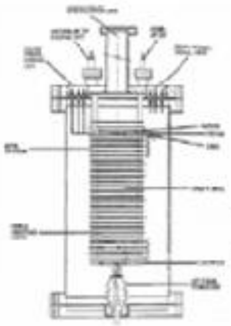
⇨ clearly a crucial issue for LAr

- Diffusion effects are small e.g. for E_{drift} ~1 KV/cm: transverse ~ mm's and longitudinal « uncertainty on V_{drift}

Light Production

- LAr is an excellent **scintillator**: $W_\gamma = 19.5$ eV giving approx. 5000 photons/mm/m.i.p
- Singlet ($\tau = 6$ns) and triplet ($\tau = 1.6\mu$s) excimers both give spectrum peaked at λ=128nm
- Light at this wavelength not energetic enough (9.7 eV) to cause secondary ionisation/excitation ⇨ transparent to scintillation light and subject only to Rayleigh scattering
- Recent evidence that there is also scintillation in near infrared 690-850 nm (Buzulutskov et al., arXiv:1102.1825)
- LAr has similar **Cherenkov** imaging capability to water : H_2O(LAr), n=1.33(1.24)

The ICARUS steps

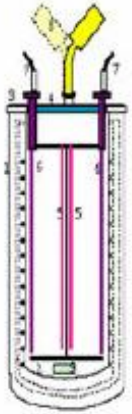


24 cm drift
wires chamber

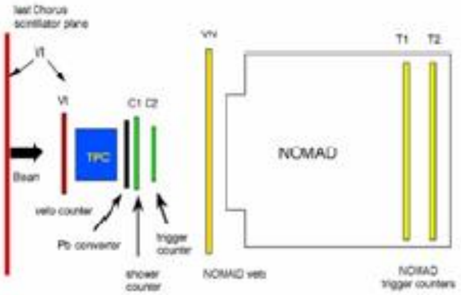
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



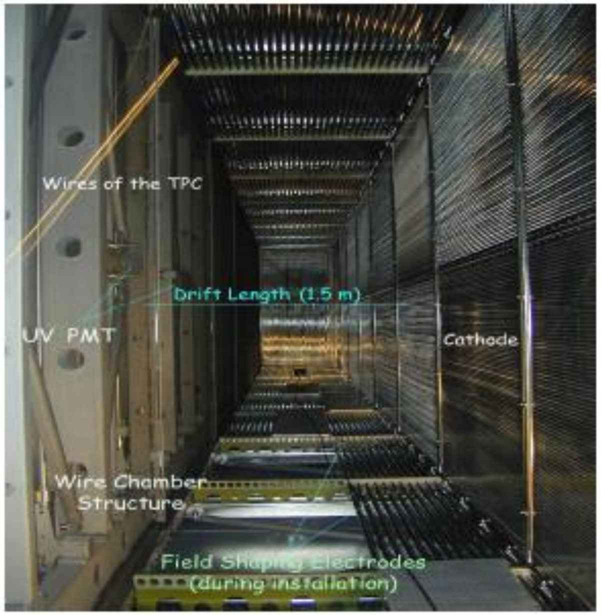
50 litres prototype
1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.



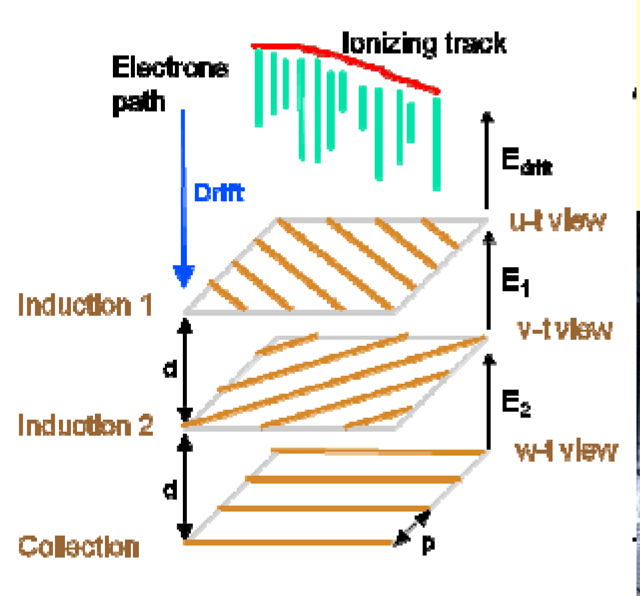
600 ton detector

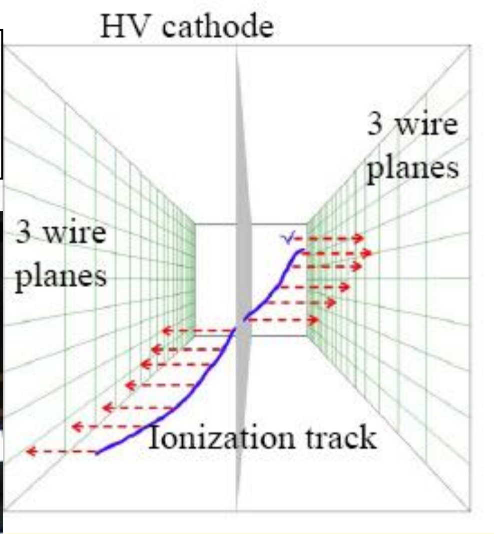
2001- present: 300 ton detector tested on surface in Pavia.
600 ton detector assembled at LNGS.

NIM A 527 (2004) 329

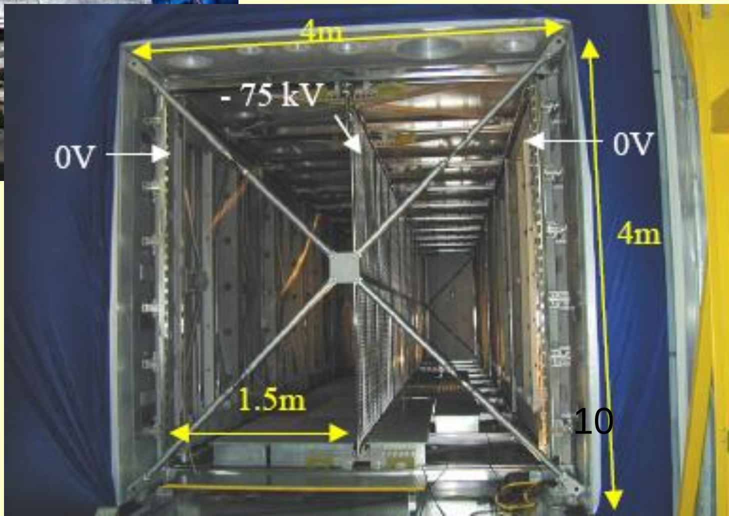
ICARUS

Max. Drift 1.5m (0.5 kV/cm), to 3 electrode planes

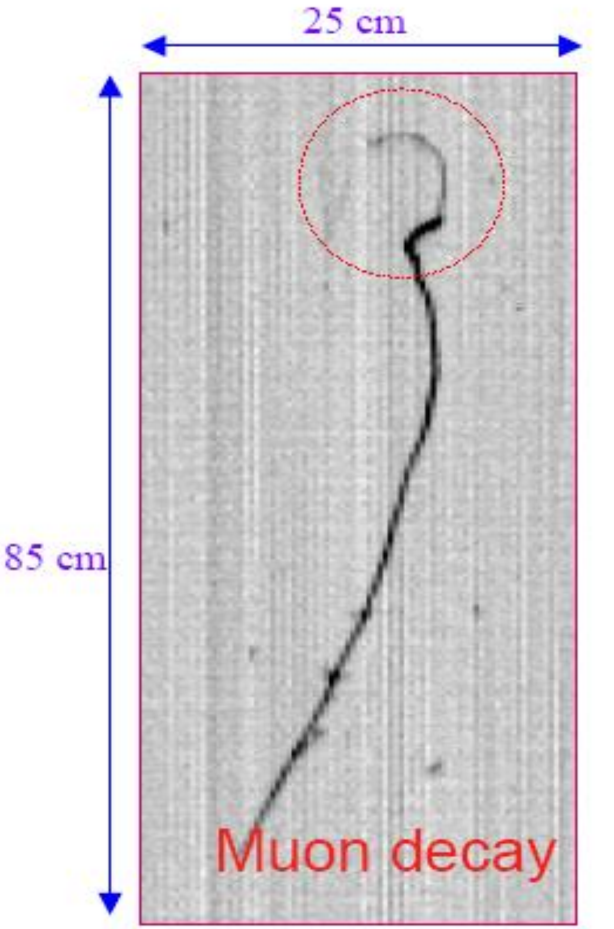




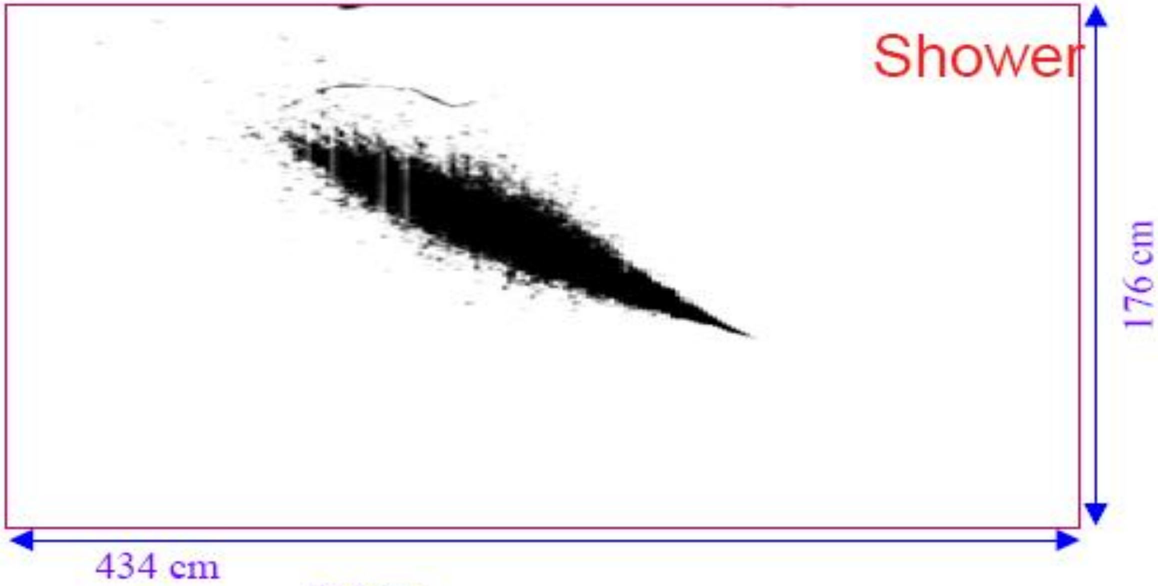
Prompt scintillation light detected by WLS PMT's and used as a \`t_0'



ICARUS TPC



Run 960, Event 4 Collection Left



Run 308, Event 160 Collection Left

Proof of Principle

The ICARUS project has proven the principle of the LAr TPC:

- Tracking device with precise event topology reconstruction
- dE/dx with high density sampling (2% X_0) for particle ID
- Energy reconstruction from charge integration (full-sampling, fully homogeneous calorimeter): $\sigma/E=11\%/\sqrt{E(MeV)}+2\%$: Michel electrons $\langle E\rangle=20MeV$

  $\sigma/E=3\%/\sqrt{E(MeV)}$: electromagnetic showers

  $\sigma/E=30\%/\sqrt{E(MeV)}$: hadronic showers

Neutrino Physics Programme

- Neutrino oscillation physics: atmospheric, solar, neutrino beams
- Proton decay
- Astrophysics: supernovae, early universe relic neutrinos
- Geo-neutrinos

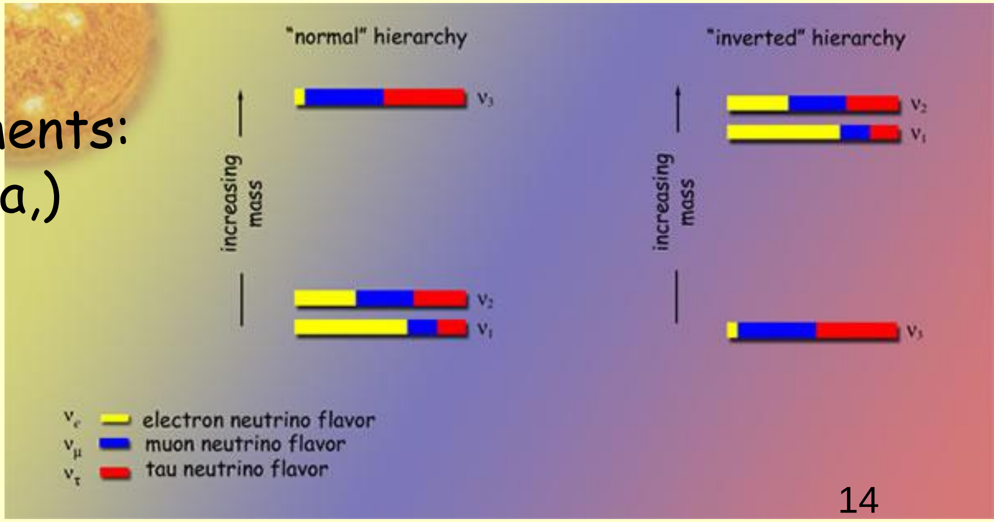
Neutrino Oscillations

- Neutrino mixing: $\theta_{23}, \theta_{13}, \theta_{12}, \delta$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{\alpha i} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix},$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Goals of next oscillation measurements:
  - -measure θ_{13} (improve on T2K, Nova,)
  - -measure CP violation in neutrinos
  - -measure neutrino mass hierachy



Neutrino oscillations

e.g. Measuring the `golden channel'

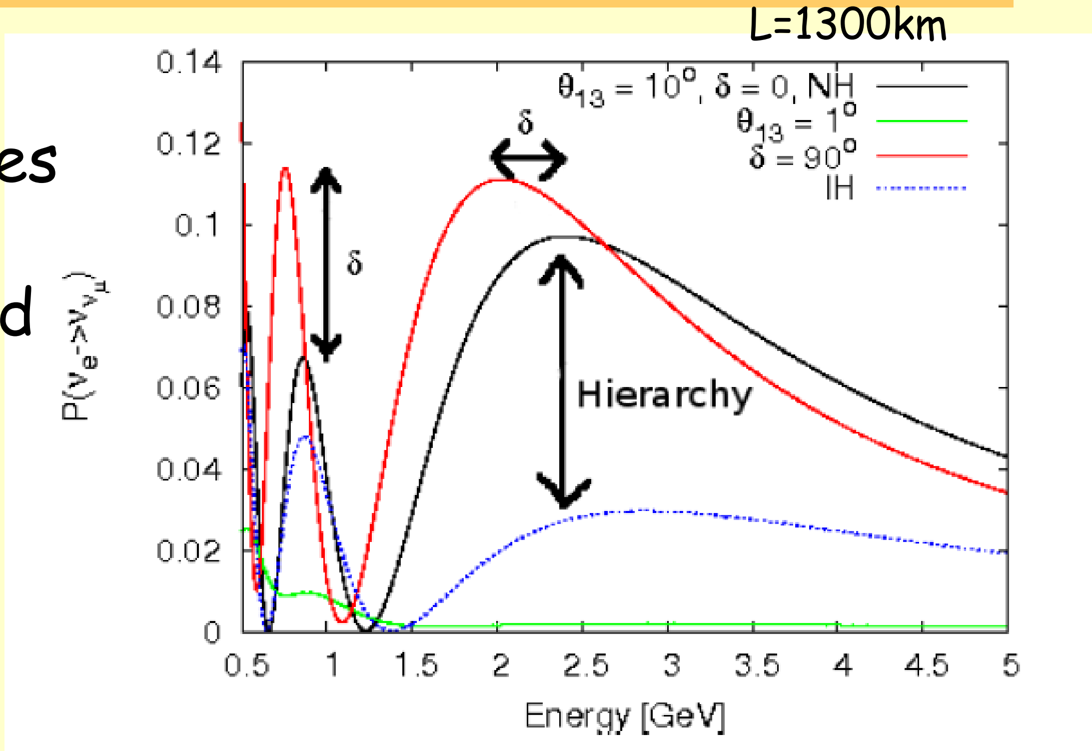
$$\begin{aligned} P_{\nu_e \to \nu_\mu} &= s_{213}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\ &+ s_{213} \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \times \\ &\quad \cos\left(\delta - \frac{\Delta m_{31}^2 L}{4E}\right) \\ &+ \alpha^2 c_{23}^2 s_{212}^2 \left(\frac{\Delta m_{31}^2 L}{2EA}\right)^2 \sin^2\left(\frac{AL}{2}\right) . \end{aligned}$$

$A = \sqrt{2} G_F n_e$ is the matter potential; $\alpha = \Delta m_{21}^2 / \Delta m_{31}^2$

Contains information on all parameters we want to measure (up to degeneracies!)

Neutrino Oscillations

Fit oscillation signal as function of energy – requires coverage of 1st and 2nd oscillation peak for required sensitivity



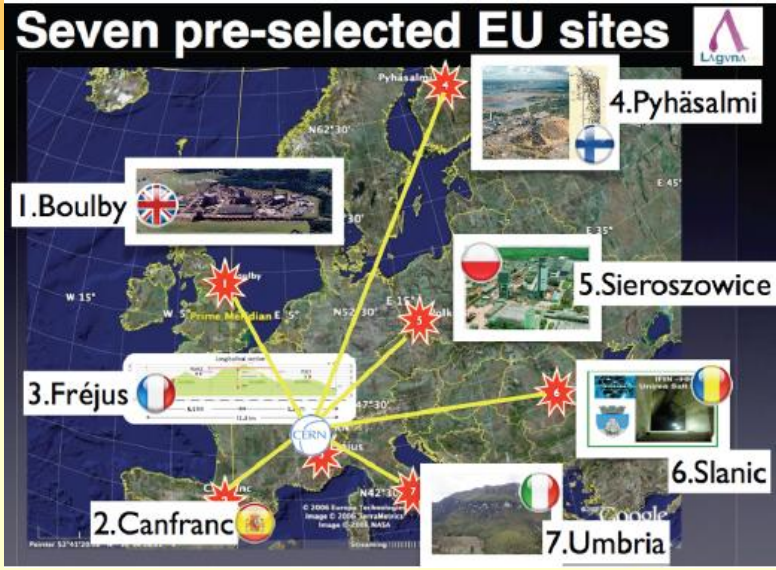
or

`Counting' experiments:

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

Not sensitive to $\delta = 0^o$, 180^o

Oscillation Facilities

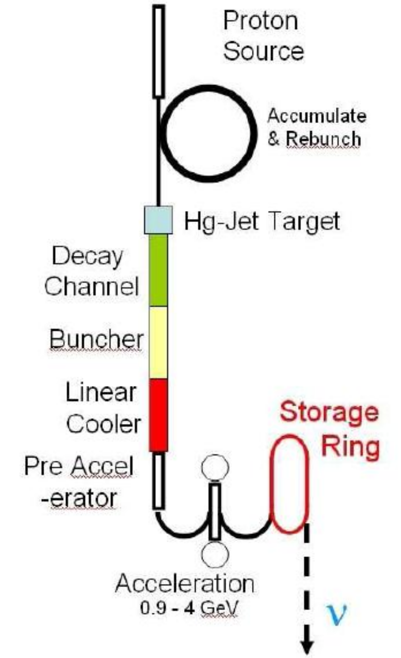


- **Super beam**: $p+N\rightarrow\pi^-+X$ and $\pi^-\rightarrow\mu^-+\nu_\mu$ to study $\nu_\mu\rightarrow\nu_x$ next generation long baseline.

  USA(FNAL to Homestake), Japan (T2K upgrade), CERN to ?

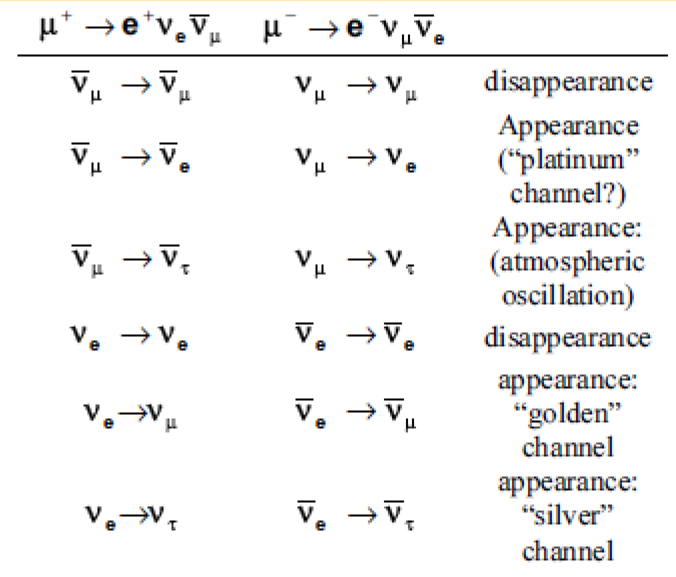
- **Beta-beam**: $\nu_e/\bar{\nu}_e$ from high-γ beta emitters (^{6}He,^{18}Ne,^{8}Li,^{8}B), pure flavour, collimated beam, well understood flux

- **Neutrino Factory**: muon storage ring, well understood flux, electron and muon flavours : $\mu^-\rightarrow e^-+\bar{\nu}_e+\nu_\mu$



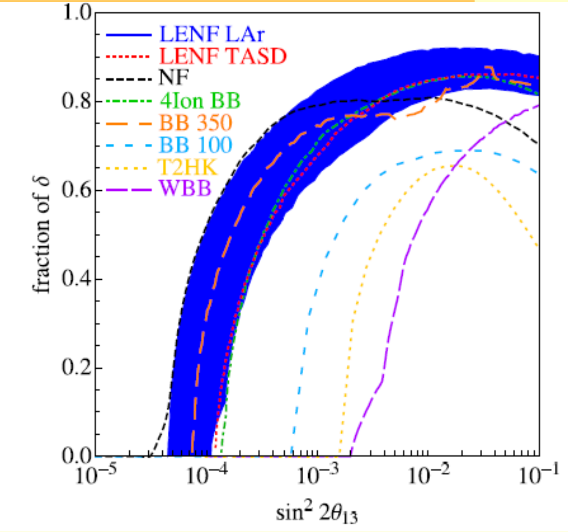
Neutrino Factory

- `Ultimate' ν-oscillation facility
- 12 oscillation processes available:



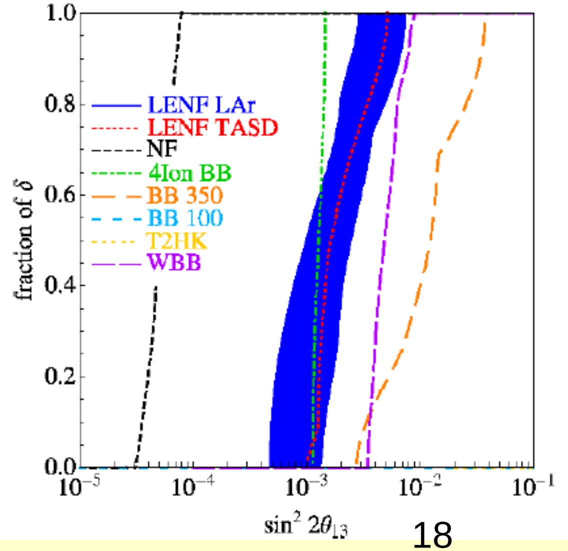
$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$	$\mu^- \to e^-\nu_\mu\bar{\nu}_e$	
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	Appearance (“platinum” channel?)
$\bar{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	Appearance: (atmospheric oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: “golden” channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: “silver” channel

CP violation



- Superbeam experiments are only competative for large θ_{13} i.e. $\sin^2 2\theta_{13} > 10^{-3}$ due to irreducible contamination of ν_μ beam with ν_e

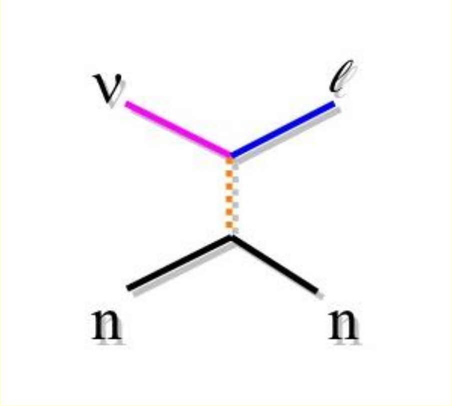
Hierarchy sensitivity:

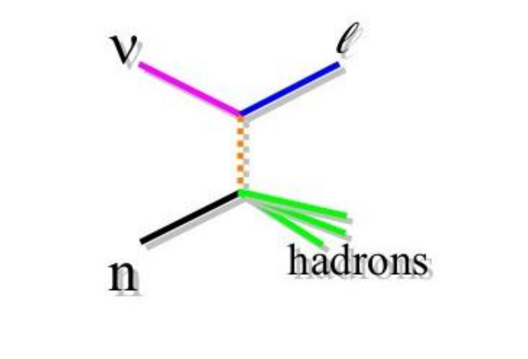


E. Fernández-Martínez, T. Li, O. Mena, S. Pascoli, Phys. Rev. D 81, 073010 (2010).

Detector: General Requirements

- High rates -> scalable to > 10kt
- Reconstruction of charged current interactions
- Particle identification: leading lepton (e,μ) in CC interactions and separate from pions ν_ℓ+N→ℓ+hadrons
- Energy resolution: $E_\nu=E_\ell+E_{had}$
- Low thresholds





Detector: Specific Requirements

Regardless of facility (Superbeam, beta-beam or N F) the ideal detector would reconstruct all oscillation channels:

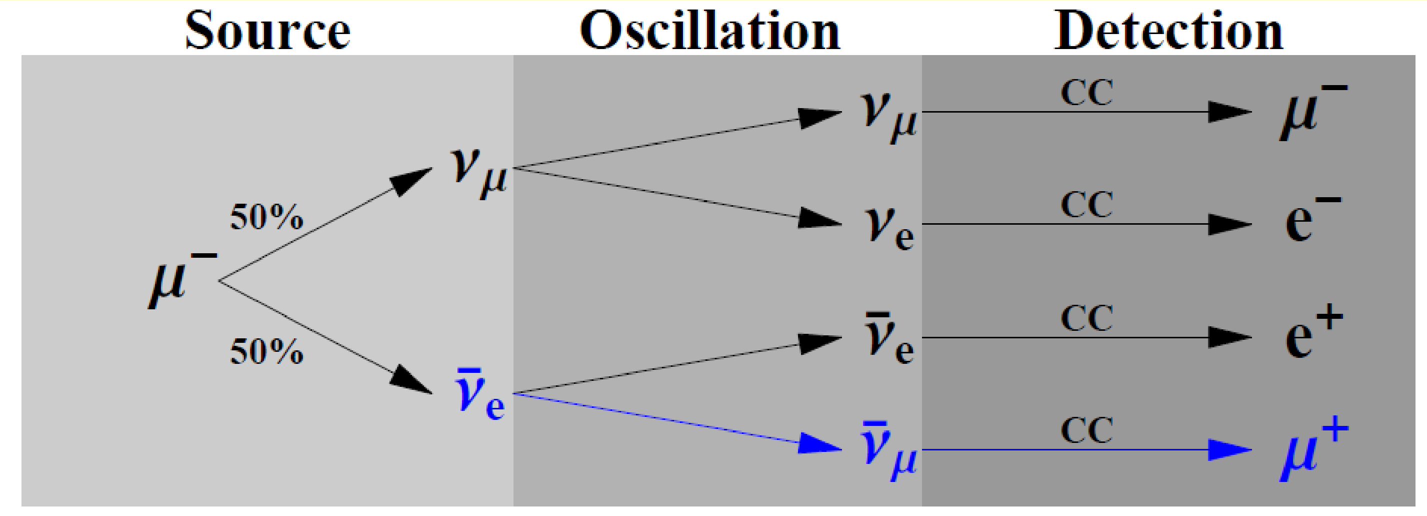
- $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu \, ; \, \overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$ disappearance
- $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e \, ; \, \overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau$ appearance
- $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu$ appearance (Golden channel)
- $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\tau$ appearance (Silver channel)

Will probably also need to be multipurpose:

- Proton decay ($p \rightarrow e^+ + \pi^0$; $p \rightarrow K^+ + \nu$), supernova neutrinos etc
- Highly isotropic: exposure to long baseline oscillations expts. from below, particle astrophysics expts. from above, p-decay expts. from within
- Affordable i.e. simple and scalable
- Probably underground (engineering, safety issues)

Detector: Specific requirements

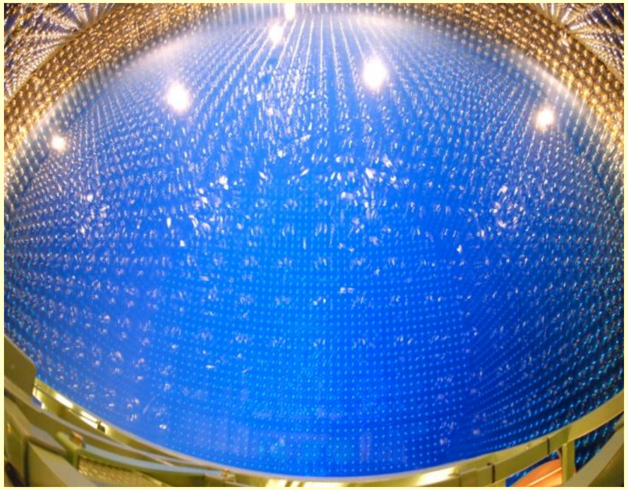
- Detectors must be able to discriminate μ^+/μ^- and e^+/e^- => magnetisation!
- e.g. The NF Golden Channel signal is `wrong-sign' muons:



Major issue for all large-scale detector options (iron calorimeter, LAr, scintillator) and rules out water Cherenkov as a NF option

Realistic Options

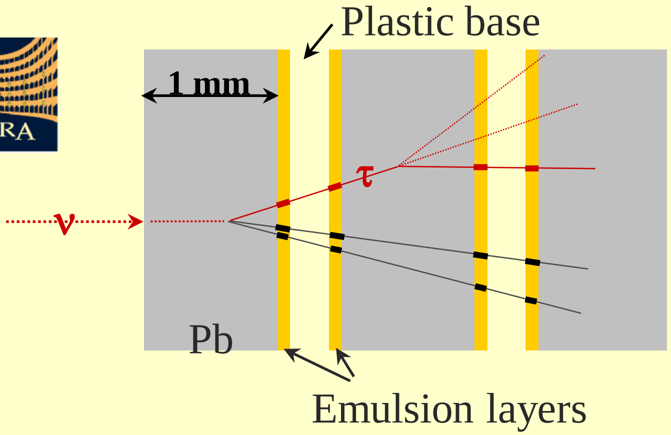
- **Water Cherenkov**



- **Tracking Calorimeter**

- **Emulsion?**

OPERA



- **Liquid argon TPC**

Water Cherenkov

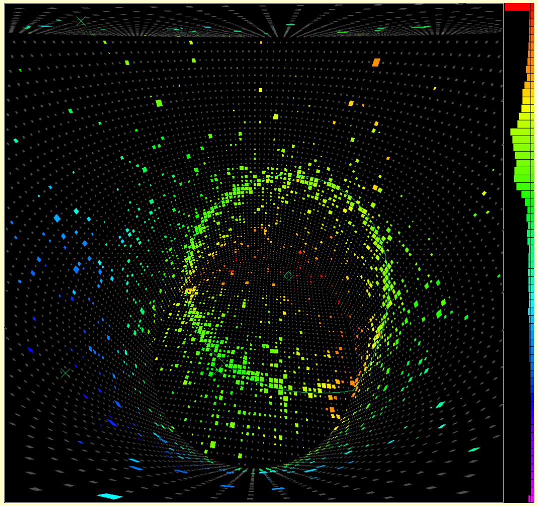
For:

- Proven technology
- Excellent e-muon separation

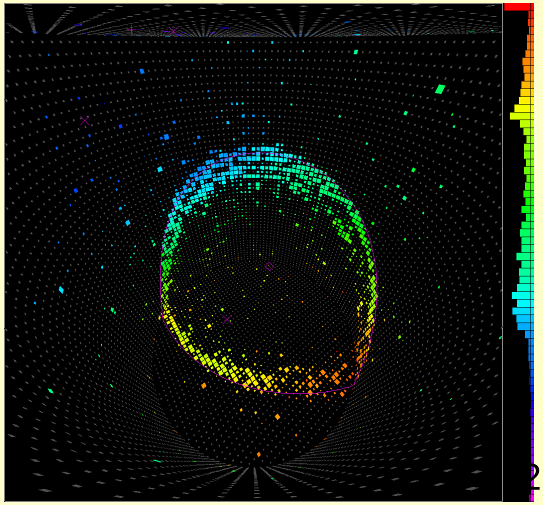
Against:

- Only a low E_ν option (0.2-1GeV)
- How to magnetise?
- Relatively poor E_ν resolution
- Rates too high for use as Near Det.
- Kaons below Cherenkov threshold in p->K^+ + ν
- Cost – maybe up to 1Mton would be needed (x20 SuperK)

Electron-like



Muon-like

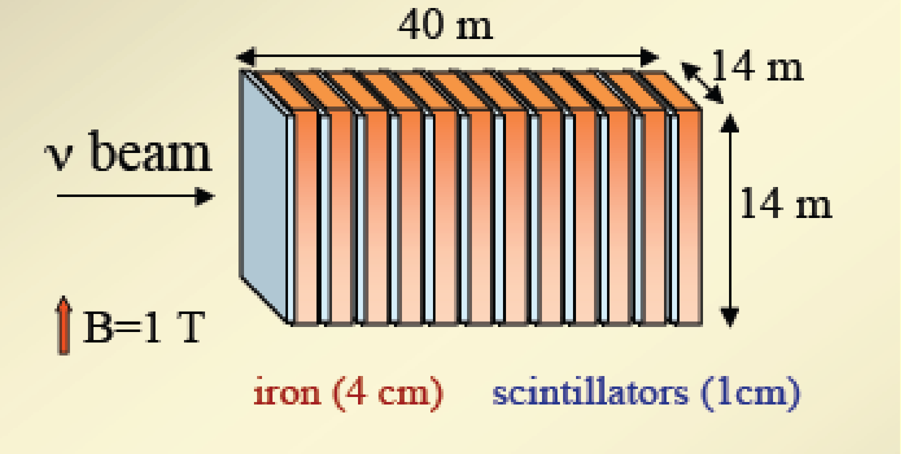


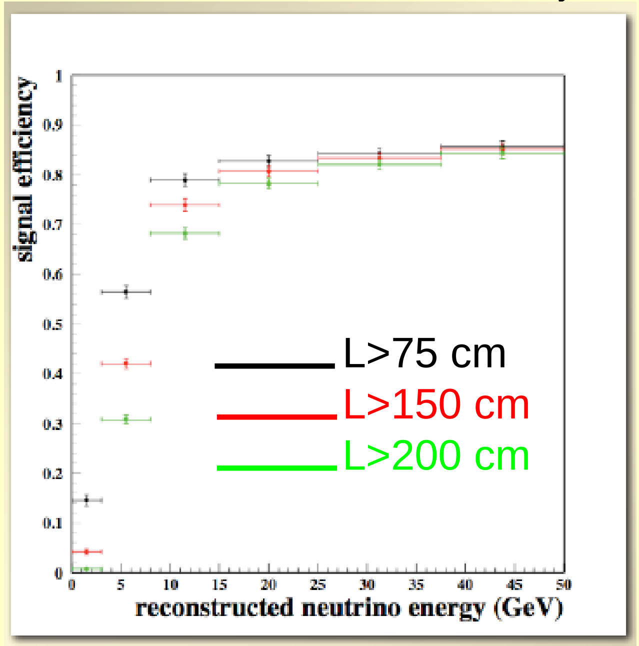
Magnetised Iron Neutrino Detector: MIND

- Iron-scintillator sandwich (like 9x MINOS)

For: relatively little R&D

Against: Detector optimised for golden channel at high-E neutrino factory only (relatively high thresholds, no electron ID)





Totally Active Scintillator Detector:TASD

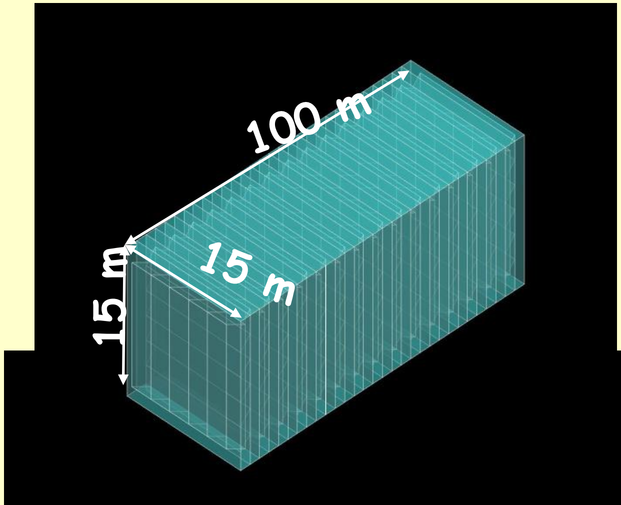
Like a larger Nova/Minerva

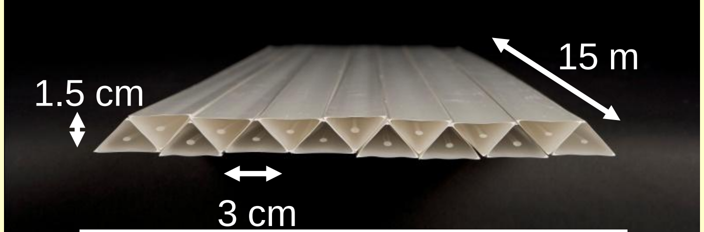
For:

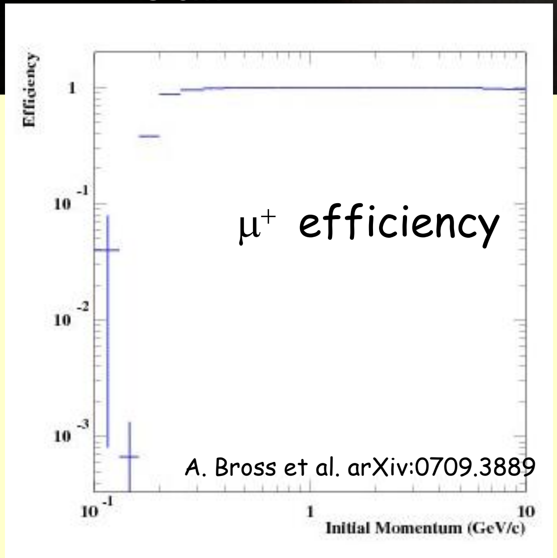
- Tried and trusted
- Few mm transverse spatial resolution
- Relatively low thresholds (100MeV)

Against:

- Large number of channels -> cost
- Magnetise?
- R&D needed to prove coextrusion/light levels
- Event reconstruction can get complicated – must match 2D measurement planes





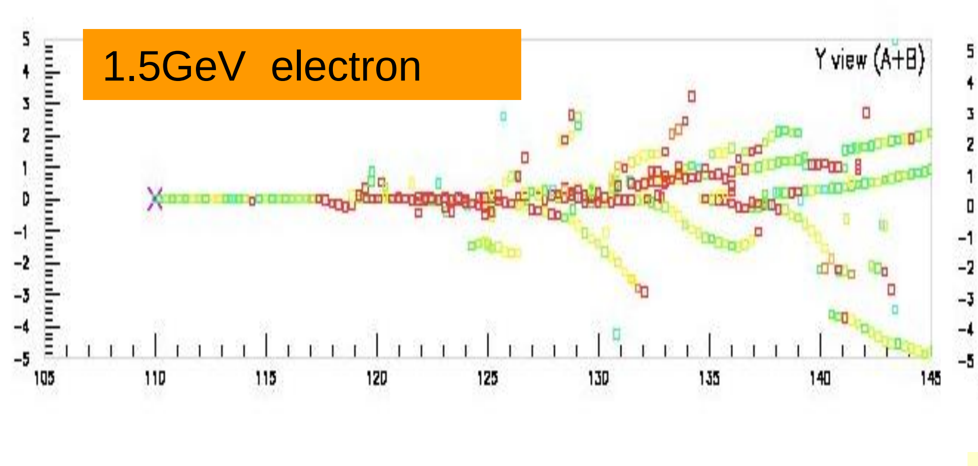


A. Bross et al. arXiv:0709.3889

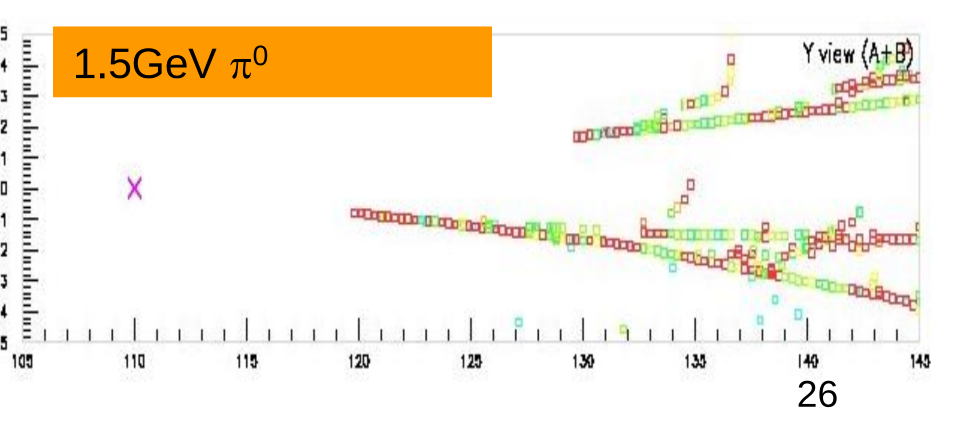
LArTPC:Particle ID

Detector ideal to discriminate e/μ/π to low thresholds

e.g. e/π^0 discrimination in appearance: $\upsilon_{\mu} \rightarrow \nu_e$ NC π^0 background rendered almost negligible



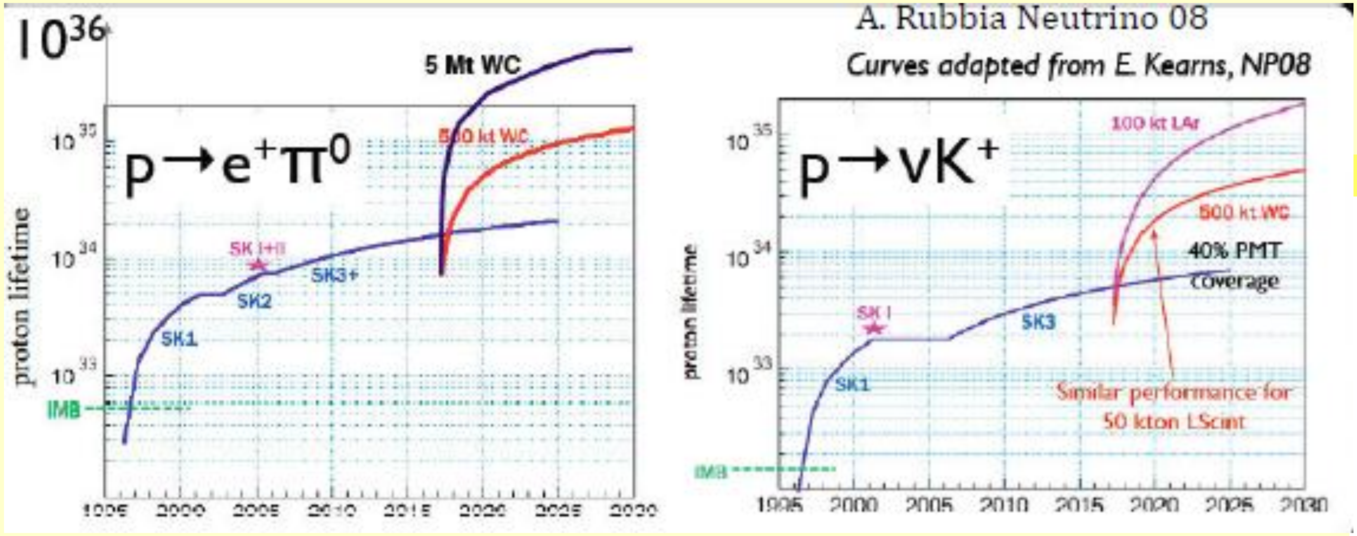
1.5GeV electron



1.5GeV π^0

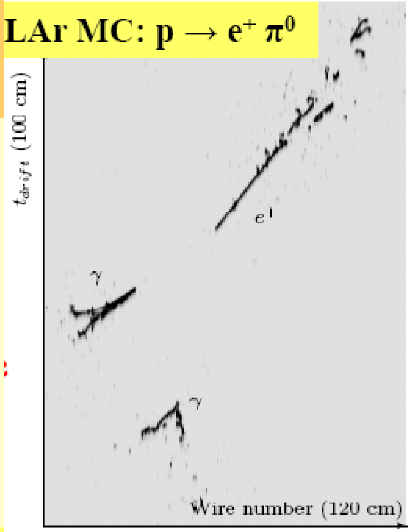
LArTPC: Proton Decay

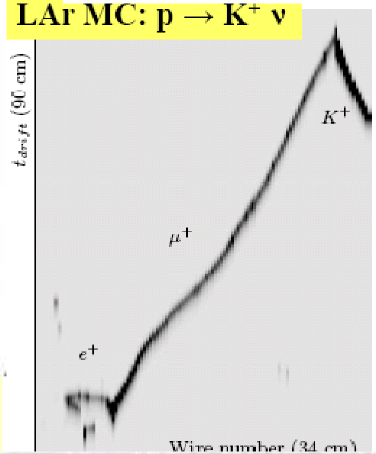
- Two main channels:

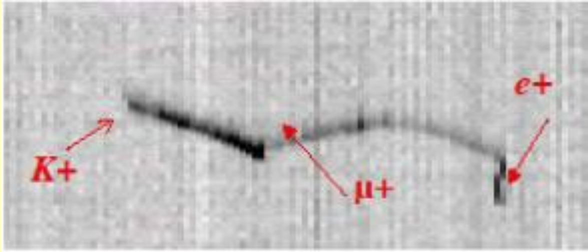

A. Rubbia Neutrino 08

Curves adapted from E. Kearns, NP08

- LAr is only way to include the kaon channel to reach ~10^{35} year limits where several theoretical models could be tested


LAr MC: $p \to e^+ \pi^0$


LAr MC: $p \to K^+ \nu$

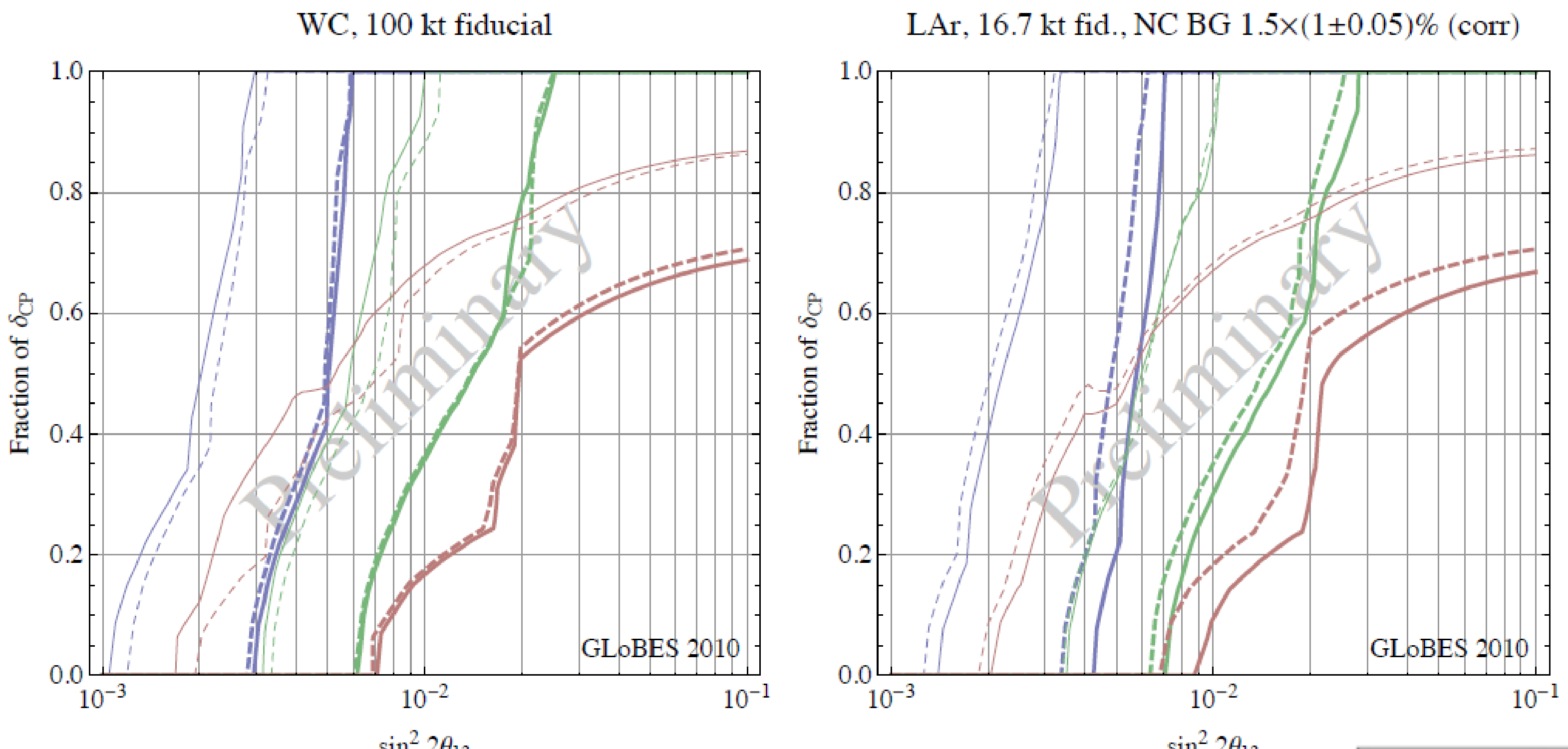


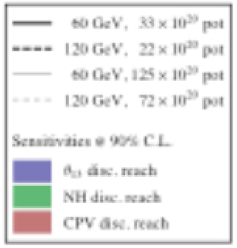
Real event in T600

A. Marchionni, NP08

LAr/H_2O Physics Reach

Study for the FNAL-Homestake (LBNE) project found ~6:1 mass equivalence between water:LAr





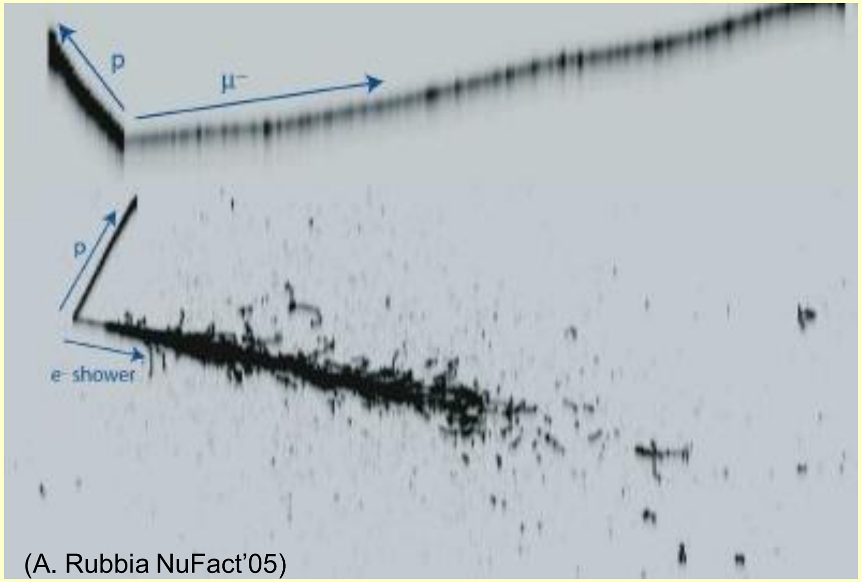
Plots by J. Kopp

- LArTPC Plots Assume:
  - WBB design for LBNE
  - 85% ν_e efficiency
  - 5% background uncertainty

Liquid Argon TPC's

For:

- Multipurpose + will deliver oscilln. program at Superbeam and NF
- True 3D imaging with pixel size~(x,y,z)=(3mmx3mmx0.3mm)
- High granularity dE/dx sampling - e/γ separation >90% (π^0 background to electrons negligible)
- Total absorption cal σ_E/E <10%
- Low energy threshold (few 10'sMeV)
- Continuously live
- Charge and scintillation light readout



(A. Rubbia NuFact'05)

Against:

- R&D needed:scalability,engineering,purity,
- B-field?

(FLARE LOI hep-ex/0408121)

Towards Large-Scale LAr TPC's

* Conclude that LArTPC's are the best match to the physics requirements of the next generation of experiment – but can they be built on scale required?

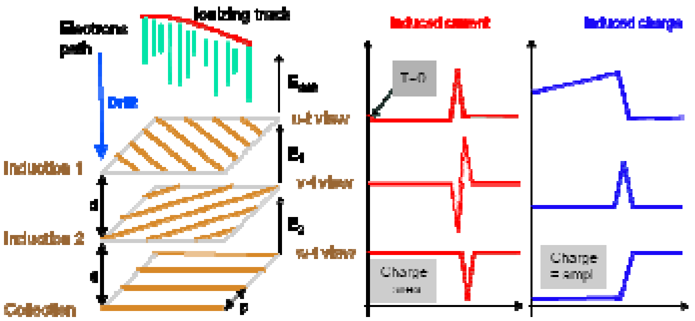
LArTPC's that are 50-100 kton (i.e. ~100 times larger than ICARUS) require:

- Recirculation and purification systems capable of achieving few x 10's ppt electronegative impurities
- Longer ionisation charge drift lengths to keep down number of readout channels per unit volume and dead space (readout planes and cathodes) => demands HV systems producing drift fields 0.5-1 kV/cm
- Huge cryogenic vessels that are leak tight enough to maintain purity and suitable for underground construction/operation

R&D 1: Readout

- ICARUS scheme: 3 wire planes at different angles, all in liquid phase
- Difficult to scale up without charge amplification: want S/N >10 but long wires give large capacitance, mech. issues etc

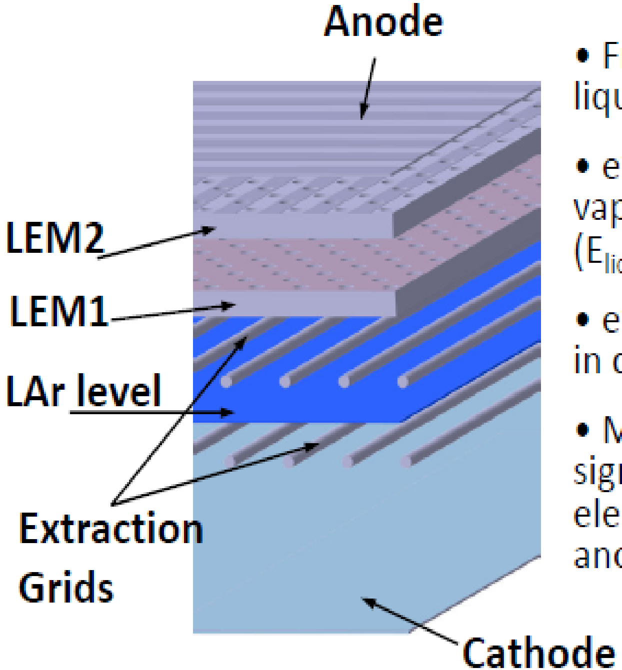
single LAr phase, wire planes



C. Rubbia, CERN Report 77-8, May 1977

double phase Ar

Large Electron Multiplier (THGEM)

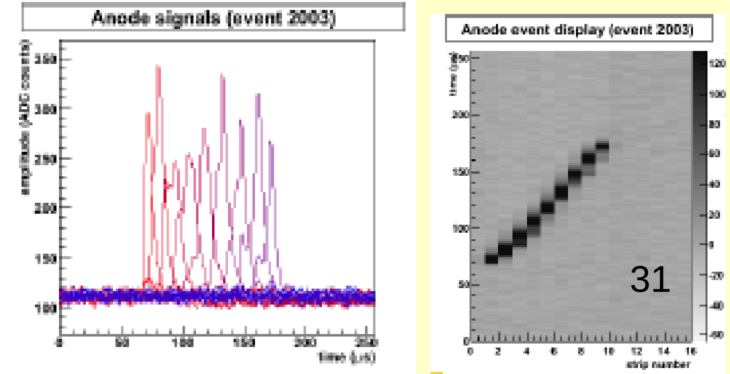


- Free e^- drift in LAr towards liquid-vapour interface.
- e^- are extracted to the vapour via extraction grids (E_{liq} > 2.5 kV/cm).
- e^- undergo multiplication in double stage LEM.
- Multiplied charge induces signals on the segmented electrodes of top LEM and anode.

A. Badertscher et al., arXiv:0811.3384

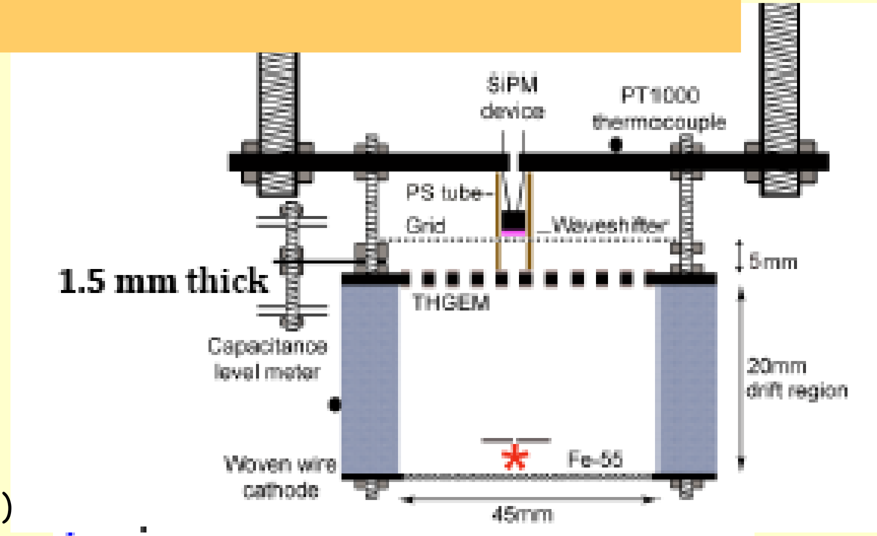
- Alternatively amplify charge in argon vapour above the liquid volume with TGEM/LEMS
- S/N~60, gain of 10 achieved

Cosmic muons



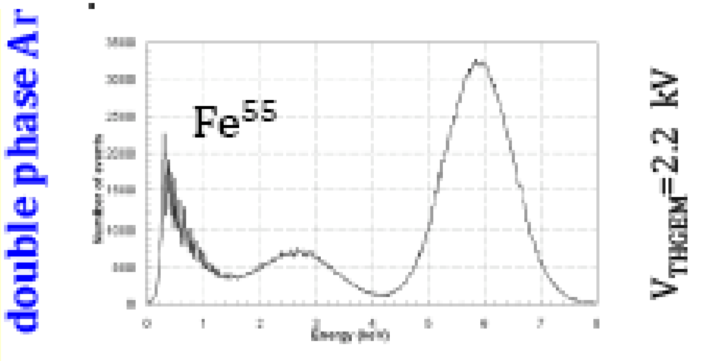
R&D 1: Readout Light Imaging TGEM Planes

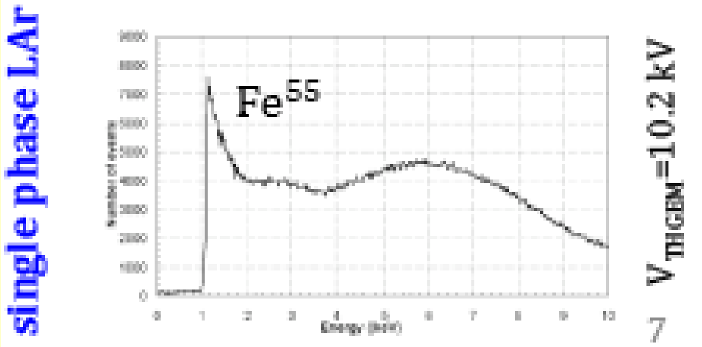
- Idea is to optically image the TGEM plane (array of photosensors, pixel detectors,..)
- LAr test-stands in Sheffield and Warwick
- Shown that SiPM's work in Lar (JINST 3 P10001(2008))
- Shown that luminescence light produced based on a single TGEM hole (JINST 4 P04002(2009))



Next steps:

- Demonstrate tracking
- Investigate pixel devices (e.g. fast CMOS sensors coming out of the LC effort?)
- NB could reduce readout channels dramatically and be largely free of electronics noise -> scalability

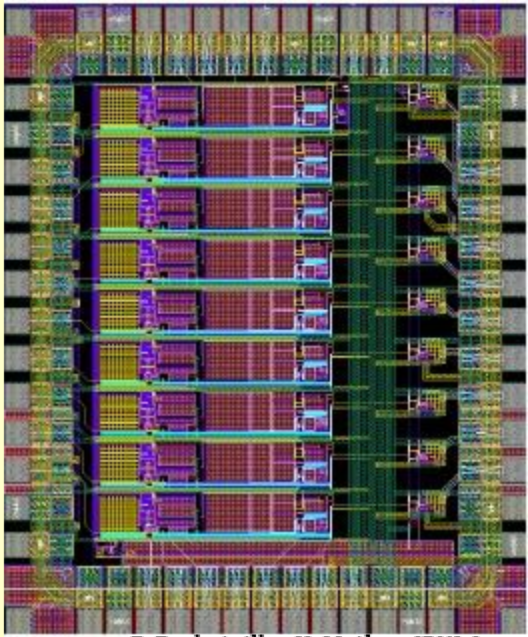




R&D 2: Electronics

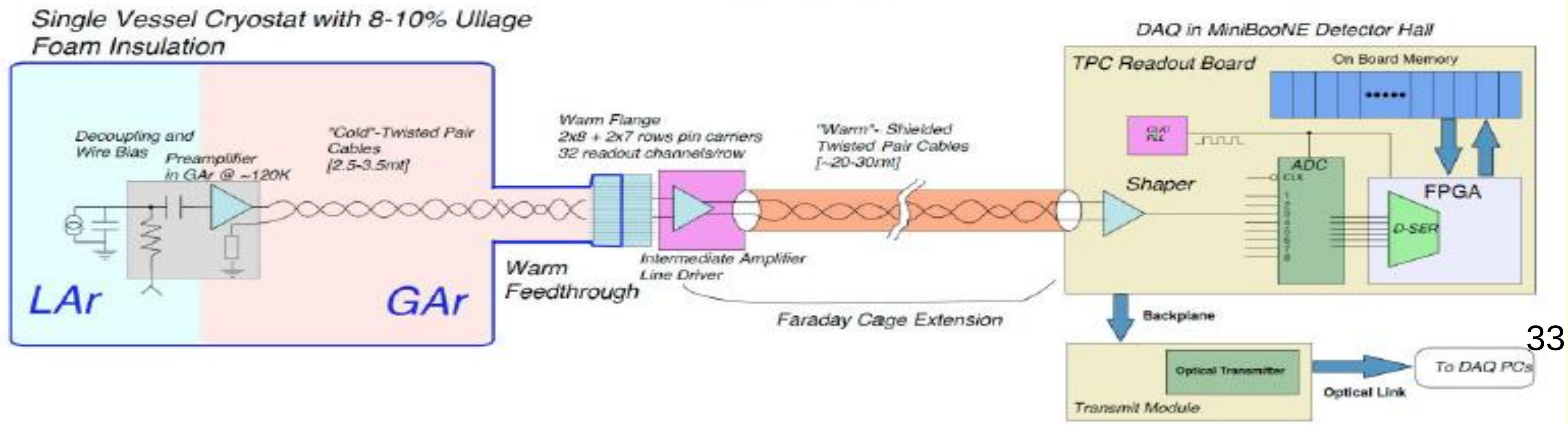
- Per-channel cost of electronics for huge detectors could be show-stopper
- Advantages to having front-end digitisation take place inside cryostat: short connections => lower Cap./noise, low temp => lower noise)
- Push to develop CMOS ASIC amplifiers (cheap) that operate in the LAr at 87K : minimise distance from readout electrodes to amplifier for S/N~10
- Expect in future digitisers and multiplexers to also be inside cyrogenic vessel => demands low heat dissipation!

0.35 μm CMOS amp. working at cryo. temps (IPNL, Lyon)



E. Bechetoille , H. Mathez, IPNL Lyon
Proceedings of Wolte-08, June 2008

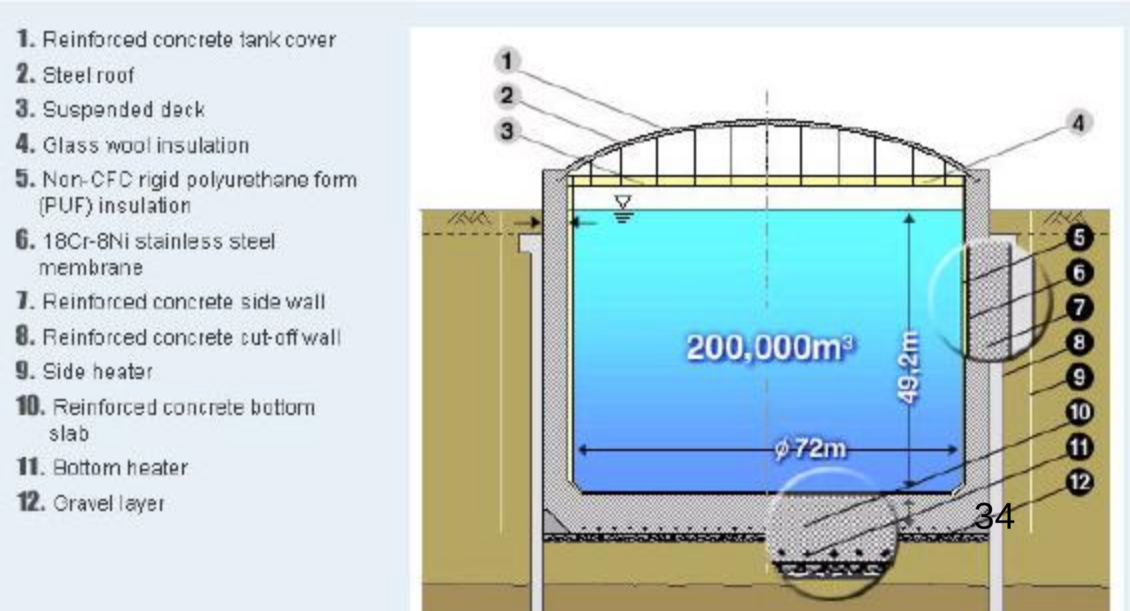
MicroBoone electronics



R&D 3:LAr Vessels

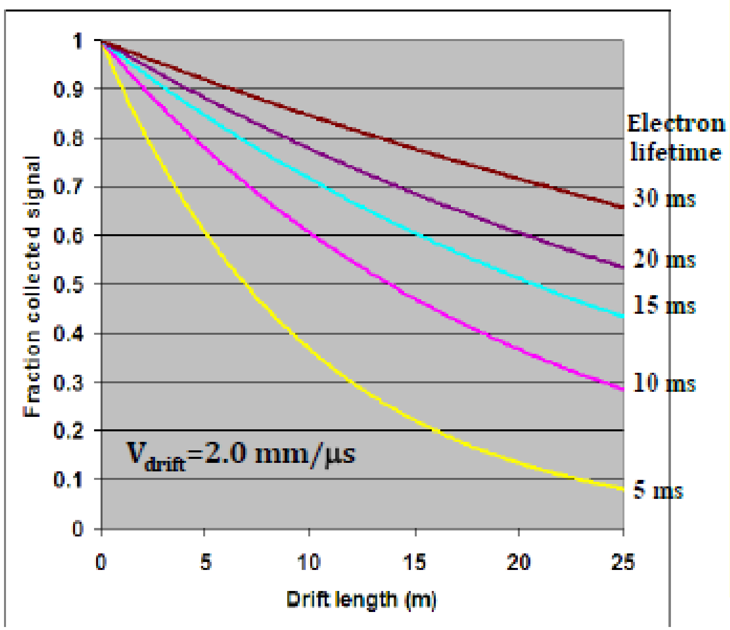
- Standard stainless steel vacuum dewars not scalable to >10,000 m^3
- Huge LNG cryo. vessels with small surface/volume ratios use perlite or foam glass insulation up to 200,000 m^3
- Boiling point LAr and CH$_4$ similar =>boil-off only 0.04%/day for 100 kton vessel
- Ar-gas purging of air (at ppm level) needed before filling: tests happening at KEK, FNAL (20 t, LAPD) and CERN (6 m^3)

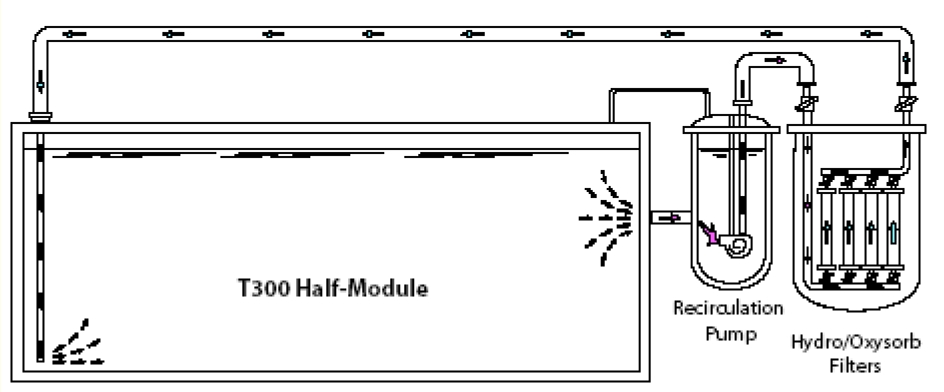
Stainless/invar LN$_2$ underground tank



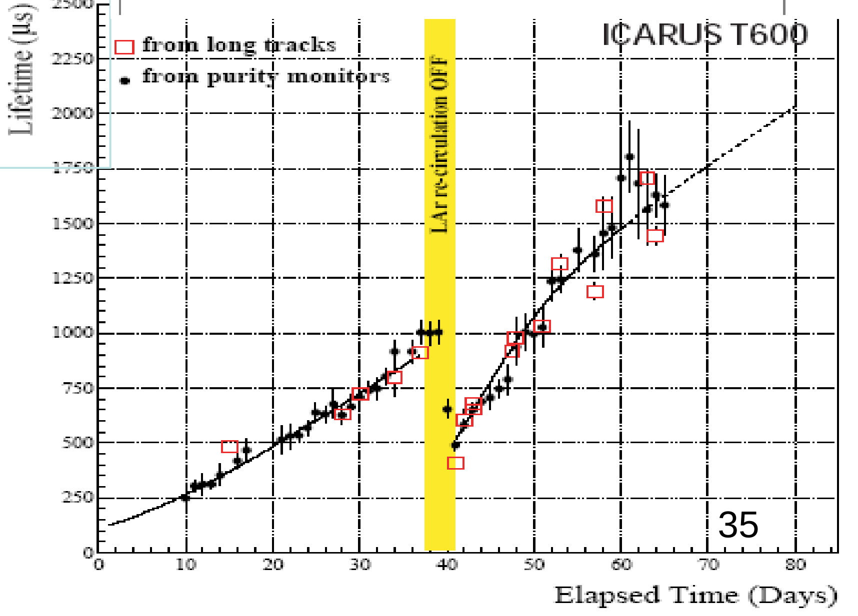
R&D 4: LAr Purity

- V_{drift}=2mm/μs at 1kv/cm drift field
- For 20m drift and >30% collected signal requires an electron lifetime of at least 10ms
- ICARUS have demonstrated >10 ms electron lifetime over several weeks using commercial Oxysorb/Hydrosorb filters
- Can this scale? ⇨ high throughput, all liquid, phase circulation and filtering needed
- Material test facility@FNAL investigating outgassing from contact materials





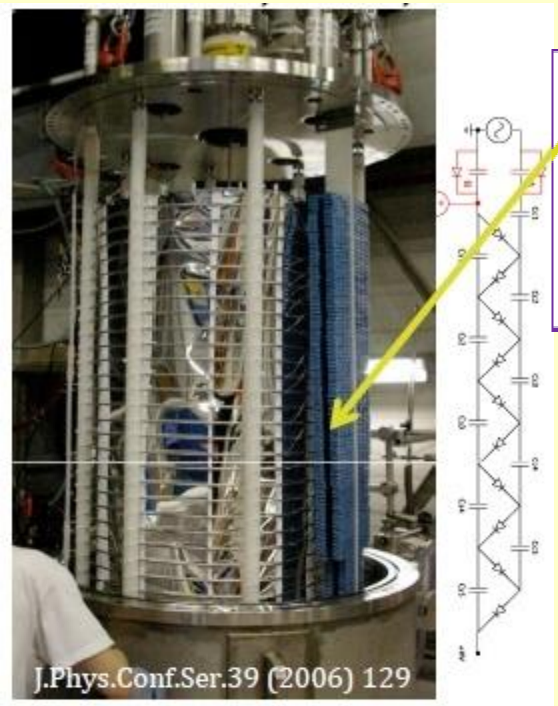
NIM A527 (2004) 329



R&D 5:Long Drift

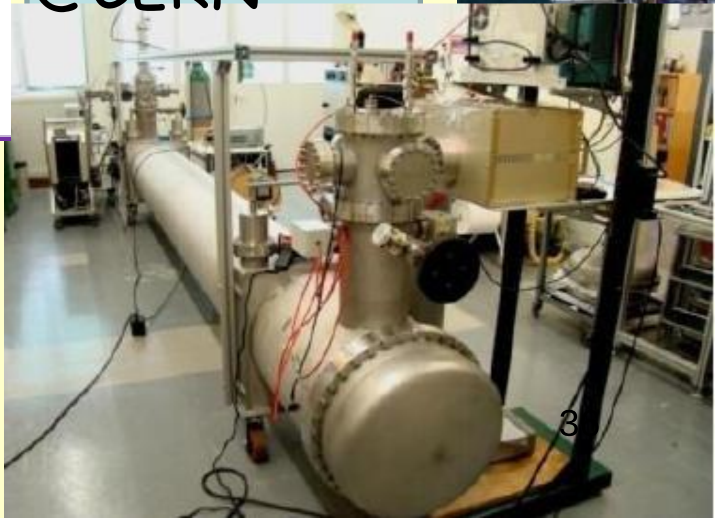
- Electron diffusion: $\sigma \sim 3$mm over 20m drift at 1kV/cm
- To get 1 kV /cm over 10 m drift requires ~ 1 MV feedthroughs!
- ArDM(RE18) generates up to 4 kV/cm internal to LAr volume and should be scalable
- High voltage and purity tests currently under way with long drift tests at Bern and CERN

ArgonTube:
5m drift test
@Uni. Bern


J.Phys.Conf.Ser.39 (2006) 129

- Cockcroft-Walton voltage multiplier immersed in LAr
- 210 stages
- max. voltage/stage 2kV

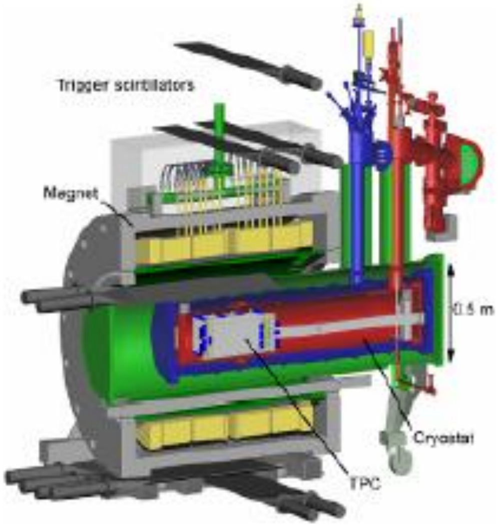
LANDD: 5m
drift test
@CERN

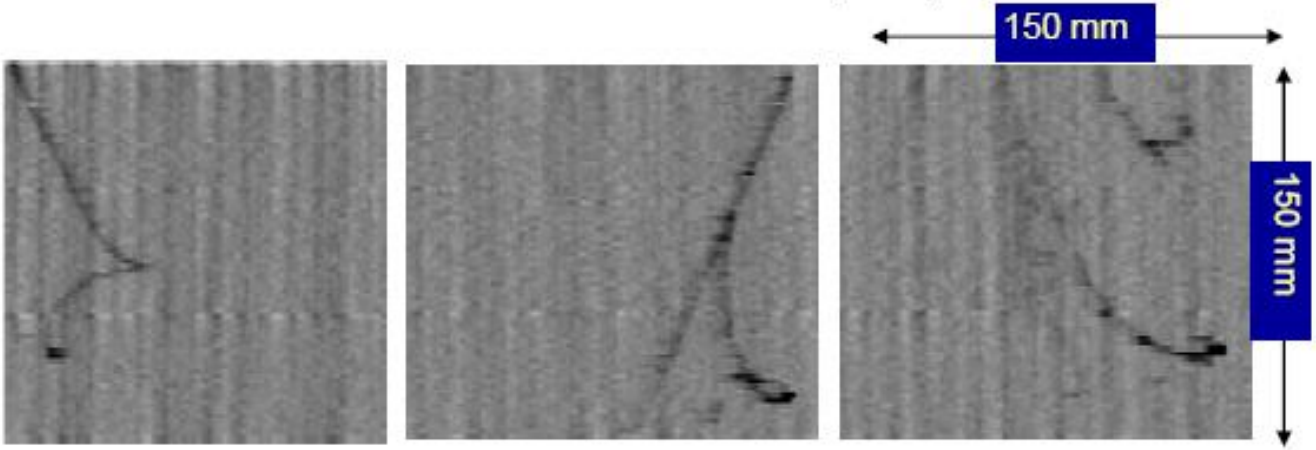


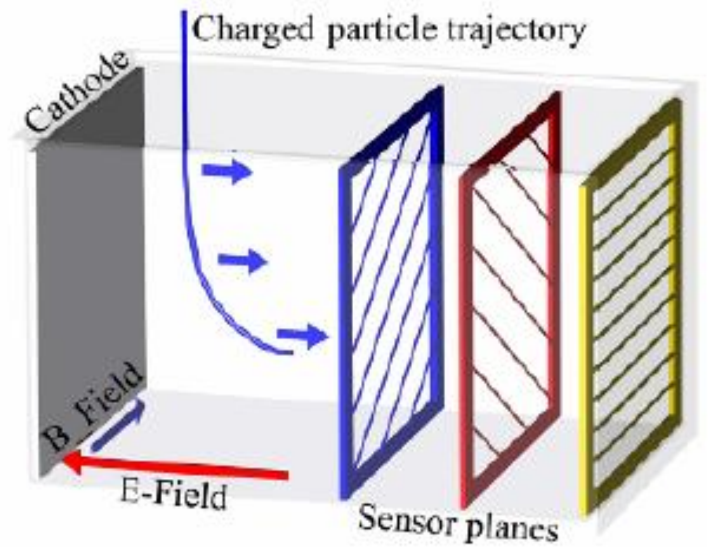
First Operation LAr TPC in B-Field

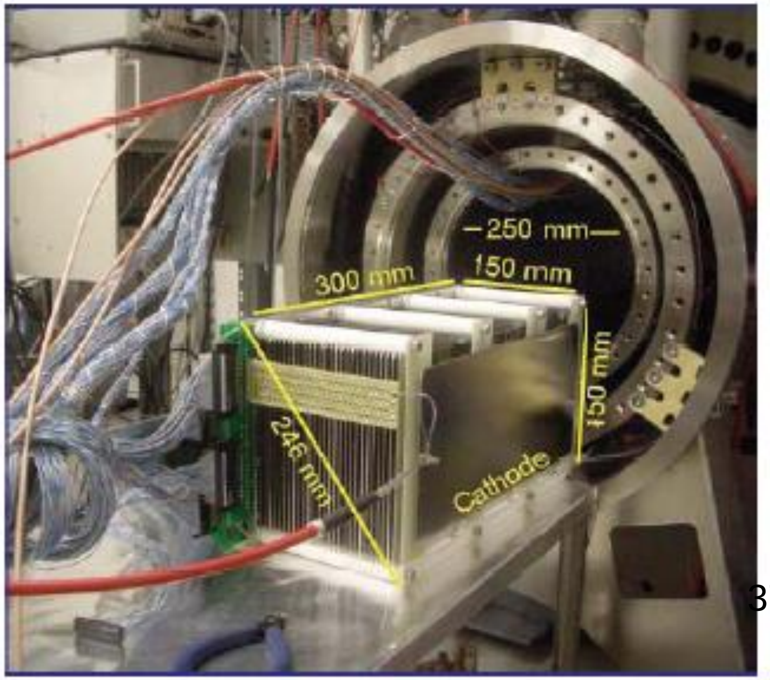
First real events in B-field (B=0.55T):

New J. Phys. 7 (2005) 63
NIM A 555 (2005) 294





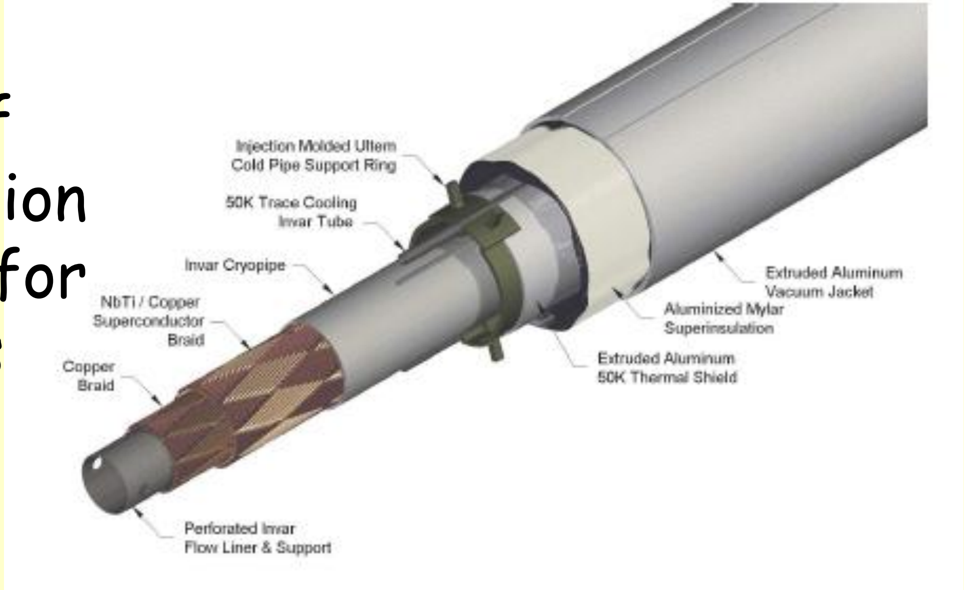




B-Field

- A significant challenge on this scale
- Conventional room temp. magnets too expensive (power consumption)
- Coventional super-conducting magnets also probably too expensive due to enormous cyrostats

- FNAL investigating use of superconducting transmission line technology developed for VLHC superferric magnets



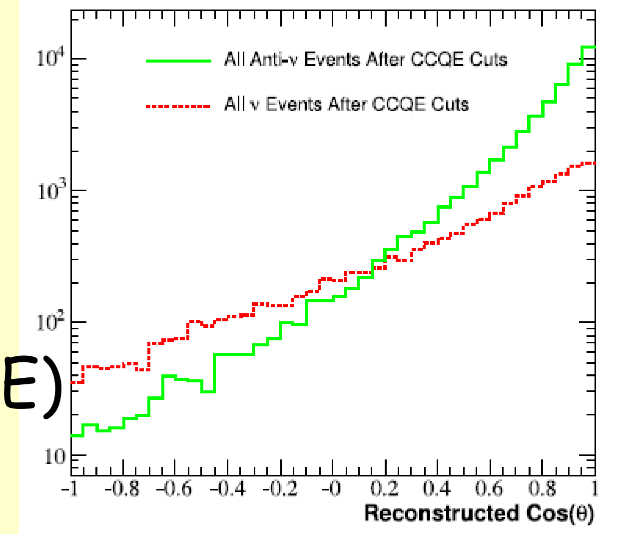
Do We Need a B-Field?

Maybe we can take advantage of the fact that $\nu_\mu \neq \bar{\nu}_\mu$!

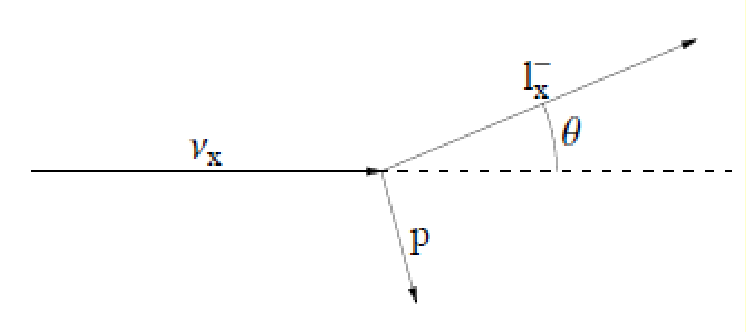
- μ+/μ- lifetimes in matter different due to μ-capture and no Michel decay electron. Already used by MiniBooNE (ν) and Kamiokande (cosmic muons)

- Muon angle w.r.t. neutrino direction sensitive to ν–helicity (used by MiniBooNE)
- Outgoing nucleon (p or n)

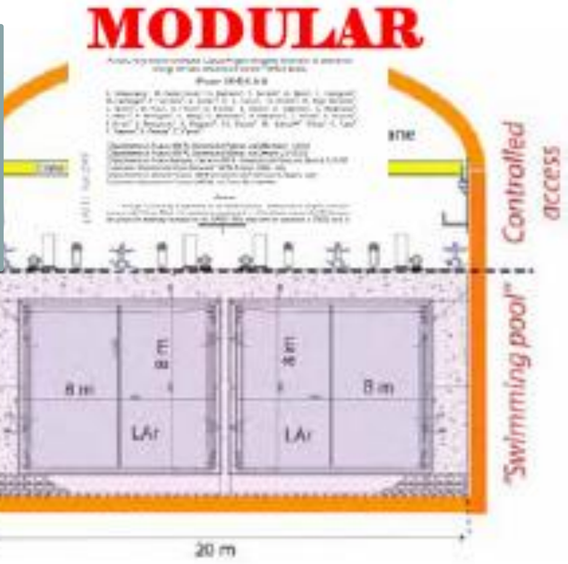
MiniBooNE hep-exp/0602051

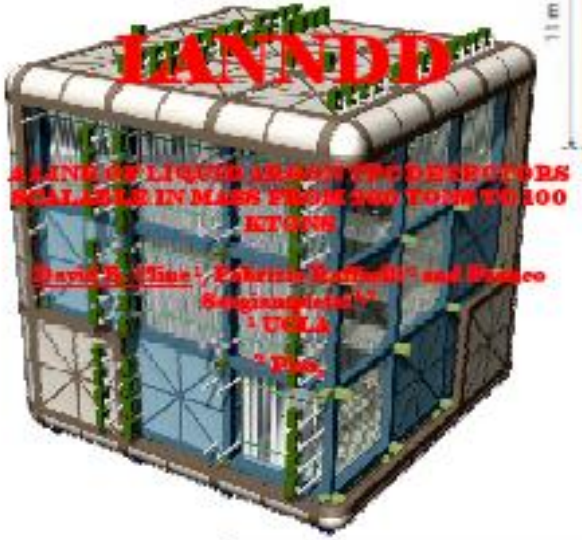


$$\nu_x + N \rightarrow l_x^- + p + N'$$
$$\bar{\nu}_x + N \rightarrow l_x^+ + n + N'$$



100kt Main concept- designs



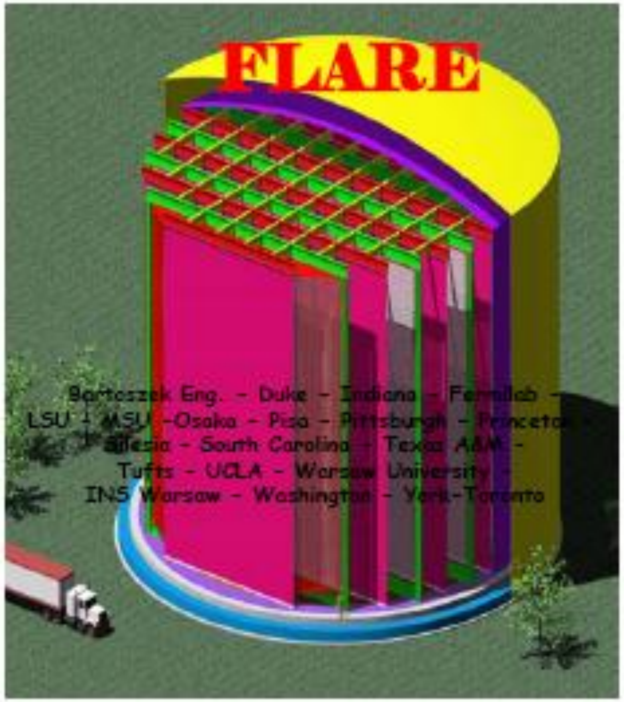


A LINE OF LIQUID ARGON TPC DETECTORS SCALABLE IN MASS FROM 200 TONS TO 100 KTONS

David B. Cline 1, Fabrizio Raffaelli 2 and Franco Sergiampietri 1,2

1 UCLA

2 Pisa



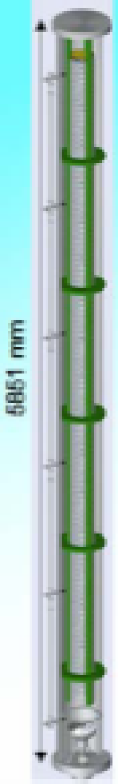
Bartoszek Eng. – Duke – Indiana – Fermilab – LSU – MSU – Osaka – Pisa – Pittsburgh – Princeton – Silesia – South Carolina – Texas A&M – Tufts – UCLA – Warsaw University – INS Warsaw – Washington – York-Toronto

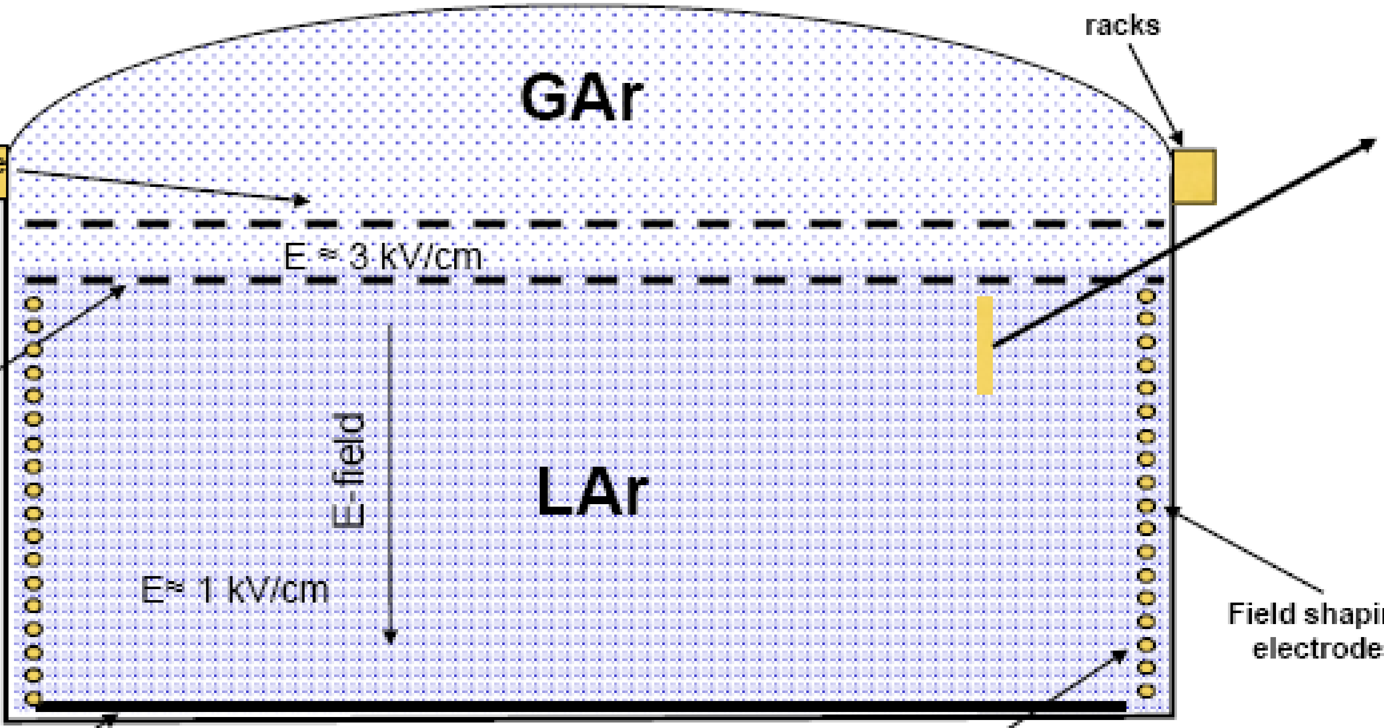
ETHZ, Bern U., Granada U., INP Krakow, INR Moscow, IPN Lyon, Sheffield U., Southampton U., US Katowice, UPS Warszawa, UW Warszawa, UW Wroclaw

Main Design Concepts I: *GLACIER*

Charge readout with extraction from liquid phase & amplification in gas phase for long drifts

ArgonTube: 5 m drift test





Electronic racks

Charge readout plane

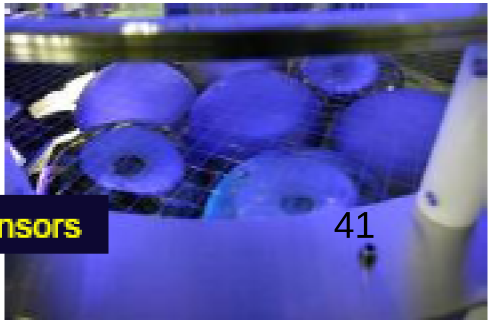
Extraction grid

Field shaping electrodes

Cathode (- HV)

UV & Cerenkov light readout photosensors

Greinacher voltage multiplier up to MV



Large area DUV sensitive photosensors

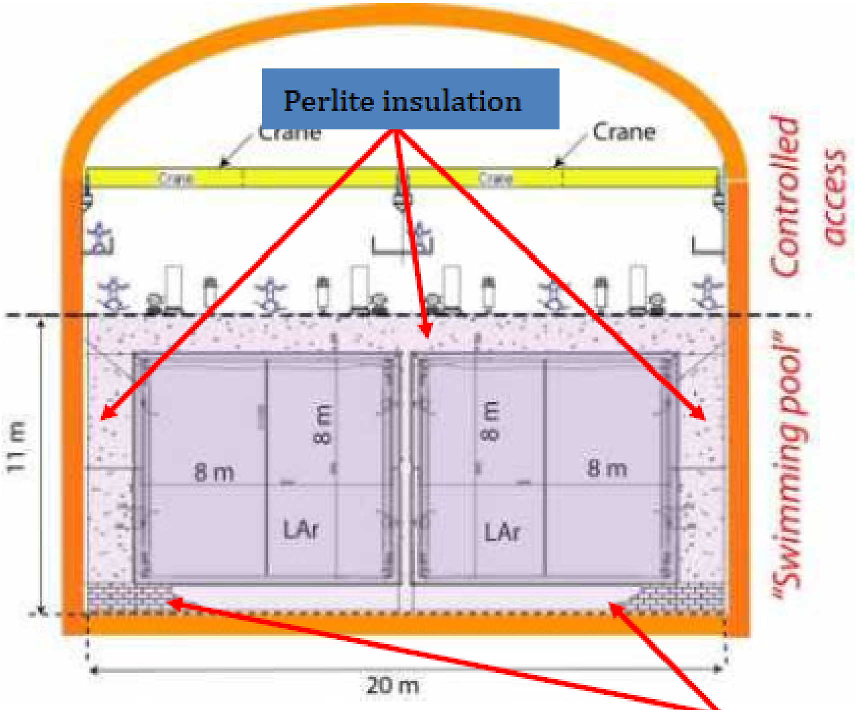
Main design concept III

MODULAR

B. Baibussinov et al., Astr. Phys. 29 (2008) 174
D. Angeli et al., JINST 4 (2009) P02003

Geometry of an ICARUS-T600 half-module (T300) "cloned" into a larger detector scaled by a factor **8/3 = 2.66**: the cross sectional area of the planes is **8 x 8 m^2** rather than 3 x 3 m^2. The length of such a detector is **~60 meters.**

10 kton



Low conductivity foam glass light bricks for the bottom support layer

- not evacuable
- 4 m drift length
- 1.5 m thickness of perlite, corresponding to ~ 4 W/m^2 thermal loss
- wires at 0°, ±60°, with ~6 mm pitch
- longitudinal wires ~30 m long

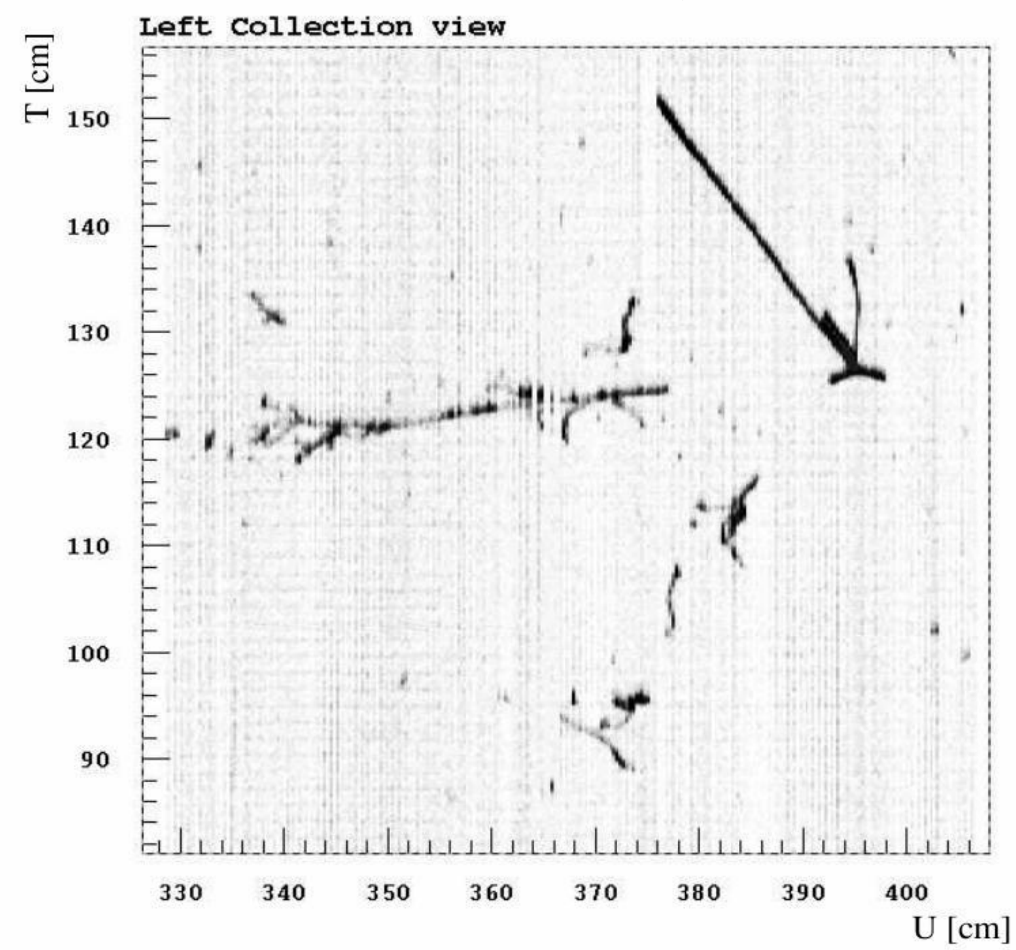
- proposed location: 10 km off-axis from LNGS
- initial sensitive volume of at least 20 kton

Reconstruction

- Algorithms not well developed – partly historical but also, it's not so easy!
- Tracks and showers develop side-by-side in the same volume

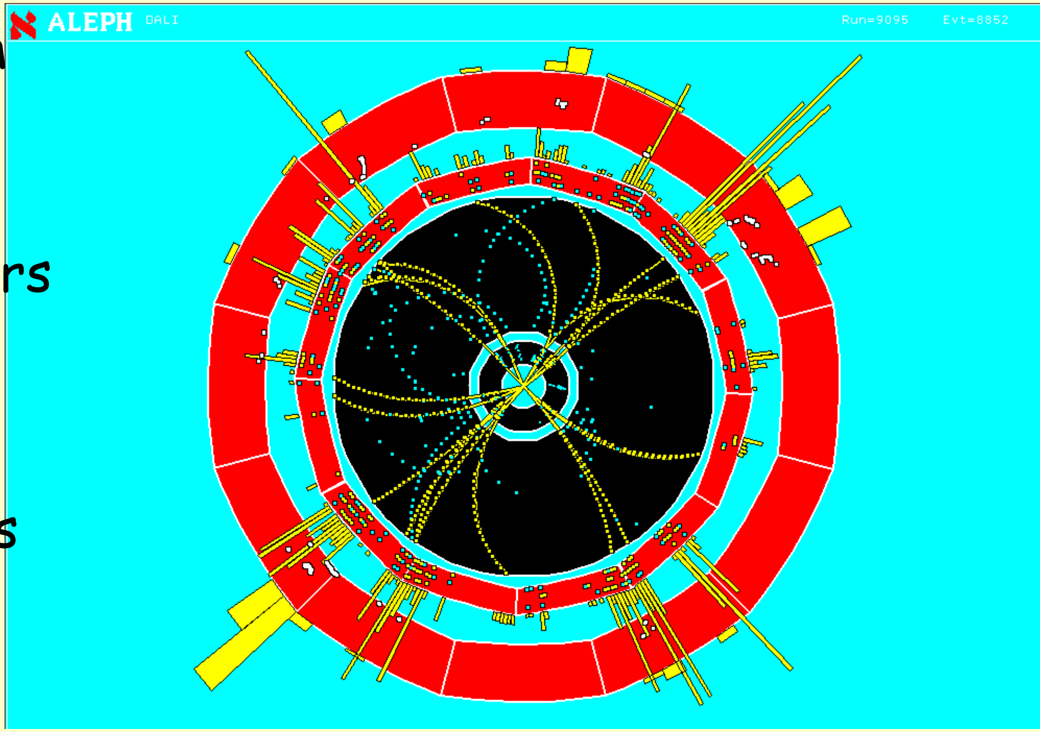
  ⇨ topologically complicated
- No well defined start point for what initiated the event
- Very high density of information: mm-scale energy deposits, delta-rays, vertices, kinks etc
- Multiple scattering occurring continuously throughout volume

ICARUS, arxiv:0812:2373



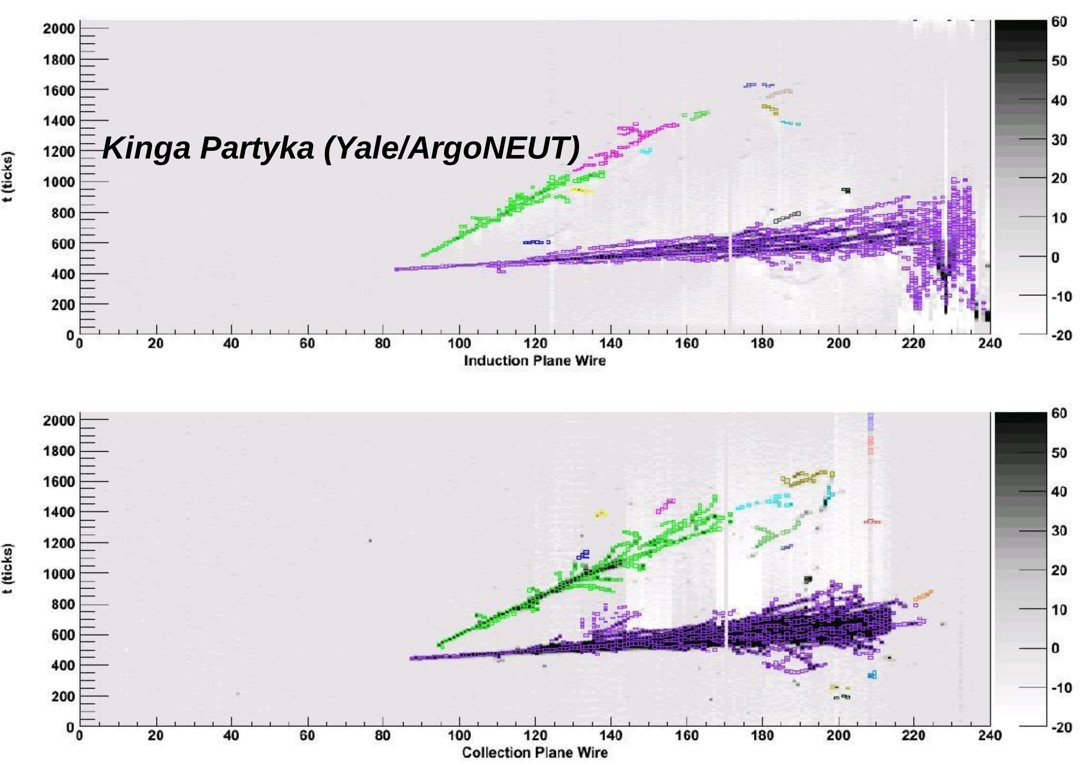
c.f. Accelerator experiments

- Relatively sparse space/pulse-height data points radiating from this point
- Tracks and showers develop in separate, optimised, sub-detectors
- Well defined interaction point
- Multiple scattering happening mostly at well-defined boundaries between sub-detectors
- Track search within a well-defined model (circle or helix) to decide on associated hits



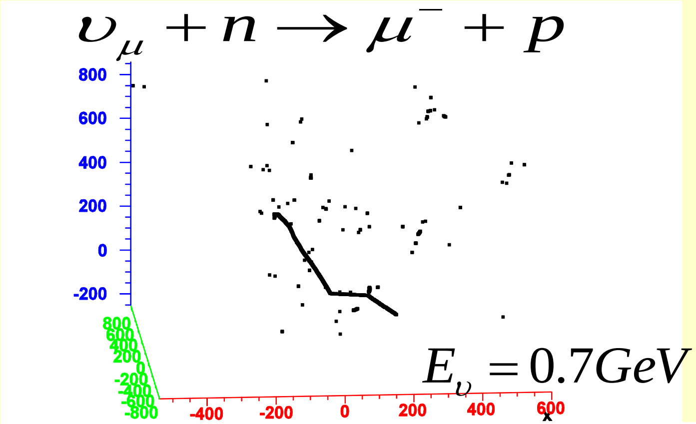
Clustering

- DBSCAN* algorithm: the `density-neighbourhood' (ε) around each point in the cluster must contain at least N_{min} other points

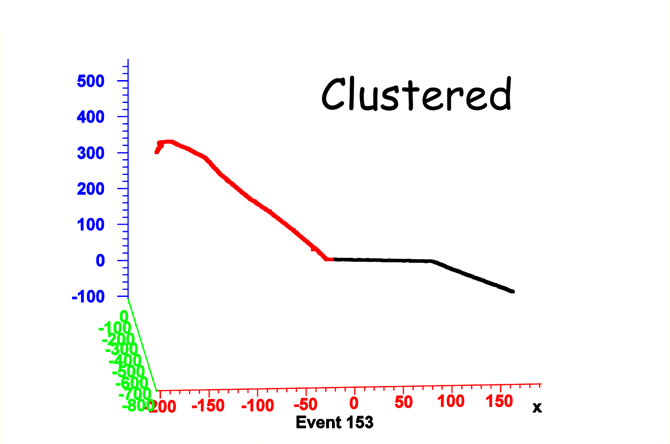


- Cellular automaton*: 3D implementation for charged-current interactions in LAr

Raw hits


$$\upsilon_\mu + n \rightarrow \mu^- + p$$

$$E_\upsilon = 0.7GeV$$


Clustered

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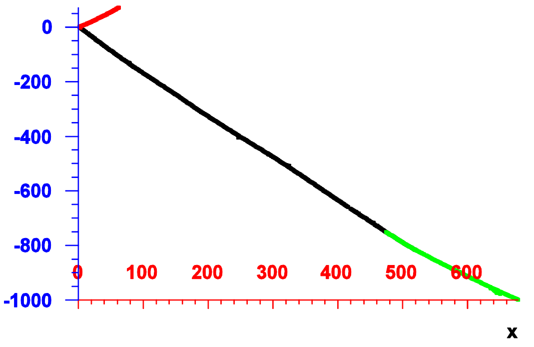
* Sander et al., Data Mining and knowledge Discovery 2, pp169-194 (1998)

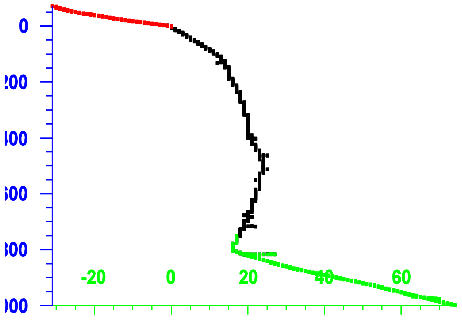
* Warwick group

Examples/issues

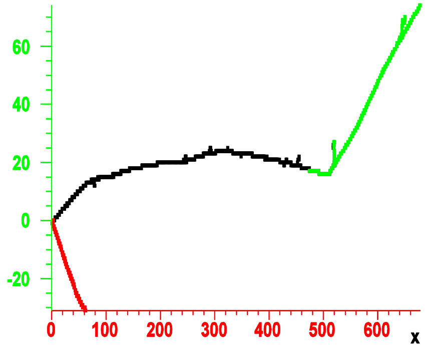
$$\upsilon_\mu + n \rightarrow \mu^- + p$$



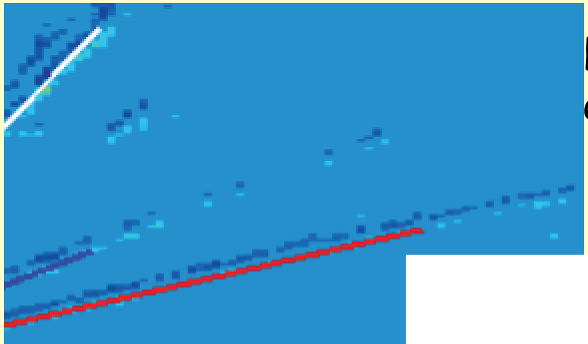
Event 106



Event 106

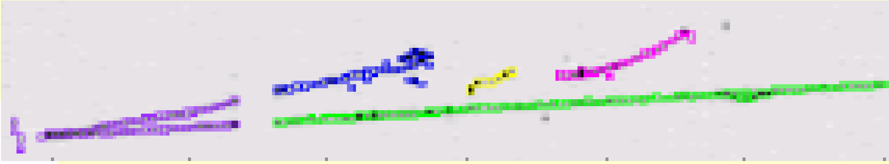


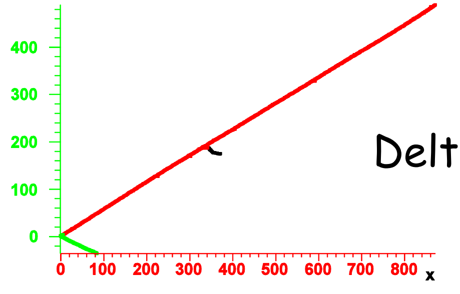
Event 106



Hough transform: end-points

DBSCAN: high density clustering



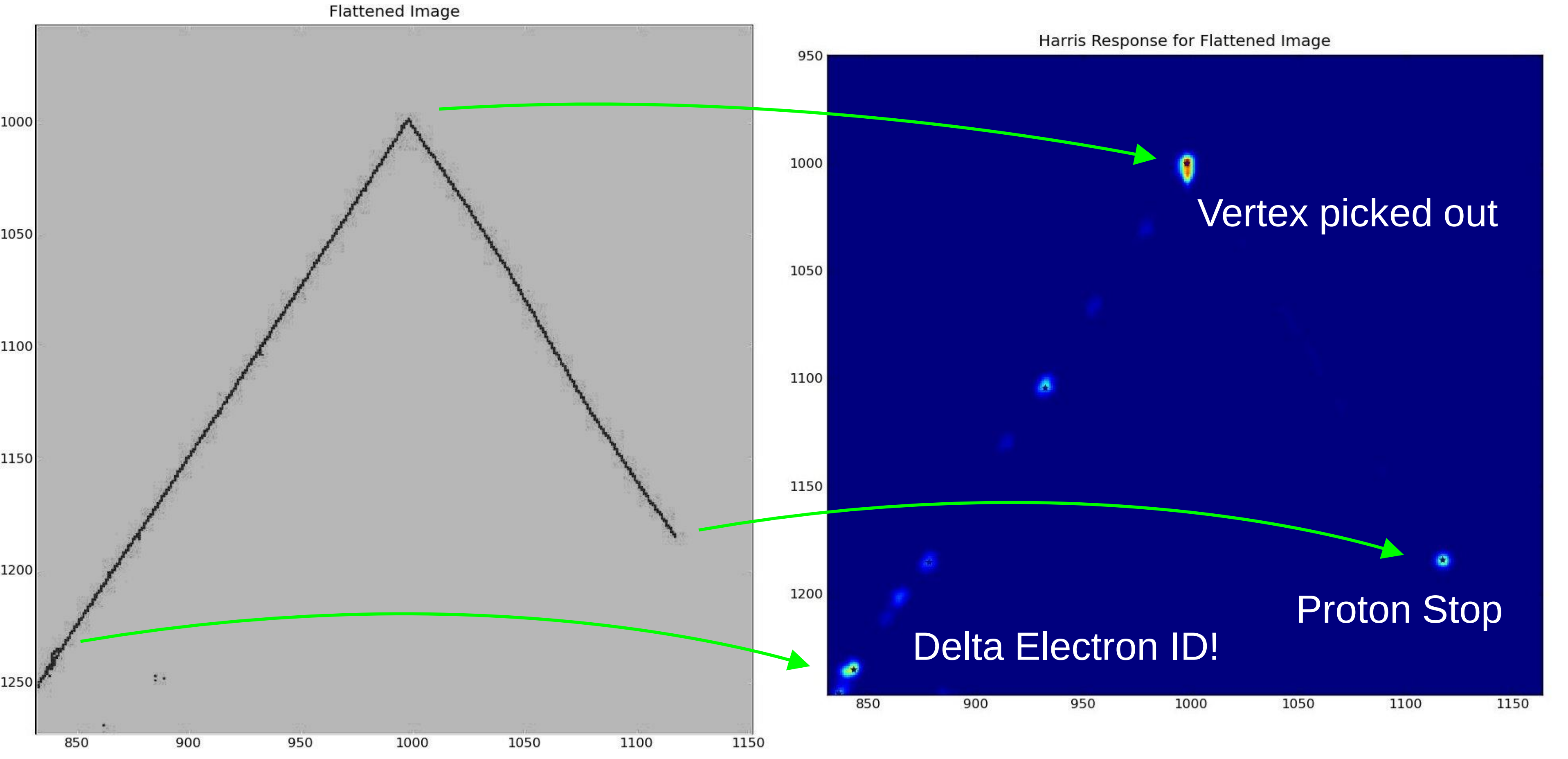


Event 127

Delta electrons

Corner Finding

- GENIE generated ν_μ CCQE events in 3T LAr TPC:



Vertex picked out

Proton Stop

Delta Electron ID!

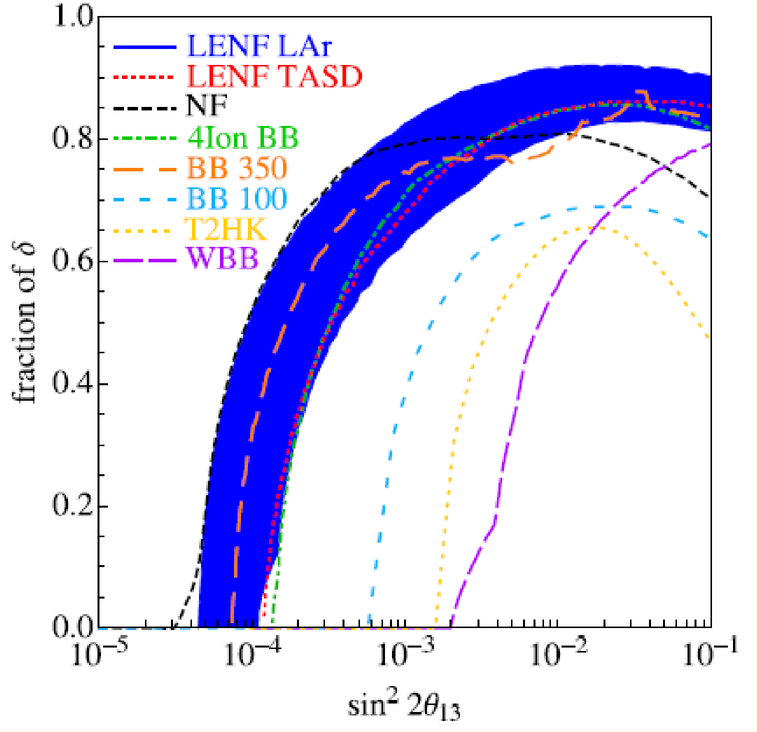
Ben Morgan, Warwick, JINST 5 P07006 (2010)

Technology Choice

- These studies to feed into the international programme for next generation project: IDS-NF, LAGUNA-LBNO, LBNE etc

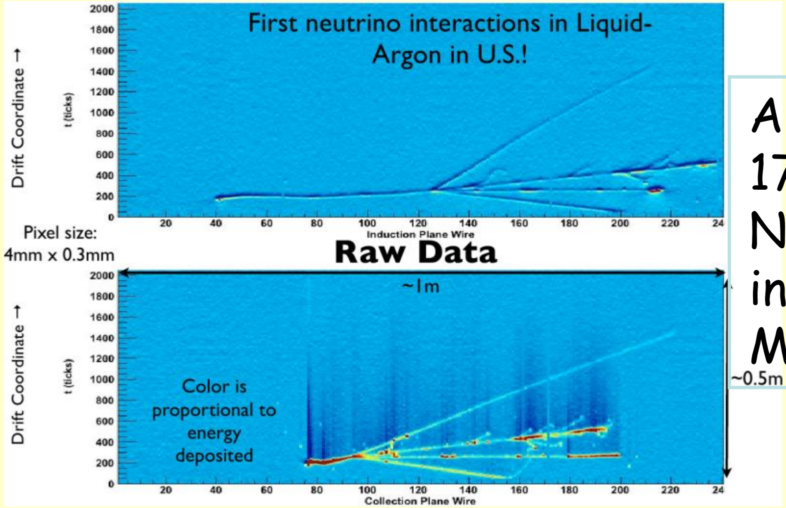
	Conservative	**Optimistic**
Efficiency - all channels	80%	80%
Systematics	5%	2%
Energy resolution - QE events	5%	5%
Energy resolution - non-QE events	20%	10%
Background on ν_μ (dis)appearance channels	5×10^{-3}	1×10^{-3}
Background on ν_e appearance channels	0.8	1×10^{-2}

B. Fleming - private communication reported in Phys. Rev. D 76, 053005 (2007).

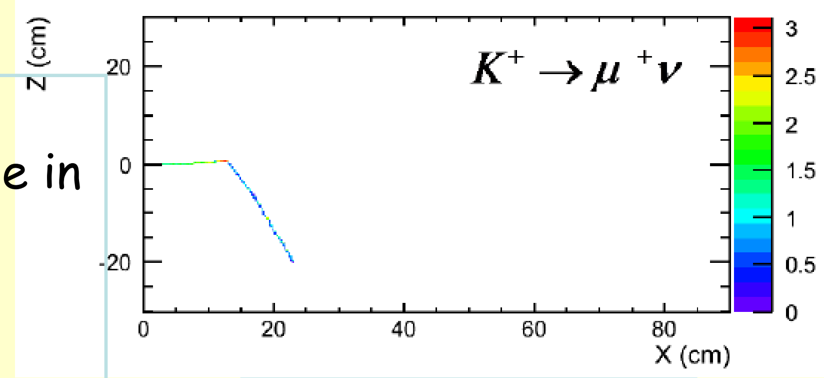


Phys. Rev. D81 073010 (2010)

Latest Results – Neutrino'10

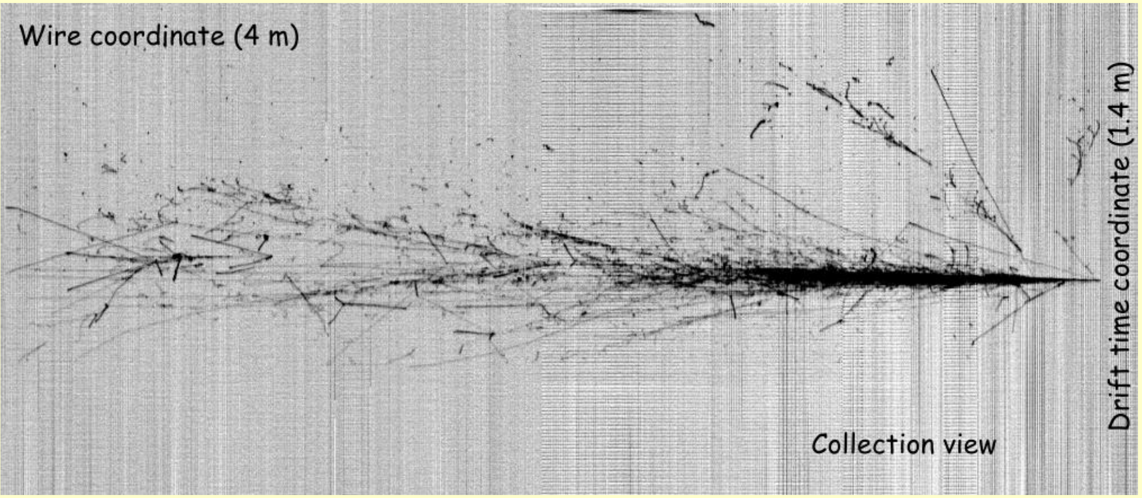


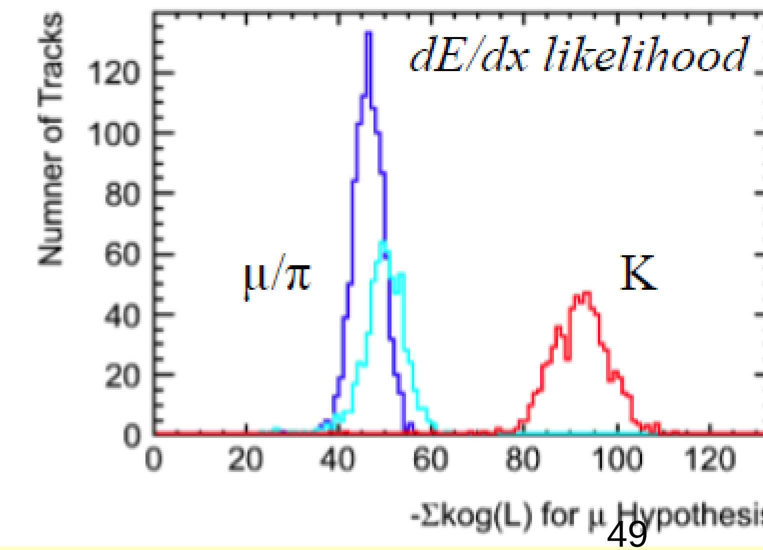
ArgoNeuT:
175L prototype in NUMI beam infront of MINOS



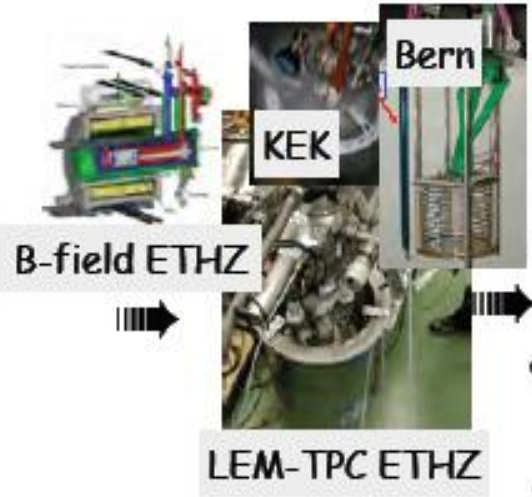
250 L prototype in 340 MeV/c K beam @JPARC

ICARUS T600: starting to collect events in CNGS beam – analyses to find τ's





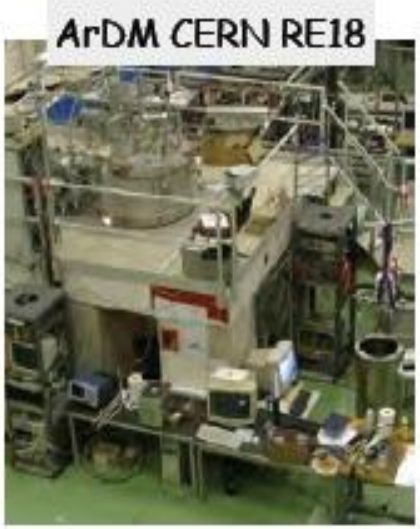
Europe



proof of principle double-phase LAr LEM-TPC on 0.1x0.1 m^2 scale

LEM readout on 1x1 m^2 scale UHV, cryogenic system at ton scale, cryogenic pump for recirculation, PMT operation in cold, light reflector and collection, very high-voltage systems, feed-throughs, industrial readout electronics, safety (in Collab. with CERN)

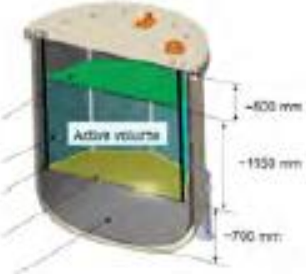
ArDM CERN RE18



direct proof of long drift path up to 5 m

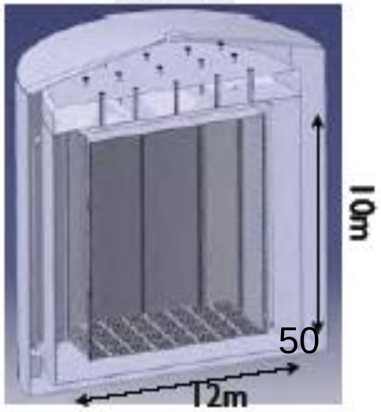
Application of LAr LEM TPC to neutrino physics: particle reconstruction & identification (e.g. 1 GeV e/μ/π), optimization of readout and electronics, possibility of neutrino beam exposure

Test beam
1 to 10 ton-scale



full engineering demonstrator for larger detectors, acting as near detector for neutrino fluxes and cross-sections measurements, …

1 kton



EU projects

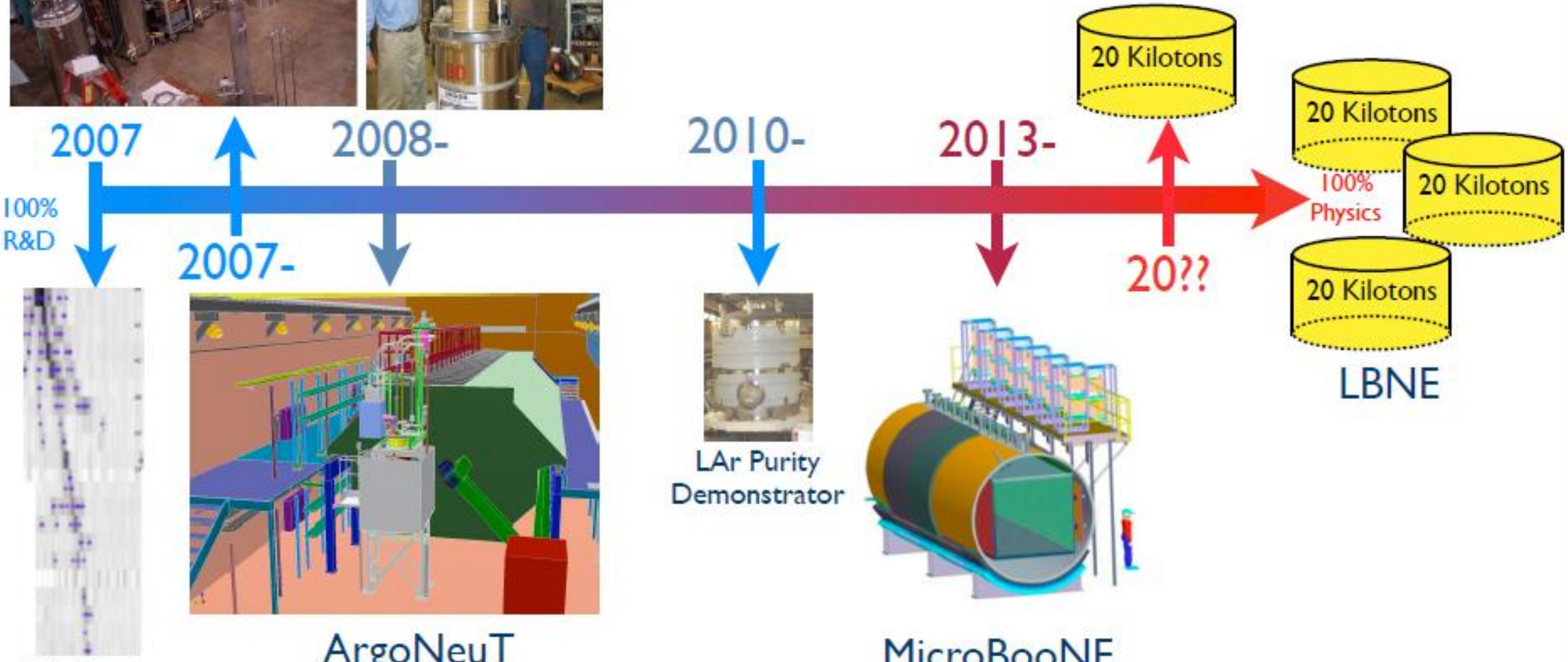
- **EUROnu(FP7 design study for neutrino oscillation facility in Europe):**
  - Machine (NF, Super-Beam, β-Beam) and target R&D
  - Detector simulation studies: MIND (NF), water Cherenkov (Super-Beam and β-Beam), scintillator and near detector (all facilities)
  - No detector R&D funded
  - Large overlap with NF-International Design Study
- **LAGUNA(FP7 design study for EURO ν-observatory):**
  - Large underground chambers: site evaluation and construction
  - Detector studies: water Cherenkov, liquid scintillator, liquid argon
  - LAGUNA-LBNO proposal: includes CERN superbeam R&D
  - No detector R&D funded
  - Recently extended (LAGUNA-LBNO) to include ν-oscillation studies
- **AIDA(Euro Integrating Activity Project):**
  - test beam infrastructure at CERN for neutrino detector prototyping (MiniMIND)

Liquid Argon Activities at Fermilab

Materials Test Stand

Electronics Test Stand

- Tremendous progress in LArTPC development in past few years at Fermilab.
- We are moving from pure R&D towards large detectors with great physics potential.



2007

100% R&D

Yale Tracks

2007-

2008-

ArgoNeuT

2010-

LAr Purity Demonstrator

2013-

MicroBooNE

20??

20 Kilotons

100% Physics

20 Kilotons

20 Kilotons

20 Kilotons

LBNE

Refs:

1.) *A Regnerable Filter for Liquid Argon Purification* Curioni et al., NIM A605:306-311 (2009)

2.) *A system to test the effect of materials on electron drift lifetime in liquid argon and the effect of water* Andrews et al., NIM A608:251-258 (2009)

Status of UK Activity

- Some small-scale LAr test-stand R&D at Liverpool, Sheffield and Warwick (all unfunded – PRD bid pending!)
- Important to keep all options open at present until decisions on the next generation of neutrino project are made – this may be around 2013 coinciding with:

  - final reports of international studies such as IDS-NF and EuroNu

  - results from T2K and reactor experiments on the size of θ_{13} (a `large' value would boost superbeam projects)
- UK groups very active in the European initiatives: IDS-NF, EuroNu, LAGUNA-LBNO, AIDA concerning machine studies, underground site development, physics studies etc
- Close links also maintained with the US LBNE programme (LAr software, electronics) and in Japan (T2K, 250L prototype reconstruction)
- A measurable θ_{13} would see momentum grow for : T2K upgrade in Japan or LBNE in the USA or LBNO in Europe , all hopefully incorporating a LArTPC!

Outlook+Conclusion

- A ~100kt LArTPC is the best-performing detector option for a next generation neutrino facility
- Possible (probable?) only one huge detector will be built => important it is multipurpose (ν–oscillations, p-decay and astrophysics) - LArTPC in good position to deliver
- Whether it gets built depends on solving remaining tech. challenges before deadlines like IDS in 2012-13 and whether value of θ_{13} warrants building Super-Beam or NF