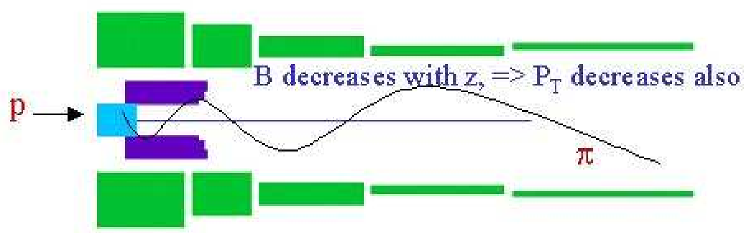
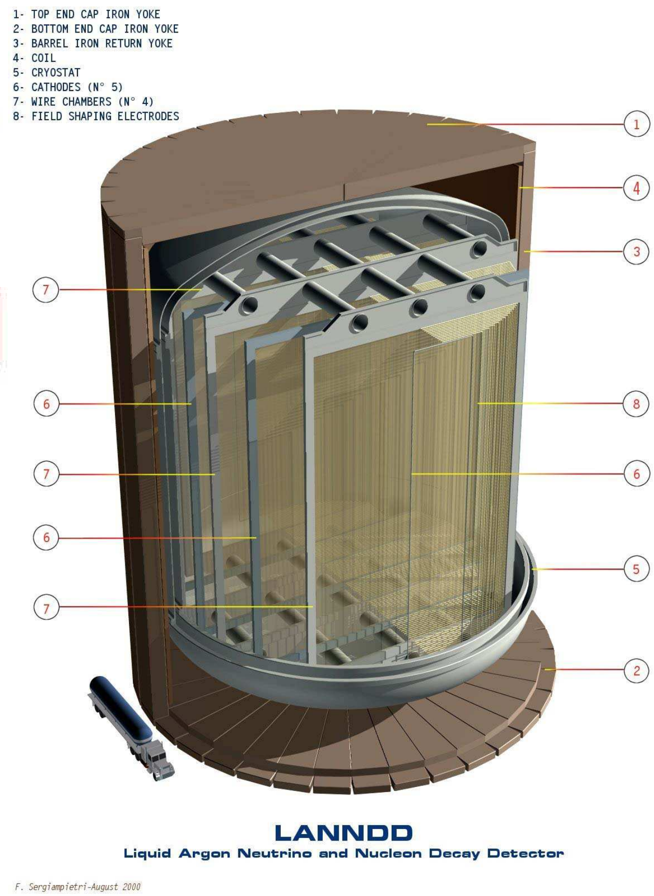
Large and Small (Far and Near) Liquid Argon Detectors for an Off-Axis NuMI Beam





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NuMI Off-Axis Experiment Detector Workshop

SLAC, Jan. 23-24, 2003

http://puhep1.princeton.edu/~mcdonald/nufact/

Post-Nobel Opportunities

Data from atmospheric and solar neutrino experiments

$\Rightarrow$ Rich follow-up physics at accelerators and reactors.

Parameter	Atmos.	Solar	Accel.	Reactor	β Decay
$\lvert\Delta M^2_{23}\rvert$	ID		*PM*		
θ_{23}	ID		*PM*		
$\lvert\Delta M^2_{12}\rvert$		ID	*PM*	*PM*	
$\mathrm{Sign}(\Delta M^2_{12})$		ID = PM			
θ_{12}		ID	*PM*	*PM*	
ν_{sterile}			*ID, PM*		
$\mathrm{Sign}(\Delta M^2_{23})$			*ID = PM*	*ID = PM*	
θ_{13}			*ID, PM*	*ID*	
Δ_{CP}			*ID, PM*		
M_ν					*ID*

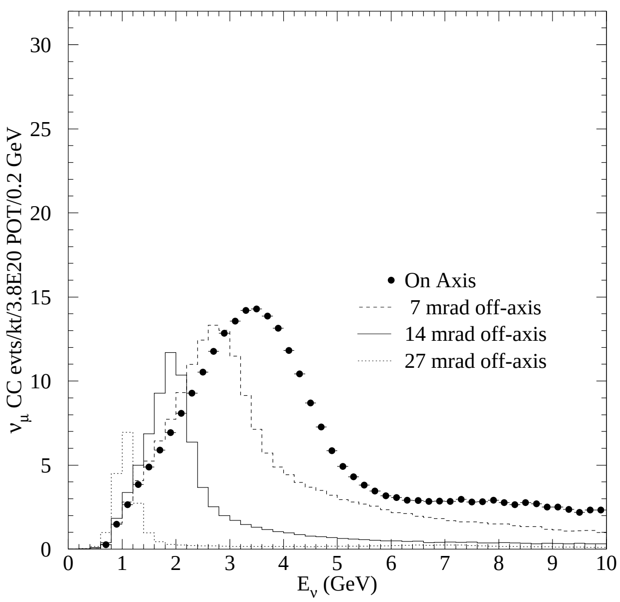
(ID = Initial Discovery, PM = Precision Measurement)

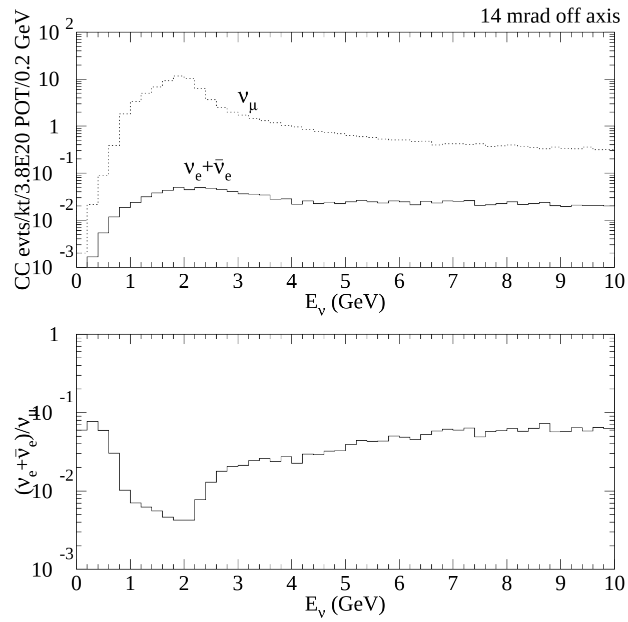
No evidence for proton decay, "theories" apparently not falsifiable,

$\Rightarrow$ Linkage with neutrino expts. should be driven by the latter.

Off-Axis NuMI Beam (P929)

- 14-mrad off-axis beam, 735 km, $\Rightarrow$ 2-GeV ν's @ 1st oscillation max for ν_2-ν_3.





- $\approx 50\ \nu_\mu$ CC events/kton in 4-5 year run.

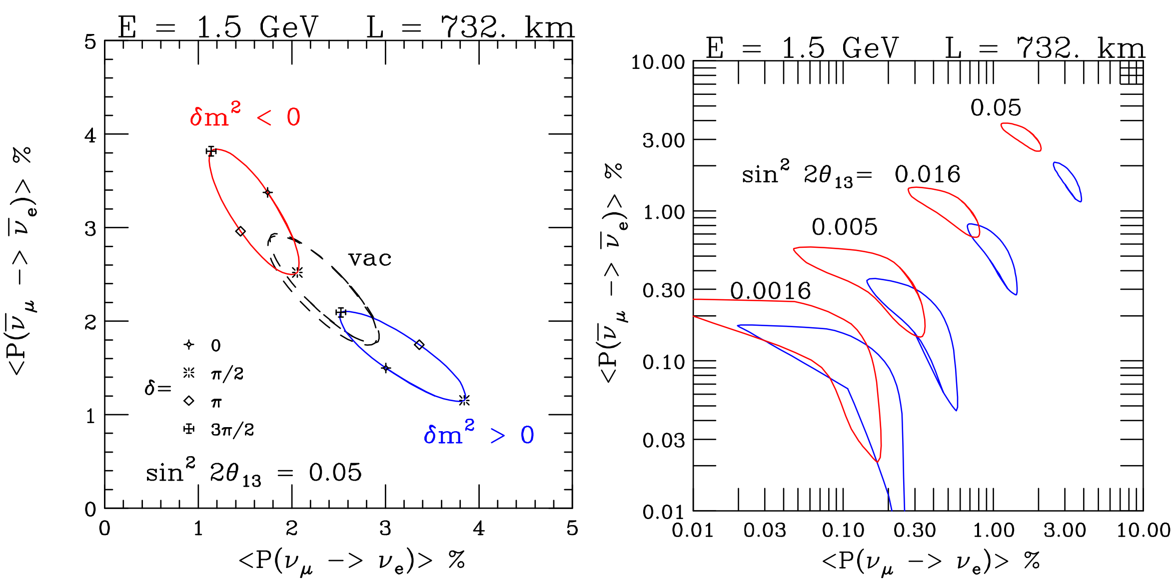
- $\nu_e/\nu_\mu \approx 5\times 10^{-3}$, $\Rightarrow$ Measurement of $\sin^2 2\theta_{13}$ via $\nu_\mu \to \nu_e$ limited to ≈ 0.01 by backgrounds.

- At this limit, a signal of 10 $\nu_\mu \to \nu_e$ oscillations
  $\Rightarrow$ 1000 ν_μ CC events,
  $\Rightarrow$ Need (at least) 20 kton detector.

- $\Rightarrow$ Will eventually want bigger detector ($\gtrsim$ 100 kton) and hotter beam (0.4 MW $\to$ 2 MW).

$\delta_{\rm CP}$ and Sign of ΔM^2_{23}

- Can untangle $\delta_{\rm CP}$ from matter effects (sign of ΔM^2_{23}) with NuMI off-axis beam only if sit close to 1st 2-3 osc max (and if $\sin^2 2\theta_{13} \gtrsim 0.03$), $\Rightarrow$ helpful to know ΔM^2_{23} better.

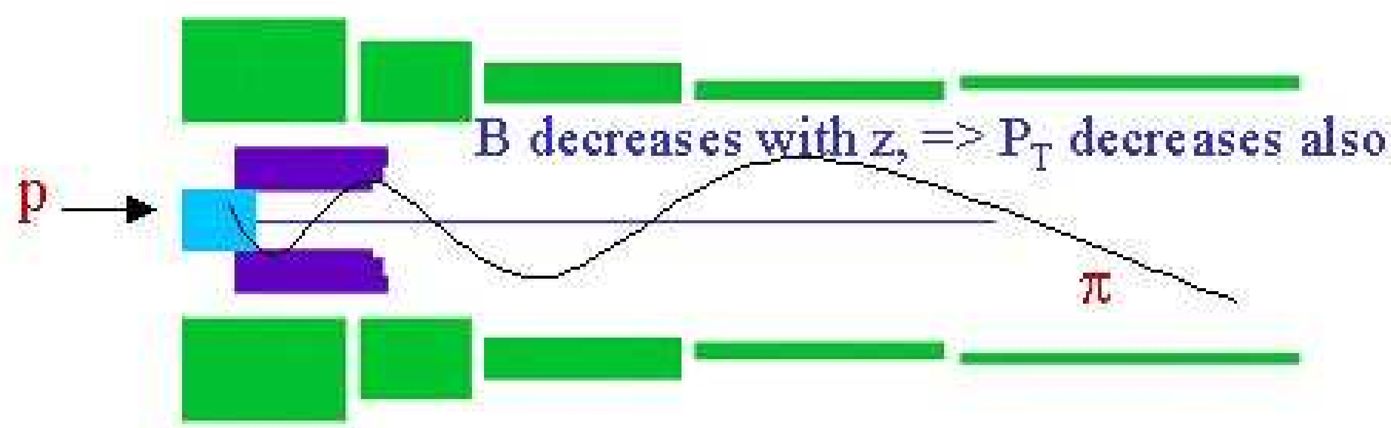


- Some improvement in sensitivity to sign of ΔM^2_{23} if go to larger distance (and slightly smaller off-axis angle), with little cost in sensitivity to $\sin^2 2\theta_{13}$.

- $\Rightarrow$ Very likely will need 2 generations of detectors (and beams!) to exploit full potential of off-axis superbeams.

The Neutrino Horn Issue for Superbeams

- 2-4 MW proton beams are achieved in BNL, CERN and FNAL scenarios via high rep rates: $\approx 10^6$/day.
- Classic neutrino horns based on high currents in conductors that intercept much of the secondary pions will have lifetimes of only a few days in this environment.
- Consider instead a solenoid horn with conductors at larger radii than the pions of interest (*c.f.*, Neutrino Factory Design).
- Adiabatic reduction of the solenoid field along the axis,
  $\Rightarrow$ Adiabatic reduction of pion transverse momentum,
  $\Rightarrow$ Focusing.

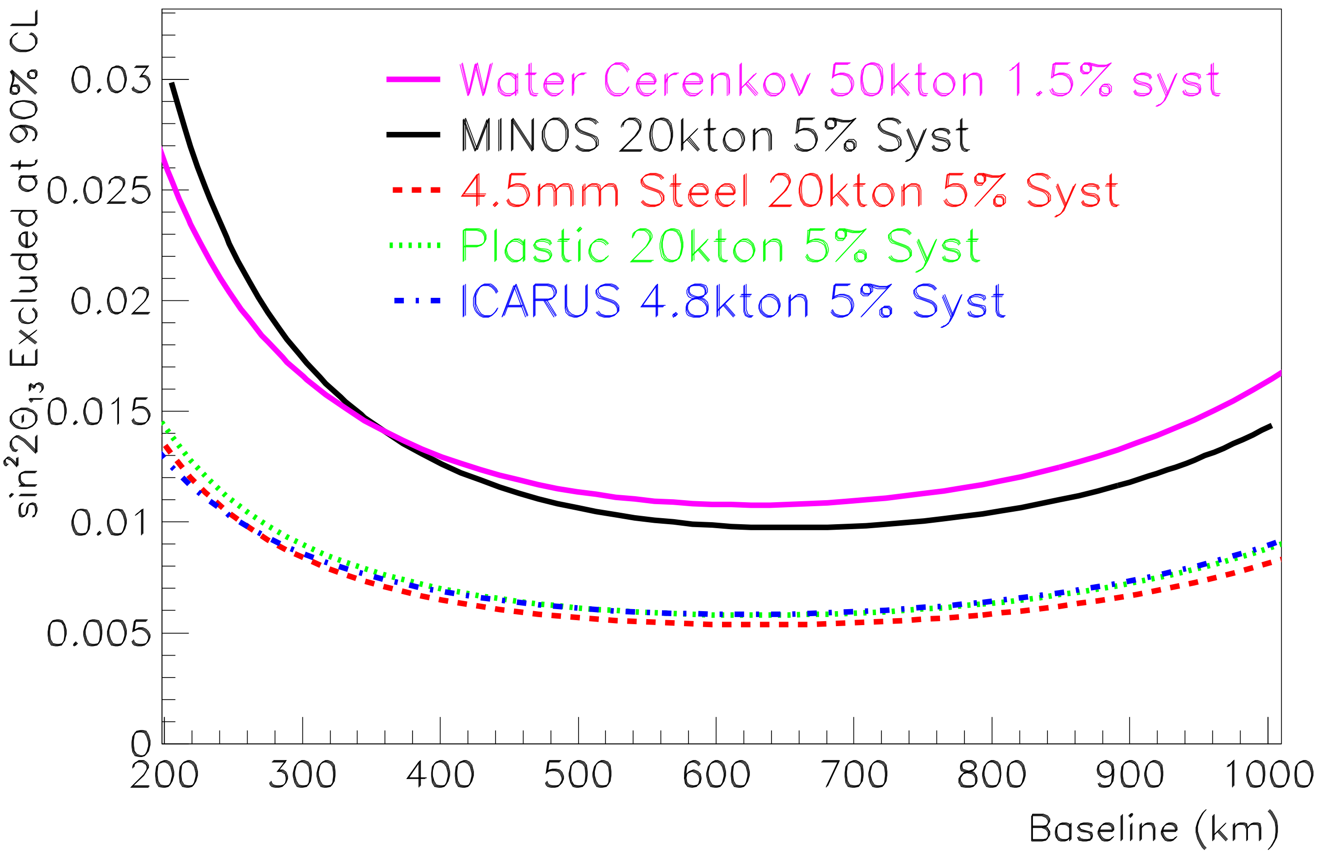


- No sign selection in horn, $\Rightarrow$ Both ν_u and $\bar{\nu}_\mu$,
  $\Rightarrow$ Detector must measure sign of final-state μ or e.

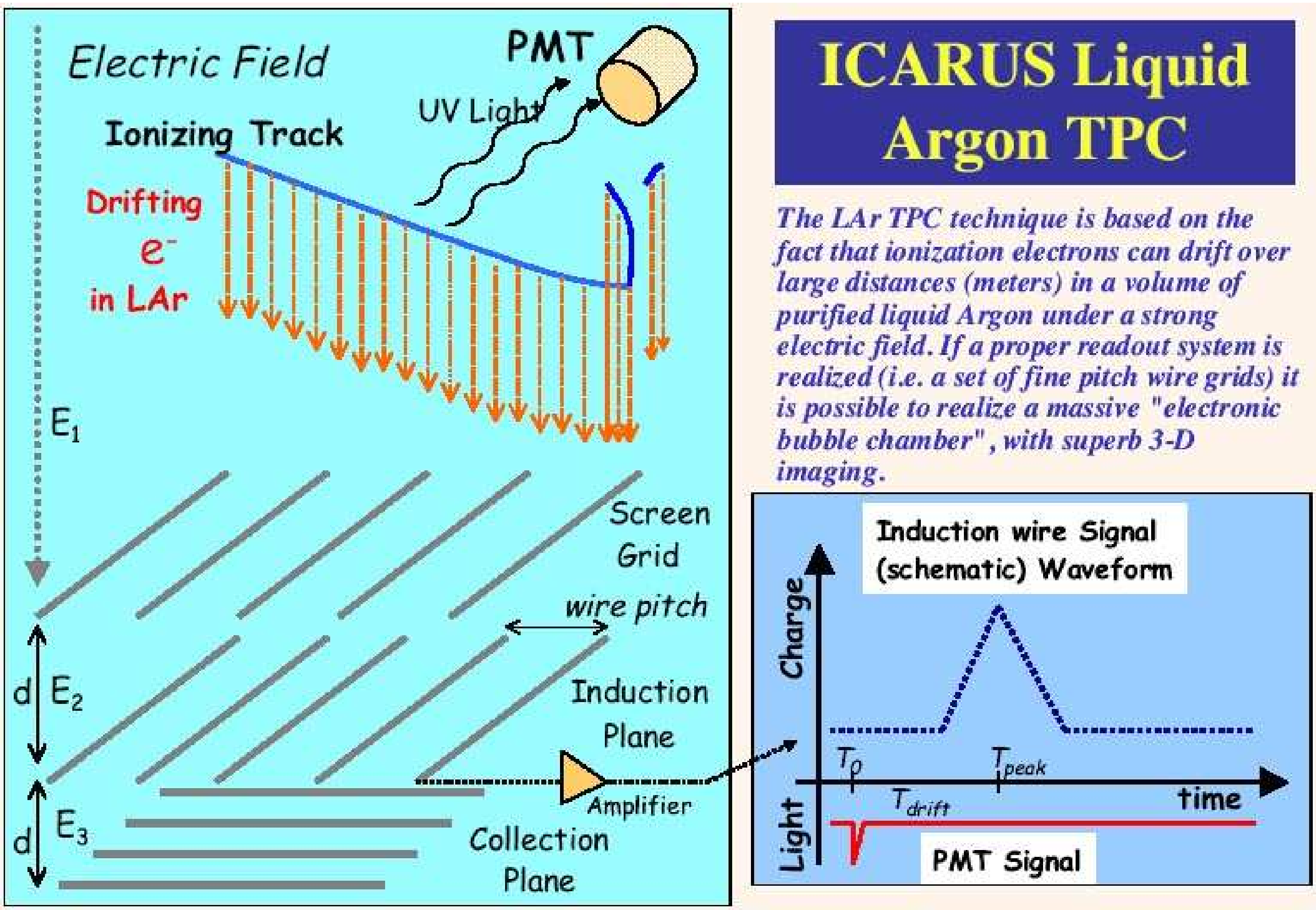
See, http://pubweb.bnl.gov/users/kahn/www/talks/Homestake.pdf

Liquid Argon the Best Detector to Study $\sin^2 2\theta_{13}$ in the NUMI Beamline

- $\approx$ 10 times better per kton than water Čerenkov for $\nu_\mu \rightarrow \nu_e$ appearance at 1-2 GeV (Harris).

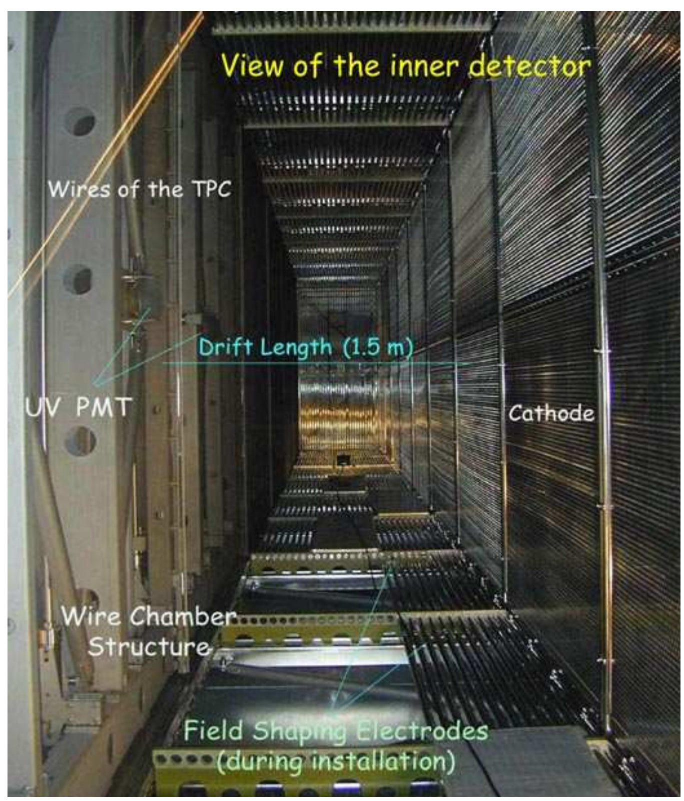


- Density = 1.4; $X_0 = 14$ cm; can drift electrons 3-5 m.
- 100% sampling tracking and calorimetry.
- Construction is simplest of large neutrino detector options.
- Best rejection of neutral current backgrounds, including soft π^0's.



Liquid argon time projection chamber conceived by C. Rubbia (1977).

Largest implementation to date is the ICARUS T600 (600 ton) module, on the surface in Pavia, Italy.
http://www.aquila.infn.it/icarus/

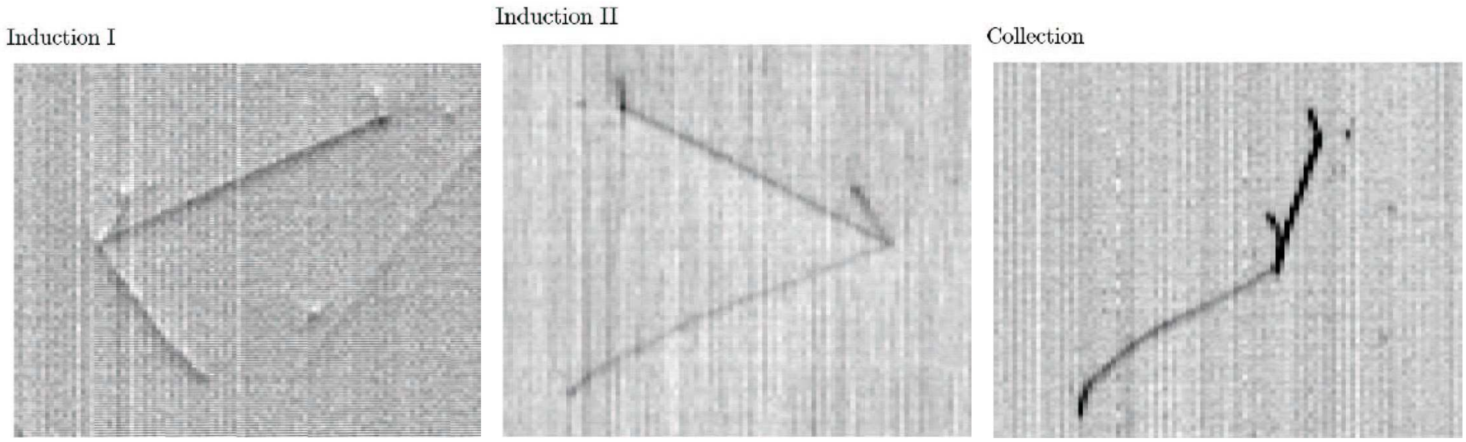


Liquid Argon TPC Properties

- 3D tracking + total-absorption calorimetry.
- Pixel size: 3 mm × 3 mm (wire planes) × 0.6 mm (via 400 ns time sampling).
- $\rho = 1.4$ g/cm^3, T = 89K at 1 atm., $X_0 = 14$ cm, $\lambda_{\rm int} = 80$ cm.
- A minimum ionizing particle yields 50,000 e/cm.
- Drift velocity of 1.5 m/msec at 500 V/cm $\Rightarrow$ 5 m drift in 3 msec.
- Diffusion coef. $D = 6$ cm^2/s $\Rightarrow \sigma = 1.3$ mm after 3 msec.
- Can have only 0.1 ppb of O_2 for a 5 m drift,
  $\Rightarrow$ Purify with Oxisorb.
- Liquid argon costs \$0.7M/kton – and is "stored" not "used".
- Large modules ($\gtrsim$ 100 kton) can be built using technology of liquid methane storage. (Total cost of a 100-kton detector is estimated to be \$200M.)

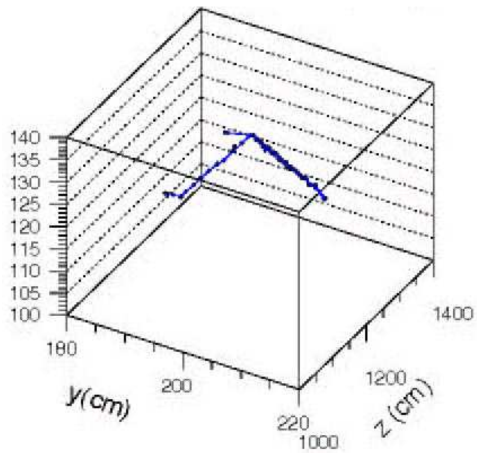

- Detector is continously "live" and can be "self-triggered" using pipelined, zero-suppression electronics.
- Operates at the Earth's surface with near zero overlap of cosmic ray events.
- Detector is compatible with operation in a magnetic field.

Events from the ICARUS T300 Cosmic Ray Test

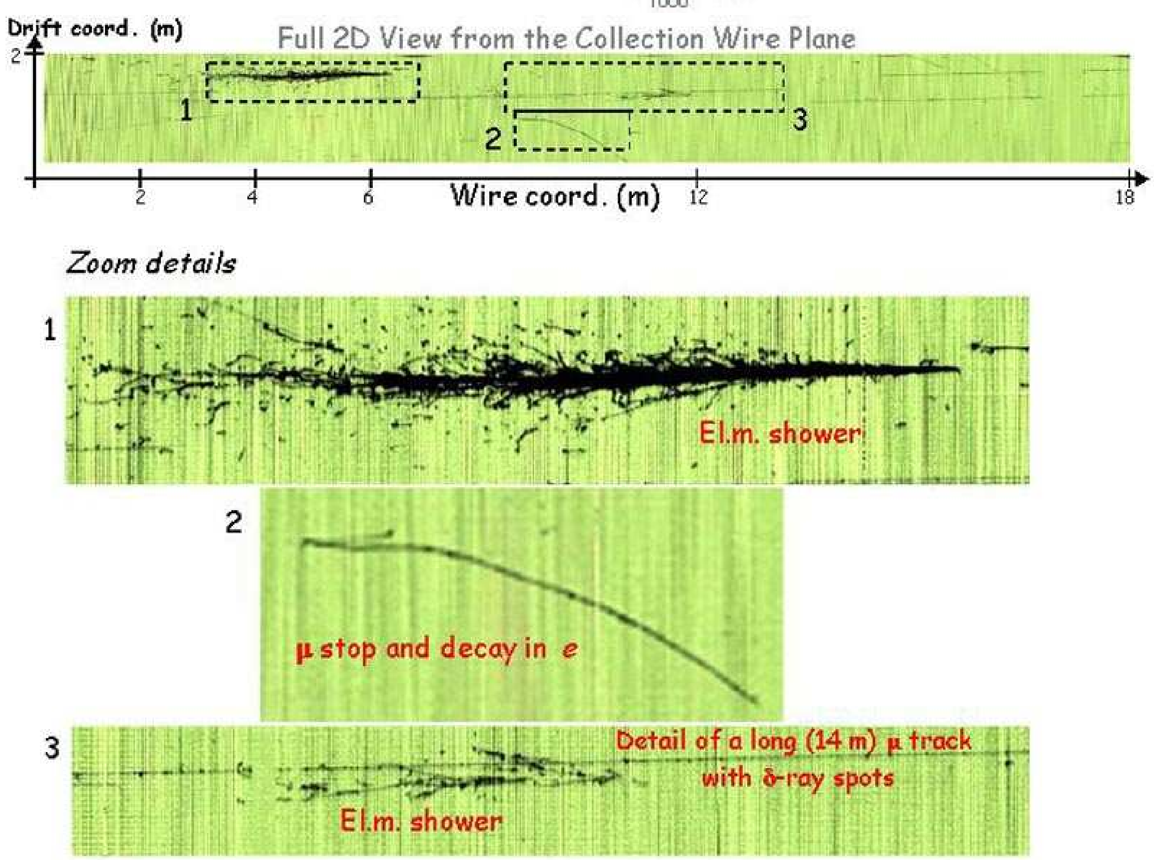


Above: 3 views of a low-energy hadronic interaction.

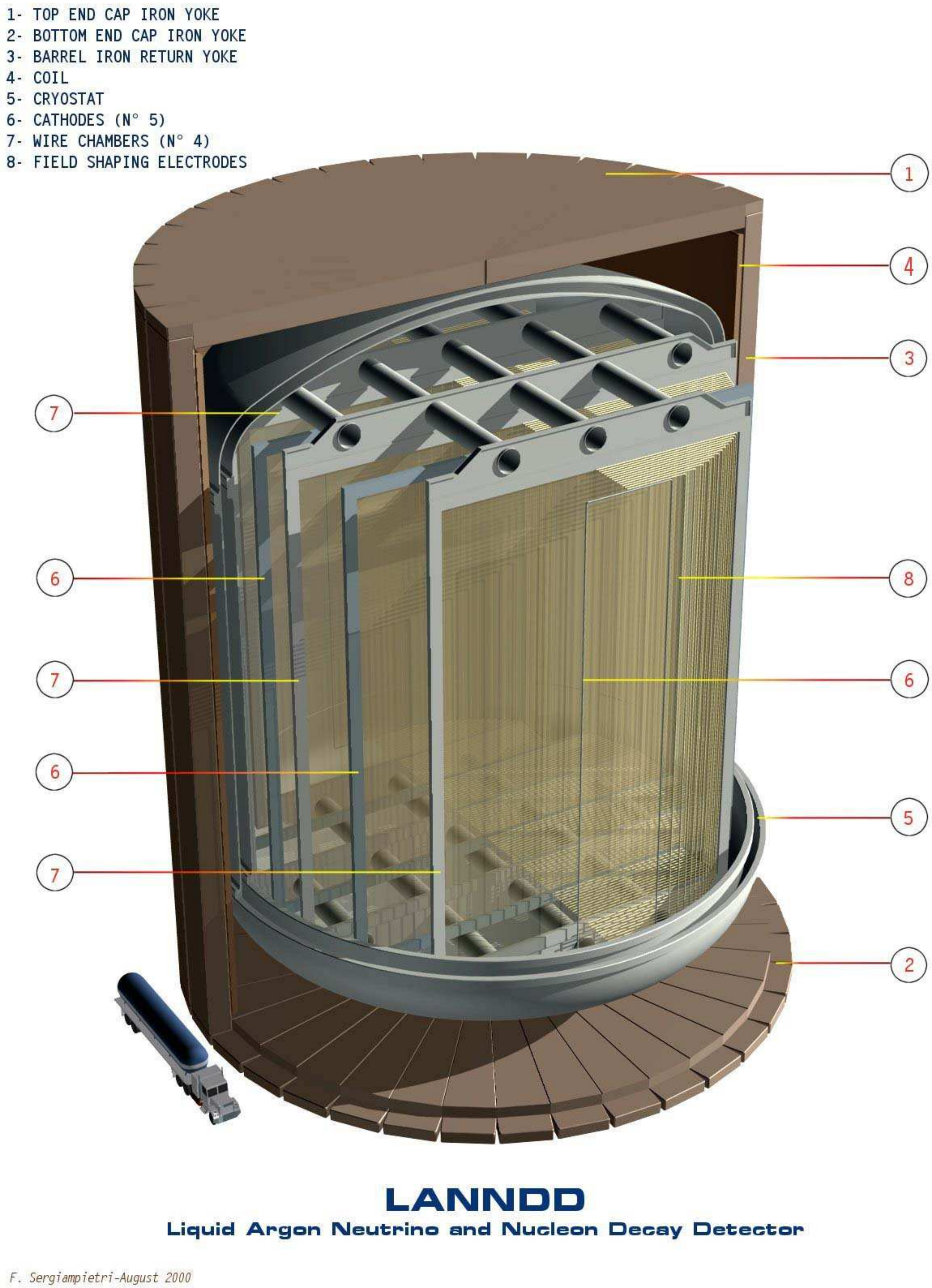
Right: Computer reconstruction.



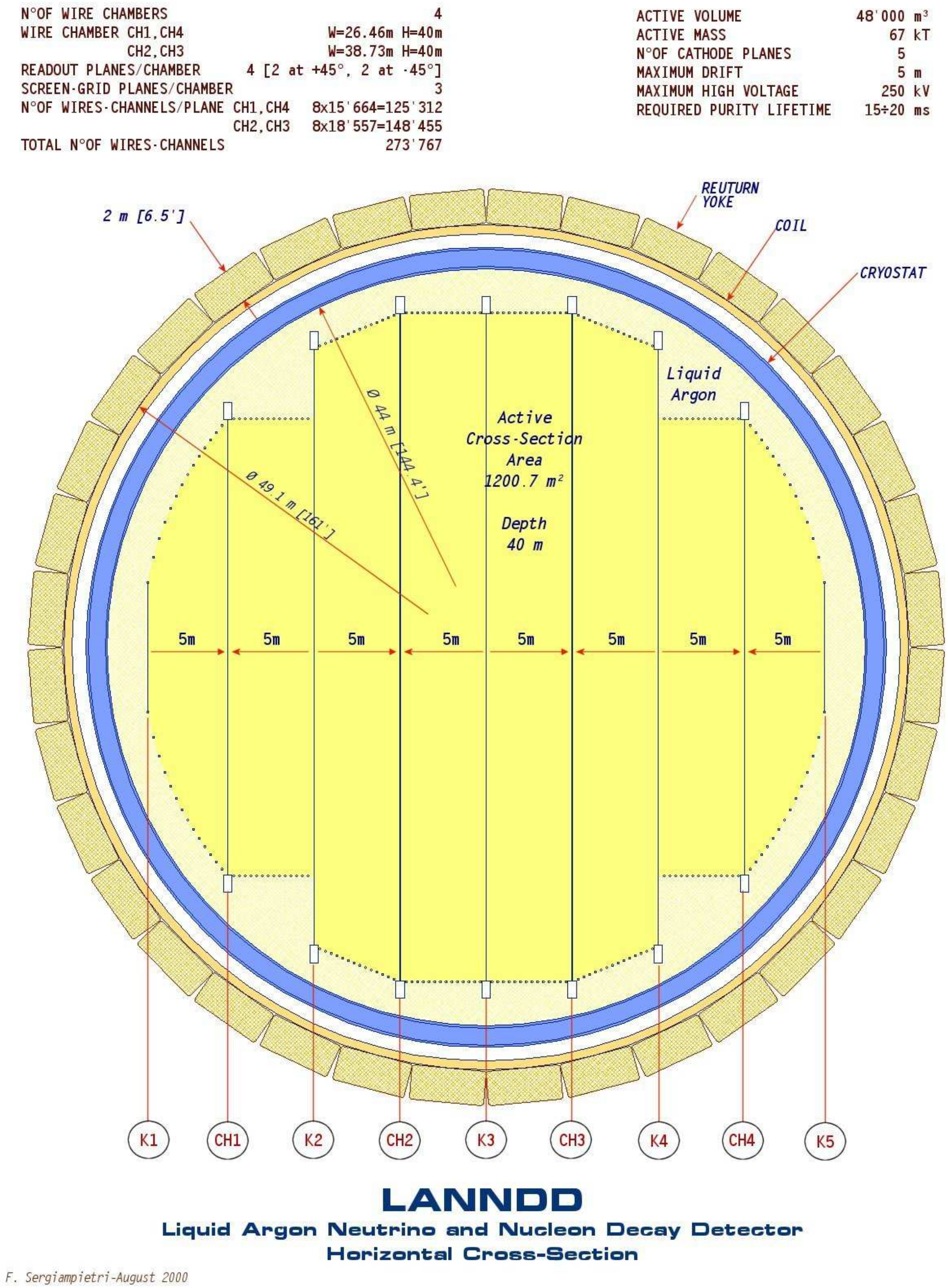
Below: Cosmic ray shower that includes a muon with a δ-ray, a stopping muon, and an electromagnetic shower.



LANNDD – 100 kton Liquid Argon Neutrino and Nucleon Decay Detector



LANNDD Top View



Max drift length of 5 m (limited by O_2 purity),

$\Rightarrow$ Several drift cells.

Is a 100-kton Liquid Argon Detector Feasible?

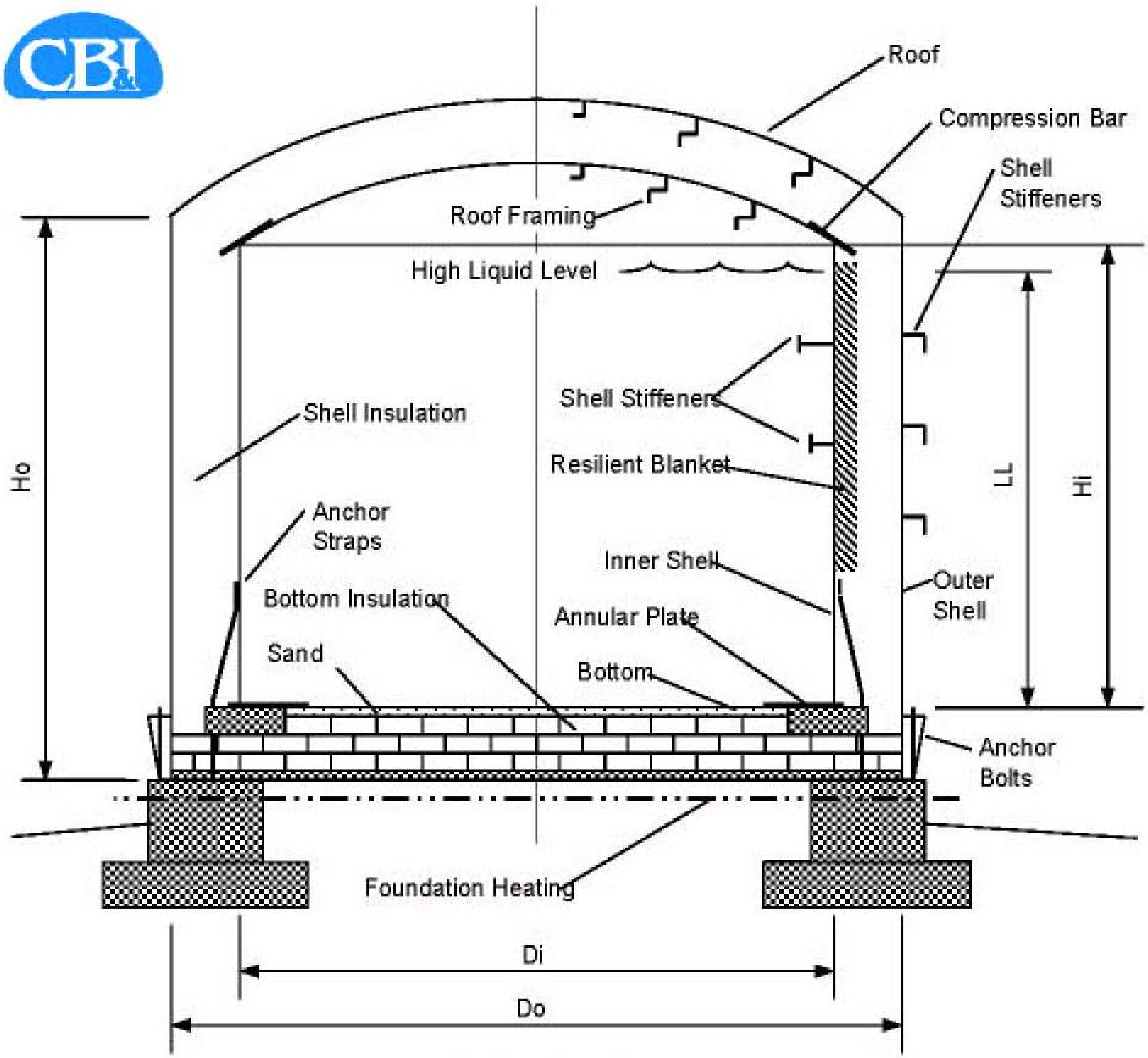
- Use mature, low-cost technology of liquid methane storage tanks (up to 300 kton based on existing structures).
  Preliminary budget estimate from industry of $<$ \$20M for a 100-kton tank, IF built on the SURFACE.

- 100 kton of liquid argon = 10% of USA annual production.
  $\Rightarrow$ Deliver one trailer-load every 2 hours from Chicago,....
  Only 5 ppm O_2 grade available in large quantities,
  $\Rightarrow$ On-site liquid-phase purification via Oxisorb (MG).
  Raw material, delivery + purification $\Rightarrow$ \$0.8M/kton.

- ICARUS electronics from CAEN @ \$100/channel.
  3 mm wire spacing $\Rightarrow$ 300k ch $\Rightarrow$ \$30M.
  9 mm wire spacing $\Rightarrow$ 100k ch $\Rightarrow$ \$10M.
  High capacity of long wires $\Rightarrow$ signal may be too weak to use 3 mm spacing.

- With neutrino beam, record every pulse (10^{-3} duty factor).
  Cosmic rays occupy $\approx 10^{-3}$ of active volume,
  $\Rightarrow \quad \approx 10$ MB data per trigger.
  $\Rightarrow$ Modest ($<$ \$10M) DAQ/computer system.

200-kton Cryogenic Tanks Used for LNG Storage



Double Wall & Double Roof Tank

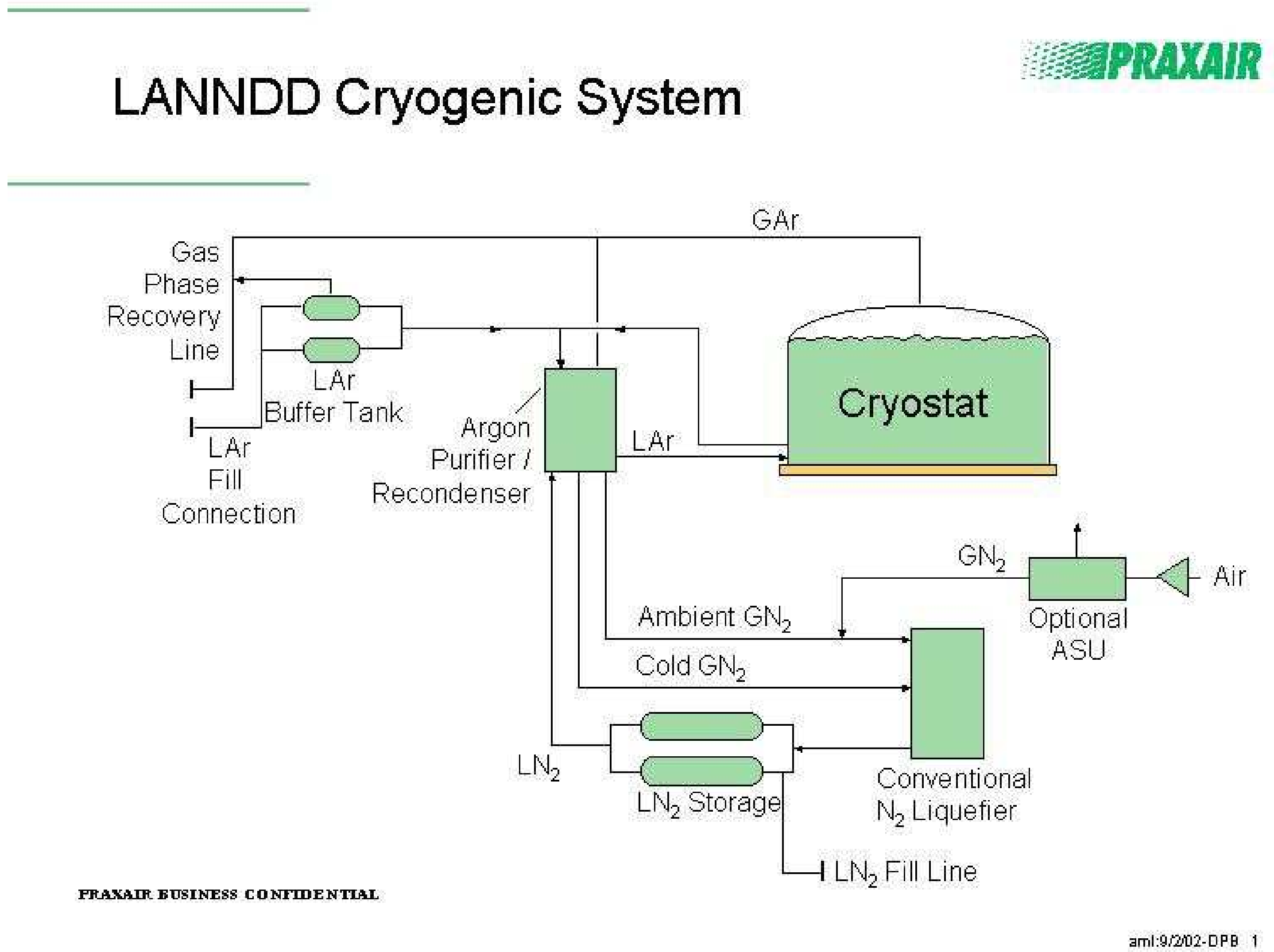
	Feet
Di =	165
Hi =	117.9803
LL =	117.7303
Do =	173
Ho =	118.0443

Chicago Bridge & Iron: can build 100-kton LAr tank for < $20M.

Strong Interest by Praxair

Praxair is the leading USA vendor of liquid argon.

The Praxair R&D Lab in Tonawanda, NY is same Union Carbide lab that provided the expertise to build the Oak Ridge gaseous diffusion plant in the 1940's.

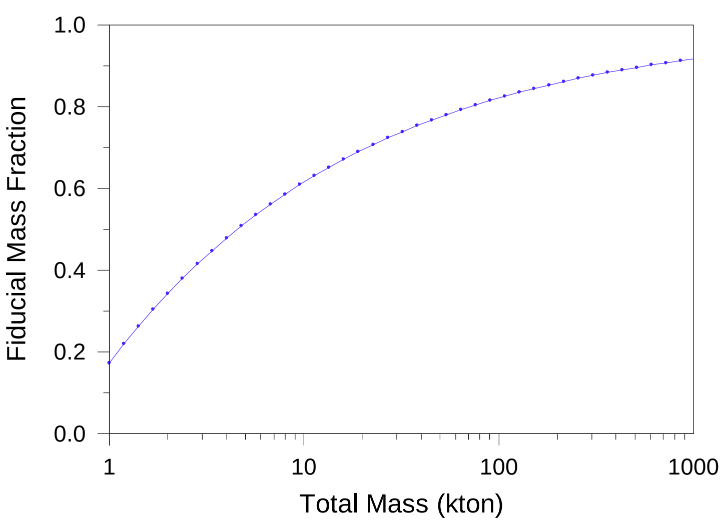


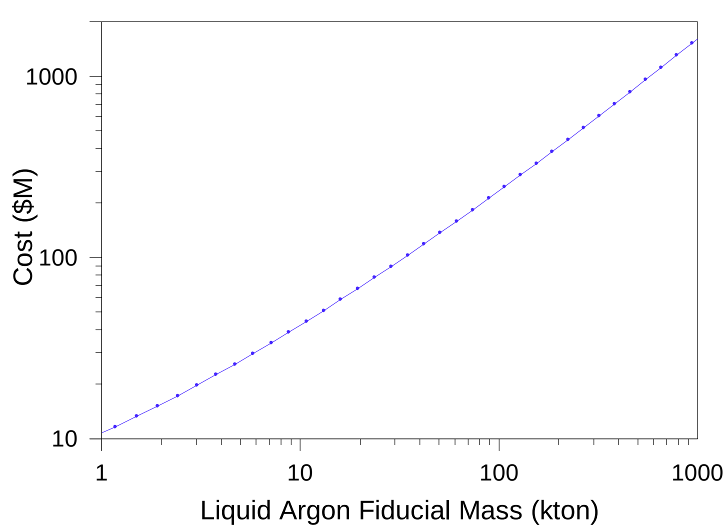
Extrapolation to Very Large Modules

Preliminary cost estimate for a liquid argon detector of 100 kton **total** mass.

Component	Scaling	Cost
Liquid argon (industrial grade)	M	\$70M
Cryo plant, including Oxisorb purifiers	M	\$10M
Surface site preparation	$M^{2/3}$	\$10M
Cryogenic storage tank	$M^{2/3}$	\$20M
Electronics (300k channels)	$M^{2/3}$	\$30M
Computer systems	$M^{2/3}$	\$10M
Subtotal		\$150M
Contingency		\$50M
Total		\$200M

Fiducial mass is for ν_e appearance events $\Rightarrow$ contain EM showers.





Cost scaling = 1.33 [\$80M $(M/100$ kton$)$ + \$70M $(M/100$ kton$)^{2/3}$].

Preliminary Cost Comparison

Scaling the **liquid argon detector** cost estimate,

⇒ **\$53M for 20 kton total mass**.

Cost estimates for a 20-kton **"particle-board" detector**:

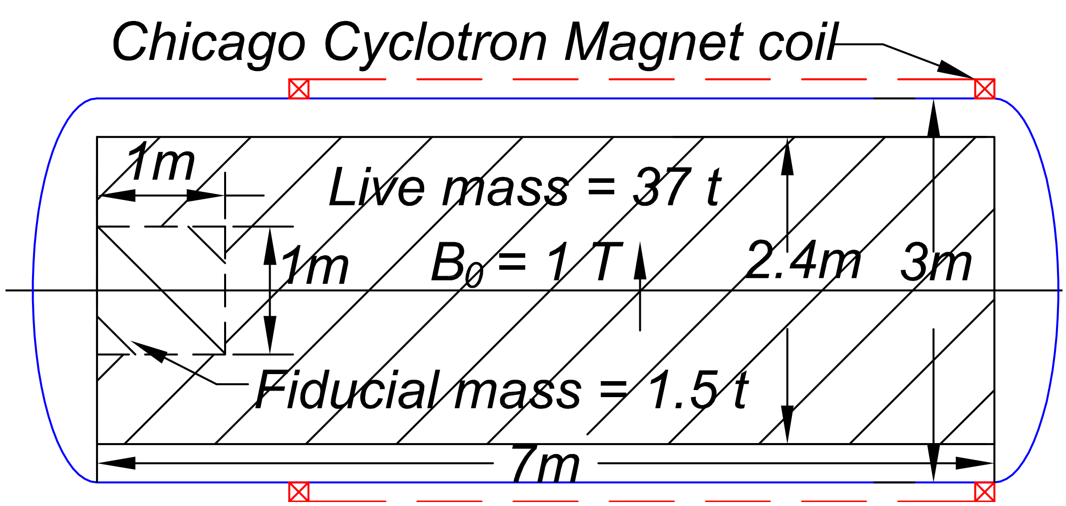
- 20 m ×20 m × 160 layers of 30 cm each (50 m deep).
- 64,000 m^2 of readout; 512,000 ch on 2.5 cm pitch.
- Readout costs based on a recent BaBar evaluation.

Component	**RPC**	**Iarocci**	**Scintillator**
Particle board	\$5M	\$5M	\$5M
Mech. Assem.	\$5M	\$5M	\$5M
Detector Cost/m^2	\$350	\$500	\$300
Detector Cost	\$22M	\$32M	\$19M
Cost/Readout Ch	\$25	\$25	\$90
Readout Cost	\$13M	\$13M	\$46M
Subtotal	\$45M	\$55M	\$75M
Total w/25% Contingency	**\$56M**	**\$69M**	**\$93M**

Next Steps

- 40-ton near detector (1.5-ton fid. mass) in off-axis NUMI beam.

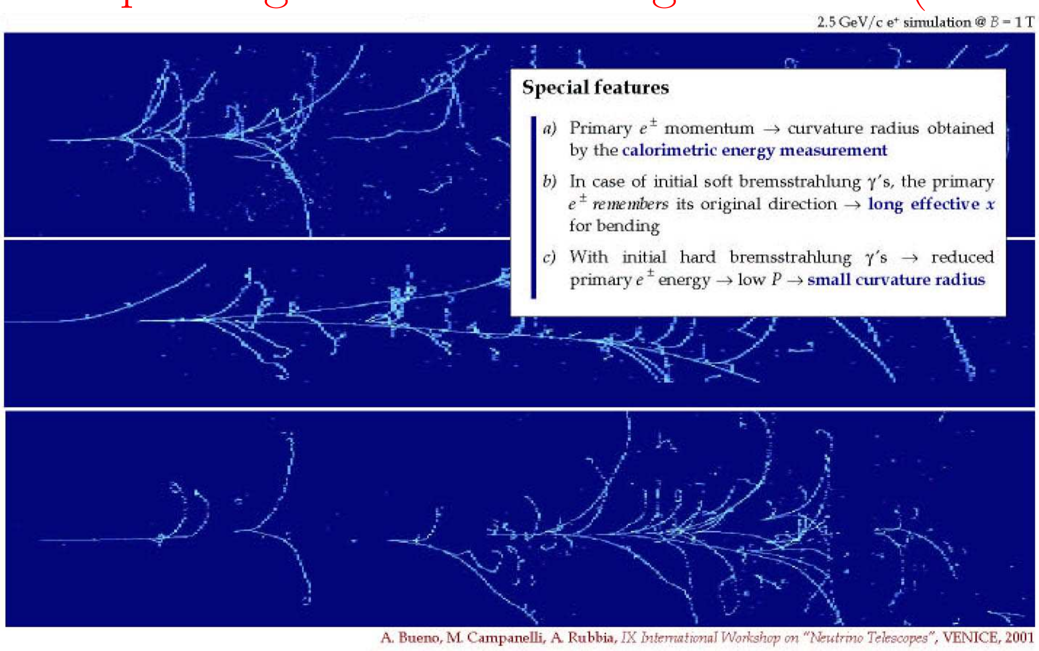
- Add Chicago Cyclotron Magnet coils to give $B \approx 1$ T over downstream (or upstream) 2/3 of detector.



$\Rightarrow 10^5$ CC ν_μ ineractions/year.

R&D (see NuMI-PUB-GEN-0880)

- Liquid-phase purification of industrial grade argon via Oxisorb or equivalent (Praxair).
- Mechanics and electronics of wires up to 60-m long.
- Cryogenic feedthroughs, possibly including buffer volume at 150K for low-noise FET's.
- Verification of operation of a liquid argon TPC at 10 atmospheres (as at bottom of a 100-kton tank).
- Study of liquid argon TPC in a magnetic field (BNL P-965).



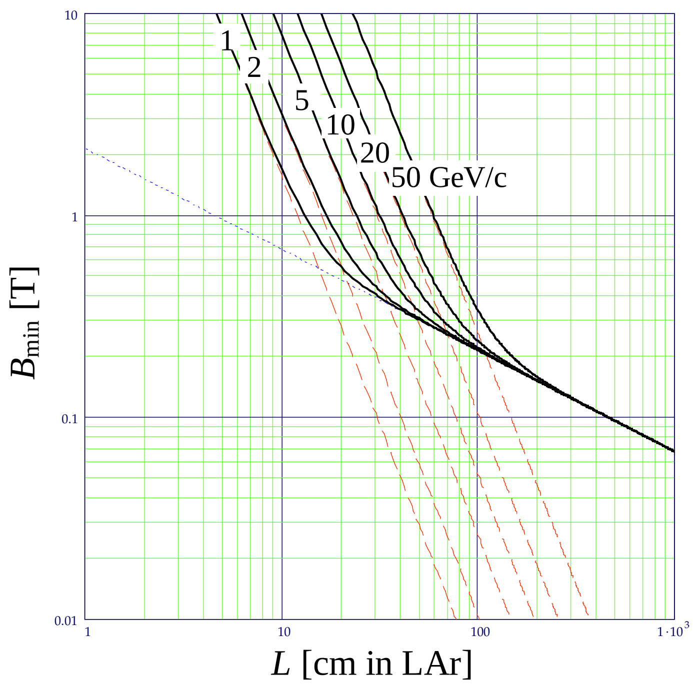
Should identify sign of $e^{\pm}$ up to ≈ 3 Gev in a 0.5-T field.

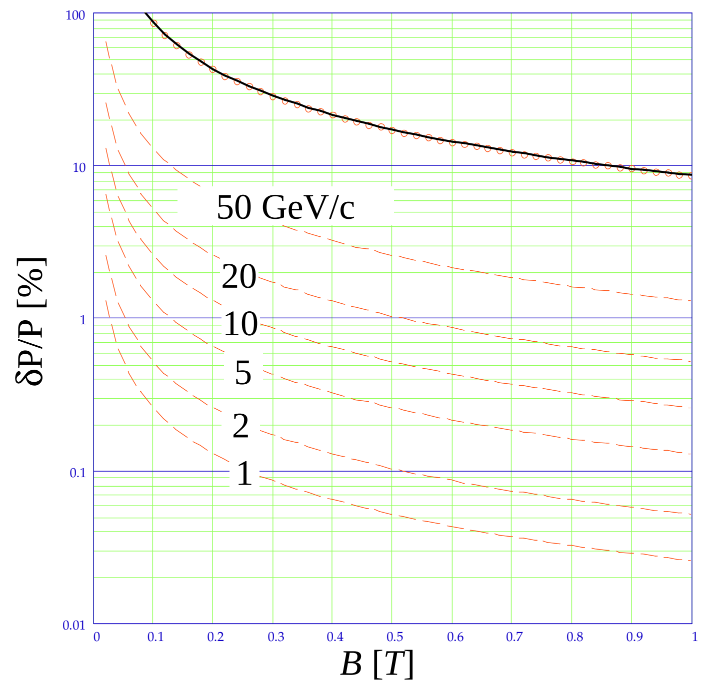
Appendix: Measuring a Muon's Sign in a Magnetized Liquid Argon TPC

In a strong magnetic field, momentum resolution (and sign discrimination) is limited by detector resolution.

But in a weak magnetic field, multiple scattering is the limit.

For example, if have 3-m track length ($= 20\ X_0$ = fiducial length for an electromagnetic shower), then have 3-σ sign discrimination for all muon momenta below 100 GeV/c in a field of 0.1 T.



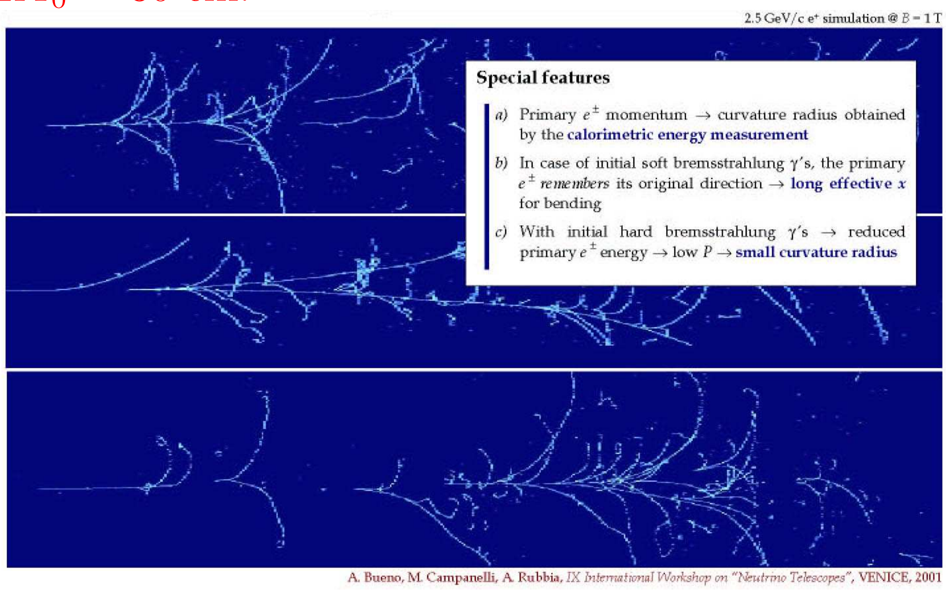


Above left: Minimum magnetic field *vs.* track length required to discriminate between positive and negative curvatures at 3-σ. Dashed curves: contribution of the detector resolution at momenta 1, 2, 5, 10, 20 and 50 GeV/c. Dotted curve: contribution of the multiple scattering in the range 1-50 GeV/c. Solid thick curves: combined contribution of detector resolution and multiple scattering in the range 1-50 GeV/c.

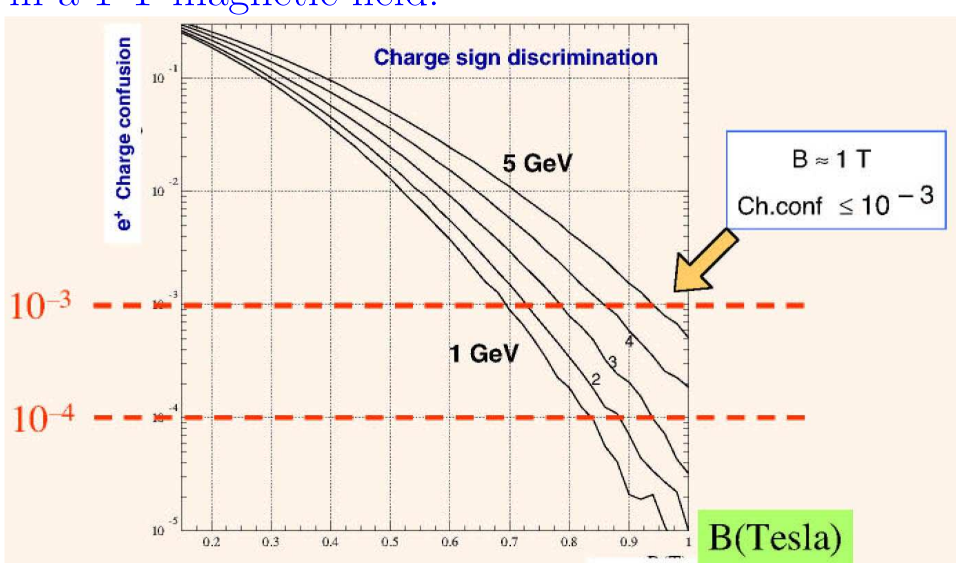
Above right: Momentum resolution *vs.* magnetic field for muons crossing 20 X_0 in liquid Argon. Dashed curves: contribution of the detector resolution at momenta 1, 2, 5, 10, 20 and 50 GeV/c. Circles: contribution of the multiple scattering independent of momentum. Solid thick curve: combined contribution of detector resolution and multiple scattering in the range 1-50 GeV/c.

Appendix: Measuring an Electron's Sign in a Magnetized Liquid Argon TPC

Because electrons "shower", the useful track length for sign discrimination is limited to $\approx 2X_0 \approx 30$ cm.



IF have 30 cm of useful track length, can get 99.9% accurate sign discrimination up to 5 GeV in a 1-T magnetic field.



But, shower fluctuations can reduce the accuracy of the sign determination.

$\Rightarrow$ **Need for experimental study!**

[GEANT simulations not yet performed – but will not truly settle the issue.]

Appendix: Off-Axis Detector Sites in the NuMI Access Shaft

[Steve Manly: http://nuint.ps.uci.edu/slides/Manly.pdf]