Proposal to Measure the Efficiency of Electron Charge Sign Determination up to 10 GeV in a Magnetized Liquid Argon Detector

(BNL P965, μLANNDD)

M.V. Diwan, R.C. Fernow, H.G. Kirk, S.A. Kahn, Z. Parsa, B. Viren
Brookhaven National Laboratory, Upton, NY 11973 USA

D.B. Cline, K. Lee, B. Lisowski, P.F. Smith
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095 USA

R.F. Burkart, W. Burgett, E.J. Feynves
Department of Physics, University of Texas at Dallas, Richardson, TX 75083 USA

A. Badertscher, A. Bueno, L. Knecht, G. Natterer, S. Navas, A. Rubbia
Institut fr Teilchenphysik, ETHZ, CH-8093 Zürich, Switzerland

J.G. Learned
Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822 USA

V. Palladino
Universita di Napoli "Federico II", 80138 Napoli, Italy

C. Cerri, F. Sergiampietri
INFN-Sezione di Pisa, 56010 S. Piero a Grado - PI, Italy

C. Lu, K.T. McDonald[1]
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544 USA

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http://puhep1.princeton.edu/~mcdonald/nufact/p965trans.pdf

[1]Spokesperson

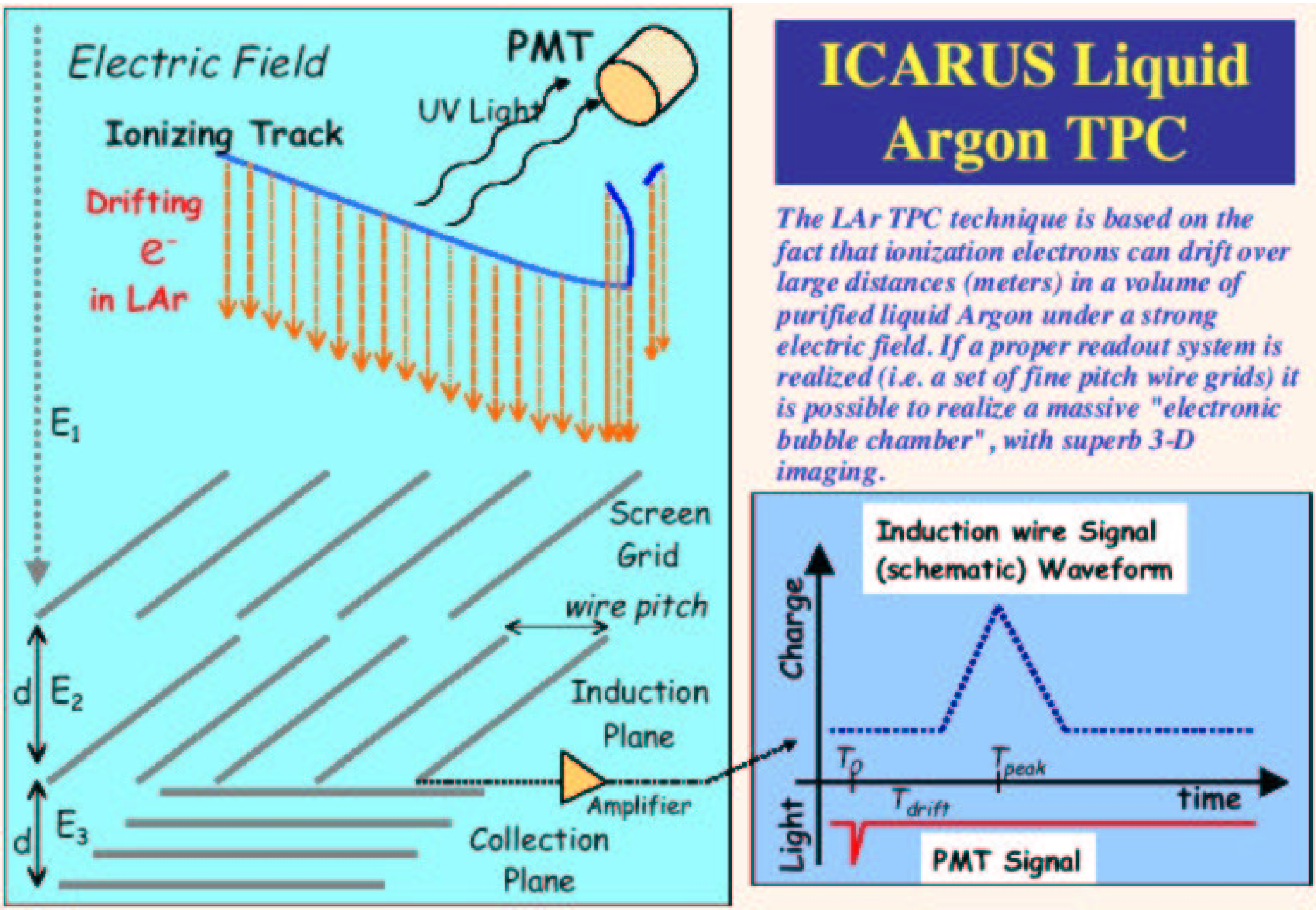
Executive Summary

The recent dramatic success of the ICARUS 300-ton liquid-argon time-projection-chamber prototype indicates that it is timely to review the possibilities for large-scale application of this technology for accelerator-based neutrino physics, neutrino astrophysics, and proton decay. A full exploration of the MNS neutrino mixing matrix (and extensions if sterile neutrinos exist) should be possible if the large mixing angle MSW solution to the solar neutrino problem, presently favored by the data, is confirmed by future measurements. A large detector for this purpose should be able to distinguish the charge of the lepton into which the neutrino converts, for which the detector should be immersed in a magnetic field.

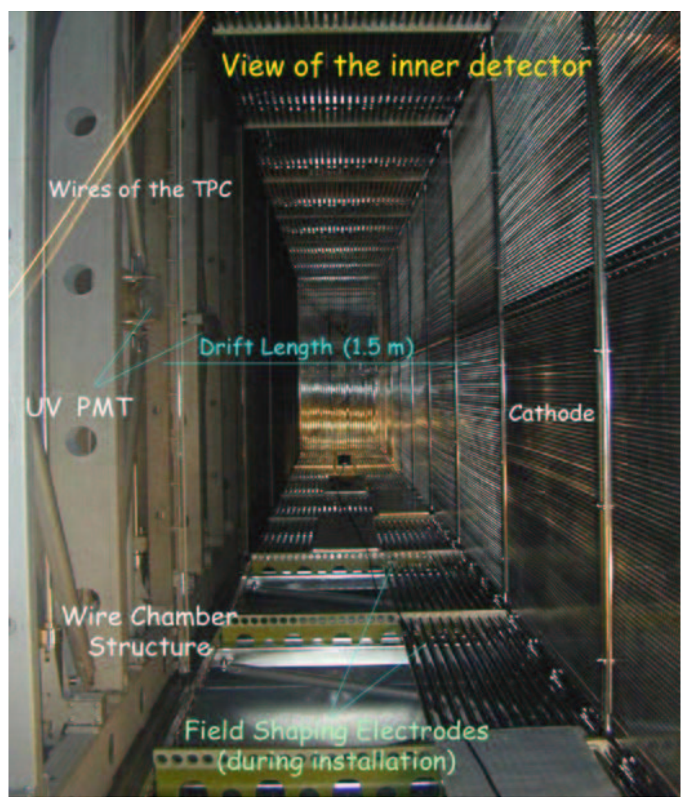
The most promising option for a large detector that can distinguish the charge of an electron is magnetized liquid argon. However, all studies to date of liquid argon detectors suitable for neutrino physics have been in zero magnetic field. We propose to study two key issues with a liquid argon detector of size $0.7 \times 0.7 \times 3.0\ \text{m}^3$, sufficient to contain an electromagnetic shower, placed in a 120D36 magnet in the AGS A3 beamline:

1. Verification that a liquid argon detector can be operated with the electric field perpendicular to the magnetic field (unlike gas-phase time projection chambers that must be operated with **E** parallel to **B**).
2. Verification that the electron charge can be determined up to several GeV by analysis of electromagnetic showers.

We request 15 shifts of slow beam time in the A3 line, with the A target in place to provide 0° secondary beams of 1-10 GeV. There should be an interval of at least one week after the first 10 shifts during which the detector would be reconfigured to have $\mathbf{E} \parallel \mathbf{B}$.



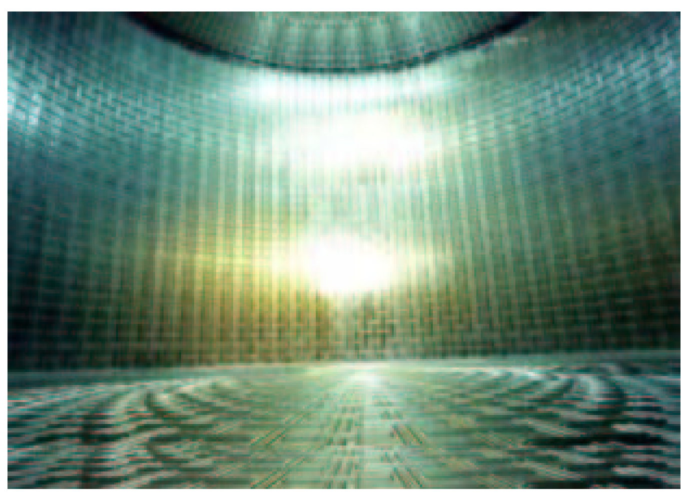
Liquid argon time projection chamber conceived by C. Rubbia (1977).



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 $\times$ 3 mm (wire planes) $\times$ 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.)

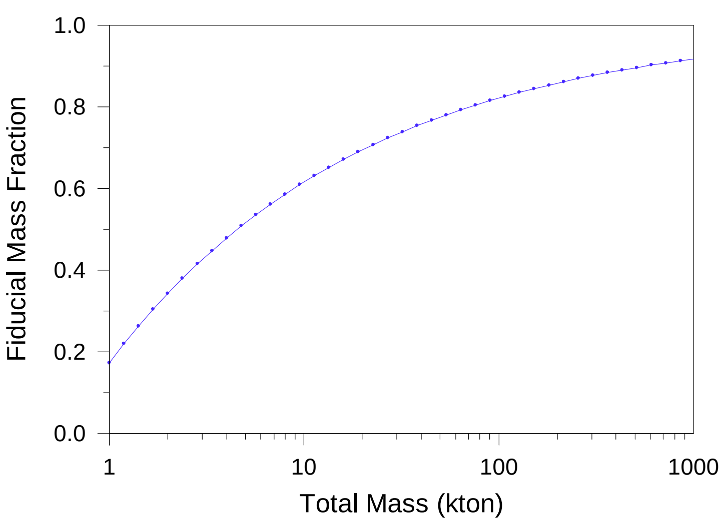
- Detector is continously "live" and can be "self-triggered" using pipelined, zero-suppression electronics.
- Detector is compatible with operation in a magnetic field.

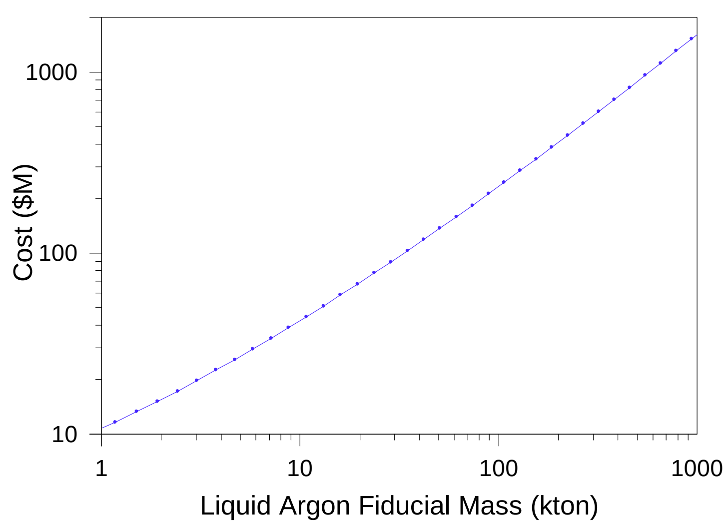
Extrapolation to Very Large Modules

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

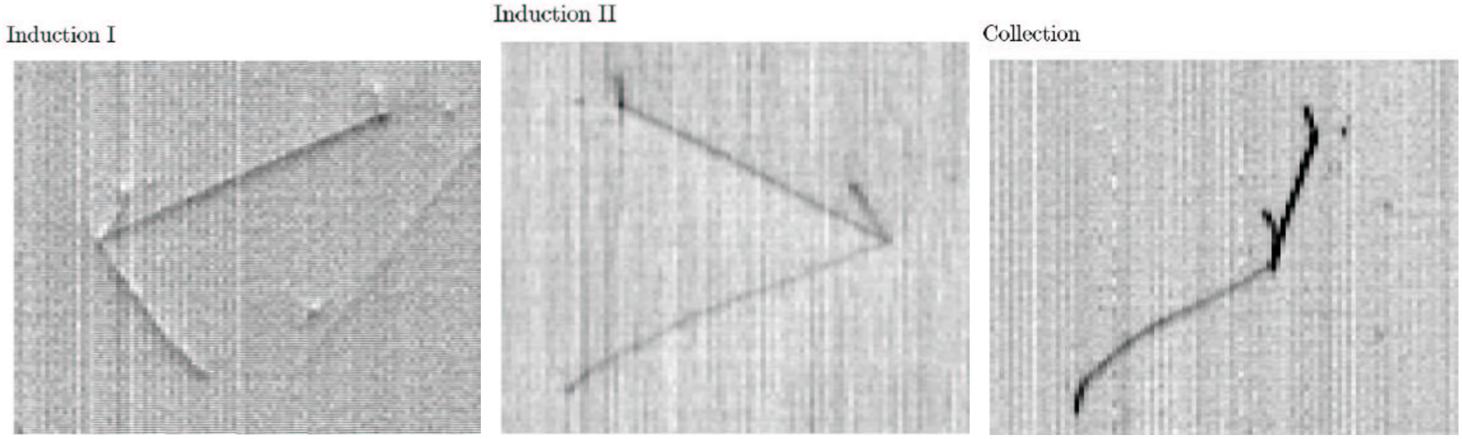
Fiducial mass is for ν_e appearance events $\Rightarrow$ contain EM showers.





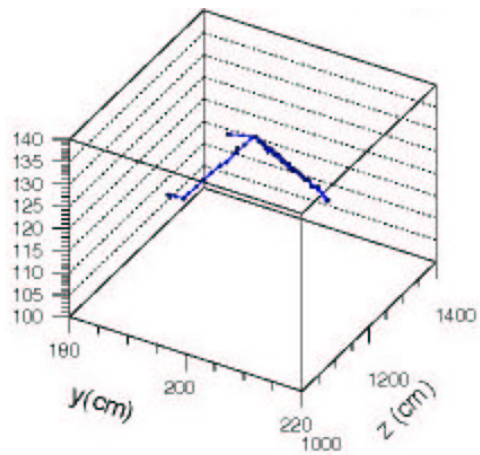
Cost scaling = 1.33 [\$80M (M/100 kton) + \$70M (M/100 kton)$^{2/3}$].

Events from the ICARUS T300 Cosmic Ray Test

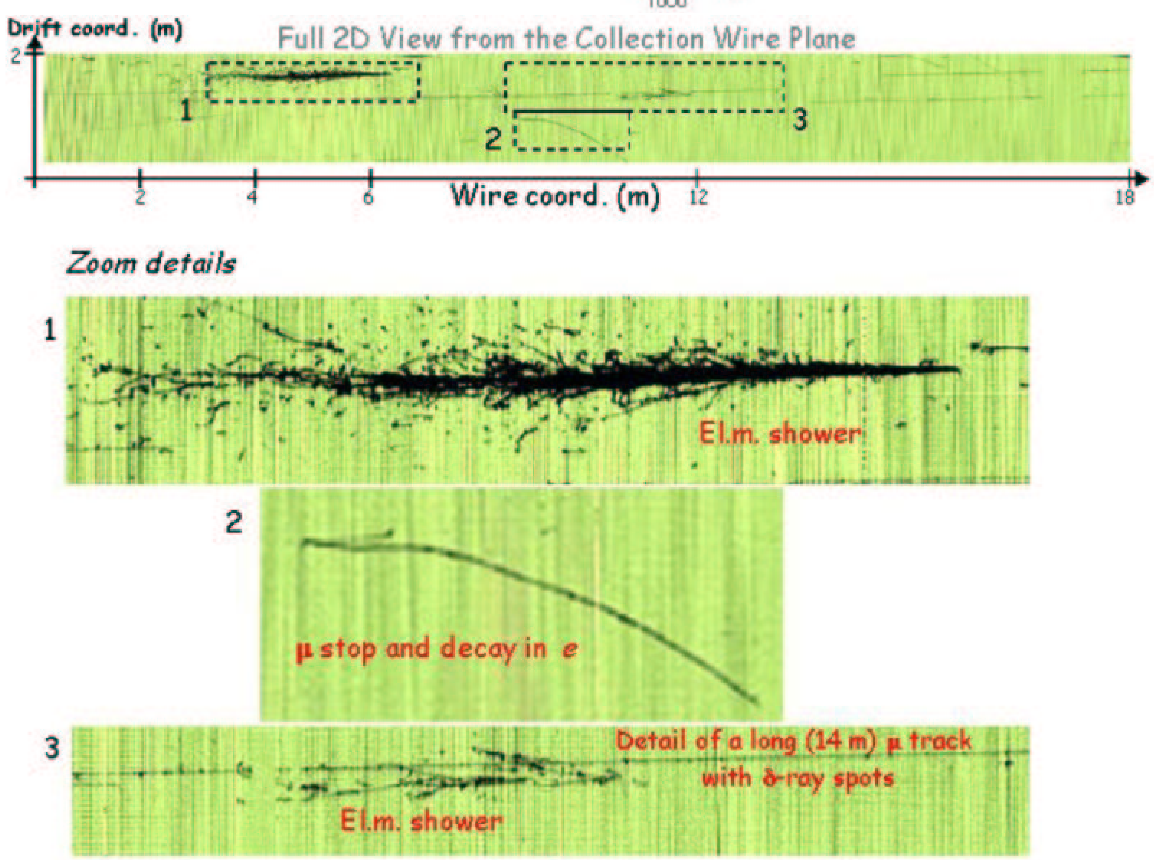


Above: 3 views of a low-energy hadronic interaction.

Right: Computer reconstruction.



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



The Role of a Magnetic Field

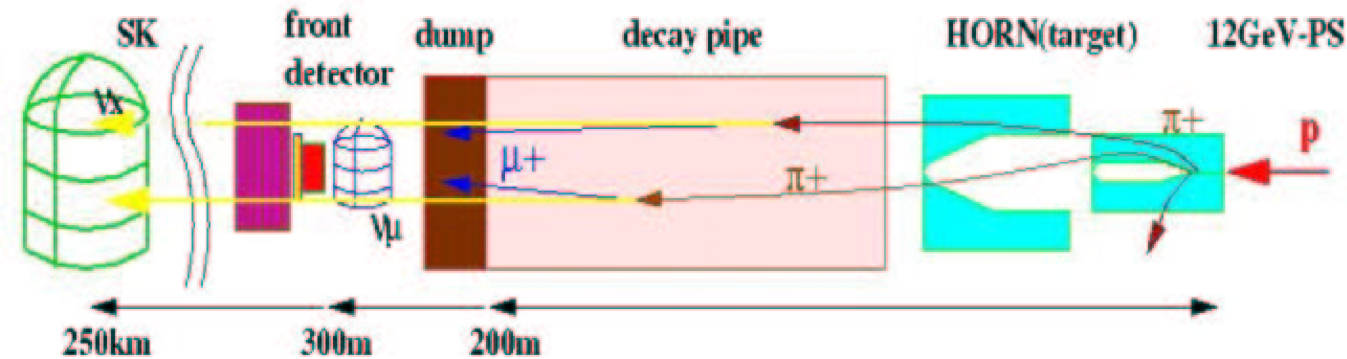
The next generation of neutrino oscillation measurements will emphasize ν_e appearance: $\nu_\mu \to \nu_e \to eX$.

$\Rightarrow$ Can measure $\sin^2 2\theta_{13}$, CP violation, as well as improved measurements of $\sin^2 2\theta_{23}$, ΔM^2_{23}, ...

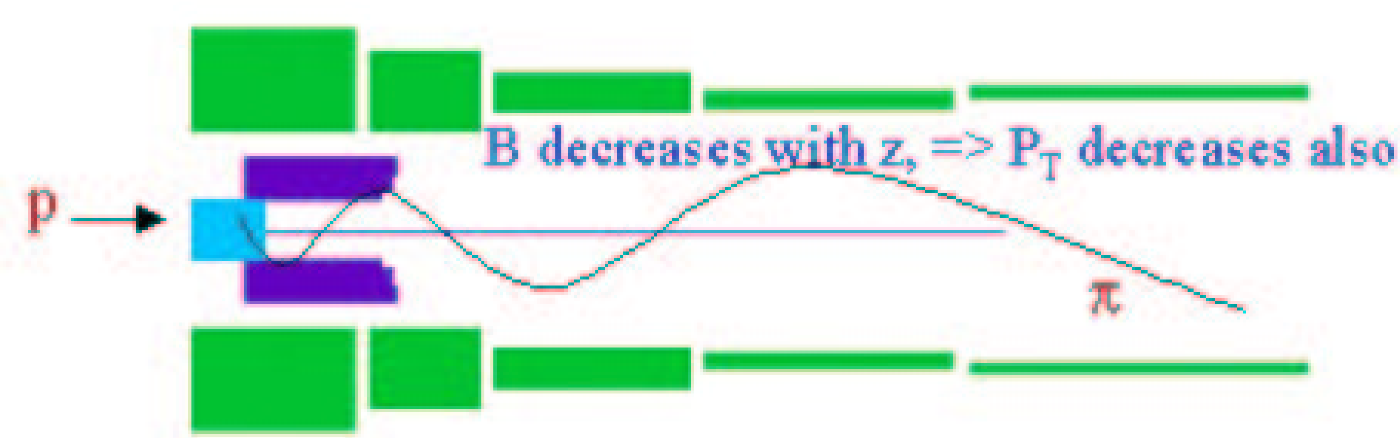
$\Rightarrow$ Good sensitivity for detector located at $\lambda/4$ of the ν_2–ν_3 oscillation,
$\Leftrightarrow L(\mathrm{km}) = 450 E_\nu(\mathrm{GeV})$.

Desire knowledge of lepton sign to **99.9% accuracy** to be consistent with other background effects.

No magnetic field required if use a "conventional" neutrino horn.



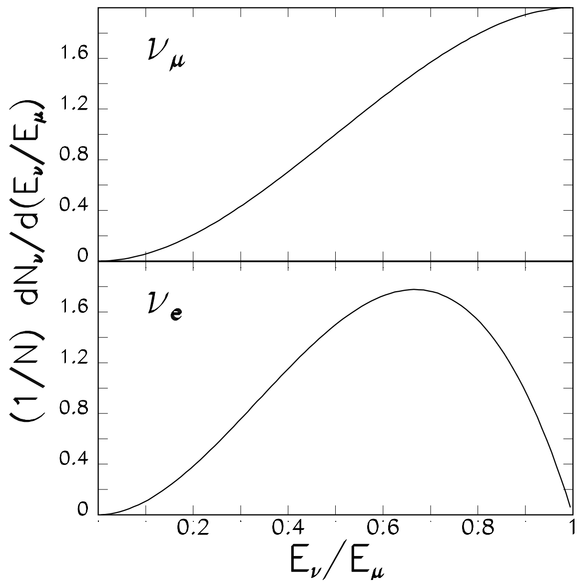
If desire $E_\nu \lesssim 1$ GeV, may be favorable to use a "solenoid horn" that collects both π^+ and π^-,
$\Rightarrow$ Detector must identify charge of final-state lepton up to ≈ 1 GeV.



A Neutrino Factory based on a Muon Storage Ring

Higher (per proton beam power) and better characterized, neutrino fluxes are obtained from μ decay.

Collect low-energy μ's from π decay,
Cool the muon bunch,
Accelerate the μ's to the desired energy,
Store them in a ring while they decay via $\mu^- \to e^- \nu_\mu \overline{\nu}_e$.
[Of course, can use μ^+ also.]



6 Classes of Experiments at a Neutrino Factory

$$\nu_\mu \to \nu_e \to e^- \quad \text{(appearance)}, \tag{1}$$
$$\nu_\mu \to \nu_\mu \to \mu^- \quad \text{(disappearance)}, \tag{2}$$
$$\nu_\mu \to \nu_\tau \to \tau^- \quad \text{(appearance)}, \tag{3}$$
$$\overline{\nu}_e \to \overline{\nu}_e \to e^+ \quad \text{(disappearance)}, \tag{4}$$
$$\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+ \quad \text{(appearance)}, \tag{5}$$
$$\overline{\nu}_e \to \overline{\nu}_\tau \to \tau^+ \quad \text{(appearance)}. \tag{6}$$

[Plus 6 corresponding processes for $\overline{\nu}_\mu$ and ν_e from μ^+ decay.]

"Appearance" and "Disappearance" (= nonoscillated) signals have opposite-sign final-state leptons, ⇒ Detector must identify lepton charge.

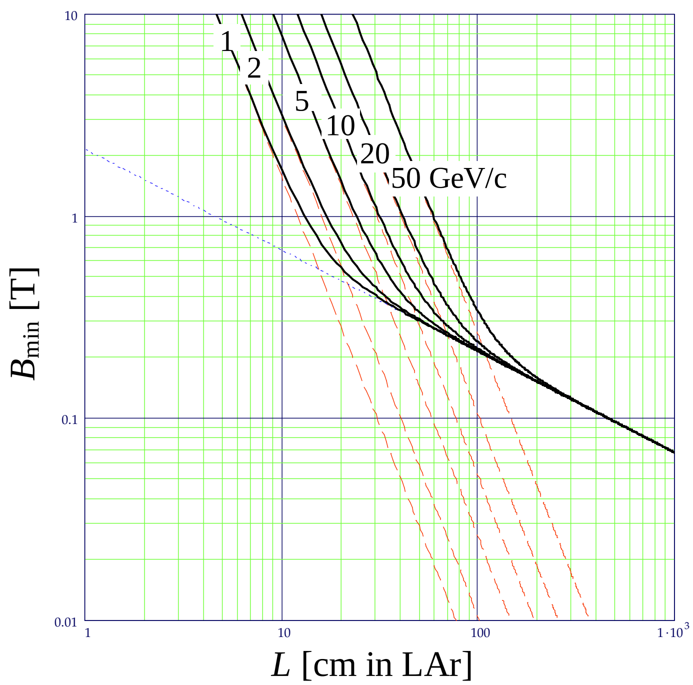
Initial Neutrino Factory energy might be 1-3 GeV, with later generation at 10-30 GeV.

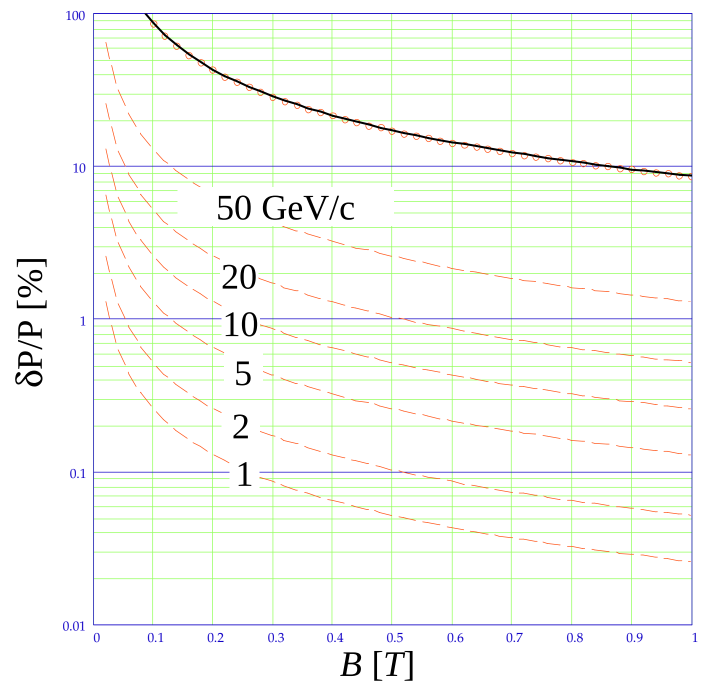
Measuring a Muon's Sign in a Magnetized Liquid Argon TPC

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.



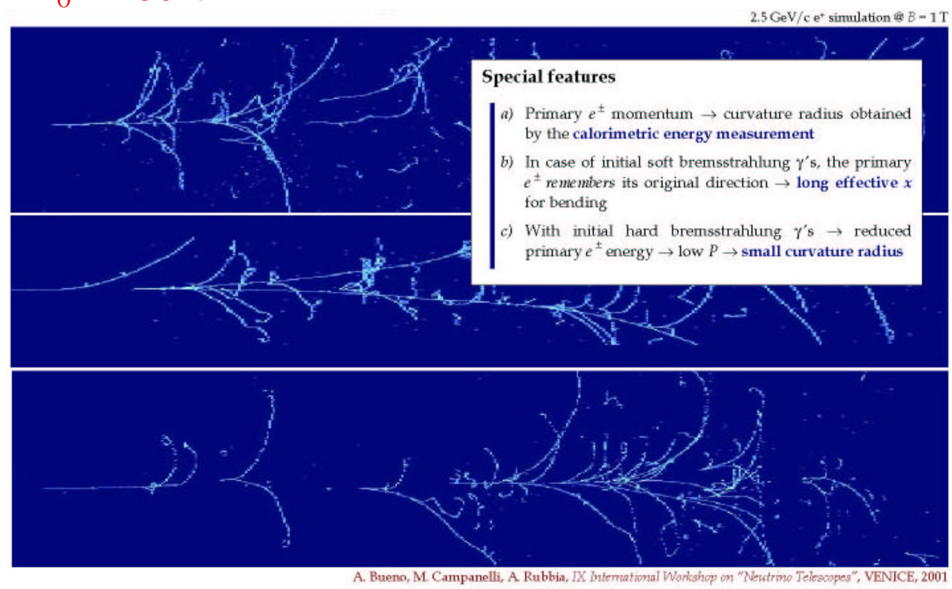


Above left: Minimum magnetic field *vs.* track length required to discriminate between positive and negative curvatures at 3-σ. Dashed curves: contribution of the detector resolution at momenta 1, 2, 5, 10, 20 and 50 GeV/c. Dotted curve: contribution of the multiple scattering in the range 1-50 GeV/c.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

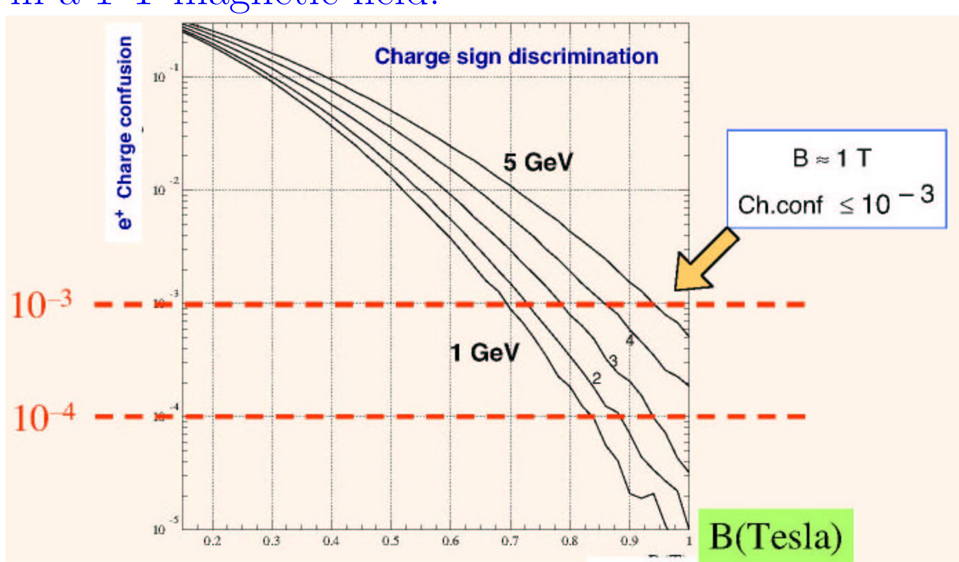
Above right: Momentum resolution *vs.* magnetic field for muons crossing 20 X_0 in liquid Argon. Dashed curves: contribution of the detector resolution at momenta 1, 2, 5, 10, 20 and 50 GeV/c. Circles: contribution of the multiple scattering independent of momentum. Solid thick curve: combined contribution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

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.



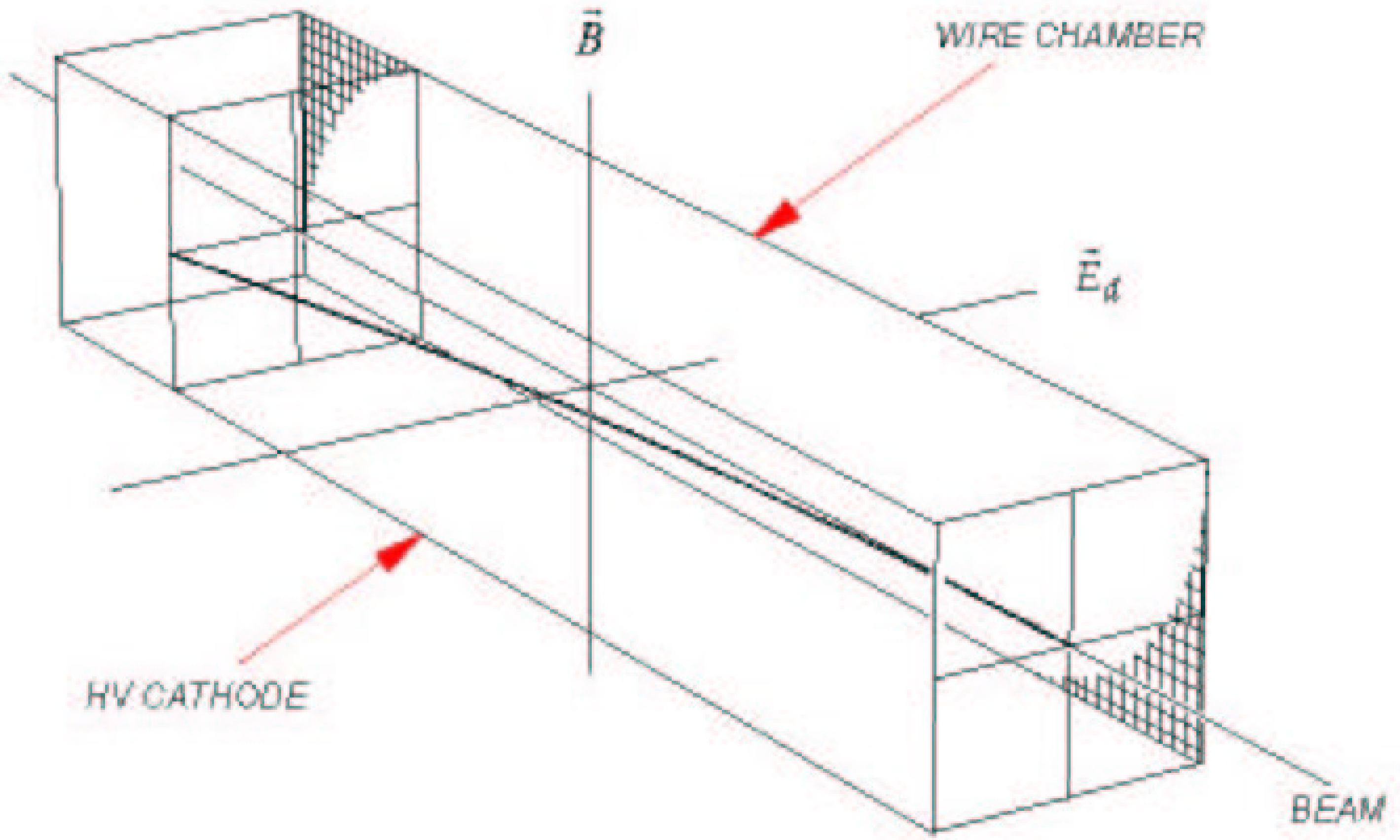
But, shower fluctuations can reduce the accuracy of the sign determination.

⇒ **Need for experimental study!**

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

The μLANNDD Proposal

- Place a liquid argon TPC of size $60 \times 60 \times 280$ cm^3 ($\pm 2X_0 \times \pm 2X_0 \times 18X_0$) in a magnetic field of 0-1 T in a secondary particle beam of 1-10 GeV. $\Rightarrow p/\pi/K/\mu/e$'s.

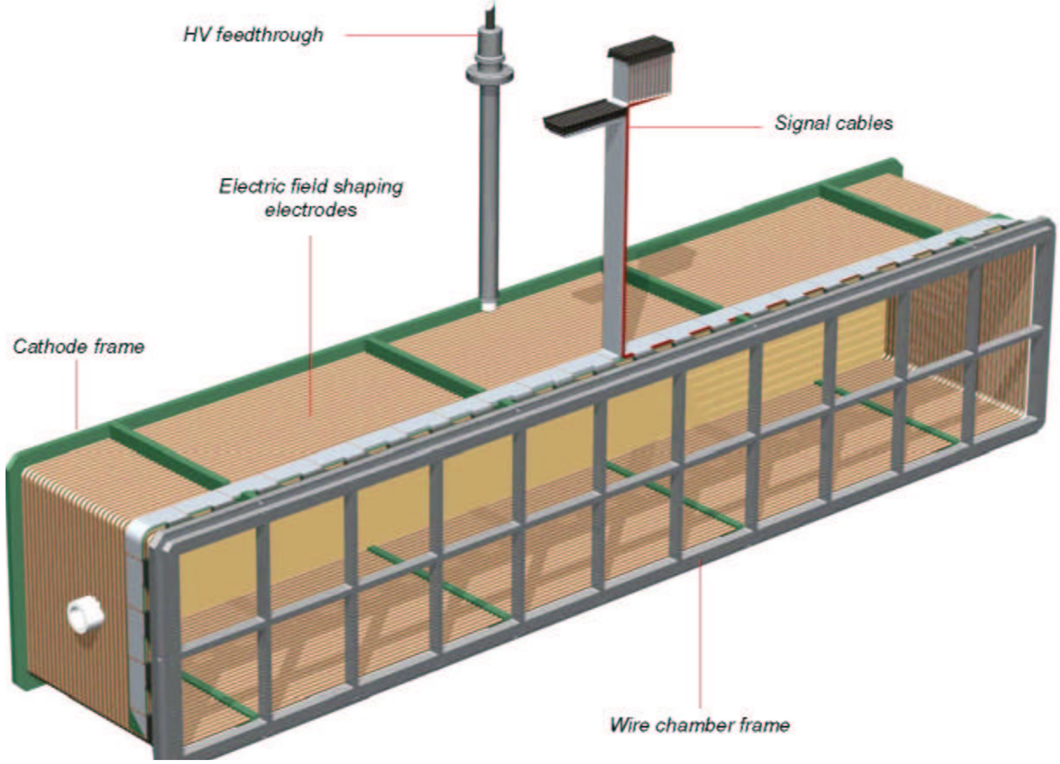


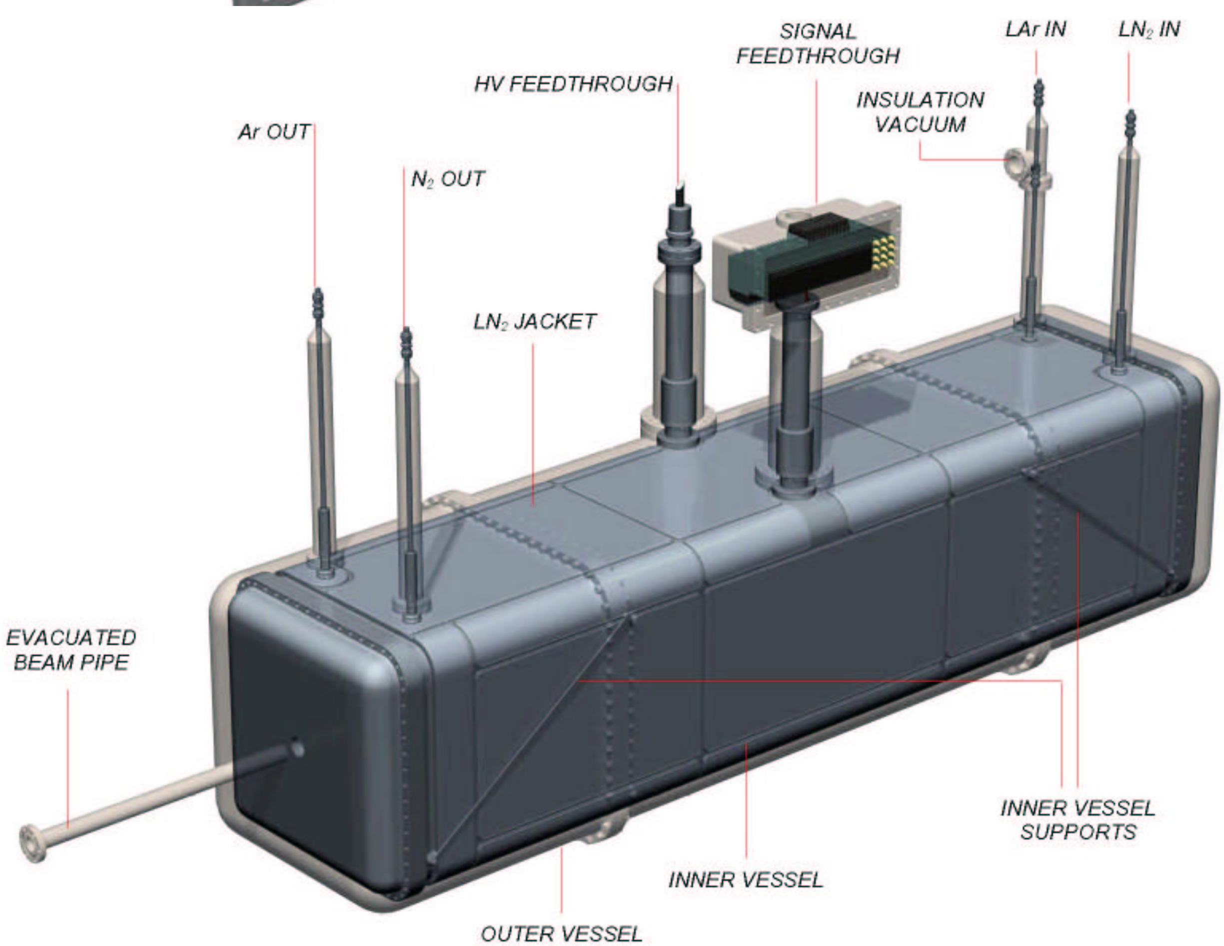
- Use $\mathbf{E} \perp \mathbf{B}$ since best accuracy in the TPC is in the time sampling along the drift coordinate – and the magnetic field bends the track in the plane $\perp$ to $\mathbf{B}$.

- Gas TPC's always use $\mathbf{E} \parallel \mathbf{B}$ to avoid Lorentz force effects – but these are negligible in liquid argon, and the electrons drift along $\mathbf{E}$ to good accuracy.

- However, it is desirable to test the TPC with $\mathbf{E} \parallel \mathbf{B}$ as well as $\mathbf{E} \perp \mathbf{B}$.

Sketches of the μLANNDD Detector

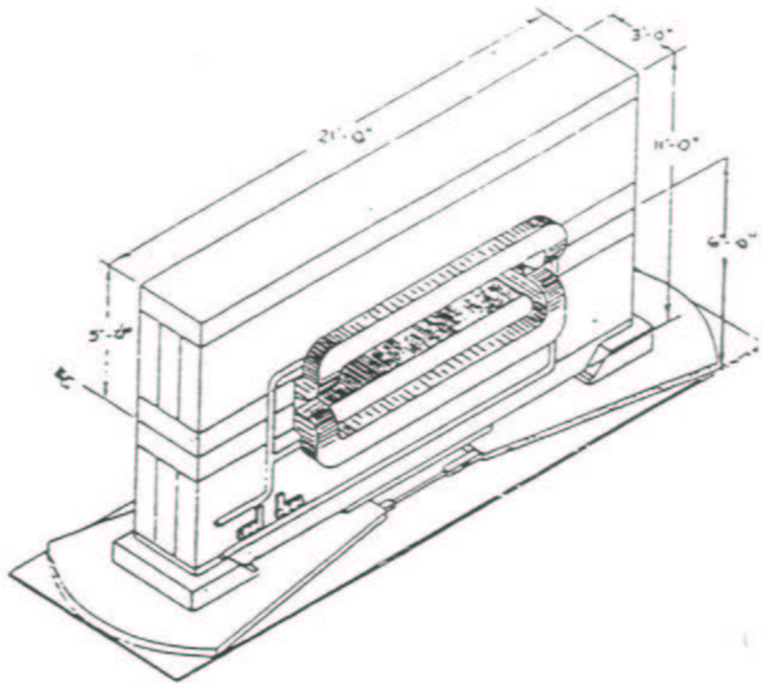




Services on top of cryostat, $\Rightarrow$ Magnetic field should be horizontal.

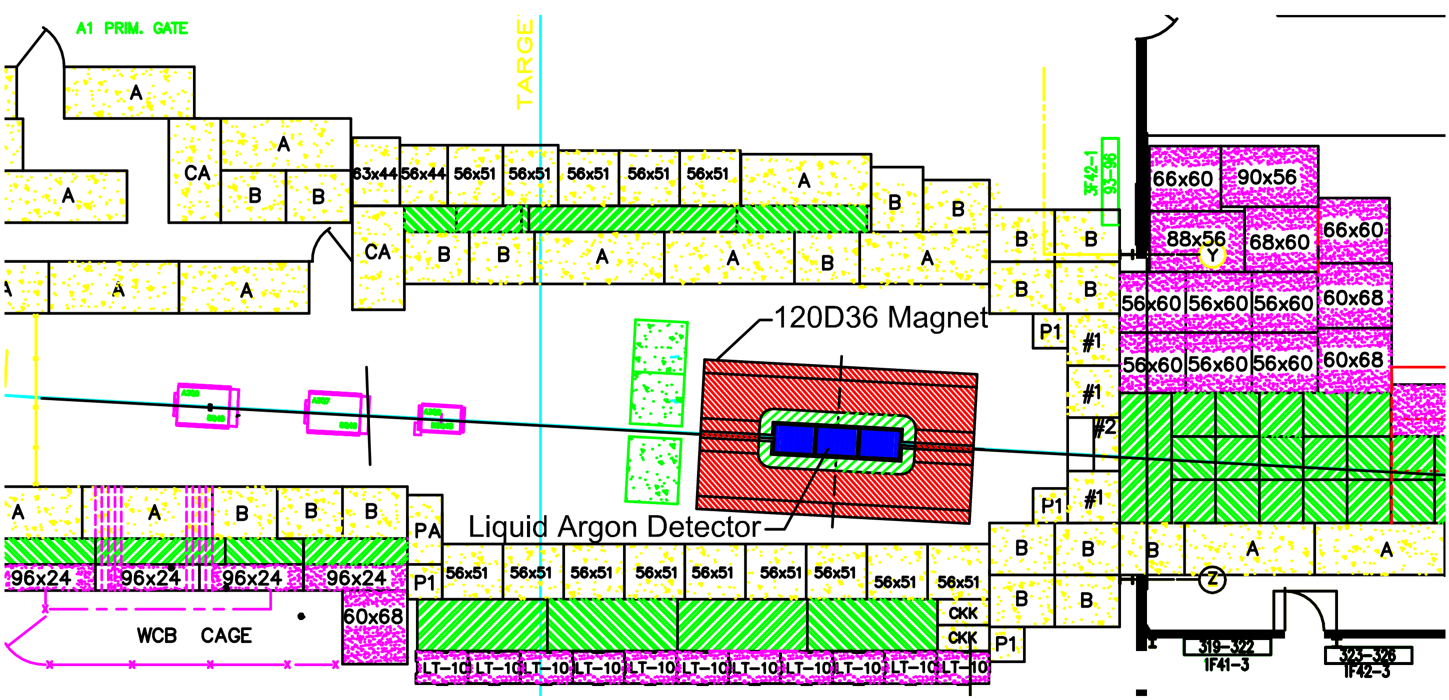
Use a 120D36 as the Analysis Magnet in the AGS A3 Line

MAXIMUM FIELD	12.5 KG
VOLTAGE	221 V
CURRENT	4500 AMPS
MEAN EFFECTIVE LENGTH (APPROX)	56.5 IN
GROSS WEIGHT	165 TONS
WATER CONSUMPTION	140 GPM
GAP	24 IN
Δ P	125 PSI
Δ T	60° F
RES OHMS	0.049 OHMS



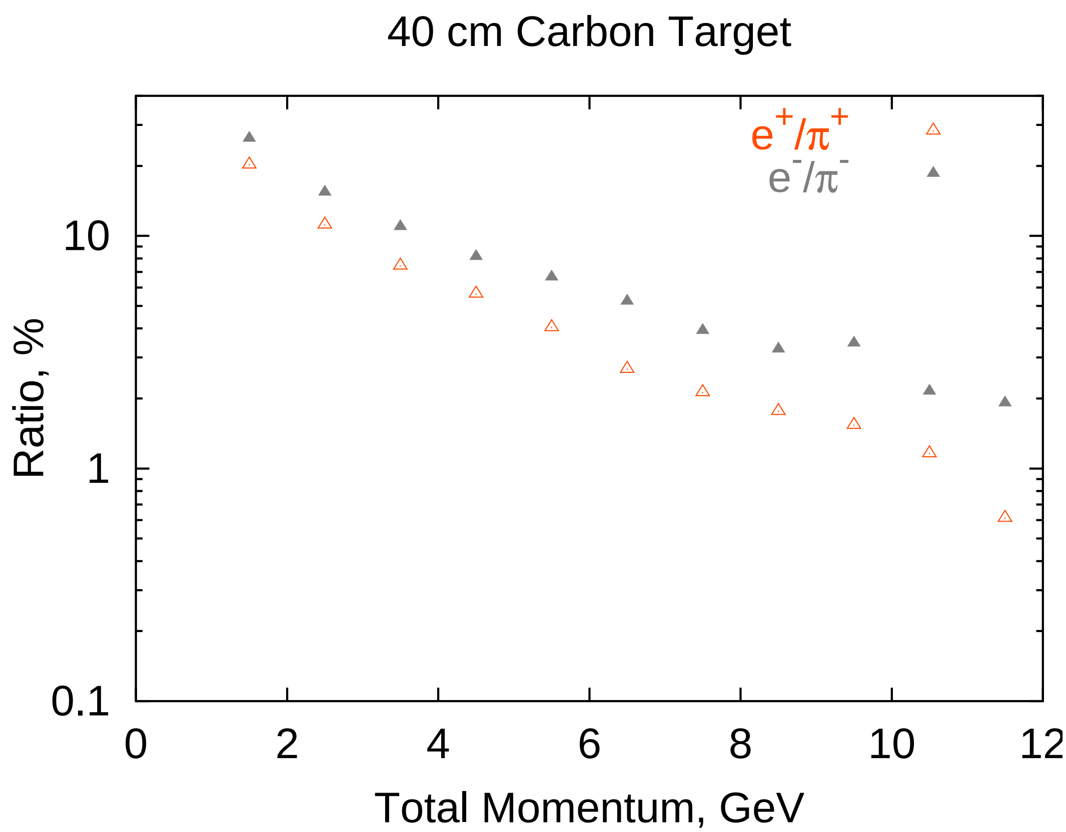
The 120D35 magnet is now in the (unused) A2 line.

It can be laid on its face in the downstream part of the A3 cave, presently used by E951 (K. McD, spokesperson).



Secondary Beam Requirements

- Drift time across 60 cm is 300 μs, $\Rightarrow$ Desire particle flux of $\approx$ 1000/s.
- Beam spot size not critical; desire FWHM $\approx 0.5''$.
- Beam particle ID not required; done in the liquid argon TPC.
- Desire maximal e/all ratio, $\Rightarrow$ Low-Z target and 0° secondary beam.
- MARS calculation for a 40-cm C target in a 24-GeV proton beam at 0°:



- Can get 2-3% electrons even at 10 GeV $\Rightarrow \gtrsim 10$ e's/s.

  $\Rightarrow$ Can collect 10,000 e's in 1/2 hour even at highest energy.

  $\Rightarrow$ Grid scan of 10 beam energies and 5 magnetic fields in 1 day.

  $\Rightarrow$ Both beam signs, and both $\mathbf{E} \perp \mathbf{B}$ and $\mathbf{E} \parallel \mathbf{B}$ in 4 days (12 shifts).
- But need $\approx$ 1 week gap in running to convert from $\mathbf{E} \perp \mathbf{B}$ to $\mathbf{E} \parallel \mathbf{B}$.

Preliminary Cost Estimate

Estimate by F. Sergiampietri (10/01):

A detailed time schedule and cost estimate can be made only after a final definition of the construction drawings and after obtaining cost and time estimates from the producers and suppliers. As an approximate approach, we can foresee the following:

Time schedule

- Final constructional plans	2 months
- Estimate requests	1 month
- Construction	5 months
- Assembling	2 months
- Home laboratory test	2 months
- Setting up in the experimental area	1 month
- Final test	0.5 month
- Data taking	1.5 months
- Data analysis	2 months

Cost estimates

- Magnet	100 k€
- Magnet power supply	50 k€
- Cryostat	50 k€
- TPC	15 k€
- Cryostat details (feedthroughs, ...)	15 k€
- Storage dewars	13 k€
- Electronics	50 k€
- High voltage power supplies	15 k€
- Various accessories and contingency	32 k€
Total	340 k€

Updates:

- Preparation of 120D36 magnet and A3 secondary beam (per C-AD) \$260k
- 15 shifts of parasitic operation of the A3 line \$50k
- Liquid Argon TPC, excluding electronics \$200k
- 1200 channels of electronics (borrowed from ICARUS) . . . . (\$100k)

Preliminary Allotment of Responsibilities

- Beamline, 120D36 magnet, operations – BNL.
- Detector Construction – Pisa, Princeton.
- Detector Electronics – ETH, Pisa, Princeton (+ other ICARUS).
- Analysis Software – BNL, ETH, ...
- Simulations – BNL, ETH, ...

P965 C-AD Impact Statement -DRAFT-

D. Lazarus 8/26/2002

Proposal to Measure the Efficiency of Electron Charge Sign Determination up to 10 GeV in a Magnetized Liquid Argon Detector (μLANNDD)

Spokesperson: K. McDonald (Priceton)

Institutions: BNL, UCLA, Texas, Zurich, Hawaii, Napoli, Pisa, Princeton

Summary:

- **Detector test relevant to ν and proton decay experiments**

Primary Beam:	25 GeV/c protons	**Secondary Beam**:	< 10 GeV electrons and positrons
Primary Beam Line:	A	**Secondary Beam Line**:	A3
Primary Beam Intensity:	<1 x 10^{12}/spill	**Secondary Beam Intensity**:	100's per spill

Special Beam Requirements: None

Hours Requested: 2 runs separated by a several days. Total beam time about 1 week

Requested Schedule:

- **FY 2004 (possibly later) - depends on securing funds to construct the detector**

Conflicts with other experiments (assuming restoration of HEP in FY2004):

- **FY2004** - None

Some Issues: P965 Impact Statement (Cont)

- C-AD Cryo Group support requirements not yet defined

C-AD Operations:

- If E949 is supported, P965 could run ~ parasitically with < 1TP beam to the A-target
- If the NSF supports the RSVP experiments, could run ~ parasitic to operation of K0PI0

C-AD Costs	**Purchases (includes shops)**	**Labor(mandays)**			**Total**
		EDIA	**Techs**	**Trades**	
• Reconfigure and install 120D36	$ 30,000	60	109	79	**$ 136,340**
• Other (contingency,cryo group support etc)	$ 6,000	12	21.8	15.8	**$ 27,268**
• Total Direct Cost	**$ 36,000**	**$ 31,991**	**$ 46,397**	**$ 49,220**	**$ 163,609**
• Indirect Cost	$ 12,870	$ 27,732	$ 40,221	$ 17,596	**$ 98,419**
TOTAL with indirect	**$ 48,870**	**$ 59,723**	**$ 86,618**	**$ 66,816**	**$ 262,028**

Other Experiment Costs

• μ-LANNDD construction	**$ 200,000**

HEEP electronics: **to be determined**

Impact On C-AD Resources -- Moderate