Magnetizing a Large Liquid Argon Detector

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Summary

To reduce the "irreducible" background of antineutrinos in a long-baseline neutrino oscillation experiment, must build a better beamline:

- Use a "solenoid horn" for beams based on π decay.
- Use a "Neutrino Factory" for beams based on μ decay.

If θ_{13} is small, these options will be needed to study CP violation in the neutrino sector.

However, such beams require that the detector distinguish neutrino interactions from antineutrino interactions.

$\Rightarrow$ Magnetized detectors!

$\Rightarrow$ Design large LArTPC's to be compatible with being immersed in a magnetic field.

Option: Magnetized Liquid Argon Detector

If the detector could tell neutrino from antineutrino events, then could use a novel "solenoid horn" neutrino beam to speed up data rate. [Slides 4-5]

An unmagnetized liquid argon TPC may be able to neutrino from antineutrino via a tag on slow protons (μBooNE should be able to confirm this):

$$\nu n \to p e^- X \quad vs. \quad \bar{\nu} p \to n e^+ X \qquad \text{where } X \text{ contains an even number of charged mesons,}$$

$$\nu n \to n e^- X \quad vs. \quad \bar{\nu} p \to n e^+ X \qquad \text{where } X \text{ contains an odd number of charged mesons,}$$

[Final-state interactions of pions in nuclei may invalidate this technique.]

However, it would be prudent to design a detector that could be augmented with a magnetic field – by winding a superconducting transmission line around the cryostat. [See slide 7]

Physics Issue:

If $\sin^2\theta_{13}$ is much less than 0.01, doesn't make sense to build a neutrino superbeam for DUSEL; rather, one should build a Neutrino Factory [Slide 6] based on neutrinos (and antinuetrinos) from decays of muons, *i.e.*, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$.

Then can detect $\nu_e \to \nu_\mu$ oscillations via a final-state muon, but must identify sign of the muon to suppress interactions of the $\bar{\nu}_\mu$.

A liquid argon TPC is an excellent detector both of neutrino superbeams and a Neutrino Factory!

Solenoid Capture System for a Superbeam

- Pions produced on axis inside the (uniform) solenoid have zero canonical angular momentum $L_z = r(P_\varphi + eA_\varphi / c) = 0, \;\Rightarrow\; P_\varphi = 0$ on exiting the solenoid.
- If the pion has made exactly 1/2 turn on its helix when it reaches the end of the solenoid, then its initial P_r has been rotated into a pure P_φ, $\Rightarrow$ $P_r = 0$ on exiting the solenoid.

$\Rightarrow$ Point-to-parallel focusing for

$$P_\pi = eBd / (2n+1)\,\pi c.$$

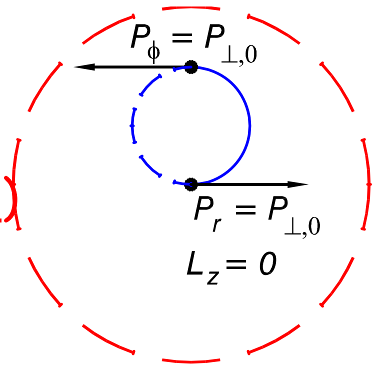
$\Rightarrow$ Narrowband (less background) neutrino beams of energies

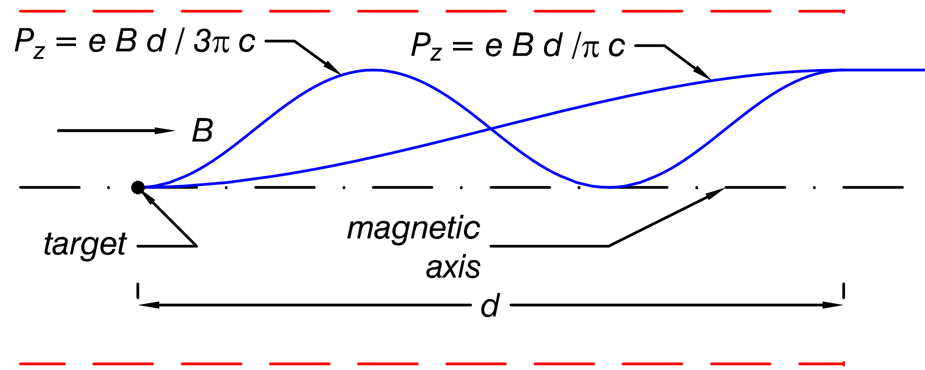
$$E_\nu \approx \frac{P_\pi}{2} = \frac{eBd}{(2n+1)2\pi c}.$$

$\Rightarrow$ Can study several neutrino oscillation peaks at once,

$$\frac{1.27 M_{23}^2[\mathrm{eV}^2]\; L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]} = \frac{(2n+1)\pi}{2}.$$

(Marciano, hep-ph/0108181)





(KTM, physics/0312022)

Study both ν and $\bar{\nu}$ at the same time.

$\Rightarrow$ Detector must tell ν from $\bar{\nu}$.

$\Rightarrow$ MIND, TASD magnetized iron detectors.

$\Rightarrow$ Liquid argon TPC that can identify slow protons:

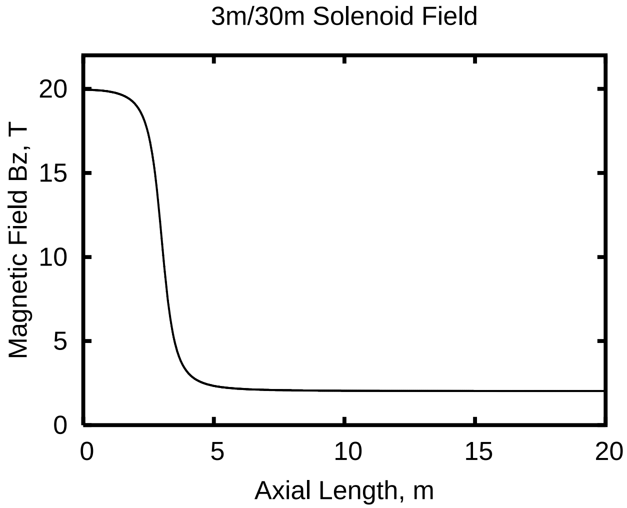
$\nu\, n \to p\, e^- X$ vs. $\bar{\nu}\, p \to n\, e^+ X$ etc.

(or magnetized liquid argon TPC).

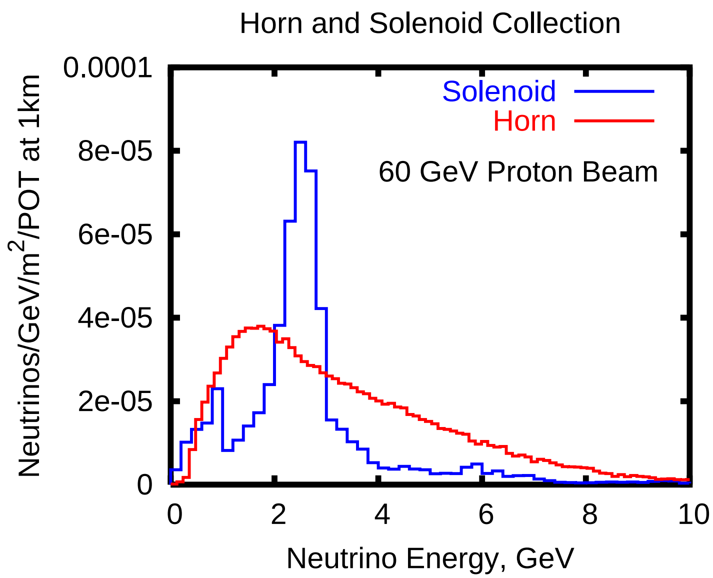
Simulation of Solenoid Horn

(H. Kirk and R. Palmer, *BNL*, NuFACT06)

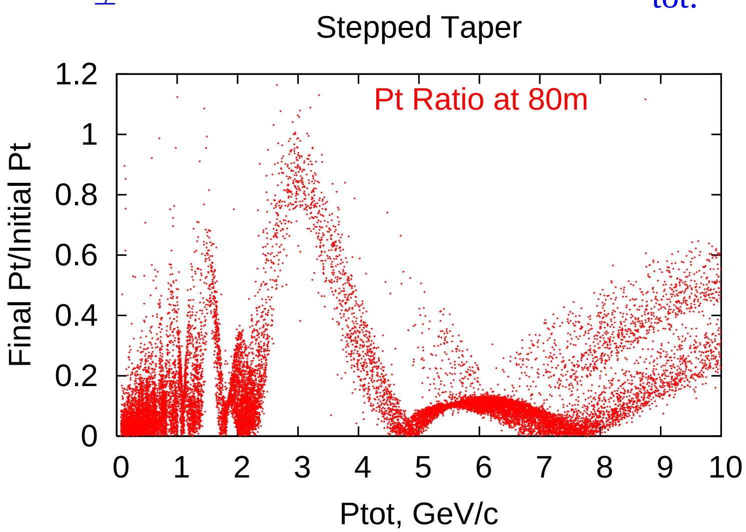
B *vs.* z for 3 + **30 m solenoid:**



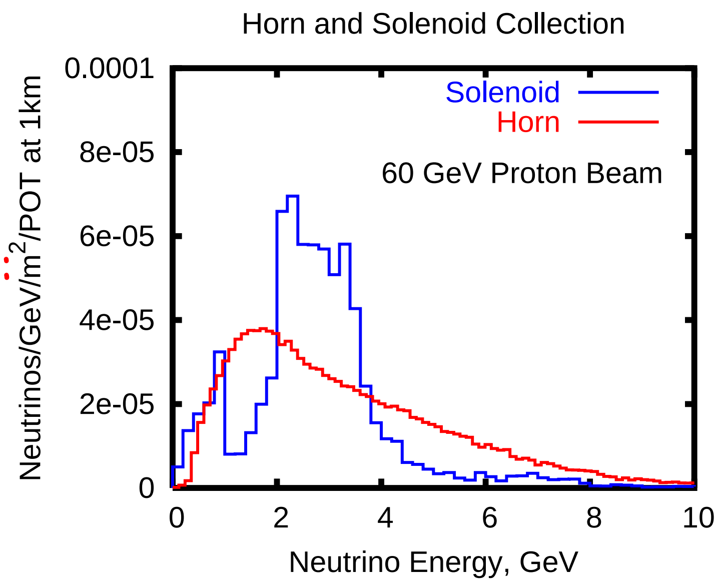
3-m solenoid gives 2 narrow peaks in ν spectrum:



$\Rightarrow P_\perp$ minimized at selected P_{tot}:

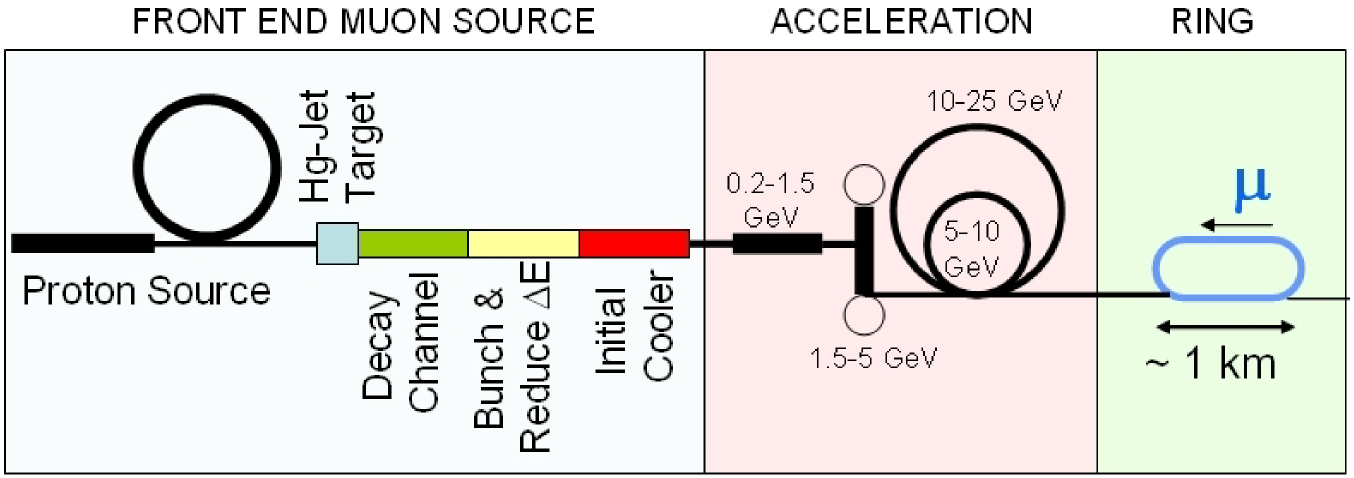


3+30-m solenoid broadens the higher energy peak:



Results very encouraging, but comparison with toroid horn needs confirmation.

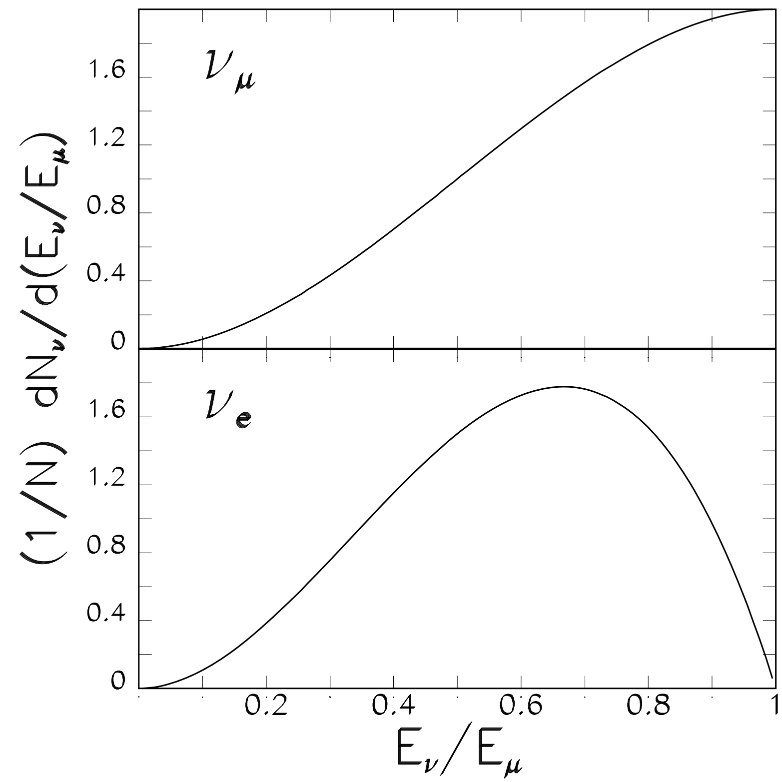
Neutrino Factory



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Neutrino spectra well known:



Six types of oscillations for μ^- (and 6 for μ^+):

$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$ (disappearance)

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ (appearance)

$\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+$ (appearance)

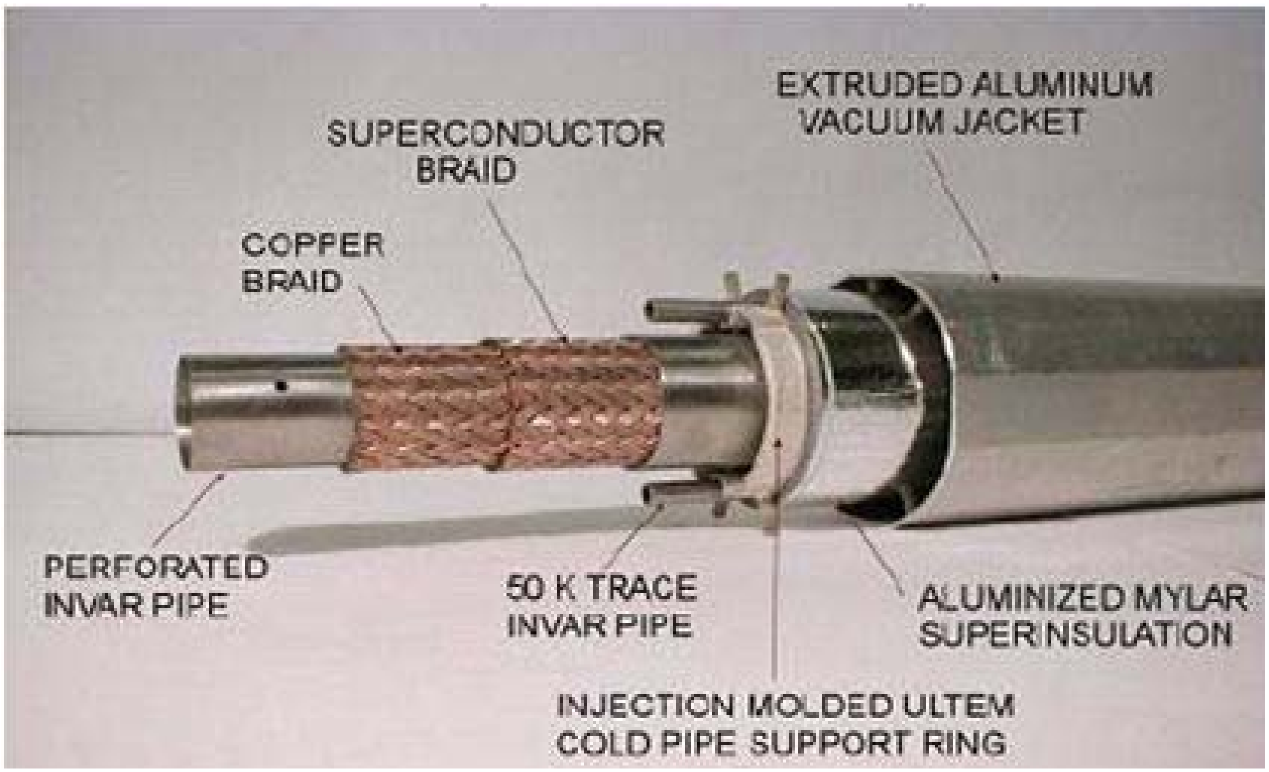
$\nu_\mu \rightarrow \nu_e \rightarrow e^-$ (appearance)

$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$ (disappearance)

$\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$ (appearance)

$\Rightarrow$ Detector must tell sign of final lepton.

Superconducting Transmission Line Can Be Wrapped Around a Large Detector



http://www.hep.princeton.edu/~mcdonald/nufact/Bross/Magnetic_Cavern_R&D.pdf

SCTL not just a "concept" – prototyped, tested and costed for the VLHC Project at Fermilab, ≈ $1k/m.

I = 7.5 MA. ⇒ B = 0.5 T for coil of ~ 50 turns.

For a 35 kton module, one turn ~ 200 m, ⇒ only ~ $10M for the coil.

Field likely to be vertical, ⇒ horizontal drift favored.

Comments about Transmission Line Magnets

Can tell μ^+ from μ^- with only $\approx$ 0.1 T field.

Need $\approx$ 0.5 T to tell e^+ from e^- up to 3 GeV.

Extreme field uniformity not needed.

Increase current density at solenoid ends to flatten the field profile.

No flux return for low cost $\Rightarrow$ extensive fringe field.

R&D needed to permit bending radius of $\approx$ 5 m (Cost $\approx$ \$2M).

Prototype magnet would be good for the DUSEL Near Detector.

Comments about the Focusing Solenoid

Solenoid cast $\propto$ stored energy $\propto$ $(B\ r)^2 d$

Length d $\propto$ p/B, where p = momentum of focus.

Maximum captured $p_T \propto$ B r.

$\Rightarrow$ Cost $\propto$ 1/B

$\Rightarrow$ Favors shorter solenoid, with higher field.

Field should be uniform within solenoid for ideal focusing.

Increase current density at solenoid ends to flatten the field profile.

No flux return.

Comments about the Target

Optimal target radius quite small for carbon target in toroidal horn (Lundberg).

$\Rightarrow$ Must mitigate severe radiation damage by FREQUENT target changes.

Solenoid focusing scheme does not constrain the target diameter.

$\Rightarrow$ Should do study to assess viability of a larger diameter carbon target.

Can also consider "waterfall" targets of mercury, or liquid lithium.

Could also consider flowing tungsten powder (Densham, RAL).