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NuFACT 05
INFN

# Neutrino Scattering in Liquid Argon TPC Detectors

- What can we learn?  Scattering at 1 GeV
- Neutrino Scattering using Liquid Argon TPCS
  - with conventional neutrino beams
  - in Superbeams era

Past neutrino experiments
relatively low energy, low statistics
bubble chamber experiments

Moved to higher energy
experiments
higher rates
new physics

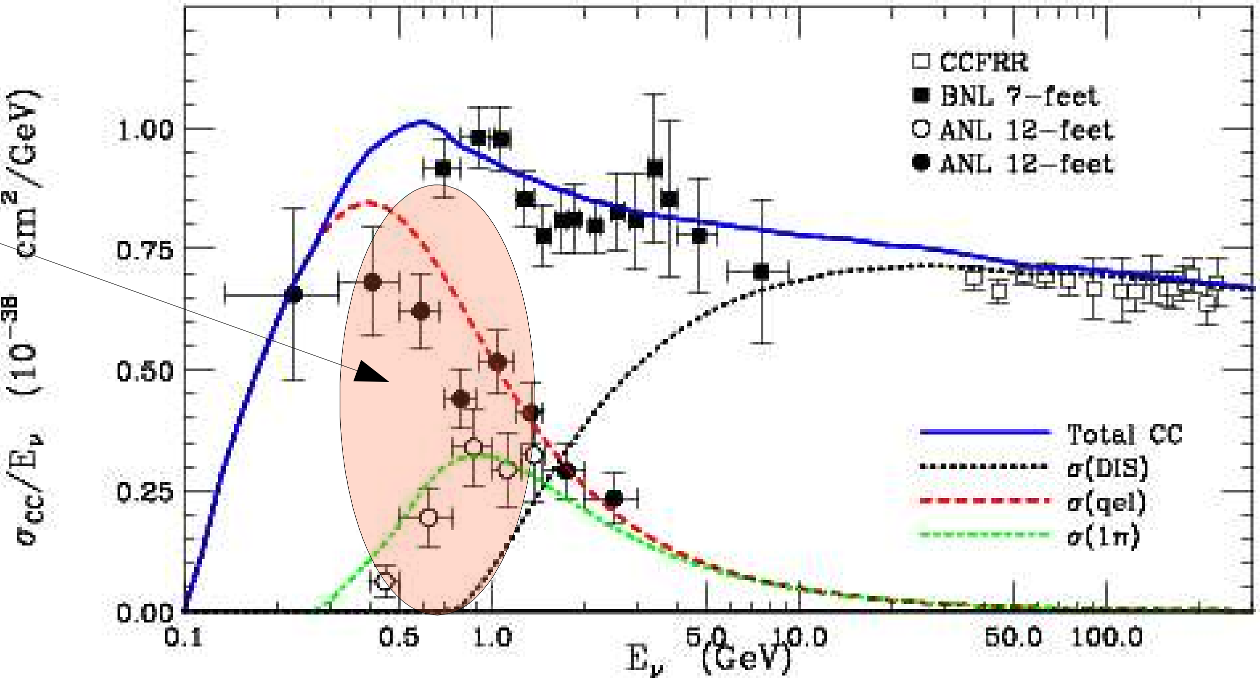
within the last decades,
neutrino oscillation physics
lots of interest
moved back to lower energies

**Rekindled interest** in
neutrino interaction physics
at low energies
high flux ν sources
higher precision detectors

# Re-kindled Interest in Low Energy Neutrino Cross Sections

- Cross sections at these energies of interest for oscillation physics

- Interesting in their own right



From the APS Neutrino Study:

"Determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino oscillation physics ...Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter."

# Ingredients for precision, low energy, neutrino cross section measurements

- High intensity beams → high event rates

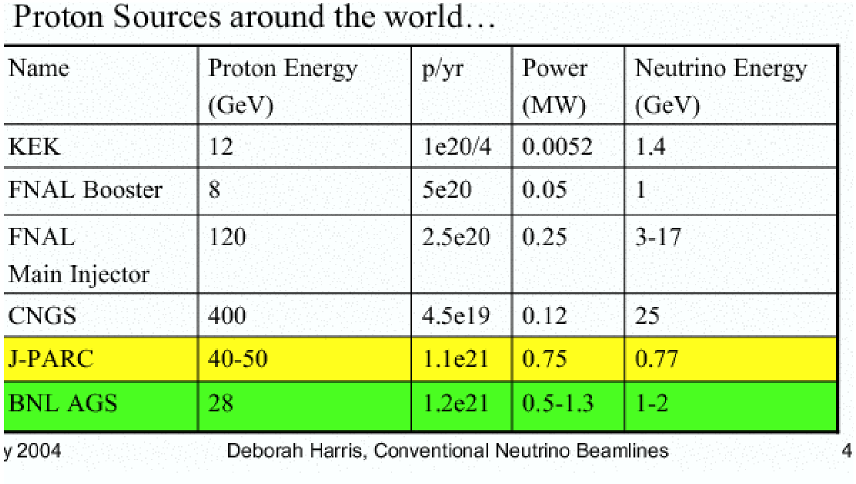
- Minimize flux uncertainties
  - 15-20% in the past → 5% expected by MiniBooNE and less by MINOS/MINERvA

- Minimize background contamination
  - low energy neutrino spectrum (below DIS turn-on and with small high energy tail)
  - fine-grained detector →good final state separation

reduced
statistical
errors

reduced
systematic
errors

# Neutrino beams are moving to lower and lower energies…

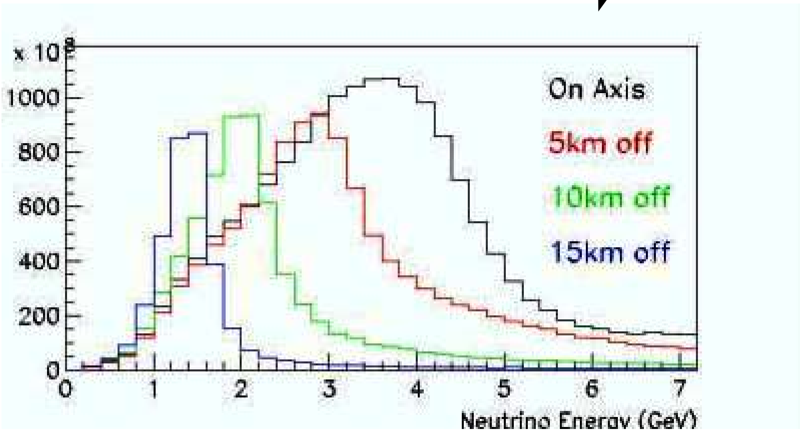


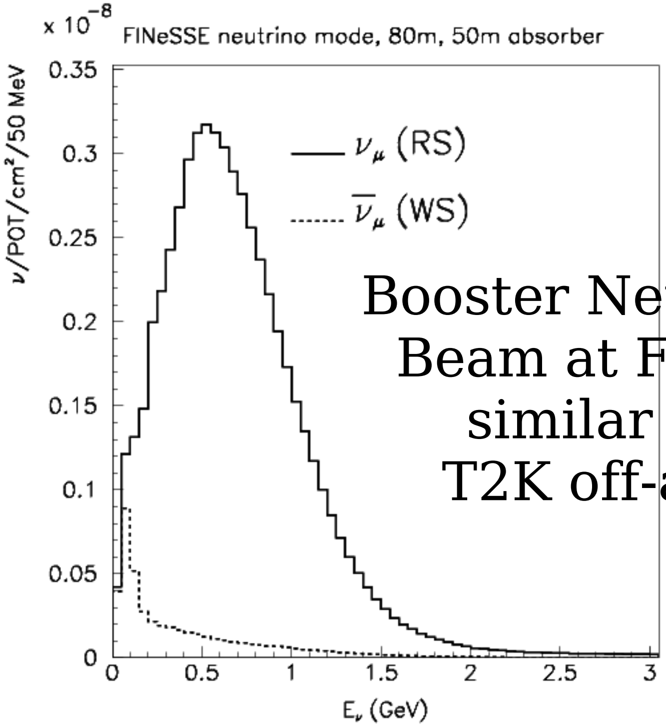
Proton Sources around the world…

| Name | Proton Energy (GeV) | p/yr | Power (MW) | Neutrino Energy (GeV) |
|---|---|---|---|---|
| KEK | 12 | 1e20/4 | 0.0052 | 1.4 |
| FNAL Booster | 8 | 5e20 | 0.05 | 1 |
| FNAL Main Injector | 120 | 2.5e20 | 0.25 | 3-17 |
| CNGS | 400 | 4.5e19 | 0.12 | 25 |
| J-PARC | 40-50 | 1.1e21 | 0.75 | 0.77 |
| BNL AGS | 28 | 1.2e21 | 0.5-1.3 | 1-2 |

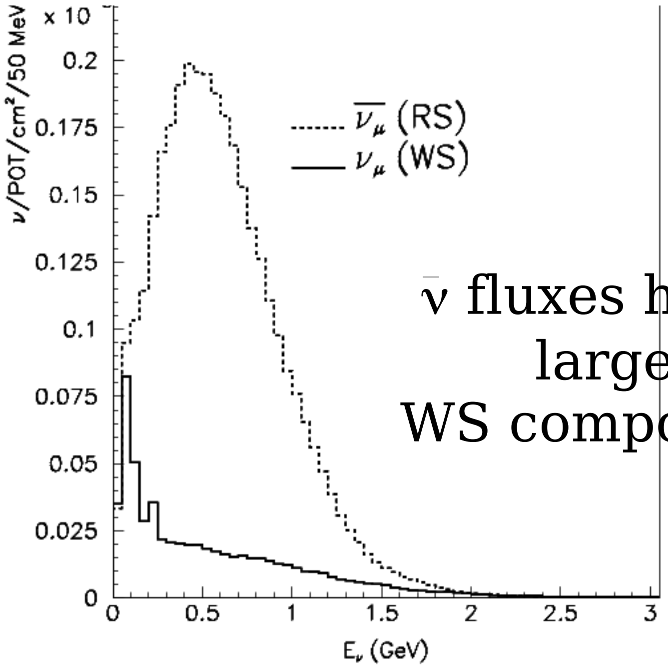
y 2004 Deborah Harris, Conventional Neutrino Beamlines 4

Go off-axis for low energy, clean beams





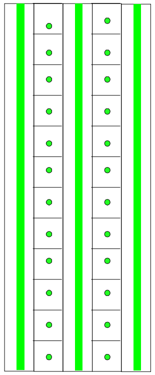
Booster Neutrino Beam at FNAL: similar to T2K off-axis



$\bar{\nu}$ fluxes have large WS component

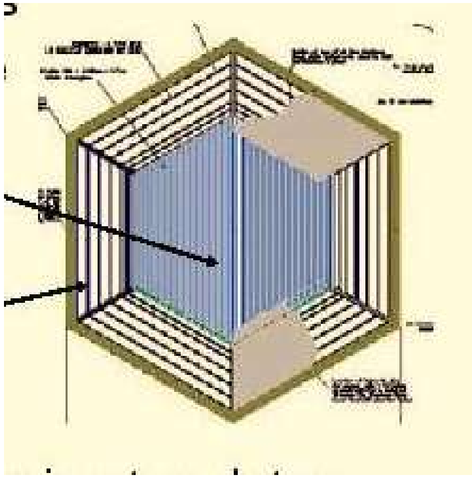
# Detection techniques:
## fine-grained, low threshold detectors:

SciBar



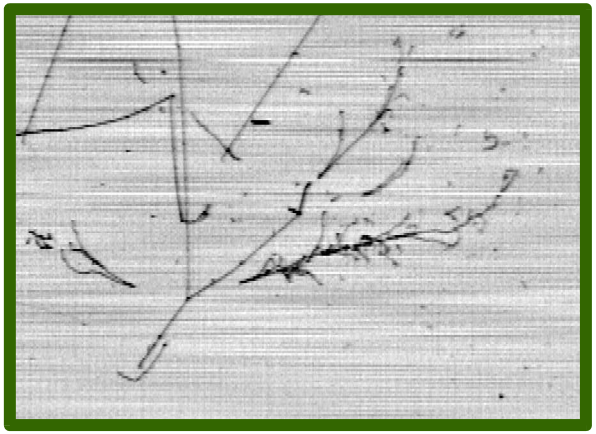
2cm x 1cm plastic scintillator bars

MINERvA

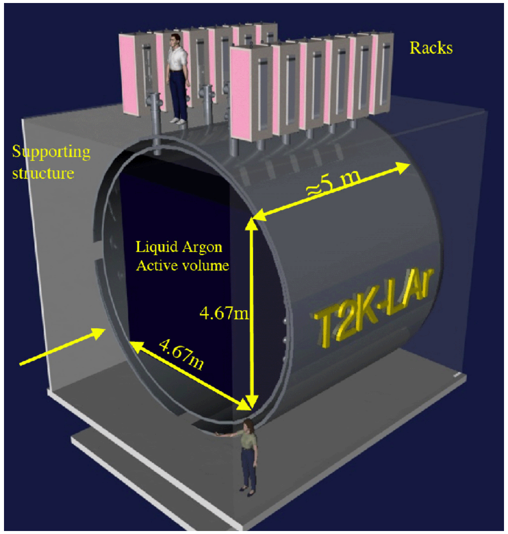


FINeSSE

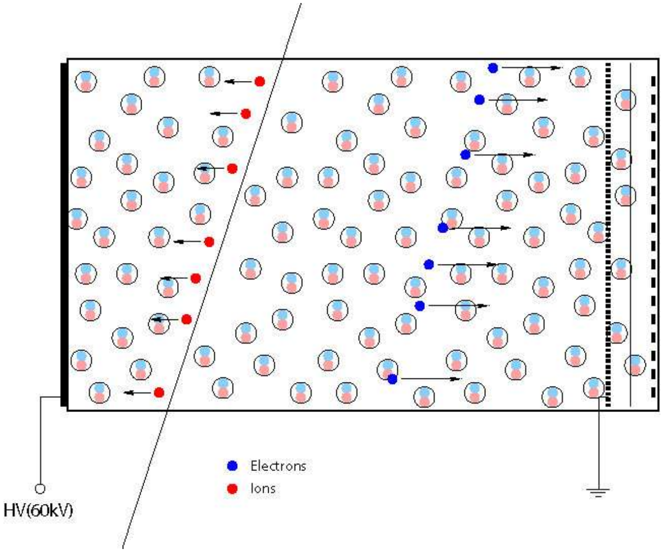
Liquid Argon Detectors

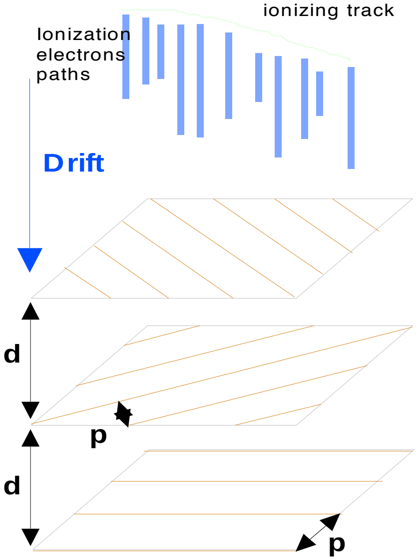


T2K 2km LArTPC

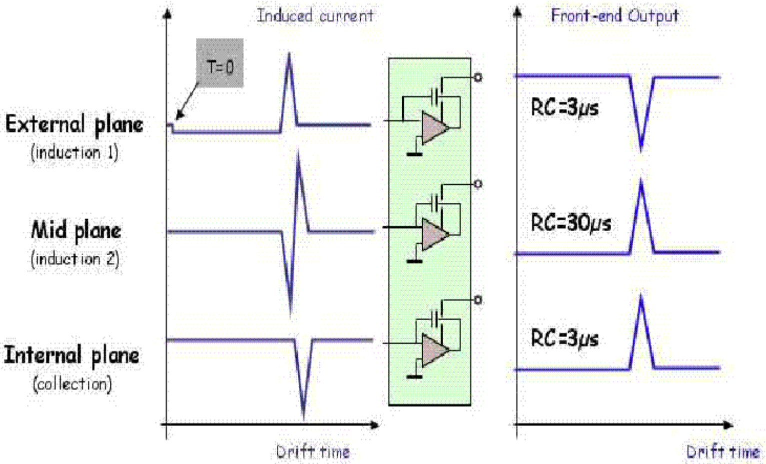


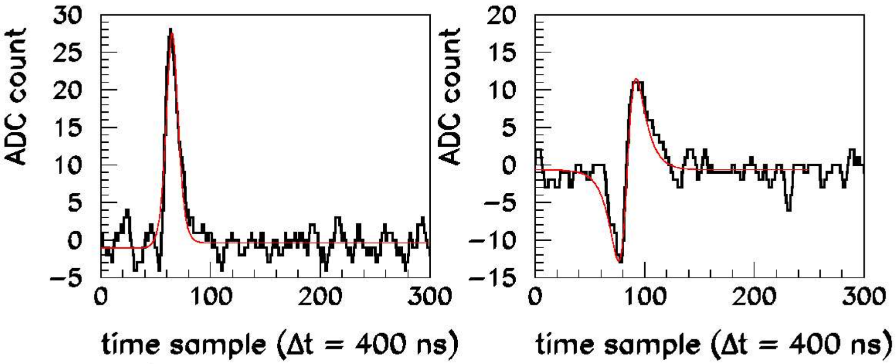
# Liquid Argon TPC detectors
# Readout ionization electrons on wire chamber planes





Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge





ICARUS TM/2001-09

Bubble chamber quality with calorimetry and active readout!

# Neutrino Scattering at 1 GeV

1)νp →νp elastic scattering to measure Δs

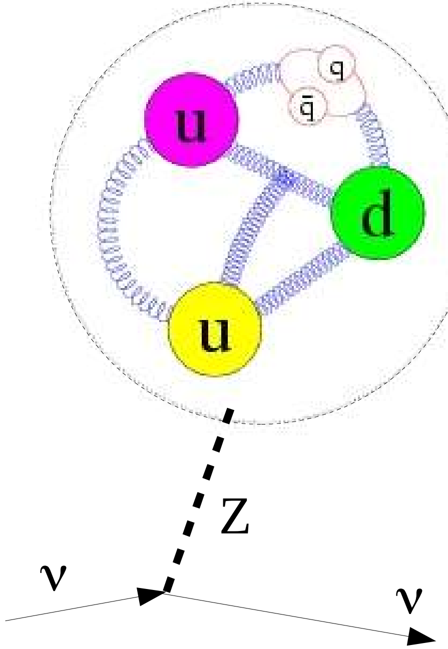
2)single pion production: unfolding coherent and resonant scatering

3)Search for non-zero neutrino magnetic moments via ν**e**→ν**e** scattering

# Neutrinos as Probes

## νp Elastic Scattering

(Δs: the strange quark contribution to the nucleon spin)



How do the nucleon constituents contribute to the total spin?

(the “proton spin puzzle”)
Valence quarks, sea quarks, gluons?
How does this fit into the fundamental theory of the nucleon?

The neutrino is a uniquely sensitive probe of the strange (sea) quarks in the nucleon.

Neutral-current neutrino-nucleon scattering may be used provide a theoretically robust measurement of Δs

$$\frac{d\sigma}{dQ^2}(\nu p \to \nu p) \propto (-G_A + G_A^s)^2$$

$$\downarrow$$

$$G_A^s(Q^2=0)=\Delta s$$

To avoid uncertainties in the flux: Measure ratio

$$\frac{\nu p \to \nu p}{\nu n \to \mu p}$$

# How well can you measure Δs?

## Simulation of R(NC/CC) measurement..

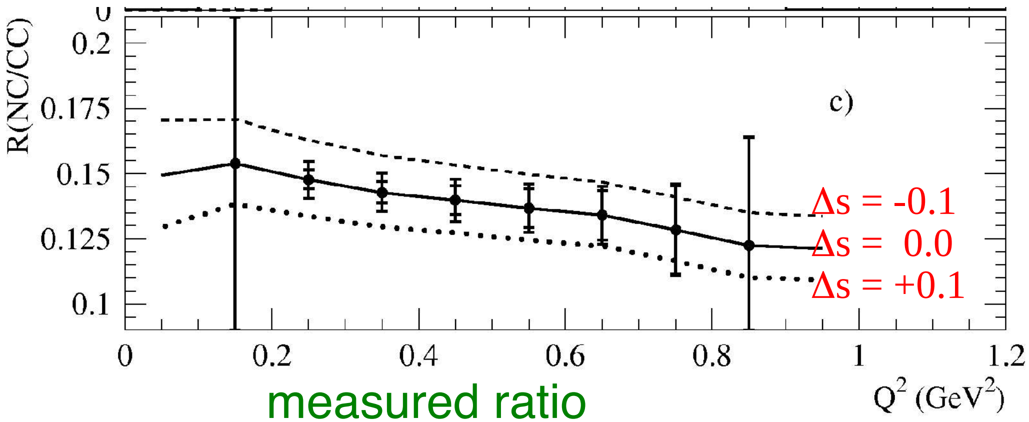
With ~75KNC events and ~180K CQQE events
in liquid scintillator detector

FINeSSE

$$R_{\nu}(NC/CC)=\frac{\sigma(\nu_{\mu}p\rightarrow\nu_{\mu}p)}{\sigma(\nu_{\mu}n\rightarrow\mu p)}$$

Including the effects of:
- statistical errors (
- systematic errors due to...
- NCn scattering misid
  (crucial, recently improved)
- other background channels
- scattering from free protons
- uncertainties in efficiencies
- $Q^2$ reconstruction

experimental (stat + sys) error:



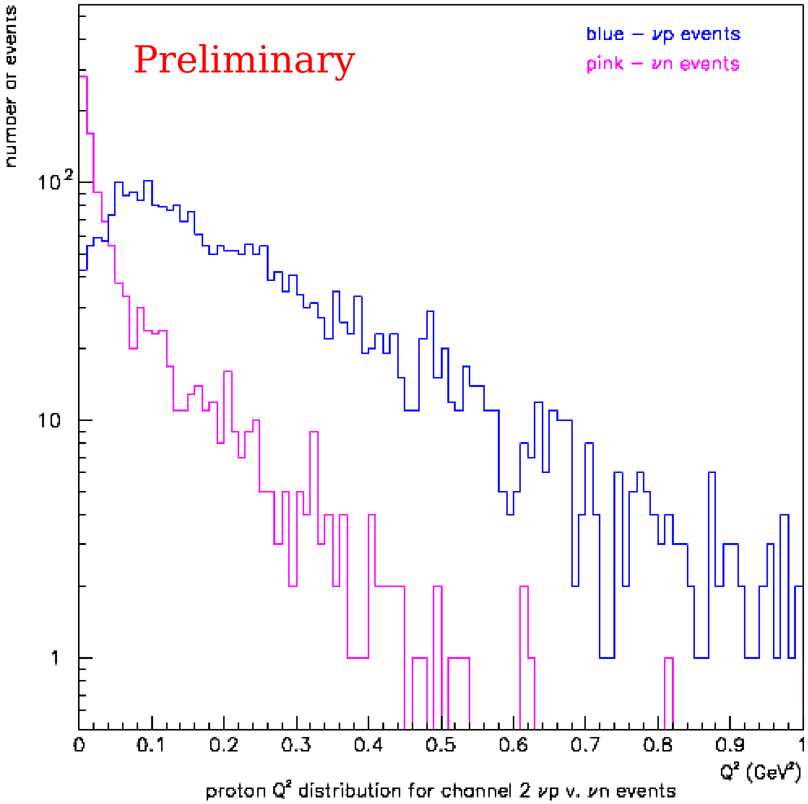
measured ratio
(stat & total errors)

**$\sigma(\Delta s) = \pm 0.025\ (\nu)$, $\sigma(\Delta s) = \pm 0.04(\bar{\nu})$**

(previous best measurement from BNL734 $\sigma(\Delta s) = \pm 0.1$)

## How well can this measurement be done in LAr?

Neutron ID: Biggest background is from contamination of νn→νn in νp→νp sample



Laura Jeanty (Yale)

sample of
νp and νn events
with one proton in the
final state

86% νp events
13% νn events
above 100 MeV

in the ball park of
how well one can do
with scintillator detectors

# How well can this measurement be done in LAr? (cont.)

Neutral pion events: Second largest contaminant

→ identifiable via topology and dE/dx

Uncertainty in scattering cross section on free protons

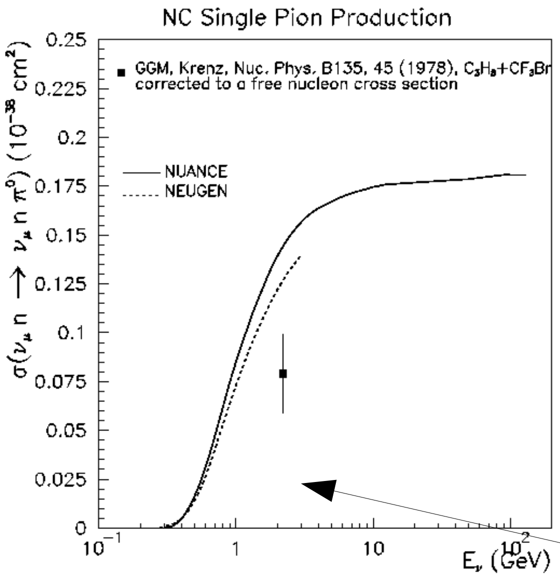
→ no free protons

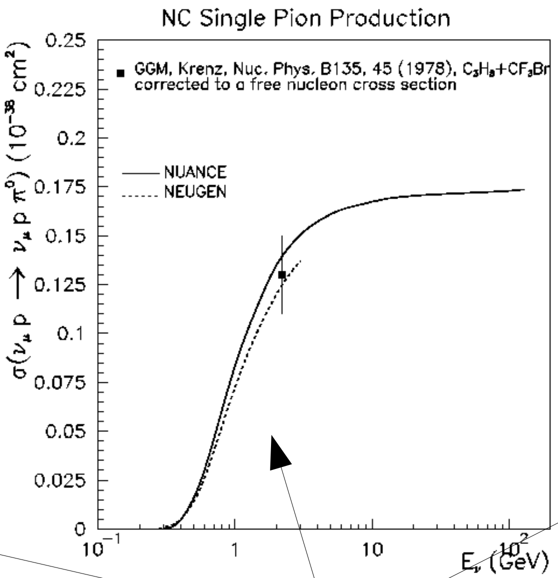
Lower energy threshold

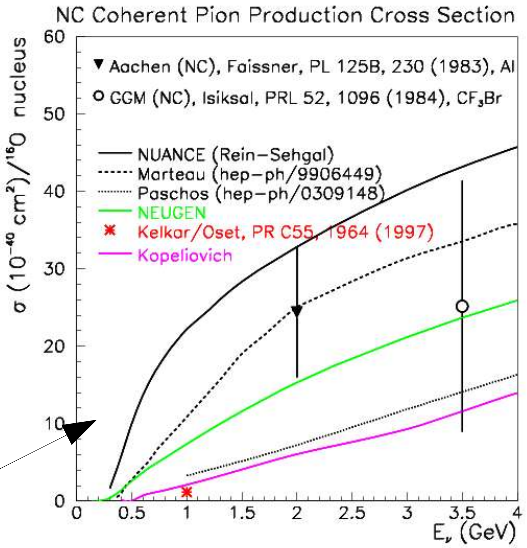
→ not clear you want to go to lower energies

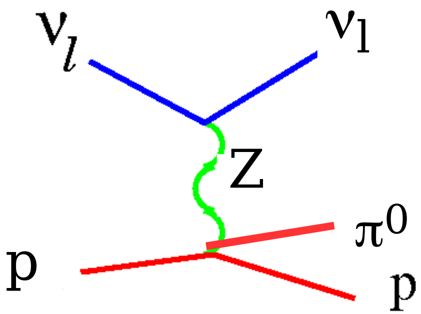
needs more careful study, but looks like an improvement

# Neutral current $\pi^0$ production: biggest background for present and future $\nu_\mu \rightarrow \nu_e$ oscillation searches









No data
below
2 GeV

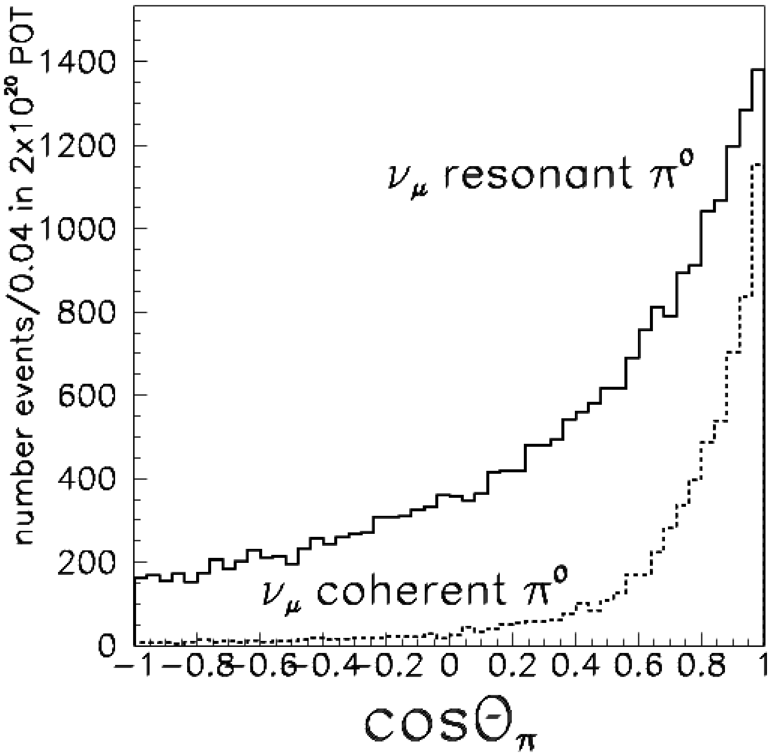
Lack of data and
conflicting predictions
→experiments assume
100% uncertainty

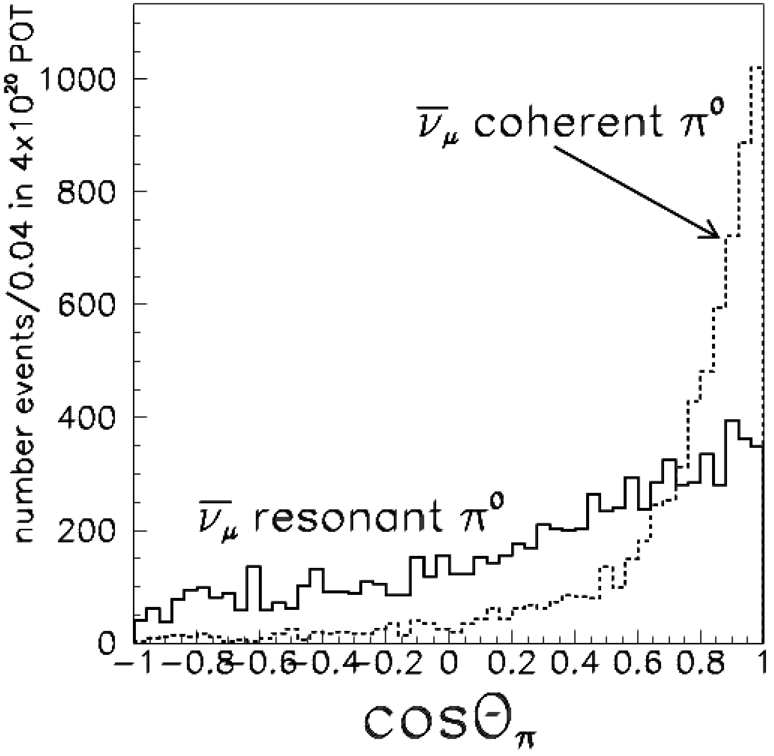
→ need fine-grained detector
to distinguish π°s from $\nu_e$s

Both kinematics and rate of π°s are not well known…

→ different contributions from resonant and coherent

Comparing $\nu$ vs $\bar{\nu}$ running (FINeSSE flux)
extract the forward peaked coherent contribution

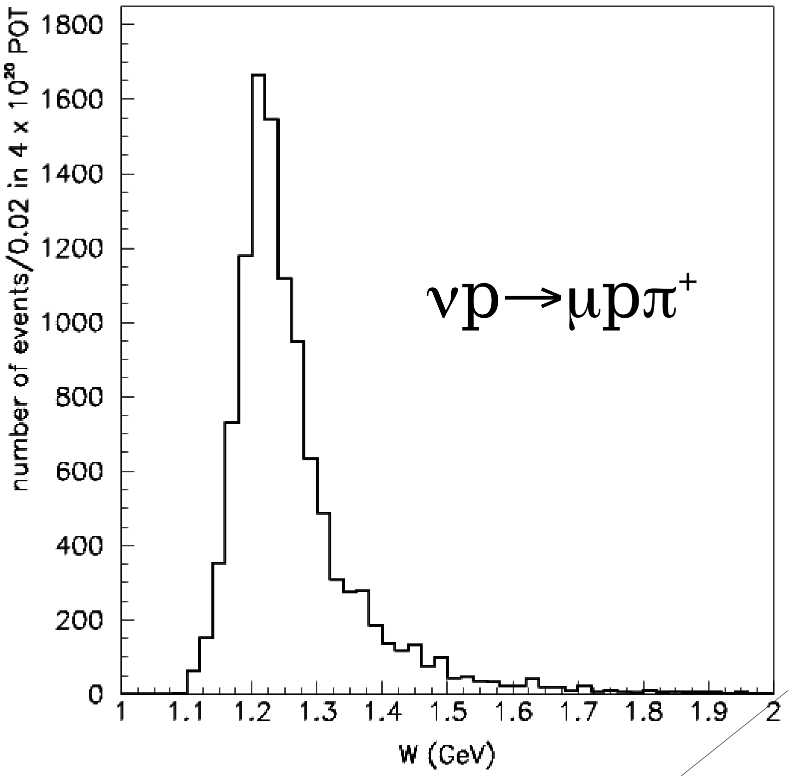


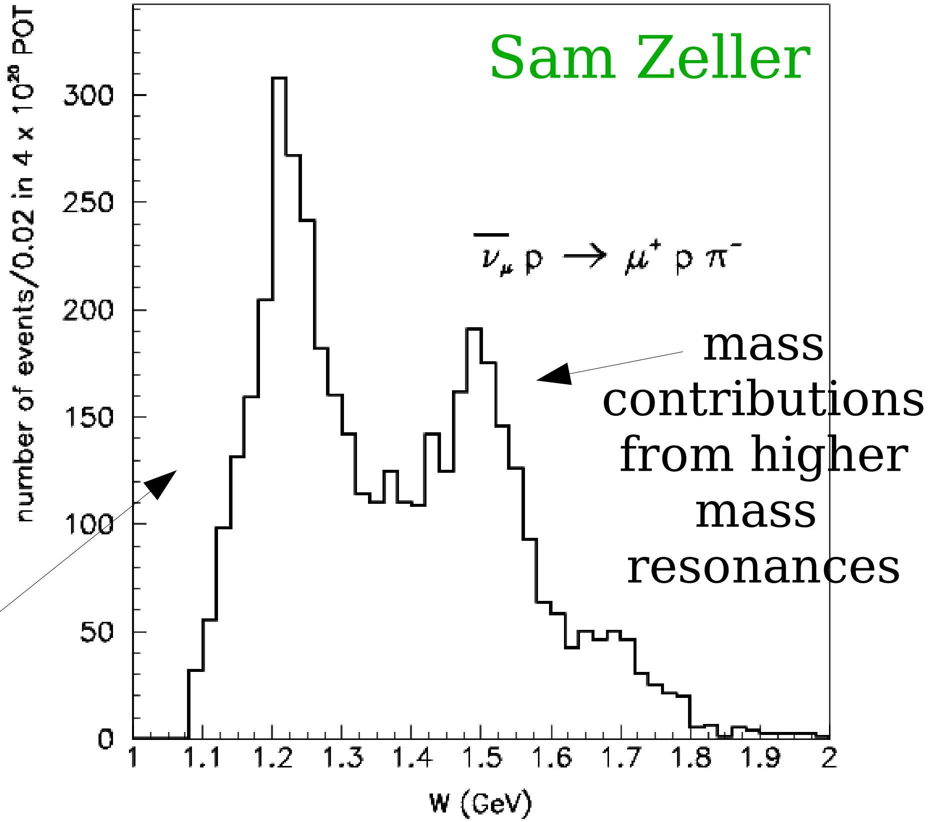


These measurements are particularly important for future $\nu_\mu \to \nu_e$ oscillation searches

# CC resonant pion production:

## Different isospin content in final state makes neutrino and anti-neutrino interactions distinct…





Sam Zeller

mass contributions from higher mass resonances

Sensitive beyond Δ(1232)

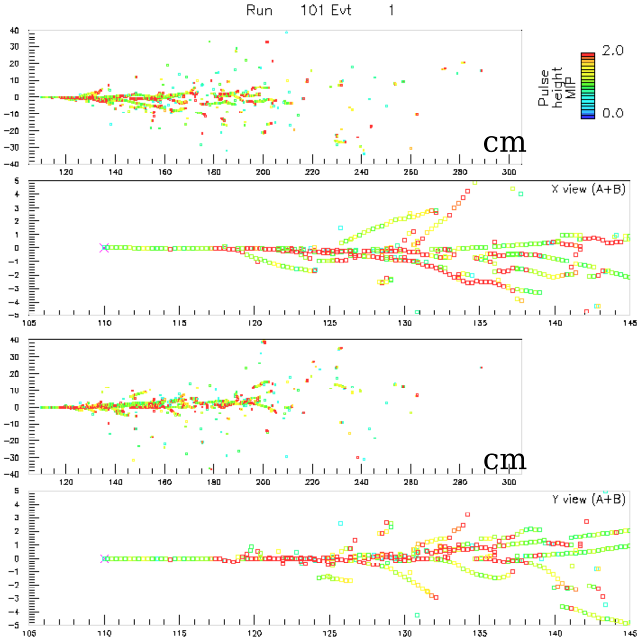
- resonant and non-resonant effects
- interference terms

# Electrons versus $\pi^0$'s at 1.5 GeV

Dot indicates hit
color indicates collected charge
green=1 mip, red=2 mips

X
plane
↓
zoom
in

Y
plane
↓
zoom
in

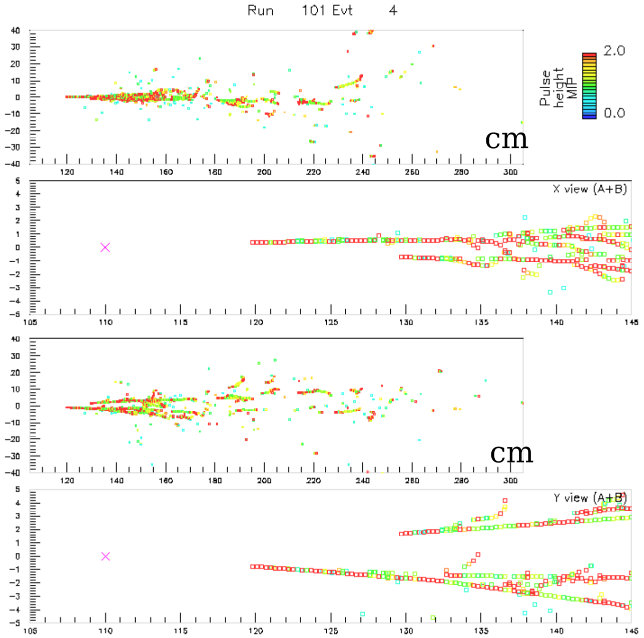


***Electrons***

*Single track (mip scale) starting from a single vertex*

X
plane
↓
zoom
in

Y
plane
↓
zoom
in



$\pi^0$

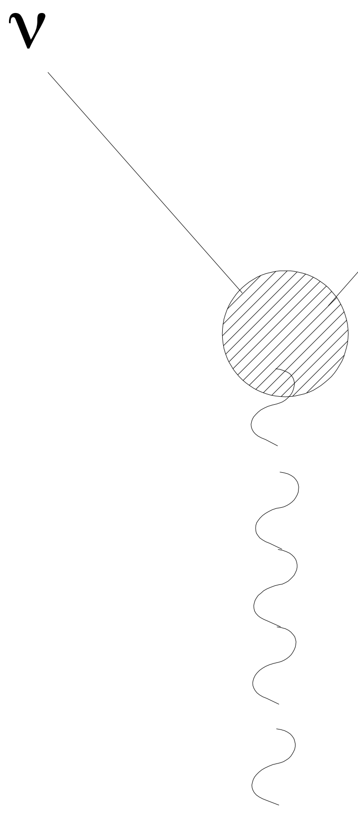
*Multiple secondary tracks can be traced back to the same primary vertex*

*Each track is two electrons – 2 mip scale per hit*

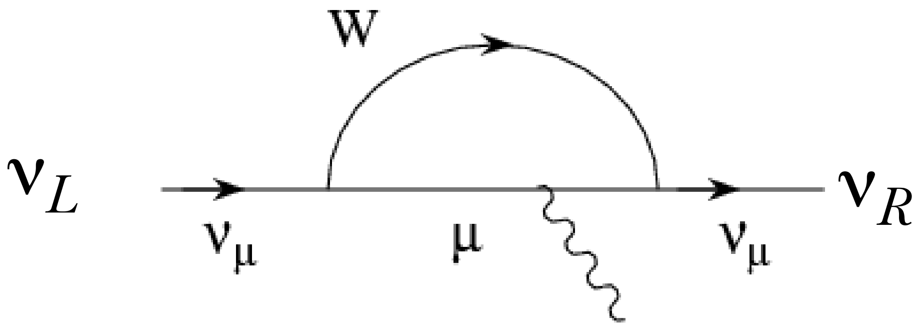
Use both topology and dE/dx to identify interactions

# Exotic Neutrino Properties with fine-grained detection at Neutrino Superbeams

# Neutrino magnetic moments



massive neutrinos imply existence of $\nu_R$

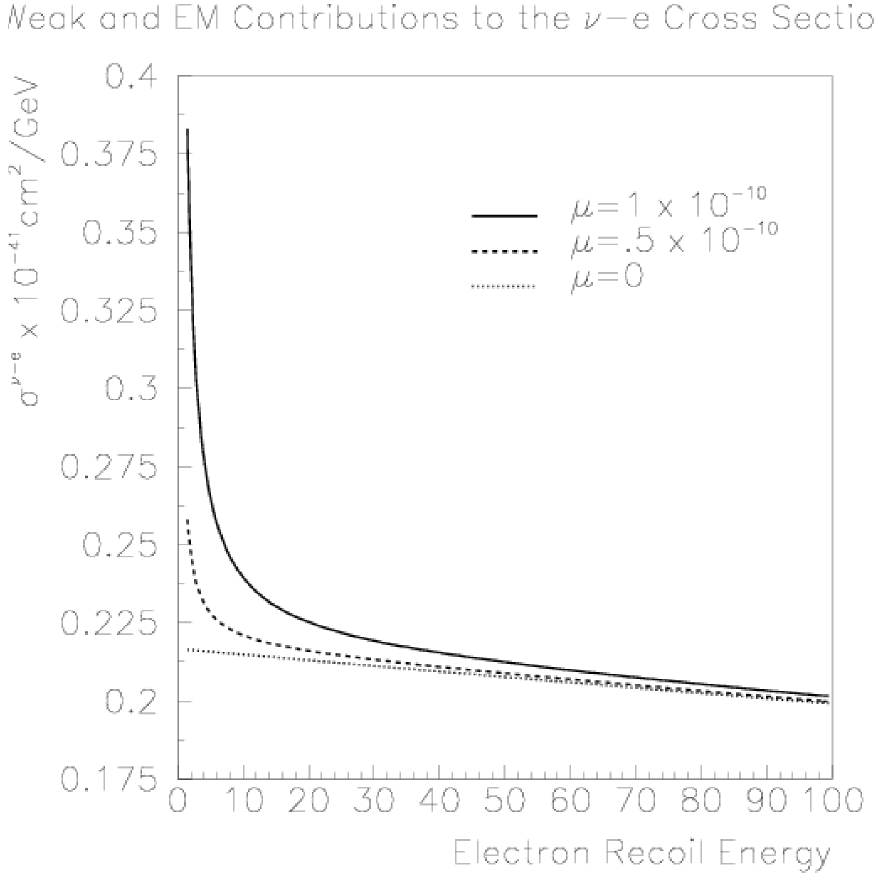


Expect a non-zero neutrino magnetic moment if you have massive neutrinos

Increase in overall cross section $\sigma_{tot} = \sigma_{weak} + \sigma_{EM}$ → Hard to measure with large flux uncertainties

$$\frac{d\sigma^{weak}}{dT} = \frac{2m_e G_F^2}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - \frac{m_e}{E_\nu} g_R g_L \frac{T}{E_\nu}\right]$$

$$\frac{d\sigma^{EM}}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$



(MeV)

shape change
in the
differential
cross section

# Limits set from experiment:

Electron neutrino magnetic moment: -> 1.0 -1.5 $10^{-10}$ $\mu_B$

- Preliminary measurement from MUNU
- SuperK shape fit

Muon neutrino magnetic moment: -> 6.8 x $10^{-10}$ $\mu_{\mathbf{B}}$

- LSND experiment: combined measurement of electron and muon neutrino magnetic moment using total $\nu e$ cross section

How is this different from $\nu_e$ searchs?

(already set better limits)

- solar $\nu_e$ measures $\mu_2$
- reactor $\overline{\nu}_e$ measures primarily $\mu_1$ and $\mu_2$
- accelerator $\nu_\mu$s would measure $\mu_1$, $\mu_2$, and $\mu_3$

Tau neutrino magnetic moment: -> $10^{-9}$ $\mu_{\mathbf{B}}$

- SuperK & SNO bounds for all neutrinos

## Ingredients for measuring $\mu_{\nu_\mu}$ at accelerators:

neutrino-electron elastic scattering cross section is low
→ high intensity and relatively large detectors

make measurement at low electron recoils
where there are lots of radioactive backgrounds
→ need low electron recoil threshold detectors
need beam structure to reduce in time background rates

↓

**Liquid Argon TPCs!**

# What happens when you push on electron recoil threshold?

Liquid Argon TPC detectors:

- forward tracks down to 5 MeV
- electron detection down to 150 keV
- energy resolution is about 5% at 5MeV

- radioactive and spallation backgrounds
  - remove with timing cuts

In Carbon Detectors

10 MeV

15% at michel endpoint

# Timing is everything!

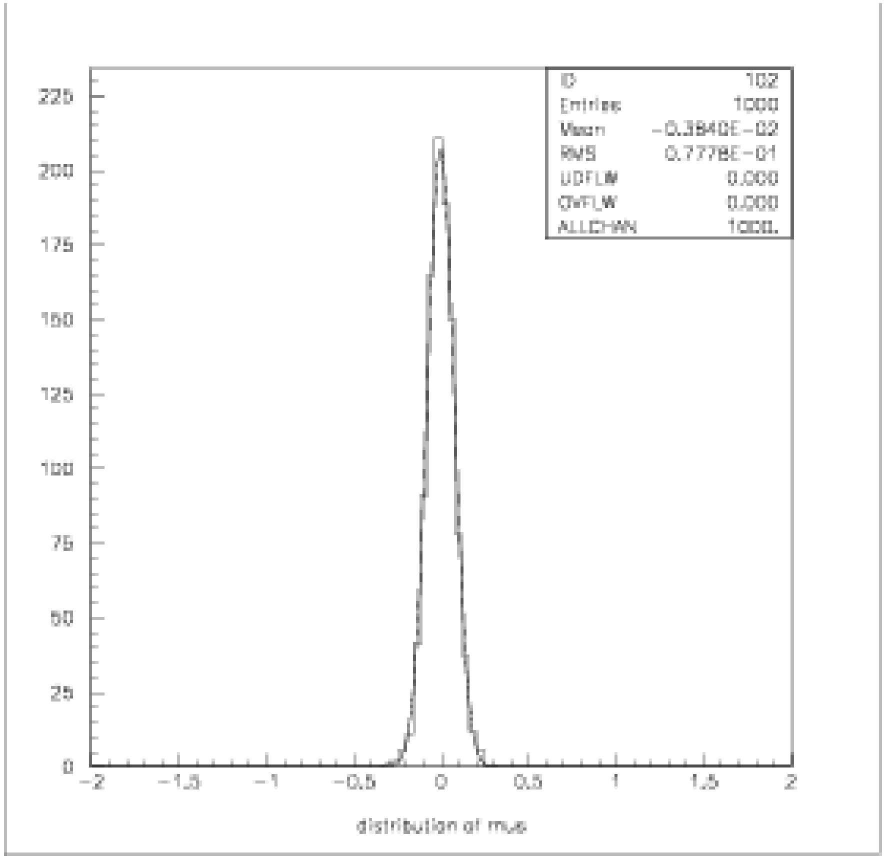
Radioactive backgrounds become large below 5 MeV
uranium, thorium, radon etc.

↓

Even largest bknd ($\gamma$s at 1 MeV) are negligeable
due to beam timing:
eg: 350 $\gamma$s per year in time
with Fermilab's BNB beam spills

# Sensitivity study:
Easiest and achievable scenario
15000 events with electron recoil threshold at 5 MeV

## An order of magnitude improvement in neutrino magnetic moments



sensitivity:

$\mu_{\nu\mu}$=6.8 x $10^{-11}\mu_B$

Significantly better
with detection of
150 kev electrons…

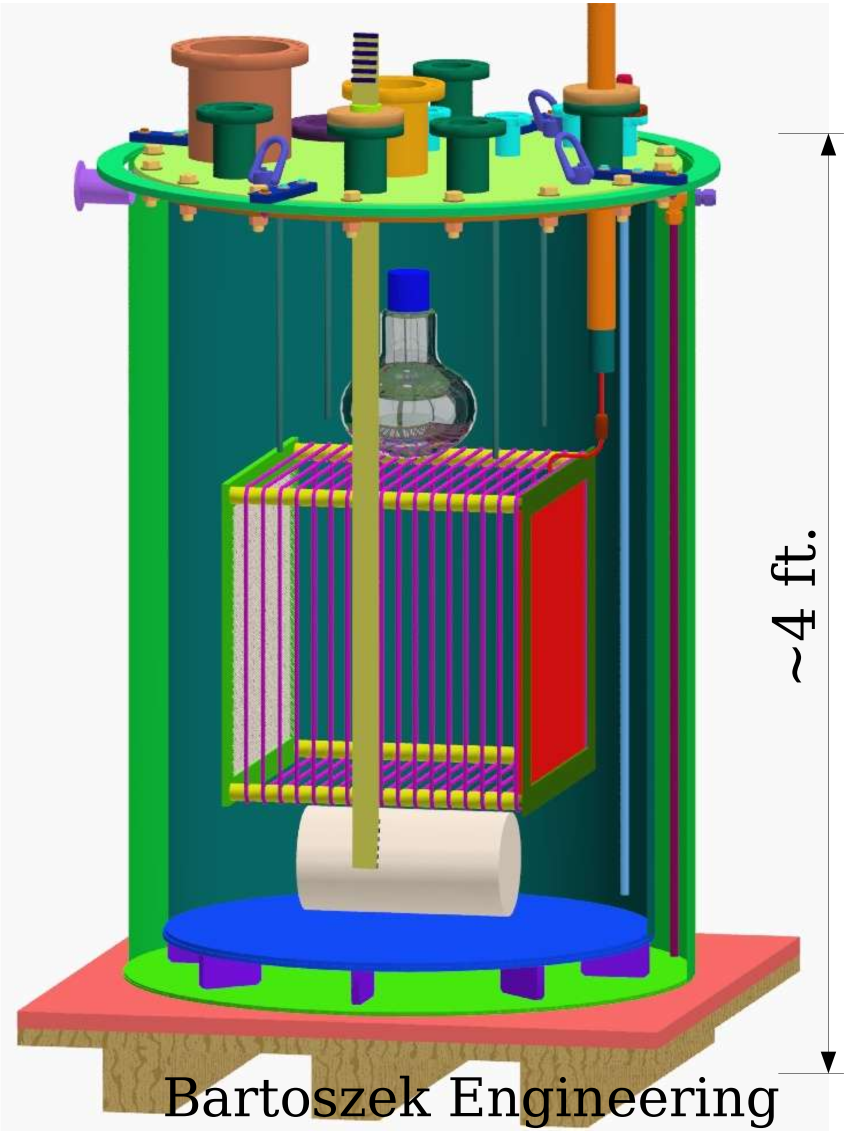
# LArTPC work underway at Yale

How good are these detectors at IDing low (~1 GeV) energy ν interactions?

↓

- understand the technology
- purity studies
- understand detector response at very low energies
- study combination of charge and light production for particle ID

Constructing small prototype vessel this summer



Bartoszek Engineering

Work funded by
DOE Advanced Detector
Research Grant

# Conclusions:

Fine-grained detection techniques are bringing us into the era of precision neutrino scattering physics

In particular, Liquid Argon TPCs hold promise to improve on all sorts of neutrino scattering measurements and searches for exotic neutrino properties:

↓

Precision cross section measurements
Improving measurement of strange spin of the proton
Extending search for non-zero neutrino magnetic moment