Bonnie T. Fleming
Flare Workshop
November 6th, 2004

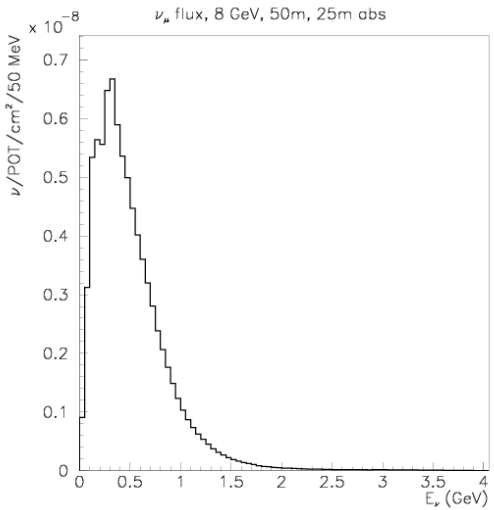
# Low energy physics with Liquid Argon TPCs

- Ingredients for low energy neutrino scattering
- Neutrino Scattering measurements
- What LarTPCs can bring you

# What is “very low energy”

What does “low energy” give you
(and not give you)

Its all about the flux...

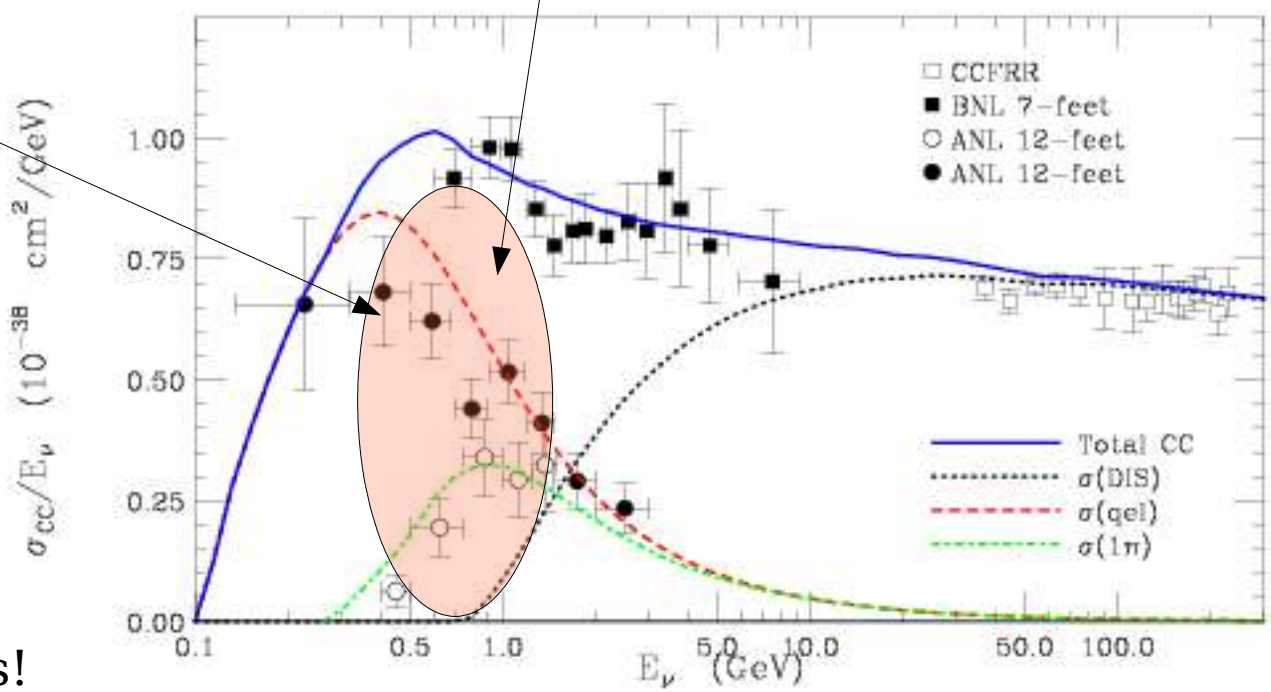



8 GeV neutrino beam flux covers low energy region

A lot going on at low energies:

quasi-elastic
single **pion**
(DIS turning on)

clean beams, but flux and cross sections dropping rapidly need intense beams!



# How do you do low energy physics well?

## Ingredients for precision, low energy, neutrino scattering measurements

- High intensity beams -> high event rates

statistical errors

- Minimize flux uncertainties
  - 15-20% in the past -> 5% expected by MiniBooNE and MINOS

systematic errors

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

Lots of interesting things....
I'll focus on:

- Measuring $\Delta s$ using $\nu p$ elastic scattering
- Searching for non-zero neutrino magnetic moments using muon neutrino-electron elastic scatters
- Understanding single pion production

Exploring ideas....

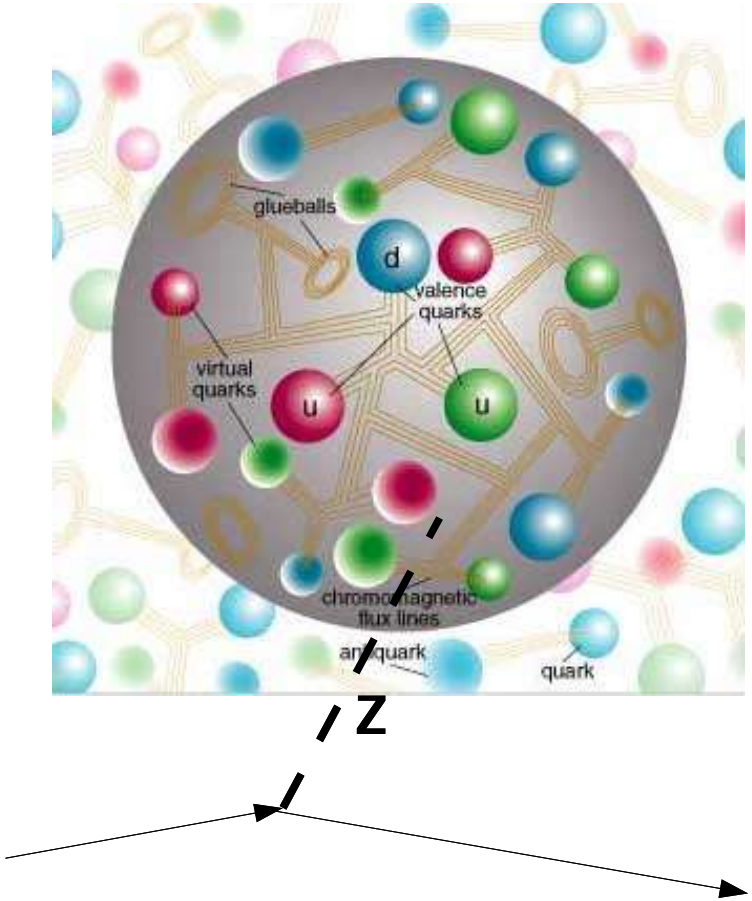
# Strange Spin of Nucleon

($\Delta s$: the strange quark contribution to the nucleon spin)

This will address a fundamental aspect of nucleon structure:

- What carries the nucleon spin! valence quarks, sea quarks, gluons?
- Can we describe the proton in terms of a fundamental theory?

These are still open questions!




Low energy neutrino scattering is a great way to probe the strange spin of the proton

# Who has already measured Δs?

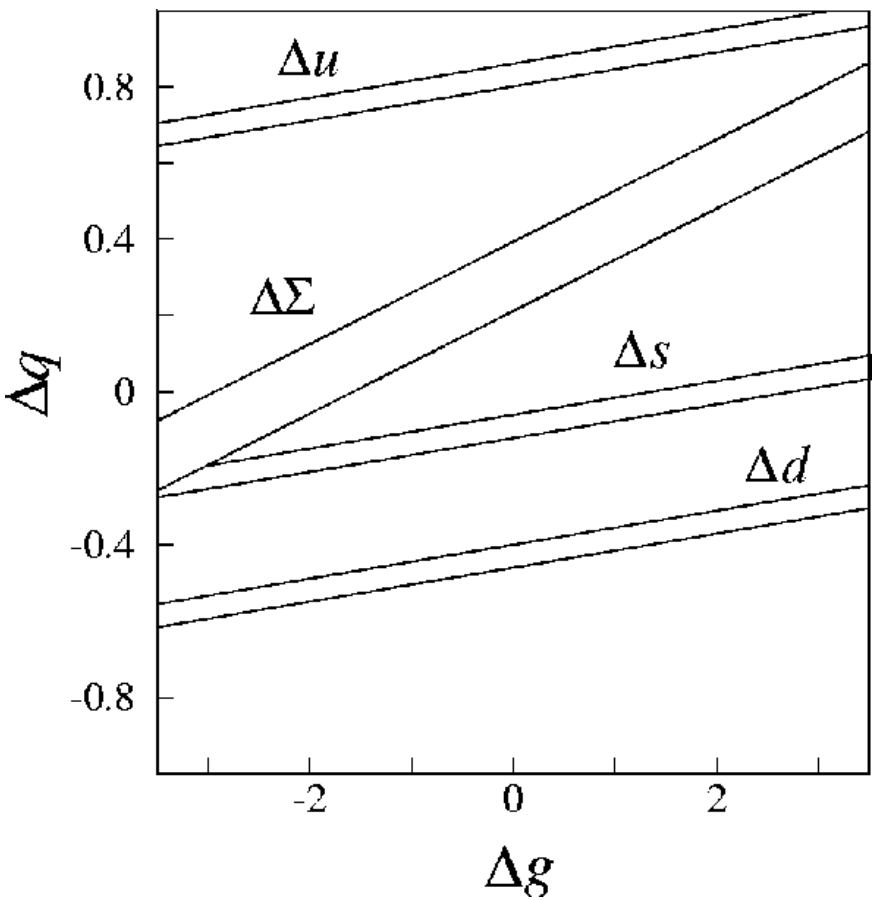
Polarized-lepton DIS (EMC, SMC, SLAC) results indicate that the fraction of proton spin carried by light quarks:

$\Delta\Sigma < 1$ where

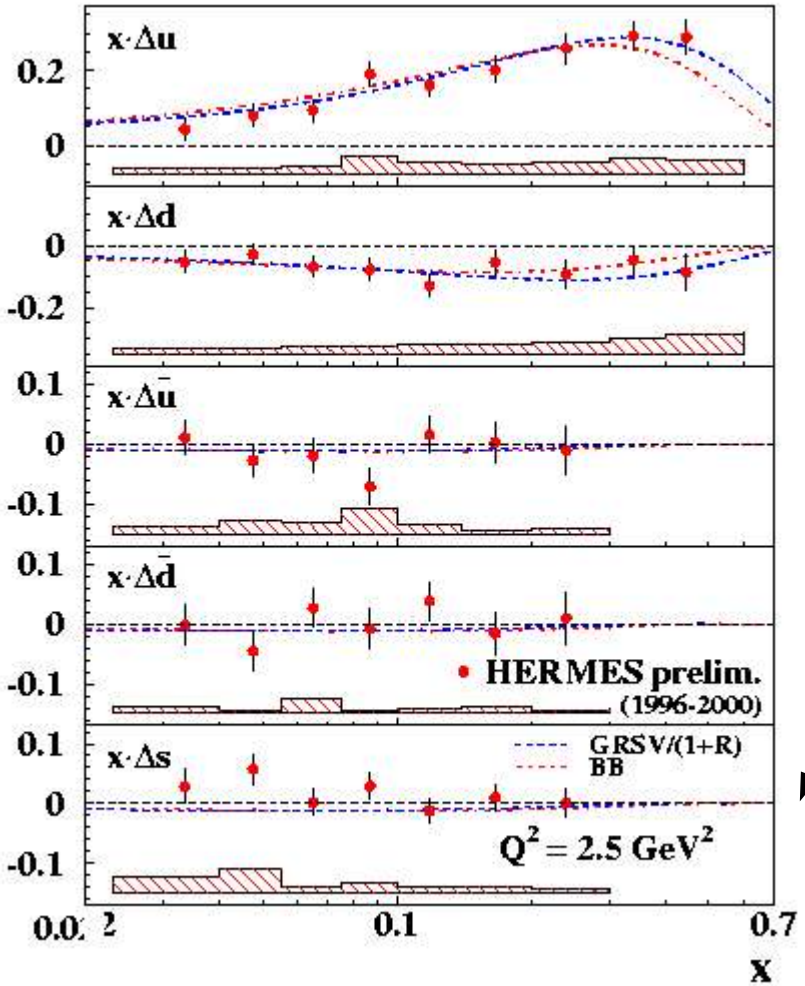
strange contribution

$\Delta s \sim -0.10 \pm 0.05$

→ strongly dependent on assumptions of SU(3) flavor symmetry



# Results from HERMES*
# (semi-inclusive data)



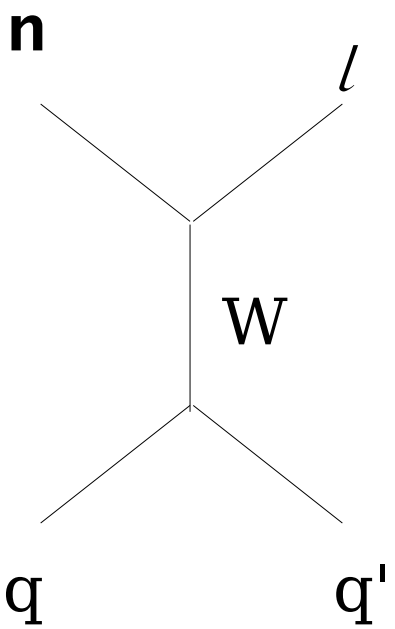

$\Delta s > 0$ !

tag **pi**, k, or p in final state in coincidence with scattered lepton

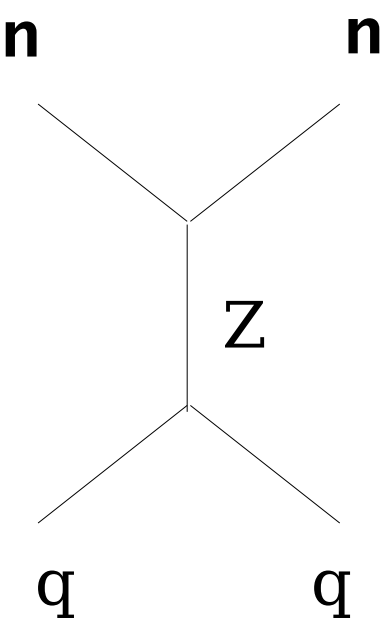
flavor tag helps probe flavor dependence of spin structure

* Int. J. Mod. Phys. A17, 3551, '02.

# Measuring Δs using neutrinos




quasi-elastic CC scattering
q=up and down quarks only




Neutral current scattering
q=any quark in the nucleon
-> strange quarks

# Neutrino-nucleon elastic scattering

- Nucleon Neutral Weak Current depends most strongly on
  $G_A$ (axial) form factor... (somewhat on $F_1$,$F_2$)

- $G_A(Q^2) = - \mathbf{t}_z g_A(Q^2) + G_A^s(Q^2)$
  - $g_A$ known (nuclear beta decay)
  - $G_A^s(Q^2=0) = \Delta s$

neutrino-proton NC cross section at low $Q^2$ -> $\Delta s$

↓

*Problem: 10% error at best on neutrino flux!*

# Take advantage of cross section ratios!

→ Ratio of neutral-current elastic scattering on protons to neutrons*:

$$R(p/n) = (\nu p \rightarrow \nu p)/(\nu n \rightarrow \nu n)$$

is quite sensitive to $G_A^s$ (**D**s) because:

$$G_A = -g_A \mathbf{t}_z + G_A^s \ , \ (\mathbf{t}_z = 1\ p, -1\ n)$$

*However, the systematic errors of neutron detection are problematic. So...*

Ratio of NC elastic scattering to CC quasi-elastic scattering:

→ $$R(NC/CC) = (\nu p, NC)/(\nu p, CC)$$

is somewhat less sensitive to $\Delta s$, but experimentally easier.

*Very small systematic error due to the uncertainty in neutrino flux!*

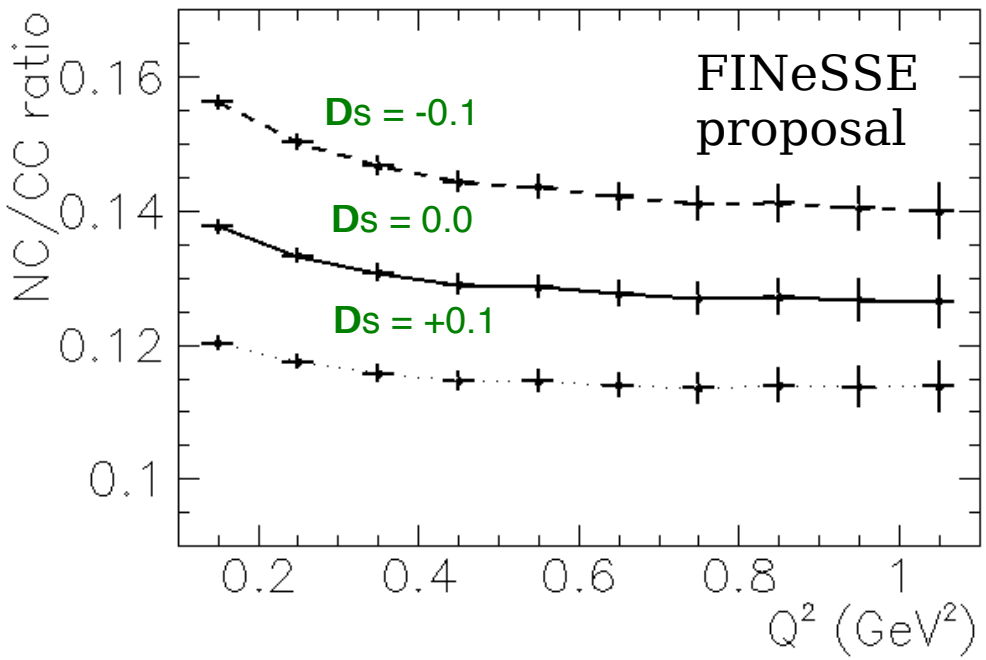
*(Garvey et al., PR C**48**, 1919, '93)

Using “conventional” detectors

# $\sigma(\Delta s) \sim 0.04$ and better

Measure NC/CC ratio
to 5%

NC/CC ratio: (vs $Q^2$)




Next generation measurements may benefit from LarTPC technology

# How much better?

- Identifying neutrons is important!
  - Dominant systematic in measuring neutrino-proton cross section
  - ($\nu p \rightarrow \nu p$)/($\nu n \rightarrow \nu n$) is more sensitive to $\Delta s$

- Eliminate error on correction for scattering on free protons (no free protons!)

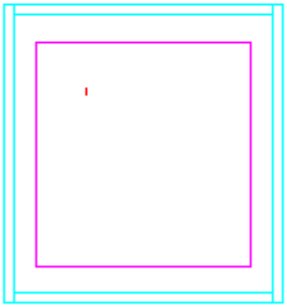
- Measure short tracks (low $Q^2$) – good resolution

  -> worry: nuclear effects

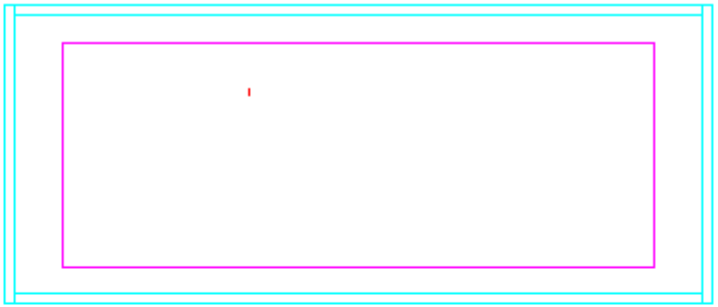
# What do neutrons and protons look like?

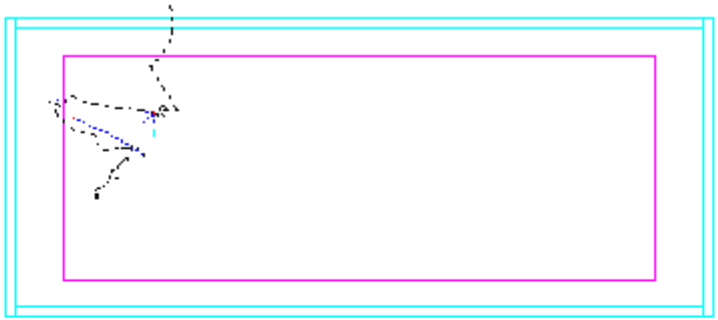
100 MeV kinetic energy events in Liquid Argon

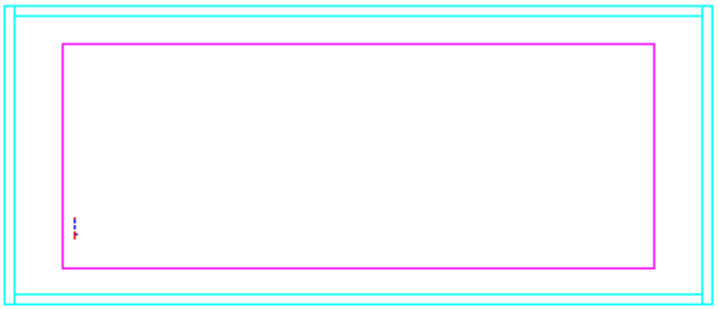
Protons: short, clear tracks



Neutrons: scatter around





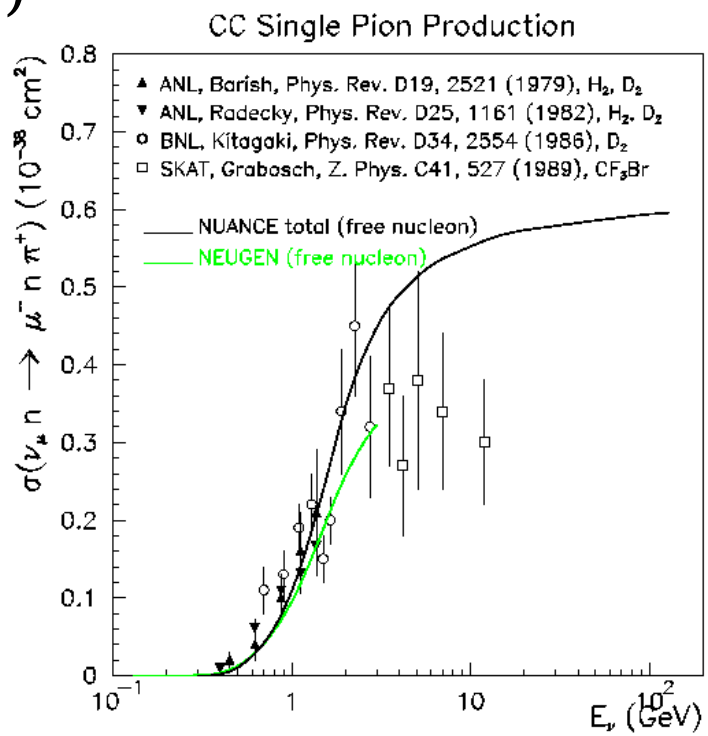


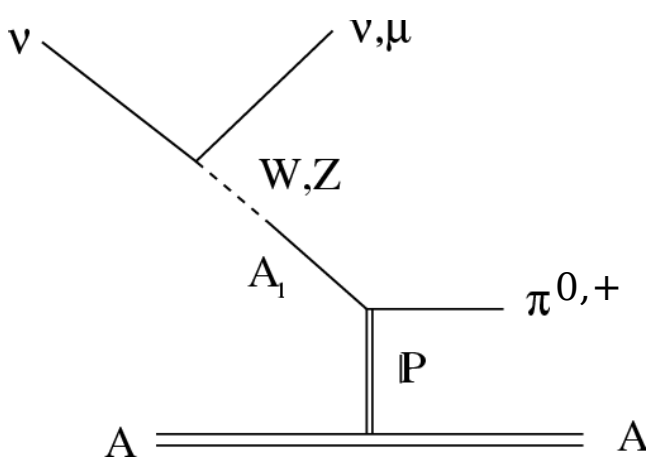
No measurements of this!

# Single Pion Production

## Resonant Production (~80%)

- resonant channels typically known ~20-40%
- interactions complicated by final state effects (**p** absorption, charge exchange)
- as in QE's, all data below 1 GeV is on light targets



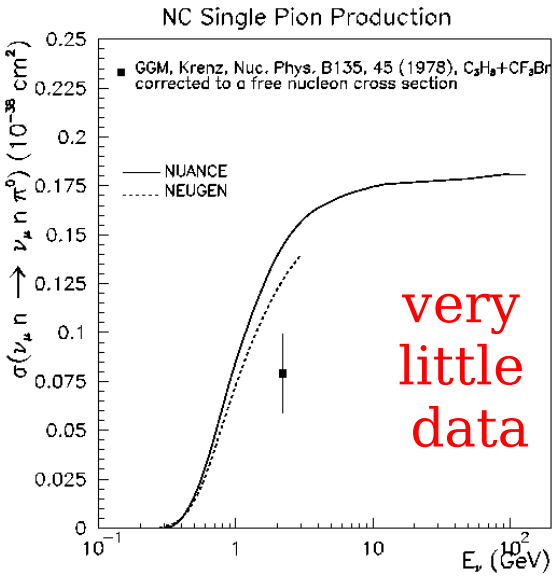

distinct kinematics:
forward scattered **p**
small energy transfer to target (low $Q^2$)

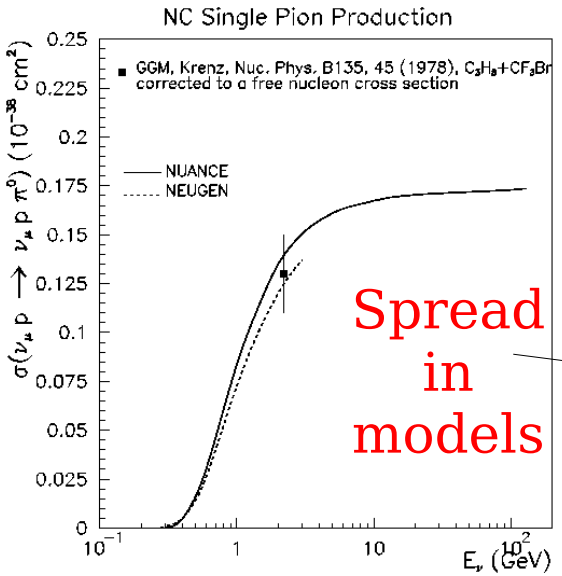
## Coherent Production (~20%)
## scatter from entire nucleus...

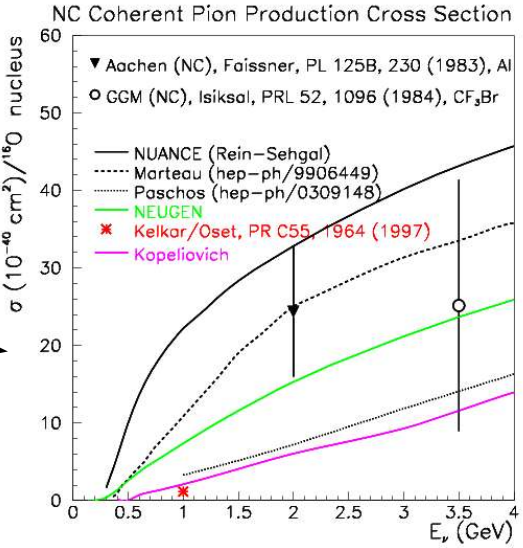
- overall rate not well known (~100% uncertainty)
- no data below 2 GeV

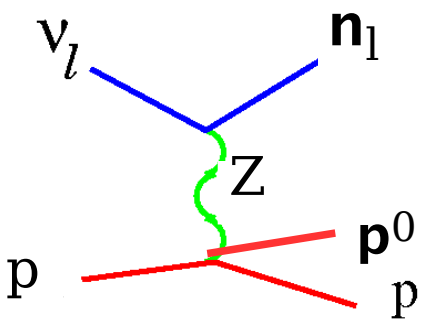
x20 variation in recent models at E~1 GeV

# Neutral current **pion** production: significant background for present and future electron neutrino appearance searches

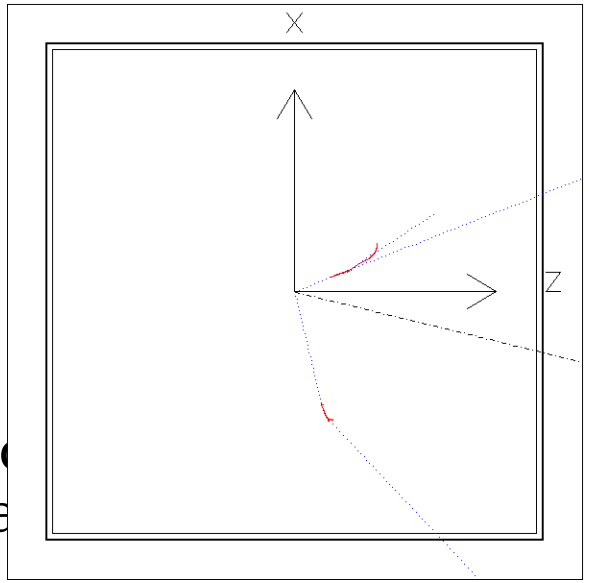


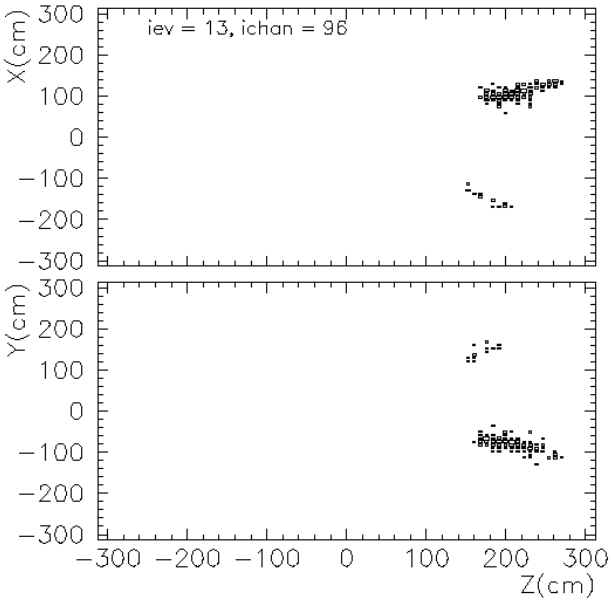



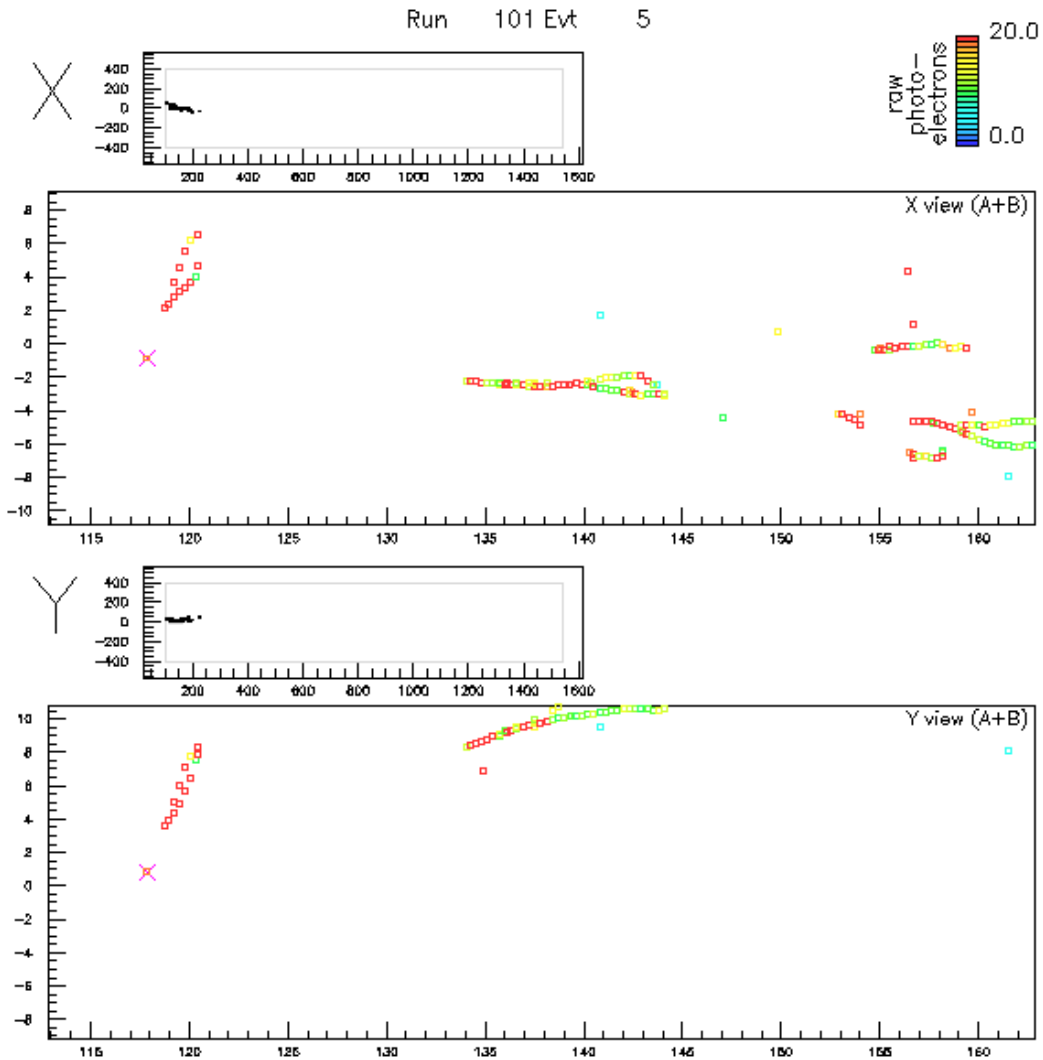




need fine-grained detec
to well measure this cha

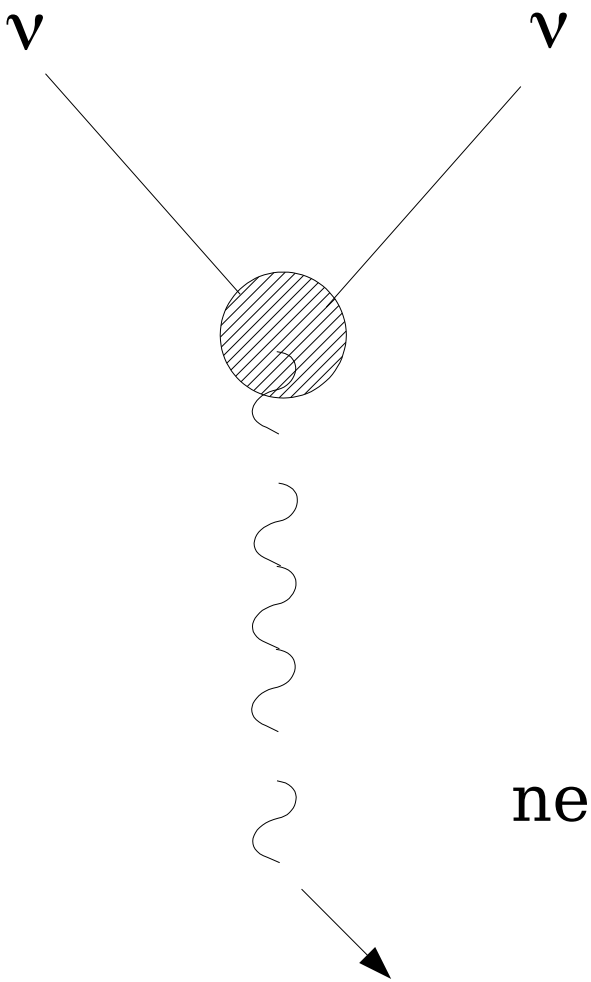


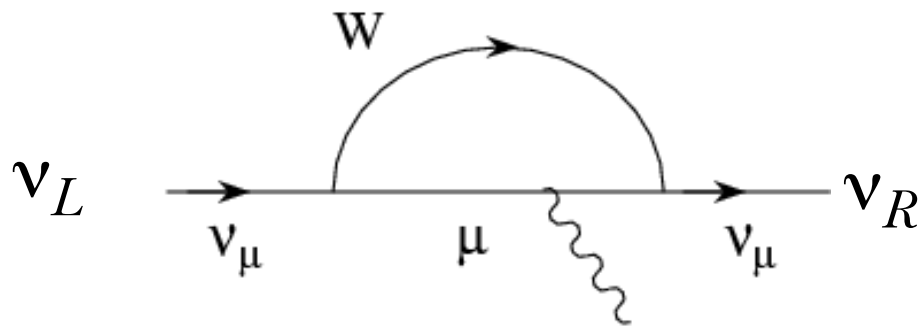
# Liquid Argon TPCs:
# excellent spatial resolution: separating single pion production from other channels



# Neutrino magnetic moments




massive neutrinos imply existence of $\nu_R$

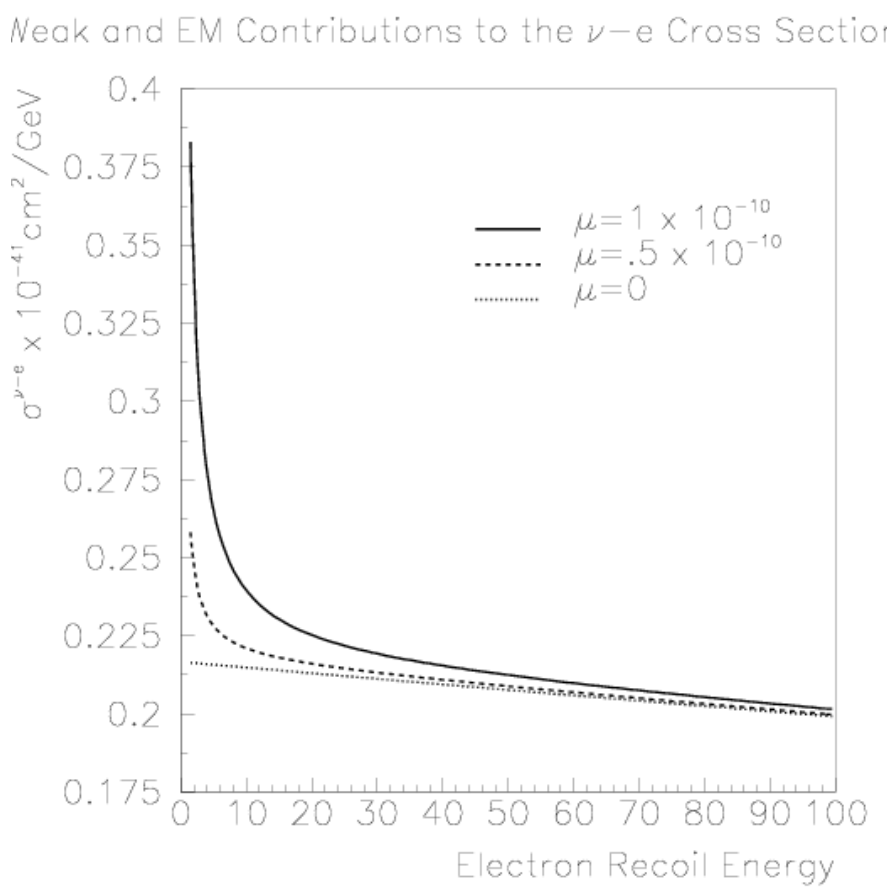



Expect a non-zero neutrino magnetic moment if you have massive neutrinos

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

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

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




shape change in the differential cross section

(MeV)

# 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 $10^{-10}$ $\mu_B$

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

Tau neutrino magnetic moment: -> $10^{-9}$ $\mu_B$

- SuperK & SNO bounds for all neutrinos

Different beyond-the-Standard-Model theories predict different sizes for this neutrino magnetic moment

Minimally Extended Standard Model

$\sim 3 \times 10^{-19} \mu_B$

SUSY models: left-right supersymmetric models

$\mu_{\nu_e} \rightarrow 5.34 \times 10^{-15} - 10^{-16} \mu_B$

$\mu_{\nu_\mu} \rightarrow 1.13 \times 10^{-12} - 10^{-13} \mu_B$

$\mu_{\nu_t} \rightarrow 1.9 \times 10^{-12} \mu_B$

Large Extra Dimensions

$\mu_\nu \rightarrow 1.0 \times 10^{-11} \mu_B$

order of magnitude lower than present limits

# 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

↓

- vary number of interactions
- and electron recoil threshold
- Neutrino energy set to 1 GeV for all these studies

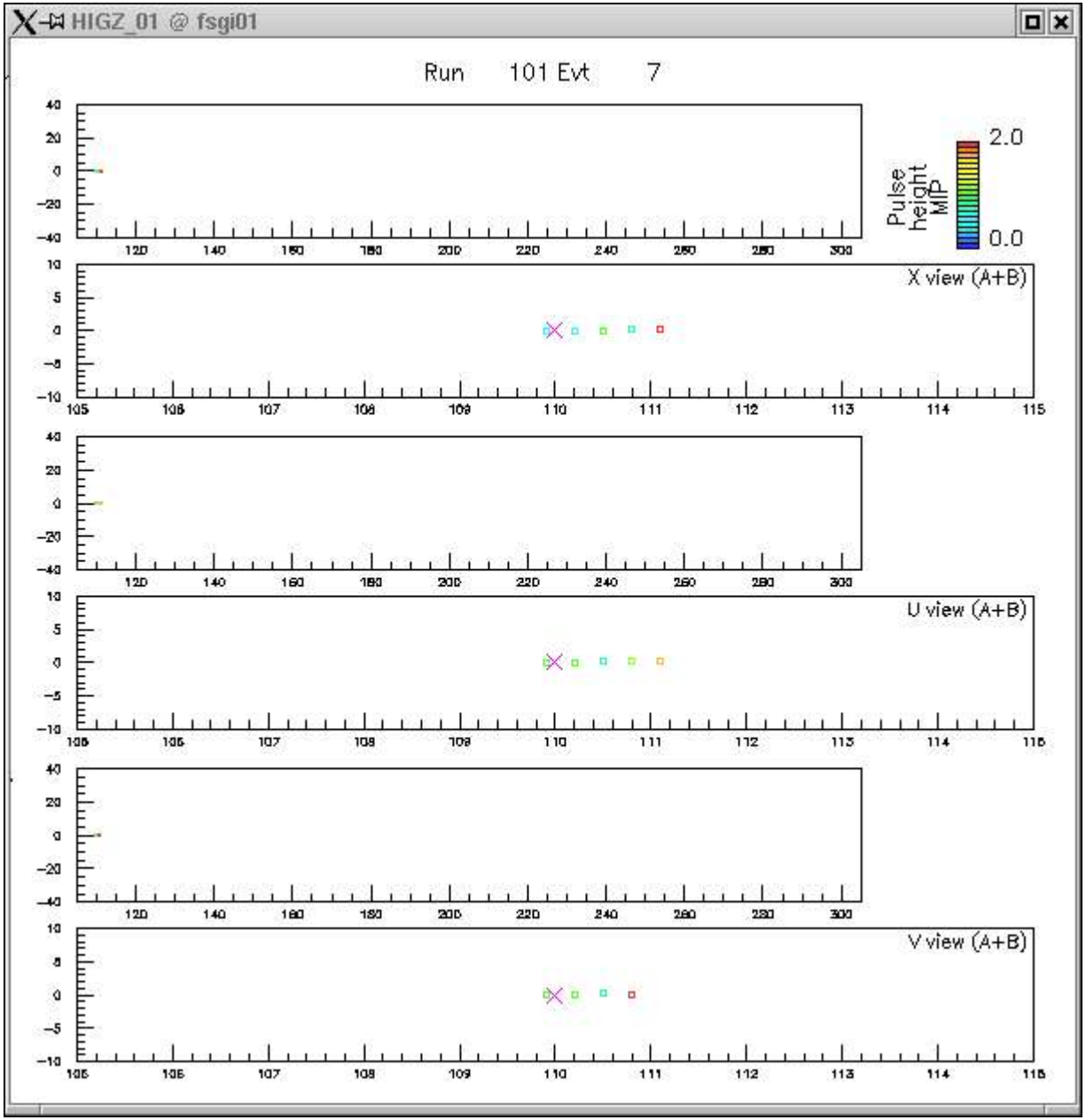
# What happens when you push on electron recoil threshold?

Carbon detectors:
difficult to ID electrons below 10 MeV

- seeing tracks
- radioactive backgrounds and spallation backgrounds
- energy resolution (at MiniBooNE: 15% at 50 MeV)

Liquid Argon TPC detectors:

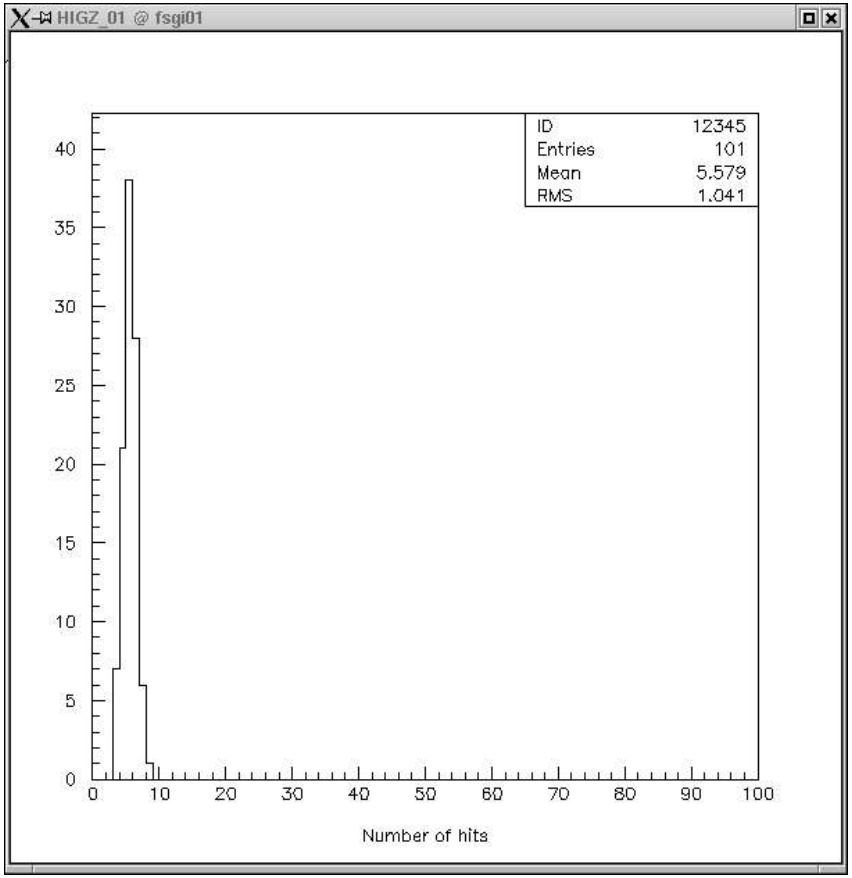
- forward tracks down to 5 MeV
- electron detection down to 150 keV
- energy resolution is about 5% at 5MeV
- radioactive backgrounds still there
    - remove with timing cuts



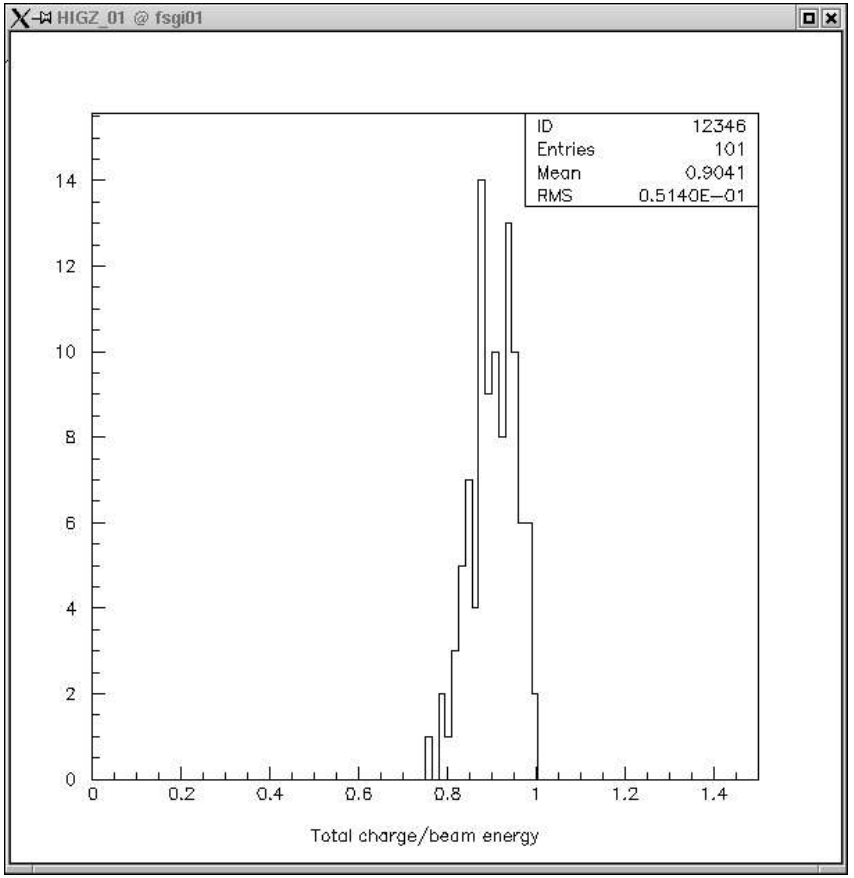

5 MeV electron track in Liquid Argon TPC

wire pitch is 3mm

Typical number of hits: 5




Energy resolution ~5%



Electron detection down to 150 keV:

ICARUS has demonstrated that they
see electrons down to:

Open questions:
Good enough energy resolution?
How good is the signal/noise?
How much scintillation light?
How worrisome are radioactive backgrounds?

# Timing is everything!

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

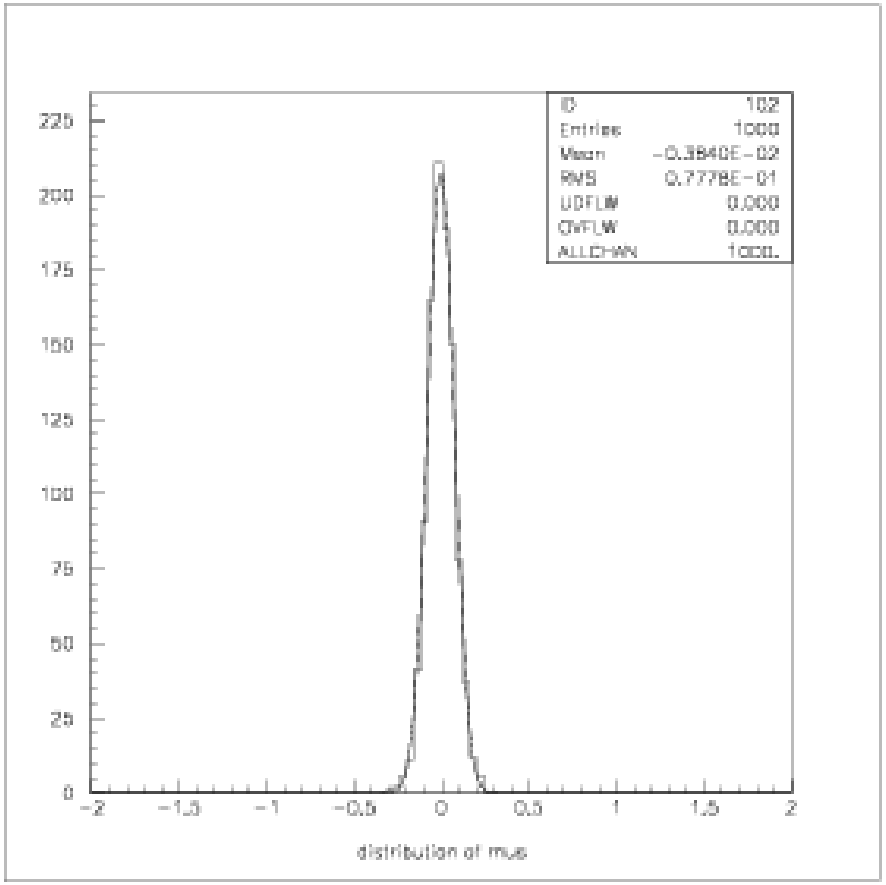
↓

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

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

↓

An order of magnitude improvement
in neutrino magnetic moments




sensitivity:
$\mu_{\nu\mu} = 6.8 \times 10^{-11} \mu_B$

# Conclusions:

Liquid Argon TPCs hold promise to improve
on all sorts of neutrino scattering measurements:

- excellent tracking and resolution
- low thresholds
- particle identification

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