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Near detector physics on the MiniBooNE beamline

- MiniBooNE beamline and neutrino production
- Proton driver/neutrino superbeam physics
- Non-oscillation physics at a near detector on the MiniBooNE beamline

High intensity, neutrino scattering physics

Neutrino energies ~ 1 GeV
light targets
high statistics

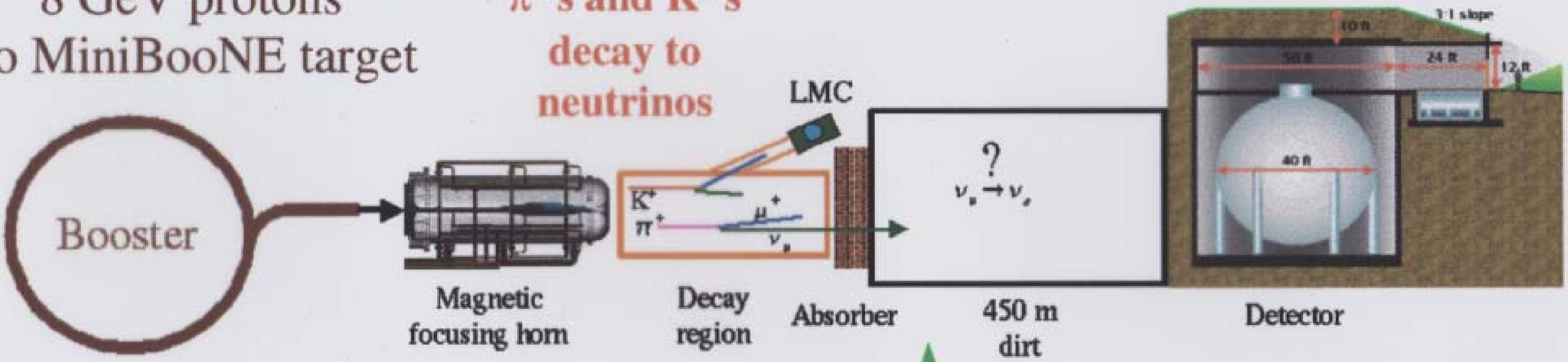
- νN elastic scattering $\rightarrow$ Δs of proton
- Neutrino magnetic moment searches
- Cross section measurements

MiniBooNE beamline

Fermilab's Booster delivers 8 GeV protons to MiniBooNE target

Existing MiniBooNE detector

π^{+}'s and K^{+}'s decay to neutrinos



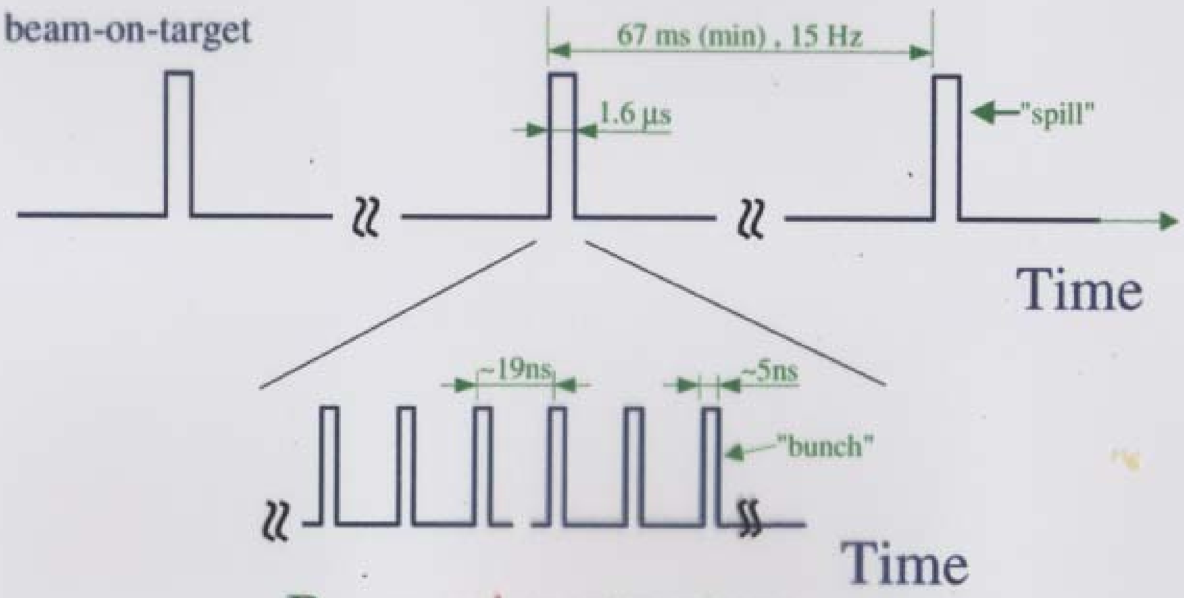
72 cm long Berylium target inside a magnetic focussing horn

Location for a near detector 100 m from neutrino production target

Fermilab Booster

protons: 400 MeV to 8 GeV
5-15 Hz
5 x 10^{12} ppp

Beam macrostructure



Beam microstructure

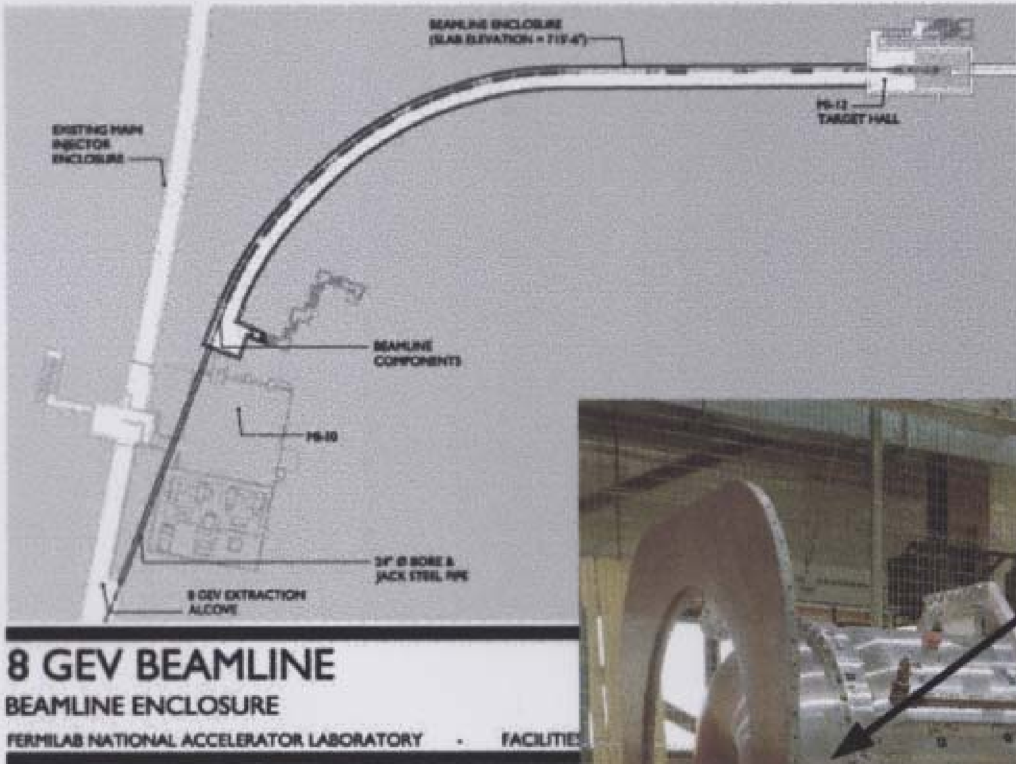
delivers beam to....

Main Injector
for
TeVatron
running

pbar production
for TeVatron

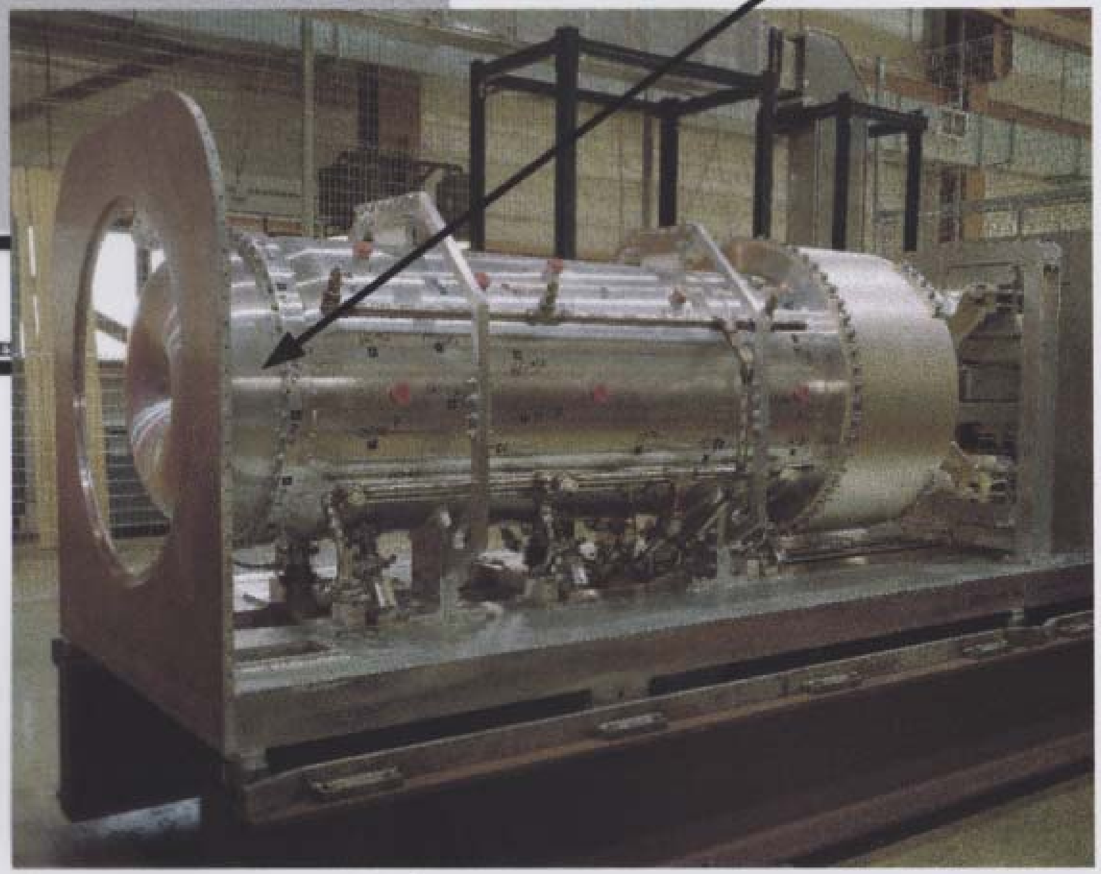
MiniBooNE

Main Injector
for
NuMI
running (2005)



8 GeV transfer line
to MiniBooNE target

72 cm long
Berylium target
inside Horn



Horn:
pulsed with 175 kA
at instantaneos rate of 15Hz
produces a 1 Tesla
magnetic field at center
→ sign selecting

Neutrino Production

$p + Be \rightarrow \pi^+, K^+, K^0_L$

pions and kaons decay primarily to ν_μ's

$\pi^+ \rightarrow \mu^+ \nu_\mu$ 99.9%

$K^+ \rightarrow \mu^+ \nu_\mu$ 63.5%

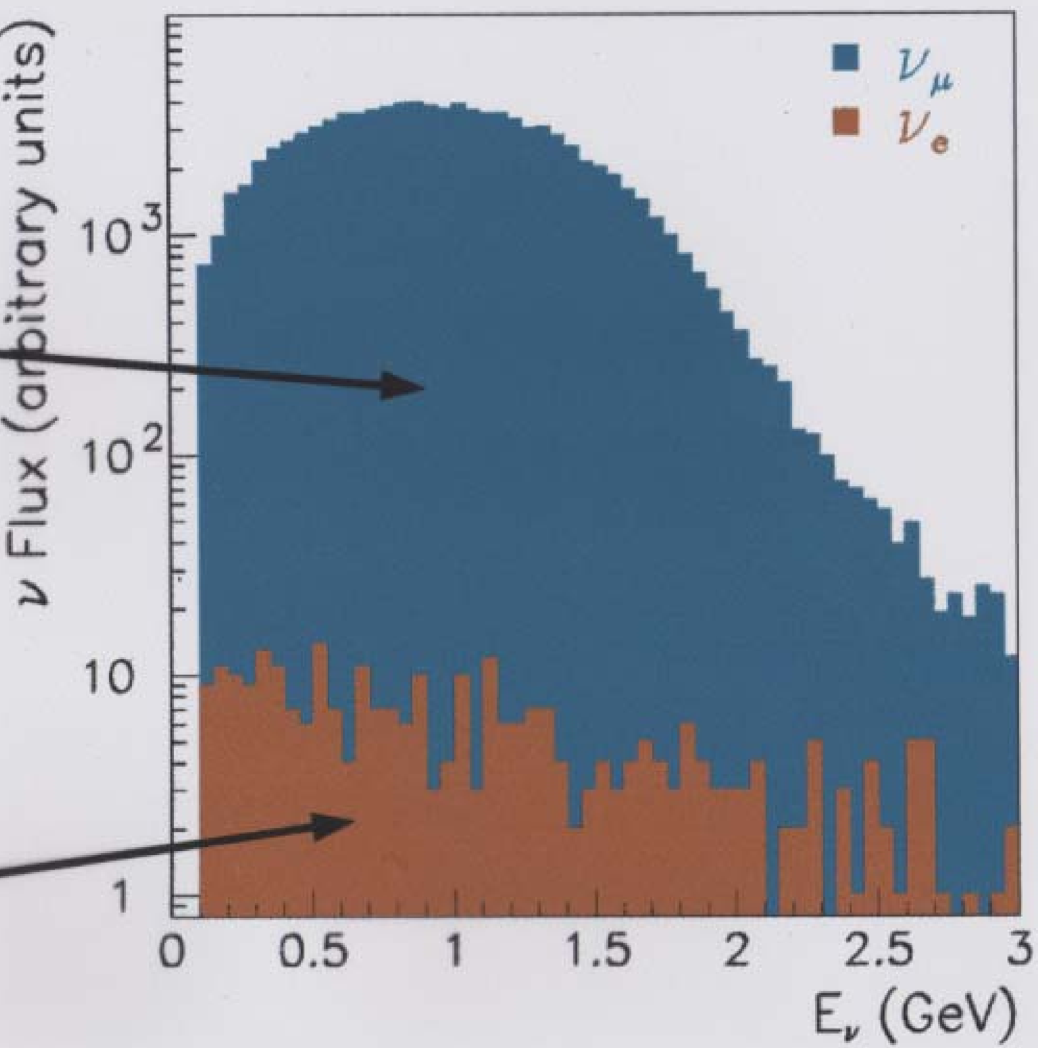
$\rightarrow \pi^+ \pi^0$ 21.2%

Intrinsic ν_e flux is small compared to ν_μ flux

$K^0_L \rightarrow \pi^+ e^- \nu_e$

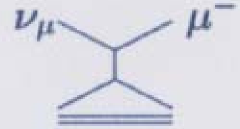
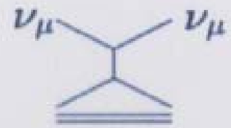
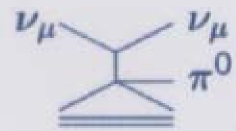
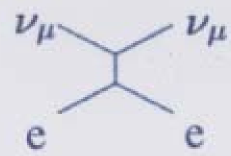
$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

ν_μ and ν_e production



Approximate event rates at MiniBooNE

→ for 5 x 10^{20} protons on target (1-2 years running)

Δs	ν_μ charged current	500,000 events	
Δs	ν_μ neutral current	70,000 events	
cross sections	π^0 resonance production:	50,000 events	
neutrino magnetic moment	ν_μ-e elastic scatters	100 events	

to do high statistics, non-oscillation physics .....

→ put detector at 100 m (as close to target as possible)

→ increase beam intensity with new proton driver

Potential proton driver facility at Fermilab:

- increase beam intensities by x4 - x5
- increase rep rate to 15Hz with beam
- increase energy to 16 GeV
- provide beam for TeVatron, Main Injector physics program, and MiniBooNE

Δs: The strange-quark contribution to the spin of the proton

Experimental results on strange quarks in the nucleon:

- neutrino DIS measures a non-zero "strange sea"

- polarized-lepton DIS (EMC, SMC, SLAC) say the nucleon spin carried by strange quarks is non-zero.

  $\Delta s \sim -0.10 \pm 0.05$ (SMC paper: PR D56, 5330,'97.)

  However, model-dependent assumptions (SU(3), $x \to 0$ extrapolation) limit conclusive interpretations. (hep-ph/0201179)

νN elastic scattering allows for a theoretically robust, complementary measurement of Δs

Measuring Δs...

The neutrino-nucleon neutral-current process is sensitive to Δs:

Nucleon Neutral Weak Current: J_μ depends on

G_a, F_1, F_2 form factors

$$-G_a(q^2) = -g_a(q^2) + G_a^s(q^2)$$

F_1 small, F_2 measured in PV e scattering

g_a known (nuclear β decay)

$$G_a^s(q^2=0) = \Delta s$$

$\nu p \to \nu p$ NC cross section yields Δs

but we must deal with cross section systematics...

Measure cross section ratios to determine Δs... while minimizing systematic errors

Ratio measurements:

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

  $$R(p/n) = \sigma(\nu p \to \nu p)/\sigma(\nu n \to \nu n)$$

  is quite sensitive to Δs due to:

  $$G_a = -g_a \tau_z + G_a^s \ , \tau_z = +1 \text{ proton, -1 neutron}$$

  However, the systematic of neutron detection are difficult.

- Ratio of NC elastic scattering to CC scattering:

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

  is somewhat less sensitive to Δs, but experimentally easier

No systematic error due to the uncertainty in neutrino flux.

Previous measurements:

→BNL 734:

$\nu_\mu p, \bar{\nu}_\mu p$ scattering w/170 ton segmented detector @E_ν~1.2 GeV (Q^2=0.4 → 1.1 GeV^2)

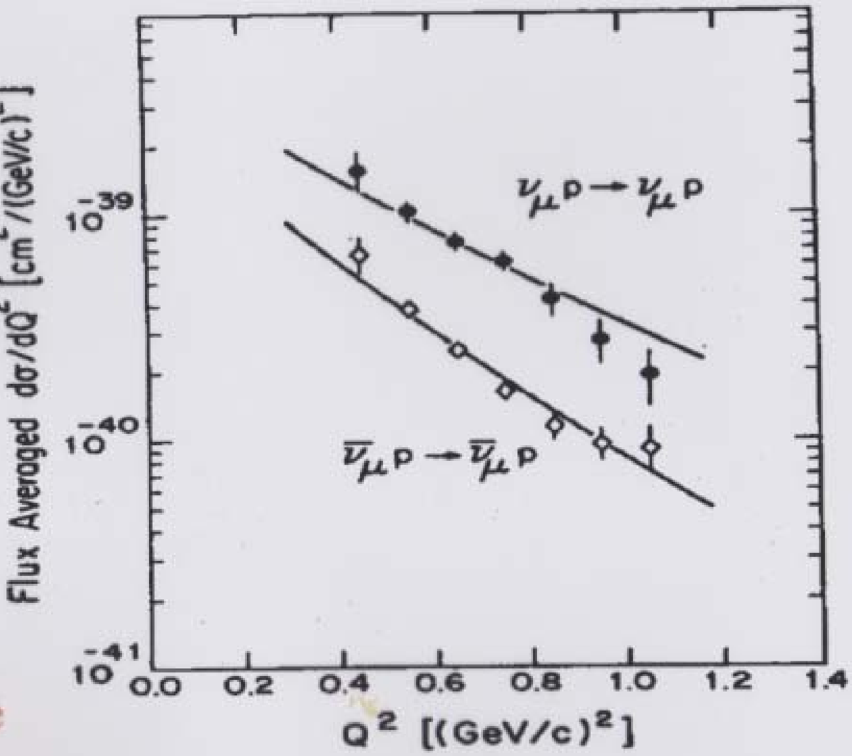
(Ahrens et al., PRD 35, 785 ('87).)

Conclusive results on Δs limited due to statistical and systematic errors.

Flux averaged crossections:

951 $\nu_\mu p$ *events*

776 $\bar{\nu}_\mu p$ *events*



→LSND: νp/νn elastic scattering at low-Q^2.

Results on Δs not conclusive due to large beam-unrelated background.

A definitive measurement of Δs using the MiniBooNE beamline

Goal: $\sigma(\Delta s) \sim 0.03$

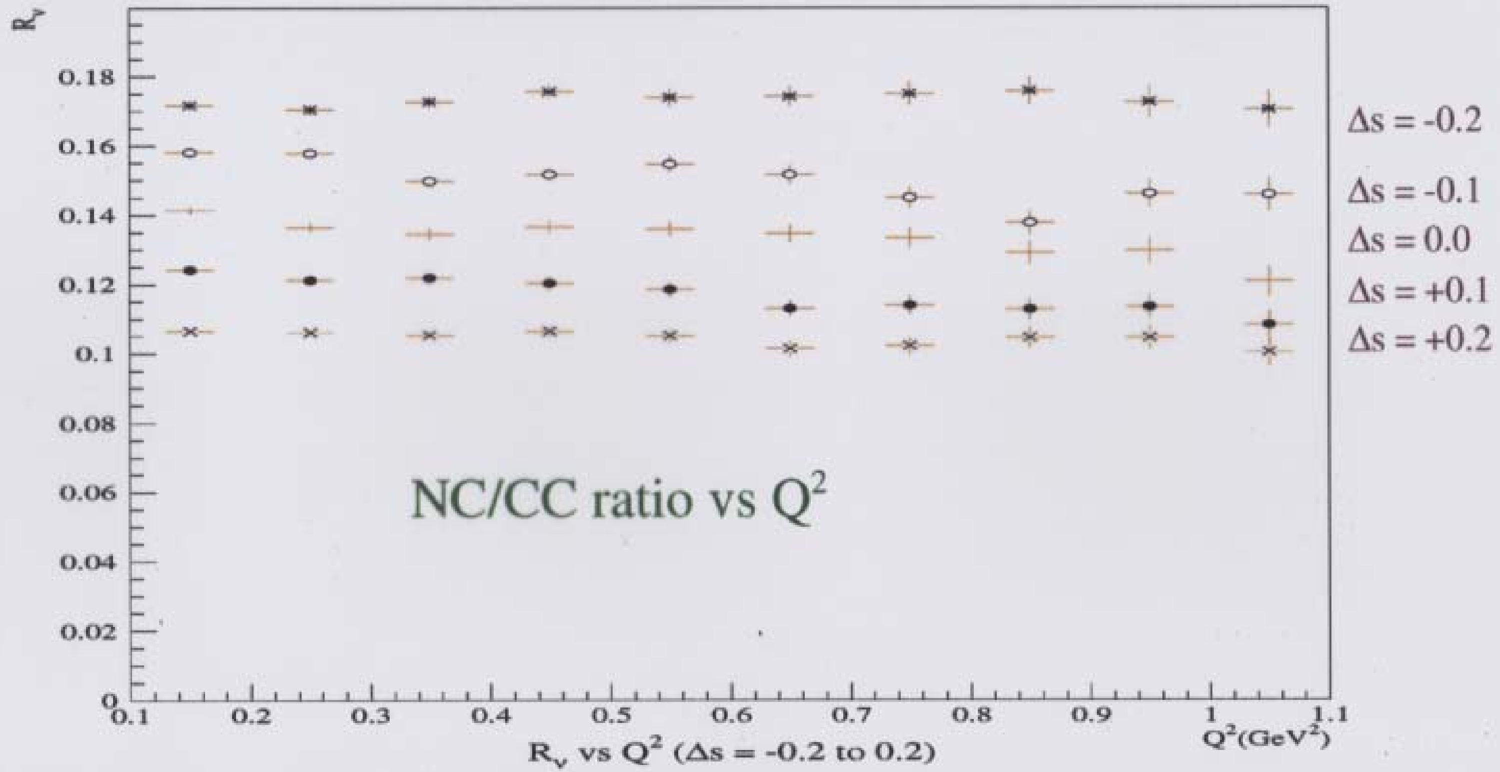
→ measure $R_{NC/CC} = \sigma(\nu p \rightarrow \nu p)/\sigma(\nu n \rightarrow \mu p)$ to 5%

Systematics Checks:
measure $R_{NC/CC}$ w/antineutrinos
study R with Q^2

Need to keep systematic errors low:
- must reduce pion backgrounds

How well can we do with MiniBooNE?

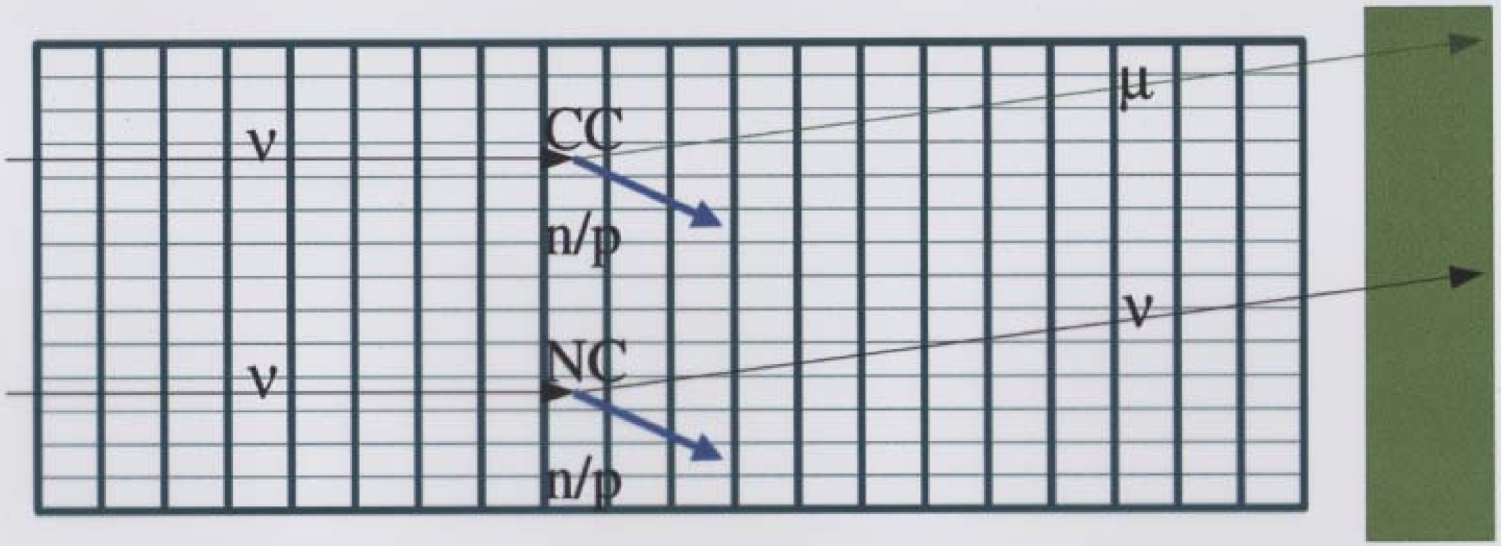
- ~ 30k NC events/year, ~250k CC events/year
(500 ton fiducial vol., 50% eff, $Q^2 = 0.1\text{-}1.1\ GeV^2$



systematic errors will make a definitive Δs measurement difficult.

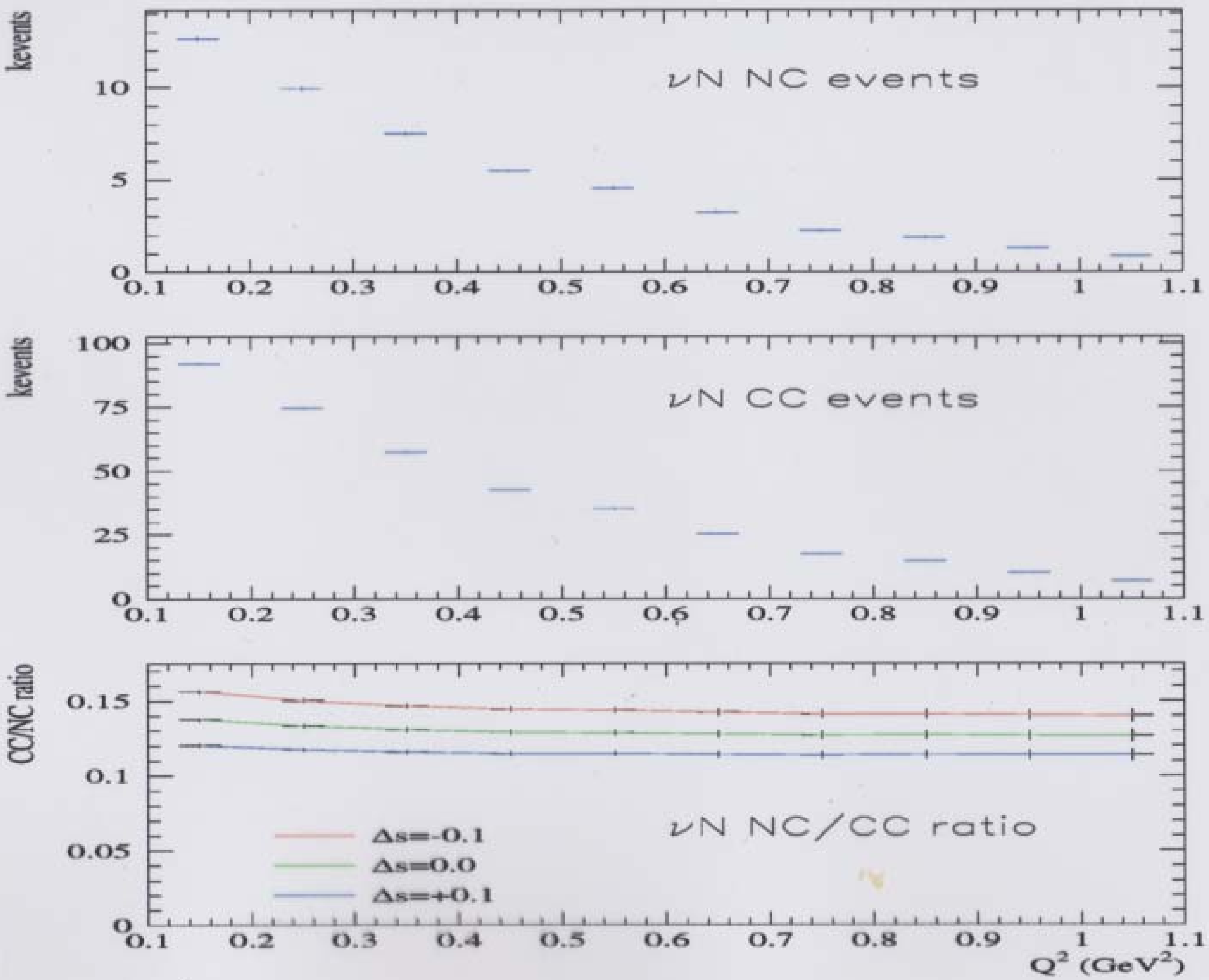
error on efficiency of proton detection in large non-segmented detector

Need a highly segmented large(ish), detector with intense neutrino flux...



- ~100 m from miniBooNE target
- active target w/tracking (~10 ton)
- (minimal) muon tracking
- particle id (p/π/μ/e) for good bckgd sep.
- take advantage of short beam spill/long cycle time

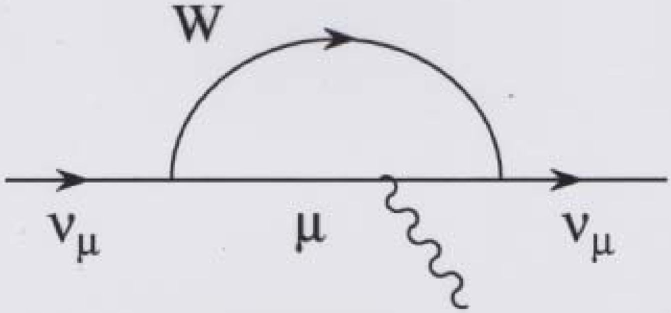
Neutrino-Nucleon Scattering in 10ton detector on miniBooNE beamline @100m in 1 year



How does a neutrino magnetic moment (NMM) arise?

⇒ Minimally extended Standard Model:

→ massive Dirac neutrinos can have a non-zero NMM



Neutrinos of mass m_ν
→ NMM of:

$$\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \times 10^{-19} \mu_B \frac{m_\nu}{1eV}$$

→ SUSY models – left-right supersymmetric models

$$\mu_{\nu_e} \cong 5.34 \times 10^{-15} - 10^{-16} \mu_B$$
$$\mu_{\nu_\mu} \cong 1.13 \times 10^{-12} - 10^{-13} \mu_B$$
$$\mu_{\nu_\tau} \cong 1.9 \times 10^{-12} \mu_B$$

→ Large Extra Dimensions

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

Limits set from previous experiments

→ *Electron ν magnetic moment*

$$\mu_{\nu_e} \leq 1.5 - 1.8 \times 10^{-10} \mu_B$$

- Super K data: shape of recoil electron spectrum
- reactor experiments: combined measurement

Future experiments plan to measure μ_{ν_e} to $\sim 10^{-12}$

→ *Muon ν magnetic moment*

$$\mu_\nu \leq 6.8 \times 10^{-10} \mu_B$$

- LSND experiment: combined measurment for electron and muon neutrino magnetic moments using total $\nu_{e,\mu} e$ elastic cross section.

→ *Tau ν magnetic moment*

$$\mu_\nu \leq 5.4 \times 10^{-7} \mu_B$$

- DONUT experiment

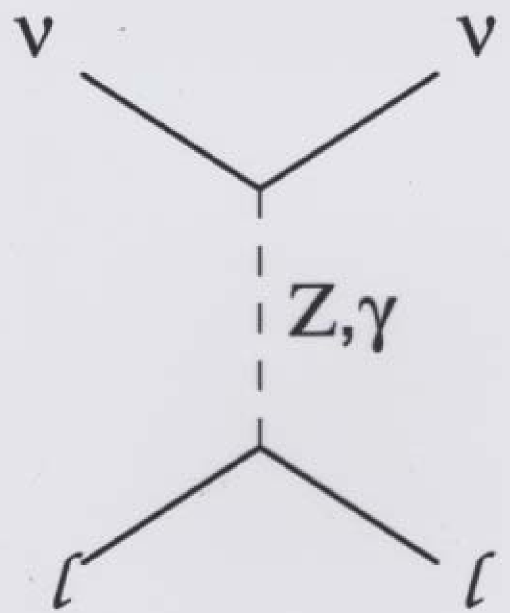
→ *Astrophysical limits*

- slow rate of plasmon decay in horizontal branch stars⋆
  → $\mu_\nu < 10^{-11} \mu_B$
- neutrino energy loss rate from supernova 1987a⋆
  → $\mu_\nu < 10^{-12} \mu_B$

⋆ model assumptions made in these cases

Conventional method to measure ν magnetic moments

→ Neutrinos with non-zero ν magnetic moment would have an electromagnetic component to neutrino neutral current cross section.



$$\sigma_{tot} = \sigma_{weak} + \sigma_{em}$$

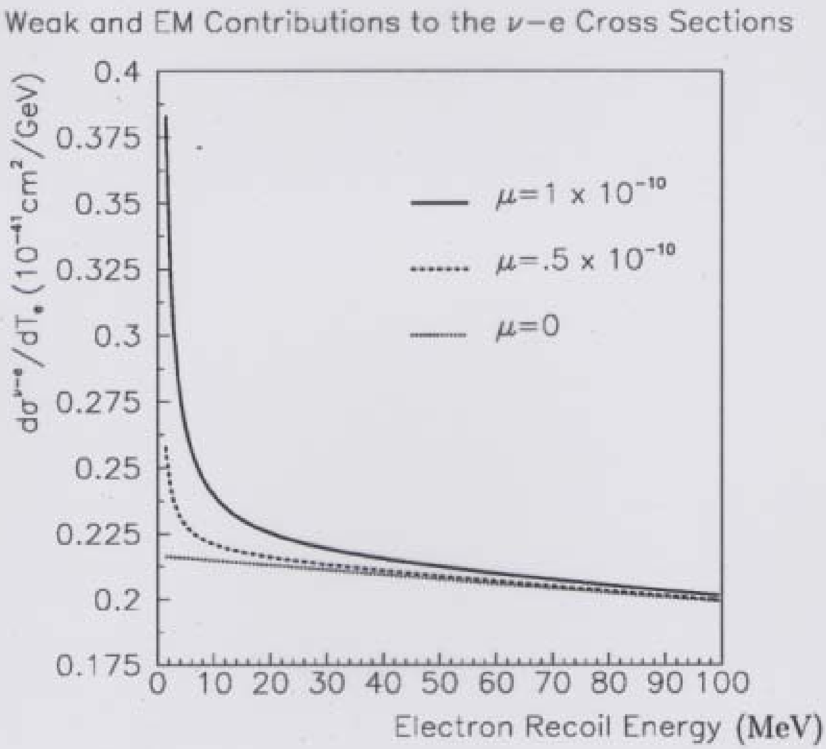
→Shape of the differential cross section depends upon any electromagnetic contribution

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

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

where T=electron recoil energy

E_ν= Neutrino energy

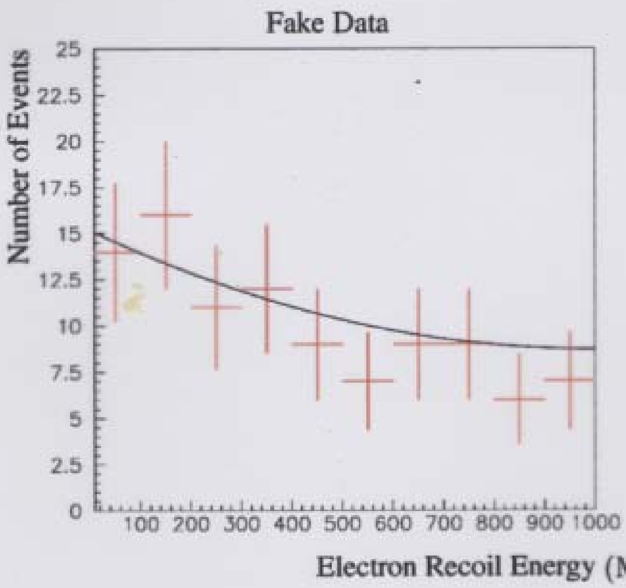


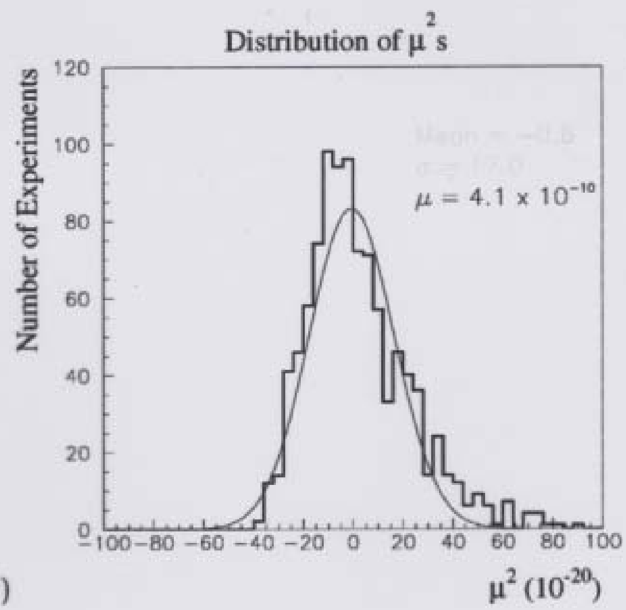
Neutrino magnetic moment measurements at MiniBooNE

100 $\nu - e$ events with $E_\nu = 1$ GeV
10 MeV $< T_e <$ 1000MeV

$$\left(\frac{\Delta\sigma}{\sigma}\right)^2 = \left(\frac{\Delta N}{N}\right)^2 + \left(\frac{\Delta F}{F}\right)^2$$

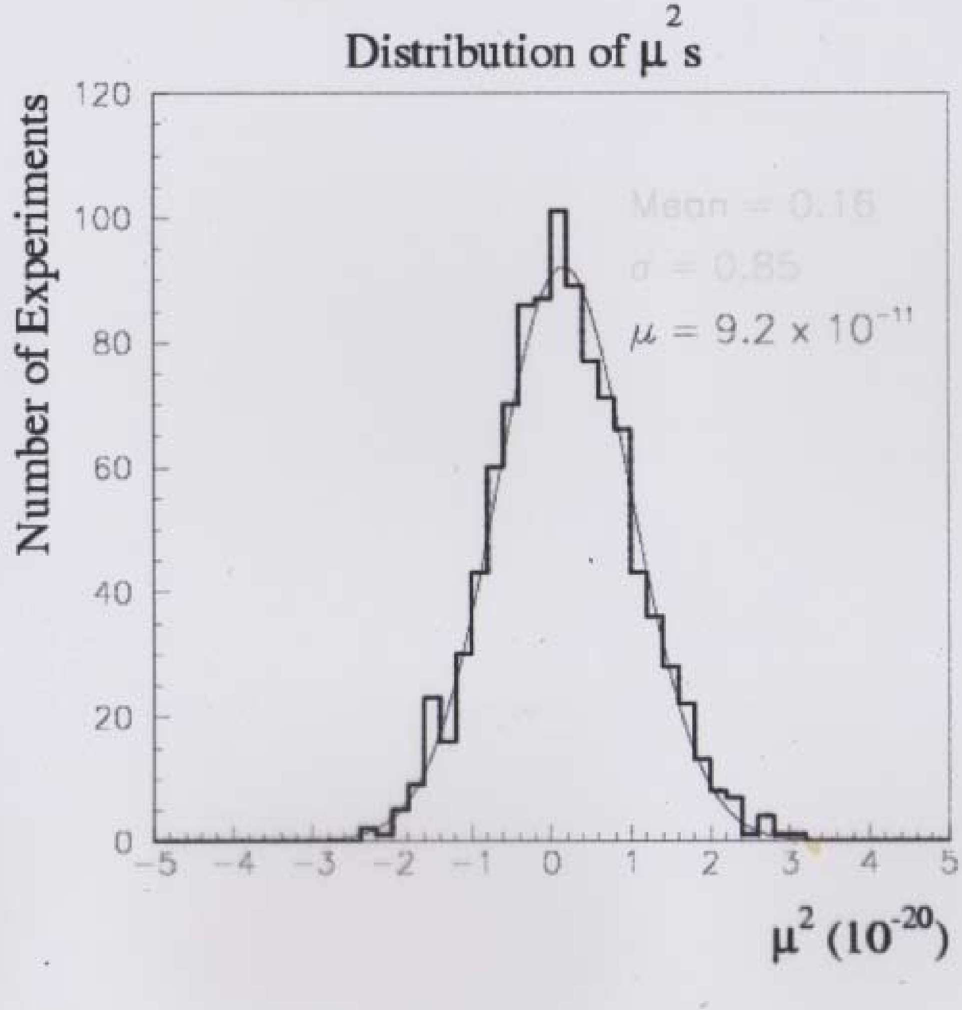
Sensitivity: $\mu_{\nu_\mu} < 6.6 \times 10^{-10} \mu_{\rm B}$
without flux error.....
Sensitivity: $\mu_{\nu_\mu} < 4.7 \times 10^{-10} \mu_{\rm B}$





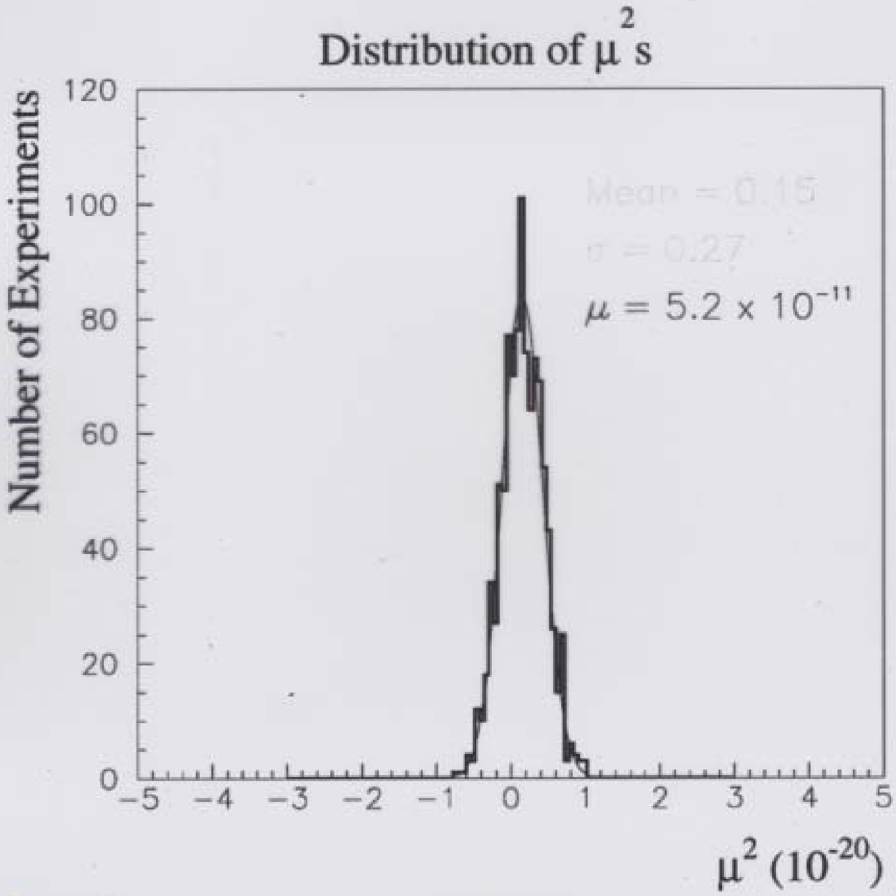
Sensitivity: $\mu_{\nu_\mu} < 4.1 \times 10^{-10} \mu_{\rm B}$

Measurements at a near detector with existing MiniBooNE beam



at a superbeam facility[1]

15000 $\nu - e$ events with $E_\nu = 1$ GeV
1 MeV $< T_e <$ 1000MeV



Sensitivity: $\mu_{\nu_\mu} < 5.2 \times 10^{-11} \mu_B$

[1] C. Ankenbrandt et. al.,"Physics study group report on physics potential at FNAL with stronger proton sources," in preparation, http://projects.fnal.gov/protondriver/

Lots of interesting physics to be done with
high intensity,
short baseline,
~1 GeV neutrino beams