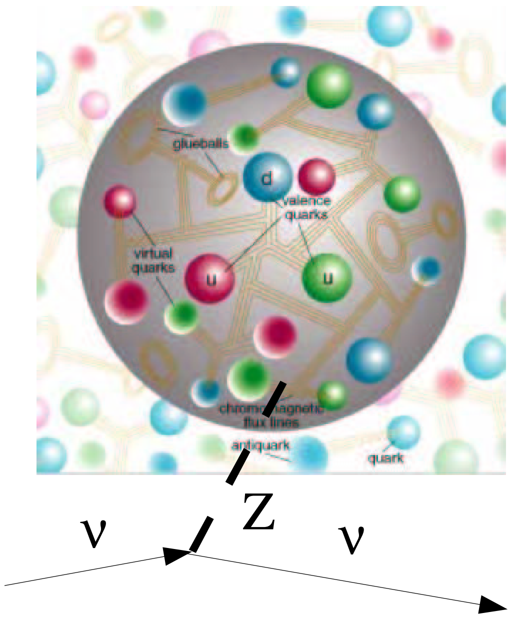
Measuring the Strange Spin* of the Nucleon with Neutrinos

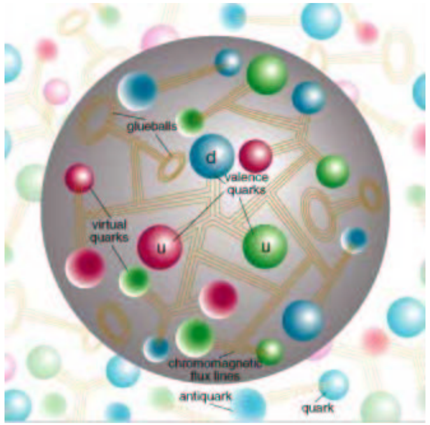
*(the strange-quark contribution to the spin of the nucleon, Δs)



- Strange quarks in the nucleon? Experimental evidence
- $\nu N \rightarrow \nu N$ scattering and Δs
- A measurement of Δs with FINeSE

R. Tayloe
Indiana University
Nufact '03, 6/03

Experiment: Strange quarks in the nucleon

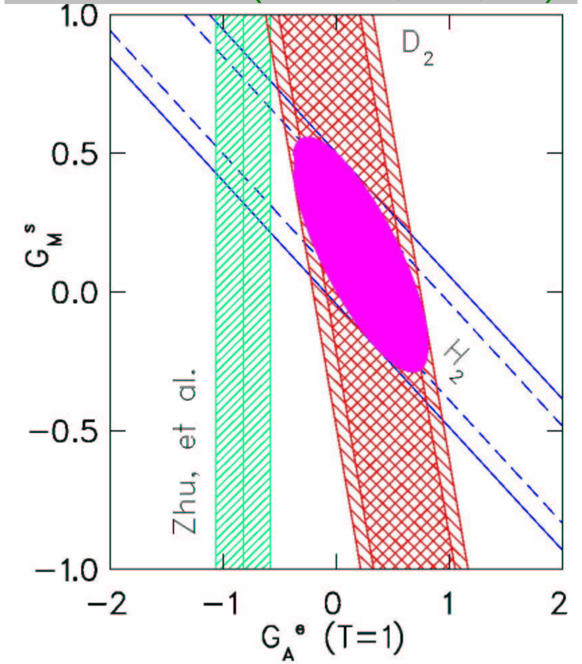


- Net strangeness of the nucleon is zero. However, QCD: valence ud quarks + sea of $\bar{q}q$ pairs.

- DIS ν scattering (e.g. NuTeV): The strange sea carries a non-zero fraction of the proton momentum.

- PV e^- scattering (e.g. SAMPLE, HAPPEX) looks for strange-quark contributions to the proton magnetic moment (μ_s) and radius (r_s). Results are not conclusive, ~consistent with 0.

from SAMPLE (Science, 290, '00)



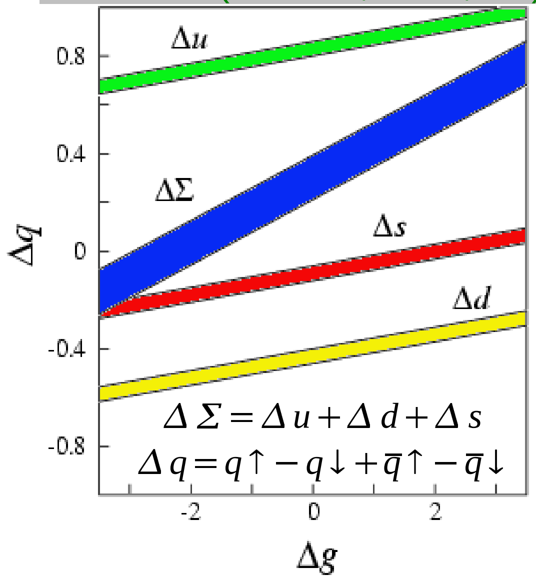
Experiment: Strange quarks in the nucleon

- Polarized-lepton DIS (EMC, SMC, SLAC) results indicate that the fraction of proton spin carried by light quarks, $\Delta\Sigma < 1$, and the fraction of the proton spin carried by the strange quarks,

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

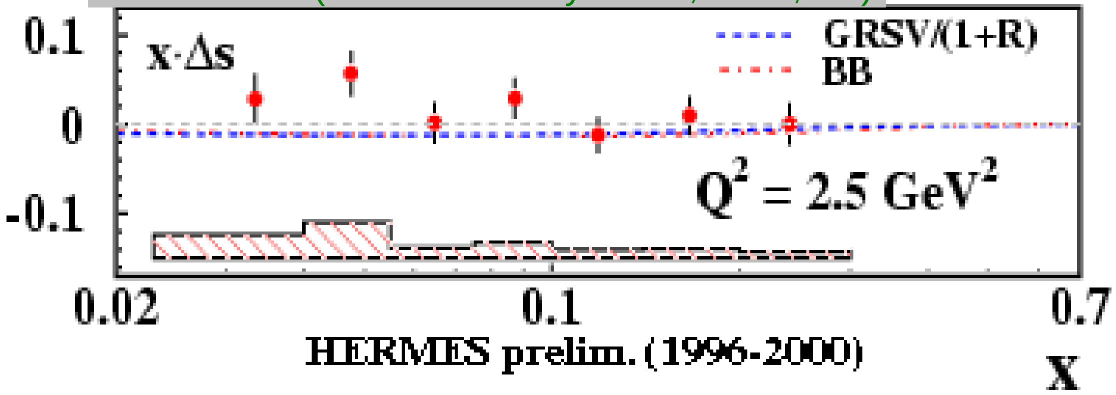
(However, scheme dependent, and assumptions of SU(3) symmetry limit conclusive interpretations.)

from SMC (PR D**56**, 5330,'97.)



- Latest results from HERMES (semi-inclusive data) indicate $\Delta s > 0$

from Hermes (Int. J. Mod. Phys. A17, 3551, '02)

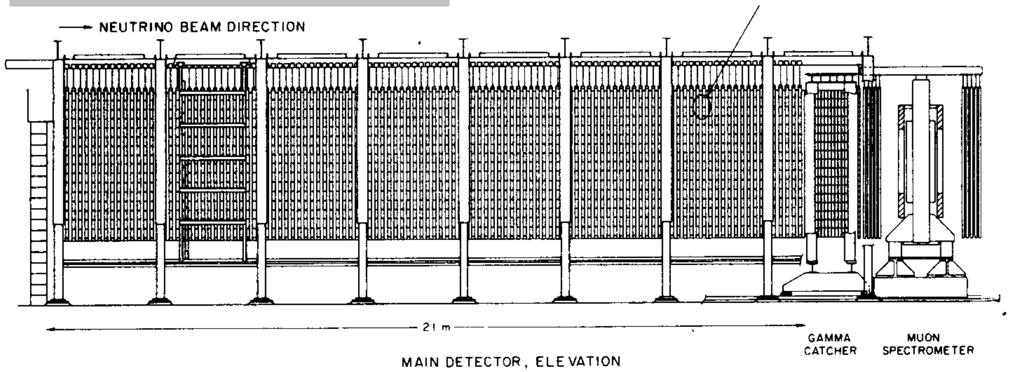


Experiment: Strange quarks in the nucleon

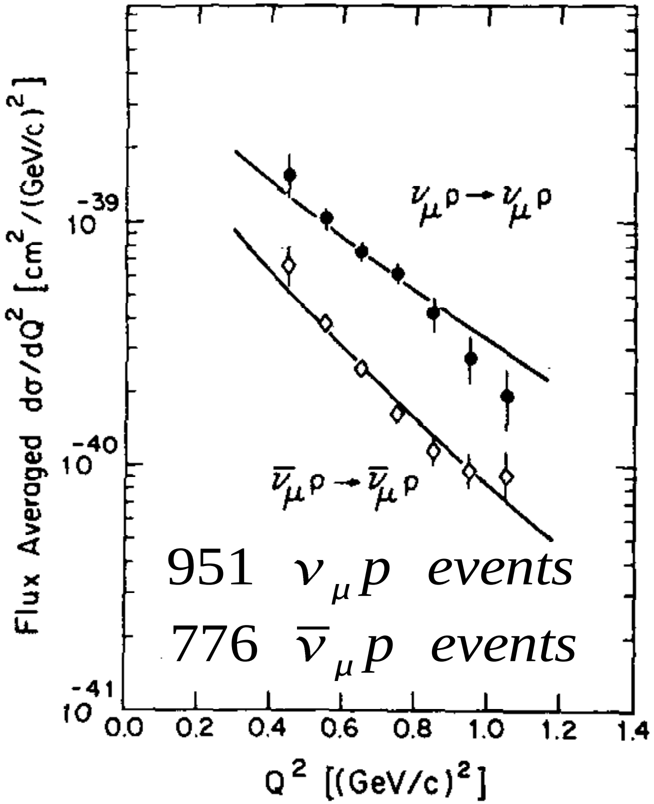
- Neutrino-Nucleon scattering is also sensitive to strange-quark contibution to proton spin. Unfortunately, results to date have been non-conclusive.

- BNL734: νp, $\bar{\nu} p$ elastic scattering w/170 ton segmented detector @E_ν~1.2 GeV (Q^2=0.4 $\rightarrow$ 1.1 GeV^2) (PRD 35, 785, '87.)

BNL734 detector



BNL734 data



$\nu N \rightarrow \nu N$ scattering and Δs

- Nucleon Weak Current: $J_\mu = \langle N | F_1 \gamma_\mu + F_2 \sigma_{\mu\nu} q^\nu + G_A \gamma_\mu \gamma_5 | N \rangle$

(assuming: T/isospin invariance, no 2nd class currents, and no pseudoscalar f.f.)

- F_1, F_2 :vector (Dirac/Pauli) form factors
  - related to quark spatial dist./mag. moment
  - (For CC) By CVC, same as those measured in elastic eN scatt.
- G_A : axial-vector form factors
  - related to quark spins
  - νN scattering is quite sensitive to this f.f., less-so in PV elastic eN scatt.
- For NC processes, strange quark (isoscalar) parts may contribute to the f.f.s (as opposed to CC):

$$G_A(Q^2) = \frac{g_A \tau_3}{(1 + Q^2/M_A^2)^2} + G_A^s(Q^2)$$

(w/ similar forms for F_1, F_2)

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

$\nu N \to \nu N$ scattering and Δs

- Differential cross section for νN, $\bar{\nu} N$ CC and NC (quasi-) elastic scattering:

$$\frac{d\sigma}{dQ^2}=\frac{G_F^2}{2\pi}\frac{Q^2}{E_\nu^2}[A\pm B\,W+C\,W^2],W=4E_\nu^2/m_p-Q^2/m_p^2$$

$$A=\frac{1}{4}[G_A^2(1+\tau)-(F_1^2-\tau F_2^2)(1-\tau)+4\tau F_1 F_2]$$

$$B=-\frac{1}{4}G_A(F_1+F_2)$$

$$C=\frac{1}{16}\frac{m_p^2}{Q^2}[G_A^2+F_1^2+\tau F_2^2]$$

$$\nu\,NC:\nu_\mu p\to\nu_\mu p,\nu_\mu n\to\nu_\mu n$$
$$\nu\,CC:\nu_\mu n\to\mu^- p$$
$$\bar{\nu}\,NC:\bar{\nu}_\mu p\to\bar{\nu}_\mu p,\bar{\nu}_\mu n\to\bar{\nu}_\mu n$$
$$\bar{\nu}\,CC:\bar{\nu}_\mu p\to\mu^+ n$$

$$G_A(Q^2)=\frac{g_A\tau_3}{(1+Q^2/M_A^2)^2}+G_A^s(Q^2)$$

- Most sensitive to G_A
- Non-strange (isovector) parts of f.f.s known
- $G_A^s(Q^2\to 0)=\Delta s$

- So, a measurement of νN NC scattering (at low Q^2) yields Δs

$\nu N \rightarrow \nu N$ scattering and Δs

- νN NC elastic scattering is uniquely sensitive to Δs

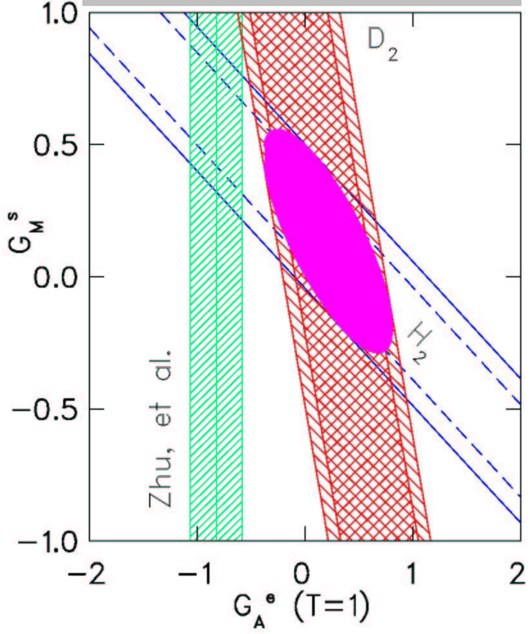
relative sensitivity to...

experiment	F_1^s	F_2^s	G_A^s
BNL734 (νN)	-0.72	-0.78	-1.23
BNL734 ($\bar{\nu} N$)	0.83	0.62	-2.11
SAMPLE (eH)	-0.86	-0.47	-0.10
SAMPLE (eD)	-0.29	-0.08	-0.02

(from Beise&McKeown, Comments Nucl. Part. Phys 20, 105 '91)

- In addition, the axial part is "clouded" in PV e scattering due to radiative corrections, anapole moment...
  (Δs measurement not possible in PV elastic e^- scattering. hep-ph/0203011)

SAMPLE results:



$\nu N \rightarrow \nu N$ scattering and Δs

- (re)analysis of the BNL734 νN, $\bar{\nu} N$ NC data

$G_A^s = 0 \rightarrow -0.21$

$F_1^s = 0 \rightarrow +0.53$

$F_2^s = 0 \rightarrow -0.40$

$M_A = 1.086 \rightarrow 1.012$ GeV

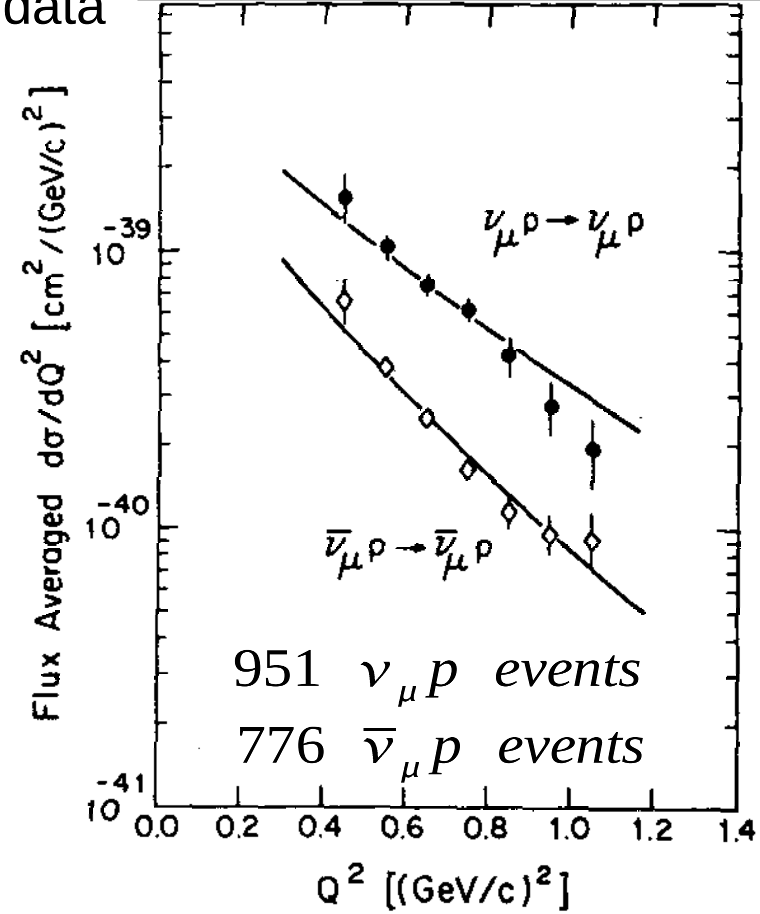
(large errors, inconclusive results)

- BNL734 also measured (NC/CC ratios):

$$R_\nu = \frac{\sigma(\nu_\mu p \rightarrow \nu_\mu p)}{\sigma(\nu_\mu n \rightarrow \mu p)} = 0.153 \pm 0.007 \pm 0.017$$

$$R_{\bar{\nu}} = \frac{\sigma(\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p)}{\sigma(\bar{\nu}_\mu p \rightarrow \mu n)} = 0.218 \pm 0.012 \pm 0.023$$

BNL734 results, reanalysis by Garvey, et al (PRC 48, 761, '93)



- G_A^s extracted from these results consistent with zero (Alberico et al, Phys. Rep. 358, 227 '02)

$\nu N \rightarrow \nu N$ scattering and Δs

- So, a measurement of νN NC cross section is sensitive to Δs, but ratios are better!
  Ratios reduce the sensitivity of result to:
  - experimental systematics (e.g. flux, efficiencies, etc.)
  - uncertainties in measured form factors (e.g. M_A)
  - nuclear effects

- R(NC p/n)

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

  - very sensitive to Δs but experimentally difficult
  - LSND attempted but cosmic-n bkgd and duty-ratio too high

- R(NC/CC)

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

  - less sensitive to Δs but experimentally easier
  - we think this is the quantity to measure!
  - A first measurement will be made with MiniBooNE, but systematics will be too large for a definitive measurement of Δs

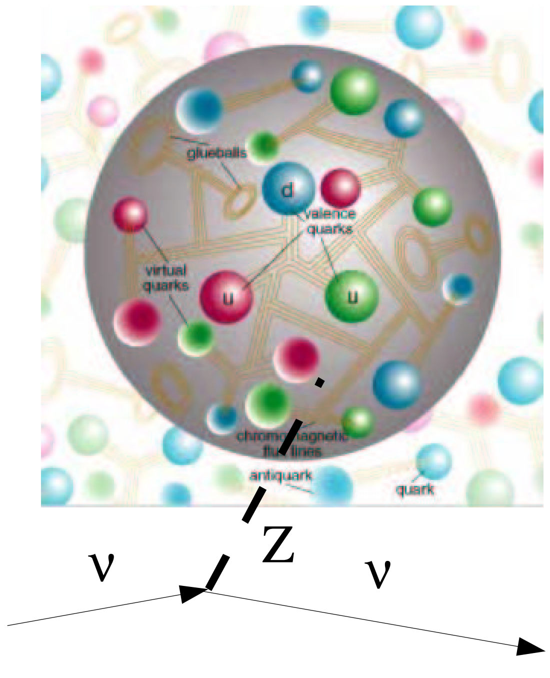
$\nu N \rightarrow \nu N$ scattering and Δs

- What carries the nucleon spin! valence quarks, sea quarks, gluons? This is still an open question and an area of intensive effort.
    - at RHIC, HERMES, COMPASS
- Also, nucleon structure in general...
    - at JLAB (Happex, G0, etc), Mainz

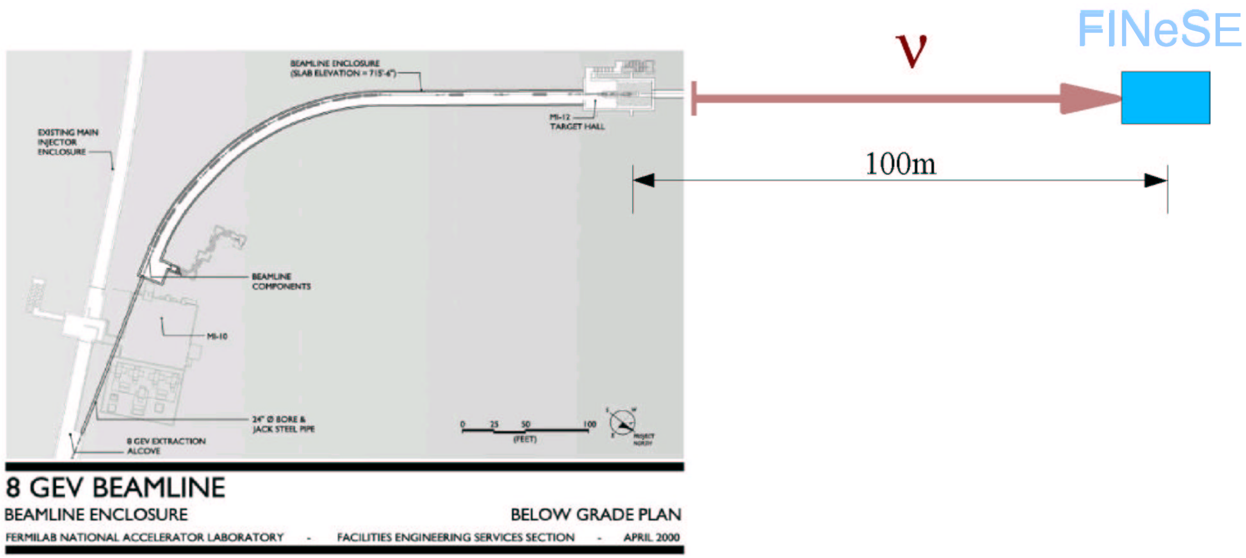
- The neutrino is a uniquely sensitive probe of the nucleon axial (spin) structure.

- The (operating!) booster neutrino beam at FNAL offers the opportunity to make these measurements.

- Let's build an experiment!



Fermilab Intense Neutrino Scattering Experiment: FINeSE



Current Collaboration:

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Fermi National Accelerator Laboratory,
C. Horowitz, T. Katori, H.-O. Meyer, R. Tayloe
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Los Alamos National Laboratory
J.-C. Peng
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Expression of Interest presented to FNAL PAC 11/15/02

FINeSE Overview

Physics:

Several important measurements in both Nuclear and Particle Physics!

- strange spin of the nucleon (Δs), nucleon form factors.
- ν cross sections (talks by Zeller, Walter, McFarland on Tues in WG1/2)
- ν oscillations (w/MiniBooNE)

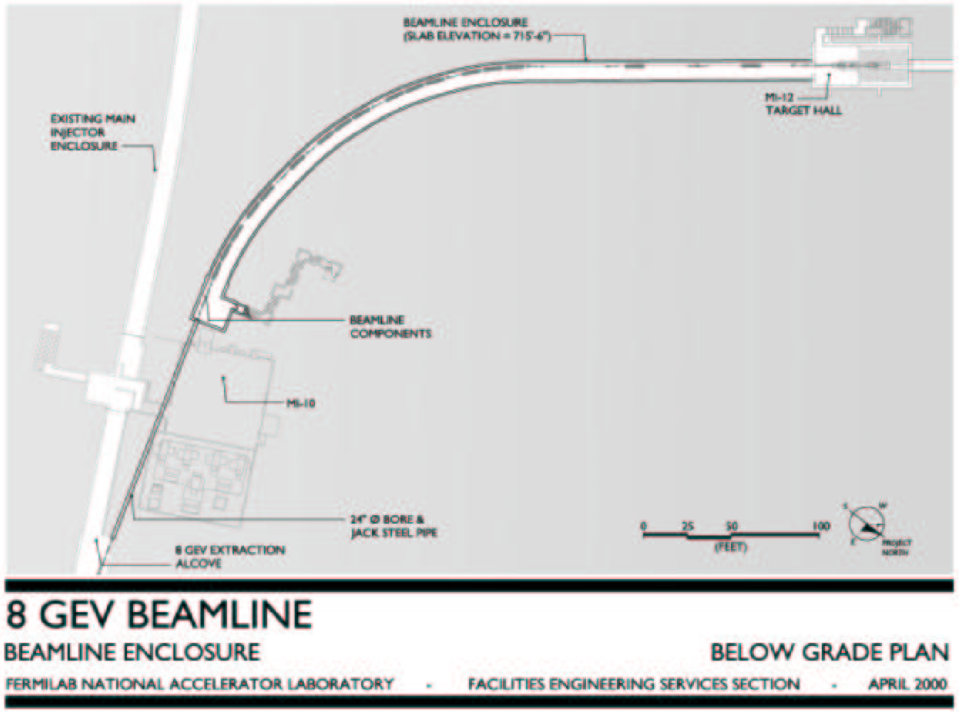
Experiment:

- 10 ton (fiducial) active-target, segmented, "tracking" detector
- located ~100m from ν target on Booster Neutrino Beamline

Requirements:

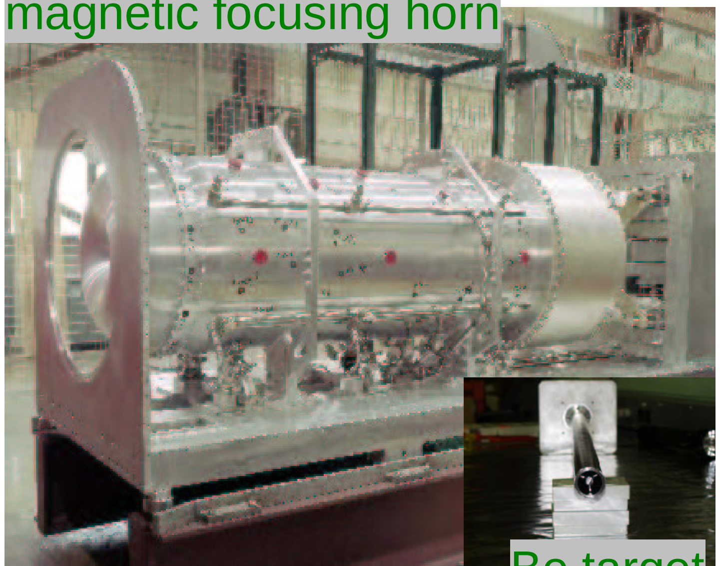
- building: ~25ft below grade
- detector: ~15 tons total
- support from NP, HEP, and FNAL
- collaboration of ~30 physicists from high-energy and nuclear physics

Booster Neutrino Beamline



8 GeV beamline

magnetic focusing horn

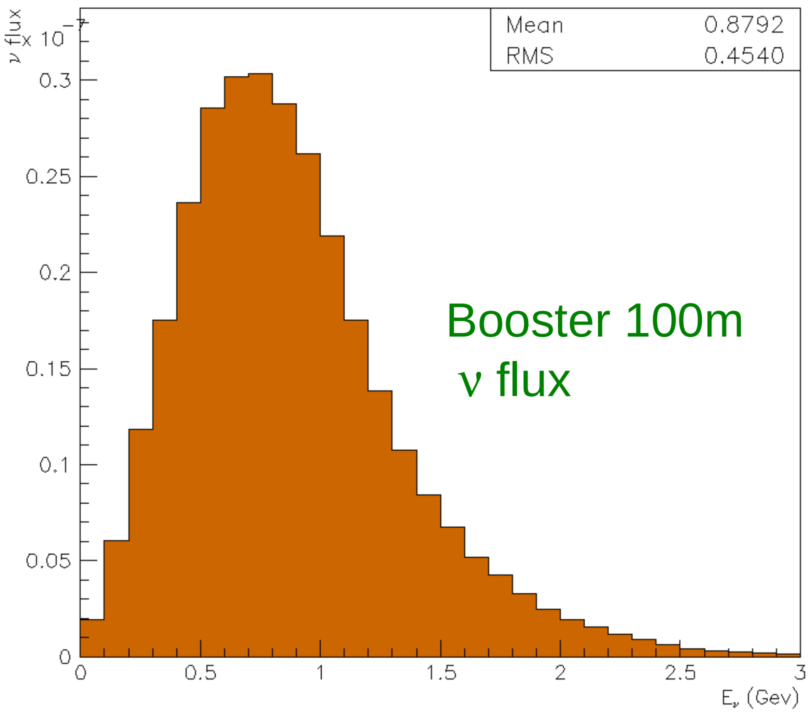


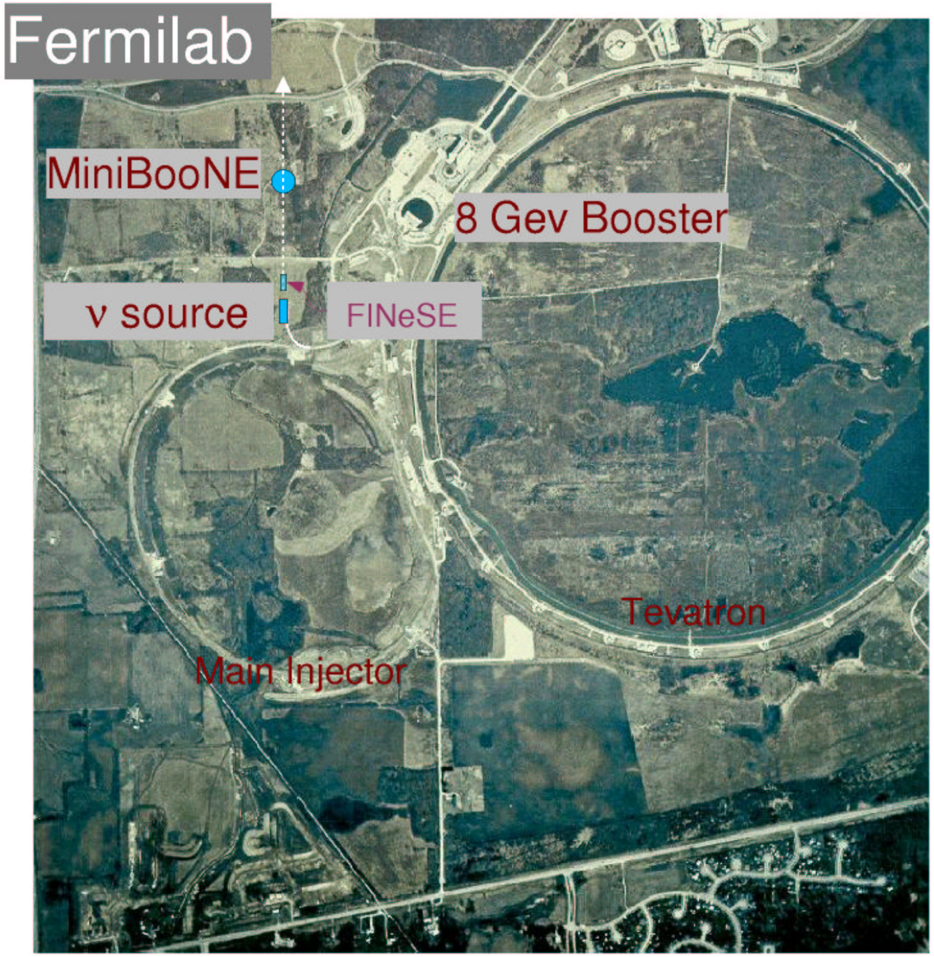
Be target

- beamline, horn, target performing well
- proton intensity approaching goal
- spare horn fabricated
- Horn polarity (and neutrino type) may
  be switched

Booster Neutrino Beamline

- 500m from ν target: MiniBooNE...
- 100m from ν target: open space!... FINeSE

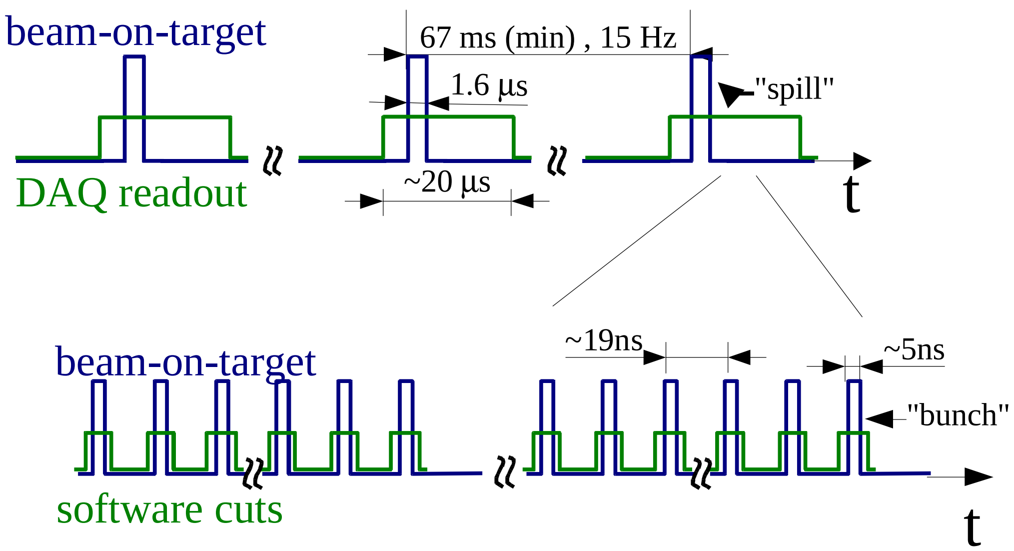




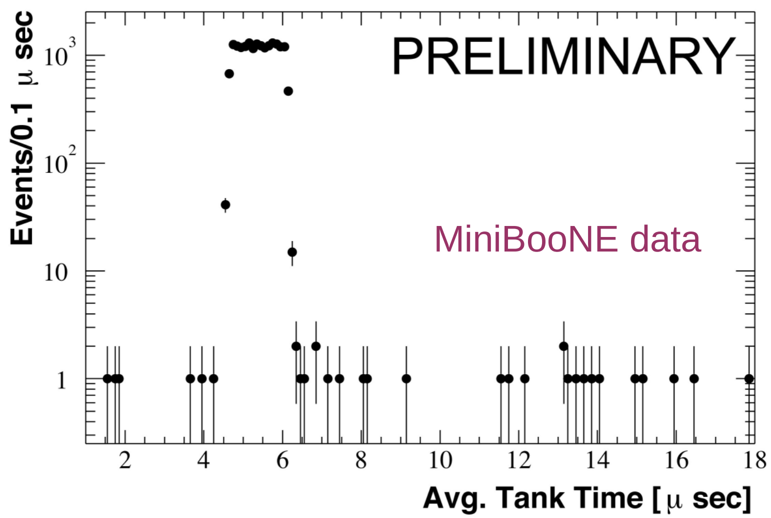
Excellent ν energy distribution for these measurements!

Booster Beam time structure

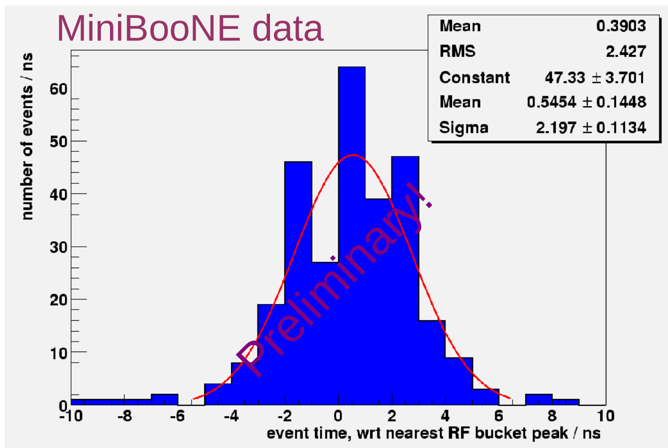
- ~1.5 µs spill width,
- with ~80 5ns bunches, ~20ns apart



(Macro) Time in beam window

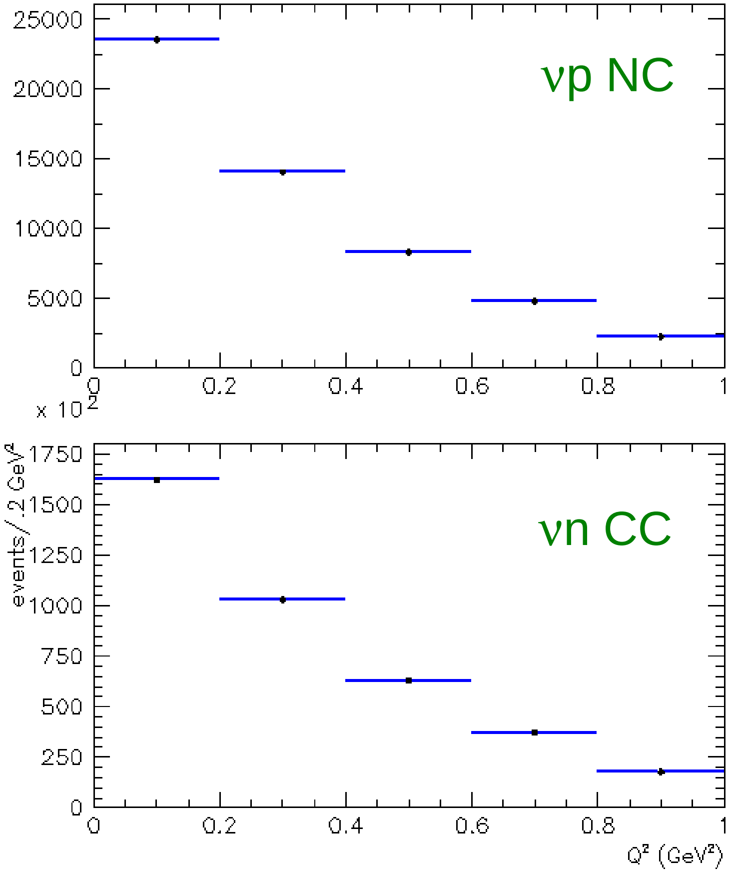


(Micro) Time w.r.t. to beam RF



FINeSE: Event Rates

Event Rates: (vs Q^2)
with a 10 ton (fiducial) detector,
5E20 POT (~1yr),
100m on Booster ν Beamline

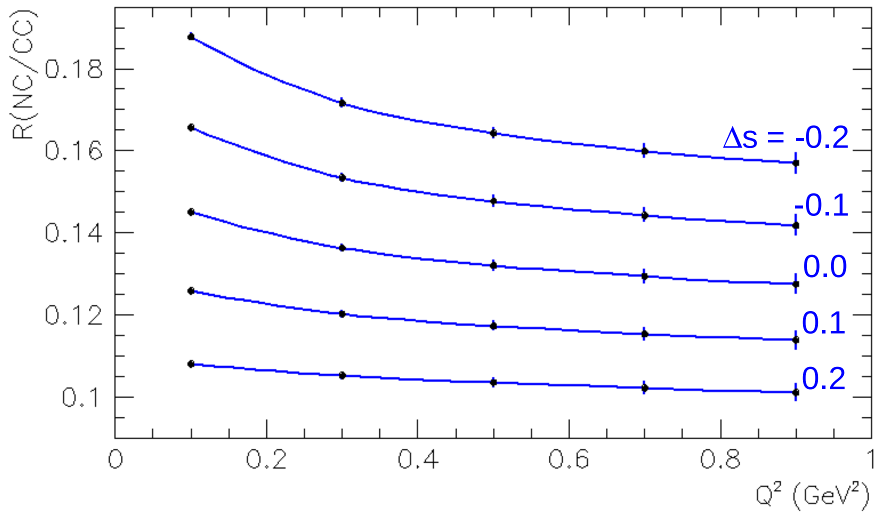


Event Rates from NUANCE*:

channel	(#/10 ton/5E20POT)
nu,n CC QE	320k
nu,p NC QE	65k
CC pi prod	230k
NC pi prod	75k

* thanks, D. Kasper, S. Zeller

R(NC/CC) vs Q^2

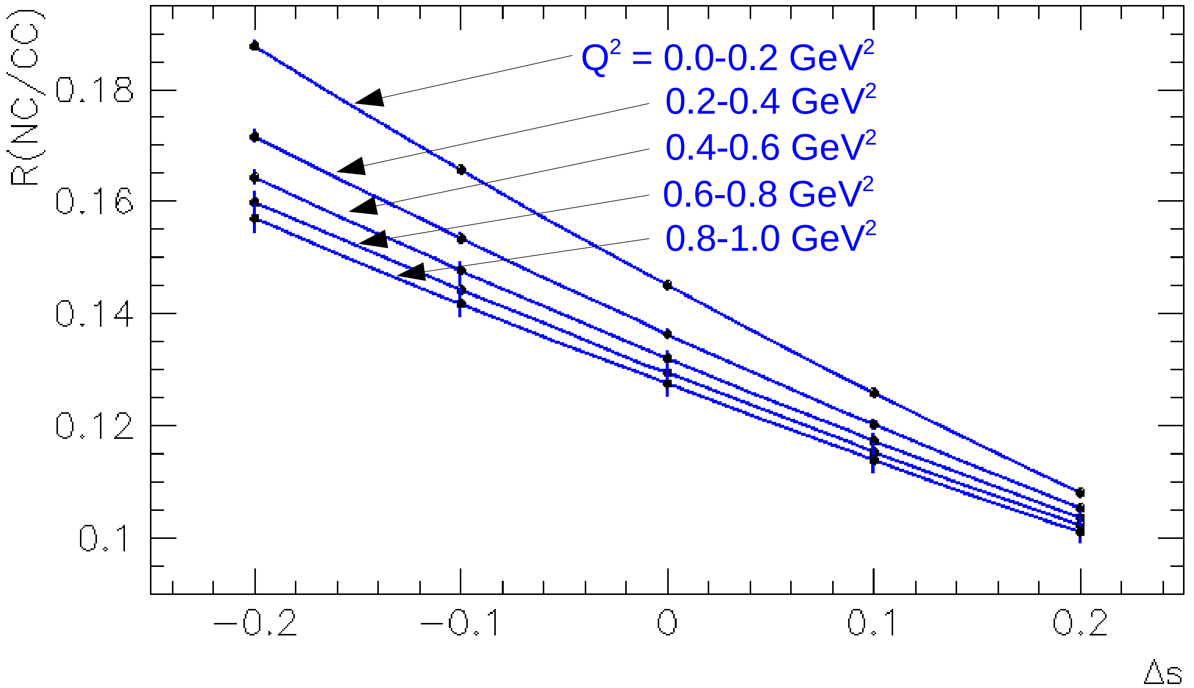


with a 10 ton (fiducial) detector,
4.2E20 POT
→ 1% statistical error on R(NC/CC)
(in Q^2 = 0.2-1.0 GeV^2)

FINeSE: sensitivity to Δs

R(NC/CC) vs Δs

with a 10 ton (fiducial) detector,
5E20 POT (~1yr),
100m on Booster ν Beamline



- Sensitivity of R(NC/CC) to Δs: σ(Δs) ~ 0.8 σ(R)/R

- so a 5% measurement of R(NC/CC) allows: σ(Δs) ~ 0.04
  (comparable to DIS scattering results).

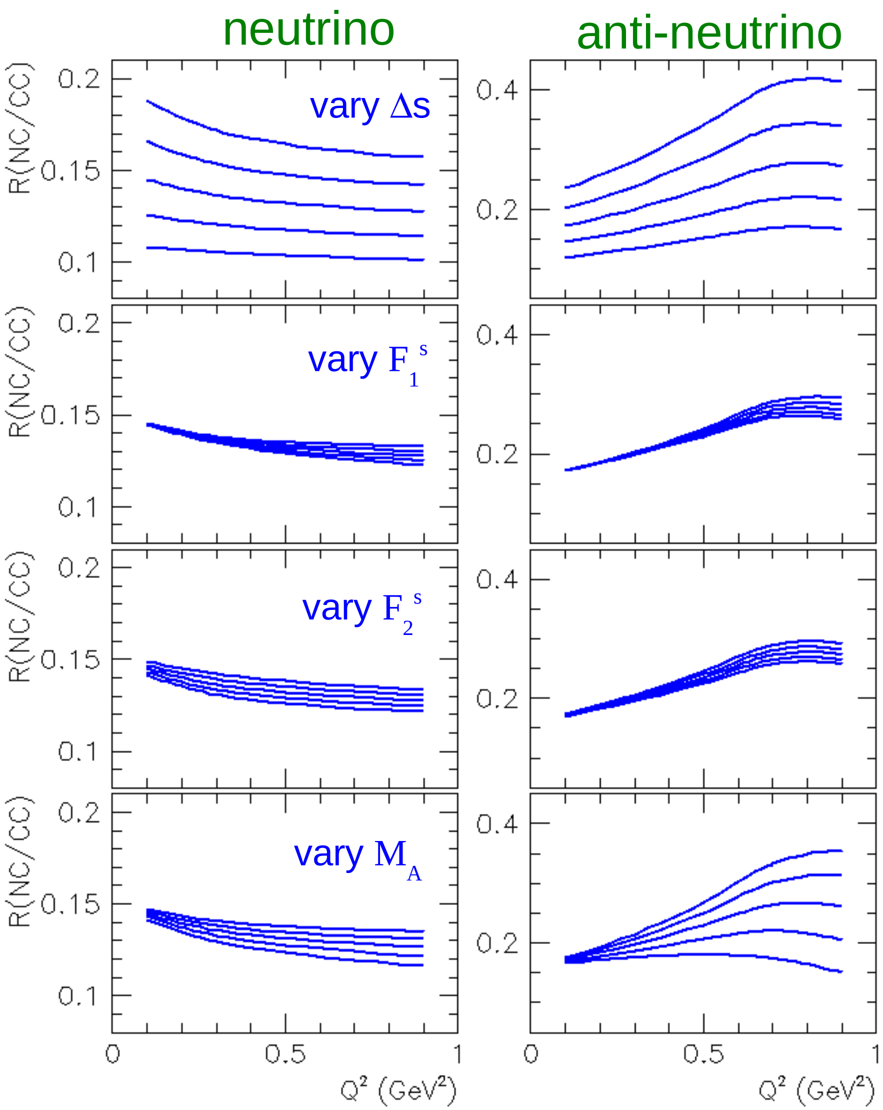
FINeSE: sensitivity to Δs and other form factors

R(NC/CC) vs Q^2 for ν and $\bar{\nu}$ with different values of F_1^s, F_2^s, G_A^s, M_A

- anti-neutrino R(NC/CC) event more sensitive to Δs

- sensitivity to other f.f.s smaller than to Δs

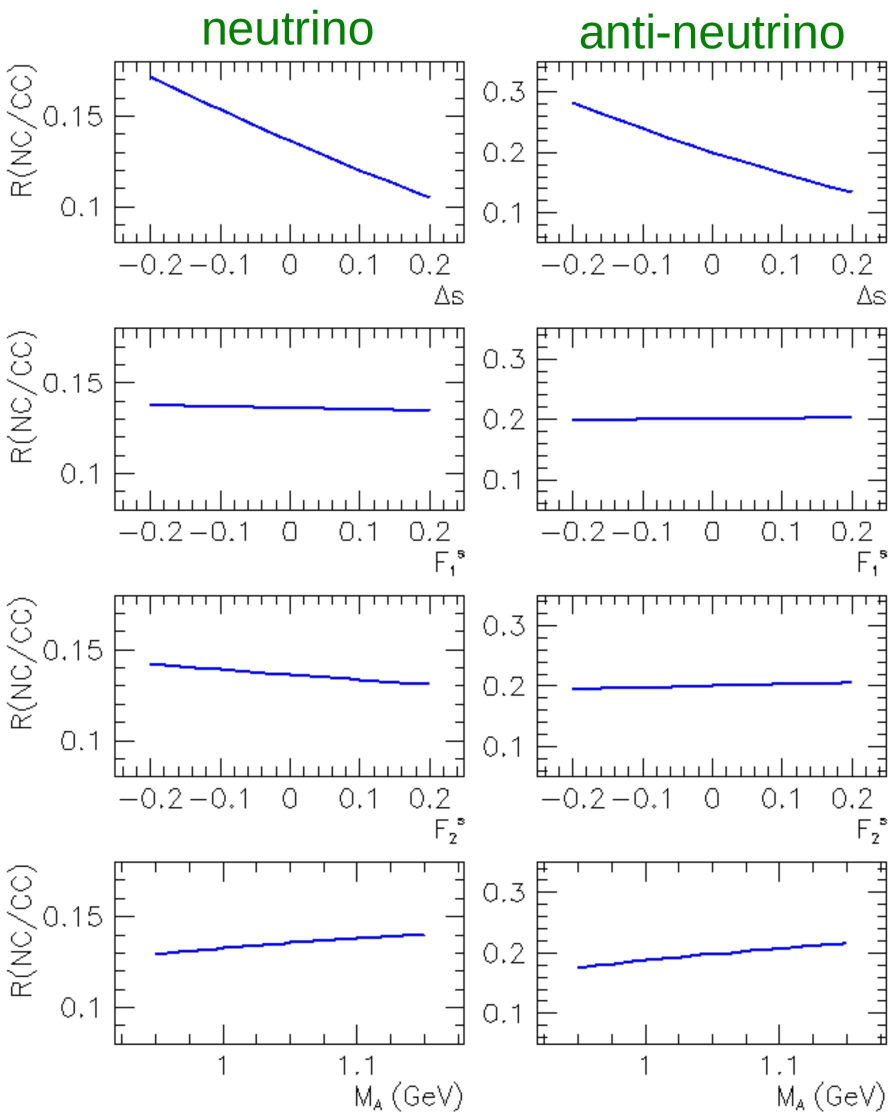
- but, with a complete data set (neutrino and antineutrino running over range of Q^2) would allow an extraction of all strange form-factors (F_1^s, F_2^s, G_A^s, M_A)



FINeSE: sensitivity to Δs and other form factors

R(NC/CC) vs F_1^s, F_2^s, G_A^s, M_A
for ν and $\bar{\nu}$

- anti-neutrino R(NC/CC) event more sensitive to Δs
- sensitivity to other f.f.s smaller than to Δs
- but, with a complete data set (neutrino and antineutrino running over range of Q^2) would allow an extraction of all strange form-factors (F_1^s, F_2^s, G_A^s, M_A)



FINeSE Detector

- Want to measure Δs with error $\leq 0.04 \Rightarrow$ R(NC/CC) to ~5%

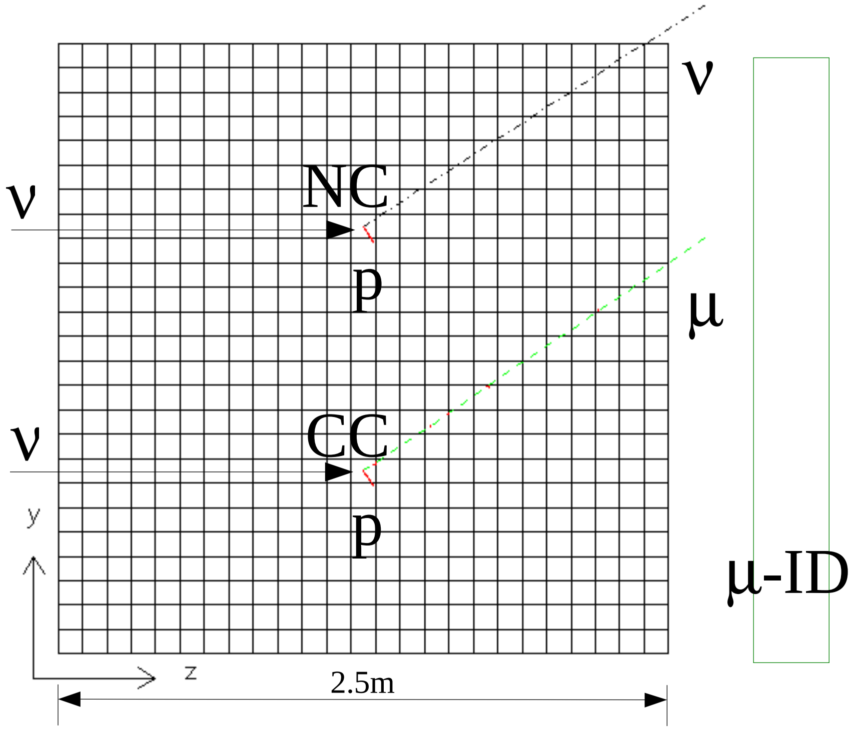
- The error on ratio (neglecting bckgnd) is dominated by error on muon detection efficiency.

$$\frac{\epsilon(NC)}{\epsilon(CC)} = \frac{\epsilon(p)}{\epsilon(p)\epsilon(\mu)} = \frac{1}{\epsilon(\mu)}$$

So need $\varepsilon(\mu)$ to 5%.

- Also, measure R(NC/CC) as function of $Q^2(=2m_p T_p)$. Need proton energy (independently of lepton energy) down to T_p~100MeV (R~10cm)

- Need a active, segmented tracking detector.



GEANT-generated event in scintillator:
Q^2 = 0.2 GeV^2, E_ν = 800MeV
T_p~100 MeV, T_μ~600 MeV

FINeSE: backgrounds

Event Rates from NUANCE:

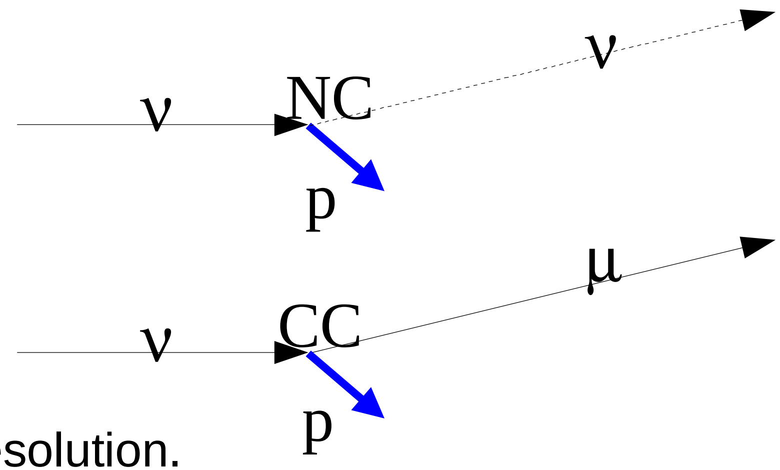
channel	(#/10 ton/5E20POT)
nu,n CC QE	320k
nu,p NC QE	65k
CC pi prod	230k
NC pi prod	75k

- Largest background worry is misid'd νp NC elastic events

  - π and μ mis-id'd as p, lose proton. (next slide)

  - CC and NC interaction in earth around detector creates neutrons that interact in detector in-time with beam. Currently under study.

  - νn NC neutrons misid'd as protons. Reduced by good tracking, energy resolution. Ideally, detect n-capture photon. Currently under study.



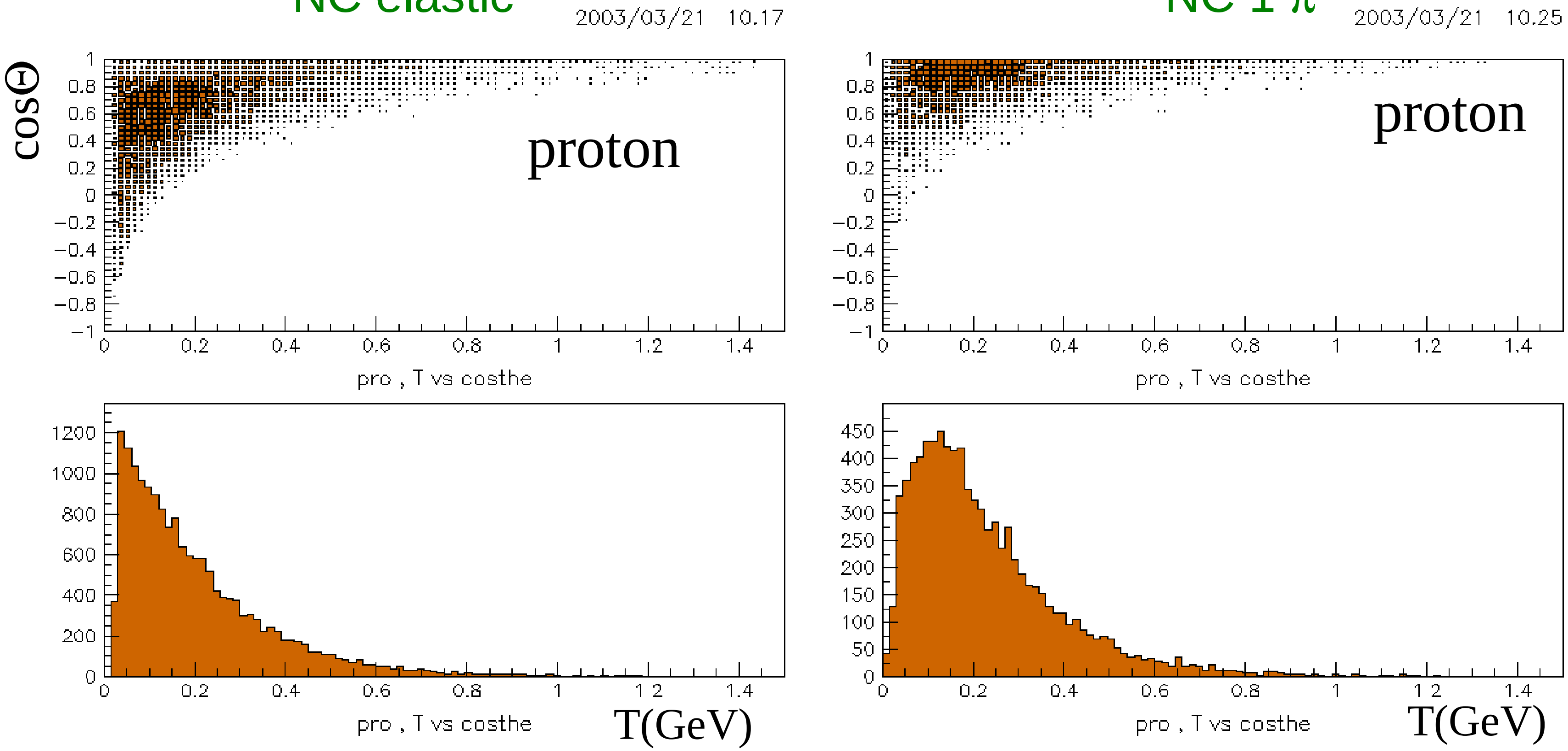
FINeSE: backgrounds

-NC 1 π not too bad, kinematics are different.

- Need π mis-id < 1 in 20
- and angular resolution 5-10° , energy resolution ~ 20%

Proton cosΘ and K.E. distributions in

NC elastic — NC 1 π

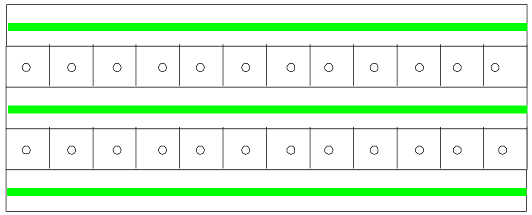


FINeSE Detector

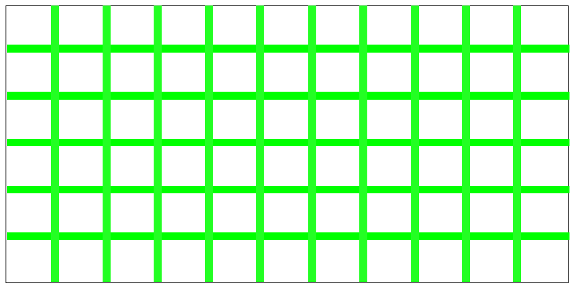
Requirements:

- active target (no dead regions, all CH_2)
- segmented, for tracking with angular resolution ~5-10°
- energy threshold ~ 100MeV protons (R~10cm) energy resolution ~20%
- particle id: p/π/μ/e separation to ~5%
- ~10 ton fiducial mass
- detector possibilities
    - "scistack" : scintillator bars with WLS fibers
    - "scibath": WLS fibers in liquid scintillator (allows xyz position recon)
    - RPCs for muon tracking

scistack



scibath



- readout possibilities
    - multianode PMTs
    - intensified CCDs
    - ?

scistack and scibath prototypes with PMT and CCD readout will be tested this summer at Indiana U. cyclotron facility (200MeV protons)

Summary

- A unique opportunity currently exists to definatively measure Δs
  using the FNAL booster neutrino beam. We will propose FINeSE to do this.

- Timeline:
  - Detector design and proposal ready this fall
  - Build hall and detector in 2004-2005
  - Ready for beam ~end of 2005.

- In addition, a hall at 100m on the FNAL booster neutrino beamline would provide a space for other physics measurements/detector tests.

- For more information:
  - contact us!
  - FINeSE www page:
    http://home.fnal.gov/~bfleming/finese.html
  - see paper by Alberico et al., (Phys. Rep. 358, 227, '02) for theoretical background

about these images