# A Letter of Intent for a Neutrino Scattering Experiment on the Booster Neutrino Beamline: FINeSSE

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FINeSSE
Fine-grained
Intense
Neutrino
Scattering
Scintillator
Experiment

R. Tayloe, Indiana U.
B.T. Fleming, Yale U.
PAC presentation,
FNAL, 4/7/05

# FINeSSE Overview

## Physics:

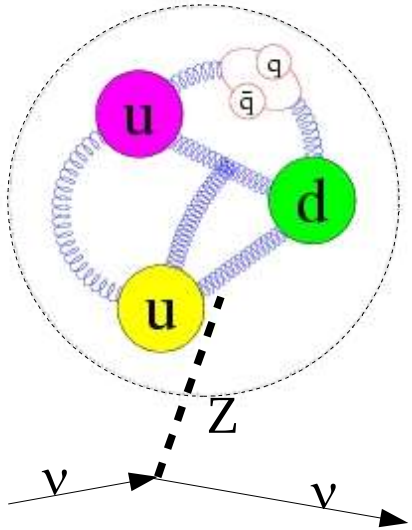
2 important measurements:

- Nucleon Structure:

  $\Delta s$, the contribution of strange quarks to spin of the nucleon

- Neutrino Physics:

  Neutrino cross sections at $E_\nu$ ~1 GeV

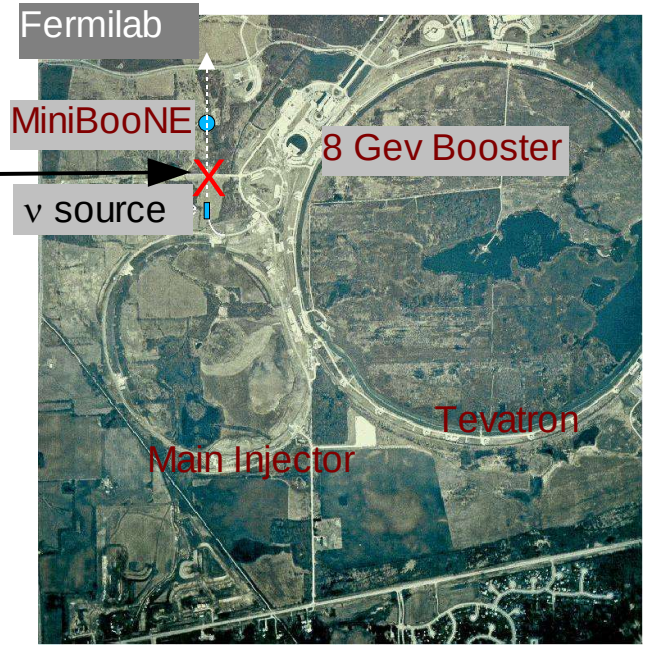



## Experiment:

- modest-sized (~10ton), economical (~$2.8M) detector...

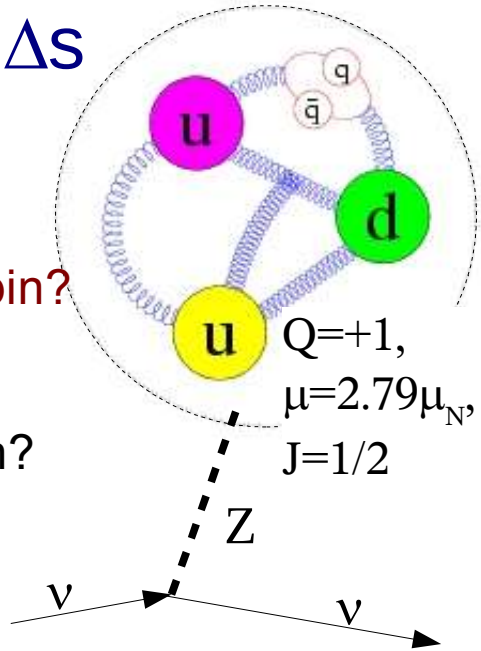
- to be located 80m from neutrino source on (existing) Booster Neutrino Beamline (BNB)...

- for a ~3yr run (6E20 POT): 1yr $\nu$ , 2yr anti-$\nu$



# FINeSSE Physics: A measurement of $\Delta s$

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




A fundamental question:
How do the nucleon constituents contribute to the total spin?
(the "proton spin puzzle")
Valence quarks, sea quarks, gluons?
How does this fit into a fundamental theory of the nucleon?

This is (still) an open question and the subject of intense effort at labs around the world.

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 $\Delta s$

...using the FNAL booster $\nu$ beamline

# Development of FINeSSE at Fermilab:

## The situation for FINeSSE at FNAL has evolved in last ~15 months:

- Recent gains in Booster (8 GeV) intensity open the possibility for additional experiments on the Booster Neutrino Beamline. From "Prospects for the Booster Neutrino Beam", M. Witherell, 8/6/04:

> With these recent improvements, we can consider seriously the prospects for doing physics with the Booster neutrino beam while operating the NuMI neutrino beam. The demands of antiproton production and NuMI operation will use most of the proton capacity of the Booster. With the proton rates now achieved from the Booster, we can see for the first time that there will be some additional protons available for the Booster neutrino line.
>
> Collaborations proposing experiments to run in the Booster neutrino beam in FY 2006 and beyond should plan their physics program on the basis of 1-2 x $10^{20}$ protons on target per year.

- Improved background rejection for the $\Delta s$ measurement, resulting in reduction of error on $\Delta s$ from $\pm 0.04 \rightarrow \pm 0.025$.

- Further work on cross section measurements and increased recognition of their importance for neutrino oscillation measurements (APS Study on Neutrino Physics).

- A plan for combined $\nu$/anti-$\nu$ running $\rightarrow$ important for $\Delta s$ and cross section measurements.

# Current measurements of $\Delta s$

Polarized Lepton Deep Inelastic Scattering (e.g. SMC)

$\Rightarrow \Delta s \sim -0.10 \pm 0.06$ (leading-order calc)

+ theoretical uncertainties:
  - extrapolation to x = 0
  - assumption of $SU(3)_f$ symmetry

SMC: Phys Lett **B412**, 414 ('97).

| | "Regge" | QCD fit |
|---|---|---|
| $\Delta u$ | $0.84 \pm 0.06$ | $0.80 \pm 0.06$ |
| $\Delta d$ | $-0.42 \pm 0.06$ | $-0.46 \pm 0.06$ |
| $\Delta s$ | $-0.08 \pm 0.06$ | $-0.12 \pm 0.06$ |

$\Delta q = q\uparrow - q\downarrow + \bar{q}\uparrow - \bar{q}\downarrow$

Semi-inclusive polarized positron scattering (HERMES):

$\Rightarrow$ "$\Delta s$" = $0.028 \pm 0.033 \pm 0.009$ ($0.023 < x < 0.60$)

HERMES: PRD **71**, 012003 ('05).

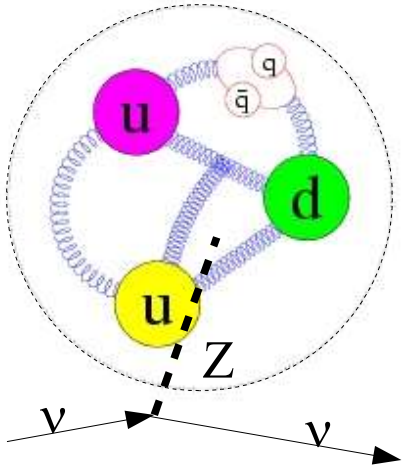
+ theoretical uncertainties:
  - limited x range
  - meson-quark factorization

- A measurement of neutrino-nucleon elastic-scattering can determine $\Delta s$ <u>directly</u> via a measurement of the neutral-current axial form factor.
  This method requires:
  - no assumptions of SU(3) symmetry
  - no extrapolation to x=0
  - no factorization

$\Rightarrow$ A more theoretically robust measurement of $\Delta s$

# $\nu N \rightarrow \nu N$ scattering and $\Delta s$

## - Axial part of Nucleon Neutral Weak Current:




$$\langle N|A_\mu^Z|N\rangle = -\left[\frac{G_F}{\sqrt{2}}\right]^{1/2} \langle N|\frac{1}{2}\{\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 s\}|N\rangle$$

$$= -\left[\frac{G_F}{\sqrt{2}}\right]^{1/2} \langle N|\frac{1}{2}\{-\overset{\Delta u}{G_A(Q^2)}\gamma_\mu\gamma_5\tau_z + \overset{\Delta d}{G_A^s(Q^2)}\gamma_\mu\gamma_5\}|N\rangle$$

- $G_A$ (non-strange, $\Delta u$-$\Delta d$) known (from n β-decay)

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

- At low $Q^2$, (NC elastic) cross section is most sensitive to axial part (unique to neutrino scattering):

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

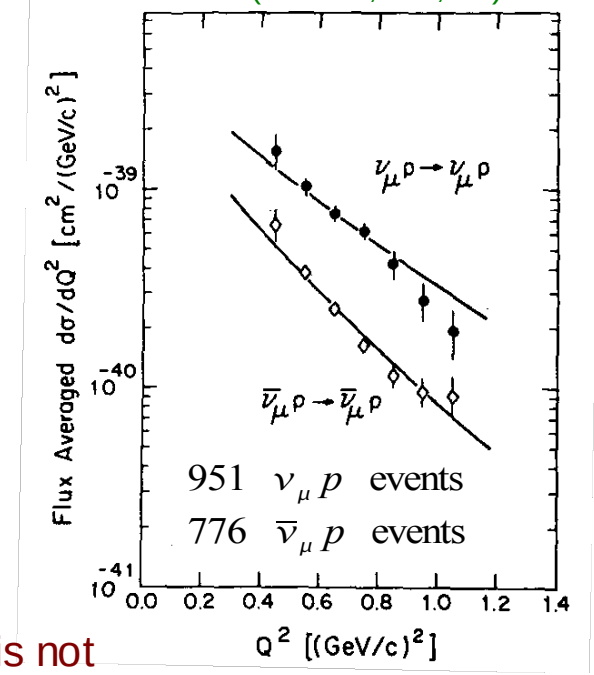
- Therefore, a measurement of $\nu N$ NC scattering (at low $Q^2$) yields $\Delta s$

# NC neutrino scattering: BNL E734

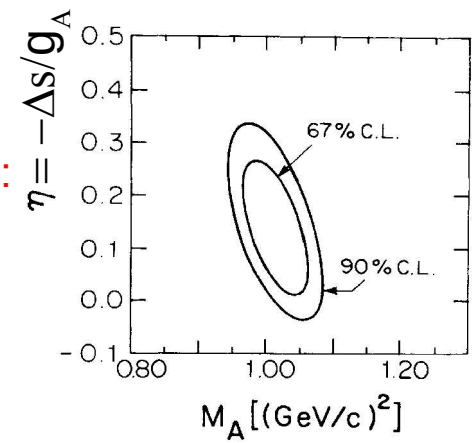
The best measurement of νN NC scattering to date is from BNL E734:

- νp, ν̲p elastic scattering,w/170 ton segmented detector,
- @$E_\nu$~1.2 GeV , $Q^2 = 0.45 \rightarrow 1.05$ GeV$^2$
- A fit to the νp, ν̲p elastic scattering diff xsection yielded:
  $\Delta s = -0.15 \pm 0.09$ (+ unquoted form factor uncertainties)
- This data has generated much interest...
  and several reanalyses: (Garvey et al., PRC48, 761, 1993; Alberico et al., Nucl. Phys. A651, 277, 1999; Pate, PRL 92, 082002, '04):

BNL734 (PRD 35, 785, '87):




-These reanalyses are interesting, however, the BNL734 data is not accurate enough for an extraction of Δs with sufficiently small errors.




- This measurement may be significantly improved with FINeSSE:
  - with more events (~10k NCp events, ~x10 E734)
  - with lower background
  - at lower $Q^2$ (down to 0.2 GeV$^2$)
  - with a ratio method : R(NC/CC) (ν and anti-ν)

# A ratio method to extract $\Delta s$

The $\nu N$ NC cross section is sensitive to $\Delta s$, and a measurement of the NC/CC ratios:

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

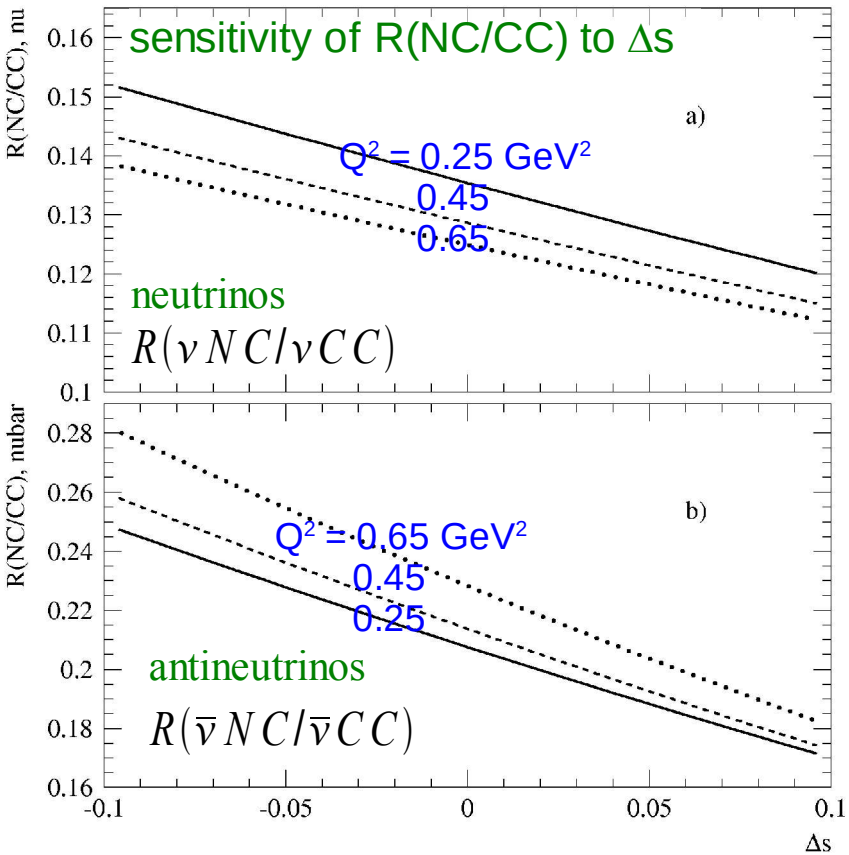
$$\overline{R_\nu}(NC/CC) = \frac{\sigma(\overline{\nu_\mu} p \to \overline{\nu_\mu} p)}{\sigma(\overline{\nu_\mu} p \to \mu n)}$$

Reduces errors due to:

- exp. systematics:
  - $\nu$ flux
  - efficiencies

- nuclear effects (in Carbon)

- form factors (e.g. $M_A$)

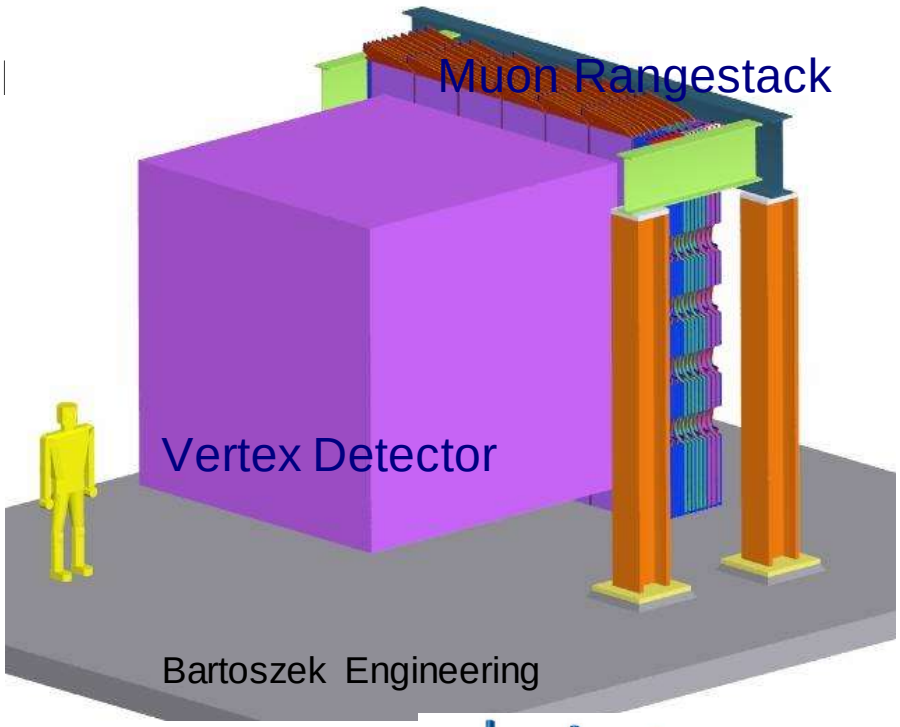


# FINeSSE Detector

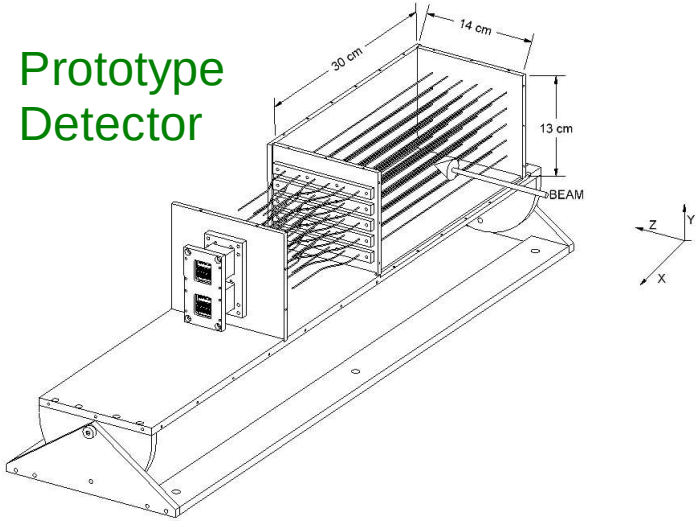
The FINeSSE detector (utilizing a novel concept) has been

- designed,
- prototyped, and
- beam-tested.

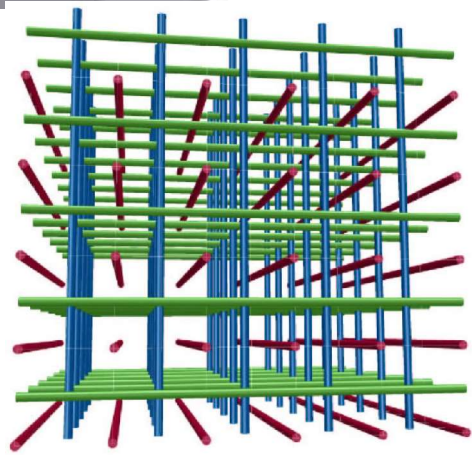
... For details see LOI.




Prototype Detector



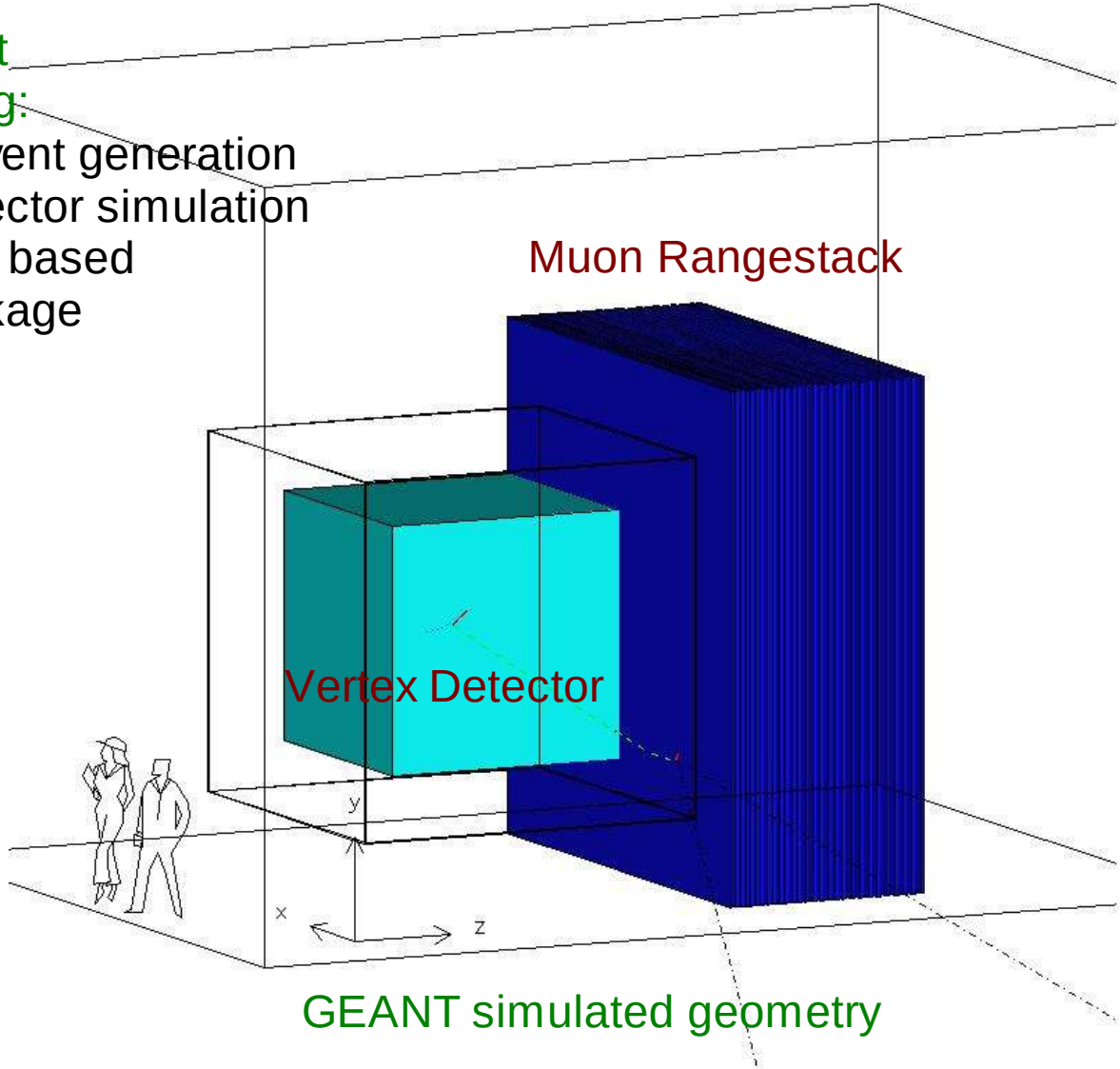

WLS fibers in Vertex Detector



# FINeSSE Detector Simulation and Reconstruction

The FINeSSE experiment has been simulated using:

- NUANCE for the event generation
- GEANT for the detector simulation
- A Hough-transform based reconstruction package

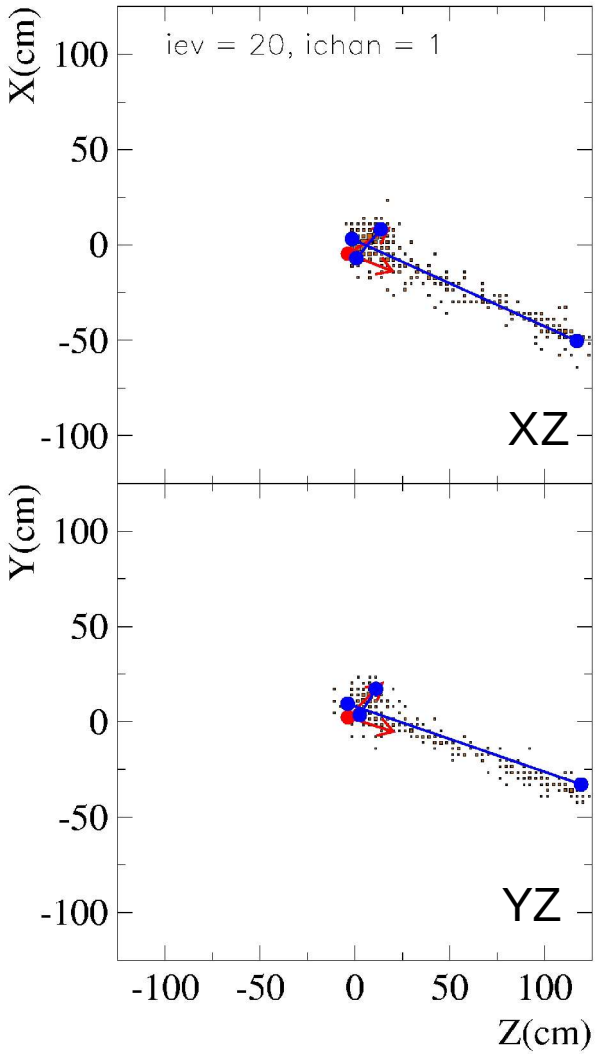



GEANT simulated geometry

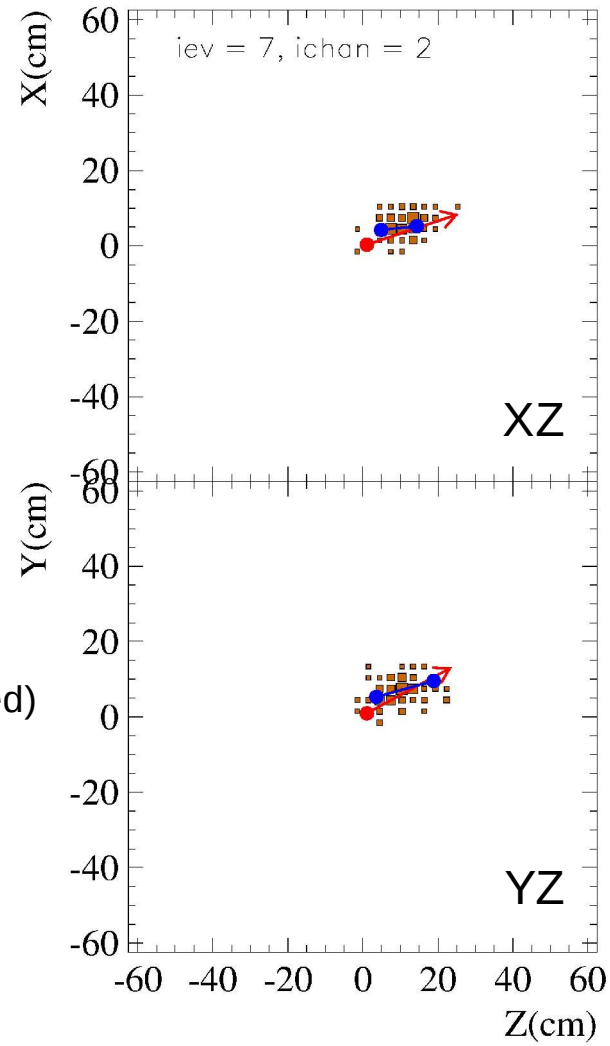
# FINeSSE Detector Simulation and Reconstruction...

simulated hits and reconstructed tracks in the Vertex Detector

CCQE event




NCp event




fiber hits,
(size ∝ # γ collected)

generated

reconstructed

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

- high purity/low background
  for NC and CCQE events

400k reconstructed MC events

$\nu NC: \nu_\mu p \rightarrow \nu_\mu p$

NCn ($\nu n \rightarrow \nu n$)
misID is kept low
by n-capture ID

| | reaction channel | | | | |
|---|---|---|---|---|---|
| **NCp cuts** | NCp | NCn | NC$\pi$ | CCQE | CC$\pi$ |
| raw events | 39098 | 37544 | 35500 | 184032 | 100630 |
| passed events | 5668 | 483 | 131 | 203 | 24 |
| efficiency (%) | 14.5 | 1.3 | 0.4 | 0.1 | 0.0 |
| fid. eff. (%) | 21.3 | 1.9 | 0.5 | 0.2 | 0.0 |
| purity (%) | 87.1 | 7.4 | 2.0 | 3.1 | 0.4 |

$\nu CC: \nu_\mu n \rightarrow \mu^- p$

| **CCQE cuts** | NCp | NCn | NC$\pi$ | CCQE | CC$\pi$ |
|---|---|---|---|---|---|
| raw events | 39098 | 37544 | 35500 | 184032 | 100630 |
| passed events | 84 | 7 | 285 | 10090 | 1789 |
| efficiency (%) | 0.2 | 0.0 | 0.8 | 5.5 | 1.8 |
| fid. eff. (%) | 0.3 | 0.0 | 1.2 | 8.0 | 2.6 |
| purity (%) | 0.7 | 0.1 | 2.3 | 82.0 | 14.5 |

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

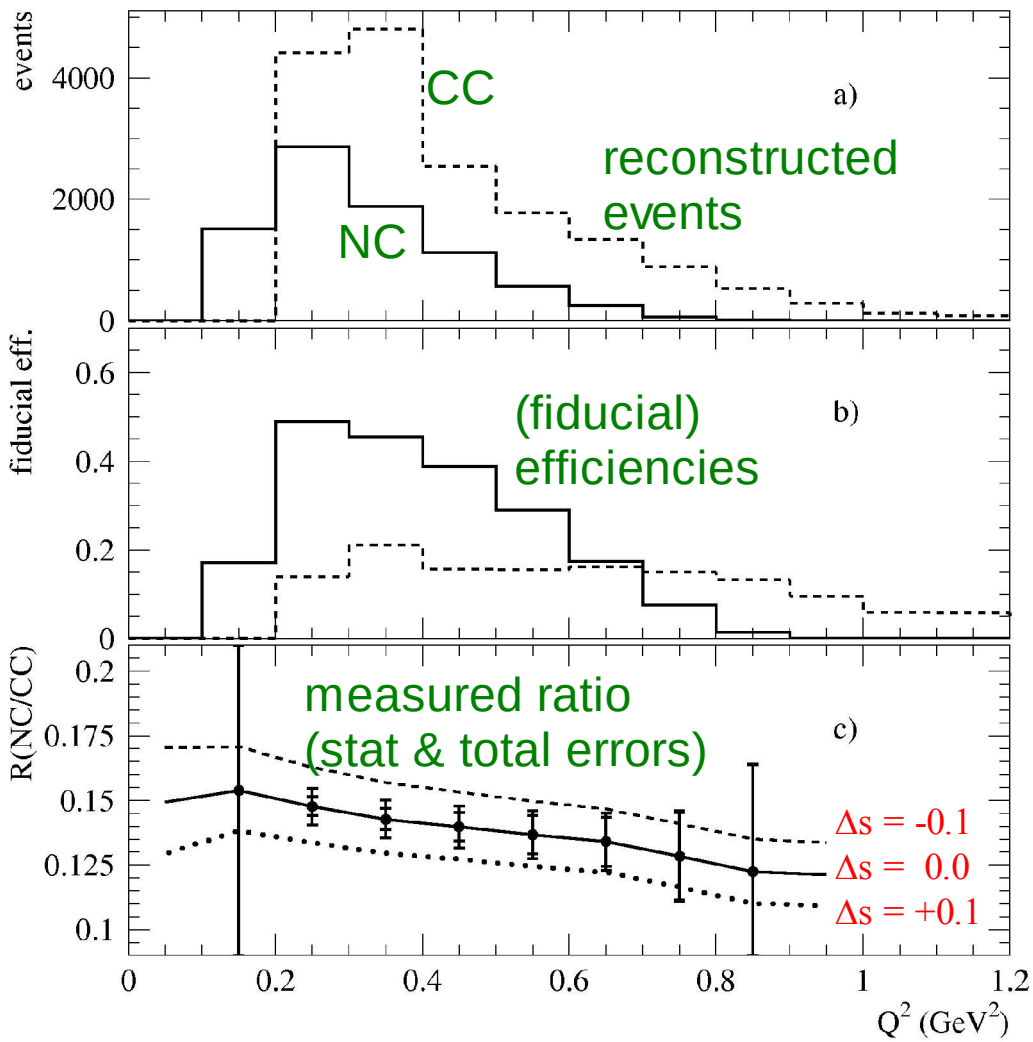
A fit to the simulated data was performed to estimate the precision of $\Delta s$ extracted from a measurement of the neutrino NC/CC ratio (1 yr nu run):

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

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

experimental (stat + sys) error:

$\sigma(\Delta s) = \pm 0.025$



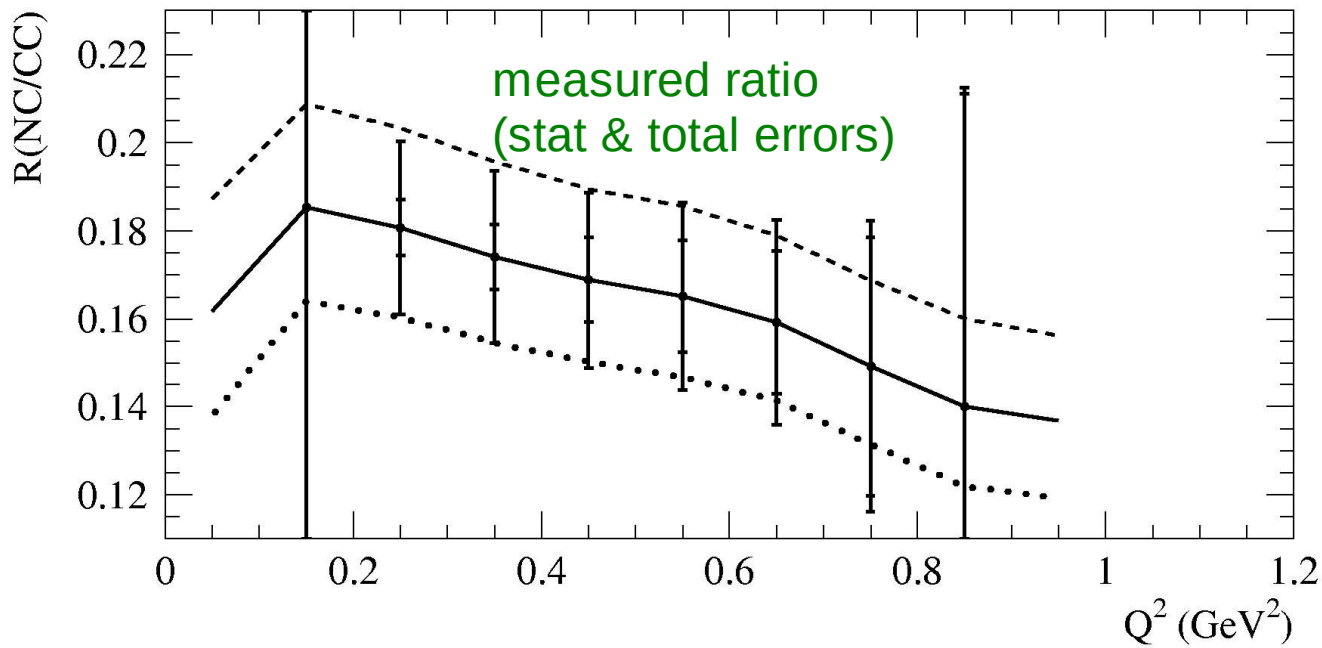
# Simulation of R(NC/CC) measurement..

A similar exercise (albeit less rigorous, full simulations on anti-ν runs underway) was performed for a 2 yr anti-ν run:

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

experimental
(stat + sys) error:

$\sigma(\Delta s) = \pm 0.04$



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

- The NC/CC ratios depend (somewhat) on $F_1^s$, $F_2^s$ (and $M_A$) also. An analysis of these "form-factor uncertainties" yields: $\sigma(\Delta s) = \pm 0.02$ (both $\nu$ and anti-$\nu$)

- Running with both $\nu$ and anti-$\nu$ will allow for these uncertainties to be investigated via $Q^2$ dependence.

- In fact, a global fit with $\nu$/anti-$\nu$/PVe data may be performed (ala Pate, PRL 92, 082002, '04) to simultaneously measure $\Delta s$ ($G_A^s$), $F_1^s$, $F_2^s$, thus eliminating the f.f. uncertainties.
  Preliminary results show this is possible.

# Summary of anticipated errors on $\Delta s$

FINeSSE:

From neutrinos (1y run at FNAL):

$\sigma(\Delta s) = \pm 0.02$

From antineutrinos (2y run at FNAL):

$\sigma(\Delta s) = \pm 0.04$

Other experiments:

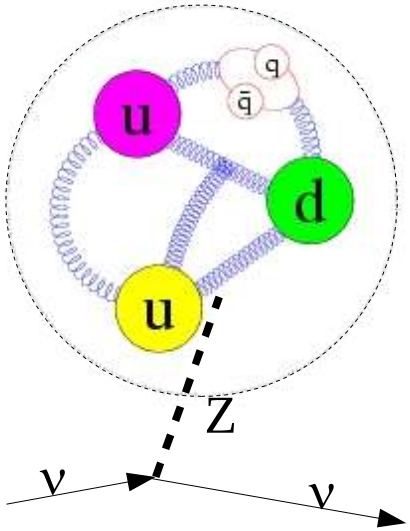
BNL E734 ($\nu$):

$\Delta s = -0.15 \pm 0.09$

SMC (polarized DIS):

$\Delta s = -0.12 \pm 0.06$

$-0.08 \pm 0.06$




FINeSSE will provide a measurement of $\Delta s$ via neutrino-scattering

- more precise and more theoretically robust than DIS experiments
- much more precise (and at lower $Q^2$) than previous $\nu$ experiment

This measurement will allow us to make a precise and conclusive statement about the strange quark contribution to the proton spin.