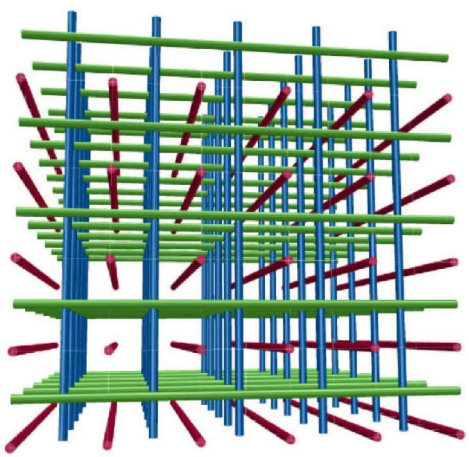
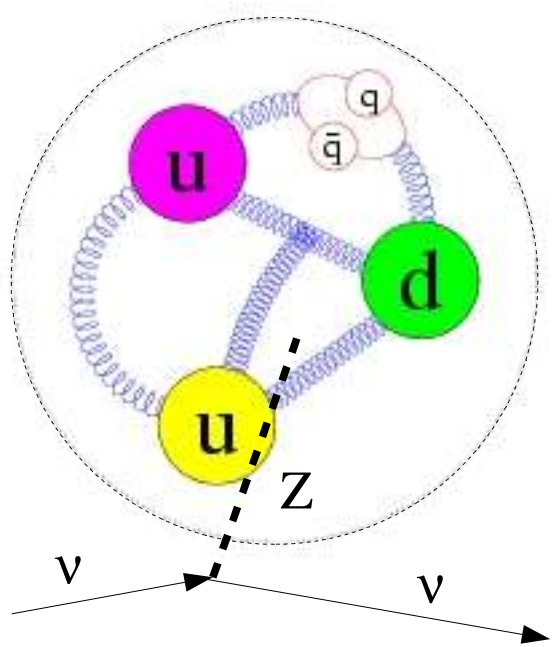
# FINeSSE

Outline:
- Neutrinos as probes of strange spin - $\Delta s$
- Neutrino cross sections
- The FINeSSE Experiment
    - detector and measurements



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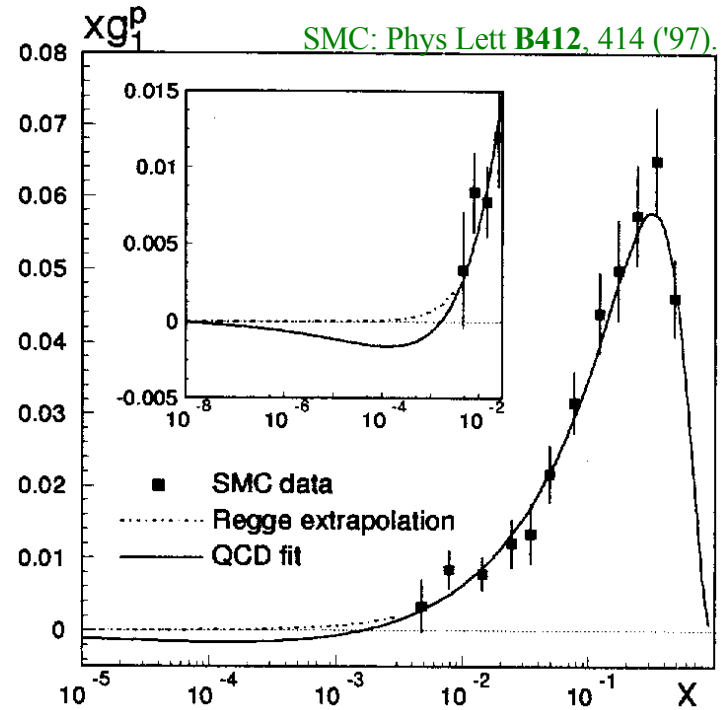
# Nucleon Structure: strange quark spin Δs

- Polarized Lepton Deep Inelastic Scattering (DIS) experiments; e.g. SLAC (ESA), CERN(EMC,SMC); have extracted the quark contributions to the spin (Δq) of the nucleon via the axial structure function: $g_1^{p,n}(x,Q^2)$.

Requires:

- integration over x $\left(\Gamma_1^{p(n)} \equiv \int_0^1 g_1^{p(n)}(x)\,dx\right)$
- use of nucleon/hyperon decay data (assumes $SU(3)_f$ symmetry)




⇒

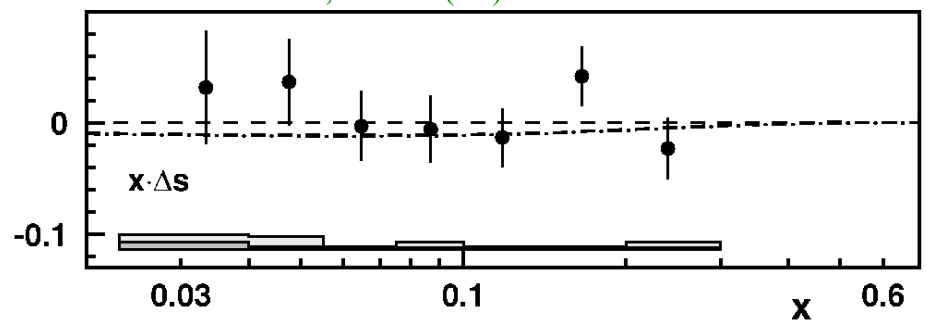
| | "Regge" | QCD fit |
|---|---|---|
| $\Delta u$ | $0.84 \pm 0.06$ | $0.80 \pm 0.06$ |
| $\Delta d$ | $-0.42 \pm 0.06$ | $-0.46 \pm 0.06$ |
| $\Delta s$ | $-0.08 \pm 0.06$ | $-0.12 \pm 0.06$ |

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$
$$\Delta q = q\uparrow - q\downarrow + \bar{q}\uparrow - \bar{q}\downarrow$$

# Nucleon Structure: strange quark spin $\Delta s$...

- In addition, recent results from HERMES in semi-inclusive scattering of polarized positrons from polarized deuterium allow for the extraction of sea-quark helicities:

HERMES: PRL **92**, 012005 ('04).




$\Rightarrow$ "$\Delta s$" = 0.03±0.03±0.01 (0.023<x<0.30)

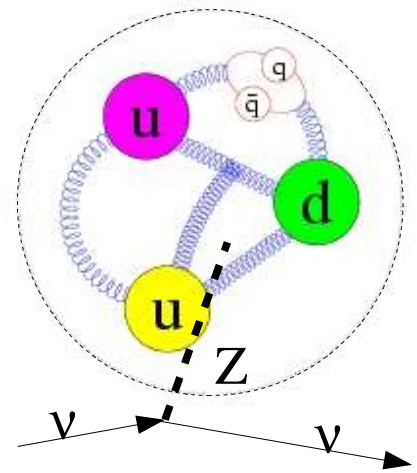
Note:
- Limited x range
- Is the (meson-quark) factorization robust?

- 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 extrapolation to x=0
  - no assumptions of SU(3) symmetry

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

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

## - Axial part of Nucleon Neutral Weak Current:




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

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

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

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

- At low $Q^2$, (NC elastic) cross section in 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 $\Delta s$

# A ratio method to extract Δs

A measurement of $\nu N$ NC cross section is sensitive to Δs...
but a cross-section ratio measurement is better!

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

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

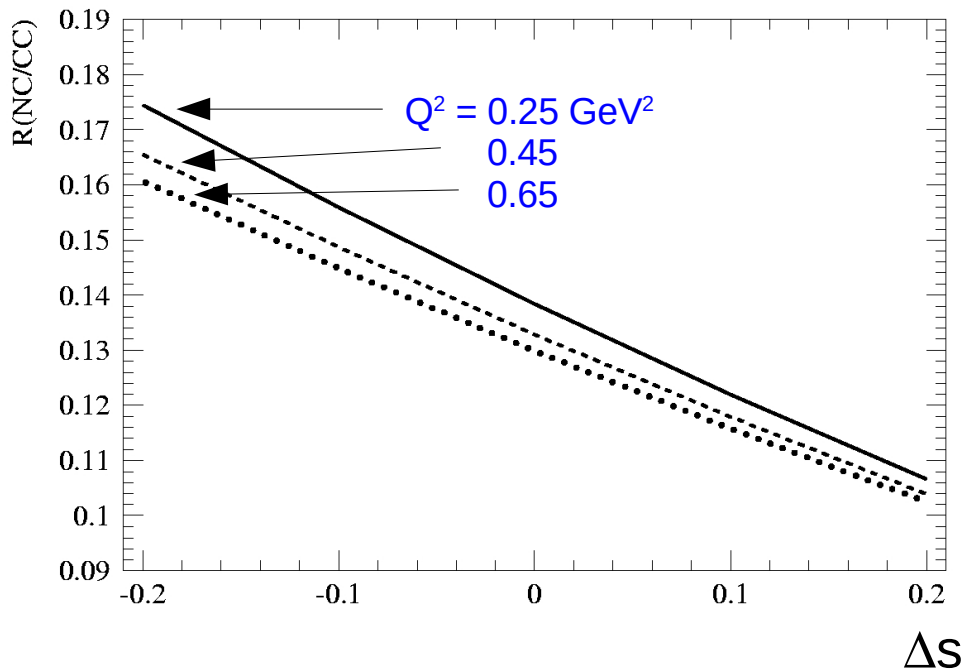
A measurement of $R_\nu$(NC/CC) reduces

- experimental systematics (e.g. flux, efficiencies, etc.)

- nuclear effects

- other form factor uncertainties (e.g. $M_A$)

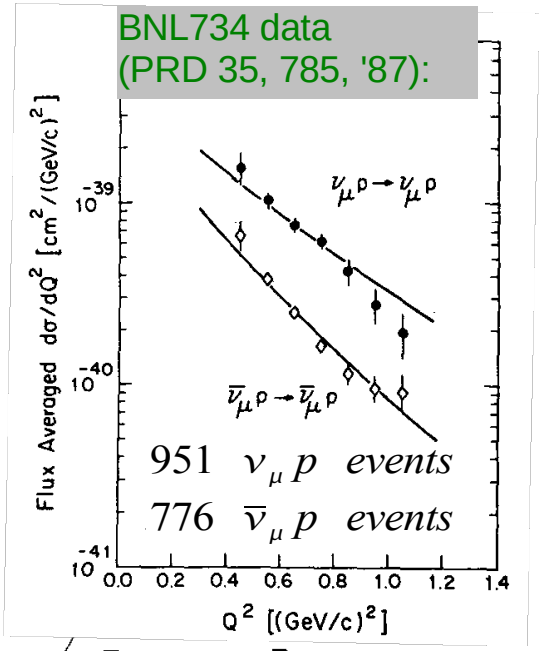
sensitivity of R(NC/CC) to Δs



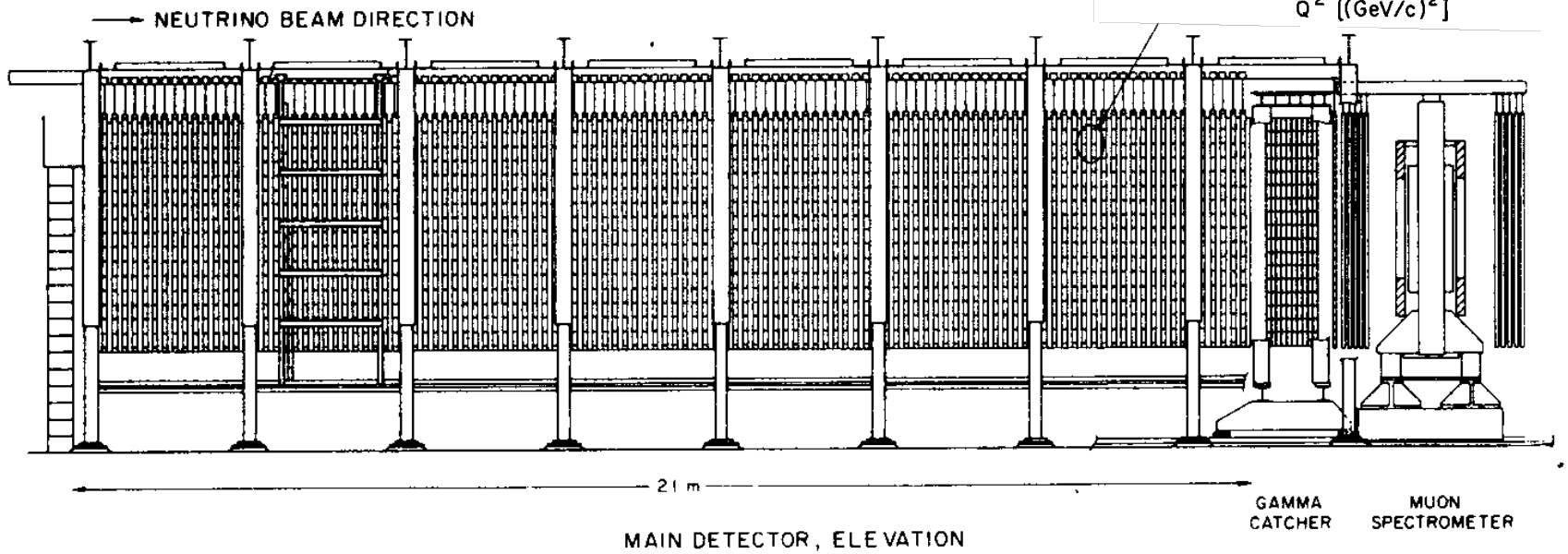
# NC neutrino scattering: BNL E734

BNL E734: $\nu p$, $\bar{\nu} p$ elastic scattering
170 ton segmented detector
@$E_\nu$~1.2 GeV , ($Q^2$=0.4 → 1.1 $GeV^2$)
(Ahrens et al.,PRD 35, 785, '87.)

BNL734 data
(PRD 35, 785, '87):

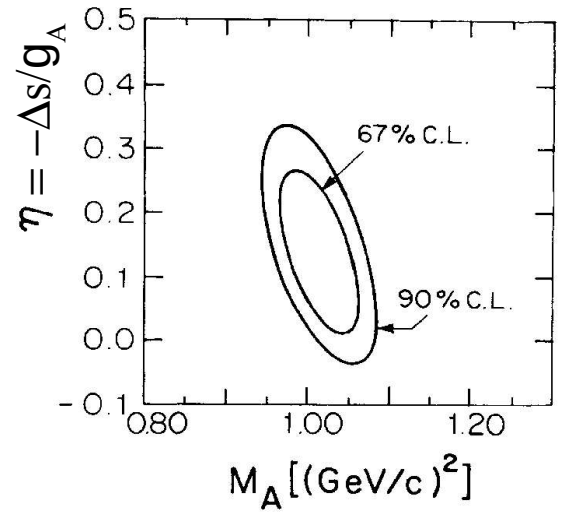



BNL734 detector



# NC neutrino scattering: BNL E734

- A fit to the $\nu p$, $\bar{\nu} p$ elastic scattering diff xsection yielded: $\Delta s = -0.15 \pm 0.09$ (Ahrens et al., PRD 35, 785, '87.)




- This data has generated much interest... and several reanalyses:
  - (Garvey et al., PRC48, 761, 1993): more realistic values for vector form factors, $Q^2$ evolution → $\Delta s = -0.21 \pm 0.10 \pm 0.10$
  - (Alberico et al., Nucl. Phys. A651, 277, 1999), considered ratios of NC,CC cross sections → $\Delta s$ consistent with above
  - (Pate, PRL 92, 082002, '04): combines E734 data with eN data from HAPPEX, yields $G_A^s(Q^2=0.5\ \mathrm{GeV}^2)$, but data not close enough to $Q^2=0$ → no $\Delta s$ extraction.

- The BNL734 data is not accurate enough for an extraction of $\Delta s$ with sufficiently small errors (i.e. to be competitive with DIS measurements)

- This data set may be improved in a new experiment...
  - 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)

# Cross section measurements with FINeSSE:

- Neutrino oscillation experiments experiments need good neutrino cross sections! (and.... they hold interesting physics as well)

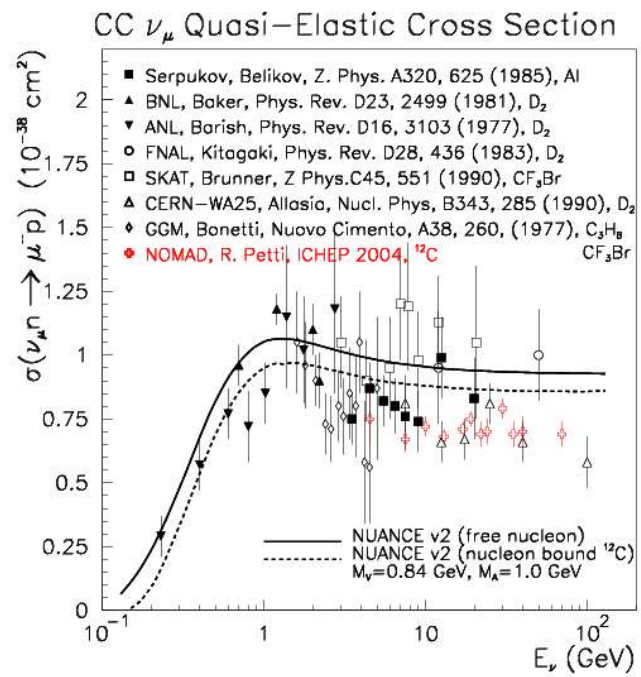
- The "APS Multidisciplinary Neutrino Study" cites this as a high priority

- FINeSSE is well-suited to make these measurements

- For both neutrinos and antineutrinos, these channels are of interest:
  - CC quasielastic
  - NC and CC charged and neutral pi production
  - coherent pi production

From APS ν study:

*The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments and is, in addition, capable of revealing exotic and unexpected phenomena, such as the existence of a neutrino magnetic dipole moment.*



# FINeSSE experiment

Physics Motivation:

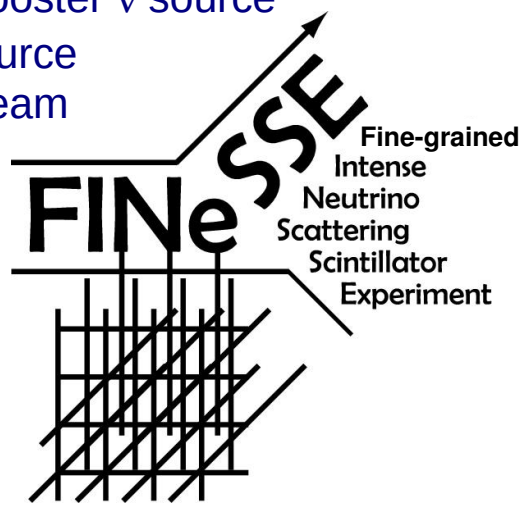
- A measurement of $\Delta s$
- Intermediate-energy cross sections

Experiment:

- at a near (~100m) location on an intense $\nu$ source
- 2 part detector:
  - 10 ton liquid-scintillator/fiber vertex detector
  - muon rangestack

Possible locations:

- FNAL: 8GeV booster $\nu$ source
- BNL: AGS $\nu$ source
- JPARC: T2K beam




FINeSSE collaboration

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# Booster Neutrino Beamline at FNAL

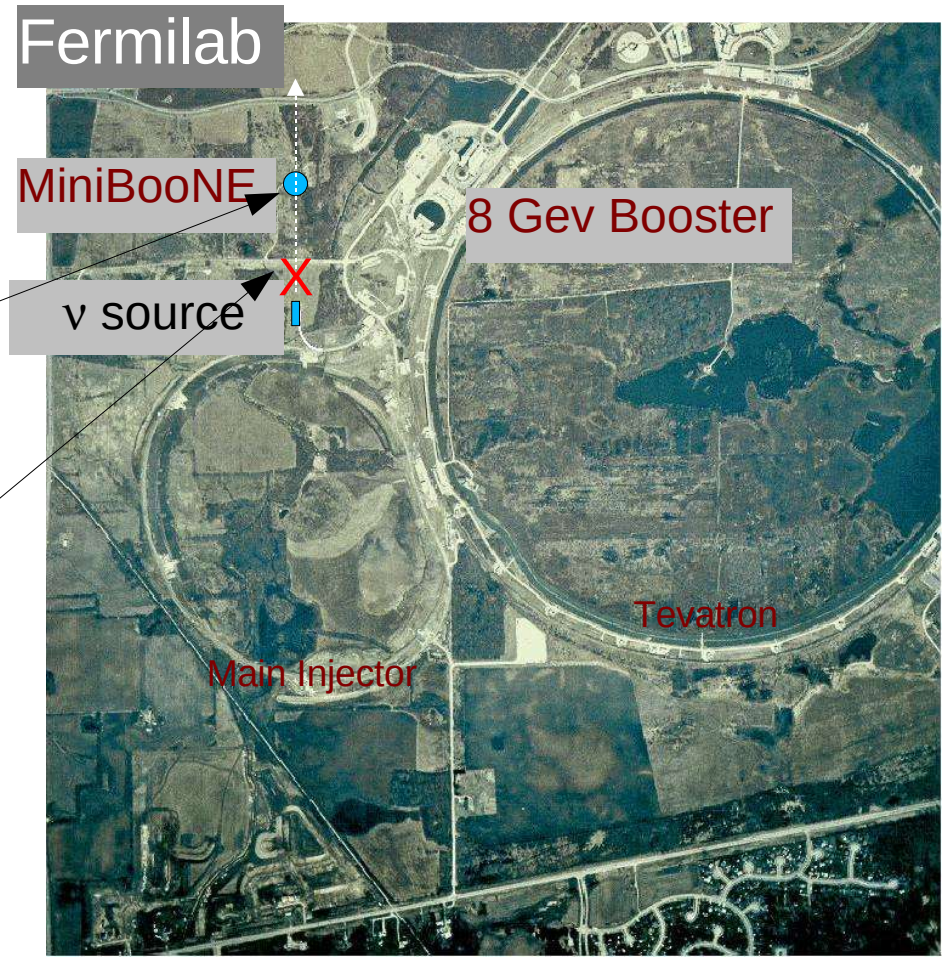
- currently delivering beam to MiniBooNE experiment (since Sept '02)

- 500m from ν target:

MiniBooNE...

- 100m from ν target:

open space!...

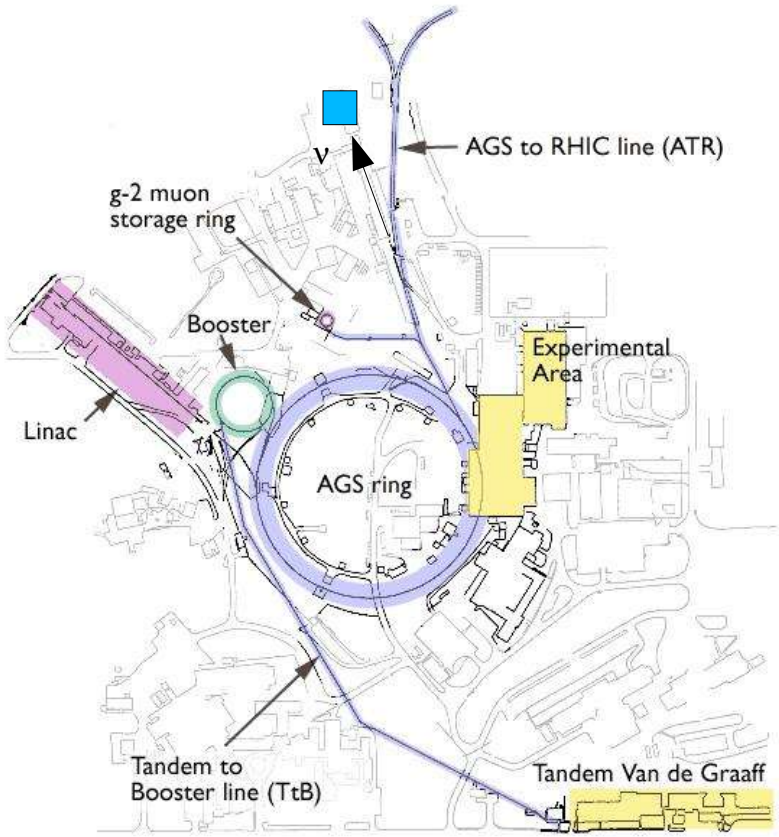


# Neutrino Beamline at BNL

- (U-line) used to deliver beam to E734 (et al)

- no neutrino source currently in place

- could use MB ν source design relatively inexpensively

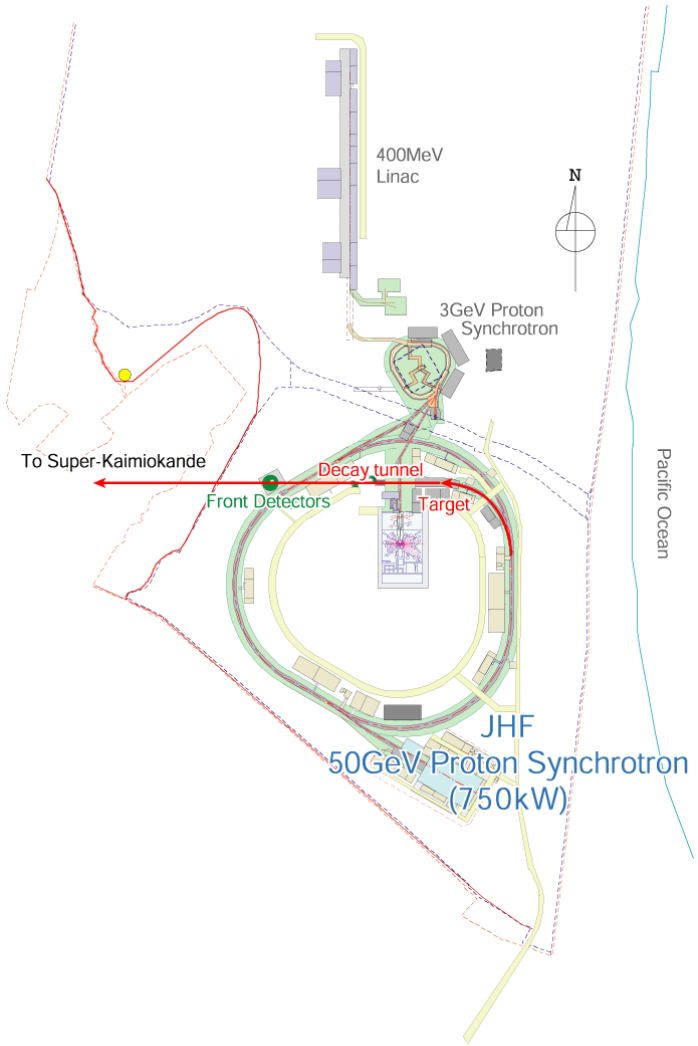


# Near location on T2K beam (JPARC, Japan)

- Currently under construction (to be complete ~2009)

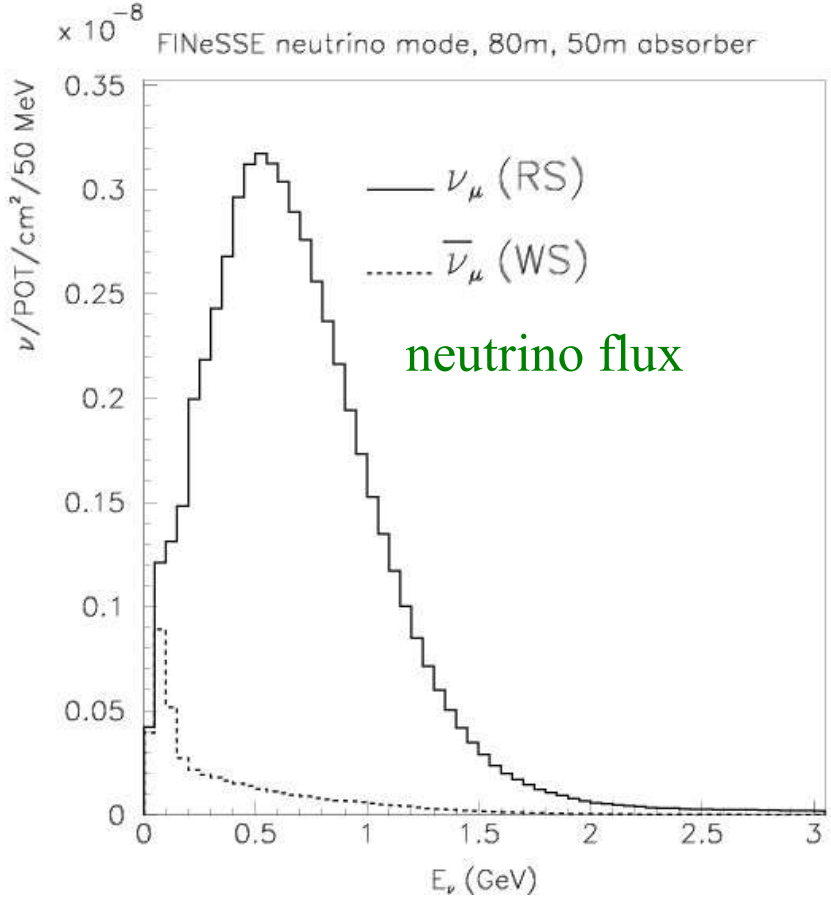
- Will deliver ν to Super-K, 295 km away

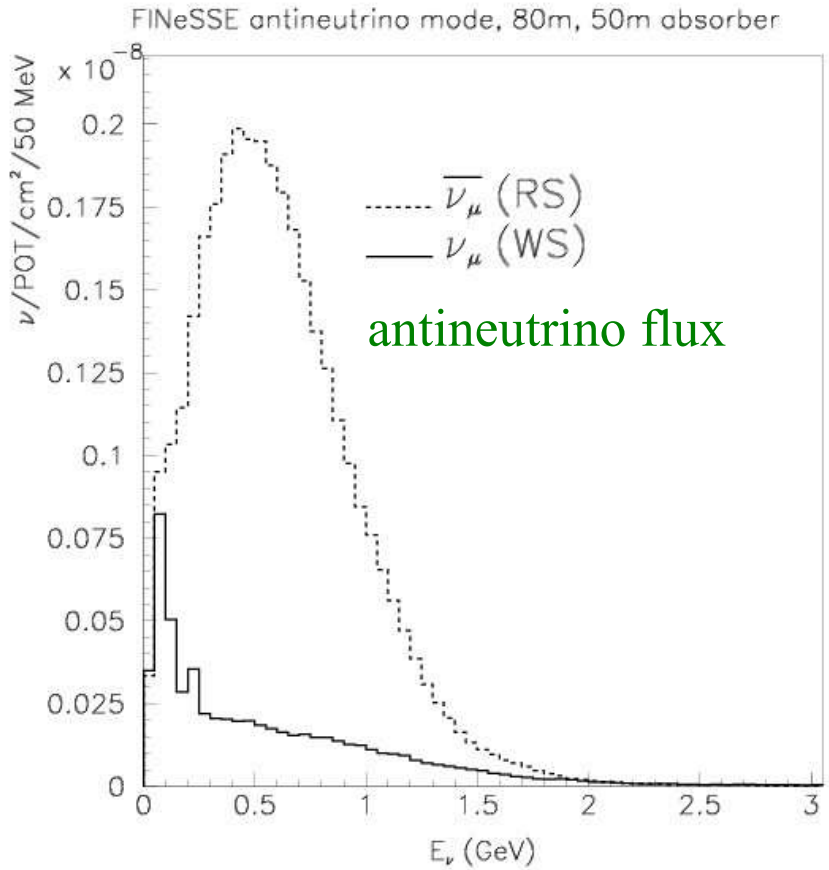
- A near-hall will be constructed at 280m for detectors to monitor beam and for “near” physics



# Neutrino Flux

- nu/antinu flux at 80m location on FNAL (8 GeV) booster nu beamline
- nu: <E> ~ 700MeV, nubar frac = 7%
- nubar:  flux ~ 60%(nu flux), <E> ~ 600MeV, nu frac = 16%
- similar fluxes may be obtained from AGS, JPARC



# Event Rates:

- with these nu/antinu fluxes, a first-rate physics program may be carried out with 1 yr nu running and 2 yr antinu and a 9 ton (fiducial) detector...

1 yr @FNAL

neutrino event rates

| Reaction | $\nu_\mu$ (RS) $10^{20}$ POT 1 ton | $\overline{\nu_\mu}$ (WS) $10^{20}$ POT 1 ton | $\nu_\mu$ (RS) $2 \times 10^{20}$ POT 9 ton |
|---|---|---|---|
| CC quasi-elastic | 10,107 | 181 | 181,930 |
| NC elastic | 4,126 | 78 | 74,275 |
| CC resonant $1\pi^+$ | 4,990 | 0 | 89,827 |
| CC resonant $1\pi^-$ | 0 | 42 | 0 |
| CC resonant $1\pi^0$ | 928 | 13 | 16,704 |
| NC resonant $1\pi^0$ | 1,301 | 19 | 23,414 |
| NC resonant $1\pi^+$ | 458 | 8 | 8,237 |
| NC resonant $1\pi^-$ | 357 | 5 | 6,422 |
| CC DIS | 253 | 2 | 4,550 |
| NC DIS | 91 | 0 | 1,642 |
| NC coherent $1\pi^0$ | 365 | 14 | 6,566 |
| CC coherent $1\pi^+$ | 603 | 0 | 10,858 |
| CC coherent $1\pi^-$ | 0 | 24 | 0 |
| other (multi-$\pi$, etc.) | 621 | 18 | 11,174 |
| total | 24,200 | 403 | 435,600 |

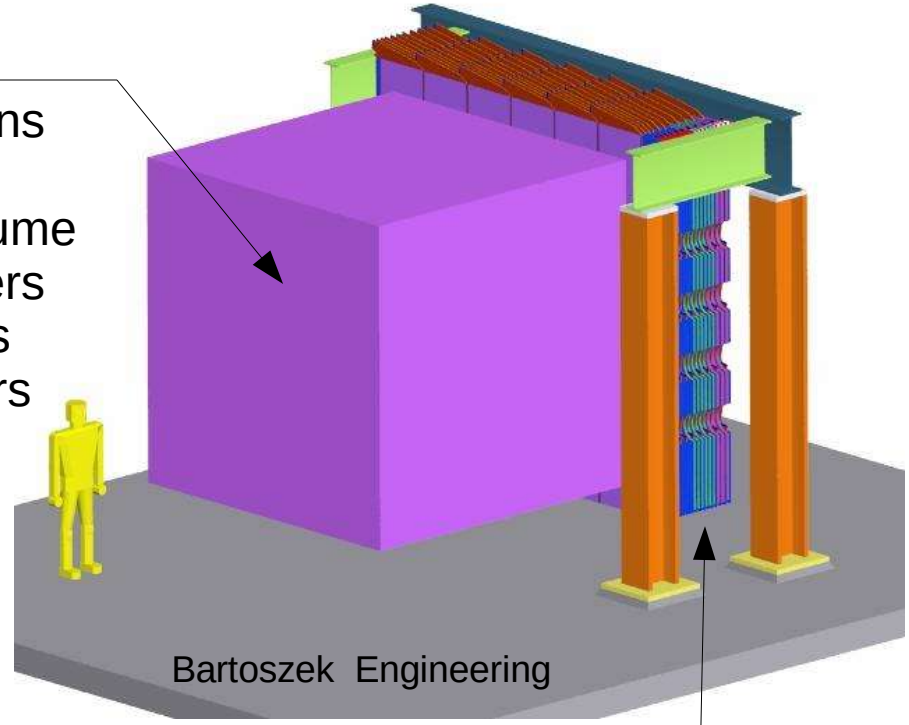
2 yr @FNAL

antineutrino event rates

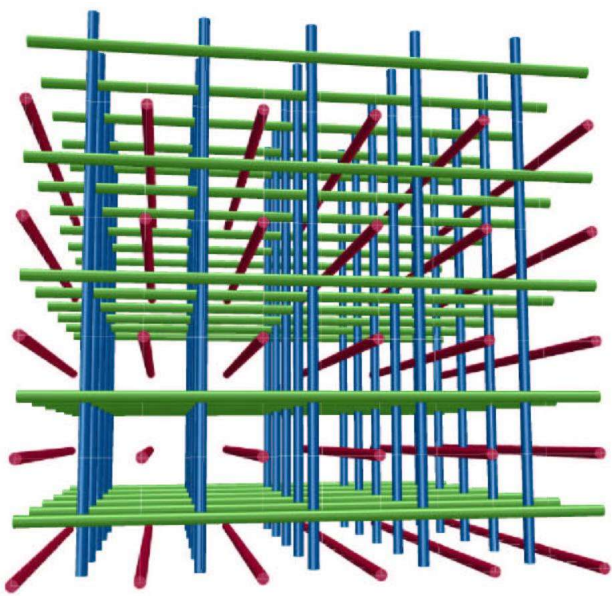
| Reaction | $\overline{\nu_\mu}$ (RS) $10^{20}$ POT 1 ton | $\nu_\mu$ (WS) $10^{20}$ POT 1 ton | $\overline{\nu_\mu}$ (RS) $4 \times 10^{20}$ POT 9 ton |
|---|---|---|---|
| CC quasi-elastic | 2,219 | 787 | 79,892 |
| NC elastic | 922 | 323 | 33,179 |
| CC resonant $1\pi^+$ | 0 | 470 | 0 |
| CC resonant $1\pi^-$ | 419 | 0 | 15,092 |
| CC resonant $1\pi^0$ | 130 | 93 | 4,666 |
| NC resonant $1\pi^0$ | 230 | 118 | 8,294 |
| NC resonant $1\pi^+$ | 83 | 43 | 2,996 |
| NC resonant $1\pi^-$ | 59 | 35 | 2,132 |
| CC DIS | 3 | 30 | 116 |
| NC DIS | 2 | 11 | 58 |
| NC coherent $1\pi^0$ | 184 | 30 | 6,624 |
| CC coherent $1\pi^+$ | 0 | 51 | 0 |
| CC coherent $1\pi^-$ | 298 | 0 | 10,714 |
| other (multi-$\pi$, etc.) | 157 | 93 | 5,644 |
| total | 4,706 | 2,086 | 169,402 |

# FINeSSE Detector

The Vertex Detector...
- to precisely track low-energy protons (and muons, pions, electrons)
- $(2.5m)^3$ active liquid scintillator volume
- 19200 (80x80x3) 1.5 mm WLS fibers on 3cm spacing with 3 orientations
- no optical separation between fibers ("scibath" method)




The Muon Rangestack...
- to track and measure the energy of muons

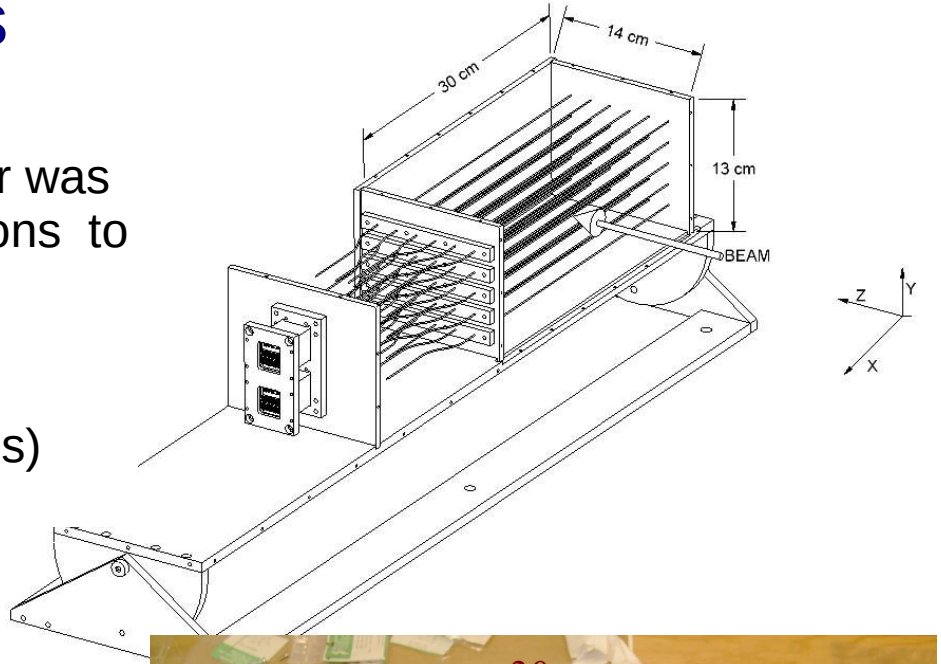


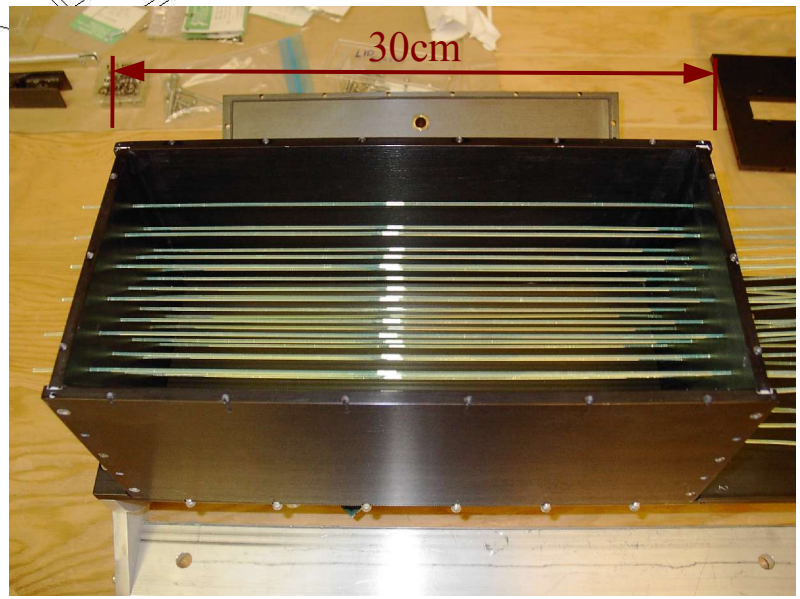
WLS fibers in vertex detector

# FINeSSE protoype tests

- A prototype “scibath” vertex detector was tested at the IUCF with 200MeV protons to determine suitability for FINeSSE

- 30 1.5mm WLS fibers immersed in liquid scintillator (all fibers along x-axis)

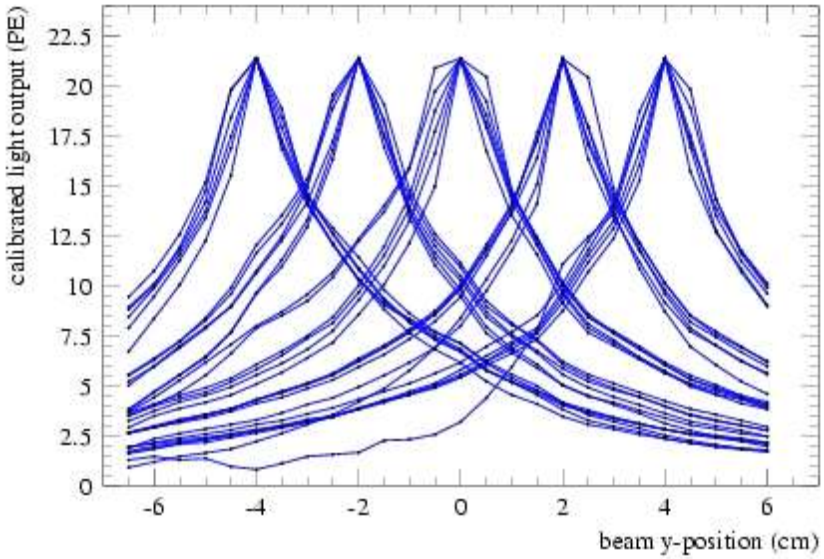




# FINeSSE protoype tests...

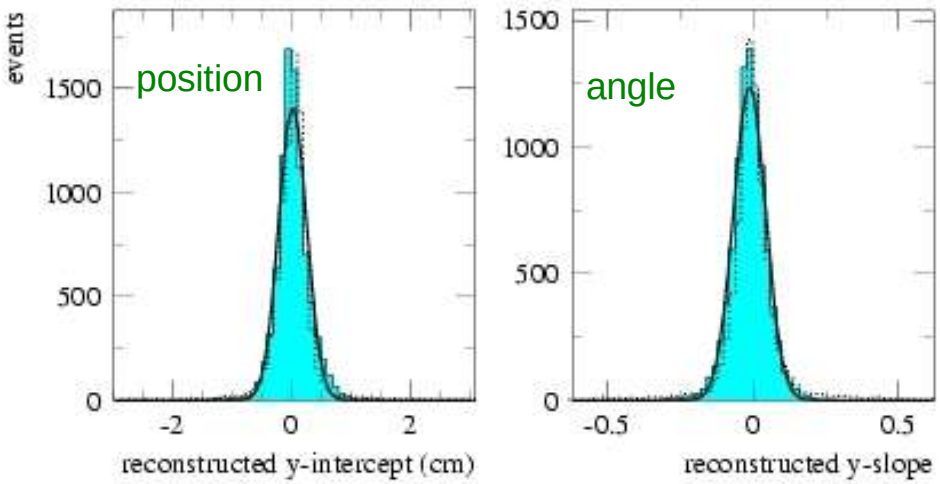
- Protons provide sufficient light in fibers:
  - 22±2 photoelectrons
  - from proton tracks near fibers

light output for a scan across 5 rows of 6 UV -> blue fibers




- proton tracks were reconstructed with resolutions:
  - position: 2.4 mm
  - angle: 3.2°

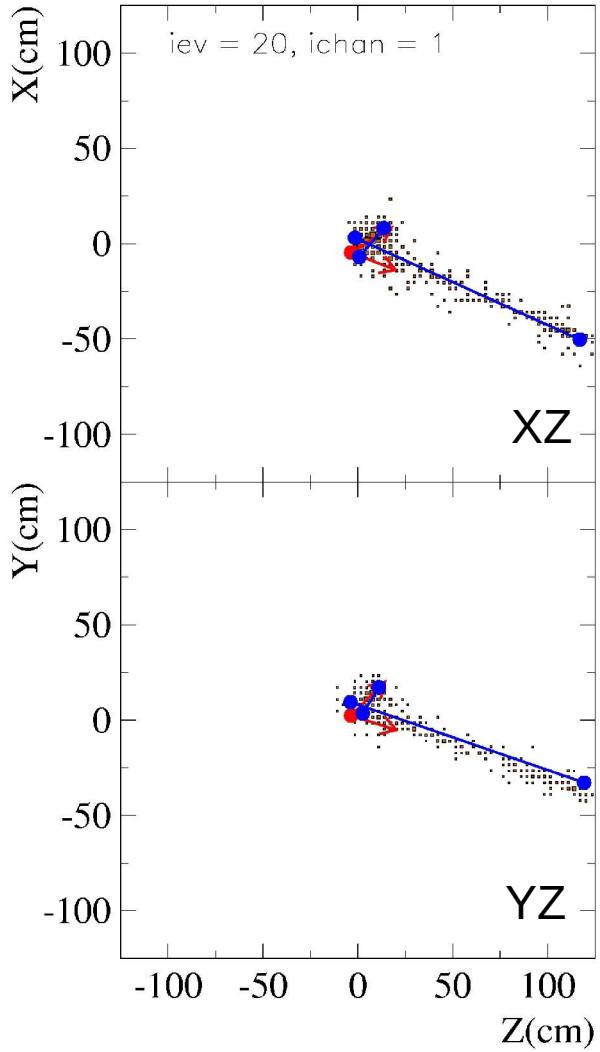
tracking distributions



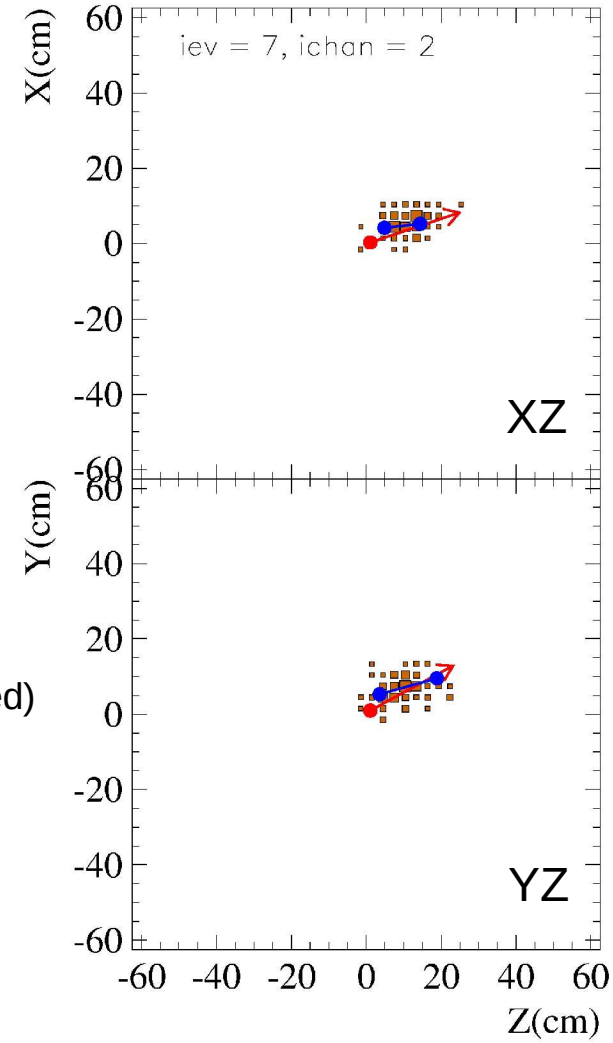
# FINeSSE Detector Simulation and Reconstruction...

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

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

| | 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..

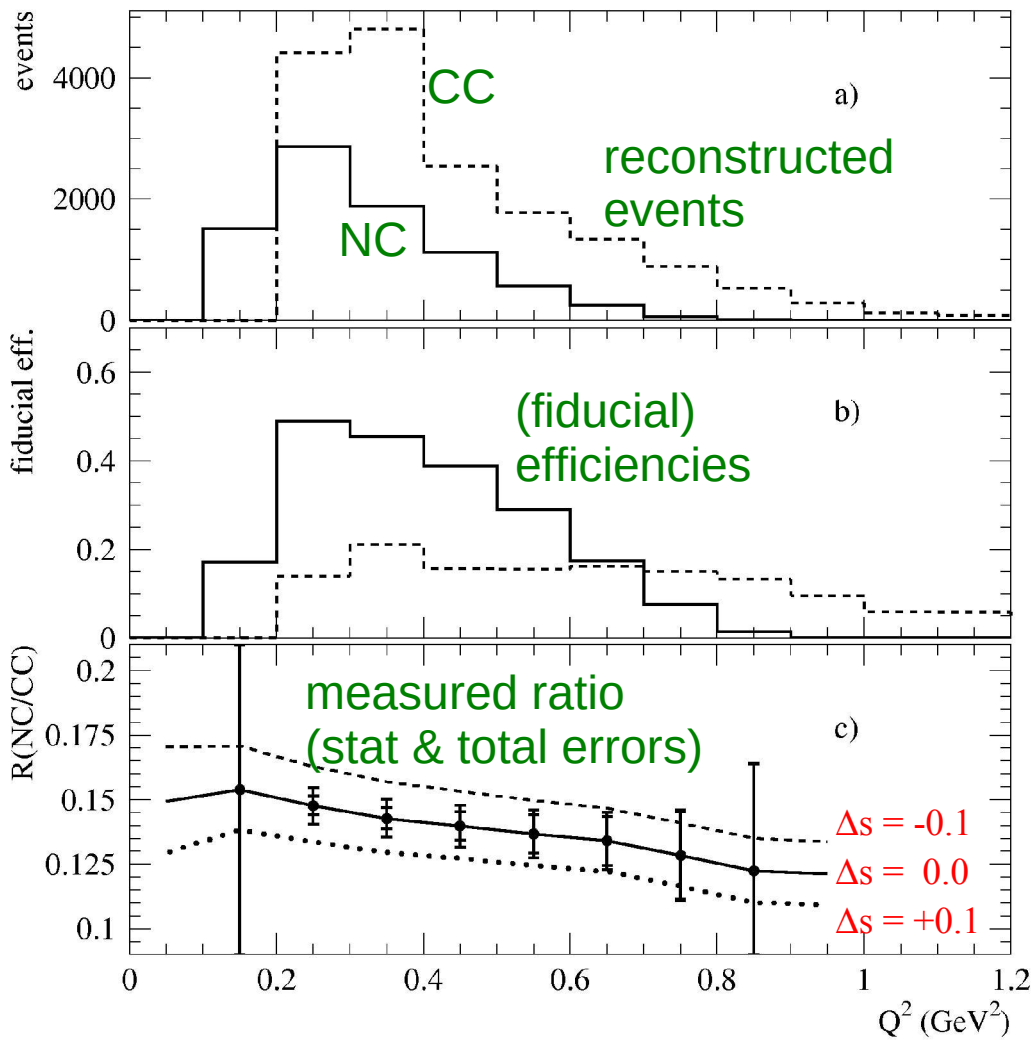
A fit to the simulated data was performed to estimate the precision of $\Delta s$ extracted from a measurment of the neutrino NC/CC ratio (1 yr nu run):

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

Included the effects of:
- statistical errors
- systematic errors due to...
- NCn ($\nu n \to \nu n$) scattering misid
- scattering from free protons
- uncertainties in efficiencies
- $Q^2$ reconstruction

experimental (stat + sys) error:

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



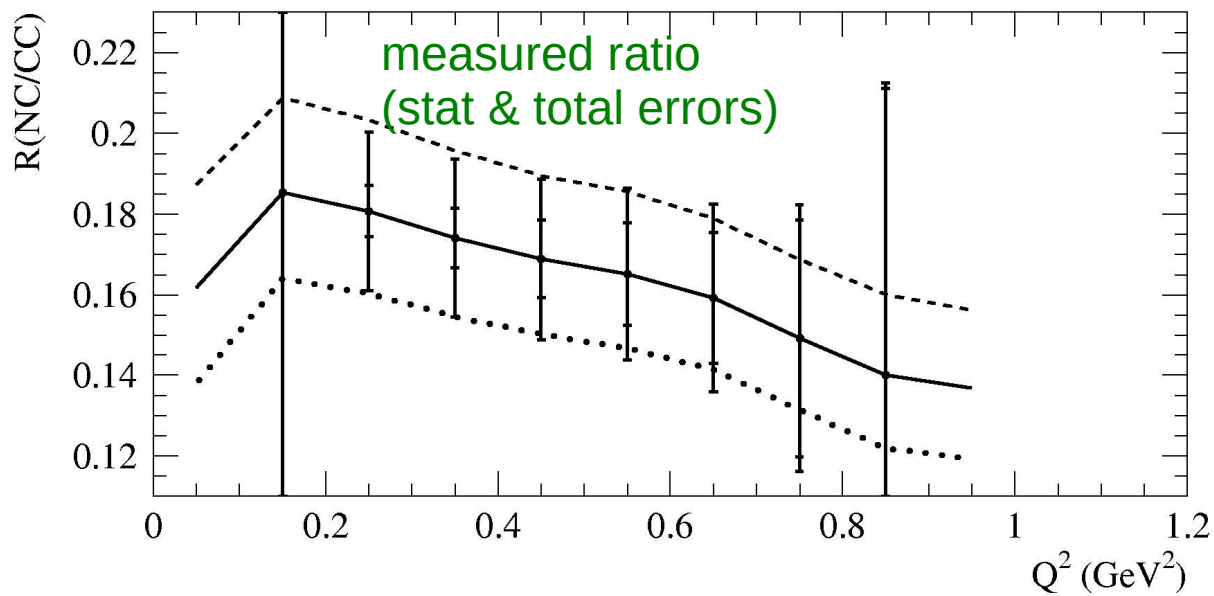
# Simulation of R(NC/CC) measurement..

A similar exercise  was performed for a 2 yr antinu run:

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

experimental (stat + sys) error:

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



# Expected errors on $\Delta s$

From neutrinos (1y run at FNAL):

$\sigma(\Delta s) = \pm 0.025$ (exp. stat. and sys.)

$\pm 0.02$ (f. f. systematic)

From antineutrinos (2y run at FNAL):

$\sigma(\Delta s) = \pm 0.04$ (exp. stat. and sys.)

$\pm 0.02$ (f. f. systematic)

Recall:

BNL E734:

$\Delta s = -0.15 \pm 0.09$ ($\pm$f.f. systematics)

polarized DIS:

$\Delta s = -0.12 \pm 0.06$

$-0.08 \pm 0.06$

This experiment will provide a precise, theoretically robust, measurement of $\Delta s$ via neutrino-scattering.

# FINeSSE status:

- BNL: LOI submitted
  PAC: physics is “compelling” and proposal encouraged.
  We are pursuing this possibility

- FNAL: LOI submitted
  PAC: can not encourage proposal at this time
  “wait and see” about future of 8GeV nu beamline

- JPARC T2K:
  initial discussions, see talk by Miyachi

Costs:
- $2.6M for detector
- at FNAL: ~$2M for building (on beam center)

# Summary

- A neutrino NC scattering experiment to measure $\Delta s$ would yield important information on nucleon spin structure.

- In addition it would provide important (and needed) xsection measurements.

- And, could be an ideal detector for a near experiment on the FNAL 8 GeV beamline to monitor flux (should one be needed).

- Our collaboration continues to work to make it happen!

More info:
- http://www-finesse.fnal.gov

FINeSSE
Fine-grained
Intense
Neutrino
Scattering
Scintillator
Experiment