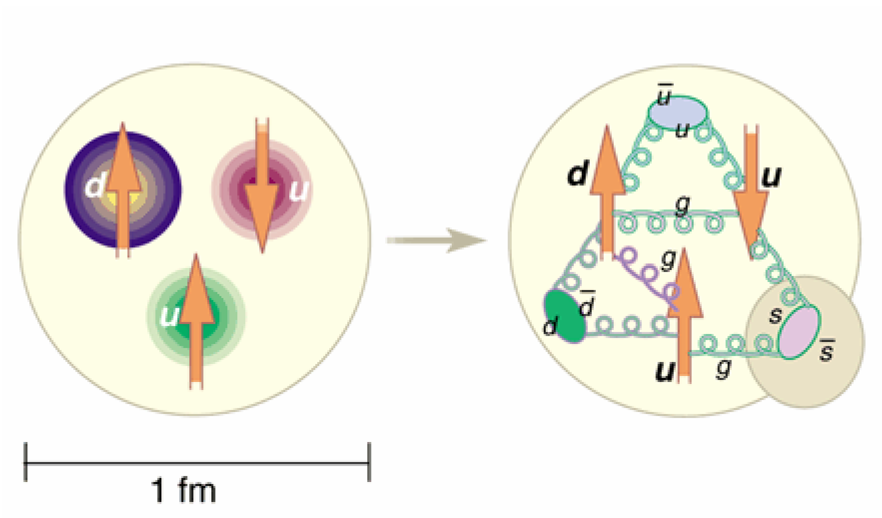
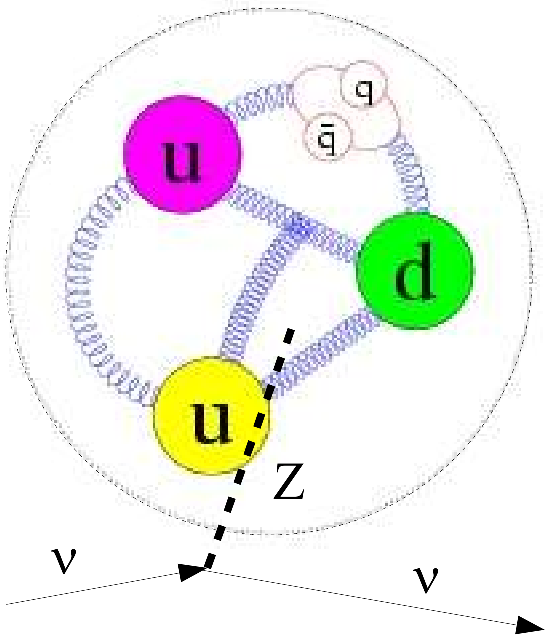
Probing Nucleon Strangeness with Neutrino Scattering

Outline:

- Nucleon structure - strange quarks, spin
- Neutrinos as probes of strange spin - G_A^s, Δs
- An experiment to measure G_A^s via neutrino neutral current scattering





R. Tayloe, Indiana U.
JLab workshop ,05/06

Nucleon Structure: strange quarks

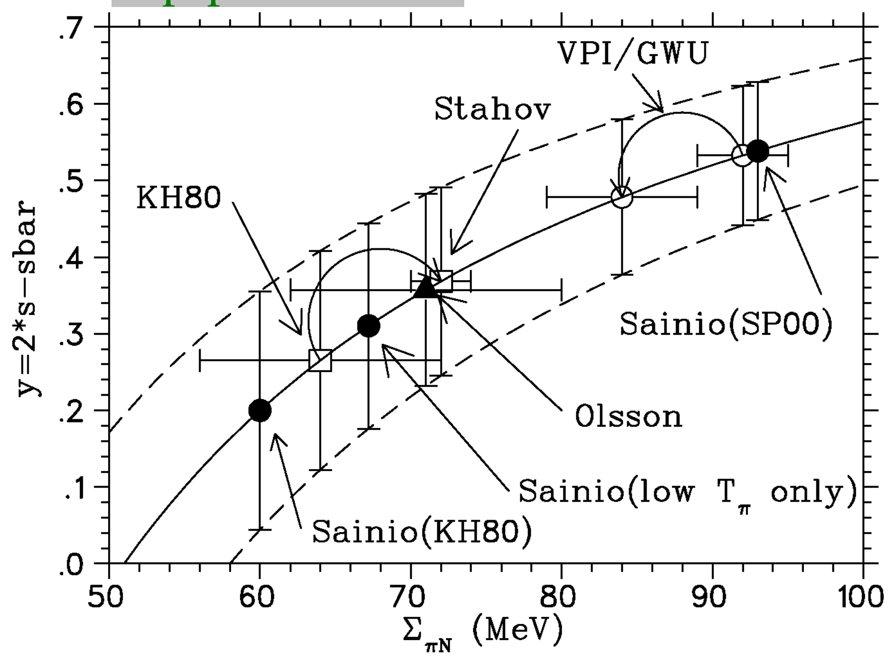
Net strangeness of the nucleon is zero.
However, QCD: valence ud quarks + sea of qqbar pairs.

mass:

π-N scattering data -> strange quarks contribute ~20% to nucleon mass

$$\frac{2\langle N|\bar{s}\,s|N\rangle}{\langle N|\bar{u}\,u+\bar{d}\,d|N\rangle}\approx 0.2$$

hep-ph/0011277



spatial distributions:

PV e^- scattering (e.g. SAMPLE, HAPPEX, G0, PVA4) looks for strange-quark contributions to the proton magnetic moment (μ_s) and radius (r_s).

Results consistent with small strange quark contribution.

Nucleon Structure: strange quarks

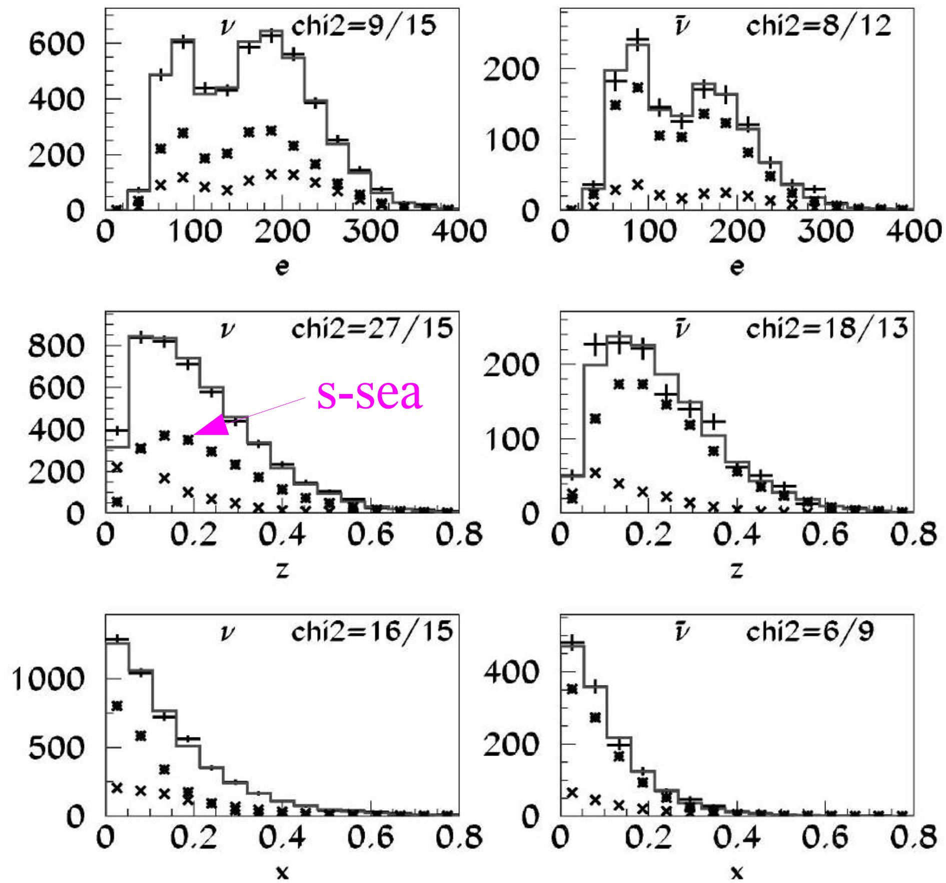
momentum:

The CCFR and NuTeV experiments measure strange-sea distributions via ν and $\bar{\nu}$ DIS dimuon production.

$$\nu_\mu + s \rightarrow \mu^- + c\,;\, c \rightarrow \mu + + \nu_\mu + s$$
$$\bar{\nu}_\mu + s \rightarrow \mu^+ + \bar{c}\,;\, \bar{c} \rightarrow \mu - + \nu_\mu + \bar{s}$$

$$\frac{2\int_0^1 [s+\bar{s}]\,dx}{\int_0^1 [u+\bar{u}+d+\bar{d}]\,dx} \approx 0.35 \pm 0.04$$

NuTeV, PRD 64, 112006

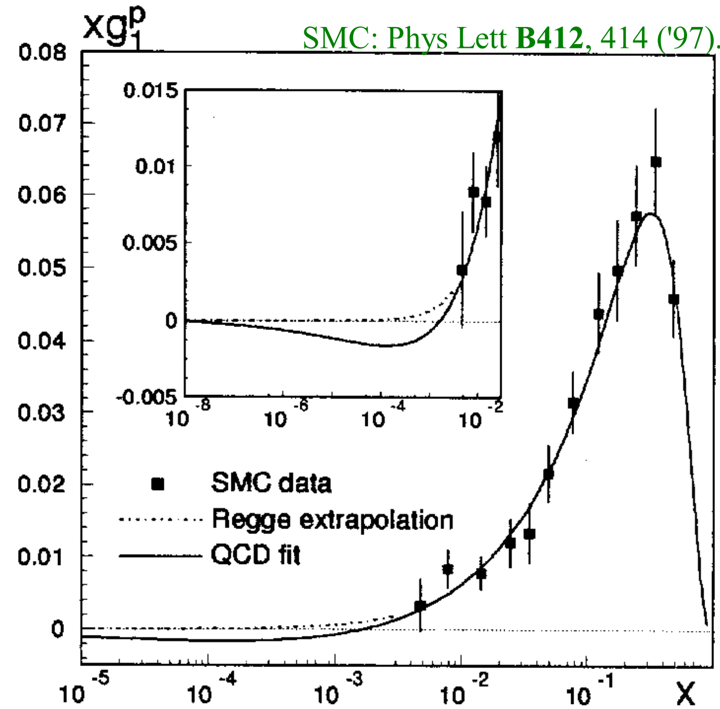


and spin: ....

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: $g_1^{p,n}(x,Q^2)$.

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



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)

⇒

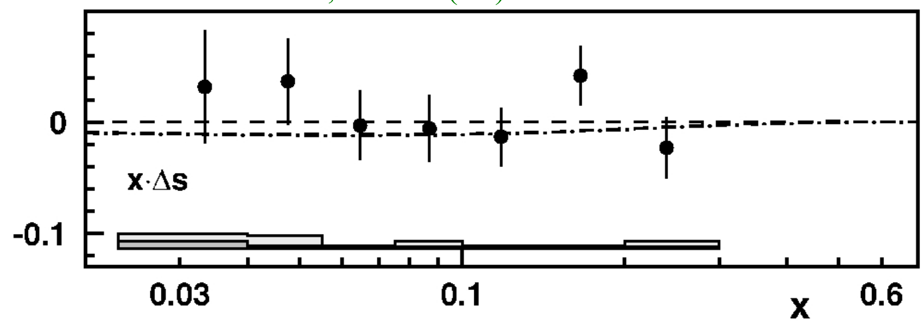
	"Regge"	QCD fit
Δu	0.84 ± 0.06	0.80 ± 0.06
Δd	-0.42 ± 0.06	-0.46 ± 0.06
Δs	-0.08 ± 0.06	-0.12 ± 0.06

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

Nucleon Structure: strange quark spin Δs...

- 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).



$\Longrightarrow$ "Δs" = 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 Δs <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

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

- Axial part of Nucleon Neutral Weak Current:

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

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

- G_A (non-strange, Δu-Δd) known (from n β-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 νN NC scattering (at low Q^2) yields Δs

A ratio method to extract Δs

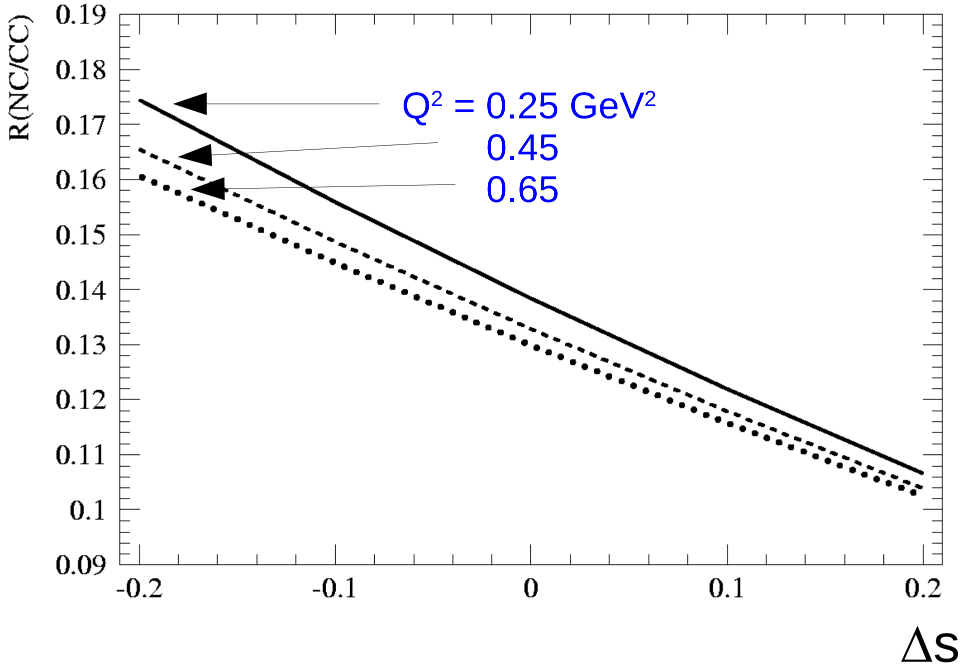
A measurement of R_ν(NC/CC) reduces

- experimental systematics (e.g. flux, efficiencies, etc.)
- nuclear effects
- other form factor uncertainties (e.g. M_A)

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

$$\bar{R}_\nu(NC/CC) = \frac{\sigma(\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p)}{\sigma(\bar{\nu}_\mu p \rightarrow \mu n)}$$

sensitivity of R(NC/CC) to Δs



A “rigorous sum rule” for NC nu scattering

From A. Thomas (hep-ex/0311029):

- measured in DIS:

$$\int_0^1 dx\, g_1^p(x,Q^2) = \left(\frac{1}{12}g_A^{(3)} + \frac{1}{36}g_A^{(8)}\right)C_{NS}(Q^2) + \frac{1}{9}g_A^{(0)}|_{\rm inv}C_S(Q^2) + \mathcal{O}(\frac{1}{Q^2}).$$

- measured in n-decay: $g_A^{(3)}$
- measured in hyperon-decay: $g_A^{(8)}$
- measured in nu NC scattering:

$$2g_A^{(Z)} = (\Delta u - \Delta d - \Delta s)_{\rm inv} + \mathscr{P}\,(\Delta u + \Delta d + \Delta s)_{\rm inv} + O(m_{t,b,c}^{-1}),$$

small

calculated (Phys.Rev. D66 (2002) 031901) correction (= -0.02)

- then the relation of quark to axial charges

$$(\Delta u - \Delta d - \Delta s)_{\rm inv} = g_A^{(3)} + \frac{1}{3}g_A^{(8)} - \frac{1}{3}g_A^{(0)}|_{\rm inv}.$$

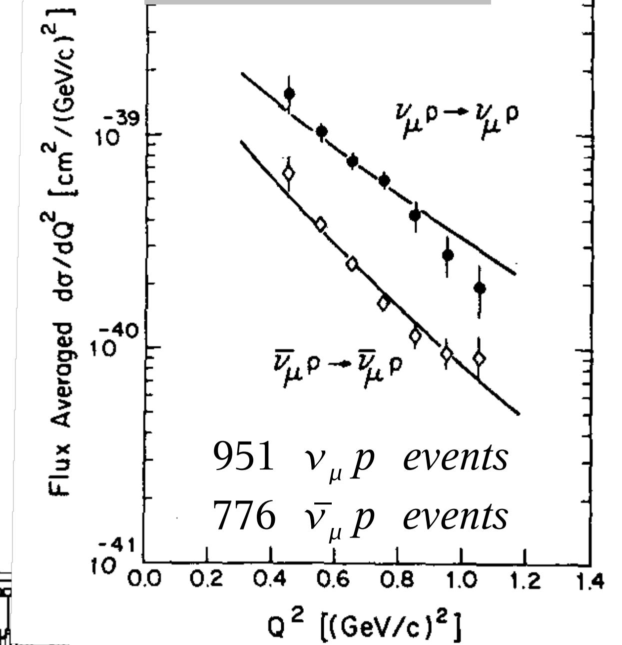
- becomes a “rigorous sum rule” relating DIS to 3 low-energy observables

- need nu NC measurement of NC axial charge, $g_A^{(Z)}$, to test this...

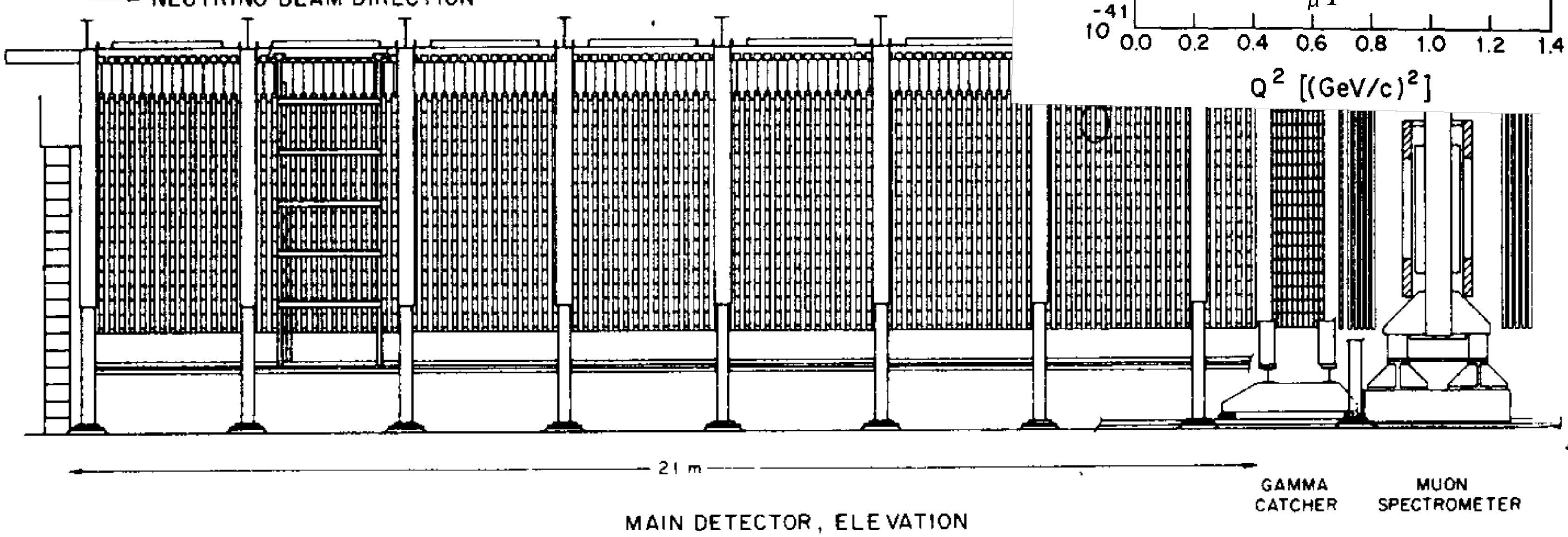
NC neutrino scattering: BNL E734

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

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

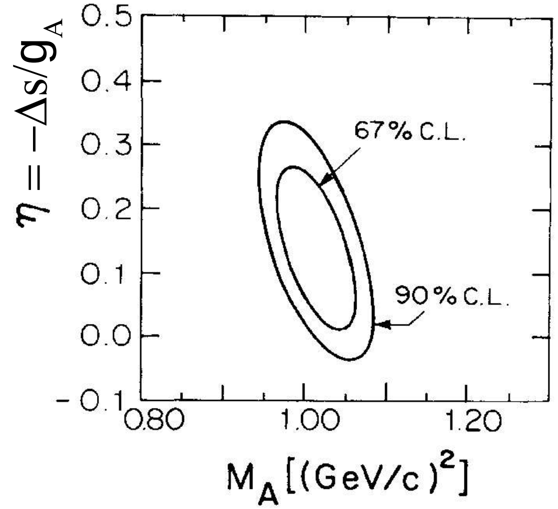


BNL734 detector



NC neutrino scattering: BNL E734

- A fit to the νp, $\bar{\nu} p$ elastic scattering diff xsection yielded: Δs = -0.15±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 → Δs = -0.21±0.10±0.10
  - (Alberico et al., Nucl. Phys. A651, 277, 1999), considered ratios of NC,CC cross sections → Δs consistent with above
  - (Pate, PRL 92, 082002, '04): combines E734 data with eN data from HAPPEX, yields $G_A^s(Q^2=0.5\ GeV^2)$, but data not close enough to $Q^2=0$ → no Δs extraction.

- The BNL734 data is not accurate enough for an extraction of Δs 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)

FINeSSE experiment

Physics Motivation:

- A measurement of Δs
- Intermediate-energy cross sections

Experiment:

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

Possible locations:

- FNAL: 8GeV booster ν source
- BNL: AGS ν source
- JPARC: T2K beam

FINeSSE collaboration

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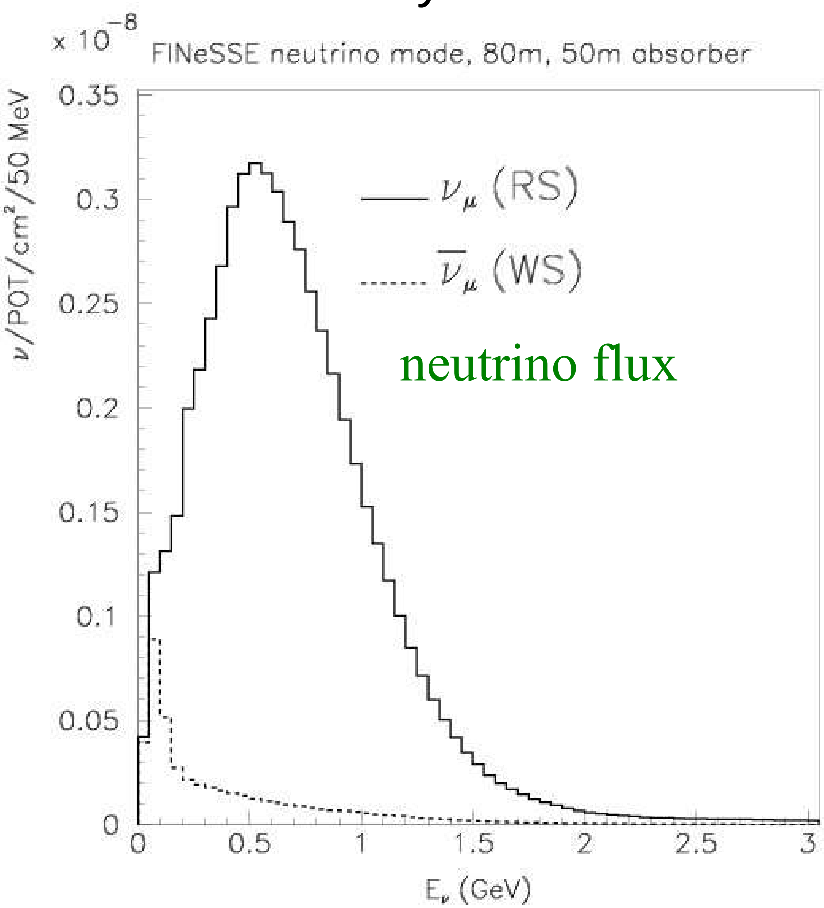
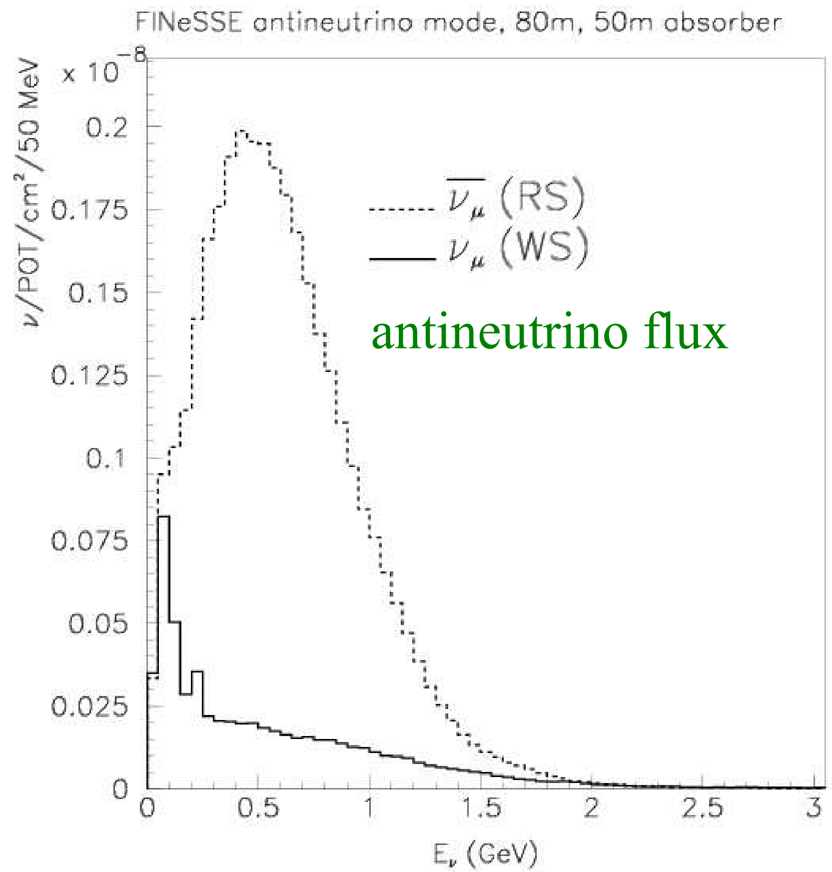
Neutrino Flux

- ν/ $\bar{\nu}$ flux at 80m location on FNAL (8 GeV) booster ν beamline
- ν: <E> ~ 700MeV, $\bar{\nu}$ frac = 7%
- $\bar{\nu}$: flux ~ 60%(ν flux), <E> ~ 600MeV, ν frac = 16%
- similar fluxes may be obtained from AGS, T2K





Event Rates:

- with these $\nu / \bar{\nu}$ fluxes, and with...
- 1 yr ν running and 2 yr $\bar{\nu}$ and a 9 ton (fiducial) detector...

1 yr @FNAL

neutrino event rates

Reaction	ν_μ (RS) 10^{20} POT 1 ton	$\overline{\nu_\mu}$ (WS) 10^{20} POT 1 ton	ν_μ (RS) 2×10^{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-π, etc.)	621	18	11,174
total	24,200	403	435,600

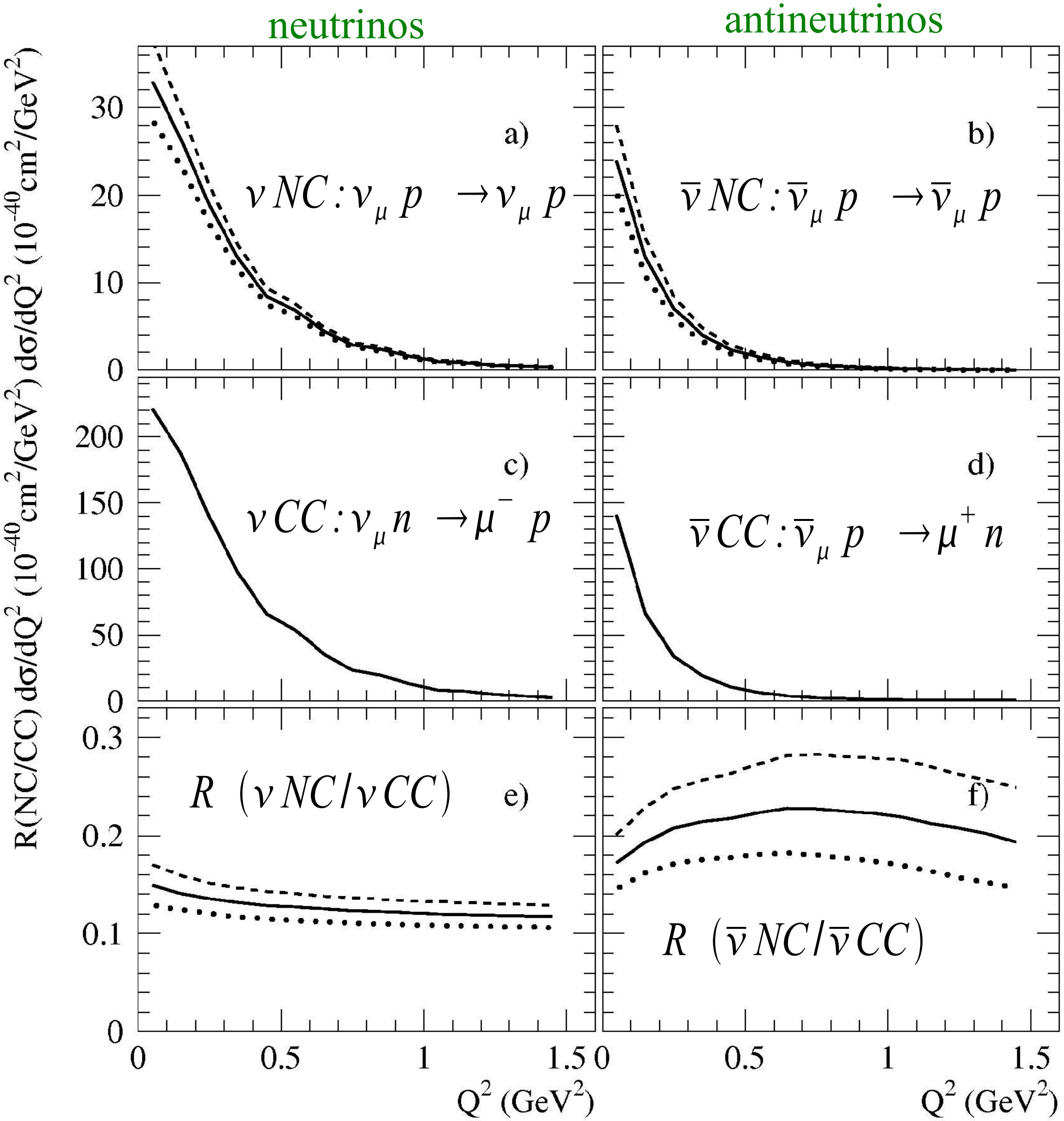
2 yr @FNAL

antineutrino event rates

Reaction	$\overline{\nu_\mu}$ (RS) 10^{20} POT 1 ton	ν_μ (WS) 10^{20} POT 1 ton	$\overline{\nu_\mu}$ (RS) 4×10^{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-π, etc.)	157	93	5,644
total	4,706	2,086	169,402

$\nu N \to \nu N$ scattering and Δs

Differential xsections, ratios for νN, $\bar{\nu}N$ CC and NC (quasi-) elastic scattering
- with different values of Δs



- flux-weighted (8 GeV flux)

- assuming dipole for Q^2 dep. of G_A, G_A^s:

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

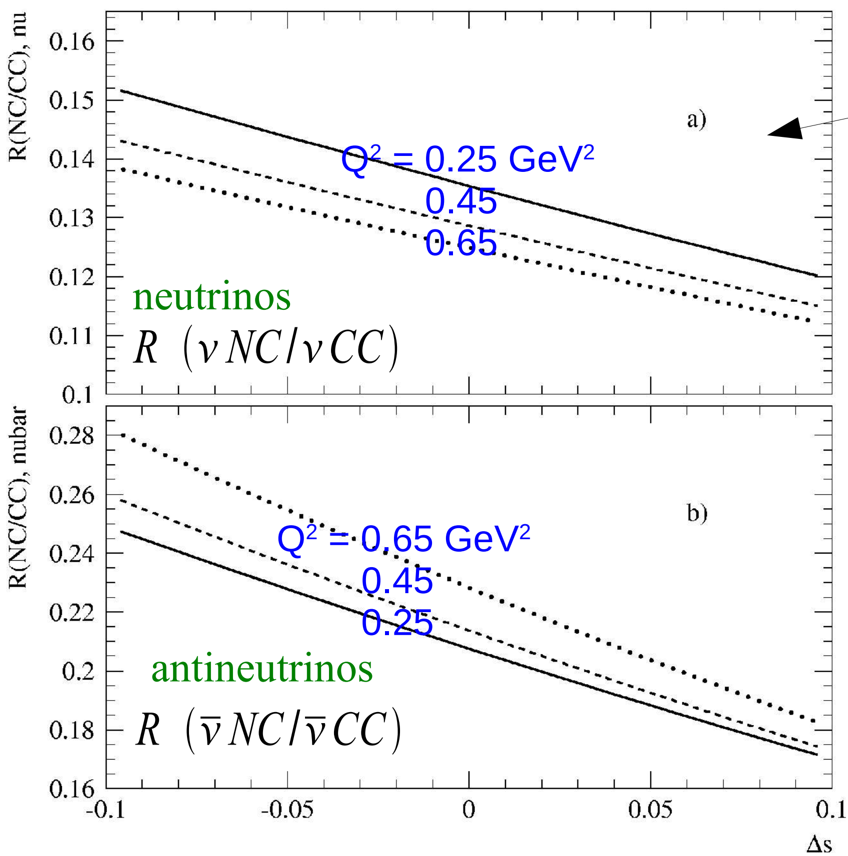
$\nu N \rightarrow \nu N$ scattering and Δs

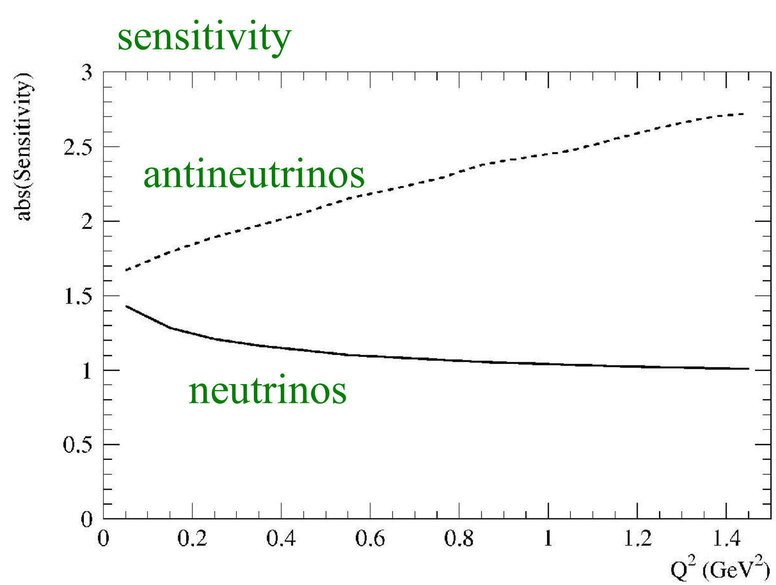
- sensitivity of R(nu), R(nubar) to Δs is large
- actually larger for R(nubar)
- Q^2 dep of R(nu), R(nubar) is different => good systematic check...

$$R = \kappa(S\,\Delta s + 1)$$

$$\sigma(\Delta s) = \frac{1}{|S|}\frac{\sigma(R)}{R}$$

S is "sensitivity" of R to Δs
S = slope of this plot





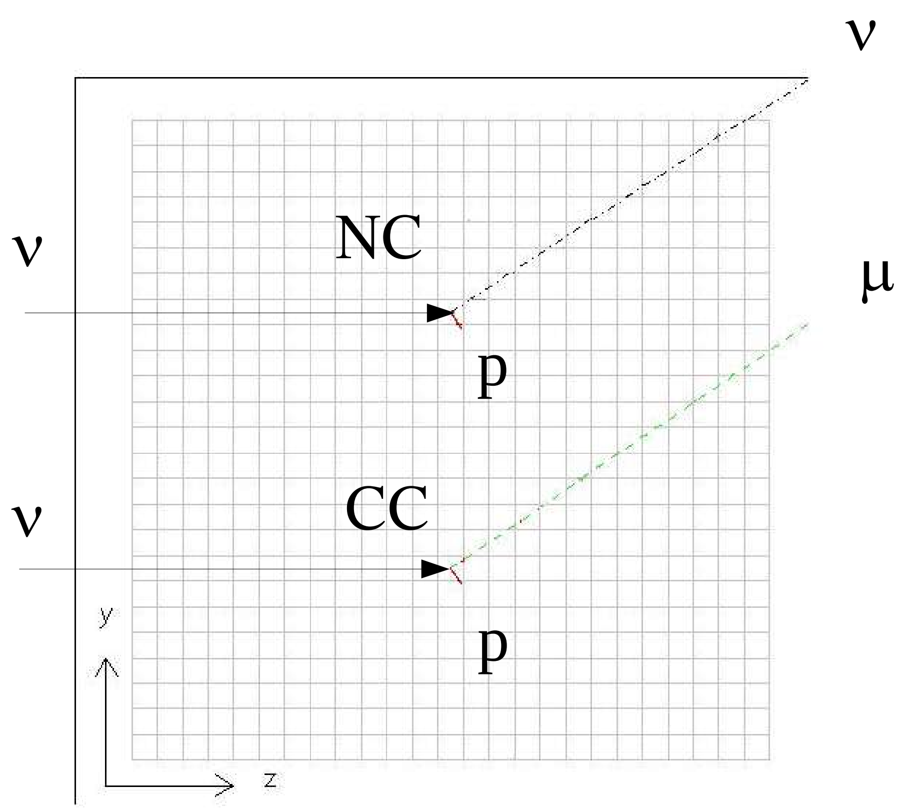
Detector Requirements

To precisely measure Δs, need a precise measurement of R(NC/CC) (to ~5%)

Also need to measure R(NC/CC) as function of $Q^2(=2m_p T_p)$ down to 0.2 GeV^2

Need:
- A ~10 ton (fiducial) detector capable of:
- proton energy measurement (independently of muon energy) down to T_p~100MeV (R~10cm)
- particle ID for NC/CC/background separation
- muon ID/tracking capability

- Need a large, low-threshold, tracking "vertex" detector
- with a muon “rangestack”

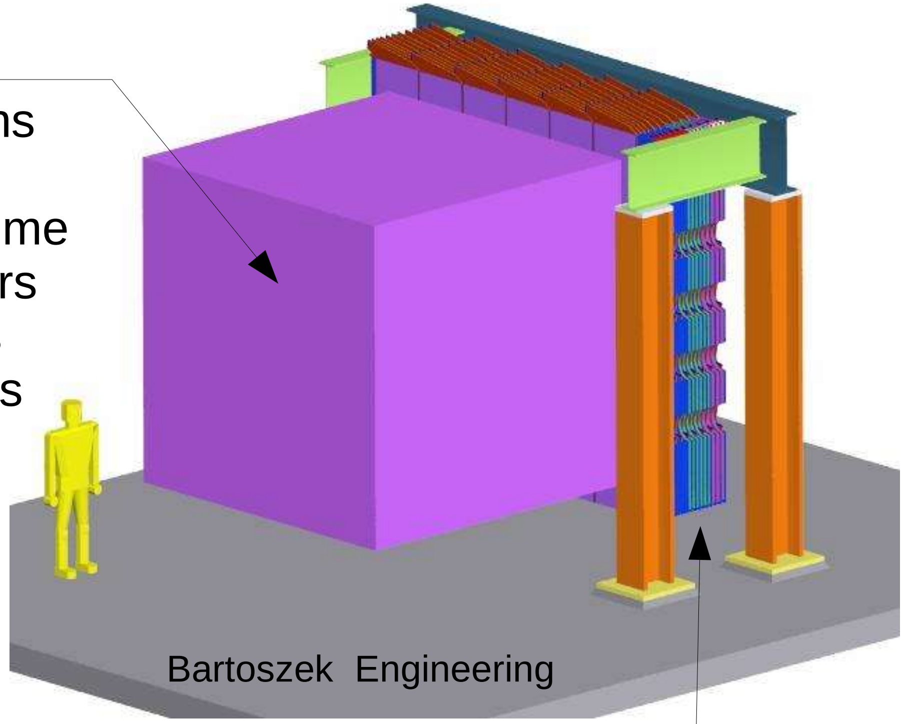


GEANT-generated events in scintillator:
Q^2 = 0.2 GeV^2 , E_ν = 800MeV
T_p~100 MeV, T_μ~600 MeV

FINeSSE Detector

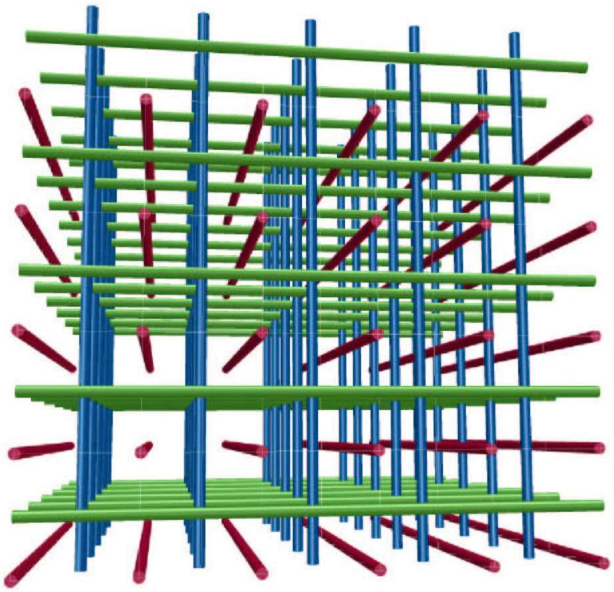
The Vertex Detector...

- 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

Simulation of R(NC/CC) measurement

- high purity/low background for NC and CCQE events has been shown

400k reconstructed MC events

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

	reaction channel				
NCp cuts	NCp	NCn	NCπ	CCQE	CCπ
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

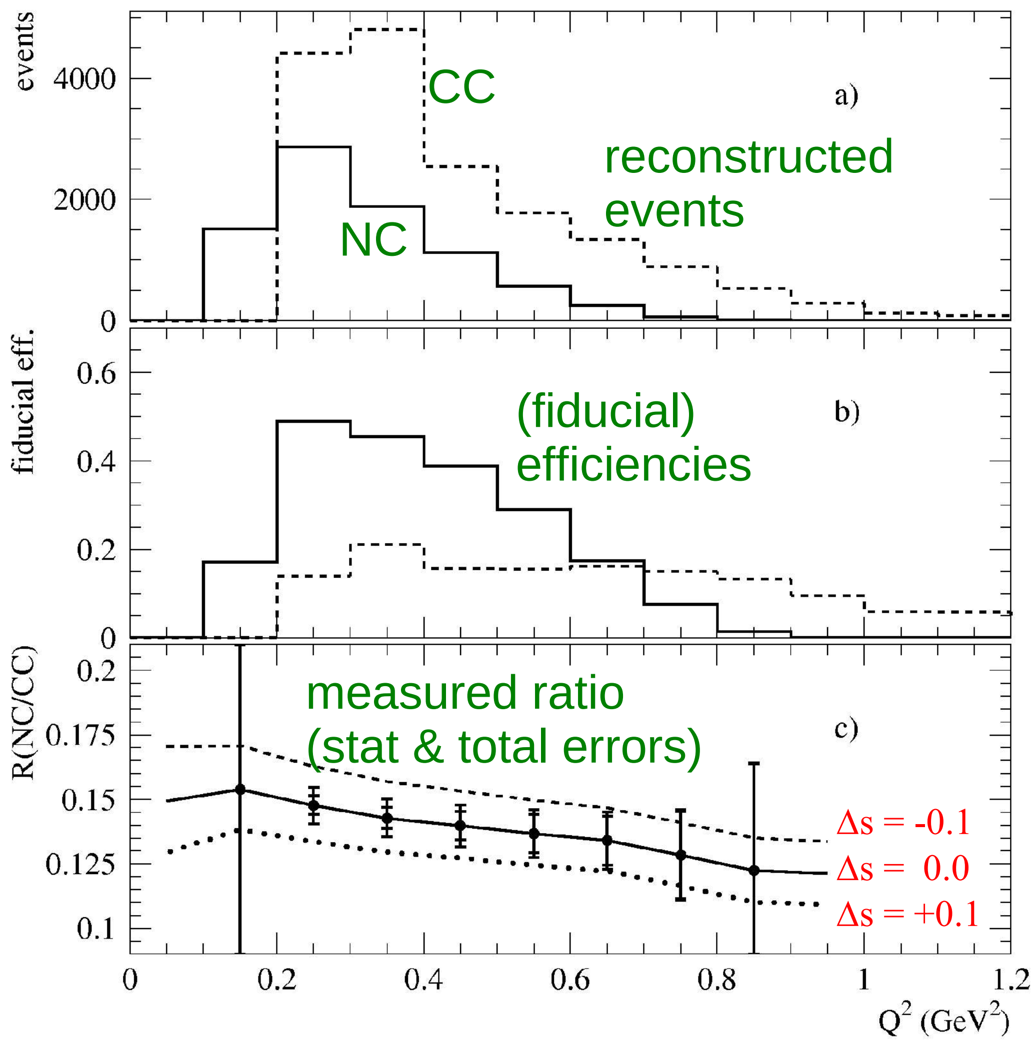
$\nu CC: \nu_\mu n \rightarrow \mu^- p$

CCQE cuts	NCp	NCn	NCπ	CCQE	CCπ
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 Δs extracted from a measurment of the neutrino NC/CC ratio (1 yr nu run):

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



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

experimental (stat + sys) error:

σ(Δs) = ±0.025

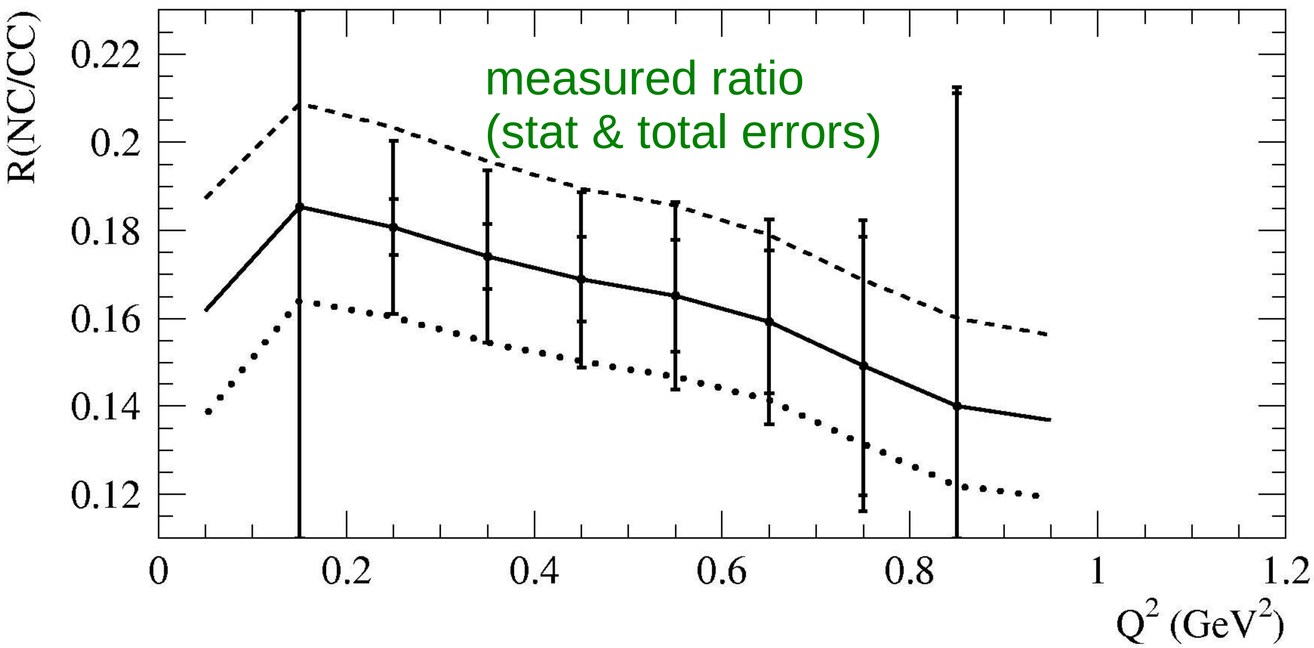
Simulation of R(NC/CC) measurement..

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

$$\bar{R}_{\nu}(NC/CC)=\frac{\sigma(\bar{\nu}_{\mu}\,p\rightarrow\bar{\nu}_{\mu}\,p)}{\sigma(\bar{\nu}_{\mu}\,p\rightarrow\mu\,n)}$$

experimental
(stat + sys) error:

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

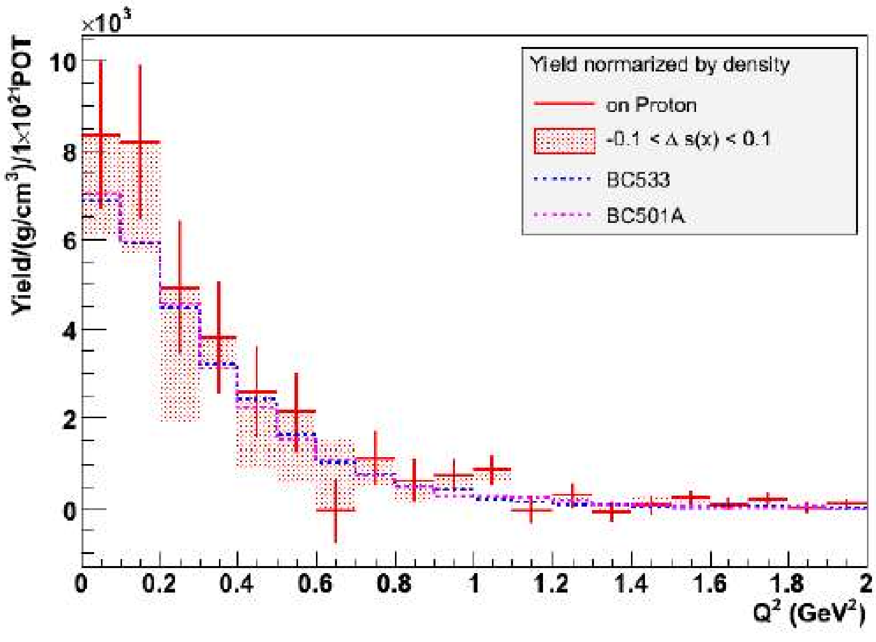


Another idea..

- group from Japan (N. Saito, et al) are looking into NC measurement at J-PARC

- extract nNC measurement on <u>free</u> protons by using scintillators with different H/C ratio

N_{NC}^{H} extraction using BC501A and BC533



2.5 degree
1.0 m^3 for each
100% detection efficiency
No background

NC neutrino scattering: some (theoretical) details

- Q^2 evolution of form factors , sensitivity to M_A uncertainties
    - Will actually measure $G_A^s(Q^2)$ for $Q^2 = 0.2\text{-}0.9$ GeV^2
    - Q^2 evolution uncertainties are reduced in ratio

- The NC/CC ratio depends upon other (unknown) strange form factors ($F_{1,2}^s$).
    - Sensitivity to $F_{1,2}^s$ is much smaller than to G_A^s
    - $F_{1,2}^s$ has been measured (G0, Happex, SAMPLE, PVA4)
    - measure nu and antinu ratios, combine with PVe data (see talk by S. Pate)

- A real-world neutrino experiment will use a nuclear target (e.g. CH_2) with *bound* nucleons.
    - This problem has been studied by many groups. While the correction is sizable for *absolute* cross sections, the uncertainty in a *ratio* is small. (eg PRC 54, 1954, hep-ph/0311053)

- (in-medium) meson exchange correlations (MECs)
    - effects have been shown to be small in light-nuclei (eg: hep-ph/0511204, PRL 74, 4993)

NC neutrino scattering: some (experimental) details

- Need neutron detection to measure nubar ratio: R($\bar{\nu}$ NC/ $\bar{\nu}$ CC)
    - This is possible (with correct detector) via $(n\,p \rightarrow d\,\gamma(2.2\,MeV))$

- "Dirt neutrons" are an important background
    - Simulations CC/NC interactions in dirt produce neutral particles that are recon'd as NC p/n events in detector
    - Simulations show they are small in 8GeV beam with FINeSSE detector (50cm thick active veto)

- Final state interactions in nucleus will modify R(NC/CC).
    - (eg pn $\rightarrow$ np in nucleus)
    - A simultaneous measurement of CC inclusive vs exclusive will enable a correction

Summary

- A neutrino NC scattering experiment to measure Δs would yield important information on nucleon spin structure.

- Calculated sensitivities for FINeSSE at FNAL:

From neutrinos (1y run at FNAL):
$\sigma(\Delta s) = \pm\, 0.025$ (exp. stat. and sys.)
± 0.02 (f. f. systematic)

From antineutrinos (2y run at FNAL):
$\sigma(\Delta s) = \pm\, 0.04$ (exp. stat. and sys.)
± 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 ± 0.06

- We are continuing work to make it happen.

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