Studying Neutrinos with FINeSSE

- Neutrinos in the Standard Model
- Using neutrinos to probe nuclear structure
- Neutrino cross sections
- Measurements with FINeSSE
Neutrinos are great probes because they are so simple!

“no mass, no charge, no problem”
“Conventional” neutrino scattering is back in vogue

Past neutrino experiments
relatively low energy, low statistics
bubble chamber experiments

Rekindled interest in
neutrino interaction physics
at low energies
• high flux neutrino sources
• higher precision detectors

Moved to higher energy experiments
higher rates
new physics

within the last decades,
neutrino oscillation physics
lots of interest
moved back to lower energies
Rekindled interest: Entering the era of precision neutrino physics

Lots of data pouring out of these experiments and lots of older data used for development of cross section monte carlos

NuINT workshops established

Durham data base project has pulled all this together!
(Zeller, Whalley, Gallagher, Hawker, Sakuda)

Different cross section monte carlos from different experiments in similiar energy ranges
  • comparisons teach us about underlying models.
    NUANCE (MiniBooNE)
    NEUGEN (MINOS)
    NEUT (K2K)
Rich energy region: different channels turning on and off

A lot going on at low energies:

- quasi-elastic single $\pi$
- (DIS turning on)

- clean beams, but flux and cross sections dropping rapidly
- need intense beams!

Significant overlap with accelerator neutrino oscillation searches

- important for oscillation physics
- parasitic beam usage
FINeSSE
Fine-grained Neutrino Scattering Experiment

Measure strange spin of proton
Measure a suite of low energy cross sections

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Low energy neutrino scattering is a great way to probe the strange spin of the proton.
Who has already measured $\Delta s$?

Polarized-lepton DIS (EMC, SMC, SLAC) extract the quark contributions to the spin of the nucleon via the axial structure function $g_1(x,Q^2)$

\[ \Delta s \sim -0.10 \pm 0.05 \]

- dependent on assumptions of SU(3) flavor symmetry
- worry about extrapolation to $x=0$

Results from HERMES
Semi-inclusive scattering: tag p, k, or π in coincidence with outgoing charged leptons. Flavor tags different quark distributions....

\[ \Delta s = 0.03 \pm 0.03 \pm 0.01 \] (0.023<\textit{x}<0.30)

- Is fragmentation understood?
  Does this agree with inclusive result?

Measurement via neutrino-nucleon elastic-scattering to determine \( \Delta s \) **directly**

This method requires:
  - no extrapolation to \( x=0 \)
  - no assumptions of SU(3) symmetry

A theoretically robust measurement of \( \Delta s \)
Measuring $\Delta s$ using neutrinos

quasi-elastic CC scattering
$q=$ up and down quarks only

Neutral current scattering
$q=$ any quark in the nucleon
$\rightarrow$ strange quarks
\[ \nu N \rightarrow \nu N \text{ scattering and } \Delta s \]

- Nucleon Neutral Weak Current depends on:

\[ \langle f \mid J_{\mu}^H \mid i \rangle = \bar{u}_f(p') \left[ \gamma_{\mu} F_1(Q^2) + i \frac{\sigma^{\mu\nu}}{2M_p} q^\nu F_2(Q^2) + \gamma_{\mu} \gamma_5 G_A(Q^2) \right] u_i(p) \]

extract axial form factor, \( G_A \)

(get \( F_1, F_2 \) from other expts)

- \( G_A(Q^2) = -\tau^z g_A(Q^2) + G_A^s(Q^2) \)

- \( g_A \) known (nuclear \( \beta \) decay)

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

Measure \( \nu p \rightarrow \nu p \) at low \( Q^2 \)
The best measurement of $\nu N$ NC scattering to date is from BNL E734:
- $\nu p, \bar{\nu} p$ elastic scattering,
- w/170 ton segmented detector,
- $@E_\nu \sim 1.2$ GeV ,
- $Q^2 = 0.45$ to $1.05$ GeV$^2$
- Ahrens et al., 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 $\rightarrow \Delta s = -0.21 \pm 0.10 \pm 0.10$

  - (Alberico et al., Nucl. Phys. A651, 277, 1999), considered ratios of NC,CC cross sections $\rightarrow \Delta s$ consistent with above

  - (Pate, PRL 92, 082002, '04): combines E734 data with eN data from HAPPEX, yields $G_A^s(Q^2=0.5 \text{ GeV}^2)$, but data not close enough to $Q^2=0 \rightarrow$ no $\Delta s$ extraction.

- The BNL734 data is not accurate enough to address the DIS measurements

systematic and statistical errors are too large
Ingredients for precision, low energy, neutrino scattering measurements

- High intensity beams -> high event rates
- Minimize flux uncertainties
  - 15-20% in the past -> 5% expected by MiniBooNE and MINOS
- Minimize background contamination
  - low energy neutrino spectrum (below DIS turn-on and with small high energy tail)
  - fine-grained detector -> good final state separation
## FINeSSE: Event Rates

### High Statistics

### FINeSSE: Event Rates

<table>
<thead>
<tr>
<th>$\nu$ Reaction</th>
<th>$\nu_\mu$ 10(^{20}) POT 1 ton</th>
<th>$\bar{\nu}_\mu$ 10(^{20}) POT 1 ton</th>
<th>$\nu_e + \bar{\nu}_e$ 10(^{20}) POT 1 ton</th>
<th>$\nu_\mu$ 6 $\times$ 10(^{20}) POT 9 ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE, $\nu_\mu n \rightarrow \mu^- p$</td>
<td>2,715</td>
<td>43</td>
<td>13</td>
<td>146,610</td>
</tr>
<tr>
<td>NC EL, $\nu_\mu N \rightarrow \nu_\mu N$</td>
<td>1,096</td>
<td>18</td>
<td>5</td>
<td>59,184</td>
</tr>
<tr>
<td>CC $\pi^+, \nu_\mu p \rightarrow \mu^- p\pi^+$</td>
<td>1,235</td>
<td>6</td>
<td>8</td>
<td>66,690</td>
</tr>
<tr>
<td>CC $\pi^0, \nu_\mu n \rightarrow \mu^- p\pi^0$</td>
<td>258</td>
<td>3</td>
<td>2</td>
<td>13,932</td>
</tr>
<tr>
<td>CC $\pi^+, \nu_\mu n \rightarrow \mu^- n\pi^+$</td>
<td>216</td>
<td>2</td>
<td>2</td>
<td>11,664</td>
</tr>
<tr>
<td>NC $\pi^0, \nu_\mu p \rightarrow \nu_\mu p\pi^0$</td>
<td>211</td>
<td>3</td>
<td>2</td>
<td>11,394</td>
</tr>
<tr>
<td>NC $\pi^+, \nu_\mu p \rightarrow \nu_\mu n\pi^+$</td>
<td>125</td>
<td>2</td>
<td>0</td>
<td>6,750</td>
</tr>
<tr>
<td>NC $\pi^0, \nu_\mu n \rightarrow \nu_\mu n\pi^0$</td>
<td>158</td>
<td>3</td>
<td>2</td>
<td>8,532</td>
</tr>
<tr>
<td>NC $\pi^-, \nu_\mu n \rightarrow \nu_\mu p\pi^-$</td>
<td>98</td>
<td>3</td>
<td>0</td>
<td>5,292</td>
</tr>
<tr>
<td>CC DIS, $\nu_\mu N \rightarrow \mu^- X$</td>
<td>80</td>
<td>0</td>
<td>3</td>
<td>4,320</td>
</tr>
<tr>
<td>NC DIS, $\nu_\mu N \rightarrow \nu_\mu X$</td>
<td>37</td>
<td>0</td>
<td>2</td>
<td>1,998</td>
</tr>
<tr>
<td>CC coh $\pi^+, \nu_\mu A \rightarrow \mu^- A\pi^+$</td>
<td>160</td>
<td>5</td>
<td>2</td>
<td>8,640</td>
</tr>
<tr>
<td>NC coh $\pi^0, \nu_\mu A \rightarrow \nu_\mu A\pi^0$</td>
<td>98</td>
<td>3</td>
<td>0</td>
<td>5,292</td>
</tr>
<tr>
<td>other</td>
<td>117</td>
<td>2</td>
<td>0</td>
<td>6,318</td>
</tr>
<tr>
<td>total</td>
<td>6,604</td>
<td>93</td>
<td>41</td>
<td>356,616</td>
</tr>
</tbody>
</table>

Event Rates for a 9 ton (fiducial) detector for FINeSSE run ~147k CCQE ~59k NC EL signal channels are ~ 60% of total
The Right Flux

“Low” energy neutrino beam produced from 8 GeV POT on target

Excellent $\nu$ energy distribution for the $\Delta s$ measurement
- High enough...
  - large elastic cross section
  - minimize nuclear effects
- and Low enough to minimize backgrounds (DIS) small
- little to no high-energy "tail"

- Low Duty Factor also $\Rightarrow$ very small cosmic background
Minimize flux error further:
Take advantage of cross section ratios!

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

\[ R(p/n) = (\nu_p \rightarrow \nu_p)/(\nu_n \rightarrow \nu_n) \]

is quite sensitive to \( G_A^s(Ds) \) because:

\[ G_A = -g_A \tau_z + G_A^s \quad (\tau_z = 1 \ p, -1 \ n) \]

However, the systematic errors of neutron detection are problematic. So...

Ratio of NC elastic scattering to CC quasi-elastic scattering:

\[ R(NC/CC) = (\nu_p, NC)/(\nu_p, CC) \]

is somewhat less sensitive to \( \Delta s \), but experimentally easier.

Very small systematic error due to the uncertainty in neutrino flux!

*(Garvey et al., PR C48, 1919, '93)*
Fine-Grained Detector
Measures both short proton tracks and longer muon tracks

- proton energy measurement down to $T_p \sim 100\text{MeV}$ ($R\sim10\text{cm}$)
- range out up to 1 GeV muons
- particle ID for NC/CC/background separation

GEANT-generated events in scintillator:

$Q^2 = 0.2 \text{ GeV}^2$, $E_n = 800\text{MeV}$
$T_p \sim 100 \text{MeV}$, $T_m \sim 600 \text{MeV}$
Two part detector

The Vertex Detector...  
- to precisely track low-energy protons

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

neutrinos
Vertex Detector: a large, low-threshold, 3D, tracking detector

Vertex Detector side view:

- \((2.5 \text{m})^3\) active liquid scintillator volume
- 19200 \((80 \times 80 \times 3)\) 1.5 mm WLS fibers on 3cm spacing with 3 orientations

- liquid scintillator
- WLS fiber array
- veto region
- PMTs + on-board electronics
- WLS fibers in vertex detector
Considered a few different detector technologies for FINeSE.....

**Scintillator stack**
- optically isolated scintillator bars with wave length shifting fibers in each bar
- ie: K2K Scibar detector
- MINOs/MINERvA detectors

**Scintillator bath**
- not optically isolated
- information in 3D
Lose events at high angles/low KE in scintillator bar type detector compared to Scibath.
Prototype "Scibath" detector built to test technology:

- 30cm x 16 cm x 16 cm box
- filled with scintillator oil
- 6x5 array of 1.5mm multi-clad WLS fiber
- readout via 16 anode MAPMT

tested at the Indiana University Cyclotron Facility in summer 2003 using low intensity, 200 MeV protons

- 6x6 mm² beam profile
- beam scanned vertically, horizontally, and at angle to prototype
Test results:

position: 15mm FWHM

light seen from near proton tracks: 17±2 PEs

Angle: 15° FWHM
Measuring muons from CCQE interactions

- Low energy muons contained in Vertex Detector and veto
- Higher energy muons are forward -- stop in Muon Rangestack

Range outs in:

- In Vertex Detector signal region
- In Vertex Detector signal region + veto
- In Vertex Detector + Muon Rangestack
Muon Rangestack is designed to:

- range out 0.15 to 1.5 GeV muons with energy resolution of 10%
- minimizing cost, space, and number of different components
- well tested and understood design

- 21 pairs of scintillator and iron absorber planes
- four sections with thickness of iron absorber = 0.5" x n (n=1 to 4) in each 1:4 scintillator:iron
  as lower energy particles range out (and only higher energy particles remain)
  iron can be thicker while retaining same energy resolution
The FINeSSE detector has been simulated using:
- NUANCE for the event generation
- GEANT for the detector simulation
- A Hough-transform-based reconstruction package
FINeSSE Detector Simulation and Reconstruction...

Simulation and reconstruction of 50-500 MeV protons and muons:

- $\Delta E \sim 15\text{MeV}$

- $\Delta \theta \sim 6^\circ$
FINeSSE Detector Simulation and Reconstruction...

simulated hits and reconstructed tracks in the Vertex Detector

CCQE event

NCp event

fiber hits, (size # g collected)

generated

reconstructed
Simulation of $R(NC/CC)$ measurement

NCp and CCQE cuts for $R(NC/CC)$ measurement:

<table>
<thead>
<tr>
<th>cut #</th>
<th>NCp cuts</th>
<th>CCQE cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>edge distance &gt; 15 cm</td>
<td>edge distance &gt; 15 cm</td>
</tr>
<tr>
<td>1</td>
<td># 3d tracks = 1</td>
<td># 3d tracks, eq. 2</td>
</tr>
<tr>
<td>2</td>
<td>$dE/dx(p) &gt; 2.5$</td>
<td>$dE/dx(p) &gt; 2.5, dE/dx(\mu) &lt; 2.5$</td>
</tr>
<tr>
<td>3</td>
<td>$\theta(p) &gt; 0.5$</td>
<td>$\theta(p) + \theta(\mu) &gt; 1.5$</td>
</tr>
<tr>
<td>4</td>
<td>no &quot;late&quot; light in vertex det.</td>
<td>no &quot;late&quot; light in vertex det.</td>
</tr>
<tr>
<td>5</td>
<td>no veto or muon stack energy</td>
<td>low &quot;remaining&quot; energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>reaction channel</th>
<th>NCp cuts</th>
<th>NCn</th>
<th>NC$\pi$</th>
<th>CCQE</th>
<th>CC$\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>raw events</td>
<td>21219</td>
<td>20487</td>
<td>19062</td>
<td>100102</td>
<td>54107</td>
</tr>
<tr>
<td>passed events</td>
<td>3929</td>
<td>1162</td>
<td>167</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>efficiency (%)</td>
<td>18.5</td>
<td>5.7</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>fid. eff. (%)</td>
<td>27.1</td>
<td>8.3</td>
<td>1.3</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>purity (%)</td>
<td>74.0</td>
<td>21.9</td>
<td>3.1</td>
<td>0.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CCQE cuts</th>
<th>NCp</th>
<th>NCn</th>
<th>NC$\pi$</th>
<th>CCQE</th>
<th>CC$\pi$</th>
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<td>raw events</td>
<td>21219</td>
<td>20487</td>
<td>19062</td>
<td>100102</td>
<td>54107</td>
</tr>
<tr>
<td>passed events</td>
<td>165</td>
<td>76</td>
<td>581</td>
<td>7323</td>
<td>1322</td>
</tr>
<tr>
<td>efficiency (%)</td>
<td>0.8</td>
<td>0.4</td>
<td>3.0</td>
<td>7.3</td>
<td>2.4</td>
</tr>
<tr>
<td>fid. eff. (%)</td>
<td>1.1</td>
<td>0.5</td>
<td>4.5</td>
<td>10.6</td>
<td>3.6</td>
</tr>
<tr>
<td>purity (%)</td>
<td>1.7</td>
<td>0.8</td>
<td>6.1</td>
<td><strong>77.4</strong></td>
<td>14.0</td>
</tr>
</tbody>
</table>

Resulting NCp and CCQE efficiencies from a 215k event sample:
FINeSSE Sensitivity to $\Delta s$

A fit to the simulated data was performed to estimate the precision of a $\Delta s$ measurement with FINeSSE:

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

Results:
$\sigma(\Delta s) = \pm 0.04$ (stats. and exp. sys.)
$= \pm 0.025$ (f. f. sys)

Recall:
BNL E734  $\Delta s = -0.21 \pm 0.10 \pm 0.10$
polarized DIS  $\Delta s = -0.14 \pm 0.03$

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

NC/CC ratio: (vs $Q^2$)

A precise, theoretically robust measurement of $\Delta s$ via Neutrino-scattering
Working to improve on this by improving detection techniques:

1) Oil studies in “Scibath”
2) Phase II: Liquid Argon TPC

• Identifying neutrons!
  • Dominant systematic in measuring neutrino-proton cross section
  • $(\nu p \rightarrow \nu p)/(\nu n \rightarrow \nu n)$ is more sensitive to $\Delta s$

• Measure short tracks (low $Q^2$) – good resolution

• Eliminate error on correction for scattering on free protons (no free protons!) (LArTPC only)
$\nu$ vs $\bar{\nu}$ running allows for sensitivity to $\Delta s$ and other form factors

$R(\text{NC/CC})$ vs $Q^2 f$
with different values of $F_1^s, F_2^s, G_A^s, M_A$

Use shape change in neutrino versus anti-neutrino running to extract other form factors and understand systematics

Considering $\nu$ and $\bar{\nu}$ running
Rich energy region: different channels turning on and off

A lot going on at low energies:
- quasi-elastic single $\pi$
  (DIS turning on)
- clean beams, but flux and cross sections dropping rapidly
  need intense beams!

- Charged Current Quasi-elastic scattering
- Pion Production channels
- Neutral current elastic electron scattering
Quasi-Elastic Scattering

Existing data:
- uncertainties dominated by 15-20% flux errors
- low statistics
  (largest published data set has ~2500 evts)
- all data below 1 GeV is on light targets ($D_2$)

use CCQE samples to unfold nuclear effects:
Interesting rollover at low $Q^2$

- not fully reproduced by any of the MCs
- same effect seen by K2K near detectors

K. Furuno, NuInt02 proceedings to be published in Nucl. Phys. B.

Pauli Supression effect? Nuclear Shadowing?

Sam Zeller
Measure CCQE's with fine-grained, high statistics experiment, down to low $Q^2$

\~150,000 charged current quasi-events expected in Vertex Detector

very pure sample: separate CC$\pi^+$, CCQE

see proton recoil in Vertex Detector and range out muons in range stack

Monte Carlo event in Vertex Detector and Rangestack

Reconstruction in Vertex Detector

fiber hits, (size $g$ collected)

generated

reconstructed
Suppression seems to be largest in CC$\pi^+$ sample
Want to easily identify these events

FINeSSE Event Display

\[ \nu_n \rightarrow \mu^- p \pi^0 \]

\[ \gamma \text{ from } \pi^0 \]

\[ \gamma \text{ from } \pi^0 \]

\[ p \]

\[ \mu^- \]
Single Pion Production

Resonant Production (~80%)

• resonant channels typically known ~20-40%
• interactions complicated by final state effects (π absorption, charge exchange)
• as in QE's, all data below 1 GeV is on light targets
Coherent Production (~20%) scatter from entire nucleus...

- overall rate not well known (~100% uncertainty)
- no data below 2 GeV

x20 variation in recent models at E~1 GeV

distinct kinematics:
forward scattered \( \mathbf{p} \)
small energy transfer to target (low \( Q^2 \))
Neutral current $\pi^0$ production: significant background for present and future $\nu_\mu \rightarrow \nu_e$ oscillation searches

- very little data
- spread in model descriptions
Preliminary MiniBooNE data suggests there may be surprises here too!
Neutral current $\pi^0$'s in FINeSSE

Fine-grained detector can separate out these events well

Counting multiple rings is harder than looking for little blobs
Even better in Liquid Argon TPCs: excellent spatial resolution: separating single pion production from other channels
$\nu e$ scattering: neutrino magnetic moments

Massive neutrinos imply existence of $\nu_R$

Increase in overall cross section

$$\sigma_{\text{tot}} = \sigma_{\text{weak}} + \sigma_{\text{EM}}$$

Weak and EM Contributions to the $\nu-e$ Cross Section

Shape change in the differential cross section
Limits set from experiment:

Electron $\nu$ magnetic moment: $\mu_{\nu_e} \rightarrow 1.0 - 1.5 \times 10^{-10} \mu_B$

- Preliminary measurement from MUNU
- SuperK shape fit

Muon $\nu$ magnetic moment: $\mu_{\nu_m} \rightarrow 6.8 \times 10^{-10} \mu_B$

- LSND experiment: combined measurement of electron and muon neutrino magnetic moment using total $\nu e \rightarrow e\nu$ cross section

How is this different from $n_e$ searches? (already set better limits)

- solar $\nu_e$ measures $\mu_2$
- reactor $\bar{\nu}_e$ measures primarily $\mu_1$ and $\mu_2$
- accelerator $\nu_m$s would measure $\mu_1$, $\mu_2$, and $\mu_3$

Tau $\nu$ magnetic moment $\mu_{\nu_\tau} \rightarrow 10^{-9} \mu_B$

- SuperK & SNO bounds for all neutrinos
Different beyond-the-Standard-Model theories predict different sizes for this neutrino magnetic moment

**Minimally Extended Standard Model**

\[ \sim 3 \times 10^{-19} \mu_B \]

**SUSY models:** left-right supersymmetric models

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

**Large Extra Dimensions**

\( \mu_\nu \rightarrow 1.0 \times 10^{-11} \mu_B \)

order of magnitude lower than present limits
ve scattering with FINeSSE

- high resolution detector to get clean sample
- low electron recoil threshold
- lots of neutrinos

FINeSSE “scibath” detector: forward electron shower

FINeSSE Phase 2 LArTPC
FINeSSE physics:
- measure strange spin of the proton
- suite of low energy neutrino cross section measurements

Working to understand in detail how well we can do but all the ingredients are there.... for the first time.

- High intensity beams → high event rates
- Minimize flux uncertainties
  - 15% in the past → 5% expected by MiniBooNE and less by MINOS/MINERνA
- Minimize background contamination
  - low energy neutrino spectrum (below DIS turn-on and with small high energy tail)
  - fine-grained detector → good final state separation
Possibilities at Brookhaven

Neutrino experiments need lots of beam....

AGS: high intensity machine
can re-invent the short experimental run for neutrino physics!

Running concurrently with RHIC (80 hours/wk)
At intensities and energies (8 GeV) anticipated for RSVP

30TP/second in 2008, just before RSVP turns on

Experimental needs: \(1.5 \times 10^{20}\) protons on target total...

4 month run!

things to be sorted out: extracting high intensity, lower energy beam....
New neutrino target blockhouse 25m from absorber

Existing Labyrinth here, but needs shielding horn PS enclosure

Decay region in U Line Tunnel: Looking upstream from beam absorber

protons from AGS

beams from AGS

U-Line berm and beam absorber

berm needs:
neutrino liner,
~10ft more overburden

space to put detector enclosure downstream of beamline
Possibilities at Fermilab:

**Booster Neutrino Beamline**

- 500m from neutrino target: MiniBooNE...

- 60-100m from neutrino target: open space!...

available for FINeSSE

1-2 x $10^{20}$ p.o.t/year in the future

-as per Mike Witherell in letter to FINeSSE on program planning website
FINeSSE

- Compelling physics...
  - Measure $\Delta s$ down to $Q^2 = 0.2$ GeV$^2$
  - Measure low energy neutrino cross sections
    (recommendation of APS Neutrino Study!)
- Still working to understand FINeSSE's reach
  - Neutrino plus anti-neutrino running?
  - Detector development...(phase 2 LArTPC?)
- Cost effective and timely
  - $2.8M$ detector (w/contingency)
  - 4 month-run at BNL!
- Makes the most of existing facilities
  - Parasitic running at FNAL and BNL
Simulation of $R(\text{NC}/\text{CC})$ measurement...

NCp events:

CCQE events:

$Q^2$ resolution

$\mathbf{s} = 0.053 \text{ GeV}^2$

$Q^2$ resolution

$\mathbf{s} = 0.079 \text{ GeV}^2$
Anti-neutrinos can help unfold coherent and resonant!
Readout with Hamamatsu MAPMTs and on board electronics

STAR PMT w/front-end electronics