Short-Baseline Neutrino Physics at an EIC

Outline:
- Motivation
    - ν properties
    - ν as probes
- ν beam and fluxes
- detectors
- measurements

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The Physics

The intense proton booster that will be required for an EIC could be used for a world-class neutrino facility.

This facility would allow a host of ν physics topics.

- ν properties (electroweak)
  - oscillation searches and measurements (at low/high Δm^2, long/short baseline)
  - ν magnetic moment
- as a probe of nucleon structure (strong)
  - form factors (low-energy)
  - structure functions (higher-energy)

I will concentrate on short baseline oscillation searches and form factor measurements.

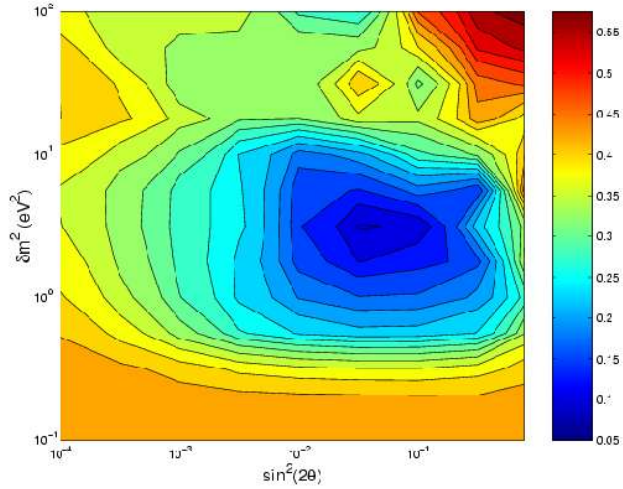
The Physics: short-baseline oscillations

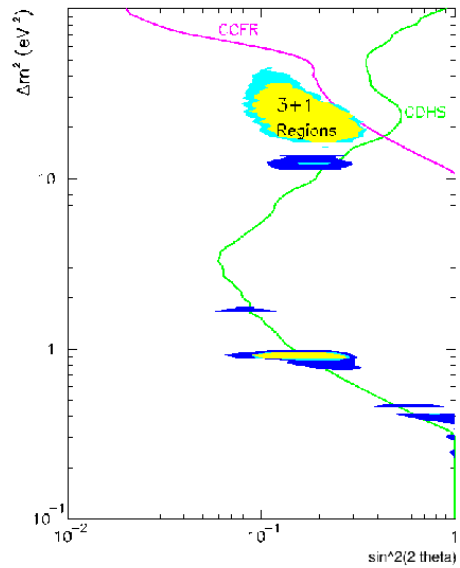
The $\Delta m^2 \sim$ 1-10 eV^2 oscillation range is an interesting region.

- astrophysics: ~1eV ν_s is a possible explanation of r-process in supernova (astro-ph/0309519, hep-ph/0205029)
  ν_μ disappearance

- LSND/MiniBooNE observations
  $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

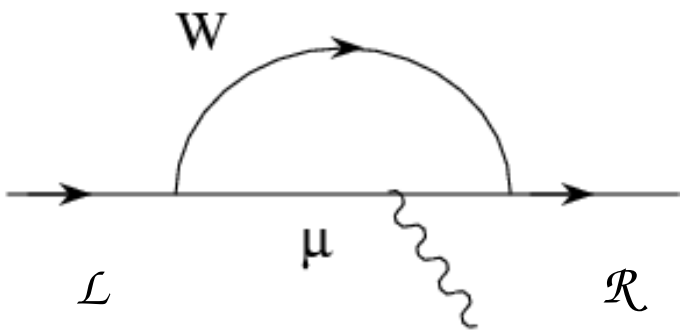
- $\Delta m^2 \sim$ 1-10 eV^2 => L/E ~ 1-0.1,
  E ~1GeV, L~1km-0.1km





The Physics: ν magnetic moment

Massive ν imply the existence of a $\nu_{\mathcal{R}}$,
therefore it is likely that μ_ν is nonzero.



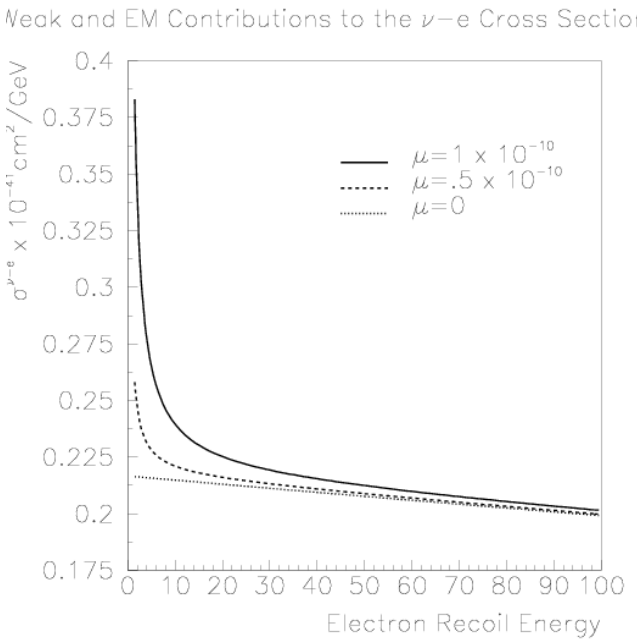
- current limit on ν_μ : $\mu_\nu \sim 6.8\times10^{-10}\,\mu_B$

- minimally extended standard model:

$$\mu_\nu \sim 3\times10^{-19}\mu_B$$

- but other models predict $\mu_\nu \sim 1\times10^{-11}\mu_B$

- measure via ν e –> ν e elastic scattering
(need a very intense beam)

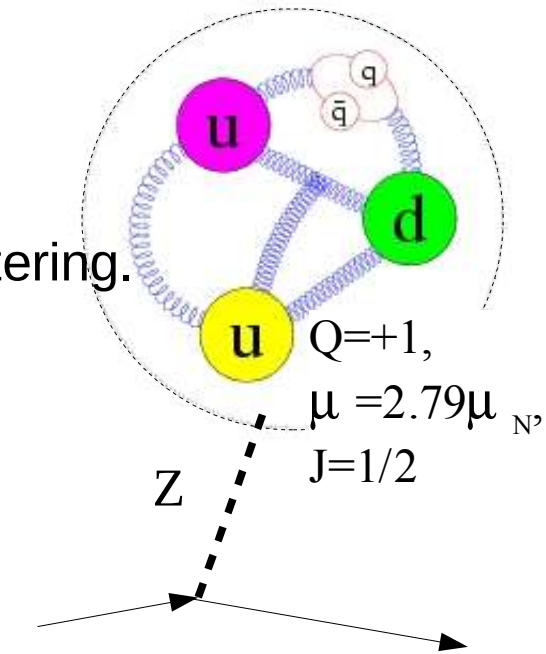


The Physics: nucleon structure

Spin structure of the nucleon:

$\Delta s <> 0$? (from SMC, SLAC, HERMES)

Δs can be measured with NC ν nucleon elastic scattering.



- Axial part of Nucleon Neutral Weak Current:

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

$$\Delta u \qquad \Delta d \qquad \Delta s$$

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

- $G_A^s(Q^2 = 0) = \Delta s$
- G_A (non-strange part of axial f.f.) known from neutron beta decay
- At low Q^2, cross section is most-sensitive to axial part (unique to neutrino scattering):
- Therefore, a measurement of νN NC scattering (at low Q^2) yields Δs

A ratio method to extract Δs

A measurement of νN NC cross section is sensitive to Δs...

but a cross-section ratio measurement is better!

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

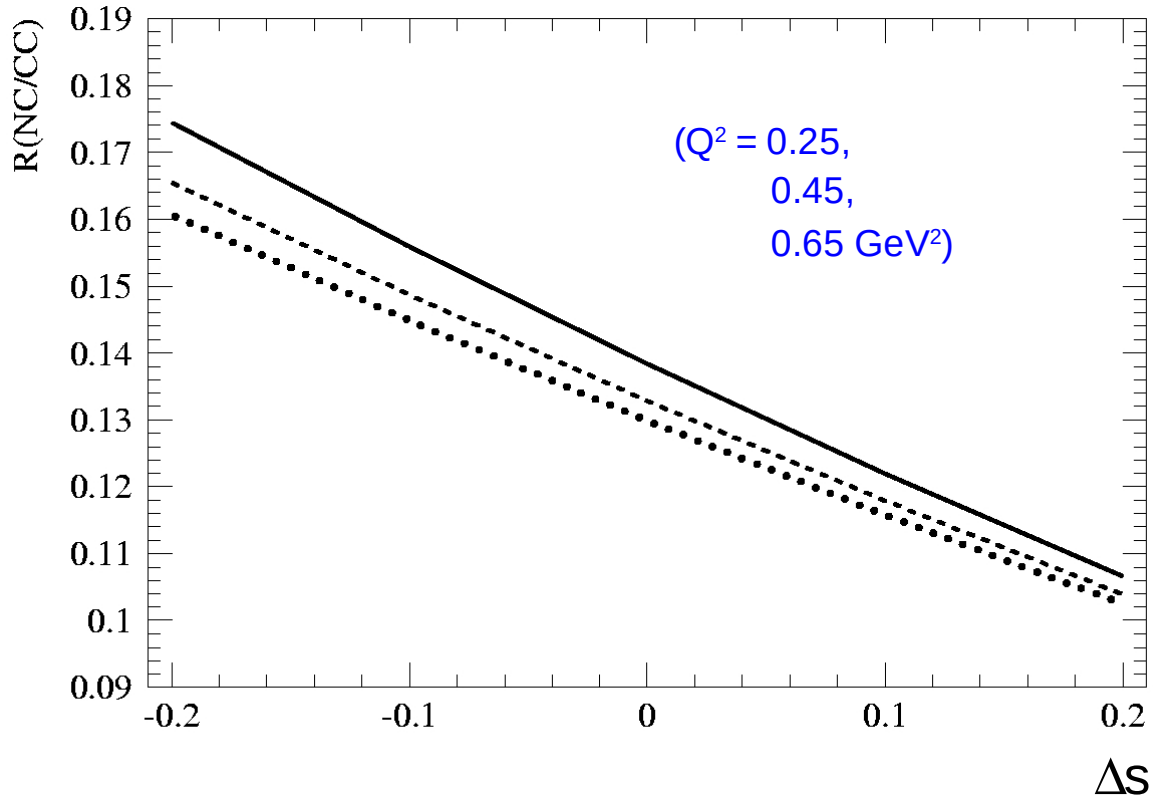
A measurement of R_ν(NC/CC) reduces

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

- uncertainties in measured form factors (e.g. M_A)

- nuclear effects

sensitivity of R(NC/CC) to G_A^s (Δs)



The ν beam

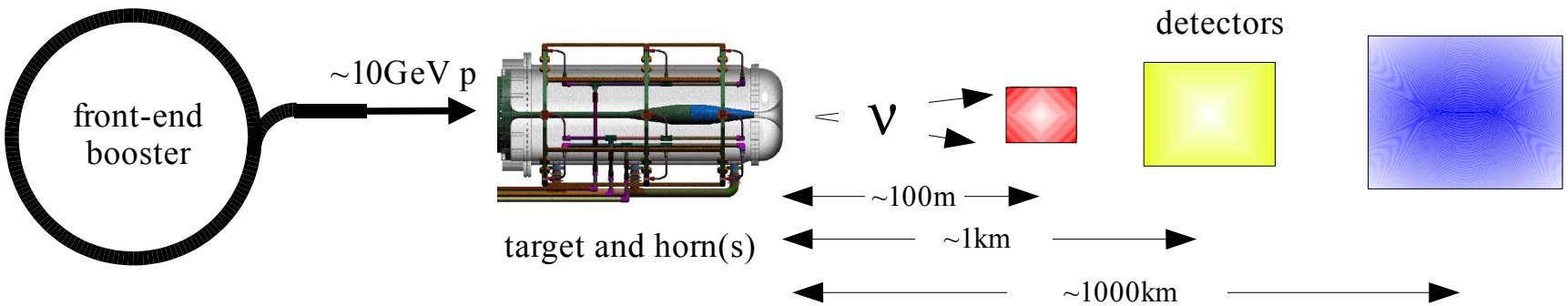
Assuming an EIC front-end proton booster with:

- E~10 GeV
- 5×10^{13} protons/pulse
- running at 10-30 Hz
- able to deliver "extra" protons to a target ~2×10^{7} secs/year

➪ $(1\text{-}3) \times 10^{22}$ protons on target (POT)/ year

This is a substantial gain over current or near-future facilities

- K2K: ~1×10^{20} POT/yr
- FNAL 8GeV booster beamline (for MiniBooNE): ~5×10^{20} POT/yr
- FNAL 120GeV nuMI beamline (for MINOS): ~5×10^{20} POT/yr
- JPARC: ~1×10^{21} POT/yr

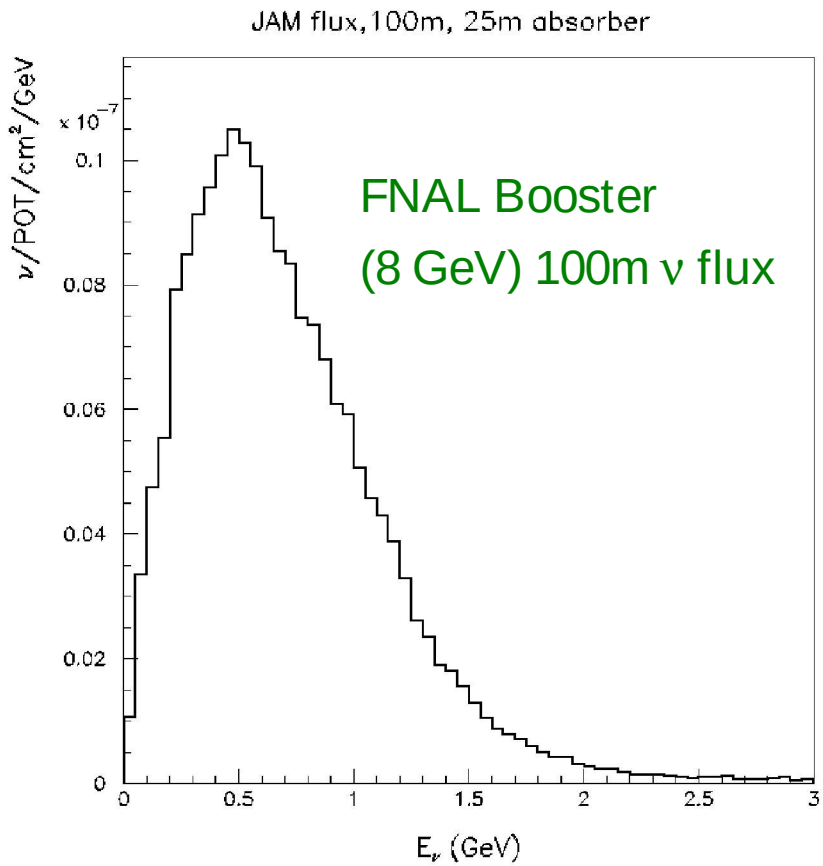


The ν beam

- at 100m
  ~10^{-10} ν_μ / POT/cm^2
  ~10^{12} ν_μ/cm^2/year

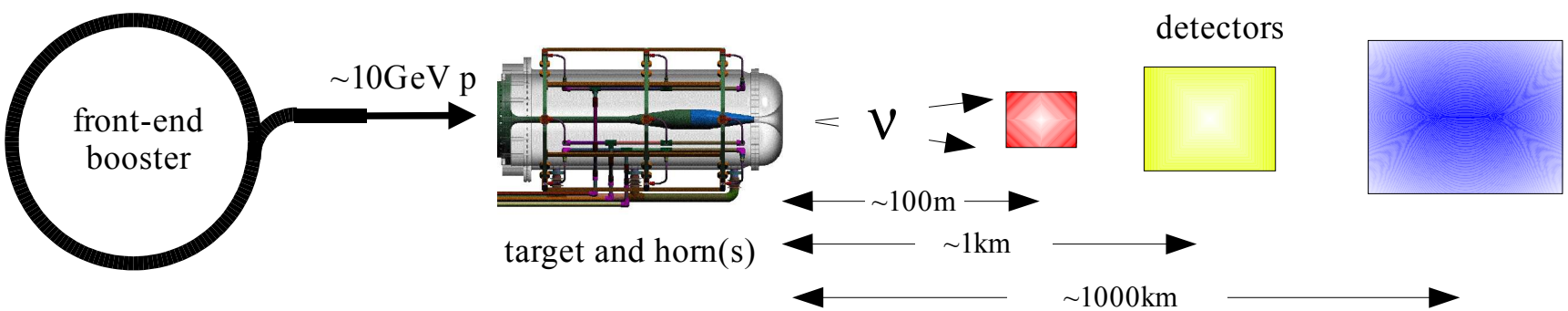
- Peak energy will be ~1 GeV
  (ideal for these measurements)

- large elastic cross section
- nuclear physics uncertainties small
- low enough that backgrounds
  (e.g. pion prod., DIS) small



A short-baseline detector scenario:

- detectors at 100m, ~1km, ~1000km (depending on osc. results)
- 100m (near) detector:
    - fine grained for good tracking, ~10tons
    - measurements: NC/CC ratio (Δs) , ν e elastic (mag. moment), +...
- 1km (intermediate) detector:
    - Cerenkov detector, ~100-1000tons
    - measurements: ν_e , $\bar{\nu}_e$ appearance, +...
- near and intermediate detctors together:
    - ν_μ disappearance



Expected Event Rates

- with 10^{22} POT/yr
- 10 ton, 100m near det. or 1000, 1km int. det.

- ~6.6 Mevents/yr!

- ~80k ν e elastic scattering events

The following ideas and results are taken from FINeSSE - an experiment recently proposed at FNAL

Event rates with FNAL Booster (8 GeV) 100m ν flux

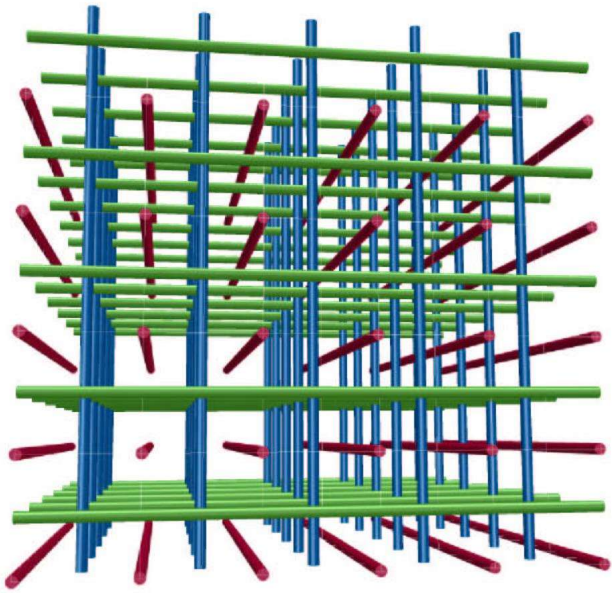
ν Reaction	ν_μ 10^{20} POT 1 ton	$\overline{\nu_\mu}$ 10^{20} POT 1 ton	$\nu_e + \overline{\nu_e}$ 10^{20} POT 1 ton	ν_μ 6×10^{20} POT 9 ton
CC QE, $\nu_\mu n \to \mu^- p$	2,715	43	13	146,610
NC EL, $\nu_\mu N \to \nu_\mu N$	1,096	18	5	59,184
CC π^+, $\nu_\mu p \to \mu^- p \pi^+$	1,235	6	8	66,690
CC π^0, $\nu_\mu n \to \mu^- p \pi^0$	258	3	2	13,932
CC π^+, $\nu_\mu n \to \mu^- n \pi^+$	216	2	2	11,664
NC π^0, $\nu_\mu p \to \nu_\mu p \pi^0$	211	3	2	11,394
NC π^+, $\nu_\mu p \to \nu_\mu n \pi^+$	125	2	0	6,750
NC π^0, $\nu_\mu n \to \nu_\mu n \pi^0$	158	3	2	8,532
NC π^-, $\nu_\mu n \to \nu_\mu p \pi^-$	98	3	0	5,292
CC DIS, $\nu_\mu N \to \mu^- X$	80	0	3	4,320
NC DIS, $\nu_\mu N \to \nu_\mu X$	37	0	2	1,998
CC coh π^+, $\nu_\mu A \to \mu^- A \pi^+$	160	5	2	8,640
NC coh π^0, $\nu_\mu A \to \nu_\mu A \pi^0$	98	3	0	5,292
other	117	2	0	6,318
total	6,604	93	41	356,616

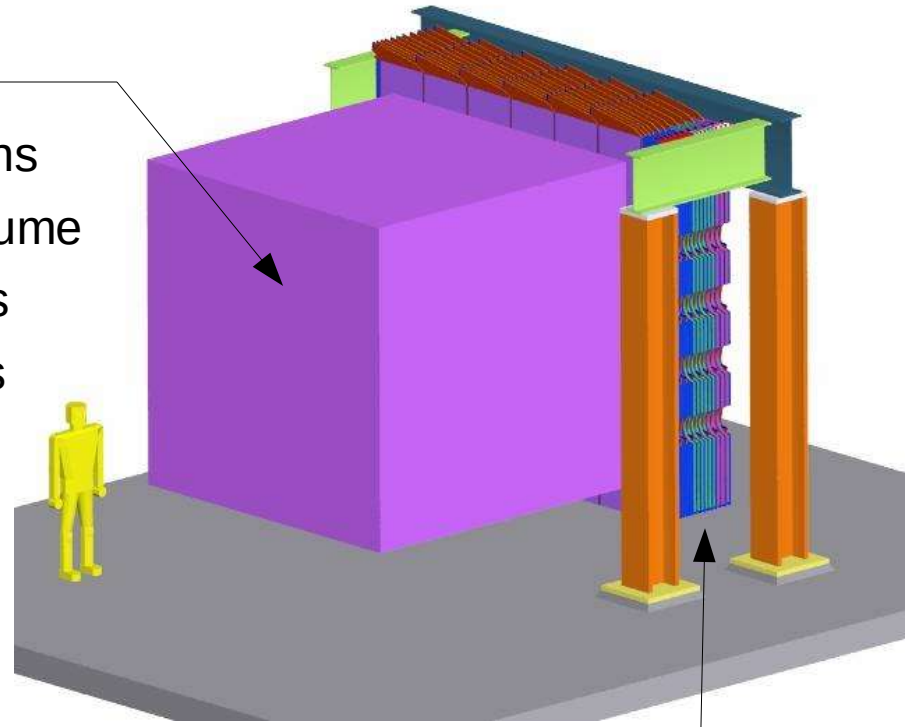
x1000

FINeSSE Detector

The Vertex Detector...

- to precisely track low-energy protons
- $(2.5m)^3$ active liquid scintillator volume
- 19200 (80x80x3) 1.5 mm WLS fibers on 3cm spacing with 3 orientations



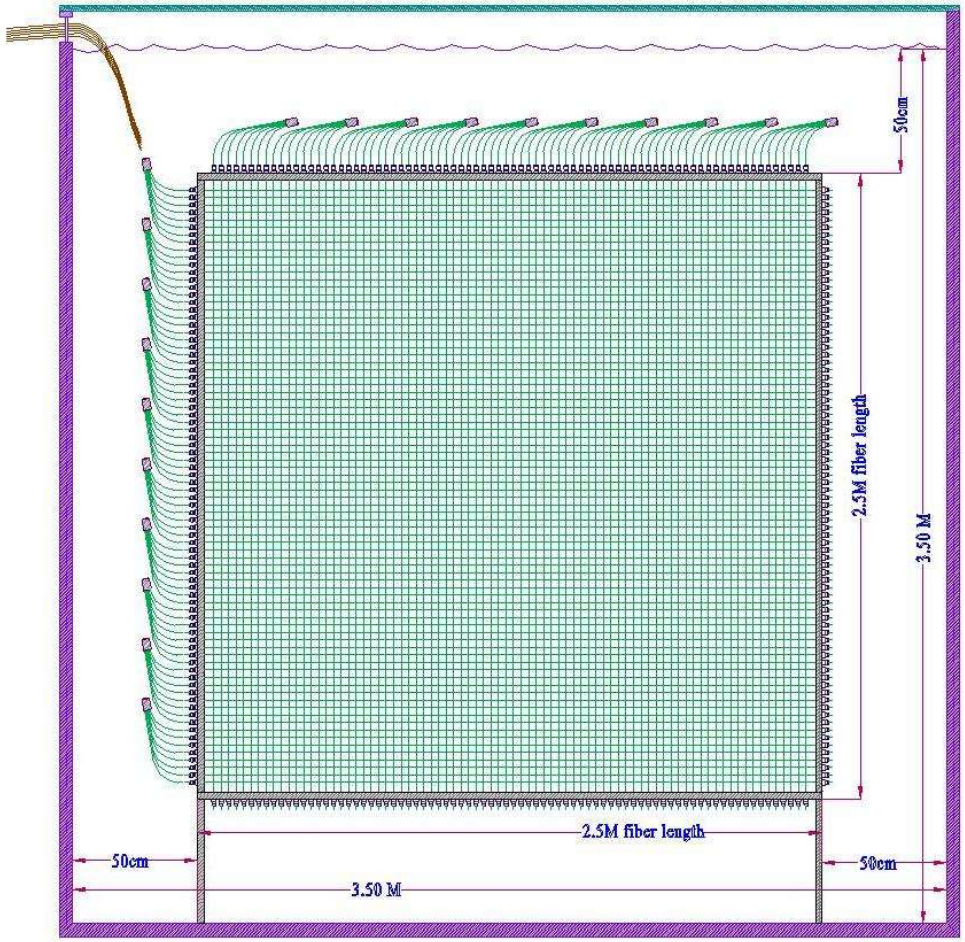


The Muon Rangestack...

- to track and measure the energy of muons

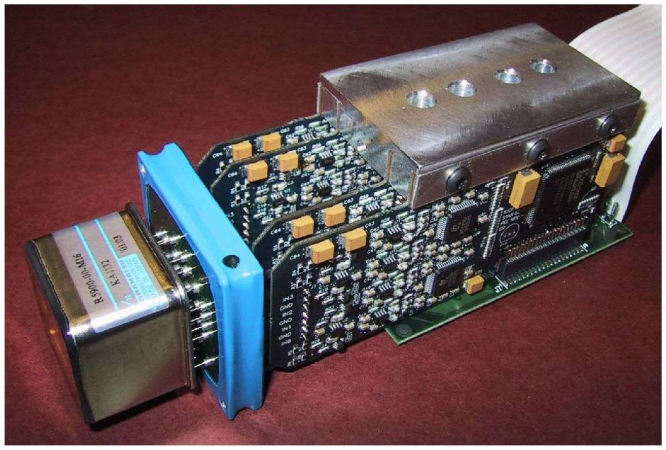
FINeSSE Vertex Detector...

Vertex Detector side view:



- read out with 64 anode PMTs and on-board electronics

STAR PMT w/front-end electronics



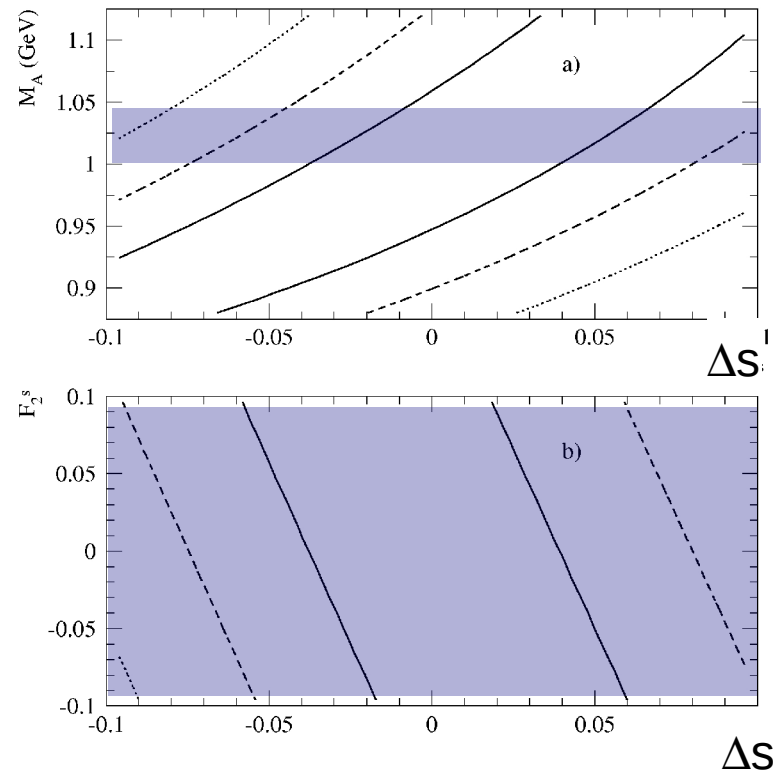
- similar scheme to that employed for STAR endcap calorimeter

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

A fit to the simulated data was performed to estimate the precision of a Δs measurement with FINeSSE:

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

χ^2 contours (1σ,2σ,3σ) from Δs fit



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 $\Delta s = -0.14 \pm 0.03$

- A precise, theoretically robust measurement of Δs via neutrino-scattering

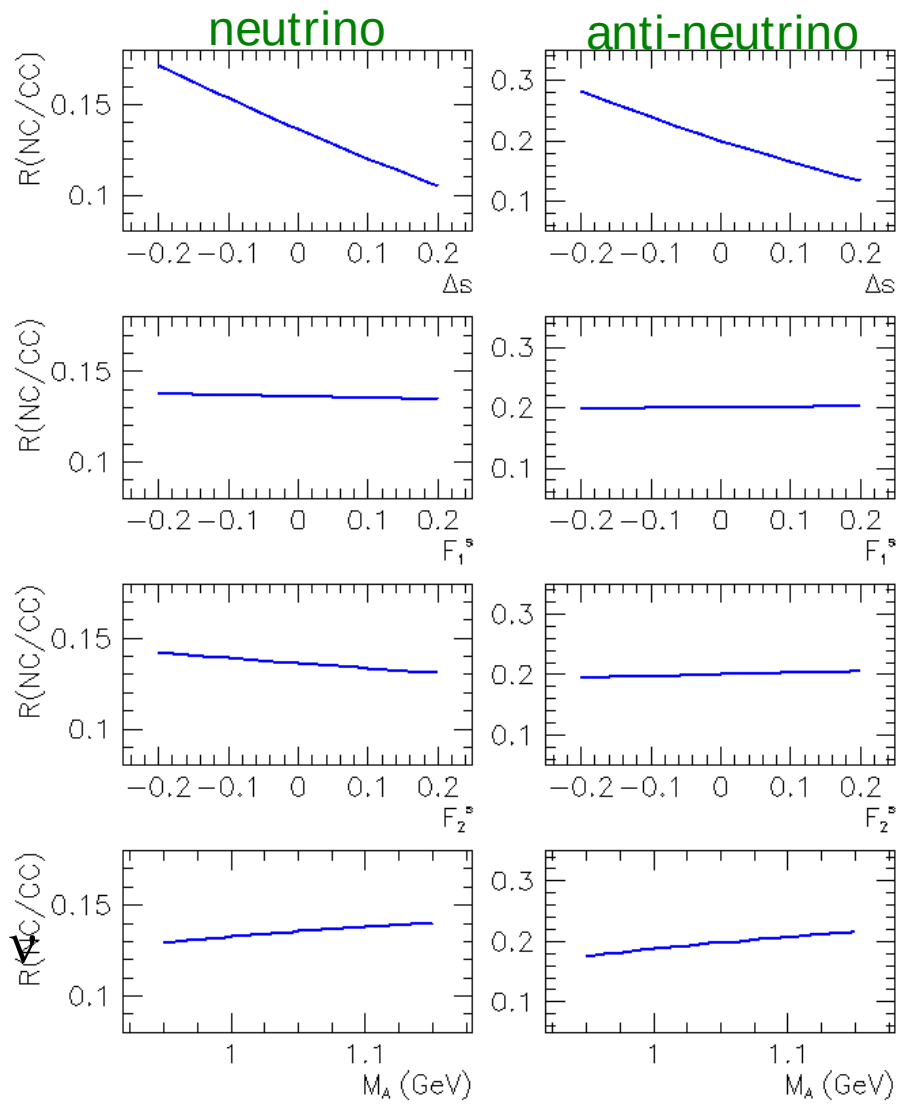
A measurement of R(NC/CC) with ν and, $\underline{\nu}$

R(NC/CC) vs F_1^s, F_2^s, G_A^s, M_A

for ν and $\underline{\nu}$

- 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)

- a measurement of NC ν at an EIC $\underline{\nu}$ beam would completely determine the nucleon axial structure.



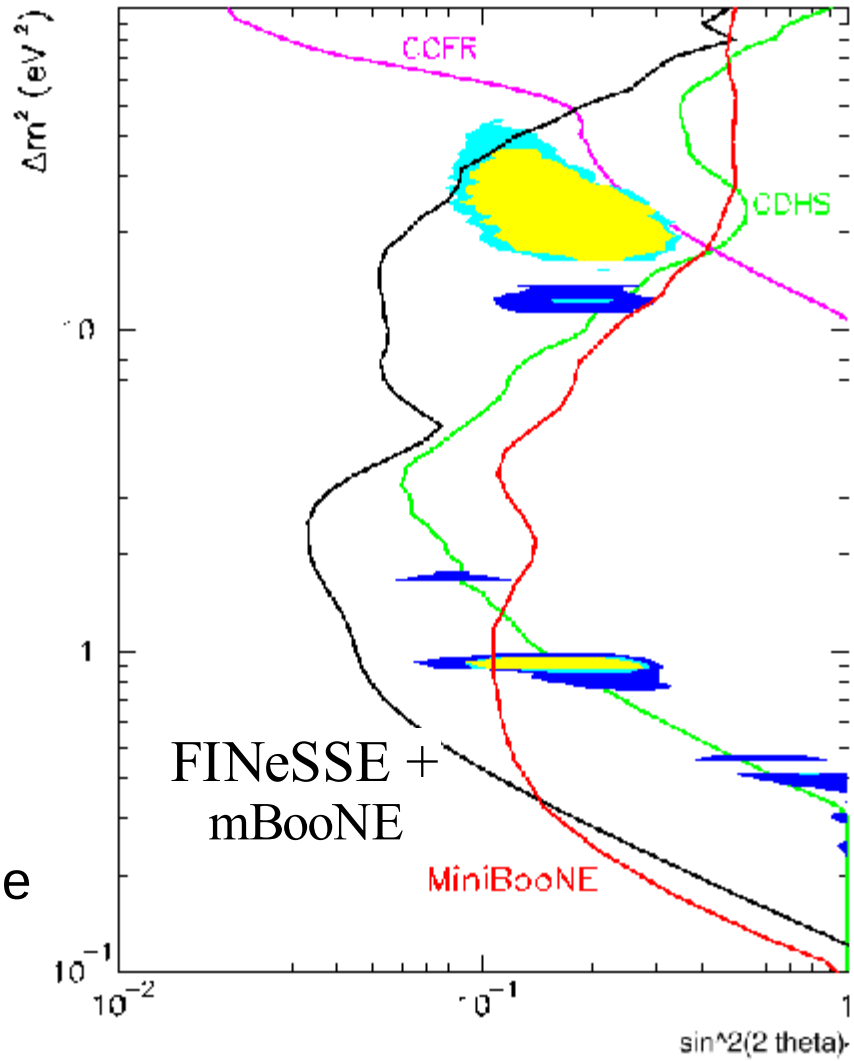
Oscillation physics with FINeSSE:

2nd major physics measurement of FINeSSE

- search for ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$) together with MiniBooNE

- covers region of parameter space favored by some astrophysical models to explain R-process in supernova (see e.g. astro-ph/0309519, hep-ph/0205029)

- a measurement of this at an EIC ν beam would significantly increase the reach of a ν_μ disappearance search



Summary:

- The intense proton booster that will be required for an EIC could be used to generate unprecedented high-flux of medium-energy neutrinos.

- This beam would allow for several important measurements:
  - oscillation searches: $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
    and $\nu_\mu \rightarrow \nu_x$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_x$
    in the $\Delta m^2 \sim 1\text{-}10 eV^2$ region
  - ν magnetic moment
  - measurement of the nucleon axial structure (Δs)

- A plan for an EIC should consider the additional physics made possible with a ν component.