A Proposal for a Near Detector Experiment on the Booster Neutrino Beamline: FINeSSE

FINeSSE
Fermilab
Intense
Neutrino
Scattering
Scintillator
Experiment

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Presentation to the FNAL PAC
12/12/03

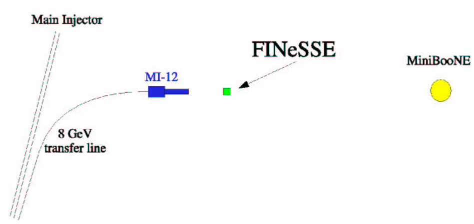
FINeSSE Overview/Outline

Physics Motivation:

- A measurement of Δs: structure of the nucleon
- A search for ν_μ disappearance: nature of the neutrino

Experiment:

- located 100m from ν target on booster neutrino beamline
- 2 part detector:
  - novel liquid-scintillator/fiber vertex detector
  - muon rangestack



Anticipated Results:

- detailed simulation of physics and detector
- reconstruction program - efficiencies, backgrounds
- physics sensitivities

Execution:

-Schedule: running in mid-2006
- Budget: detector - \$2.8M , building - \$1.6M

topics in...
green - covered by Rex
blue - " " Bonnie

FINeSSE Collaboration:

- 30 people
- 6 Universities
- 2 National Labs
- collaborators include postdocs and students
- both nuclear and particle physicists
- mix of senior and junior scientists

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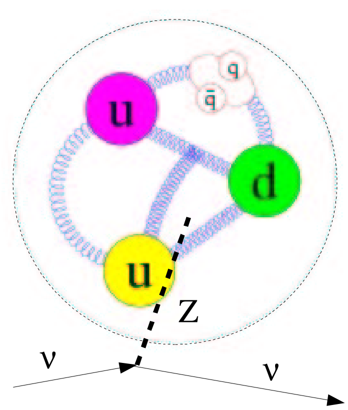
FINeSSE: A measurement of Δs
(Δs: the strange quark contribution to the nucleon spin)

This will address a fundamental aspect of nucleon structure:

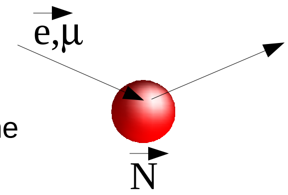
- What carries the nucleon spin! valence quarks, sea quarks, gluons? Can we describe the proton in terms of a fundamental theory? This is still an open question and an area of intensive effort.

- The neutrino is a uniquely sensitive probe of the strange quarks in the nucleon via NC scattering and the interpretation is theoretically robust.

- The (operating!) Booster Neutrino beam at FNAL offers the unique opportunity to make this measurement now.



Polarized-DIS measurements of Δs



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

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

⇒ $\Delta s = -0.14 \pm 0.03$, $\Delta\Sigma = 0.16 \pm 0.08$ (to leading-order in QPM)
(Filippone and Ji, Adv.Nucl.Phys.26:1,2001)

However, considering QCD radiative effects (NLO), the Q^2-evolution of g_1 (and ΔΣ) are scheme-dependent...

A measurement of Neutrino-Nucleon scattering provides a more theoretically robust measurement of Δs

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

νN → νN scattering and Δs

- Axial part of Nucleon Neutral Weak Current:

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

- $G_A^s(Q^2 = 0) = \Delta s$
- G_A (non-strange part of axial f.f.) known from neutron beta decay
- At low Q^2, most-sensitive to axial f.f. (unique to neutrino scattering)

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

- Therefore, a measurement of νN NC scattering (at low Q^2) yields Δs

NC neutrino scattering: BNL E734

- BNL E734: νp, $\bar{\nu}$p elastic scattering w/170 ton segmented detector @E_ν~1.2 GeV

  (Q^2=0.4 → 1.1 GeV^2) (PRD 35, 785, '87.)

  Δs = -0.15±0.09

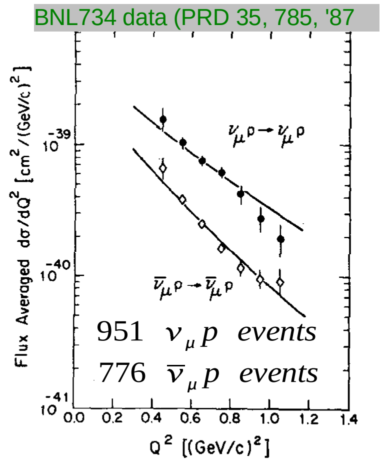
- This data has be re-analyzed several times:

  Δs = -0.21±0.10±0.10

  (Garvey et al, Phys Rev C48, 761, 1993)

- The accuracy of the BNL734 data is not sufficient for an extraction of Δs with small errors

- FINeSSE will improve on this with:
  - more events : ~x10
  - a ratio method : R(NC/CC)
  - at lower Q^2 : 0.2 GeV^2



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!

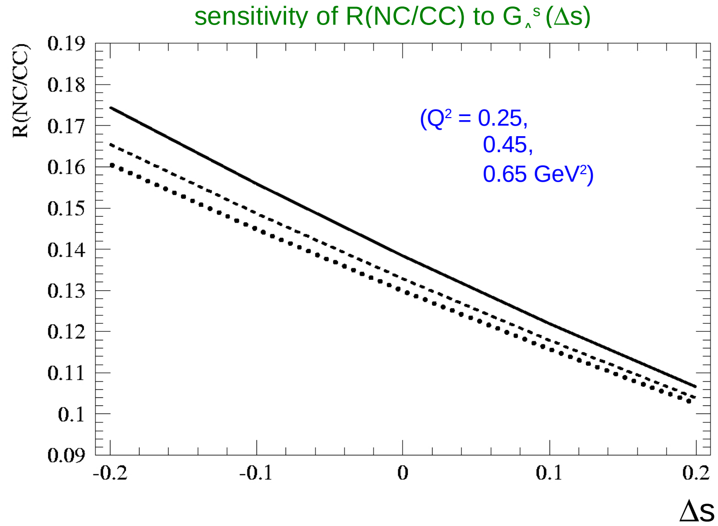
- A measurement of R_ν(NC/CC)...

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

will reduce the sensitivity of result to:
- experimental systematics (e.g. flux, efficiencies, etc.)
- uncertainties in measured form factors (e.g. M_A)
- nuclear effects

- This is the quantity that FINeSSE will measure in order to extract Δs

Sensitivity of R(NC/CC) to Δs



Slope is sensitivity of R(NC/CC) to Δs
$\Rightarrow$ R(NC/CC) to 5% will yield Δs to ± 0.04

In addition:
A measurement of Δs is important for certain dark matter searches where the neutralino-nucleus cross section depends on quark spins. (Ellis et al, hep-ph/0106148.)

Booster Neutrino Beamline

- 500m from ν target:

  MiniBooNE...

- 100m from ν target:

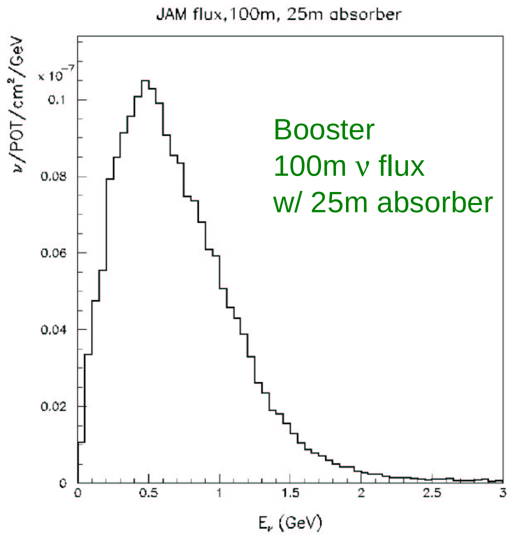
  open space!...

available for FINeSSE

Booster Neutrino Flux

Booster flux at 100m:

- 9.55×10^{-9} ν_μ/POT/cm^2
- Mean E_ν = 700MeV
- Require 6×10^{20} POT (2 yrs) well within range possible in the NuMI era as quoted by Proton committee report



Excellent ν energy distribution for the Δs measurement

- E is high enough...
  - large elastic cross section
  - nuclear physics uncertainties small
- and low enough that backgrounds (e.g. pion prod., DIS) small
- little to no high-energy "tail"

- Low Duty Factor also => very small cosmic background

FINeSSE: Event Rates

Event Rates with a 9 ton (fiducial) detector, 6E20 POT (~2yrs) @ 100m on Booster ν Beamline

~147k CCQE
~59k NC EL

signal channels are ~ 60% of total

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

FINeSSE Detector Requirements

To measure Δs with error ≤ 0.04, need R(NC/CC) to ~5%

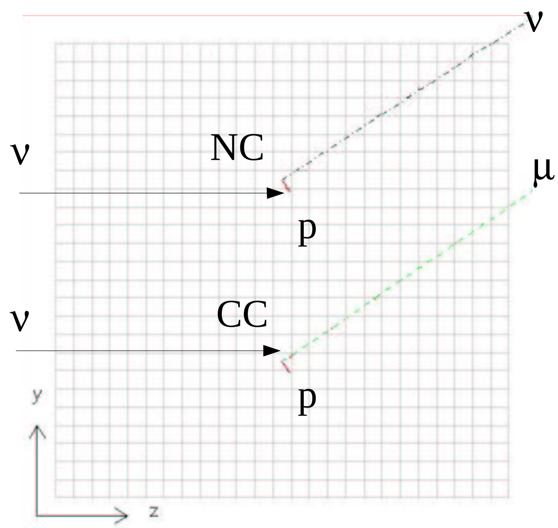
Also need to measure R(NC/CC) as function of $Q^2 (=2m_p T_p)$ down to 0.2 GeV^2

Need:
- A 9 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

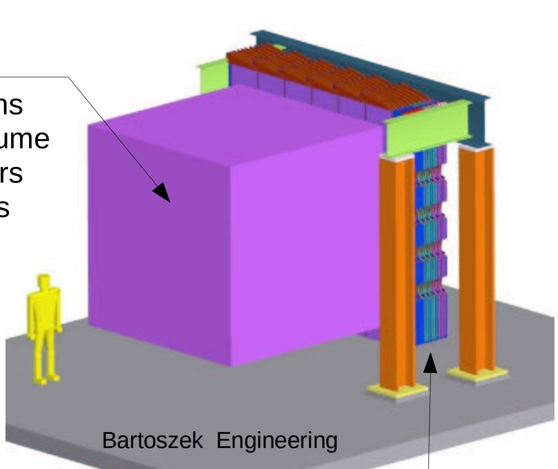
- Need a large, low-threshold, tracking "vertex" detector

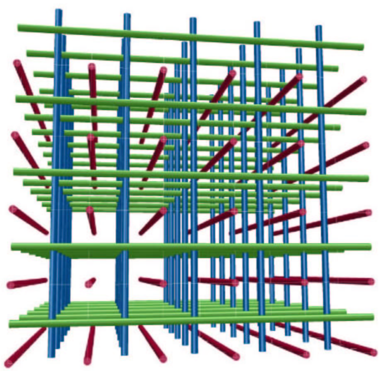


GEANT-generated events in scintillator:
Q^2 = 0.2 GeV^2, E_ν = 800MeV
T_p~100 MeV, T_μ~600 MeV

FINeSSE Detector

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



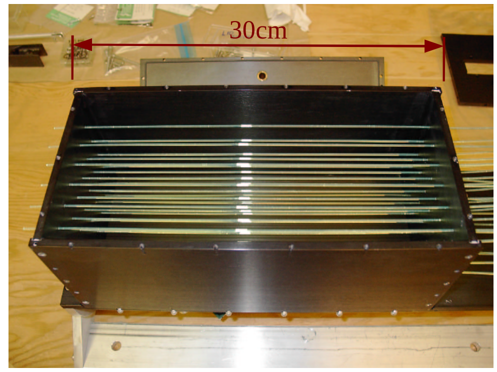


WLS fibers in vertex detector

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

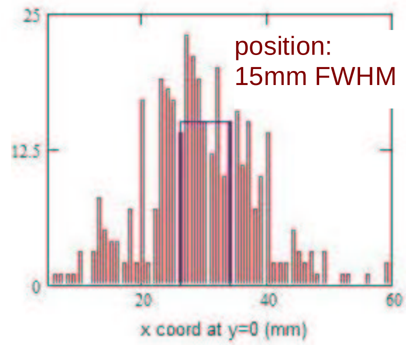
FINeSSE Vertex Detector...

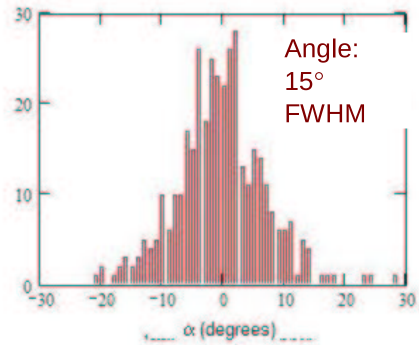
- A prototype vertex detector was tested at the IUCF with 200MeV protons this summer to determine suitability for FINeSSE



Test results:

light seen from near proton tracks: 17±2 PEs

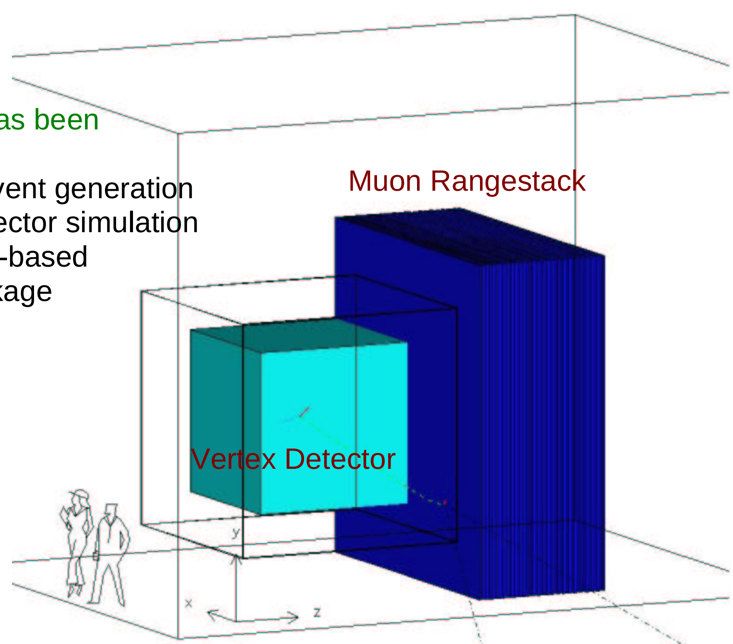




FINeSSE Detector Simulation and Reconstruction

The FINeSSE detector has been simulated using:

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



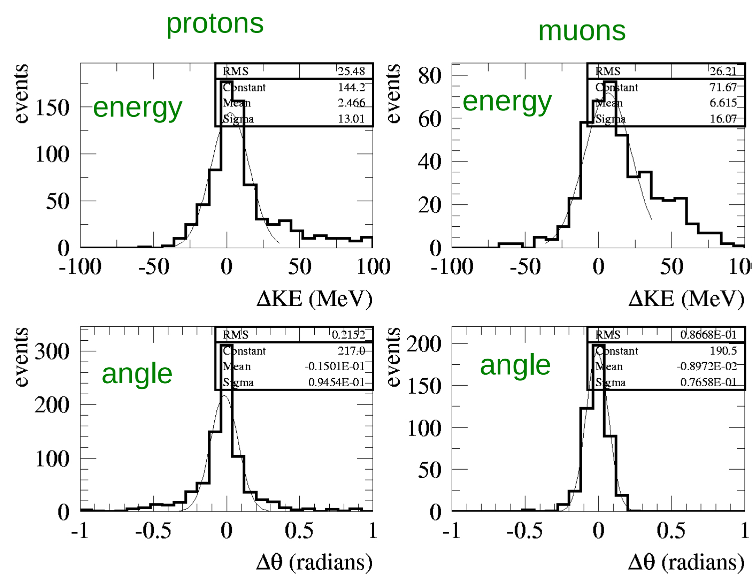
GEANT simulated geometry

FINeSSE Detector Simulation and Reconstruction...

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

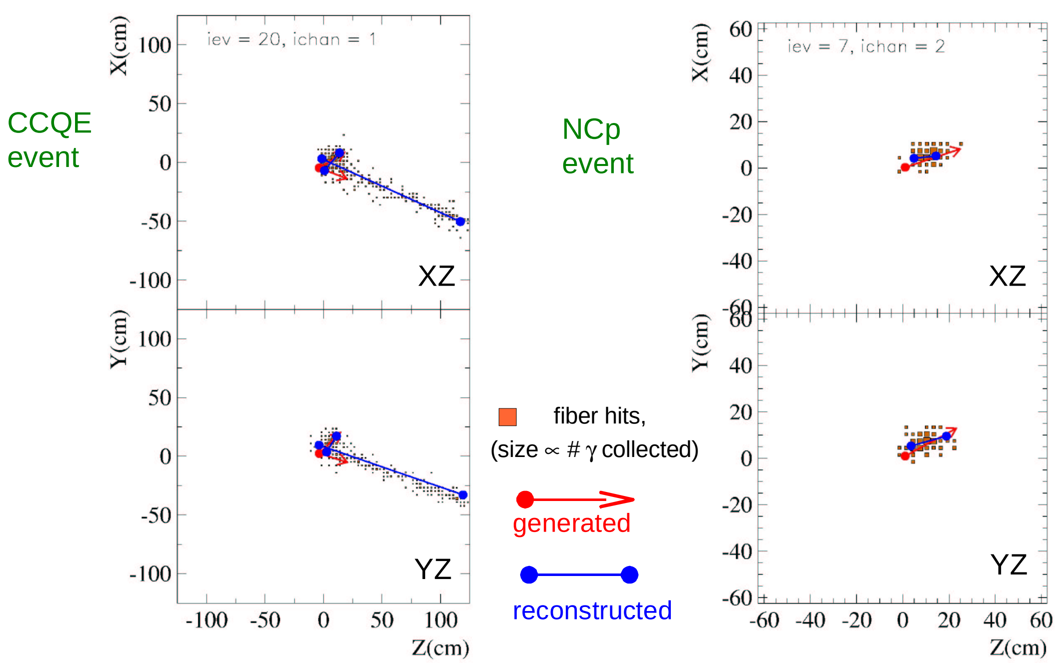
- ΔE ~15MeV

- $\Delta\Theta$ ~6°
  (in agreement with prototype tests)



FINeSSE Detector Simulation and Reconstruction...

simulated hits and reconstructed tracks in the Vertex Detector



Simulation of R(NC/CC) measurement

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

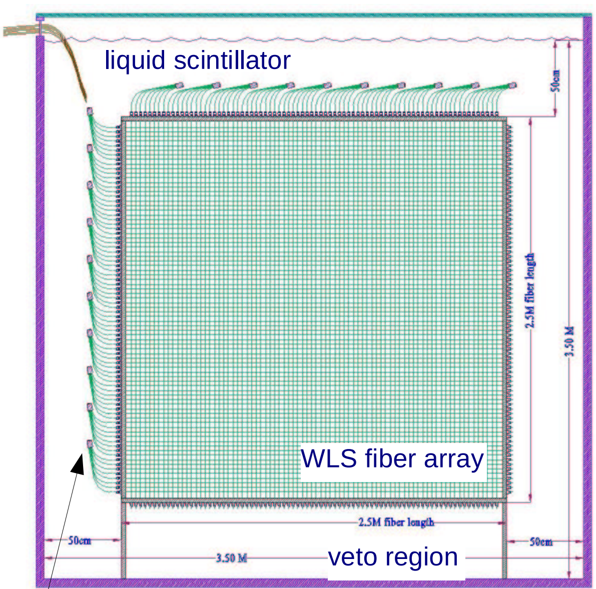
cut #	NCp cuts	CCQE cuts
0	edge distance > 15cm	edge distance > 15cm
1	# 3d tracks = 1	# 3d tracks.eq.2
2	$dE/dx(p) > 2.5$	$dE/dx(p) > 2.5, dE/dx(\mu) < 2.5$
3	$\theta(p) > 0.5$	$\theta(p) + \theta(\mu) > 1.5$
4	no "late" light in vertex det.	no "late" light in vertex det.
5	no veto or muon stack energy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

Resulting NCp and CCQE efficiencies from a 215k event sample:

	reaction channel				
NCp cuts	NCp	NCn	NCπ	CCQE	CCπ
raw events	21219	20487	19062	100102	54107
passed events	3929	1162	167	48	4
efficiency (%)	18.5	5.7	0.9	0.0	0.0
fid. eff. (%)	27.1	8.3	1.3	0.1	0.0
purity (%)	74.0	21.9	3.1	0.9	0.1
CCQE cuts	NCp	NCn	NCπ	CCQE	CCπ
raw events	21219	20487	19062	100102	54107
passed events	165	76	581	7323	1322
efficiency (%)	0.8	0.4	3.0	7.3	2.4
fid. eff. (%)	1.1	0.5	4.5	10.6	3.6
purity (%)	1.7	0.8	6.1	77.4	14.0

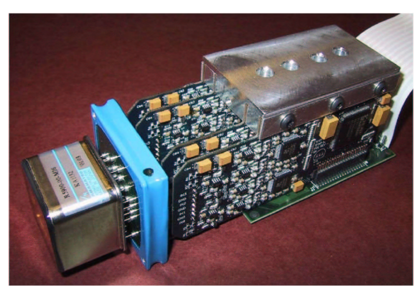
FINeSSE Vertex Detector...

Vertex Detector side view:



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

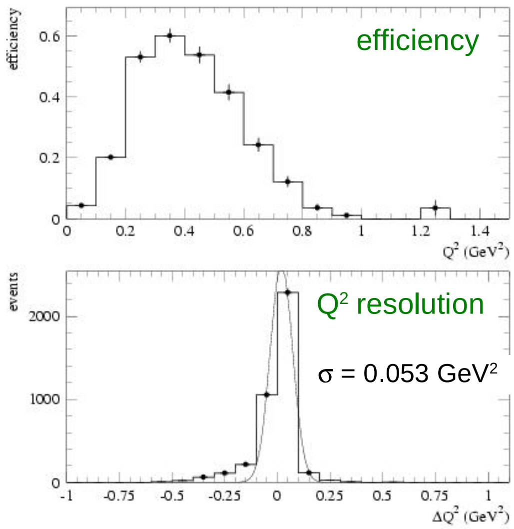
STAR PMT w/front-end electronics



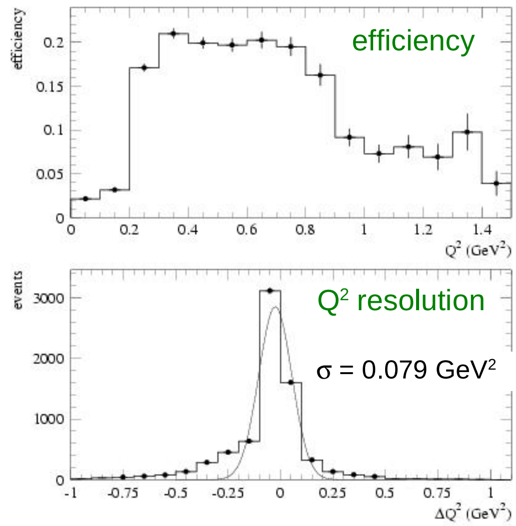
- similar scheme to that employed for STAR endcap calorimeter

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

NCp events:



CCQE events:



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

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

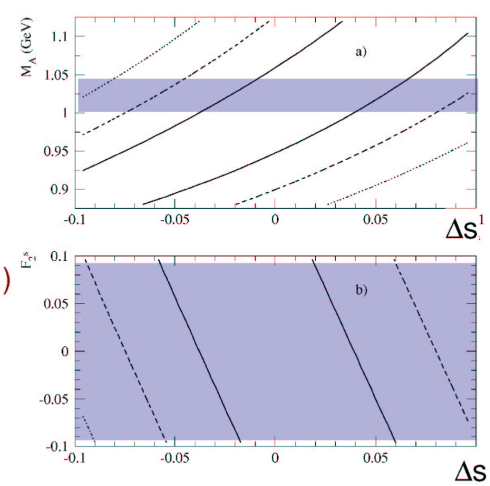
Included the effects of:
- statistical errors
- systematic errors due to...
- NCn ($\nu n \to \nu n$) scattering misid
- scattering from free protons
- uncertainties in efficiencies
- Q^2 reconstruction
- nuclear model uncertainties
- form factor uncertainties

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

Recall:

BNL E734 $\Delta s \equiv -0.21 \pm 0.10 \pm 0.10$
polarized DIS $\Delta s \equiv -0.14 \pm 0.03$

χ^2 contours ($1\sigma, 2\sigma, 3\sigma$) from Δs fit



⇒ A precise, theoretically robust measurement of Δs via Neutrino-scattering

FINeSSE at NuMI?

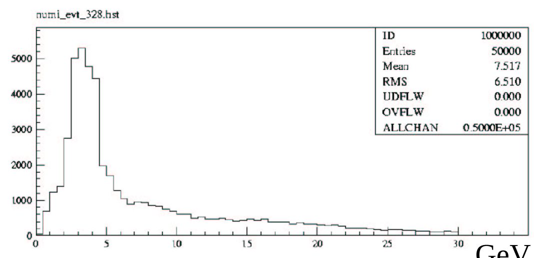
events/ton/1E20POT

	FINeSSE	NuMI near
CC QE	2715	7502
NC EL	1096	2876
CC res pi+	1451	11672
NC res pi0	369	2698
NC coh pi0	96	619
CC coh pi+	160	1181
CC DIS	80	31771
NC DIS	37	11132
total	6604	80864

The physics goals of FINeSSE can not be executed with the NuMI near neutrino beam due to...

- neutrino flux: high energy tail results in slightly more NC EL signal (x 2.6) but much higher potential background (x 12).

- background from low-energy neutron production in the “dirt” would make the NC measurement difficult to impossible. (~14 times rate at ~100MeV)



NuMI low E flux

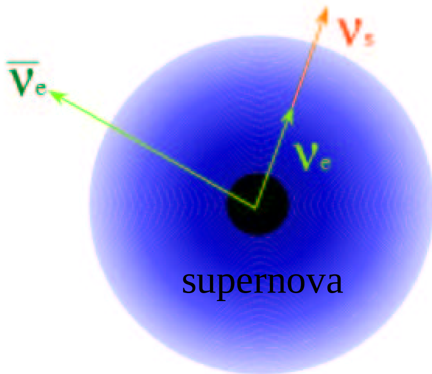
- and ν_μ disappearance w/MiniBooNE in NuMI is impossible

ν_μ ν_μ ν_μ ν_μ ν_μ

FINeSSE continued...

- ν_μ disappearance
- CCQE events in the detector
- Additional physics
- Cost and schedule

How are neutron rich, heavy metals produced?
favored mechanism→r-process nucleosynthesis



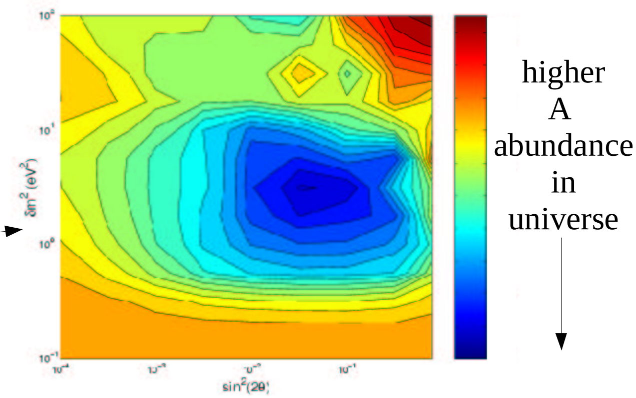
But neutrons produced by anti neutrinos are gobbled up by neutrinos!

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\nu_e + n \rightarrow e^- + p$$

Allow oscillations to sterile neutrinos, with "matter enhancement"

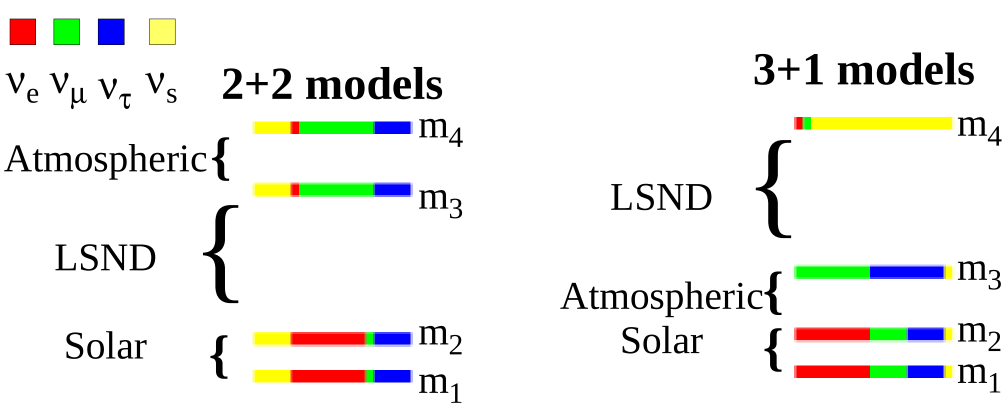
Mechanism requires high mass sterile neutrinos
$3\ eV^2 \leq \Delta m^2 \leq 70\ eV^2$
allowed regions

astro-ph/0309519
hep-ph/0205029



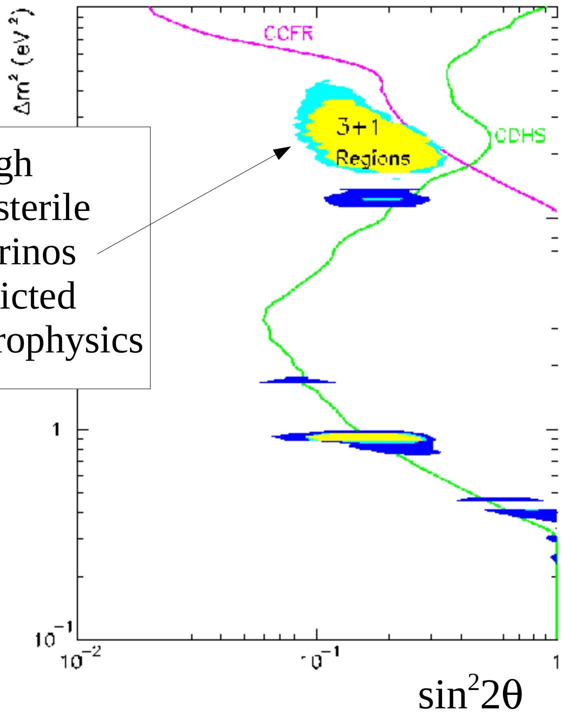
Sterile neutrinos do not interact weakly, but can oscillate to Standard Model neutrinos

Pop out of most beyond the Standard Model theories!
- Supersymmetry
- GUTs
- Extra Dimensions



Look for sterile neutrinos at short baseline using ν_μ disappearance

ν_μ disappearance



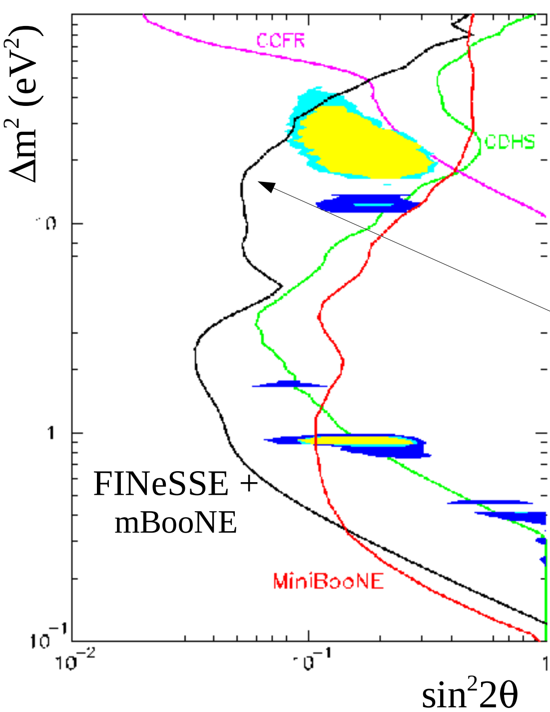
high
mass sterile
neutrinos
predicted
from astrophysics

3+1 allowed regions

Combined fit of
LSND and null short
baseline experiments

Existing Limits
- CCFR
- CDHS

FINeSSE sensitivity



MiniBooNE
will address low Δm^2
allowed regions
limited by knowledge
of the flux

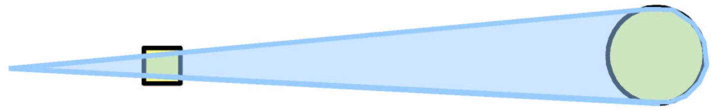
FINeSSE measures
flux before neutrinos
can oscillate

FINeSSE + MiniBooNE
sensitive to all 3+1 allowed
regions at
90% confidence level

Comparing ν_μ interactions at FINeSSE and MiniBooNE

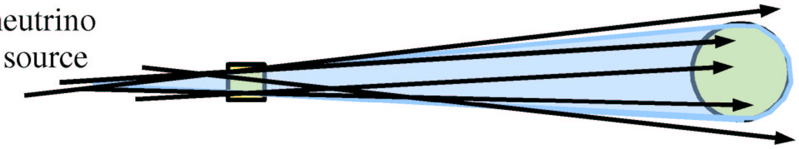
Ideal world:

- use flashlight beam, point source neutrino beams
  - know origination point of beam -- know L very well
  - energy and angular acceptance are the same in each detector



Real world

- finite distance over which neutrinos are produced
  - uncertainty in L
  - differences in energy and angular acceptance in detectors



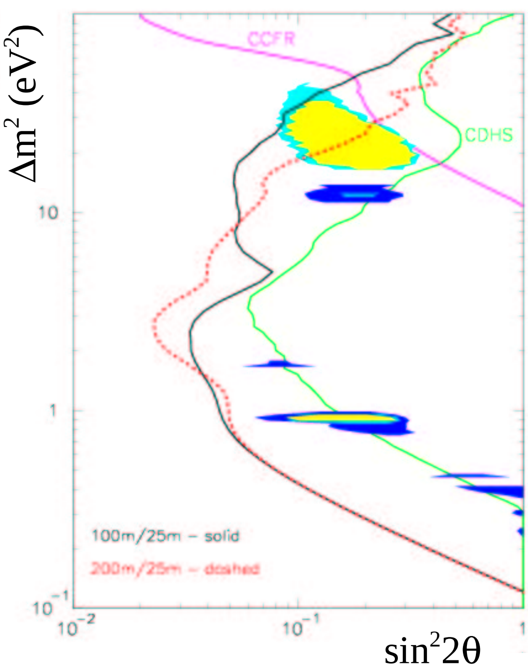
at FINeSSE:

- Minimize systematic errors between two detector
- Maximize flux

→ optimize distance to detector and length of decay channel

Optimizing detector location

→ determine sensitivity with detector at 100m, 150m, 200m..



Reduce parallax by moving the detector sufficiently far away

Problems:

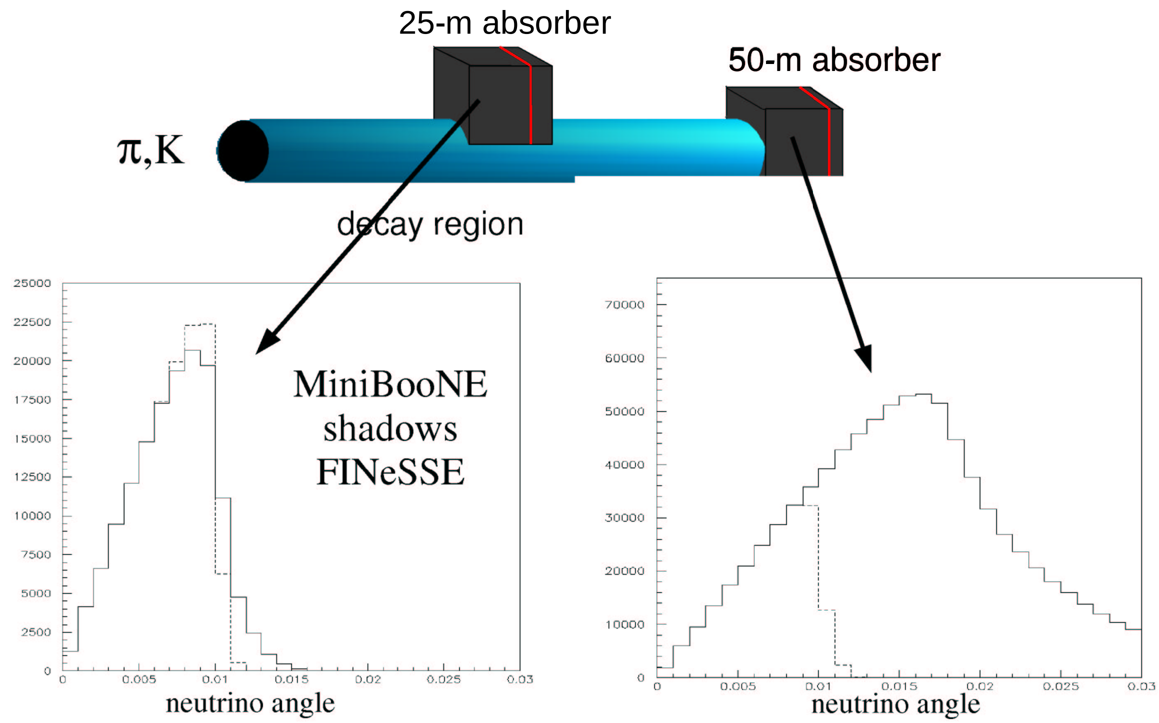
- no longer measuring un-oscillated flux
- reduce statistics for this and other FINeSSE analyses

↓

Lose sensitivity to high mass region with detector at 200m

Detector location at 100m is best for oscillation analysis

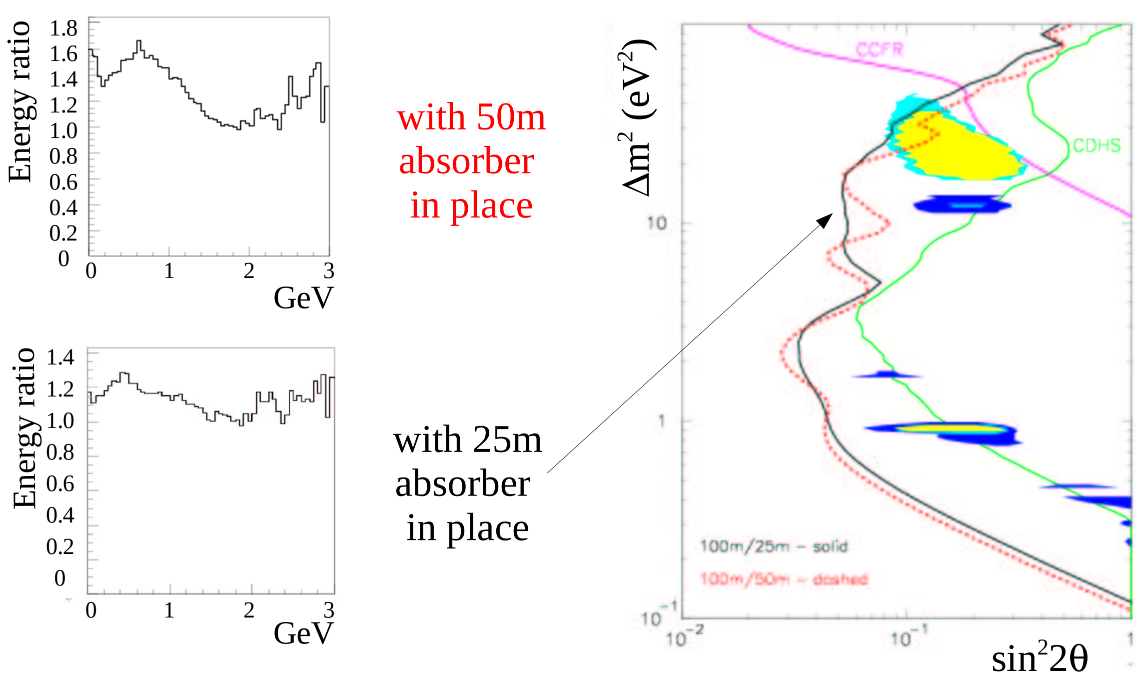
Optimize decay channel length



Angular spread of incoming neutrinos similar at MiniBooNE and FINeSSE with 25m absorber in place.

Parallax translates into wiggles in energy differences

minimize wiggles and make sure they do not look like wiggles from an oscillation signal



FINeSSE ν_μ disappearance sensitivity

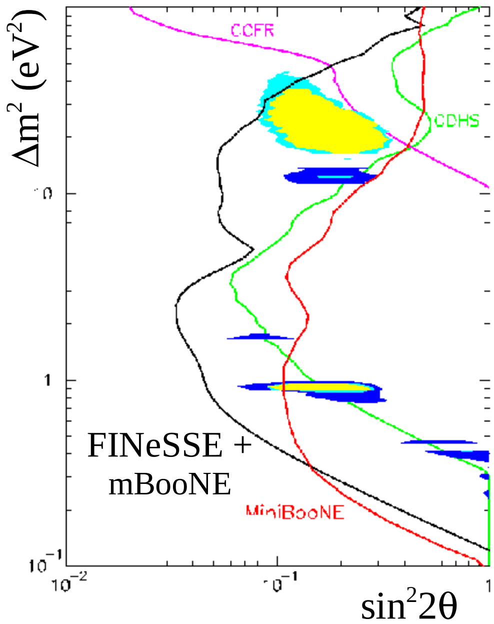
Optimized beamline configuration
- detector at 100m
- 25m absorber in place

Expected ν_μ CCQE event rates
6×10^{20} POT (2 year run)
- at FINeSSE: 103K
- at MiniBooNE: 205K

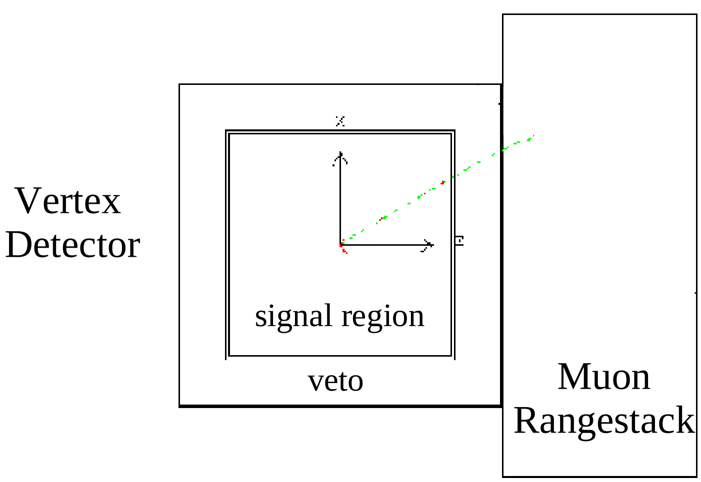
assumes standard MiniBooNE cuts and efficiencies

Systematic uncertainties

Source	fractional error
Overall Normalization	0.20
Relative Normalization	0.02
Shape Uncertainty	0.10
Relative Energy Scale	0.05

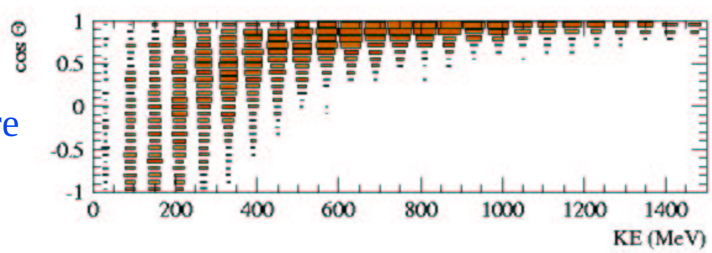


ν_μ CCQE events in FINeSSE



ν_μ disappearance event sample:
- 100K events within Vertex Detector fiducial volume
- outgoing particles contained within FINeSSE subdetectors

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



Events contained in each subdetector vs. True Energy

Contained events = final state particles range out in

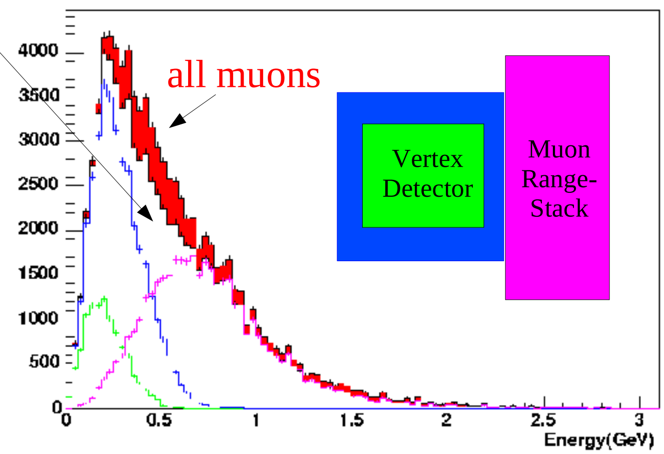
In Vertex Detector signal region

or

In Vertex Detector signal region + veto

or

In Vertex Detector + Muon Rangestack



[redacted]

Acceptance vs. True Energy

- Overall: 86%
- drops off at higher energies: less relevant for this analysis

---

$\nu_\mu n \rightarrow \mu^- p$ event efficiency and resolution

(from NUANCE v3 sample of 100K events)

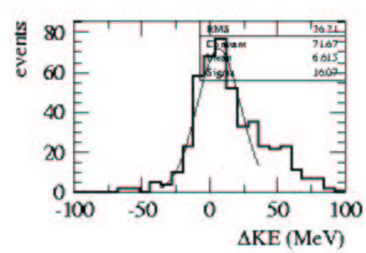
	CCQE	NC	CCπ	NCπ	Coh.
raw events	4201	6968	1968	1118	450
after cuts	3555	7	1159	217	163
efficiency (%)	85	0.1	59	19	36

Cuts require:
- reconstructed tracks
- long tracks
- low level of late light

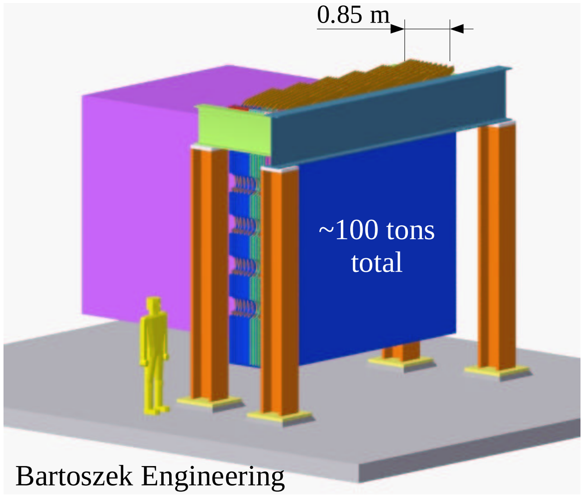
Will be further reduced by imposing kinematic constraints

146K events x 86% acceptance then x 85% efficiency 107K events

10 % energy resolution in Vertex Detector



Expect similar efficiencies and resolutions for contained events in Vertex Detector veto and Muon Rangestack



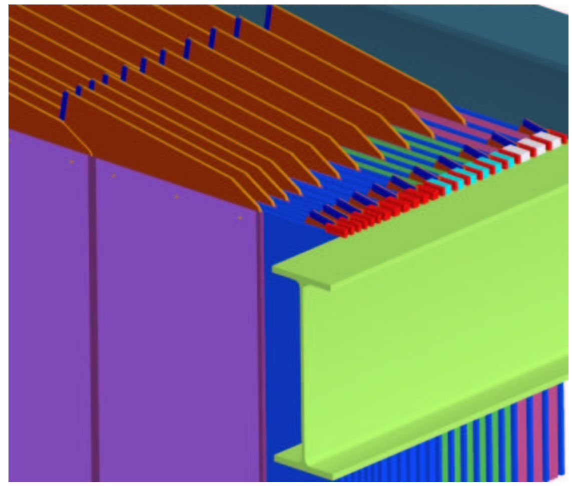
Muon Rangestack is desgined to:

- range out .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

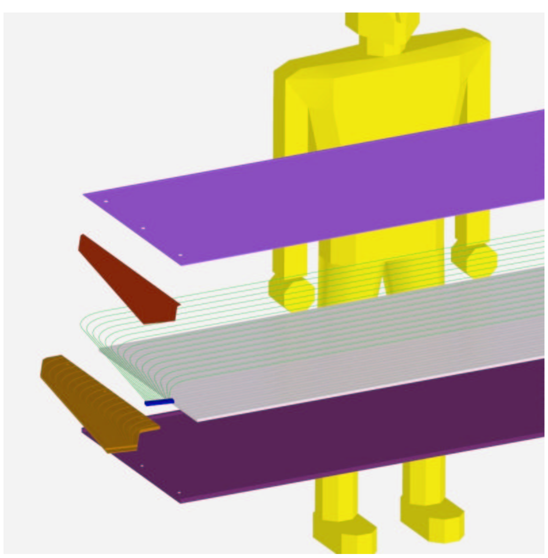
→ 1:4 scintillator:iron

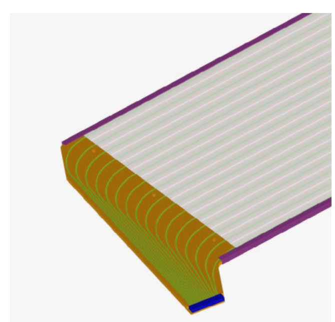
as lower energy particles range out (and only higher energy particles remain) iron can be thicker while retaining same energy resolution



Scintillator planes are comprised of 4.1cm x 1cm x 4m strips in alternating X,Y orientations

→ "mini-MINOS" design





→ Polystyrene scintillator strips:

- TiO_2 outer layer
- groove down one side for WLS fiber

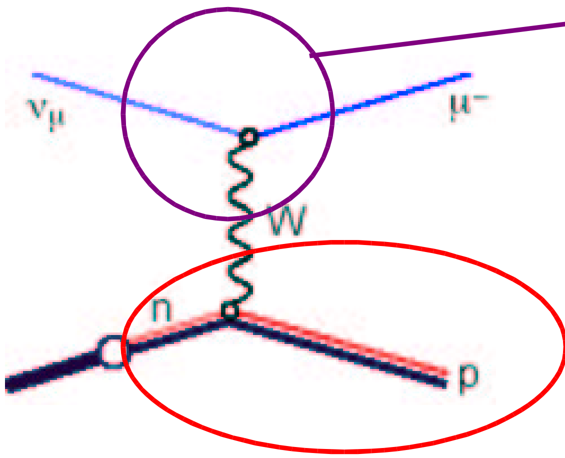
→ Groups of 16, surrounded by 1mm aluminum can attached to 0.5" iron

Readout via MAPMTs as for Vertex Detector

expected light output inferred from MINOS tests: ~twice that in MINOS far detector

Additional physics -- CCQE data sample

- Important for analyses that rely on QE events (SK, off-axis)
- Interesting to compare to JLAB data



MiniBooNE measures QE rate very well.

MB	550k	(by 2005)
FINeSSE	145K	(2006-7)

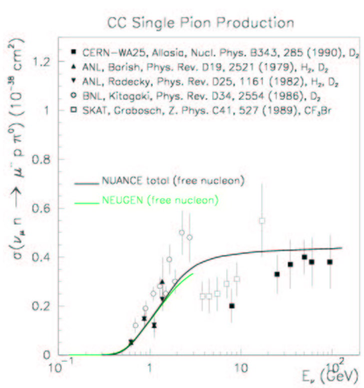
What can FINeSSE add?

Improved systematics on measurements of this vertex!

- low backgrounds (<2% $\bar{\nu}$ events, almost no DIS)
- better Q^2 reconstruction than MiniBooNE
  (full reconstruction $\Rightarrow$ no assumptions about incoming ν angle)
- better final state particle identification
- better interaction identification

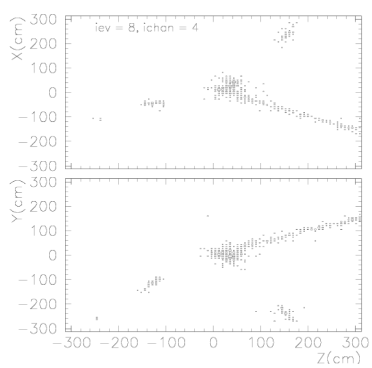
Additional physics:

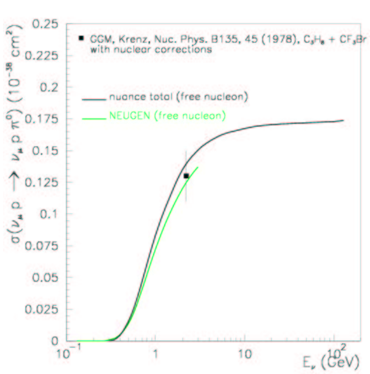
π^0 production: dominant background in $\nu_\mu \rightarrow \nu_e$ oscillation searches



$\nu_\mu n \rightarrow \mu^- p \pi^0$:
existing data at low energy on light targets

in FINeSSE

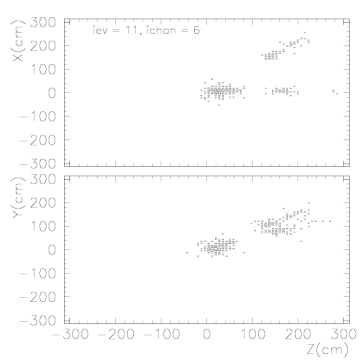




$\nu_\mu n \rightarrow \nu_\mu p \pi^0$

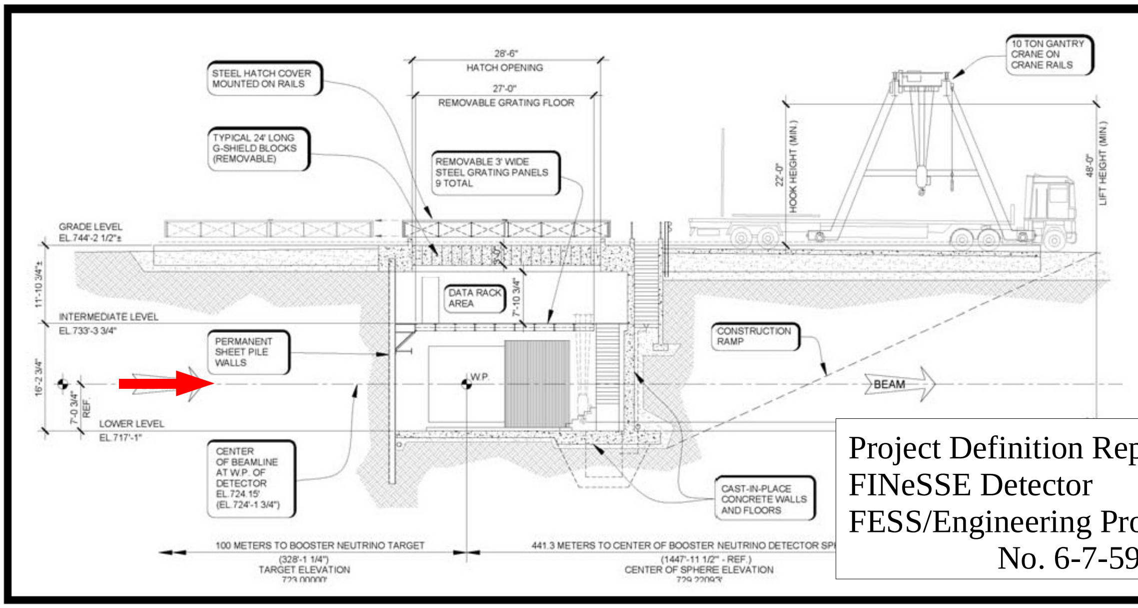
very little NC single pion production data

in FINeSSE



Detector Enclosure:

- at ν_μ beam level (25 ft. below ground)
- enclosure houses detector and electronic



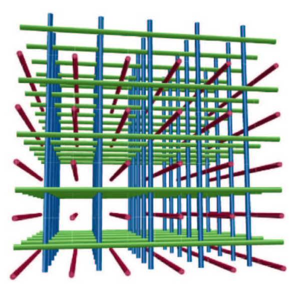
Project Definition Report
FINeSSE Detector
FESS/Engineering Project
No. 6-7-59

FESS cost estimate: $1.6 M (includes contingency, EDIA, Indirect costs)

Detector cost drivers:

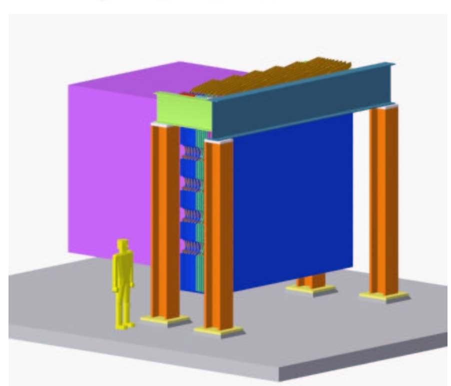
Vertex Detector:

36 tons Scintillator oil	$185K
tank and fiber grid	$209K
WLS fiber	$119K
19968 channels	$434K
312 MAPMTs	$398K



Muon Rangestack:

Scintillator and fiber	$36K
34 M64 PMTs	$43K
2176 channels	$45K
Iron planes	$327K



Computing &Installation $254K

→ Total: 2.8 Million (including contingency)

submit NSF MRI for detector - January '04

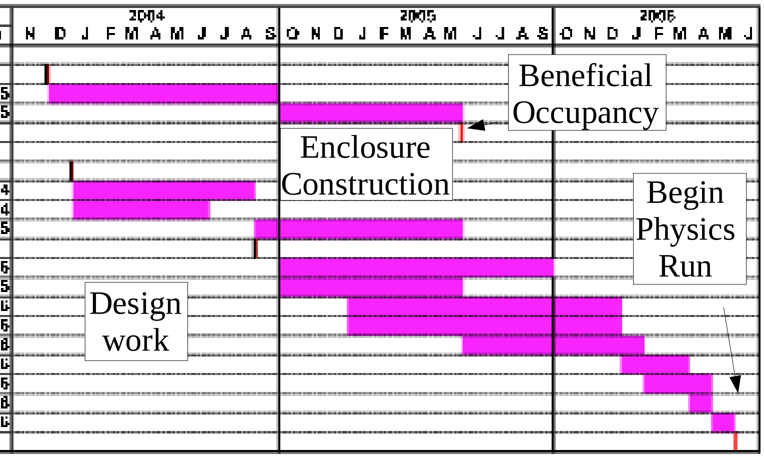
FINeSSE Schedule

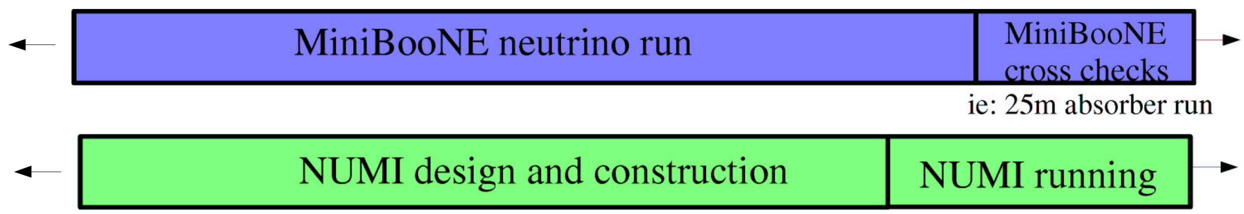
aggressive but achievable

•timely physics

•takes advantage of a running beamline and experiment

Item Milestones are in red.	Date(s) Start	Finish
Enclosure Construction		
Construction Funds Available	12/04	
CDR to Bld Award	12/04	10/05
Civil Construction (See PDR)	10/04	08/05
Enclosure complete; Ready for B.O.	06/05	
Detector Construction		
project approval	01/04	
detector mechanical design and	01/04	09/04
detailed electronics design and	01/04	06/04
parts procurement	09/04	08/05
major funding begins	09/04	
build fiber assemblies	10/05	10/06
build scibath assembly line	10/05	08/05
build electronics components	01/05	01/06
build range stack components	01/05	01/06
assemble vertex detector	06/05	02/06
install range stack detector	01/06	04/06
attach electronics	02/06	04/06
install vertex detector	04/06	05/06
commission detector	05/06	01/06
ready for beam	08/06	





FINeSSE

- brings important and timely physics to growing FNAL neutrino program
  - measure of the strange spin of the proton
  - search for sterile neutrinos and high Δm^2

- novel detection technique

- relatively low cost
  less than $5M → $2.8M detector (NSF), $1.6M enclosure (FNAL) *loaded costs!*

- adds value to already committed resources
  - located on a running beamline
  - increases the physics reach of an existing experiment

FINeSSE

→ set forth a compelling physics case using a novel detection technique

→ demonstrated physics reach of experiment

→ shown feasibilty of detector and enclosure

We are asking the Fermilab PAC to recommend to the directorate to:

Grant FINeSSE stage 1 approval

- submitting NSF MRI by January 22nd, 2004 (as requested by the NSF)
- continuing enclosure design work -- CDR
- first stages of TDR

→ *on schedule for first beam to FINeSSE in mid-2006!*