Bonnie T. Fleming
LBL Seminar
November 16th, 2004

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!

Standard Model

12 elementary particles and how they interact

up	charm	top
down	strange	bottom
electron	muon	tau
electron neutrino	muon neutrino	tau neutrino

electromagnetic force

strong force

weak force

"no mass, no charge, no problem"

“Conventional” neutrino scattering is back in vogue

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

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 in
neutrino interaction physics
at low energies

- high flux neutrino sources
- higher precision detectors

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 similary energy ranges

- comparisons teach us about underlying models.

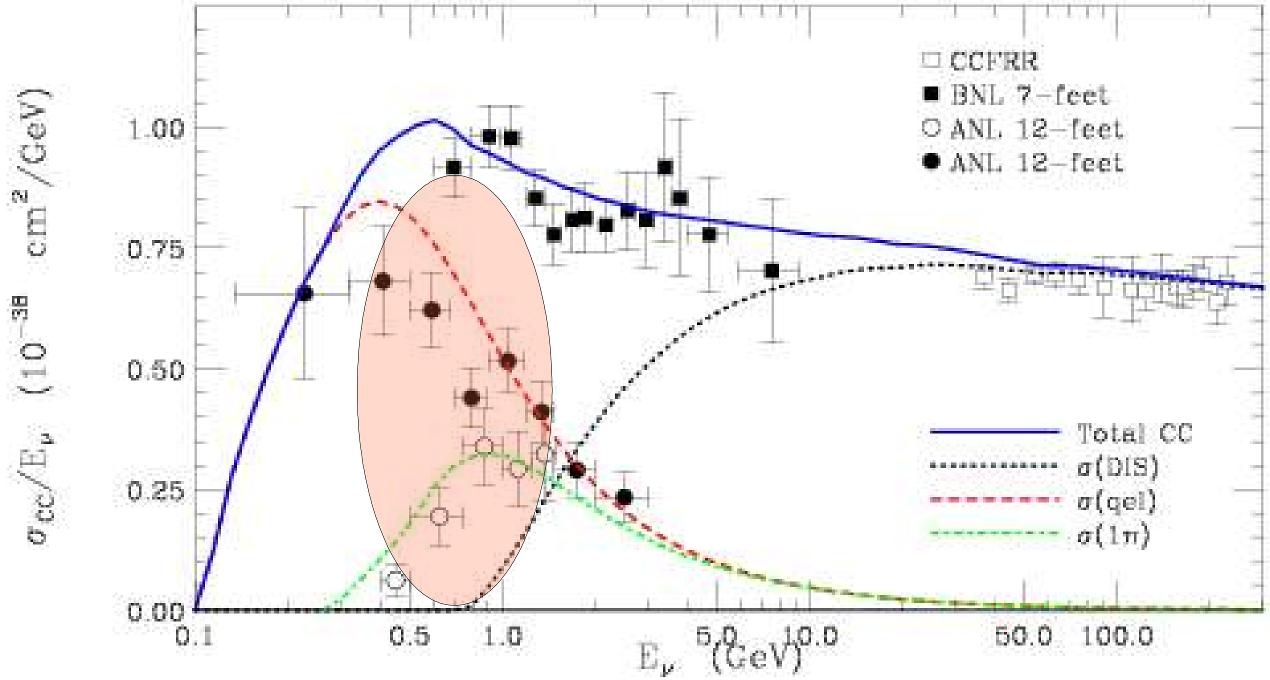
NUANCE (MiniBooNE)
NEUGEN (MINOS)
NEUT (K2K)

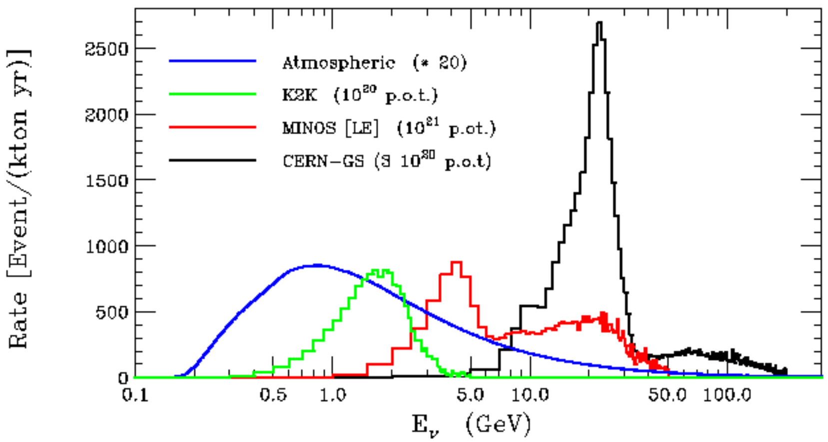
Rich energy region: different channels turning on and off

A lot going on
at low energies:

quasi-elastic
single π
(DIS turning on)

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





Signficifant 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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Columbia University, Nevis Labs, Irvington, New York

S. Brice, D. Finley
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J. Doskow, C. Horowitz, T. Katori, H.-O. Meyer, R. Tayloe, G. Visser
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C. Green, G. T. Garvey, W. C. Louis, G. McGregor,
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Yale University, New Haven, Connecticut

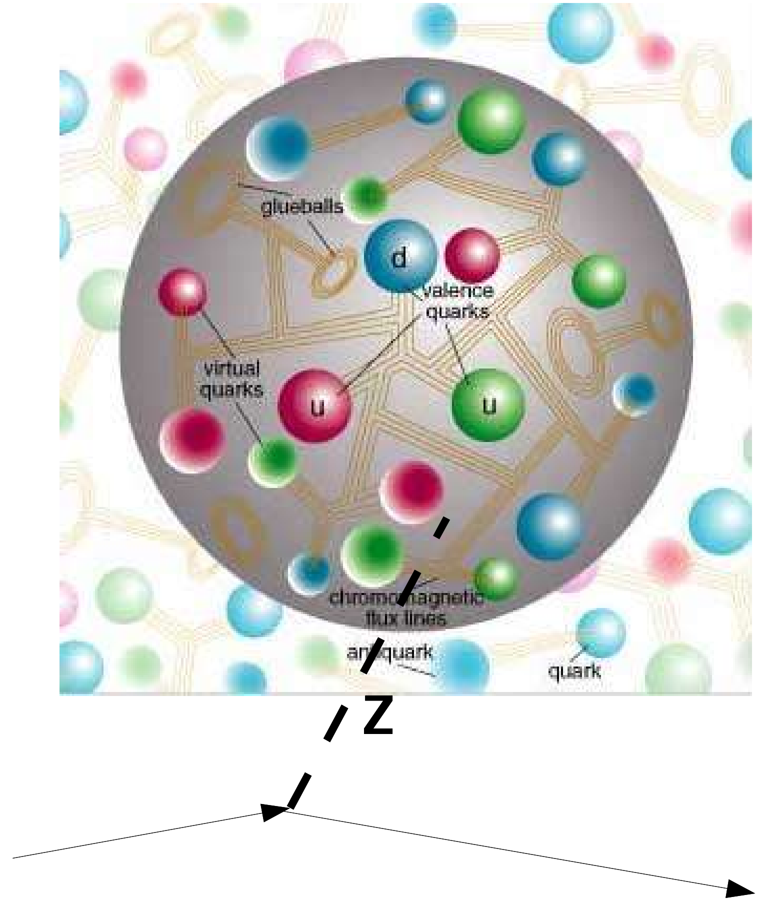
Strange Spin of Nucleon

(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?

RHIC spin will tell us a lot, but not Δs...



Low energy neutrino scattering is a great way to probe the strange spin of the proton

Who has already measured Δs?

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

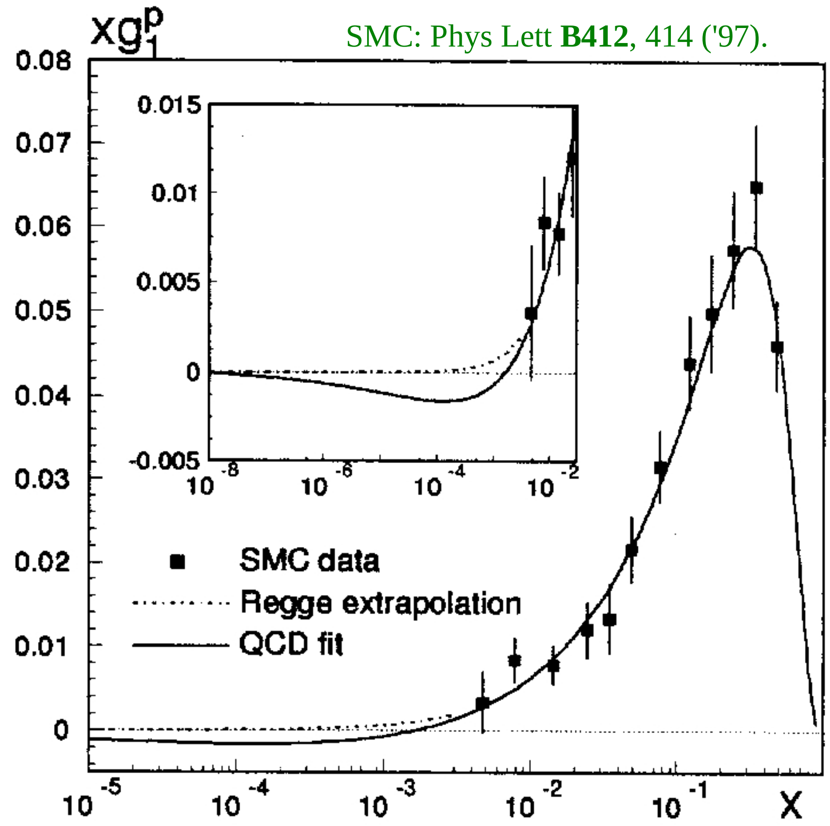
↓

strange contribution

$\Delta s \sim -0.10 \pm 0.05$

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

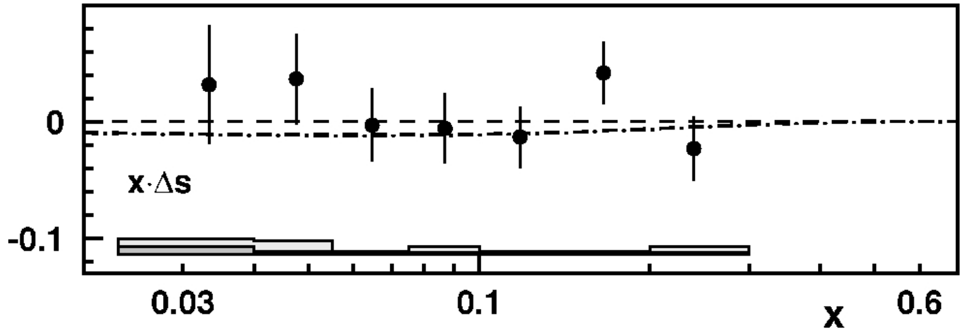
SMC: Phys Lett **B412**, 414 ('97).



Results from HERMES

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

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



"Δs" = 0.03±0.03±0.01 (0.023<x<0.30)

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

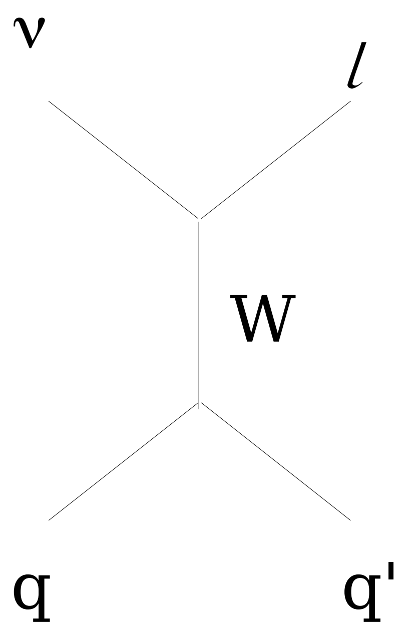
Measurement via neutrino-nucleon elastic-scattering to determine Δs directly

This method requires:

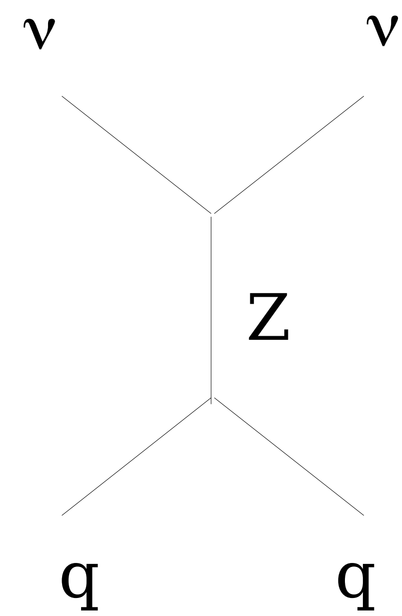
- no extrapolation to x=0
- no assumptions of SU(3) symmetry

A theoretically robust measurement of Δs

Measuring Δs using neutrinos



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



Neutral current scattering
q=any quark in the nucleon
-> strange quarks

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

- Nucleon Neutral Weak Current depends on:

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

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

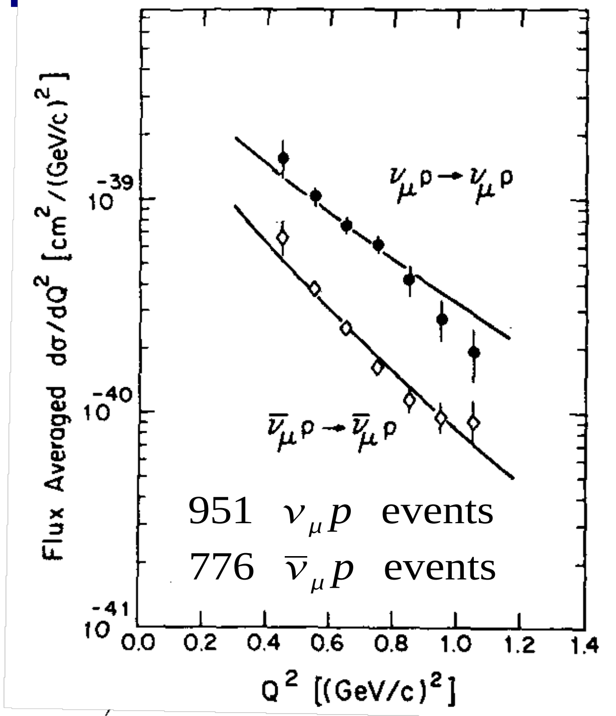
Measure $\nu p \rightarrow \nu p$ at low Q^2

NC neutrino scattering: BNL E734

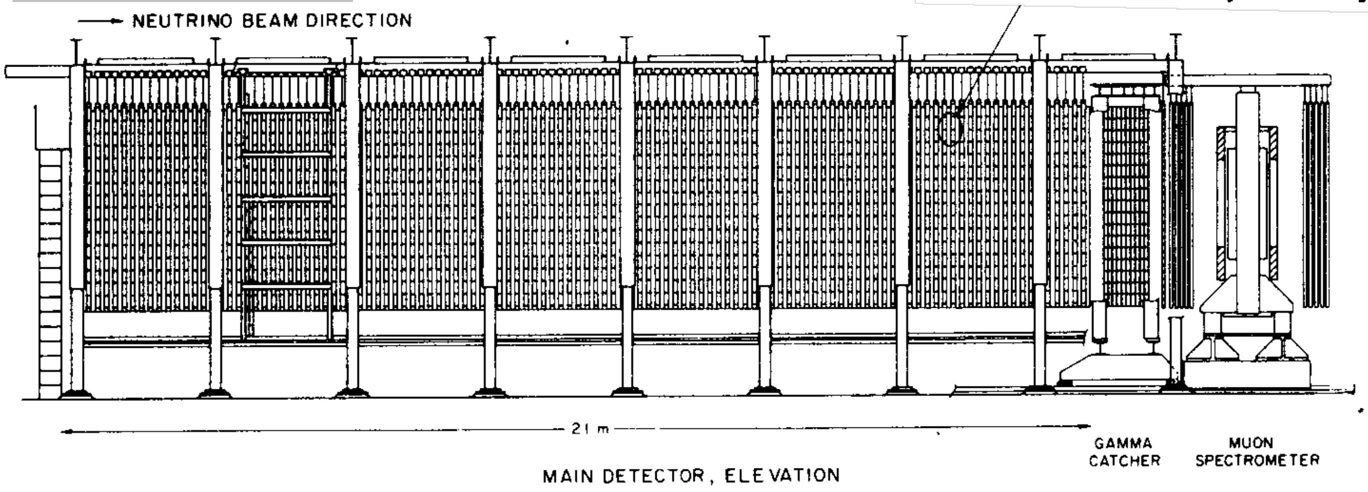
The best measurement of νN NC scattering to date is from BNL E734:

- νp, $\bar{\nu}$p elastic scattering,
- w/170 ton segmented detector,
- @E_ν~1.2 GeV ,
- Q^2 = 0.45 to 1.05 GeV^2
- Ahrens et al.,PRD 35, 785, '87.

BNL734 (PRD 35, 785, '87):

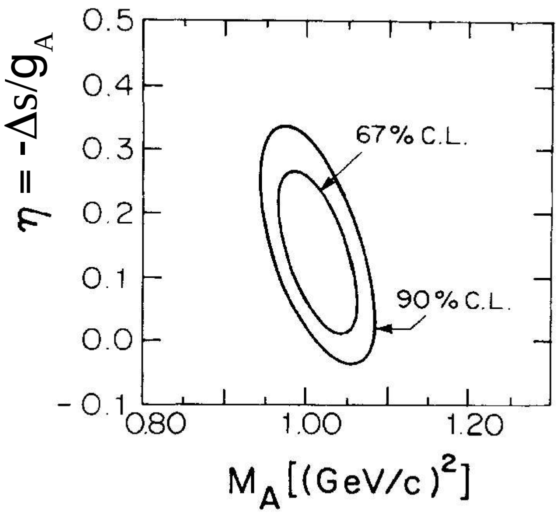


BNL734 detector



NC neutrino scattering: BNL E734

- A fit to the $\nu \bar{p}$, νp 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 → Δs consistent with above

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

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

systematic and statistical errrors 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

statistical errors

systematic errors

High Statistics

FINeSSE: Event Rates

Event Rates for a 9 ton (fiducial) detector for FINeSSE run

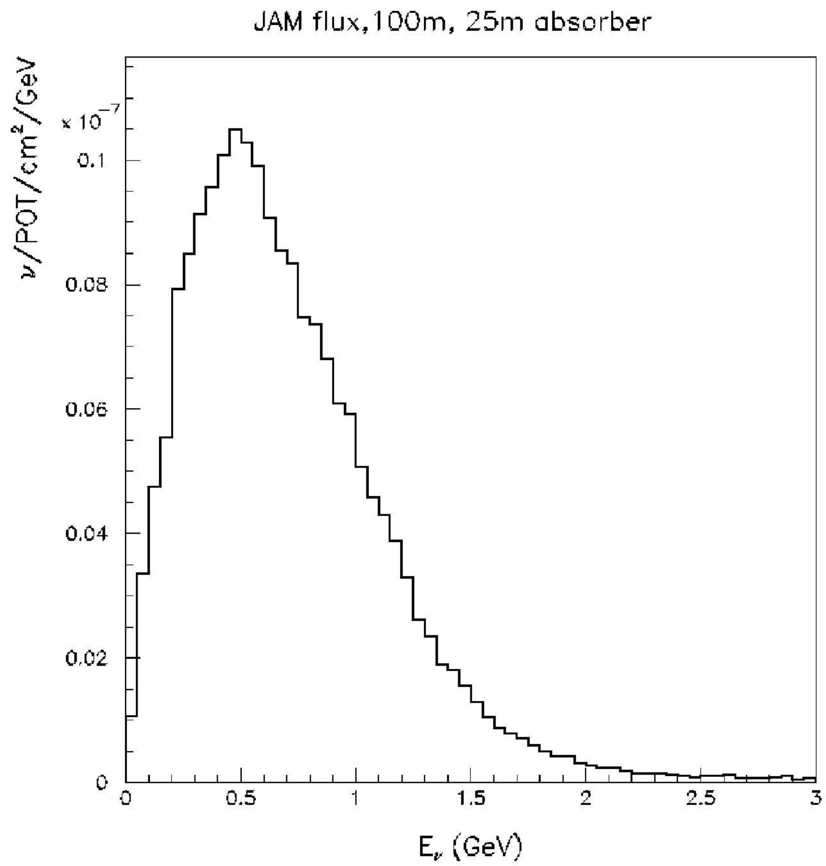
~147k CCQE
~59k NC EL

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

The Right Flux

"Low" energy neutrino beam produced from 8 GeV POT on target



Excellent ν energy distribution for the Δs 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 => 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)= (νp -> νp)/(νn -> νn)

is quite sensitive to G_A^s (Δs) 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)= (νp, NC)/(νp, CC)

is somewhat less sensitive to Δs, but experimentally easier.

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

*(Garvey et al., PR C**48**, 1919, '93)

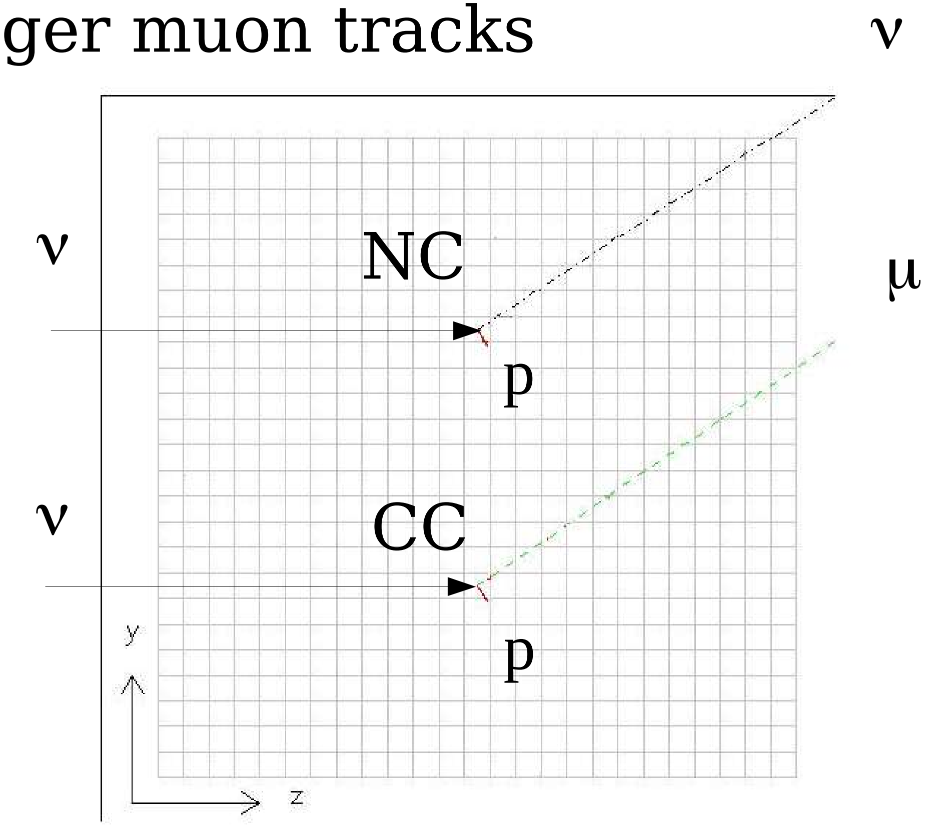
Fine-Grained Detector

Measures both short proton tracks and longer muon tracks

-proton energy measurement down to T_p~100MeV (R~10cm)

-range out up to 1 GeV muons

- particle ID for NC/CC/background separation

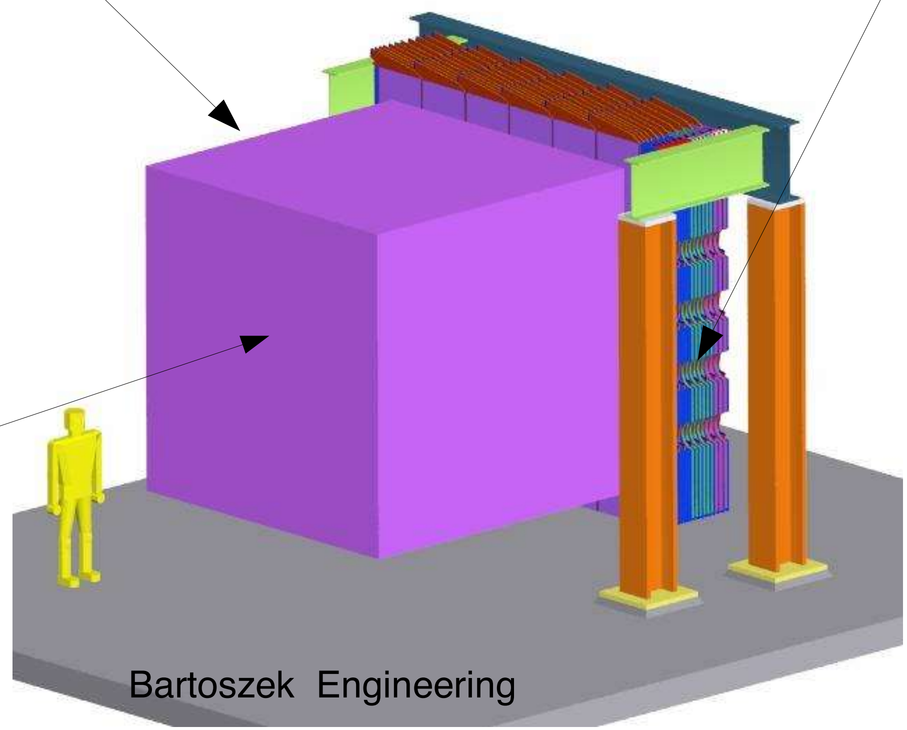


GEANT-generated events in scintillator:
Q^2 = 0.2 GeV^2 , E_n = 800MeV
T_p~100 MeV, T_m~600 MeV

Two part detector

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

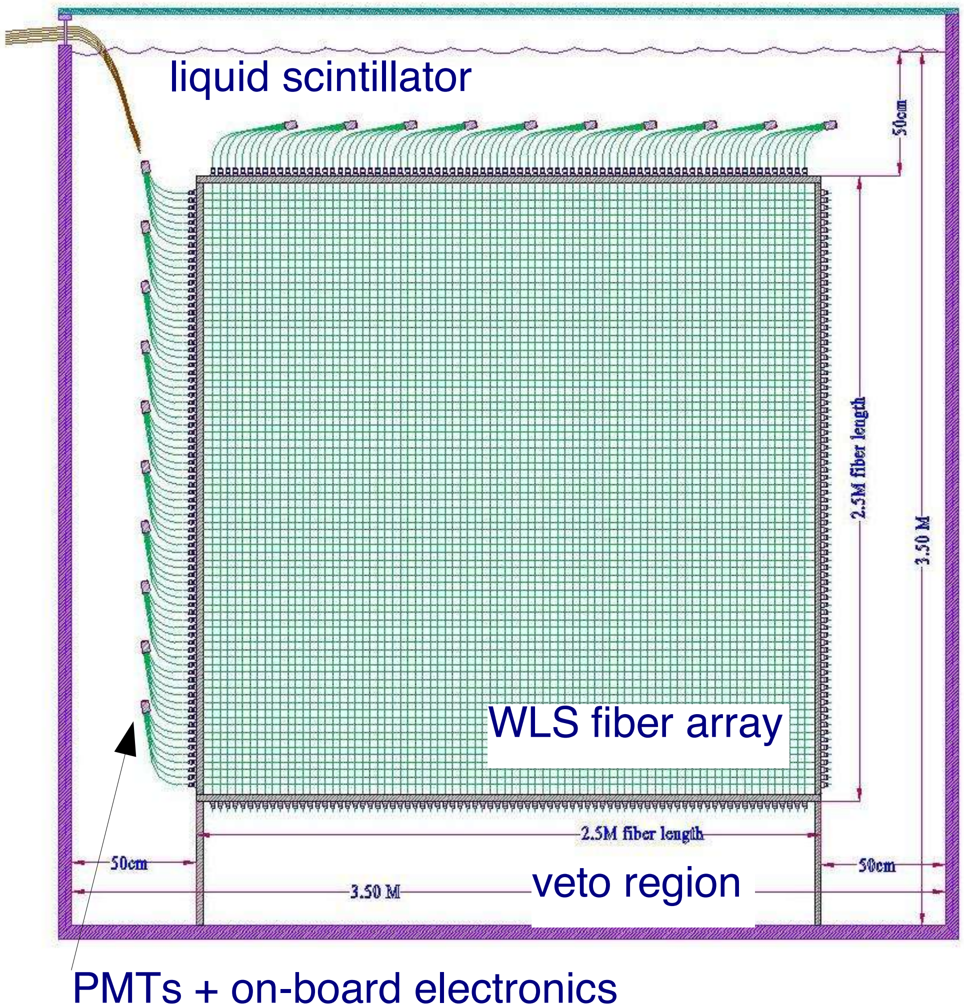
The Muon Rangestack...
- to track and measure the energy of muons



neutrinos

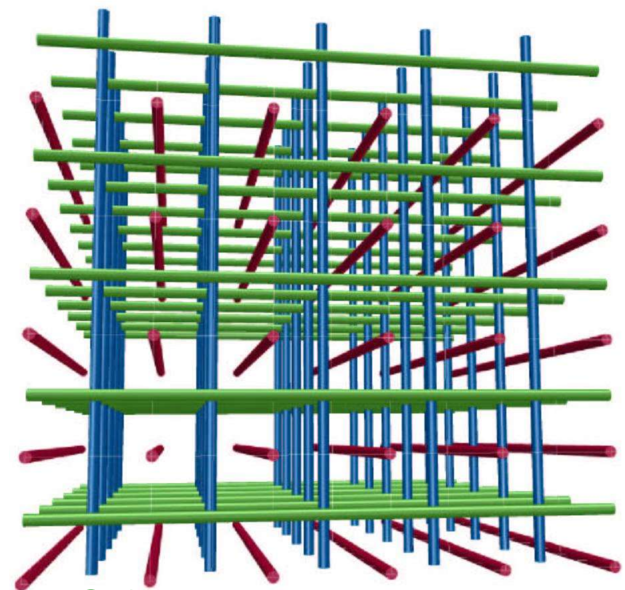
Vertex Detector: a large, low-threshold, 3D, tracking detector

Vertex Detector side view:



$(2.5m)^3$ active liquid scintillator volume

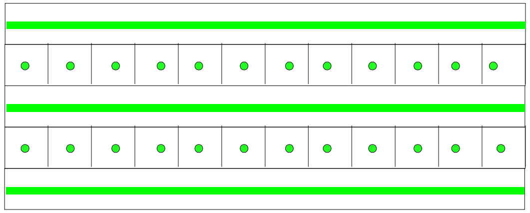
- 19200 (80x80x3) 1.5 mm WLS fibers on 3cm spacing with 3 orientations



WLS fibers in vertex detector

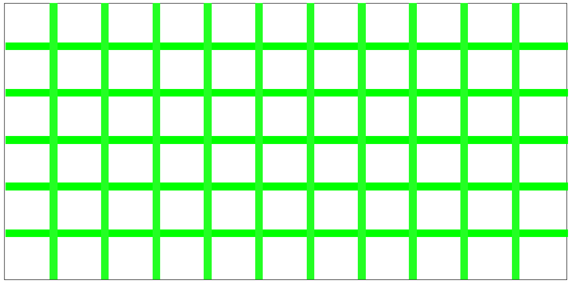
Considered a few different detector technologies for FINeSE.....

Scintillator stack



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

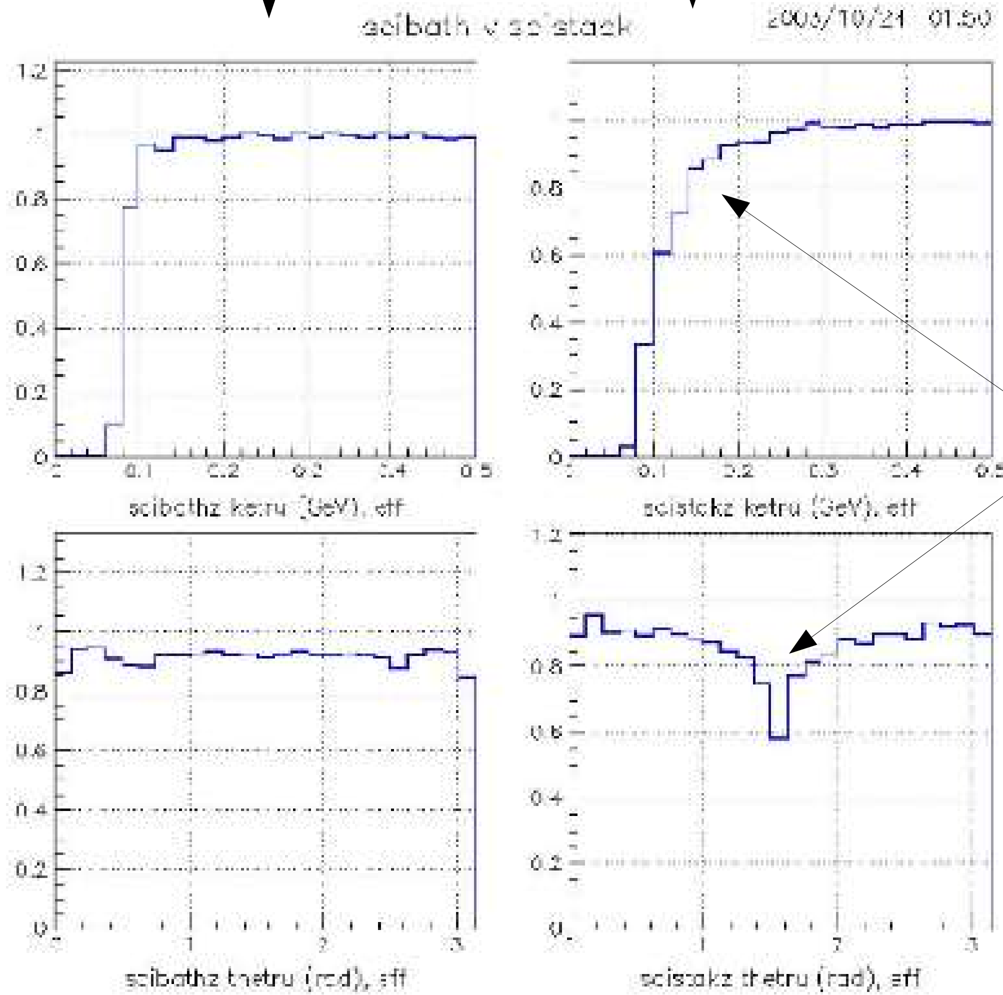
Scintillator bath



- not optically isolated
- information in 3D

Scibath

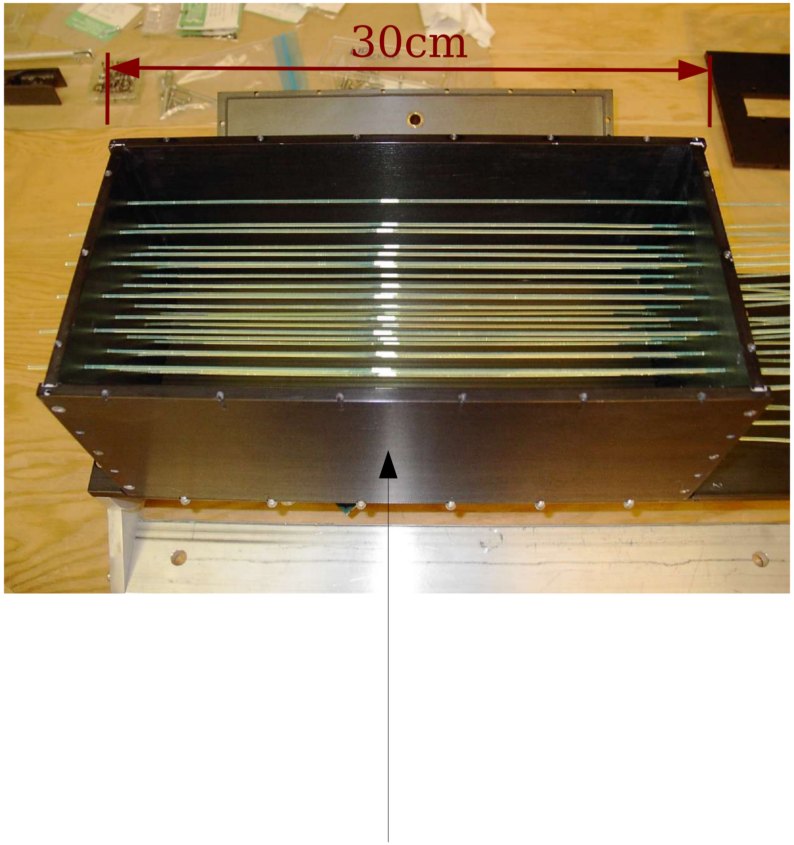
Plastic scintillator stack



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

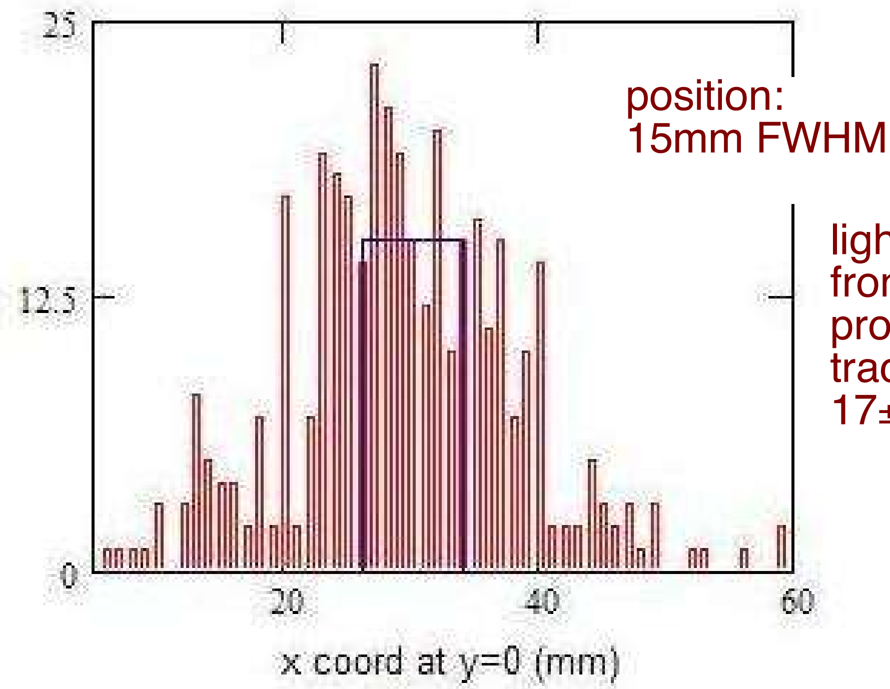


IUCF 200 MeV proton beam

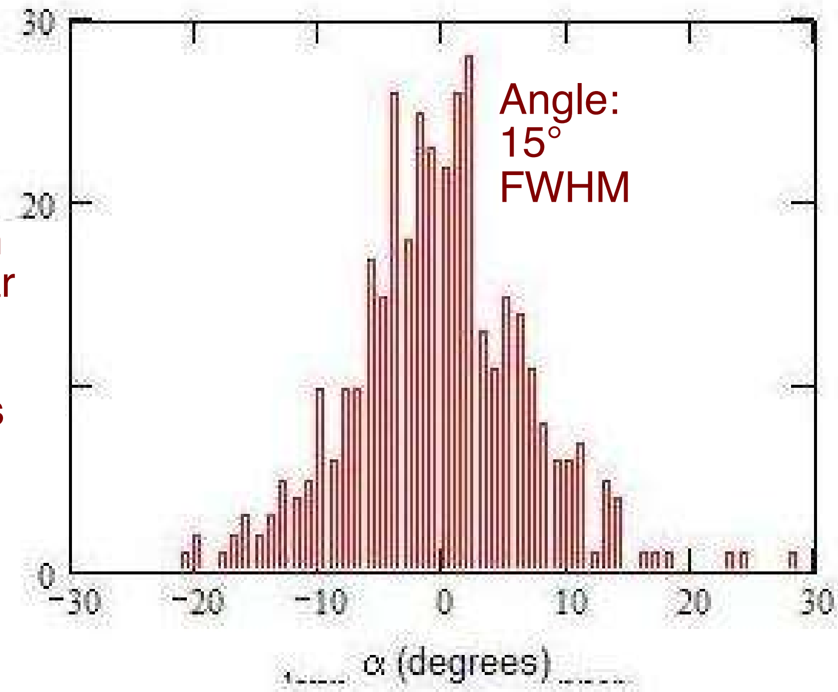
tested at the Indiana University Cyclotron Facility in summer 2003 using low intensity, 200 MeV protons

- 6x6 mm^2 beam profile
- beam scanned vertically, horizontally, and at angle to prototype

Test results:

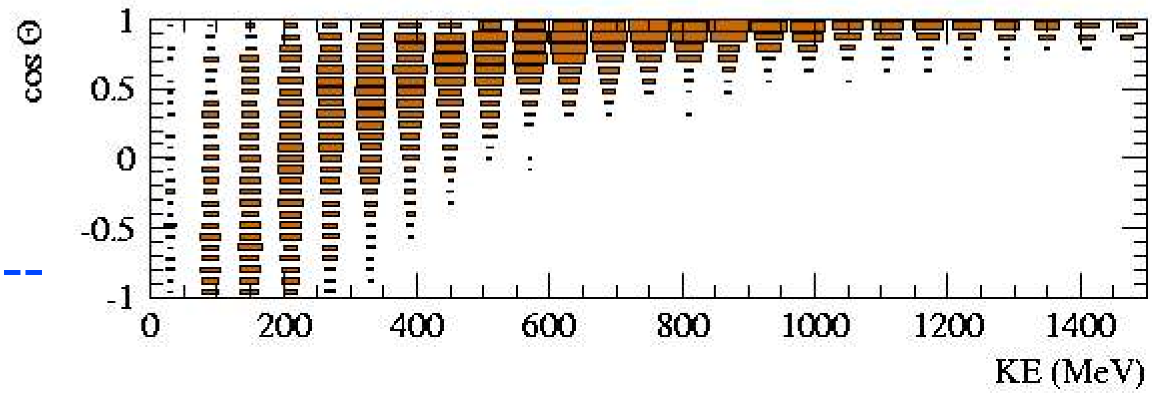


light seen from near proton tracks: 17±2 PEs



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:

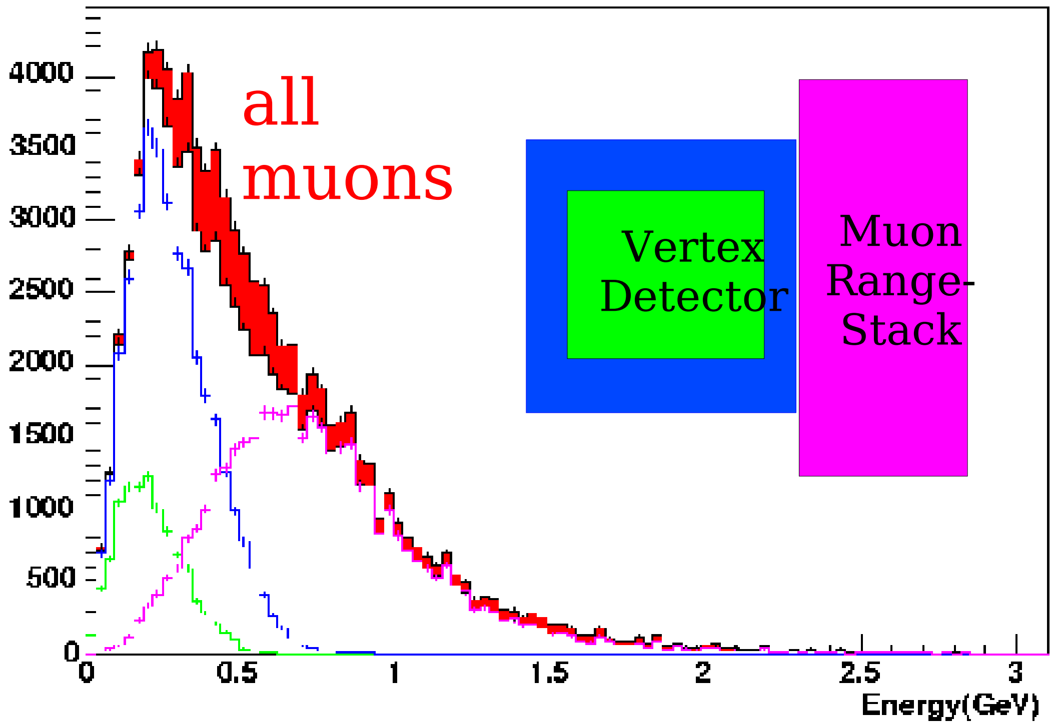
In Vertex Detector signal region

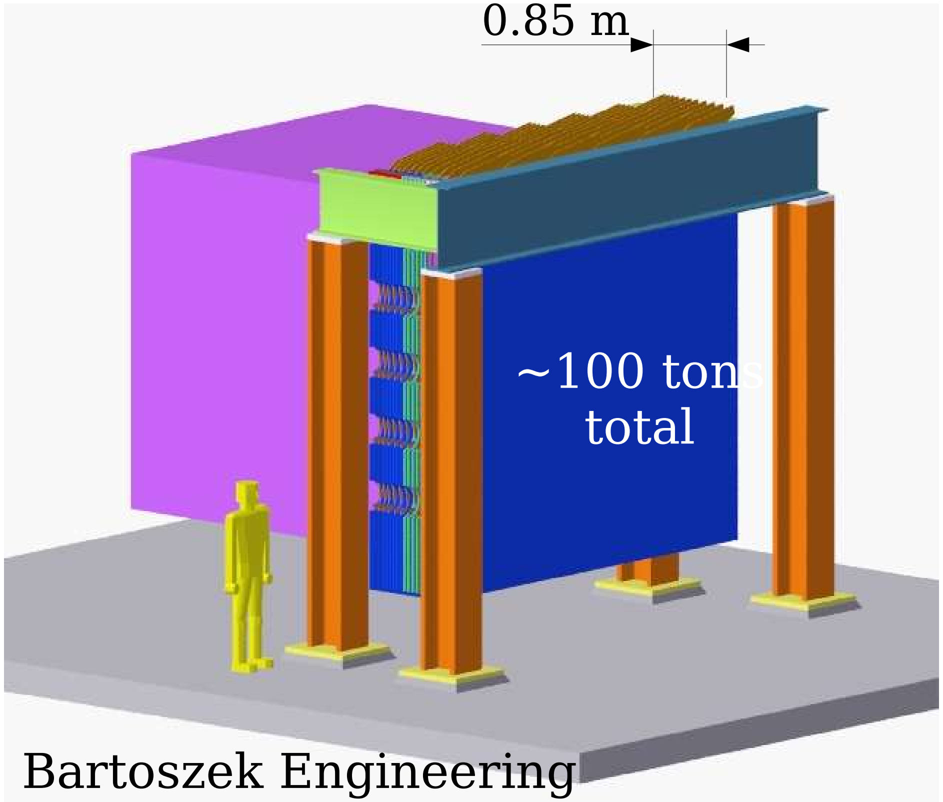
or

In Vertex Detector signal region + veto

or

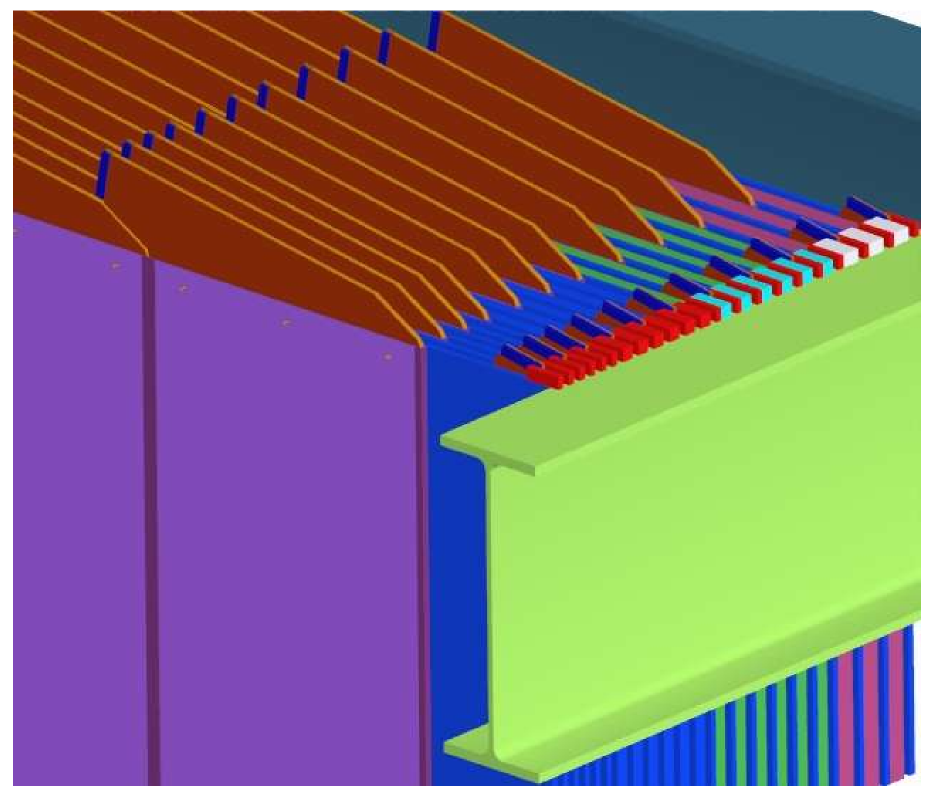
In Vertex Detector + Muon Rangestack





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

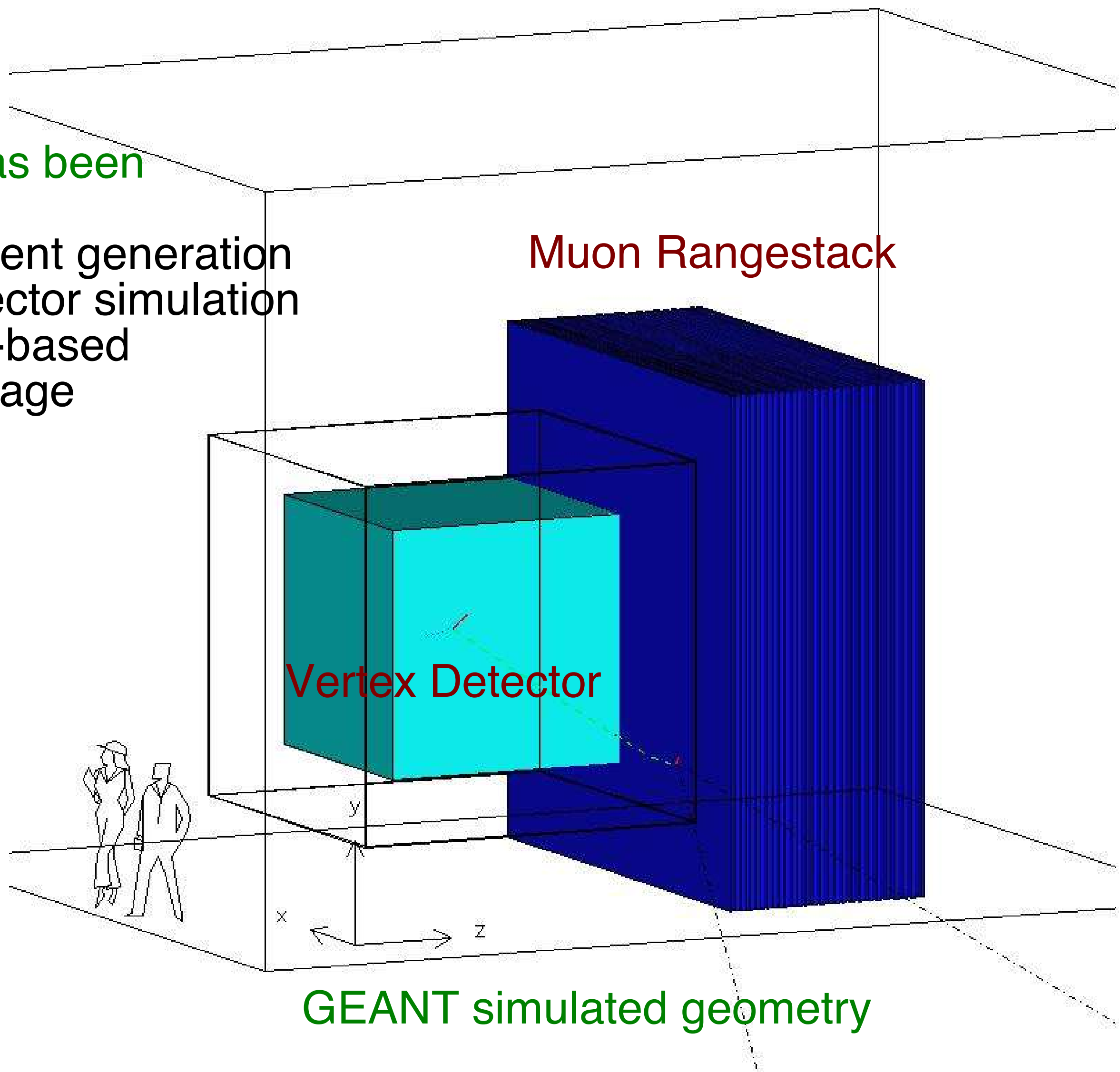


- 21 pairs of scintillator and iron absorber planes
- four sections with thickness of iron absorber = 0.5" x n (n=1 to 4) in each 1:4 scintillator:iron

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

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

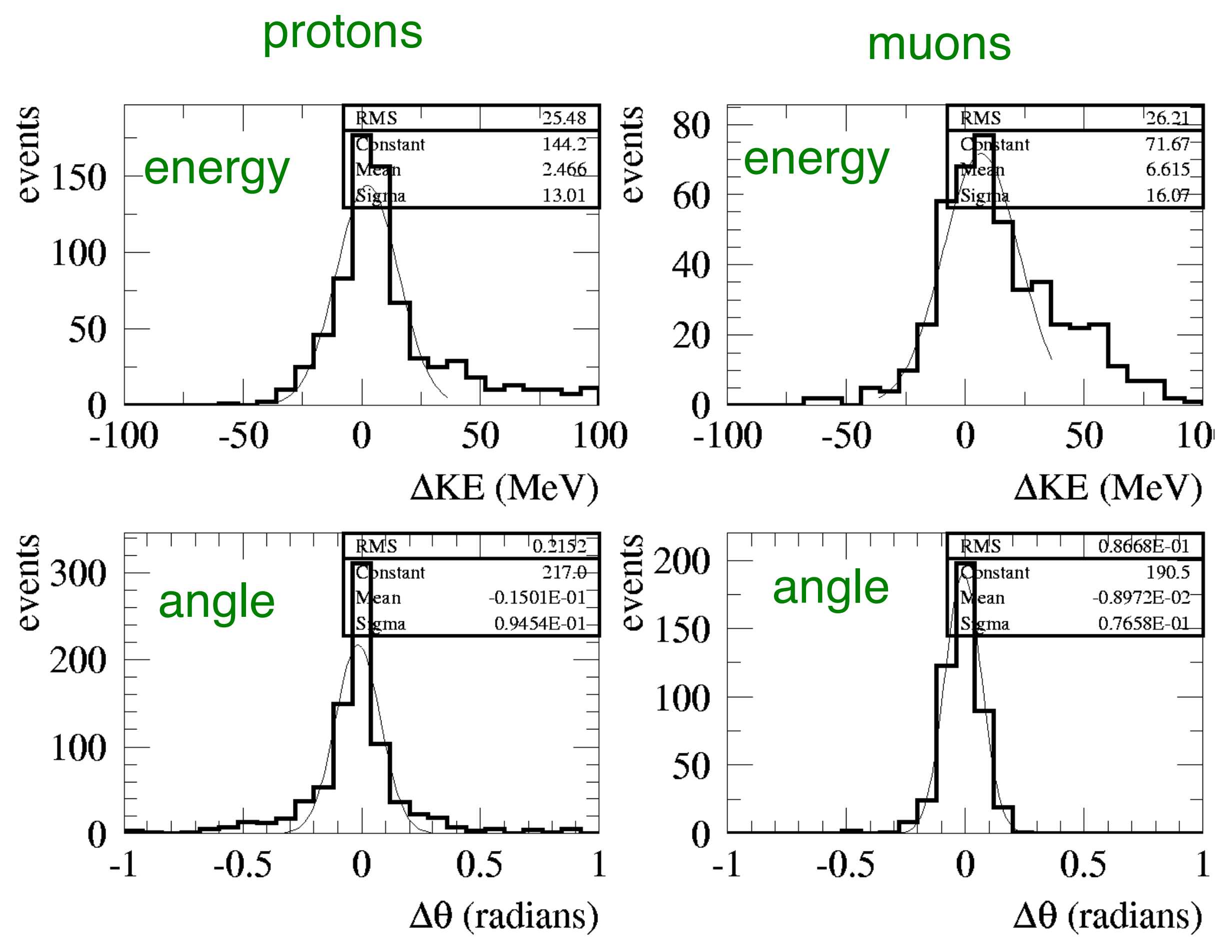


GEANT simulated geometry

FINeSSE Detector Simulation and Reconstruction...

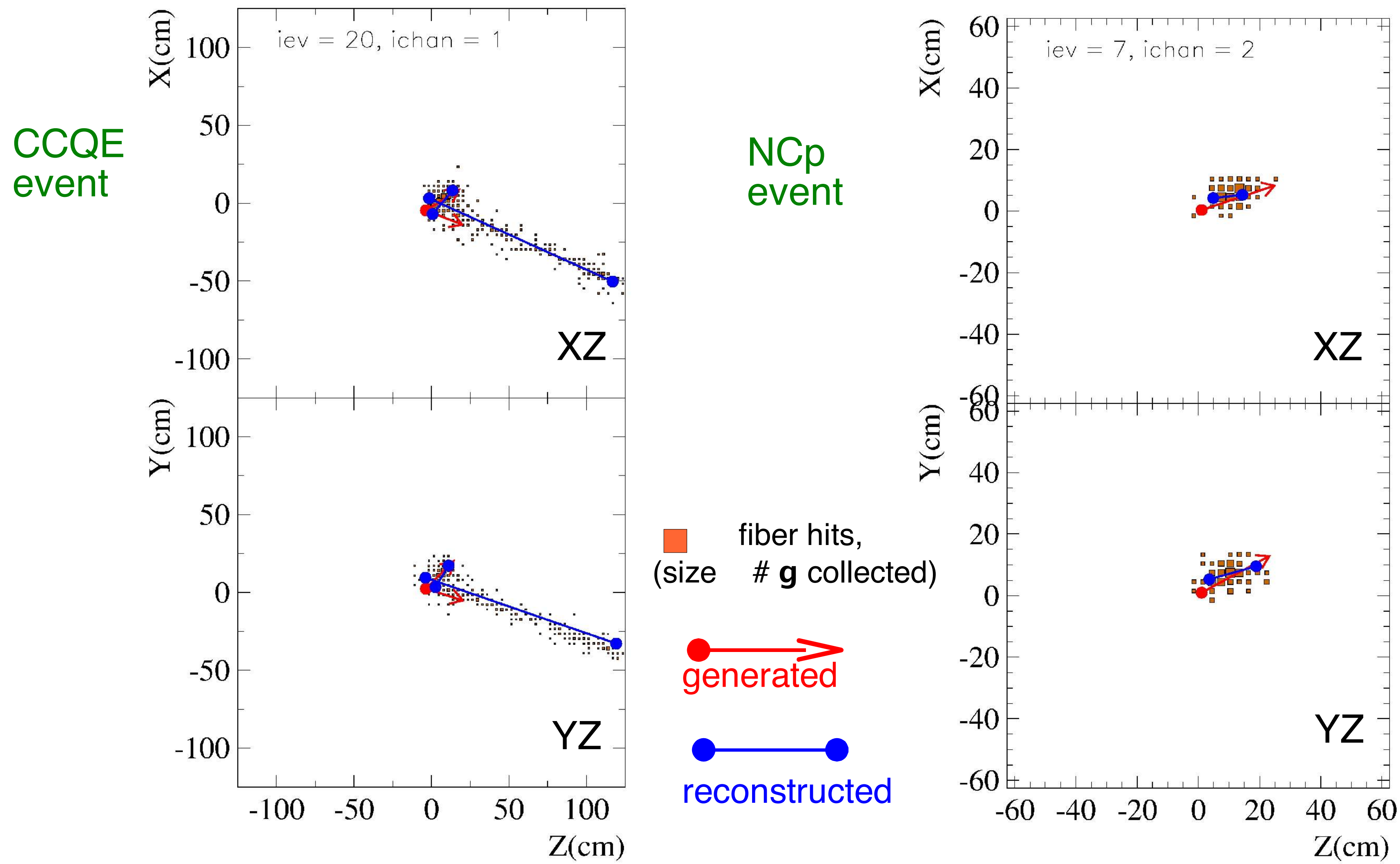
Simulation and reconstruction of 50-500 MeV protons and muons:

- $\Delta E \sim 15$MeV
- $\Delta\theta \sim 6°$



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 Sensitivity to Δs

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 (νn→νn) scattering misid
- scattering from free protons
- uncertainties in efficiencies
- Q^2 reconstruction
- nuclear model uncertainties
- form factor uncertainties

Results:

σ(Δs) = ±0.04 (stats. and exp. sys.)

=± 0.025 (f. f. sys)

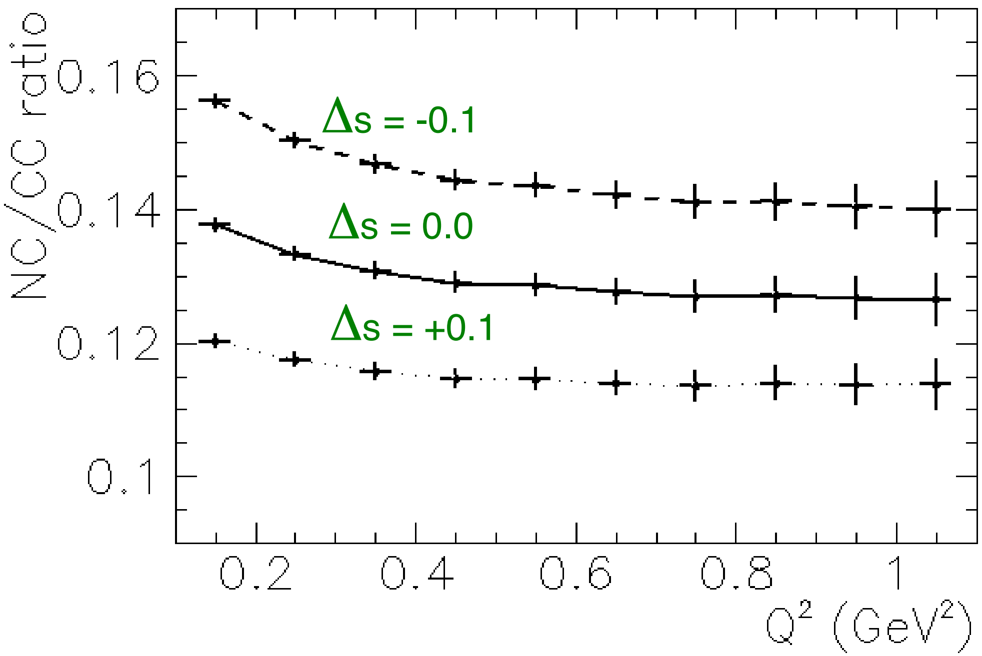
Recall:

BNL E734 Δs = -0.21± 0.10± 0.10

polarized DIS   Δs = -0.14± 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 Δs 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
  - ($\nu p \to \nu p$)/($\nu n \to \nu n$) is more sensitive to Δs

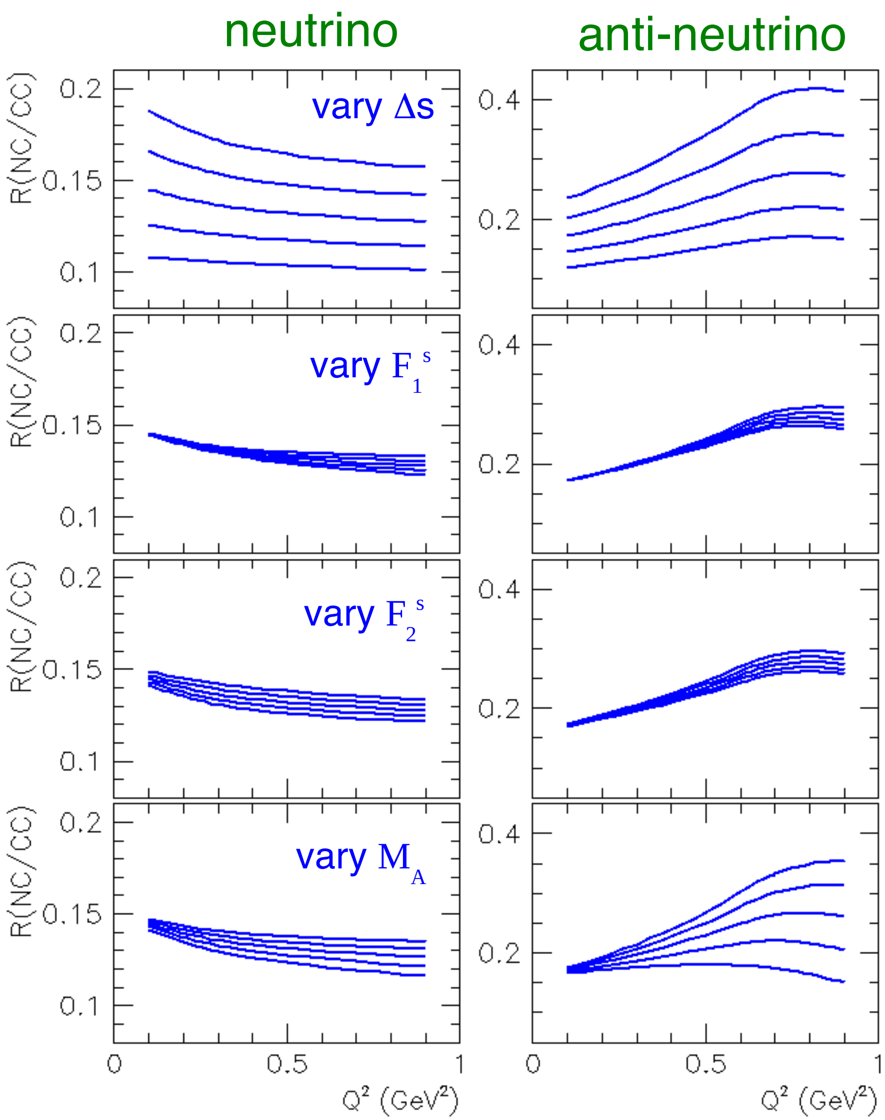
- Measure short tracks (low Q^2) – good resolution

- Eliminate error on correction for scattering on free protons (no free protons!) (LArTPC only)

ν vs $\bar{\nu}$ running allows for sensitivity to Δs and other form factors

R(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



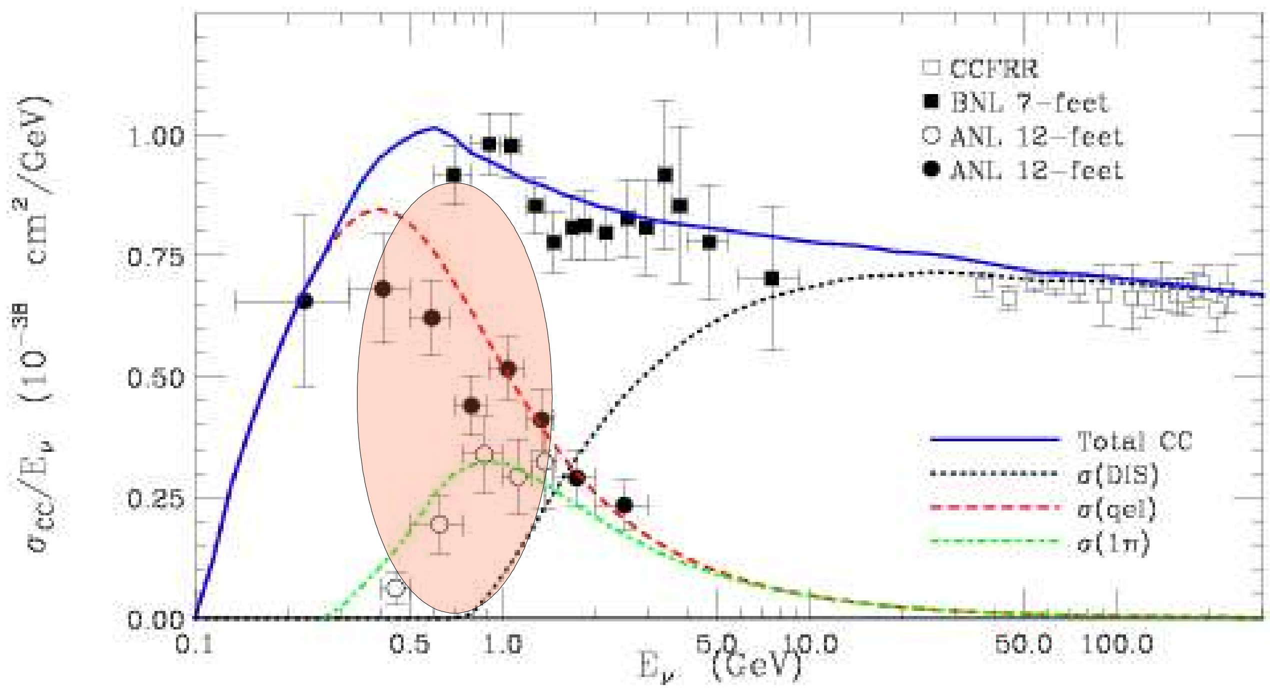
Considering ν and $\bar{\nu}$ running

Rich energy region: different channels turning on and off

A lot going on
at low energies:

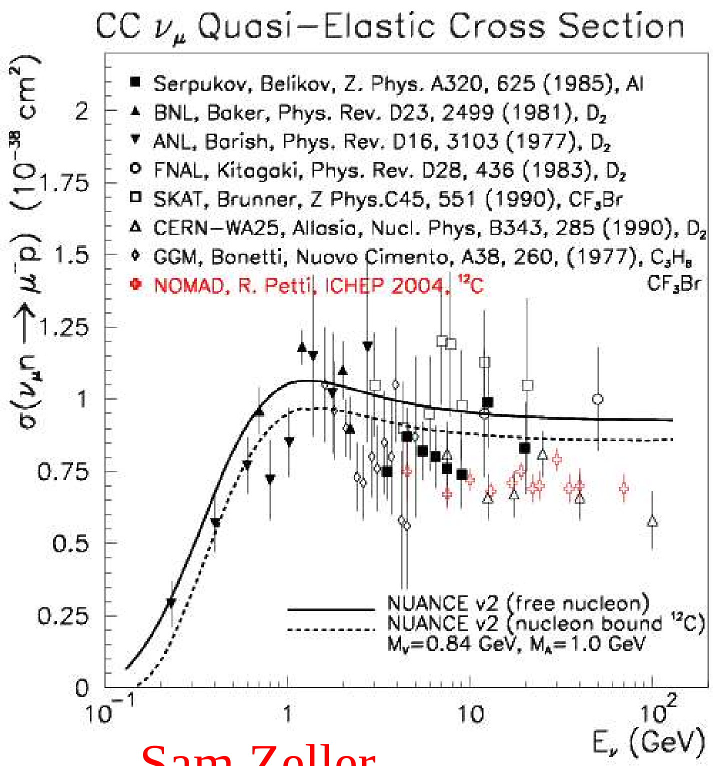
quasi-elastic
single π
(DIS turning on)

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



Sam Zeller

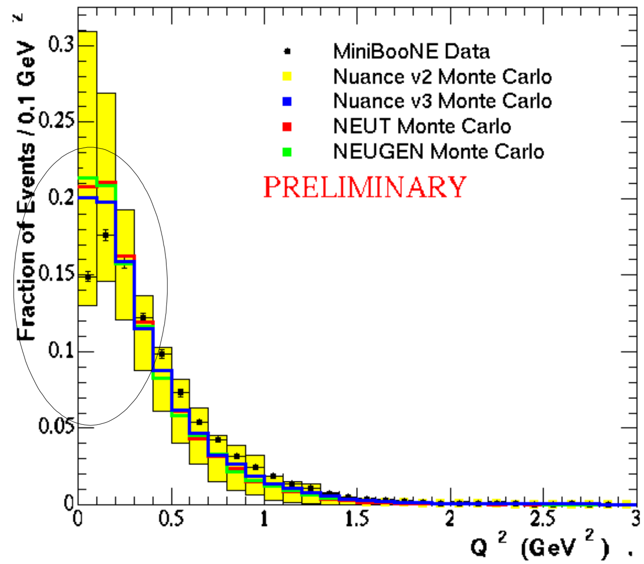
Existing data:

- 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)

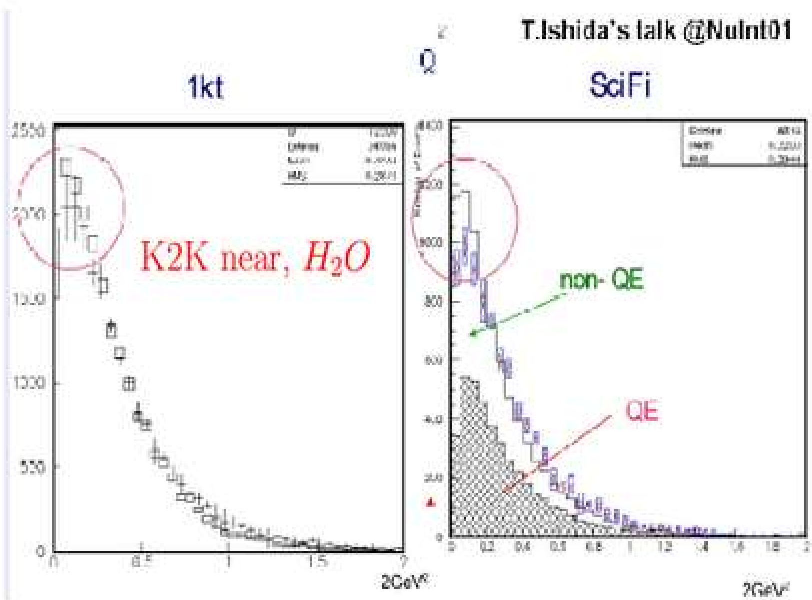
use CCQE samples to unfold nuclear effects:

Interesting rollover at low Q^2

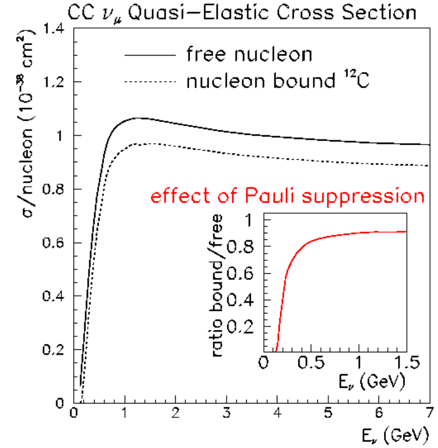
- not fully reproduced by any of the MCs
- same effect seen by K2K near detectors



K. Furuno, NuInt02 proceedings to be published in Nucl. Phys. B.
Baker *et al.*, Phys. Rev. **D23**, 2499 (1981)



Pauli Supression effect?
Nuclear Shadowing?

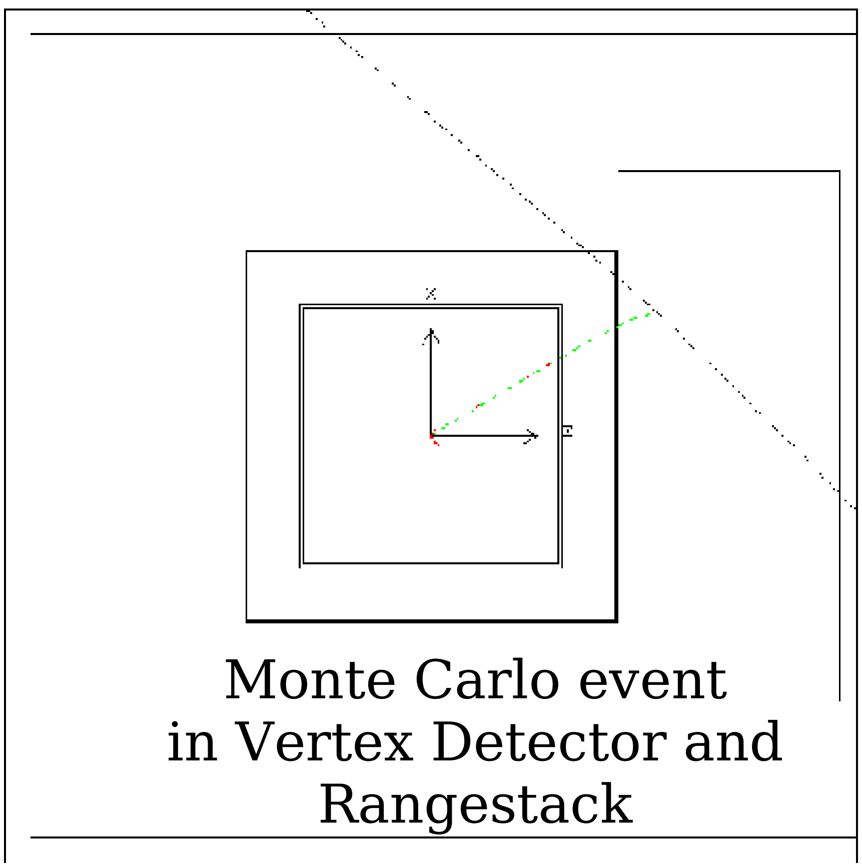


Sam Zeller

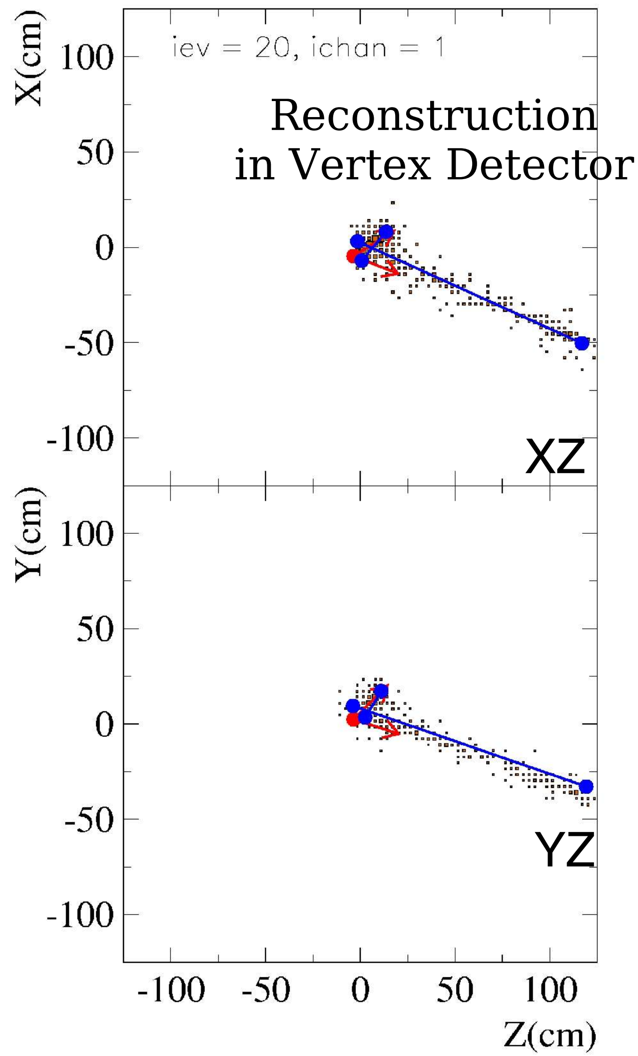
Measure CCQE's with fine-grained, high statistics experiment, down to low Q^2

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

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



Monte Carlo event in Vertex Detector and Rangestack

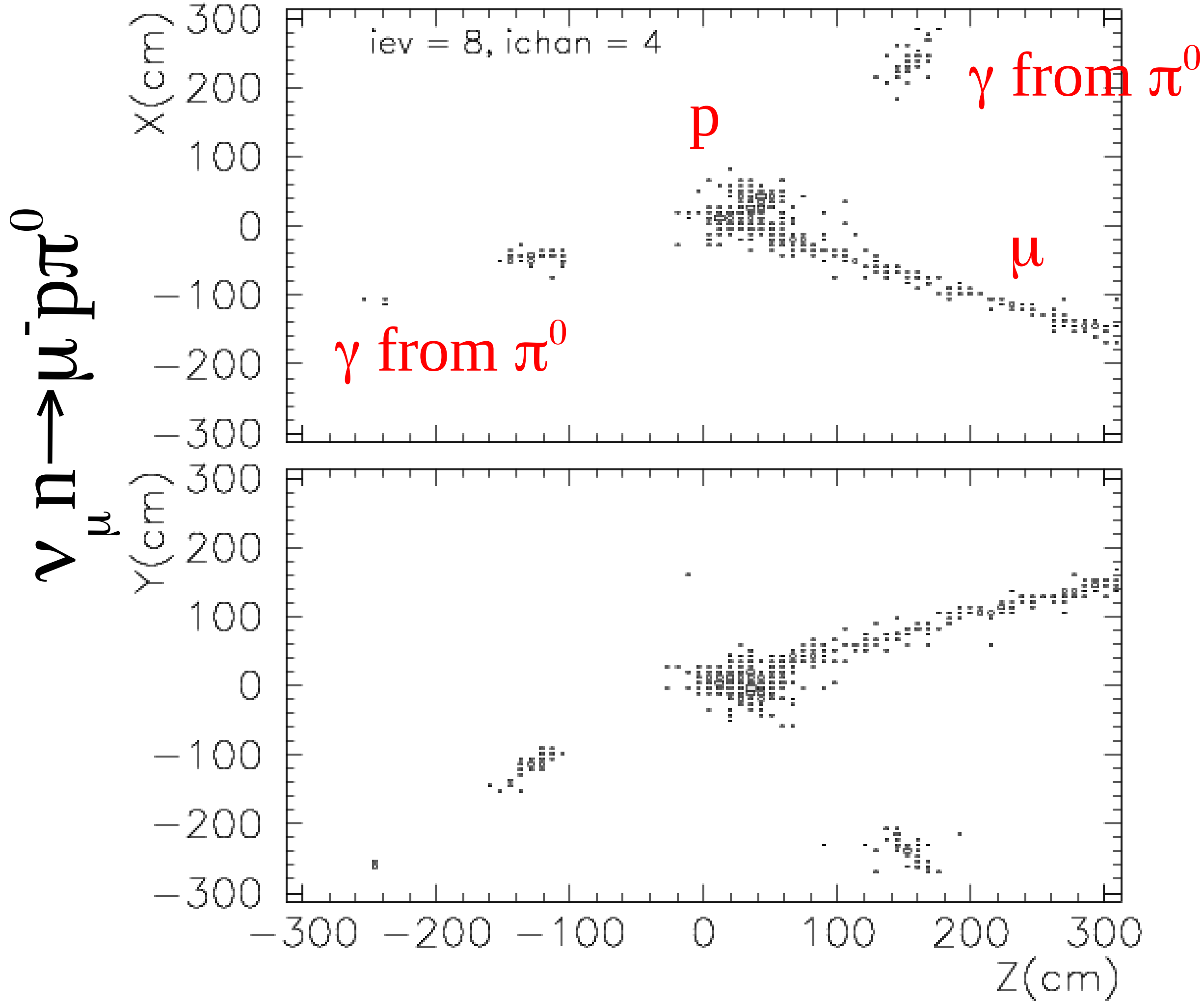


see proton recoil in Vertex Detector and range out muons in range stack

Suppresion seems to be largest in $CC\pi^+$ sample

Want to easily identify these events

FINeSSE Event Display

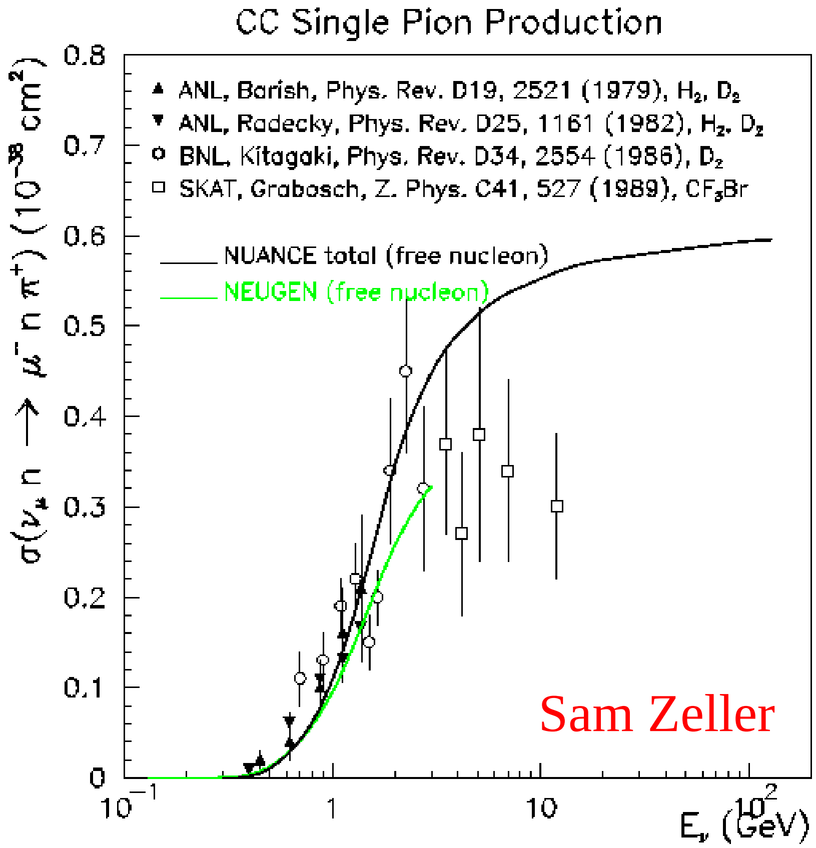


Single Pion Production

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

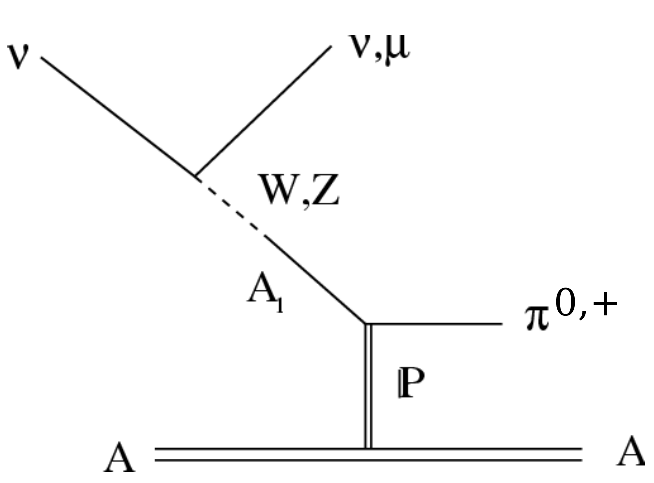
$\nu_\mu n \rightarrow \mu^- n p^+$

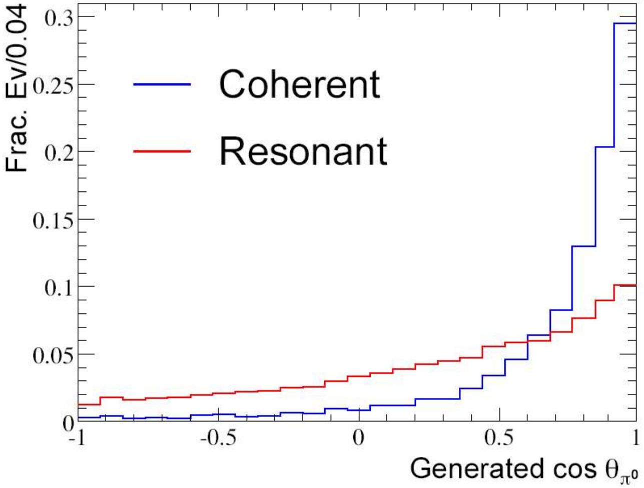


Coherent Production (~20%)
scatter from entire nucleus...

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

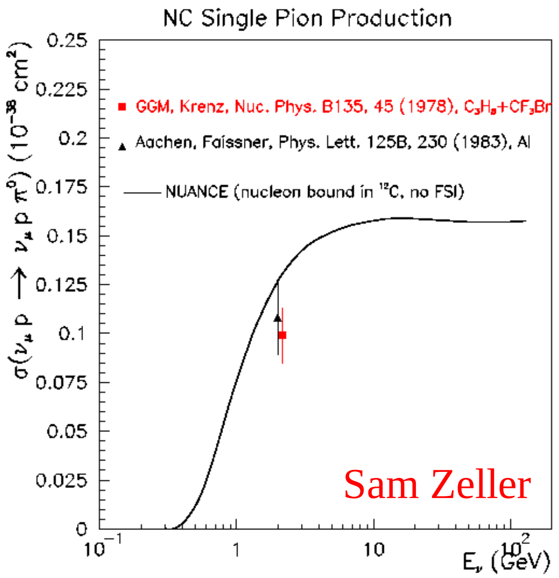
x20 variation in recent models at E~1 GeV

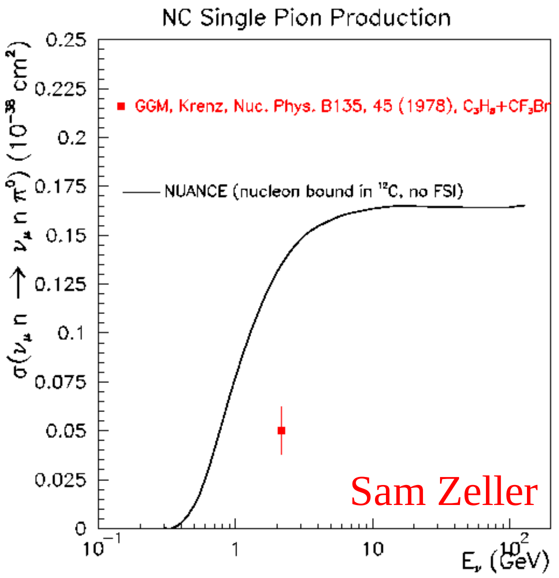




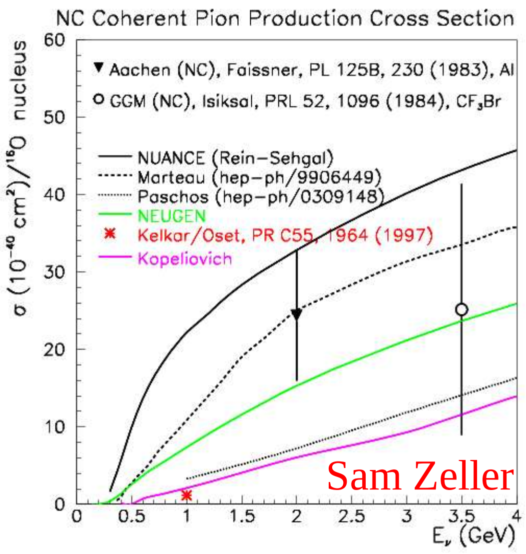
distinct kinematics:
forward scattered **p**
small energy transfer to target (low Q^2)

Neutral current π^0 production: significant background for present and future $\nu_\mu \rightarrow \nu_e$ oscillation searches

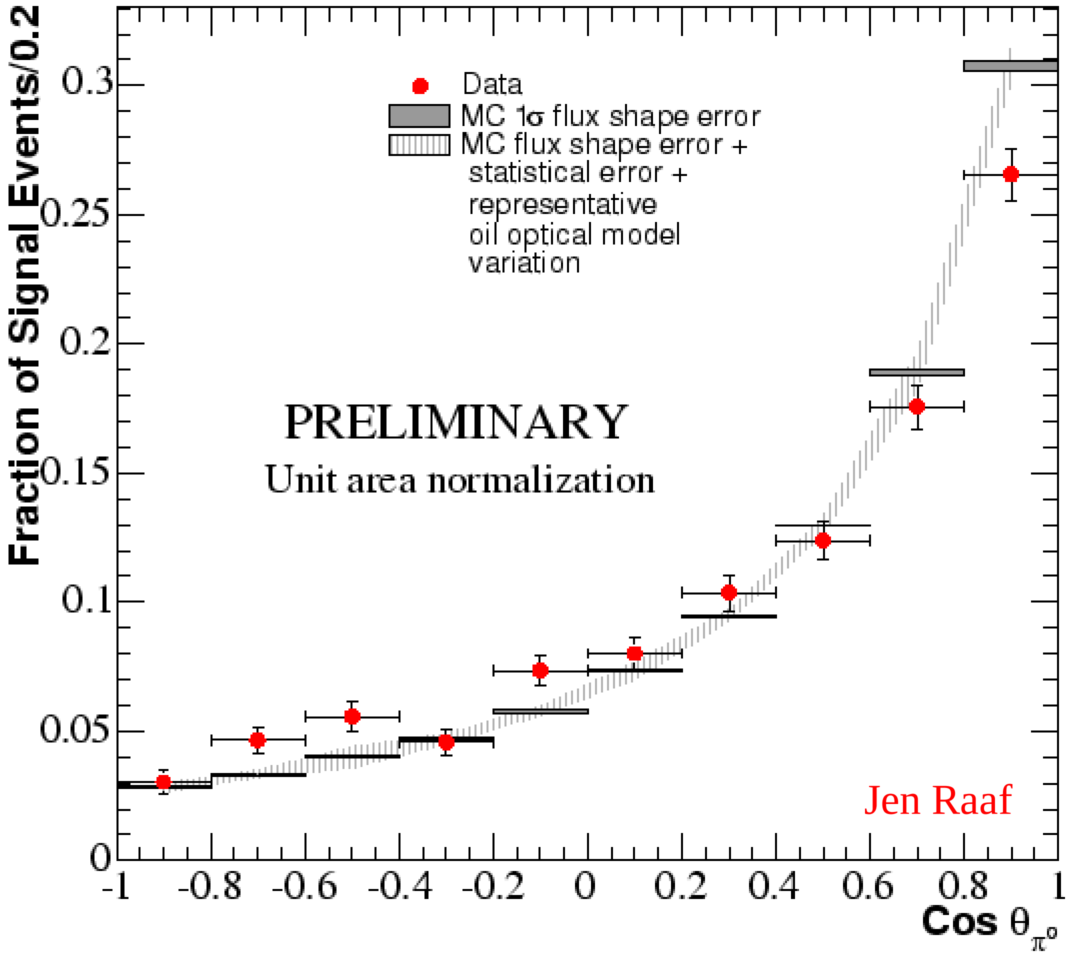


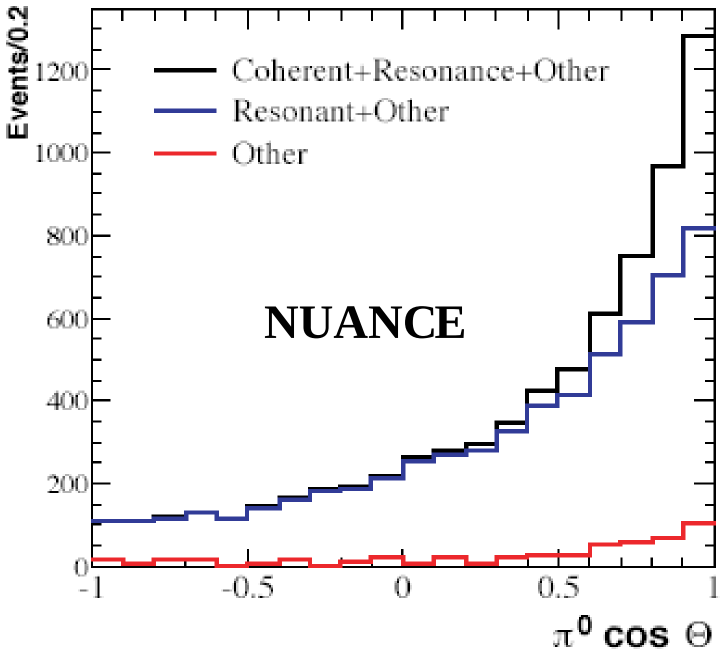


- very little data
- spread in model descriptions

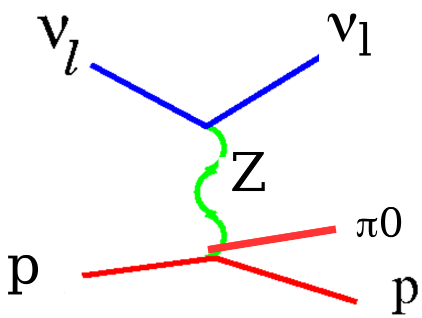


Preliminary MiniBooNE data suggests there may be surprises here too!



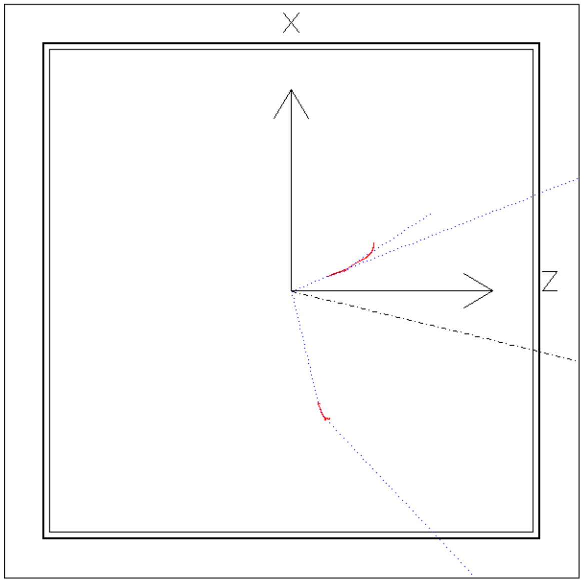


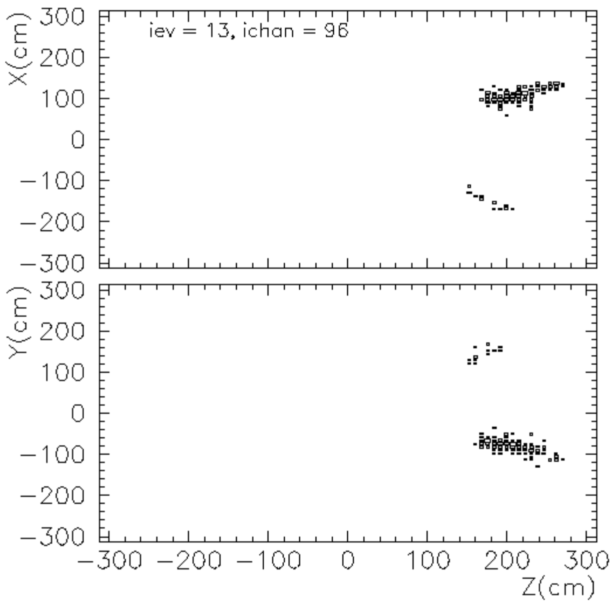
Neutral current π^0s in FINeSSE



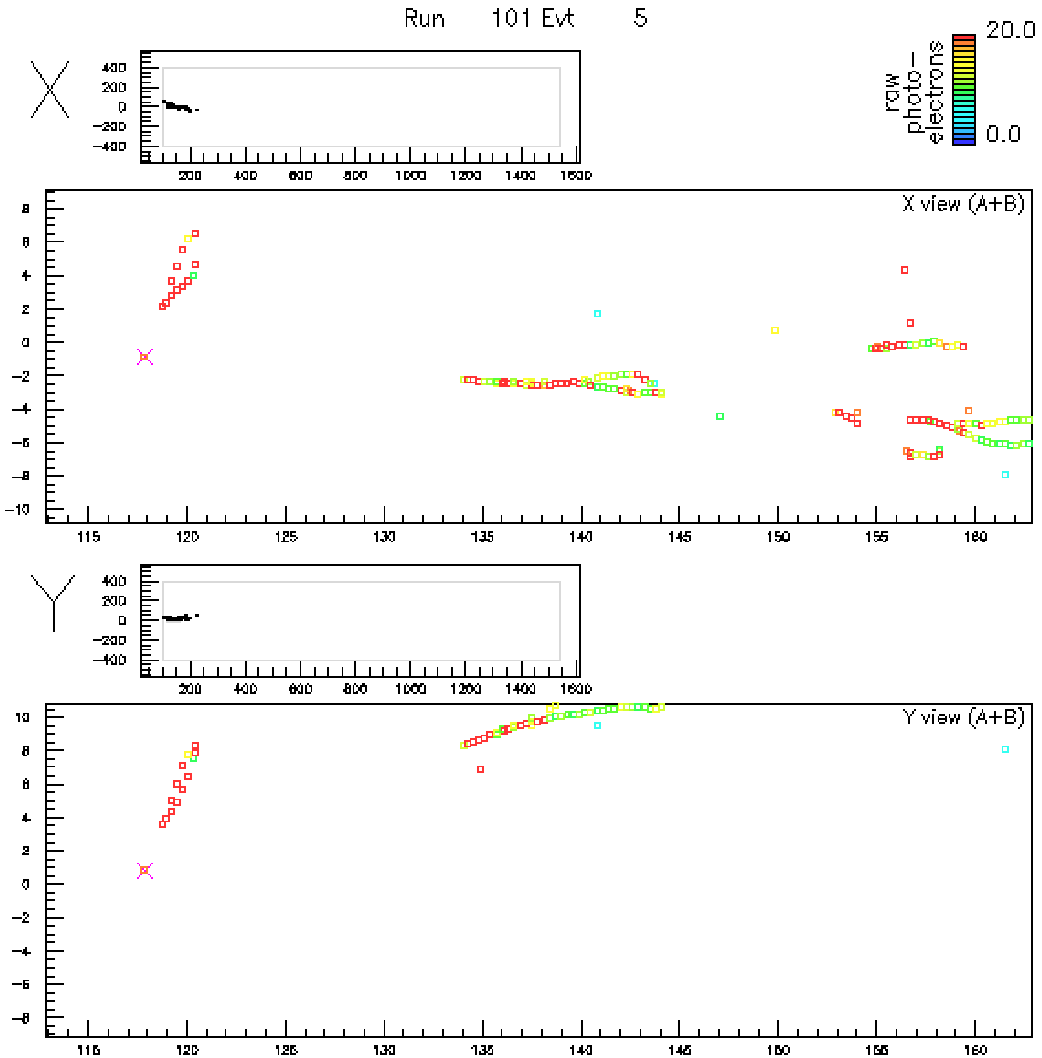
Fine-grained detector can separate out these events well

Counting multiple rings is harder than looking for little blobs

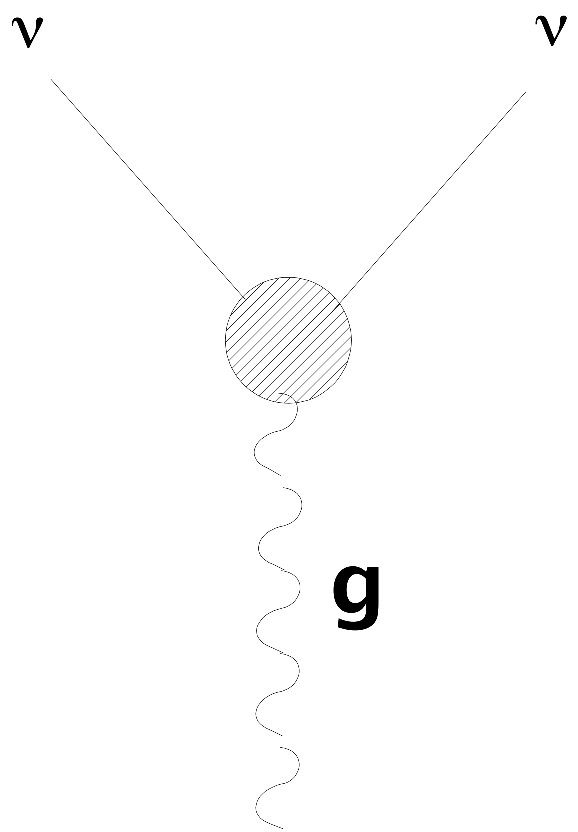




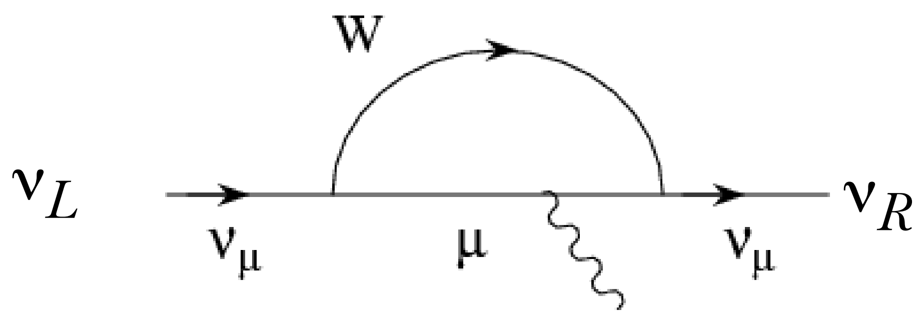
Even better in Liquid Argon TPCs: excellent spatial resolution: separating single pion production from other channels

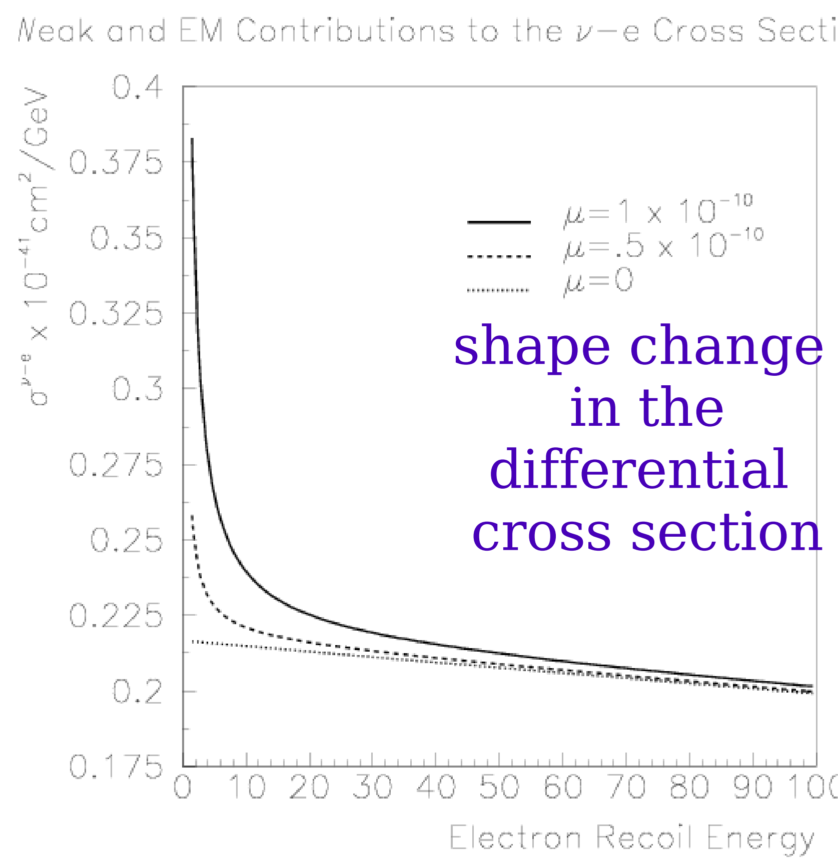


νe scattering: neutrino magnetic moments



massive neutrinos imply existence of ν_R





shape change in the differential cross section

Increase in overall cross section

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

Limits set from experiment:

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

- Preliminary measurement from MUNU
- SuperK shape fit

Muon ν 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 νe→νe cross section

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

- ➔ solar ν_e measures μ_2
- ➔ reactor $\bar{\nu}_e$ measures primarily μ_1 and μ_2
- ➔ accelerator ν_ms would measure μ_1, μ_2, and μ_3

Tau ν 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

$\mu_{\nu_e} \rightarrow 5.34 \times 10^{-15} - 10^{-16}\ \mu_B$

$\mu_{\nu_\mu} \rightarrow 1.13 \times 10^{-12} - 10^{-13}\ \mu_B$

$\mu_{\nu_t} \rightarrow 1.9 \times 10^{-12}\ \mu_B$

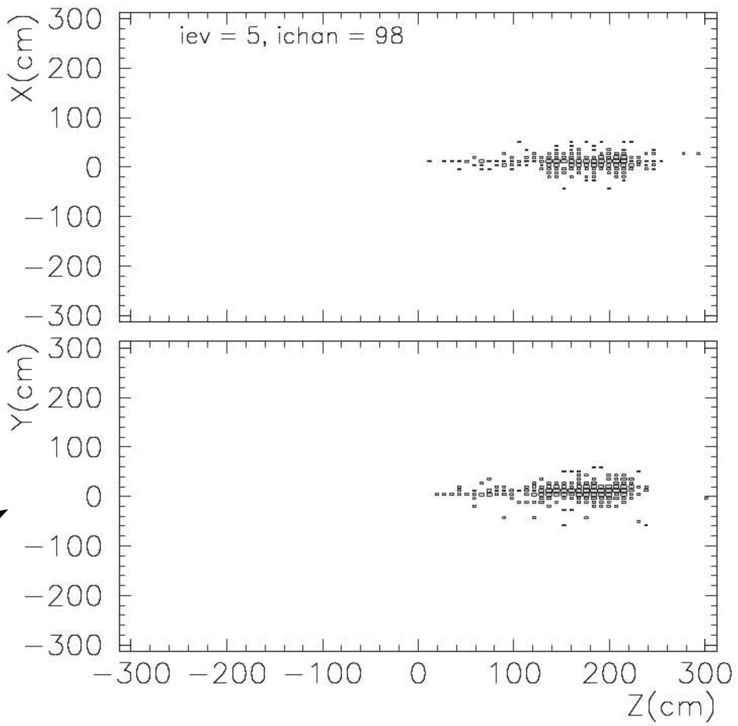
Large Extra Dimensions

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

order of magnitude lower than present limits

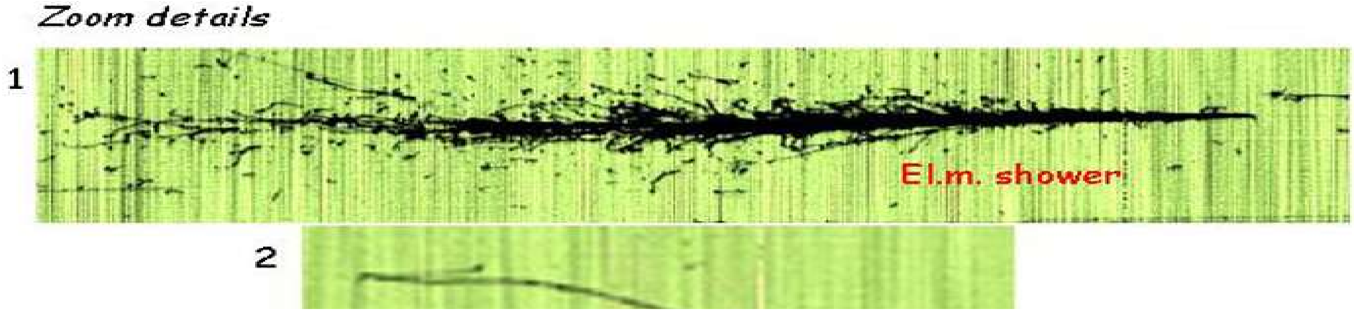
νe scattering with FINeSSE

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



FINeSSE “scibath” detector: forward electron shower

FINeSSE Phase 2 LArTPC



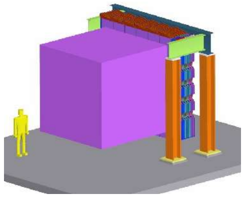
FINeSSE physics:

- 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/MINERvA
- Minimize background contamination
  - low energy neutrino spectrum (below DIS turn-on and with small high energy tail)
  - fine-grained detector →good final state separation

Beam



Detector

Possibilities at Brookhaven

Neutrino experiments need lots of beam....

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

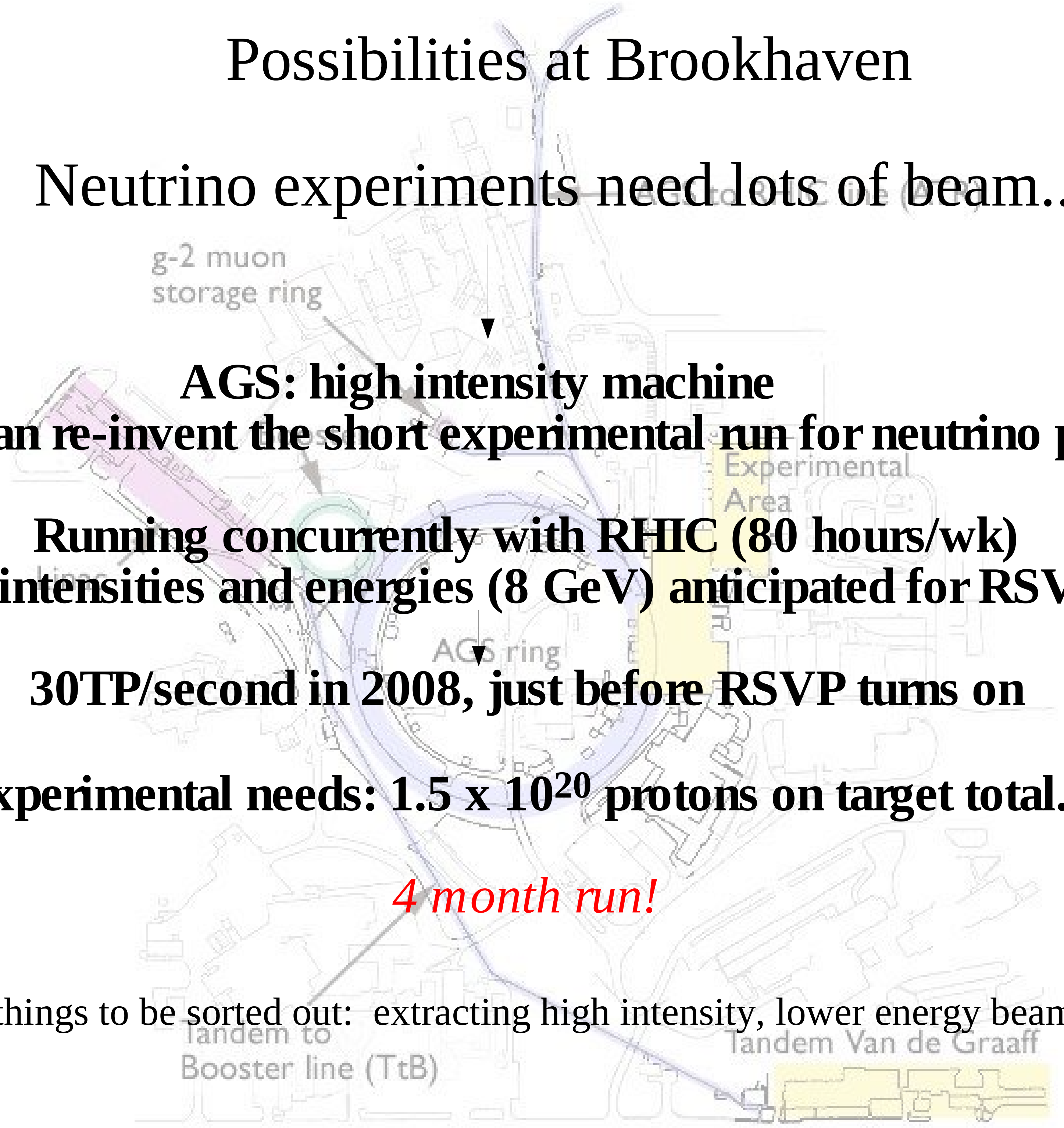
Running concurrently with RHIC (80 hours/wk)
At intensities and energies (8 GeV) anticipated for RSVP

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

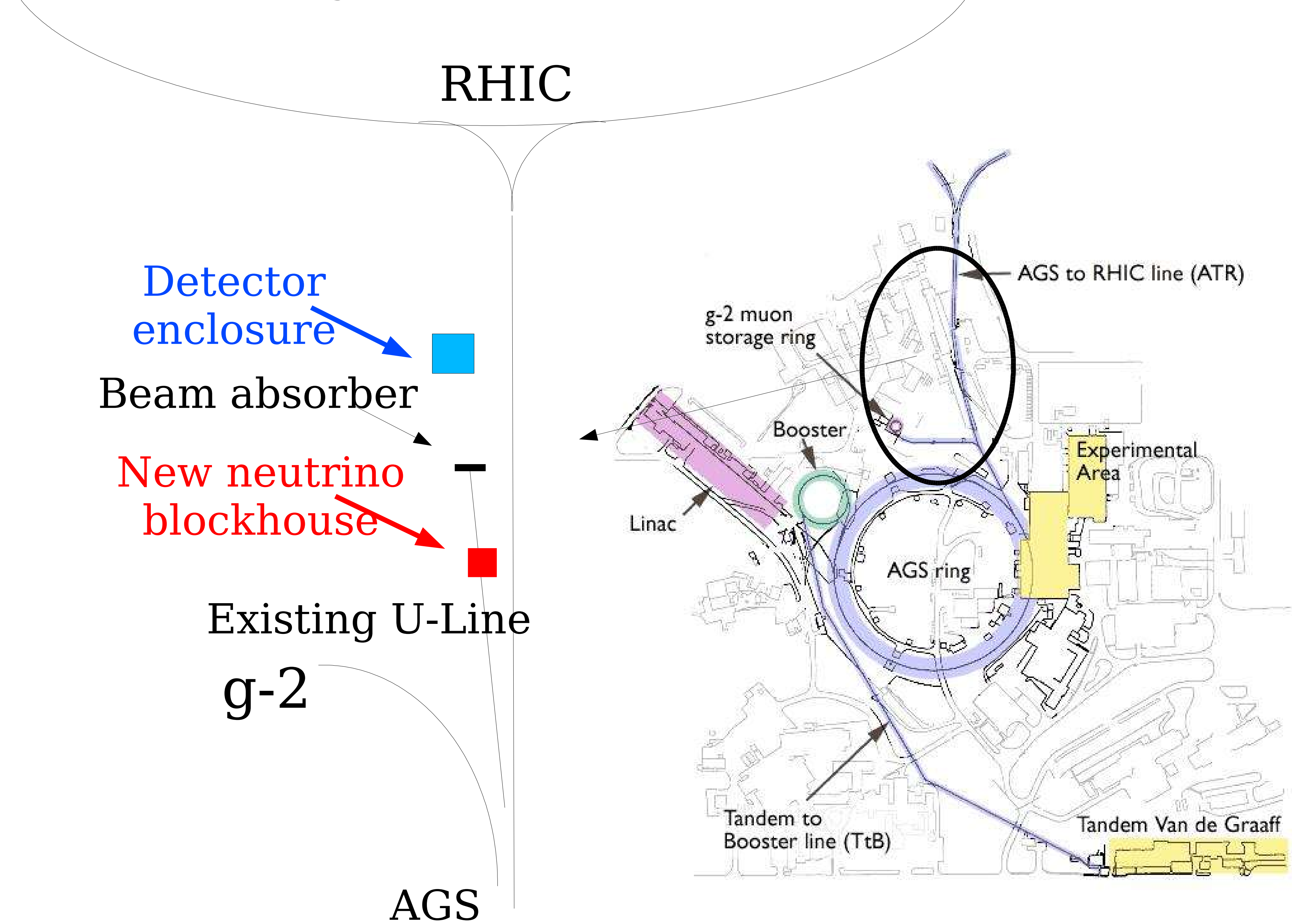
Experimental needs: 1.5 x 10^{20} protons on target total...

4 month run!

things to be sorted out: extracting high intensity, lower energy beam....



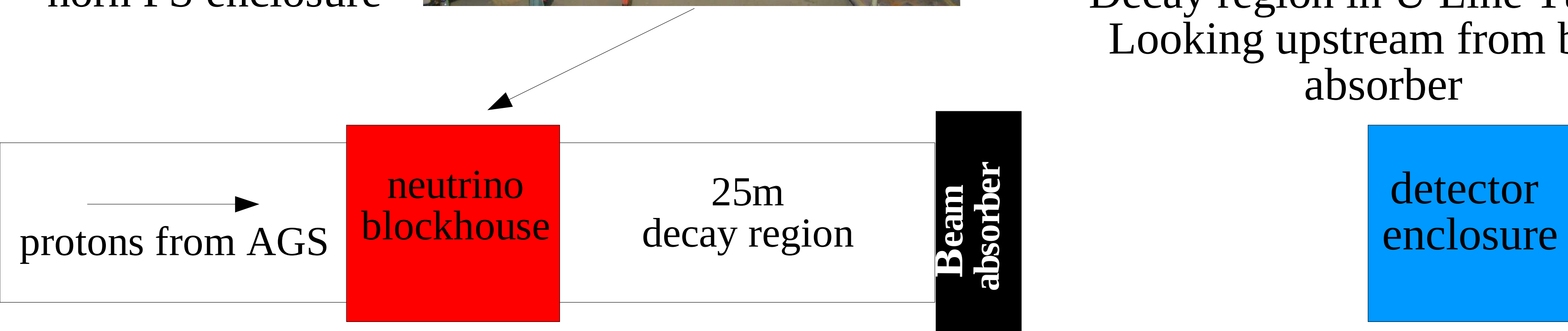
Existing/Updateable beamline at BNL:



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



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

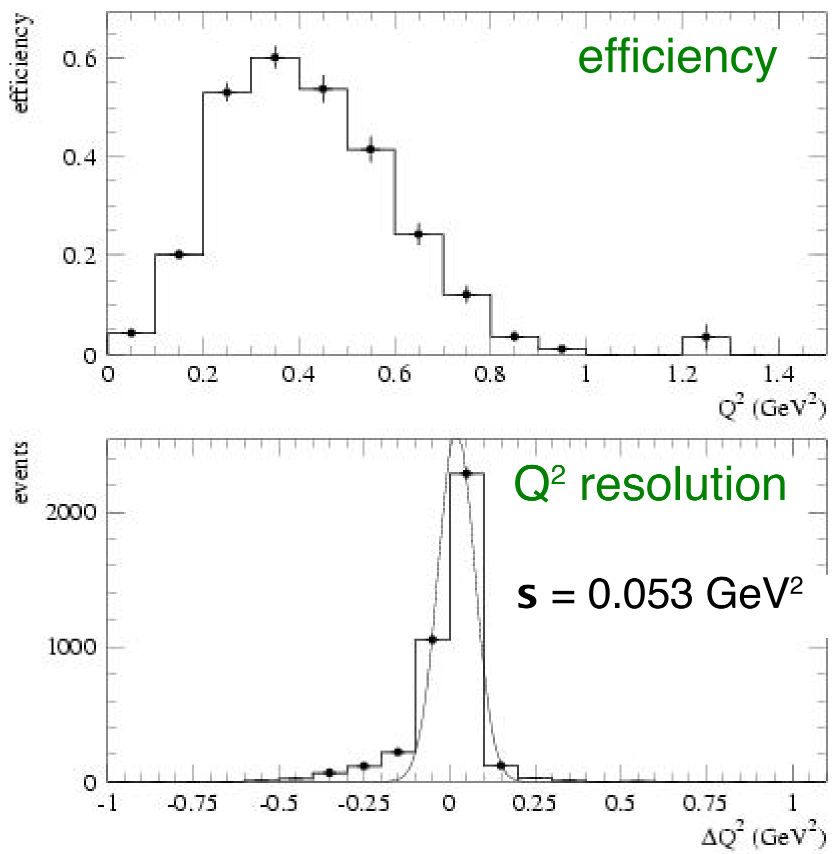
-as per Mike Witherell in letter to FINeSSE on program planning website

FINeSSE

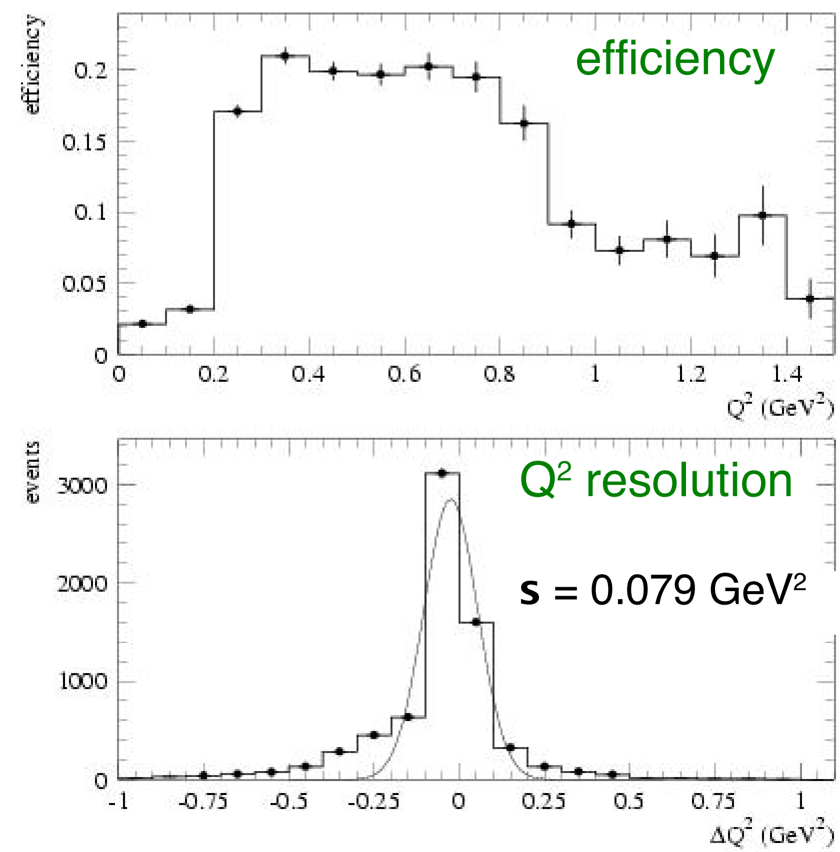
- Compelling physics...
  - Measure Δs down to $Q^2=0.2$ GeV^2
  - Measure low energy neutrino cross sections (recommendation of APS Neutrino Study!)
- Still working to understand FINeSSE's reach
  - Neutrino plus anti-neutrino running?
  - Detector development...(phase 2 LArTPC?)
- Cost effective and 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(NC/CC) measurement...

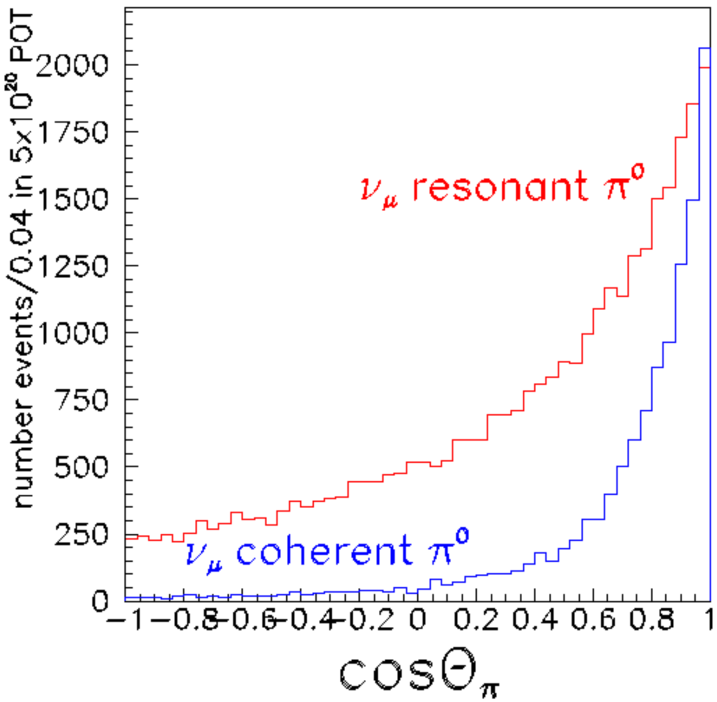
NCp events:

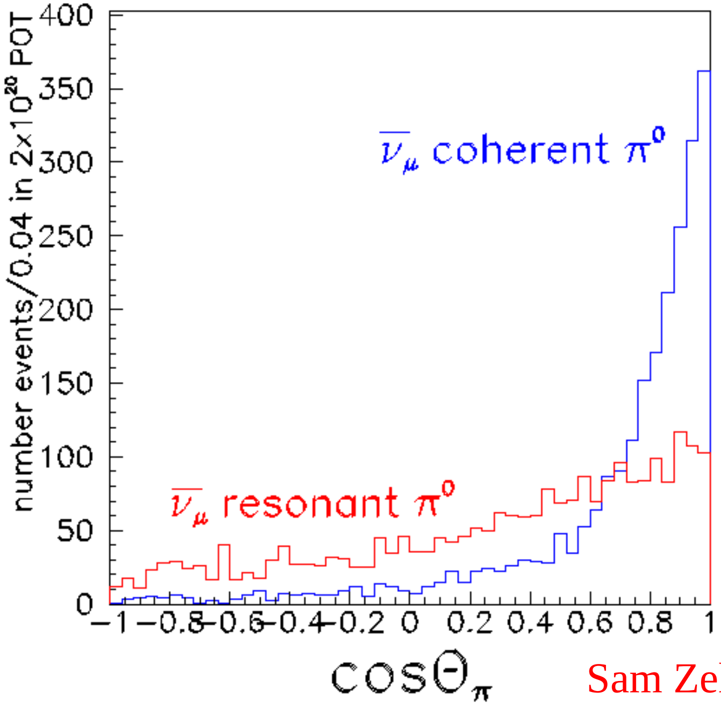


CCQE events:



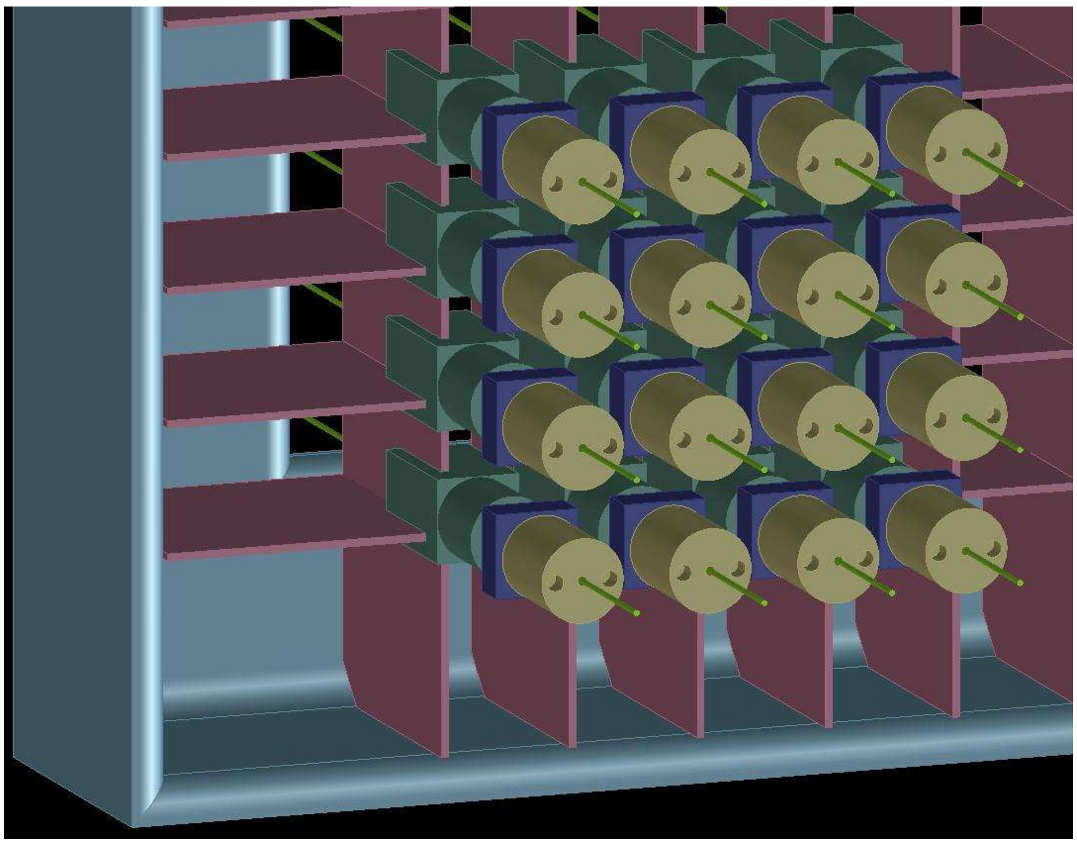
Anti-neutrinos can help unfold coherent and resonant!





Sam Zeller

Readout with Hammamatsu MAPMTs and on board electronics



STAR PMT w/front-end electronics