Bonnie T. Fleming
SB Workshop
March 5th, 2004

APS Neutrino Study -- 2004
Neutrino Super Beams, Detectors, and Proton Decay
BNL/UCLA Workshop

Short Baseline physics

→ Neutrino Scattering Physics (B. T. Fleming)

→ Oscillation Physics (A. Bazarko)

→ Near detector physics at T2K (C. McGrew)

- physics motivations
- experiments at existing and future facilities
- making progress

Physics at short baselines

- Neutrino Scattering physics
  - Cross section measurements for next generation neutrino experiments
  - Form factor measurements
  - DIS measurements
  - $\sin^2\theta_W$ measurement
  - pentaquark searches and strangeness
  - neutrino magnetic moment searches

- Impact on astrophysics
- Other things?

Lots of great SBL physics in near and far term...

Improvements with superbeams!!!

how big? what new physics?

Short baseline neutrino facilities

Running:
- K2K near hall
- FNAL Booster ν beamline at 500m

Near future:
- NuMI near hall (on and off axis) - 120 GeV
- Near locations on FNAL 8 GeV Booster ν beamline
- JPARC near halls (280m and 2km)
- BNL 3 GeV?

Farther future:
- near detector locations at a proton driver at
  - Fermilab Proton Driver 5, 8, 120 GeV
  - Brookhaven proton driver 28 GeV
  - JLab ELIC injector, 10+ GeV

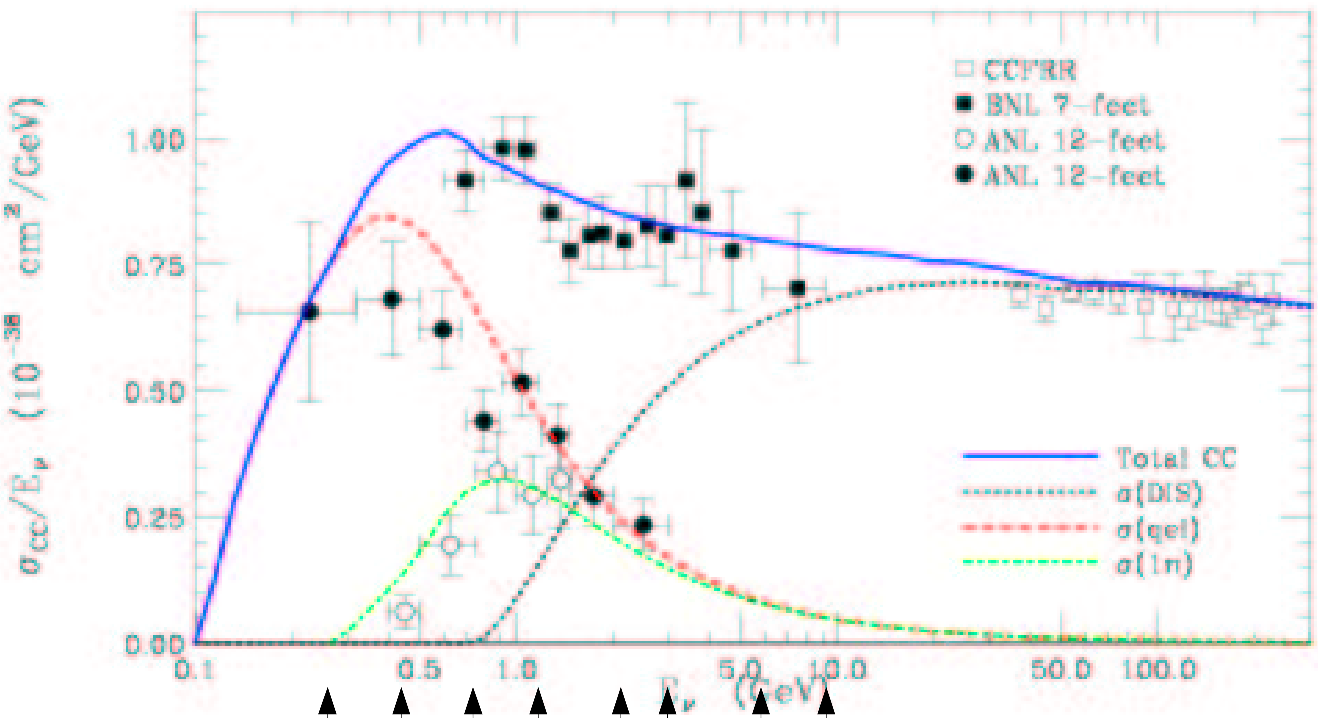
Short baseline detection technologies

- Cerenkov detectors
- Calorimeters
- plastic and liquid scintillator detectors
- Liquid Argon TPC
- others?

Challenges for different physics measurements:

- resolution -- more fine-grained (testing ground?)
- flux uncertainties
- neutron detection
- others?

Different proton energy → Different neutrino energy spectra



BNL 3 GeV
Booster

K2K
T2K

NuMI low, medium,
and high energy beams

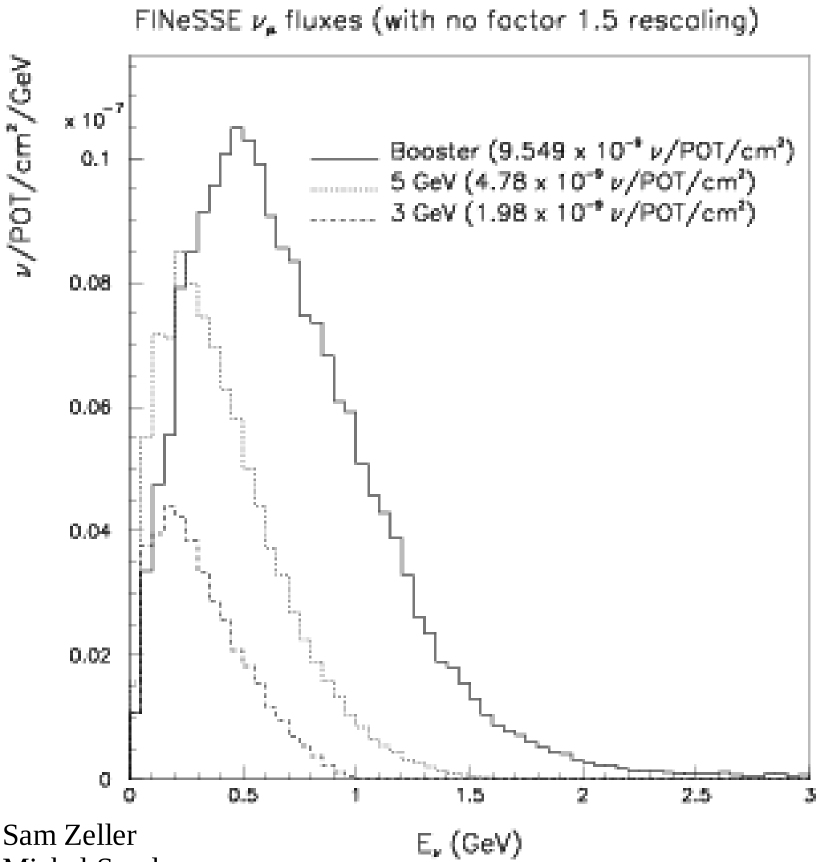
AGS

FNAL 5 or 8
GeV Linac
JLab?

At low energies:
➔clean beams, but
flux and cross sections
dropping rapidly

At higher energies:
➔single π turns on.
➔ DIS turns on

Different neutrino spectra → Different physics



Sam Zeller
Michel Sorel

8, 5, and 3 GeV POT
on MiniBooNE
target+horn
with 25m decay region

horn optimized
for 8 GeV flux

- good for measurements with pion backgrounds
- bad for measuring pion production cross sections and DIS
- good for short and long baseline oscillation physics?

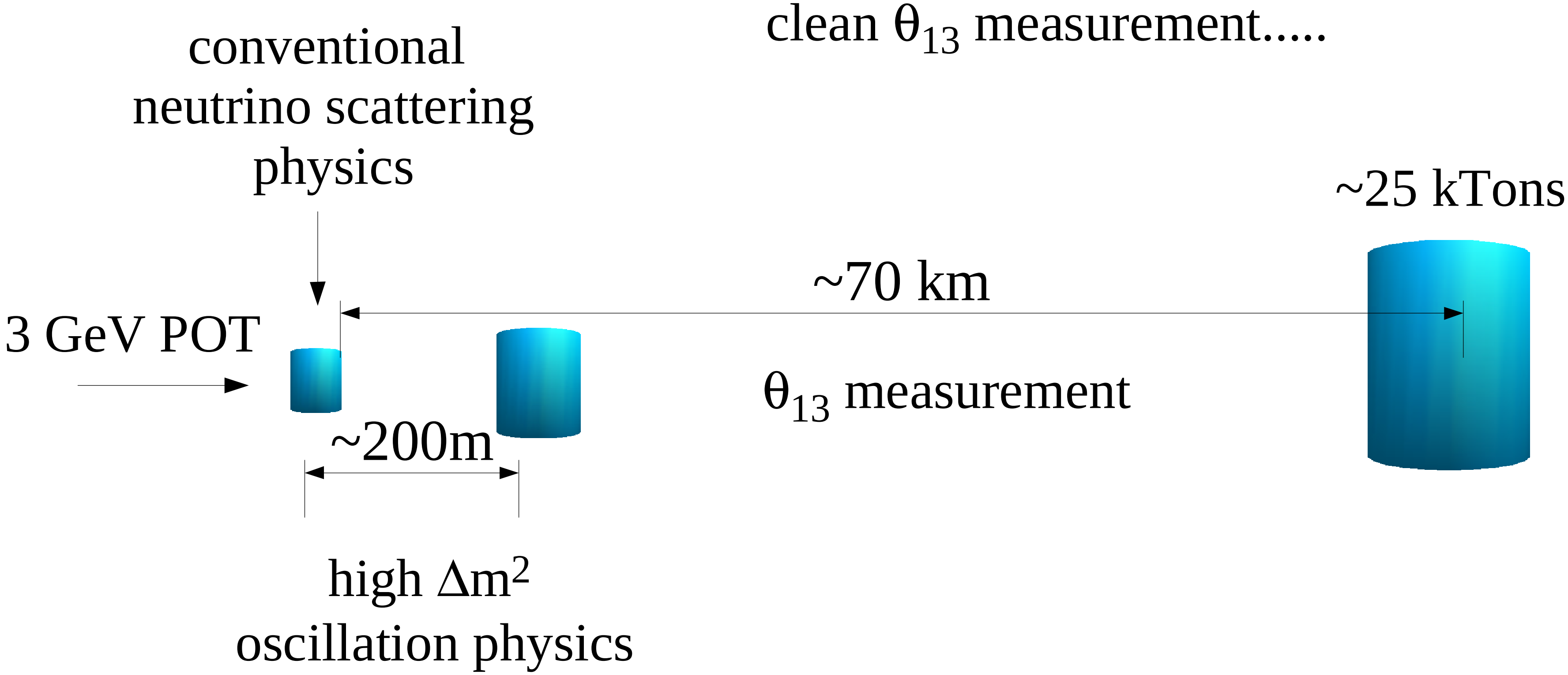
Reaction	# ν_μ events (1 × 10^{20} POT, per ton detector)
CC QE, $\nu_\mu n \to \mu^- p$	267
NC EL, $\nu_\mu N \to \nu_\mu N$	123
CC π^+, $\nu_\mu p \to \mu^- p \pi^+$	34
CC π^0, $\nu_\mu n \to \mu^- p \pi^0$	6
CC π^+, $\nu_\mu n \to \mu^- n \pi^+$	3
NC π^0, $\nu_\mu p \to \nu_\mu p \pi^0$	6
NC π^+, $\nu_\mu p \to \nu_\mu n \pi^+$	3
NC π^0, $\nu_\mu n \to \nu_\mu n \pi^0$	5
NC π^-, $\nu_\mu n \to \nu_\mu p \pi^-$	3
CC DIS, $\nu_\mu N \to \mu^- X$	0
NC DIS, $\nu_\mu N \to \nu_\mu X$	0
CC coh π^+, $\nu_\mu A \to \mu^- A \pi^+$	8
NC coh π^0, $\nu_\mu A \to \nu_\mu A \pi^0$	6
other	0
total	464

3 GeV beam = no π production

Get rid of main background in ν_e appearance searches

rates are lower..... statistics increase when L decreases

no π^0 background $\rightarrow$ clean near detector measurements
clean SBL measurements
clean θ_{13} measurement.....

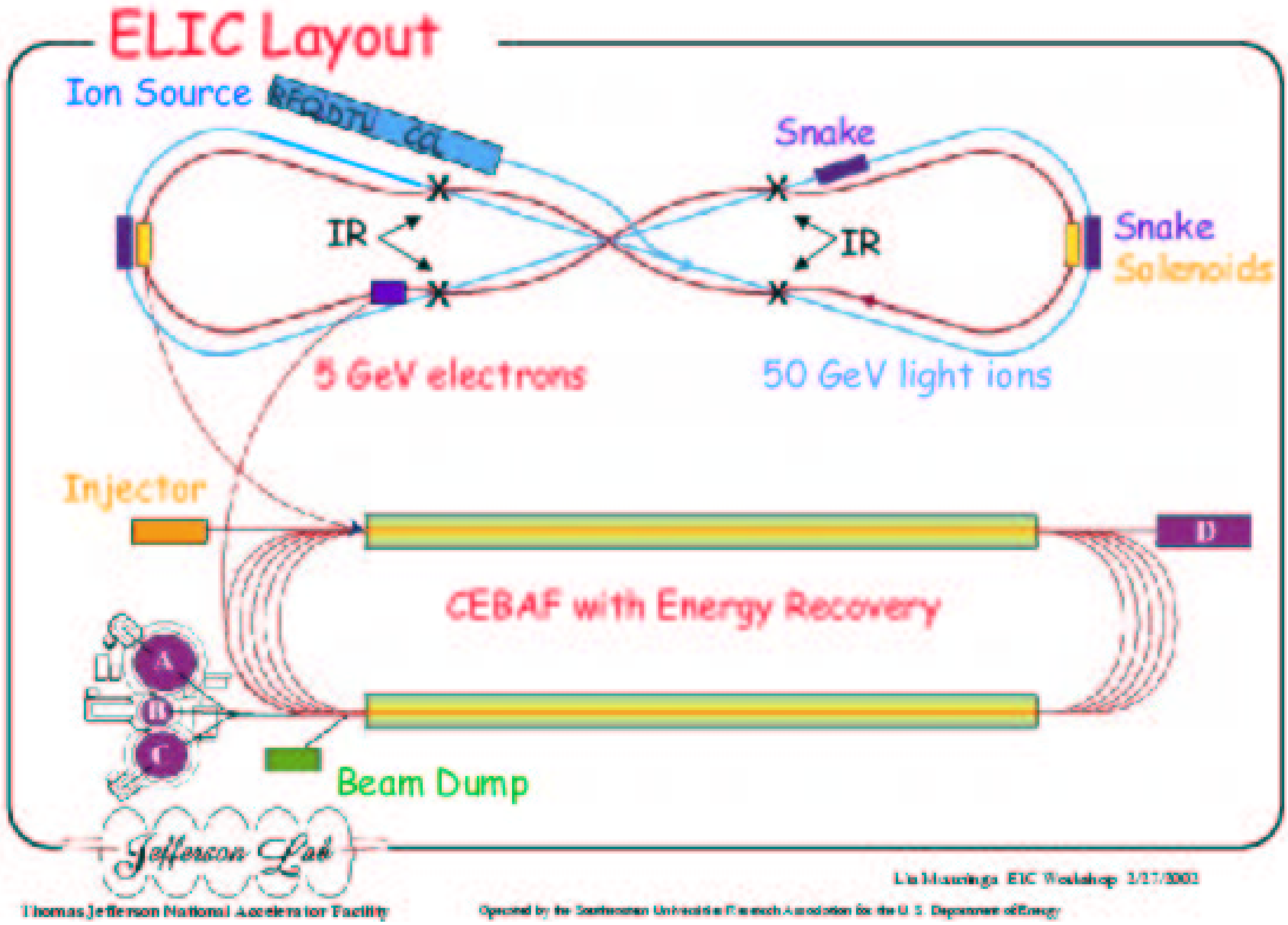


$\longrightarrow$ with x 10 statistics from BNL Booster
measure $\sin^2 2\theta_{13}$

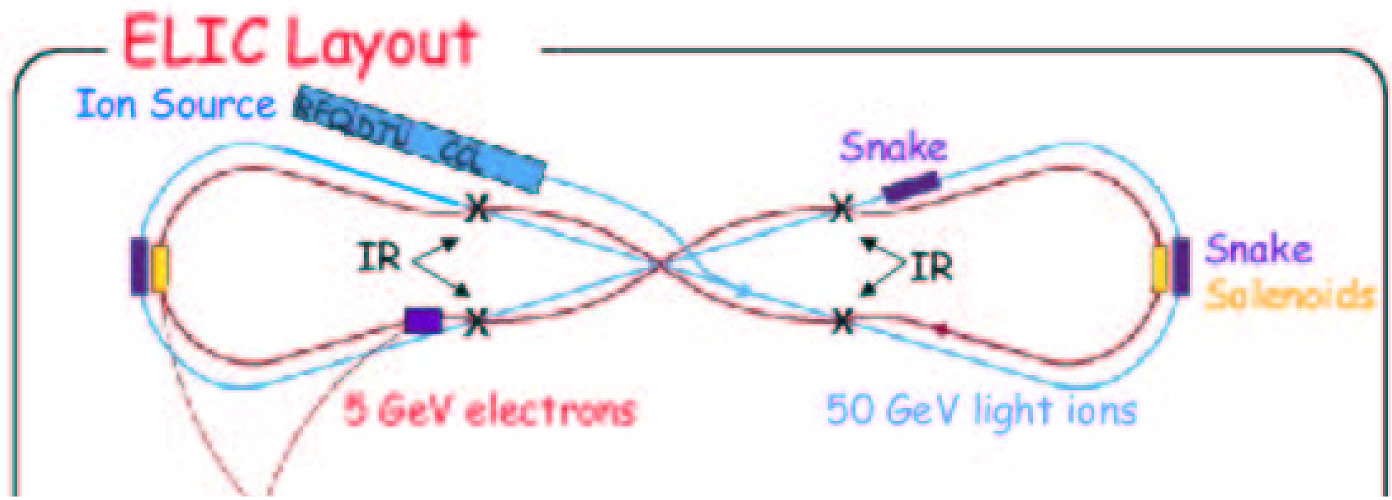
- VERY new idea
- need 3 GeV high intensity BNL Booster

Neutrino beam program at JLab:

- parasitic running of neutrino SB program off ELIC booster
- beta beams along arms of ELIC collider rings



Analogous idea to running AGS for a neutrino program while it is a feeder for RHIC and eRHIC



Injectors for 50 GeV light ion (protons up to Argon) ring:

- 200 MeV LINAC
- 10+ GeV, 10-30 Hz Booster
  - → would sit idle during 10+ hour collider store

Pros:
10^{22} POT/year
good LBL lengths
in design stage

Cons:
small site
in design stage

Neutrino session at upcoming EIC workshop at JLAB to explore these ideas

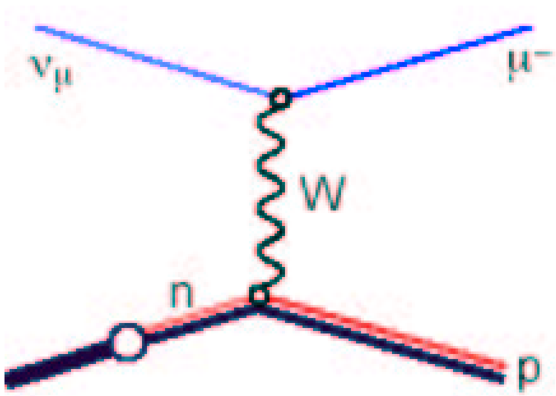
Cross section measurements important for the next generation of neutrino physics experiments

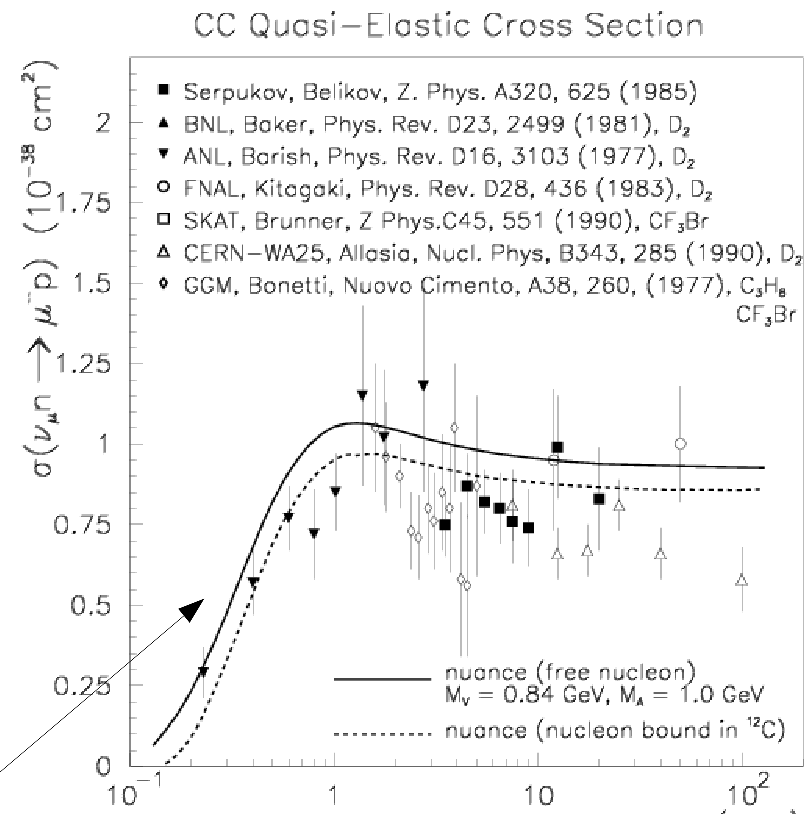
- ➔ ν_μ CCQE cross section
- ➔ Neutral current π^0 production
- ➔ Charged current single π channels

*To what precision do
we need to know these for
the next generation of short
and long baseline
measurements?*

*where will we measure
them?*

ν_μ CCQE cross section





Sam Zeller

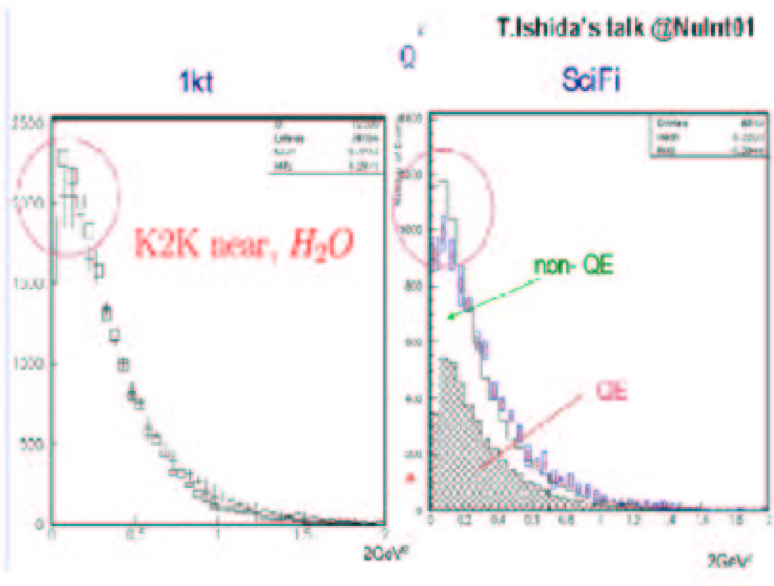
Uncertainties in the .5 - 10 GeV

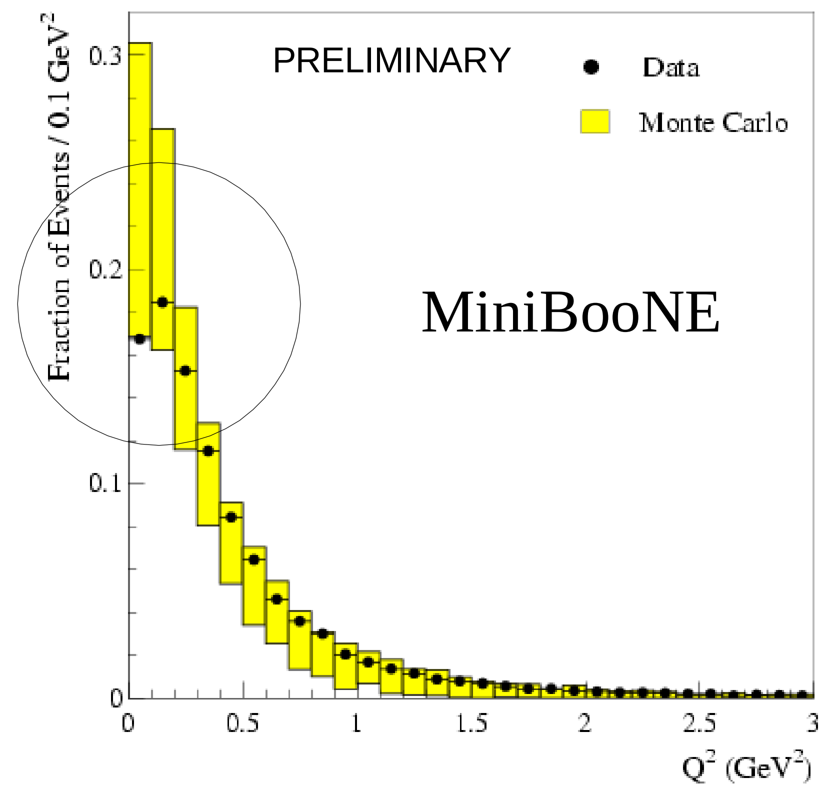
no heavy target data at low E_ν

Important right now for oscillation measurements

Turnover at low Q^2?

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





Could be a "nuclear effect"

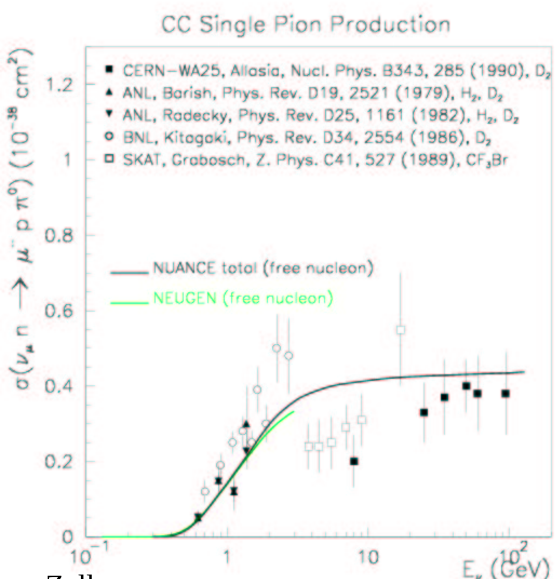
- too large to be explained by Pauli Blocking
- At NuInt03 problem was "fixed" by changing M_A by 10% (unphysical)
- Other nuclear models?

Need to understand this for oscillation measurements!!!

The "M_A fix" lowered the expected QE σ in the energy-region where SK is most sensitive (a significant source of the recent Δm^2 change)

Measure single π cross sections: backgrounds for

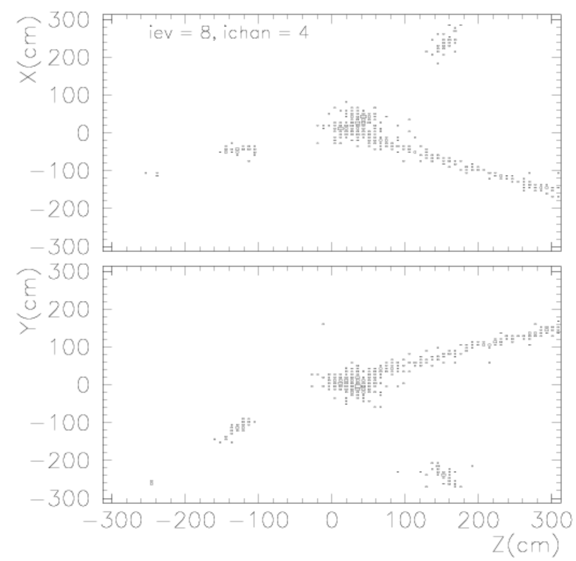
- CCQE samples
- ν_e appearance samples



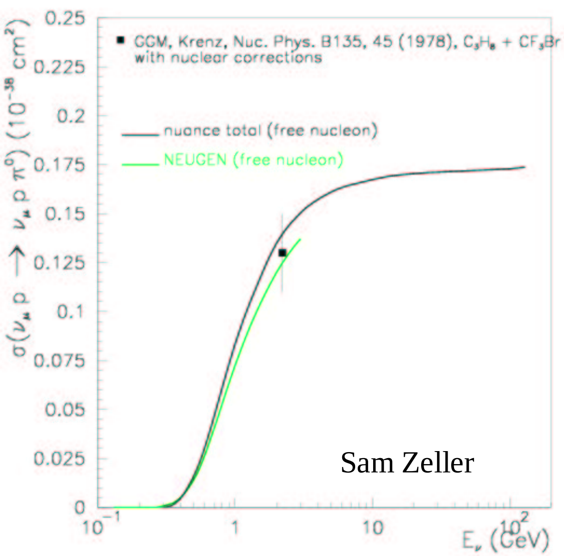
Sam Zeller

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

in
FINeSSE
fine-grained
scibath
detector



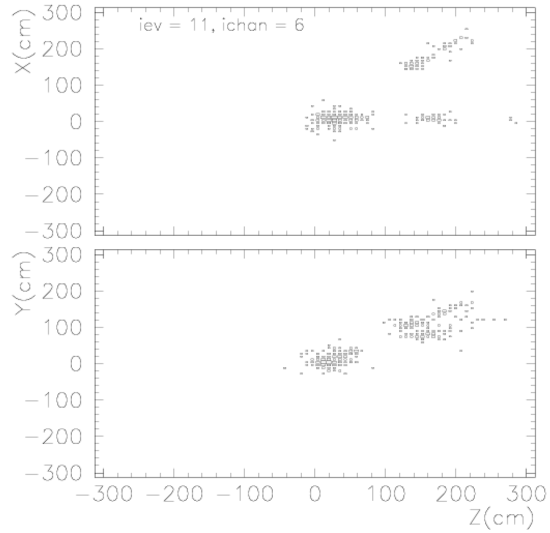
NC π^0 production: dominant background in $\nu_\mu \rightarrow \nu_e$ oscillation searches



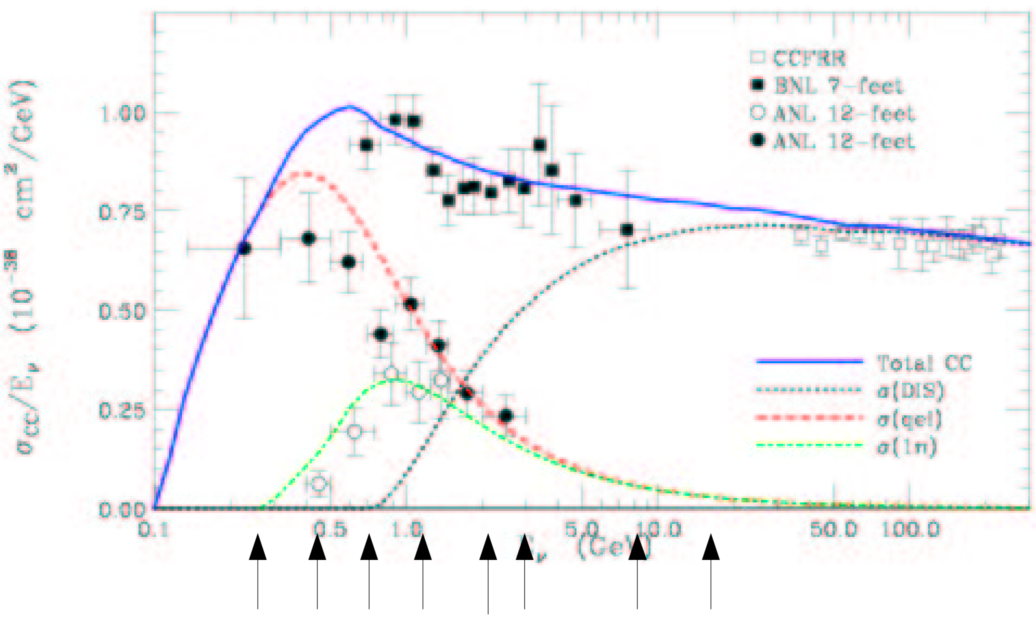
$\nu_\mu p \rightarrow \nu_\mu p \pi^0$

very little NC single pion production data

in FINeSSE scibath detector



how well do we need to know these for oscillation measurements?

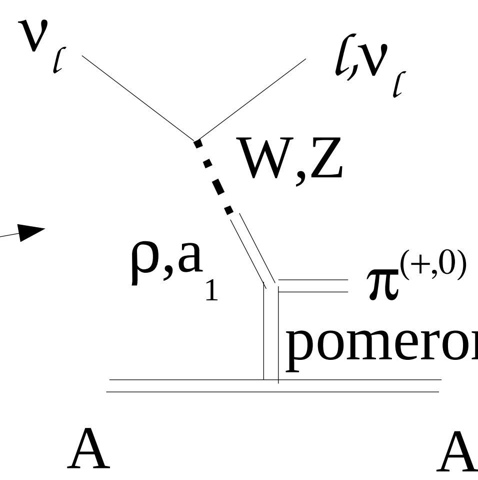


measure flux averaged cross section for each energy spectrum

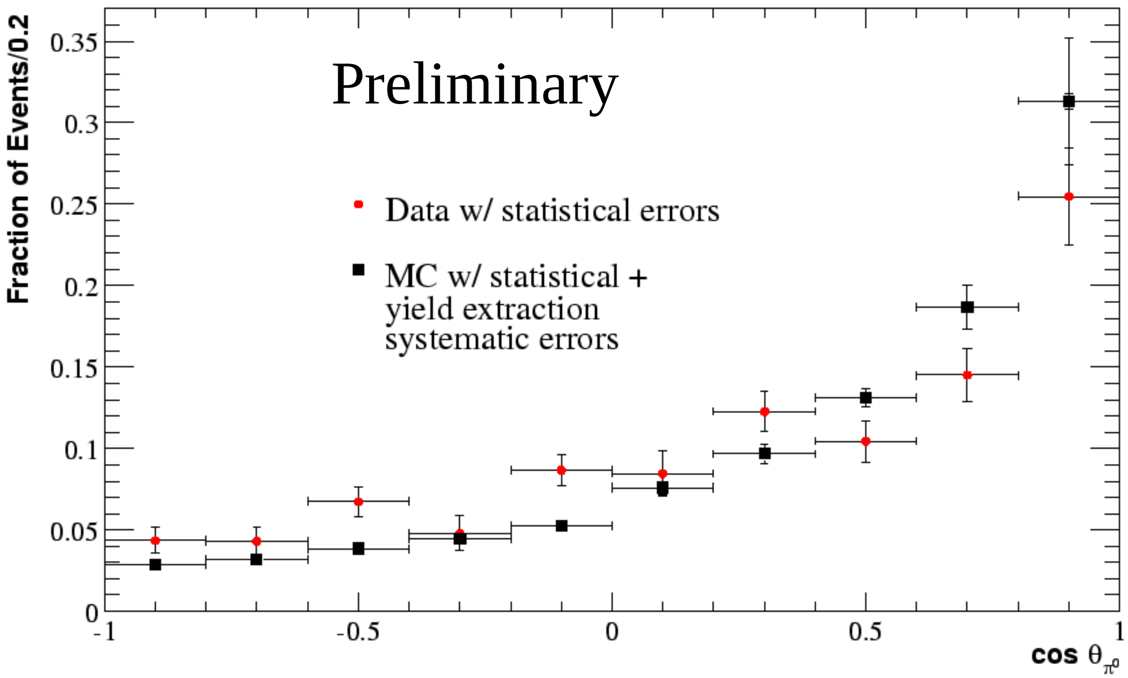
Coherent pion production

NC or CC production

5% of total cross section



signature: very forward final state pion



Angular distribution of MiniBooNE π^0 sample

- Consistent with recent K2K data (LP '03)
- Consistent with models with less coherent production

Physics at short baselines

- Neutrino Scattering physics
  - Cross section measurements for next generation neutrino experiments
  - **Form factor measurements**
  - **DIS measurements**
  - **$\sin^2\theta_W$ measurement**
  - **pentaquark searches and strangeness**
  - **neutrino magnetic moment searches**

← conventional neutrino scattering physics

- Impact on astrophysics
- Other things?

Low Q^2: Measure $G_A^S\ (Q^2=0)=\Delta s$

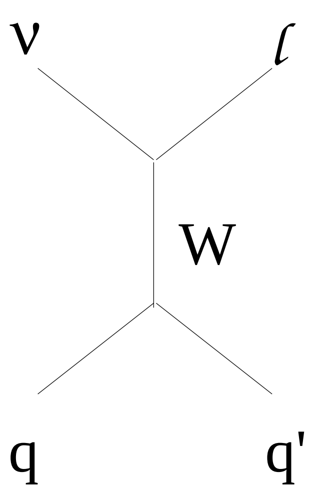
(Δs: the strange quark contribution to the nucleon spin)

This will address a fundamental aspect of nucleon structure:

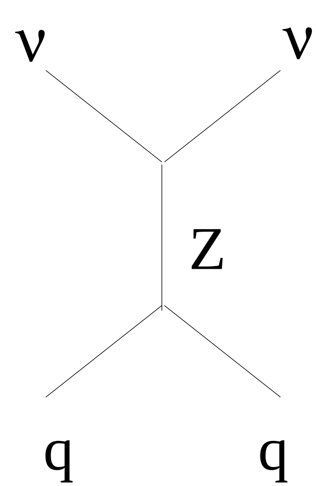
- What carries the nucleon spin! valence quarks, sea quarks, gluons?
- Can we describe the proton in terms of a fundamental theory?

These are still open questions!

⟶ Δs is important for certain dark matter searches where the neutralino-nucleus cross section depends on quark spins.



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



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

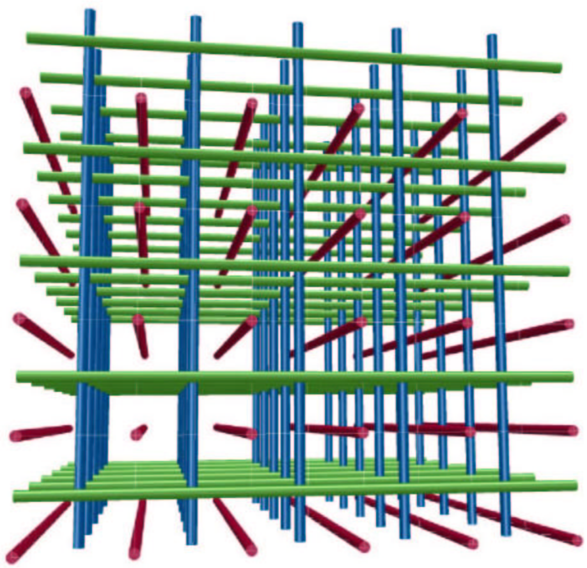
Difficult to measure $\nu p \rightarrow \nu p$ with large flux uncertainties:
measure the ratio $\nu p \rightarrow \nu p / \nu n \rightarrow \mu p$

Detector Requirements

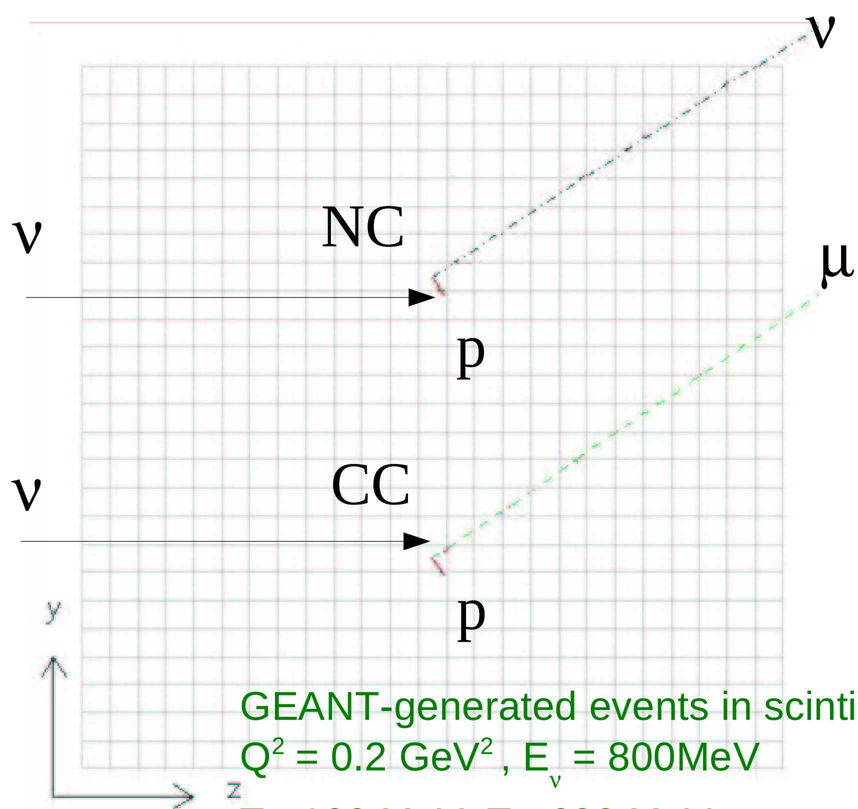
To measure Δs with error ≤ 0.04, need R(NC/CC) to ~5%

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

- Need a large, low-threshold, FULLY ACTIVE, homogeneous tracking "vertex" detector

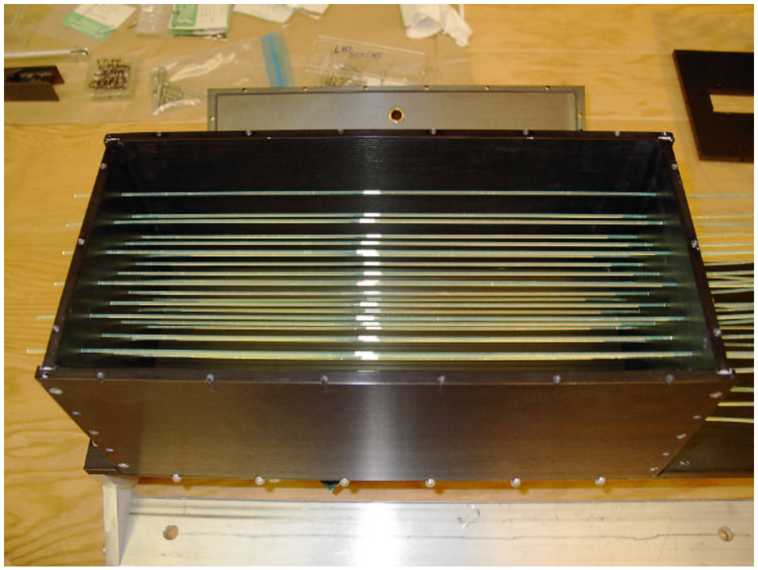


WLS fibers in vertex detector



GEANT-generated events in scintillator: $Q^2 = 0.2\ \mathrm{GeV}^2$, $E_\nu = 800\mathrm{MeV}$

$T_p \sim 100$ MeV, $T_\mu \sim 600$ MeV



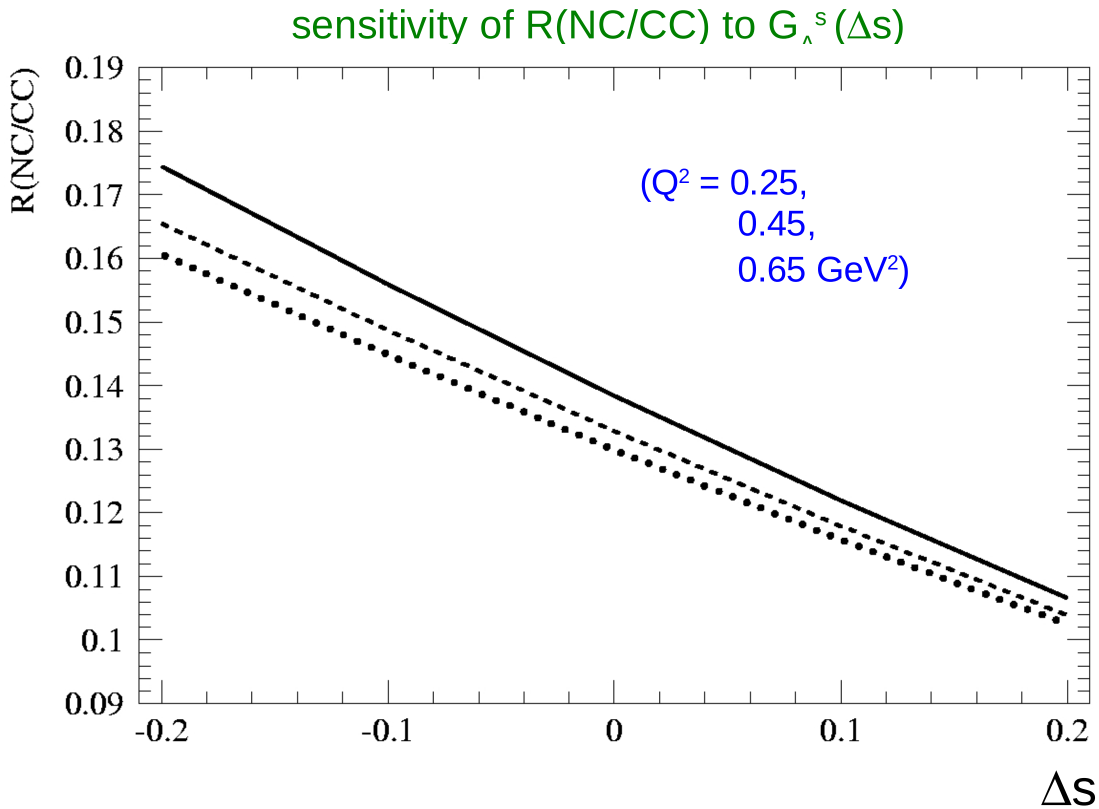
Difficult to measure $\nu p \rightarrow \nu p$ with large flux uncertainties:
measure the ratio $\nu p \rightarrow \nu p / \nu n \rightarrow \mu p$

→ Sensitivity of R(NC/CC) to Δs

FINeSSE will measure this ratio to...

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

big improvement over previous neutrino measurements of Δs



more improvements....

→ go to low energies (3 GeV BNL beam) for clean measurement

→ detector with better resolution→better neutron detection (ie: LAr TPC)

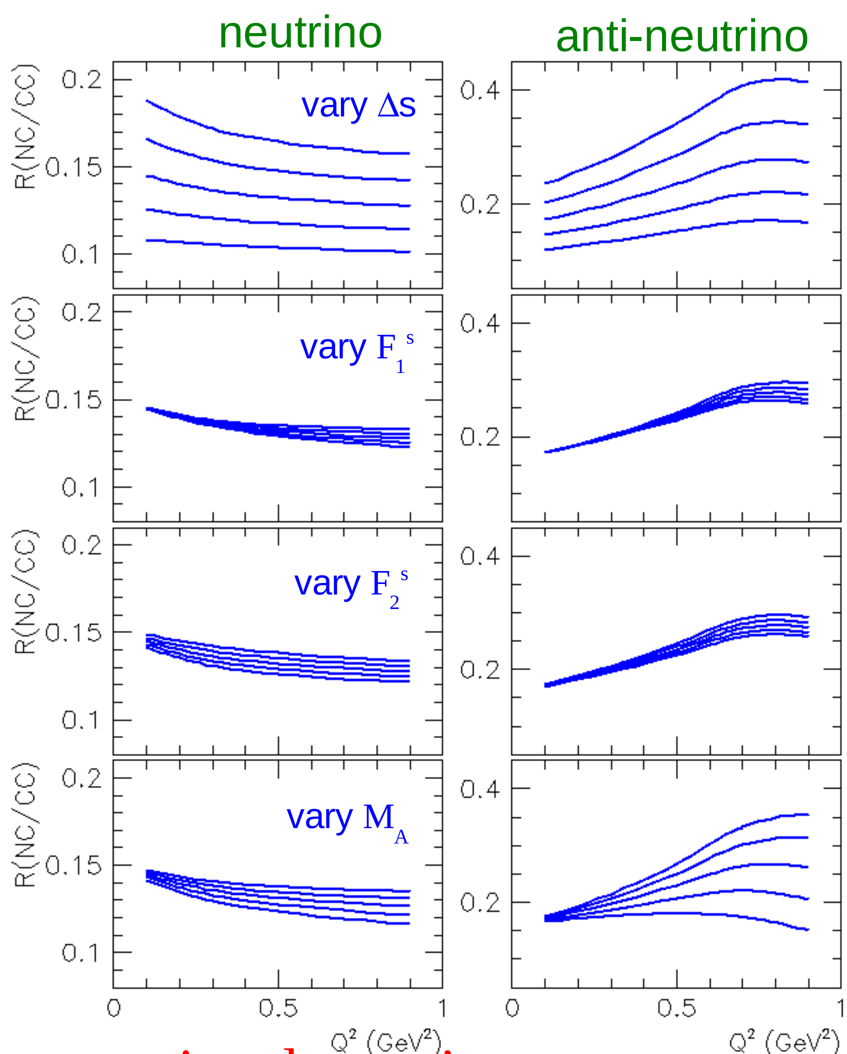
ν vs $\bar{\nu}$ running allows for sensitivity to Δs and other form factors

R(NC/CC) vs Q^2 for ν and $\bar{\nu}$ with different values of F_1^s, F_2^s, G_A^s, M_A

- anti-neutrino R(NC/CC) event more sensitive to Δs

- sensitivity to other f.f.s smaller than to Δs

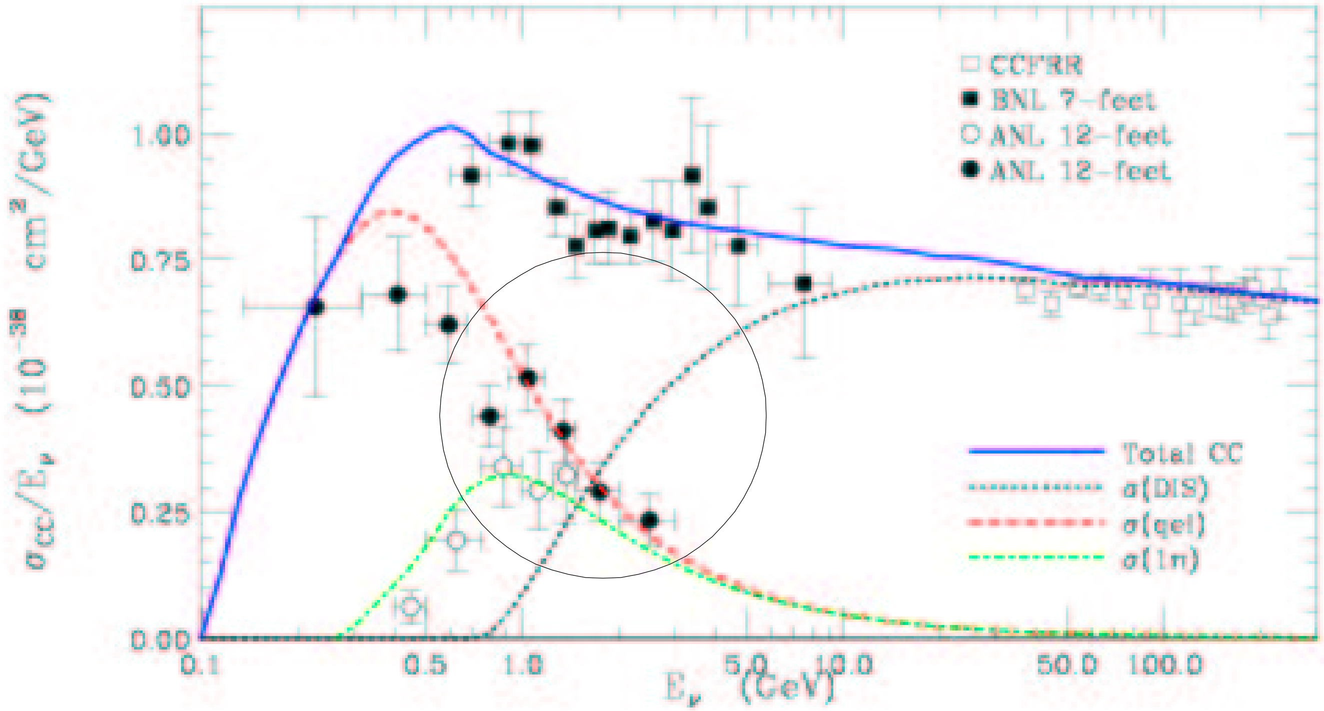
- but, with a complete data set (neutrino and antineutrino running over range of Q^2) would allow an extraction of all strange form-factors (F_1^s, F_2^s, G_A^s, M_A)

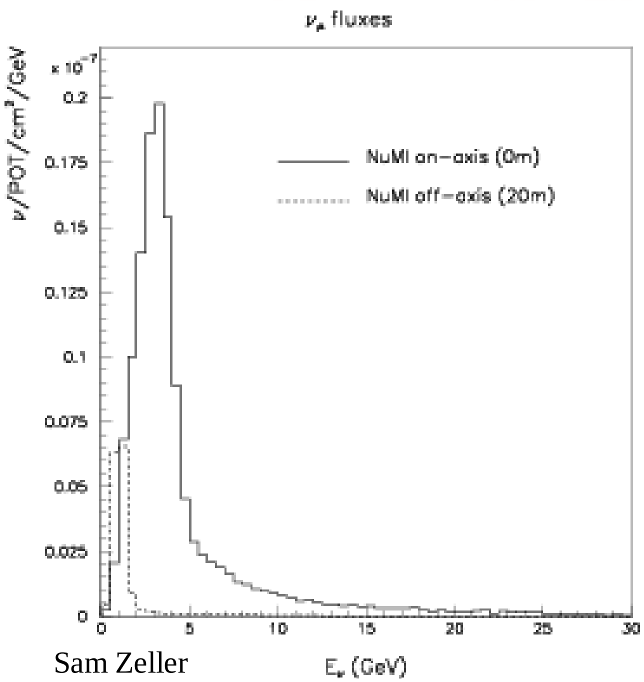


takes a long time at conventional neutrino sources...
Improvements with Superbeams?

Cross sections at higher energies

MINERvA Experiment





Sam Zeller

NuMI low energy on axis and off axis fluxes

above where DIS turns on

ν Reaction	on-axis NuMI 10^{20} POT, 1 ton	Booster $100\,m, 25\,m$ abs 10^{20} POT, 1 ton	off-axis NuMI (20 m) 10^{20} POT, 1 ton
CC QE, $\nu_\mu n \to \mu^- p$	7,502	2,715	744
NC EL, $\nu_\mu N \to \nu_\mu N$	2,878	1,096	287
CC π^+, $\nu_\mu N \to \mu^- N \pi^+$	11,672	1,451	622
CC π^0, $\nu_\mu n \to \mu^- p \pi^0$	2,672	258	111
NC π^0, $\nu_\mu N \to \nu_\mu N \pi^0$	2,698	369	130
NC π^+, $\nu_\mu p \to \nu_\mu n \pi^+$	1,169	125	48
NC π^-, $\nu_\mu n \to \nu_\mu p \pi^-$	962	98	37
CC DIS, $\nu_\mu N \to \mu^- X$	31,771	80	547
NC DIS, $\nu_\mu N \to \nu_\mu X$	11,132	37	197
CC coh π^+, $\nu_\mu A \to \mu^- A \pi^+$	1,181	160	64
NC coh π^0, $\nu_\mu A \to \nu_\mu A \pi^0$	619	98	34
other	6,608	117	151
total	80,864	6,604	2,972

Sam Zeller

high event rate
lots of DIS

Physics Goals with MINERvA beam

- Quasi-elastic ($\nu + n \dashrightarrow \mu^- + p$, 300 K events off 3 tons CH)
  - Precision measurement of $\sigma(E_\nu)$ and $d\sigma/dQ$ important for neutrino oscillation studies.
  - Precision determination of axial vector form factor (F_A), particularly at high Q^2
  - Study of proton intra-nuclear scattering and their A-dependence (C, Fe and Pb targets)

- Resonance Production (e.g. $\nu + N \dashrightarrow \nu / \mu^- + \Delta$, 600 K total, 450K 1π)
  - Precision measurement of σ and $d\sigma/dQ$ for individual channels
  - Detailed comparison with dynamic models, comparison of electro- & photo production, the resonance-DIS transition region -- duality
  - Study of nuclear effects and their A-dependence e.g. $1\pi \longleftrightarrow 2\pi \longleftrightarrow 3\pi$ final states
- Coherent Pion Production ($\nu + A \dashrightarrow \nu / \mu^- + A + \pi$, 25 K CC / 12.5 K NC)
  - Precision measurement of $\sigma(E)$ for NC and CC channels
  - Measurement of A-dependence
  - Comparison with theoretical models

from H. Gallagher

Physics Goals cont.

- Nuclear Effects (C, Fe and Pb targets)
  - Final-state intra-nuclear interactions. Measure multiplicities and E_{vis} off C, Fe and Pb.
  - Measure NC/CC as a function of E_H off C, Fe and Pb.
  - Measure shadowing, anti-shadowing and EMC-effect as well as flavor-dependent nuclear effects and extract nuclear parton distributions.

- MINERνA and Oscillation Physics
  - MINERνA measurements enable greater precision in measure of Δm, $\sin^2\theta_{23}$ in MINOS
  - MINERνA measurements important for θ_{13} in MINOS and off-axis experiments
  - MINERνA measurements as foundation for measurement of possible CP and CPT violations in the ν–sector

- σ_T and Structure Functions (2.8 M total /1.2 M DIS events)
  - Precision measurement of low-energy total and partial cross-sections
  - Understand resonance-DIS transition region - duality studies with neutrinos
  - Detailed study of high-x_{Bj} region: extract pdf's and leading exponentials over 1.2M DIS events

from H. Gallagher

Physics Goals cont.

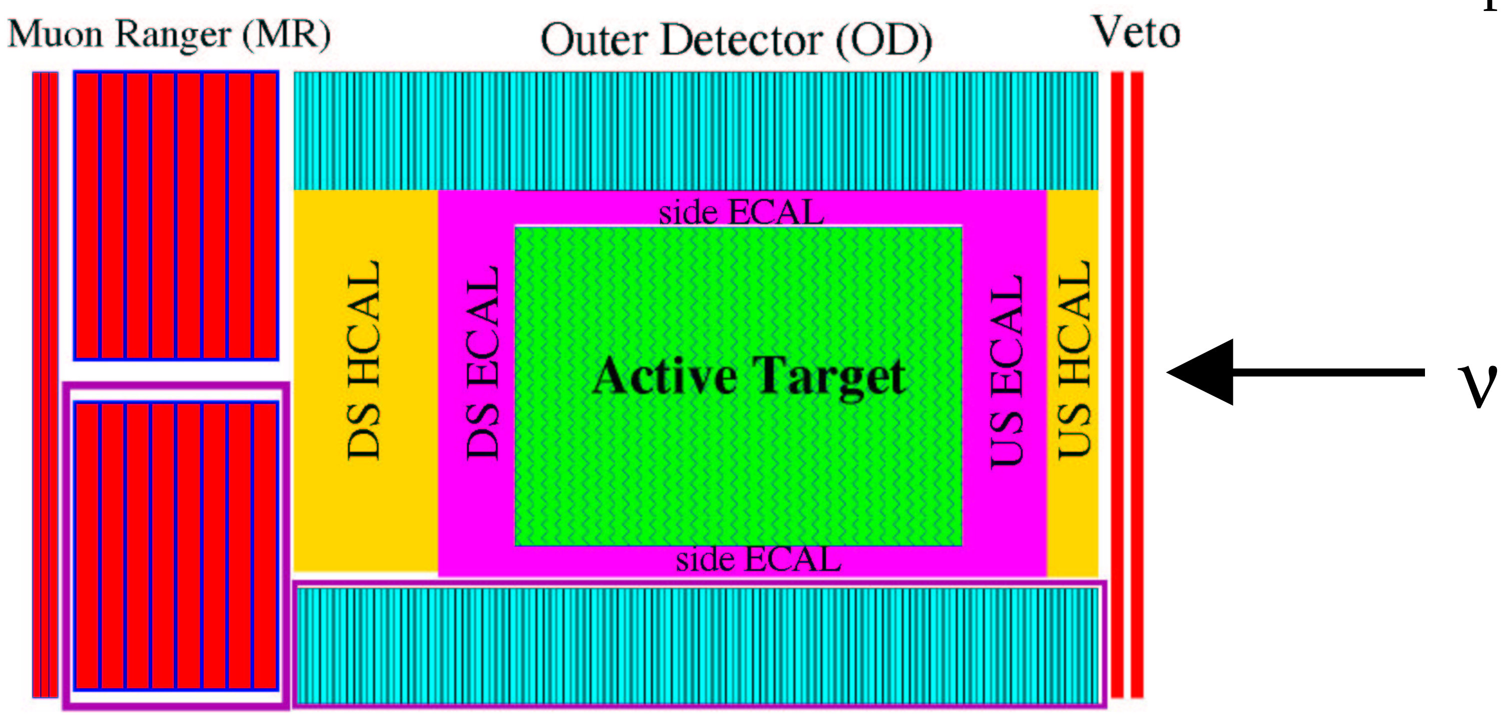
- Strange and Charm Particle Production (> 60 K **fully** reconstructed exclusive events) -
  - Exclusive channel $\sigma(E_\nu)$ precision measurements - importance for nucleon decay background studies.
  - Statistics sufficient to reignite theorists attempt for a predictive phenomenology
  - Exclusive charm production channels at charm threshold to constrain m_c
- Generalized Parton Distributions (few K events)
  - Provide unique combinations of GPDs, not accessible in electron scattering (e.g. C-odd, or valence-only GPDs), to map out a precise 3-dimensional image of the nucleon. MINERνA would expect a few K signature events in 4 years.
  - Provide better constraints on nucleon (nuclear) GPDs, leading to a more definitive determination of the orbital angular momentum carried by quarks and gluons in the nucleon (nucleus)
  - provide constraints on axial form factors, including transition nucleon --> N* form factors

from H. Gallagher

How much improvement can we get using Superbeams?
When are the measurements systematics limited?

Detector Overview

MINERvA
Experiment

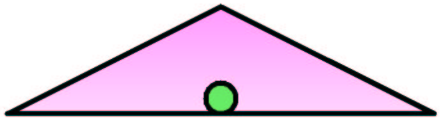


- Active target, surrounded by calorimeters
  - upstream calorimeters are Pb, Fe targets
- Magnetized side and downstream tracker/calorimeter

from K. McFarland

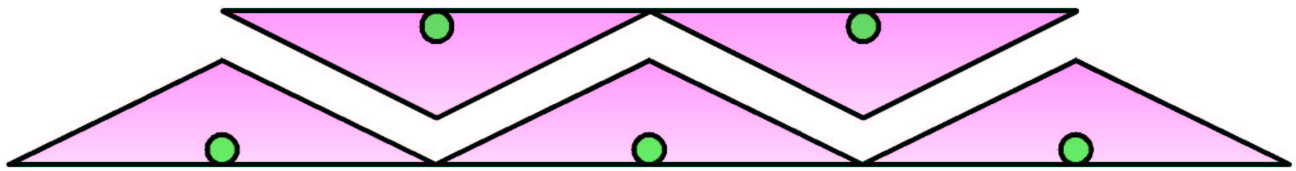
Fully-Active Target: Extruded Scintillator

MINERvA Experiment

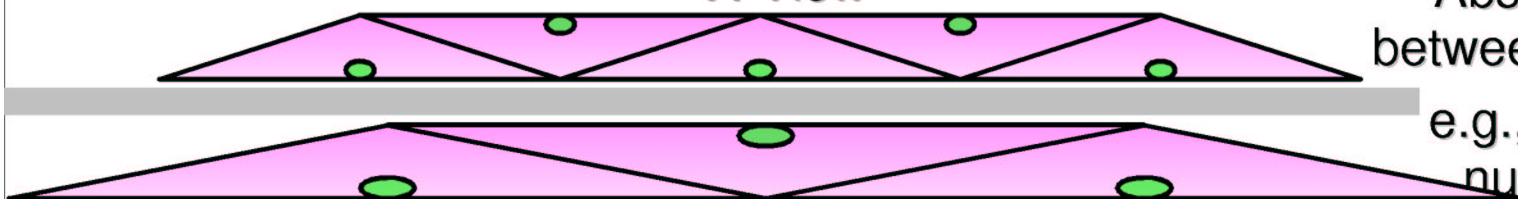


Basic element: 1.7x3.3cm triangular strips.
1.2mm WLS fiber readout in grove at bottom

Assemble into planes



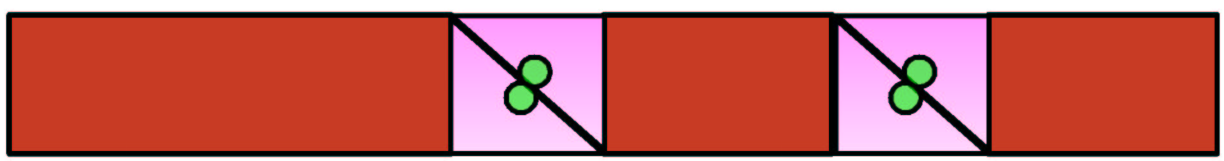
X-View



U/V-View

Absorbers between planes
e.g., E- or H-CAL, nuclear targets

Or replace strips with absorber (outer detector)



from K. McFarland

→ detection technology being considered for T2K 280m near detector

Coherent Pion Production

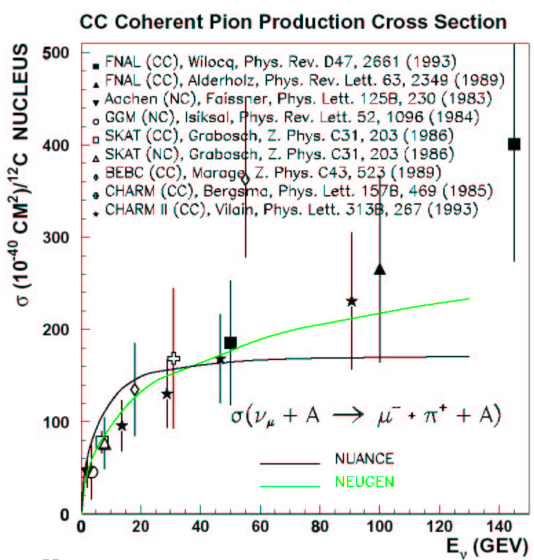
MINERνA: 25 K CC / 12.5 K NC events off C - 8.3 K CC/ 4.2 K NC off Fe and Pb

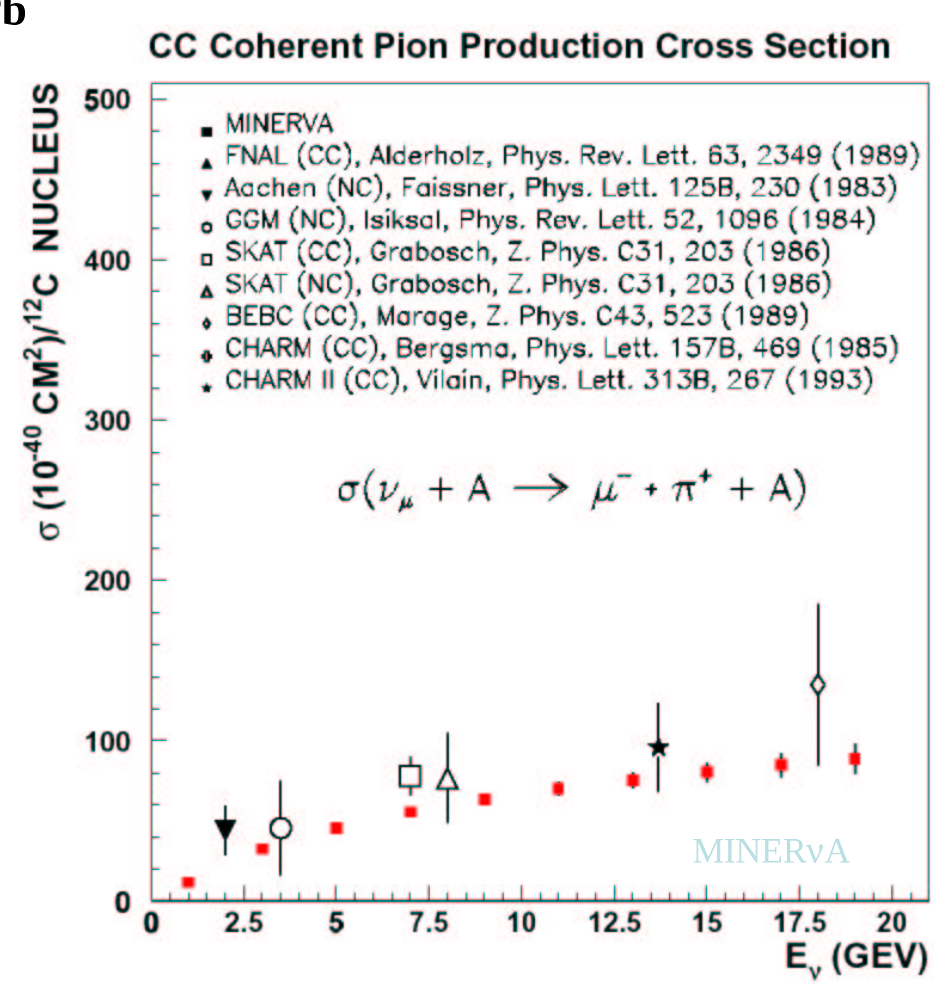
•Characterized by a small energy transfer to the nucleus, forward going π. NC (π^0 production) significant background for ν_μ --> .ν_e oscillation search

•Data has not been precise enough to discriminate between several very different models.

•Expect roughly (30-40)% detection efficiency with MINERνA.

•Can also study A-dependence with MINERνA





Sam Zeller

from Ken Hicks, Ohio University

Pentaquark searches

- *Minimum content: 4 quarks and 1 antiquark* $qqqq\bar{q}$
- *"Exotic" pentaquarks are those where the antiquark has a different flavor than the other 4 quarks*
- *Quantum numbers cannot be defined by 3 quarks alone.*

Example: $uuds\bar{s}$, non-exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

Strangeness = 0 + 0 + 0 − 1 + 1 = 0

Example: $uudd\bar{s}$, exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

Strangeness = 0 + 0 + 0 + 0 + 1 = +1

→ *Help us unfold quark dynamics in the nucleon*

Summary of Experiments

Evidence (since October 2002):

- LEPS (4.6 σ, peak at mass = 1.54 GeV)
- ITEP (4.5 σ, peak at mass = 1.539 GeV)
- CLAS γd (5.5 σ, peak at mass = 1.542 GeV)
- SAPHIR (4.8 σ, peak at mass = 1.540 GeV)
- νs -- WA21, E180 (6.7 σ, m = 1533 +/- 5 MeV)
- CLAS γp (7.8 σ, m = 1555 +/- 5 MeV)
- pK^0 from HERMES(~5 σ, m = 1527 MeV)
- 2nd one: Ξ^{--} from CERN (~8 σ, m = 1865 MeV)
- NEW: pK^0 from ZEUS (~5 σ, m = 1525 MeV)

from Ken Hicks, Ohio University

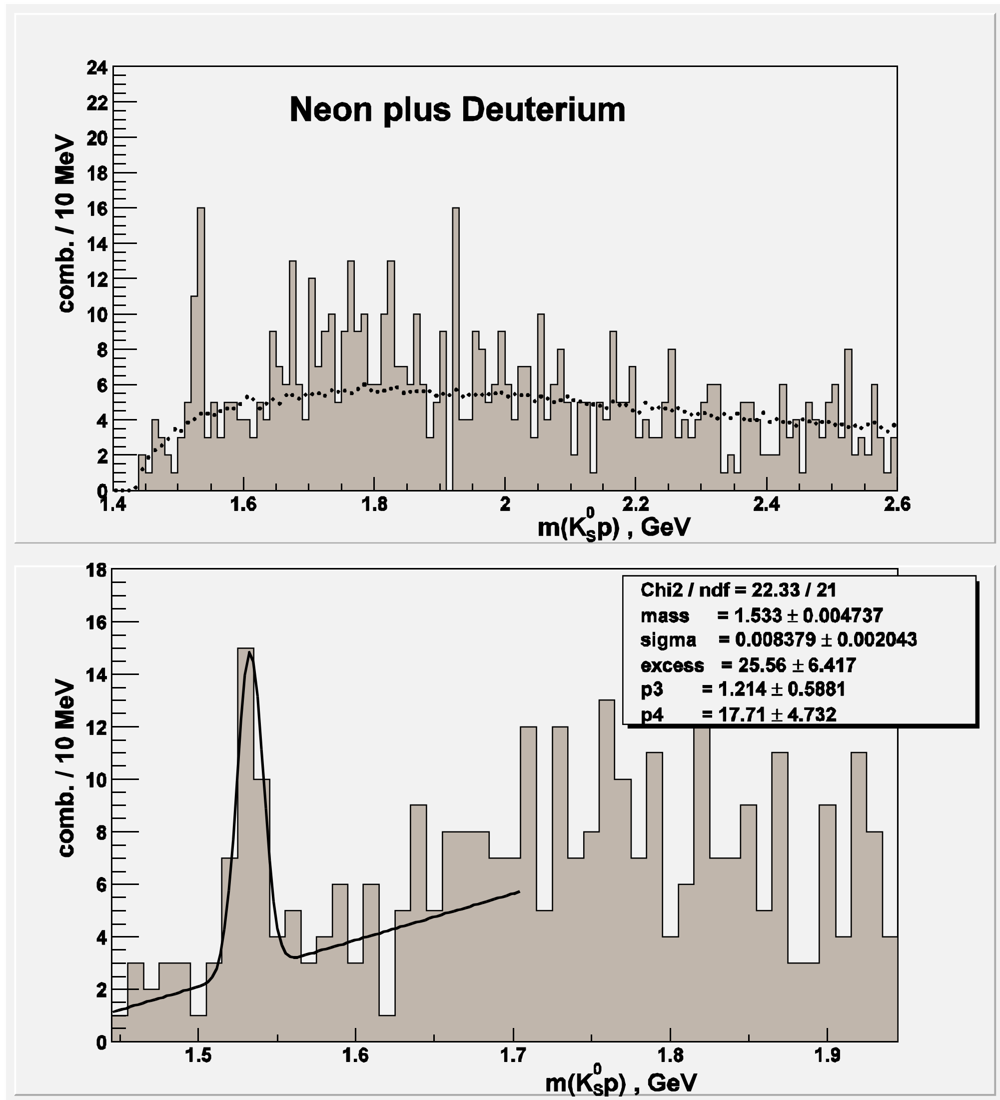
from Ken Hicks, Ohio University

Neutrino scattering

Courtesy of Dolgolenko (ITEP)

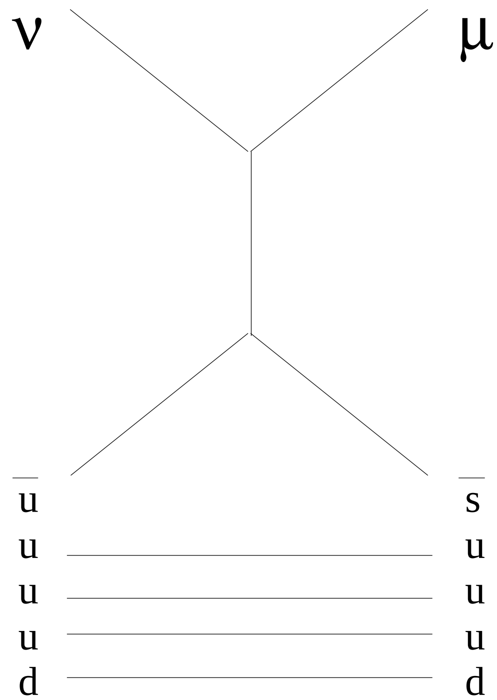
Reanalysis of bubble chamber experiments from WA21, WA25, WA59, E180, E632

$M(K_s p)$ spectrum



[illegible]

Looking for Pentaquarks using neutrinos:
understand underlying theory of nucleon dynamics



Can we see these at existing or future SBL experiments?

Using what detectors?

- final state particle separation
- energy resolution

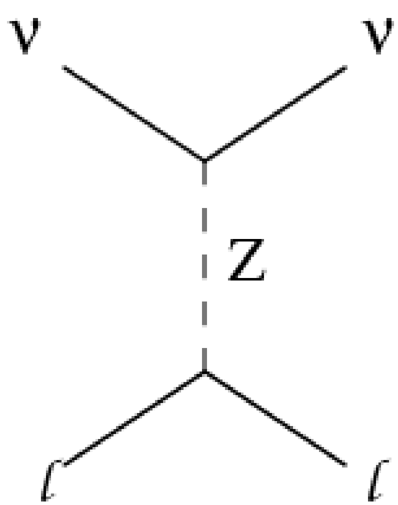
→ need fine-grained detector

What can the neutrino experiments tell us that we don't already know from other experiments?
Differentiate between theories of nuclear dynamics?

Address the NuTeV $\sin^2\theta_W$ result:

Measure $\sin^2\theta_W$ using νe elastic scattering

- very well known cross section
- no QCD uncertainties



Conventional superbeams:

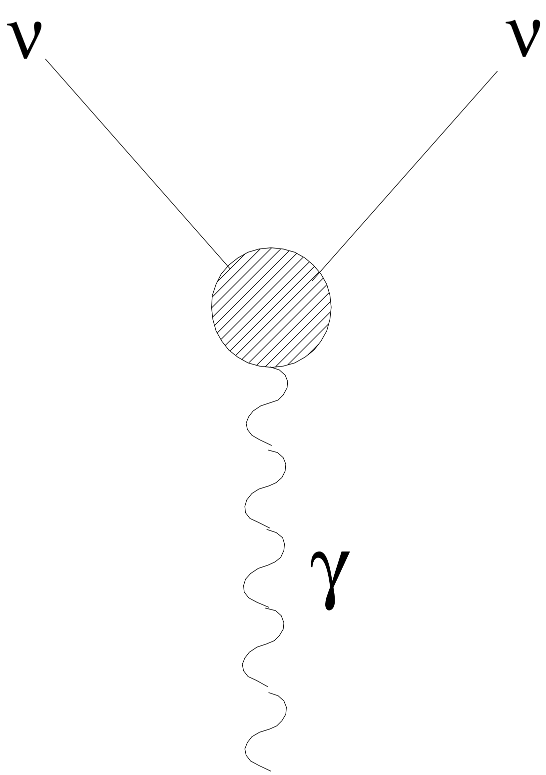
$\nu_\mu e \to \nu_\mu e$

need LOTS of statistics!

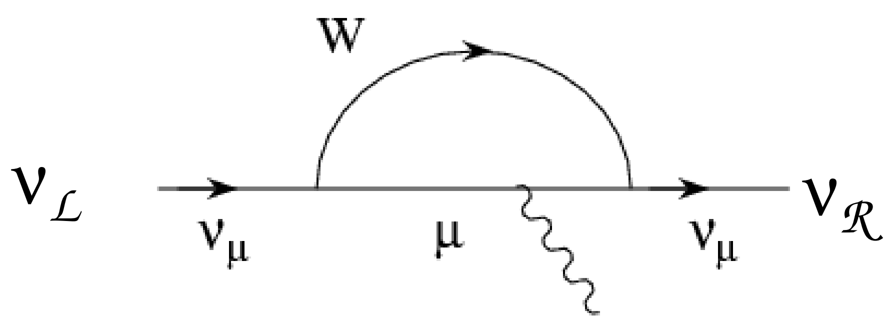
Studies have been done on this for neutrino factories (K. McFarland, B. King, J. Yu)

Difficult to do without high statistics: normalization error.....

Neutrino magnetic moment searches?



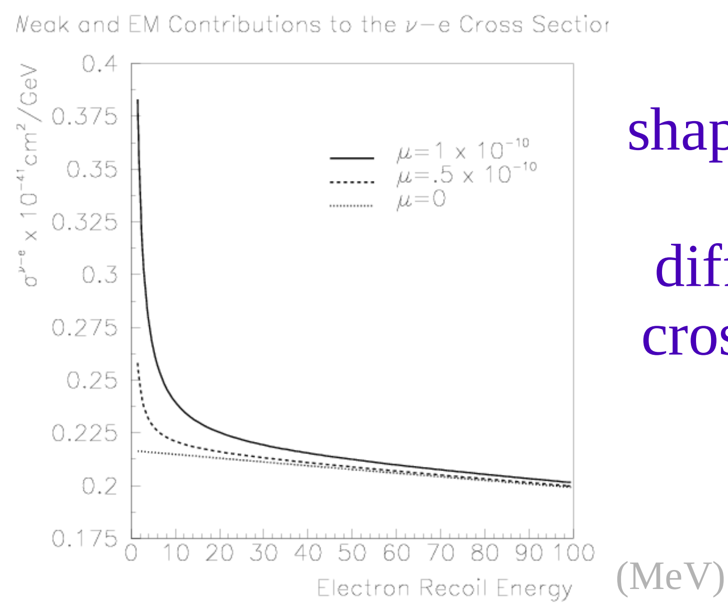
massive neutrinos imply existence of $\nu_{\mathcal{R}}$



increase in overall cross section

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

flux error a big issue!



shape change in the differential cross section

Different beyond-the-Standard-Model theories predict different sizes for this neutrino magnetic moment

Minimally Extended Standard Model

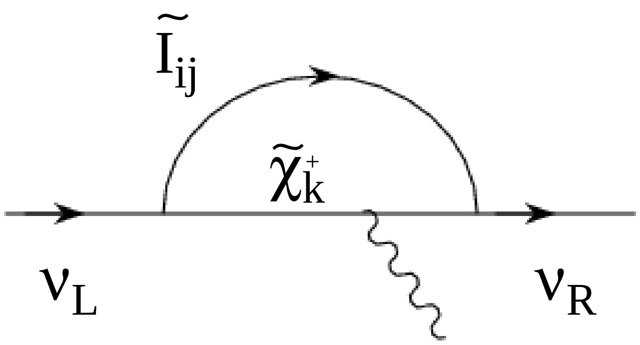
$$\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \times 10^{-19} \mu_B$$

SUSY models→left-right supersymmetric models

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

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

$$\mu_{\nu_\tau} \cong 1.9 \times 10^{-12}\ \mu_B$$



Large Extra Dimensions

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

Limits set from experiment and astrophysics:

Electron ν magnetic moment: $\mu_{\nu_e} \rightarrow 1.5 - 1.8 \times 10^{-10}\ \mu_B$

- superK data: shape of recoil electron spectrum
- reactor experiments: combined measurement

Muon ν magnetic moment: $\mu_{\nu_\mu} \leq 6.8 \times 10^{-10}\ \mu_B$

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

Tau n magnetic moment $\mu_{\nu_\tau} \leq 10^{-9}\ \mu_B$

- SuperK & SNO bounds for all neutrinos

Slow rate of plasmon decay in horizontal branching stars

$\mu_\nu \leq 10^{-11}\ \mu_B$

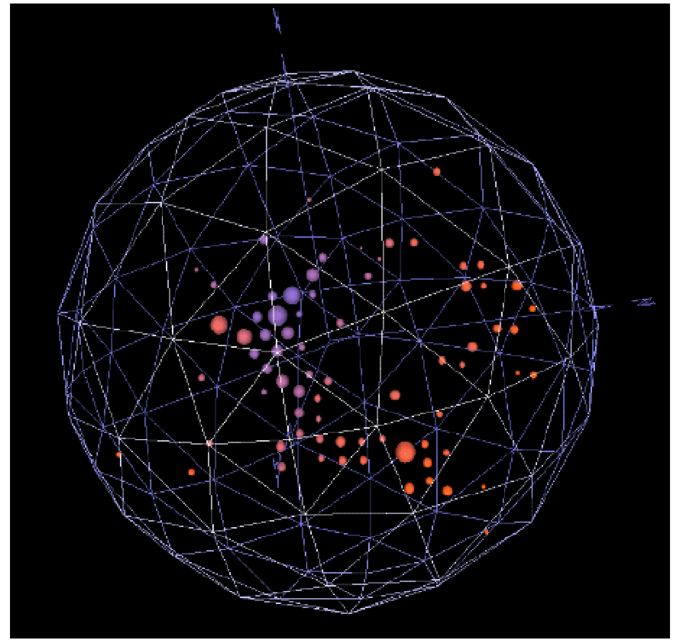
Neutrino energy loss rate from supernova 1987A

$\mu_\nu \leq 10^{-12}\ \mu_B$

Running SBL experiements
looking.....

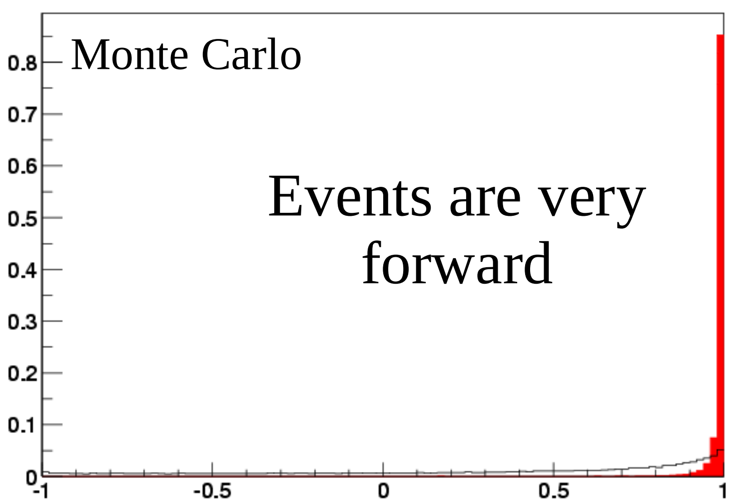
at MiniBooNE.......

$\nu_\mu e \rightarrow \nu_\mu e$
interactions
produce
clear signature
in detector

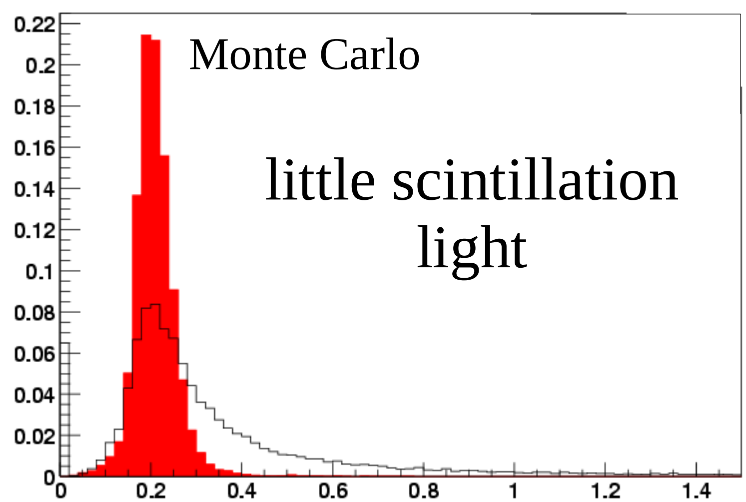


$\nu_\mu e \rightarrow \nu_\mu e$

all events



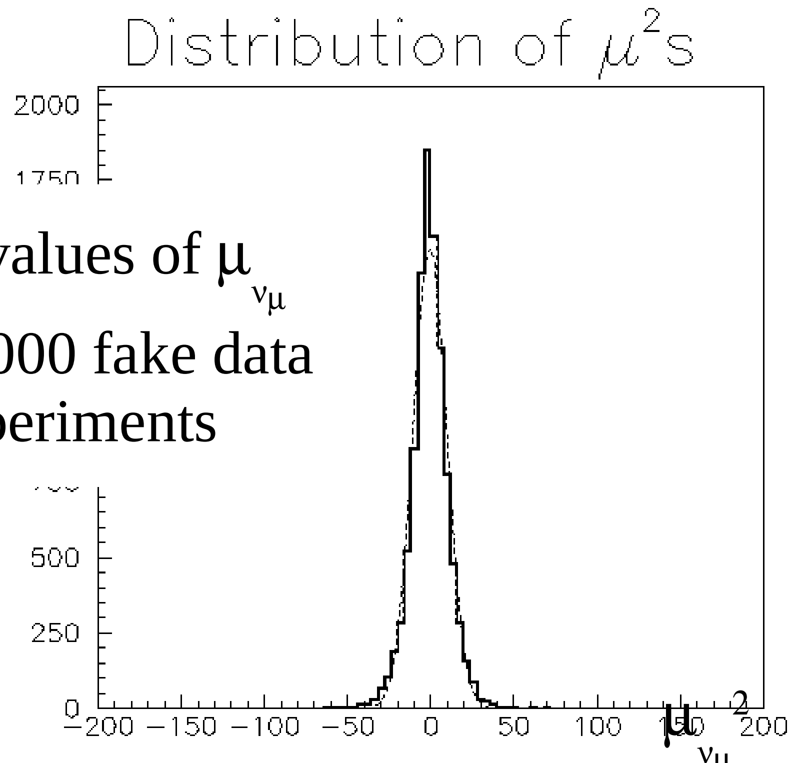
$\cos\theta_z$



$\frac{\text{Scintillation}}{\text{Cerenkov}}$

Expected MiniBooNE sensitivity to neutrino magnetic moment

for 100 νe elastic scatters with electron recoils from 10-1000 MeV
determine MiniBooNE sensitivity by
throwing events against weak cross section



fitted values of μ_{ν_μ}

for 10,000 fake data experiments

fit these data to
weak + EM cross section
to recover fit μ_ν

sensitivity:
$\mu_{\nu_\mu} = 3.2 \times 10^{-10} \mu_B$

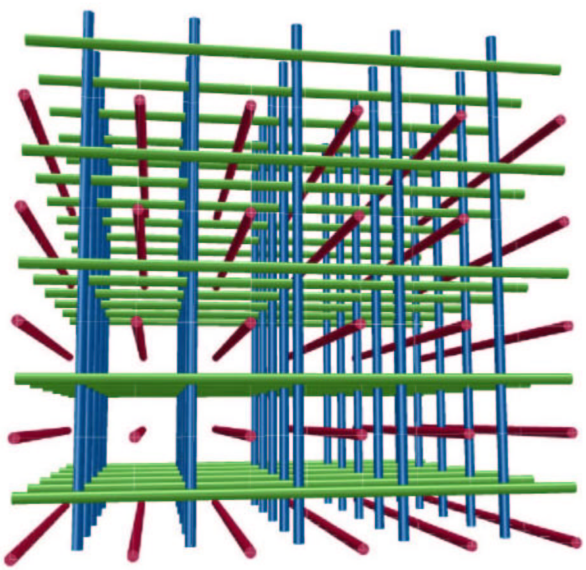
Neutrino Magnetic Moment measurements at future detectors

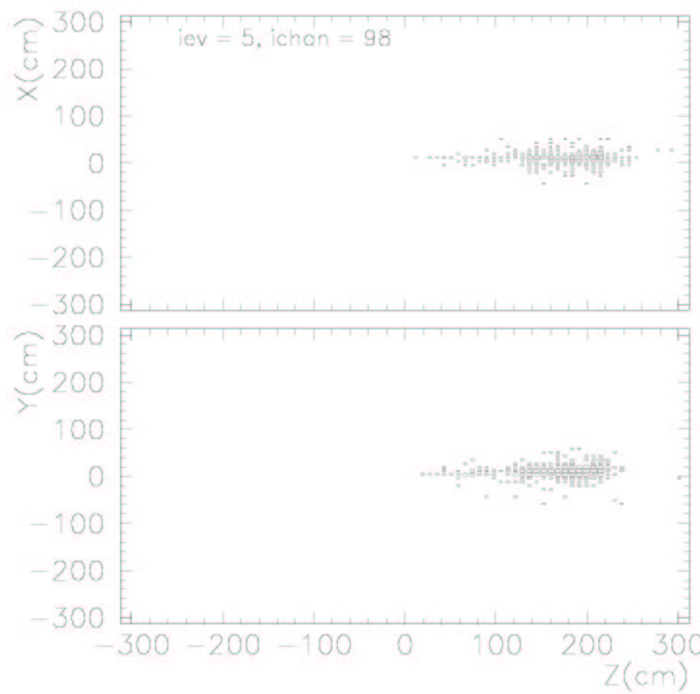
Improve measurement with

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

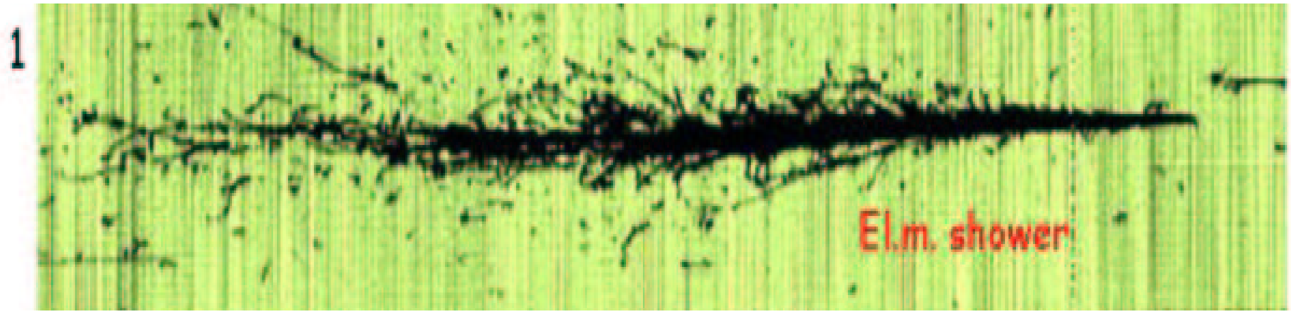
The FINeSSE Experiment:
at FNAL, JPARC, BNL.....

liquid scintillator with grid
of WLS fibers strung throughout



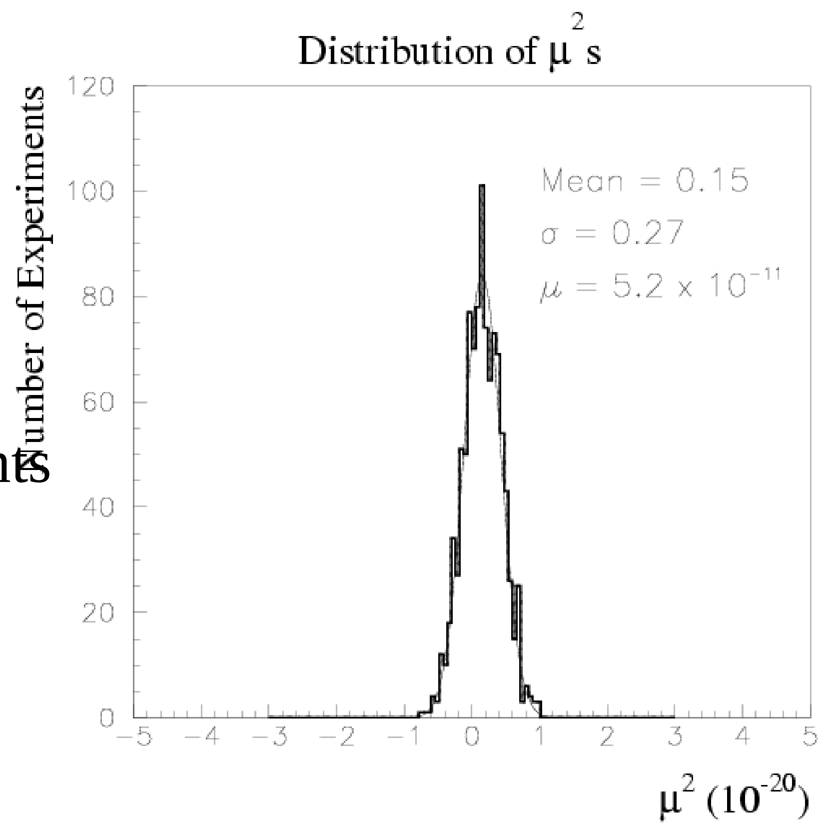


Liquid Argon TPC → energy threshold of a few MeV



With 15,000 events
(x 100 mBooNE statistics)
1 MeV electron
recoil resolution

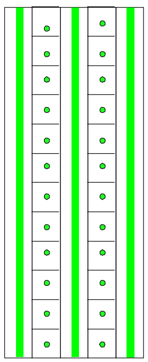
into range of magnetic moments
predicted by
Large Extra Dimensions



Detection techniques:

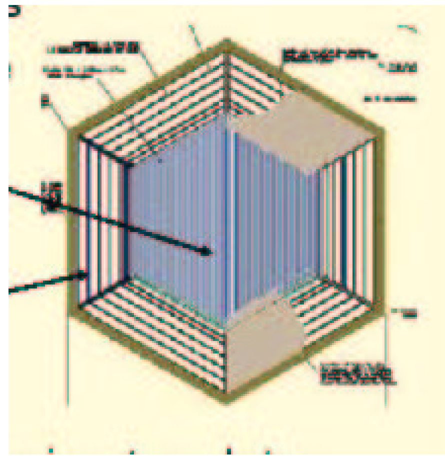
fine-grained, low threshold detectors:

SciBar



2cm x 1cm plastic scintillator bars

MINERvA

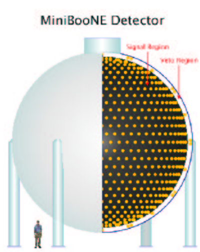


JPARC? BNL?

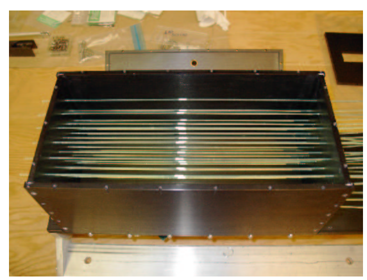
R&D under way for plastic scintillator detectors

liquid scintillator detectors?

MiniBooNE



FINeSSE



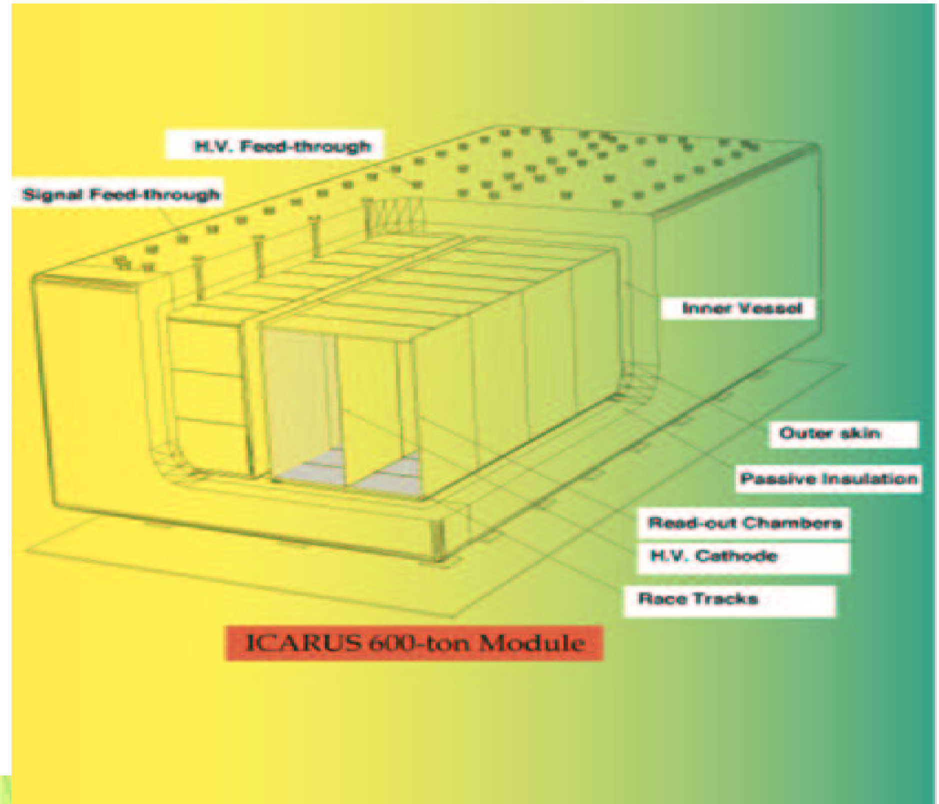
LAr TPCs ?

What detector R&D do we need to do now to prepare for the SB era?
Overlap with detection techniques at far detectors -- testing ground...

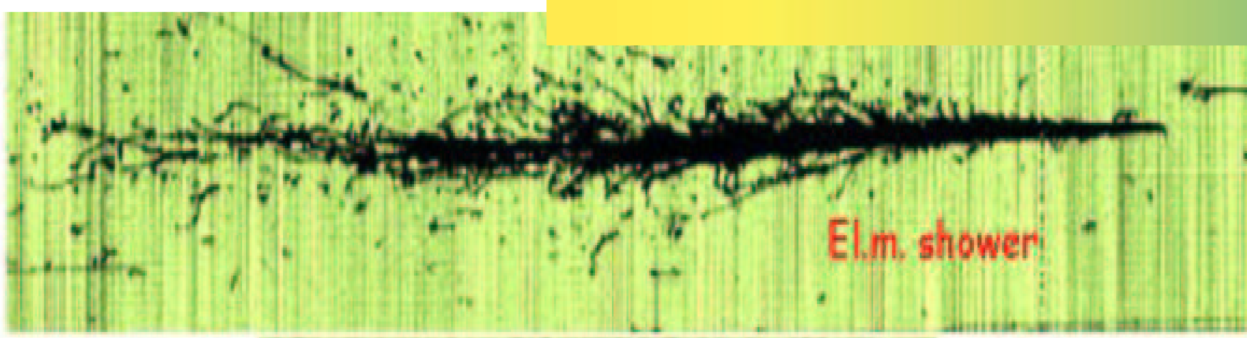
Liquid Argon TPCs:

mature technology

need more US expertise!

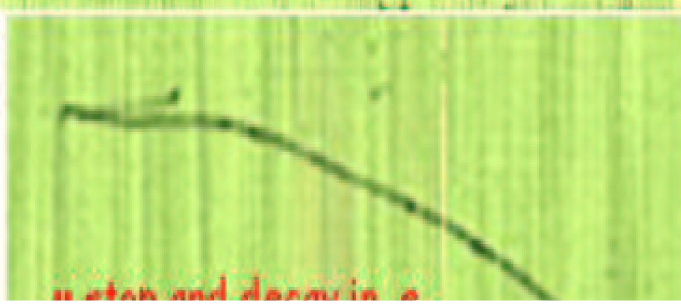


1



A future technology for SBL and LBL...

2



Short Baseline neutrino scattering physics

Lots of really good physics at short baseline!
Explore this at existing and future facilities

- What facilities and detectors do we need to do the physics?
- How do the US plans for SBL physics fit into the global program?
- Connections to nuclear and astro physics communities should be pursued. What is the best way to do this?

working group website:
http://home.fnal.gov/~bfleming/sbl_sb.html