NuFact05 - WG2

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Neutrino Scattering Physics and Experiments At SuperBeams and Neutrino Factories

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What are the Open Questions in Neutrino Physics

From the APS Multi-Divisional Study on the Physics of Neutrinos

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate the symmetry CP?
- Are there "sterile" neutrinos?
- Do neutrinos have unexpected or exotic properties?
- What can neutrinos tell us about the models of new physics beyond the Standard Model?

The answer to almost every one of these questions involves understanding how neutrinos interact with matter!

Among the APS study assumptions about the current and future program is that already existing will be:

"determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino-oscillation physics and the neutrino astronomy of astrophysical and cosmological sources. **Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter."**

Neutrino Scattering Physics at SuperBeams (SB) and Neutrino Factories (NF) brings together Several Communities

- EPP - motivated by increased understanding of physics relevant to neutrino oscillation experiments (exclusive cross sections, nuclear effects), properties of the neutrino and structure of nucleon
- NP - motivated by understanding of physics complementary to the Jlab program such as form factors, quark-hadron duality, nuclear effects and structure of nucleon
- ApP - role of neutrinos in stellar evolution…….

Neutrinos from Low E Protons

Limited scope of physics topics

Minimize backgrounds from higher energies

Specialized study of very low-energy phenomena

Neutrinos from Higher E Protons

Extended scope of physics topics to cover quasi-elastic to DIS

Must understand/study "backgrounds"

Neutrino energies similar to JLab

Motivation: Astroparticle Physics

- The understanding of core collapse within super novae is an important open question.
- SN are an intense source of neutrinos.
- Expected integrated ν flux:
  - <E> = 12 - 18 MeV
  - Total $E(\nu_e)$ = 2-10 x 10^{52} ergs (out of a total E_G of 1-5 x 10^{53} ergs)
  - Total $E(\nu_x)/E(\nu_e)$ = 1 to 2
- Energy transport within SN mostly by neutrinos, ν_τ and ν_μ, since no CC interactions and thus longer path length.
- Opacity of SN dominated by ν - N elastic scattering.
- For example, the incorrect elastic scattering cross section caused simulations to explode (Oak Ridge) when the correct ones did not.

Motivation: Nuclear Physics Interest

Significant overlap with Jefferson Lab physics for $E_\nu = 1\text{-}15$ GeV

Four major topics:

Nucleon Form Factors - particularly the axial vector FF

Duality - transition from resonance to DIS (non-perturbative to perturbative QCD)

Parton Distribution Functions - particularly high-x_{BJ}

Generalized Parton Distributions - multi-dimensional description of partons within the nucleon

Motivation: Elementary Particle Physics

Neutrino Oscillation Experiments

- $\overset{(-)}{\nu}_e$ appearance needs:
  - Coherent pion production cross sections
  - NC and CC π (+,- and 0) production cross sections
  - High y $\overset{(-)}{\nu}_\mu$ CC cross sections
  - **Control neutrino/anti-neutrino systematics at 1 percent level for mass hierarchy and CP studies.**

- High Statistics $\overset{(-)}{\nu}_\mu$ disappearance needs:
  - Measurements of nuclear effects in neutrinos
  - "neutrino energy calibration"
  - Ratio of Quasi-elastic to non-Quasi-elastic cross sections

Review of Neutrino Scattering Physics Topics
What will we know at the time of SB and NF Facilities?

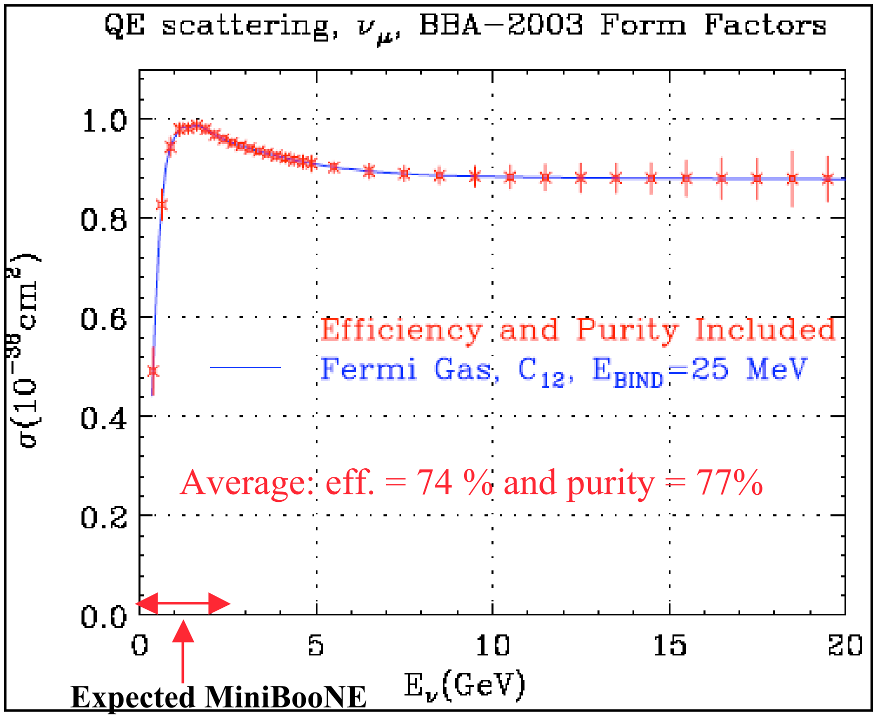
also of interest to NP community - better done with low E protons

- *Quasi-elastic - axial vector form factor*
- *NC elastic scattering - Δs*
- ν e elastic scattering - ν magnetic moment
- *Resonance Production - 1pi*
- *Resonance Production - npi, transition region - resonance to DIS*
- *Deep-Inelastic Scattering*
- Coherent Pion Production
- Strange and Charm Particle Production
- σ_T , *Structure Functions and PDFs*
  - *High-x parton distribution functions*
  - *Spin-dependent PDFs*
- *Nuclear Effects*
- *Generalized Parton Distributions*

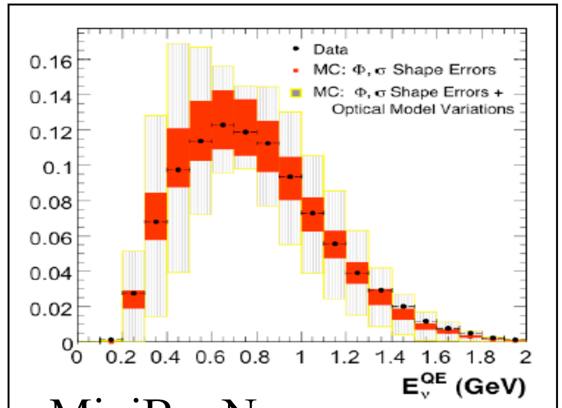
CC ν–Nucleus Quasi-Elastic Measurements

Will have MiniBooNe, K2K and MINERνA (and T2K-I) Results

Jeff Nelson - WG2



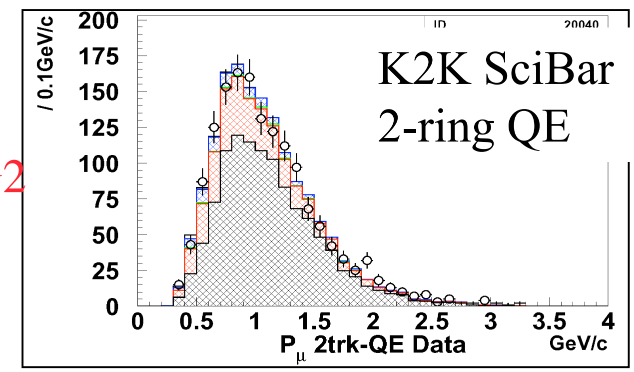
and K2K measurements



MiniBooNe

Ion Stancu - WG2

L. Ludovici - WG2



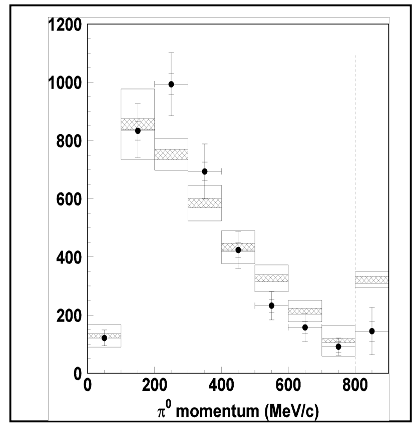
We will have studied **ν - nucleus** elastic scattering by the time of SB.

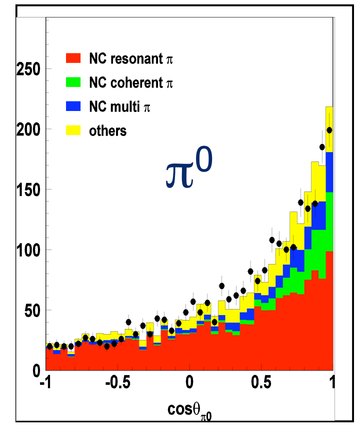
Except for possible MiniBooNe, low E sample, we will NOT have elastic $\bar{\nu}$ -nucleus and certainly not ν / $\bar{\nu}$ - nucleon as well

ν–Nucleus CC Resonant Single-Pion Production

Will have MiniBooNe, K2K and MINERνA (and T2K-I) Results

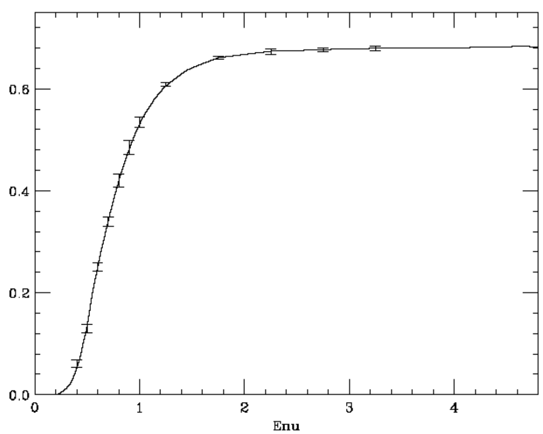
- Treatment of nuclear effects unclear
- Renewed theoretical interest
  - Rein - Sehgal used for decades
- **Sato-**Uno-Lee Dynamical model gives a better fit to (poor) data
- Paschos - Lalakulich with nuclear effects





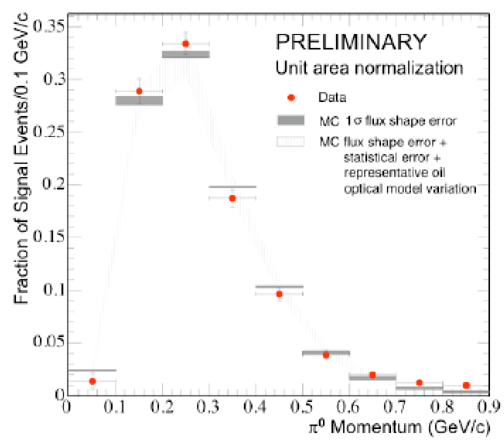
K2K

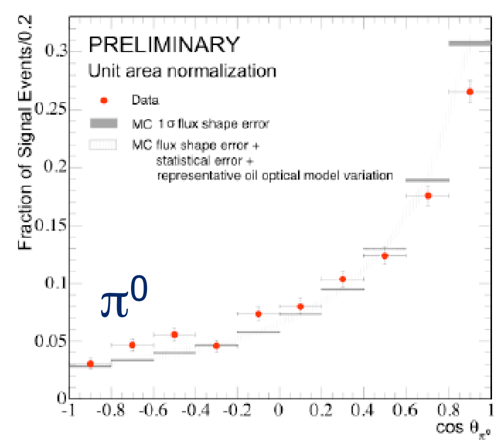
MINERνA Resonance Production - Δ



Total Cross-section and dσ/dQ² for the Δ^{++} assuming 50% detection efficiency

Errors are statistical only

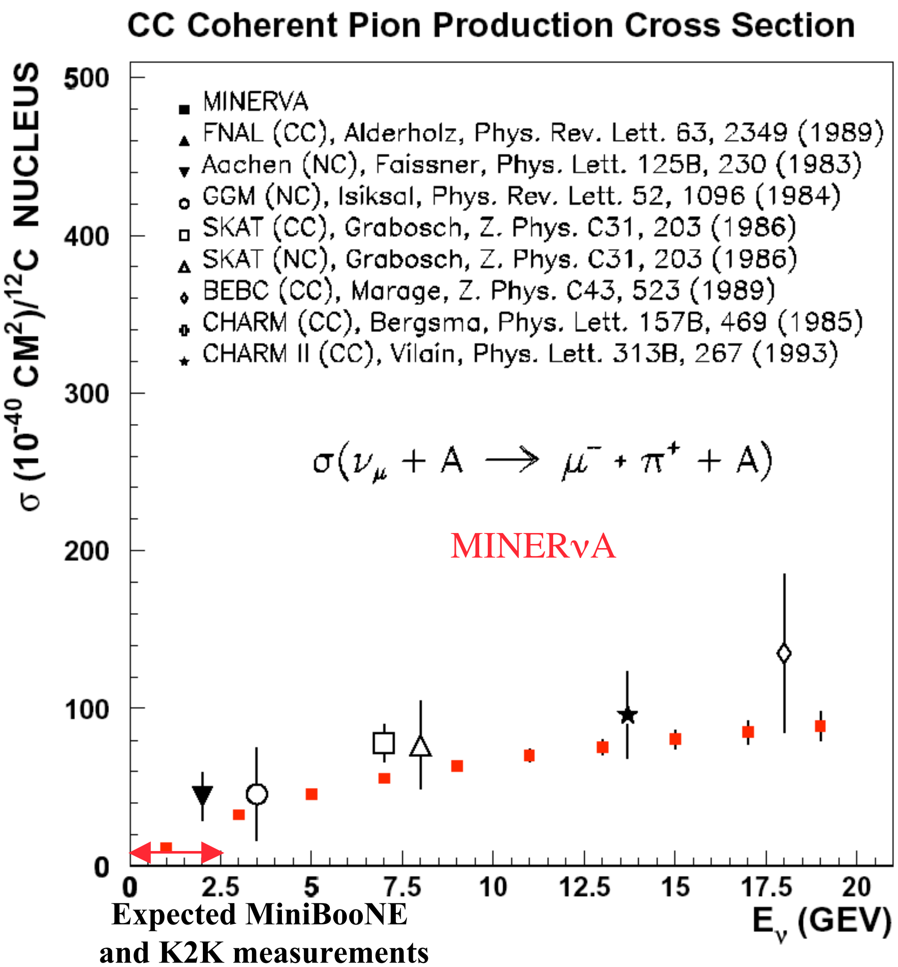




MiniBooNe

ν Coherent Pion Production

MiniBooNe, K2K and MINERνA (and T2K-I) Results



F. Sanchez - K2K Neutrino-Carbon Coherent Pion Production

J. Monroe- Charged Current Neutrino Scattering Physics at MiniBooNE

J. Nelson - MINERνA

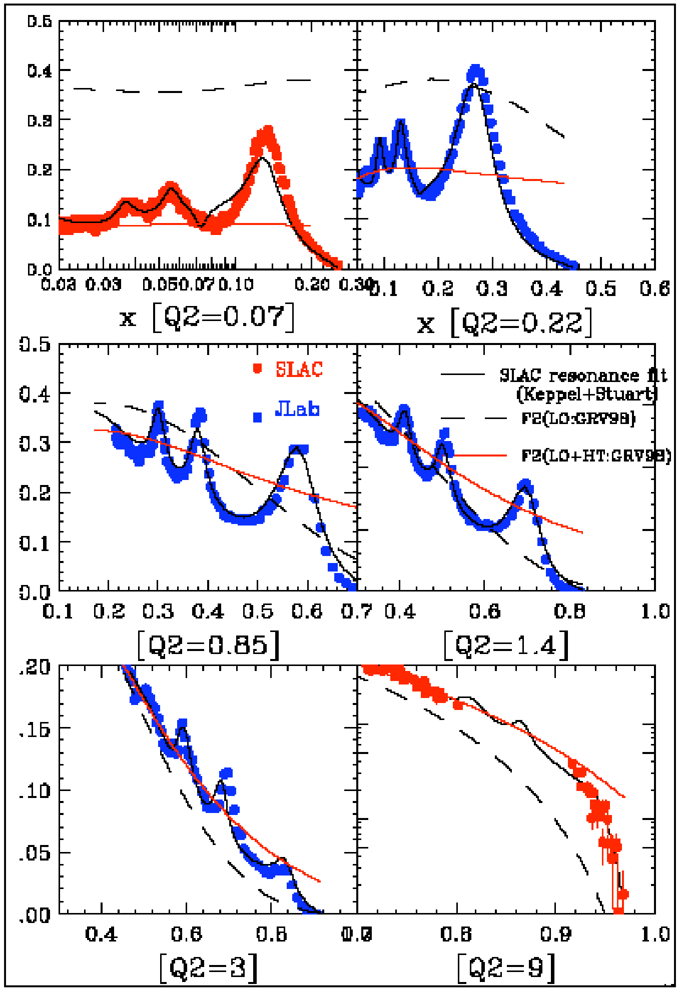
We will understand ν coherent scattering well by the time of FPD.

Except for a possible MiniBooNe low E sample, we will NOT have measured $\bar{\nu}$ - coherent scattering.

ν–Nucleus Resonant Multi-π Production / Transition to DIS
Quark/Hadron Duality

- Recent JLAB data have revived interest in quark/hadron duality
- Bodek and Yang have shown that DIS cross-sections can be extended into the resonance regime, and match the “average” of the resonant cross-section

- We need more than just the “average” knowledge of the transition region - hills and valleys
- Beyond kinematic range of K2K and MiniBooNe.
- MINERνA will study this region with ν nucleus interactions

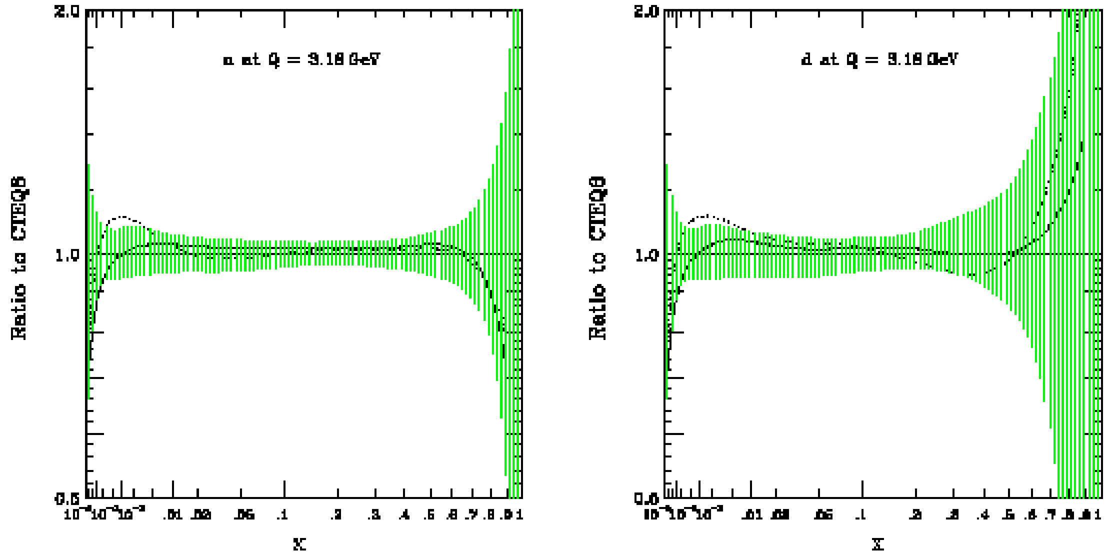


Bodek and Yang

Parton Distribution Functions

Fig. 9 : Uncertainty bands for the u- and d-quark distribution functions at $Q^2 = 10\,\mathrm{GeV}^2$. The solid line is CTEQ5M1 and the dotted line is MRST2001.

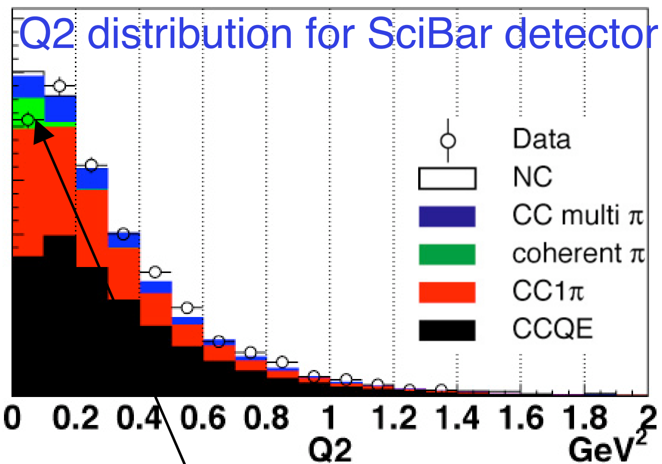
CTEQ uncertainties in u and d quark fits



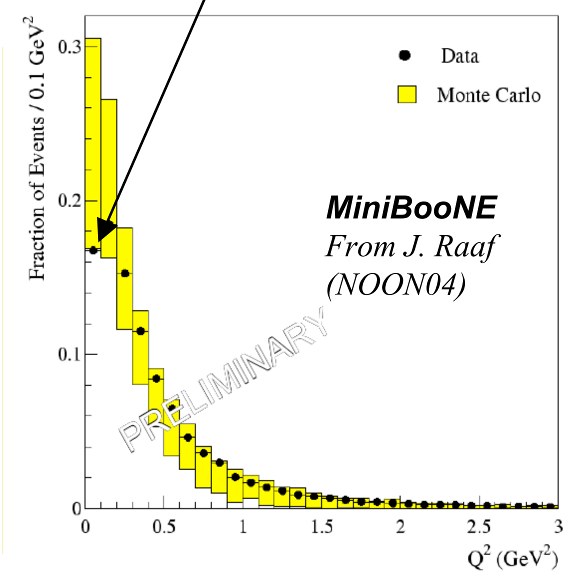
- MINERνA will investigate but with ν **nucleus** interactions. High x nuclear effects have to be understood.
- Need **p and n targets** to get clean PDF measurements.
- Polarized PDFs will require **NF intensities and beam size.**

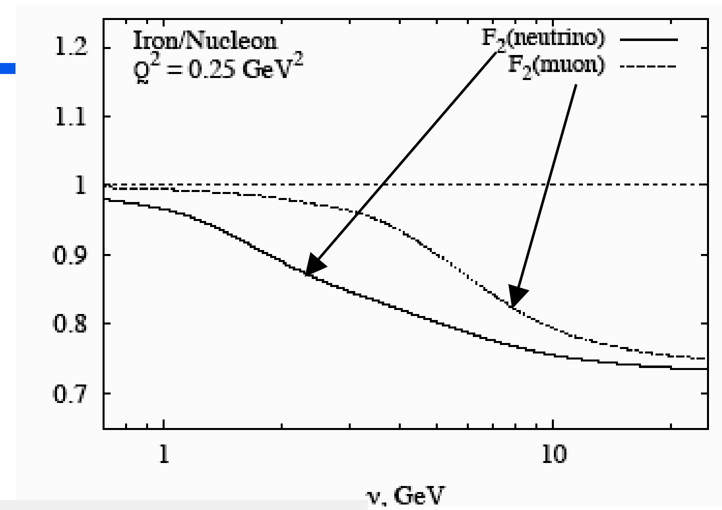
Difference between ν–A and μ–A Nuclear Effects

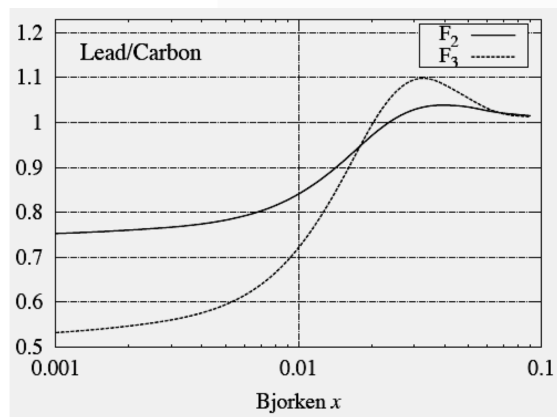
Sergey Kulagin



Larger than expected rollover at low Q^2

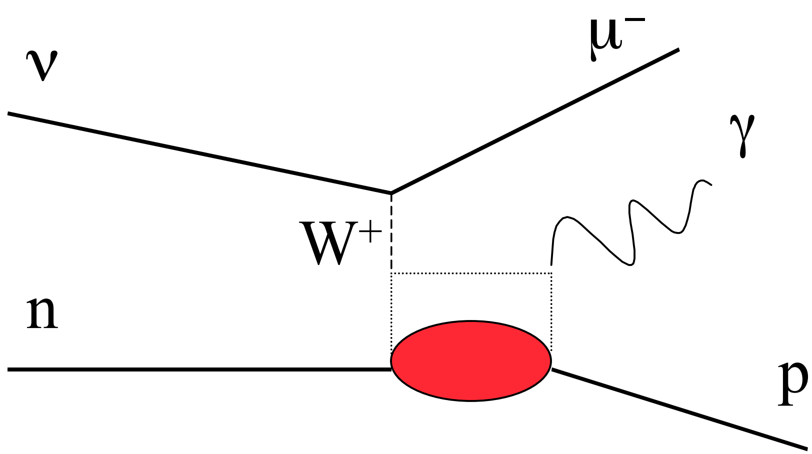






Need significant $\bar{\nu}$ statistics to fully understand nuclear effects with the weak current

Generalized Parton Distributions
Weak analog of DVCS



W> 2 GeV, t small, E_γ large -
Exclusive reaction

- Weak DVCS would allow flavor separation of GPD's.
- Cross section small need huge neutrino flux
- Would prefer off nucleon rather than nucleus
- Start with what we can get - best with **NF intensities**

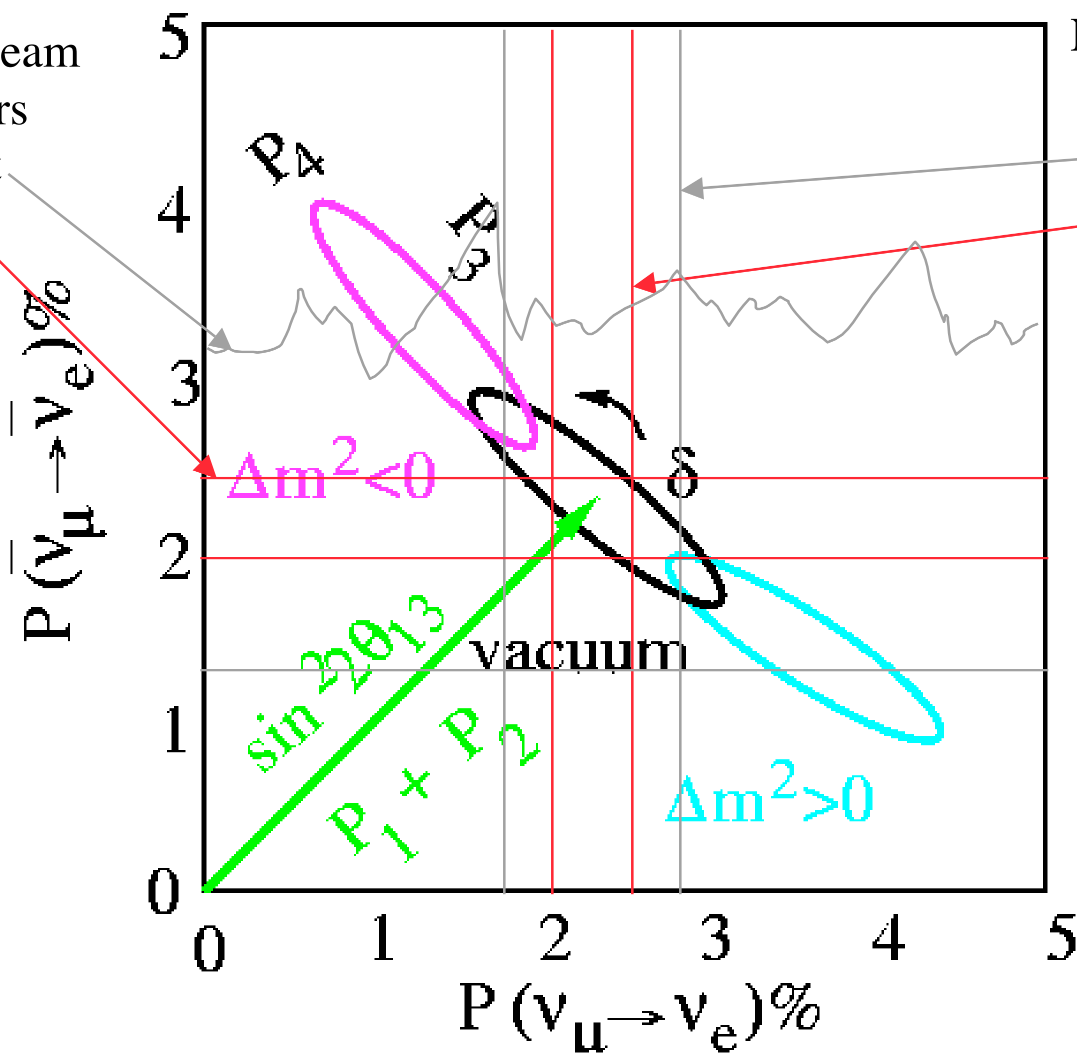
The Goals of a Neutrino Scattering Program at SB and NF - What do we need?

- **HIGH-STATISTICS ANTINEUTRINO EXPOSURE**
  - **Need to improve purity of $\overline{\nu}$ beam at SB?**
- **SB NARROW BAND BEAM FOR DETAILED LOOK AT $\overline{\text{NC}}$?**
  - **Is off-axis beam sufficiently narrow?**
- **HYDROGEN AND DEUTERIUM TARGET FOR ν and $\overline{\nu}$**
  - **Need a fully-active detector for details of interaction vertex SB and NF**
- **IMPROVED DETECTOR TECHNIQUES**
  - **Particularly good neutron detection for $\overline{\nu}$**
  - **Need a large polarized target for spin-dependent studies at NF**

Why do we need an $\bar{\nu}$ Beam?

Control ν / $\bar{\nu}$ systematics at the 1 percent level for mass hierarchy and CP studies.

NUE WITH SuperBeam
Stat: 50 Kt, 5 years
w/o $\bar{\nu}$ scatt. expt
w $\bar{\nu}$ scatt. expt



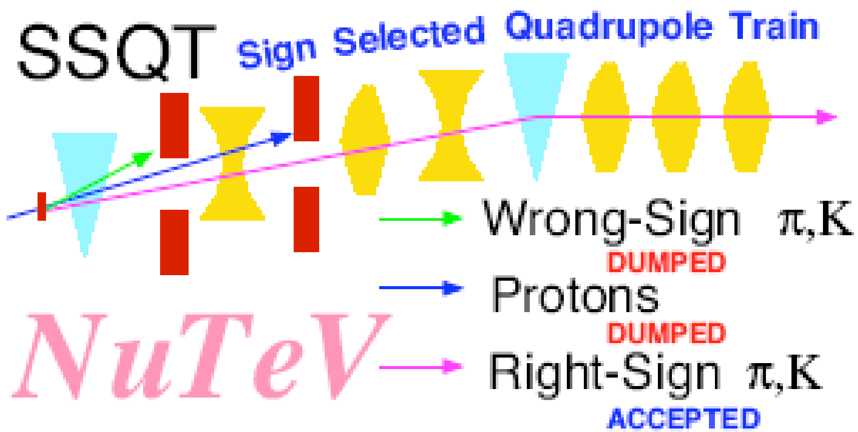
NUE no SuperBeam
Stat: 50 Kt, 5 years
w/o ν scatt. expt
w ν scatt. expt

An efficient $\bar{\nu}$ Beam? - Time for "designer" beams?

Overview of Neutrino Beams - R. Bernstein FNAL

- Horn Beams (NuMI, K2K, CNGS…)
  - High Intensity - particularly at low E_ν
  - Efficient ν but very impure $\bar{\nu}$ beams at low energy
  - NuMI LE $\bar{\nu}$ beam yields **1.1 ν events** for every **1.0 $\bar{\nu}$ event** !
- Dichromatic (Narrow-band) Beams - Is off-axis sufficient?
  - Select mesons of particular momentum $\longrightarrow$ minimal spread of E_ν
  - Low Intensity but optimal for studying NC physics
- Quadrupole Triplet
  - Mixed ν and $\bar{\nu}$
  - High Intensity and energy
- Sign-selected quadrupole train
  - Excellent separation of ν and $\bar{\nu}$
  - Lower intensity than the Quadrupole Triplet
  - Better understood ν_e

Need a Very Efficient $\overline{\nu}$ Beam optimized for low E_ν



- Basically Wedge QT between Dipoles:
- Resulting beam is almost purely ν or $\overline{\nu}$:
  ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is ~1.8% electron neutrinos
  - But Troublesome $K_L \rightarrow \nu_e$ Gone, Since K_L Head off Into Dumps, Away From Beam Direction
- About Half of QT flux/per proton
  - Switch All Polarities to Change
  - Move Dumps Transversely

Resulting beam is almost pure $\overline{\nu}$ beam:
ν in $\overline{\nu}$ mode = 4×10^{-3}
Lose factor five in intensity compared to 2-horn beam
(+ factor 3-5 compared to ν)

The Goals of a Neutrino Scattering Program at SB and NF - What do we need - **detectors**?

- **HIGH-STATISTICS ANTINEUTRINO EXPOSURE**
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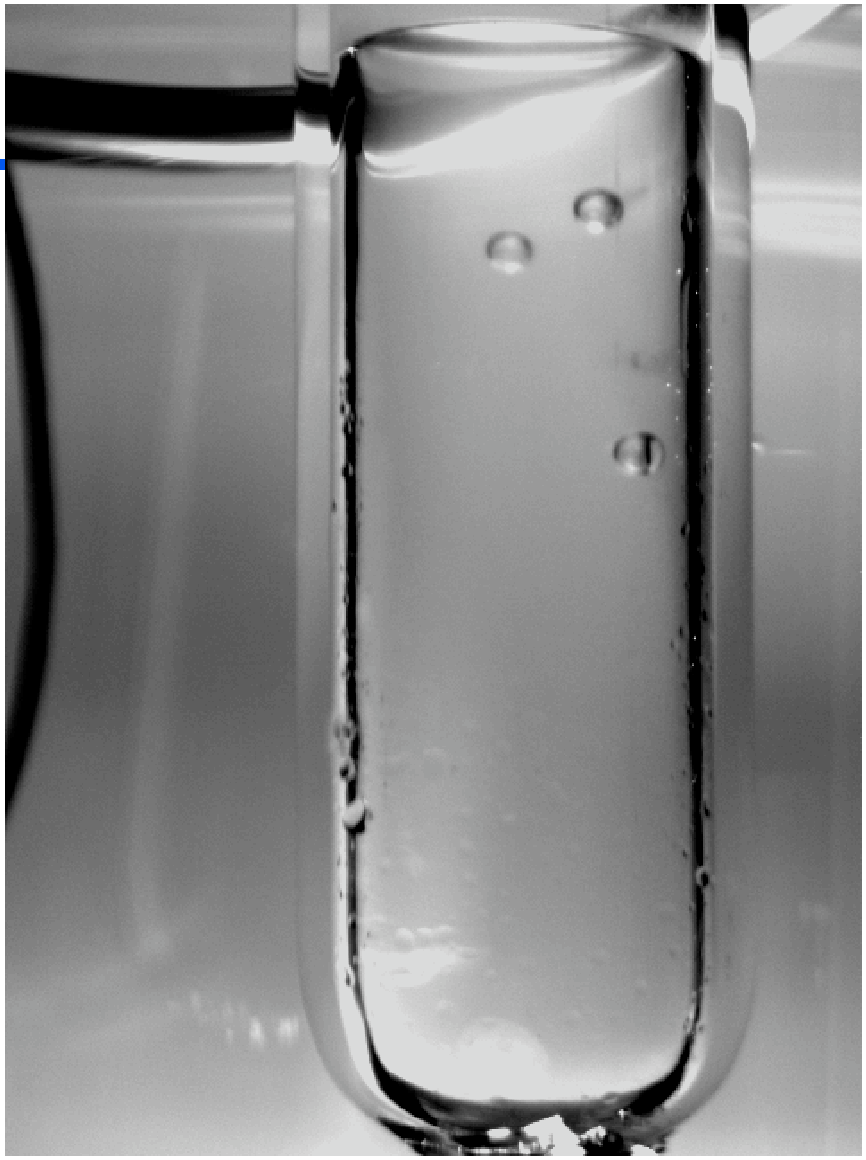
Detectors for SB and NF Experiments

- One type of detector needed exclusively for ν scattering physics.
  - **Fully active H_2 and D_2 target/detector**
- Need to overcome aversion to the idea **“BUBBLE CHAMBER”.**
- Bubble Chamber technique again becoming important for WIMP searches.
- Significant advances in “clean” chambers able to remain sensitive for minutes/hour.
  - Due to significant progress in site deactivation techniques to suppress nucleation on surfaces.
- CCD readout/camera technology for BC is being refined.
  - fully electronic readout and processing of Bubble Chamber events.
- Development of larger chambers an objective of COUPP collaboration now running WIMP-search BC in NuMI Near Hall.

Chicagoland Observatory for Underground Particle Physics



The University of Chicago Kavli Institute for Cosmological Physics and Enrico Fermi Institute

J. Bolte, J. Collar, J. Hall, D. Nakazawa, B. Odom, K. O'Sullivan, A. Raskin, J. Vieira

Fermi National Accelerator Laboratory

M.B. Crisler, D. Holmgren, J. Krider, C.M.Lei, R. Plunkett, E. Ramberg, A. Sonnenschein, R. Schmitt

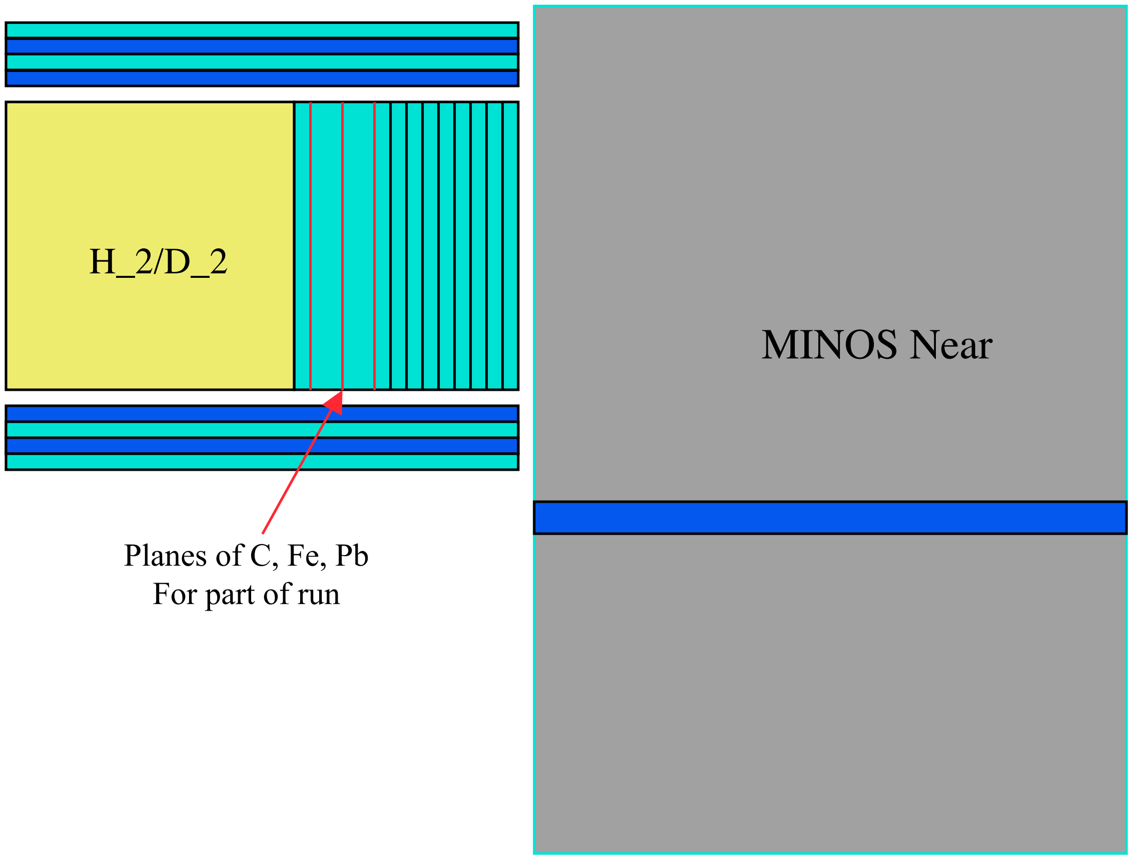
Example: A Liquid H_2/D_2(/O/Ar) Target for MINERνA in the NuMI Beam with the Fermilab Proton Driver SB

Fid. vol:
r = 80 cm. l = 150 cm.

1.5 M CC events in LH_2

3.5 M CC events in LD_2

per year he-ν running.



Parton Distribution Functions: d_v and u_v

Example: what would we do with a hydrogen target

$\nu/\bar{\nu}$ - Proton Scattering

$$F_2^{\nu p} = 2x\,(d + \bar{u} + s)$$

$$F_2^{\bar{\nu} p} = 2x\,(u + \bar{d} + \bar{s})$$

At high x $\rightarrow$

$$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}$$

No messy nuclear corrections!

$$xF_3^{\nu p} = 2x\,(d - \bar{u} + s)$$

$$xF_3^{\bar{\nu} p} = 2x\,(u - \bar{d} - \bar{s})$$

$$F_2^{\nu p} - xF_3^{\nu p} = 4x\bar{u}$$

$$F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} = 4xu$$

EPP and NP interest in PDFs
Need $\bar{\nu}$ and p/n target

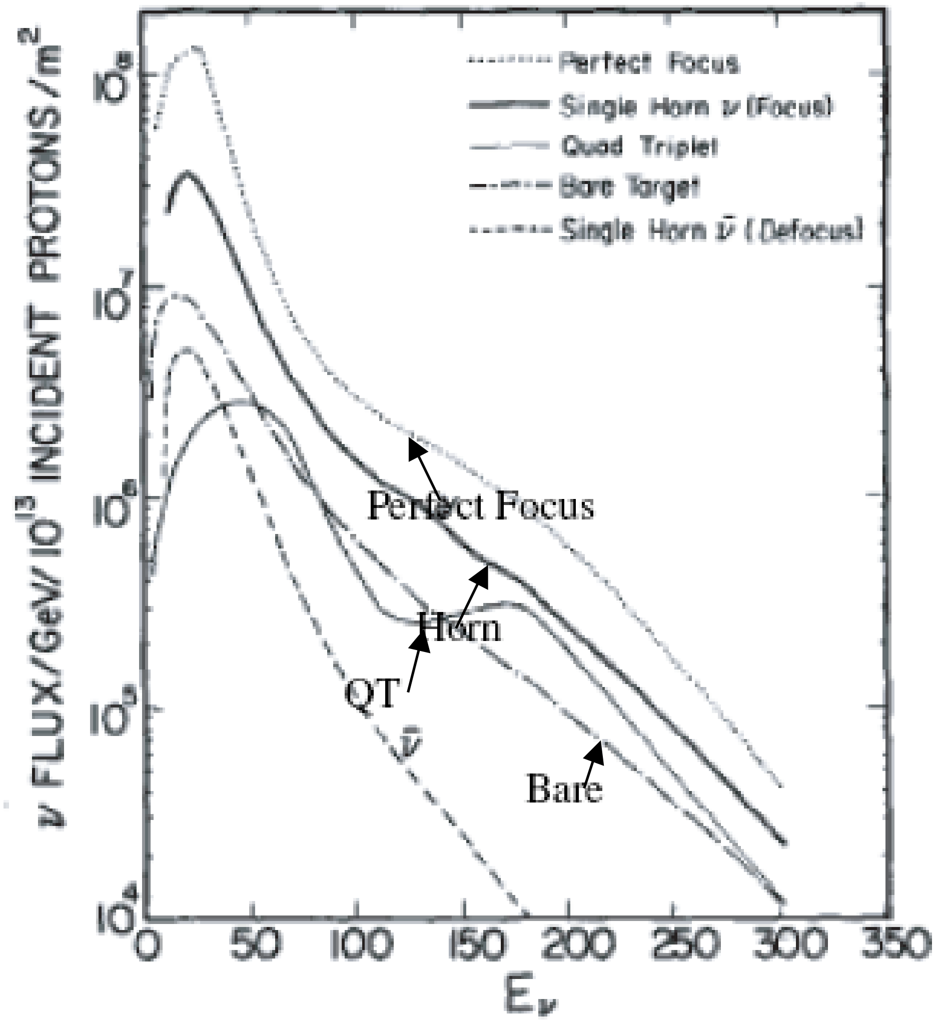
Summary
Thoughts for Discussion in WG2

- At the start of the SuperBeam, we will have reasonable results for neutrino-nucleus interactions including exclusive cross-sections, form factors and nuclear effects.

- We will need a SuperBeam, with both lower-E_p (?) and higher-E_p ν program, with designer $\bar{\nu}$ beam and H_2 BC to have similar results for:
  - $\bar{\nu}$ - nucleus cross-sections,
  - ν and $\bar{\nu}$ - proton and neutron (D_2) cross-sections,
  - ν / $\bar{\nu}$ - e elastic scattering
  - high-statistics narrow-band studies of NC (and CC) channels

- We will need a Neutrino Factory with a liquid H_2/D_2 target/detector and a large polarized target to finish up details of $\bar{\nu}$-n/p physics, study GPDs and polarized PDFs.

Relative ν Flux



Jorge G. Morfín - Neutrino Scattering Physics