

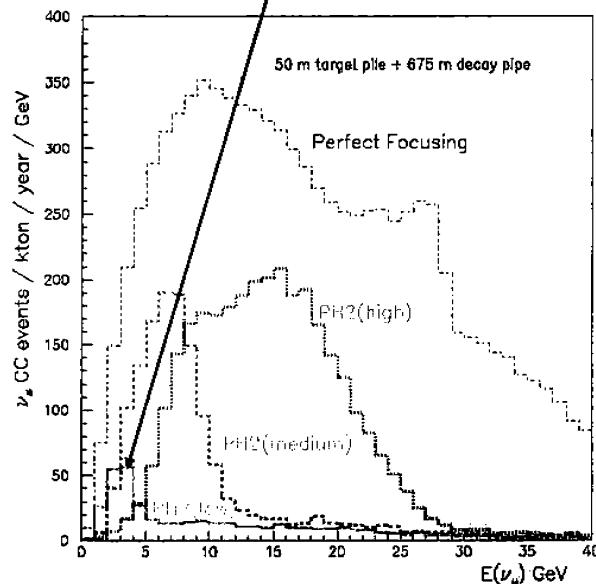
Neutrino Physics in the DIS (and Resonance and Quasi-Elastic) Regime(s)

Cynthia Keppel
EIC Workshop

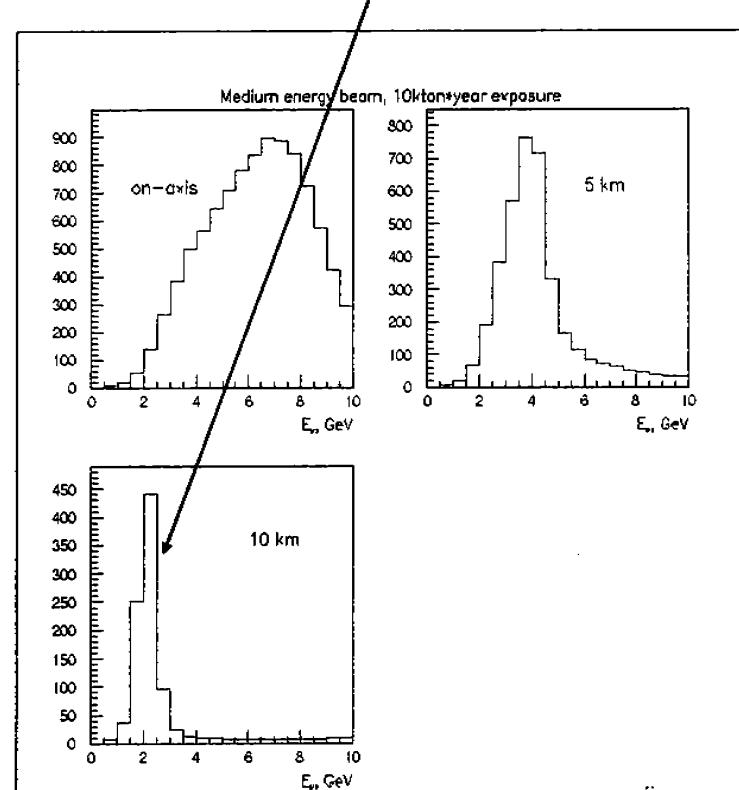
Jefferson Lab
March 2004

Current/Future ν Oscillation Experiments use Few GeV ν on C, O₂, Fe, ??? Nuclei

MINOS: Neutrino Beam



NuMI Off-axis Neutrino Beam



We need to understand low energy ν -Nucleus interactions for oscillation experiments!

Neutrino Scattering in the NuMI Beam

What's covered by “low-energy” ν -Nucleus interactions?

- ◆ Cross sections of exclusive states
- ◆ Bridging the gap from resonance to DIS
- ◆ Nuclear Effects
 - ▼ x_{Bj} -dependent nuclear effects (shadowing, anti-shadowing, EMC-effect...)
 - ▼ Pauli suppression
 - ▼ Nuclear binding
 - ▼ Nuclear correlations,
 - ▼ Extended Fermi gas model, spectral functions,
 - ▼ Hadron formation length and nuclear transparency,
 - ▼ Final state interactions.

Steps (not necessarily time-ordered) in ν -Nucleus Interactions

- ◆ Incoming neutrino imparts q (momentum and energy) via an IVB to a nucleus.
- ◆ Depending on x, q :
 - ▼ The interaction proceeds under shadowing, anti-shadowing or EMC effect.
 - ▼ the IVB interacts with the entire nucleus, ≥ 1 nucleon or with one or more quarks.
- ◆ For interactions with a nucleon, the target nucleon (off shell) carries initial p and E_k within the nucleus.
- ◆ The (excited) $A-1$ nucleus recoils with $-p$ and proceeds to a ground state via γ -emission or boil-off protons or other breakup mechanisms.
- ◆ A hadronic state is created (quasi-elastic, resonance, continuum, DIS...).
 - ▼ Pauli Blocking influences final state nucleon momentum (quasi-elastic).
- ◆ The produced hadronic state proceeds through the nucleus.
 - ▼ Nuclear transparency, formation zone, and nuclear densities influence final state interactions.
- ◆ A **visible** final hadronic state and **visible** neutrino energy are recorded.

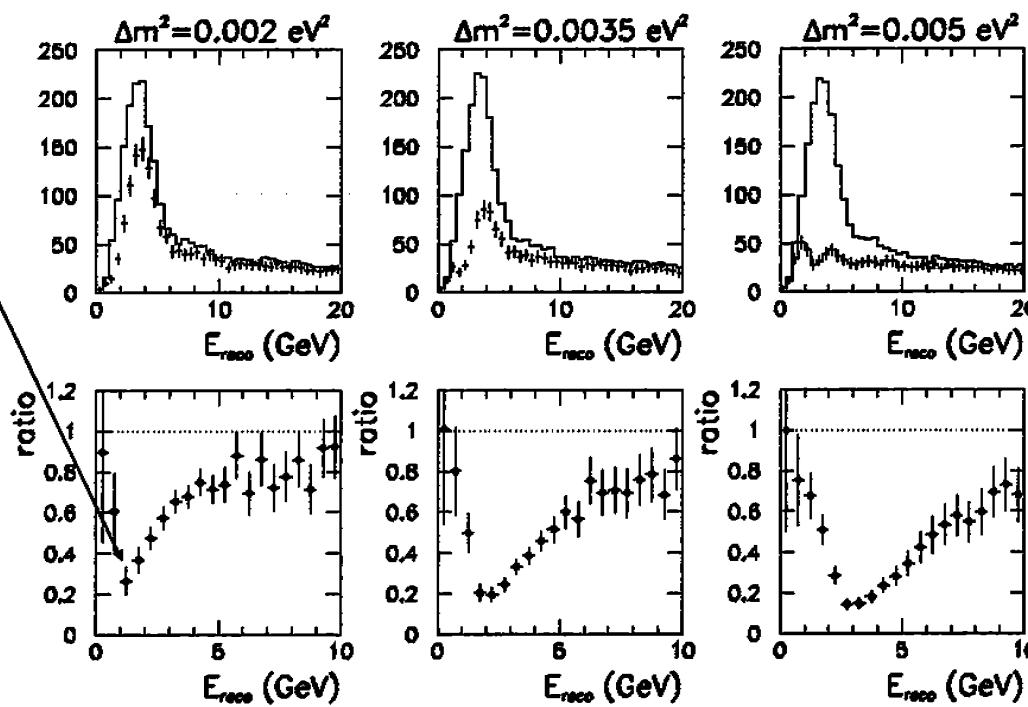
Why do we care about low energy phenomena?

- ◆ E_{vis} is not E_ν - effect on the measurement of oscillation parameters
- ◆ Understanding backgrounds to $\nu\mu \rightarrowtail \nu_e$
 - ▼ NC resonant 1 π^0 production (direct or through nuclear effects)
 - ▼ Coherent 1 π^0 production
- ◆ Observed hadronic state (particle type and kinematics) not necessarily the produced state
 - ▼ Interaction kinematics perturbed via nuclear effects
 - ▼ Quasi-elastic events lost or mimicked by resonance via nuclear effects

How Important are Low-energy Neutrinos?

Seeing the “dip” in the oscillation probability is a goal of MINOS

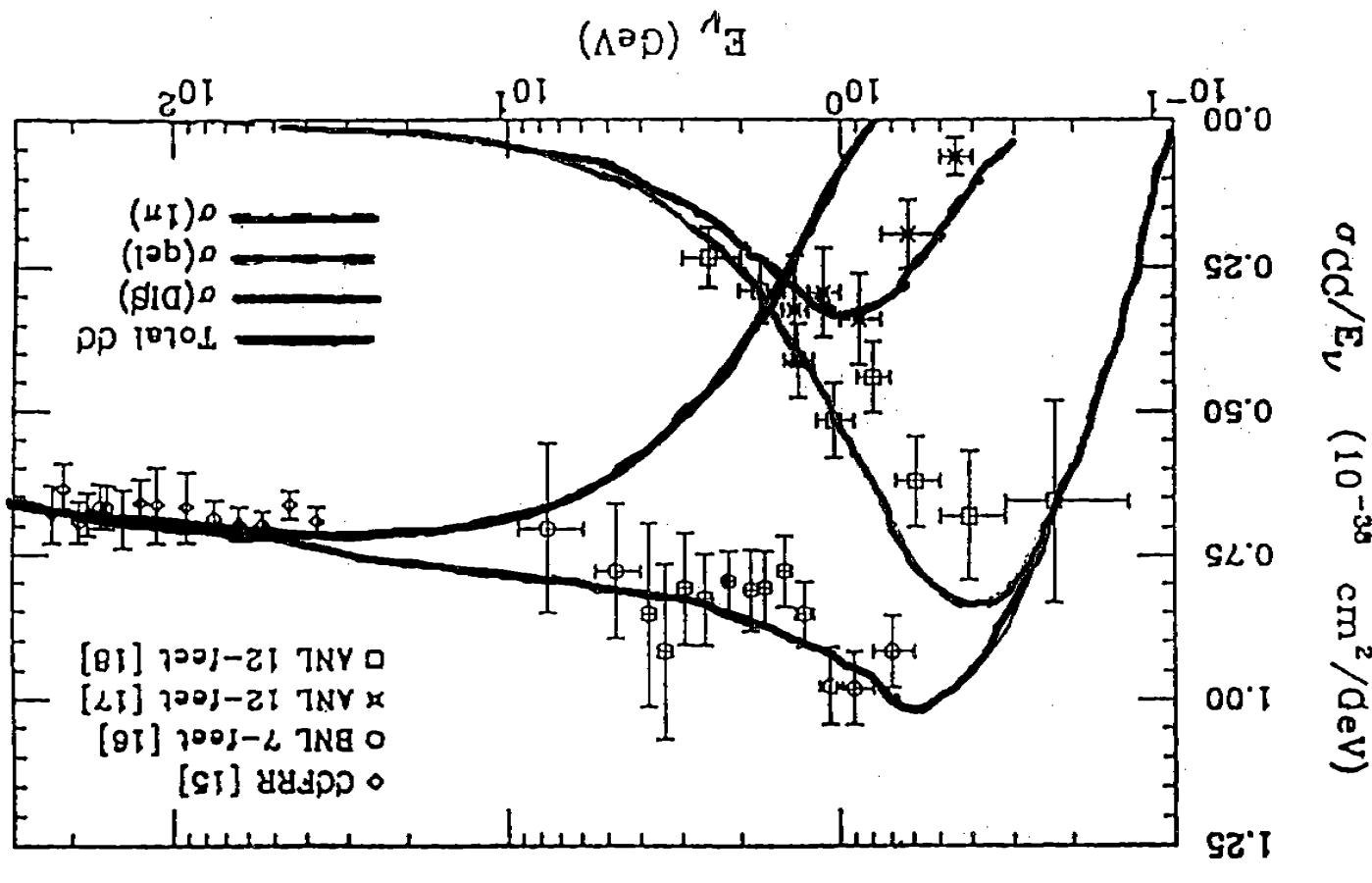
VERY Difficult at low Δm^2 .



- CC energy distributions have two important complications at low energy:
- Difference between E_{vis} and E_ν due to nuclear effects (particularly re-scattering, absorption).
- A required subtraction of NC events that fake low energy CC.
- In both cases MINOS, as well as all other oscillation experiments, will have to rely on MC - only as good as the input!.

- ◆ The interaction proceeds under shadowing, anti-shadowing or EMC effect.
- ▲ Can't blindly use e/u - A results for v - A since axial vector current participation
- ▲ Evidence nuclear effects different - valence and sea quarks, theory hint of same for $u \neq d$
- ▲ Use nuclear pdf's (Kumano or Eskola et al).
- ◆ For interactions with a nucleon, the target nucleon (off shell) carries initial p and E_K
- ▲ Bodek-Ricthie extended Fermi-gas model invalid at high P_F (NOMAD/CHORUS)
- ▲ Use spectral functions (O. Benhar) - careful since some encompass "EMC-effect"
- ◆ A hadronic state is created (quasi-elastic, resonance, continuum, DIS...).
- ▲ Limited experimental data.
- ▲ For decades only $v \rightarrow N^*$ by Rein-Schegel from 70's, now Lee-Sato for $v + N \rightarrow u + \Delta$
- ▲ From resonances to DIS: duality arguments and recent work by Bodek-Yang on low Q , high x pdfs
- ◆ The produced hadronic state proceeds through the nucleus.
- ▲ Major stage in the process. Introduce very significant changes in the number and identity of hadrons (pion absorption and charge exchange) and total visible energy
- ▲ Dual-parton Model with Formation Zone Intranuclear Cascade and Nuclear Transparency

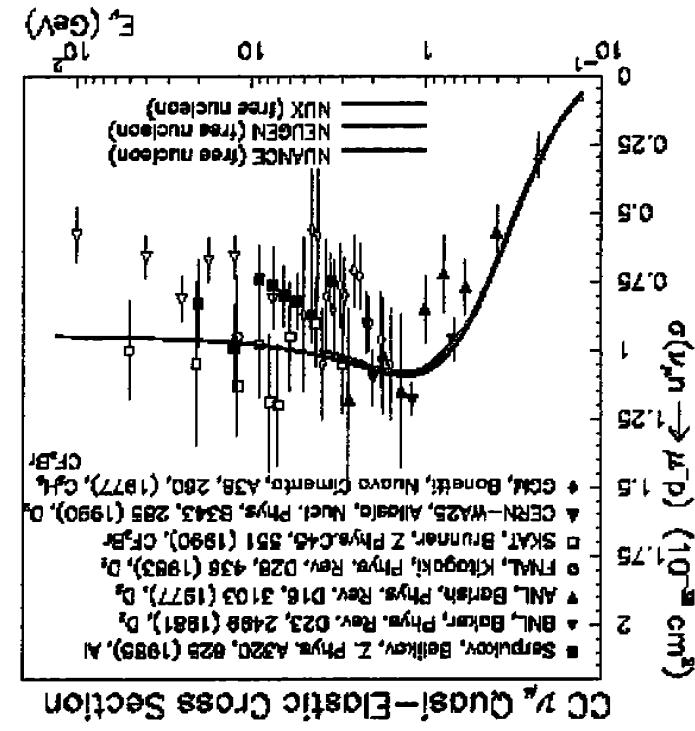
State of our Knowledge for these Steps



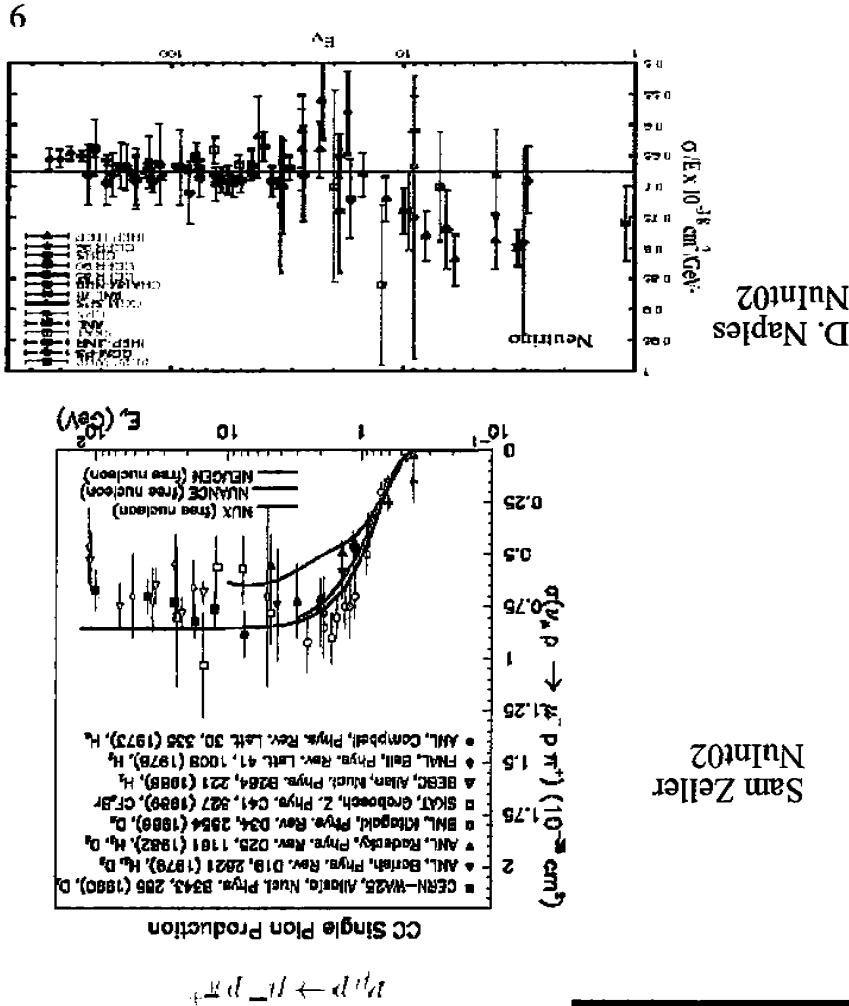
Energy

Experimental Input - Make-up of OT at Low

Workshop on Neutrino-Nucleus Interactions in the Few GeV Region



Just What Experimental Input is Available?



A factor of 10 higher intensity is being proposed
here, for ~ 20 GeV protons (~ 2 GeV peak ν)

Current/Near Future Experimental Investigations of these Topics

- ♦ Fermilab Booster Neutrino Beam - 8 GeV Protons
 - ▲ MiniBooNE Experiment
 - ▲ FINeSE Experiment
- ♦ KEK Neutrino Beam - 12 GeV Protons
 - ▲ Original K2K Near Detectors
 - ▲ New SciBar Detector
- ♦ Fermilab NuMI Beam - 120 GeV Protons
 - ▲ MINERVA Experiment

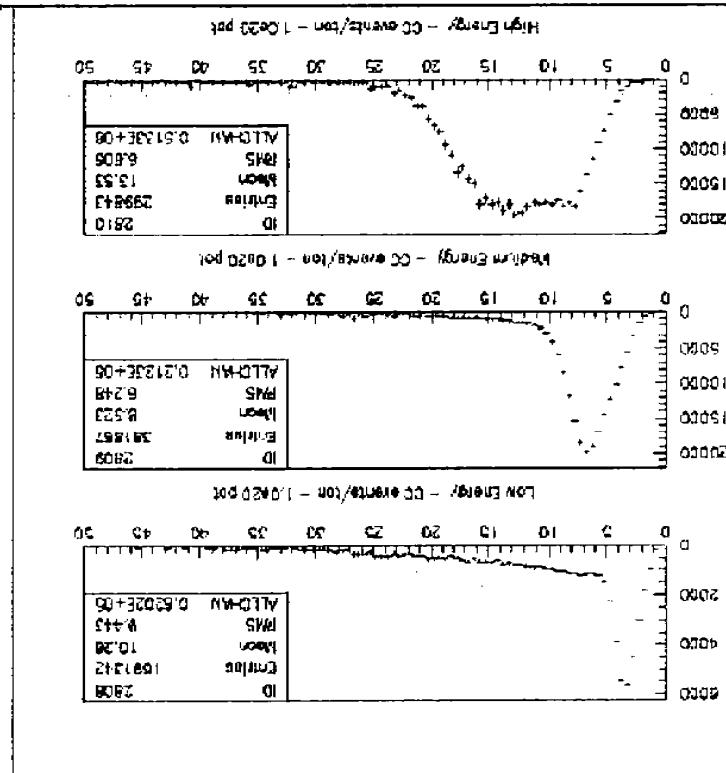
- ◆ One wants to be below τ threshold to measure subdominant oscillation
- ◆ Minimize backgrounds - narrow energy spectrum around desired energy
- ◆ θ_{13} small (≤ 0.1) - maximize flux at the desired energy (near oscillation max)
- ◆ How do we measure this sub-dominant oscillation?
- ◆ Above can be accomplished with the $v_\mu \leftrightarrow v_e$ transition.

- ◆ The physics issues to be investigated are clearly delineated:
 - Need measurement of missing oscillation probability ($\theta_{13} = \theta_{1e}$)
 - Need determination of mass hierarchy (sign of Δm^2_{31})
 - Search for CP violation in neutrino sector
 - Measurement of CP violation parameters
 - Testing CPT with high precision
-
- ◆ The dominant oscillation parameters will be known reasonably well from solar/reactor v and from SuperK, K2K, MINOS, CNGS

Next Generation Example: NuMI Off-axis Experiment

NuMI ν-energy Distributions and Event Rates in the Near Detector Hall

With E-907 at Fermilab to measure particle spectra from the NuMI target, expect to know neutrino flux to $\approx \pm 3\%$.



rate = 1210 K events/ton - year.

rate = 1575 K events/ton - year

E_{peak} = 12.0 GeV, $\langle E_{\nu} \rangle = 13.5$ GeV,

◆ he-configuration: Events-

s-me rate = 540 K events/ton - year.

= 675 K events/ton - year

E_{peak} = 7.0 GeV, $\langle E_{\nu} \rangle = 8.5$ GeV, rate

◆ me-configuration: Events-

GeV, rate = 200 K events/ton - year.

E_{peak} = 3.0 GeV, $\langle E_{\nu} \rangle = 10.2$ GeV

◆ le-configuration: Events - ($E_{\nu} > 0.35$

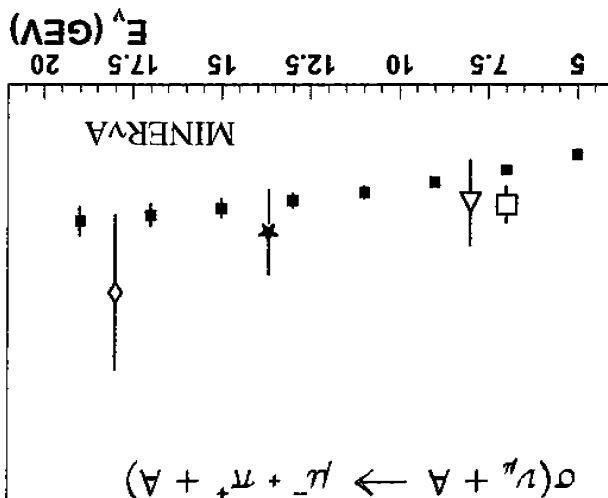
NuMI running at start-up.

◆ With 2.5×10^{20} pot per year of

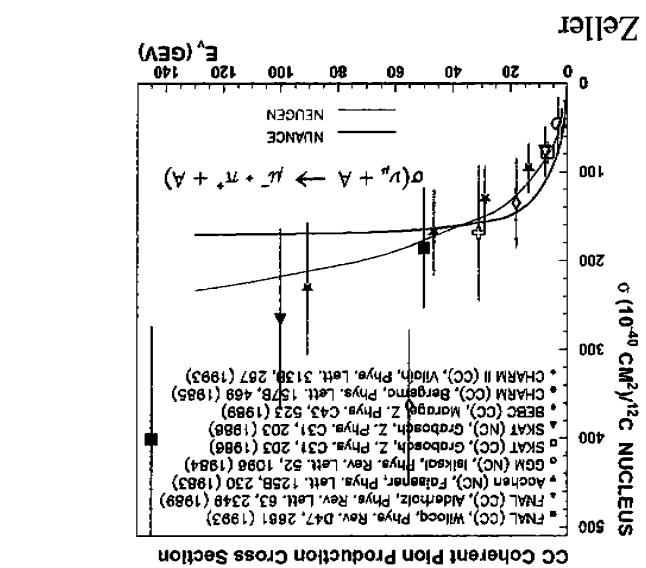
Cohere nt Pion Production

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

13



MINERVA Proposal

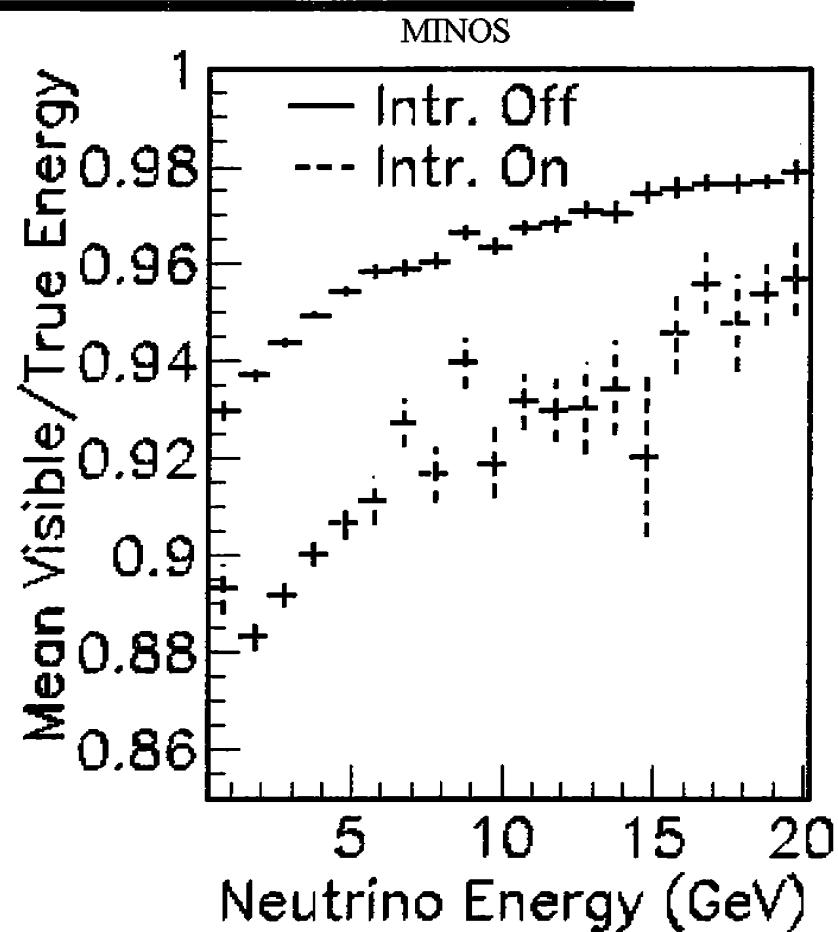


- Characterized by a small energy transfer to the nucleus, forward going π^+ . NC (π^0 production) to the nucleus, forward going π^+ . NC (π^0 production) between several different models.
- Data has not been precise enough to discriminate search between several different models.
- Expect roughly (30-40)% detection efficiency with MINERVA.
- Can also study A-dependence with MINERVA.

Nuclear Effects

MINERvA: 2.8M events off Carbon and 940 K events off of Fe and Pb

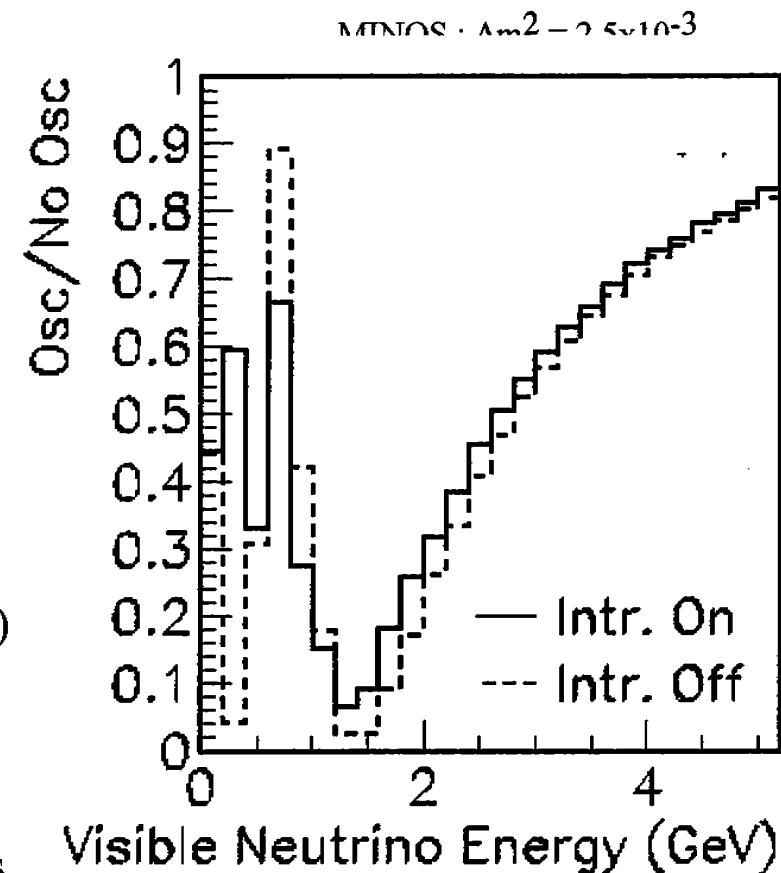
- ◆ Neglecting initial target nucleon state, two types of nuclear effects to consider:
 - ▼ Final State Interactions
 - ▼ Modified Interaction Probabilities
- ◆ **Final State Interactions**
 - ▼ Intranuclear scattering causing change in direction and energy loss (absorption) of secondary pions and nucleon. Not as well known as needed.
 - ▼ Will cause $E_{\text{vis}} < E_{\nu}$
 - ▼ **Important for neutrino oscillation analyses**
 - ▼ **MINERvA will measure multiplicities and E_{vis} off of C, Fe and Pb targets**



Assist Oscillation Analyses

(summary of individual channel contributions)

- ◆ Measurement of Δm^2 (e.g. MINOS)
 - ▼ Understanding intra-nuclear scattering effects
 - ▼ Improved measurements of pion / nucleon absorption
 - ▼ Improved measurement of pion production cross-sections
 - ▼ These combine with absorption probability to produce further uncertainties in plot at right
- ◆ Measurement of θ_{13} (e.g. MINOS/Off-axis)
 - ▼ Precision measurement of coherent pion, and resonant pion cross-sections and angular distributions.
 - ▼ Measurement of ν_e content of NuMI beams

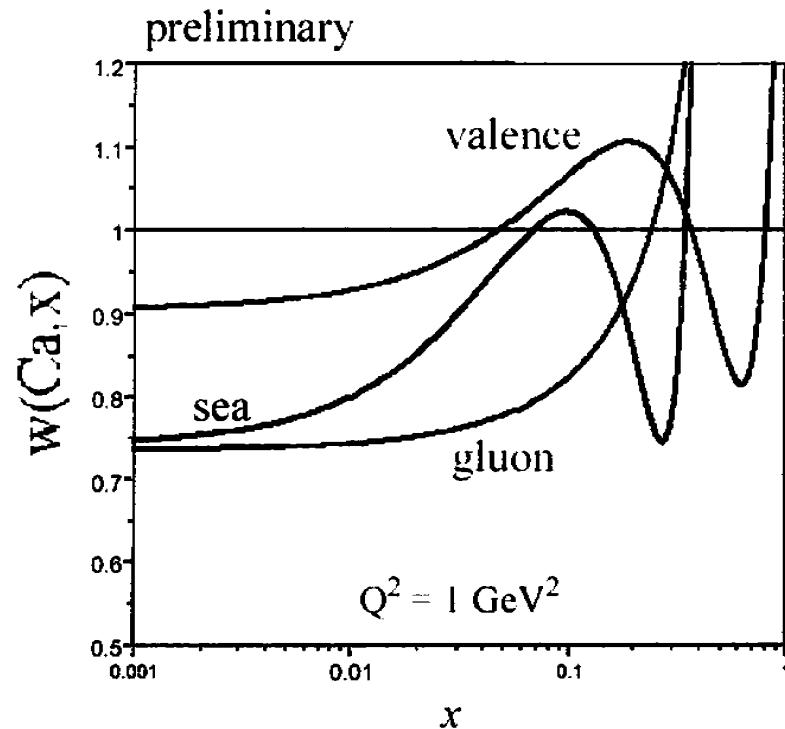


Nuclear Effects

◆ Modified Interaction Probabilities

- ▼ Shadowing Region ($x_{Bj} < 0.1$): Expect a difference in comparison to e/ μ - nucleus results due to axial-vector current and quark-flavor dependent nuclear effects.
- ▼ EMC-effect ($0.2 < x_{Bj} < 0.7$): depends on explanation of the effect
- ▼ Fermi Motion Effect ($x_{Bj} > 0.7$): should be the same as e-nucleus scattering
- ▼ With sufficient v : measure flavor dependent effects.
- ◆ NC/CC off C, Fe and Pb
 - ▼ Over 100 K CC and 30 K NC with $E_H > 5$ GeV on Fe and Pb, times 3 for Carbon.

Kumano fit for flavor-dependent effects



Parton Distribution Functions: What Can We Learn With All Six Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon's constituents:

Using Leading order expressions:

$$F_2^{\bar{v}N}(x, Q^2) = x[u + \bar{u} + d + \bar{d} + 2s + 2c]$$

$$F_2^{vN}(x, Q^2) = x[u + \bar{u} + d + \bar{d} + 2s + 2\bar{c}]$$

$$xF_3^{\bar{v}N}(x, Q^2) = x[u + d - \bar{u} - \bar{d} - 2s + 2c]$$

$$xF_3^{vN}(x, Q^2) = x[u + d - \bar{u} - \bar{d} + 2s - 2\bar{c}]$$

◆ Does $s = s$ and $c = c$ over all x ?

◆ If so.....

$$F_2^v - xF_3^v = 2(\bar{u} + \bar{d} + 2\bar{c}) = 2U + 4\bar{c}$$

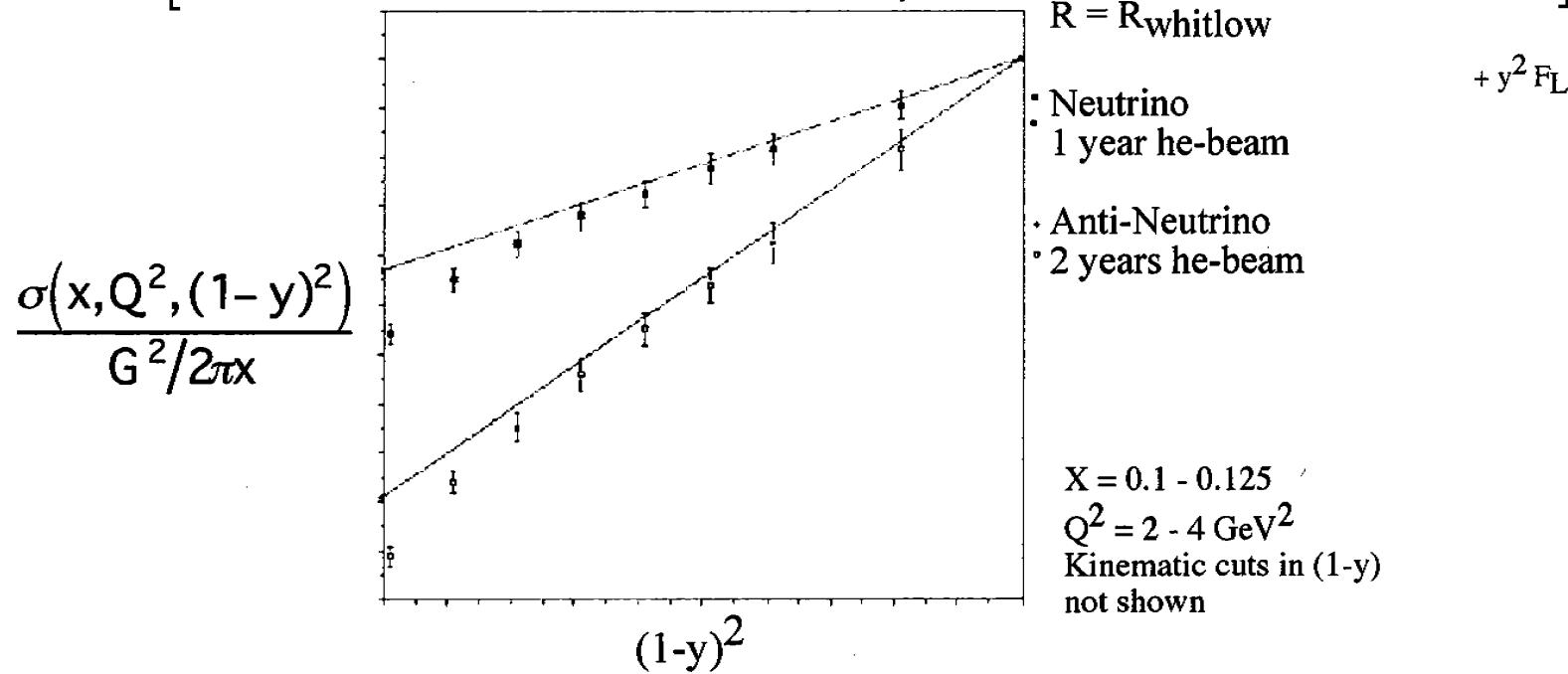
$$F_2^{\bar{v}} - xF_3^{\bar{v}} = 2(\bar{u} + \bar{d} + 2\bar{s}) = 2U + 4\bar{s}$$

$$xF_3^v - xF_3^{\bar{v}} = 2[(s + \bar{s}) - (\bar{c} + c)] = 4s - 4c$$

Six Structure Functions for Maximal Information on PDF's

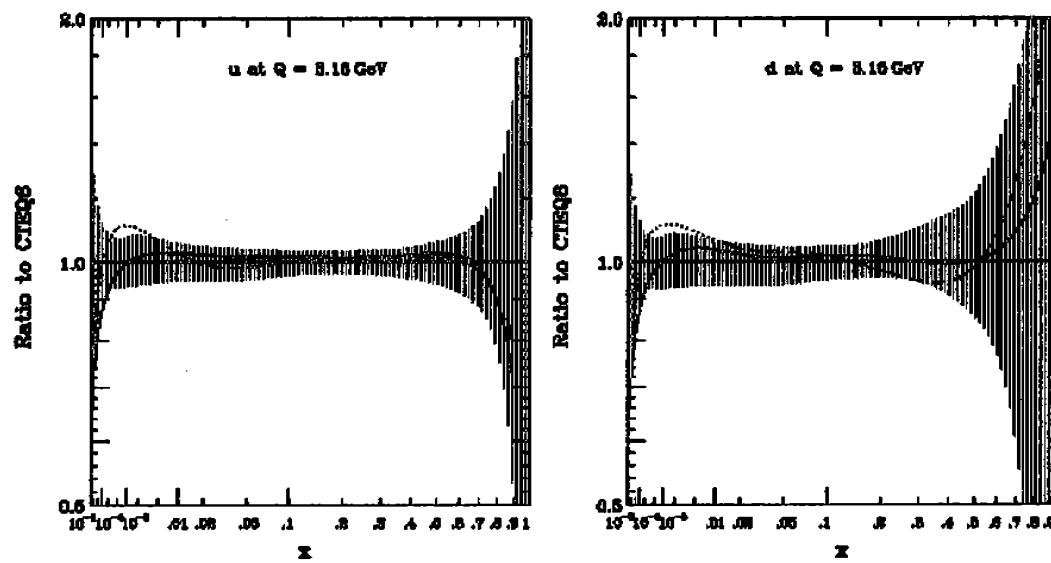
$$\frac{d\sigma^{\nu A}}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left[\frac{1}{2} (F_2^{\nu A}(x, Q^2) + x F_3^{\nu A}(x, Q^2)) + \frac{(1-y)^2}{2} (F_2^{\nu A}(x, Q^2) - x F_3^{\nu A}(x, Q^2)) \right]$$

$$\frac{d\sigma^{\bar{\nu} A}}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left[\frac{1}{2} (F_2^{\bar{\nu} A}(x, Q^2) - x F_3^{\bar{\nu} A}(x, Q^2)) + \frac{(1-y)^2}{2} (F_2^{\bar{\nu} A}(x, Q^2) + x F_3^{\bar{\nu} A}(x, Q^2)) \right]$$



High x_{Bj} parton distributions

How well do we know quarks at high- x ?

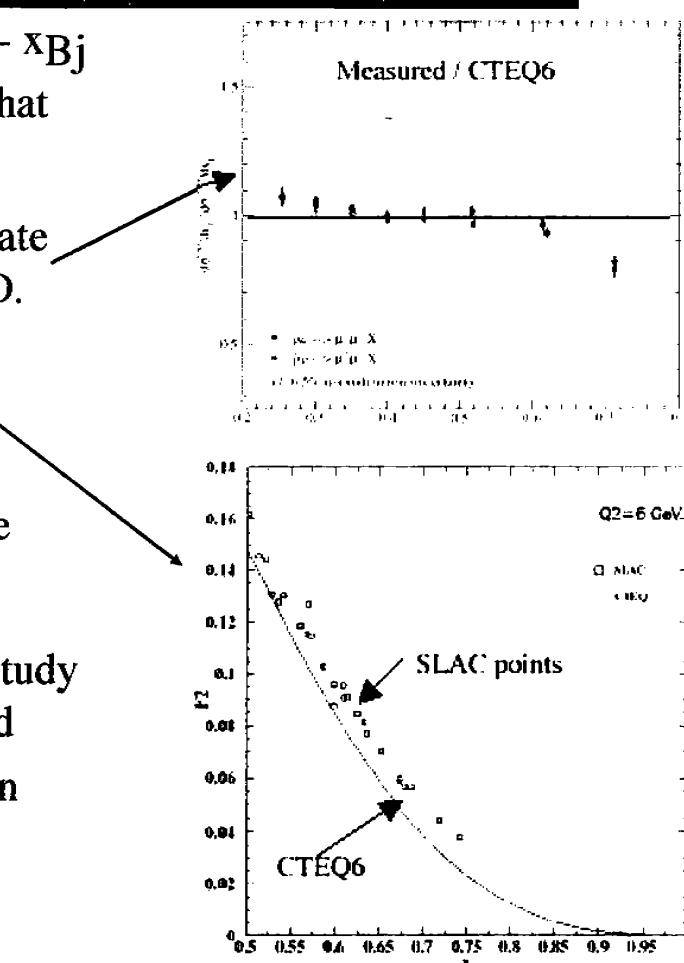


Wu-Ki Tung

- ◆ Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10 \text{ GeV}^2$. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.

High- x_{Bj} Parton Distribution Functions

- ◆ The particular case of what is happening at high- x_{Bj} is currently a bit of controversial with indications that current global results are not correct
- ◆ Drell-Yan production results (E-866) may indicate that high- x_{Bj} (valence) quarks OVERESTIMATED.
- ◆ A Jlab analysis of Jlab and SLAC high x DIS indicate high- x_{Bj} quarks UNDERESTIMATED
- ◆ CTEQ / MINERvA working group to investigate high - x_{Bj} region.
- ◆ MINERvA will have over 1.2 M DIS events to study high - x_{Bj} Close examination of the non-PQCD and pQCD transition region, in context of quark-hadron duality, with axial-vector probe.



MINERvA Proposal

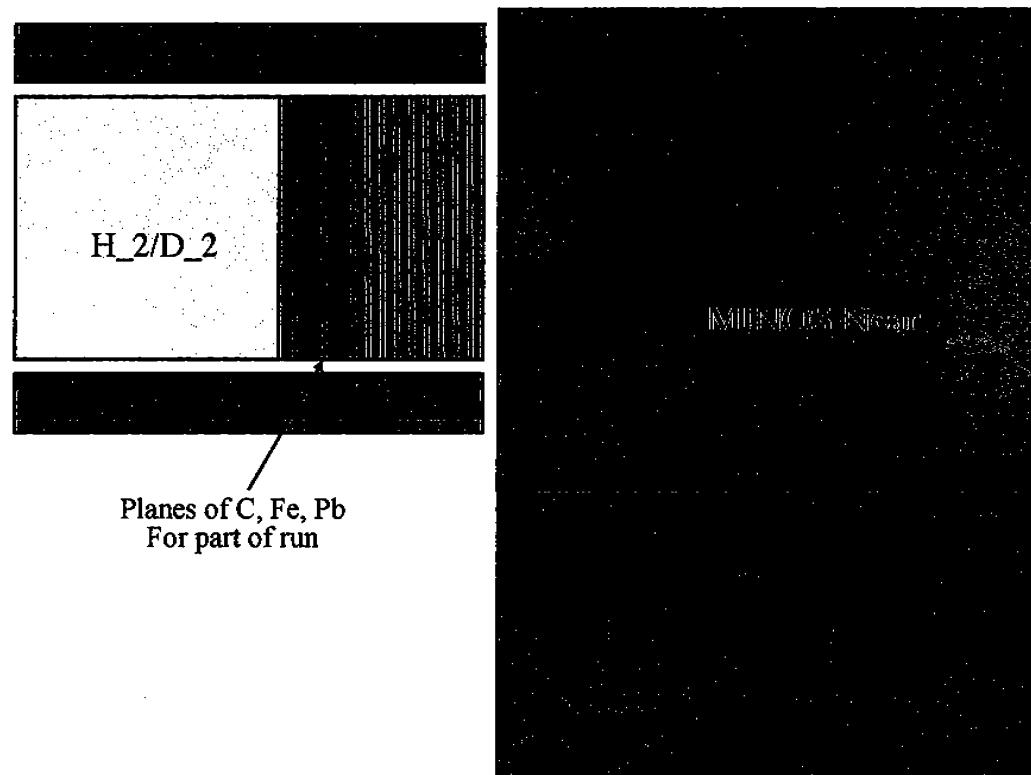
Higher Intensity Allows (?) a Liquid H₂/D₂(/O/ Ar) Target

MINERvA Fid. vol:
 $r = 80 \text{ cm}$. $l = 150 \text{ cm}$.

350 K CC evts in
LH₂ 800 K CC evts in
LD₂ per year he- ν
running.

Technically **easy**/
inexpensive to build and
operate.

Meeting **safety**
specifications the **major**
effort.



Parton Distribution Functions

◆ Statistical Errors for 1 year of he-v MINERvA

x_{Bj}	CH	LH ₂	LD ₂
.6 - .65	0.6%	2.2%	1.5%
.65 - .7	0.7	2.6	1.7
.7 - .75	1.0	3.7	2.5
.75 - .8	1.3	5	3
.8 - .85	2	7	5
.85 - .9	3	11	7
.9 - 1.0	4	14	10

Would also facilitate
unprecedented studies of low
Q₂ evolution of sea / valence
distributions at lower x!

Basic Conceptual Design:

(A. Bodek, D. Casper and G. Tzanakos)

Overall dimensions and relative volumes currently being determined

EM Calorimeter:

2 mm = 1.5 mm Pb

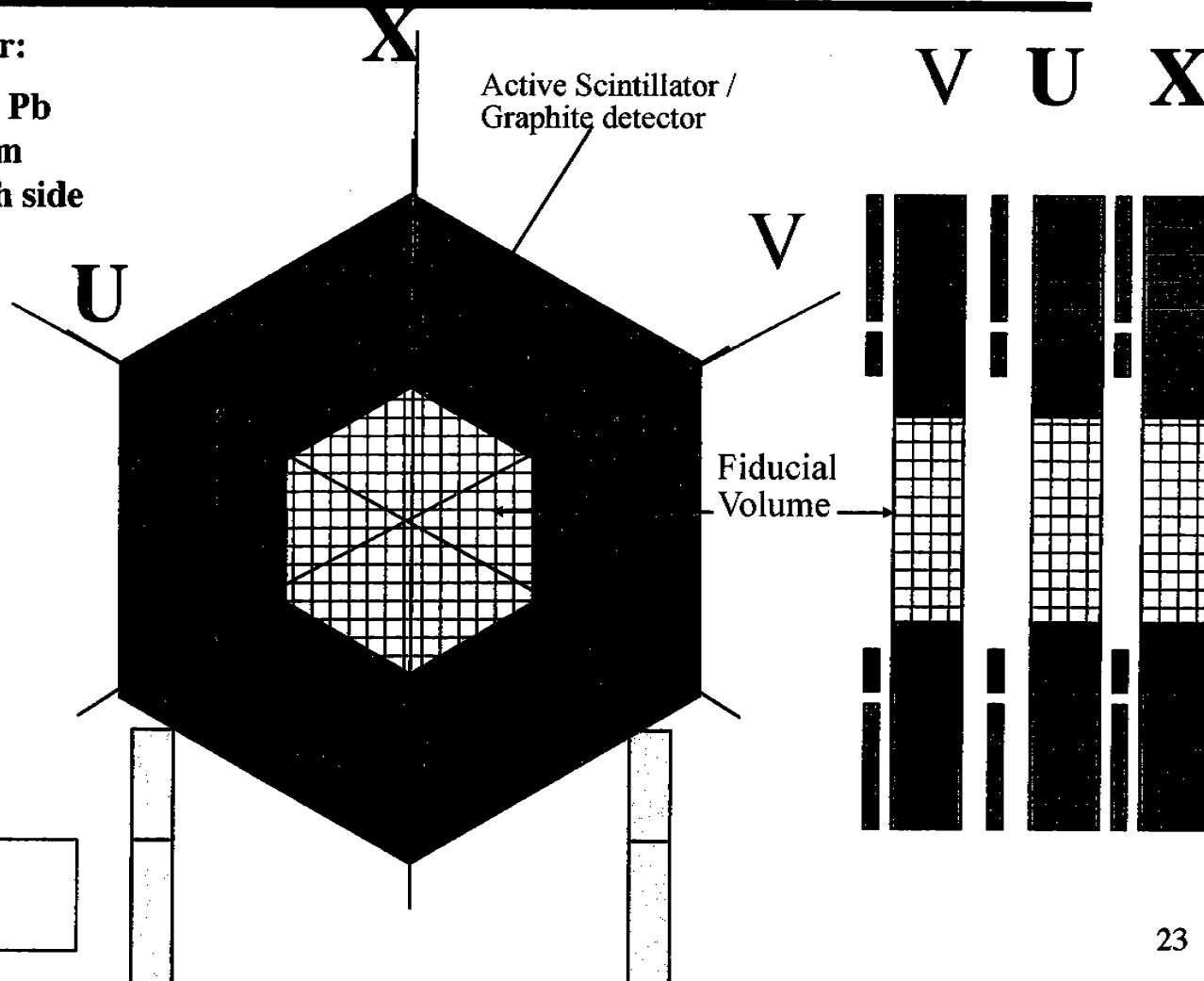
and two **0.25 mm**

stainless on each side



Downstream end:
EM Calorimeter
plus HadCal

Coils - bottom
sides only



MINER ν A Detector:

Basic Conceptual Design - Coordinator: K. McFarland

- ◆ Triangular \approx (2-3 cm base x 1-2 cm height) scintillator (CH) strips with fiber readout. **Fully Active** ($\lambda_{int} = 80$ cm, $X_0 = 44$ cm) / alternate with C planes $> \rho$ and nuclear tgt.



- ◆ Favored Photo-sensor: MAPMT (M64 a la MINOS)
- ◆ Example fid. vol: ($r = .8$ m $L = 1.5$ m): 3 tons pure plastic or 5 tons with graphite
 $R = 1.5$ m - $p: \mu = .45$ GeV/c, $\pi = .51$, $K = .86$, $P = 1.2$
 $R = .75$ m - $p: \mu = .29$ GeV/c, $\pi = .32$, $K = .62$, $P = .93$
- ◆ **Nuclear targets: of C, Fe and Pb.-**
- ◆ **Surround fully active detector with em-calorimeter, hadron-calorimeter and magnetized μ -id / spectrometer**
- ◆ **Use MINOS near detector as forward μ -identifier / spectrometer.**
- ◆ **Attempt to constrain detector size so can be moved to an off-axis position.**

Detector (3 ton CH, 2 ton A): Event Rates; CC - $E_\mu > 0.35$ GeV

Event rates (2.5×10^{20} protons per year)

	MINOS Parasitic (3 years)	Off-axis Parasitic (1 year, me- ν)	Prime User (1 year, he-ν)	Prime User (2 year, he -ν)
CH	2.60 M	2.10 M	4.80 M	2.70 M
C	1.70 M	1.40 M	3.20 M	1.80 M
Fe	1.70 M	1.40 M	3.20 M	1.80 M
Pb	1.70 M	1.40 M	3.20 M	1.80 M
LH ₂		0.15 M	0.35 M	0.20 M
LD ₂		0.35 M	0.80 M	0.45 M

ν -Scattering Physics Topics with Proposed Beam Energies and Statistics

Measure during initial MINOS exposure

- ◆ Quasi-elastic neutrino scattering and associated form-factors.
- ◆ (Contribution of the strange quark to proton spin through ν elastic scattering.)
- ◆ Resonance production region.
- ◆ Nuclear effects involving neutrinos, including NC/CC ratio.

Need antineutrinos for (maximal) physics output

- ◆ $\sin^2\theta_W$ via the ratio of NC / CC (as well as $d\sigma/dy$ from ν -e scattering) to check the surprising NuTeV result.
- ◆ Very high-x parton distribution functions.
- ◆ Nuclear effects for valence and sea quarks.
- ◆ Parton distribution functions (pdf) via all 6 structure functions.
- ◆ Leading exponential contributions of pQCD.
- ◆ Charm physics including the mass of the charm quark m_C (improved accuracy by an order of magnitude, V_{cd} , $s(x)$ and, independently, $s(\bar{x})$).
- ◆ Strange particle production for V_{us} , flavor-changing neutral currents and measurements of hyperon polarization.

Physics of the Proposal

- ◆ Quasi-elastic Reaction - MINOS 3 year run, 3 ton fid. Vol - 420 K events
 - ▼ Precision measurement of $\sigma(E_\nu)$ and $d\sigma/dQ$, constrain ν -beam systematics
 - ▼ Precision determination of F_A
 - ▼ Study of nuclear effects and their A-dependence e.g. proton intra-nuclear rescattering
- ◆ Resonance Production (Δ , N^* ..) Exclusive channels - 450 K 1- π events
 - ▼ Precision measurement of σ and $d\sigma/dQ$ for individual channels
 - ▼ Detailed comparison with dynamic models, comparison of electro- & photo production in 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
- ◆ Nuclear Effects - > 1700 K events per nuclear target
 - ▼ Measure π and p multiplicities as a function of E_ν and A : convolution of quark flavor-dependent nuclear effects and final-state intra-nuclear interactions
 - ▼ Measure NC/CC as a function of E_H off different nuclei
 - ▼ Measure shadowing, anti-shadowing and EMC-effect as well as flavor-dependent nuclear effects and extract nuclear parton distributions

Physics of the Proposal - continued

- ◆ Total Cross-section and Structure Functions - 1200 K transition, > 1000 K DIS
 - ▼ Precision measurement of low-energy total cross-section
 - ▼ Understand resonance-DIS transition region - duality studies with neutrinos
 - ▼ Detailed study of high- x_{Bj} region: extract pdf's and leading exponentials
- ◆ Coherent Pion Production - 200 K plastic plus nuclear targets
 - ▼ Precision measurement of $\sigma(E)$ for NC and CC channels
 - ▼ Measurement of A-dependence
 - ▼ Comparison with theoretical models models
- ◆ MINERvA and Oscillation Physics -
 - ▼ MINERvA measurements enable greater precision in measure of Δm , $\sin^2\theta_{23}$ in MINOS
 - ▼ MINERvA measurements fundamental for θ_{13} in MINOS and off-axis experiments
 - ▼ MINERvA measurements as foundation for measurement of possible CP and CPT violations in the ν -sector

Physics of the Proposal - continued

- ◆ Strange and Charm Particle Production -
 - ▼ Exclusive channel $\sigma(E_\nu)$ precision measurements - importance for nucleon decay background studies.
 - ▼ Hyperon Production yielding new measurements of CKM using ν
 - ▼ Exclusive charm production channels at charm threshold to constrain m_c
- ◆ Generalized Parton Distributions -
 - ▼ 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
 - ▼ 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 $\rightarrow N^*$ form factors