"Conventional" Neutrino Physics in the Near and Not-so-Near Future

Is there anything left to learn from ν Deeply Inelastic Scattering?

Jorge G. Morfin
Fermilab

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HERA is not the **only** place to study Deeply Inelastic Scattering

- $\sigma_{\nu N}$ is many orders of magnitude smaller than σ_{eN}. Events are hard to accumulate.
- However, $\nu/\bar{\nu}$ have ability to resolve flavor of nucleon's constituents: ν interacts with d, s, $\bar{u}$, and $\bar{c}$ while $\bar{\nu}$ interacts with u, c, $\bar{d}$ and $\bar{s}$.
- $\nu/\bar{\nu}$ have definite spin/helicity states, can they be used to determine partonic spin contribution to the nucleon?
- **The ν is a very effective partner in determining the partonic and spin structure of the nucleon via measurement of the structure functions.**

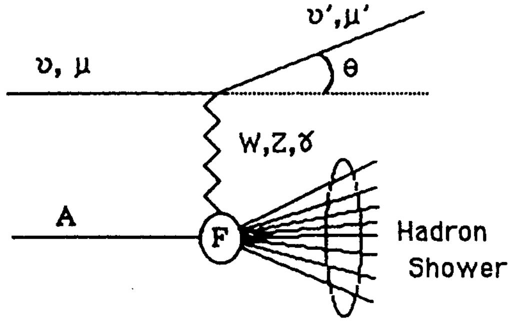
- Standard Kinematic Variables:

$$Q^2 = 4EE'\sin^2\theta/2 = -q^2$$

$$\nu = E - E'$$

$$x_{Bj} = Q^2 / 2M\nu$$

$$y = \nu / E$$



The Vocabulary of Deep Inelastic Lepton-Hadron Scattering

$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G_F^2 ME}{\pi\left(1+Q^2/M_W^2\right)} *$$

$$\left[F_2^{\nu N}(x,Q^2)\left(\frac{y^2+(2Mxy/Q)^2}{2+2R_L^{\nu N}(x,Q^2)}+1-y-\frac{Mxy}{2E_\nu}\right)+xF_3^{\nu N}(x,Q^2)y\left(1-\frac{y}{2}\right)\right]$$

$$R_L(x,Q^2) = \frac{F_2(x,Q^2)}{2xF_1(x,Q^2)}\left(1-(2Mx/Q)^2\right)-1$$

Structure Function Measurements:

- Start with unpolarized functions.
- Latest measurements of F_2 and xF_3 from CCFR. Results from E-815/NuTeV "soon".

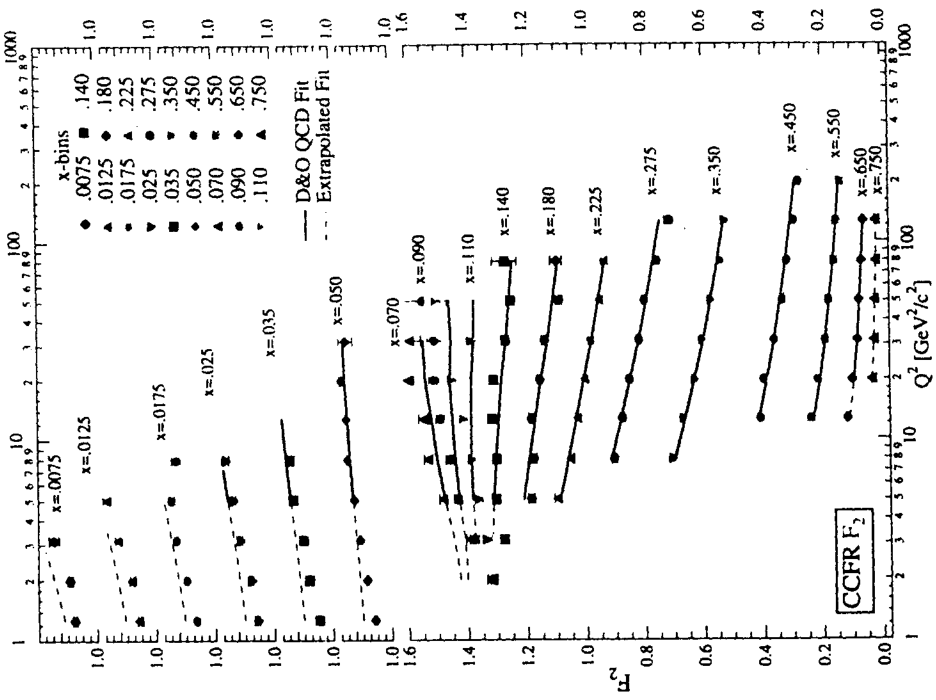
- Based on 950,000 ν events and 170,000 $\bar{\nu}$ events.

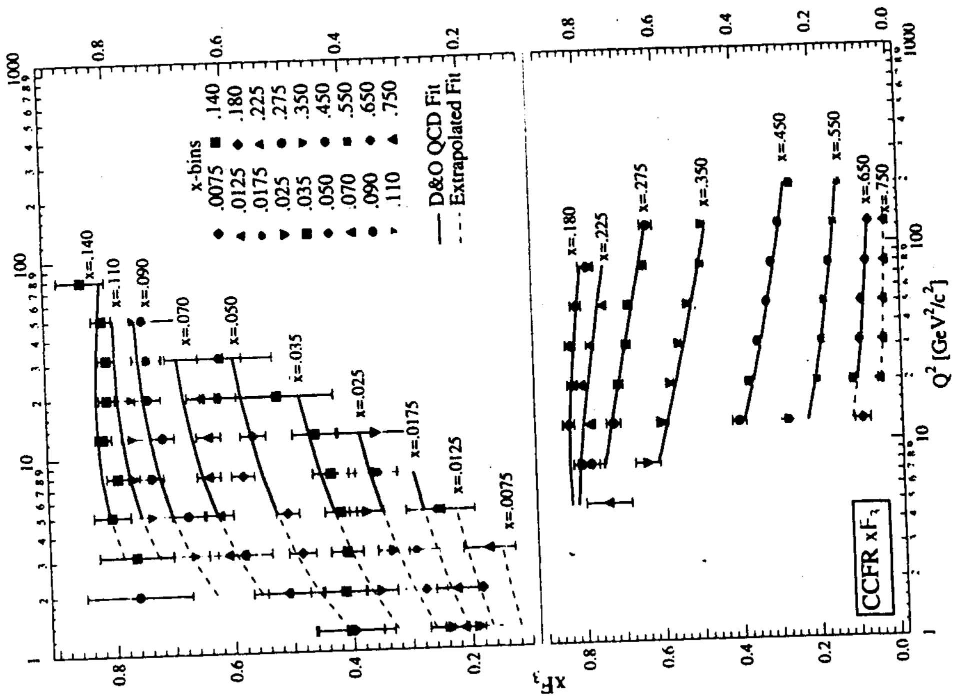
- Errors:

  F_2: stat. (1-3)%,

  xF_3: stat (2-10)%

  Systematic errors about the same size





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Current Status of Neutrino Measurements of $R_L(x,Q^2)$ - on Fe

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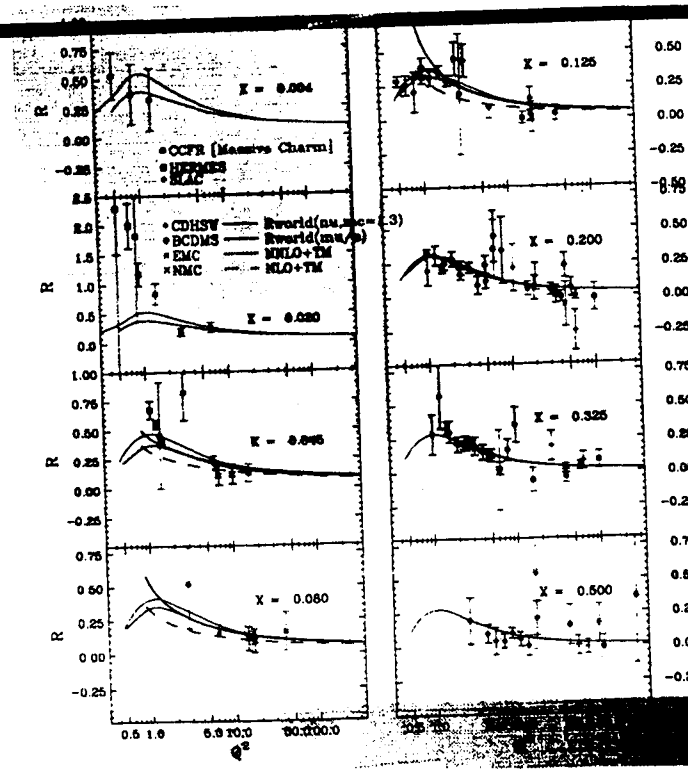

■ **Heavy nuclear targets** needed to accumulate sufficient statistics. **Measuring ν-Fe not ν-N**

■ **Statistics and systematics not yet at level to allow extraction of all possible information.**

Independent ν and $\bar{\nu}$ structure functions not yet well measured!

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Effect of These Compromises: Measured Structure Functions

$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G_F^2 ME}{\pi\left(1+Q^2/M_W^2\right)} *$$

$$\left[F_2^{\nu N}(x,Q^2)\left(\frac{y^2+(2Mxy/Q)^2}{2+2R_L^{\nu N}(x,Q^2)}+1-y-\frac{Mxy}{2E_\nu}\right)+xF_3^{\nu N}(x,Q^2)y\left(1-\frac{y}{2}\right)\right]$$

$$\frac{d^2\sigma^{\bar{\nu} N}}{dxdy} = \frac{G_F^2 ME}{\pi\left(1+Q^2/M_W^2\right)} *$$

$$\left[F_2^{\bar{\nu} N}(x,Q^2)\left(\frac{y^2+(2Mxy/Q)^2}{2+2R_L^{\bar{\nu} N}(x,Q^2)}+1-y-\frac{Mxy}{2E_{\bar{\nu}}}\right)-xF_3^{\bar{\nu} N}(x,Q^2)y\left(1-\frac{y}{2}\right)\right]$$

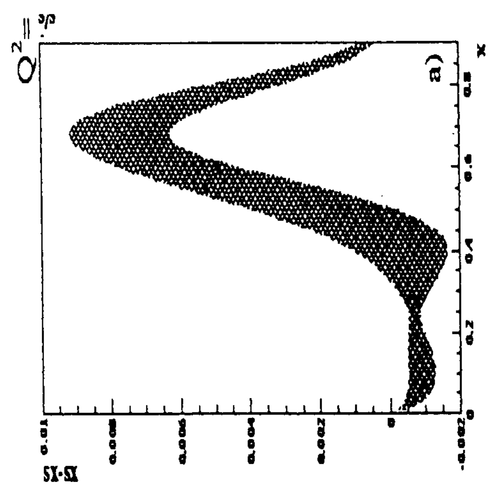
$$R_L(x,Q^2) = \frac{F_2(x,Q^2)}{2xF_1(x,Q^2)}\left(1-(2Mx/Q)^2\right)-1$$

$$F_2^{\overline{\nu}N}(x,Q^2) = x\left[u + \overline{u} + d + \overline{d} + 2\overline{s} + 2c\right]$$
$$F_2^{\nu N}(x,Q^2) = x\left[u + \overline{u} + d + \overline{d} + 2s + 2\overline{c}\right]$$
$$xF_3^{\overline{\nu}N}(x,Q^2) = x\left[u + d - \overline{u} - \overline{d} - 2\overline{s} + 2c\right]$$
$$xF_3^{\nu N}(x,Q^2) = x\left[u + d - \overline{u} - \overline{d} + 2s - 2\overline{c}\right]$$

- What do we gain by measuring separate ν and $\overline{\nu}$ structure functions?
- Does $s = \overline{s}$ and $c = \overline{c}$ over all x? $F_2^{\nu} - F_2^{\overline{\nu}} = 2[(s - \overline{s}) + (\overline{c} - c)]$
- If so.....

$$F_2^{\nu} - xF_3^{\nu} = 2(\overline{u} + \overline{d} + 2\overline{c}) = 2U + 4\overline{c}$$
$$F_2^{\overline{\nu}} - xF_3^{\overline{\nu}} = 2(\overline{u} + \overline{d} + 2\overline{s}) = 2U + 4\overline{s}$$
$$xF_3^{\nu} - xF_3^{\overline{\nu}} = 2[(s + \overline{s}) - (\overline{c} + c)] = 4\overline{s} - 4\overline{c}$$

$\overline{s(x)}$ from CDHSW data?



F. Zomer, Eur.Phys.J C12:243,2000

– the CDHSW ν data at low y are larger than both CCFR data and the QCD prediction while their $\overline{\nu}$ data agree with CCFR data

◁ $\frac{d^2\sigma}{Edxdy}(\nu, y = 0) \sim [q + \bar{q}] = (u + \bar{u}) + (d + \bar{d}) + s.$
$\frac{d^2\sigma}{Edxdy}(\bar{\nu}, y = 0) \sim [q + \bar{q}] = (u + \bar{u}) + (d + \bar{d}) + \bar{s}$

– Thus, the CDHSW data could introduce a large asymmetry between s and $\bar{s}$ ($s > \bar{s}$) because u and d are well constrainted

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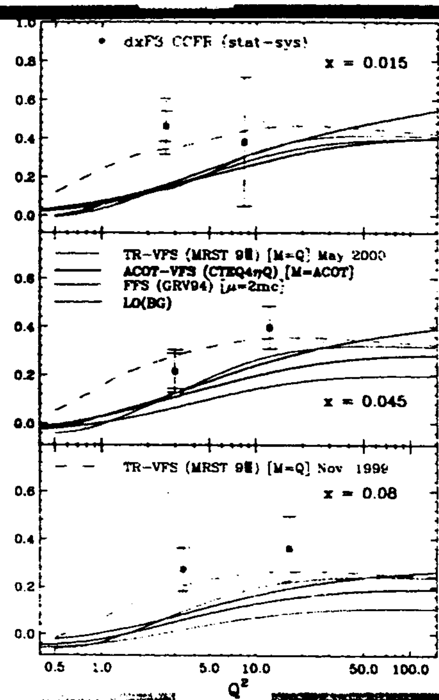
- ΔxF_3 sensitive to s and c (model dependent). Extract directly from data-model independent.
- Extraction of F_2 also dependent on ΔxF_3.

$d^2\sigma(\nu+\bar{\nu})\, C \approx (1-y+\ \ y^2)F_2 + (y-y^2)\Delta xF_3$

- Newly extracted F_2^{ν} at low x (< 0.1) now agrees with F_2^{μ}, a long-standing problem. has been eliminated!
- NuTeV results with increased $\bar{\nu}$ data "soon".



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How (In Principle) to Extract all SIX Measured Structure Functions

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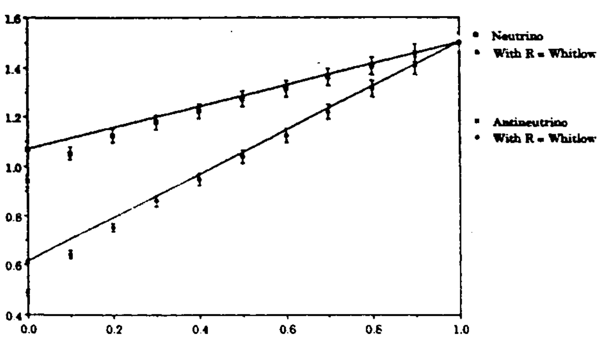
$$\frac{d\sigma^{\nu A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\nu A}(x,Q^2) + xF_3^{\nu A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\nu A}(x,Q^2) - xF_3^{\nu A}(x,Q^2)\right)\right]$$

$$\frac{d\sigma^{\bar{\nu} A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) - xF_3^{\bar{\nu} A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) + xF_3^{\bar{\nu} A}(x,Q^2)\right)\right]$$

$-2y^2F_L(x,Q^2)$

$$\frac{\sigma\left(x,Q^2,(1-y)^2\right)}{G^2/2\pi x}$$



x = .10
$Q^2 = 3$ GeV^2

$(1-y)^2$

- Statistics: need sufficient events in each x - Q^2 bin to populate $(1-y)^2$ distribution for fit to R, slope and intercept. Goal: Order 1% or better.
- Beam systematics: minimize "wiggle" in slope and intercept. Goal: Order 2% or better
- Measured quantities: need good calibration for confidence in $(1-y)^2$ and to understand migration/ smearing between x-Q^2 bins. Goal: Better than CCFR / NuTeV.
- Particularly vicious complications involving treatment of the charm quark.

Effect of These Compromises: Heavy Nuclear Targets

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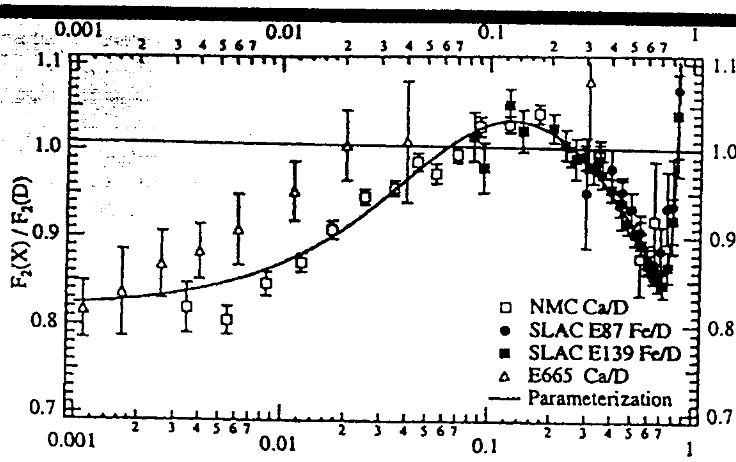


- nuclear effects measured (with high statistics) in μ-A <u>not in ν-A</u>.
- from low-to-high x_{Bj} go through: shadowing, anti-shadowing, "EMC" effect, Fermi motion.

- In general, $\nu/\bar{\nu}$ can isolate nuclear effects **for valence quarks from the sum of all quarks.**
- More specifically, recall

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

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

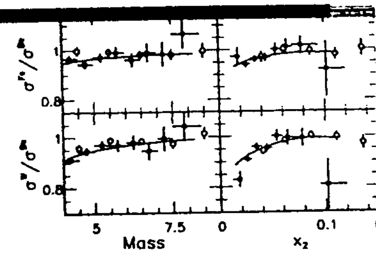
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2[(s + \bar{s}) - (\bar{c} + c)] = 4\bar{s} - 4\bar{c}$$

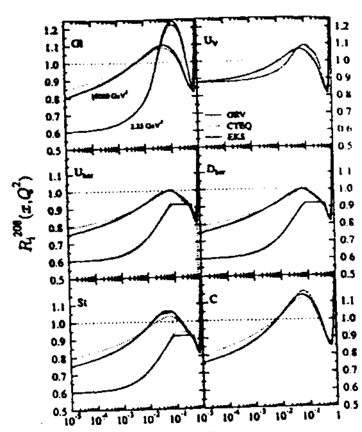
- Could measure nuclear effects on individual partons...

Any Indication of a Difference in Nuclear Effects of Valence and Sea Quarks?

- Nuclear effects similar in Drell-Yan and DIS for x < 0.1. Then no "anti-shadowing" in D-Y[a] while "anti-shadowing" seen in DIS (5-8% effect in NMC). Indication of difference in nuclear effects between valence & sea quarks?

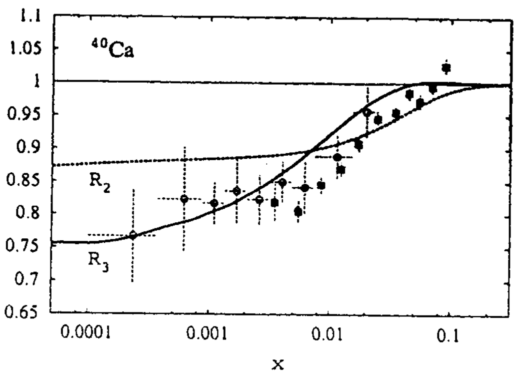
- This quantified by K.J. Eskola[b] et al within LO (t = 2) DGLAP using initial nuclear distributions from CTEQ4L and GRV-LO and assume scale evolution of nuclear parton densities is perturbative.

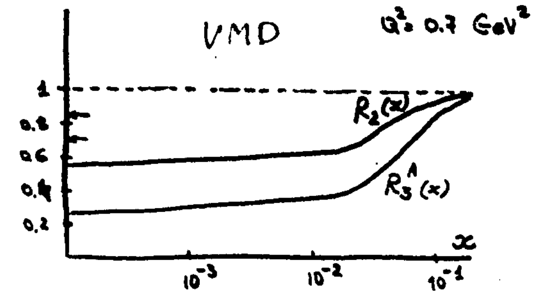




[a] hep-ex/9906010 [b] hep-ph/9807297

- S.A.Kulagin has calculated shadowing for F_2 and xF_3 in ν-A interactions based on a non-perturbative parton model.
- At 5 GeV^2, ratio of shadowing $xF_3 : F_2 \approx 0.5$ at x = .02 to ≈ 2 at x = .0001.
- Most recently calculated shadowing in VMD region (lower Q^2 : dominant for x < .01) and finds significantly stronger shadowing.

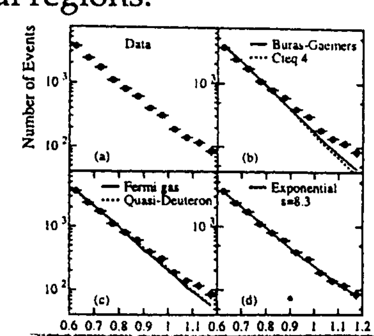




Another Open Nuclear Effects Question: Behavior of F_2 as x --> 1.0 in Nuclear Environment

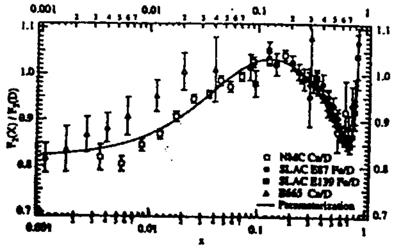
- Need to add more than Fermi gas model to simple nucleon model to reproduce behavior of F_2 at high x in nucleus.
- Few-nucleon-correlation and multi-quark models allow quarks to have higher momentum ---> high x tail with $F_2 \propto e^{-ax}$.
- Analyses by SLAC, BCDMS, CEBAF and CCFR with values of a varying 7 < a < 17 in various kinematical regions and targets.
- BCDMS and CCFR are in similar kinematical regions:

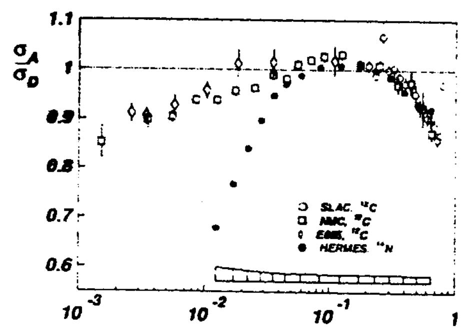
BCDMS (μ + C): a = 16.5 ± 0.5
CCFR (ν + Fe): a = 8.3 ± 0.7 ± 0.7(syst.)



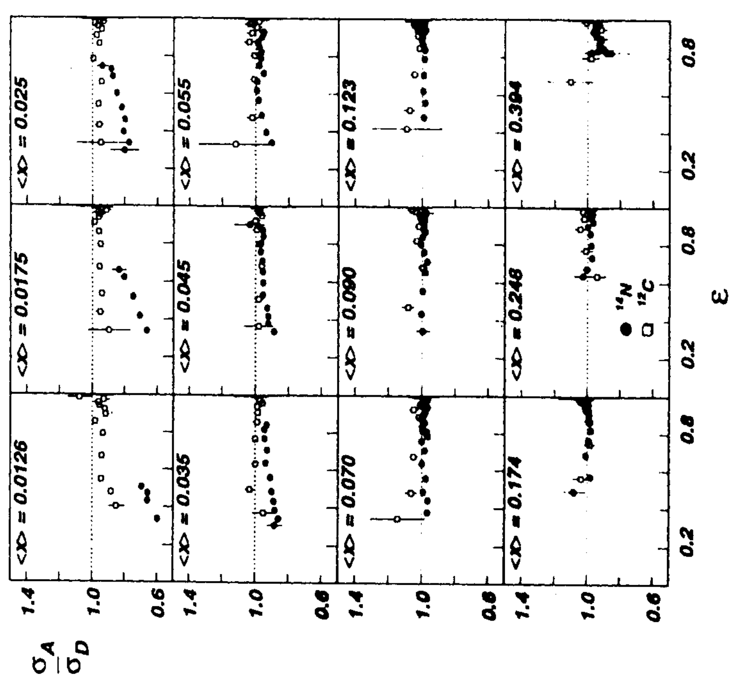
- Is a dependent on nucleus?
- Is a dependent on ν vs. μ?

- NMC and E665 data for $Q^2 > 1.0$ and essentially no Q^2 dependence seen.
- HERMES data at $.01<x<0.1$ has $Q^2 < 1.0$.
- HERMES effect translates into an enhancement in F_L and a suppression in $2xF_1$ due to nuclear effects.
- Being tested with further data at HERMES and JLab.





More plots for HERMES effect



In e/μ-N scattering $\frac{d^2\sigma}{dx\,dy} \sim 2xF_1(1+\epsilon R)$ $\quad \epsilon = \frac{2(1-y)}{1+(1-y)^2}$

- $\frac{\sigma_A}{\sigma_D} = \frac{F_2^A(1+\epsilon R_A)(1+R_D)}{F_2^D(1+\epsilon R_D)(1+R_A)}$

▷ So if $\epsilon \to 1$, $\frac{\sigma_A}{\sigma_D} = \frac{F_2^A}{F_2^D}$,

A good agreement between NMC C & HERMES N data

▷ Strong R dependence

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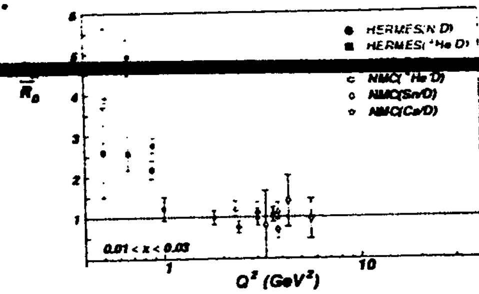
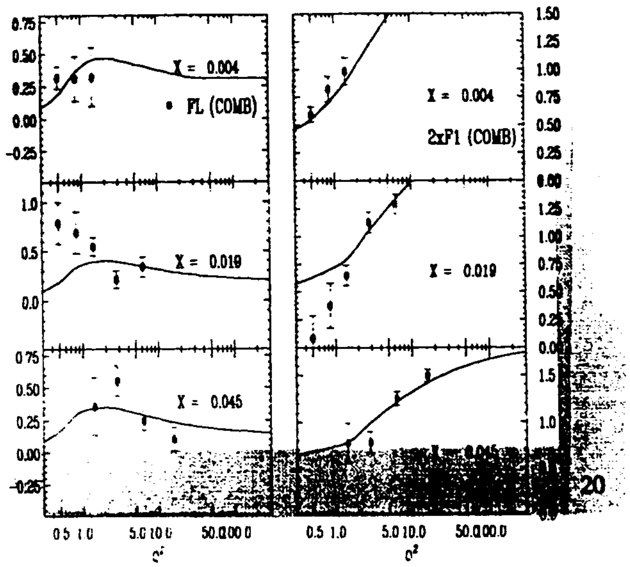
ν scattering.



- Use CCFR F_2 data and R_{world} (with no HERMES effect) to determine F_L and $2xF_1$.
- Observe an interesting blip at x = 0.019 in the "right" Q^2 region.
- Why no effect in the x =.004 bin?
- Any reason to expect a difference in nuclear dependence of R: ν vs. e/μ?



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Goals in Study of Nuclear Effects with ν/ ν scattering

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- Overall Goal: Measure nuclear effects across full x_{Bj}-range in ν/$\bar{\nu}$ scattering off a variety of targets.
- Goal: Measure nuclear effects separately for F_2 and xF_3. What are the nuclear effects for valence quarks alone?
- Goal: Determine nuclear dependence of R at low x and Q^2
- Long-term Goal: High statistics ν/ ν scattering experiment on H_2 and D_2 as well as heavy nuclei.

Open Questions:

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- **NuMI**
  - Uses high intensity Main Injector with 120 GeV protons and horn focussed π & K beam for ν.
  - MINOS (Oscillation Expt.) using low-energy ν beam on schedule for 2003.
  - 2nd generation high energy DIS expt. in 2006?
- **Neutrino Factory**
  - Uses muon storage ring with production of ν_μ and ν_e via decay of $\mu^\pm$
  - Possible in 2010 - 2015 time frame

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NuMI ν/ $\bar{\nu}$ events: Intensity and Kinematic Domain

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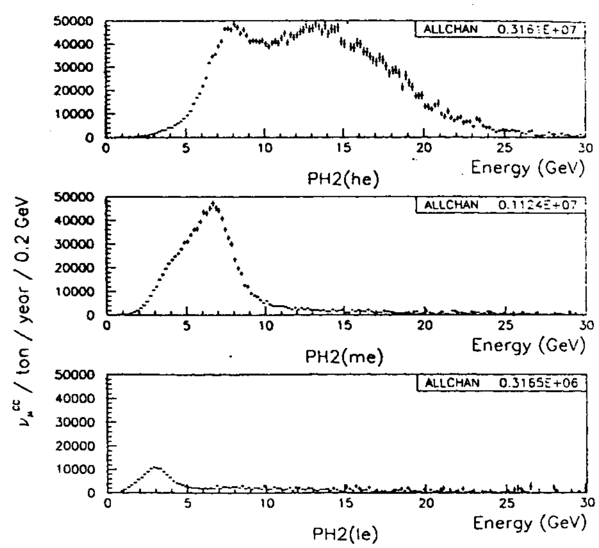
3.7×10^{20} protons/year on the NuMI target will yield

2.5×10^6 CC ν
0.6×10^6 CC $\bar{\nu}$
events / year-ton

high energy-configuration

Event Rates at MINOS Near Detector



$W^2 > 5$ GeV^2 (26 M events) In units of 10^5 events/year

x	Q^2 = 0	2	4	8	16	>30 GeV^2
x = 0						
	22.6	.1	. 04			
.03						
	15.6	. 6	. 1	. 05		
.05						
	17.6	2.4	. 5	.06	.01	
.075						
	14.9	5.6	. 6	.2	.02	
.10						
	11.5	6.5	1.7	.25	.02	
.125						
	8.9	7.1	3.1	.2	.03	
.15						
	13.1	11.9	8.5	1.3	.3	
.20						
	12.1	18.3	17.8	6.5	.8	.01
.30						
	2.2	13.6	17.1	11. 9	2.0	.03
.45						
	.9	1.7	6.9	6.9	2.8	.2
.65						
	.1	. 5	1.4	.8	.5	.01
1.0						

(Expect ≈ **100,000 events** x > 0.75)

Modified Near Detector (MIDIS) for a High Energy Beam Run

- Standard MINOS near detector: Solid scintillator planes with fiber readout between 2.5 cm thick Fe plates (0.40 ton fiducial/ plate) yielding 16 tons in 40 plane target region.
- This translates into 40 M ν events/yr. and 10 M $\bar{\nu}$ / yr. in the fiducial volume.

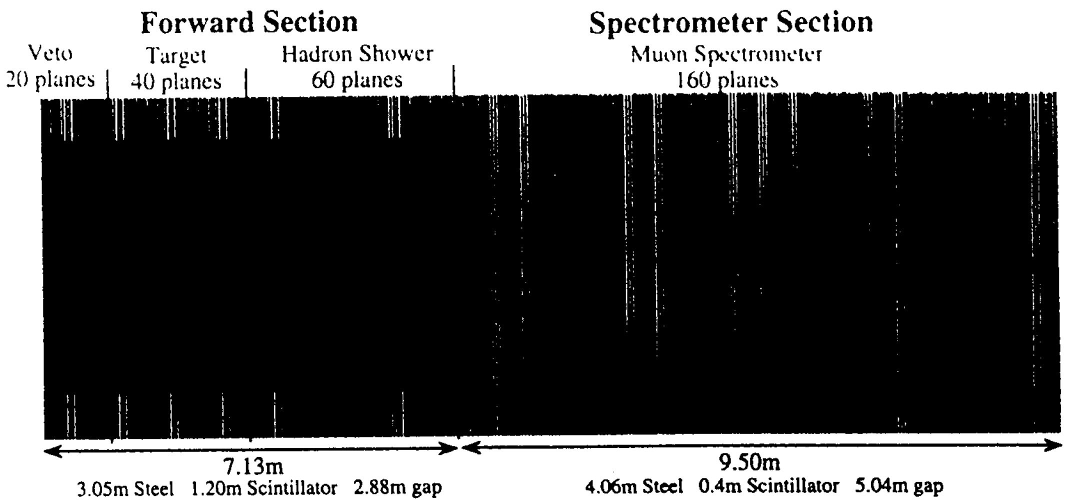
MIDIS Near Detector

- Retain 11 fiducial tons of Fe with 26 planes.
- Assume 12 (instrumented) planes of C (≈ 4 M fiducial events / yr.), 2 plane of W (5 M events) and 2 year ν and 2 year $\bar{\nu}$ run.
- Ratios: beam syst. cancel.
- Assume C-Fe-W relative target syst. same as Tevatron Muon Expt. O (1 %) added in quadrature.

Solid scintillator planes with fiber readout sandwiched between 2.5 cm thick Fe plates.

Instrumented out to $r \approx 1m$: 0.6 ton/plate

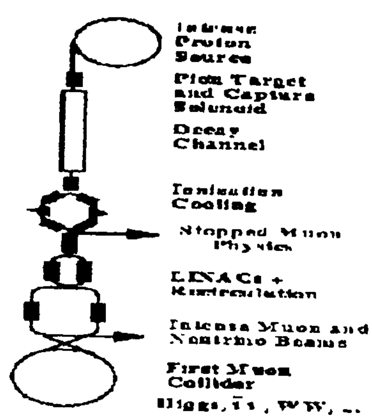
0.40 ton fiducial: 1.00 M ν events/plate - yr: $\bar{\nu} = \nu / 4.0$



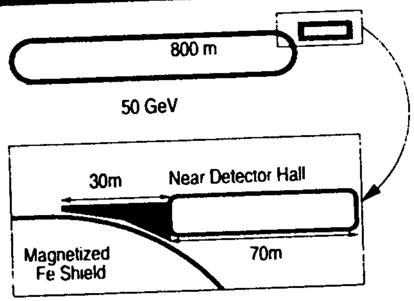
Further in the Future: DIS with Neutrinos from a Muon Storage-Ring/Collider

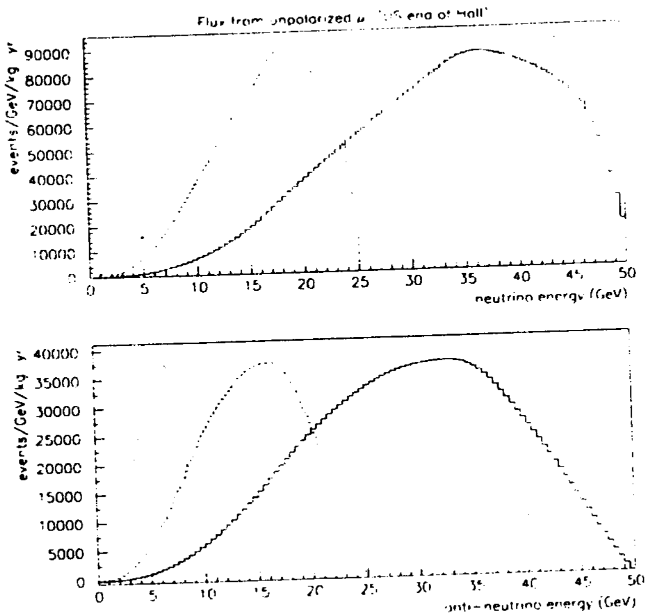
How does a muon collider work?

- Intense Proton Source (8 - 16 GeV, 10^{21-22} /year)
- Pion Target and Capture Solenoid
- Decay Channel (yield 10^{20-21} muons /year)
- Ionization Cooling Section
- LINAC + Storage Ring
- Muon Collider
- DIS from μP collider and intense ν beams



Fluxes





50, 25, 10 GeV μ beams shown

If lengths scale with E_μ $\Longrightarrow$ short-baseline $N_\nu \propto E_\nu$

The Opportunity

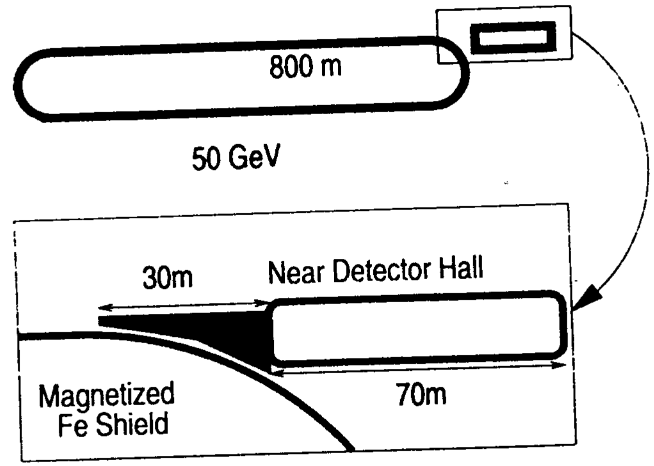
10^{20}/yr μ decays in the green straight section $\Rightarrow$

5–8% of all interactions in detector 10 cm in radius

40–50% of all interactions in detector 50 cm in radiu

$\approx 1.5\text{–}3 \times 10^6 \times \frac{E_\mu}{50\ \mathrm{GeV}}$/kg/yr at beam center

(FNAL Neutrino Factory Study Group Parameters)



c.f.: [illegible]

Beam	$\langle E_\nu \rangle$ [GeV]	ν per
NuTeV/CCFR (Fermilab)	100	[illegible]
CHORUS/NOMAD (CERN)	30	[illegible]
MINOS Near (Fermilab)	15	[illegible]
Neutrino Factory	30	5 ~ 10

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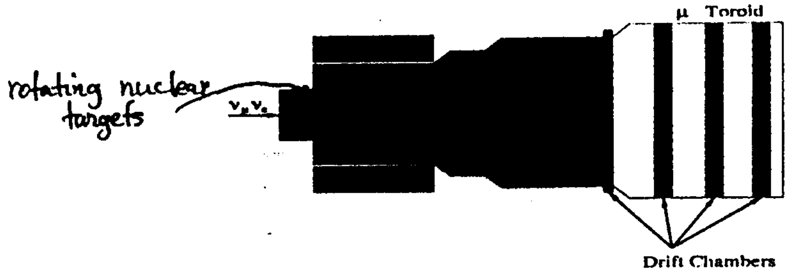

- Liquid deuterium cryogenic target followed by rotating high A targets.
- All targets (r = 10 cm) acquire 10^7 ν_μ events and 4 x 10^6 $\bar{\nu}_e$ /year.
- D_2 @ 50 cm long, C @ 3.7 cm and W @ 0.45 cm

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Compare Event Rates for Two Future Experiments

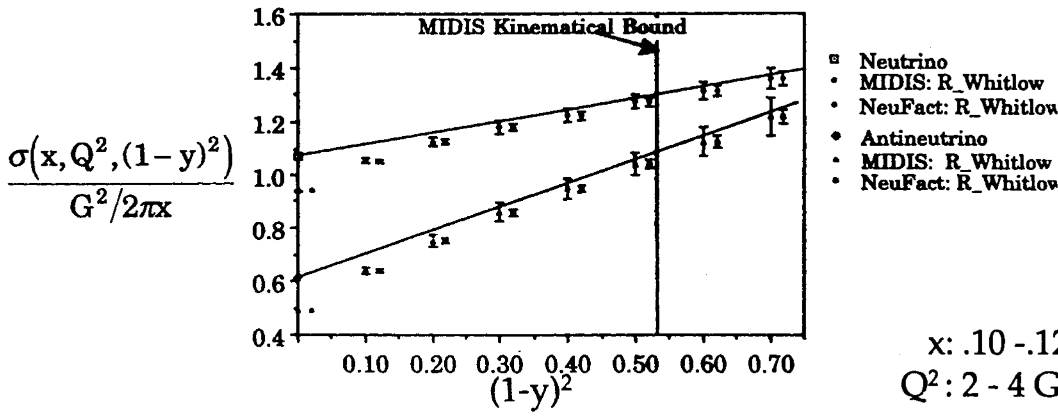
MIDIS in the NuMI Beam

- 3.7 x 10^{20} protons/year on the NuMI target.
- 2.5 x 10^6 CC ν or 0.6 x 10^6 CC $\bar{\nu}$ events /ton-year (in high energy configuration)
- Know $\phi(E_\nu)$ and $\int\phi(E_\nu)$ to < 2%
- First Beam 2003. HE beam run > 2006

Near Detector/50 GeV NuFact
(50 m away from 800 m straight section)

- 10^{20} μ decays/year
- 4.0 x 10^6 CC ν_μ and 1.7 x 10^6 CC ν_e events/kg-year (fid. vol. r < 10 cm)
- Know $\phi(E_\nu)$ and $\int\phi(E_\nu)$ to < 1.0 %
- First Beam .... a bit after MINOS runs are finished

- **MIDIS**: 26 M ν (Fe) evts (6.5 M$\bar{\nu}$ evts) /year in fid. vol.
- Analysis based on four year run
- **NuFact**: Analysis based on 2 year run
- Statistical errors **negligible** at small values of $(1-y)^2$
- R value now dominated by systematic errors



x: .10 -.125
Q^2: 2 - 4 GeV^2

MIDIS / NuFact ν Nuclear Shadowing Measurement

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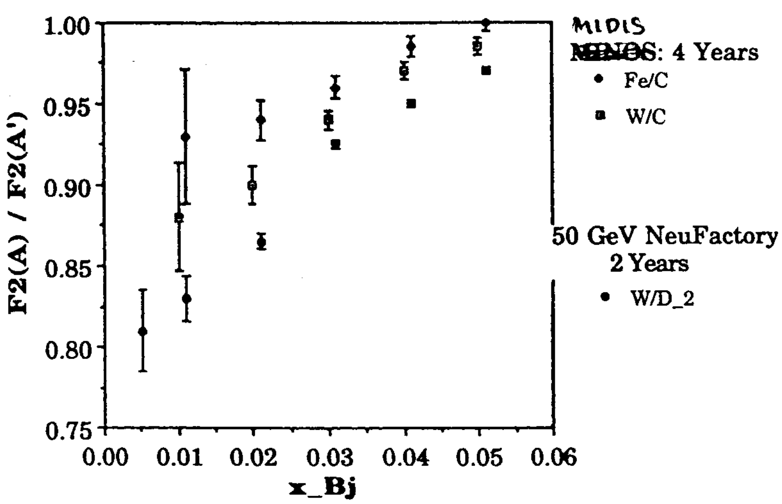
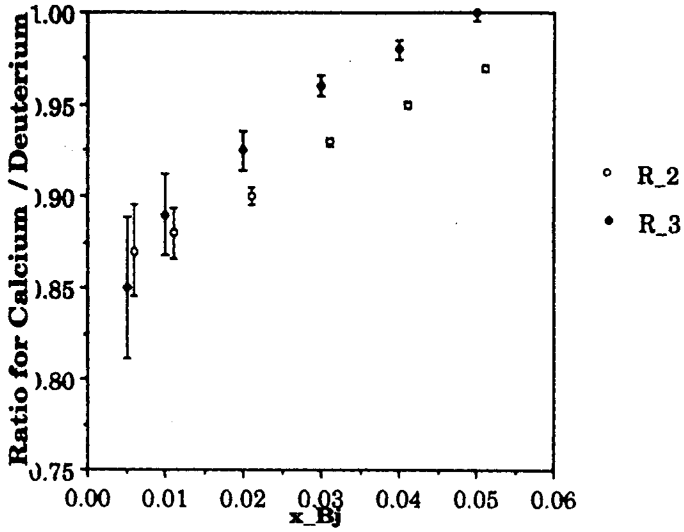
J. G. Morfin
June 2000



Kulagin's Non Perturbative Parton Model



SUMMARY

- **NuMI/MIDIS** will offer an intense, lower energy ν beam to explore with impressive statistics and reasonable systematics among other topics:
  - a first look at precision measurements of separate ν /$\overline{\nu}$ F_2, xF_3 & R.
  - study of ν /$\overline{\nu}$ nuclear effects, particularly HERMES effect!

- NuFact, a "few years" after MIDIS, with H_2, D_2, and nuclear targets as well as polarized targets:
  - improve statistical and systematic errors of MIDIS measurements.
  - Complete measurements of the partonic spin structure of nucleon.
  - High statistics charm production with "clean" final state.
  - Precision electroweak measurements; ν-e scattering.

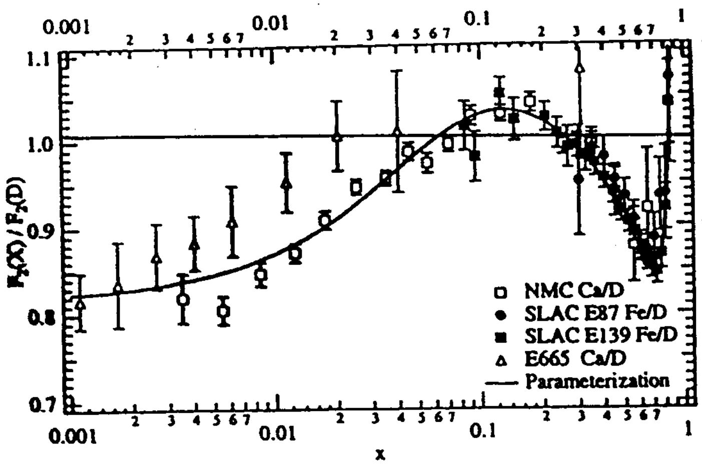
Nuclear Effects in D.I.S.

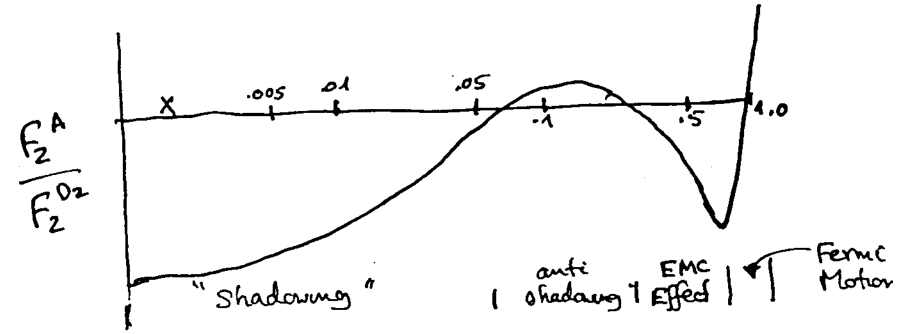
ν-DIS experiments needed nuclear targets to increase luminosity ($\rho_{Fe}/\rho_{H_2} \approx 10^2$)

In 1983 EMC compared results of μ-Fe with μ D_2 and discovered $F_2^{D_2} \neq F_2^{Fe}$

SLAC experimenters went back and reanalysed old data and confirmed "EMC Effect". Then ran a dedicated experiment

Further experimental results: BCDMS, NMC, E665 (μ, ν) extended range in x_{Bj} & Q^2, increased statistics and minimized systematical errors





1) Shadowing —

a) Vector Meson Dominance (primarily low Q^2)

q q̄ } ρ ω φ (Nucleus)

b) Parton Fusion Models

Uncertainty Principle $\Delta z \sim \frac{1}{x}$

For low x Δz greater than nucleon sep

⇒ partons from neighboring nucleons or

Gluons at higher x created by $q\bar{q}$ pairs at l

or $q + g \rightarrow q$ at higher x

2) Anti-shadowing

a) Momentum Sum Rule

b) Regge models

c) Contributions from real part of scatt ampl

"EMC Effect"

a) Conventional Nuclear Physics – Bound nucleon mass ≠ free nucleon mass $x = Q^2/2M\nu$
Can reproduce data but internally inconsistent

b) Cluster Models – multiquark (6, 9, 12 ...) clusters in the nucleus or presence of a π or a Δ in the nucleus ...

c) QCD models – reproduce the data

Fermi Motion

Smears measured F_2