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April 2001

The Future of ν Deep-Inelastic Scattering Experiments

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The Vocabulary of Deep Inelastic Lepton-Hadron Scattering

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Standard Kinematic

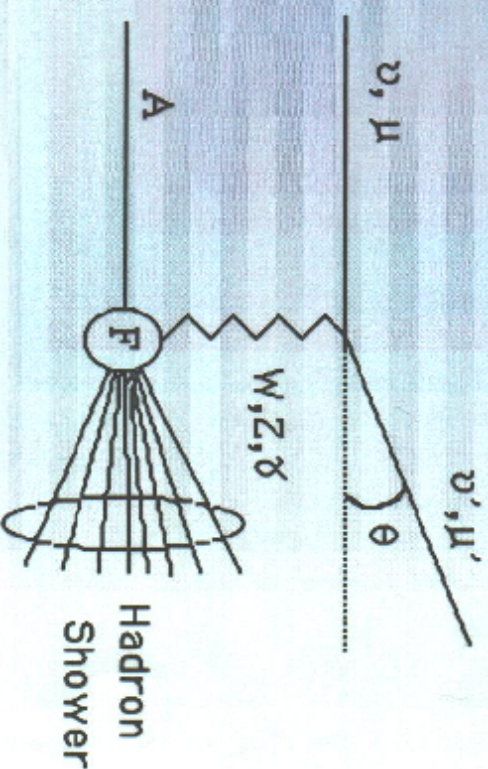
Variables:

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

$$\nu = E - E'$$

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

$$y = \nu / E$$





The Advantages of Neutrino DIS Experiments

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- Neutrinos have the ability to directly resolve flavor of the nucleon's constituents: V interacts with $d, s, \bar{u}$, and $\bar{c}$ while $\bar{V}$ interacts with u, c, d and s .

- $V/\bar{V}$ have definite spin/helicity states, which can be used to determine partonic spin contribution to the nucleon

- The V is a very effective partner to the electron/muon in determining the partonic and spin structure of the nucleon via measurement of the structure functions.



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Although Successful - ν DIS Studies Can Be Improved

- 1) Heavy nuclear targets have been required to accumulate sufficient statistics - measuring ν - Fe not ν - N.
- 2) No high statistics measurement of these nuclear effects (interesting in their own right). Had to assume ν - Fe same as μ /e - Fe to include ν data in global fits. Particularly limiting for valence quark and high x parton distribution functions
- 3) Statistics and systematics have not yet reached the level to allow extraction of all possible information. **Independent** ν and $\bar{\nu}$ structure functions have not yet been well measured.
- 4) Although CCFR/NuTeV have made great progress. Beam systematics will still be a limit for high statistics experiments.

1) - 3) indicate need for more intense ν & $\bar{\nu}$ beams

while 4) suggests need for better knowledge of those beams

Global Fitting Needs

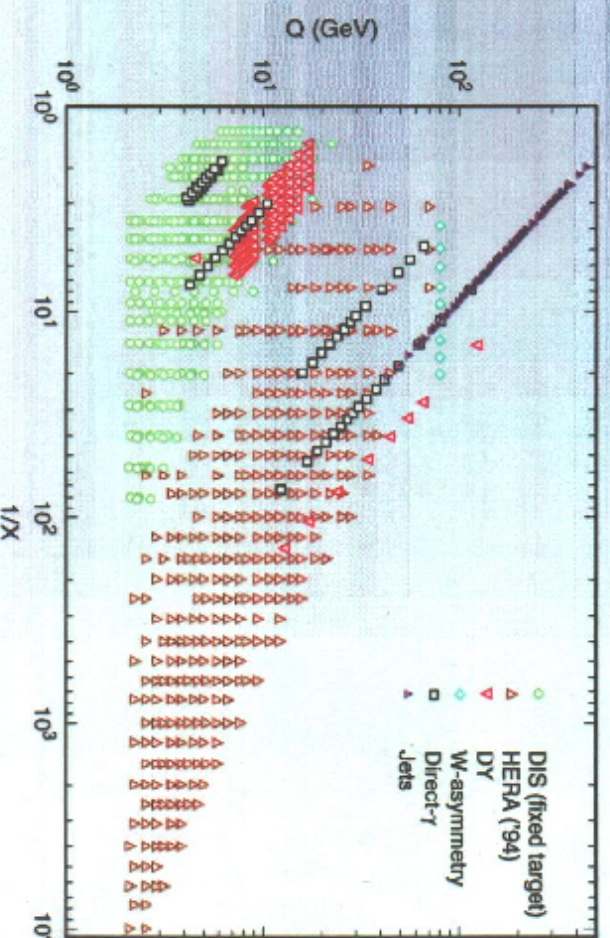
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- Improved Statistics at high x .

- (Fit into the resonance region?)

- Improved understanding of leading exponential contribution.

- Improved understanding of nuclear corrections and/or $v - H_2/D_2$





How Do We Address these Needs?

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♦ NuMI

- ♦ Uses high intensity Main Injector (plus new Proton Driver) with 120 GeV protons and horn focussed π & K beam for ν .
- ♦ A 2nd generation higher energy DIS expt. could happen > 2007?
- ♦ Knowledge of beam improved over other horn-focussed beams.

♦ Neutrino Factory

- ♦ Uses muon storage ring with production of ν_μ and ν_e via decay of $\mu^\pm$
- ♦ Entry level facility possible in 2010 - 2015 time frame.
- ♦ Excellent knowledge of beam.

<u>Beam</u>	<u>$\langle E_\nu \rangle$ (GeV)</u>	<u>Evts/kg-year</u>
CCFR/NuTeV	100	O(10)
NuMI (HE - configuration)	17	$(.3 - 1.0) \times 10^4$
ν Factory (25 GeV μ)	17	3×10^5



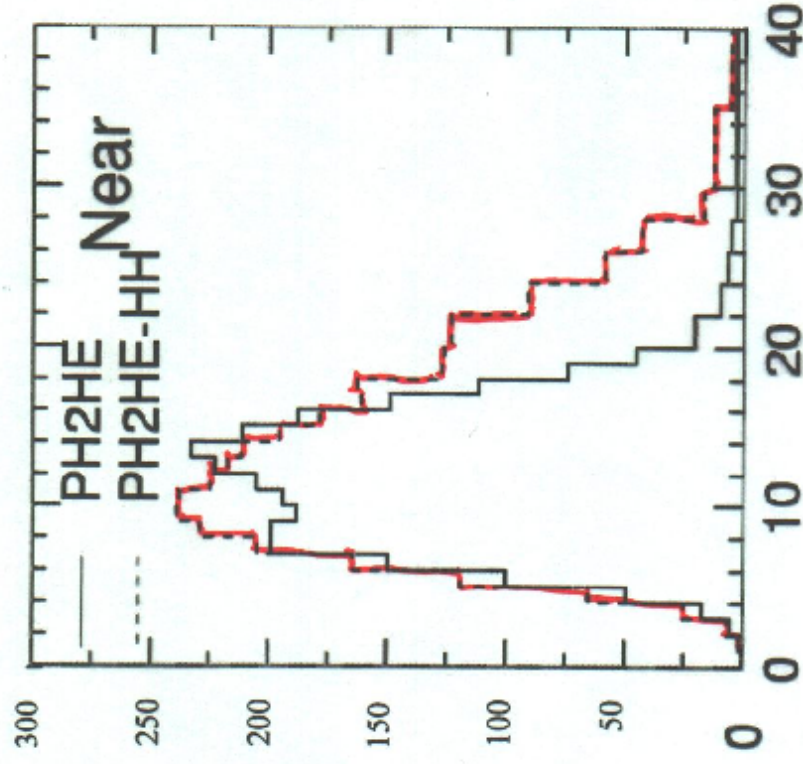
NuMI $\nu/\bar{\nu}$ events: High Energy Configuration

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- Three configurations (Zoom-lens) of the two focusing parabolic horns - low, medium and "high energy" beams
- A horn based narrow-band beam has been studied
- Auxiliary experiment(P-907) to measure π , K, p production spectra off the NuMI target. --> $\phi(E_\nu)$ and $\int \phi(E_\nu)$ to $\leq 2\%$

**$(3.0 - 10.0) \times 10^3$ CC ν events /
kg-year. $\bar{\nu}$ yield 1/4**

Events / kg - year - GeV





Neutrino Event Kinematic Domain: H-E Configuration - MINOS Near Detector

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

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

(Expect $\approx 100,000$ events $x > 0.75$)

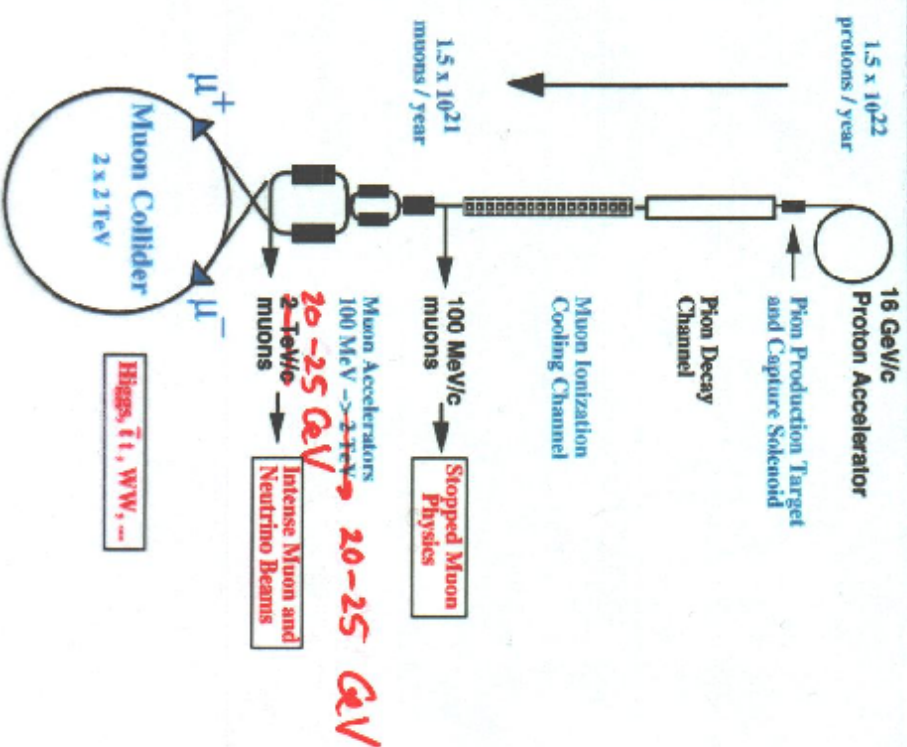


Further in the Future: DIS with Neutrinos from a Muon Storage-Ring/Collider

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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 $\rightarrow$ NuFact
- ✿ Muon Collider





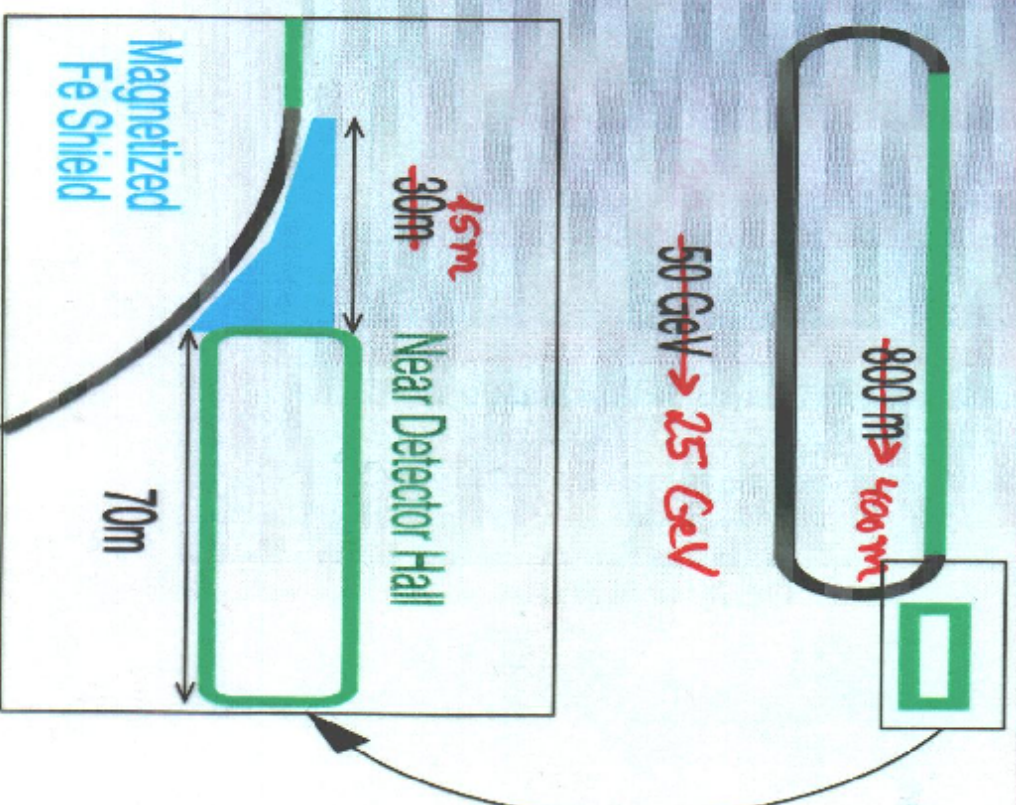
The Neutrino Factory

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- 10^{20} 25 GeV μ decays in the straight section yields $\approx 1.5 \times 10^6$ events/kg-year within $r = 10$ cm.

- Radial Distribution:
6% within $r = 10$ cm
45% within $r = 50$ cm).

- Not only is the event rate a factor 100 increase over NuMI but concentrated in center allowing smaller detectors

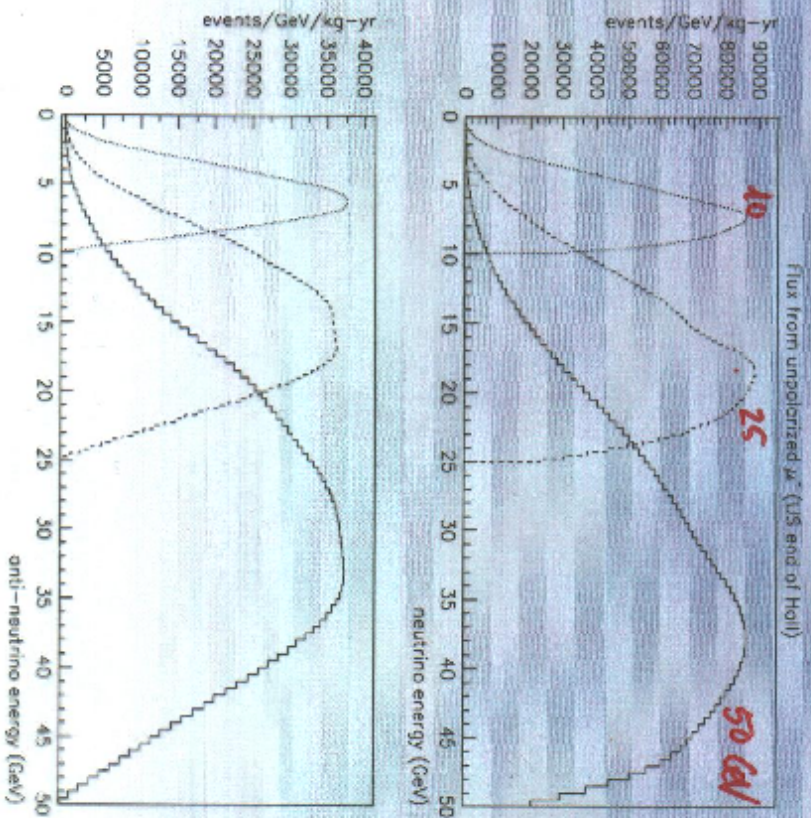




Neutrino Factory: Event Energy and Radial Distribution

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10, 25 and 50 GeV Muons





Neutrino Factory: Kinematic Range

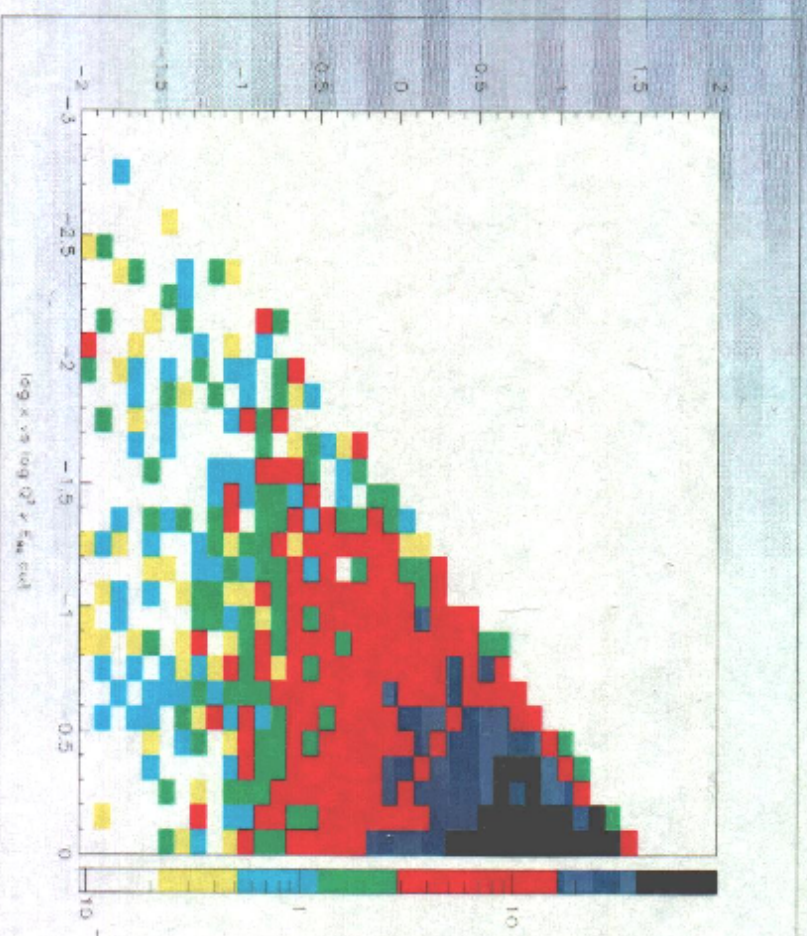
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✿ $E_{\mu} = 20 \text{ GeV}$

✿ $E_{\nu(\text{peak})} = 14 \text{ GeV}$

✿ $E_{lep} > 2 \text{ GeV}$

✿ VERY SIMILAR to
NuMI with same cuts



K. McFarland



Compare Event Rates for Two Future Experiments

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MIDIS in the NuMI Beam

- 10^{20-21} protons/year on the NuMI target.

Near Detector/⁴²⁵50 GeV NuFact
(¹⁵50 m away from ⁴⁰⁰800 m straight section)

- 10^{20} μ decays/year

- $(.3 - 1.0) \times 10^4$ CC ν or
 $(.7 - 2.5) \times 10^3$ CC $\bar{\nu}$ events /kg-yr
(in high energy configuration)

- 4.0×10^6 CC ν_{μ} and
 1.7×10^6 CC ν_e events/kg-year
(fid. vol. $r < 10$ cm)

- Know $\phi(E_{\nu})$ and $\int \phi(E_{\nu})$ to
< 2%

- Know $\phi(E_{\nu})$ and $\int \phi(E_{\nu})$ to
< 1.0 %

- First Beam 2003.
HE beam run > 2006

- First Beam a bit after
MINOS runs are finished

Measuring all SIX Structure Functions

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$$\frac{d^2\sigma^{VN}}{dx dy} = \frac{G_F^2 ME}{\pi(1+Q^2/M_W^2)} *$$

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

$$\frac{d^2\sigma^{VN}}{dx dy} = \frac{G_F^2 ME}{\pi(1+Q^2/M_W^2)} *$$

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

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

What Information is yet to be Gained?

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$$\begin{aligned} F_2^{V^N}(x, Q^2) &= x[u + \bar{u} + d + \bar{d} + 2\bar{s} + 2c] \\ F_2^{V^N}(x, Q^2) &= x[u + \bar{u} + d + \bar{d} + 2s + 2\bar{c}] \\ xF_3^{V^N}(x, Q^2) &= x[u + d - \bar{u} - \bar{d} - 2\bar{s} + 2c] \\ xF_3^{V^N}(x, Q^2) &= x[u + d - \bar{u} - \bar{d} + 2s - 2\bar{c}] \end{aligned}$$

• What do we gain by measuring separate v and $\bar{v}$ structure functions?

• Does $s = \bar{s}$ and $c = \bar{c}$ over all x ? $F_2^V - F_2^{\bar{V}} = 2[(s - \bar{s}) + (\bar{c} - c)]$

• If so.....

$$\begin{aligned} F_2^V - xF_3^V &= 2(\bar{u} + \bar{d} + 2\bar{c}) = 2U + 4\bar{c} \\ F_2^{\bar{V}} - xF_3^{\bar{V}} &= 2(\bar{u} + \bar{d} + 2\bar{s}) = 2U + 4\bar{s} \\ xF_3^V - xF_3^{\bar{V}} &= 2[(s + \bar{s}) - (\bar{c} + c)] = 4\bar{s} - 4\bar{c} \end{aligned}$$



The Challenge of d/u at High x

John Arrington - ANL

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Neutron Structure Function.

Nucleon structure functions at large x are sensitive to valence quark distributions.

The ratio of F_2^p/F_2^n allows one to separate up and down quark distributions.

SU(6) symmetry

d^v/u^v ratio

1/2

2/3

diquark S=1 suppression

0

1/4

diquark S_z=1 suppression

1/5

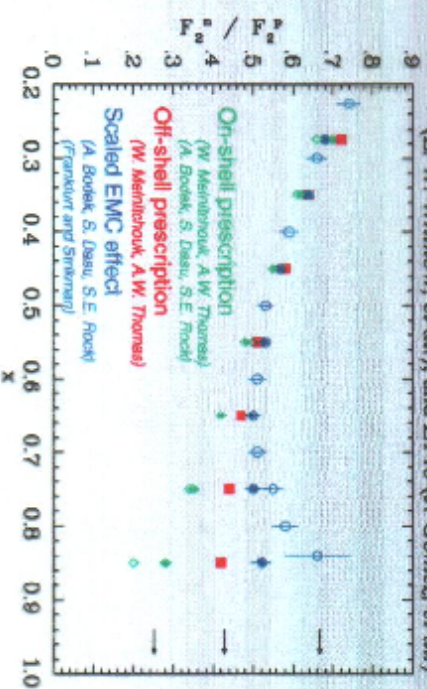
3/7

(Farrar and Frankfurt, Brodsky et al.)

Extracting the neutron structure function from deuteron measurements requires a model of the nuclear effects.

Proton and deuteron data from SLAC E139

(L. W. Whitlow, et al.), and E140 (J. Gomez, et al.)



The extraction of F_2^n is limited by our understanding of nuclear effects in deuterium.

✿ A high statistics experiment with v and $\bar{v}$ off a hydrogen target gives d/u (relatively) cleanly

$$\bar{F}_2^{VP}(x, Q^2) = 2x[u + \bar{d} + \bar{s} + c]$$

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

$$\bar{x}F_3^{VP}(x, Q^2) = x[u - \bar{d} - \bar{s} + c]$$

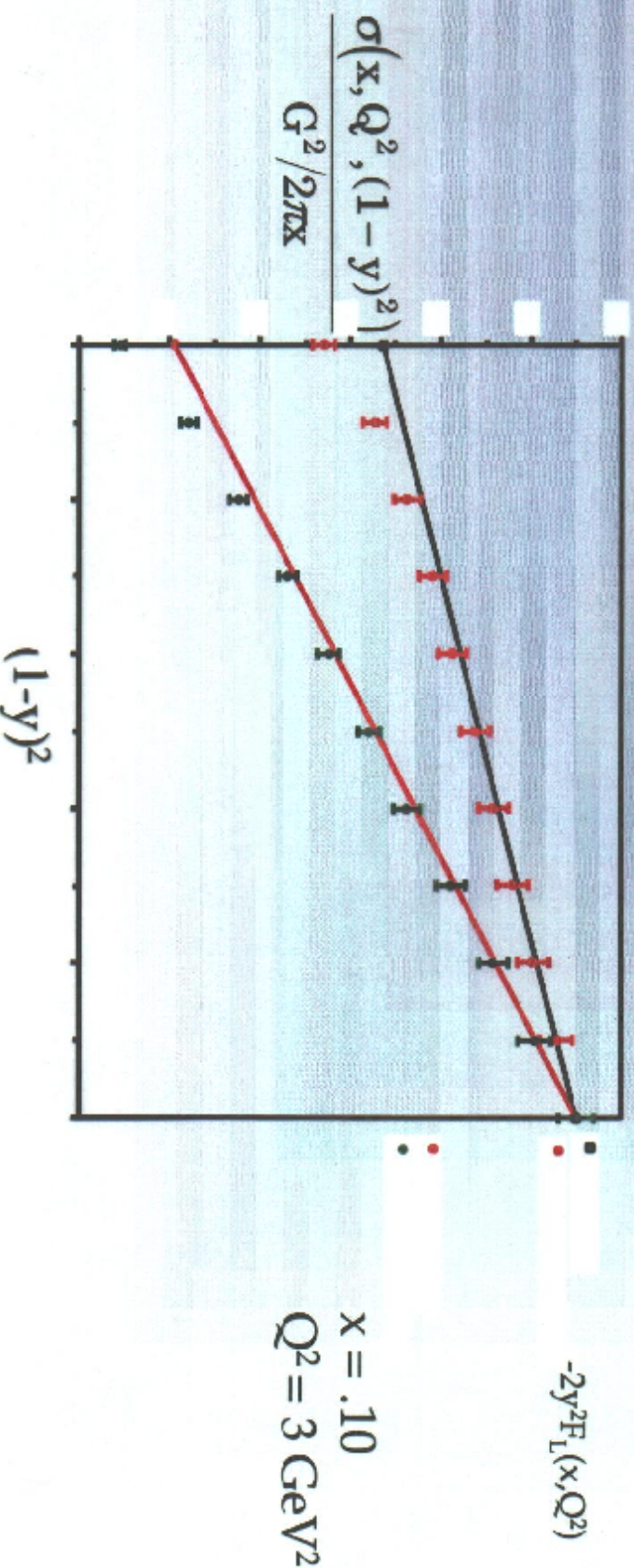
$$xF_3^{VP}(x, Q^2) = x[-\bar{u} + d + s - \bar{c}]$$

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

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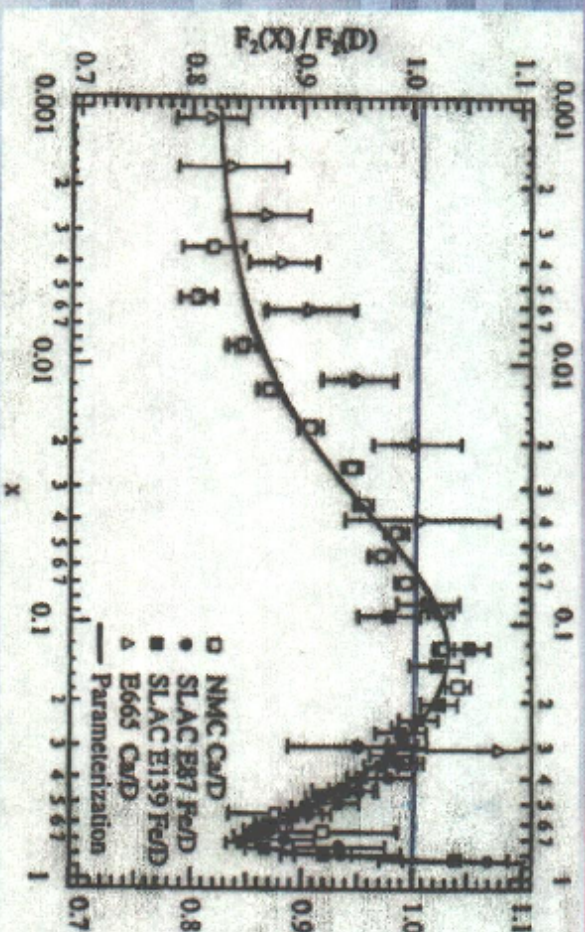
$$\frac{d\sigma^{\nu A}}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left[\frac{1}{2} \left(F_2^{\nu A}(x, Q^2) + x F_3^{\nu A}(x, Q^2) \right) + \frac{(1-y)^2}{2} \left(F_2^{\nu A}(x, Q^2) - x F_3^{\nu A}(x, Q^2) \right) \right]$$

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



What About these Nuclear Effects?

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- Nuclear effects measured (with high statistics) in μ -A **not in ν**
- 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.



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

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- 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 and by S. Kumano et al^c (this workshop)
hep-ph/0103208

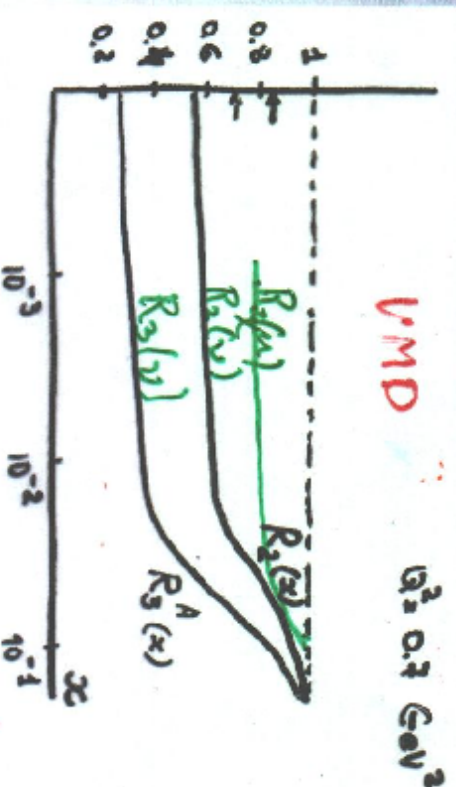
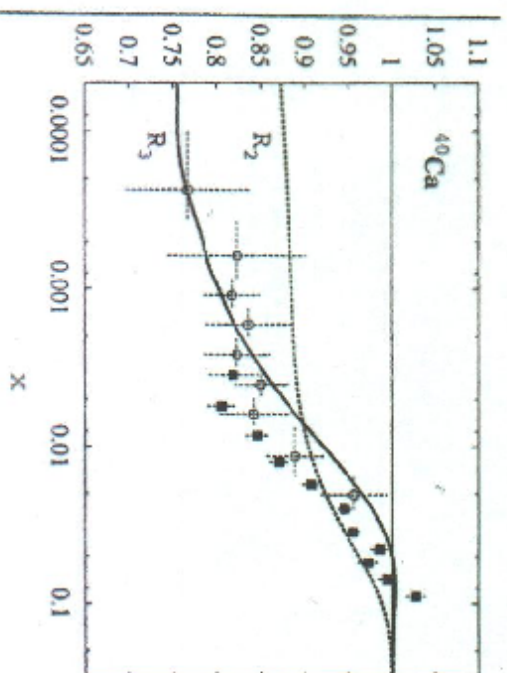
^a hep-ex/9906010 ^b hep-ph/9807297 ^c hep-ph/0103208



A Specific Look at ν Scattering Nuclear Effects

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- 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.





Second Near Detector (MIDIS)

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- ❖ Standard MINOS near detector: Solid scintillator planes with fiber readout between 2.5 cm thick Fe plates.
- ❖ 15 ton fiducial mass $\rightarrow$ 45 M ν CC events / year. $\bar{\nu} = \nu / 4.0$.

MIDIS Near Detector ("Quick" Parasitic Variant)

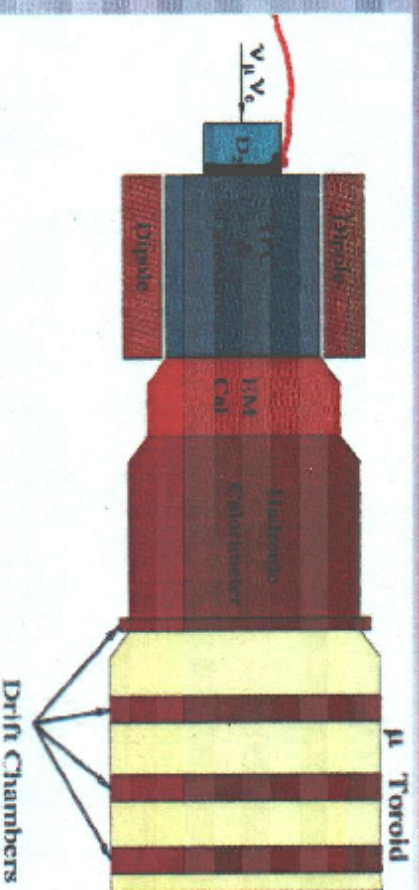
- ❖ MINOS near detector as (expensive) muon id / spectrometer.
- ❖ Assume directly upstream of MINOS, 12 planes ($r = .75m$) of C (≈ 4 M fiducial events / year) and 2 plane of W (5 M events) - (**x Factor 3 with P-Driver**) .

MIDIS Near Detector for High Energy Beam (under study)

- ❖ Mainly planes of CH or CH₂ scintillator alternating with C planes .
- ❖ Subtract C from scintillator to get H₂.
- ❖ 1 m³ of scintillator yields 3 M CC events / year.

Near Detector for Neutrino Factory

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J. Yu

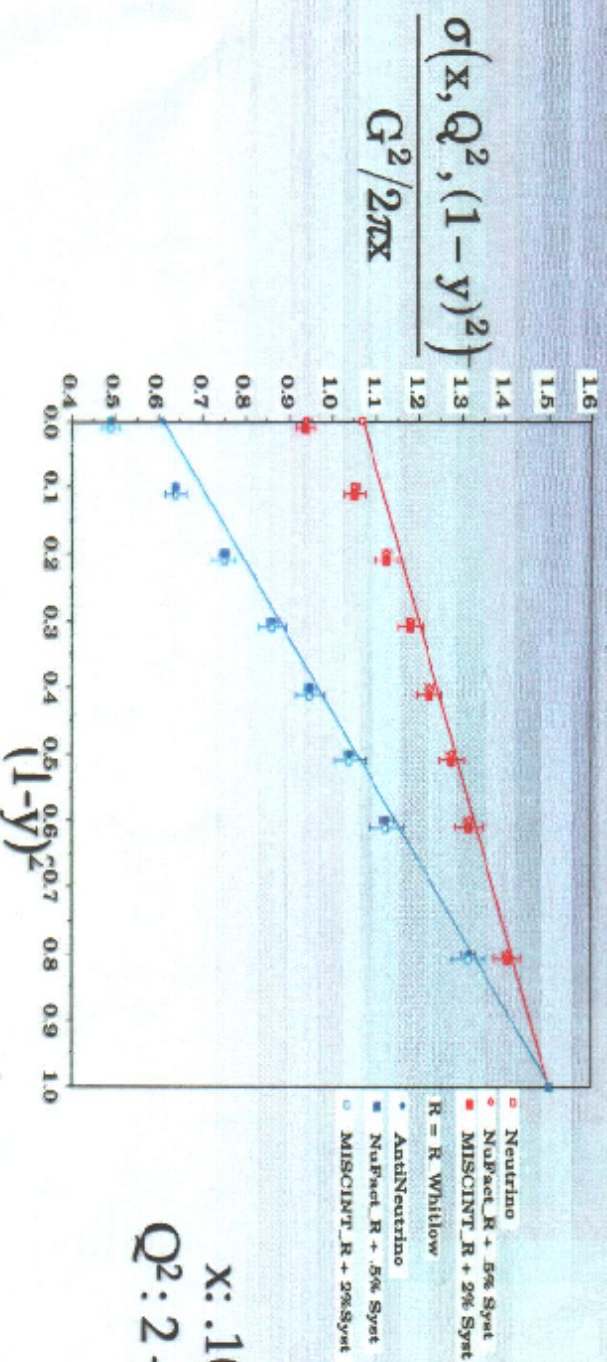
- ✿ Liquid hydrogen/deuterium cryogenic target (followed by high A targets).
- ✿ All targets ($r = 10$ cm) acquire $10^7 \nu_\mu$ events and $4 \times 10^6 \bar{\nu}_e$ /year.
- ✿ H_2 @ 120 cm long or D_2 @ 50 cm, C @ 3.7 cm and W @ 0.45 cm



MIDIS/NuFact 6-Structure Function Measurement ($W^2 \geq 5 \text{ GeV}^2$ & $E_{\text{lep}} \geq 1 \text{ GeV}$)

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- MIDIS: 26 $M V_\mu$ - Fe and 2 $M V_\mu$ - Scint evts /year. $\bar{V}_\mu = V_\mu / 4$
- Analysis based on 2 year run of each type.
- NuFact: 6 $M V_\mu$ - D_2 evts /year 2 year run
- Statistical errors negligible except at high values of $(1-y)^2$
- Completely dominated by systematic errors



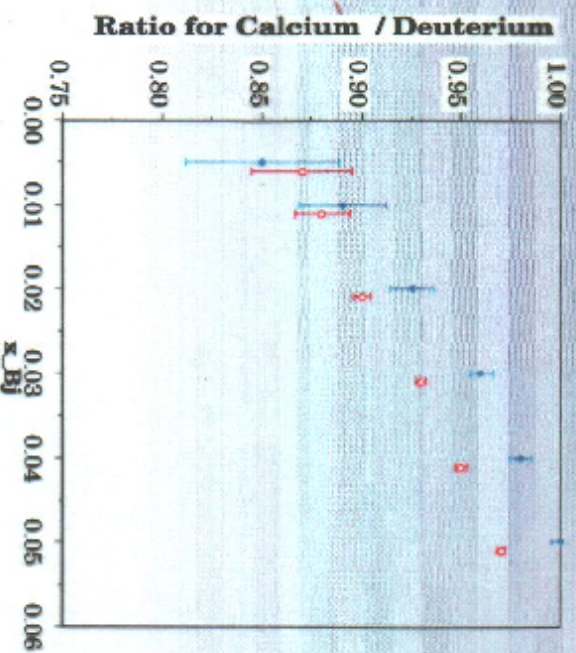
x: .10-.125
 $Q^2: 2-4 \text{ GeV}^2$



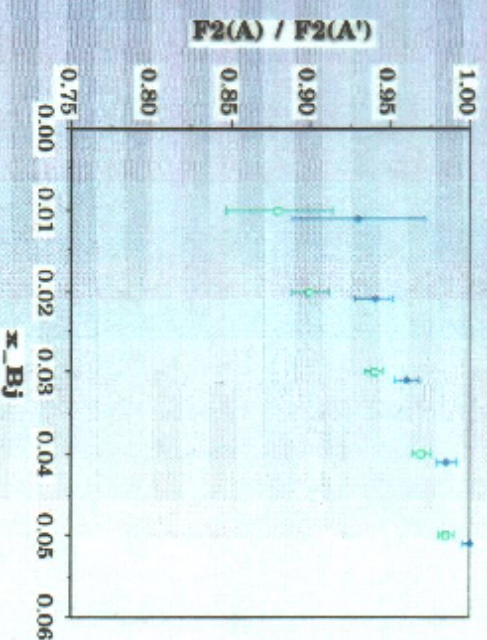
MIDIS / NuFact ν Nuclear Shadowing Measurement

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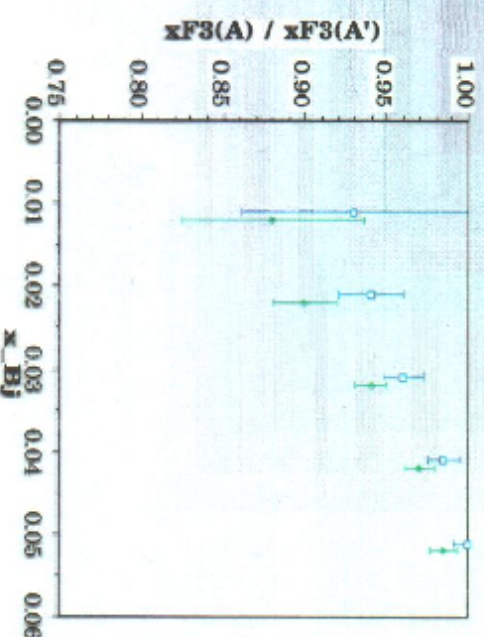
- Taking ratios: beam syst cancel.
- Assume relative target syst. same as Tevatron Muon Expt. O (1%).
- In the right kinematic region to investigate the HERMES effect.



NuFact



FeC
W/C



FeC
W/C

MIDIS



NuFact-Specific Physics Topics: Polarized Target

M. Velasco

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- Sufficiently intense and compact ν beam to envision reasonable statistics in $O(10 \text{ kg})$ polarized target.
- Recent development of an "ICE" targets which is a solid polarizable HD material ($\rho = 0.11 \text{ g/cm}^3$). $P_H = 80\%$ and $P_D = 50\%$.
- ICE target with $r = 20 \text{ cm}$ and $l = 50 \text{ cm}$ would accumulate $20 \text{ M events / year}$ ($10^{20} \mu$).
- Could also use more traditional polarized butanol target a la SMC with $r = 6 \text{ cm}$ and $l = 60 \text{ cm}$ would get the same statistics but with $P = 0.1$.

* Additional parity violating spin S.F. $g_3, g_4 + g_5 \pm$ combinations
Based on $^{+4-}$ of $\nu + \bar{\nu}$ scattering i.e. -
 $J_2: u + d$ contributions cancel $\Rightarrow g_3^{\nu D_2} - g_3^{\bar{\nu} D_2} = -2(g_3^u + g_3^d)$



NuFact-Specific Physics Topics: Reference

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• For more details on the NuFact topics covered in this brief summary plus other topics such as:

- ◆ Charmed Particle Production and Analysis
- ◆ Electroweak Physics
- ◆ Rare neutrino properties such as magnetic moment..... see

The Potential for Neutrino Physics at Muon

Colliders and Dedicated High Current Muon Storage Rings, I. Bigi et al, BNL 68106, Jan.

2001 (submitted to Physics Reports)

NuFact'01 - Tsukuba, Japan - 24 May - 1 June

*Physics at a Neutrino Factory - FN-002
April, 2000*



SUMMARY

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♦ **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 measurements of separate $\nu / \bar{\nu}$ F_2 , xF_3 & R
- ♦ study of $\nu / \bar{\nu}$ nuclear effects, particularly HERMES effect!
- ♦ Detailed study of high- x parton distribution functions.

♦ **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
- ♦ ⁴¹Complete ⁴¹measurements of the partonic spin structure of nucleon
- ♦ High statistics charm production with "clean" final state ($E_\mu \geq 50$ GeV)
- ♦ Precision electroweak measurements; ν - e scattering