Measuring F_2^n at the EIC

Alberto Accardi

Nuclear Chromo-Dynamics with an EIC

Argonne National Laboratory

April 7 - 9, 2010

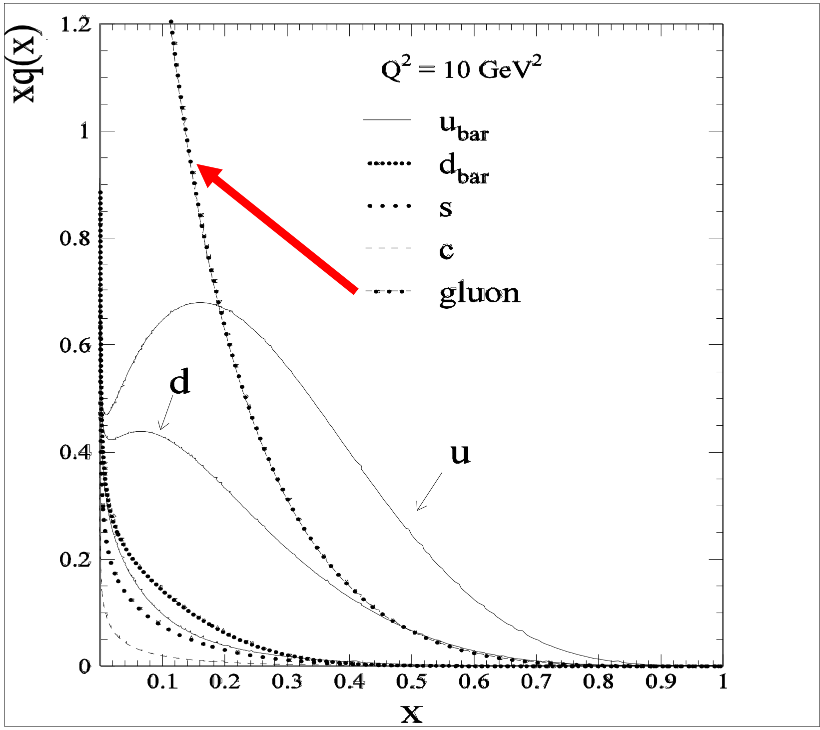
Gratefully acknowledging help from C.Keppel, R.Ent

Jefferson Lab

HAMPTON UNIVERSITY

$F_2^p - F_2^n$ yields non-singlet PDF

- Nucleon made of singlet (gluons, sea) and non-singlet (valence) distributions
- Assuming a charge-symmetric sea, p-n isolates the non-singlet (at LO)
- Q^2 evolution for non-singlet is independent of gluons
- Direct handle on nucleon quark structure
- Needed to pin down singlet, hence gluons (complementary to F_L)
- Provides determination of α_S free of g(x) shape (a problem in F_2^p analyses)



Non perturbative nucleon structure at large x

- F_2^n/F_2^p (d/u) sensitive to different models

$$F_2^p(x) \underset{x\to 1}{\approx} x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

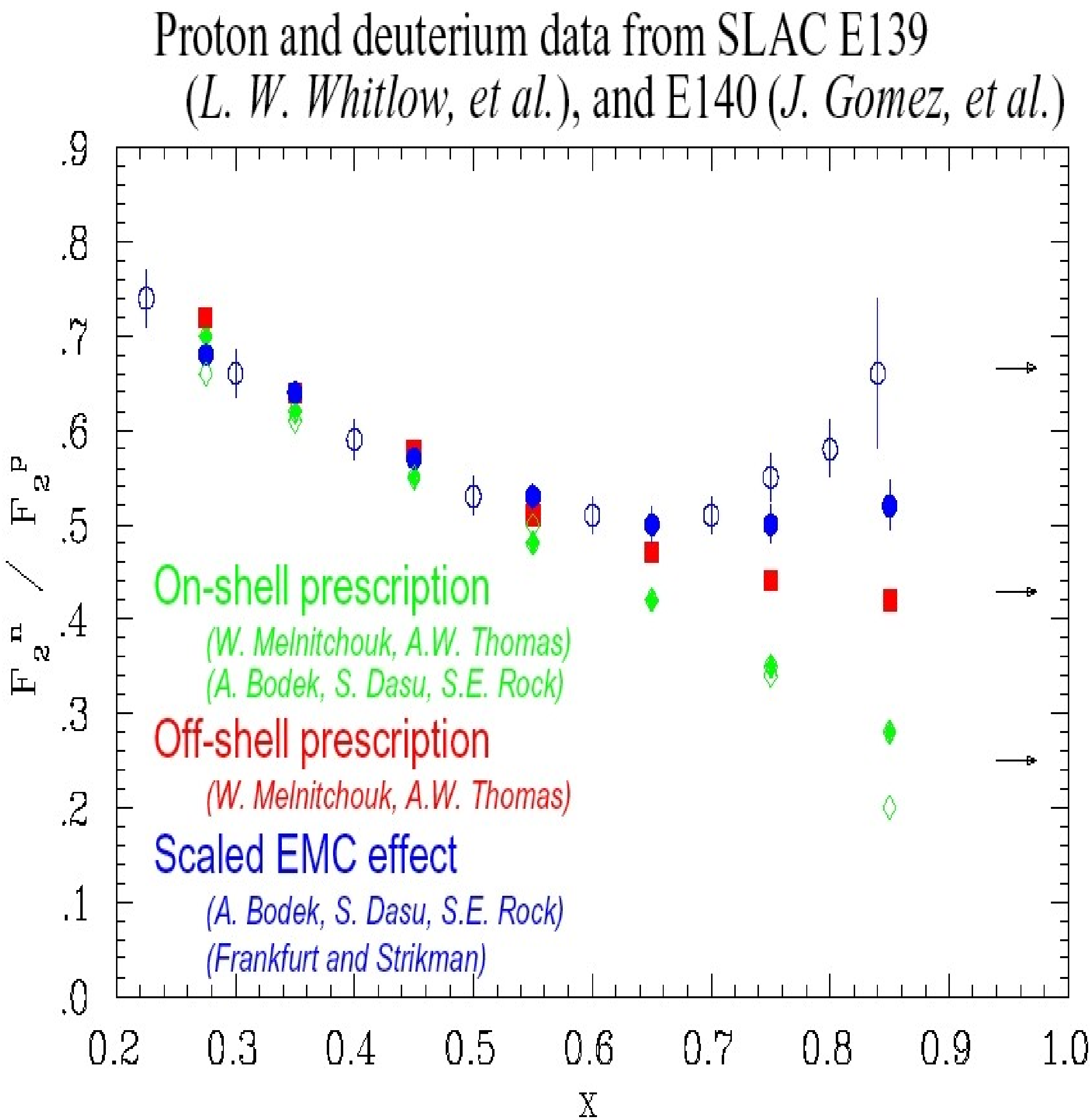
$$F_2^n(x) \underset{x\to 1}{\approx} x\left(\frac{4}{9}d(x)+\frac{1}{9}u(x)\right)$$

$$\frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+d/u}$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

E.g.,
Isgur, PRD59 (1999)
Brodsky et al., NPB441 (1995)
Melnitchouk, Thomas, PLB377 (1996)

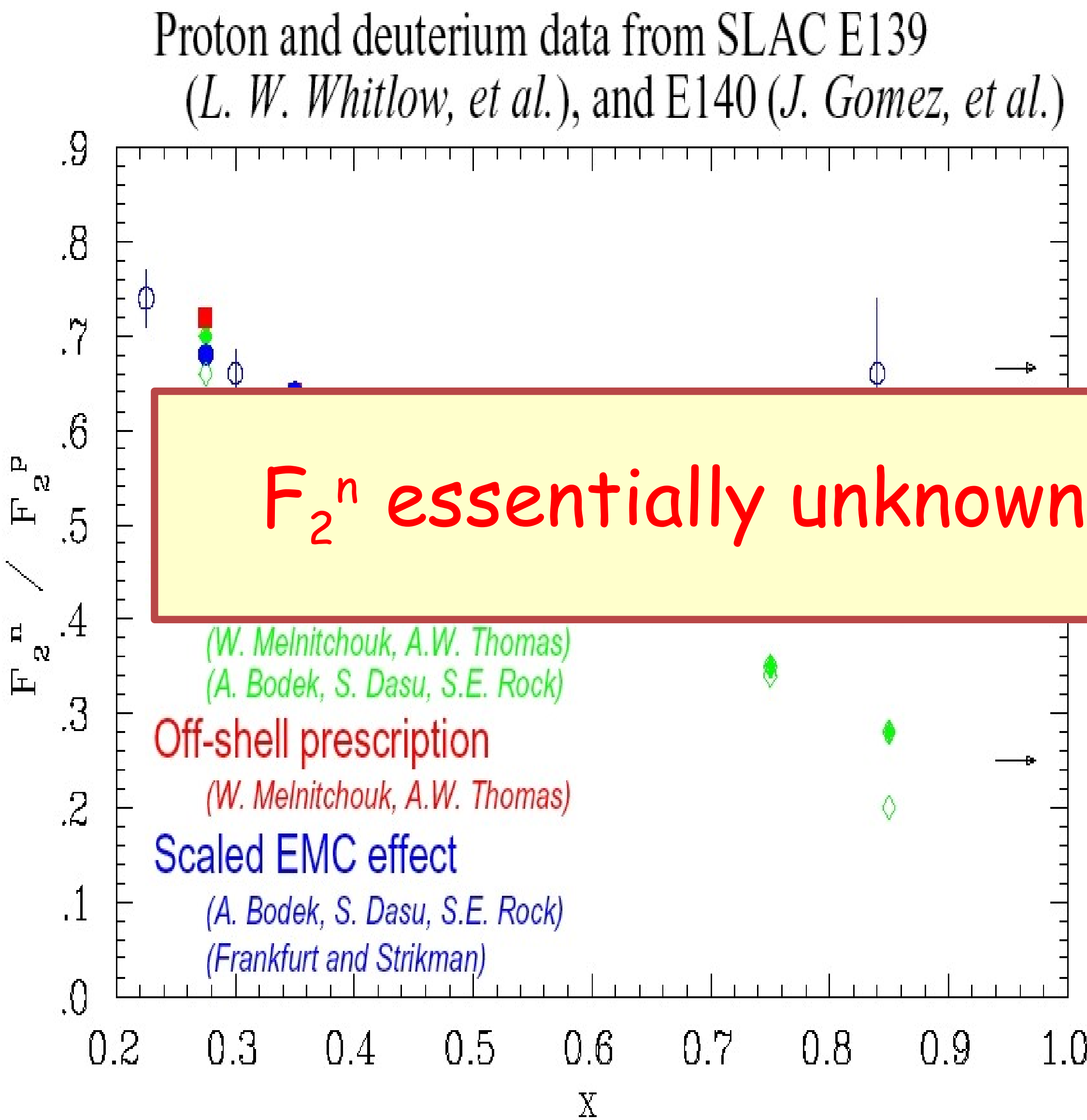
But, there is no free neutron target!



Neutron derived from Deuterium target by “subtracting” proton

Large uncertainty in unfolding nuclear effects:
- Fermi motion & binding
- off-shell effects,
- coherent scattering,
- final state interactions,
- nucleon modification (“EMC”effect)
- ...

But, there is no free neutron target!



Neutron derived from Deuterium target by "subtracting" proton

n

cts:

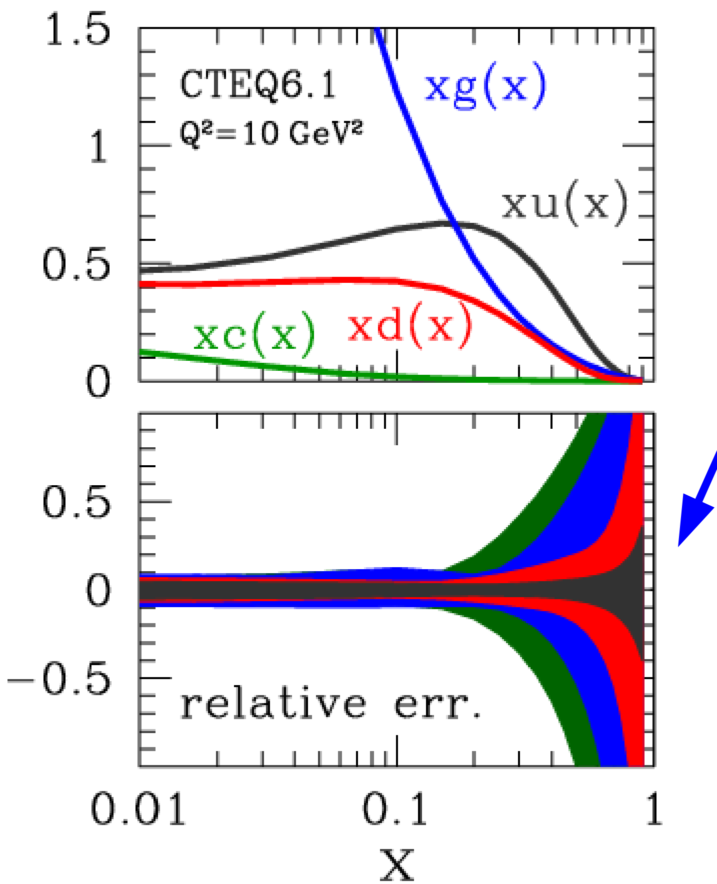
ding

- off-shell effects,
- coherent scattering,
- final state interactions,
- nucleon modification ("EMC"effect)
- ...

F_2^n essentially unknown at large x !!

No help available from (or for) global fits, either

- Large uncertainties in quark and gluon PDF at $x > 0.4$ – e.g., CTEQ6.1



- **PDF errors**
  - propagation of exp. errors into the fit
  - statistical interpretation
  - reduced by enlarging the data set

- **Theoretical errors**
  - often poorly known
  - difficult to quantify
  - **can be dominant**

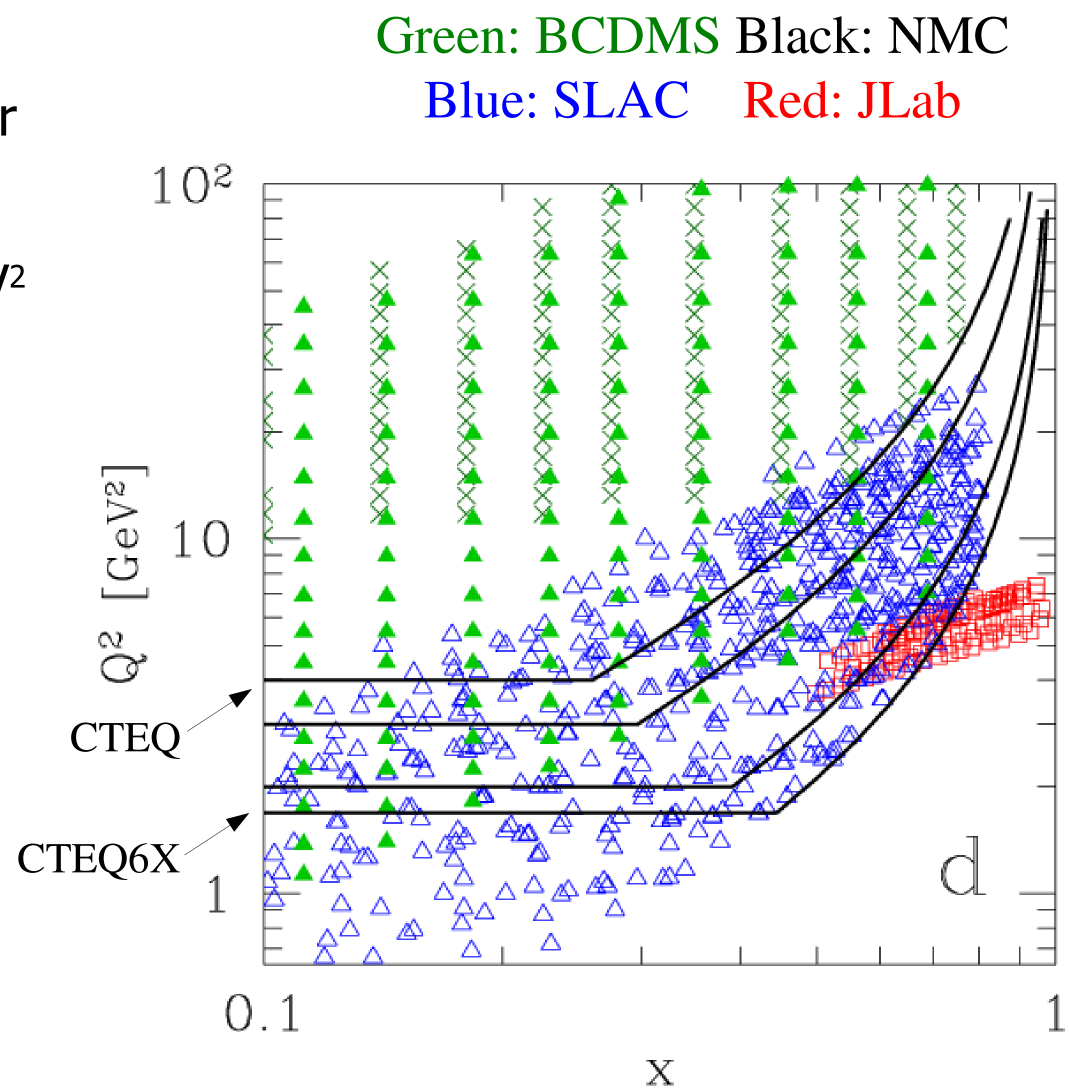
"CTEQ6X" study to optimize large-x Region

[Accardi et al, PRD 81, 034016 (2010)]

- Relax W, Q cuts to allow for expanded DIS data set :

  $W^2 > 3$ GeV^2, $Q^2 > 1.69$ GeV^2

- Consider
  - target mass effects
  - higher-twist contribution
  - nuclear corrections



"CTEQ6X" study to optimize large-x Region

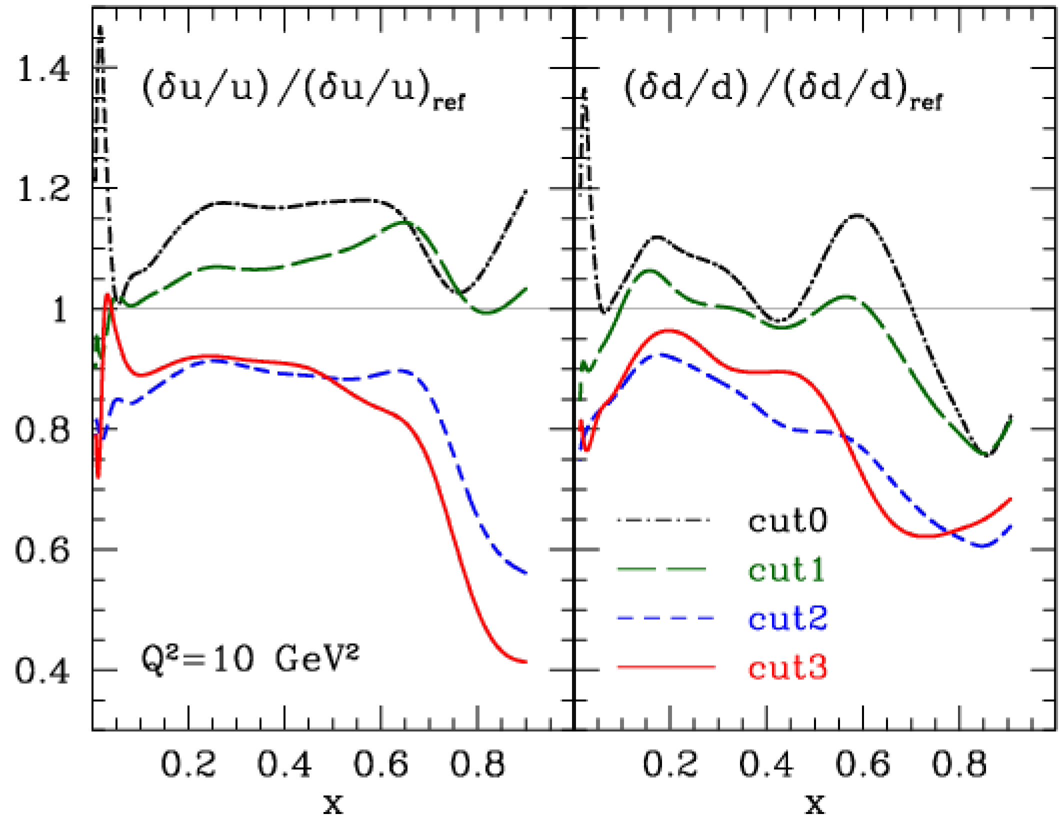
[Accardi et al, PRD 81, 034016 (2010)]

- Relax W, Q cuts to allow for expanded DIS data set :

  $W^2 > 3\ GeV^2$, $Q^2 > 1.69\ GeV^2$

- Consider
  - target mass effects
  - higher-twist contribution
  - nuclear corrections

- Reduced "exp." uncertainty at large x (ref ~ CTEQ6.1)



"CTEQ6X" study to optimize large-x Region

[Accardi et al, PRD 81, 034016 (2010)]

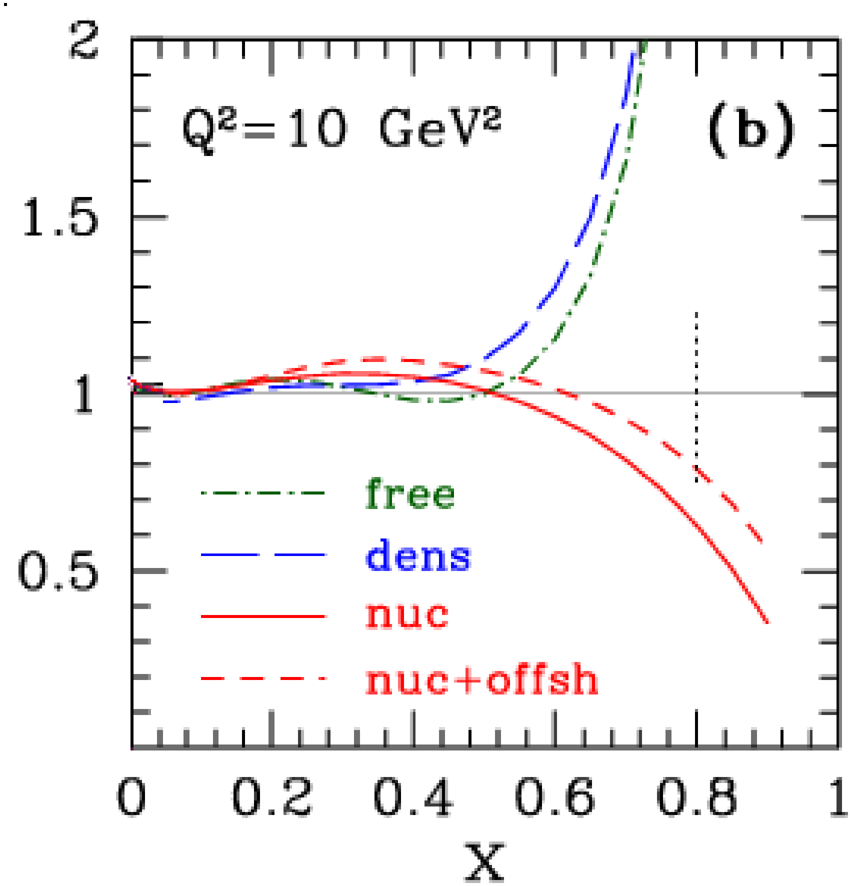
- Relax W, Q cuts to allow for expanded DIS data set :

  $W^2 > 3\ GeV^2$, $Q^2 > 1.69\ GeV^2$

- Consider
  - target mass effects
  - higher-twist contribution
  - nuclear corrections

- Reduced "exp." uncertainty at large x (ref ~ CTEQ6.1)

- **Large theory uncertainty due to nuclear corrections**



nucl = nuclear smearing in Weak Binding Approximation (+ off shell corrections)

dens = density-scaled EMC effect, extrapolated to deuterium

free = deuterium as sum of proton and neutron structure functions

"CTEQ6X" study to optimize large-x Region

[Accardi et al, PRD 81, 034016 (2010)]

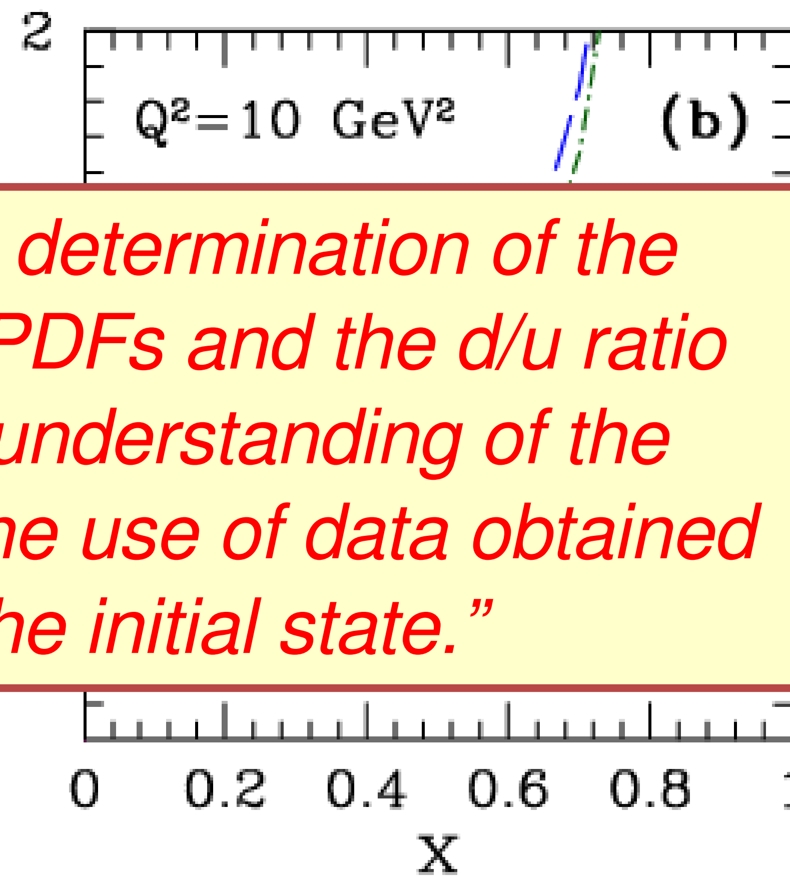
- Relax W, Q cuts to allow for expanded DIS data set :

  W²

- Co
  - t
  - h
  - r

- Re
  at

- **Large theory uncertainty due to nuclear corrections**



"Further progress in the determination of the behavior of the large-x PDFs and the d/u ratio requires either a better understanding of the nuclear corrections or the use of data obtained using free nucleons in the initial state."

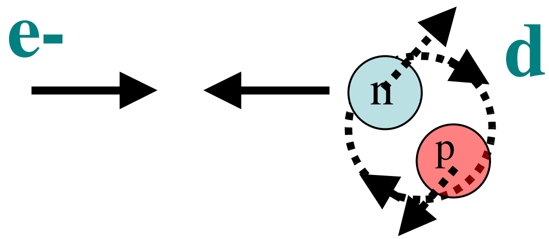
nucl = nuclear smearing in Weak Binding Approximation (+ off shell corrections)

dens = density-scaled EMC effect, extrapolated to deuterium

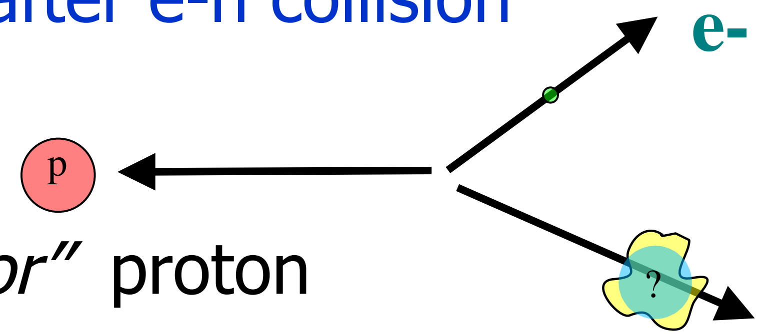
free = deuterium as sum of proton and neutron structure functions

The spectator tagging approach: An effective neutron target from Deuterium

before collision



after e-n collision



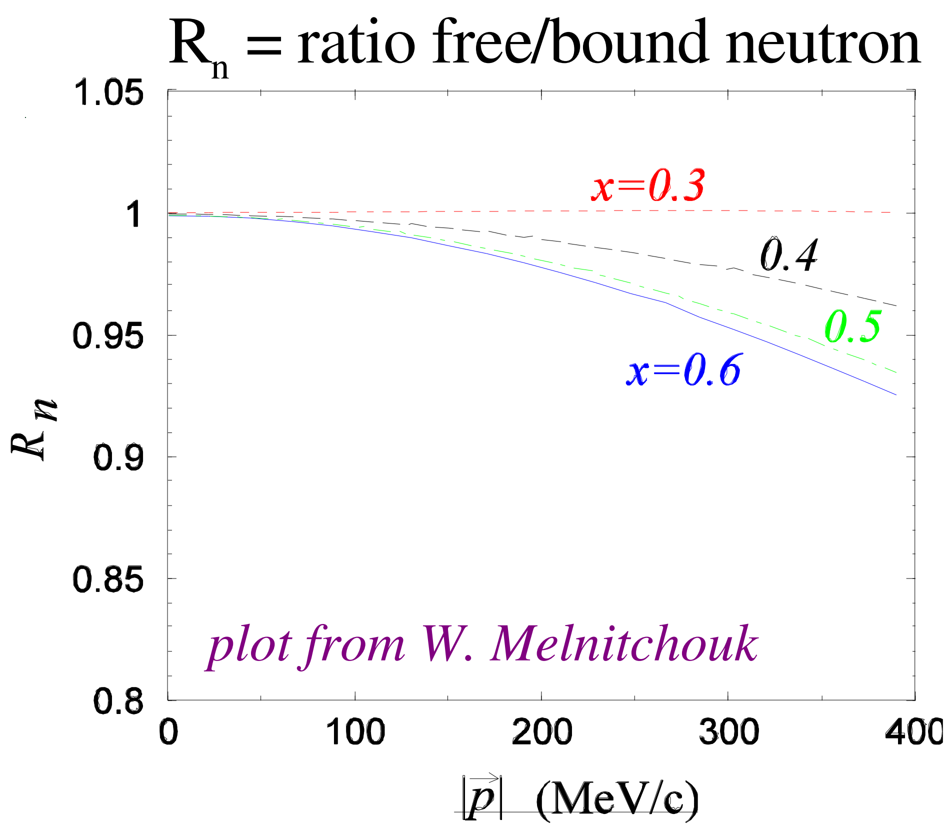
"*spectator*" proton

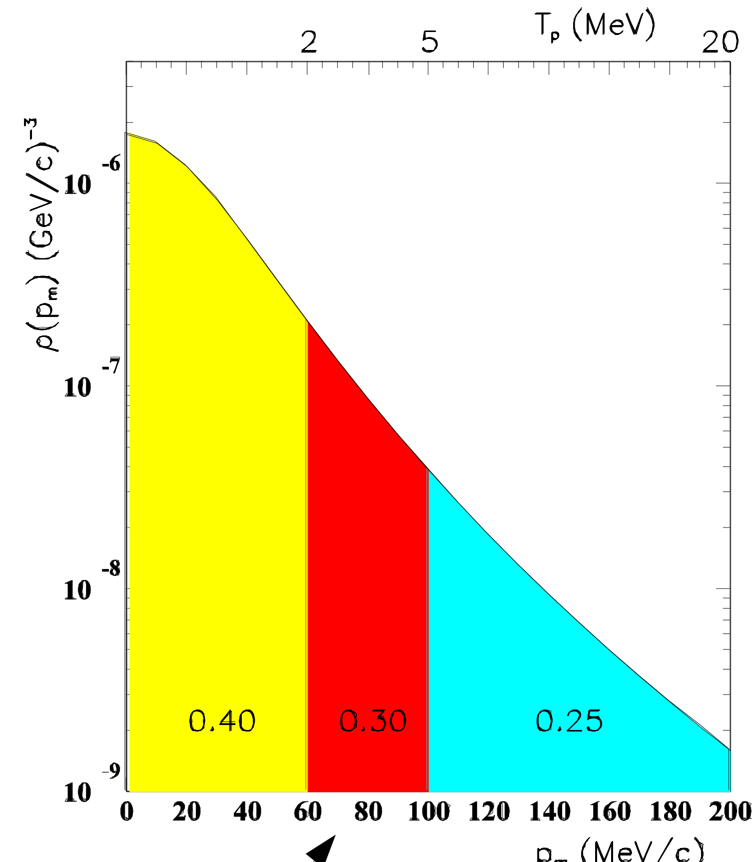
standard DIS event
- from a neutron target!

Existing fixed-target experiments:
- **E-94-102**: PRC73 (2006)
- **BONUS**: paper in progress

Requirements 1 - "VIPs" (Very Important Protons)

Deuteron ~ free p + free n
only at small nucleon momenta





BONUS cuts
30% of D wave function

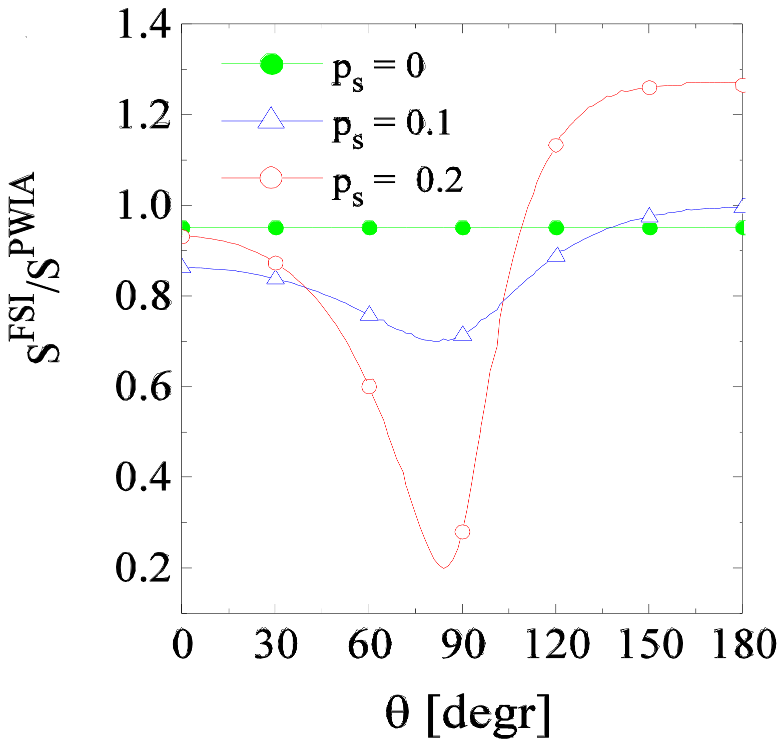
Requirements 2 - Backwards Protons

Backward angle compared to γ^*
to minimize Finale State Interactions

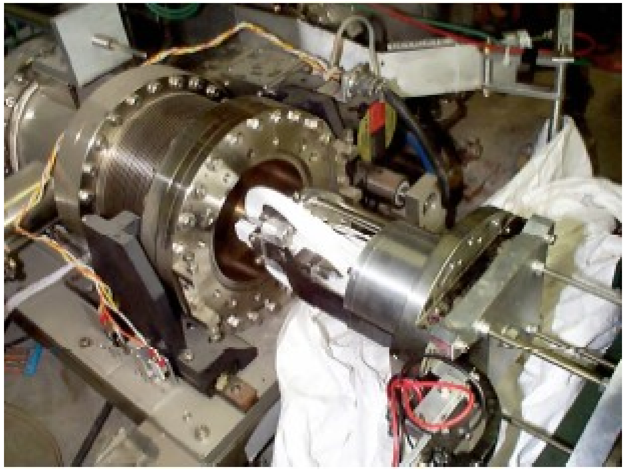
Example: BONUS cuts

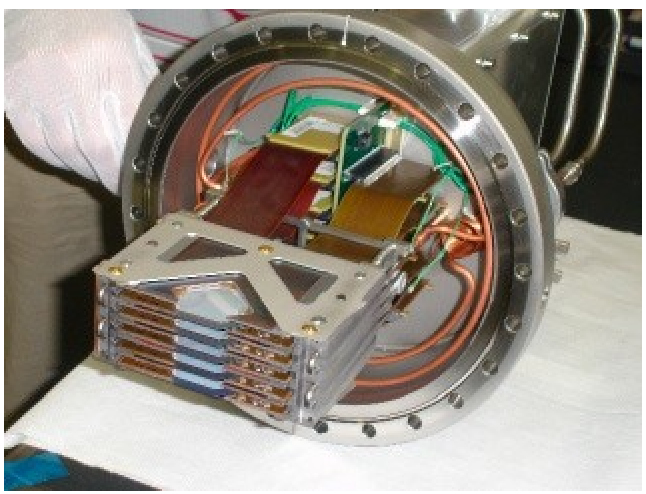
$60\text{ MeV} < p_s < 100\text{ MeV}$

$\theta_s > 110^\circ$



Proton Tagging





100 mr horizontal crossing angle for ion beam would require large 40Tm magnet at 20 meter from the IP.

Spectator proton tagging:

- Δ(bend) 30 GeV vs. 29.9 GeV = 1.3 mr
- If roman pots after 4 m

5 mm @ p_s=100 MeV/c

15 mm @ p_s=300 MeV/c

Roman pots (photos at CDF (top) and LHC (bottom), …) ~ 1 mm from beam achieve proton detection with < 100μ resolution

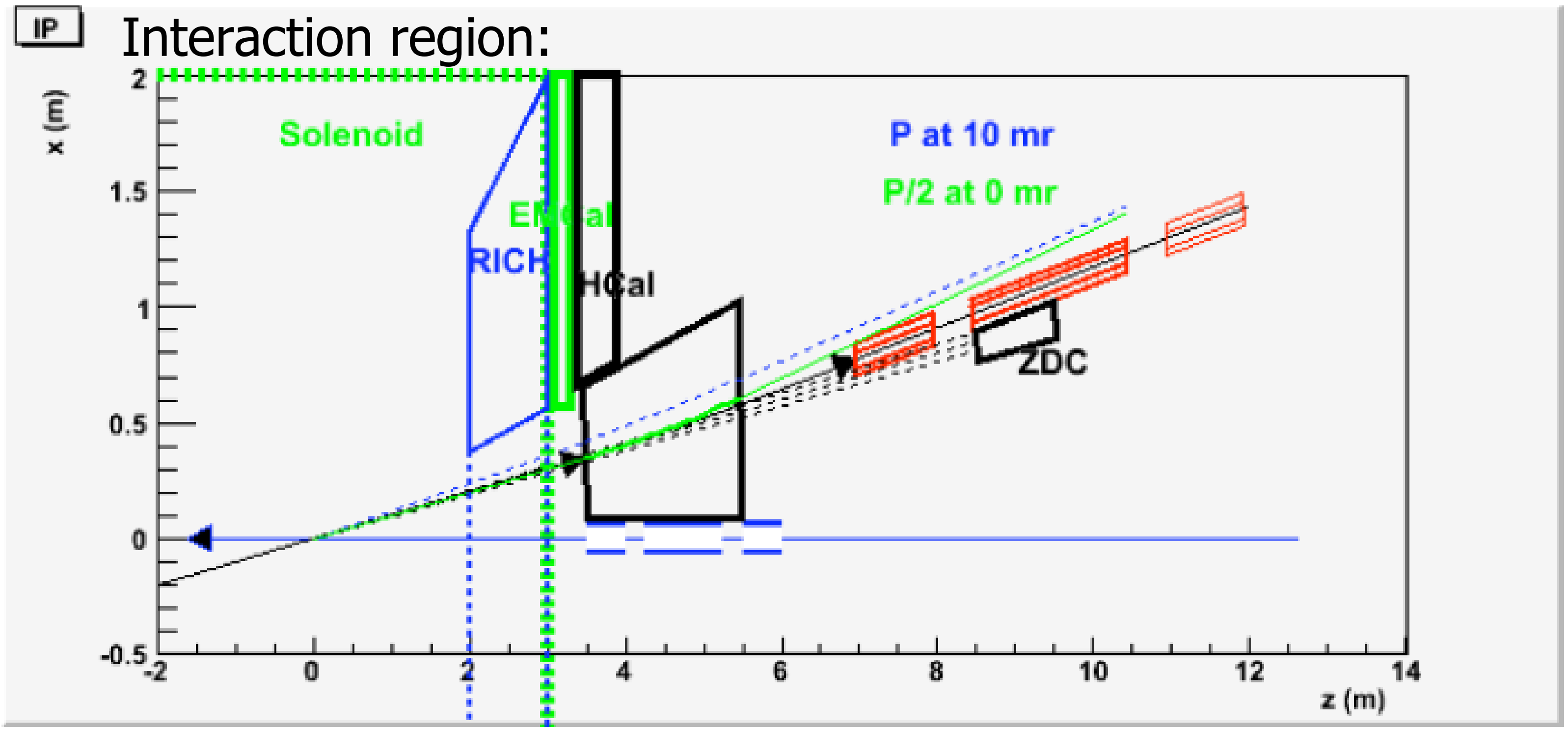
→ Proton tagging concept looks doable, even if the horizontal crossing angle was reduced by a factor of two or three.

Neutron Tagging

- Neutron tagging in Zero Degree Calorimeter
  - Bound vs. free proton structure functions
  - Extensive program of DVCS on tagged protons and neutron

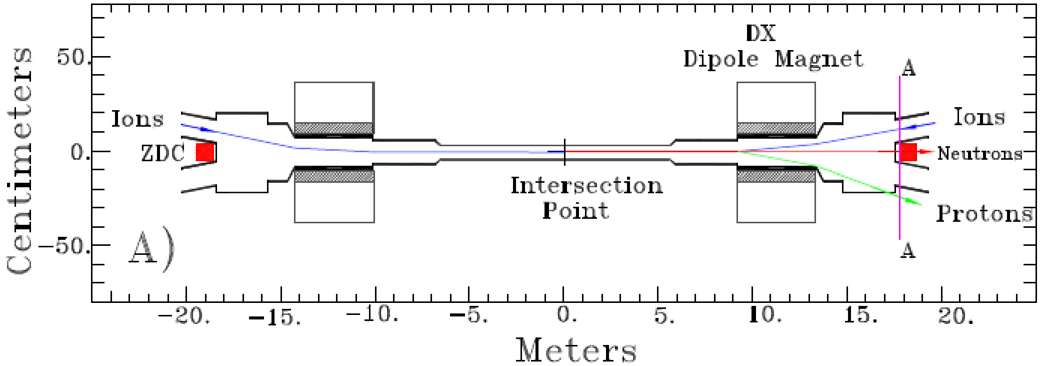
[C.Hyde, Rutgers'10]

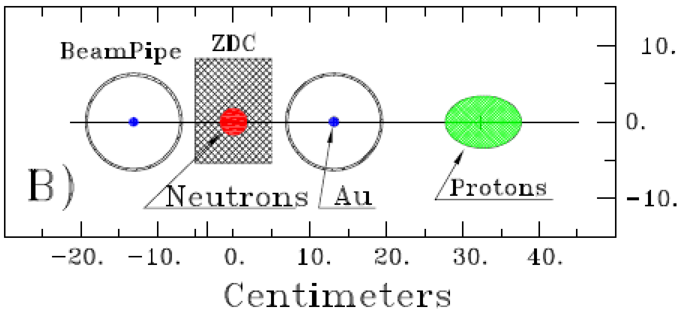
Interaction region:



Neutron Tagging

The RHIC Zero Degree Colorimeters   arXiv:nucl-ex/0008005v1





- EIC@JLab case: 40 Tm bend magnet at 20 meters from IP → very comparable to above RHIC case!
- 40 Tm bends 60 GeV protons with 2 times 100 mr

→ deflection @ a distance of about 4 meters = 80 cm (protons)

→ no problem to insert Zero Degree Calorimeter in this design

Zero Degree Calorimeter properties:

- Example: for 30 GeV neutrons get about 25% energy resolution

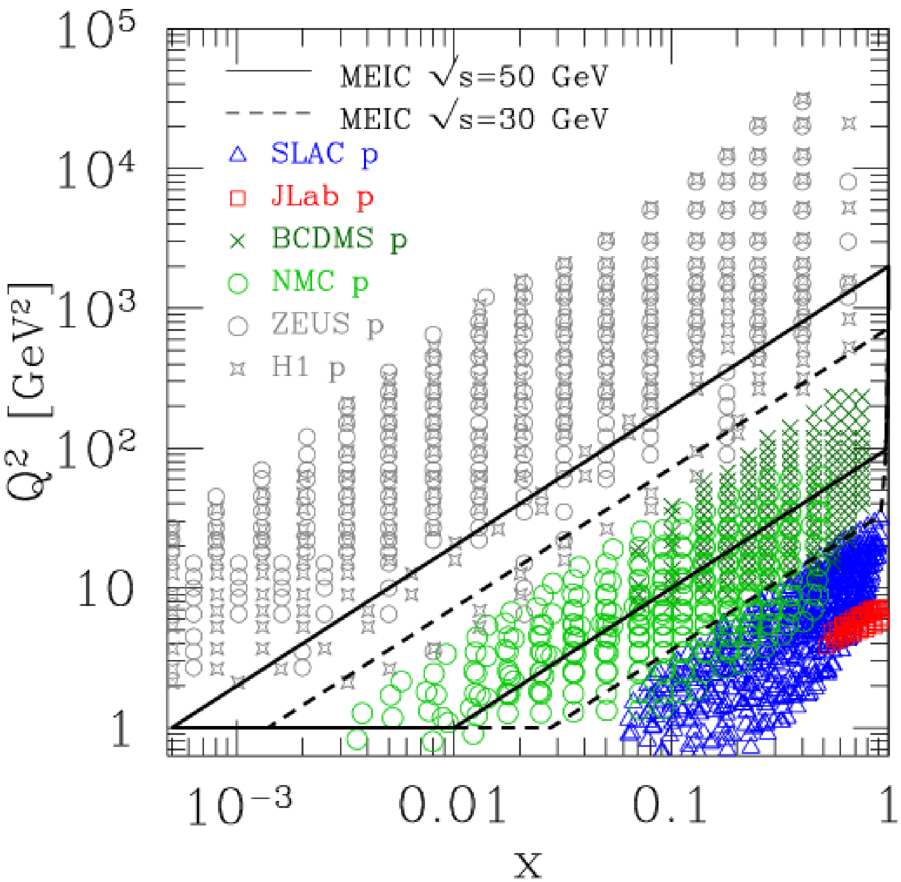
(large constant term due to unequal response to electrons and photons relative to hadrons)

→ Should be studied more whether this is sufficient

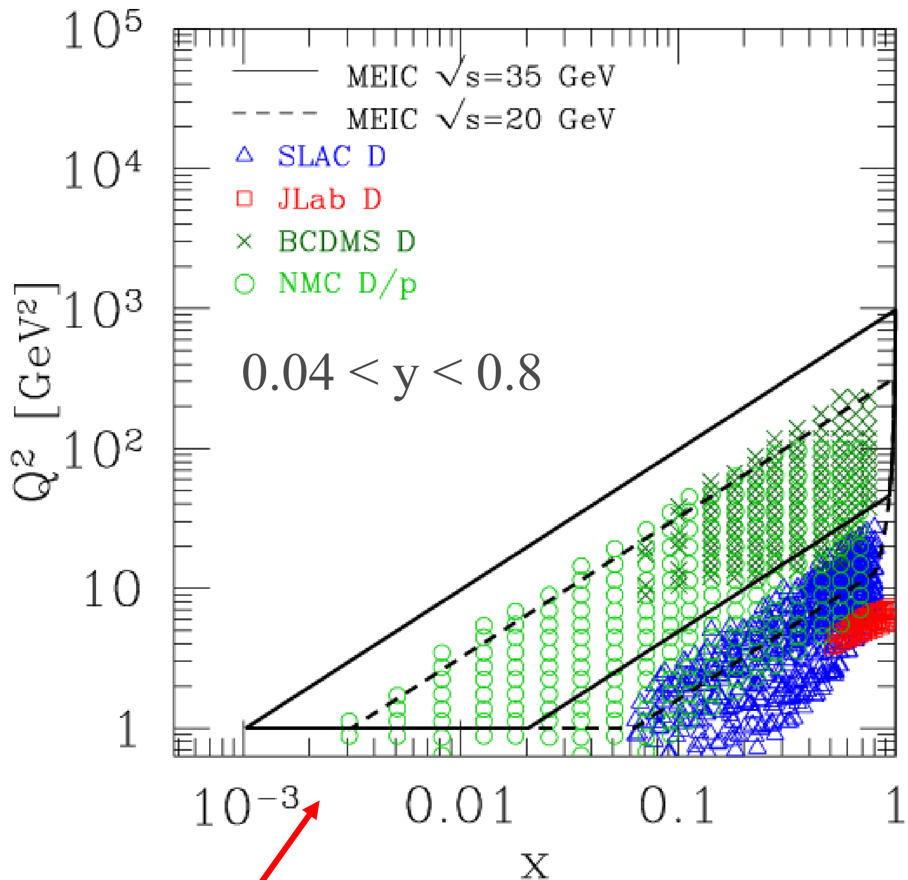
- Timing resolution ~ 200 ps
- Very radiation hard (as measured at reactor)

Projected Results I - F_2 Phase Space

proton



deuteron - *much less data*



MEIC will probe lower x in the shadowing region, and higher Q^2 at large x.

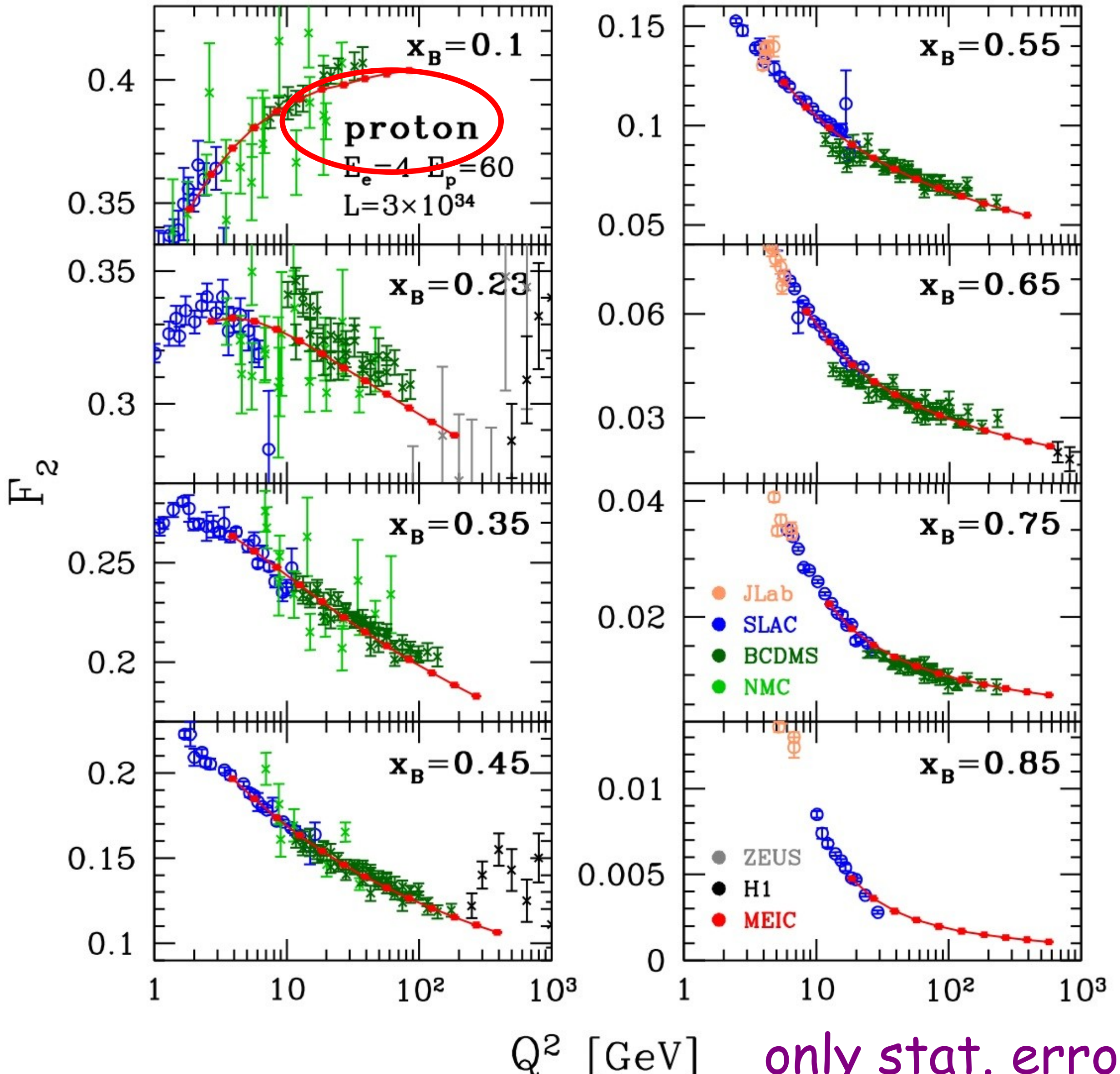
Projected Results II – Structure functions

Disclaimer:
The following binning and rates are PRELIMINARY

R.Ent and I are working on more detailed estimates including the small-x region...

...and would enjoy your help if you are interested!

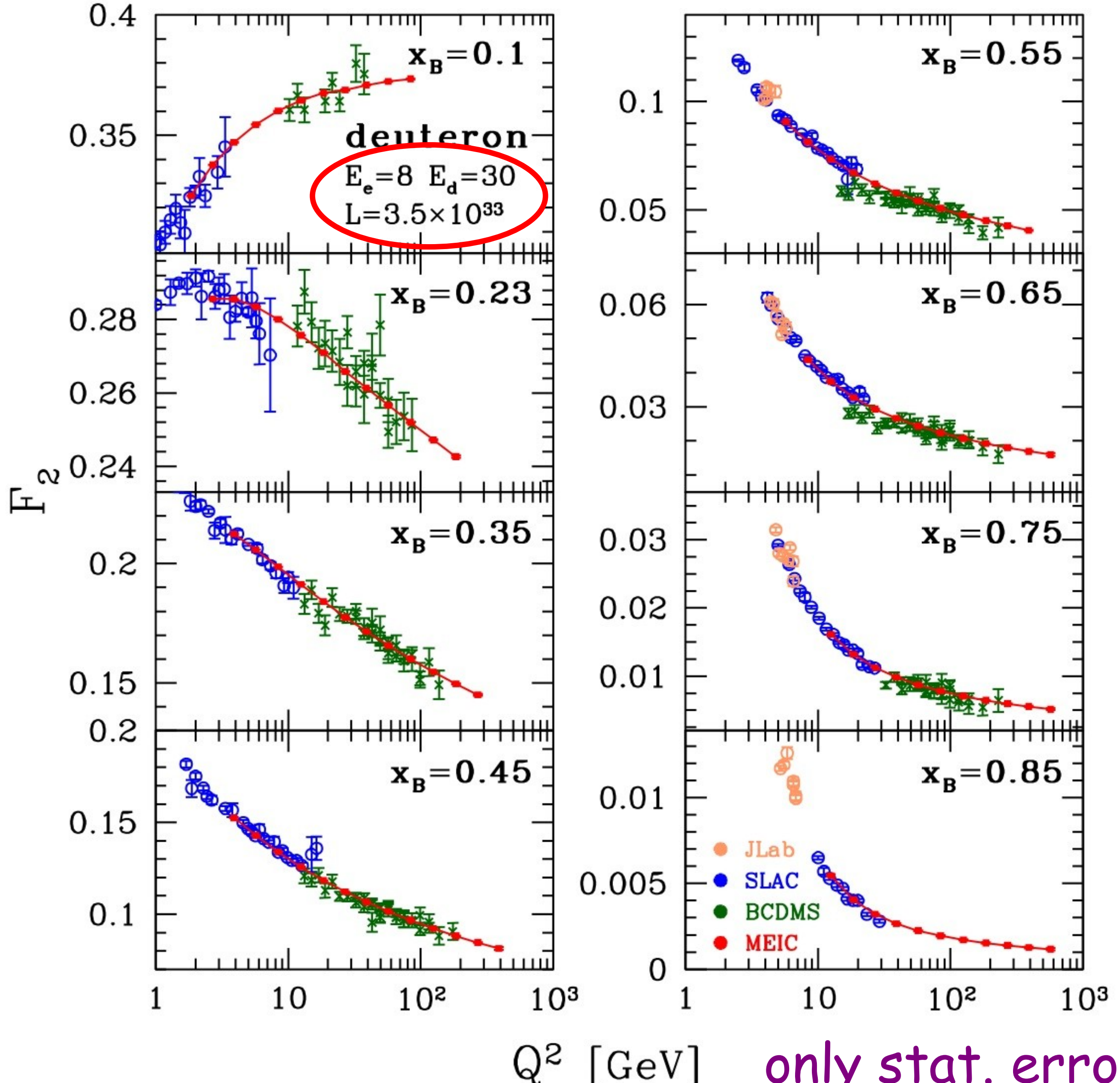
Projected Results IIa - F_2^p with CTEQ6X PDFs



- E_e = 4 GeV, E_p = 60 GeV (s = 1000)
  - larger s (~4000 MeRHIC, or ~2500 MEIC) would cost luminosity
- 0.004 < y < 0.8
- Luminosity ~ 3 x 10^{34}
- 1 year of running (26 weeks) at 50% efficiency, or **230 fb^{-1}**
- Somewhat smaller Q^2 reach and large luminosity is better choice at large x, $\sigma \sim (1-x)^3$

only stat. errors on projected results

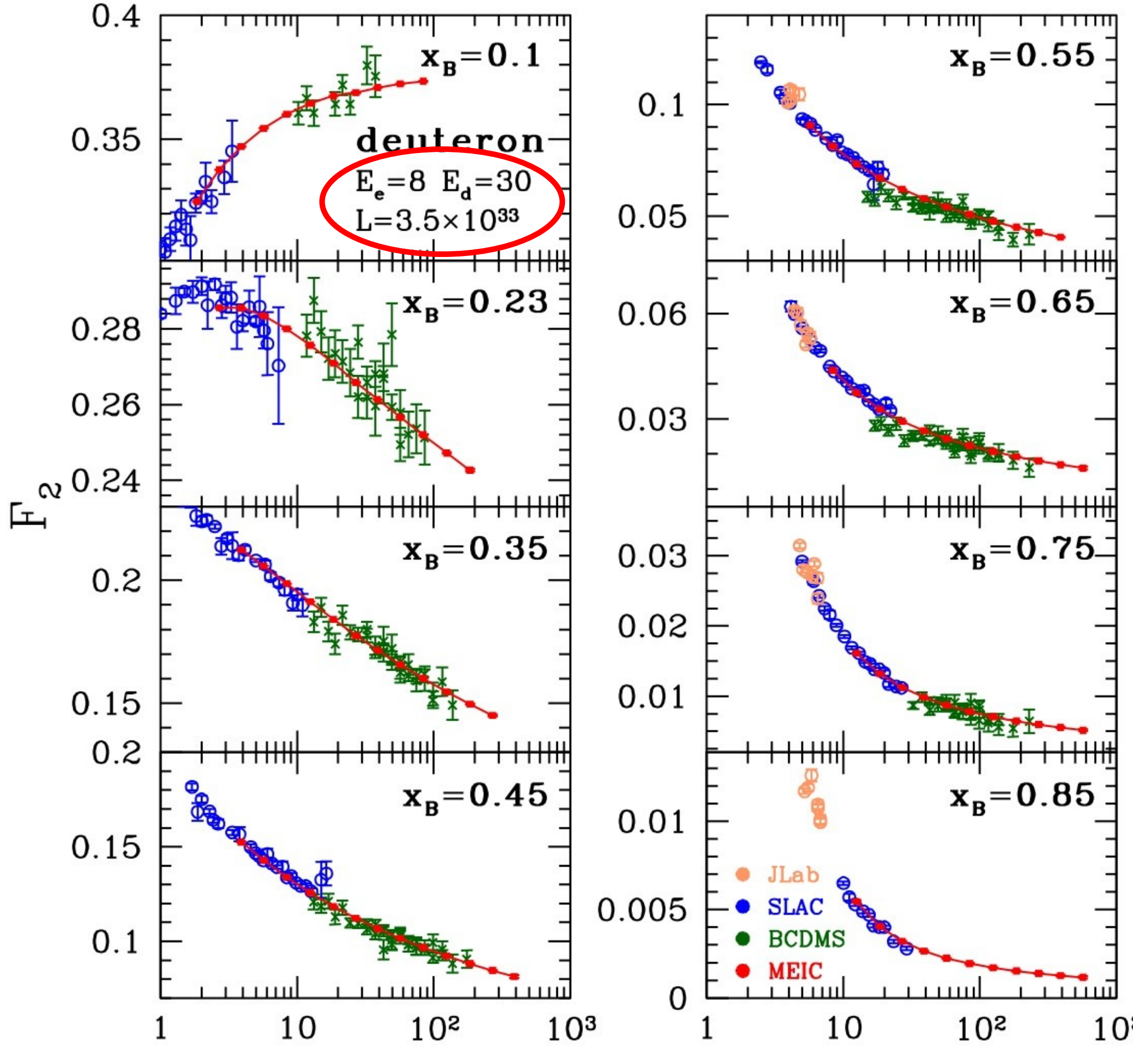
Projected Results IIb - F_2^d



- E_e = 8 GeV, E_N = 30 GeV (s = 1000)
- Luminosity ~ 3.5 x 10^{33} (scales with synchrotron limit)
- Smaller neutron str. fn. + reduced luminosity = factor of 10 loss in rate.
- One year of running (26 wk) at 50% efficiency, or **35 fb^{-1}**

only stat. errors on projected results

Projected Results IIb - F_2^d

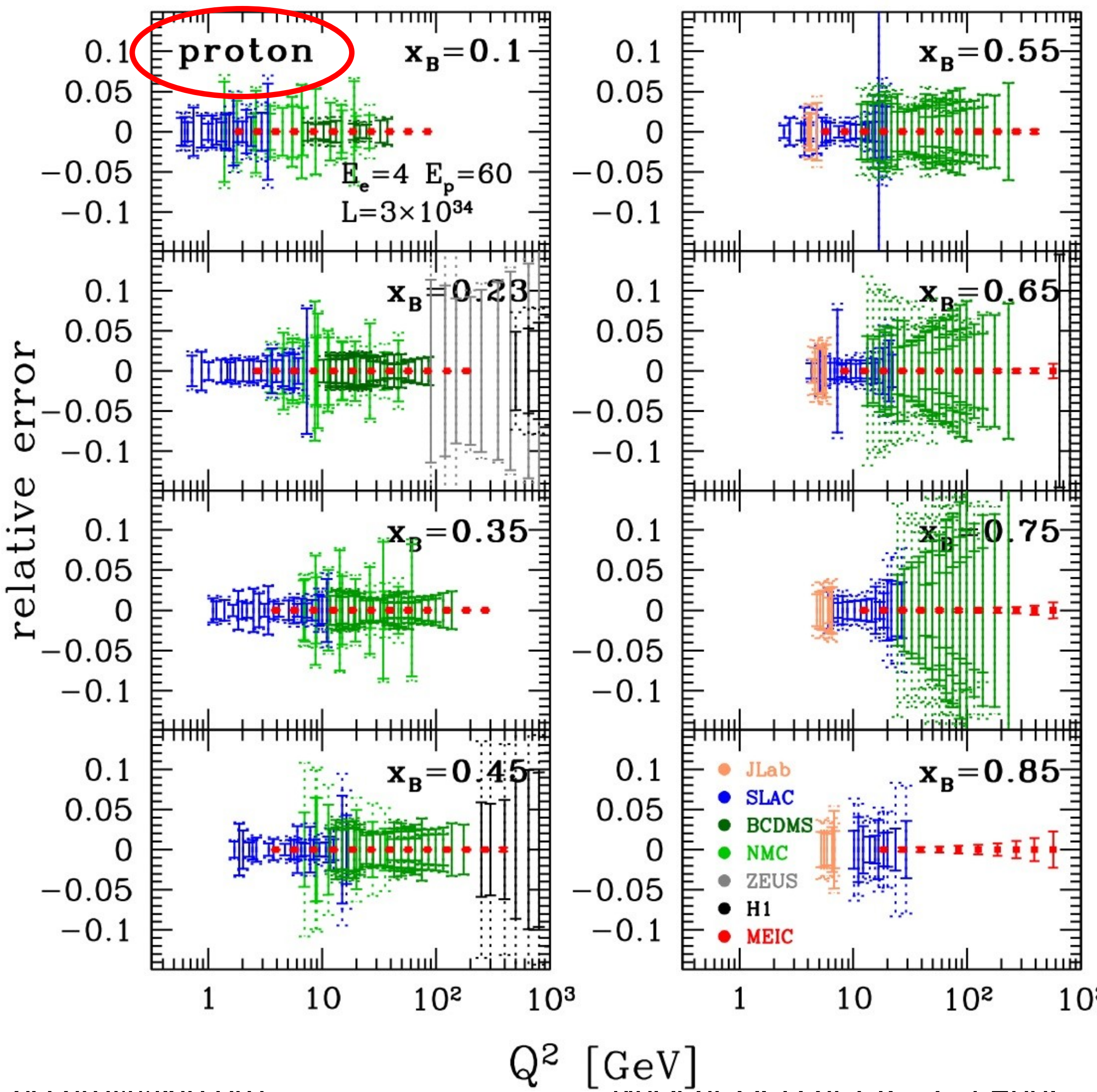


- E_e = 8 GeV, E_N = 30 GeV (s = 1000)
- Luminosity ~ 3.5 x 10^{33} (scales with synchrotron limit)
- Smaller neutron str. fn. + reduced luminosity = factor of 10 loss in rate.
- One year of running (26 wk) at 50% efficiency, or **35 fb^{-1}**

Can tag spectator proton, measure neutron, concurrently

only stat. errors on projected results

Projected Results IIIa - F_2^p Relative Uncertainty



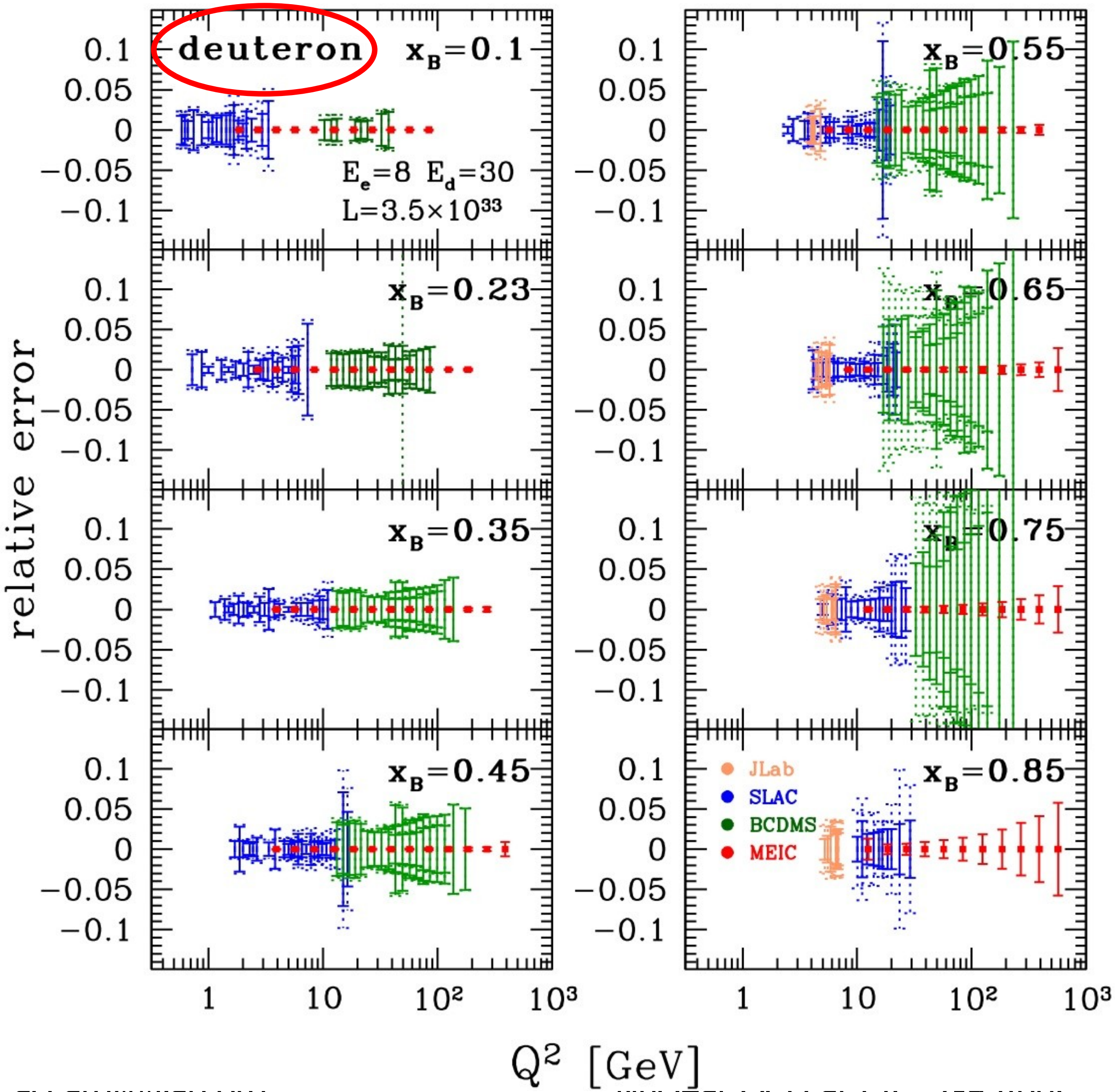
Solid lines are statistical errors, dotted lines are stat+syst in quadrature

For MeRHIC the luminosity is probably down by a factor of ~10, so these error bars will go up ~50%

Huge improvement in Q^2 coverage and uncertainty

Will, for instance, greatly aid global pdf fitting efforts

Projected Results IIIa - F_2^d Relative Uncertainty

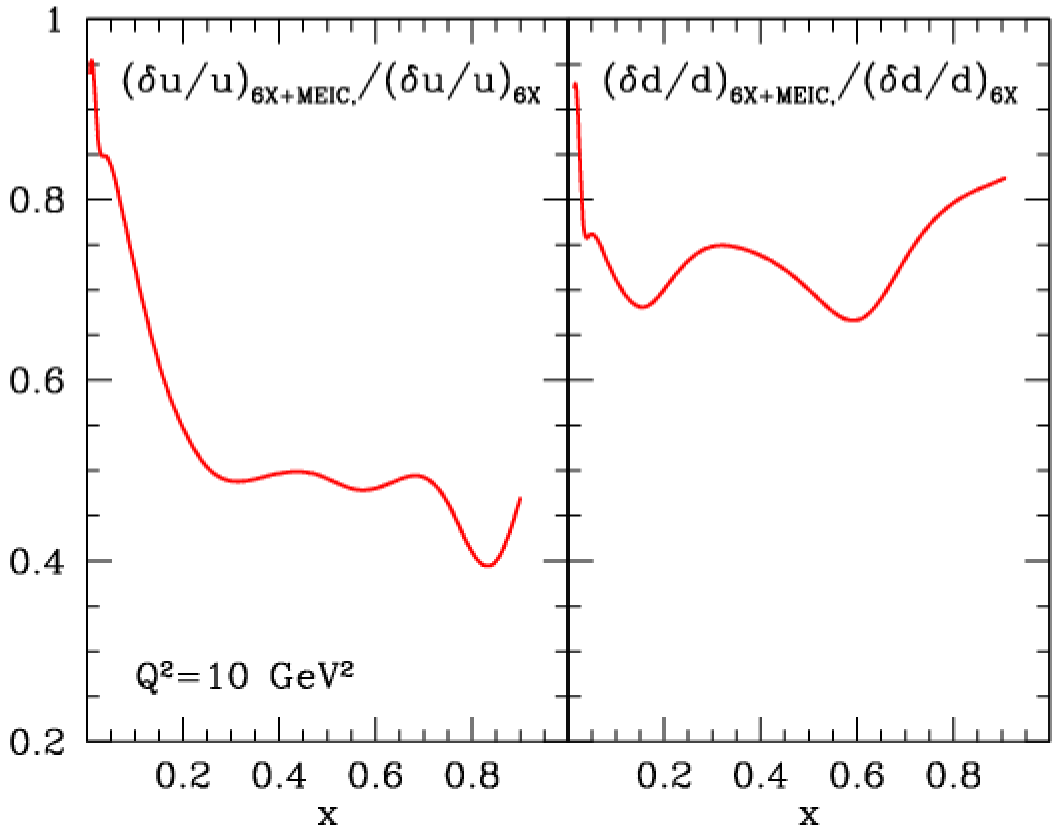


Even with a factor 10 less statistics for the deuteron the improvement compared to NMC is impressive

EIC will have excellent kinematics to measure n/p at large x!

And, there's more physics to do as well……

Projected Results IV – impact on global fits

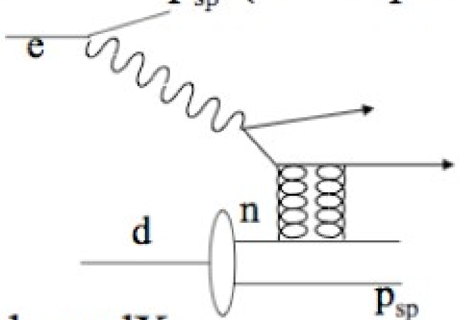


Sensible reduction in PDF error,
likely larger than shown if energy scan is performed

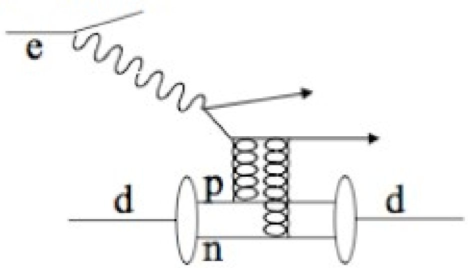
Other physics to do, with and without tagging

Diffraction on a neutron

– $ed \rightarrow enXp_{sp}$ $(ed \rightarrow epXn_{sp})$



– $ed \rightarrow edX$



Higher-Z tagging

^{4}He(e,e'^{3}He)X or ^{4}He(e,e'^{3}He)X

⇒ bound p and n

⇒ origin of EMC effect

Parity Violating DIS

$$\vec{e}_L(\vec{e}_R)\, p \longrightarrow e\, X$$

L/R electron asymmetry

⇒ γ/Z interference ∝ *d/u*

^{3}He - ^{3}H mirror nuclei

$$\frac{^3H}{^3He} \approx \frac{n}{p}\,\frac{2+p/n}{2+n/p}$$

nuclear corrections cancel in ratio

And...

Pion structure function,
nuclear shadowing in deuterium,
charged-current cross sections, ...

Conclusions and Outlook

- **Spectator tagging will open up an exciting physics program**
  - Detector design – angular & momentum resolution
  - Rate estimates needed ↳ ongoing: see S.White's talk
  - p vs. n tagging:
    - ✓ "effective" neutron target
    - ✓ control nuclear effects on an "effective" proton
  - Tagging with ^{4}He targets ???
    - ✓ EMC effect

- **Bread and butter: untagged DIS**
  - Detailed rates: F_2 and F_L , p and D
  - Impact on global fits
    - ✓ large-x
    - ✓ small-x and saturation

F_2^n/F_2^p: Textbook Physics - d/u at large x

Quark-Parton Model

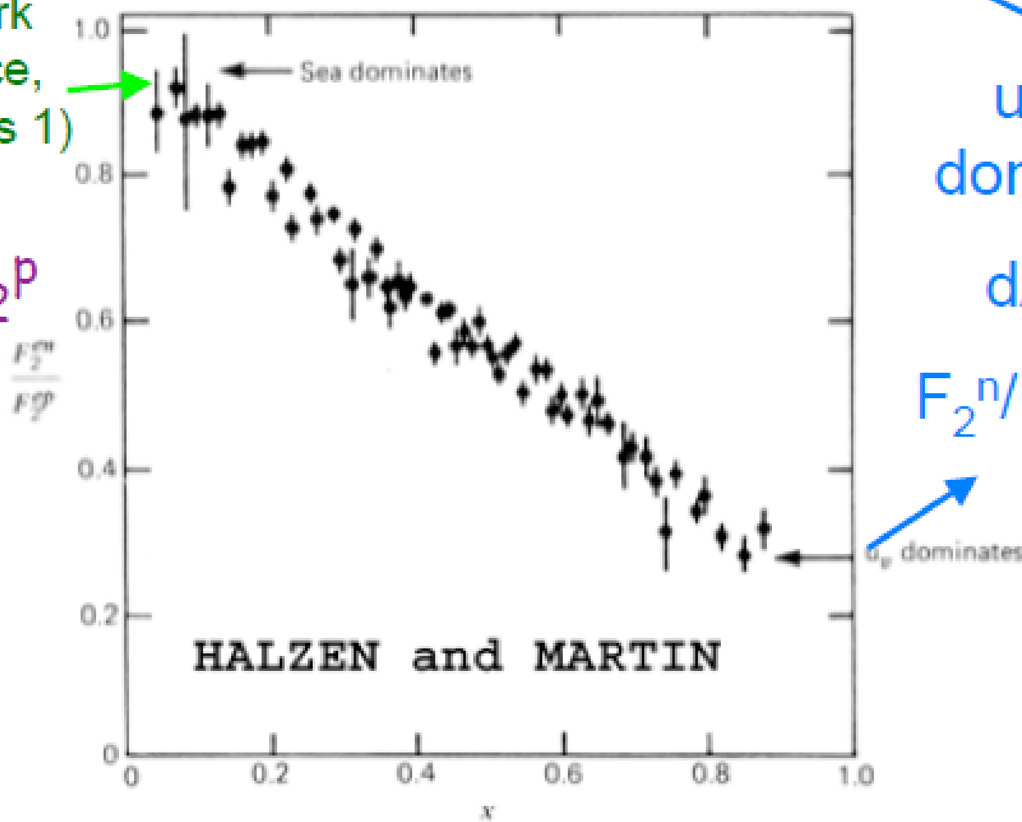
$$F_2^p(x) = x\sum_q e_q^2(q(x)+\overline{q}(x)) \underset{x\to 1}{\approx} x\left(\frac{4}{9}u(x)+\frac{1}{9}d(x)\right)$$

$$F_2^n(x) \underset{x\to 1}{\approx} x\left(\frac{4}{9}d(x)+\frac{1}{9}u(x)\right)$$

$$\frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+d/u}$$

(sea quark dominance, approaches 1)

F_2^n/F_2^p



u quark dominance,

d/u -> 0

F_2^n/F_2^p -> 1/4

x -> 1

BUT.......

F_2^p - F_2^n may help determine α_S

- The strong coupling constant is *the least* well measured fundamental constant

Particle Data Group, 2007

Coupling Constant or Mass	Value	Relative Experimental Error (ppb x 10^{-9})
Fine structure constant α	1/137.035999679(94)	3.7 x 10^{-9}
Fermi constant G_F	1.16639(1) GeV^{-2}	8.6 x 10^{-6}
Z boson mass	91.1876(21) GeV	2.3 x 10^{-5}
W boson mass	80.398(25) GeV	4.8 x 10^{-4}
Gravitational constant G_N	6.67428(67) x $10^{-11} m^3 kg^{-1} s^{-2}$	1.5 x 10^{-3}
Strong coupling constant α_S	0.1176(20)	1.7 x 10^{-2}

- Extracting $'\Upsilon_S$ from DIS (HERA, BCDMS, NMC,….):
  - $'\Upsilon_S$ very small for BCDMS, but NMC requires higher twist correction to minimize dependence of $'\Upsilon_S$ on minimum Q^2 used
  - Want high x region at moderate Q^2, wide range of x, Q^2 to test lnQ^2 evolution
  - Evolution of F_2^p - F_2^n is independent of the gluon distribution, provides determination of $'\Upsilon_S$ free of xg shape (a problem in F_2^p analyses)

F_2^n/F_2^p fundamental to understanding proton structure

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

Predictions for d/u at large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

u, d same shape u = 2d

SU(6) spin-flavor symmetry:

The mass difference between N and Δ implies symmetry breaking

Predictions for d/u at large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

SU(6) symmetry broken - scalar valence diquark, u dominance

S=0 diquark dominance

- d/u=(0)/(1/2)=0
- Hyperfine-perturbed quark model (Isgur *at al*.) with one-gluon-exchange; MIT bag model with gluon exchange (Close & Thomas); Phenomenological quark-diquark (Close) and Regge (Carlitz) arguments

Predictions for d/u at large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

$$|p\uparrow\rangle = \frac{1}{\sqrt{2}}|u\uparrow(ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u\uparrow(ud)_{S=1}\rangle - \frac{1}{3}|u\downarrow(ud)_{S=1}\rangle - \frac{1}{3}|d\uparrow(uu)_{S=1}\rangle - \frac{\sqrt{2}}{3}|d\downarrow(uu)_{S=1}\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Valence Quark	1/4	0
pQCD	3/7	1/5

S_z = 0, di-quark dominance, spin projection is zero

- d/u=(1/9)/(1/2+1/18)=1/5
- pQCD with helicity conservation (Farrar and Jackson); quark counting rules (Brodsky *et al.)*

[There are even more predictions…]