Measuring F_2^n (F_2^d) at the (m)EIC: Some preliminary thoughts

EIC Collaboration Meeting

SUNY Stony Brook

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

Quark-Parton Model

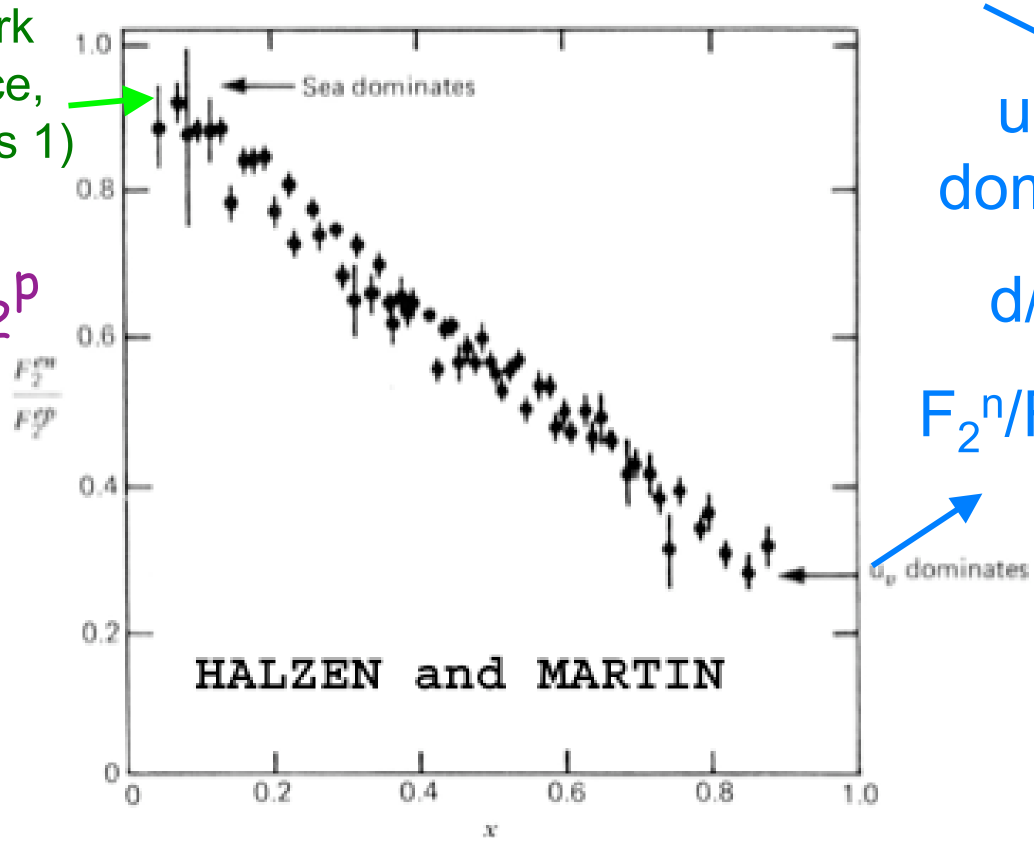
$$F_2^p(x) = x\sum_q e_q^2 (q(x) + \bar{q}(x)) \underset{x\to 1}{\approx} x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x)\right)$$

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

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

(sea quark dominance, approaches 1)

F_2^n/F_2^p



u quark dominance,

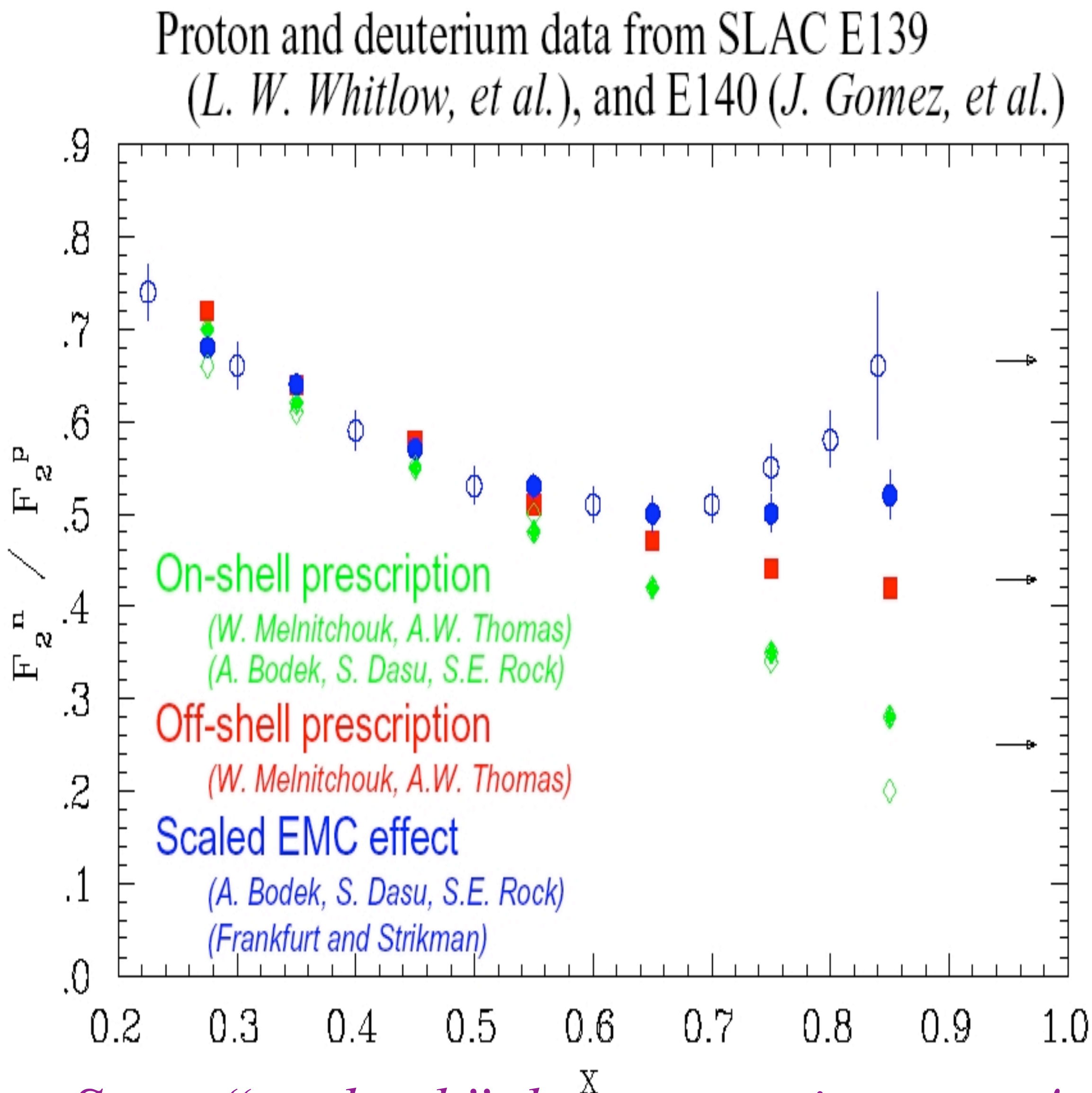
d/u –> 0

F_2^n/F_2^p –> 1/4

x –> 1

BUT......

….the data are from proton and *deuteron* scattering



Neutron structure typically derived from deuterium target by subtracting proton

Large uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function, coherent scattering, final state interactions, nucleon structure modification ("EMC"effect)……………..

Same "textbook" data as previous page!

$0.2 < F_2^n/F_2^p < 0.8$?!

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

Proton Wavefunction (Spin and Flavor Symmetric)

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

$$-\frac{1}{3}\left|d\uparrow(uu)_{S=1}\right\rangle - \frac{\sqrt{2}}{3}\left|d\downarrow(uu)_{S=1}\right\rangle$$

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}

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u, d same shape u = 2d

SU(6) spin-flavor symmetry:

The mass difference between N and Δ implies symmetry breaking

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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

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Nucleon Model	F_2^n/F_2^p	d/u
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Valence Quark	1/4	0
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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…]

F_2^n/F_2^p (and, hence, d/u) is essentially unknown at large x:

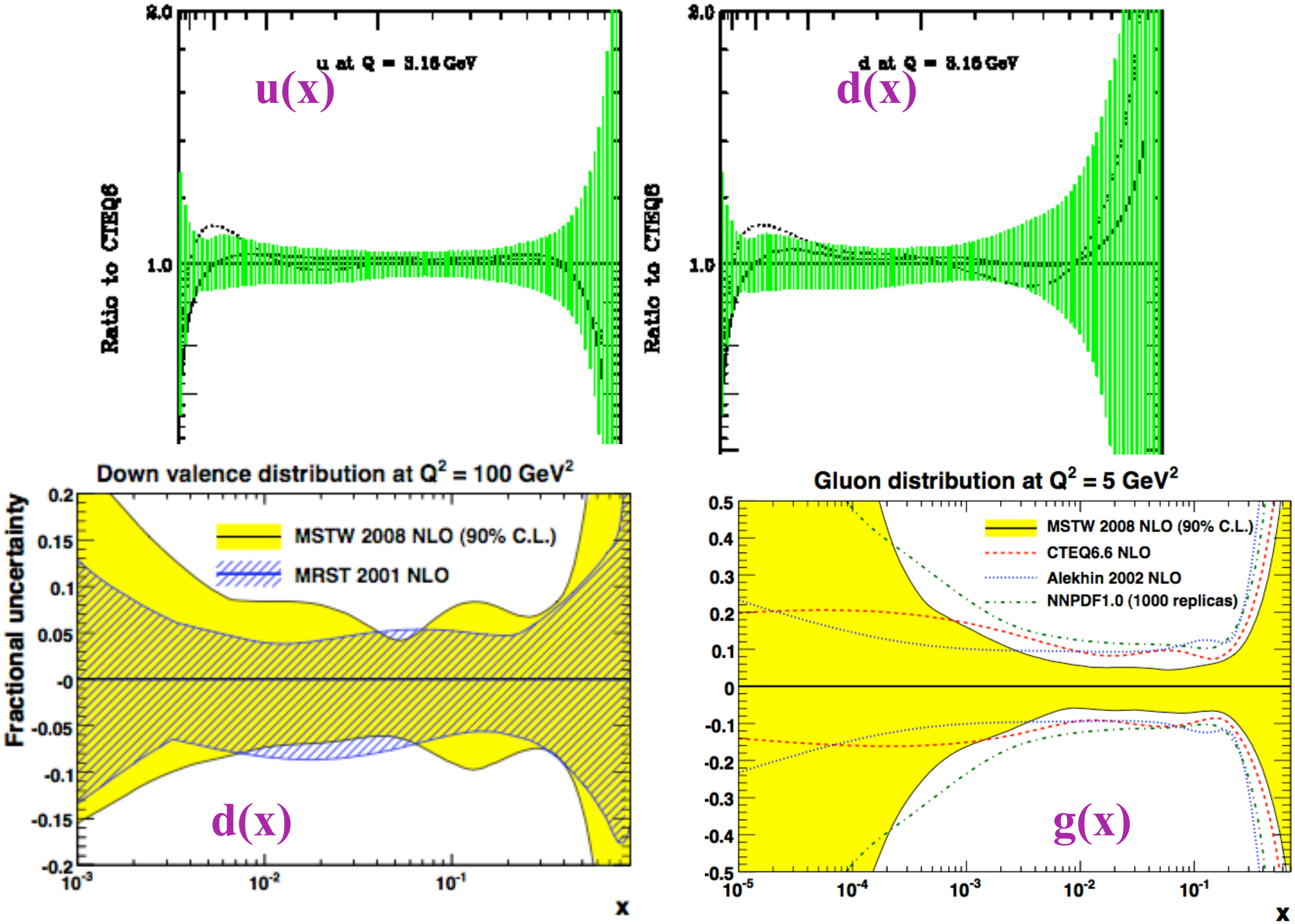
- Conflicting fundamental theory pictures
- Data hindered by lack of free neutron target

Review Articles :

Isgur, Phys. Rev. D59, 34013 (1999)
Brodsky et al., Nucl. Phys. B441, 197 (1995)
Melnitchouk and Thomas, Phys. Lett. B377, 11 (1996)

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

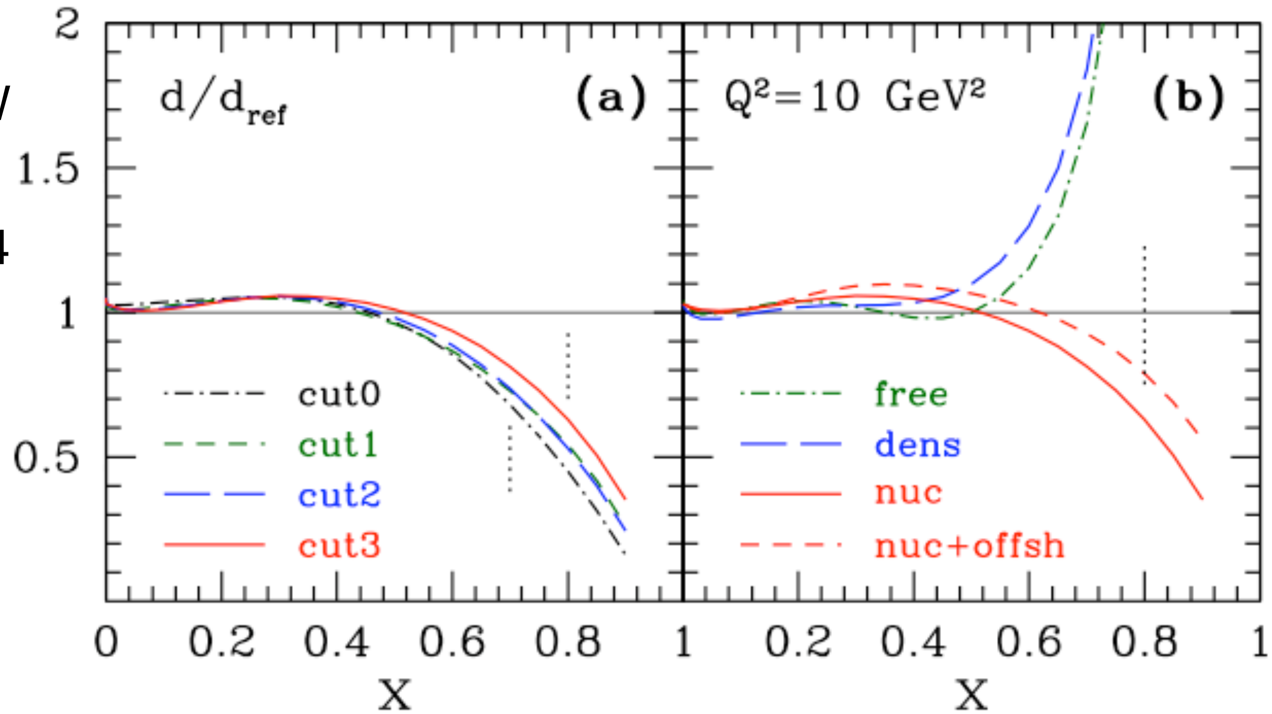
Large x (x > 0.1) -> Large PDF Uncertainties



"CTEQ6X" Study to Optimize Large x Region

arXiv:0911.2254v1 [Accardi et al, CTEQ6X], 2009, *accepted to PRD*

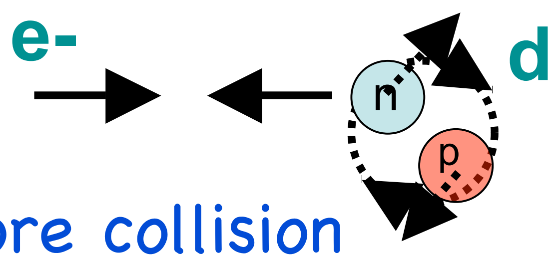
- Relax W, Q cuts to allow for expanded data set (SLAC, Jlab, Drell-Yan, W assymmetry,….)
- $W^2 > 12.25$ GeV^2, $Q^2 > 4$ GeV^2 down to $W^2 > 3$ GeV^2, $Q^2 > 1.69$ GeV^2
- Consider target mass corrections, higher twist, and nuclear corrections (more to come)
- Dotted lines indicate regions unconstrained by data.



"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."

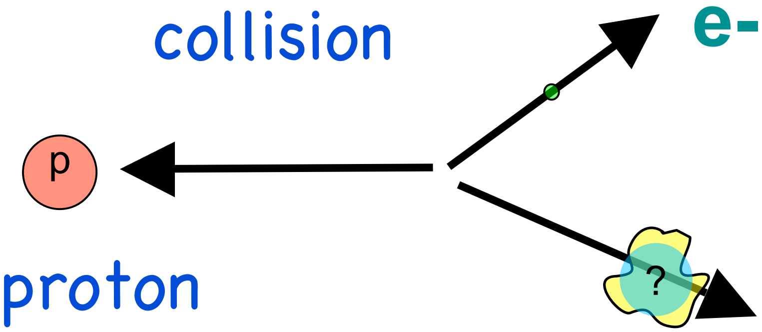
Let's look at how the EIC might obtain this free neutron data……

The Spectator Tagging Approach: An Effective Free Neutron Target from Deuterium....



before collision

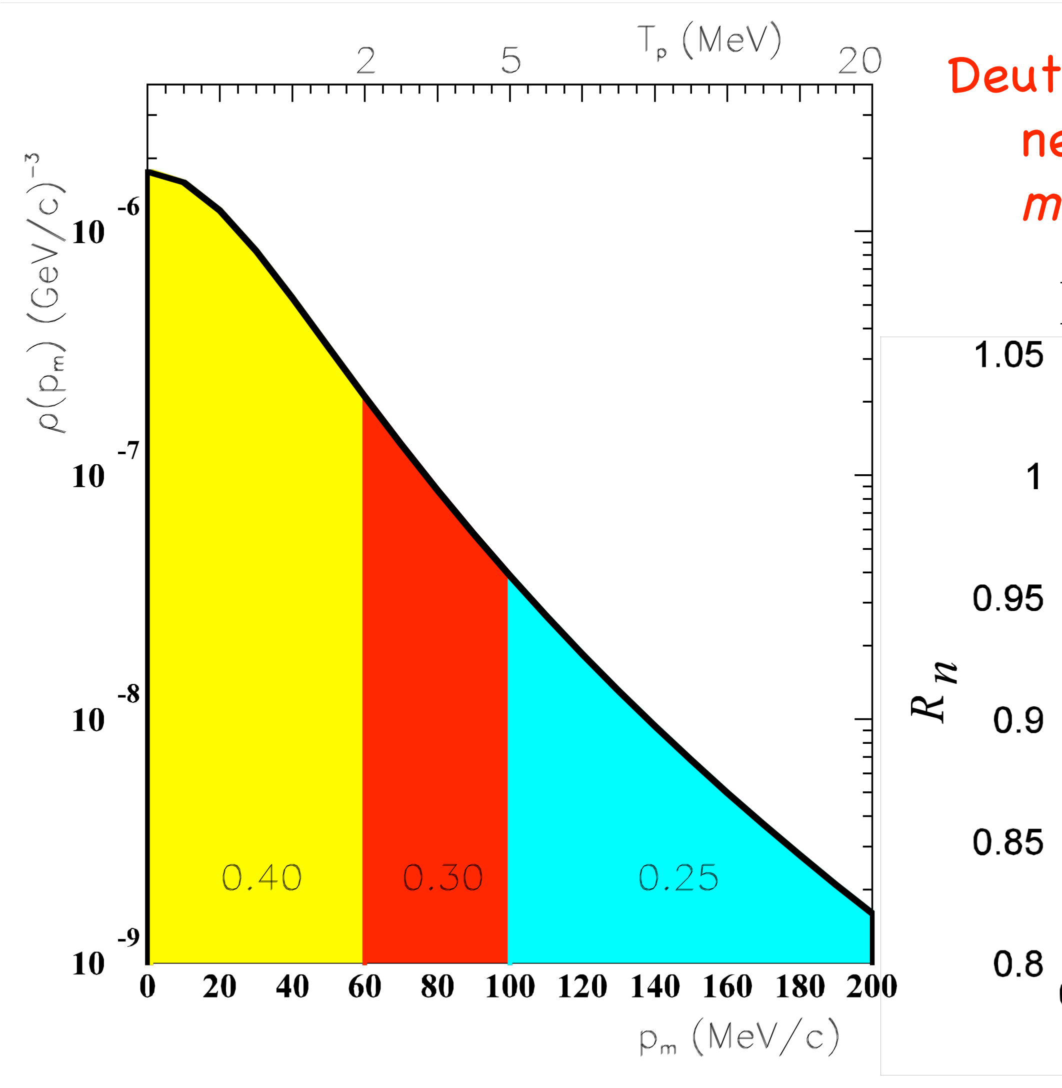
after e-n collision



"spectator" proton

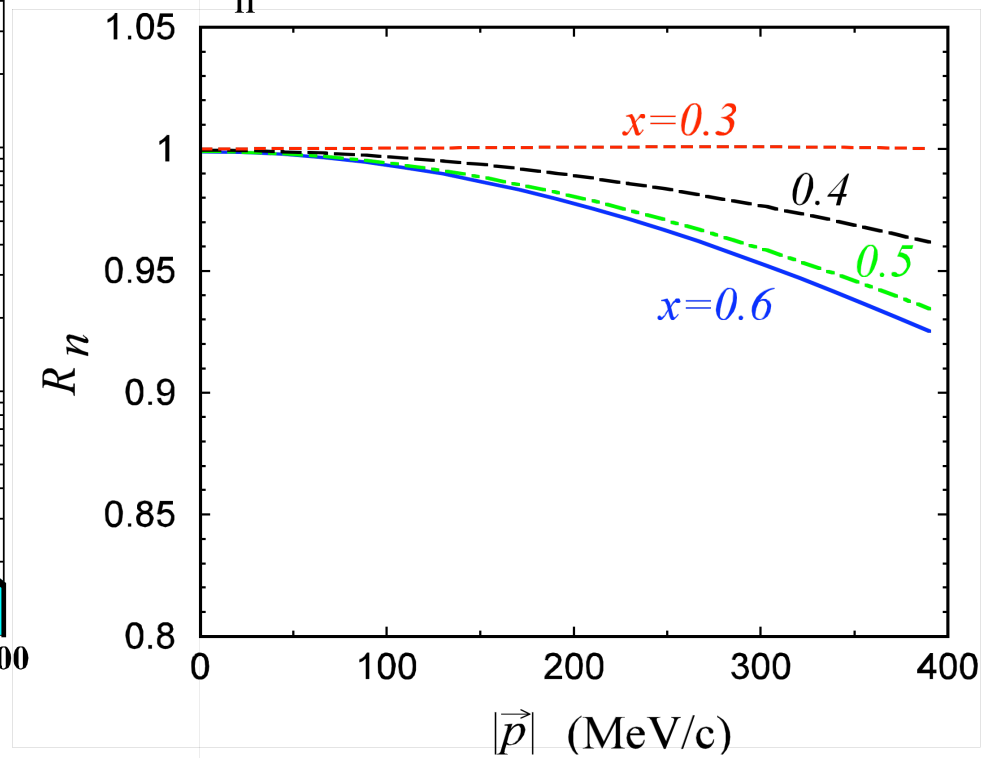
standard DIS event – *from a neutron target!*

Need "VIPs" (Very Important Protons)



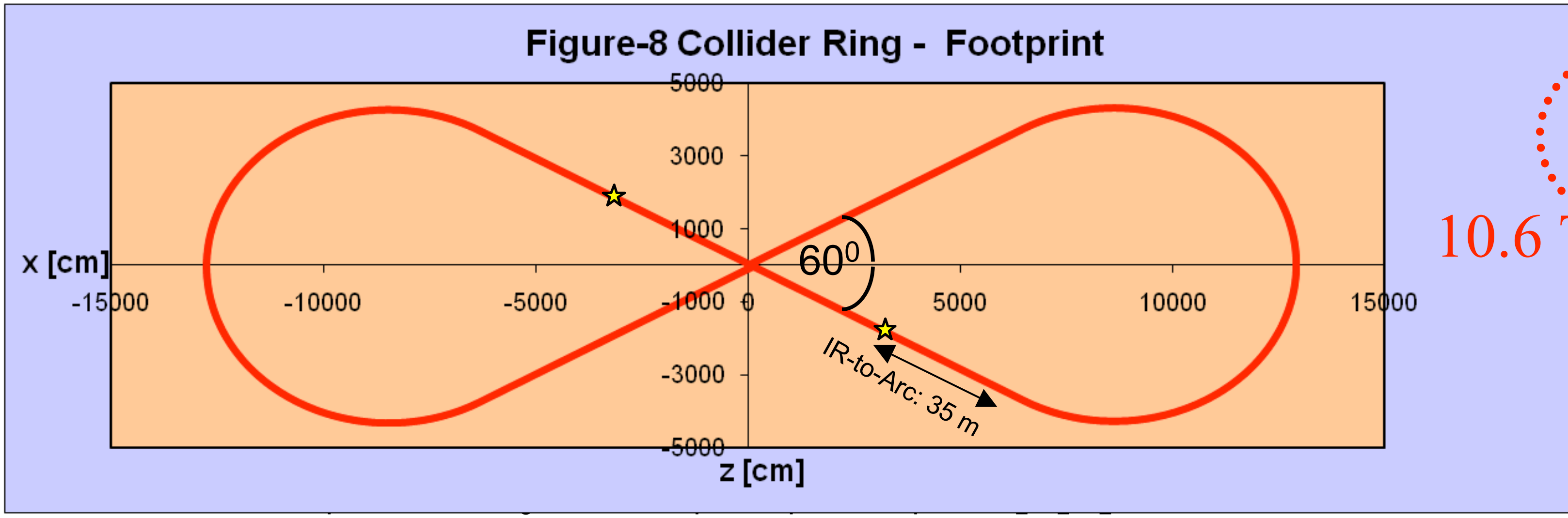
Deuteron ~ free proton + free neutron *only at small nucleon momenta*

R_n = ratio free/bound neutron



plot from W. Melnitchouk

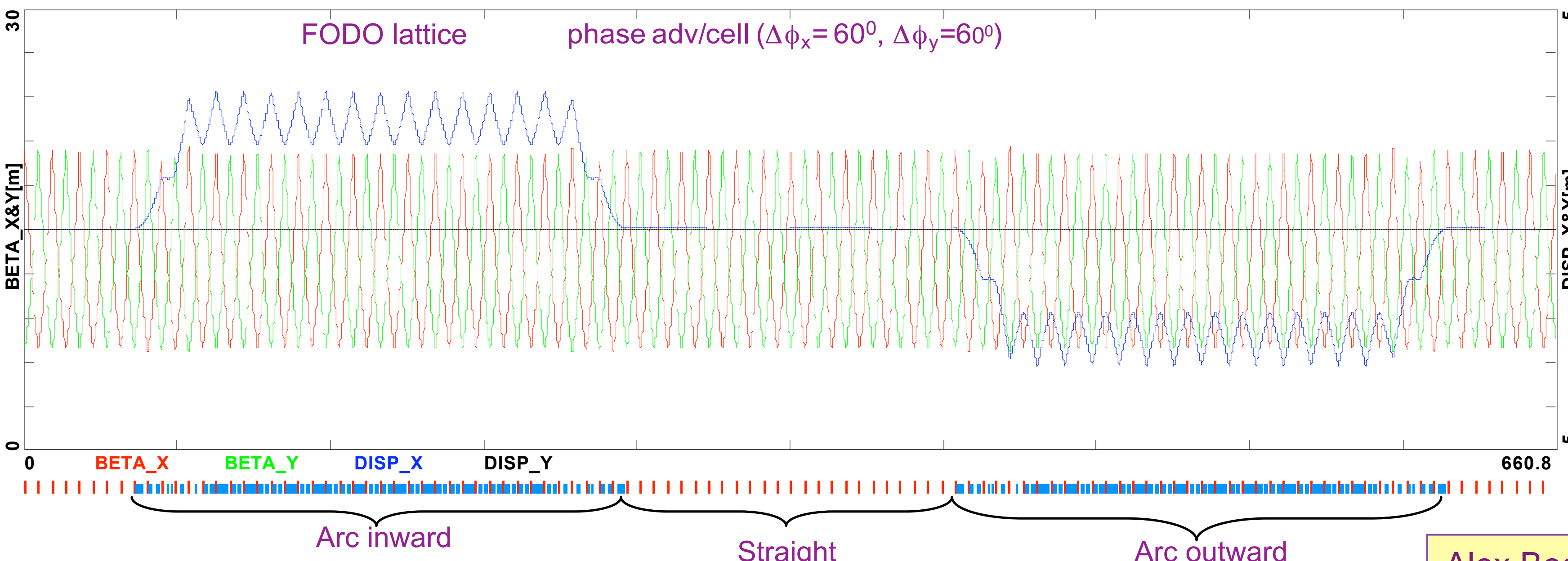
ELIC Figure-8 Ion Ring – Arc Optics 60 GeV



Arc dipoles
$Lb=200 cm
$B=53 kG

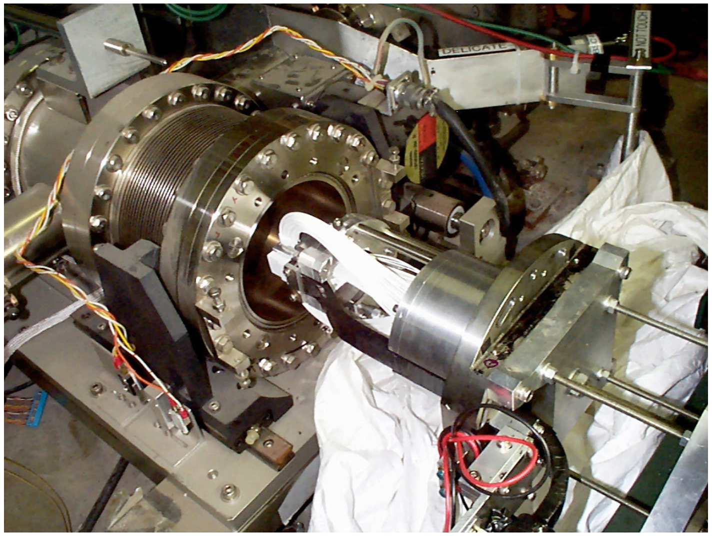
10.6 Tm

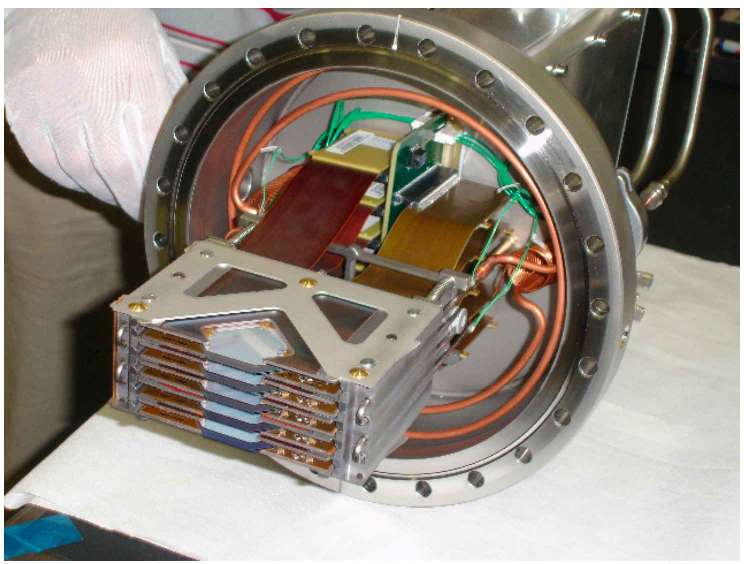
Arc quads
$Lb=40 cm
$G= ±**8.5** kG/cm



Alex Bogacz

Proton Tagging





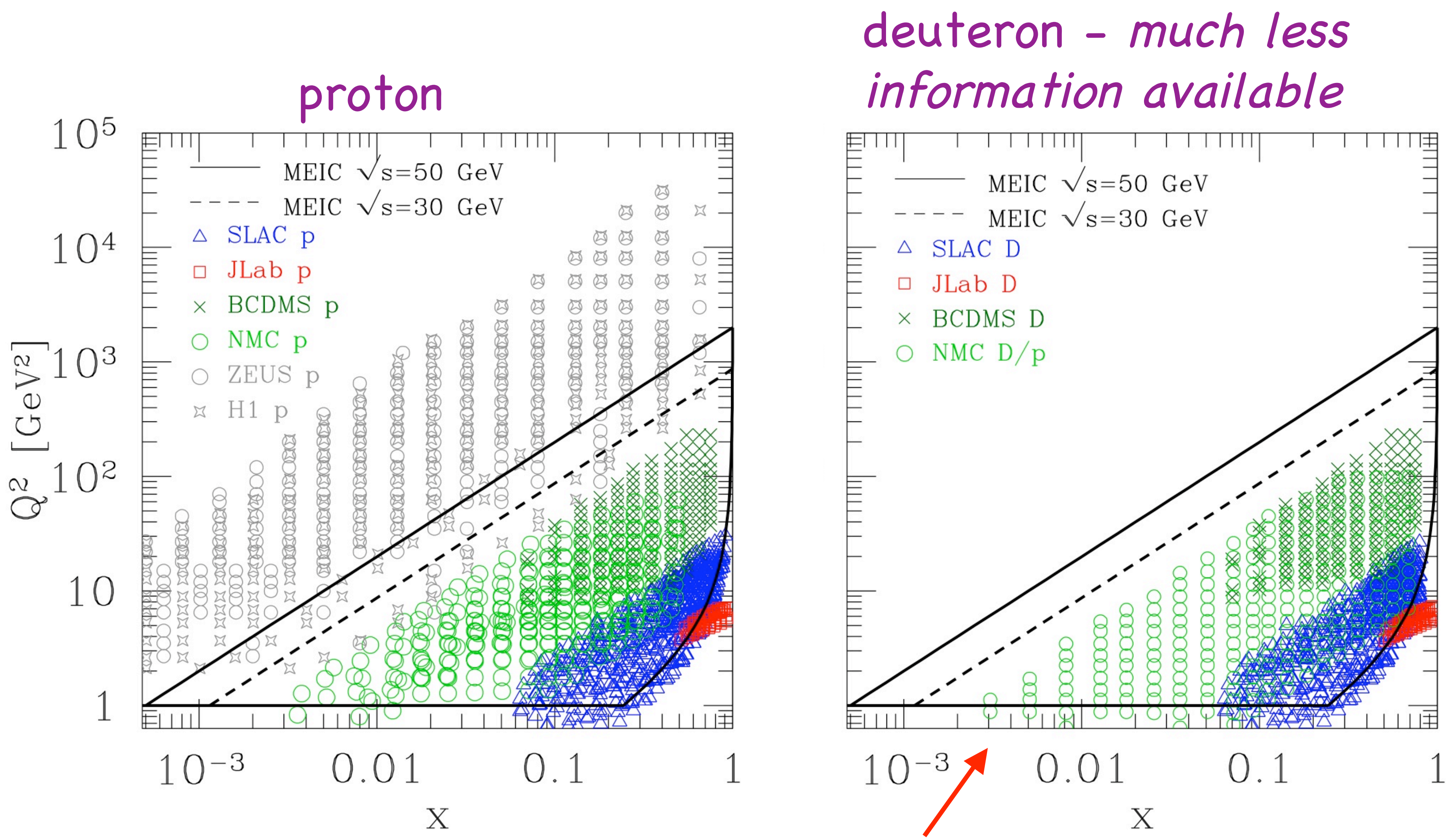
- 10.6 Tm: 30 GeV/nucleon beam bends 106.0 mr

- corresponds to a primary beam bend of 21.2 cm at 1 m after the dipole exit

-1.0% (300 MeV/c) bends 107.07 mr, or 21.4 cm, (too) close to 21.2 cm!

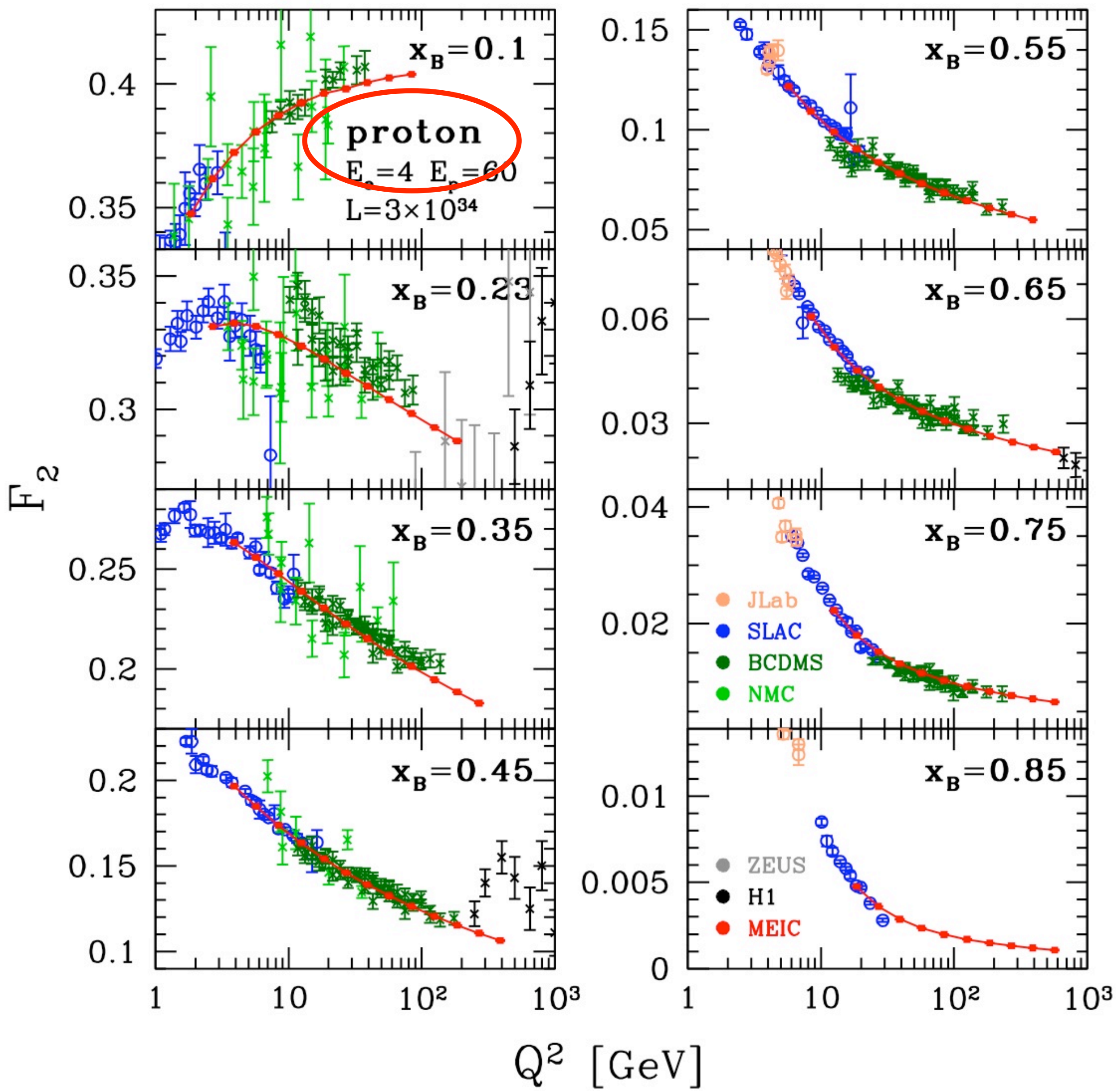
- Try after 4 dipoles, 2 m long with 1 m between, now a separation of (11 + 8 + 5 + 2) * 0.2 cm = 5.2 cm (or 1.7 cm for 0.33%, 100 MeV/c, and 3.4 cm for 0.67%, 200 MeV/c)
- Could go further (halfway) into the arc
- Roman pots (photos at CDF (top), LHC (bottom),……) ~1mm from beam achieve proton detection with < 100μ resolution
- *Proton tagging concept needs work, but looks doable!*
- Neutrons more difficult - needs some thought

Projected Results I - F_2 Structure Function Phase Space (plots from A. Accardi, kinematics from R. Ent)



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

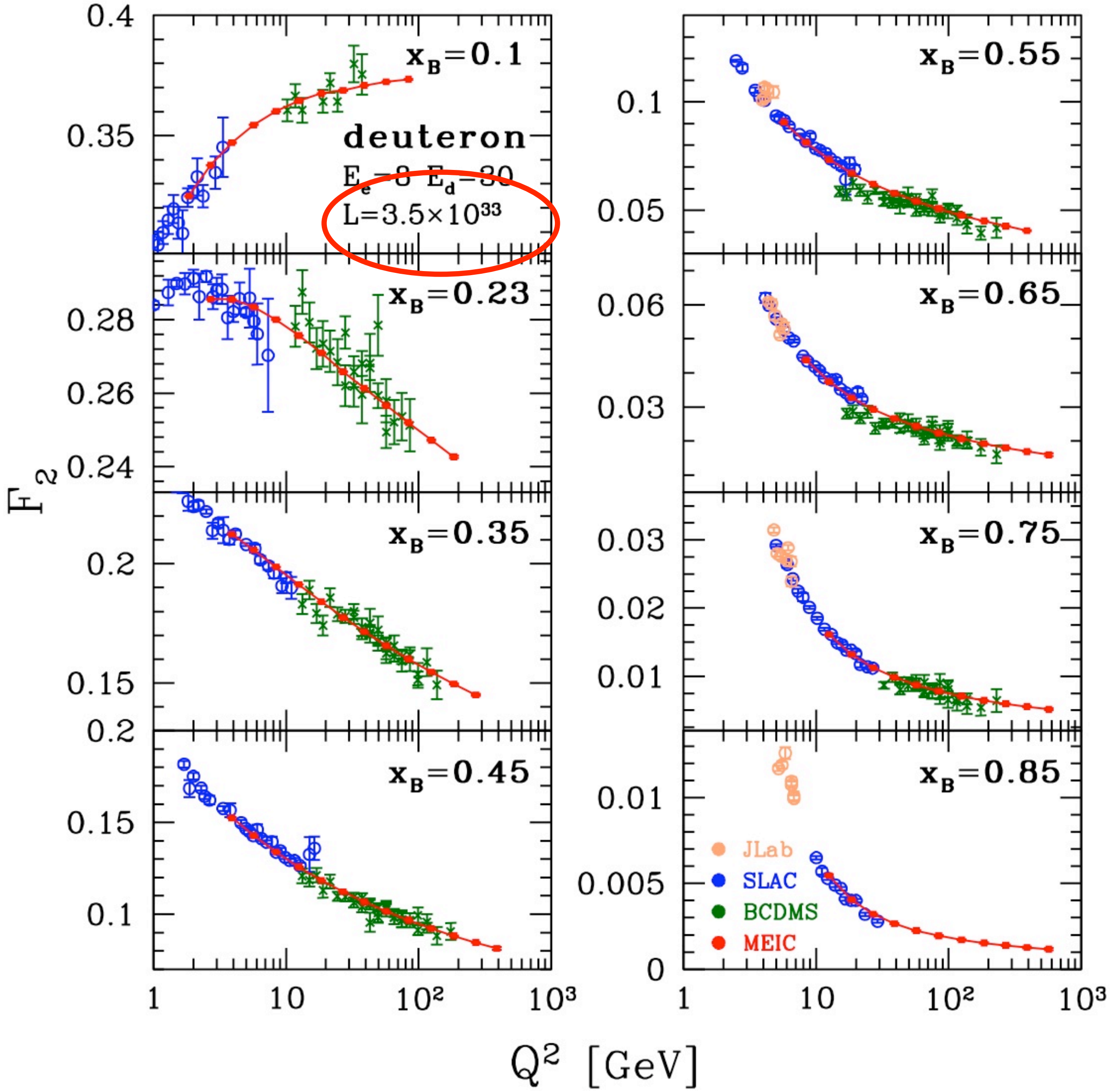
Projected Results IIa - F_2^p Structure Function (from CTEQ6X pdfs)



- E_e = 4 GeV, E_p = 60 GeV (s = 1000)
  - larger s (~4000 MeRHIC, or ~2500 MEIC) would cost luminosity
- Somewhat smaller Q^2 reach and large luminosity is better choice at large x, σ ~ $(1-x)^3$
- Luminosity ~ 3 x 10^{34} for MEIC (possible 10^{33} for MeRHIC)
- 0.004 < y < 0.8
- One year of running (26 weeks) at 50% efficiency, or 230 fb^{-1}

statistical errors only on projected results

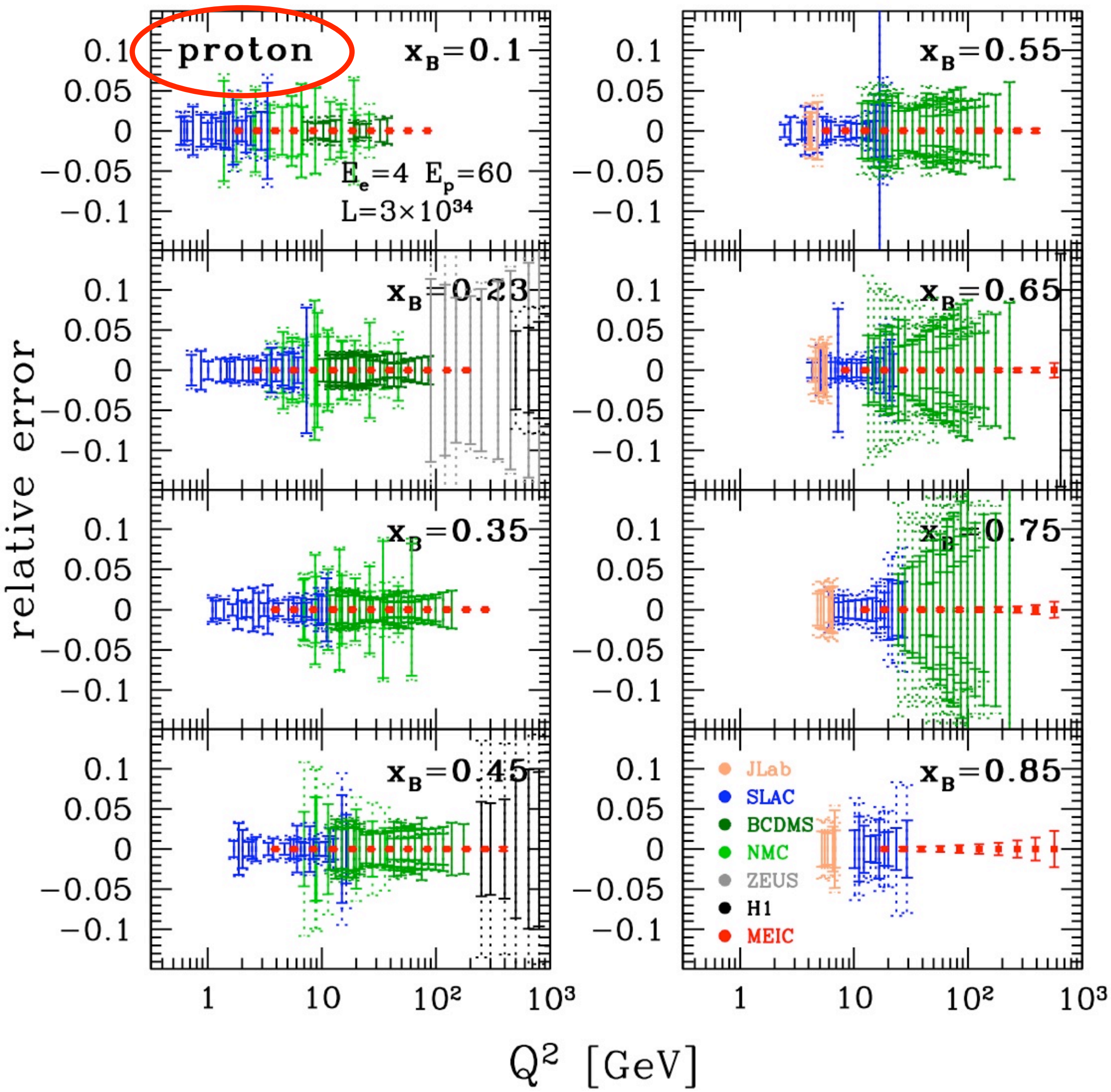
Projected Results IIb - F_2^d Structure Function



- E_e = 8 GeV, E_N = 30 GeV (s = 1000) luminosity ~ 3.5 x 10^{33} for MEIC (scales with synchrotron limit)
- Smaller neutron structure function, reduced luminosity, lose about a factor of 10 loss in rate.
- One year of running (26 weeks) at 50% efficiency, or 35 fb^{-1}
- *Can tag spectator proton, measure neutron, concurrently*

statistical errors only on projected results

Projected Results IIIa - F_2^p Structure Function Relative Uncertainty



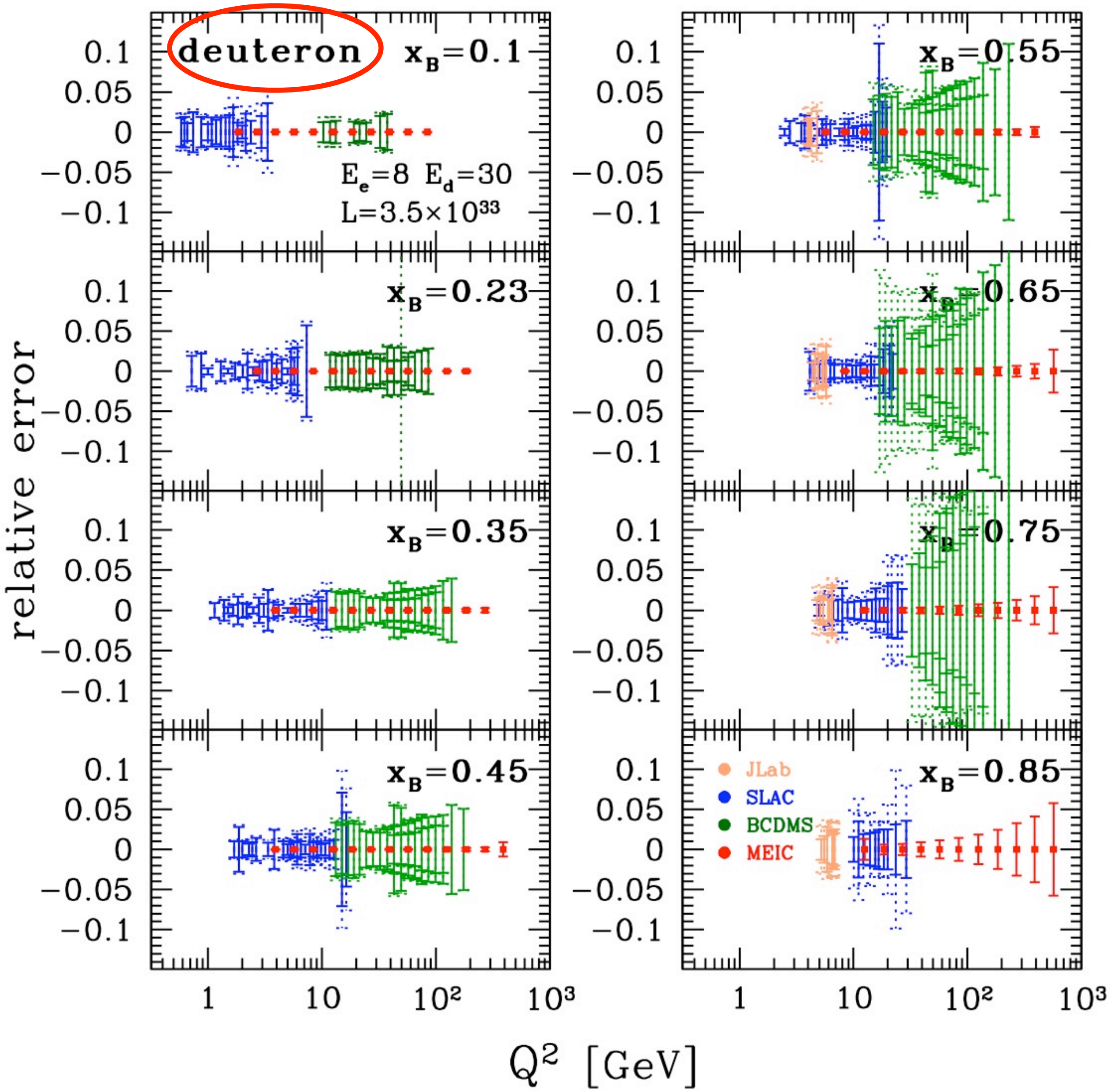
Solid lines are statistical errors, dotted lines are stat+syst in quadrature

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 IIIb – F_2^d Structure Function Relative Uncertainty



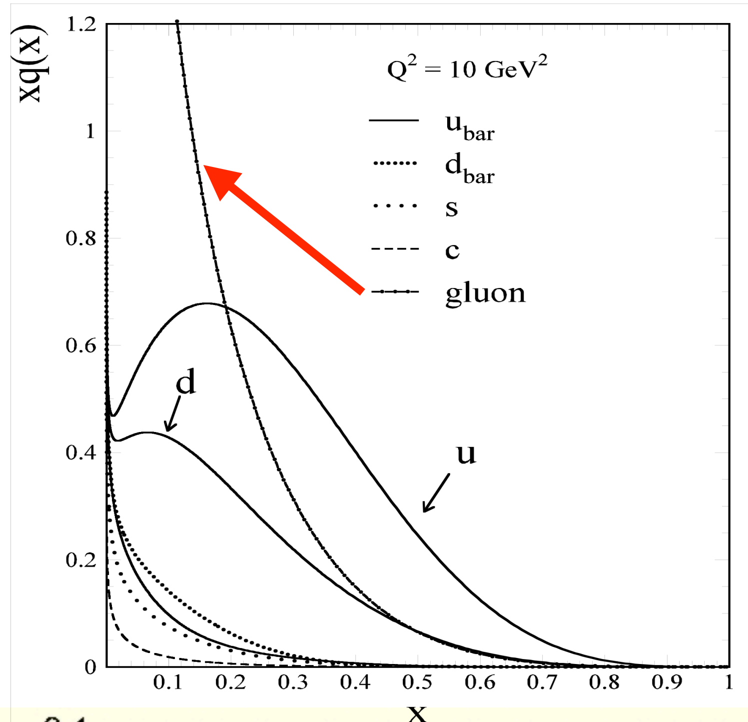
Even with a factor 10 less statistics for the deuteron the improvement compared to NMC is impressive

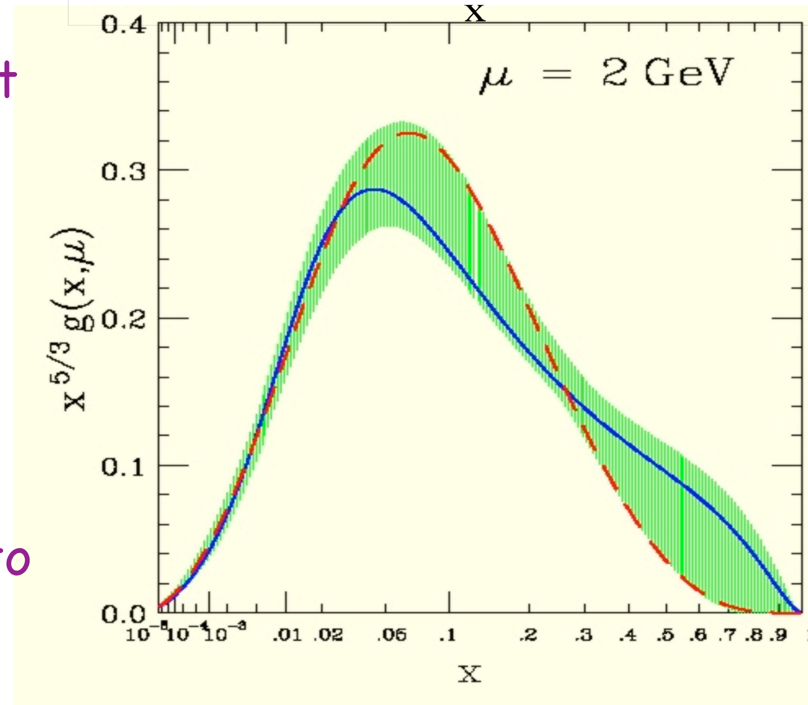
EIC will have excellent kinematics to measure n/p at large x!

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

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

- Nucleon structure composed of singlet (gluons, sea) and non-singlet (valence) distributions
- At moderate x (~0.3), singlet comparable to non-singlet
- Large uncertainties on singlet distribution - - in structure function measurements, comes from (small) scaling violations in F_2
- Q^2 evolution is simpler for the non-singlet (reduced number of splitting functions)
- Assuming a charge-symmetric sea, p-n isolates the non-singlet
- Such measurements provide a direct handle on the quark structure of the nucleon
- Also, need to pin down non-singlet (p-n) to extract singlet (complementary to F_L)





F_2^p – F_2^n may help determine α_S

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

Particle Data Group, 2007

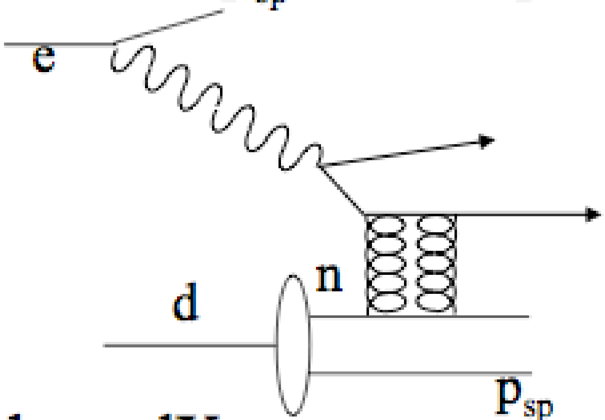
Coupling Constant or Mass	Value	Relative Experimental Error (ppb x 10^{-9})
Fine structure constant α	1/137.035999679(94)	3.7 x 10^{-9}
Fermi constant G_F	1.16639(1) GeV^{-2}	8.6 x 10^{-6}
Z boson mass	91.1876(21) GeV	2.3 x 10^{-5}
W boson mass	80.398(25) GeV	4.8 x 10^{-4}
Gravitational constant G_N	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 α_S from DIS (HERA, BCDMS, NMC,….):
  - α_S very small for BCDMS, but NMC requires higher twist correction to minimize dependence of α_S on minimum Q^2 used
  - Want high x region at moderate Q^2, wide range of x, Q^2 to test $\ln Q^2$ evolution
  - Evolution of F_2^p – F_2^n is independent of the gluon distribution, provides determination of α_S free of xg shape (a problem in F_2^p analyses)

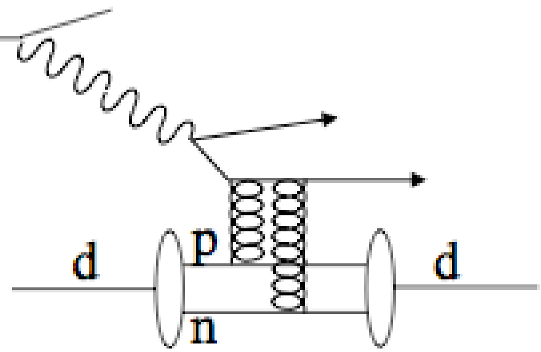
Other physics to do….

Diffraction

- Running with ed, plus tagging, allows study of:
  - $ed \rightarrow enXp_{sp}$ $(ed \rightarrow epXn_{sp})$



  - $ed \rightarrow edX$



- Is structure of diffractive exchange same in electron neutron and electron proton scattering?
- Is diffractive exchange produced coherently off deuteron same as that from proton?

And that's not all! Pion structure function, nuclear shadowing in deuterium, charged-current cross sections, higher Z targets……..!!!!!!………

Conclusions

- *Much* work to do
  - tagger detector design considerations
  - more detailed analysis
  - FSI, other nuclear effects
  - impact in global fits
  - improvements in radiative corrections
  - etc. etc. etc…….

- Spectator tagging should open up an exciting physics program for the EIC

Pre-EIC data to come….

- Spectator tagging at Jefferson Lab (BONUS 6 and 12 GeV)
- Constraints on large-x d-quarks from
  - *Inclusive scattering from mirror nuclei ^3H and ^3He*
  - *p+pbar :*
    - DY at large x_F
  - *p+p :*
    - W-asymmetries at large rapidity
  - ν+*p* and ν-*bar*+*p :*
    - WA21 already has data
      (but need to reconstruct cross-sections from published "quark distributions"... very hard)
    - MINERνA with a hydrogen target - not yet approved