Neutron structure functions at JLab and the EIC

Alberto Accardi
Hampton U. & Jefferson Lab

HU nuclear physics group meeting
25 May 2009

Outline

- **Motivations**
  - Why large-*x*
  - Why neutrons
- **Up and down: the CTEQ6X fit**
- **Constraining d-quarks at large *x***
- **Neutrons at Jlab**
- **Neutrons at the EIC**
- **Conclusions**

Motivations

Why large x ?

- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) New physics as excess on QCD large p_T spectra ⇔ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - spin structure of the nucleon *at small x*
  - neutrino oscillations

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Why large x ...and low Q^2 ?

- JLab and SLAC have precision DIS data at large x , BUT low Q^2
  - need of theoretical control over

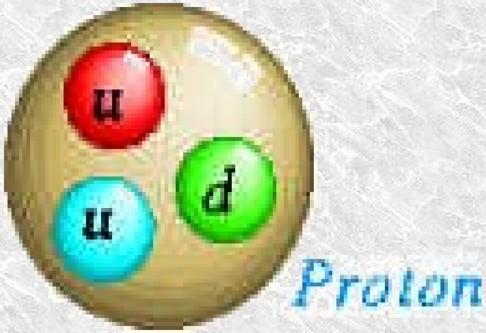
1) higher twist $\propto \Lambda^2/Q^2$
2) target mass corrections (TMC) $\propto x_B^2\, m_N^2/Q^2$
3) nuclear corrections
4) quark-hadron duality

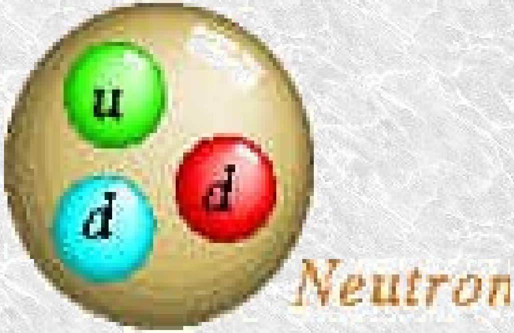
this talk

5) jet mass corrections (JMC) $\propto m_j^2/Q^2$
6) heavy-quark mass corrections $\propto m_Q^2/Q^2$
7) large-x resummation
8) large-x DGLAP evolution
9) parton recombination at large x
10) perturbative stability at low-Q^2
11) ...

Why neutrons?

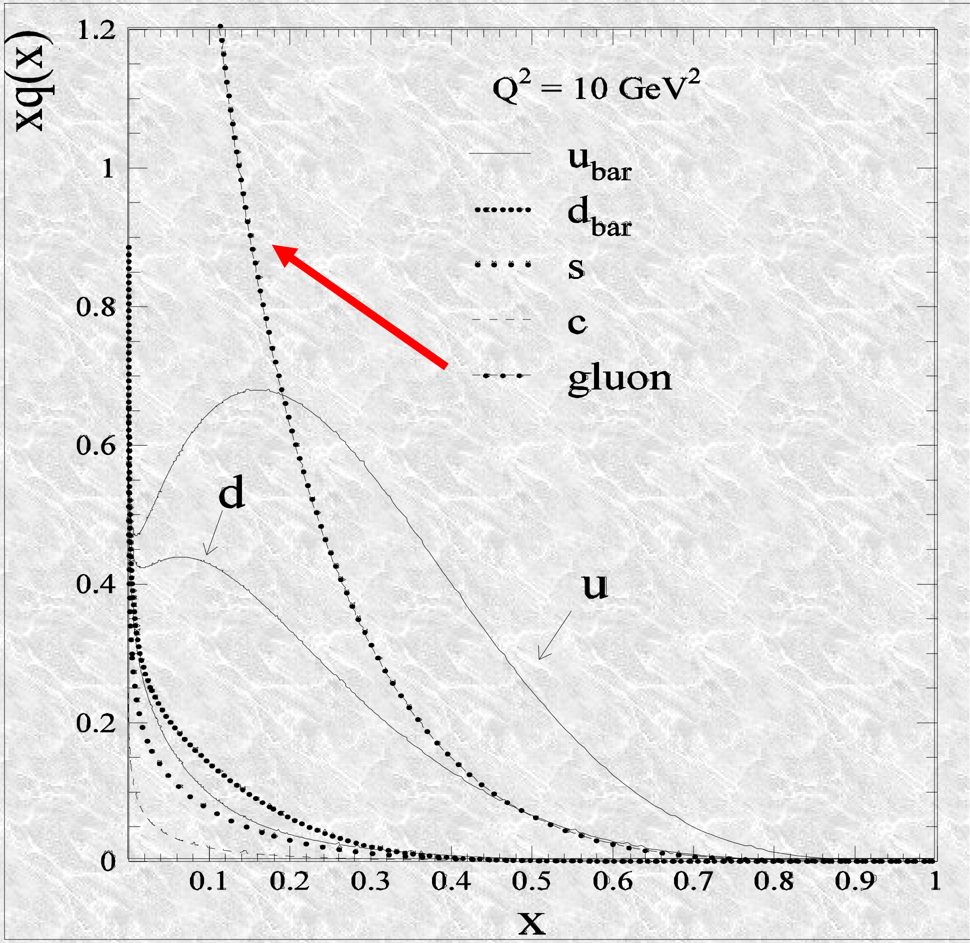
- Most direct information on valence *d*-quark
- But... free neutron beams are somewhat rare:
  - Use instead light nuclei (^{2}H, ^{3}H, ...)
- Nuclear corrections:
  - binding, Fermi motion
  - nucleons are off-shell
  - other causes of EMC effect
  - anti-shadowing
  - shadowing
- A worthwhile effort?





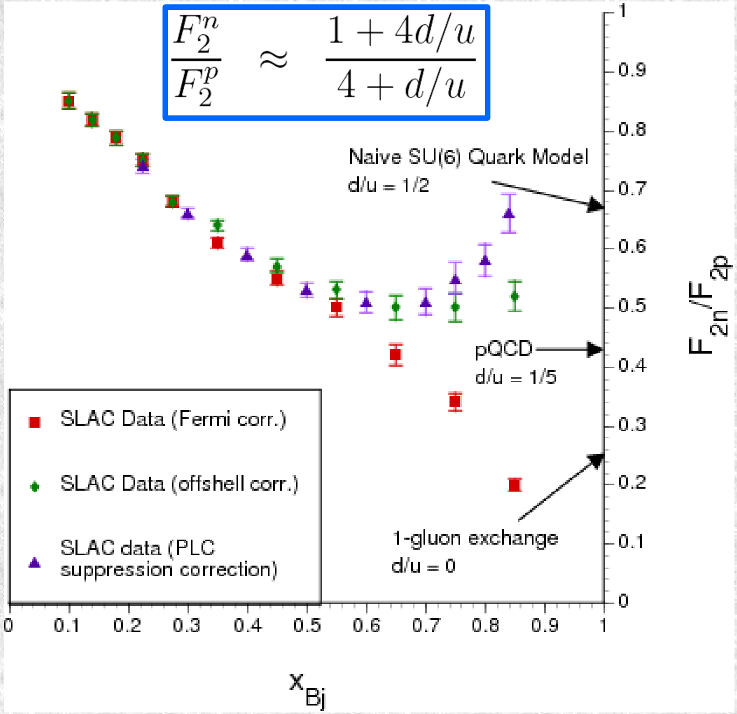
$F_2^p - F_2^n$ yields non-singlet PDF

- 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)

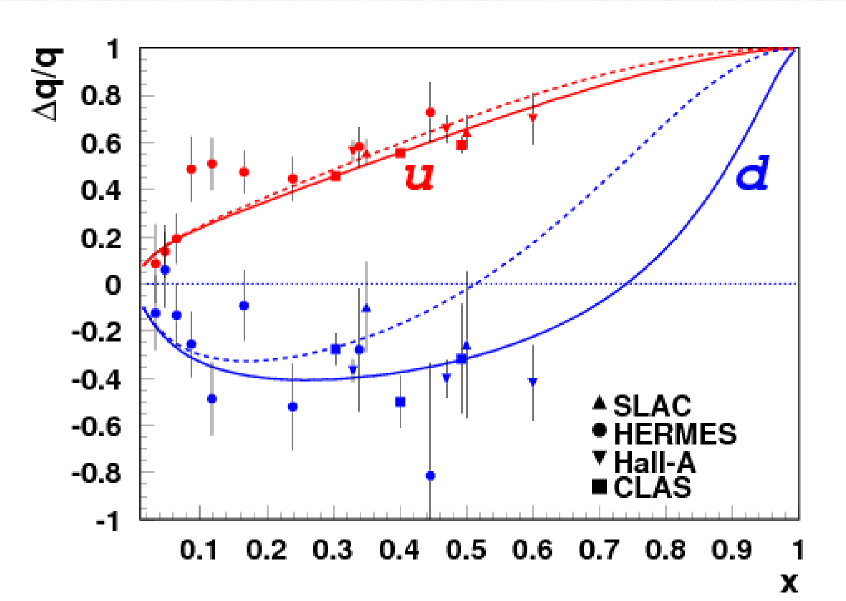


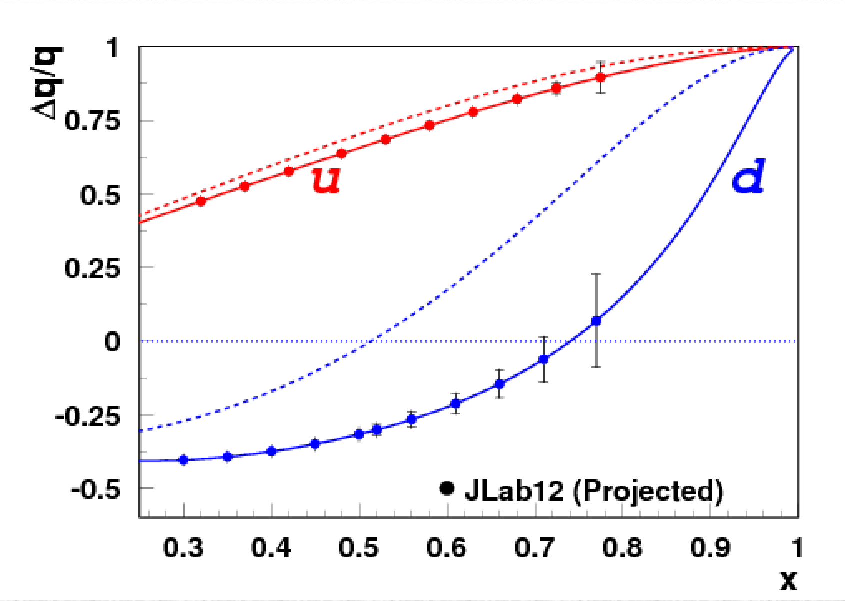
Non perturbative nucleon structure

d/u ratio



Δu/u, Δd/d ratios





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Up and down: the CTEQ6X fit

Accardi, Christy, Keppel, Melnitchouk, Monaghan, Morfín, Owens,

Phys. Rev. D 81, 034016 (2010)

(a Jlab/HU/CTEQ collaboration)

CTEQ6X vs. CTEQ

- **CTEQ**

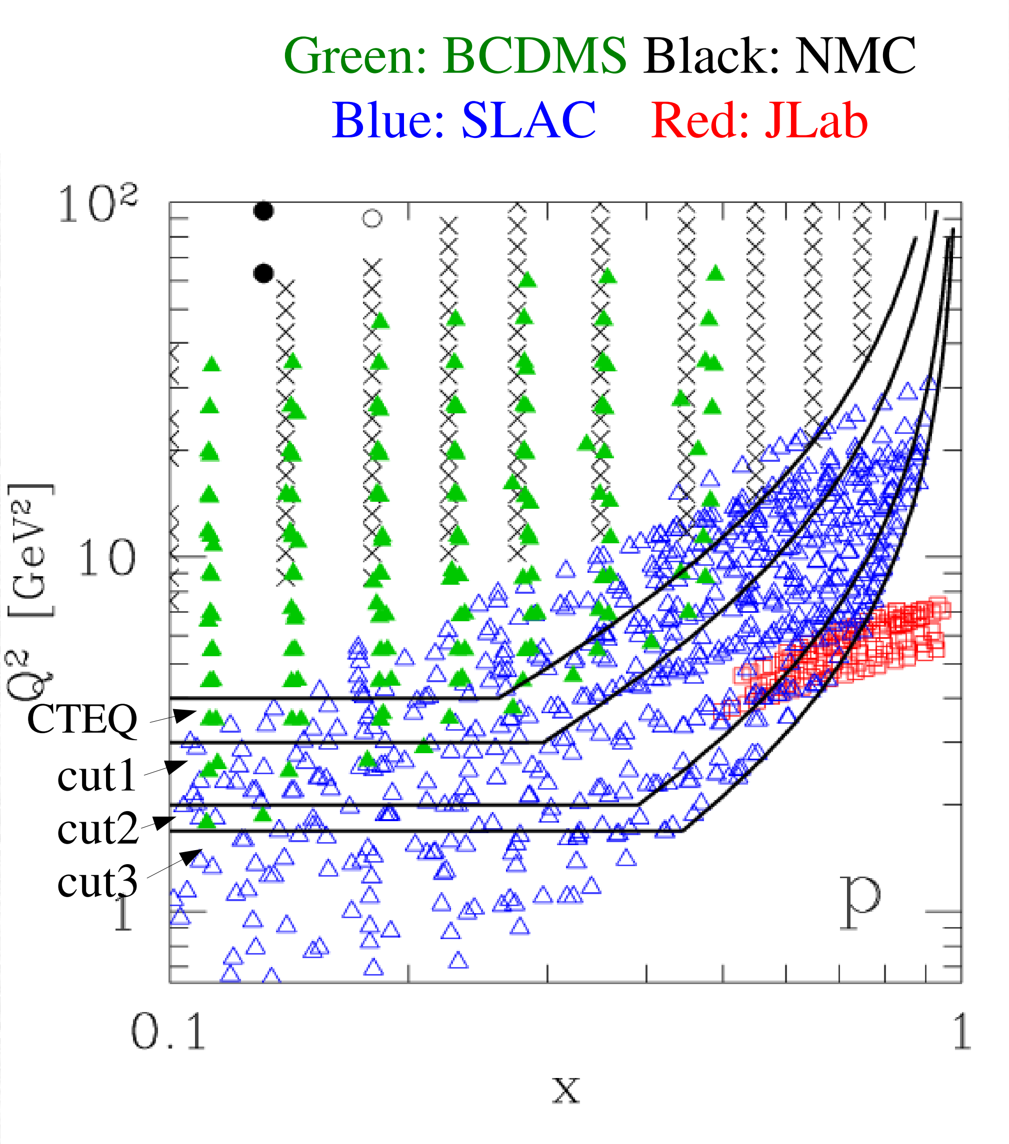
$$Q^2 \geq 4\ \mathrm{GeV}^2 \quad W^2 \geq 12.25\ \mathrm{GeV}^2$$

  - not so large *x*, not too low Q^2
  - hope $1/Q^2$ corrections not large

- **CTEQ6X**
  - **TMC, HT, deuteron corrections**
  - Progressively lower the cuts:

	Q^2 [GeV^2]	W^2 [GeV^2]
CTEQ ≡ cut0	4	12.25
cut1	3	8
cut2	2	4
cut3	1.69	3

  - Better large-*x*, low-Q^2 coverage



CTEQ6X vs. CTEQ

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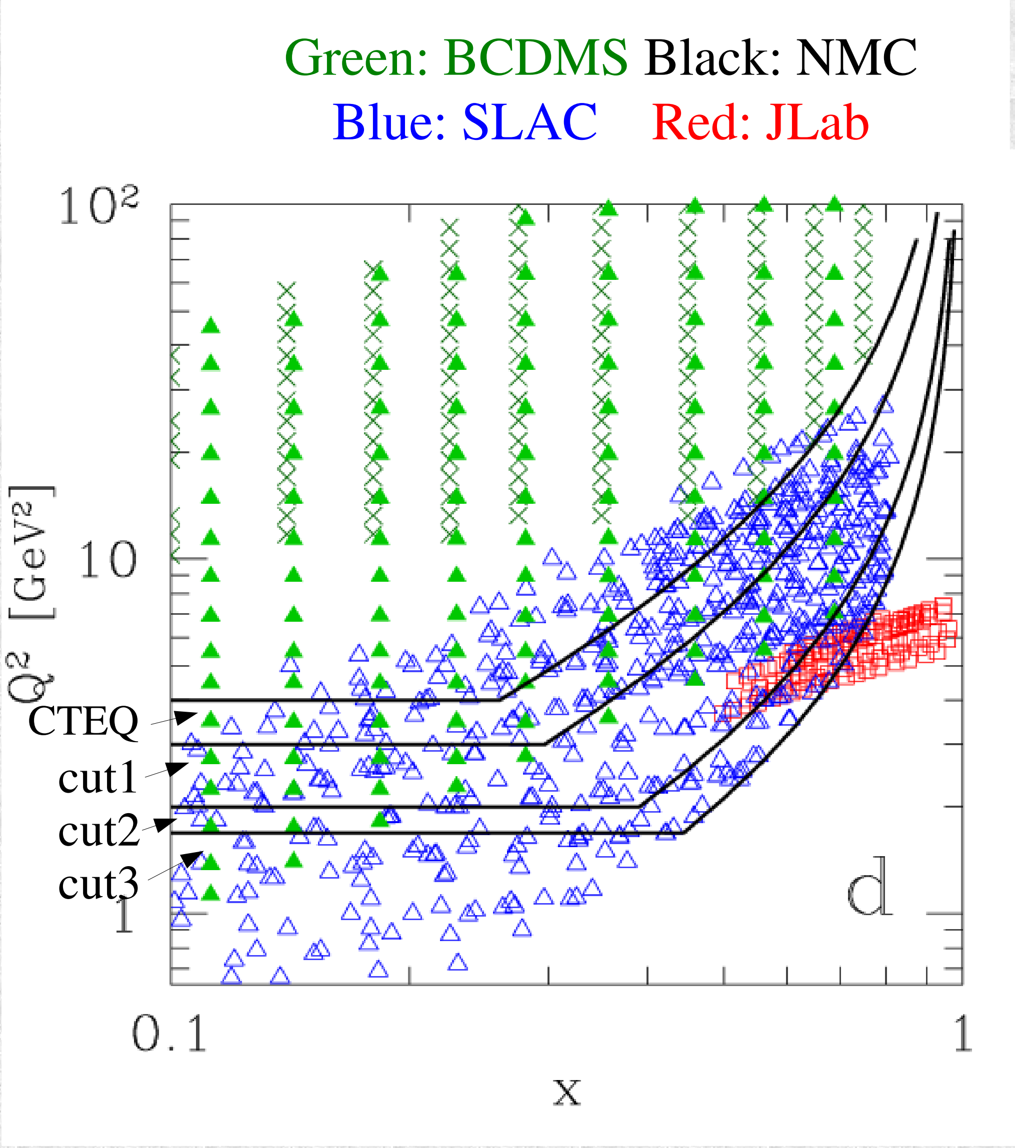
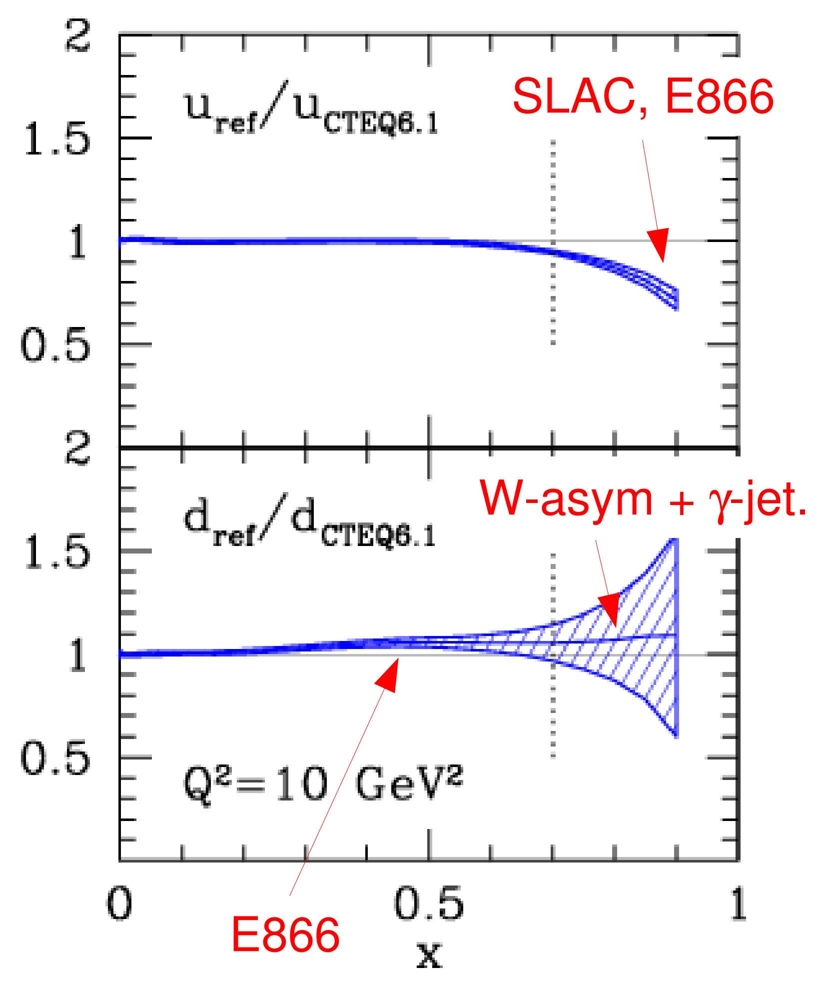


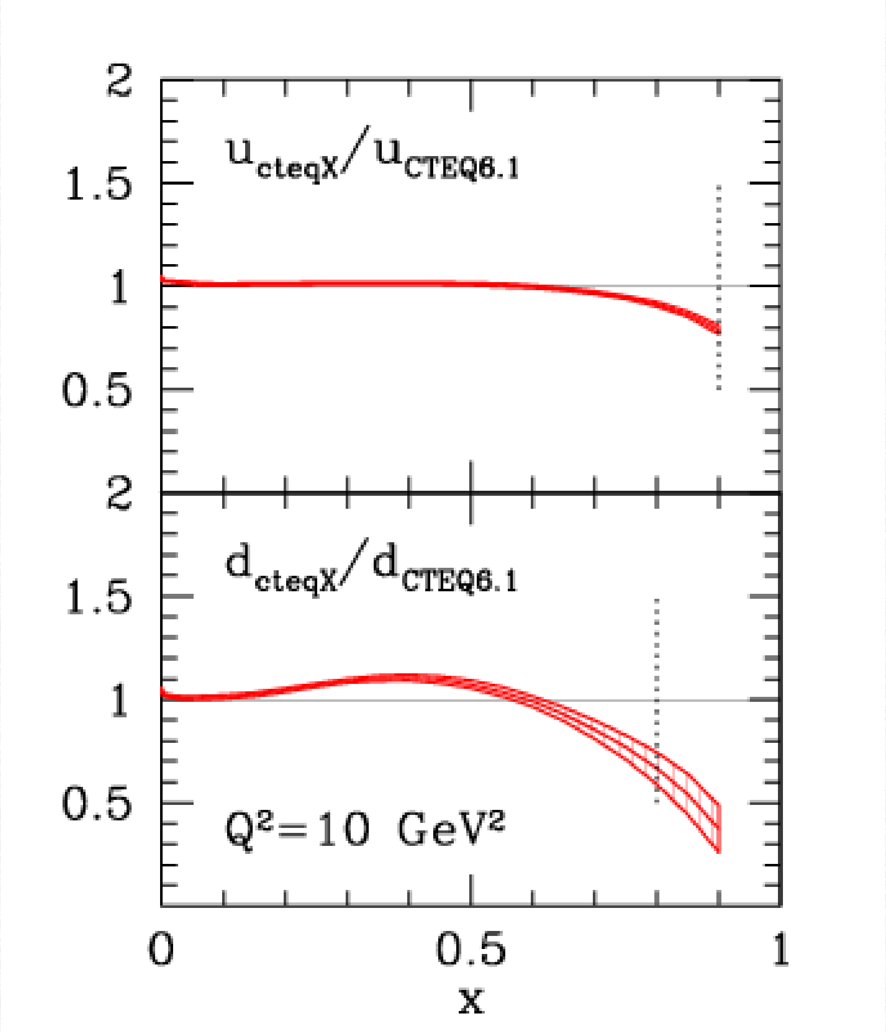
Reference fit vs. CTEQ6.1



- **Reference fit:**
  - cut0, no corrections
  - PDF errors with Δχ=1

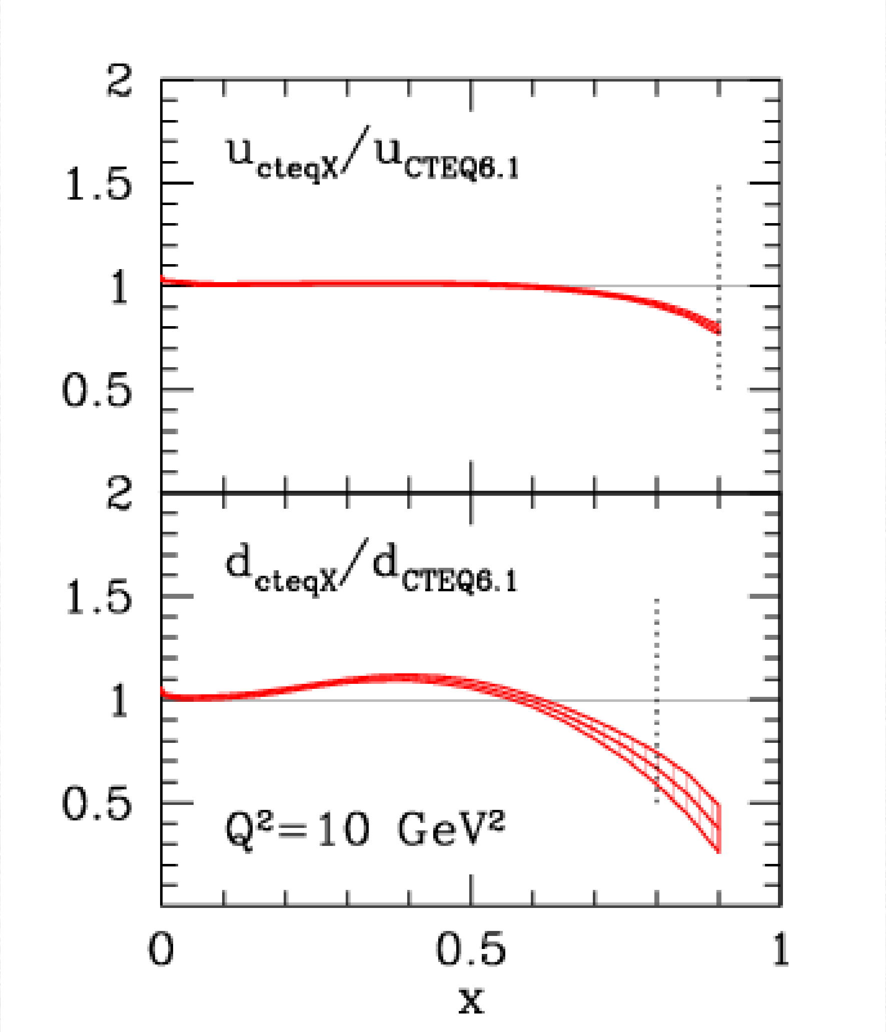
	data	CTEQ6.1
DIS	(JLab)	NO
	SLAC	NO
	NMC	√
	BCDMS	√
	H1	√
	ZEUS	√
DY	E605	√
	E866	NO
W	CDF '98 (ℓ)	√
	CDF '05 (ℓ)	NO
	D0 '08 (ℓ)	NO
	D0 '08 (e)	NO
	CDF '09 (W)	NO
jet	CDF	√
	D0	√
γ+jet	D0	NO

CTEQ6X vs CTEQ6.1



- **CTEQ6X fit:**
  - cut3, TMC+HT
  - deuteron corrections
- **TMC, HT compensate each other**
- **u-quark:**
  - almost unchanged
- **d-quark suppressed**
  - *due to deuteron corrections*
- **Reduced PDF errors**
  - about 30-50%

CTEQ6X vs CTEQ6.1



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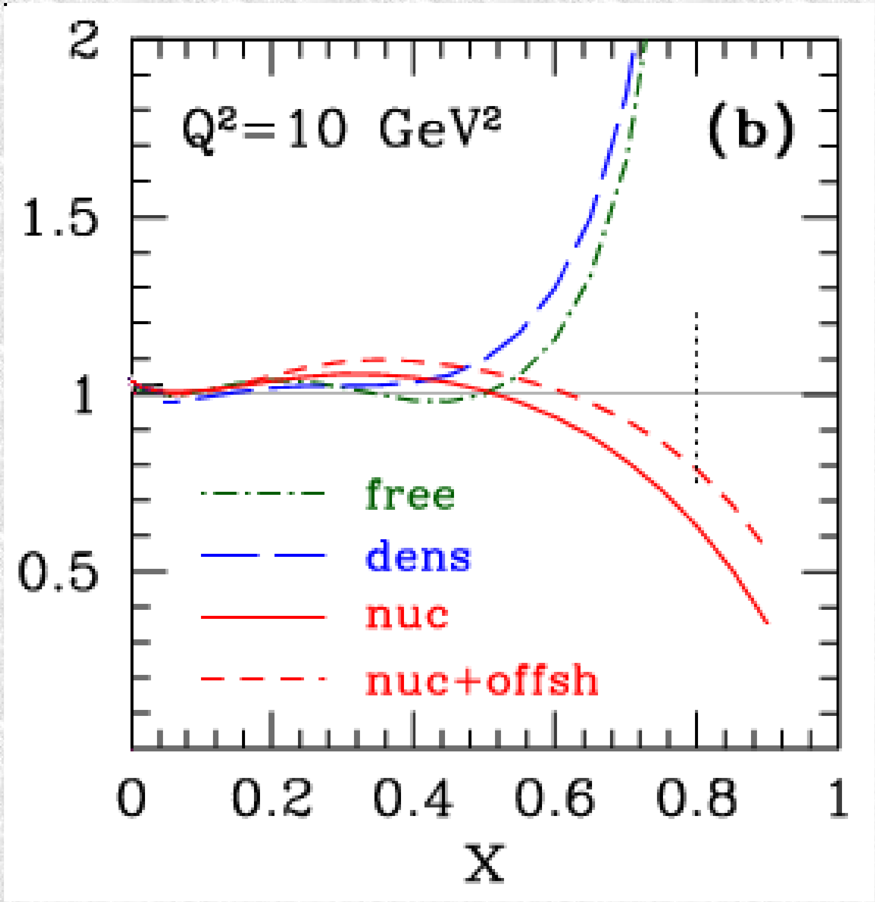
Deuterium corrections



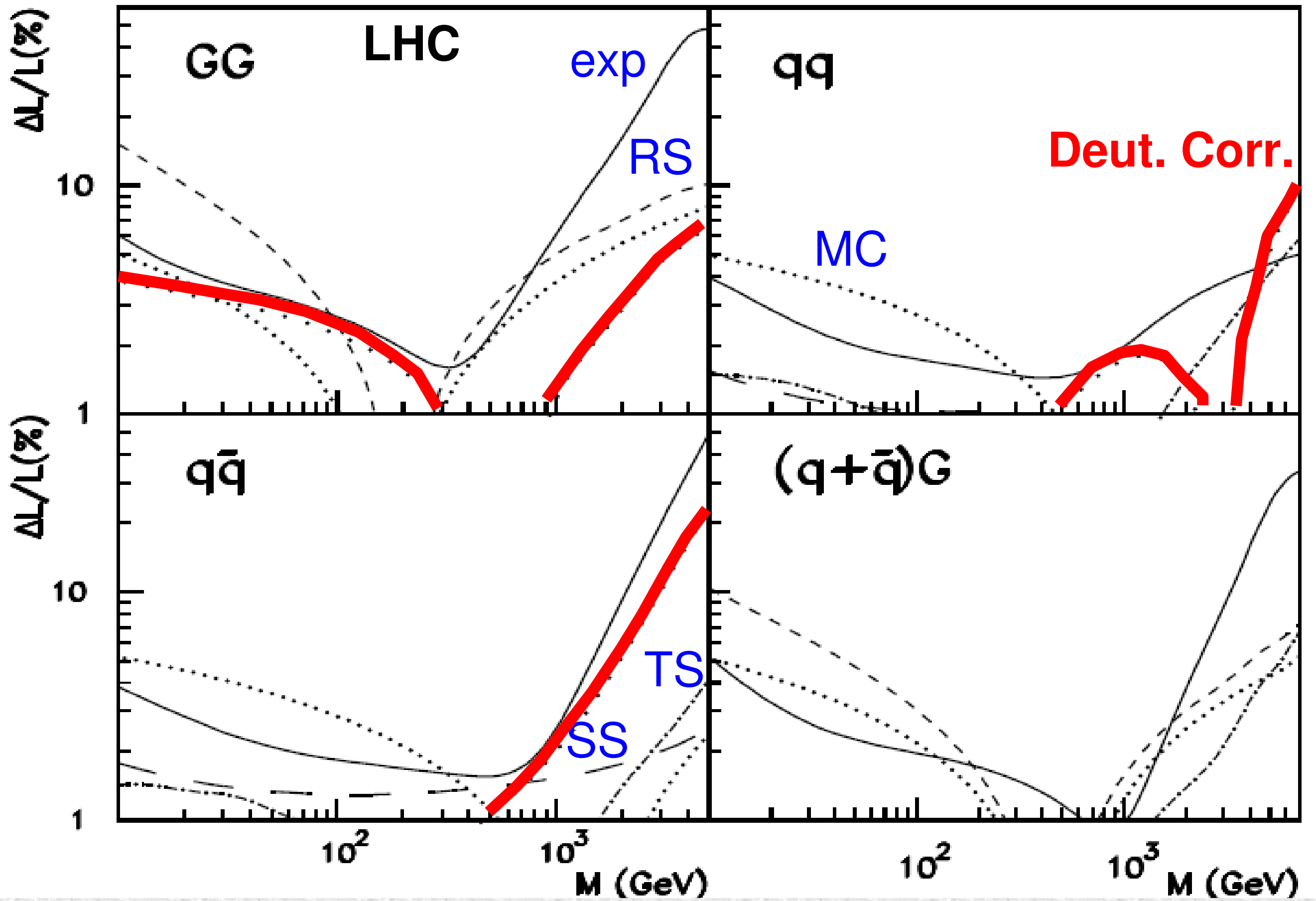
- ***d*-quarks are very sensitive to deuterium corrections**
- Off-shell corrections completely absorbed by the d-quark

free = free p+n
dens = density model corrections
nuc = WBA smearing model
offsh = off-shell corrections

`[Melnitchouk et al., '94]`

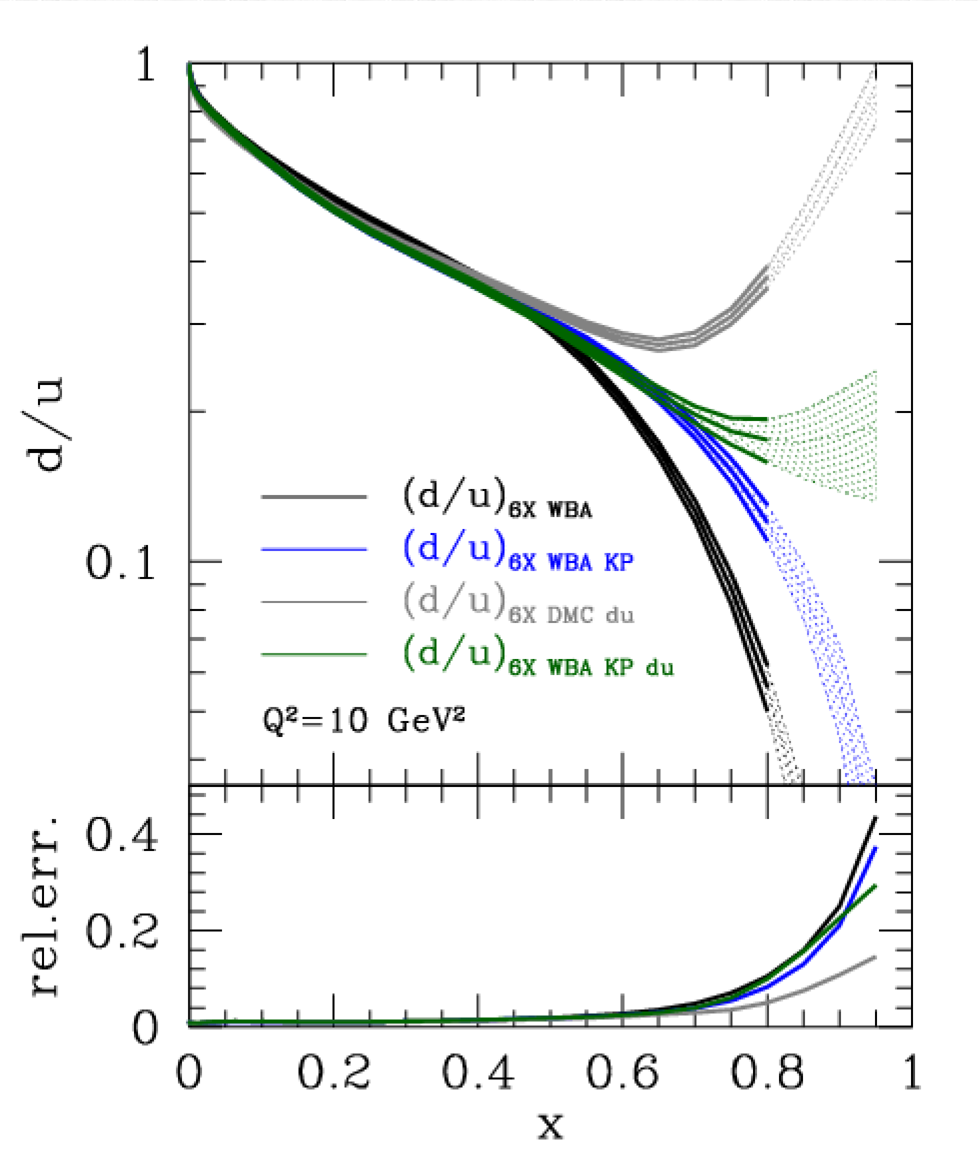
Impact on LHC

- Parton luminosities: $$L_{i,j}(M) = \frac{1}{S}\int_{M^2/s}^{1} \frac{dx}{x} q_i(x, M^2) q_j(M^2/(xs), M^2)$$
- **Nuclear model uncertainty ~10% at large *x*:**
  - **dominates *Z* cross-sections used as luminosity monitor**


[Alekhin PRD63 (2001)]

exp = experimental
RS = renorm. scale
MC = charm mass
TS = charm threshold
SS = strangeness suppr.

d/u fits - preliminary



- **Allow d/u to be finite at x=1**
  - new parametrization at Q_0

$$d'(x) = d(x) + c x^{\alpha} u(x)$$

$$d/u \xrightarrow{x \to 1} c$$

- d/u limit completely correlated to nuclear correction!
- **HUGE theoretical uncertainty!**

WBA = WBA smearing model
DMC = density model
KP = Kulagin-Petti off-shell corr.
du = new d-quark parametrization

d-quarks at large x

d-quarks at large x

- **Large theoretical undertainties on *d*-quark at large *x***
  - coming from deuteron corrections
    (no deuteron ⇒ d unconstrained at large *x*)
  - unavoidable at the moment: model dependent

- **How to progress?**
  - **Avoid them**
    - Free nucleon targets ↪ not enough data so far
  - **Constrain them**
    - Q^2 dependence of D/p ratios at large x
    - Use quasi-free nucleon targets
    - Use ratio of ^{3}He - ^{3}H mirror nuclei

Free nucleon targets

- Constraints on large-*x* *d*-quarks from
  - *p+p(bar)* : <u>DY at large x_F</u> $$p\,p(\bar p) \longrightarrow \mu^+\,\mu^-\,X$$
  - *p+p(bar)* : <u>W-asymmetry at large rapidity</u> $$p\,p(\bar p) \longrightarrow W^\pm\,X$$
    `[D0 and CDF]`
  - ν+*p* and ν-*bar*+*p* $$\nu(\bar\nu)\,p \longrightarrow l^\pm\,X$$
    - `WA21 already has data`
      `(but hard to reconstruct cross-sections from published “quark distributions”)`
    - `MINERνA with a hydrogen target`
  - Parity Violating DIS * $$\vec e_L(\vec e_R)\,p \longrightarrow e\,X$$
    - L/R electron asymmetry ⇒ γ/Z interference ∝ *d*/*u*
  - Charged current structure functions $$e\,p \longrightarrow \nu\,X$$
    `[H1 and ZEUS]`

* `planned for Jlab at 12 GeV`

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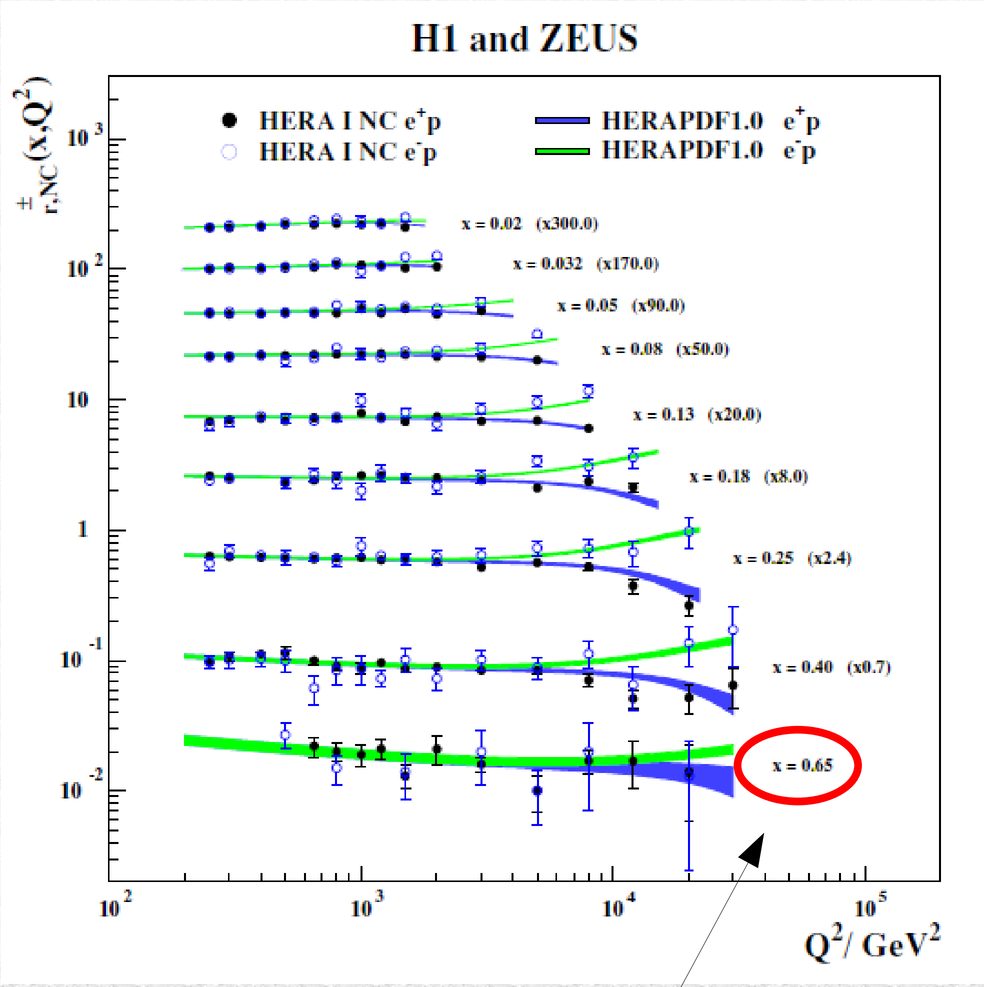
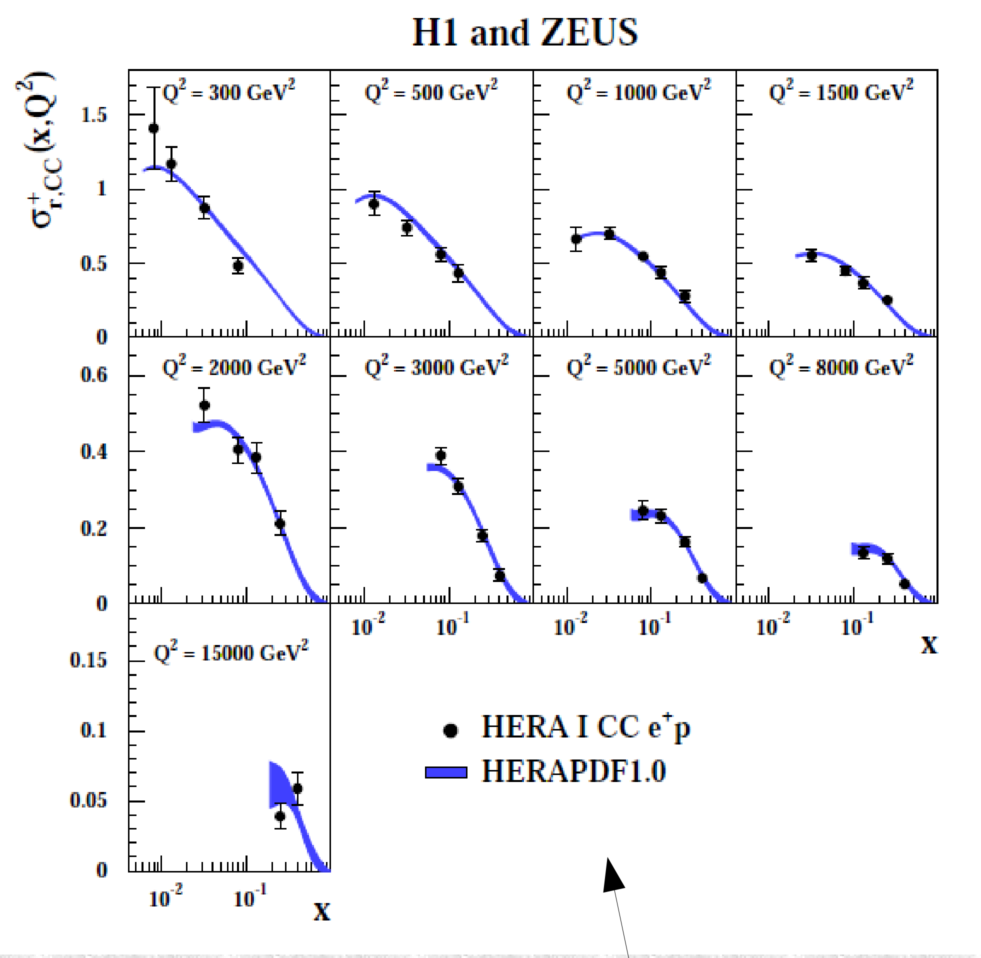
HERA combined data

[JHEP 1001,2010]

- H1 and ZEUS combined data on e^+-p and e^--p collisions, NC & CC



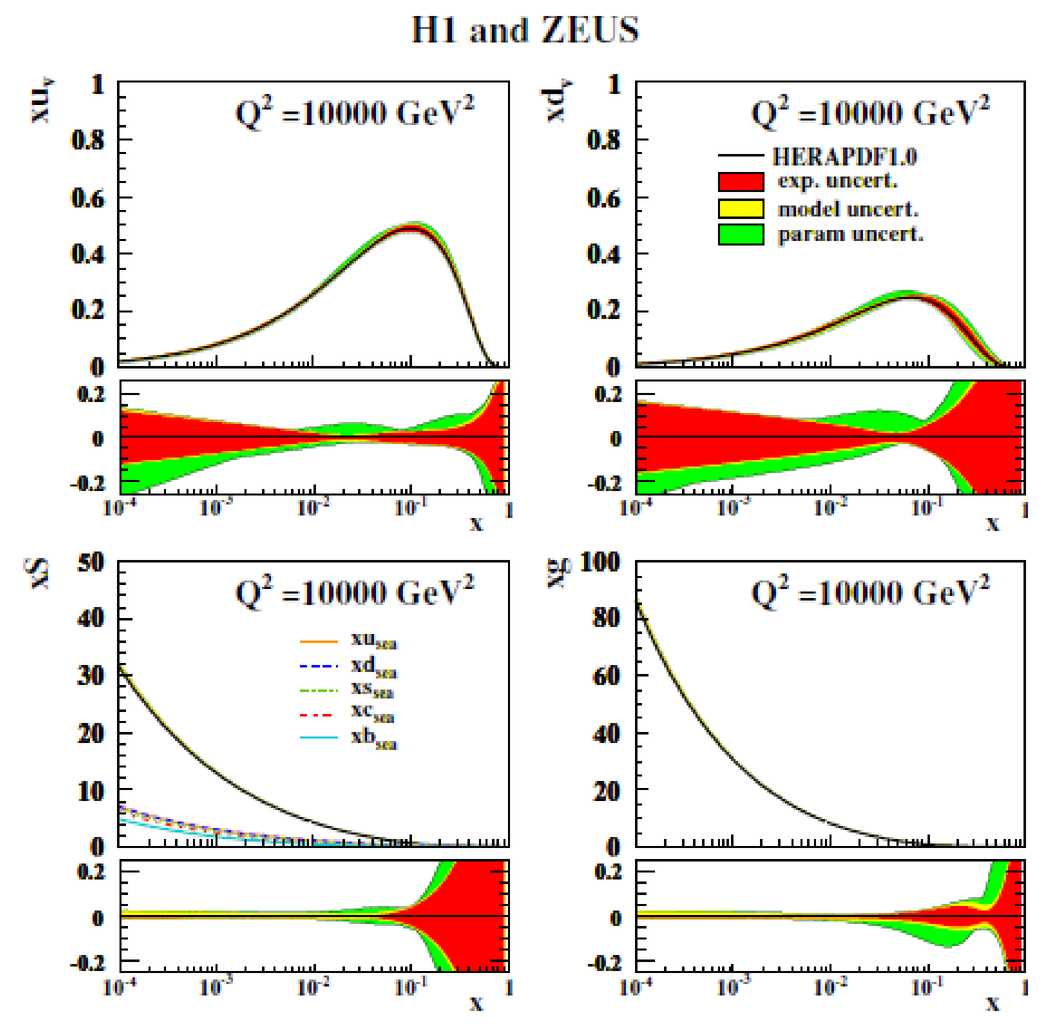


Reaches into the critical x range

Too limited x coverage

HERA combined data

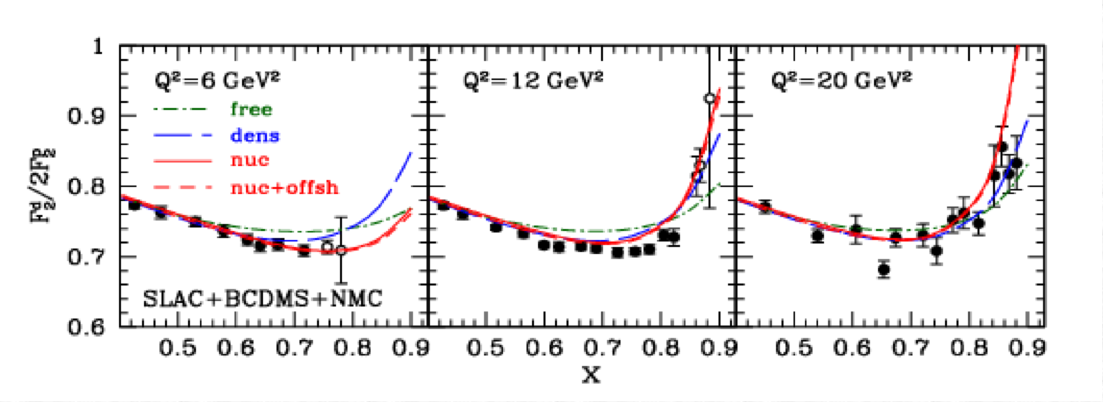
[JHEP 1001,2010]



- These data alone insufficient for *d*-quark at large *x*
  - combine with deuterium data, cross check nuclear corrections

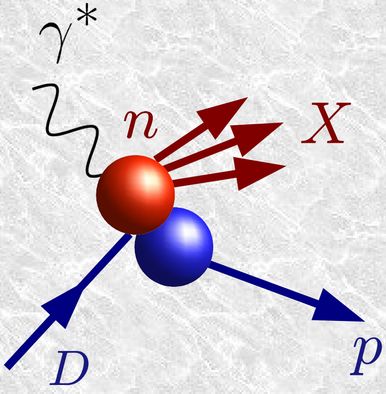
Constraining the nuclear corrections

- Q^2 dependence of D/p ratios at large x



- Quasi-free nucleon targets *
  `[BONUS, E94-102 and EG6 at JLab 6 GeV]`

$$e\,A \longrightarrow e\,(A-1)\,X$$



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

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

* `planned for Jlab at 12 GeV`

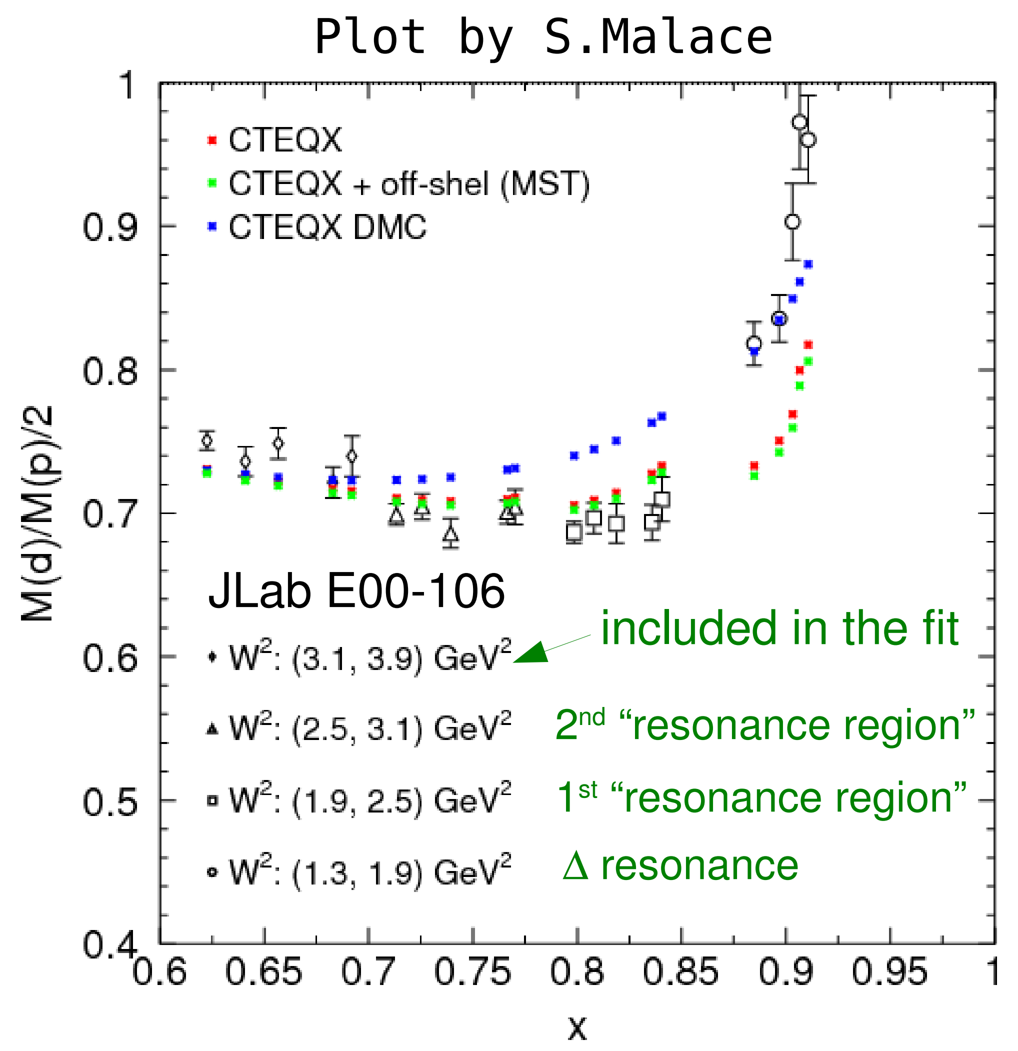
Neutrons at JLab

Bound neutrons in the resonance region...

- Truncated moments, plotted at an "average" x

  Malace et al, PRC80,035207,2009

$$M = \int_{W=[W_m,W_M]} dx\, F_2(x)$$



Plot by S.Malace

- Quark-hadron duality works to less than 5% up to Δ region

- Q^2 runs with x – correct CTEQ6X shape

- Density Model seems ruled out?

- maybe too small Q^2 leverage

...and beyond

Precision measurements of the F_2 structure function at large x in the resonance region and beyond

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University of South Carolina, Columbia, South Carolina 29208

I.M. Niculescu (Spokesperson) and G. Niculescu
James Madison University, Harrisonburg, Virginia 22807

A. Accardi, I. Albayrak, O. Ates, E. Christy, C. Jackson, C. Keppel (Spokesperson),
M. Kohl, Y. Li, P. Monaghan, A. Pushkapumari, J. Taylor, T. Walton, and L. Zhu
Hampton University, Hampton, Virginia 23668

R. Ent, H. Fenker, D. Gaskell, M.K. Jones, D. Meekins, P. Solvignon, G. Smith, and L. Tang
Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

A. Asaturyan, A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan, and S. Zhamkochyan
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T. Horn
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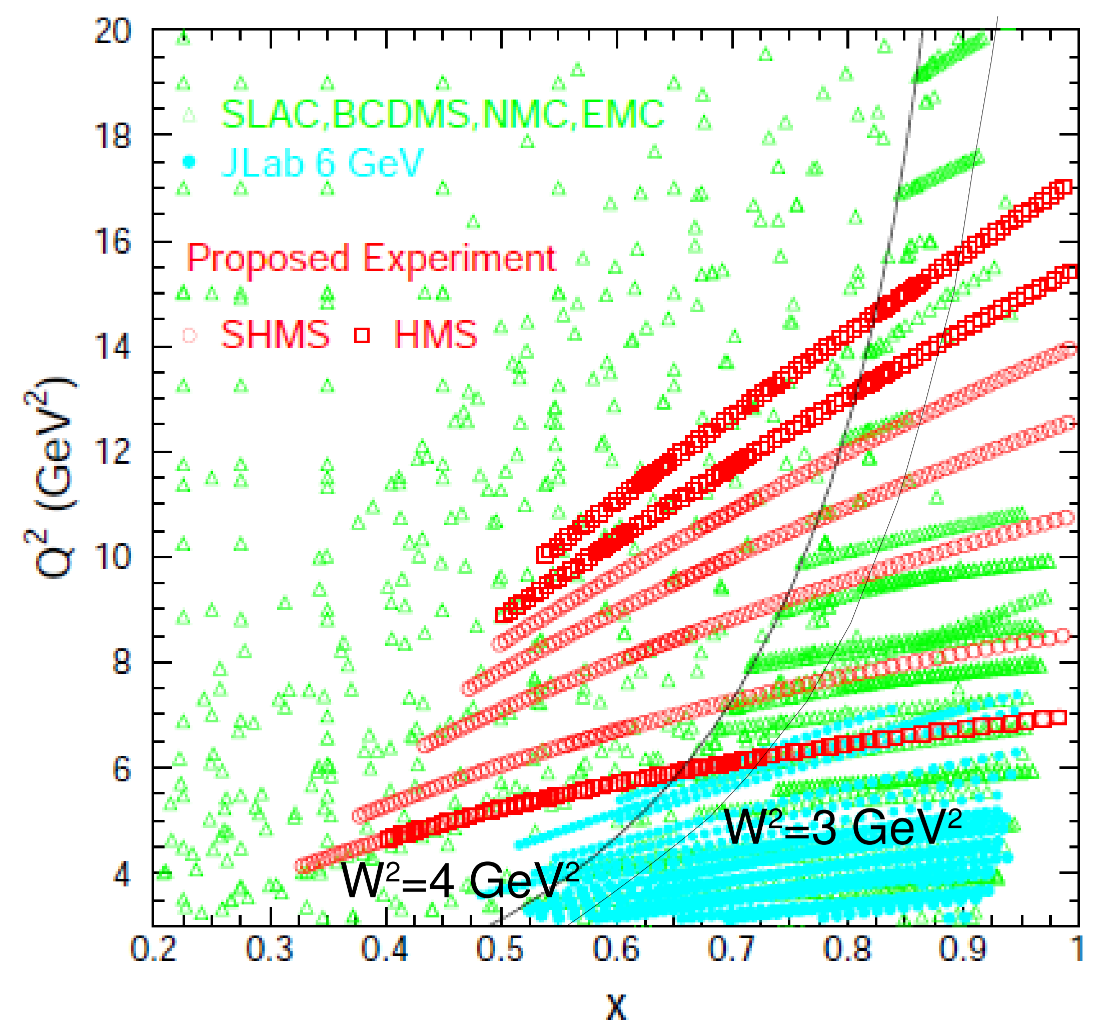
(Dated: December 11, 2009)

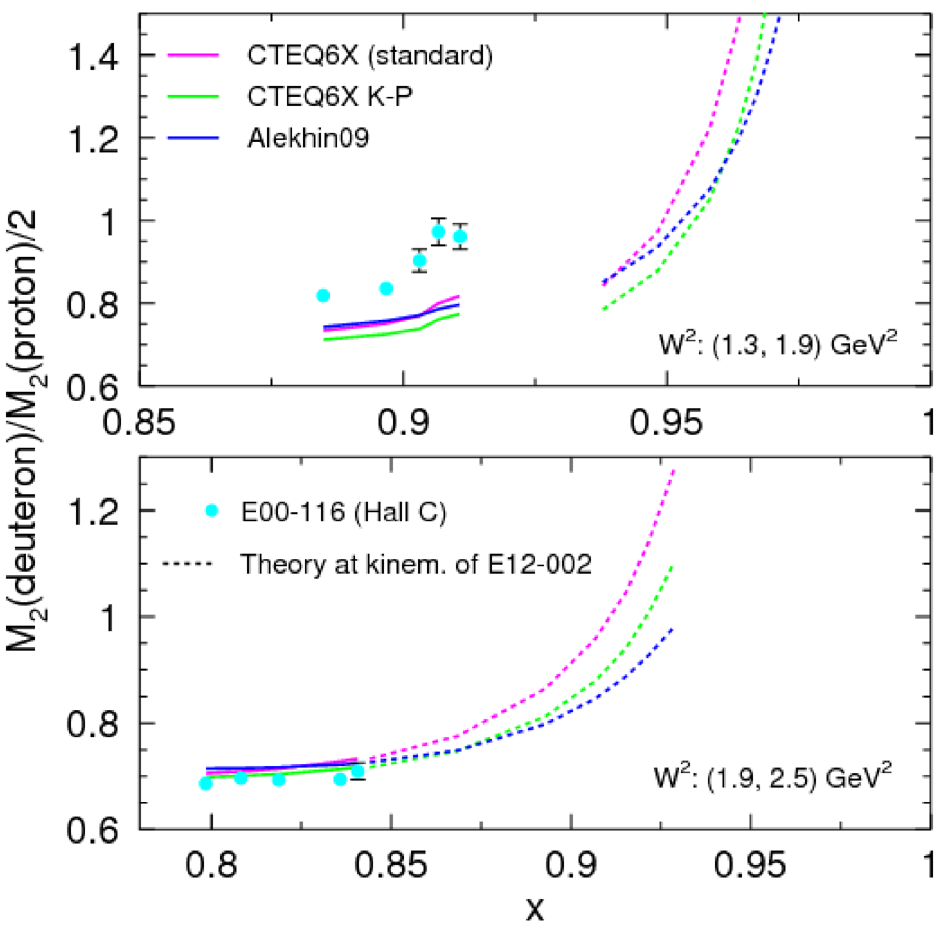
...and beyond



- Much larger Q^2 leverage
- may really discriminate nuclear correction methods
- we will also consider SLAC resonance data

Truncated moments @ 12 geV

Plot by S.Malace



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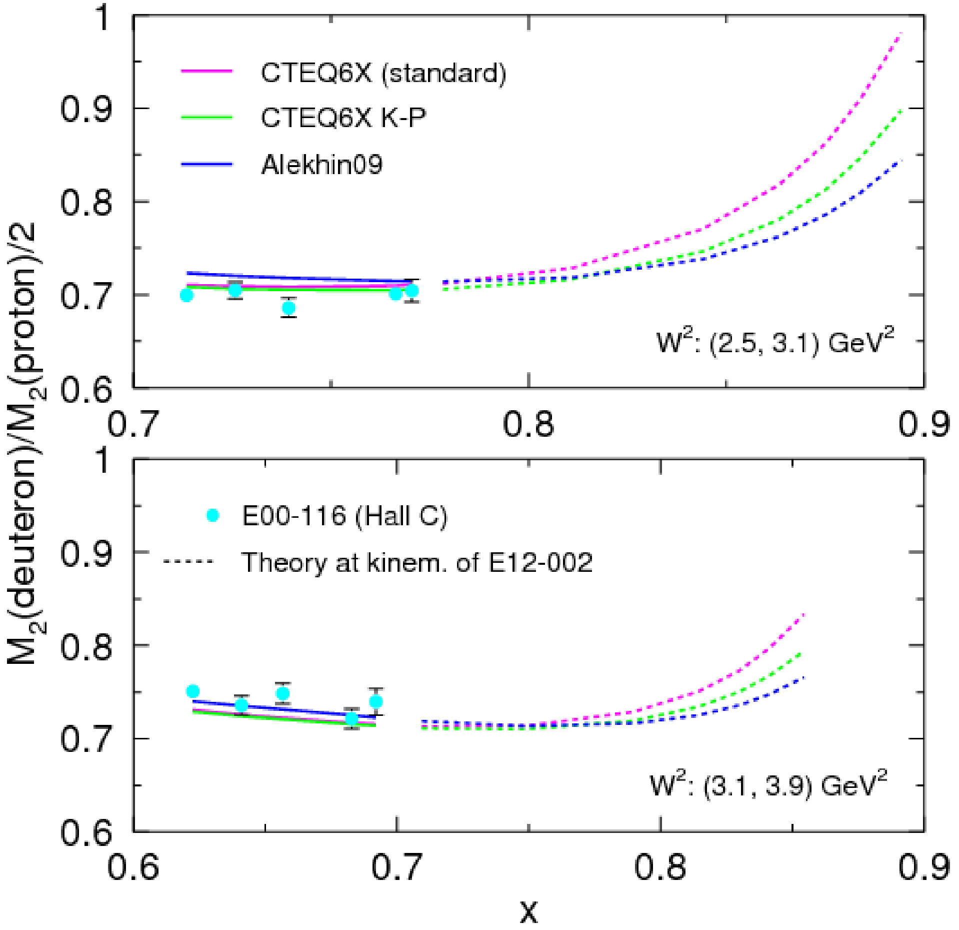

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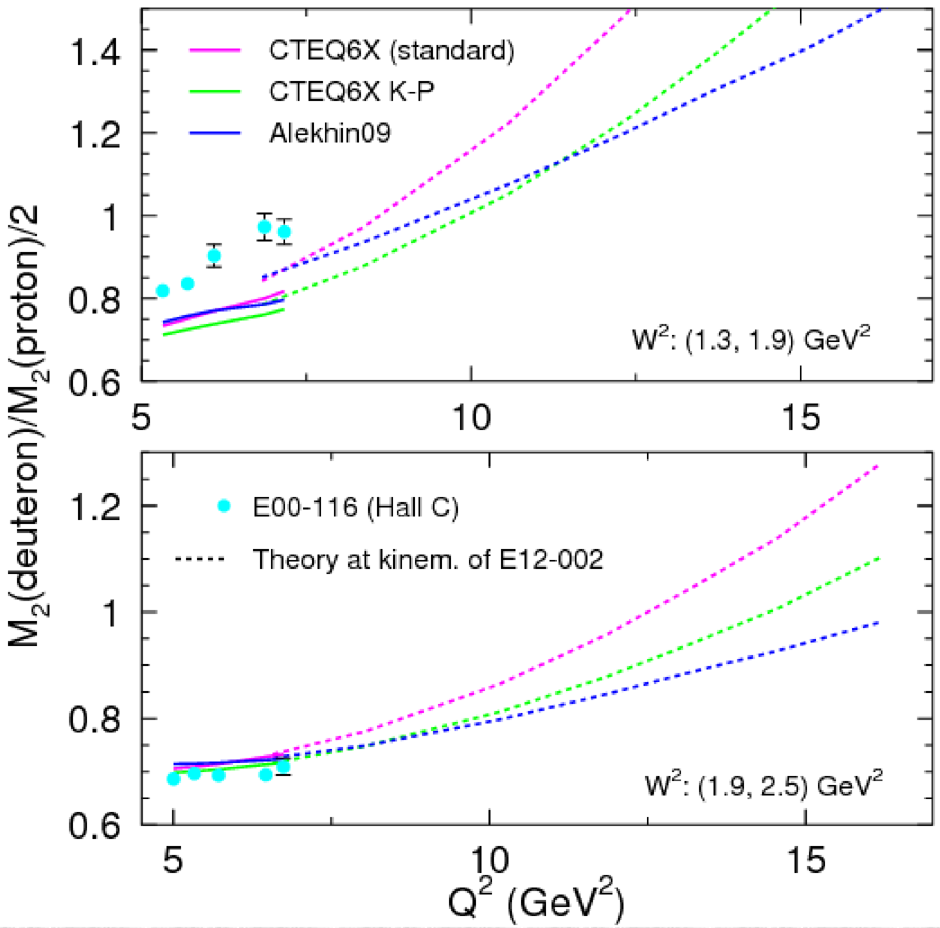
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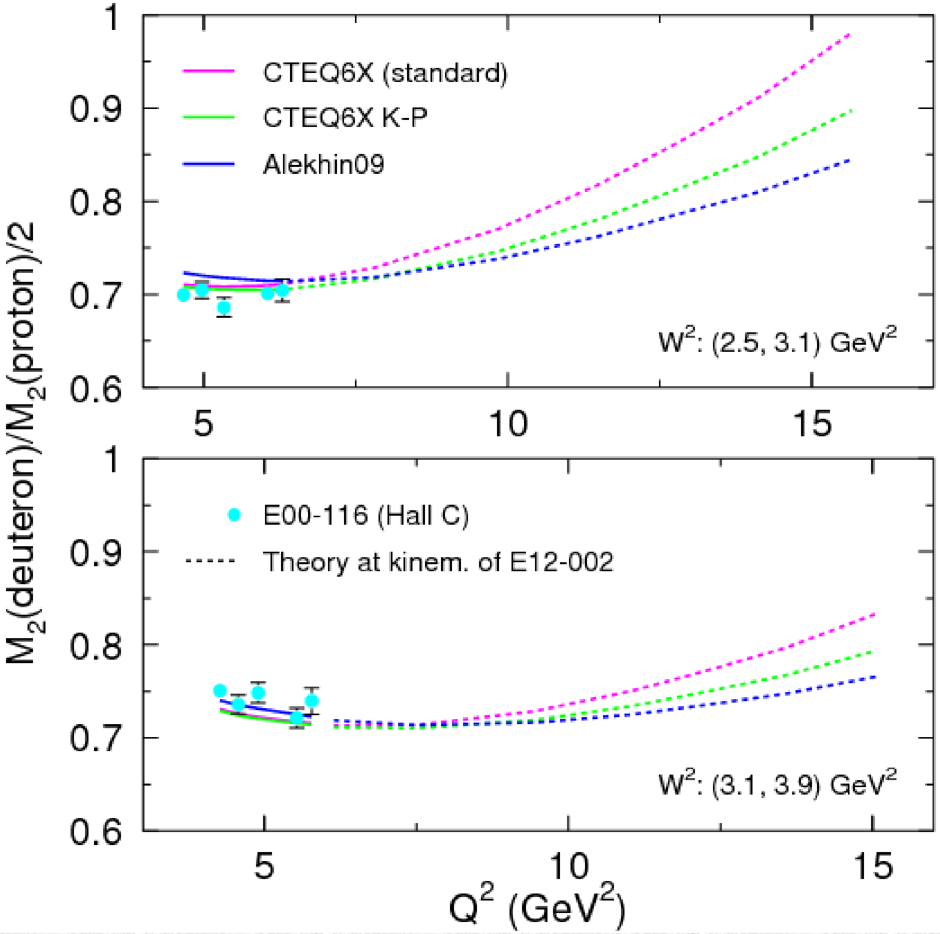
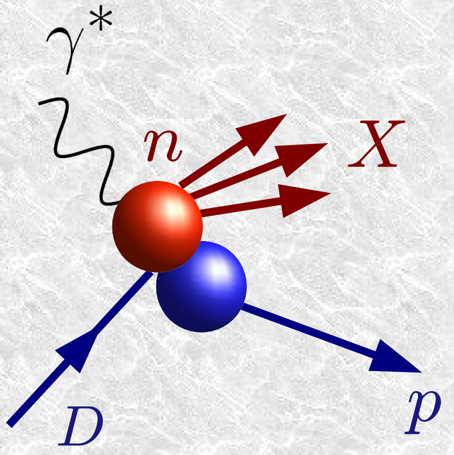

Plot by S.Malace

Quasi-free nucleon targets - BONUS



- DIS on deuterium with tagged proton
  - tagged proton momentum is measured
  - neutron off-shellness can be reconstructed

$$e\,D \longrightarrow e\,p\,X$$

- Study the off-shell dependence of $F_2(n)$ and quark PDFs

$$q \equiv q_D(x, Q^2, p^2)$$

- Extrapolate to a free neutron target $p^2 \rightarrow {M_n}^2$

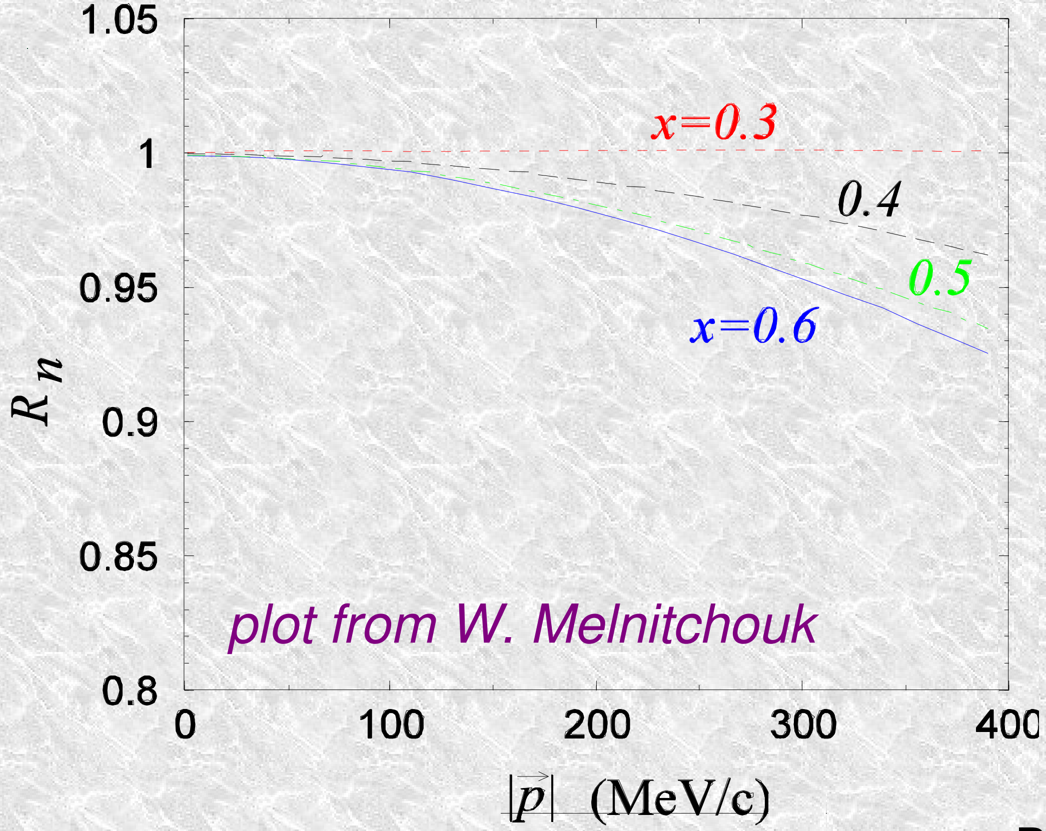
`Sargsian, Strikman, PLB639:223,2006`

Requirements 1 - "VIPs" (Very Important Protons)

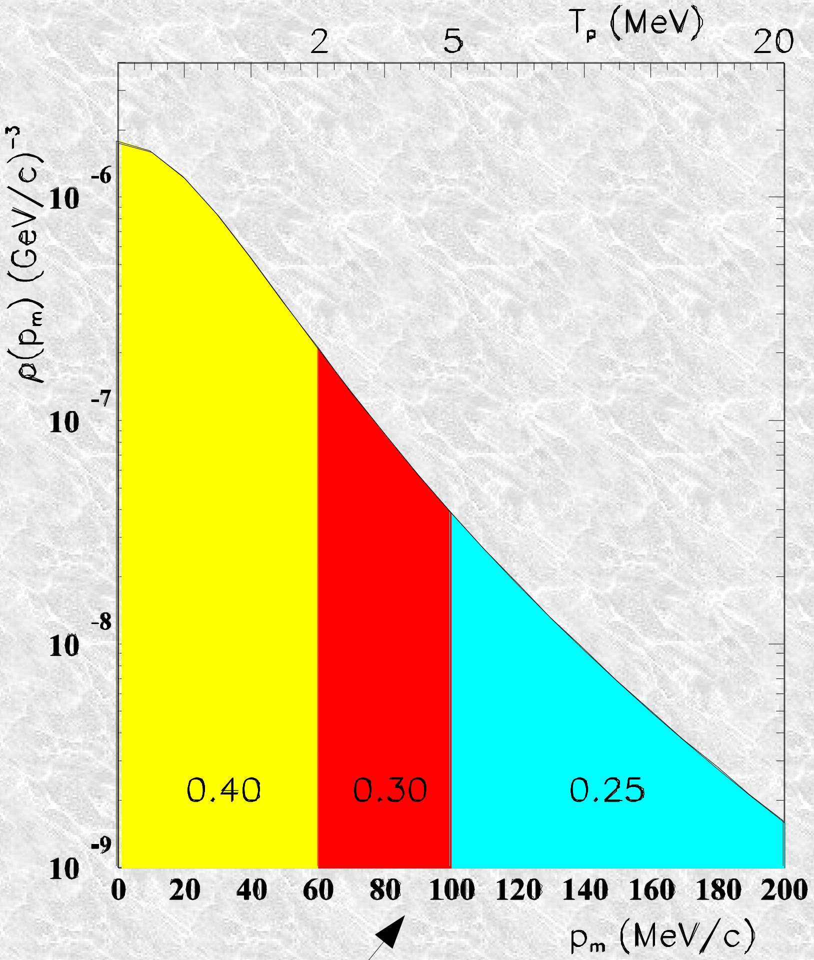
Deuteron ~ free p + free n

only at small nucleon momenta

R_n = ratio free/bound neutron



plot from W. Melnitchouk



BONUS cuts
30% of D wave function

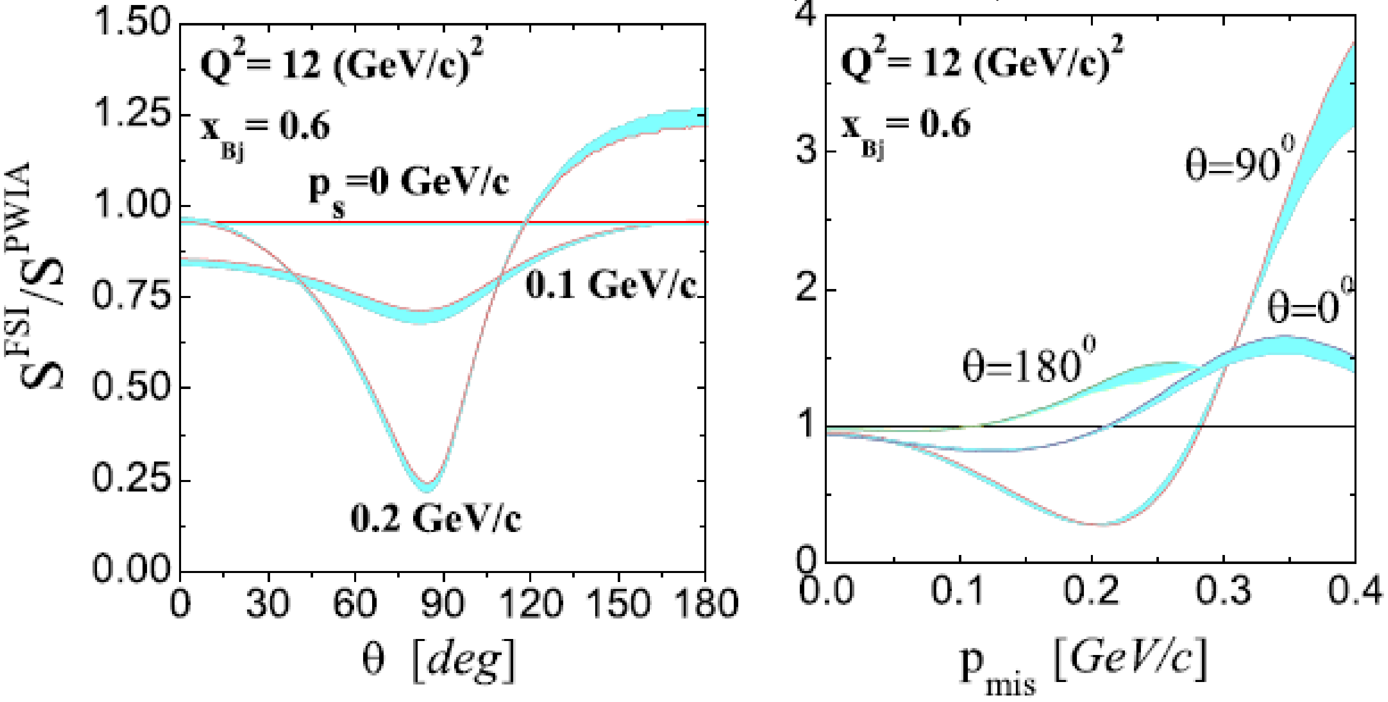
Requirements 2 - Backwards Protons

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

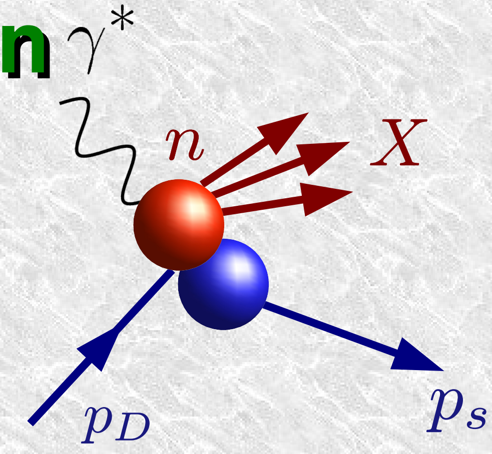
Example: BONUS cuts 60 MeV < p_s < 100 MeV

$\theta_s > 110^\circ$

Alvioli et al., PRC81,2010



Experimental BONUS neutron



- Experimentally:

$$F_{2n}^{BONUS}(x_n, Q^2, p_s, \theta)$$

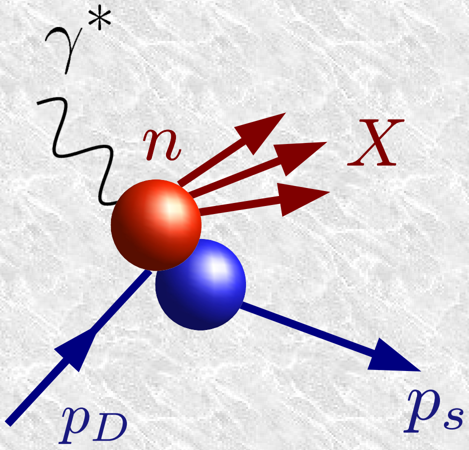
$$= \frac{N_D^T(x_n, Q^2, p_s, \theta)}{N_D(x, Q^2)} \times \left[\frac{N_D^T(\bar{x}_n, Q^2, p_s, \theta)}{N_D(\bar{x}, Q^2)}\right]^{-1} \times \frac{\sigma_D^{fit}(x, Q^2)}{2(1-y_e)\frac{4\pi\alpha}{xQ^4}}$$

where $x_n = \dfrac{Q^2}{2p_n \cdot q} = \dfrac{x}{y}$

- Assume $\sigma_D \approx \dfrac{4\pi\alpha}{xQ^4}(1-y_e)F_{2D}$

$$F_{2n}^{BONUS}(x_n, Q^2, p_s, \theta) = F_{2D}^T(x_n, Q^2, p_s, \theta) \times \frac{F_{2D}(\bar{x}, Q^2)}{2F_{2D}^T(\bar{x}_n, Q^2, p_s, \theta)}$$

Theoretical BONUS neutron



- Tagged and untagged F2 in impulse approx.

$$F^T_{2D}(x_n, Q^2, p_s, \theta) = \mathcal{S}_{n/D}(y, p_n^2, \gamma) F_{2n}(x_n, Q^2, p_n^2)$$

$$F_{2D}(x, Q^2) = \sum_{i=n,p} \int d\tilde{y} d\tilde{p}^2 \mathcal{S}_{i/D}(\tilde{y}, \tilde{p}^2, \gamma) F_{2i}(\bar{x}/\tilde{y}, Q^2, \tilde{p}^2)$$

NOTE: $f_{n/D}$ is the same used in the CTEQ6X paper

- Therefore,

$$F_{2n}^{BONUS}(x_n, Q^2, p_s, \theta) = F_{2n}(x_n, Q^2, p_n^2) D(\bar{x}, Q^2, y, p_n^2)$$

$$D(\bar{x}, Q^2, y, p_n^2) = \frac{\sum_{i=n,p} \int d\tilde{y} d\tilde{p}^2 \mathcal{S}_{i/D}(\tilde{y}, \tilde{p}^2, \gamma) F_{2i}(\bar{x}/\tilde{y}, Q^2, \tilde{p}^2)}{2 F_{2n}(\bar{x}/y, Q^2, p_n^2)}$$

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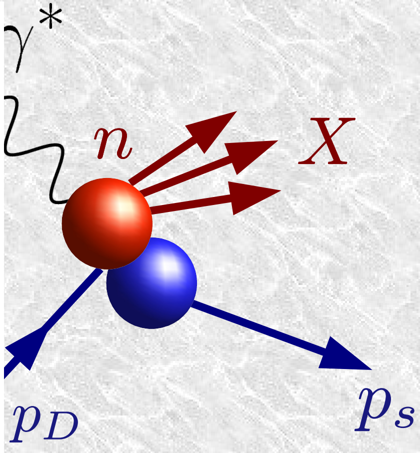
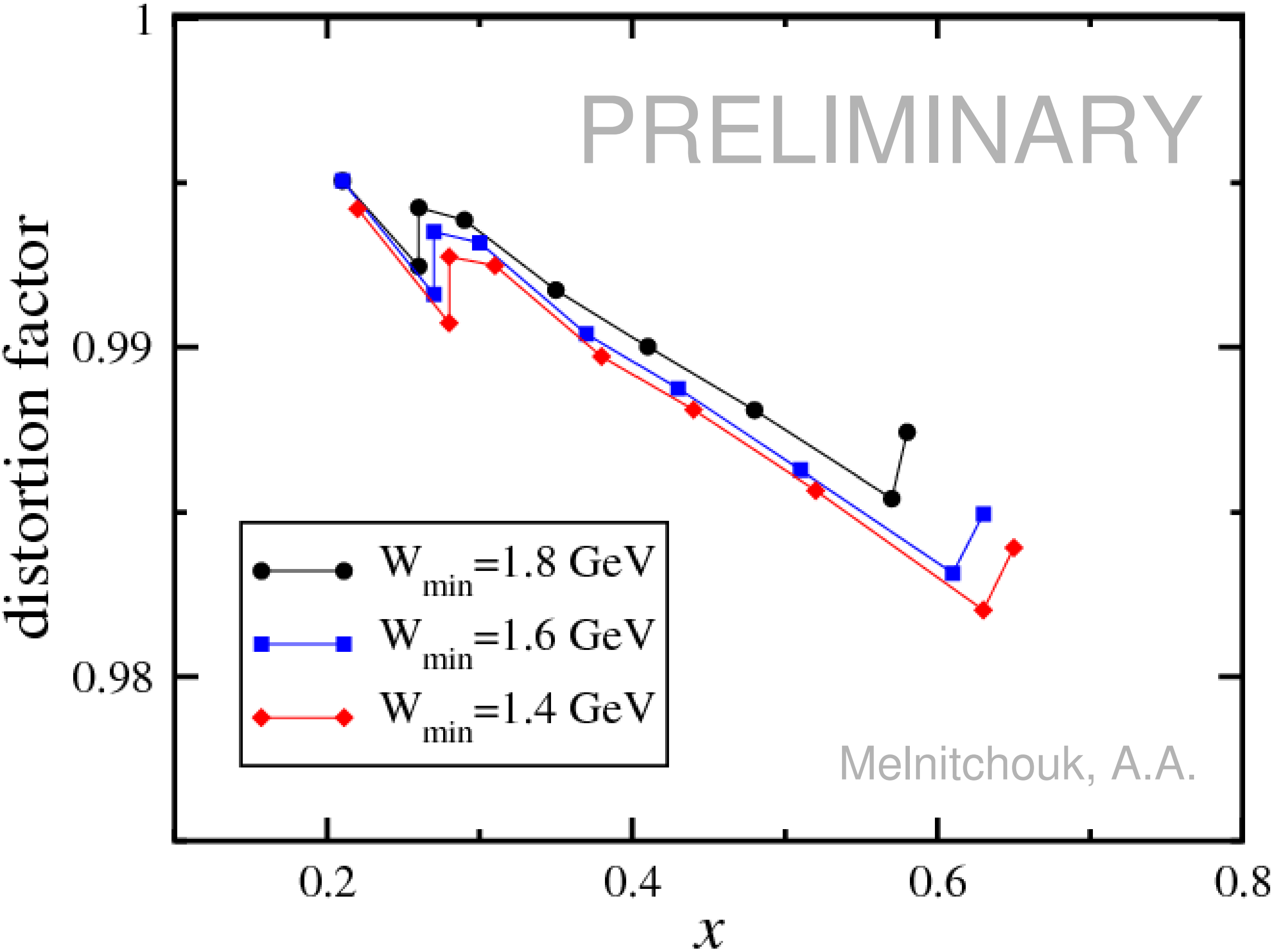


- Tagged a

$F^T_{2D}(x_n, Q$

$F_{2D}(x, Q^2$

NOTE: f



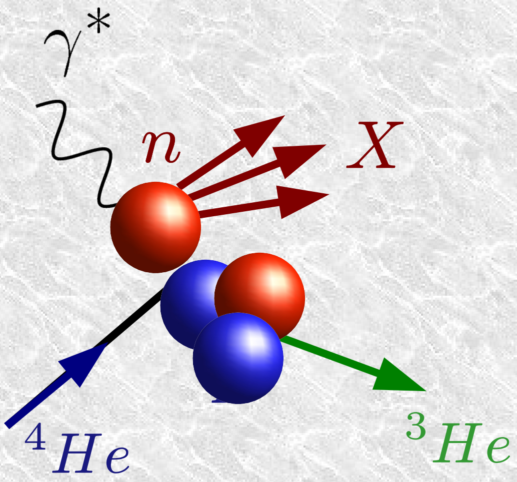
- Therefor

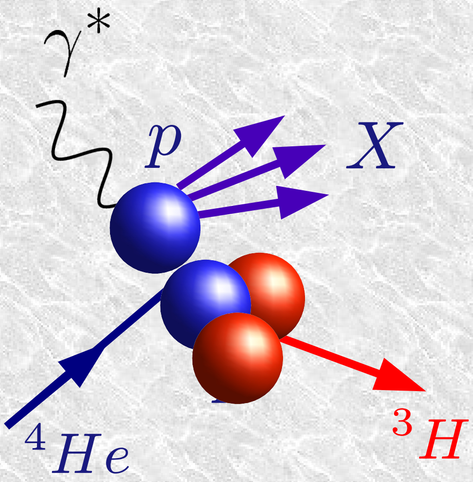
$$F_{2n}^{BONUS}(x_n, Q^2, p_s, \theta) = F_{2n}(x_n, Q^2, p_n^2) D(\bar{x}, Q^2, y, p_n^2)$$

$$D(\bar{x}, Q^2, y, p_n^2) = \frac{\sum_{i=n,p} \int d\tilde{y} d\tilde{p}^2 \mathcal{S}_{i/D}(\tilde{y}, \tilde{p}^2, \gamma) F_{2i}(\bar{x}/\tilde{y}, Q^2, \tilde{p}^2)}{2F_{2n}(\bar{x}/y, Q^2, p_n^2)}$$

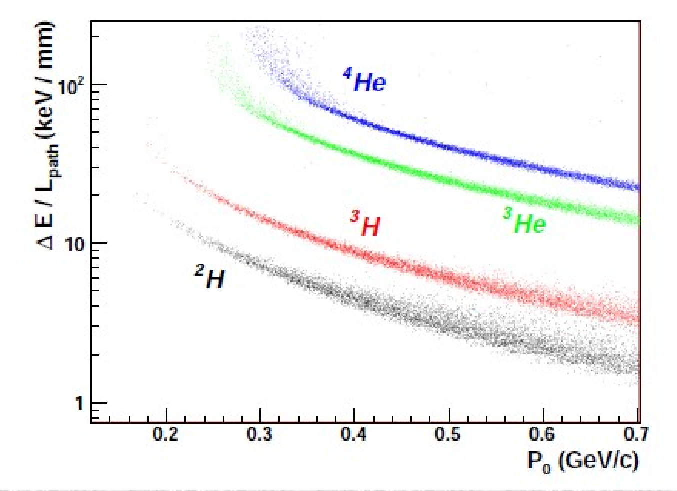
Quasi-free nucleon targets - EG6

- DIS on ^{4}He with tagged ^{3}He or ^{3}H
  - <u>neutron & proton</u> off-shellness reconstructed





- Study the off-shell dependence of $F_2(n)$ & $F_2(p)$



- Compare off-shell $F_2(n/D)$ to $F_2(n/^4He)$
  - <u>any nuclear dependence?</u>
  - may want to check also ^{3}He with tagged D
- Extrapolate to a free proton target $p^2 \to M_n{}^2$
  - and <u>CHECK the extrapolation</u> procedure

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Quasi-free nucleon targets – 12 GeV

- **BONUS11** – conditionally approved proposal

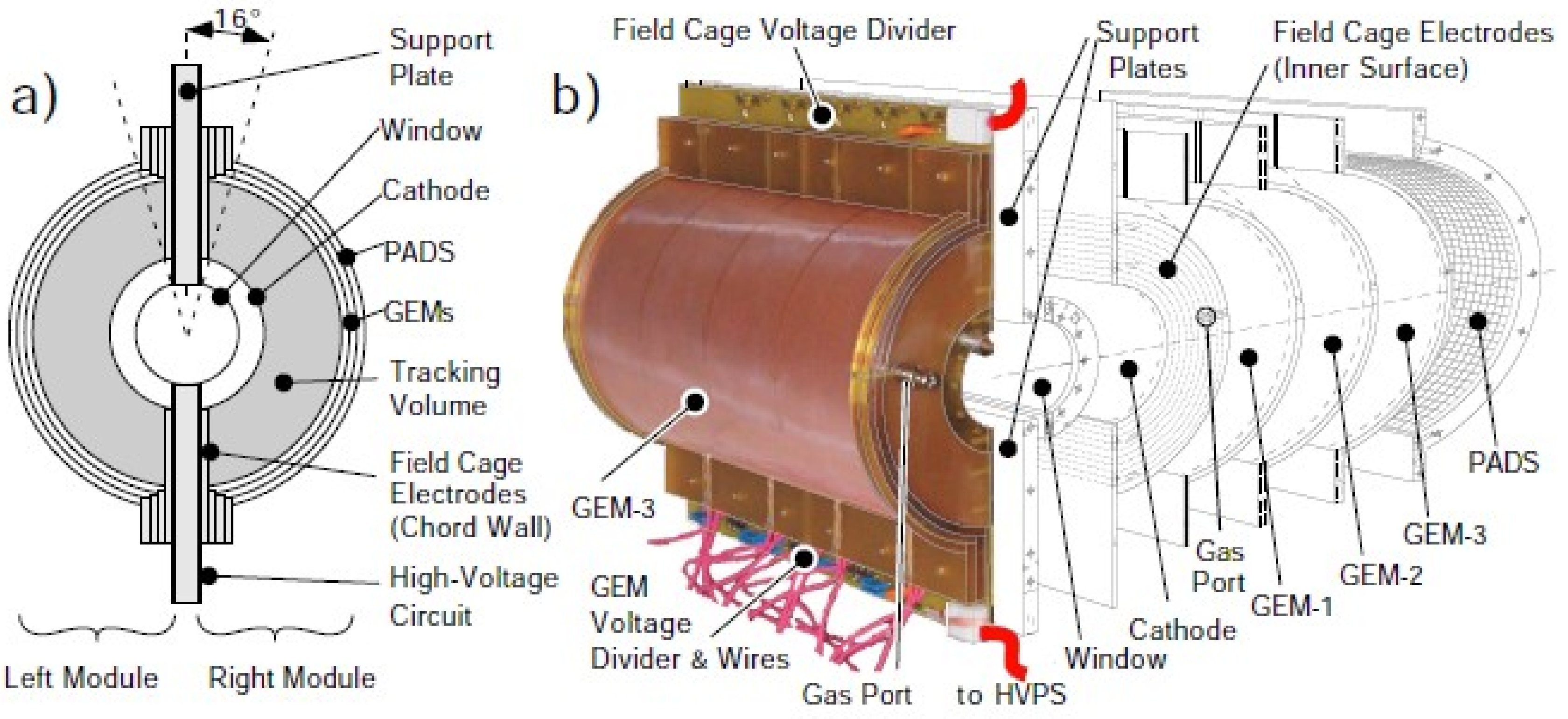

Figure 14: Photograph and Schematic Diagram of the BONUS RTPC (from [60]). a) Cross-section view through the center of the detector. b) Photograph of the left module with the readout padboard removed and a complementary exploded view exposing the components of the right module.

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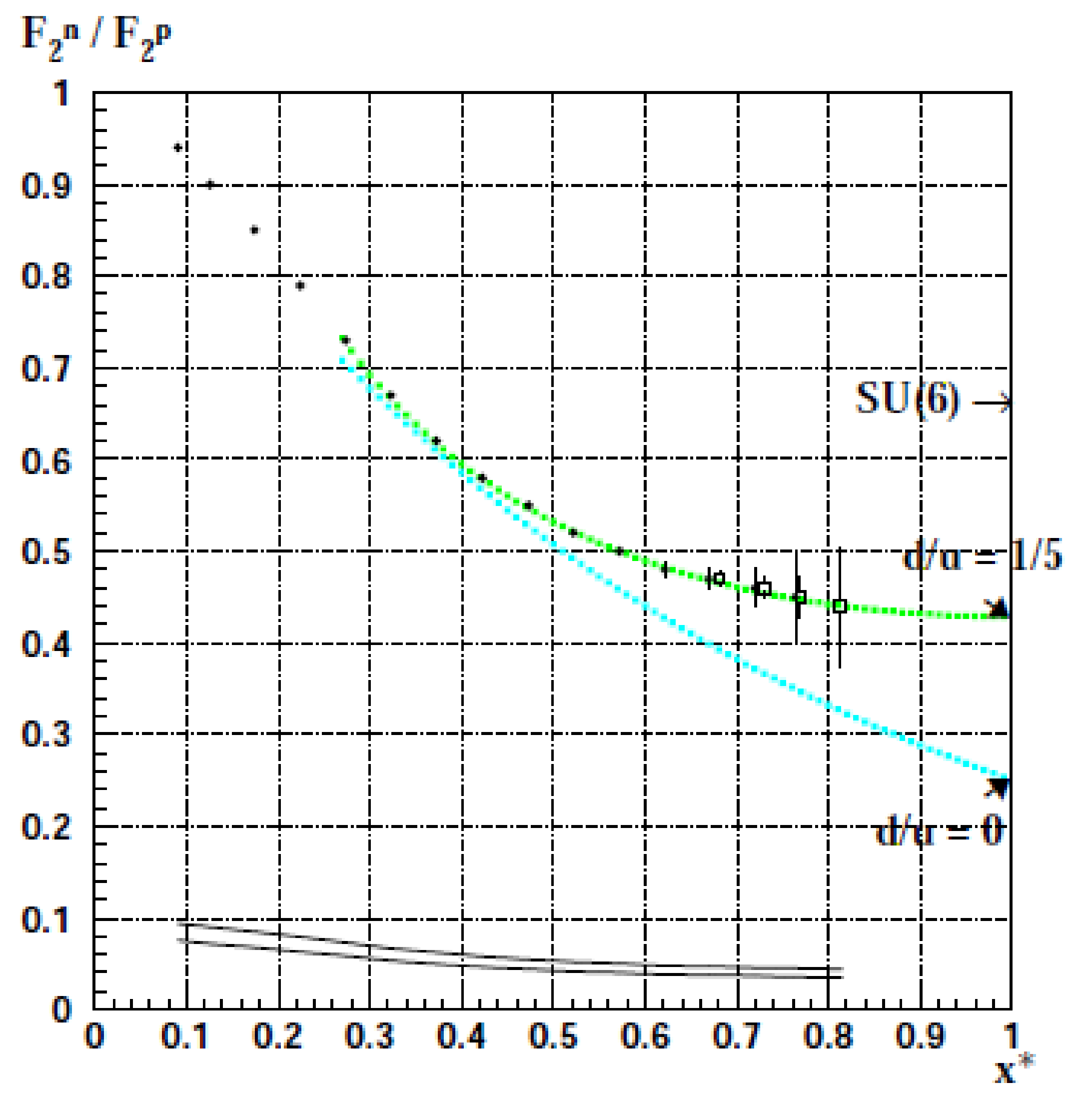
Quasi-free nucleon targets – 12 GeV

- **BONUS11** – conditionally approved proposal



Quasi-free nucleon targets – 12 GeV

- **LOI, evolution of EG6** – blessed by PAC35

Nuclear Exclusive and Semi-inclusive Physics with a New CLAS12 Low Energy Recoil Detector

K. Hafidi[†‡], J. Arrington, D.F. Geesaman, R. J. Holt, A. El Alaoui[†],
R. Dupré[†], B. Mustapha, D. H. Potterveld, P. E. Reimer

Argonne National Laboratory, Argonne IL 60439, USA

L. Zhu[†]

Hampton University, Hampton, VA 23668, USA

S. Dhamija

Florida International University, Miami, Fl 33199, USA

A. Accardi[1], V. Burkert, D. Gaskell[†], F.-X. Girod[†],
V. Guzey, H. Fenker, V. Kubarovsky, S. Stepanyan[†]

Jefferson Laboratory, Newport News, VA 23606, USA

D. Dutta[†]

Mississippi State University, Mississippi State, USA

C. Salgado

Norfolk State University, Norfolk, VA 23504, USA

S. Danagoulian

North Carolina A&T State University, NC 27411, USA

A. Daniel

Ohio University, Athens, OH 45701, USA

M. Amarian[†], S. Bueltmann, G. Gavalian, S. Kuhn, L. Weinstein

Old Dominion University, Norfolk, VA 23529, USA

JLab Letter of Intent to PAC35 *14 December 2009*

- New recoil detector, slightly different from BONUS11
  - full 2π acceptance
  - larger volume: better en.loss, momentum resolution
  - …

Outlook:
the Electron-Ion Collider

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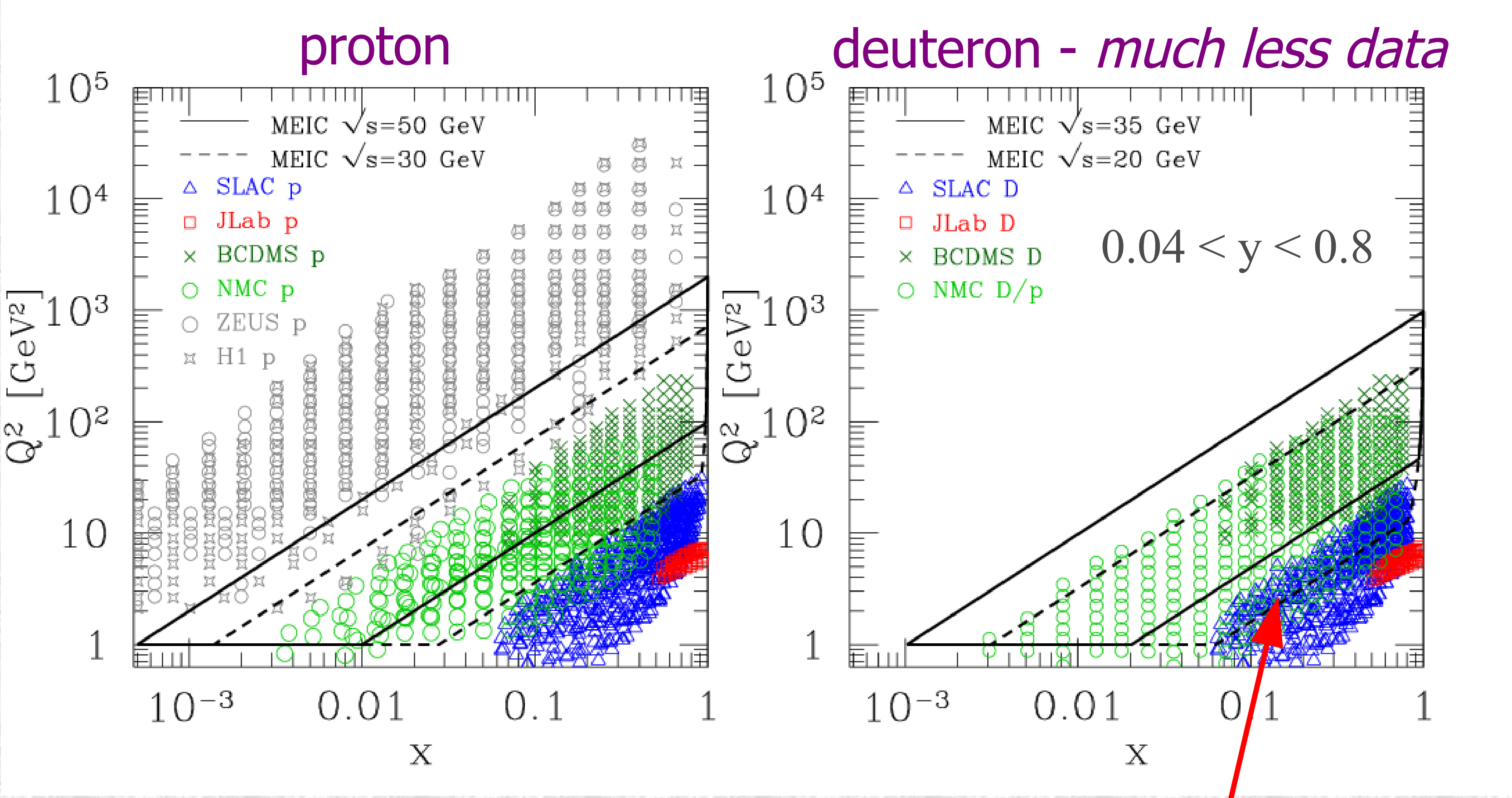
The EIC for dummies

- Future US-based e+p (e+A) collider – 2 designs:
  - *BNL – MeRHIC:* 4+250 GeV $\mathcal{L} = 10^{32}$ cm^{-2}/s^{-1}
  - *Jlab – MEIC:* 3+60 up to 11+60 $\mathcal{L} = 4\times10^{34} - 4\times10^{32}$ cm^{-2}/s^{-1}



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

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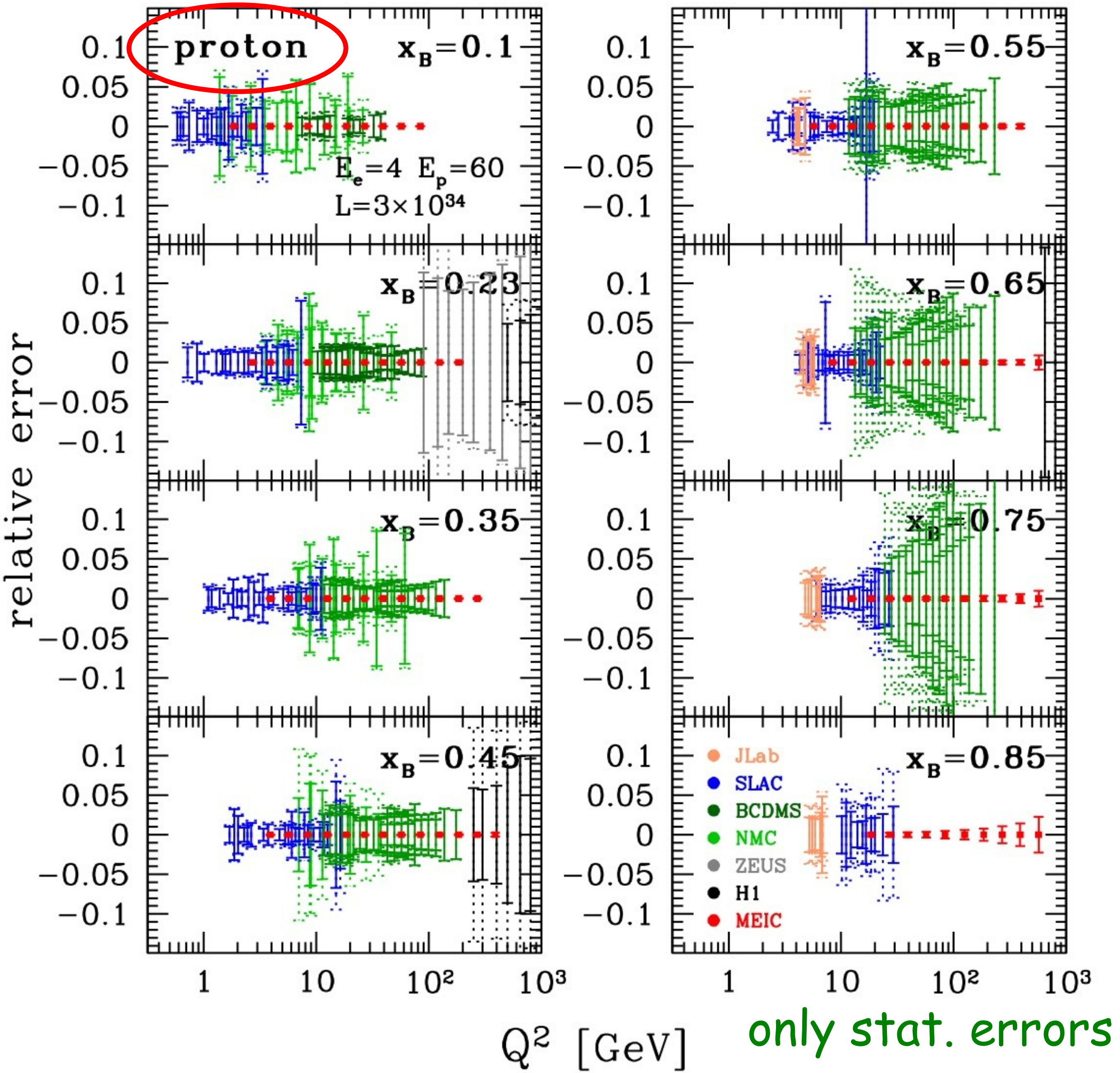
Projected Results - F_2^p Relative Uncertainty

[Accardi, Ent, in progress]



- MEIC 4+60
- 1 year of running (26 weeks) at 50% efficiency, or **230 fb^{-1}**

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%

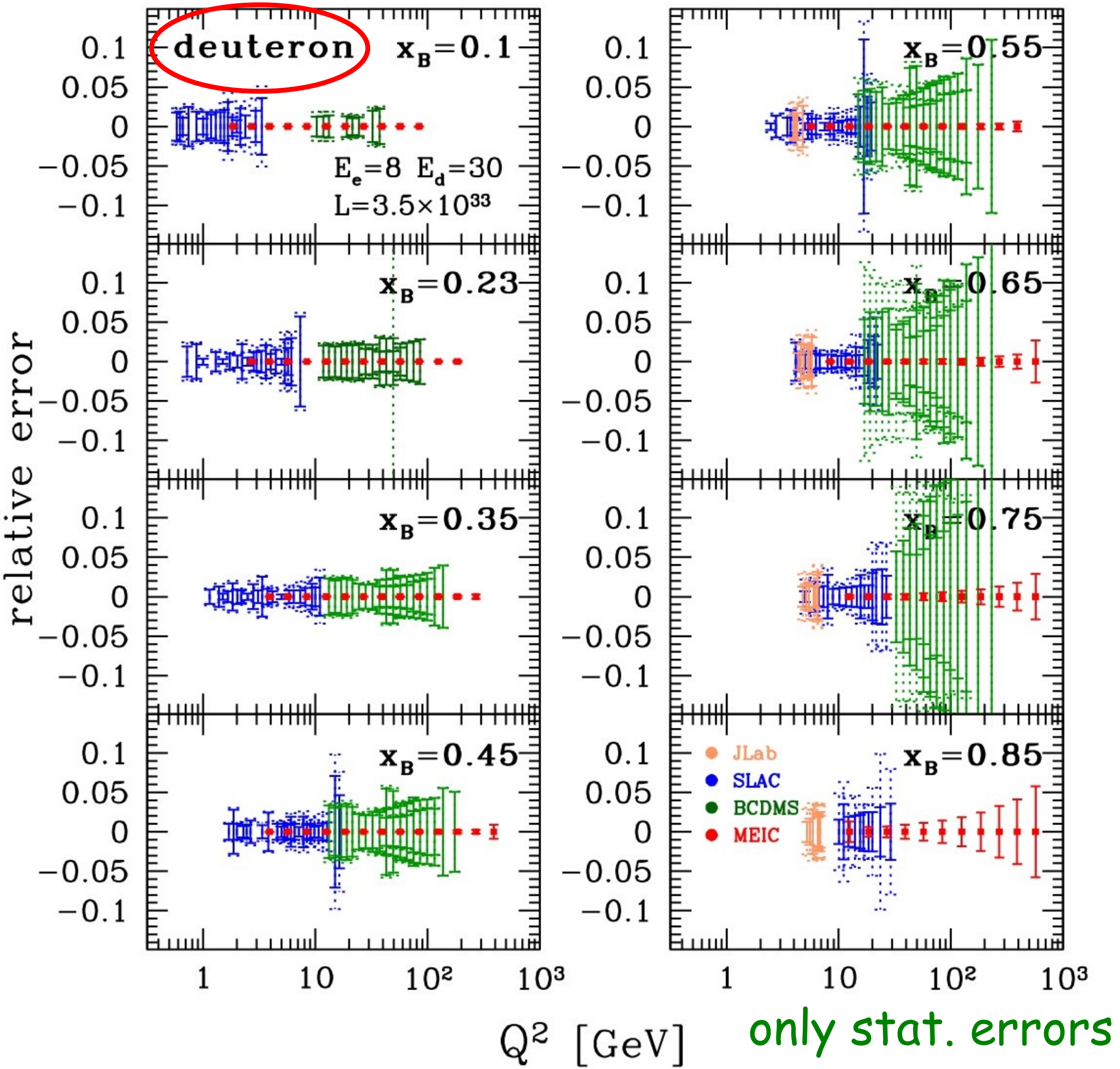
Huge improvement in Q^2 coverage and uncertainty

Will, for instance, greatly aid global pdf fitting efforts

only stat. errors on projected results

Projected Results - F_2^d Relative Uncertainty

[Accardi, Ent, in progress]



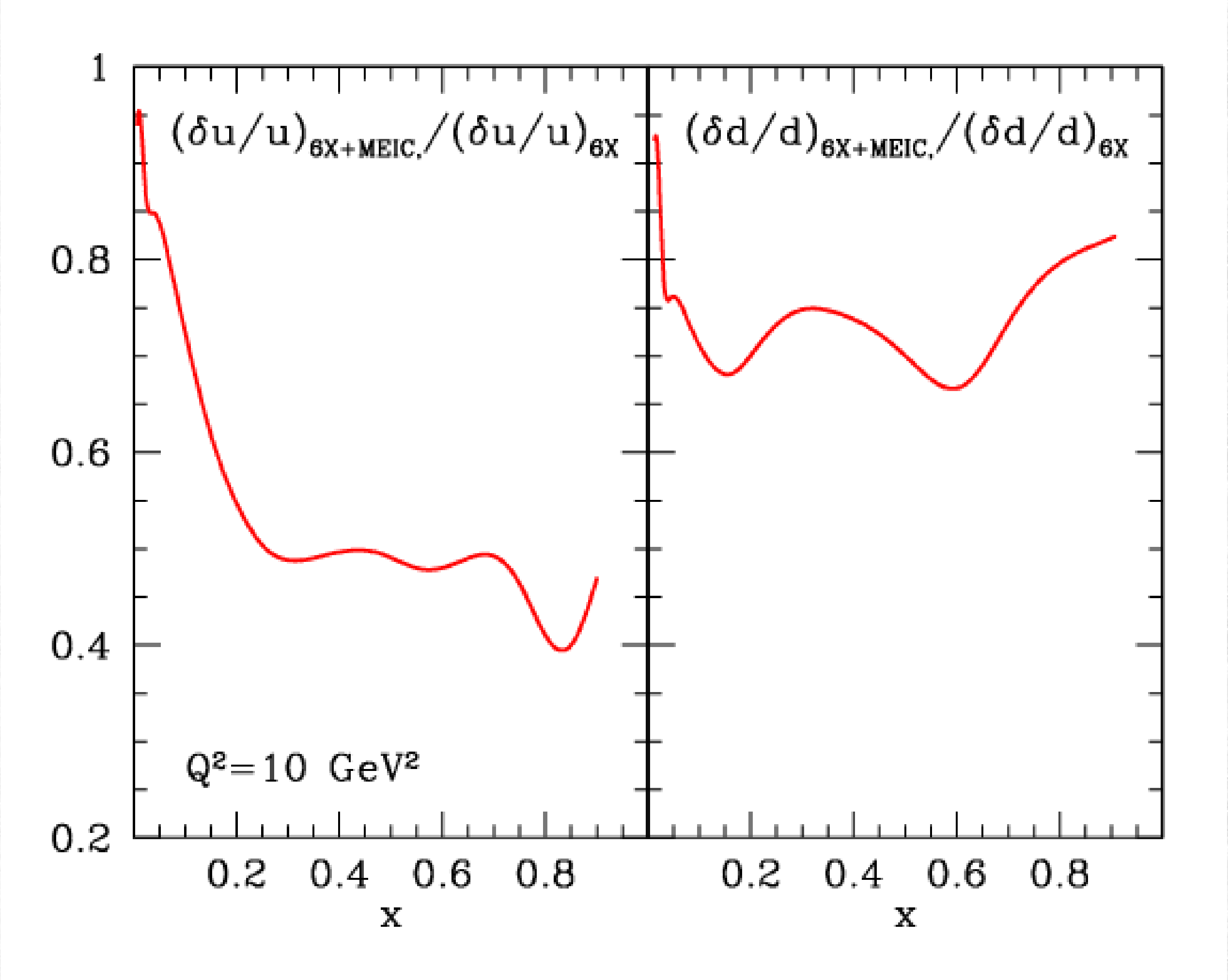
- MEIC 4+30
- 1 year of running (26 weeks) at 50% efficiency, or 35 **fb^{-1}**

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!

only stat. errors on projected results

Impact on global fits



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

Spectator Proton Tagging

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

Assume Deuterium @ 60 GeV/nucleon

Proton-beam tagging after 4 m

80 cm – average
5 mm @ p_s=100 MeV/c
15 mm @ p_s=300 MeV/c
} spectator momentum relative to average

→ Spectator proton detection "easy", e.g., wire chambers (no need of roman pots)

- Need to fold in intrinsic beam spread to check resolution, (especially angular!)

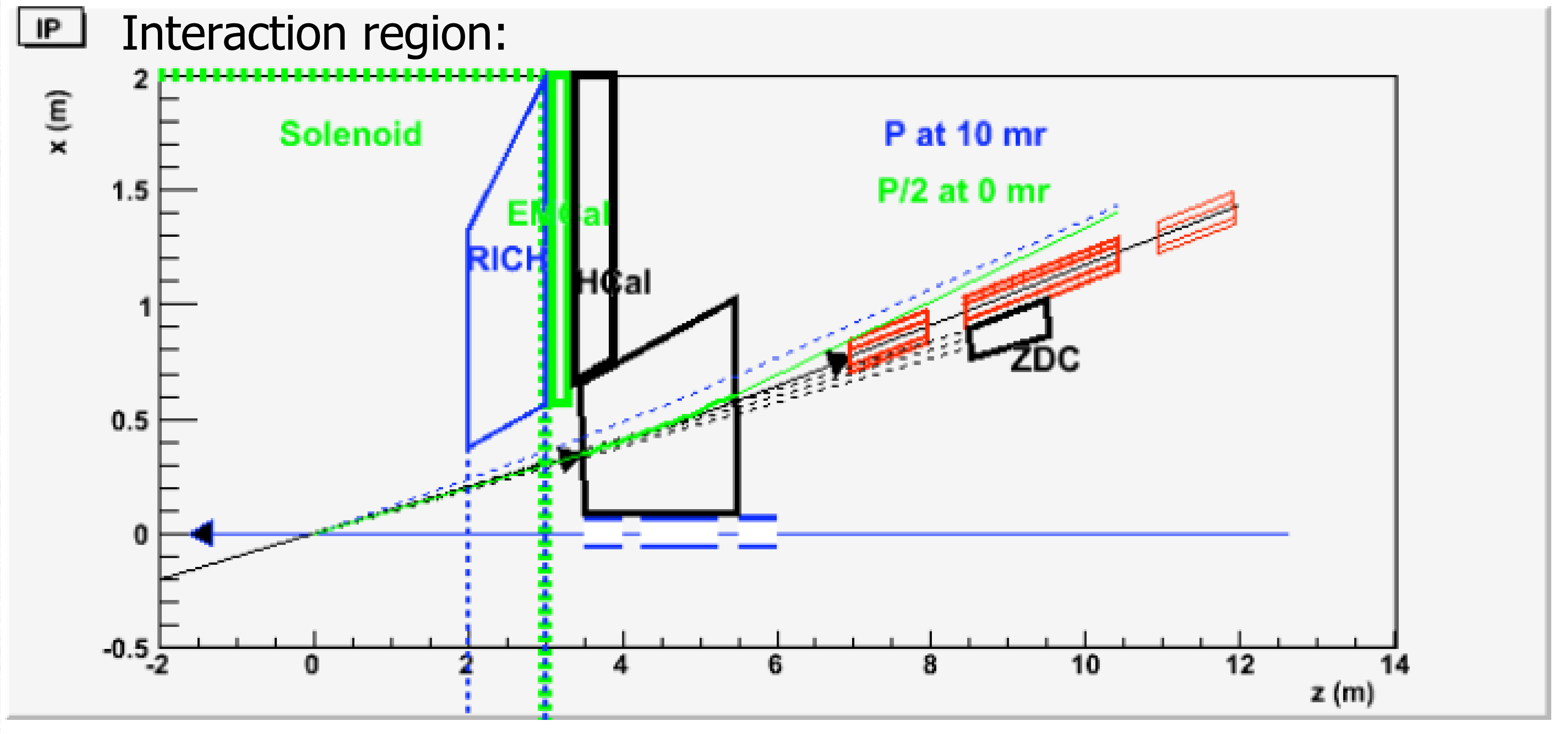
→ Tagging concept looks doable, even if the horizontal crossing angle was reduced by a factor of two or three.

→ Perhaps also D, 3H, 3He tagging doable, though closer to beam

Neutron Tagging

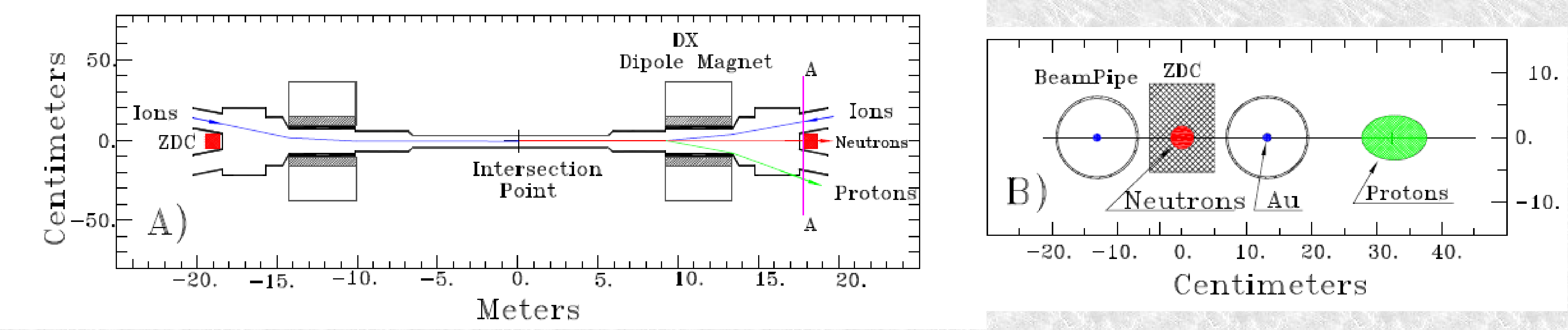
- Neutron tagging in Zero Degree Calorimeter
  - Bound vs. free proton structure functions
  - Extensive program of DVCS on tagged protons and neutron

`[C.Hyde, Rutgers'10]`



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)

Structure functions at the EIC - summary

- **Bread and butter: inclusive DIS**
  - Detailed rates: F_2 and F_L , p and D
  - charm and bottom str.fns.?
  - Impact on global fits
    - ✓ large-x
    - ✓ small-x and saturation

- **Spectator tagging will open up an exciting physics program**
  - Ongoing detector design – angular & momentum resolution
  - Rate estimates needed
  - p vs. n tagging:
    - ✓ “effective” neutron target
    - ✓ control nuclear effects on an “effective” proton
  - Tagging with ^3H, ^3He, ^4He targets ???
    - ✓ EMC effect

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Conclusions

- **Flavor separation at large *x* important**
  - to understand the nucleon structure
  - for phenomenological applications
- **but needs theoretical corrections**
  - target/hadron/quark mass, HT, nuclear corrections, ...

- **u, d quarks:** ongoing CTEQ6X studies

- Lots of progress available at the Jlab 6 & 12, and the EIC

The future is bright ... and busy!

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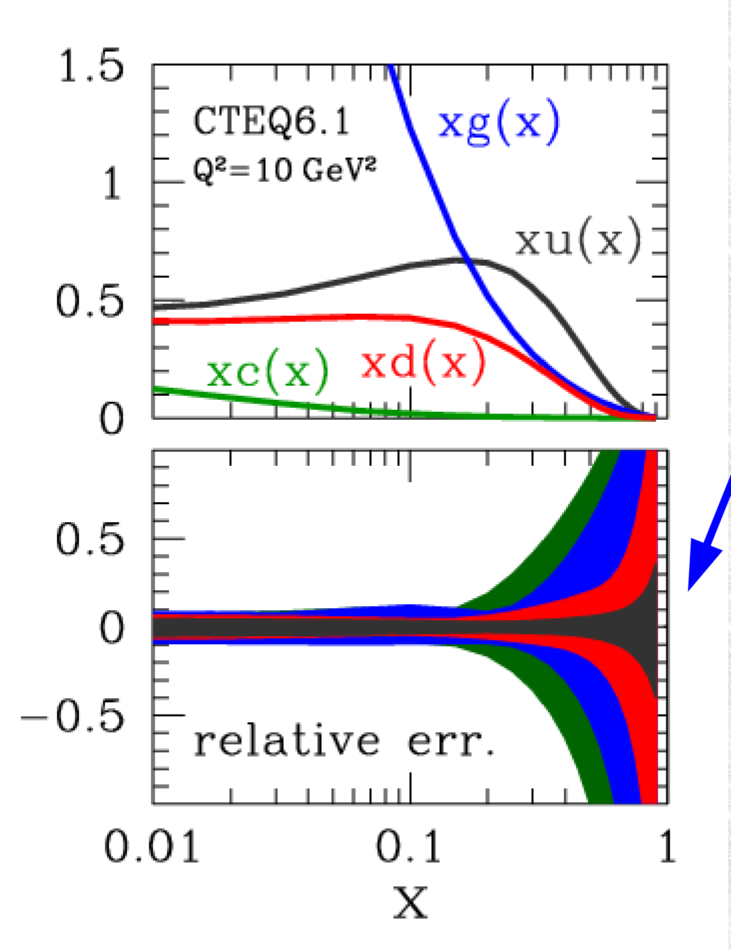
BACKUP SLIDES

Why large x ?

- 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**

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HU, 25 May 2010

Why large x ?

- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron

    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2

    2) New physics as excess on QCD large-p_T spectra ⇔ large x PDF

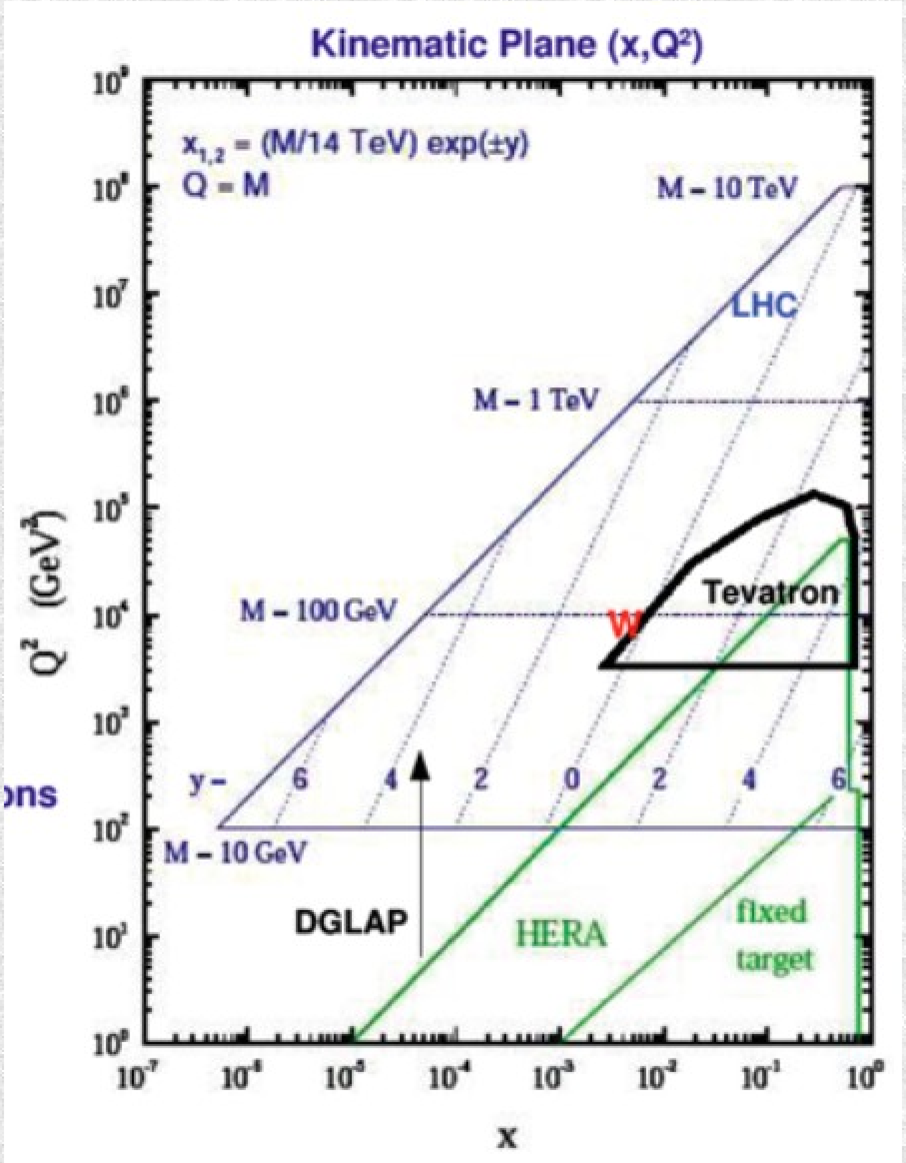
  - Example: Z' production

$$M_{Z'} \gtrsim 200 \text{ GeV} \quad x = \frac{m_T}{\sqrt{s}} e^y$$

$$x \geq 0.02 \text{ (LHC)}, \ 0.1 \text{ (Tevatron)}$$

but recent work raises the bar:

$$M_{Z'} \gtrsim 900 \text{ MeV}$$



Why large x ?

- Large uncertainties in quark and gluon PDF at $x > 0.4$
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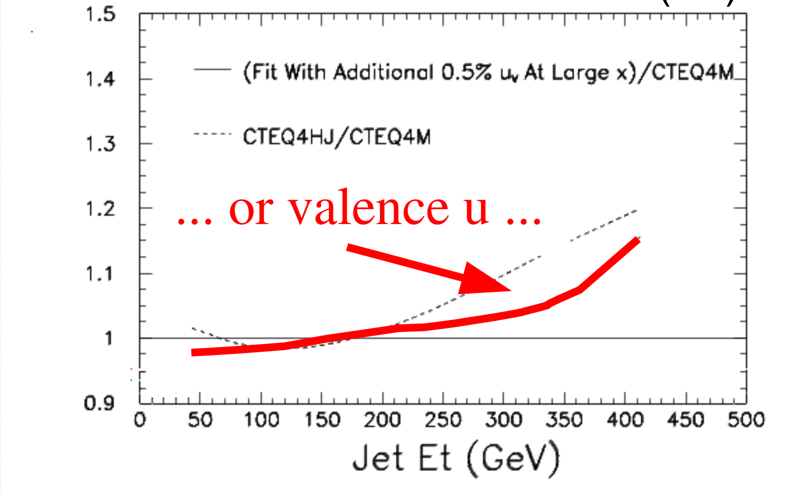
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) New physics as excess on QCD large-p_T spectra ⇔ large x PDF
  - Example 2: 1996 CDF p_T excess

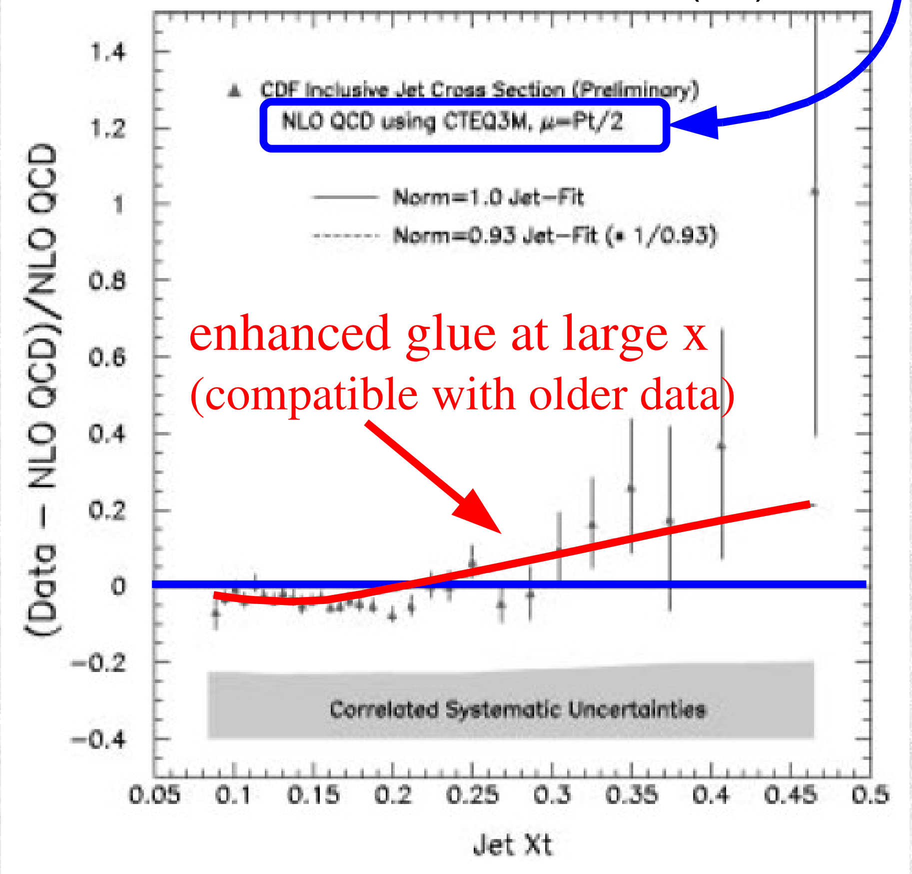
Kuhlmann et al. PLB409(97)



... or valence u ...

NLO state of the art at the time

Kuhlmann et al. PLB476(00)

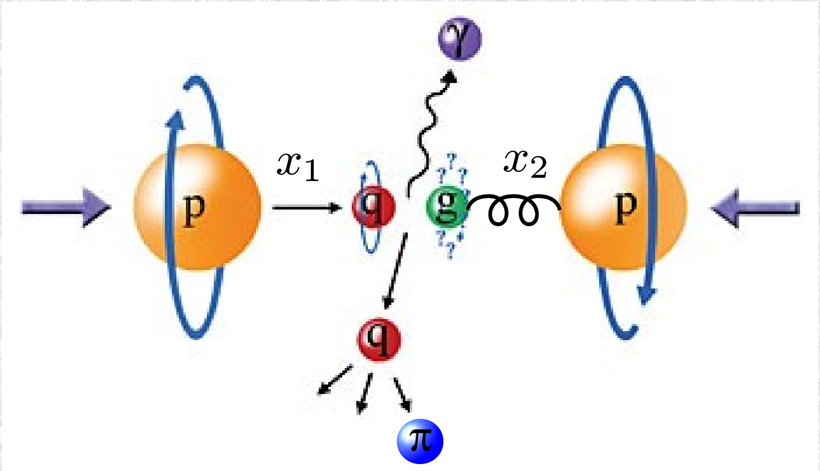


enhanced glue at large x (compatible with older data)

Why large x ?

- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) New physics as excess on QCD large p_T spectra ⇔ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - spin structure of the nucleon – most spin at large-x, but also, e.g.,

$$\sigma(p\vec{p} \to \pi^0 X) \propto \Delta q(x_1) \Delta g(x_2) \hat{\sigma}^{qg\to qg} \otimes D_q^{\pi^0}(z)$$



$$x_1 \sim \frac{p_T}{\sqrt{s}} e^{y}$$

$$x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}$$

Why large x ?

- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) New physics as excess on QCD large p_T spectra ⇔ large x PDF
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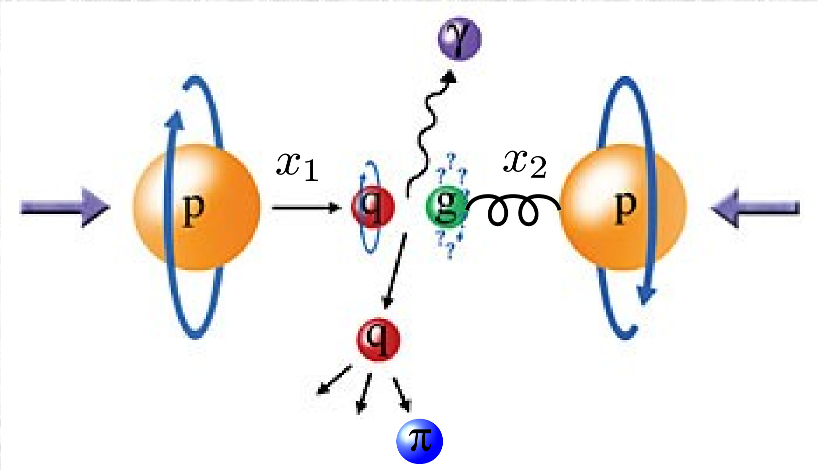

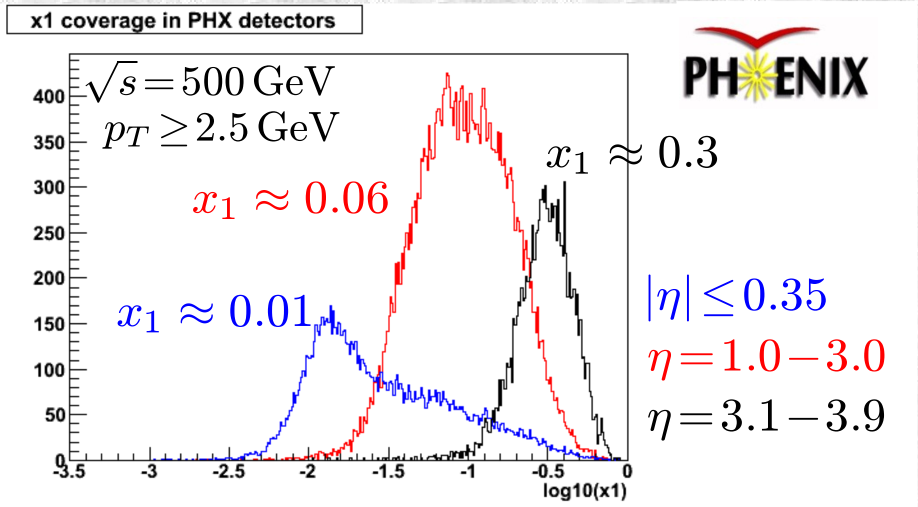

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Target mass corrections

- Nachtmann variable: $\xi = \frac{2x_B}{1+\sqrt{1+4x_B^2 m_N^2/Q^2}} < 1$ at $x_B = 1$

- **Standard Georgi-Politzer** (OPE)
  [Georgi, Politzer 1976; see review by Schienbein et al. 2007]
  - leads to non-zero structure functions at $x_B > 1$ (!)

- **Collinear factorization** [Accardi, Qiu, JHEP 2008; Accardi, Melnitchouk 2008]
  Structure fns as convolutions of parton level structure fns and PDF

$$F_{T,L}(x_B, Q^2, m_N) = \sum_f \int_\xi^{\frac{\xi}{x_B}} \frac{dx}{x}\, h^f_{T,L}\left(\frac{\xi}{x}, Q^2\right) \varphi_f(x, Q^2)$$

  - **respects kinematic boundaries**

- **ξ-rescaling**, uses $x_{\max} = 1$ [Aivazis et al '94; Kretzer,Reno '02]

$$F^{nv}_{T,L}(x_B, Q^2, m_N) \equiv F_T^{(0)}(\xi, Q^2)$$

  - leads to non-zero structure functions at $x_B > 0$ (!)

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“Higher-Twists” parametrization

- Parametrize by a multiplicative factor:

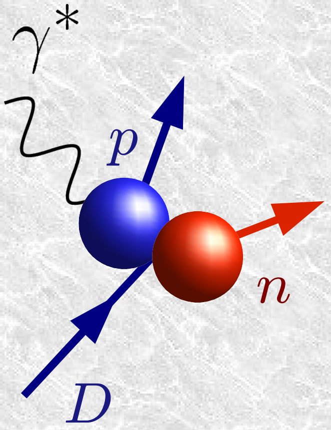
$$F_2(data) = F_2(TMC) \times \left(1 + \frac{C(x_B)}{Q^2}\right)$$

with

$$C(x_B) = a\,x^b\,(1 + c\,x)$$

- **Important:** C(x_B) includes
  - dynamical higher-twists (parton correlations)
  - all uncontrolled power corrections:
    - √ TMC model uncertainty, Jet Mass Corrections
    - √ NNLO corrections (power-like at small *Q*)
    - √ ...

Deuterium corrections



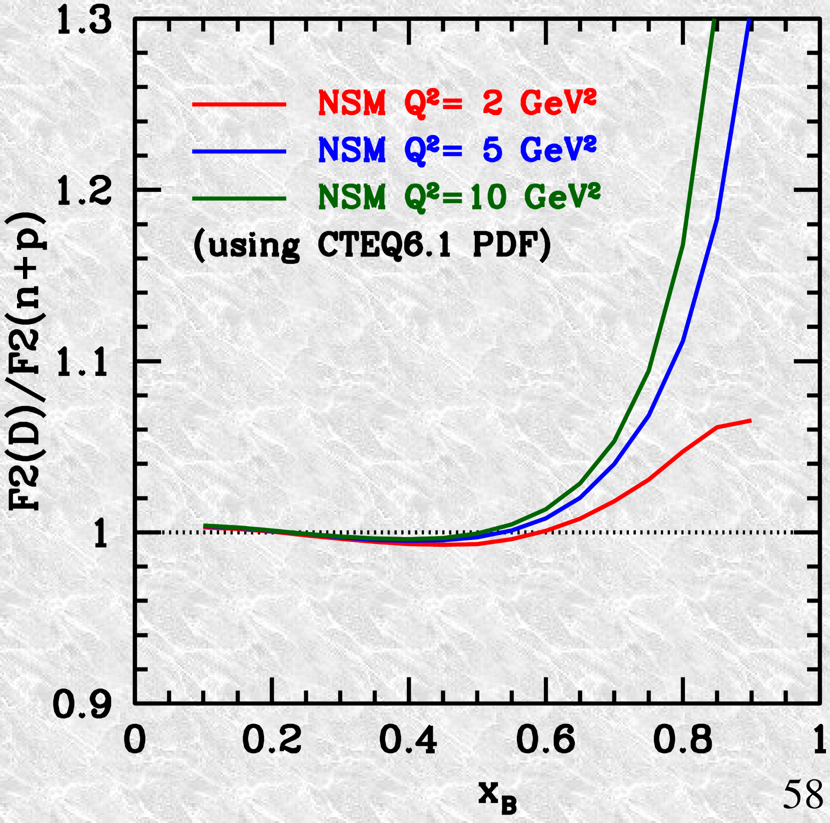
- Nuclear Smearing Model `[Kahn et al., PRC79(2009)` `Accardi,Qiu,Vary, *in preparation*]`
  - nucleon Fermi motion and binding energy
  - use non-relativistic deuteron wave-function
  - finite-Q^2 corrections

$$F_{2A}(x_B) = \int_{x_B}^{A} dy \mathcal{S}_A(y,\gamma,x_B) F_2^{TMC}(x_B/y, Q^2)$$

$$\gamma = \sqrt{1 + 4x_B^2 m_N^2/Q^2}$$

$$\frac{x_B}{y} = -\frac{q^2}{2p_N \cdot q}$$

  - off-shell effects can be included in S_A



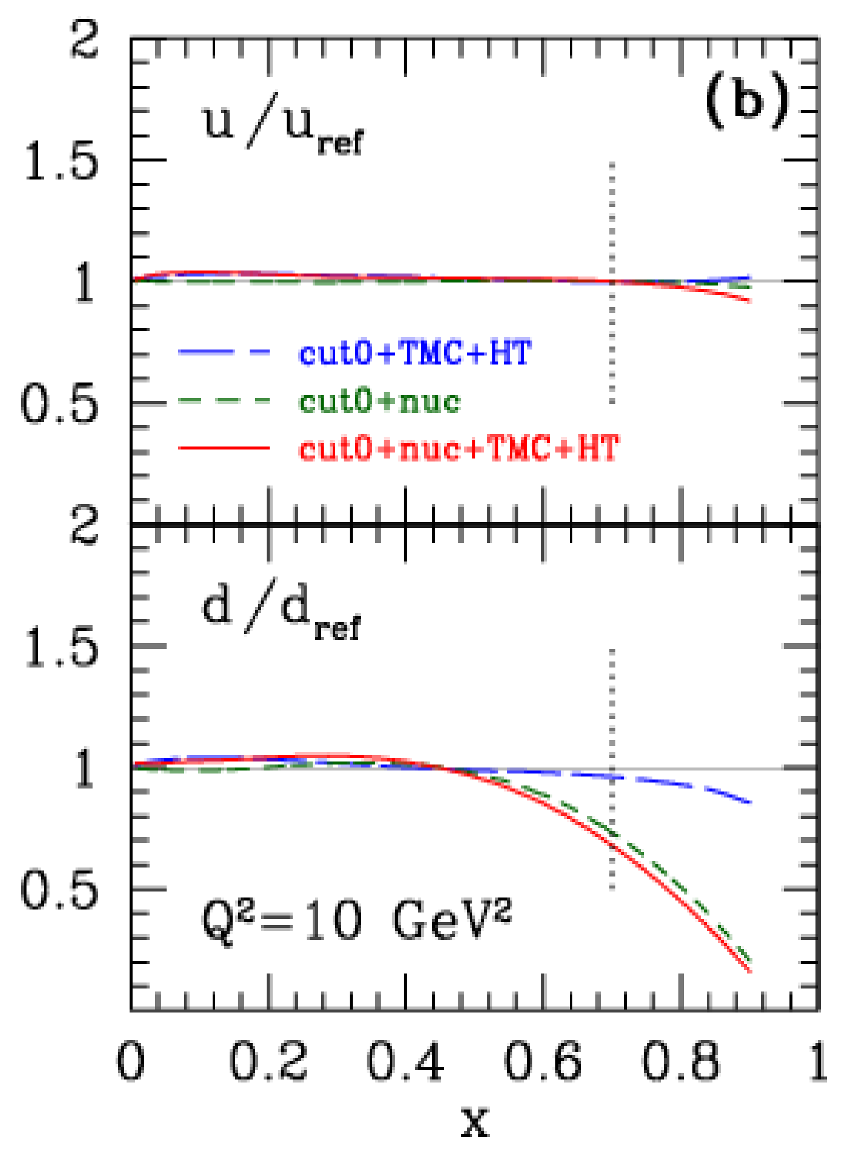
Effects of corrections on reference fit

- Apply the theoretical corrections one at a time

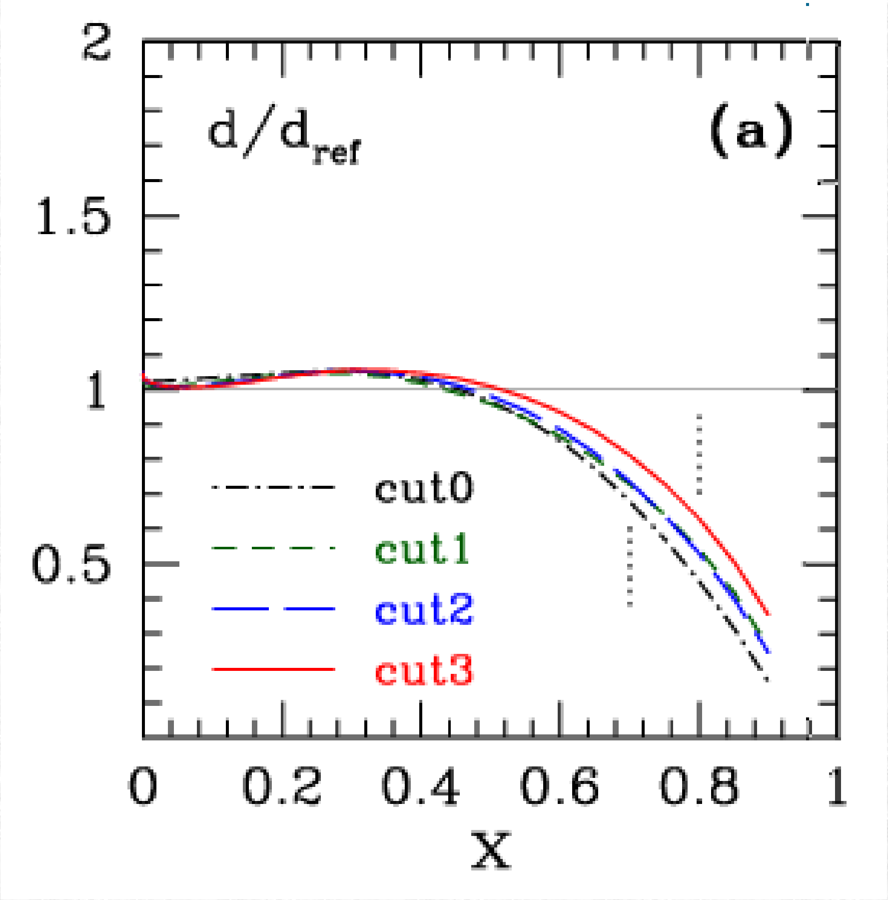
- 2 important lessons:

  - **cut0 removes TMC+HT** (as desired)

  - **nuclear corrections are large starting from $x > 0.5$!!** ("safe cuts" aren't safe everywhere)

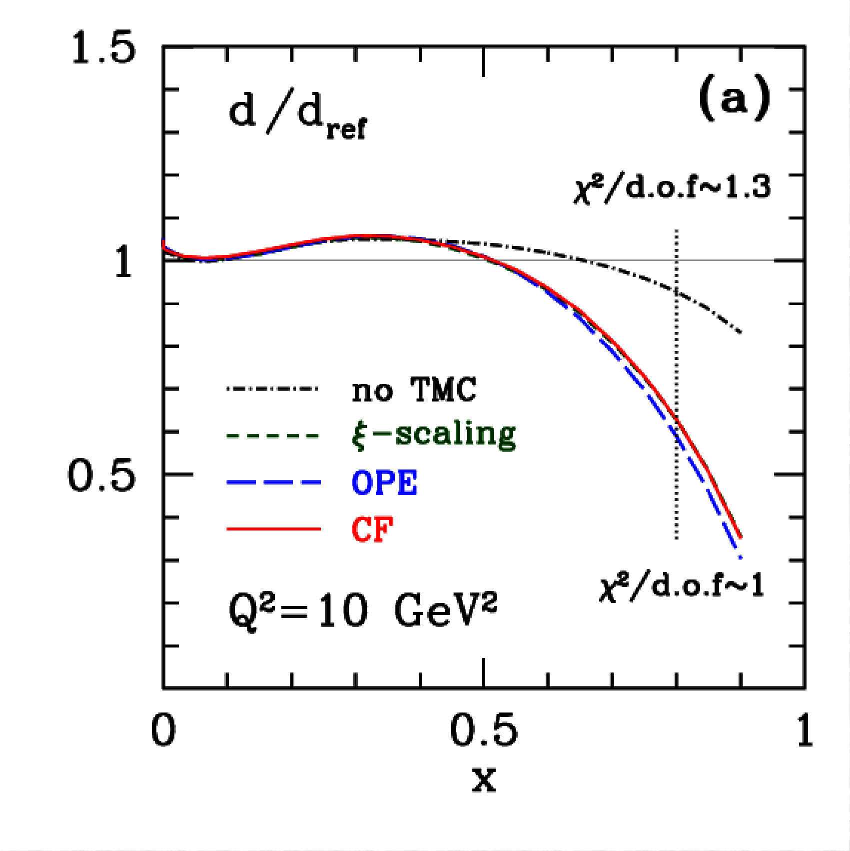


Stability of the d-quark fit



- **Relatively stable against kinematic cuts**, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at x=0.5–0.7 in the nominal range of validity of cut0

TMC vs HT



- **Extracted twist-2 PDF much less sensitive to choice of TMC**
  - fitted HT function compensates the TMC
  - except when no TMC is included
- **Inclusion of TMC allow for economical HT parametrization** (3 params)

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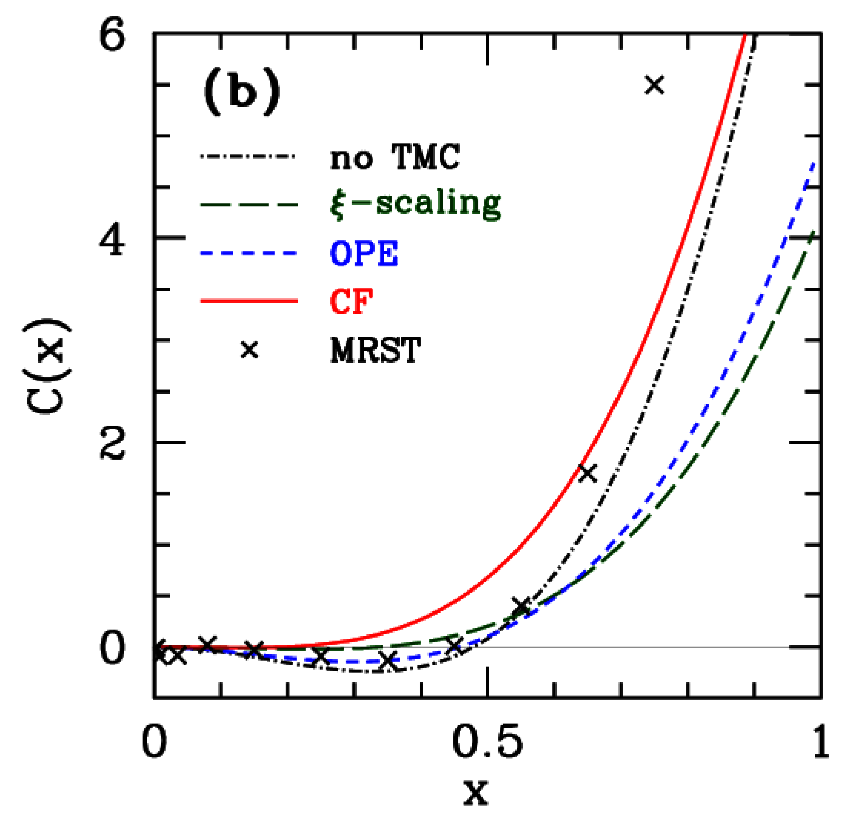
TMC vs HT



- **Extracted higher-twist term depends on the type of TMC used**
  - $Q^2 > 1.69$ GeV^2 and $W^2 > 3$ GeV^2 (referred to as “cut03”)
  - lower cuts ⇒ $x_B < 0.85$ compared to $x_B < 0.7$ in CTEQ/MRST
  - No evidence for negative HT

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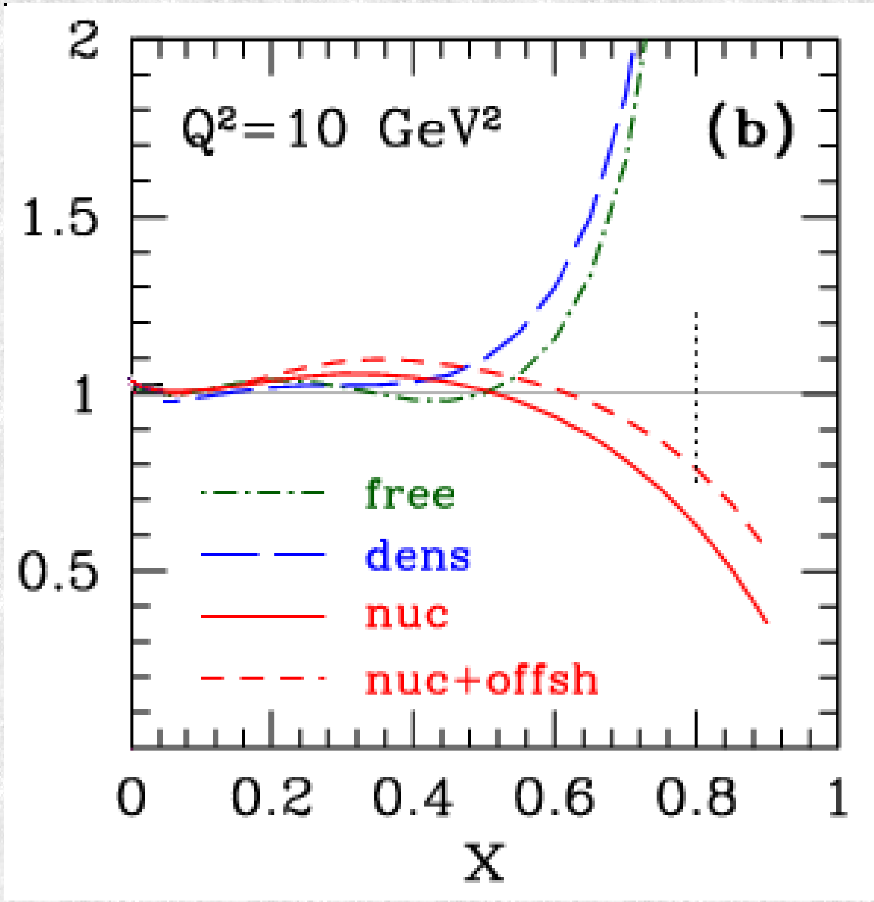
Off-shell corrections



$$F_2^p = \frac{4}{9} x\ u(1 + \frac{d}{4u})$$ no corrections

$$F_2^d = \frac{5}{9} x\ u(1 + \frac{d}{u}).$$ O.S. corrections

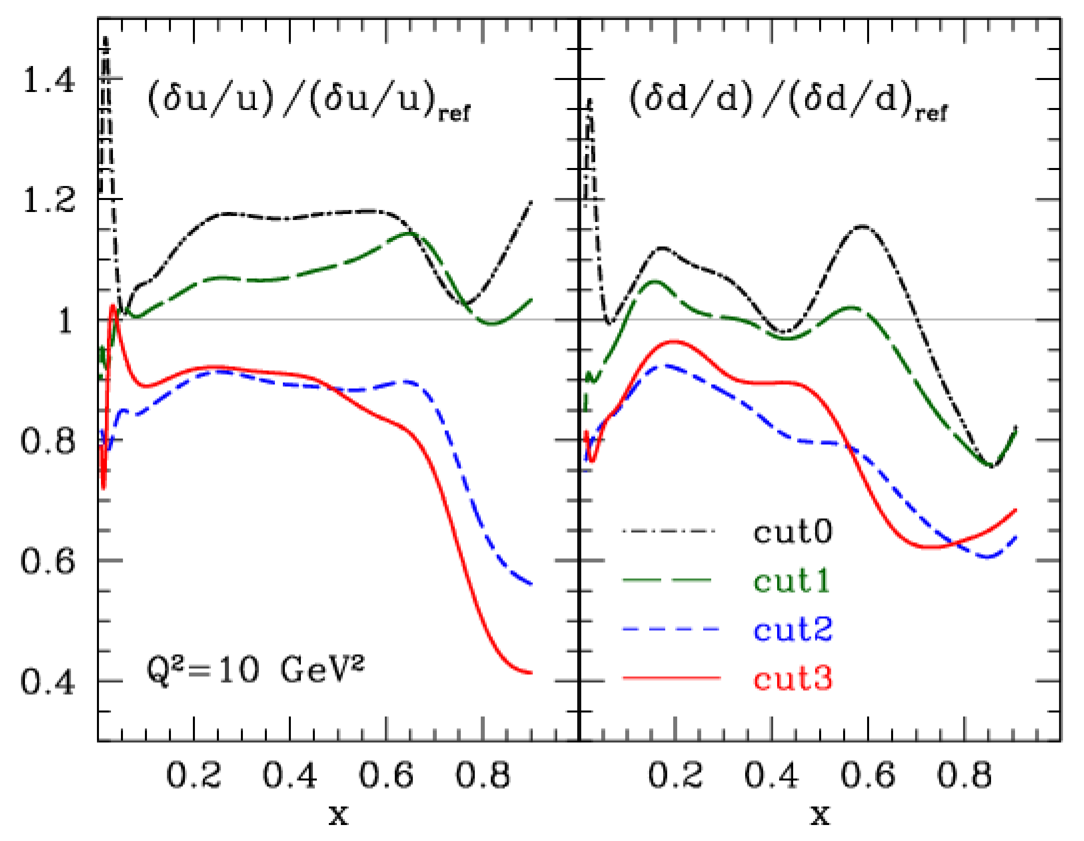
$$\frac{\delta d}{d} = \frac{4}{3} \frac{\delta F_2^d}{F_2^d} (1 + \frac{1}{d/u}).$$

1.5% on F_2^d ⇒ 40% on *d*-quark !!!

- **d-quark is strongly correlated to choice of Off-Shell correction !**
  - on-shell or mild off-shell correction ⇒ d-quark suppression
  - might as well be enhanced...
- **Need to constrain the models !** – see later

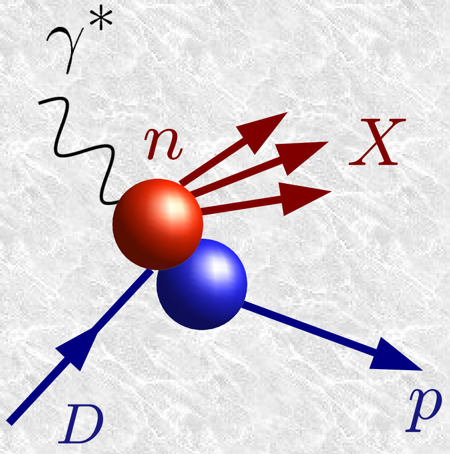
Experimental uncertainties: PDF errors

- **PDF errors at large *x* are reduced by lowering the cuts**
  - Note: these are exp. errors propagated in the fit
  - nuclear correction uncertainty for d-quarks likely larger than this!



Quasi-free nucleon targets

`BONUS and E94-102 experiments at JLab`



- DIS on deuterium with tagged proton
  - tagged proton momentum is measured
  - neutron off-shellness can be reconstructed

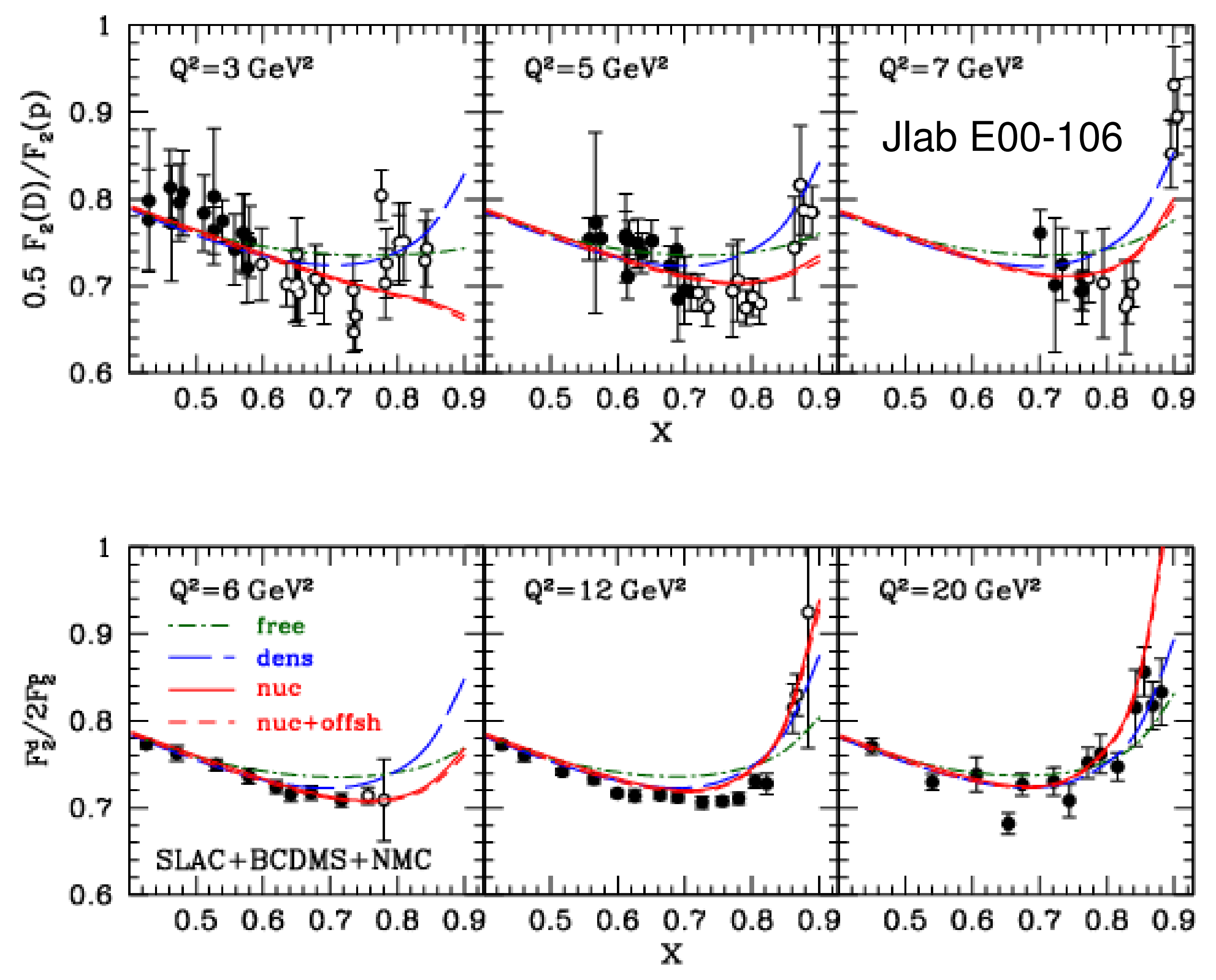
- Study the <u>off-shell dependence</u> of $F_2(n)$ and quark PDFs

$$q \equiv q_D(x, Q^2, p^2)$$

- <u>Extrapolate</u> to a free neutron target $p^2 \to {M_n}^2$

D/p ratios

- **Strong Q^2 dependence of nuclear smearing**
  - **use fixed x_B data up to larger Q^2**
  - needs resonance region ⇒ quark-hadron duality
  - off-shell corrections can't be constrained



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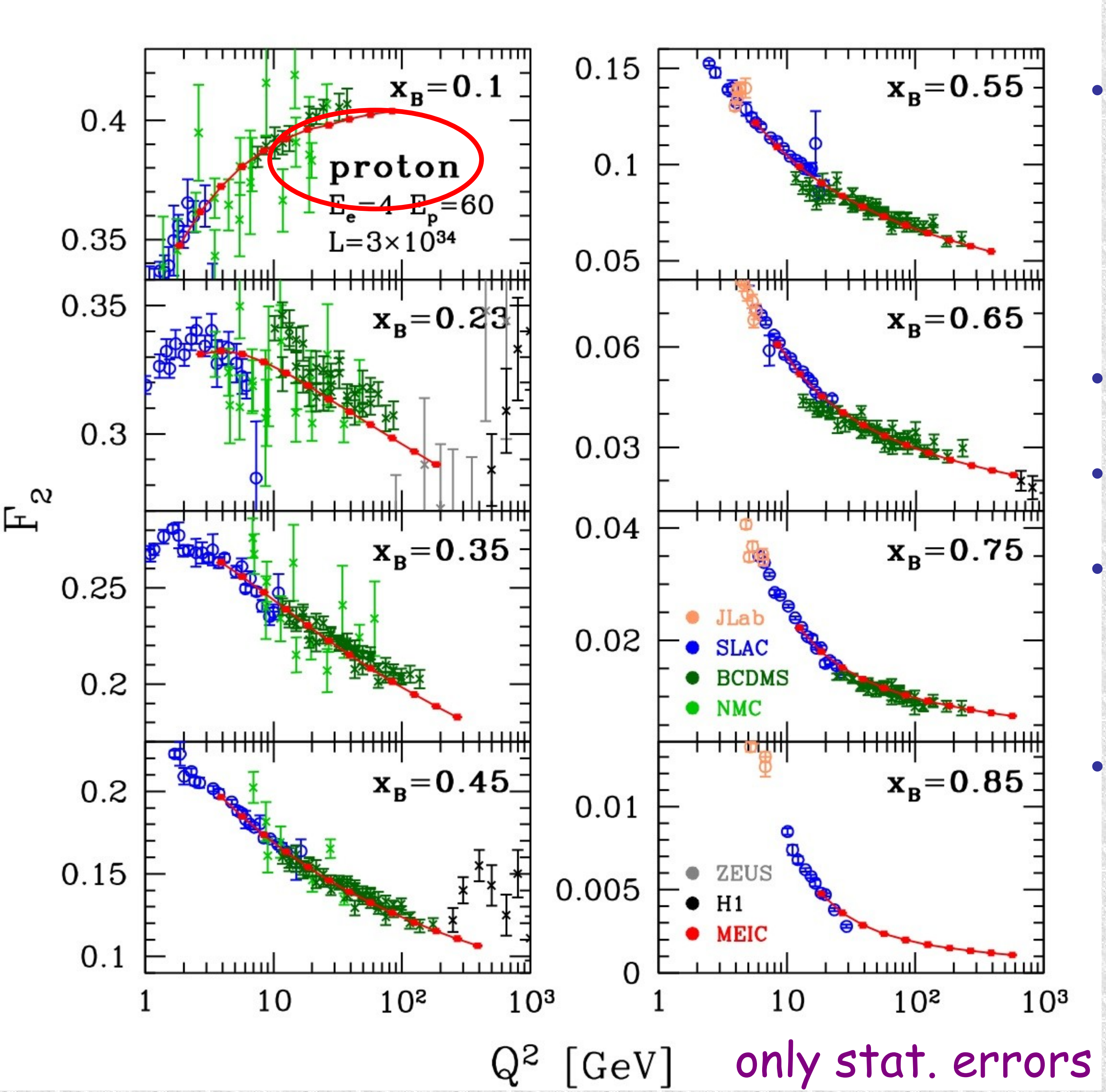
Projected Results IIa - F_2^p with CTEQ6X PDFs



- $E_e = 4$ 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 $\mathbf{fb^{-1}}$**
- 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

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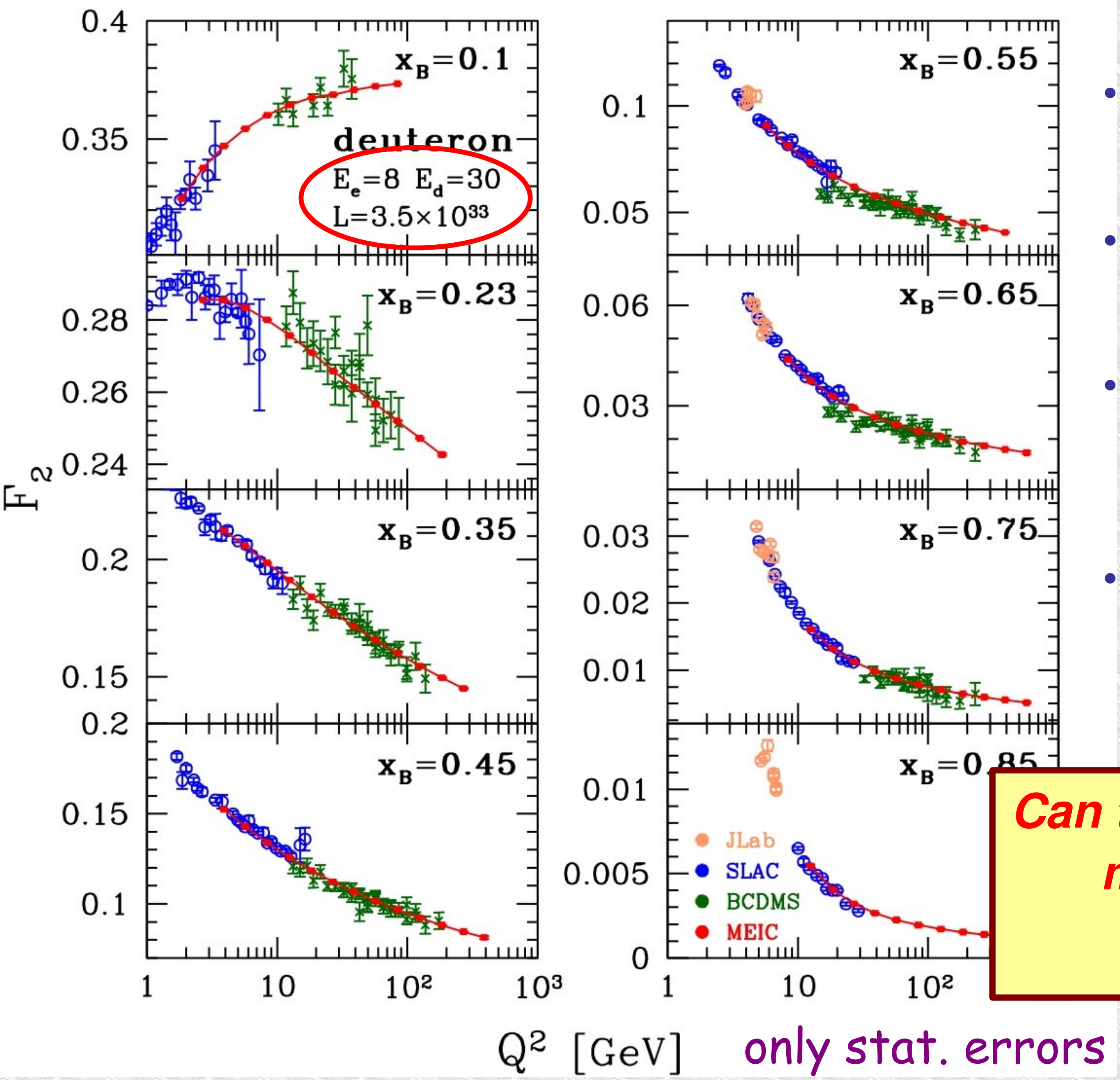
Projected Results IIb - F_2^d



- 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