Parton flavor separation at large fractional momentum

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Outline

- **Introduction**
  - Quark, gluons and nucleons
  - Parton distributions
  - Global fits
- **Why large fractional momentum (*x*)**
- **Up and down: the CTEQ6X fit**
- **Gluons, intrinsic charm**
- **Outlook: the Electron-Ion Collider**

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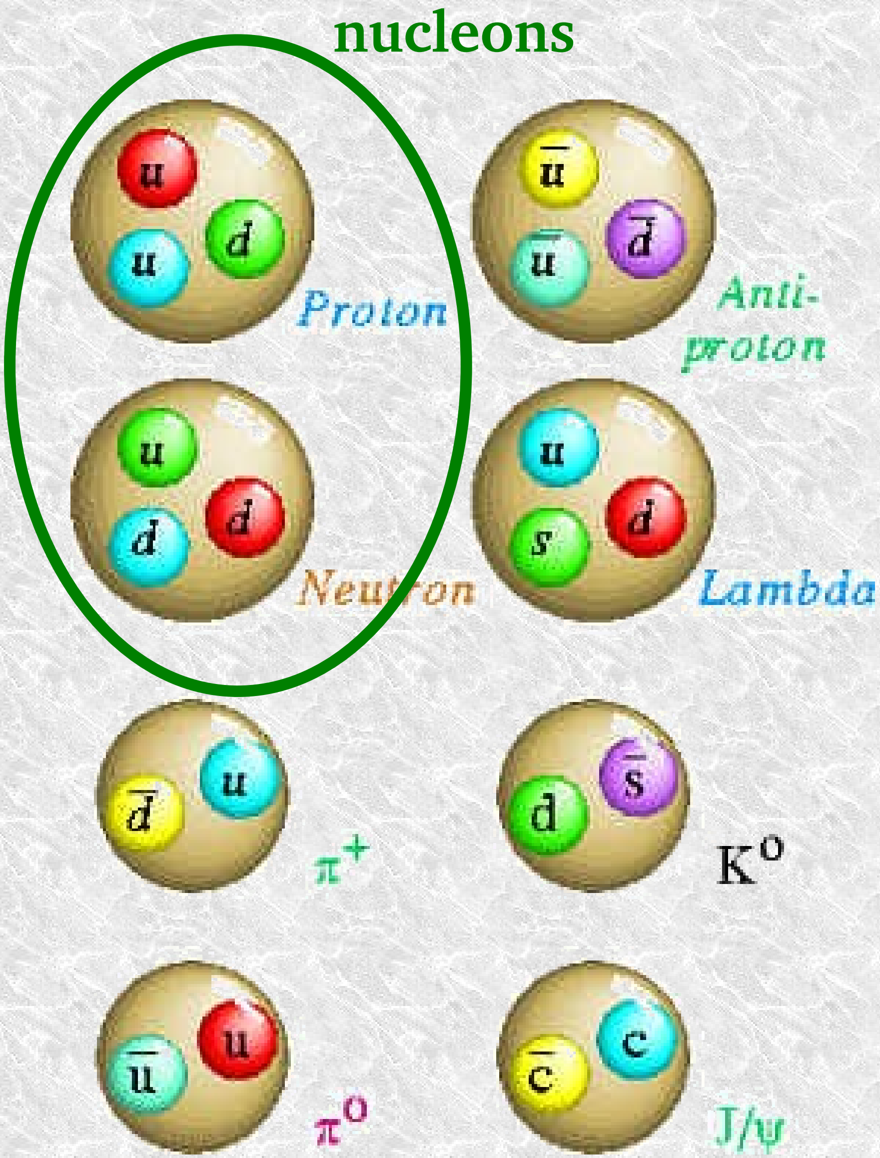
Quarks, gluons and nucleons

Hadrons are made of quarks



- 6 flavors (and 3 colors):

  up, down, strange – `light`
  charm, bottom, top – `heavy`

- confined in colorless hadrons
  - mesons – 2 quarks
  - baryons – 3 quarks
  - tetraquarks (?)
  - pentaquarks (???)

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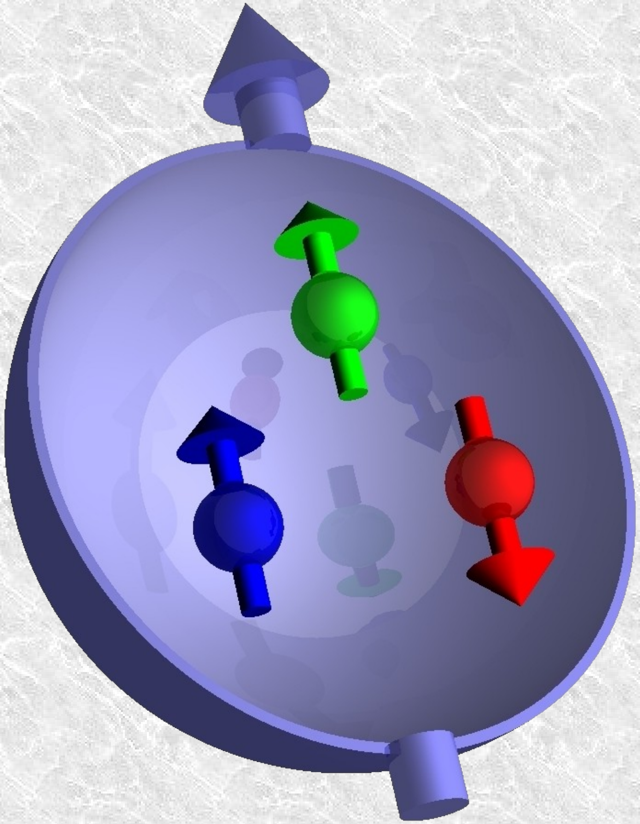
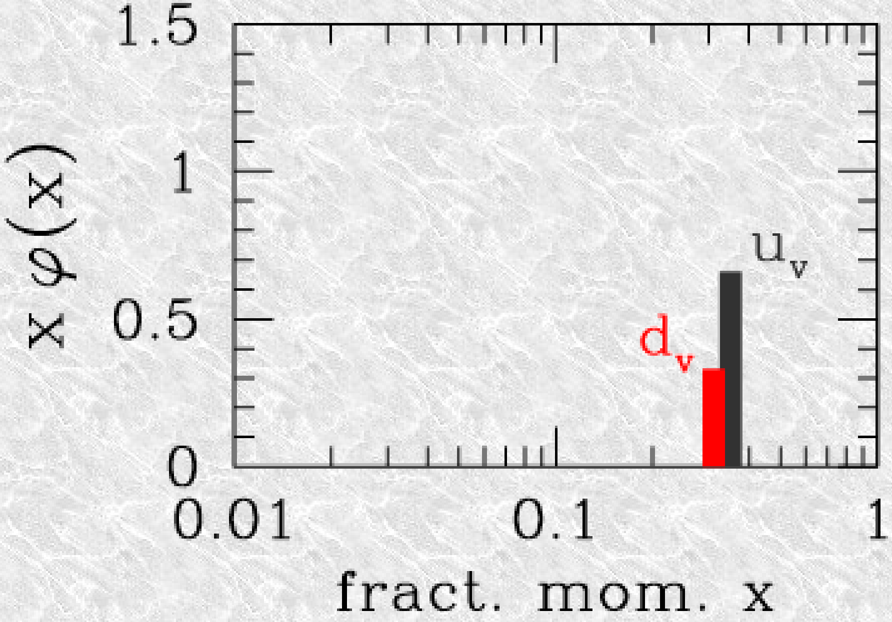
Nucleons are made of 3 quarks...





Fractional momentum: $x = \frac{p^+_{\text{parton}}}{p^+_{\text{nucleon}}}$ $p^{\pm} = \frac{1}{\sqrt{2}}(p_0 \pm p_3)$

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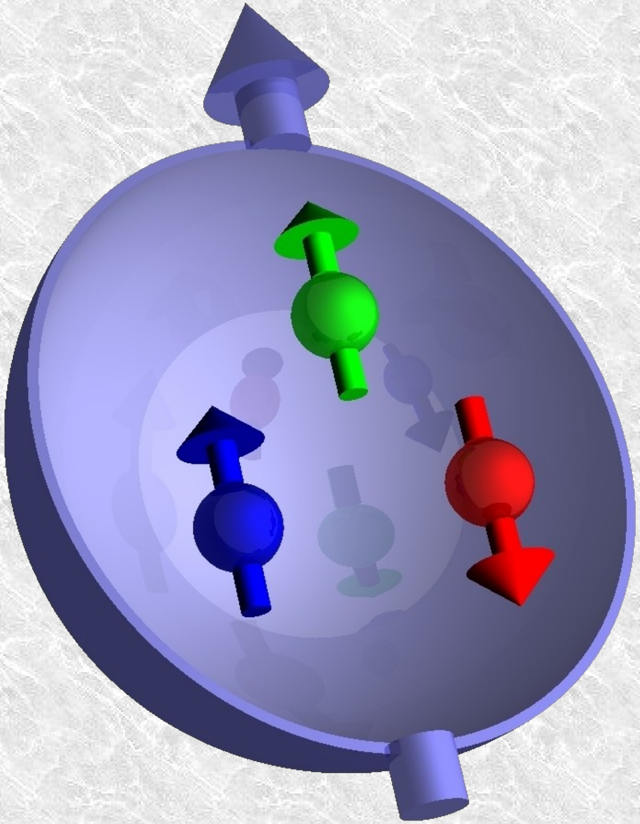
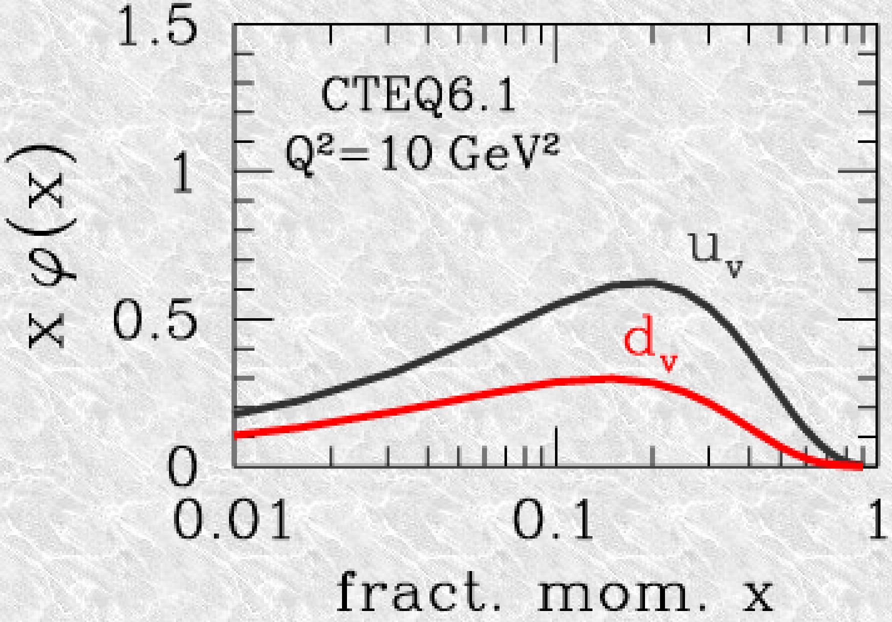
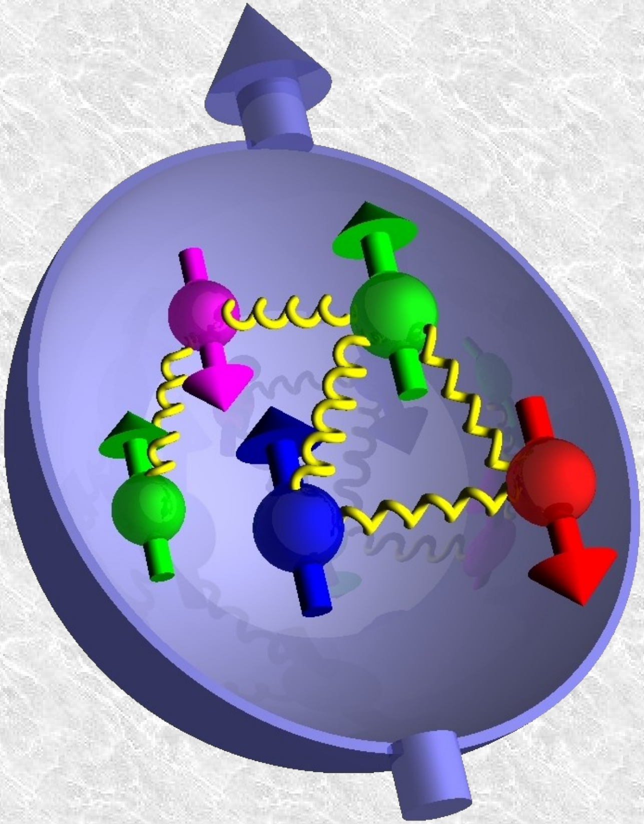
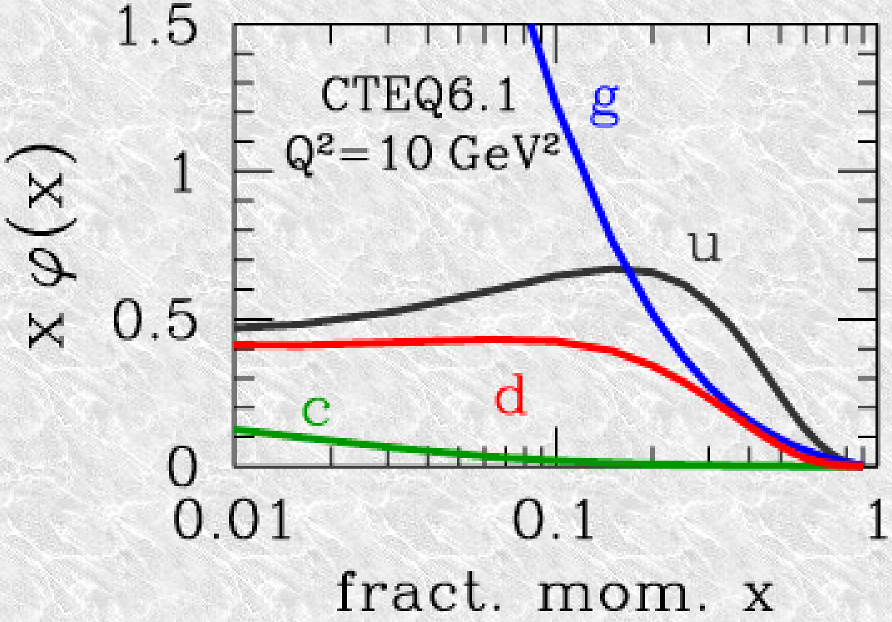




Fractional momentum: $x = \frac{p^+_{\text{parton}}}{p^+_{\text{nucleon}}}$ $p^\pm = \frac{1}{\sqrt{2}}(p_0 \pm p_3)$

... and gluons, sea quarks ...





Fractional momentum: $x = \frac{p^+_{\rm parton}}{p^+_{\rm nucleon}}$ $p^\pm = \frac{1}{\sqrt{2}}(p_0 \pm p_3)$

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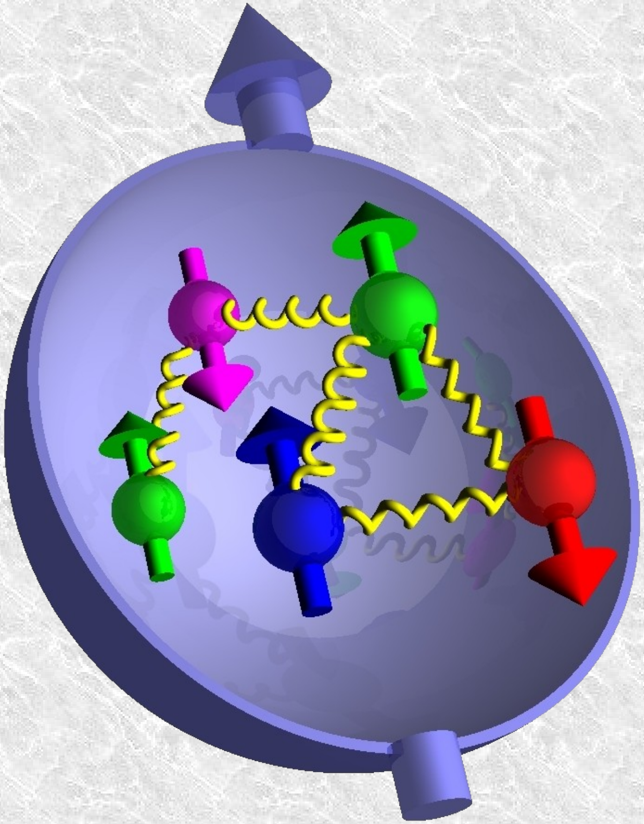
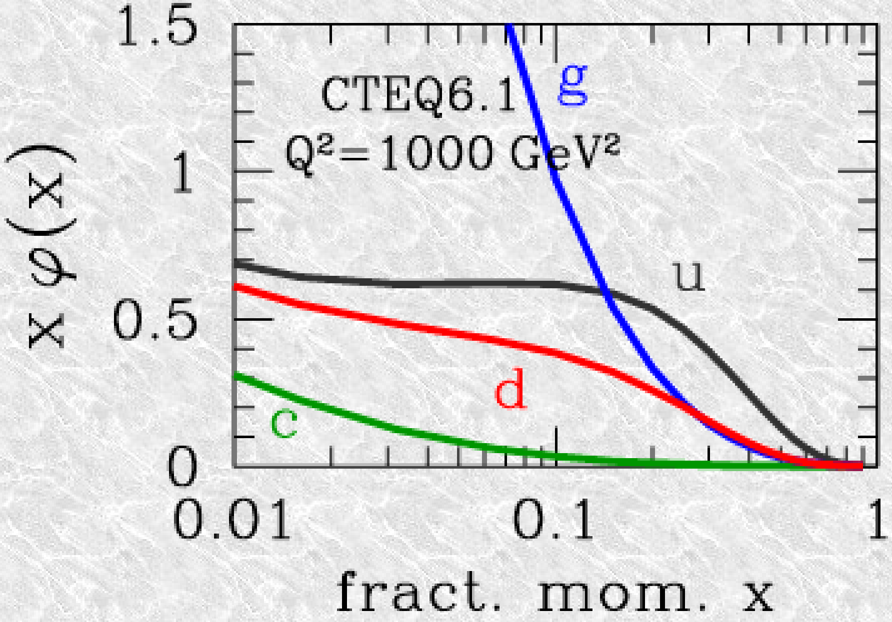
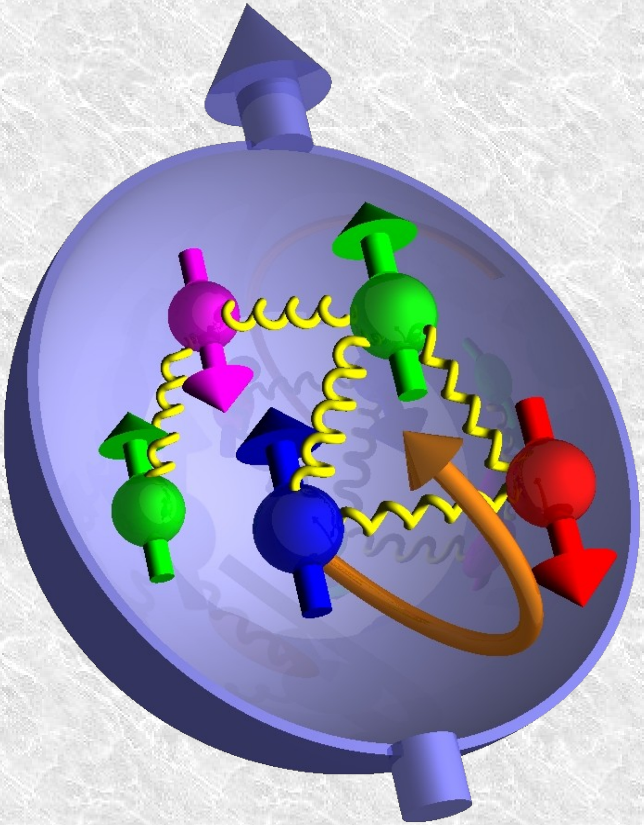




Fractional momentum: $x = \frac{p^+_{\text{parton}}}{p^+_{\text{nucleon}}}$ $p^\pm = \frac{1}{\sqrt{2}}(p_0 \pm p_3)$

... spinning and orbiting around !



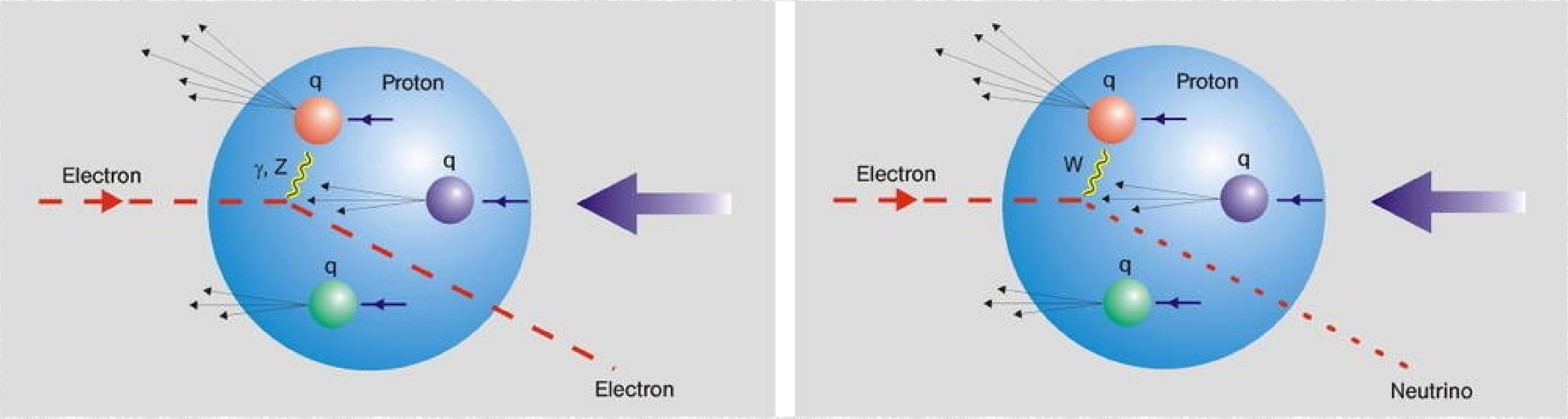
... but this is another story ...

Probing the nucleon parton structure

- Need a large momentum transfer $Q^2 = q_\mu q^\mu$ to resolve the parton structure

- Example 1: **Deep Inelastic Scattering (DIS)**

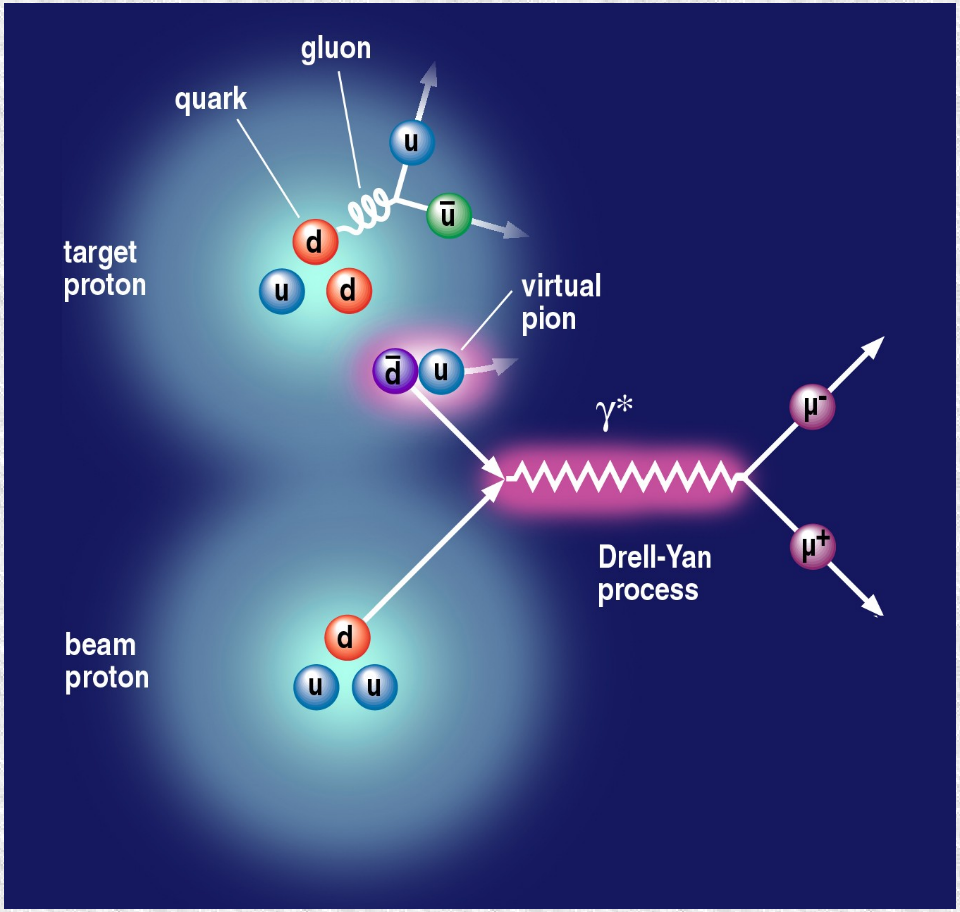
$$Q^2 = p^2_{\gamma,Z}$$



Probing the nucleon parton structure

- Need a large momentum transfer $Q^2 = q_\mu q^\mu$ to resolve the parton structure

- Example 2: **Drell-Yan lepton pair creation (DY)**



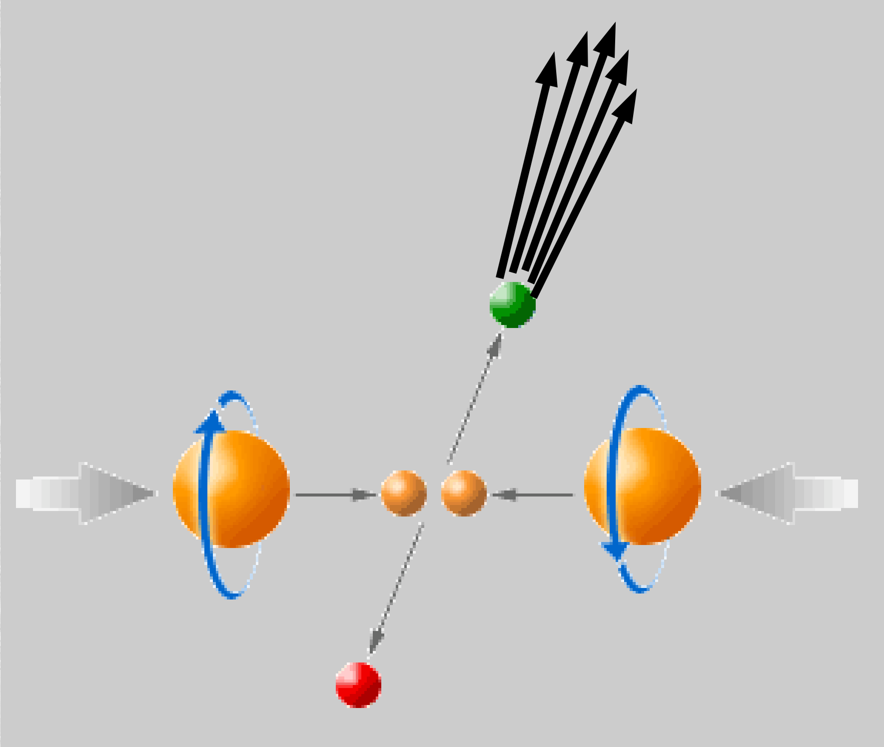
$$Q^2 = (p_\ell + p_{\bar{\ell}})^2$$

Probing the nucleon parton structure

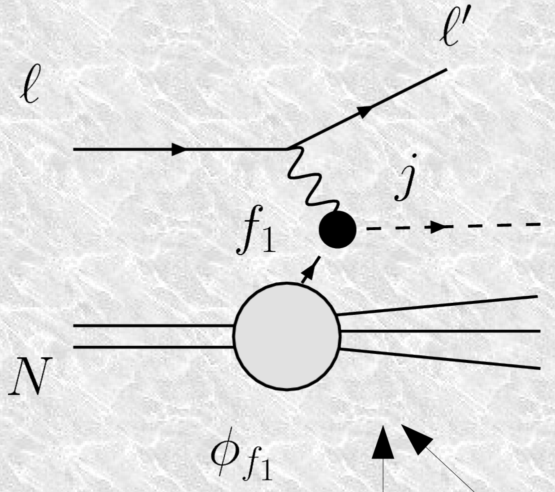
- Need a large momentum transfer $Q^2 = q_\mu q^\mu$ to resolve the parton structure

- Example 3: **jet production in p+p collisions**

$$Q^2 = E_{jet}^2$$



Factorization of hard scattering processes



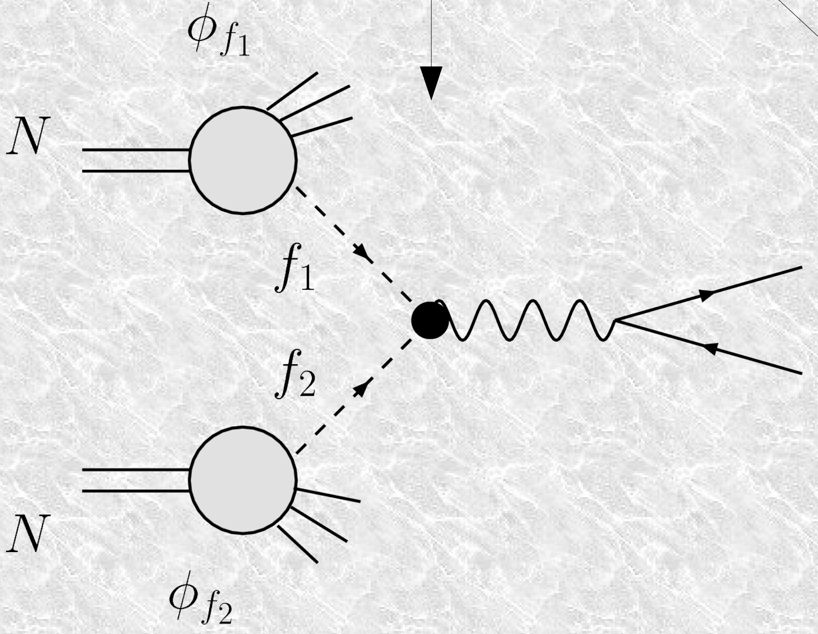
- **perturbative QCD factorization** of short and long distance physics

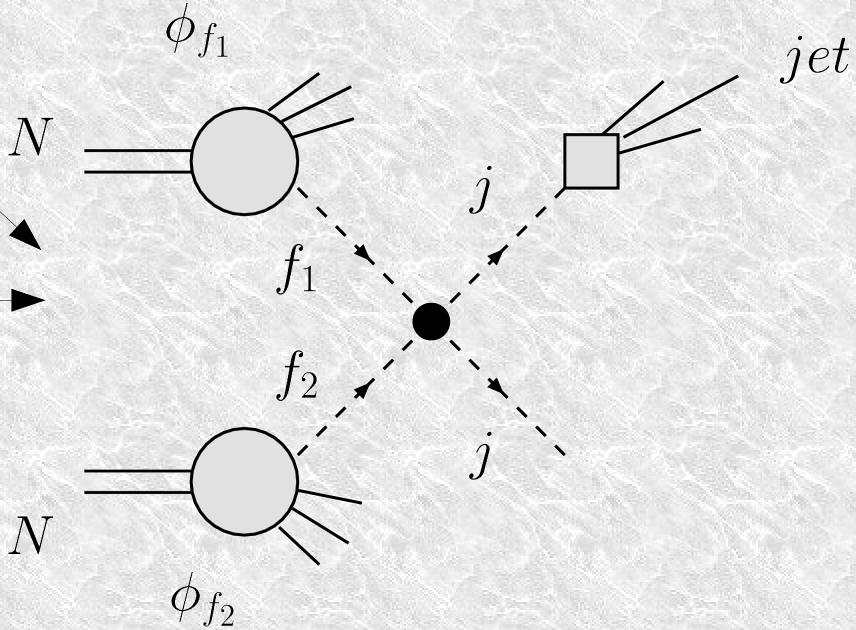
$$d\sigma_{\text{hadron}} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat{\sigma}^{f_1 f_2 \to ij}_{\text{parton}} \otimes \phi_{f_2}$$

Parton Distribution Fns
(from inclusive DIS)

pQCD
cross section

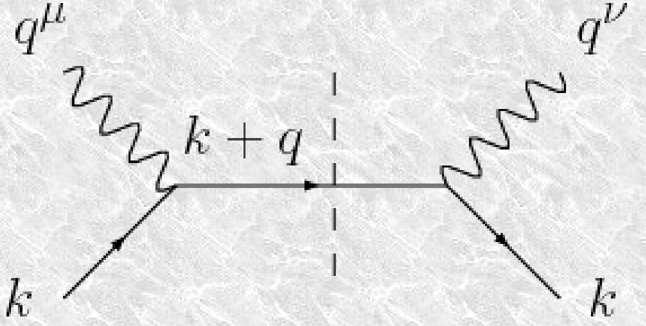
- **Universality**: PDF from DIS describe also DY, p+p→ jets+X, ...





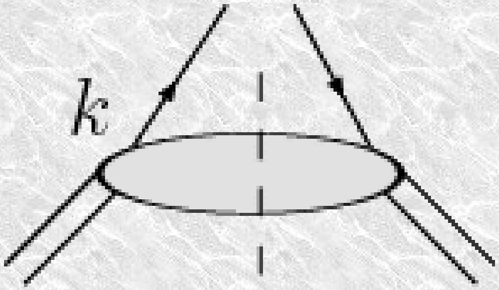
Factorization of hard scattering processes

- Hard scattering, computable in pQCD – e.g., in DIS (at Leading Order)



$$= -\frac{1}{2}\Big(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\Big) e_f^2 \delta\Big(1+\frac{q^2}{2k\cdot q}\Big) + \Big(k_\mu - q_\mu \frac{k\cdot q}{q^2}\Big)\Big(\mu \leftrightarrow \nu\Big)\frac{e_f^2}{k\cdot q}\delta\Big(1+\frac{q^2}{2k\cdot q}\Big)$$

- PDF – field theoretical definition (at Leading Order)



$$\varphi_q(x) = \int \frac{dz^-}{2\pi} e^{iz^-k^+} \langle p|\bar{\psi}(z^- n)\frac{\gamma\cdot\bar{n}}{2}\psi(0)|p\rangle$$

Global PDF fits

- **Problem:** we need a set of PDFs in order to calculate a particular hard-scattering process

- **Solution:**
  - Choose a data set for a choice of different hard scattering processes
  - Generate PDFs using a parametrized functional form at initial scale Q_0; evolve them from Q_0 to any Q using DGLAP evolution equations
  - Use the PDF to compute the chosen hard scatterings
  - Repeatedly vary the parameters and evolve the PDFs again
  - Obtain an optimal fit to a set of data.

- Examples: CTEQ6.6, MRST2008 for unpolarized protons
  DSSV, LSS for polarized protons

- For details, see J. Owens' lectures at the 2007 CTEQ summer school

Global PDF fits as a tool

- **Test new theoretical ideas**
  - *e.g.*, constrain amount of intrinsic charm
- **Phenomenology explorations**
  - *e.g.*, can CDF / HERA "excesses" be at all due to glue/quark underestimate at large x?
- **Test / constrain models**
  - *e.g.*, by extrapolating d/u at $x=1$
  - Possibly, constrain nuclear corrections
- **Limitations**
  - existing data
  - experimental errors
  - theoretical errors

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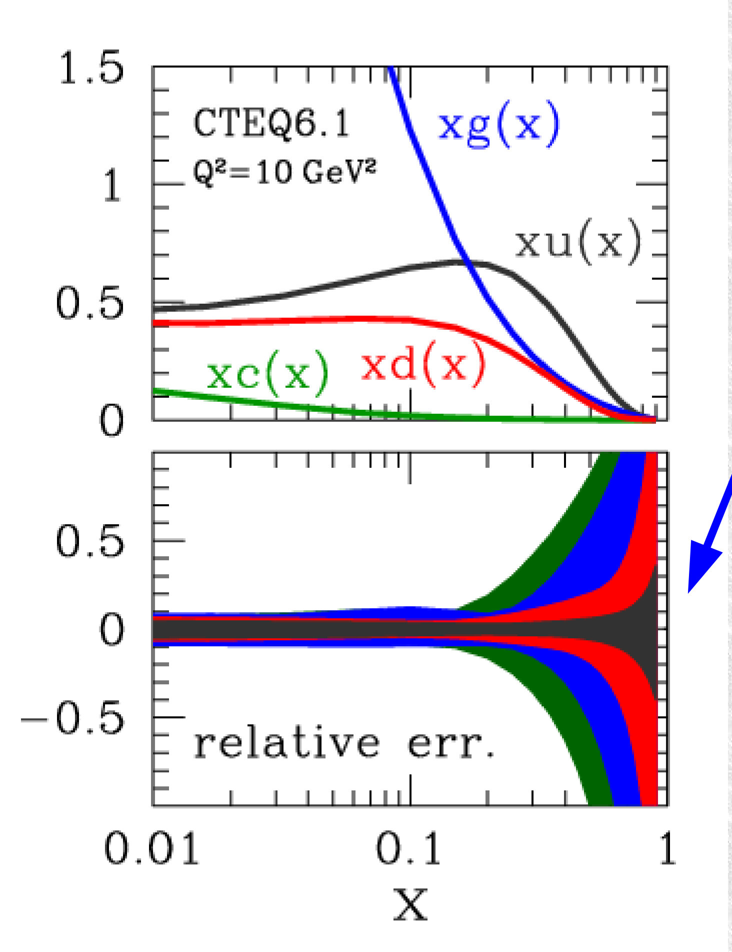
Why large x ?

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**

Why large x ?

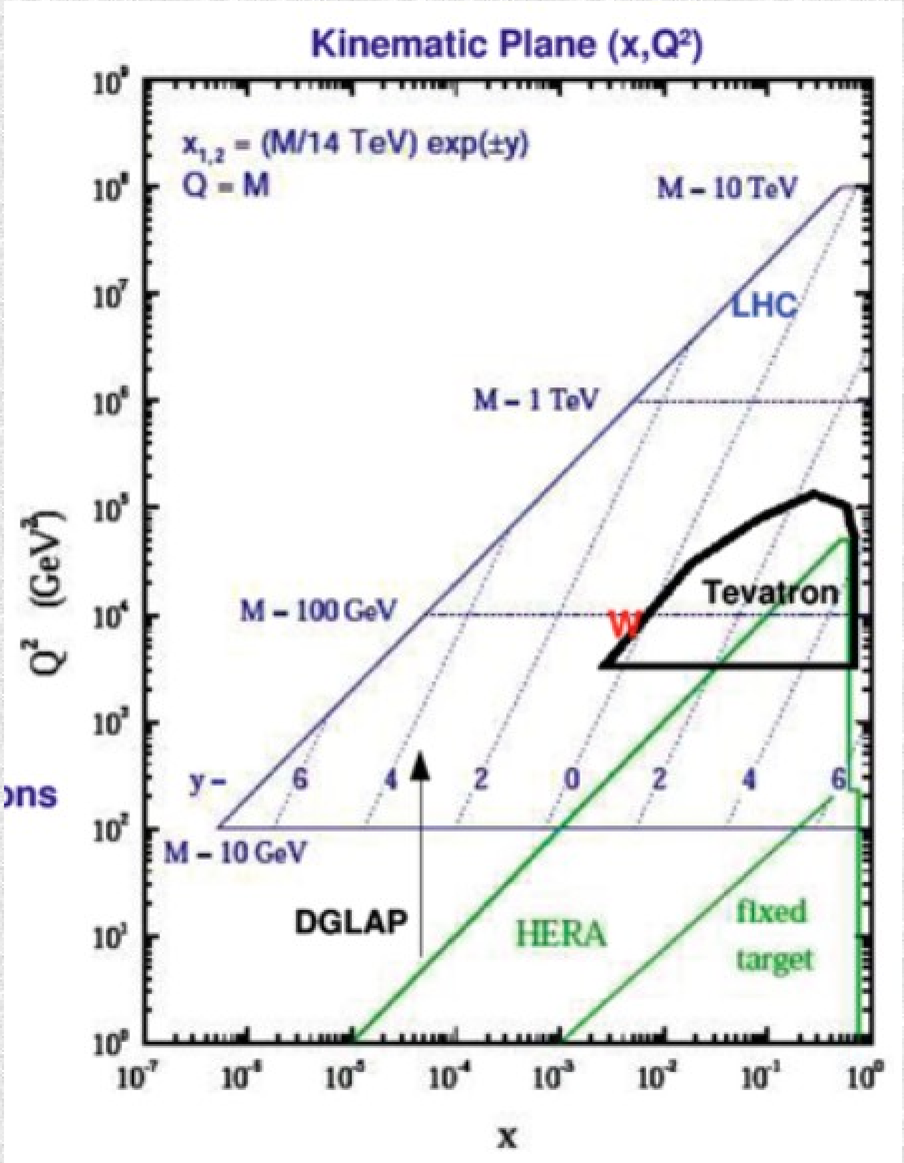
- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) QCD background in high-mass new physics searches
    2) Lumi monitoring at high mass (Z, W cross-section)
  - Example: Z' production

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

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

but recent work raises the bar:

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



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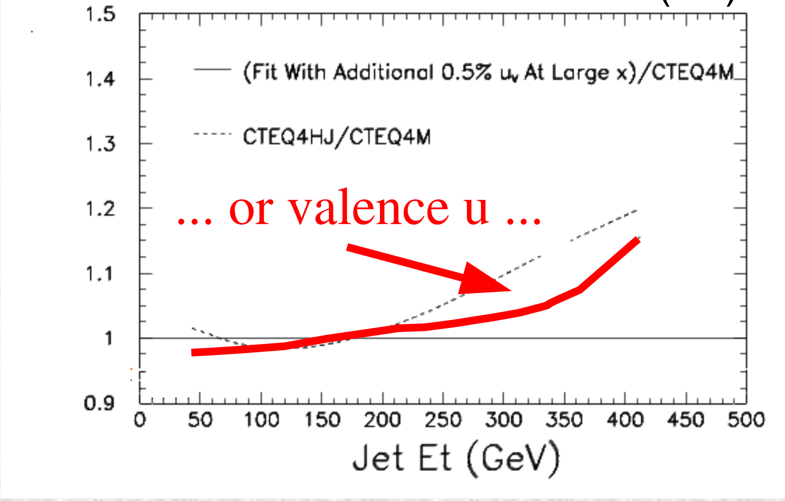
  - Example 2: 1996 CDF p_T excess

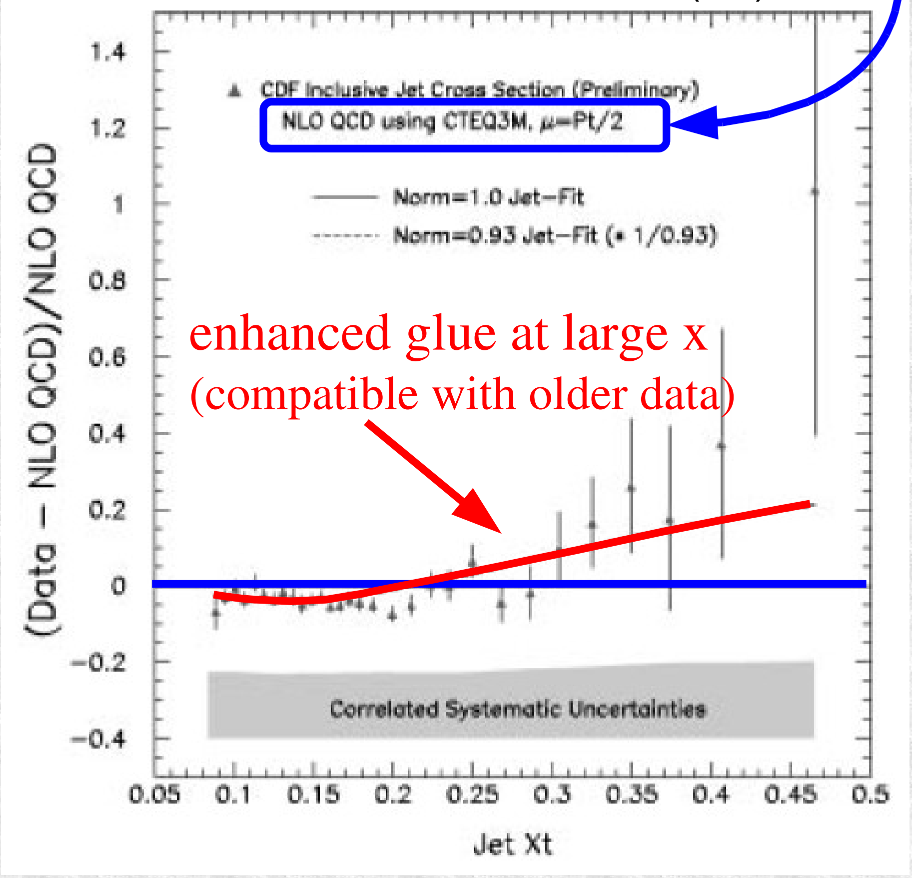
Kuhlmann et al. PLB409(97)



... 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 $x > 0.5$
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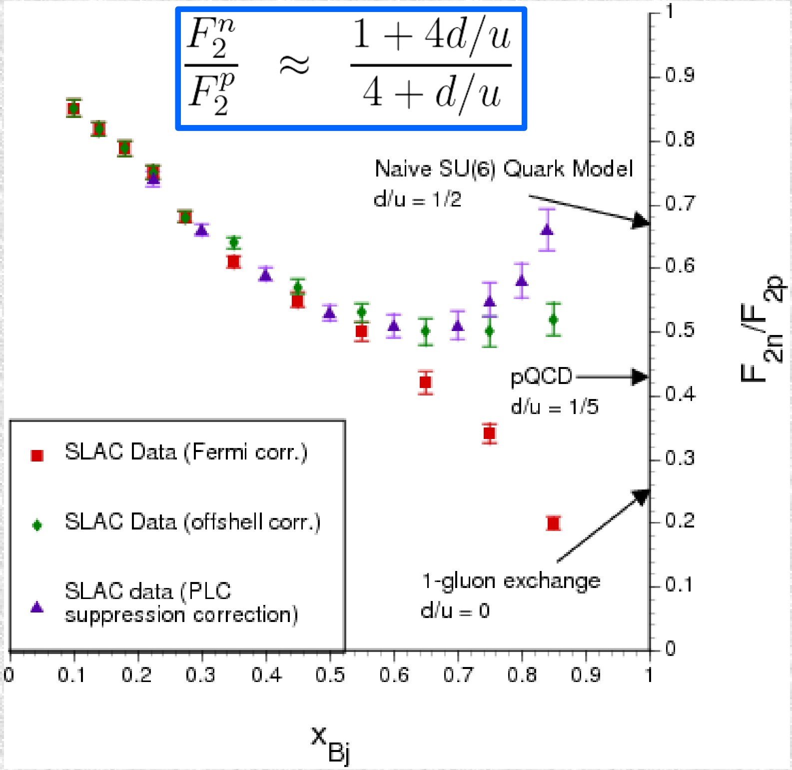
  - non-perturbative nucleon structure – e.g., d/u at $x \to 1$



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

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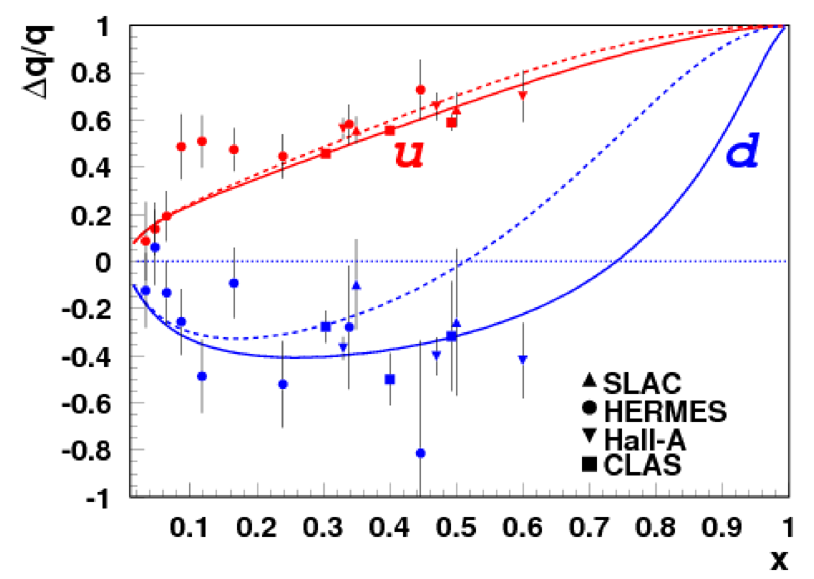

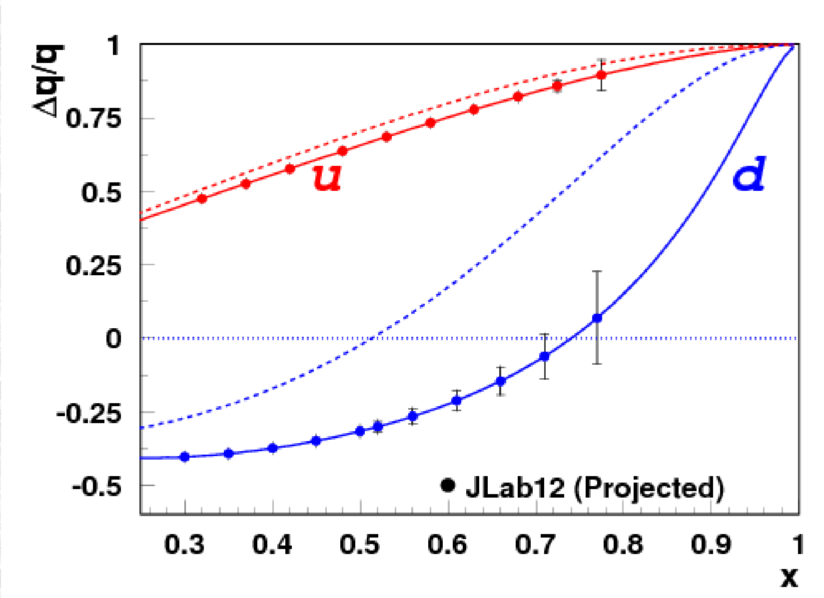

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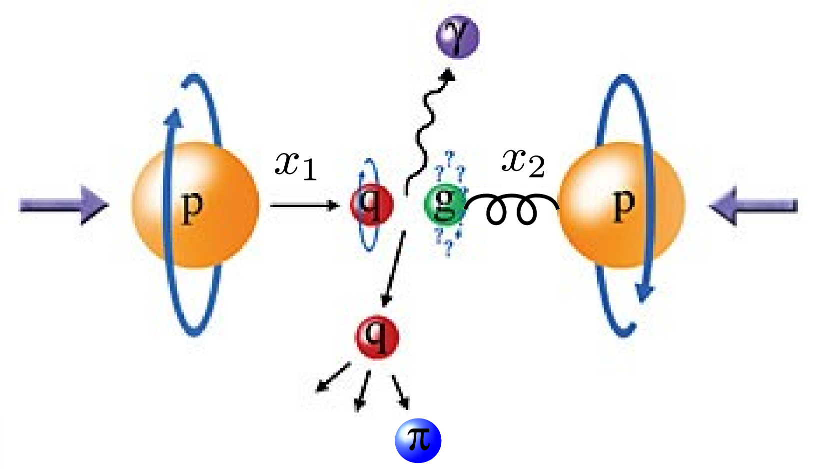
    2) Luminosity monitoring at high-mass – *Z*,*W* cross sections
  - non-perturbative nucleon structure
  - spin structure of the nucleon *at small x*

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



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

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

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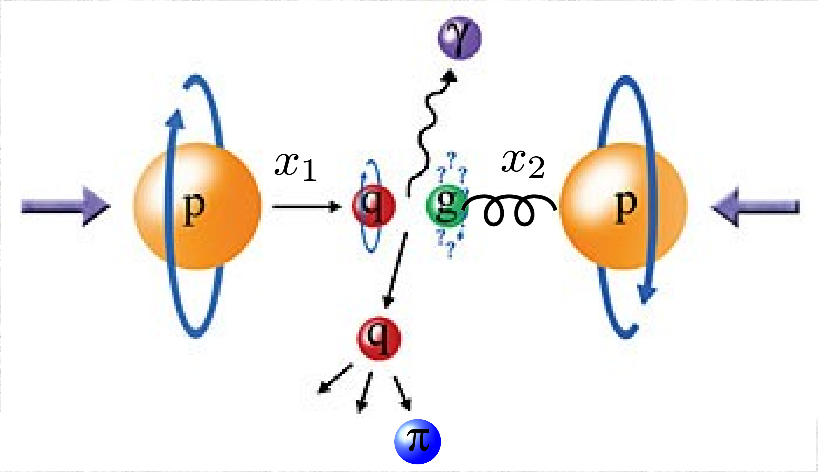

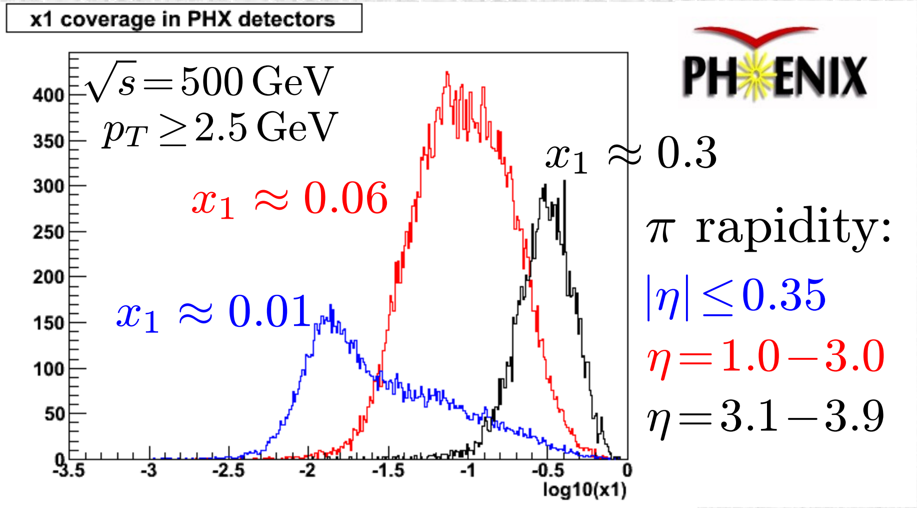

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    2) Luminosity monitoring at high-mass – Z, W cross sections
  - non-perturbative nucleon structure
  - spin structure of the nucleon *at small x*
  - neutrino oscillations

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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) heavy-quark mass corrections $\propto m_Q^2/Q^2$
4) nuclear corrections

this talk

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

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Up and down: the CTEQ6X fit

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

Phys. Rev. D 81, 034016 (2010)

Collaboration and goals

- **JLab / Fermilab/ Florida State U. collaboration**
  - A. Accardi, E. Christy, C. Keppel, W. Melnitchouk,
    P. Monaghan, S.Malace, J. Morfín, J. Owens

- Initial Goals:
  - Extend PDF global fits to larger values of x_B and lower values of Q
  - Wealth of data from older SLAC experiments and newer Jlab, DY
  - see if PDF errors can be reduced using new JLAB data

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CTEQ6X vs. CTEQ

- **CTEQ**

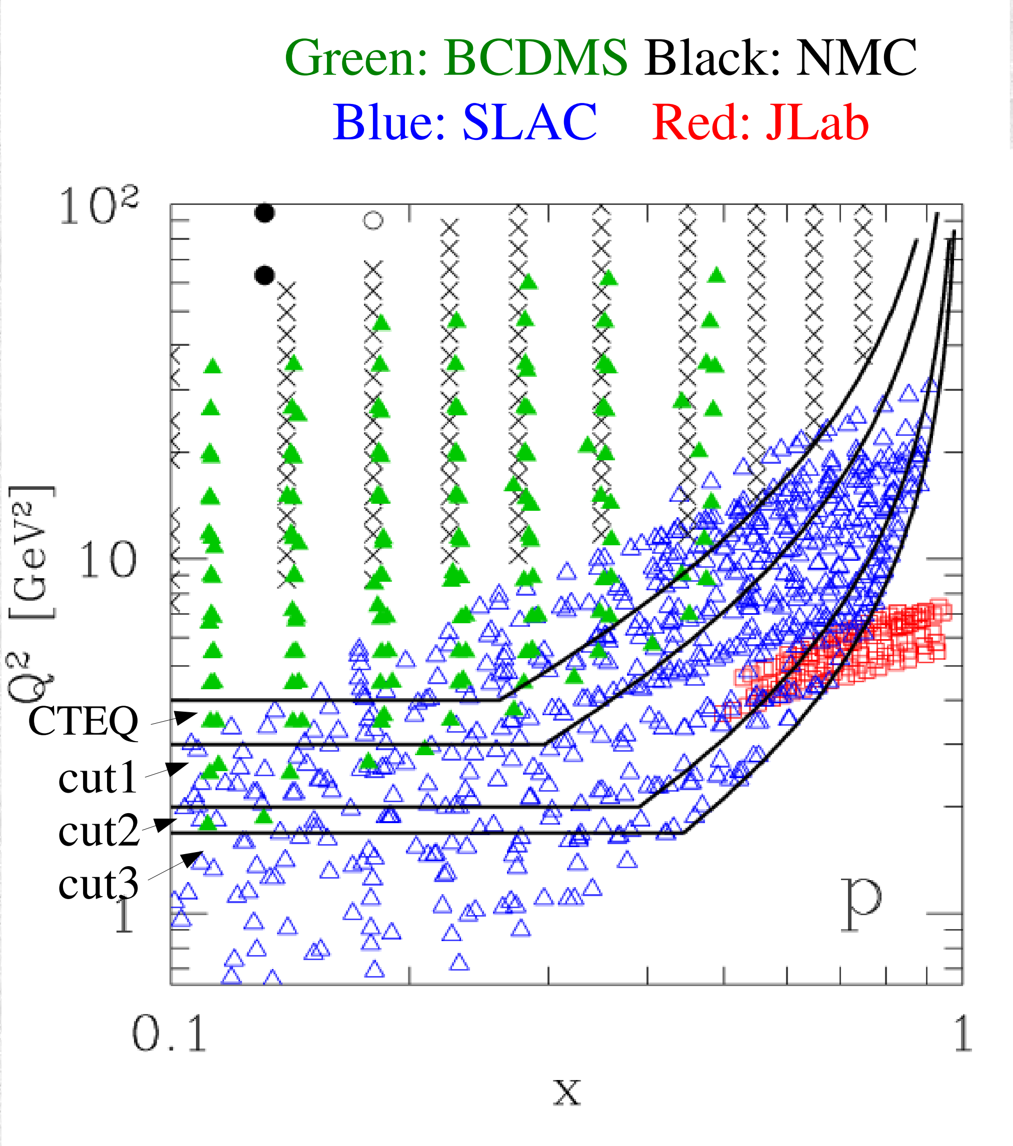
$$Q^2 \geq 4\ \mathrm{GeV}^2 \quad W^2 \geq 12.25\ \mathrm{GeV}^2$$

  - 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



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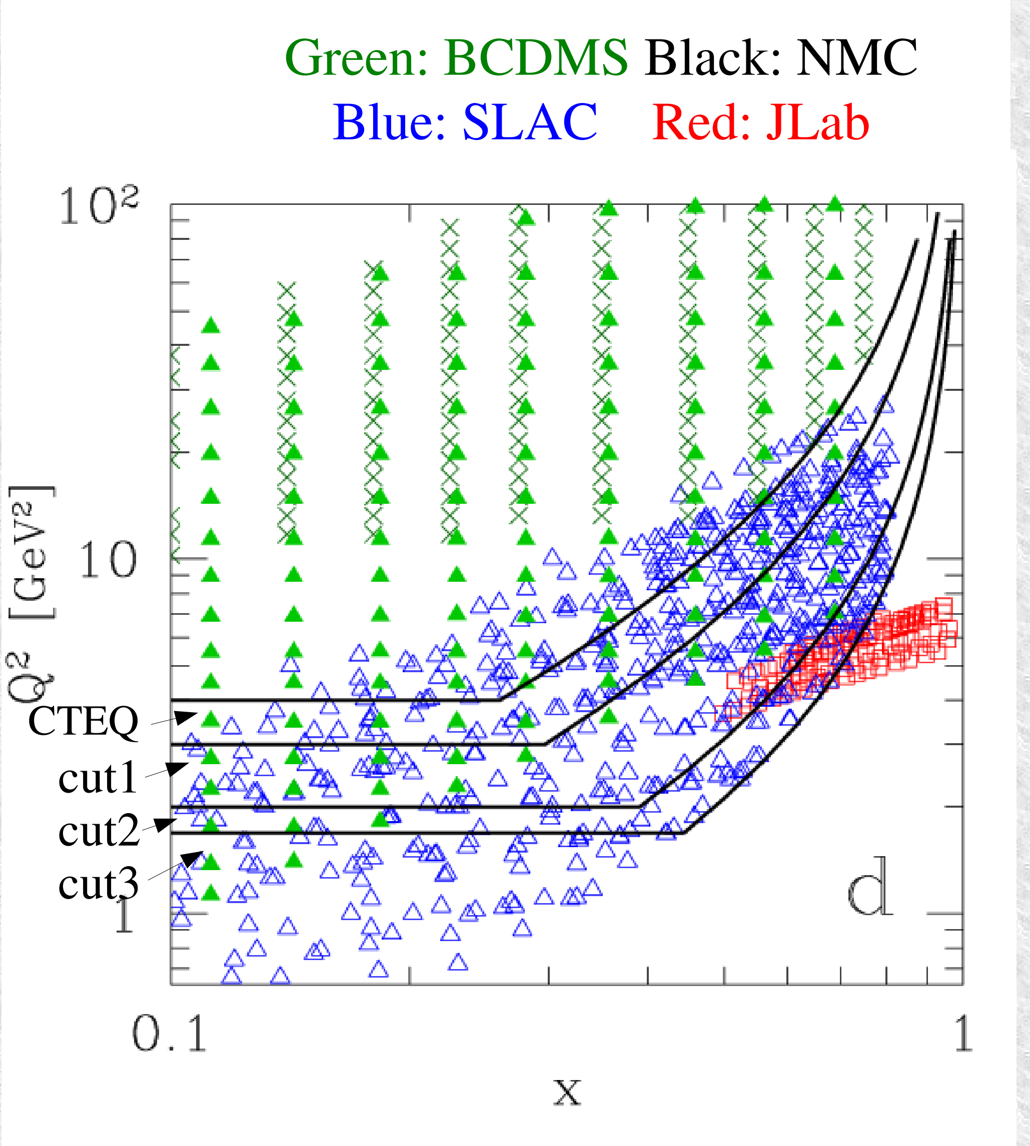

Target mass corrections

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

- **Standard Georgi-Politzer** (OPE)
  [Georgi, Politzer 1976; see review by Schienbein et al. 2007]
  [see also Leader, d'Alesio, Murgia, 2009]
  - 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-scaling**, uses CF with $x_{\max} = 1$ [Aivazis et al '94; Kretzer,Reno '02]

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

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

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"Higher-Twists" parametrization

- Parametrize by a multiplicative factor (same for *p* and *n*, for simplicity):

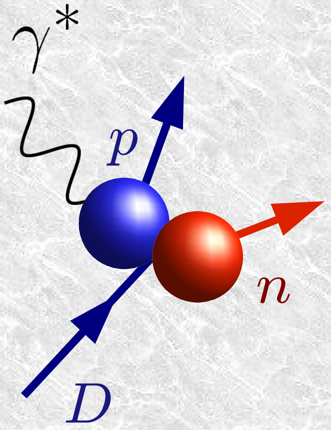
$$F_2(data) = F_2(TMC) \times \left(1 + \frac{C(x_B)}{Q^2}\right)$$

with

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

- **Important:** C(x_B) includes
  - dynamical higher-twists (parton correlations, e.g., $\langle p|\bar{\psi} D_A D_A \psi|p\rangle$)
  - all uncontrolled power corrections:
    - √ TMC model uncertainty, Jet Mass Corrections
    - √ NNLO corrections (power-like at small *Q*)
    - √ large-x resummation
    - √ ...

Deuterium corrections



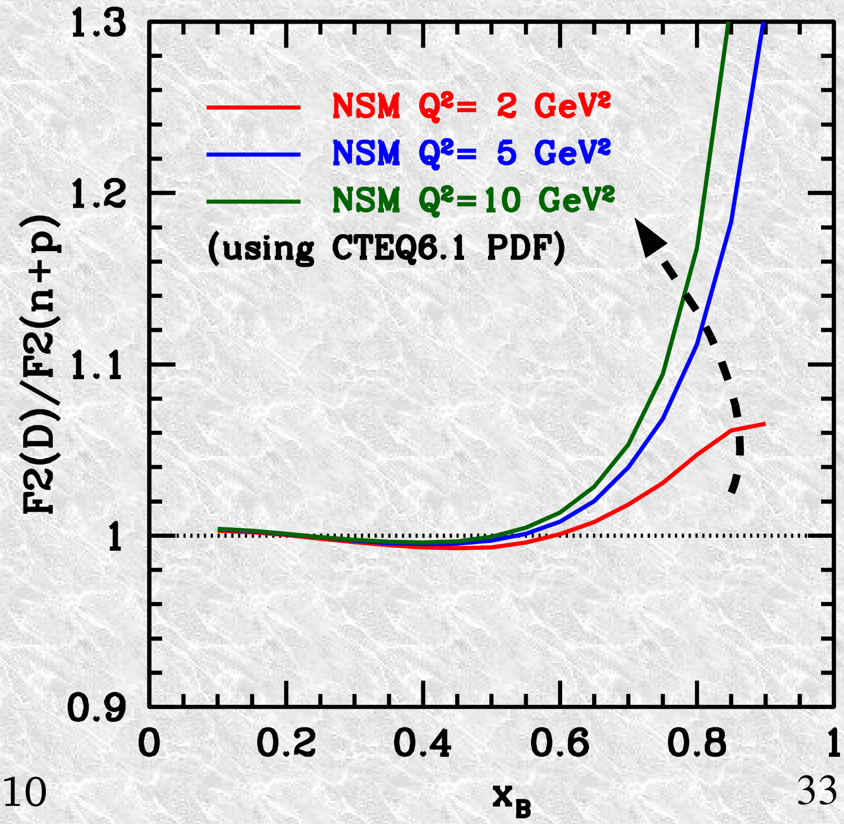
- Nuclear Smearing Model [Kahn et al., PRC79(2009)
 Accardi,Qiu,Vary, *in preparation*]
    - nucleon Fermi motion and binding energy
    - use non-relativistic deuteron wave-function
    - finite-Q^2 corrections

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

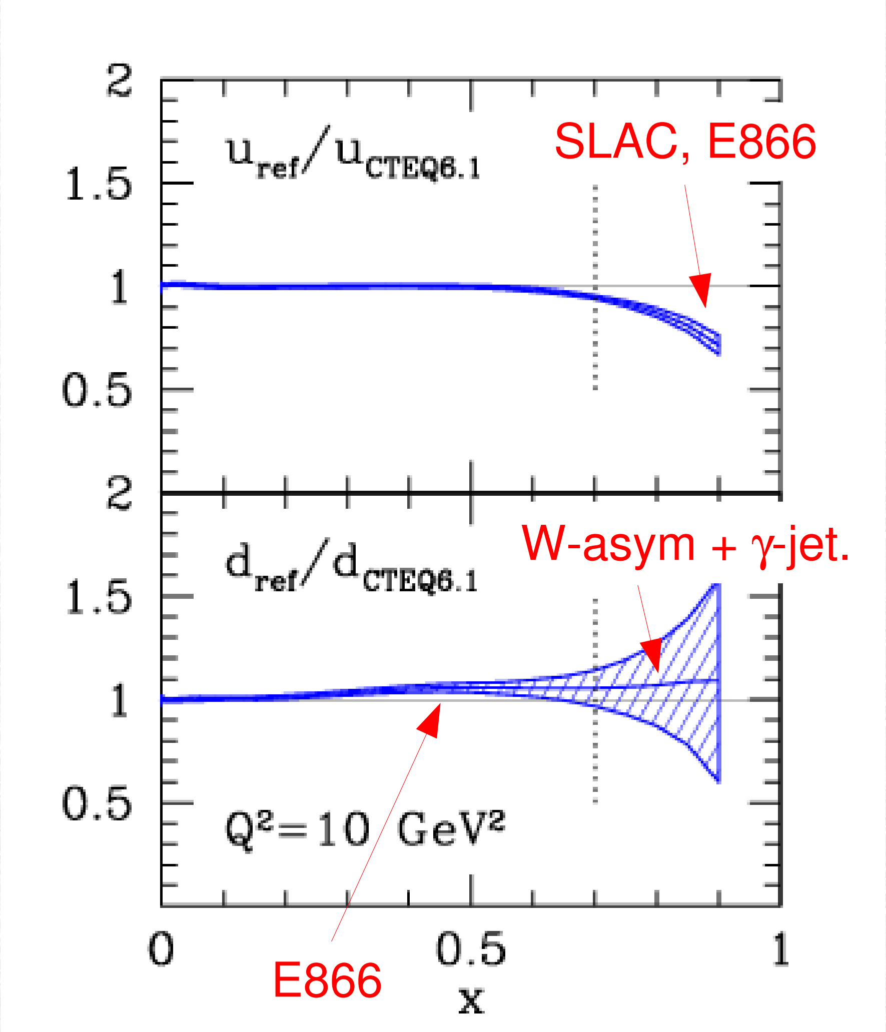
$$\gamma = \sqrt{1+4x_B^2 m_N^2/Q^2}$$

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

- off-shell effects can be included in S_A



Reference fit vs. CTEQ6.1



SLAC, E866

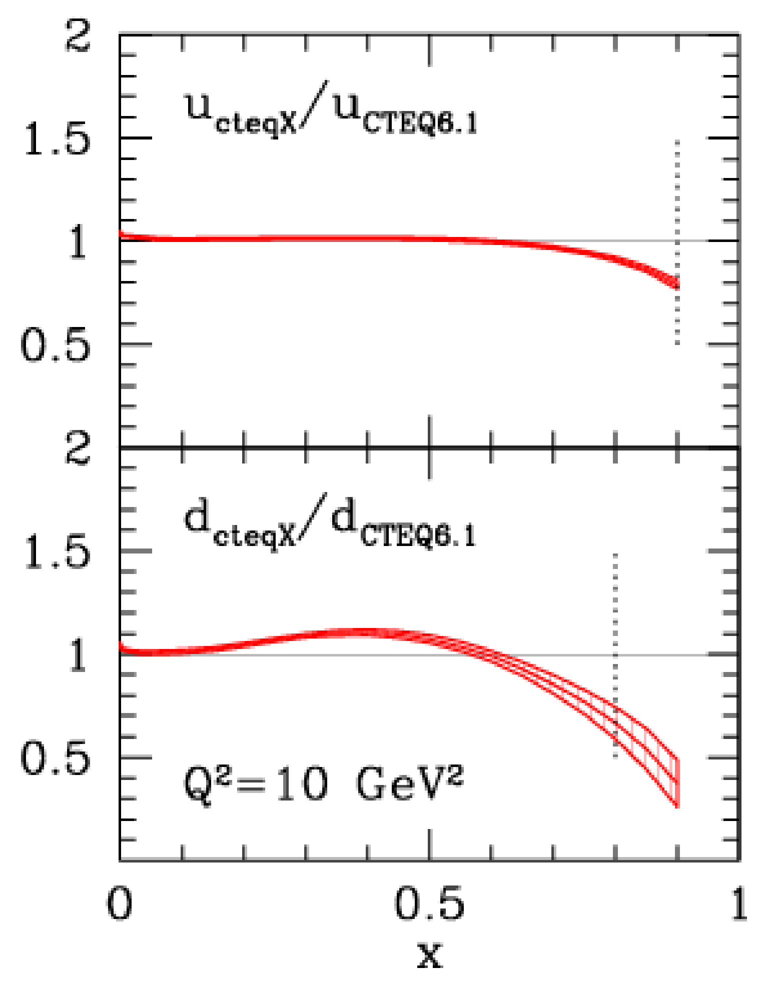
W-asym + γ-jet.

E866

- **Reference fit:**
  - cut0, no corrections
  - PDF errors with $\Delta\chi=1$

	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%

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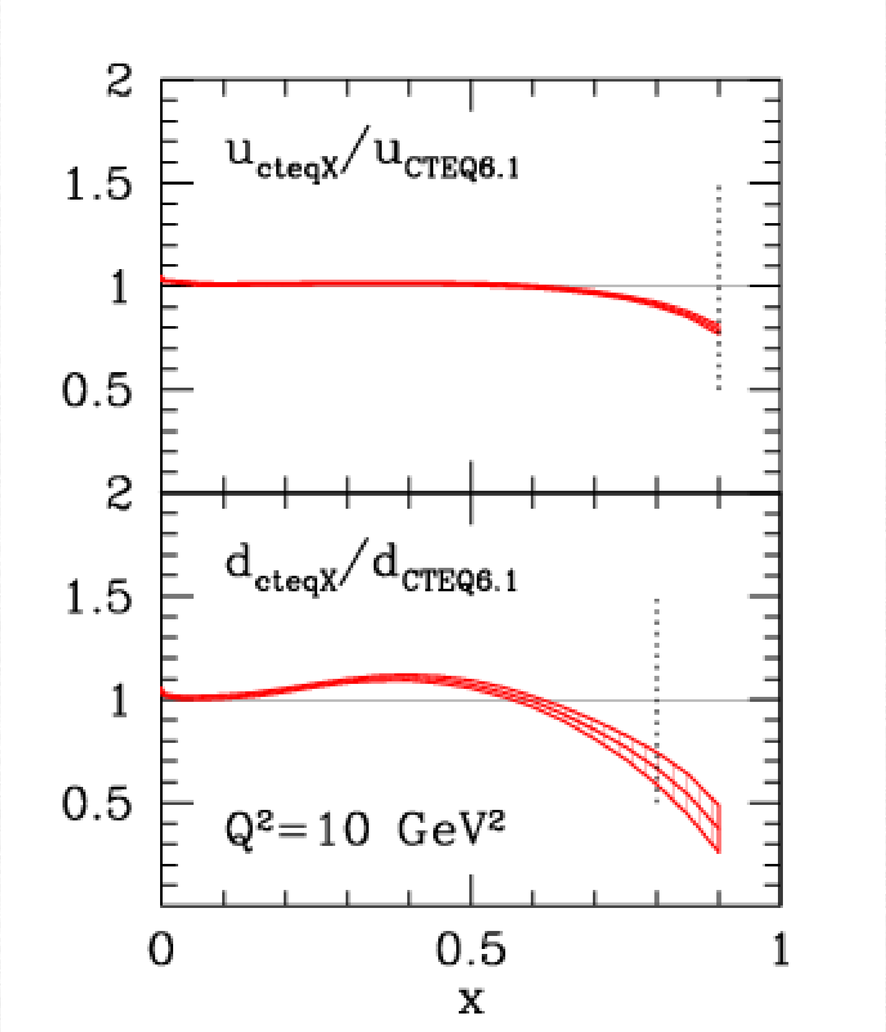
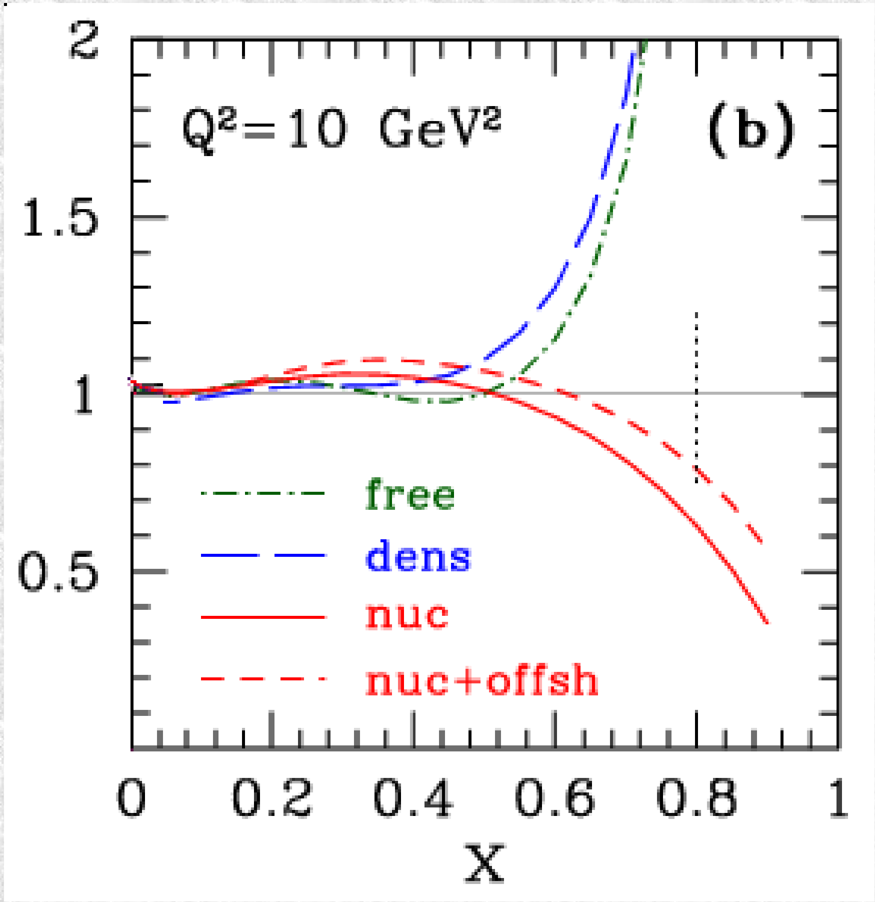
CTEQ6X vs CTEQ6.1



- **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%

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]

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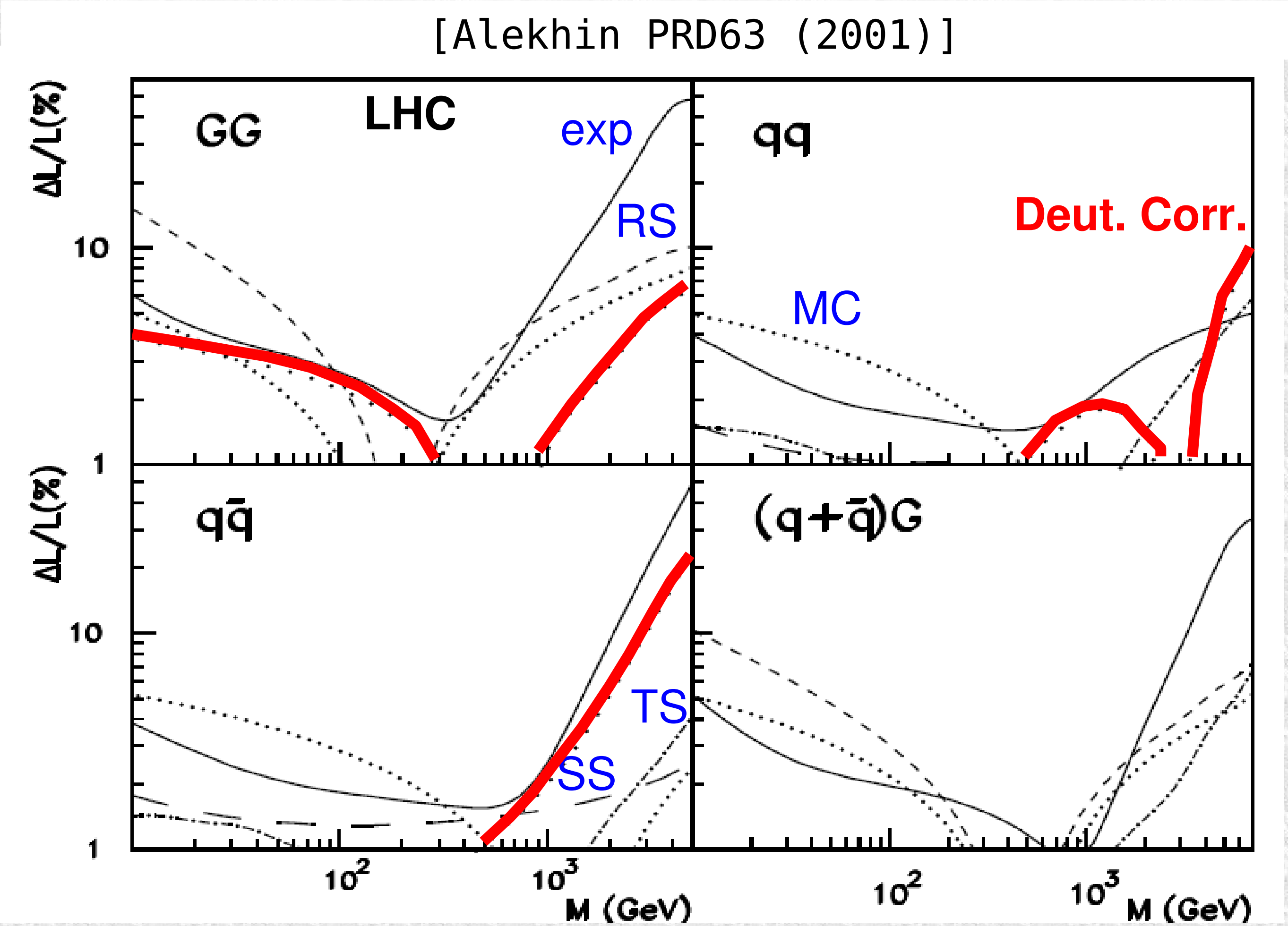
Impact on LHC

- 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-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 (maybe)
    - Use quasi-free nucleon targets
    - Use ratio of ^{3}He - ^{3}H mirror nuclei

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Free nucleon targets

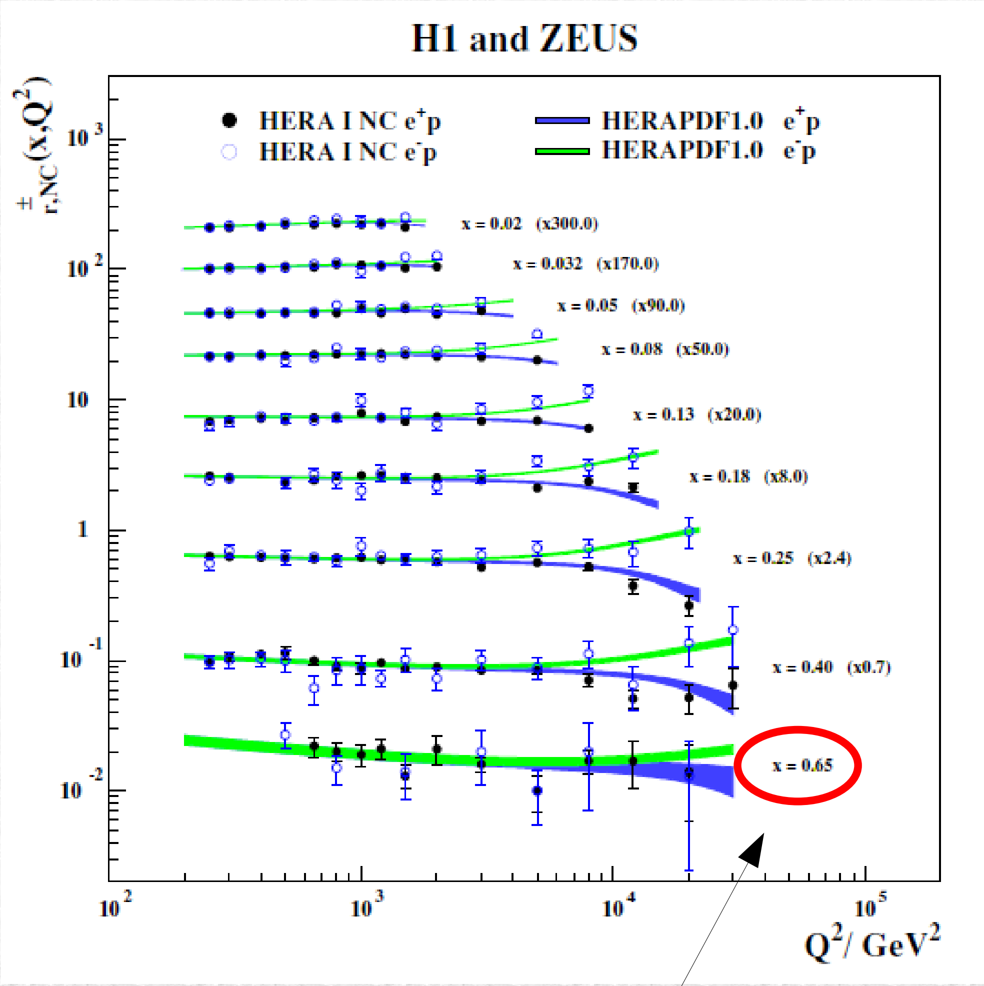
- Constraints on large-x d-quarks from
  - *p+p(bar)* : DY at large x_F $$p\,p(\bar p) \longrightarrow \mu^+\,\mu^-\,X$$
  - *p+p(bar)* : W-asymmetry at large rapidity $$p\,p(\bar p) \longrightarrow W^\pm\,X$$
    `[D0 and CDF]`
  - ν+*p* and ν-*bar*+*p* $$\nu(\bar\nu)\,p \longrightarrow l^\pm\,X$$
    - `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]`

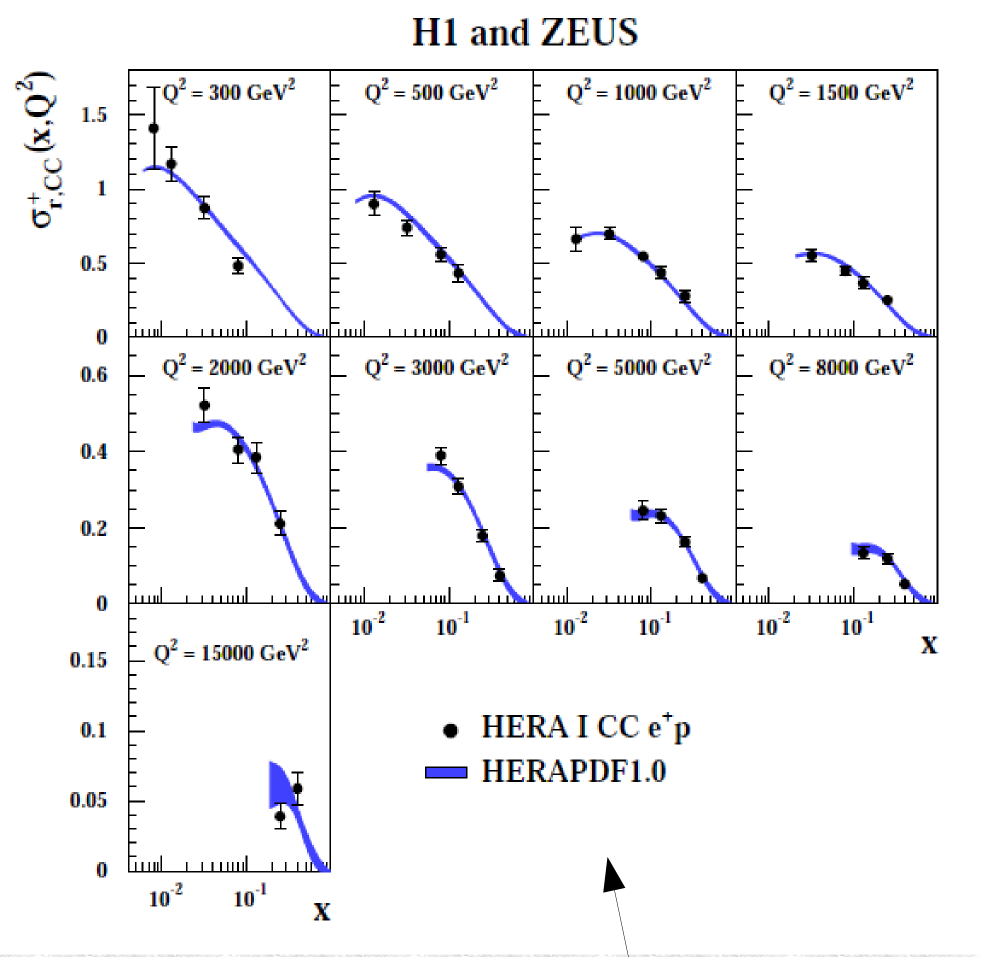
* `planned for Jlab at 12 GeV`

HERA combined data

[JHEP 1001,2010]

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



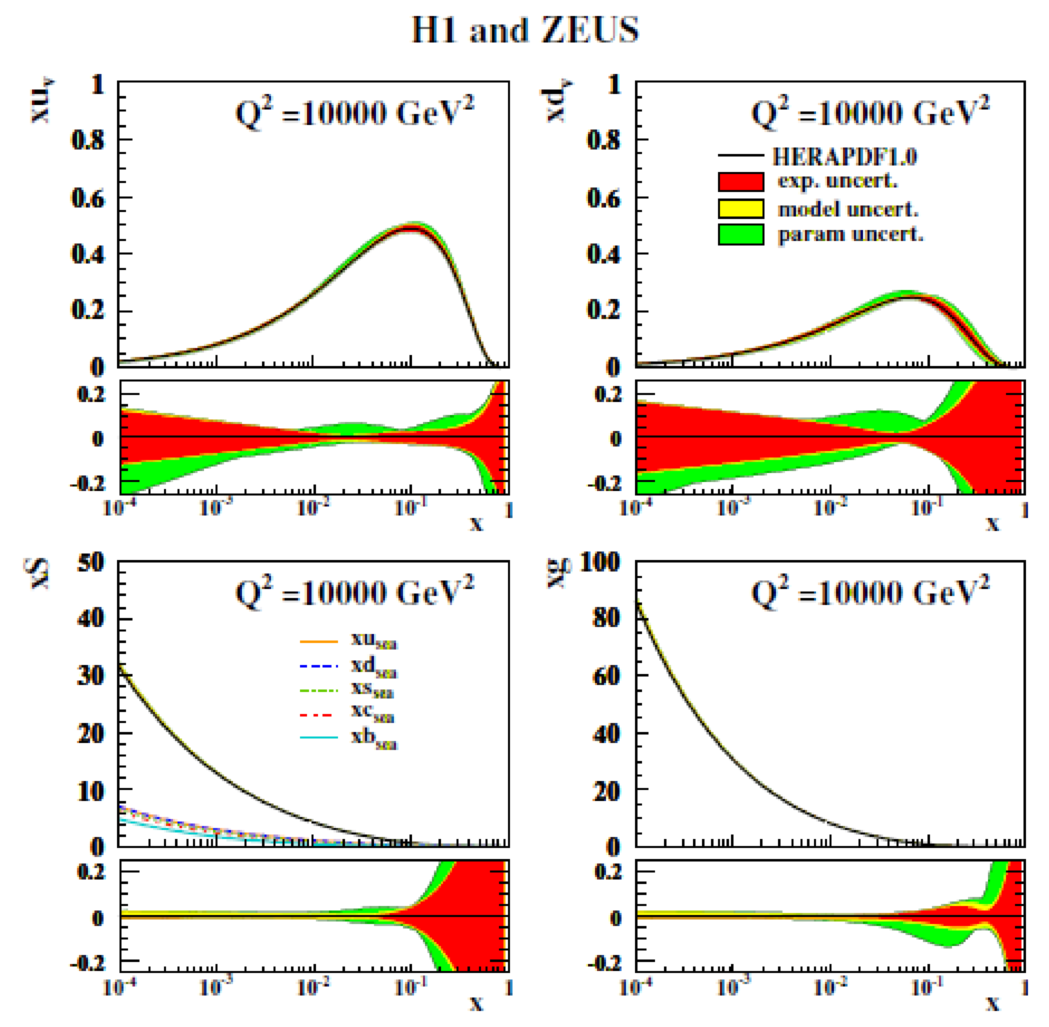


Reaches into the critical *x* range

Too limited *x* coverage

HERA combined data

[JHEP 1001,2010]

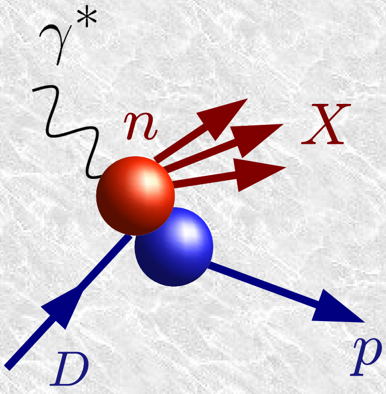


- These data alone insufficient for *d*-quark at large *x*
  - combine with deuterium data, cross check nuclear corrections

Constraining the nuclear corrections

- 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

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Gluons

Observables for gluons

- **Jets in *p*+*p* collision** – CT09
  - limited statistics
  - only very large Q^2, and smallish x

- $\boldsymbol{dF_2 / d(\ln Q^2)}$
  - indirect
  - limited leverage at large x, large errors

- **Longitudinal** $\boldsymbol{F_L}$
  - directly sensitive to gluons
  - so far not many data points
  - JLab / JLab12 will improve large-x coverage, but low Q^2

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F_L – HT and perturbative stability

- HT for F_L have little constraints from theory, some guidance from renormalon calculations
  - Perturbatively unclear at large x
  - When fitted, large at NLO, decrease at NNLO

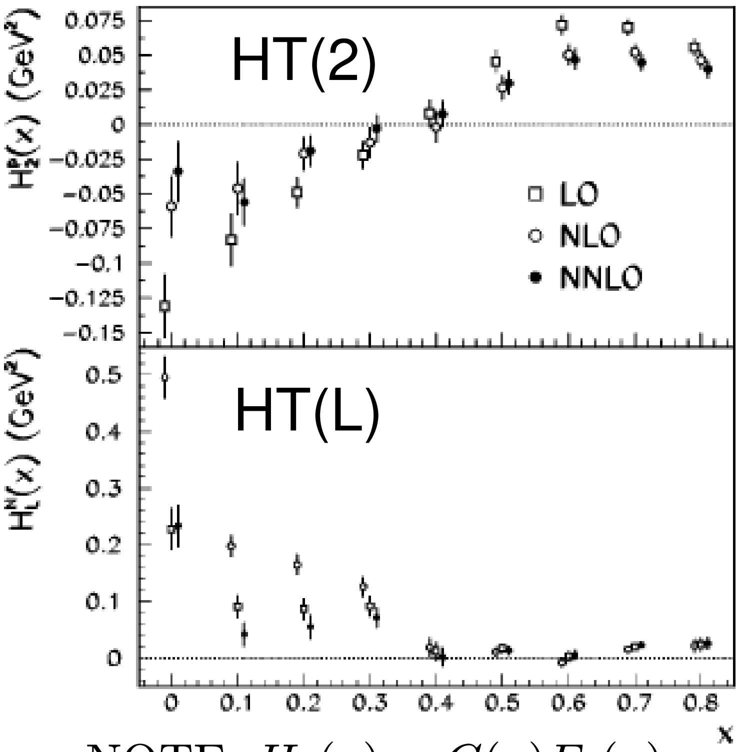
- *“The high x and low Q^2 domain is 'dangerous'. This is another reason, along with target mass, to avoid fitting data in this region”*

  [Martin, Stirling, Thorne, PLB635(06)]

- Should we dare more?

  [see e.g., Alekhin et al., arXiv:0710.0124]

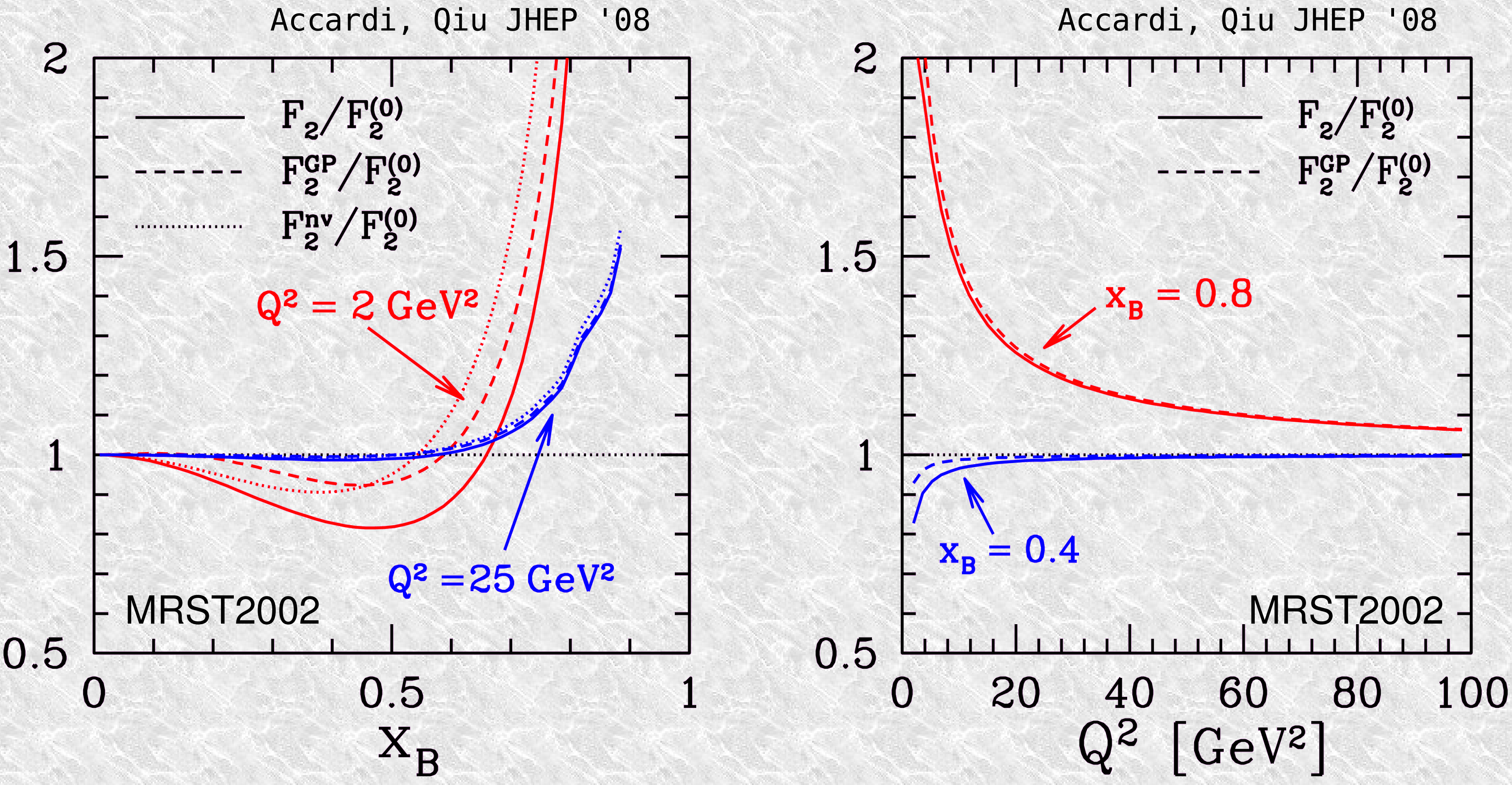
Alekhin, PHYSICAL REVIEW D **68**, 014002 (2003)



NOTE: $H_2(x) = C(x)F_2(x)$

Target Mass Corrections

- Difference between Coll. Fact. [Accardi,Qiu] and OPE [Georgi,Politzer] for F_2
  - different slope in Q^2 ⇒ **different gluons from $dF_2/d(\ln Q^2)$!**



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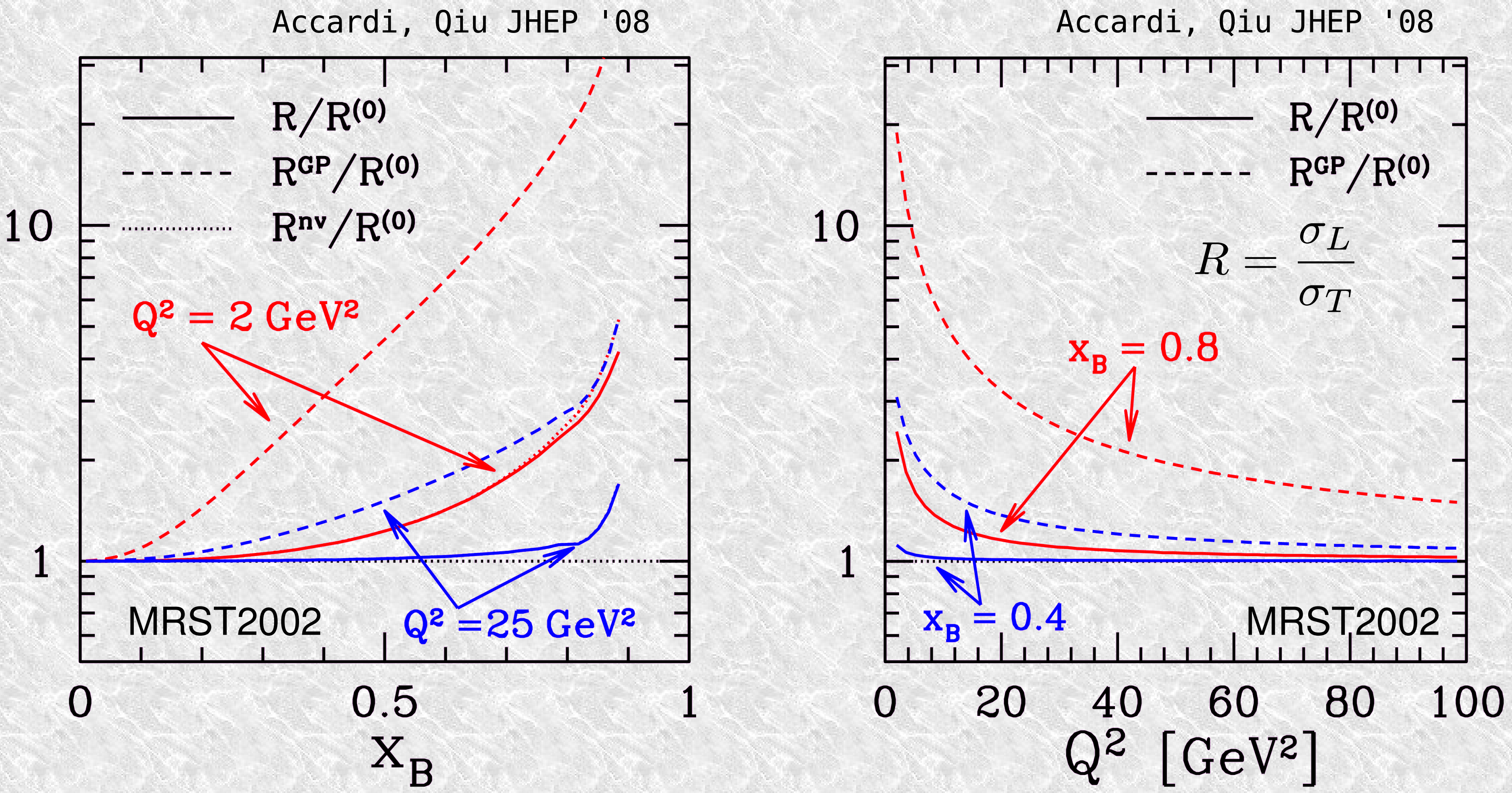
Target Mass Corrections

- **Very different F_L correction**
  - Can the differences be absorbed in HT terms ?
  - **Play F_L and F_2 off each other ⇒ can differentiate TMC method ??**



Intrinsic charm

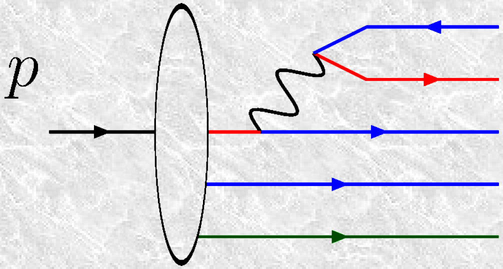
Intrinsic vs. radiative charm

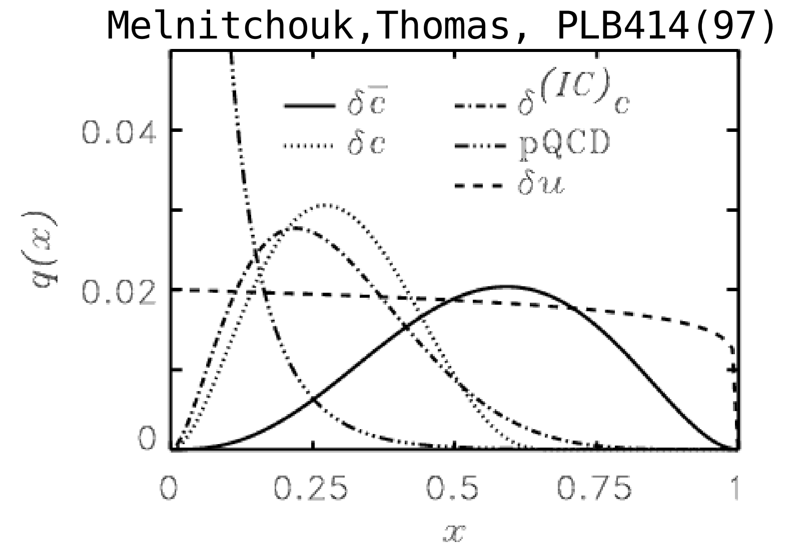
- Usual assumption in global fits: at threshold

Pumplin, PRD73(06),
Brodky et al., PRD73(06)
+ references teherein

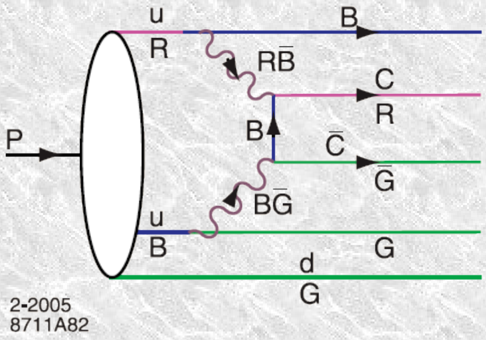
$$c(x, Q_c \approx m_c) = 0$$

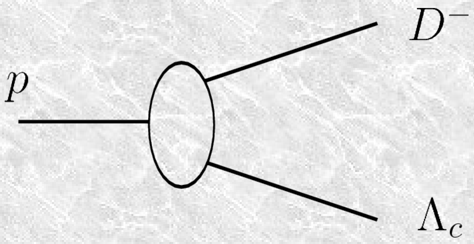
  - charm generated during DGLAP evolution




Melnitchouk,Thomas, PLB414(97)

- but QCD predicts intrinsic charm

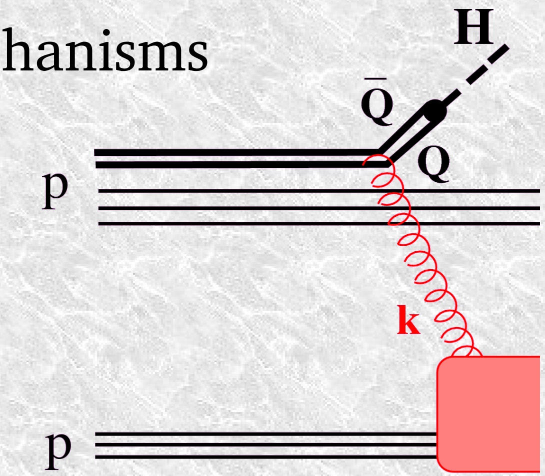




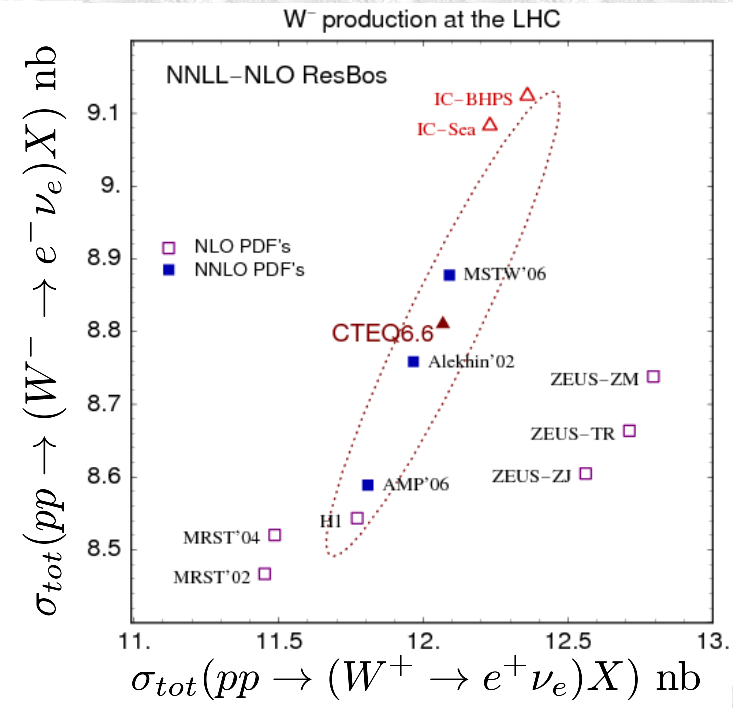
  - a c-cbar pair fluctuation already exists, peaked at large x~0.4
  - fully participates in DGLAP evolution
  - *c, cbar* asymmetry: small @ NLO (pQCD) or large (nonpert. models)

Phenomenological implications

- SM and beyond at **Tevatron and LHC**
  - Higgs and single top production sensitive to heavy quarks
  - Novel Higgs production mechanisms at large $x_F \approx 0.7$-0.9
    `[Brodsky et al. PRD73(06), NPB907(09)]`



  - W production



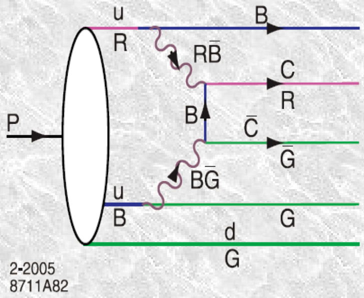
`[Nadolsky et al. PRD78(08)]`

Indications from global fits

[Pumplin, Lai, Tung, PRD75(07)]

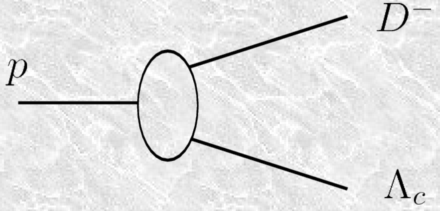
- 3 models at $\mu = m_c$
  [see Pumplin PRD 73(06) for review of models]

1) Brodsky-Hoyer-Peterson-Sakai [PLB 93 (80)]



$$\begin{aligned} c(x) &= \bar{c}(x) \\ &= A\,x^2\left[6x(1+x)\ln x + (1-x)(1+10x+x^2)\right] \end{aligned}$$

2) meson-cloud model
[Navarra et al '96, '98;
Melnitchouk,Steffens,Thomas '97,'99]



$$c(x) = Ax^{1.897}(1-x)^{6.095}$$
$$\bar{c}(x) = \bar{A}x^{2.511}(1-x)^{4.929}$$

3) phenomenological "sea-like"

$$c(x) = \bar{c}(x) \propto \bar{d}(x) + \bar{u}(x)$$

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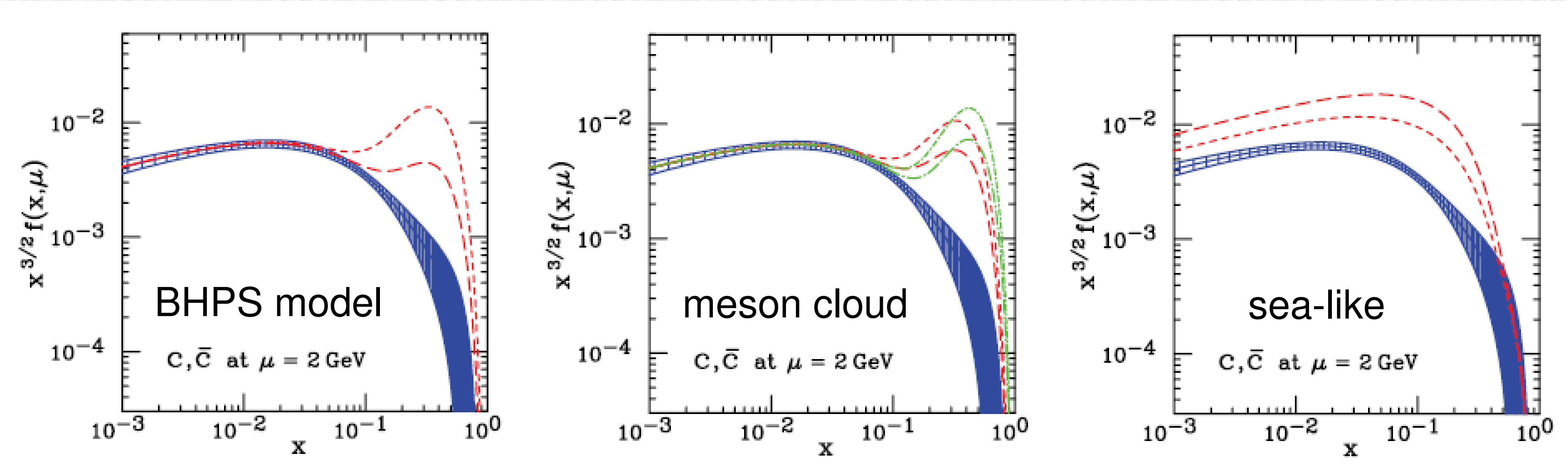
Indications from global fits

[Pumplin, Lai, Tung, PRD75(07)]

- All models allow **IC = 0-3% intrinsic charm**
  - Evolution redistributes IC to lower *x*, but large-*x* peak persists
  - sea-like spread out over *x*

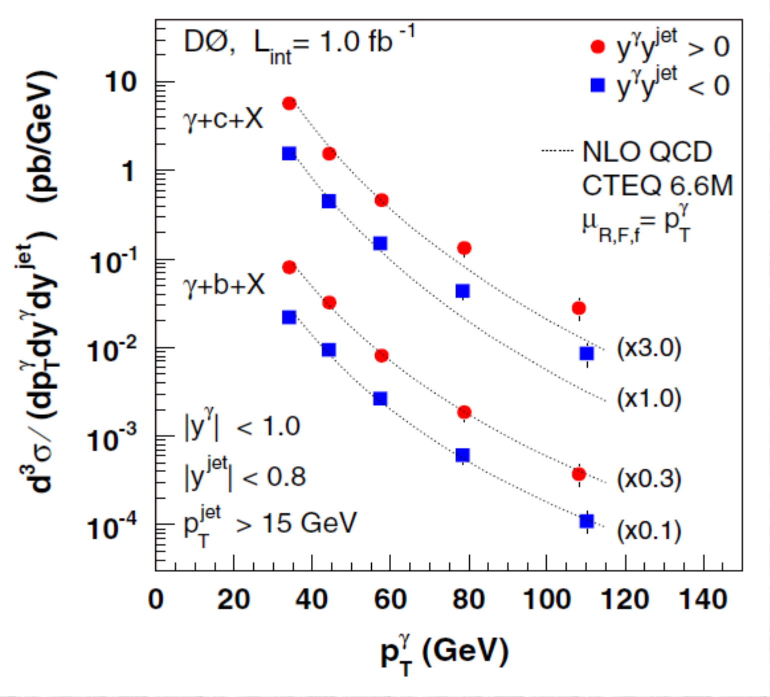


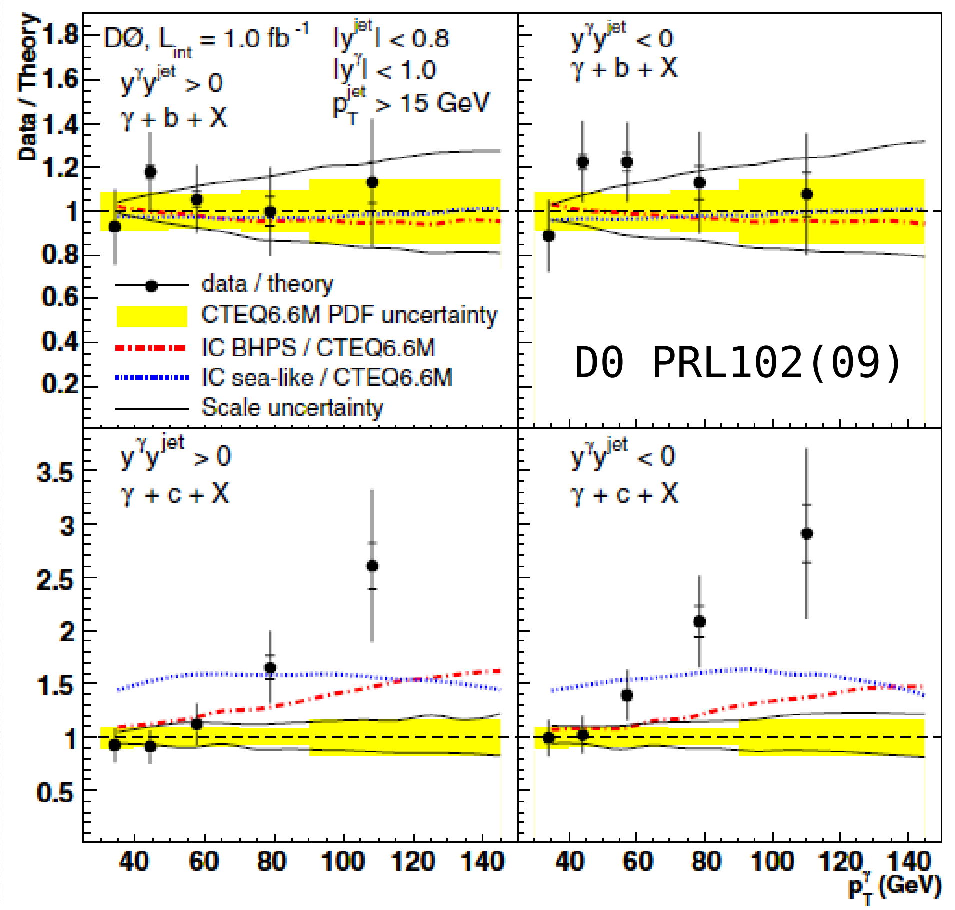
Experimental evidence - D0

- D0 measured excess of γ+charm jets compared CTEQ6.6 `[D0, PRL102(09)]`

$$g + Q \to \gamma/Z + Q$$

$$q + \bar{q} \to \gamma/Z + g \to \gamma/Z + Q\bar{Q}$$





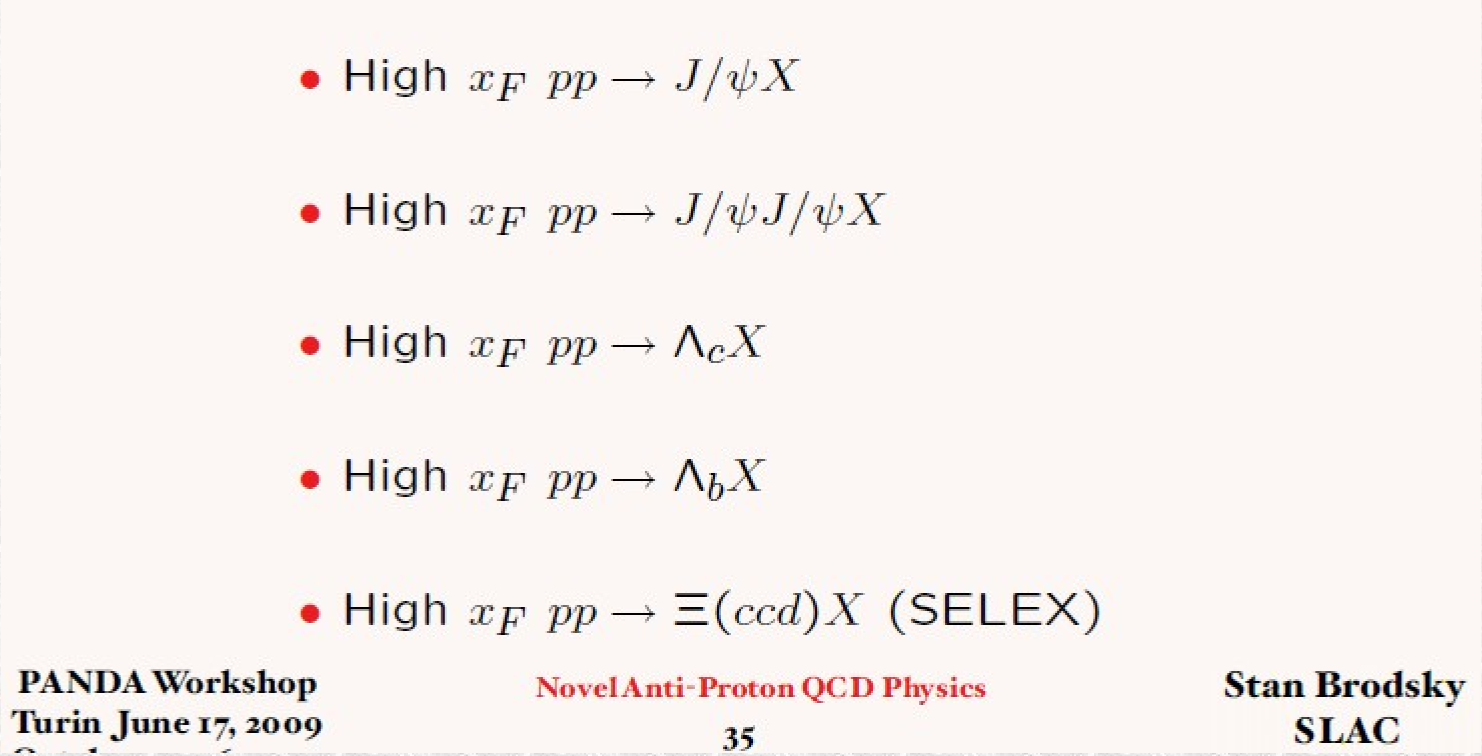
$0.01<x<0.3$ and $10^3<Q^2<10^4$

- Difference due to
  - intrinsic charm?
  - underestimate of $g \to c\bar{c}$?

How to measure – hadronic collisions

- **γ/Z + charm jet**
  - sensitive to $g + Q \to \gamma/Z + Q$ and $q + \bar{q} \to \gamma/Z + g \to \gamma/Z + Q\bar{Q}$
  - $y_\gamma y_{jet} > 0$ and $y_\gamma y_{jet} < 0$ sensitive to different x_1, x_2
  - allows constraints on Q, Qbar, and gluons
  - angular dependence to distinguish above sub-processes

- Also,



- High x_F $pp \to J/\psi X$
- High x_F $pp \to J/\psi J/\psi X$
- High x_F $pp \to \Lambda_c X$
- High x_F $pp \to \Lambda_b X$
- High x_F $pp \to \Xi(ccd)X$ (SELEX)

PANDA Workshop
Turin June 17, 2009

Novel Anti-Proton QCD Physics

35

Stan Brodsky
SLAC

How to measure – DIS

- **HERA charm and bottom events**
  - already included in the fits
  - most data at small *x*, where $\gamma\, g \to c\bar{c}$ dominates over $\gamma\, c \to c\, X$
  - **needs larger *x***

- **JLab 6/12**
  - Ideally placed across the charm threshold
  - D+ vs. D- sensitive to c/cbar asymetry

- **EIC (LHeC ??)**
  - jet measurements are possible
  - larger Q^2 range than Jlab, larger *x* than HERA

Target and heavy-quark mass corrections

- DIS in collinear factorization: `[Accardi, Qiu JHEP '08]`
  - currently being revisited

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

f parton mass

Nachtmann variable

$$\xi_f = \xi \left[1 - \frac{\xi^2}{x^2}\frac{m_f^2}{Q^2}\right]^{-1} \xrightarrow{m_f \to 0} \xi \xrightarrow{M_N \to 0} x_B$$

$$x_f^{min} = \xi \frac{Q^2 + (c-1)m_f^2 + \Delta[m_f^2, -Q^2, c m_f^2]}{2Q^2} \xrightarrow{m_f \to 0} \xi \xrightarrow{M_N \to 0} x_B$$

$$x_f^{max} = \xi \frac{Q^2/x_B + 3m_f^2 + \Delta[m_f^2, -Q^2, Q^2(1/x_B - 1)]}{2Q^2} \xrightarrow{m_f \to 0} \xi/x_B \xrightarrow{M_N \to 0} 1$$

$$\Delta[a, b, c] = \sqrt{a^2 + b^2 + c^2 - 2(ab + bc + ca)} \qquad \xi = 2x_B/\left(1 + \sqrt{1 + 4x_B^2 M_N^2/Q^2}\right)$$

Outlook:
the Electron-Ion Collider

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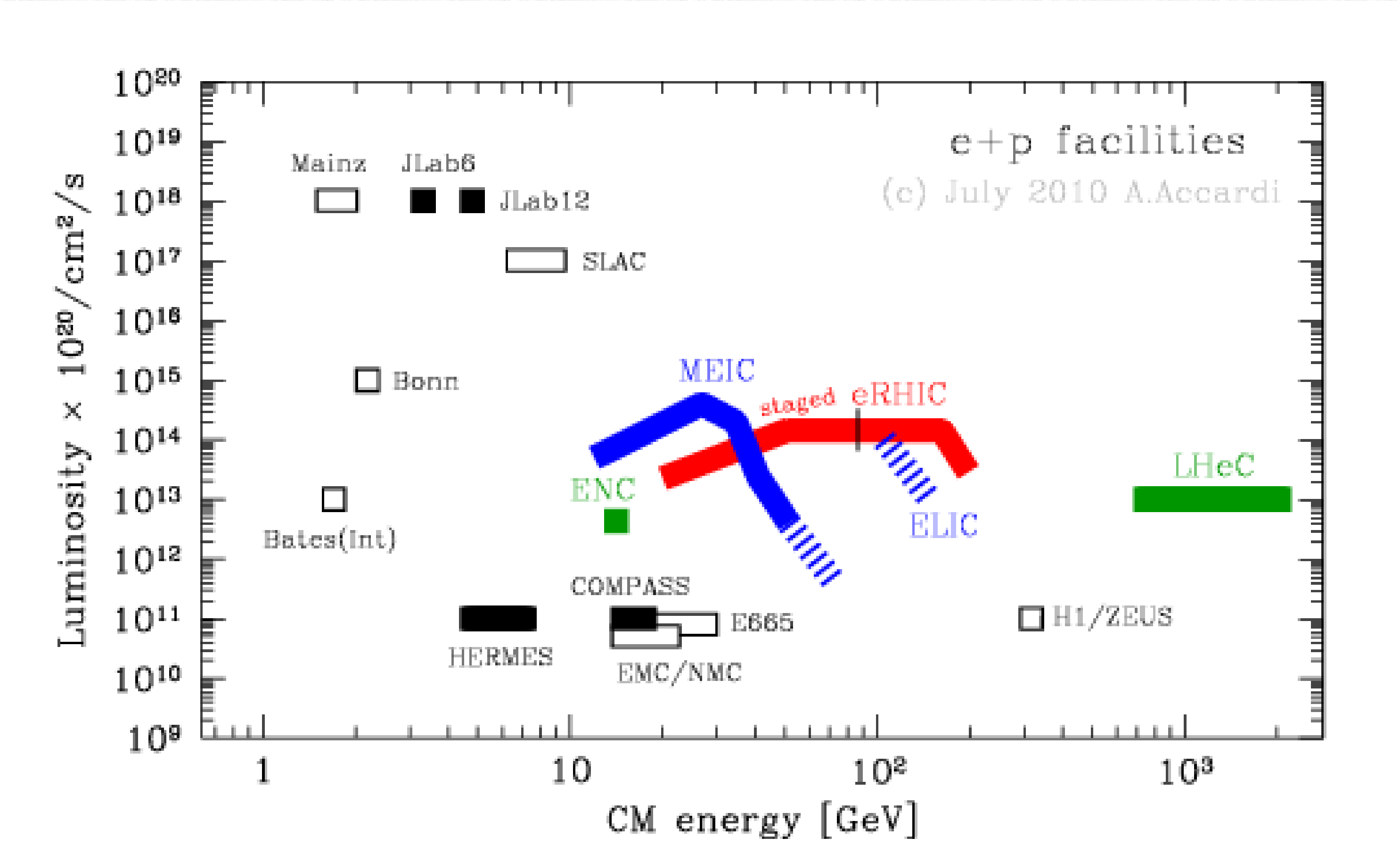
The EIC for dummies

- Future US-based e+p (e+A) collider – 2 designs:
  - *BNL – eRHIC:* E_e=5-30 GeV E_p=250 GeV $\mathfrak{L}\sim10^{34}$ cm^{-2}/s^{-1}
  - *Jlab – MEIC:* E_e=3-11 GeV E_p=60 GeV $\mathfrak{L}\sim10^{34}$ cm^{-2}/s^{-1}



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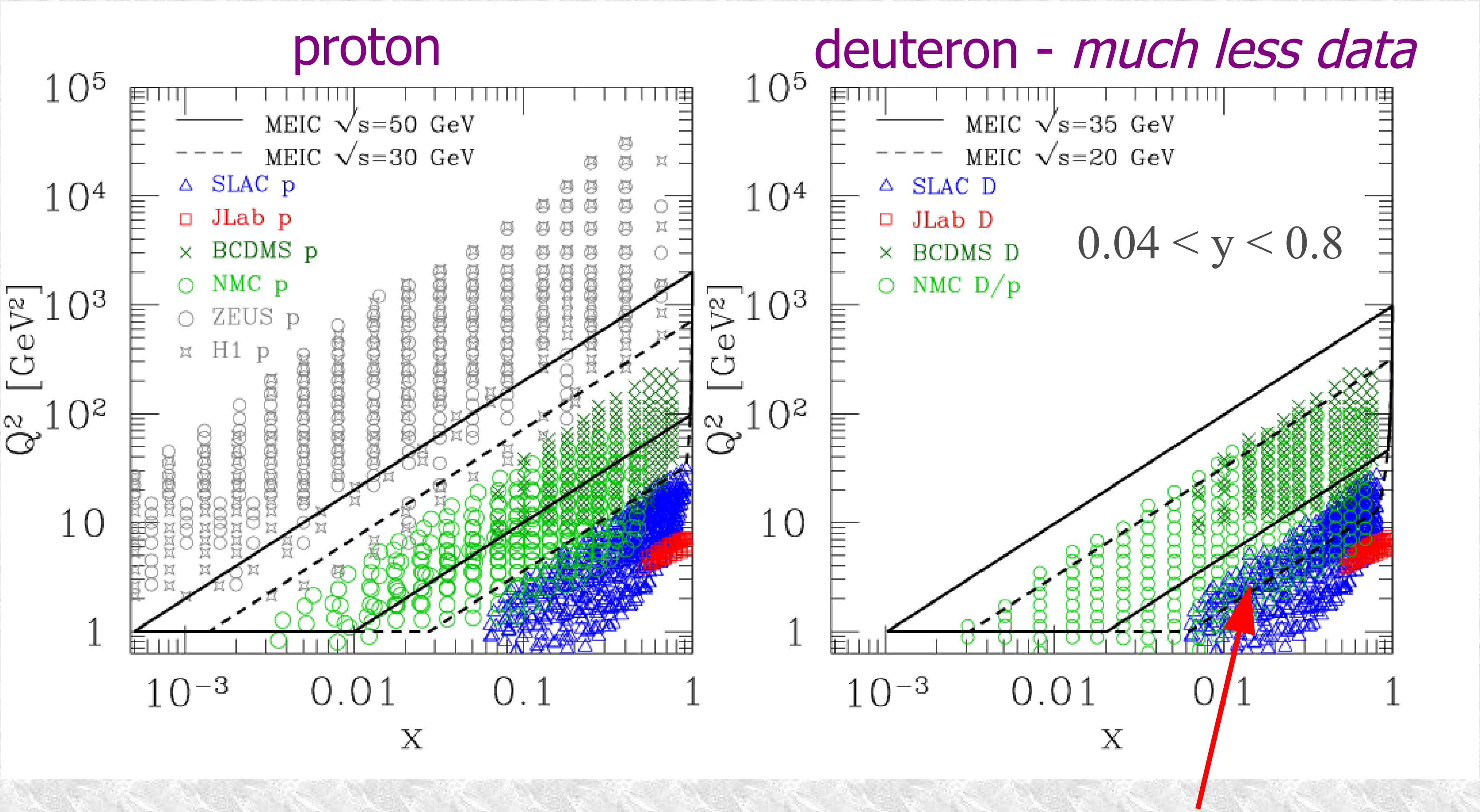
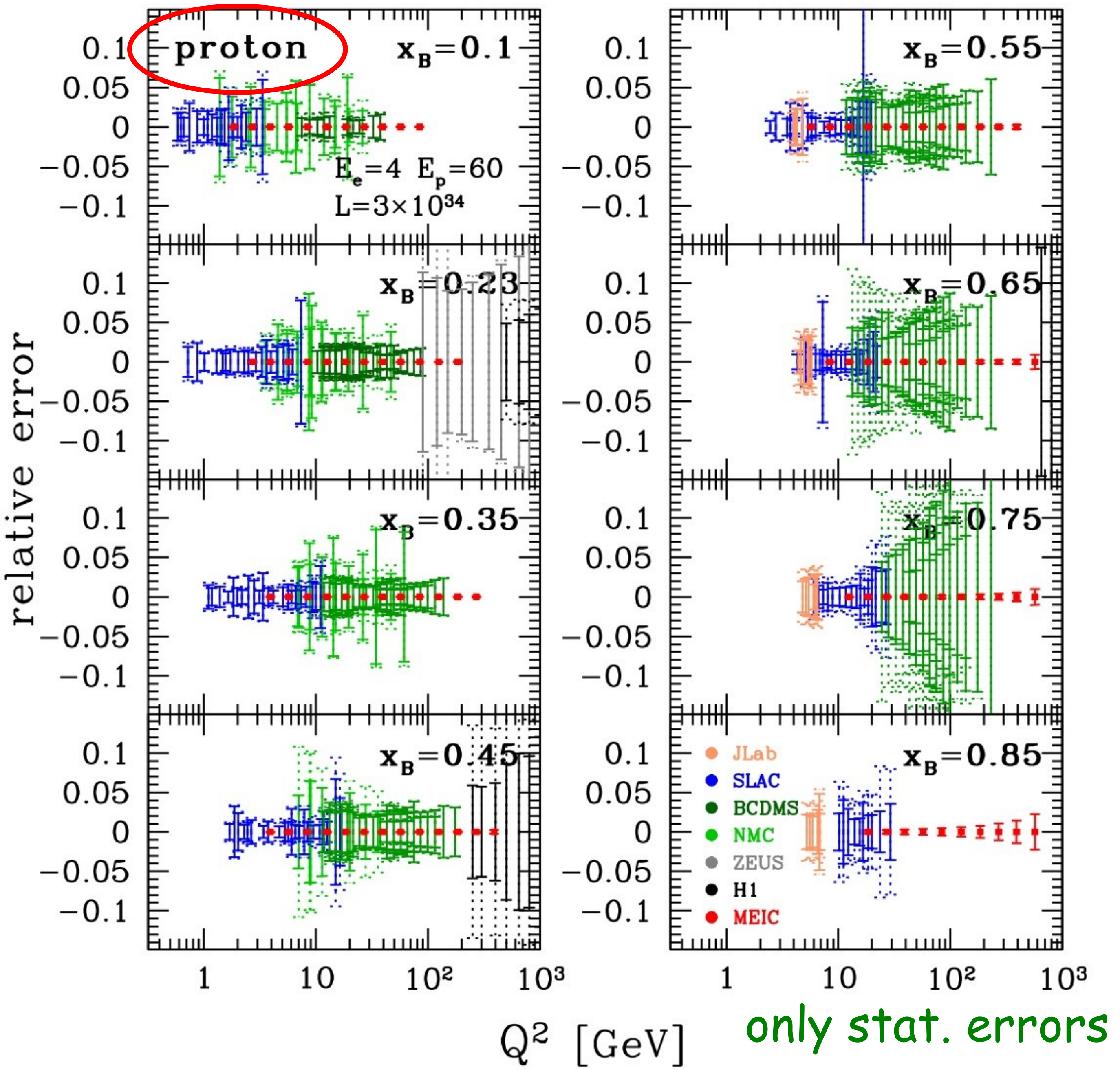


MEIC will probe lower x in the shadowing region, and higher Q^2 at large x.

Projected Results - F_2^p Relative Uncertainty

[Accardi, Ent, in progress]



only stat. errors on projected results

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

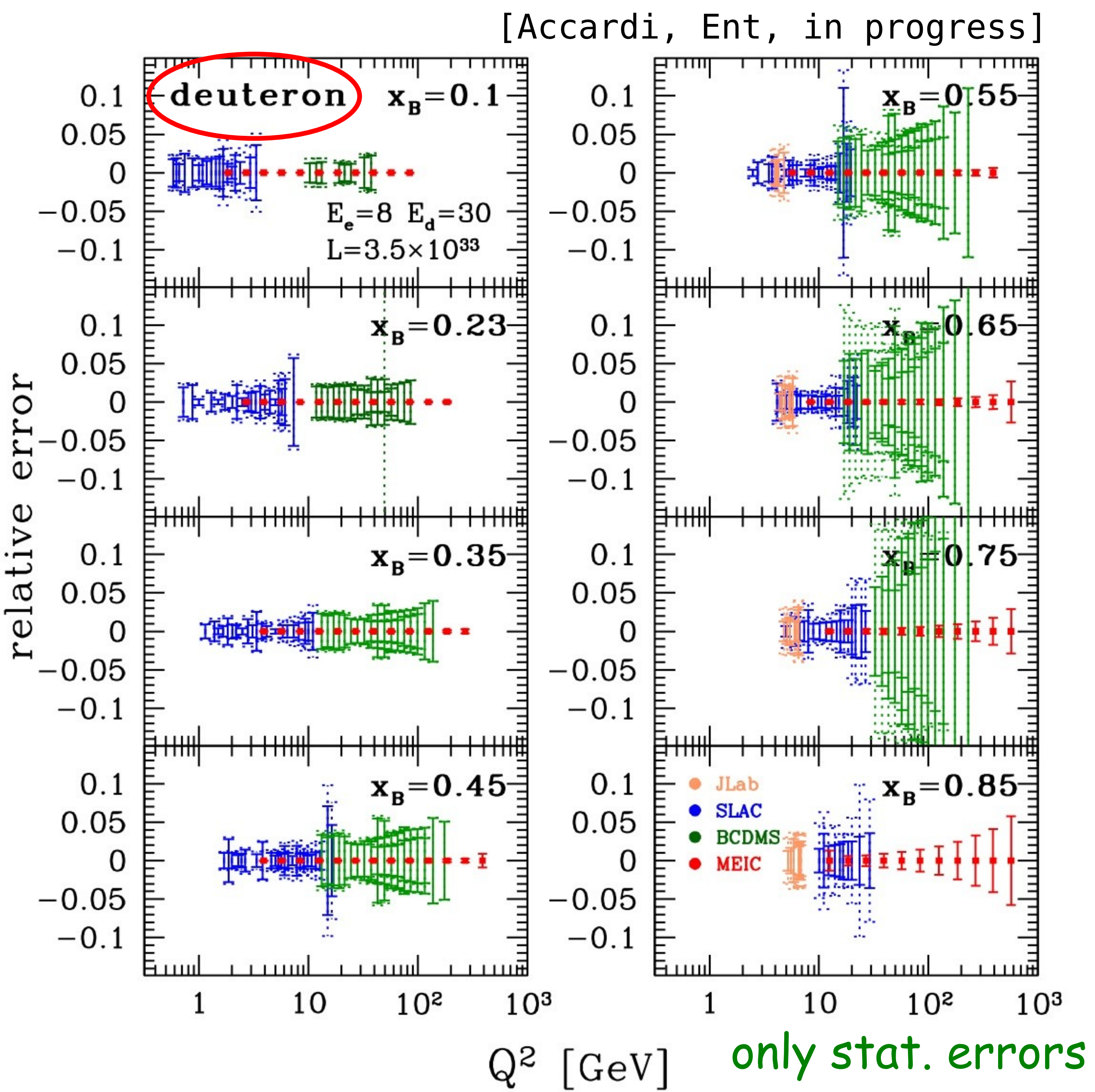
Solid lines are statistical errors, dotted lines are stat+syst in quadrature

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

Projected Results - F_2^d Relative Uncertainty



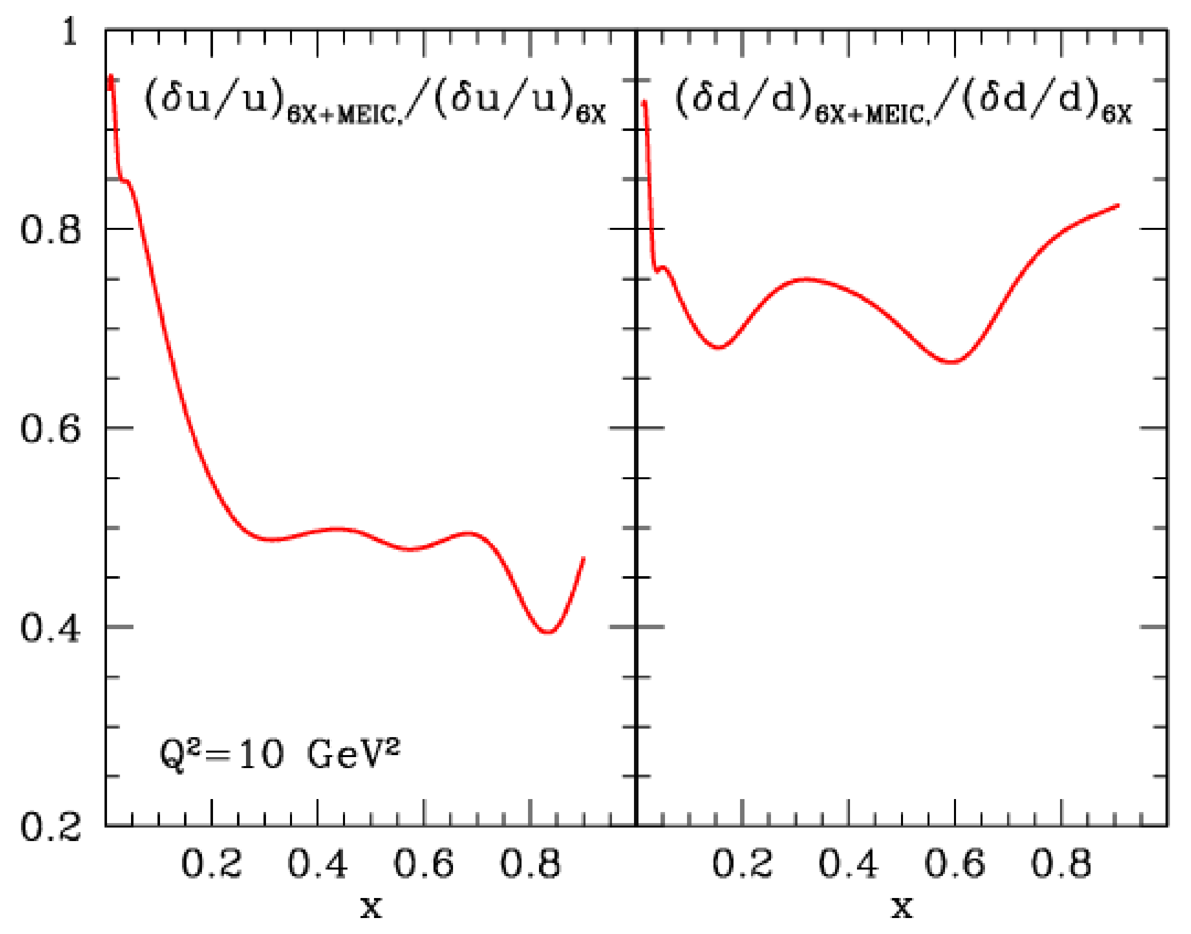
- MEIC 4+30
- 1 year of running (26 weeks) at 50% efficiency, or 35 **fb^{-1}**

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

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Structure functions at the EIC

- **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

- **Electroweak structure functions**
  - flavor separation, charge symmetry violation, new spin str.fns.
  - requires high luminosity – needed rates under study

- **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 ^{4}He targets ???
    - ✓ EMC effect

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
- **Gluons:** will be included in the CTEQ6X global fit
- **Intrinsic charm:** interesting direction for the future

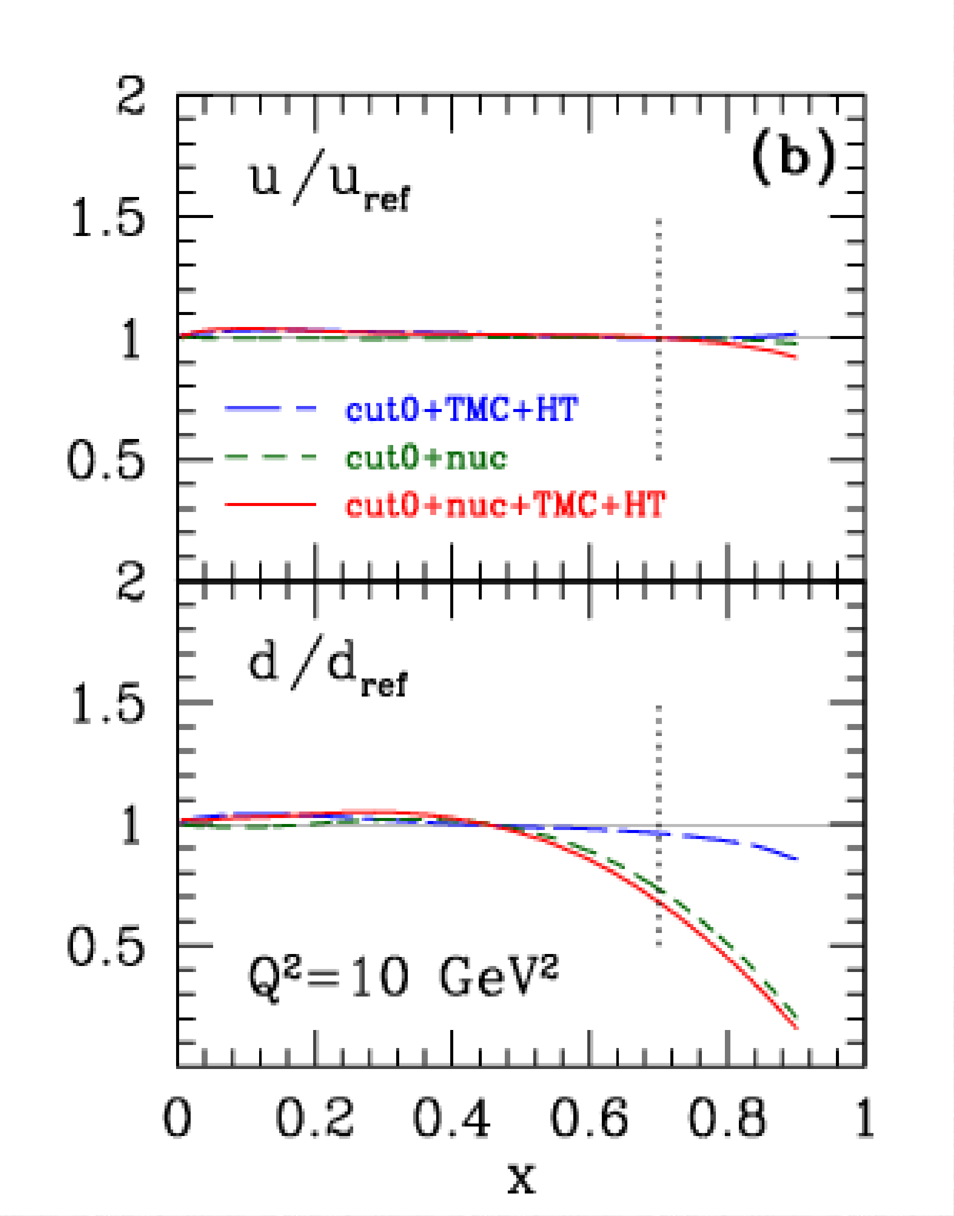
- Lots of progress available at the EIC

The future is bright ... and busy!

BACKUP SLIDES

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)



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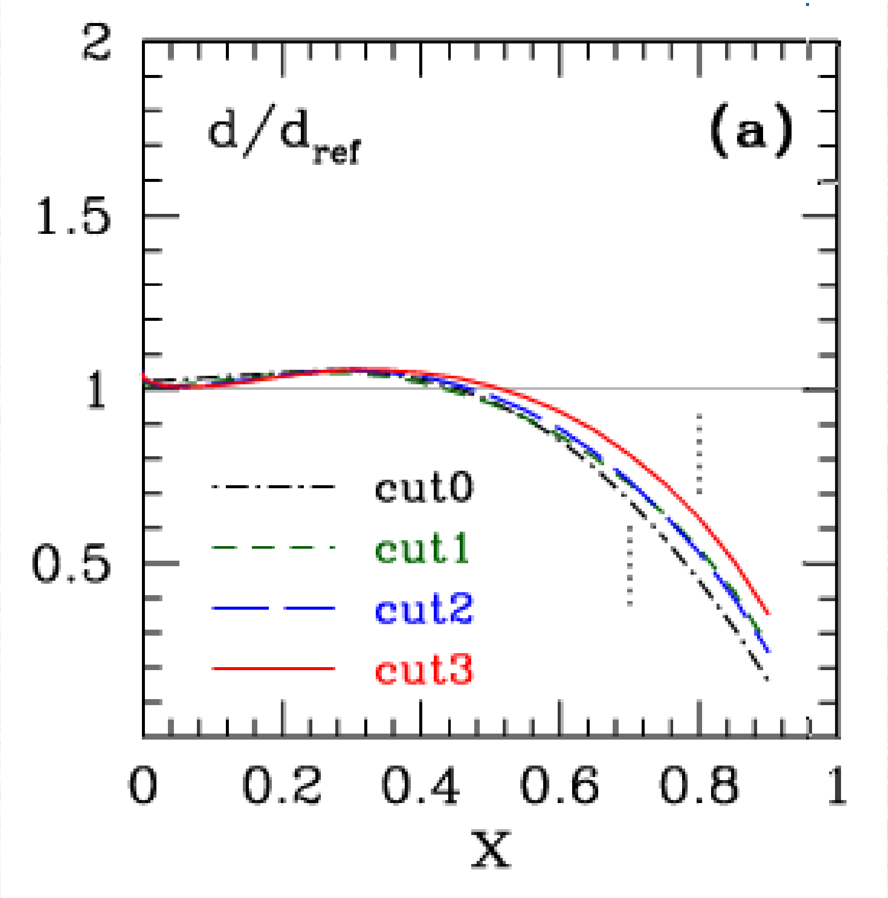
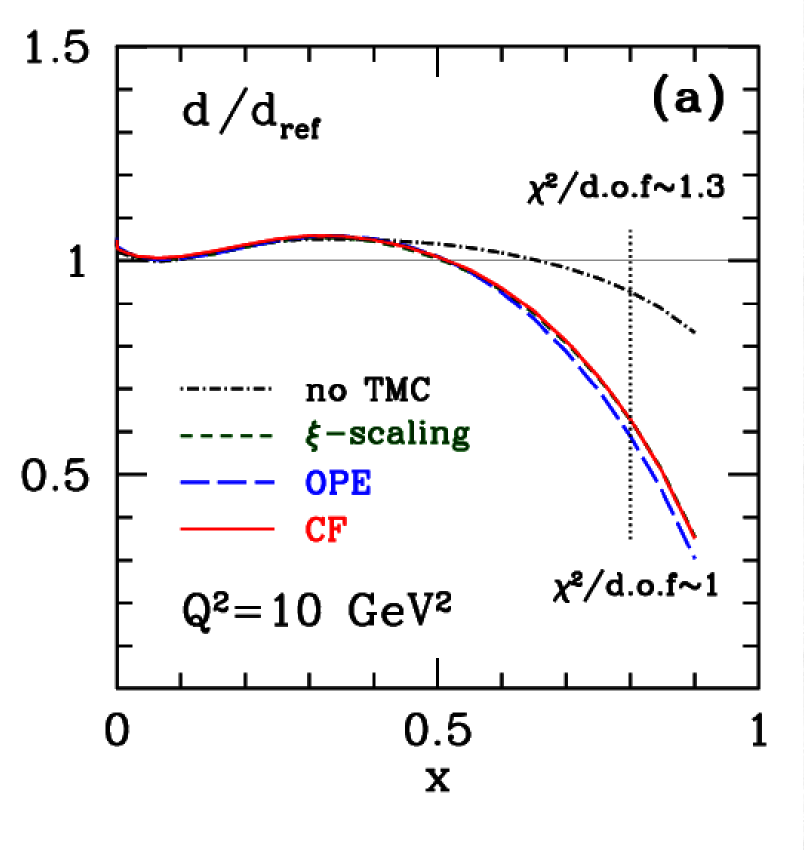
Stability of the d-quark fit



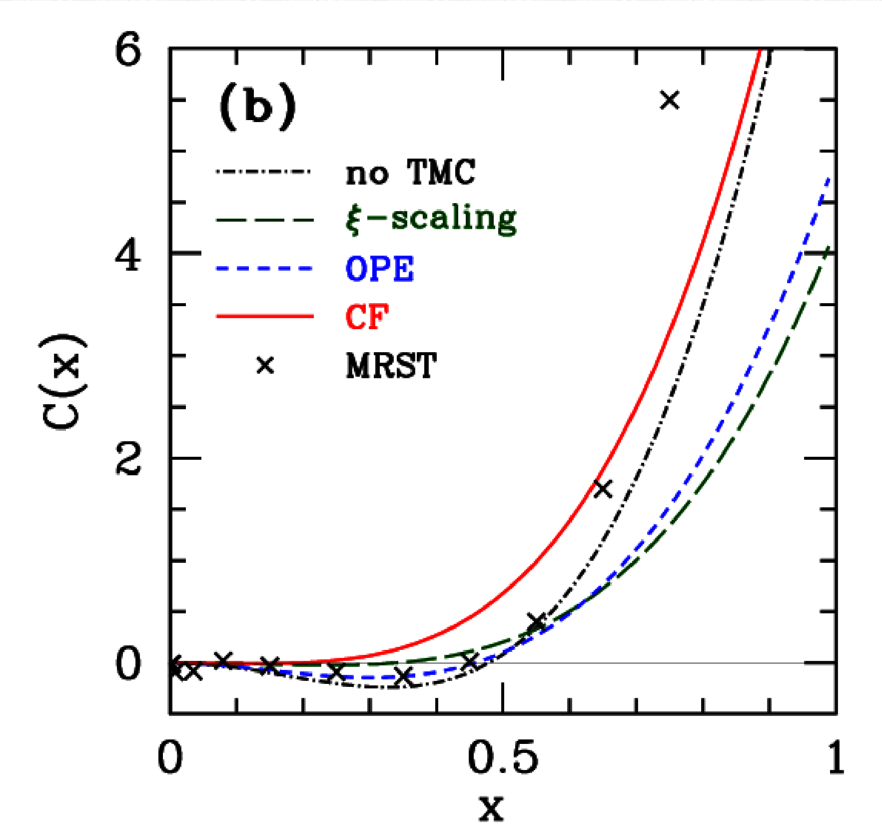
- **Relatively stable against kinematic cuts**, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at x=0.5–0.7 in the nominal range of validity of cut0

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)

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 $\Rightarrow x_B < 0.85$ compared to $x_B < 0.7$ in CTEQ/MRST
  - No evidence for negative HT

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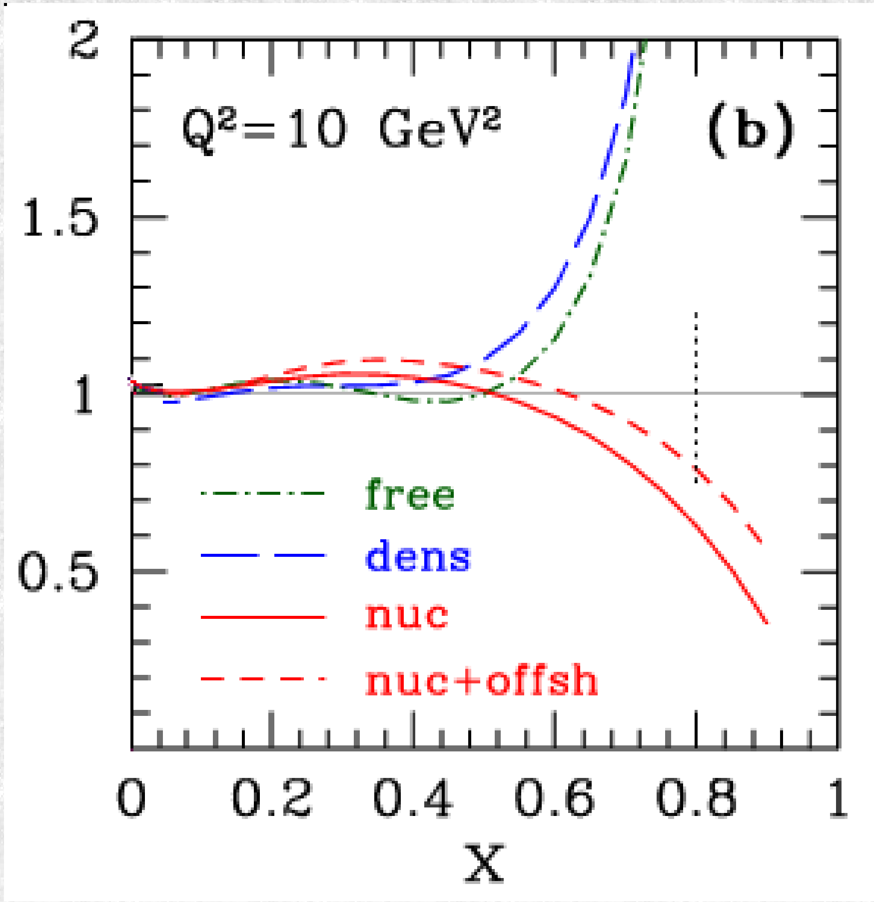
Off-shell corrections



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

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

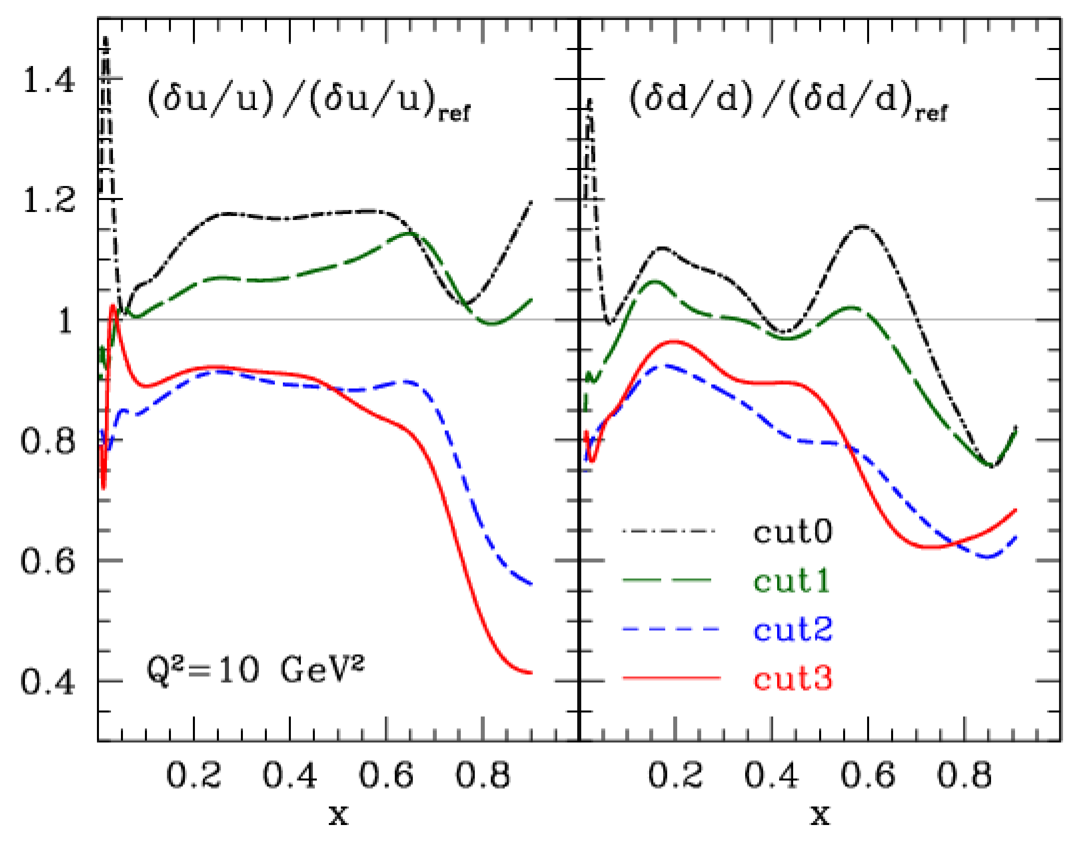
$$\frac{\delta d}{d} = \frac{4}{3} \frac{\delta F_2^d}{F_2^d} (1 + \frac{1}{d/u}).$$

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

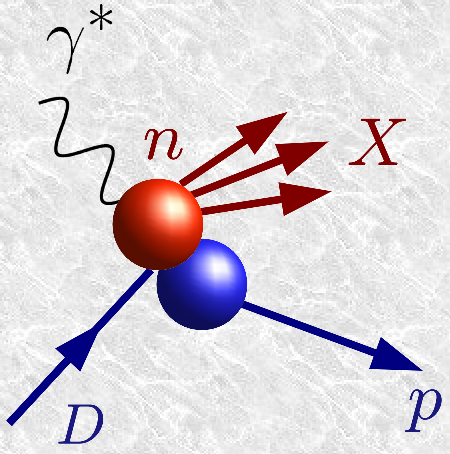
Experimental uncertainties: PDF errors

- **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

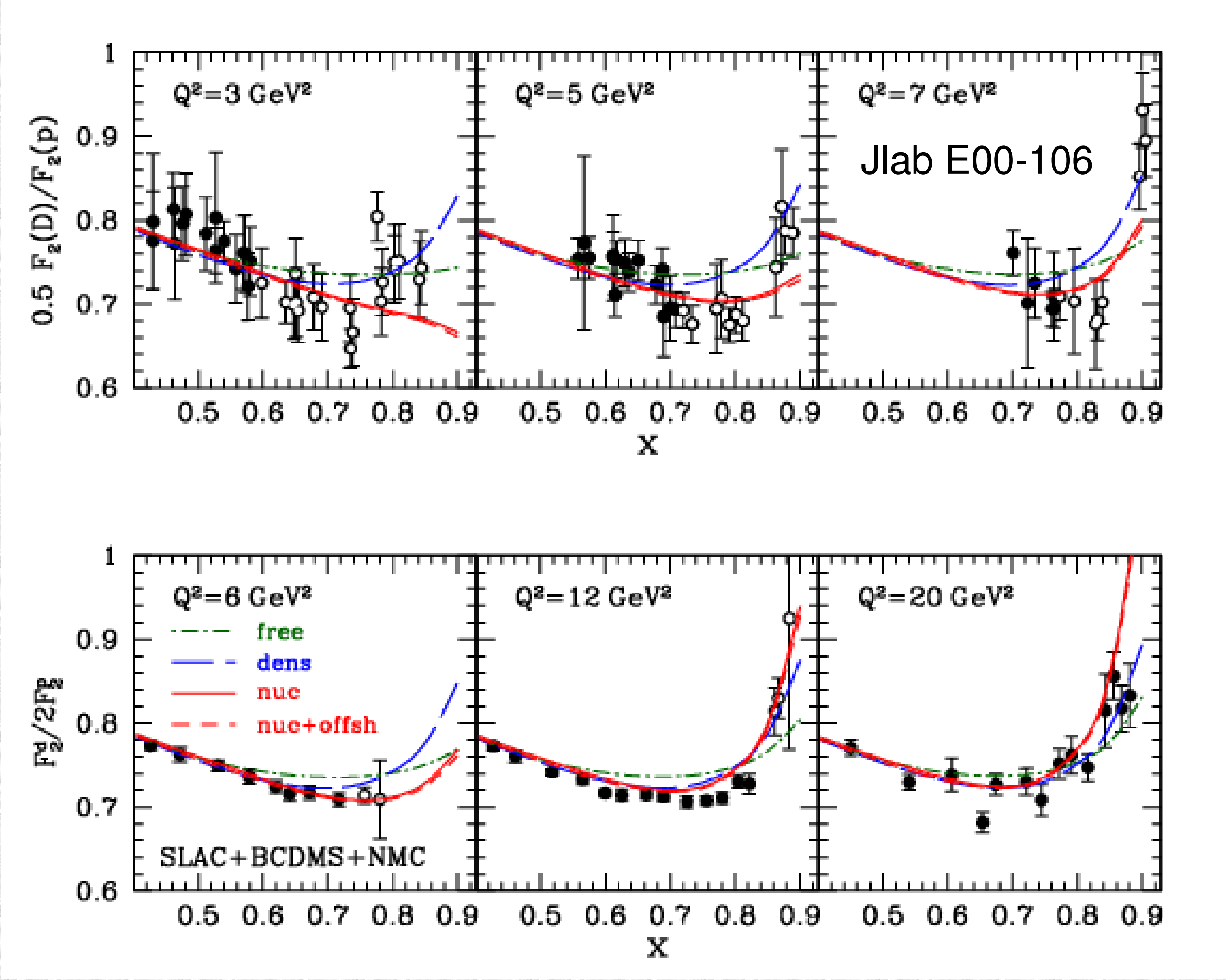
- Study the off-shell dependence of $F_2(n)$ and quark PDFs

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

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

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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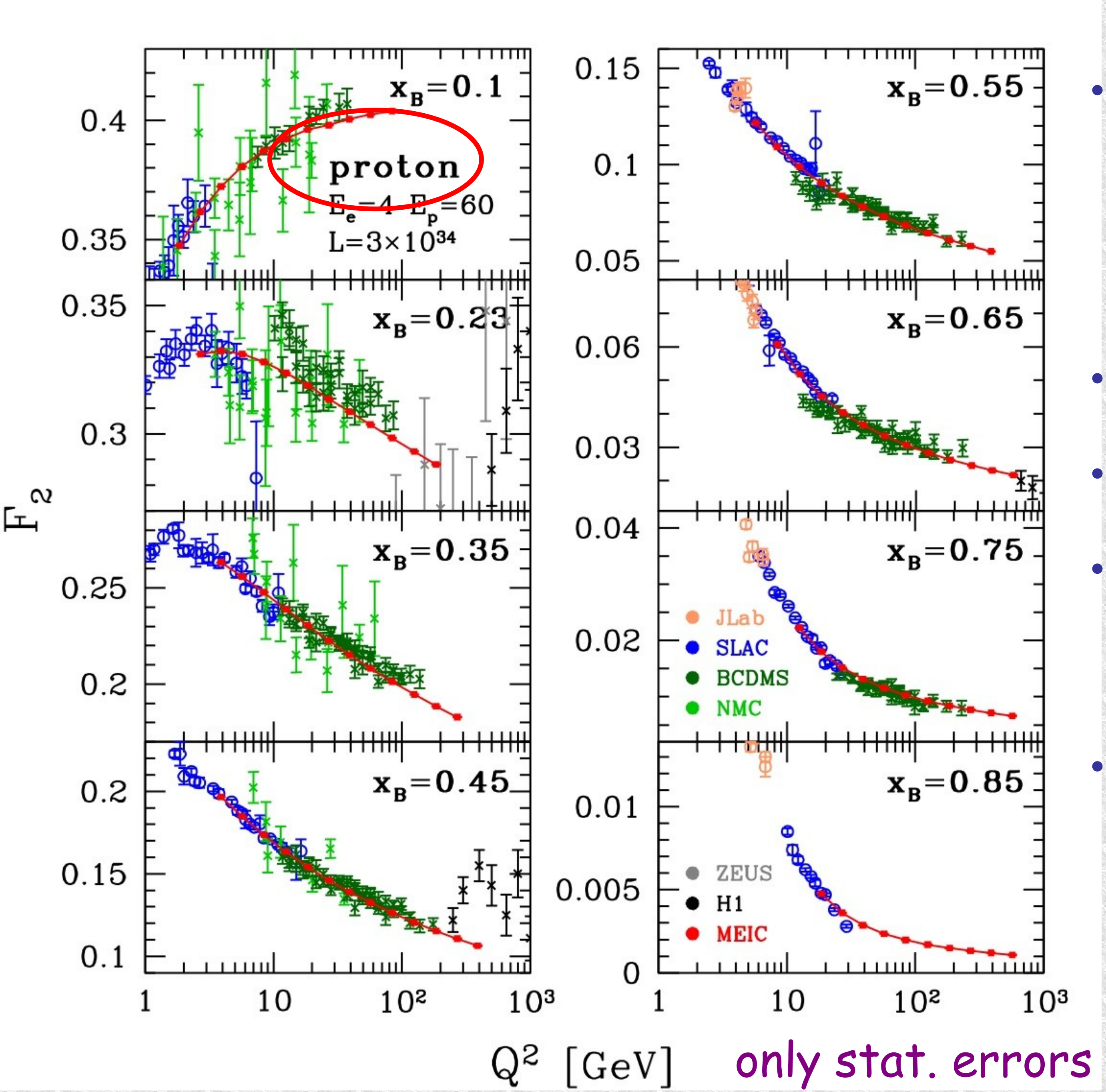
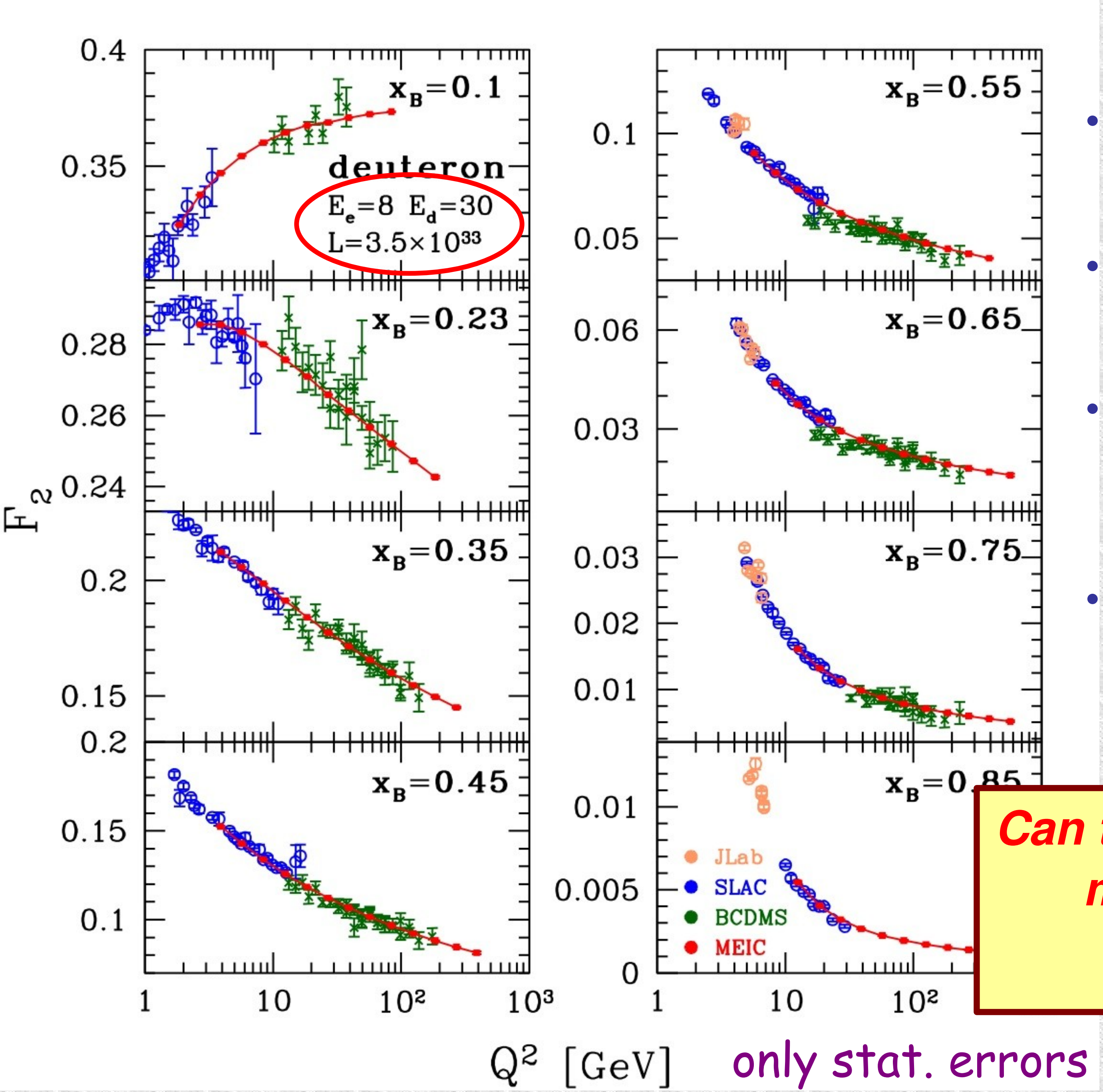
Projected Results IIa - F_2^p with CTEQ6X PDFs



- 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 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}**

Can tag spectator proton, measure neutron, concurrently

only stat. errors on projected results

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Pavia U., 13 Jul 2010