Subleading effects in a QCD global fits

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HiX 2010, Jefferson Lab
13-15 October 2010

Outline

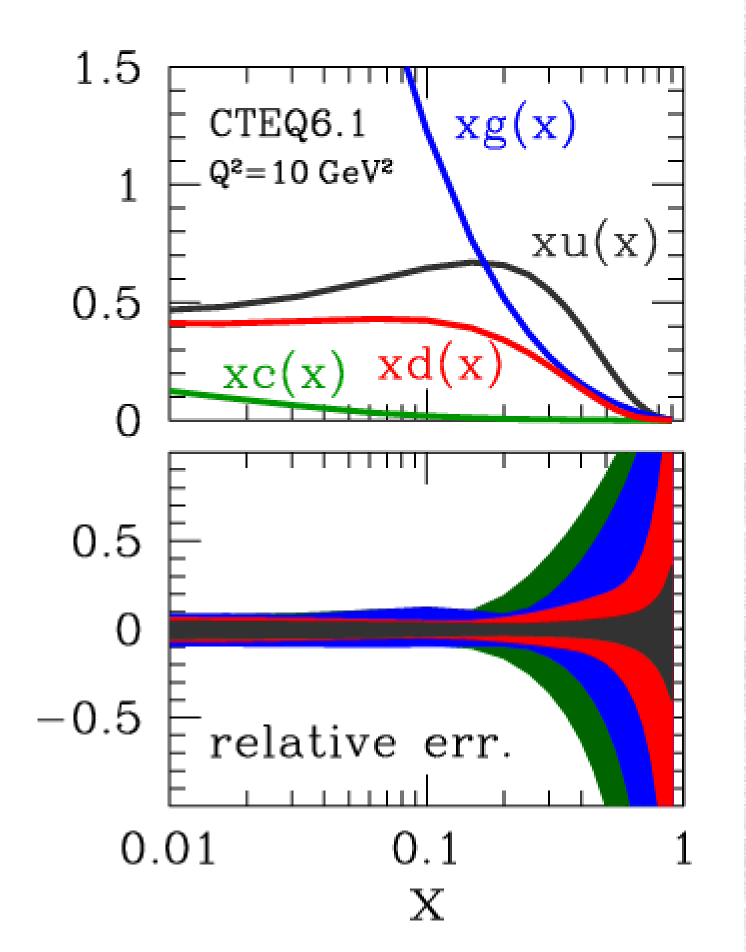
- Why large-x, low-Q^2 ?
- Up and down: the CTEQ6X fit
  - target mass corrections
  - higher-twists
  - nuclear corrections
- Constraining d-quarks at large x
- Quark-hadron duality
- Conclusions

Why large x ?

Why large x ?

- Large (experimental) 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 $\Leftrightarrow$ large x PDF
    2) Luminosity monitoring at large mass:
       Z, W cross-sections
  - Non-perturbative nucleon structure:
    d/u, $\Delta u/u$, $\Delta d/d$ at $x \to 1$
  - Spin structure of the nucleon *at small x*
  - Neutrino oscillations



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) ...

Up and down: the CTEQ6X fit

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

Phys. Rev. D 81, 034016 (2010)

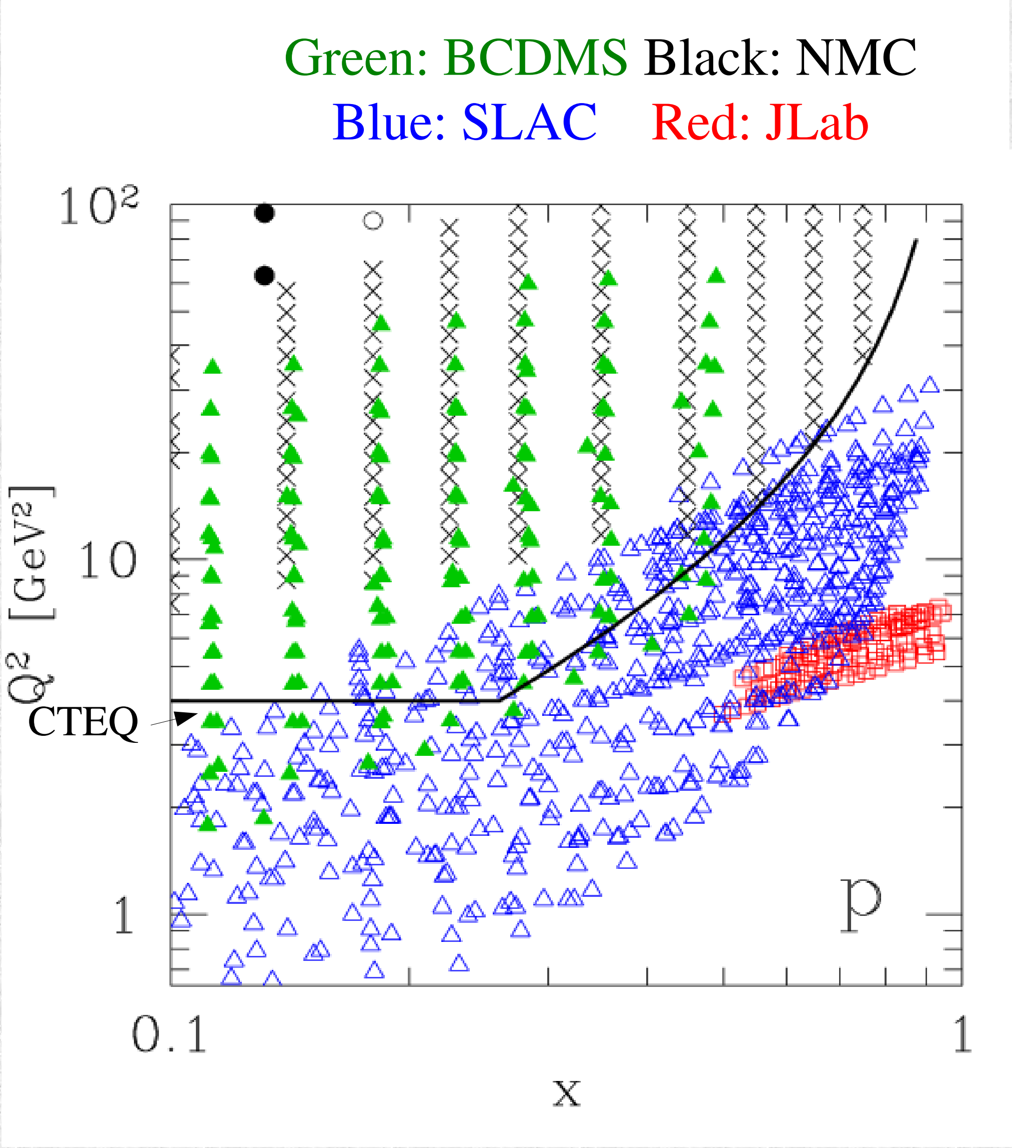
(a JLab/HU/CTEQ collaboration)

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



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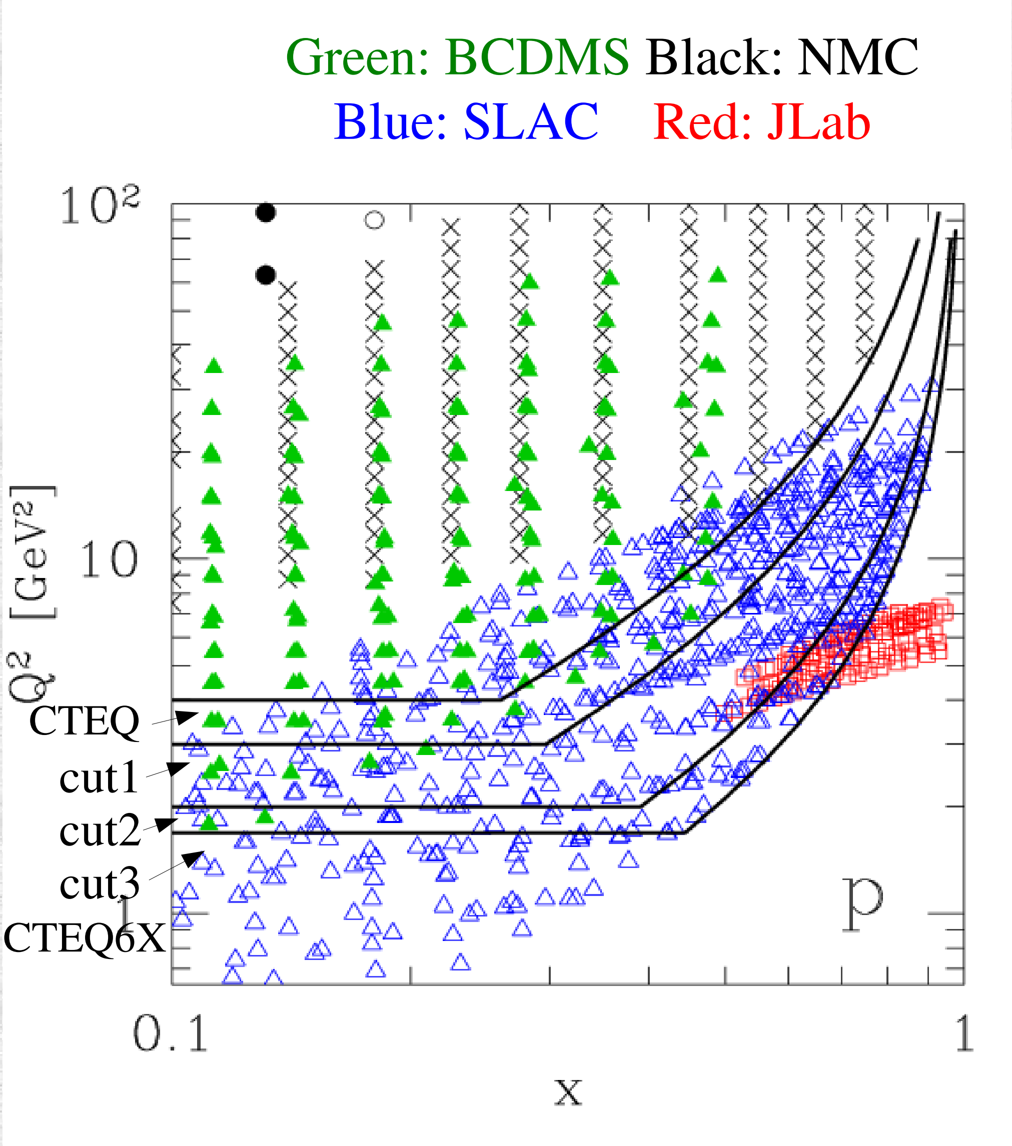
- **CTEQ6X**
  - **TMC, HT, deuteron corrections**
  - Progressively lower the cuts:

		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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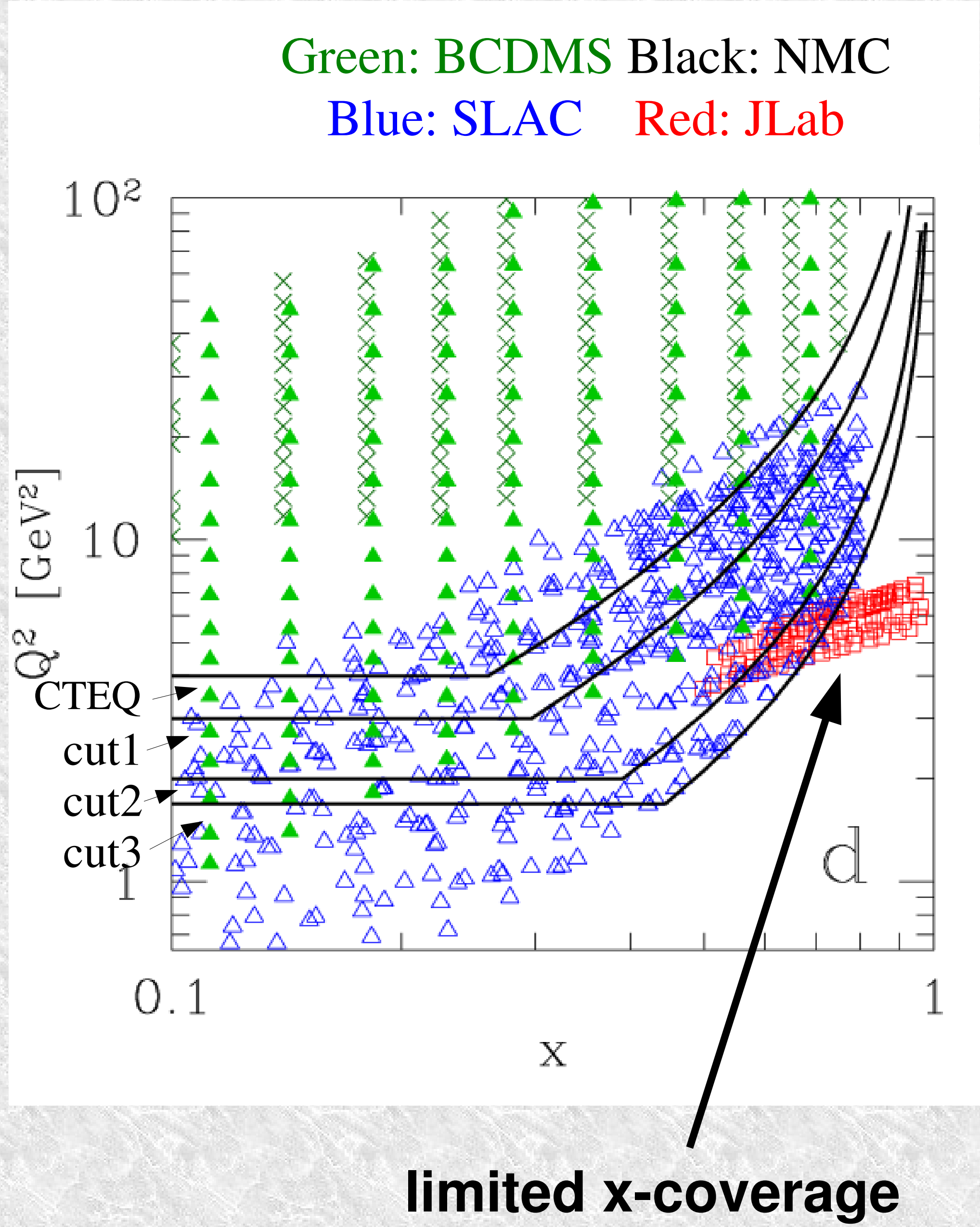


Target mass corrections

- 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]
  - 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]

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

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

Unpolarized SIDIS at LO

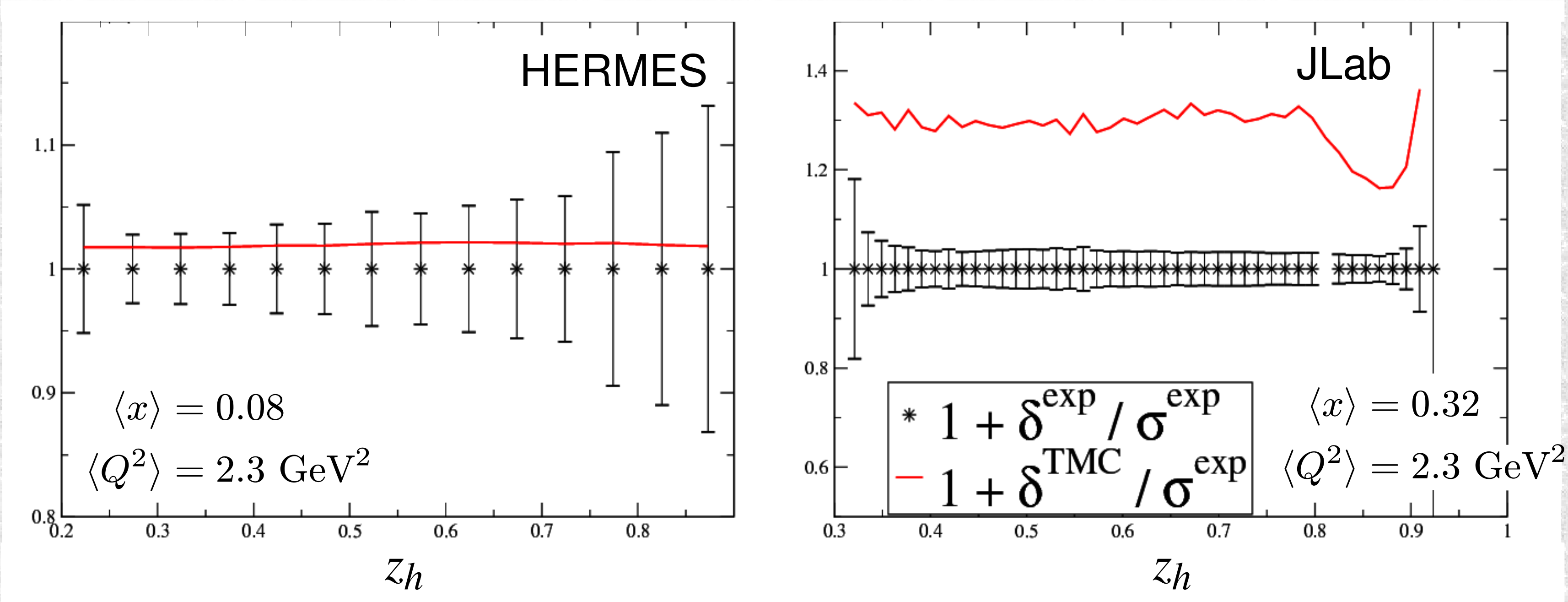
[Accardi, Hobbs, Melnitchouk, JHEP 0911:084,2009]

$$\frac{d\sigma^h}{dz_h} \sim \sum_q e_q^2 \varphi_q(\xi) D_q^h(\zeta_h)$$

TMC also for hadron fragmentation

$$\zeta_h = \frac{1}{2} z_h \frac{\xi}{x_B}\left[1 + \sqrt{1 - 4\frac{x_B^2}{z_h^2}\frac{m_N^2 m_h^2}{Q^4}}\right]$$

hadron mass correction



- **Large corrections at Jefferson Lab!** (because of large-x, mostly)

"Higher-Twists" parametrization

- Parametrize by a multiplicative factor:

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

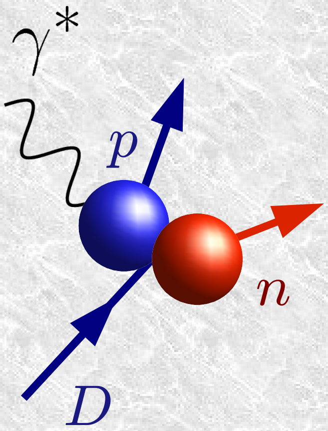
with

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

- **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

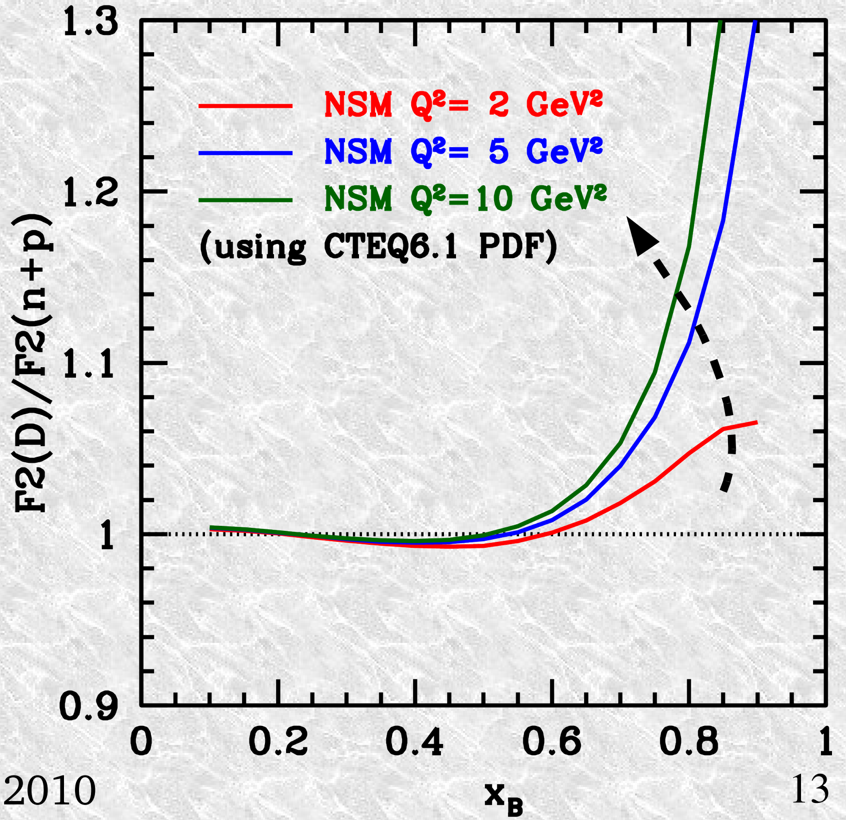
- Nuclear Smearing Model [Kahn et al., PRC79(2009) Accardi,Qiu,Vary, *in preparation*]
  - nucleon Fermi motion and binding energy
  - use non-relativistic deuteron wave-function
  - finite-Q^2 corrections



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

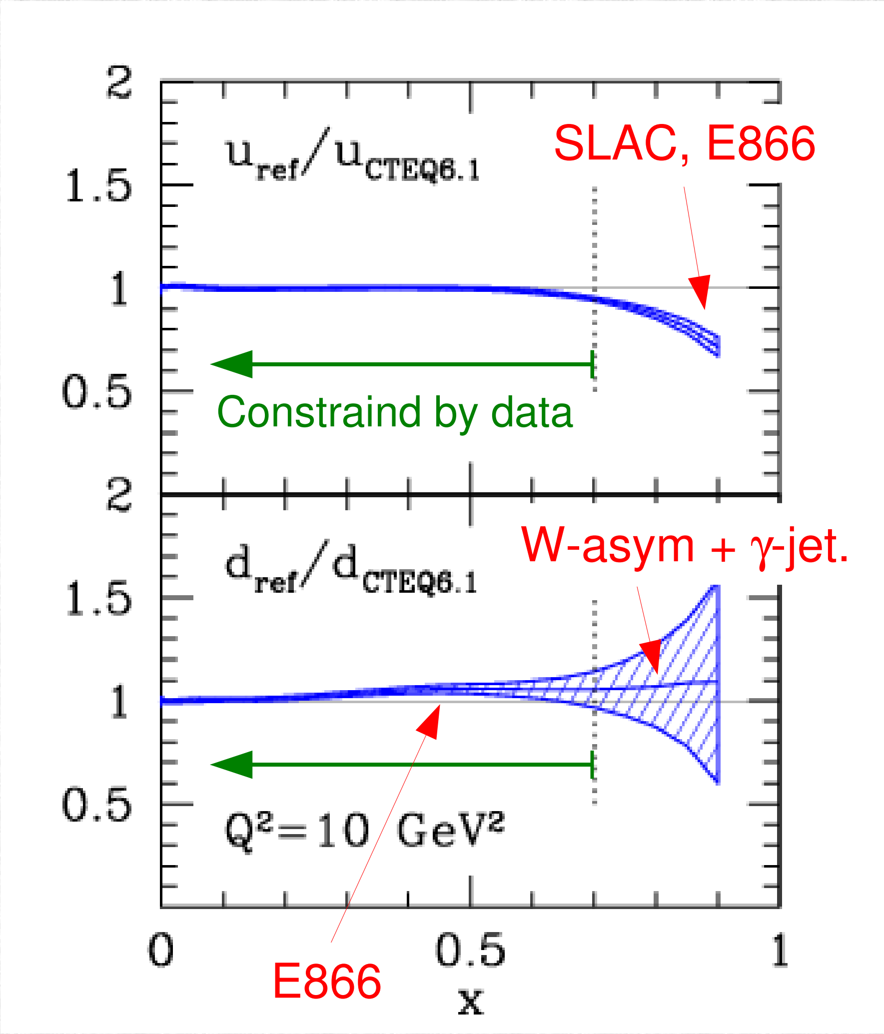
$$\gamma = \sqrt{1 + 4x_B^2 m_N^2/Q^2}$$

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



  - off-shell effects can be included in S_A
- **Not a subleading correction!**

Reference fit

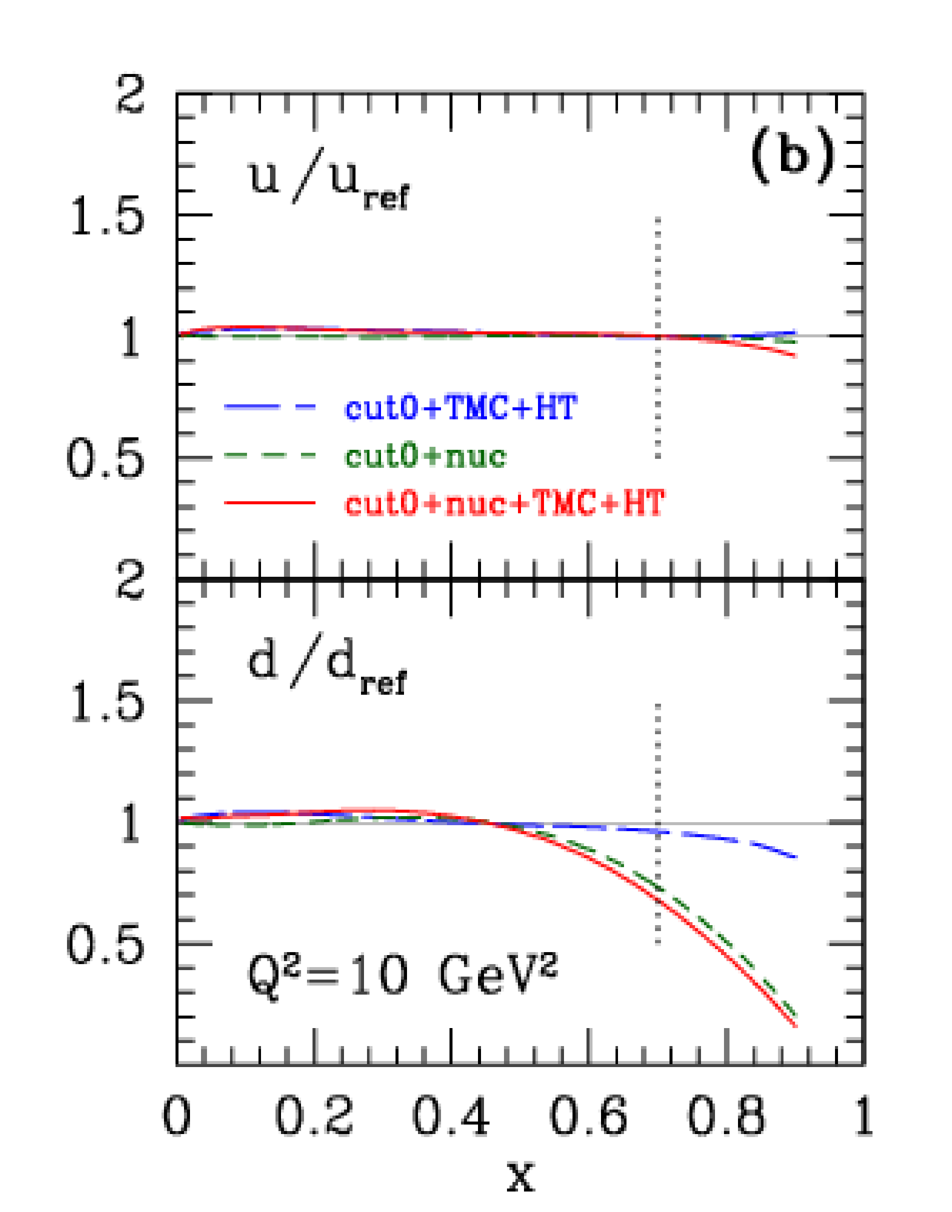


- **Reference fit:**
  - cut0, no corrections
  - PDF errors with $\Delta\chi=1$

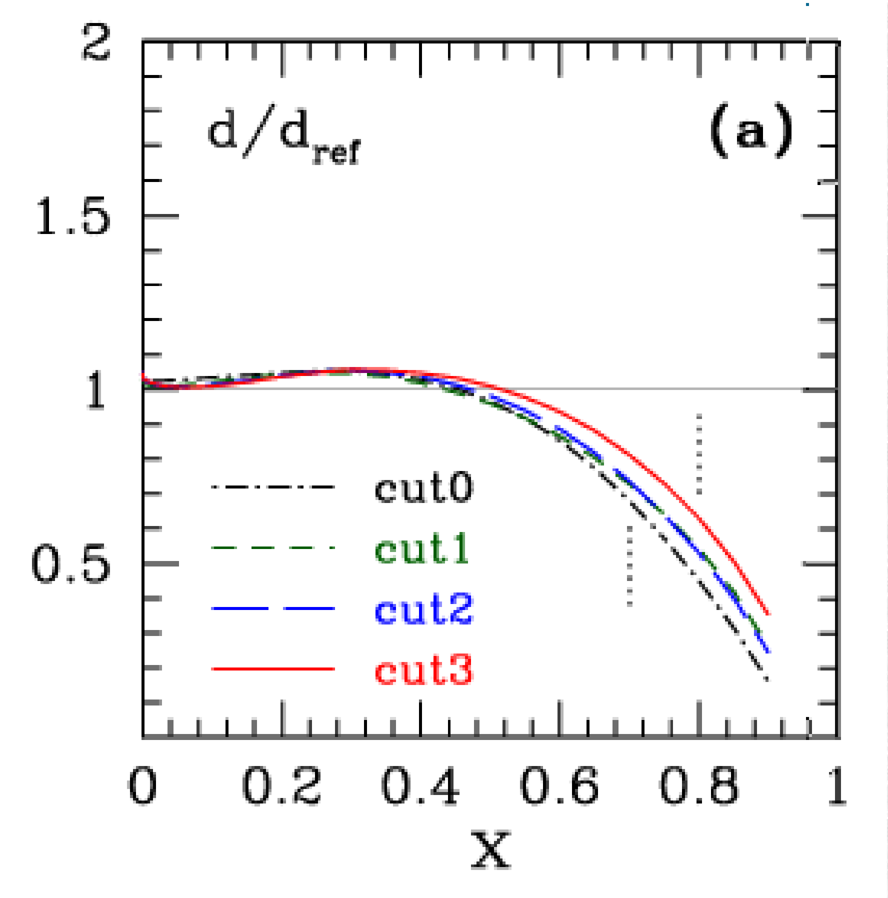
	data	CTEQ6.1
DIS	(JLab)	NO
	SLAC	NO
	NMC	√
	BCDMS	√
	H1	√
	ZEUS	√
DY	E605	√
	E866	NO
W	CDF '98 (ℓ)	√
	CDF '05 (ℓ)	NO
	D0 '08 (ℓ)	NO
	D0 '08 (e)	NO
	CDF '09 (W)	NO
jet	CDF	√
	D0	√
γ+jet	D0	NO

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)

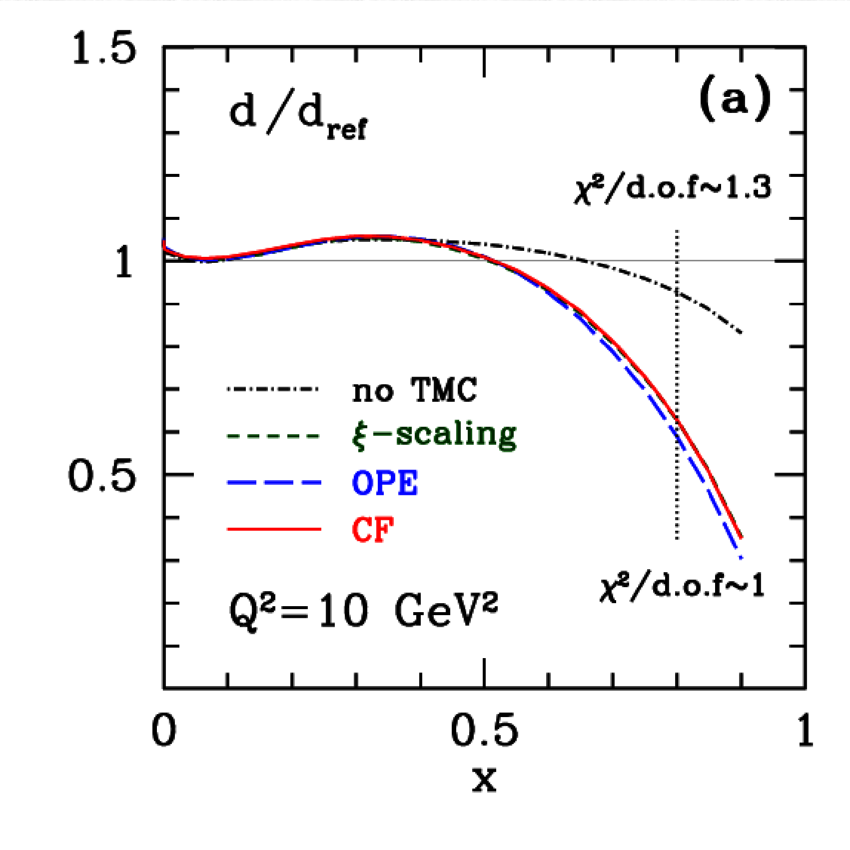


Stability of the d-quark fit



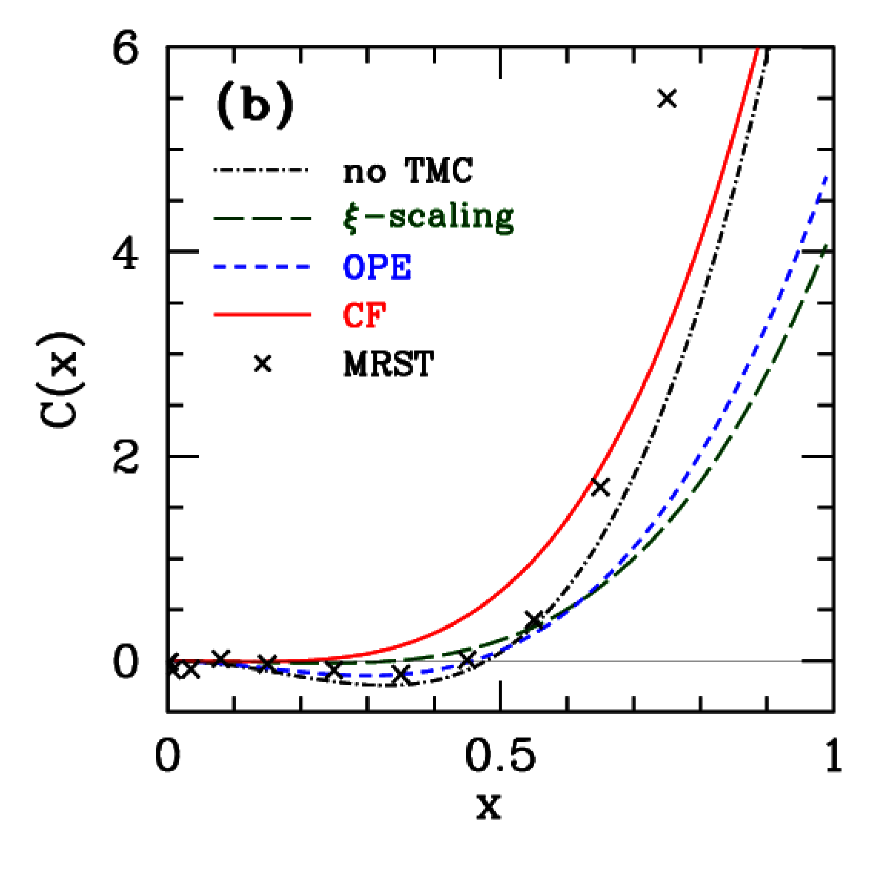
- **Relatively stable against kinematic cuts**, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at x=0.5–0.7 in the nominal range of validity of cut0

TMC vs HT



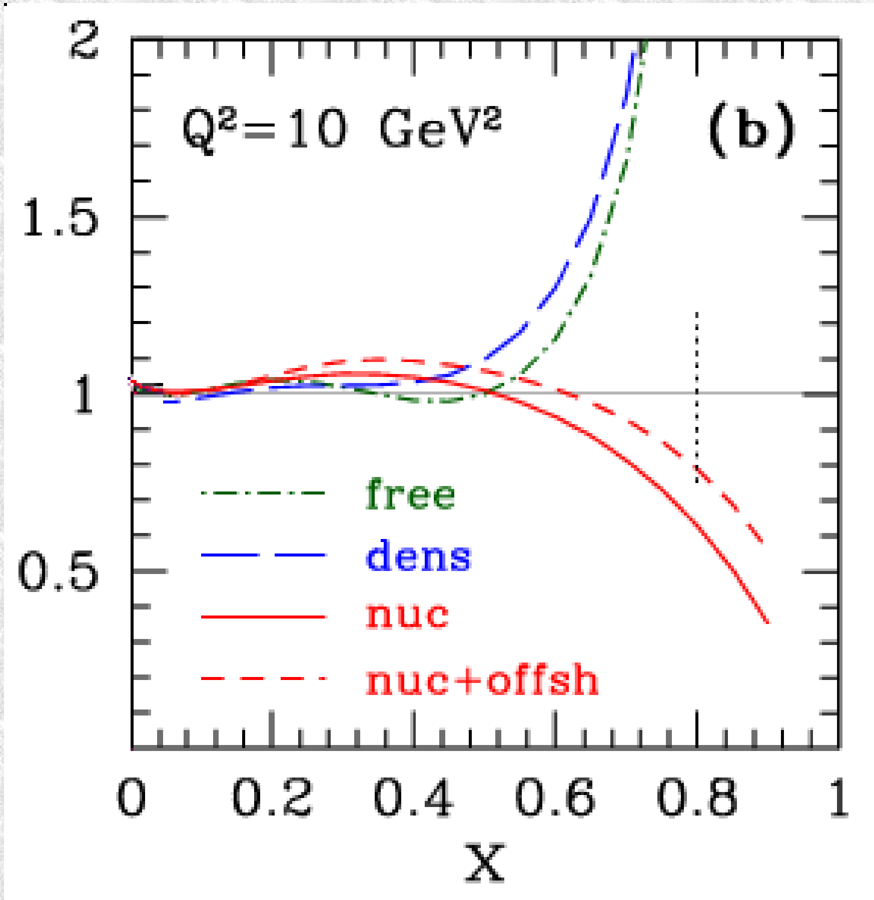
- **Extracted twist-2 PDF much less sensitive to choice of TMC**
  - fitted HT function compensates the TMC
  - except when no TMC is included
- **Inclusion of TMC allow for economical HT parametrization** (3 params)

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 with CF target mass corrections

Deuterium corrections



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

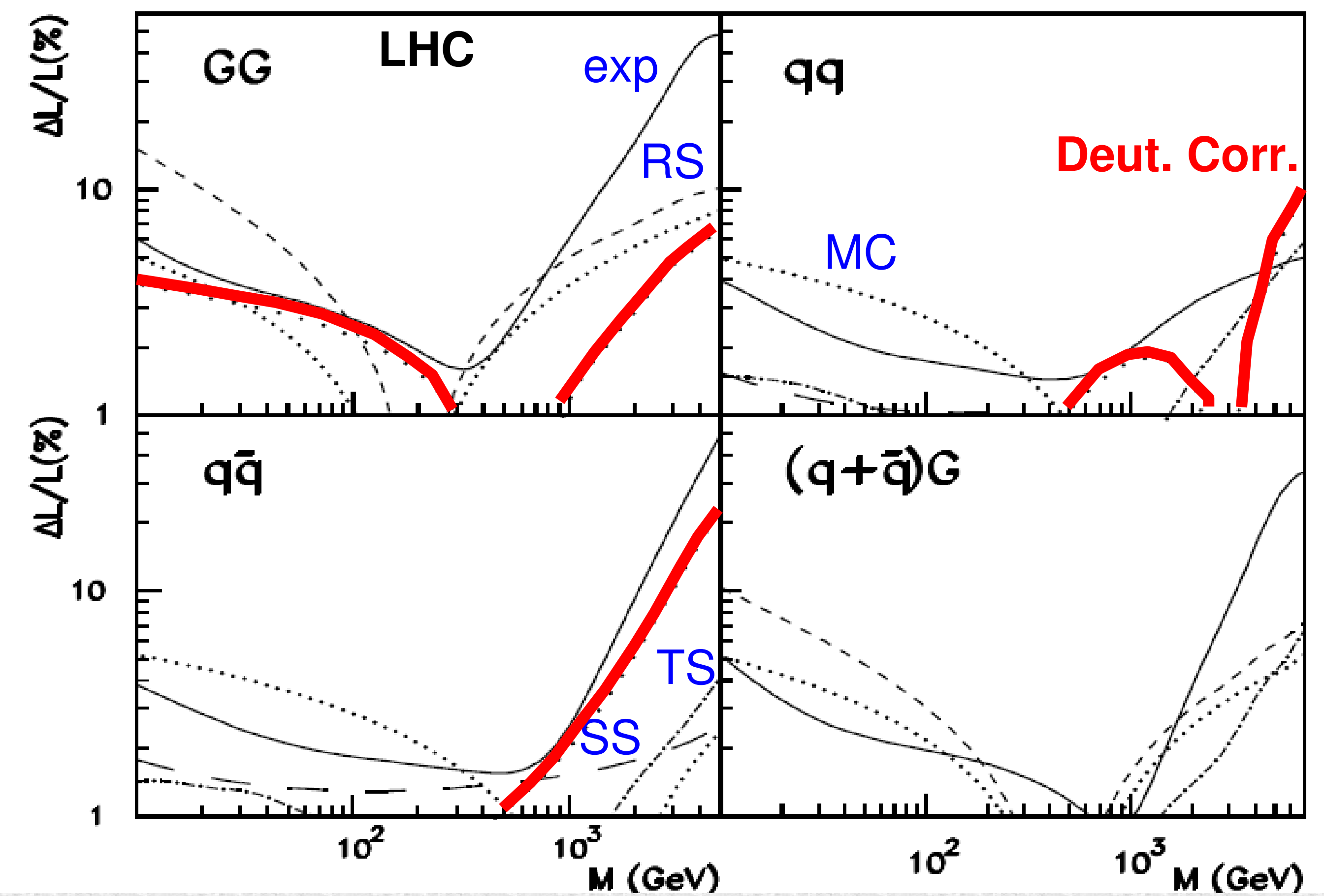
free	= free p+n
dens	= density model corrections
nuc	= WBA smearing model
offsh	= off-shell corrections

`[Melnitchouk et al., '94]`

Impact on LHC

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

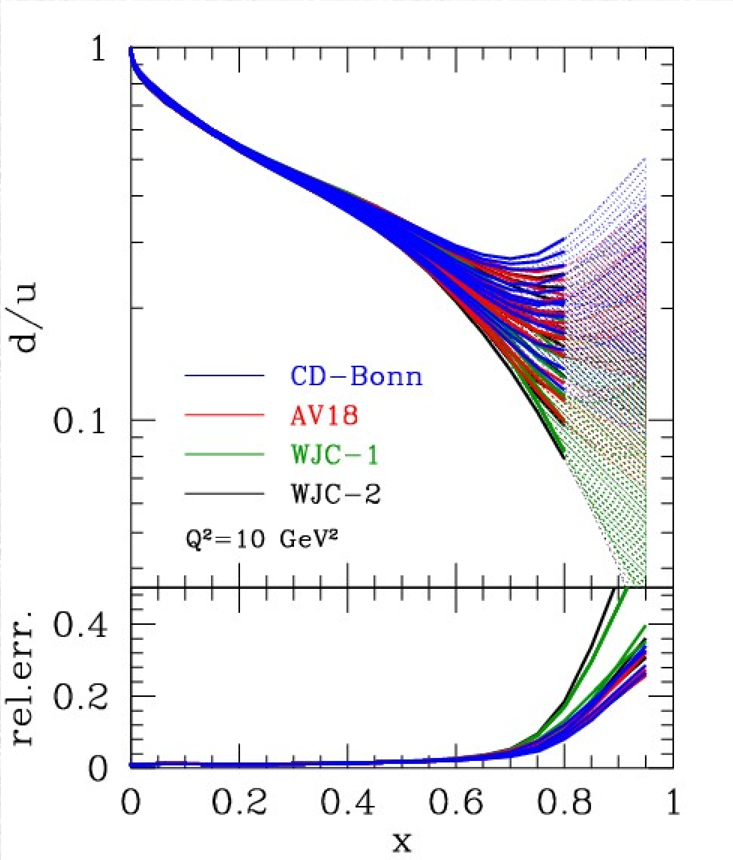
[Alekhin PRD63 (2001)]

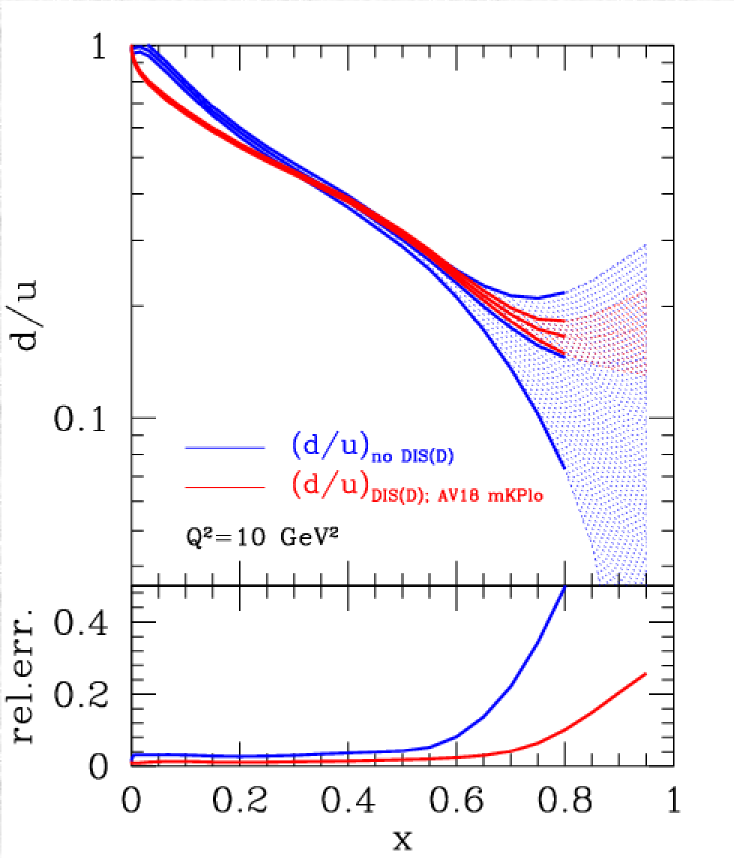


exp = experimental
RS = renorm. scale
MC = charm mass
TS = charm threshold
SS = strangeness suppr.

Nuclear corrections uncertainty

- Discussed in detail by Jeff Owens – [here, d(x) -> d(x) + c x^{α} u(x)]
- Same order of magnitude as removing Deuterium data





- **Need cross check: data on free nucleons, or minimization of nuclear effects**

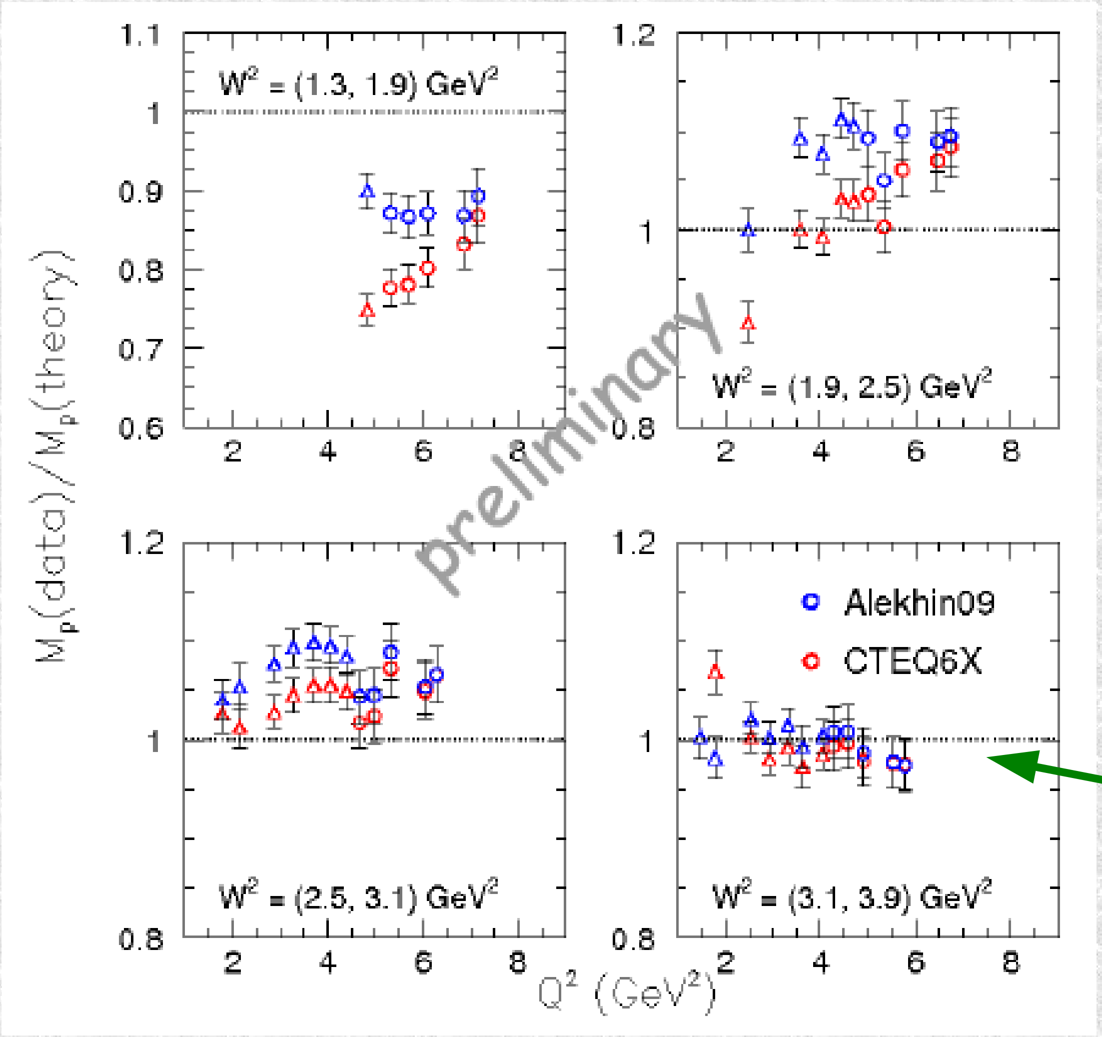
Quark-hadron duality

Test of Quark-hadron Duality

[Accardi, Malace, in preparation]

- Truncated moments, plotted at an "average" x $$M = \int_{W=[W_m,W_M]} dx\, F_2(x)$$

  Malace et al, PRC80,035207,2009

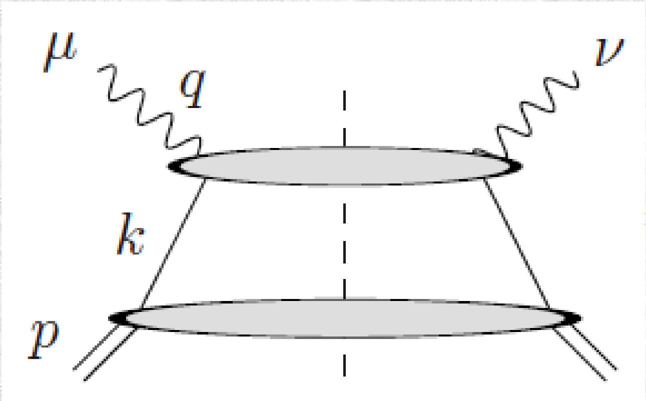


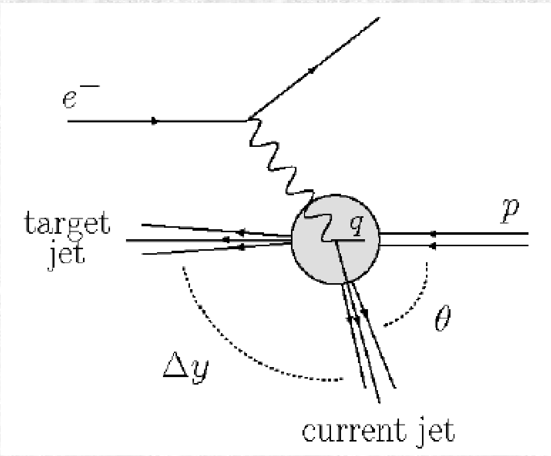
included in the CTEQ6X

Test of Quark-hadron Duality

[Accardi, Malace, in preparation]

- But: where can we expect the handbag diagram to be valid??





- Current and jet separation in rapidity $y = \frac{1}{2} \ln p_h^+ / p_h^-$
  - with LO kinematics,

$$\Delta y \approx y_q - y_p = \log \frac{2\sqrt{2}\nu}{Q} \frac{1}{\sqrt{1 - Q^2/(2MxE)}}$$

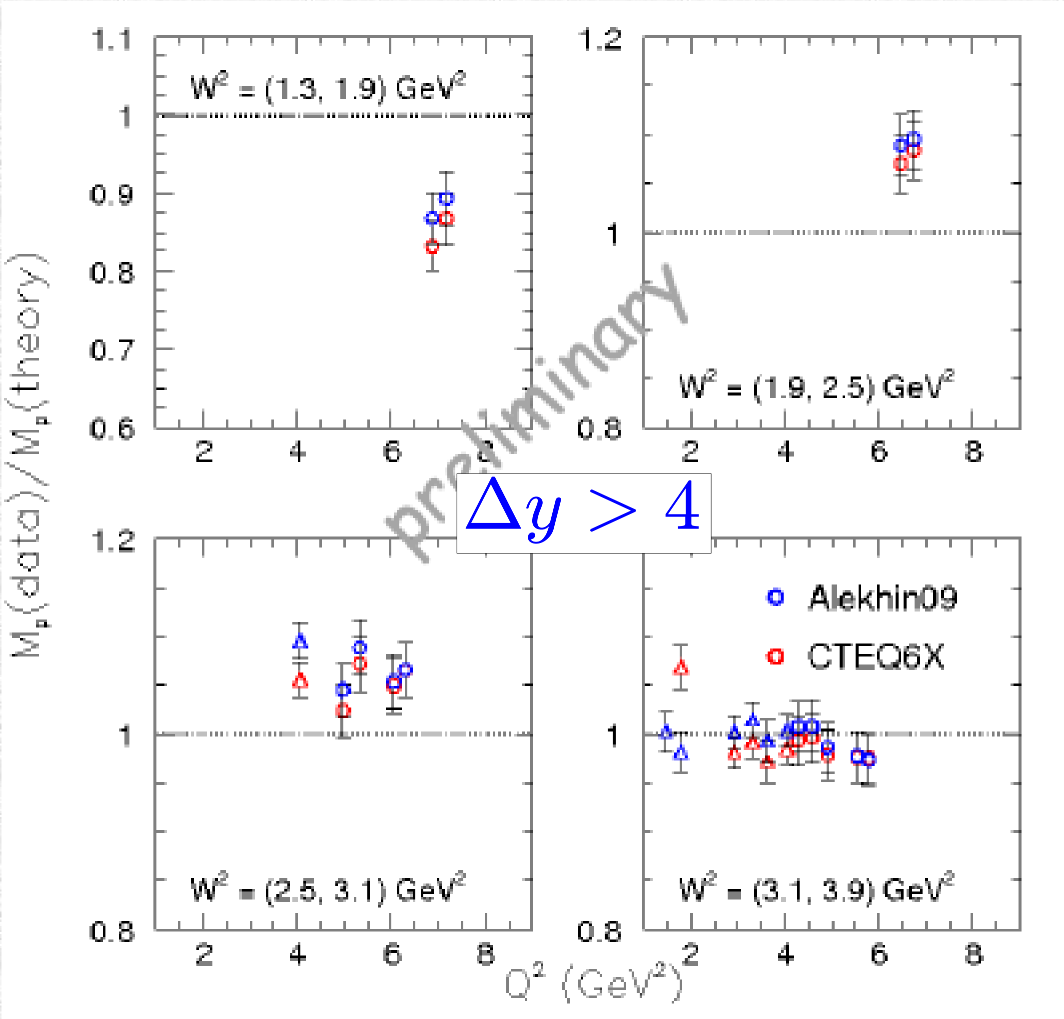
- Berger criterion: $\Delta y > 2 \ (4)$

[Berger, ANL-HEP-CP-87-045, 1987; Mulders, hep-ph/0010199]

Test of Quark-hadron Duality

[Accardi, Malace, in preparation]

- *Quark-hadron duality works to 5-10%*
  - Conversely, **can use M_n in global fits to reach higher x**



Conclusions

- **Large-x, low-Q2 region manageable in global PDF fits**
- **Large, dominant nuclear corrections uncertainty**
- **For d-quark, need data on free nucleons, large-x**
  - scarce for now, needs new experiments, rebinning of existing data

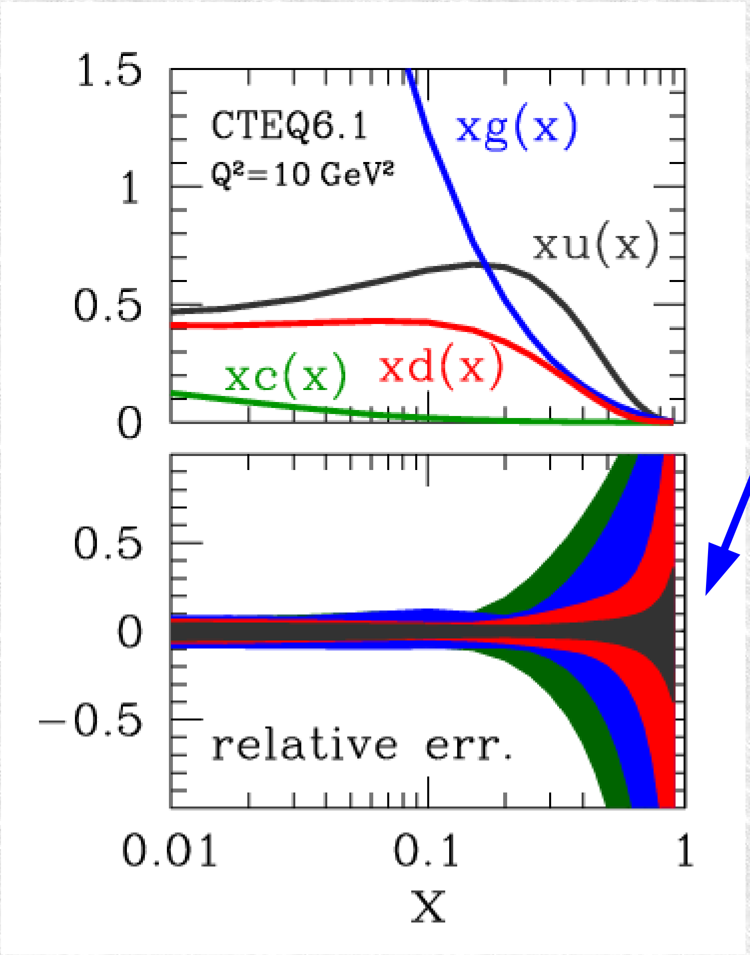
In the near future...

- Nuclear corrections systematics [CTEQ-X, in preparation]
  - effects on d/u ratio, Drell-Yan, W-asy, ... [see J.Owens' talks]
- Applications to quark-hadron duality [Malace, Accardi, in prep.]
  - use resonance region data in global PDF fits?
- Applications to spectator-tagged DIS [Accardi, Melnitchouk]

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**

Why large x ?

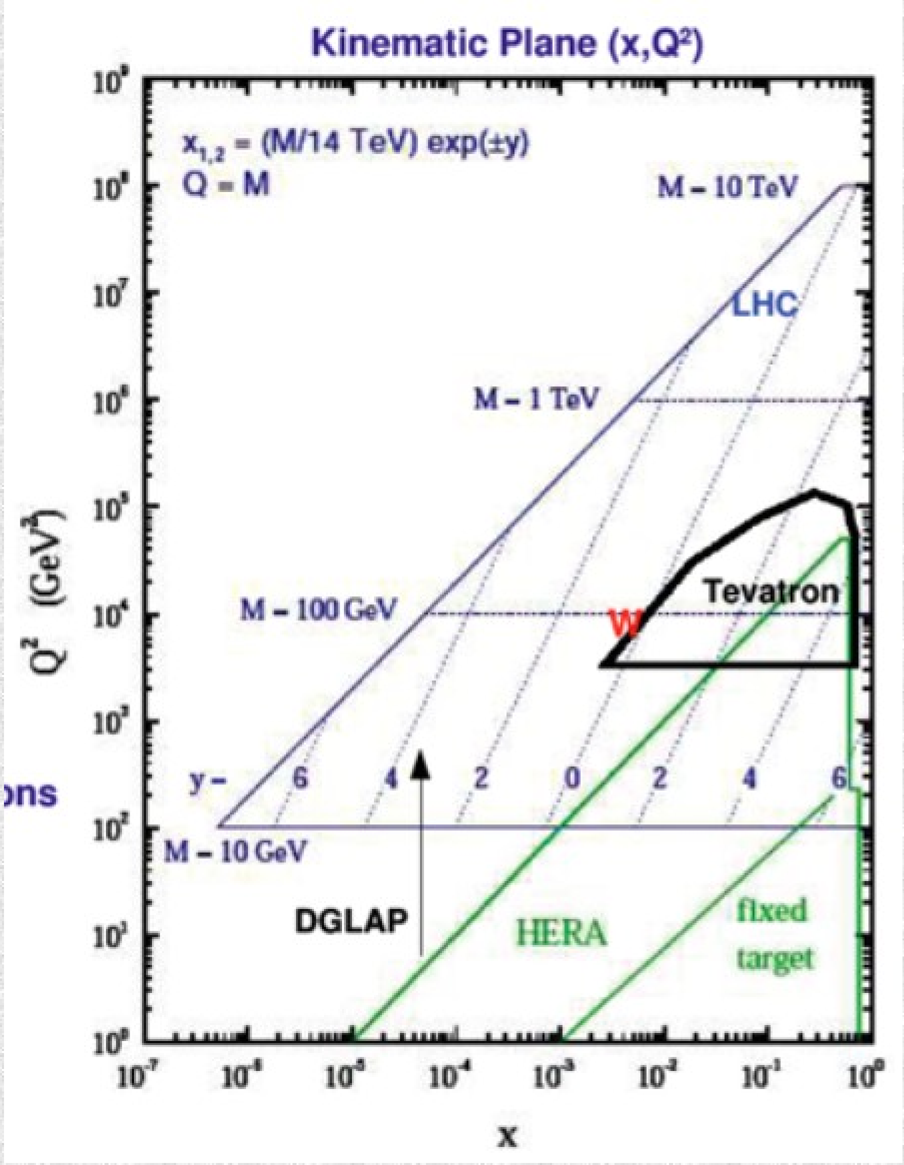
- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) New physics as excess on QCD large-p_T spectra ⇔ large x PDF
  - Example: Z' production

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

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

but recent work raises the bar:

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



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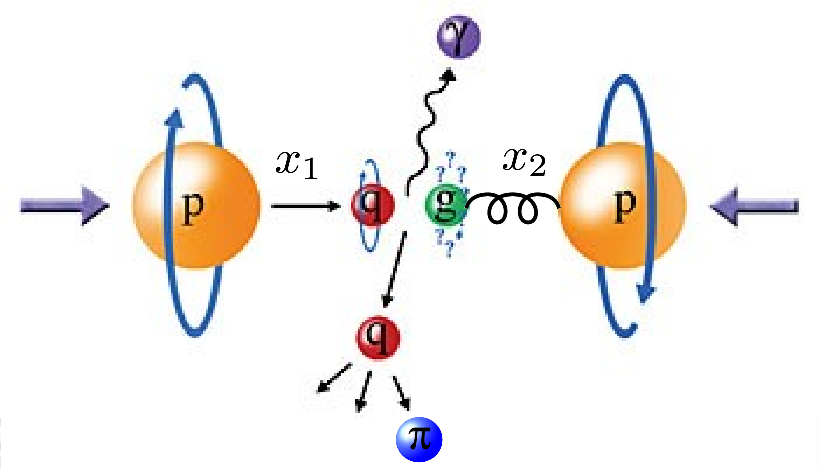
  - spin structure of the nucleon – most spin at large-x, but also, e.g.,

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



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

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

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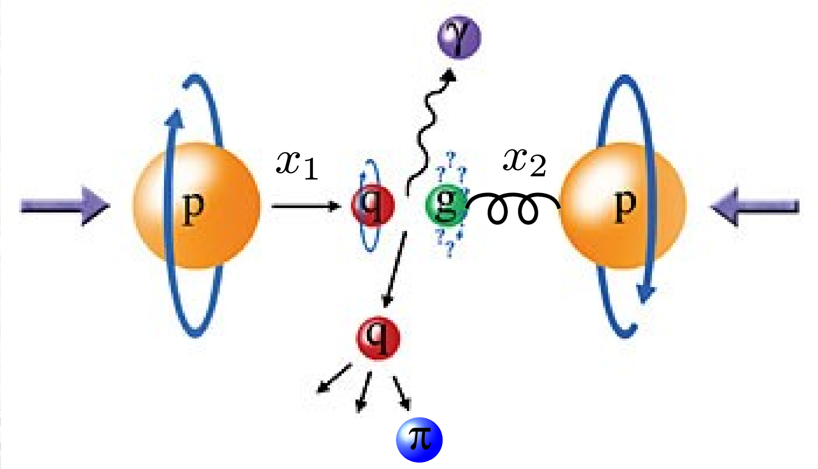
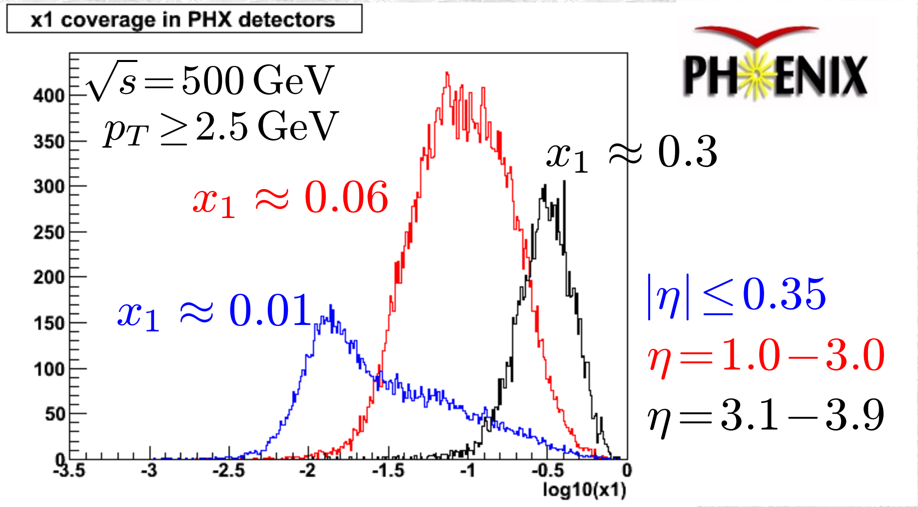
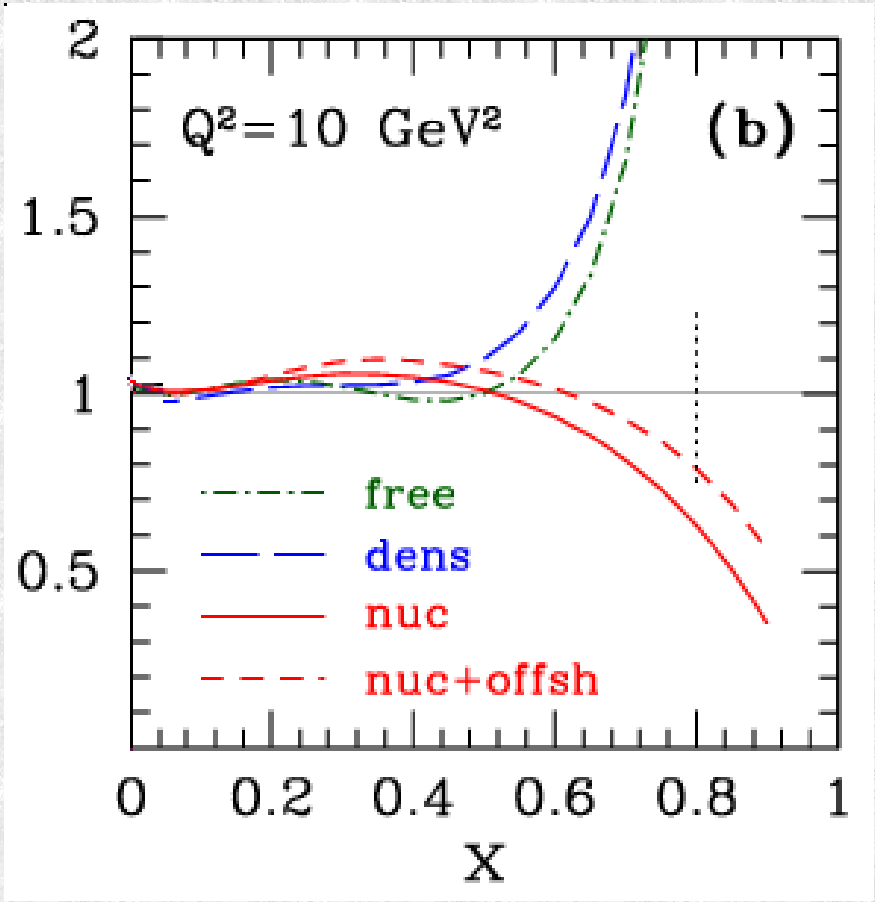




Off-shell corrections



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

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

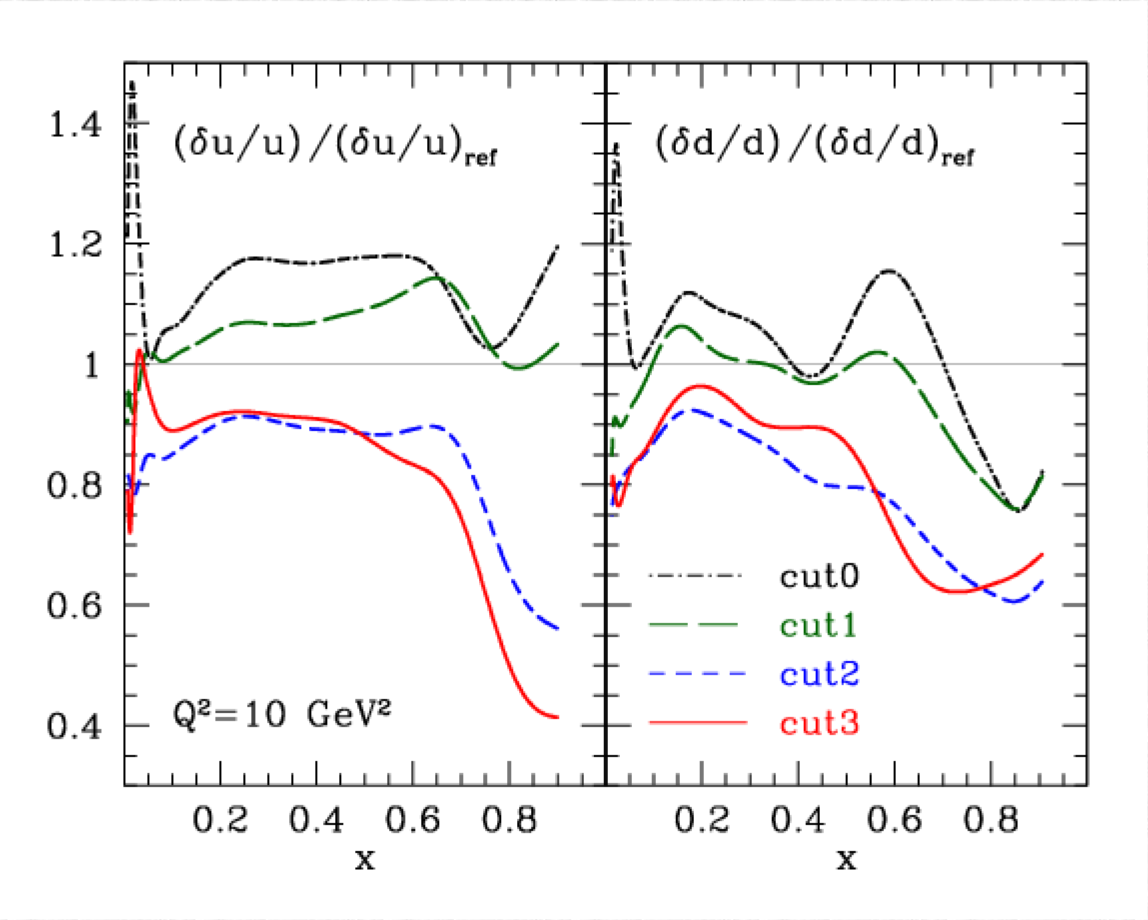
$$\frac{\delta d}{d} = \frac{4}{3} \frac{\delta F_2^d}{F_2^d} (1 + \frac{1}{d/u}).$$

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!



Constraining d-quarks at large x

d-quarks with free nucleon targets

- Weak constraints from
  - *p+p(bar)* : DY at large x_F
    (compensated by small *u*-quark variations)

    $$p\,p(\bar{p}) \longrightarrow \mu^+\,\mu^-\,X$$

  - jets, gamma+jet
    (gluons absorb remaining variations)

    $$p\,p(\bar{p}) \longrightarrow jet\;X$$
    $$p\,p(\bar{p}) \longrightarrow \gamma\;jet\;X$$

- Weak interactions: direct access to d-quark, but limited *x*-coverage so far:
  - *p+p(bar)* : W-asymmetry at large rapidity
    [D0 and CDF]
  - Charged current structure functions
    [combined H1 and ZEUS data]

d-quarks with free nucleon targets

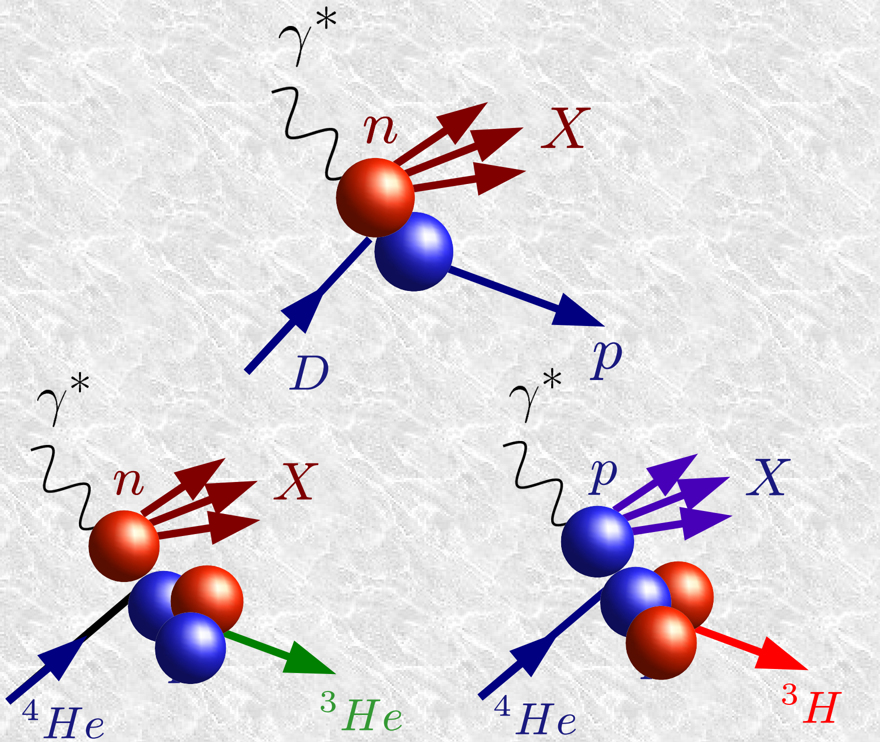
- Weak interactions – new experiments
  - ν+*p* and ν-*bar*+*p* $\nu(\bar{\nu})\, p \longrightarrow l^{\pm}\, X$
    - WA21 already has data
      (but hard to reconstruct cross-sections from published "quark distributions")
    - MINERνA with a hydrogen target
  - Parity Violating DIS * $\vec{e}_L(\vec{e}_R)\, p \longrightarrow e\, X$
    - L/R electron asymmetry ⇒ γ/Z interference ∝ d/u

* planned for Jlab at 12 GeV

Minimizing nuclear corrections

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

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



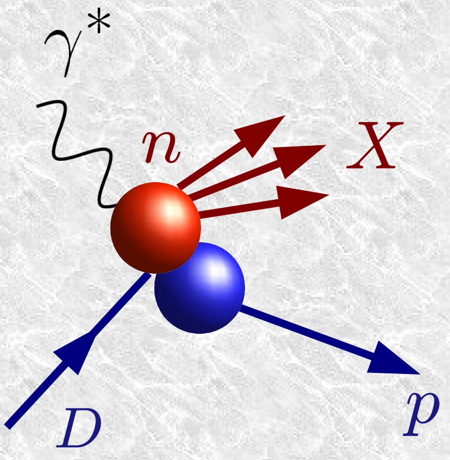
- ^{3}He - ^{3}H mirror nuclei *

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

* planned for Jlab at 12 GeV

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

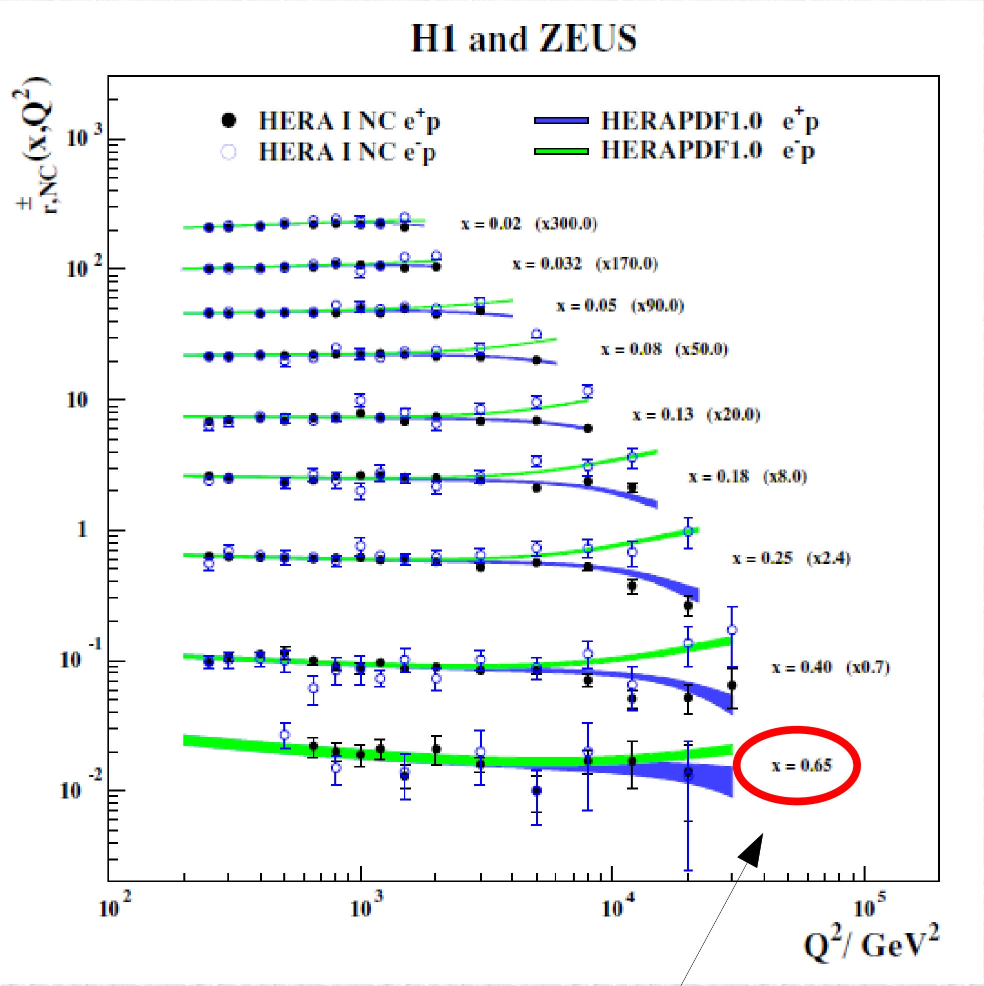
$$q \equiv q_D(x, Q^2, p^2)$$

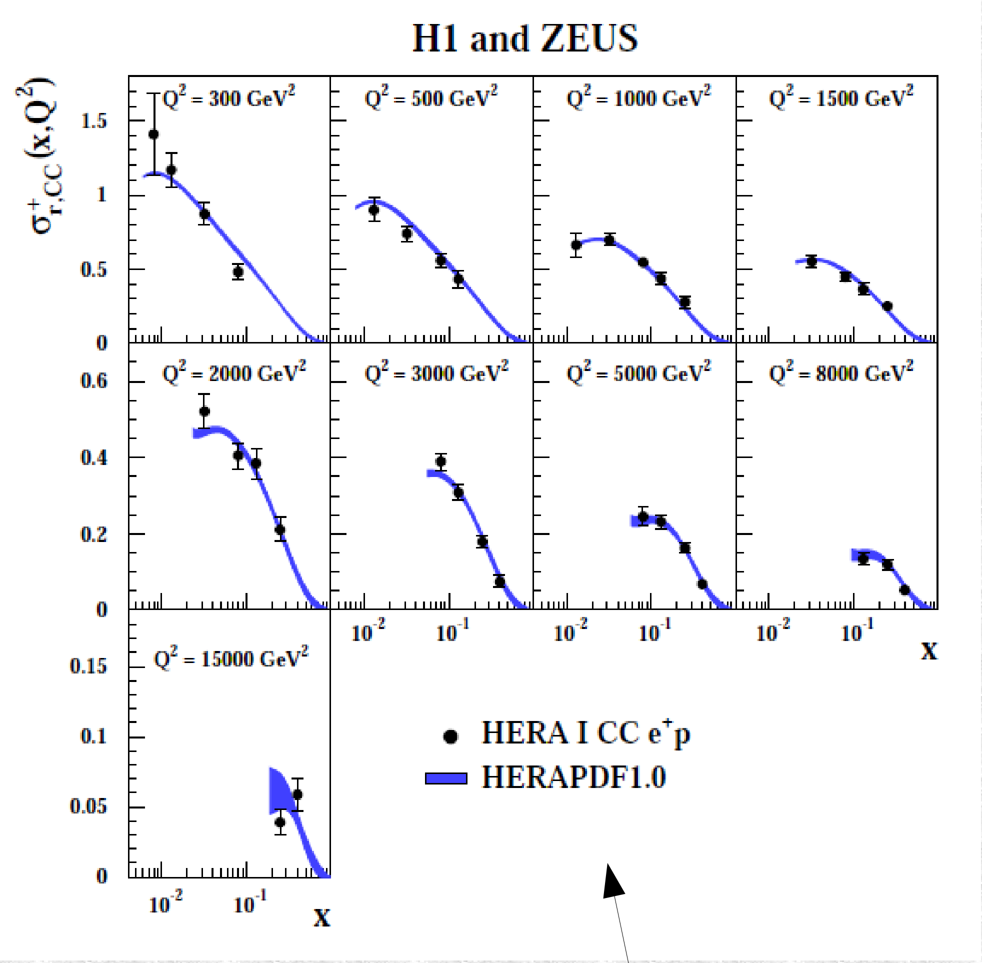
- Extrapolate to a free neutron target $p^2 \to M_n{}^2$

HERA combined data

[JHEP 1001,2010]

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



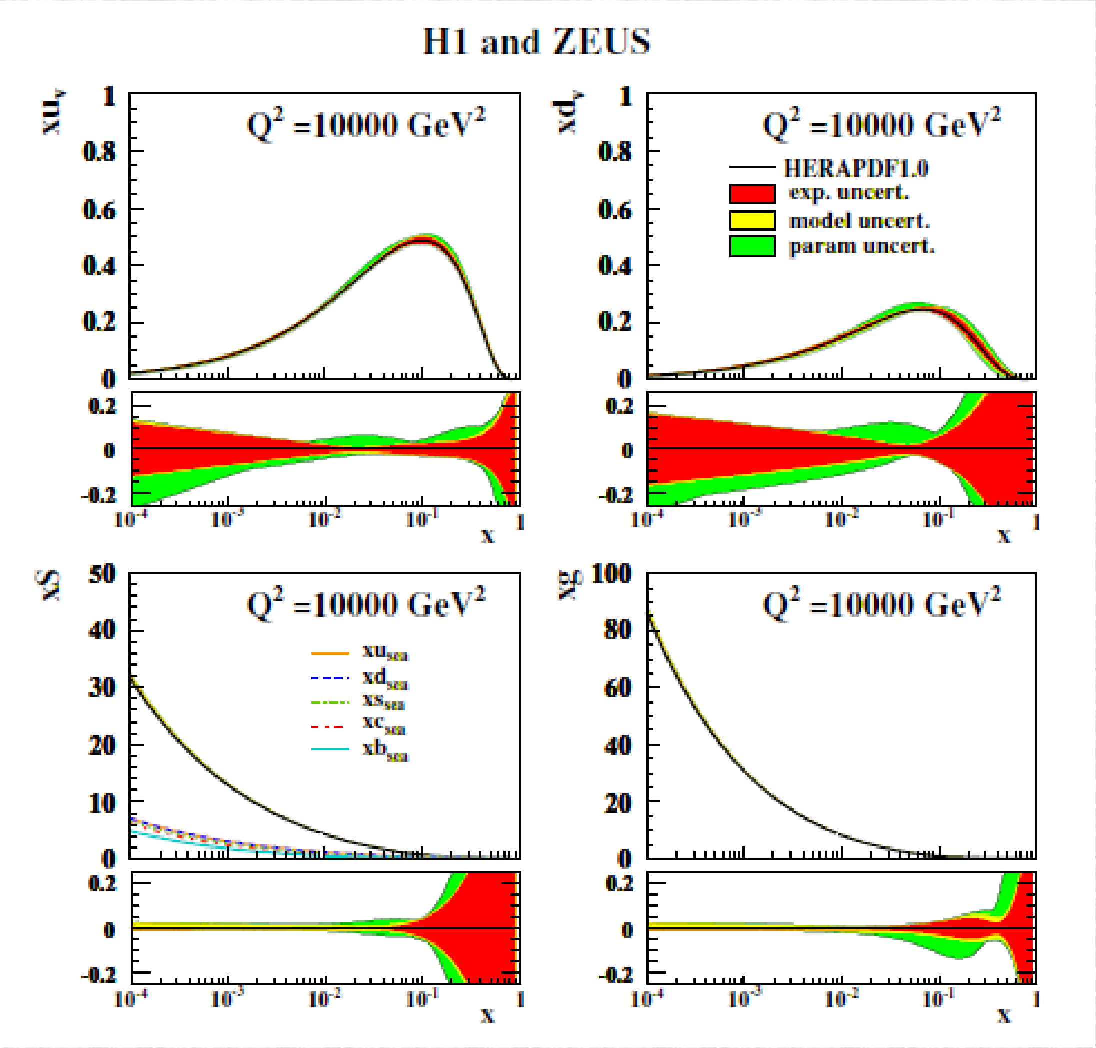


Reaches into the critical x range

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