Flavor separation at large x

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Outline

Why large x (and low-Q^2)

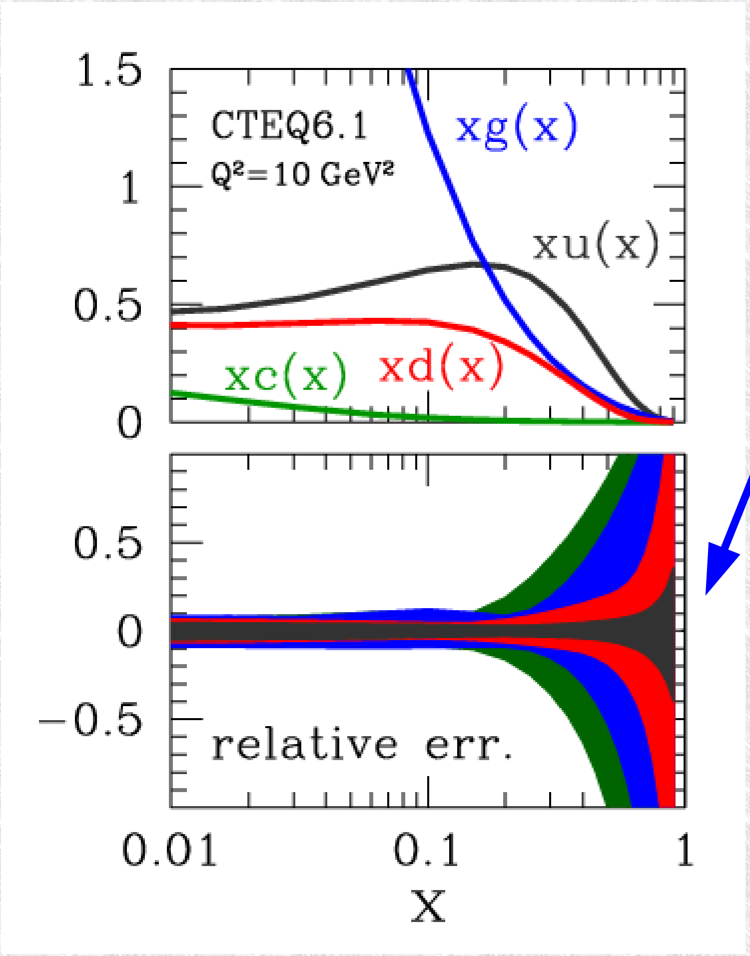
- Up and down: the CTEQ6X fit
- Gluons
- Intrinsic charm

Conclusions

Why large-x, low-Q^2?

Why large x and low Q^2 ?

- 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 and low Q^2 ?

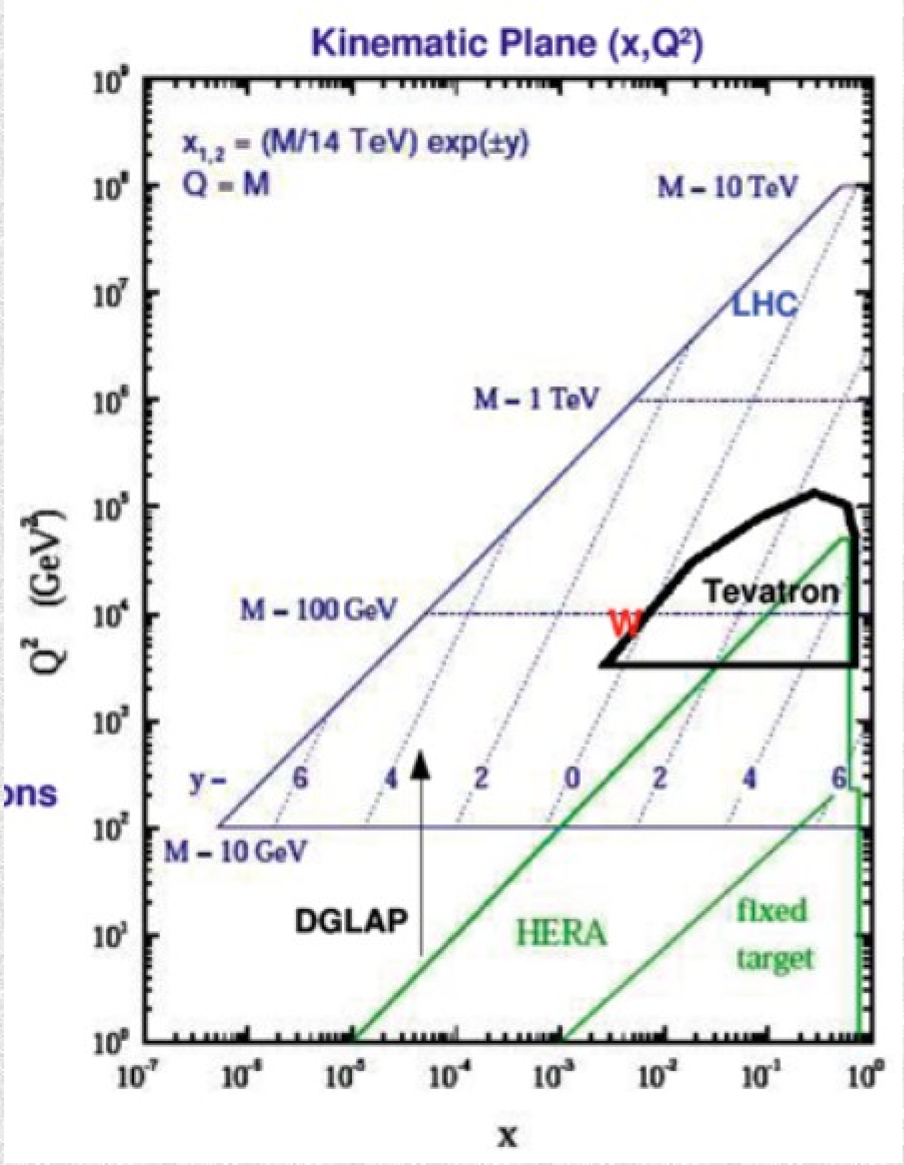
- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) QCD background in high-mass new physics searches
  - Example: Z' production

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

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

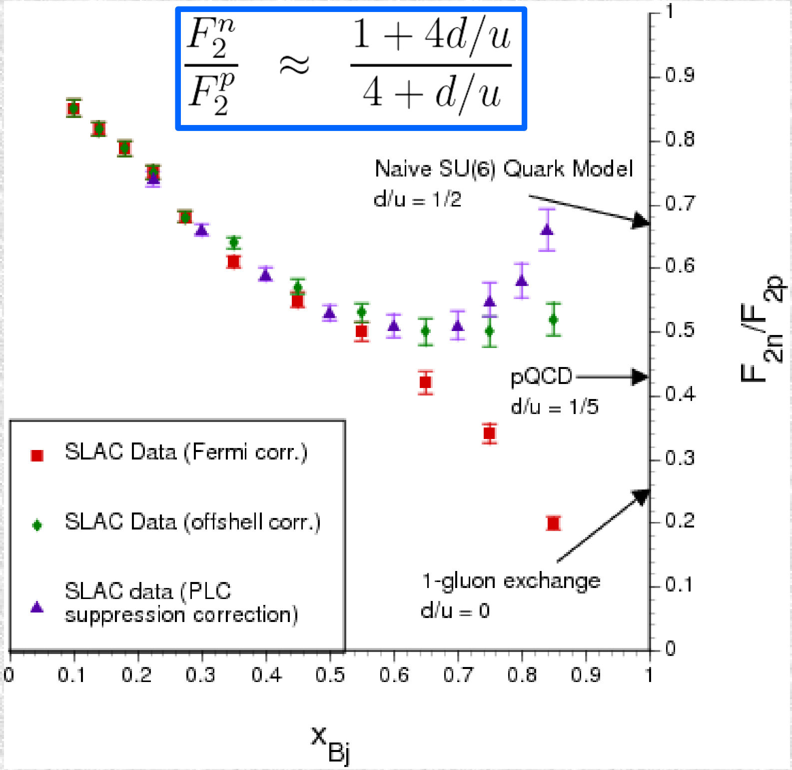
but recent work raises the bar:

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



Why large x and low Q^2 ?

- 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 in large p_T spectra ⇔ large x PDF
    2) QCD background in high-mass new physics searches
  - non-perturbative nucleon structure – e.g., d/u at $x \to 1$



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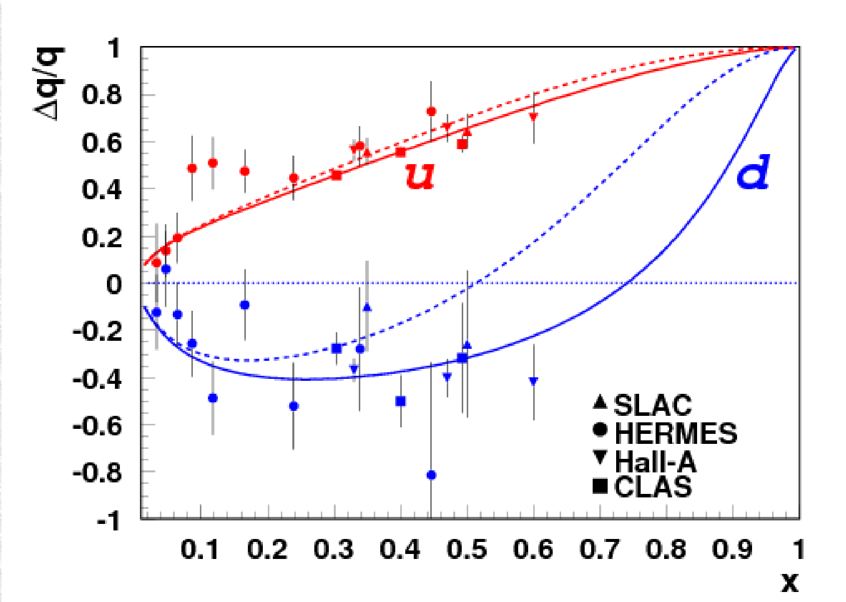

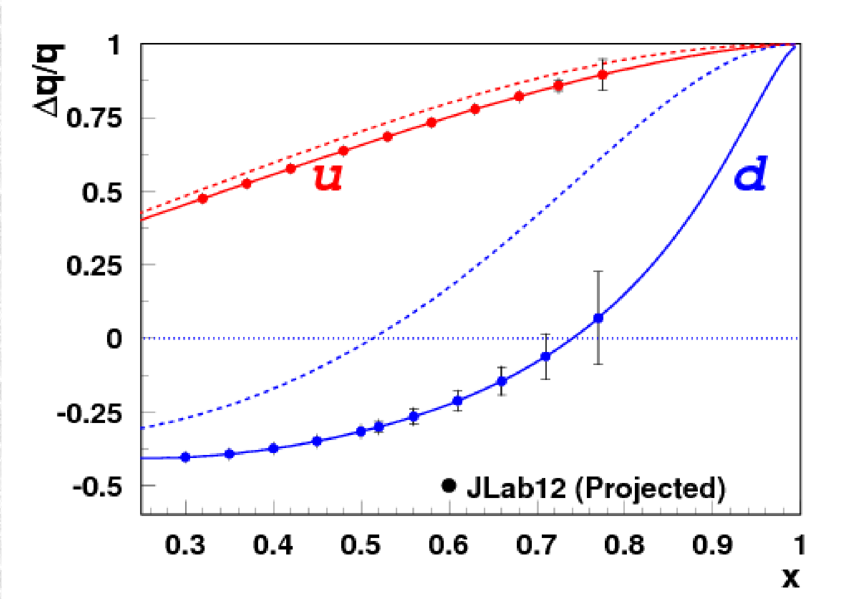

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- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) New physics as excess in large p_T spectra $\Leftrightarrow$ large x PDF
    2) QCD background in high-mass new physics searches
  - non-perturbative nucleon structure
  - spin structure of the nucleon *at small x* [see R.Seidl's talk]
  - 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) 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) ...

Up and down: the CTEQ6X fit

Accardi, Christy, Keppel, Melnitchouk, Monaghan, Morfín, Owens,
Phys. Rev. D 81, 034016 (2010)

CTEQ6X vs. CTEQ

- **CTEQ**

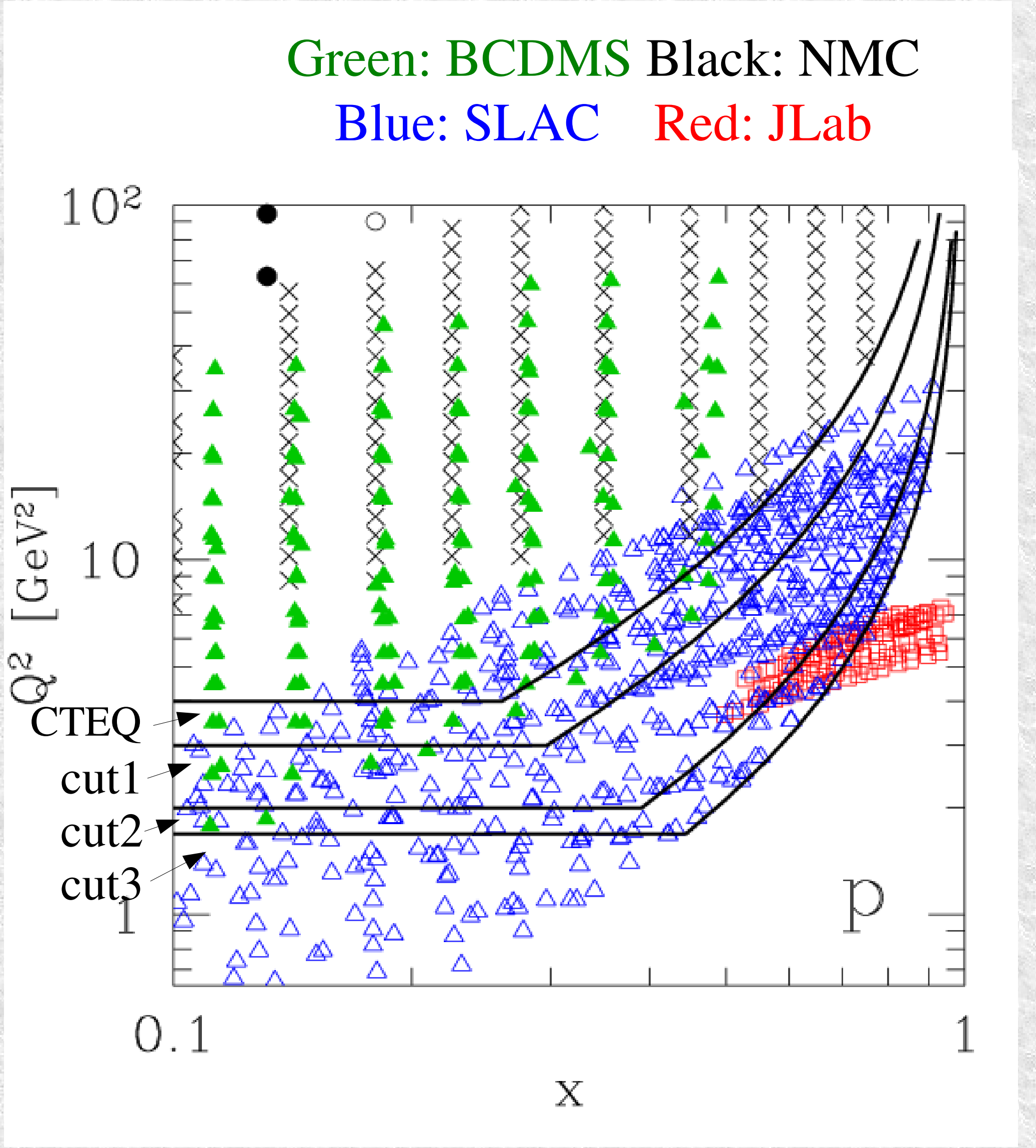
$$Q^2 \geq 4\ \mathrm{GeV}^2 \quad W^2 \geq 12.25\ \mathrm{GeV}^2$$

  - 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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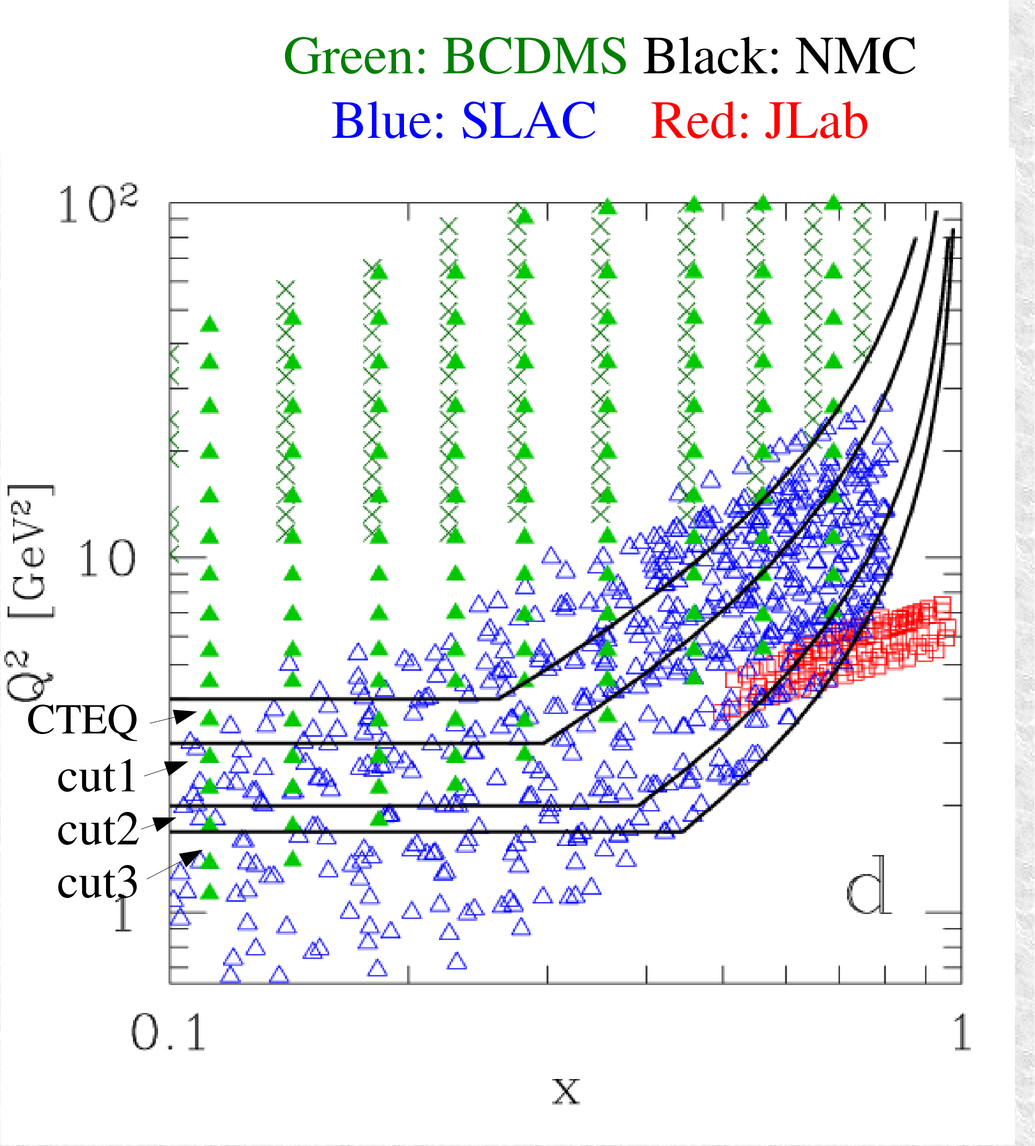
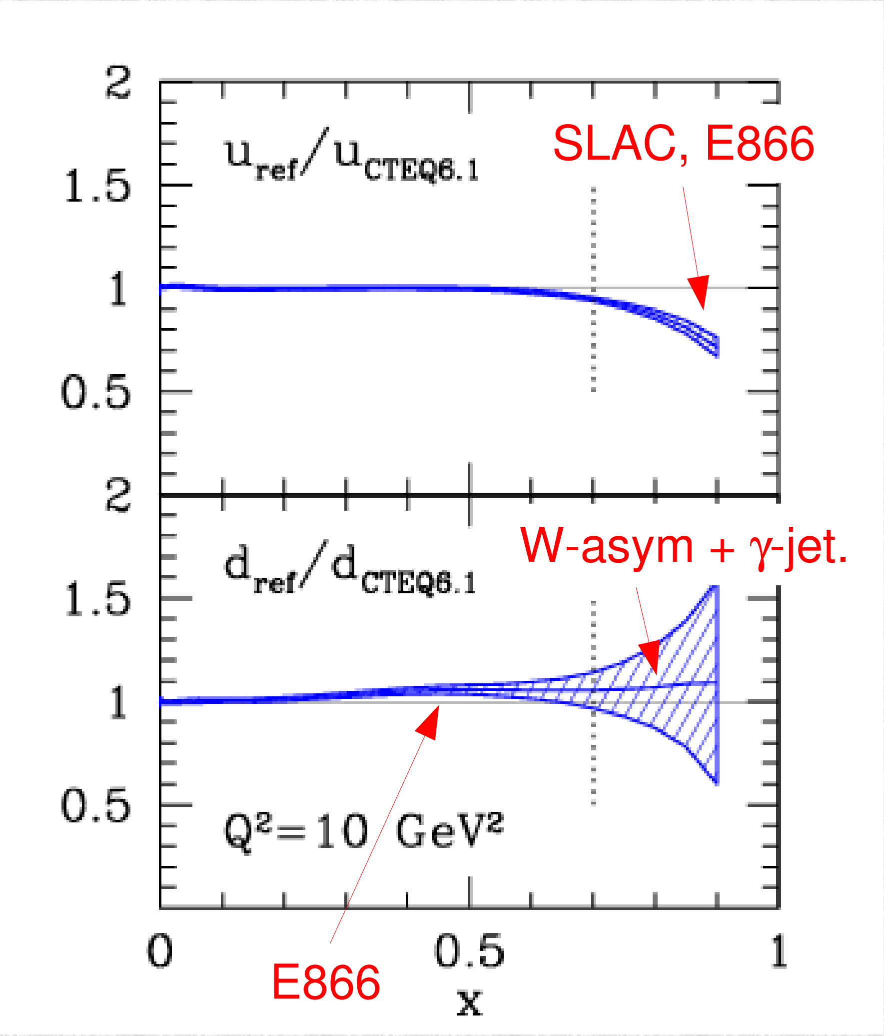


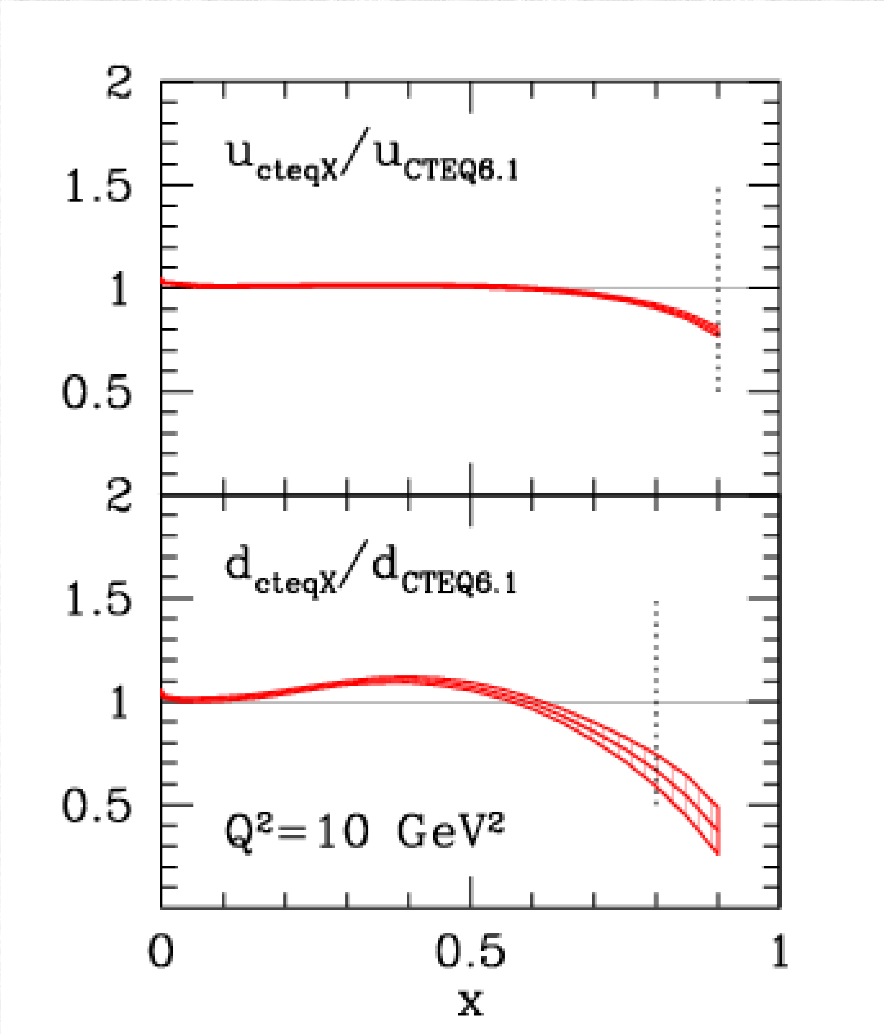
Reference fit vs. CTEQ6.1



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

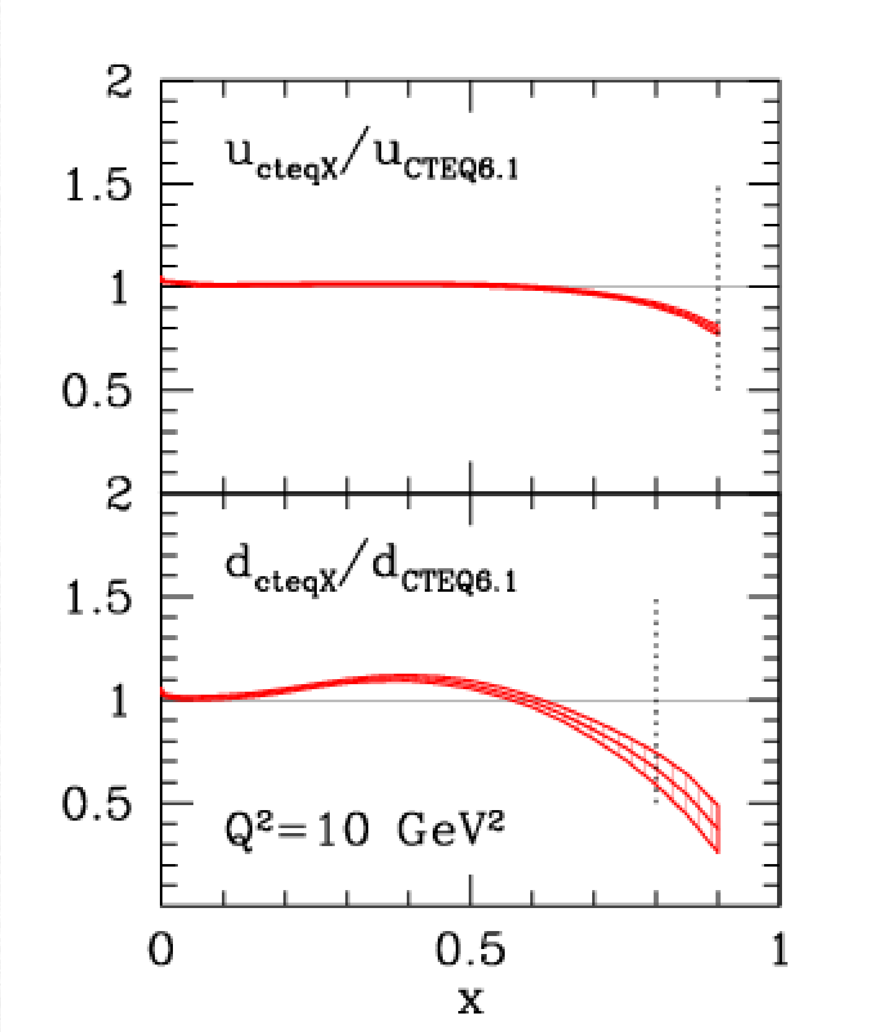
	data	CTEQ6.1
DIS	(JLab)	NO
	SLAC	NO
	NMC	$\surd$
	BCDMS	$\surd$
	H1	$\surd$
	ZEUS	$\surd$
DY	E605	$\surd$
	E866	NO
W	CDF '98 (ℓ)	$\surd$
	CDF '05 (ℓ)	NO
	D0 '08 (ℓ)	NO
	D0 '08 (e)	NO
	CDF '09 (W)	NO
jet	CDF	$\surd$
	D0	$\surd$
γ+jet	D0	NO

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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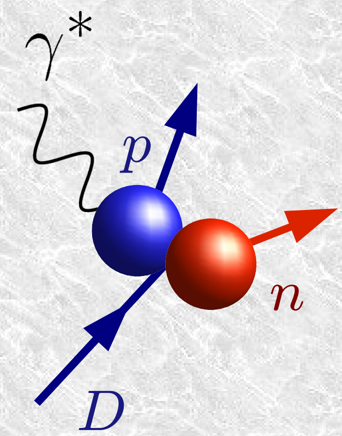
  - cut3, TMC+HT
  - deuteron corrections
- **TMC, HT compensate each other**
- **u-quark:**
  - almost unchanged
- **d-quark suppressed**
  - *due to deuteron corrections*
- **Reduced PDF errors**
  - approx factor 2

Deuterium corrections

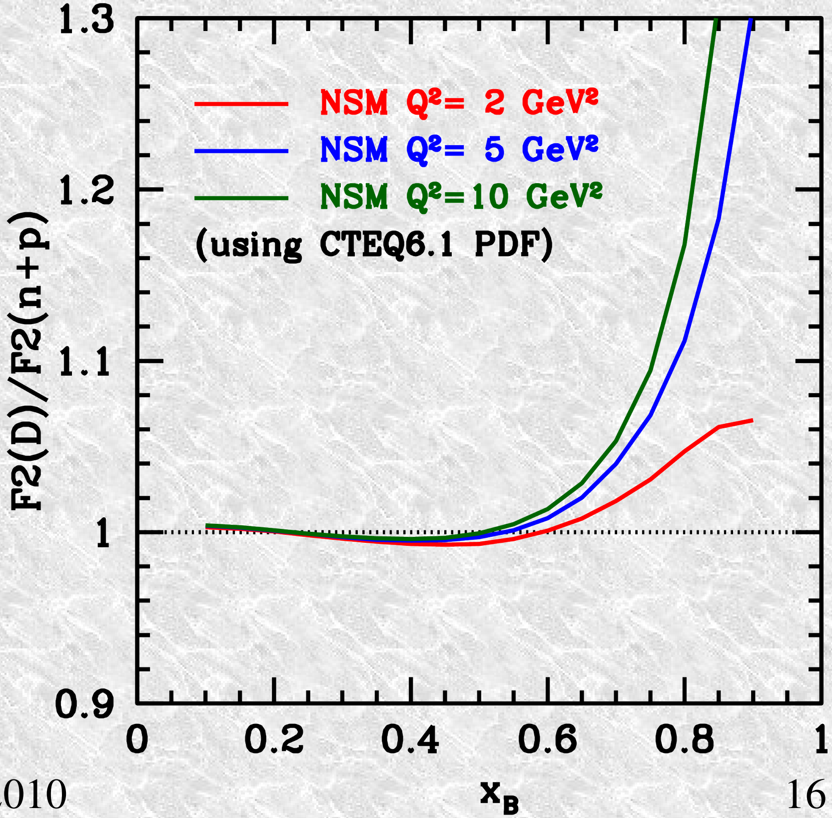
- Nuclear Smearing Model [Kahn et al., PRC79(2009) Accardi,Qiu,Vary, *in preparation*]
  - nucleon Fermi motion and binding energy
  - use non-relativistic deuteron wave-function
  - **finite-Q^2 corrections** (very important!)



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

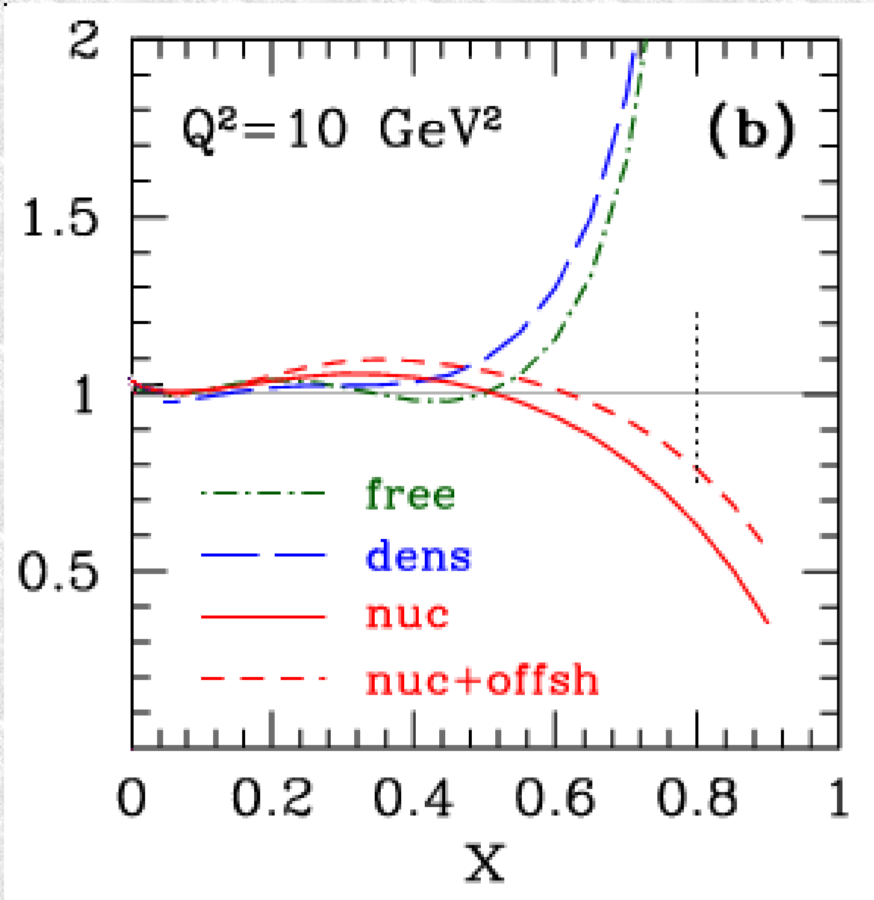
$$\gamma = \sqrt{1 + 4x_B^2 m_N^2 / Q^2}$$

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



- off-shell effects can be included in S_A

Deuterium corrections



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

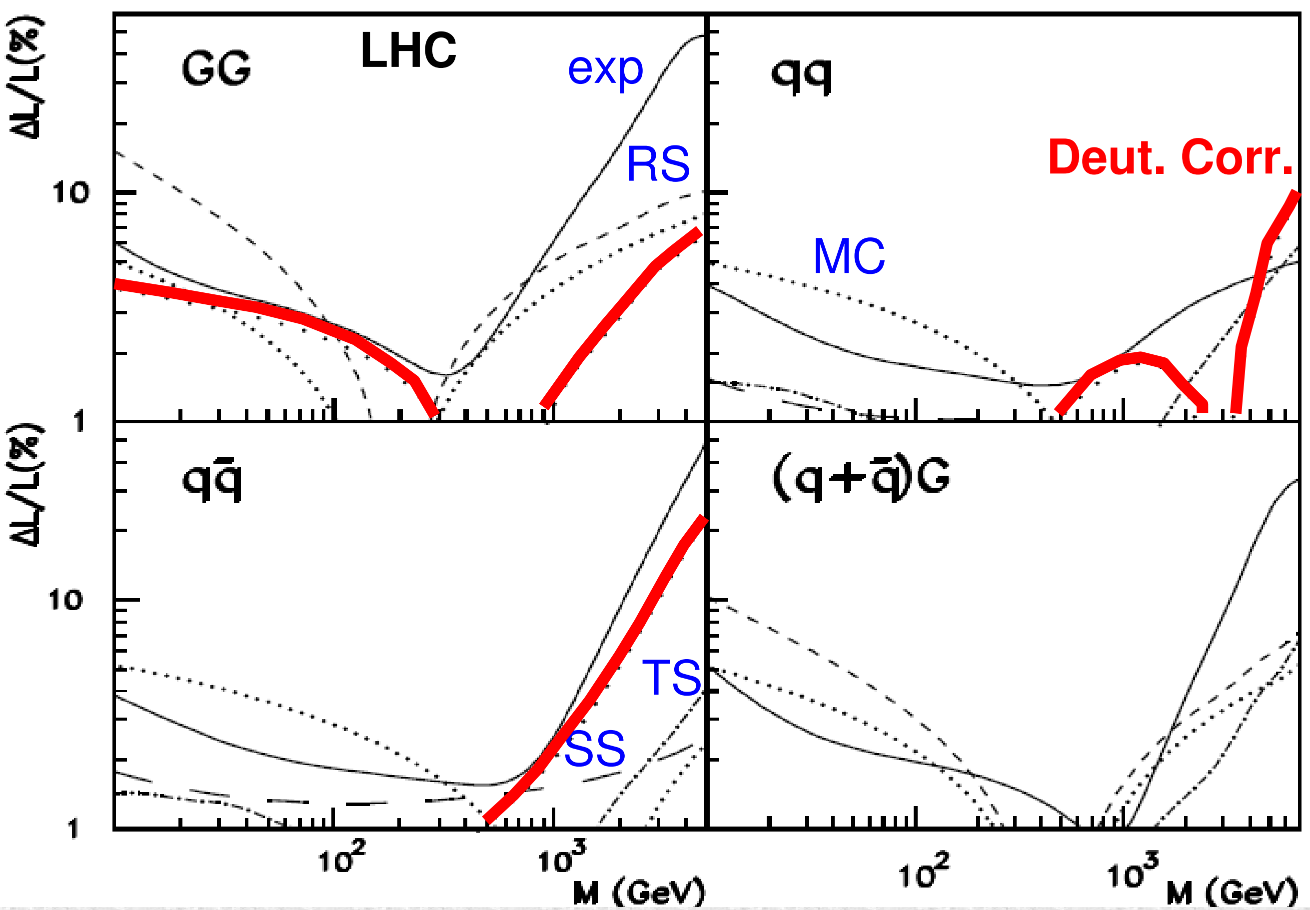
free	= free p+n
dens	= density model corrections
nuc	= WBA smearing model
offsh	= off-shell corrections

[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-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

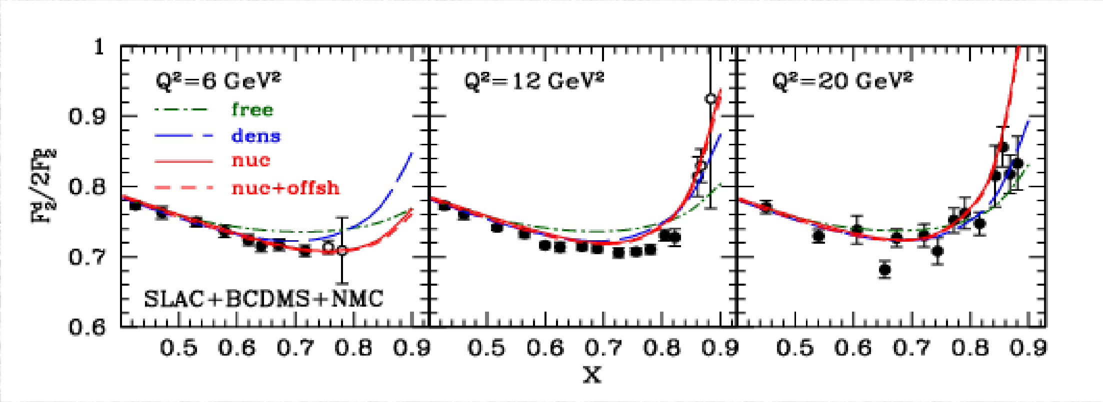
Free nucleon targets

- Constraints on large-x d-quarks from
  - *p+p(bar)* : 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 ZEUS]
  - 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

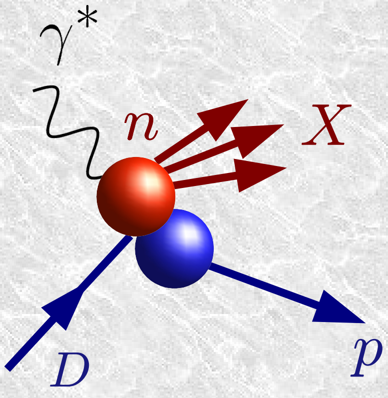
Constraining the nuclear corrections

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



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

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



- ³He - ³H mirror nuclei *

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

* planned for Jlab at 12 GeV

Gluons

Observables for gluons

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

- $dF_2 / d(\ln Q^2)$
  - indirect
  - little leverage at large x, large errors

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

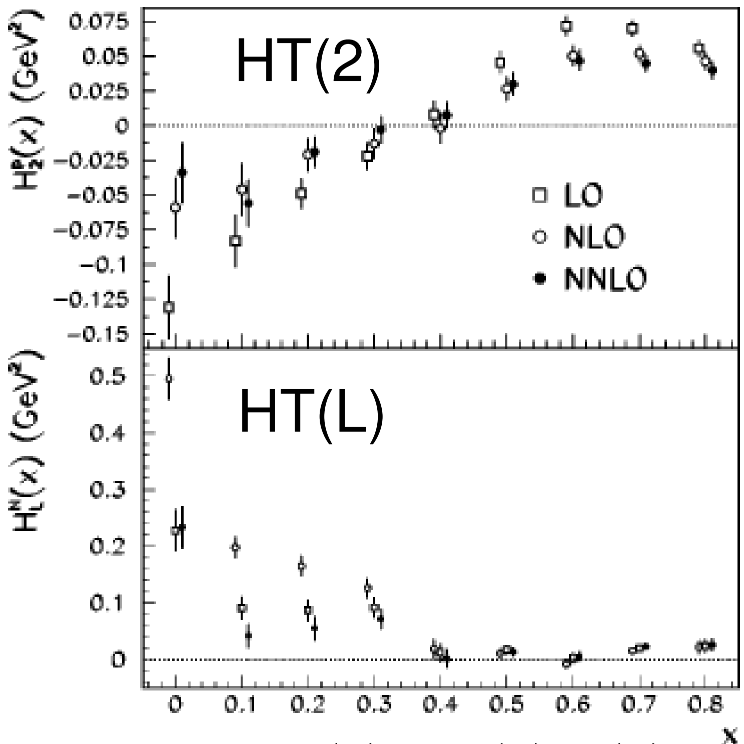
F_L – HT and perturbative stability

- 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]

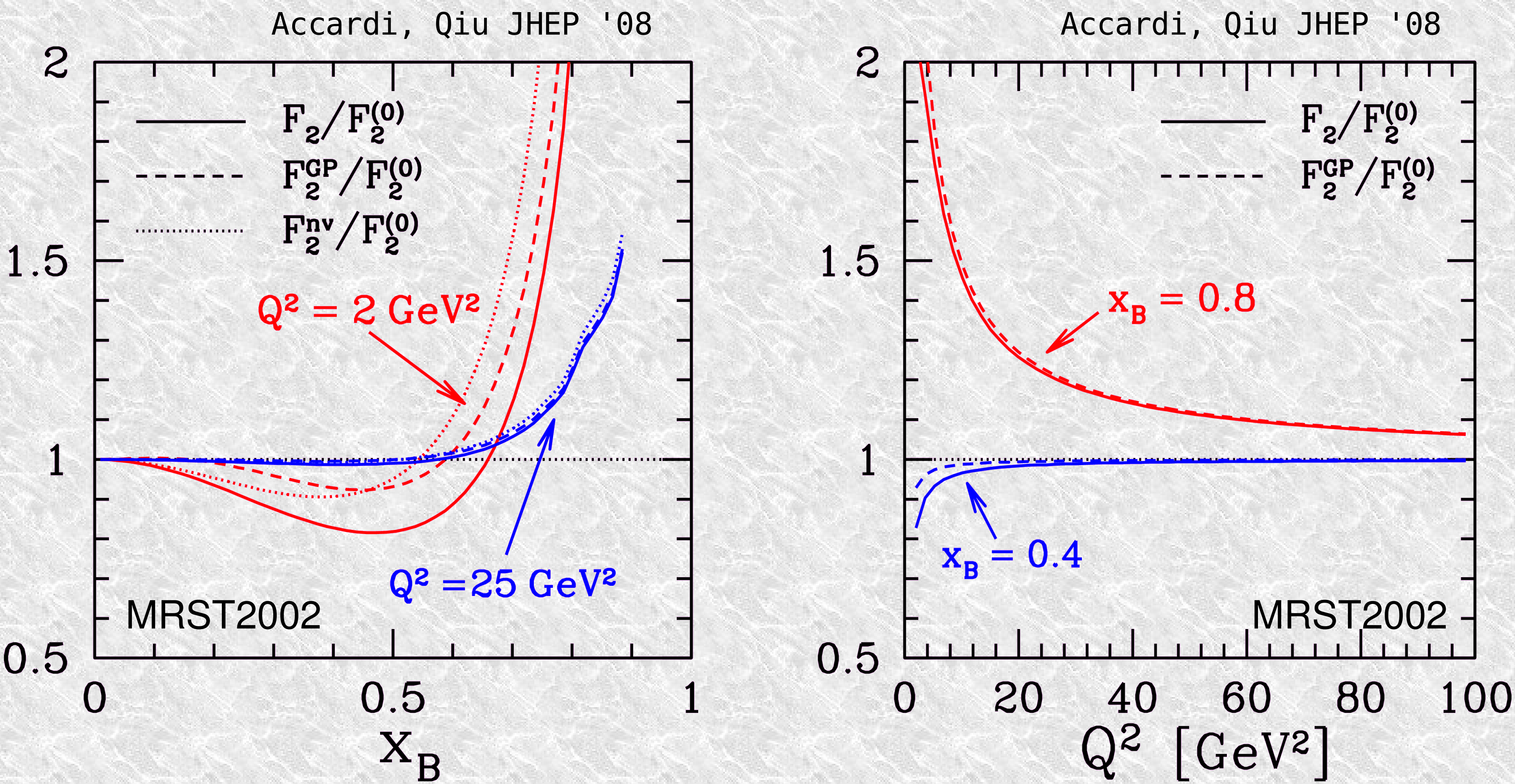
Alekhin, PHYSICAL REVIEW D **68**, 014002 (2003)



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

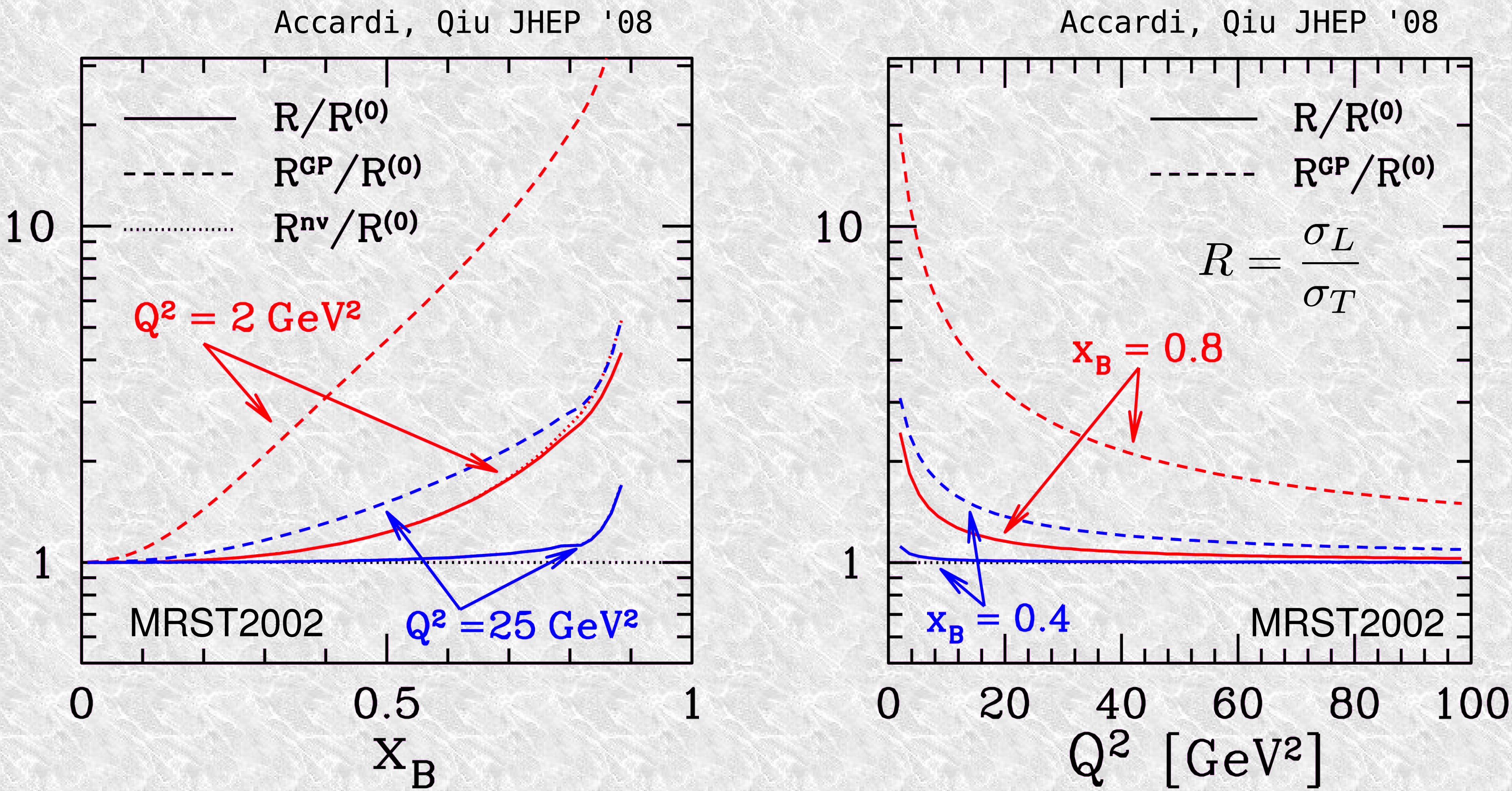
Target Mass Corrections

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



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

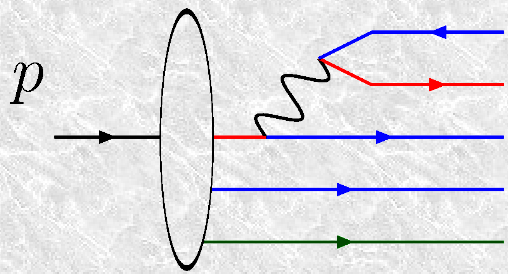
Intrinsic vs. radiative charm

- Usual assumption in global fits: at threshold

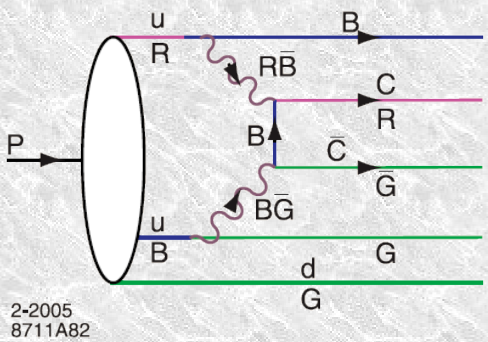
Pumplin, PRD73(06),
Brodky et al., PRD73(06)
+ references teherein

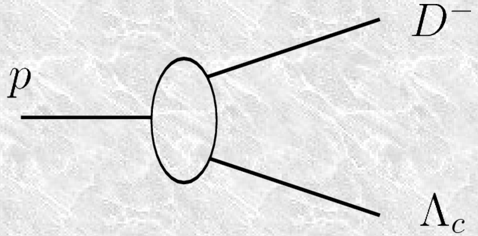
$$c(x, Q_c \approx m_c) = 0$$

  - charm generated during DGLAP evolution

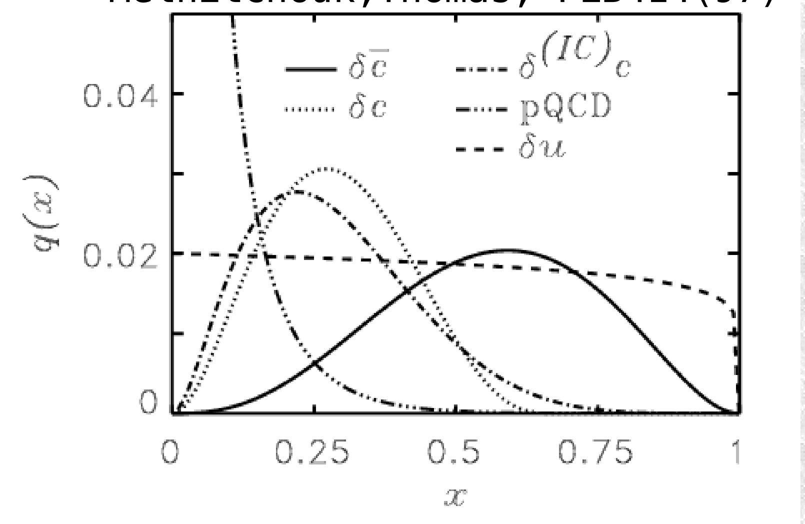


- but QCD predicts intrinsic charm





Melnitchouk,Thomas, PLB414(97)



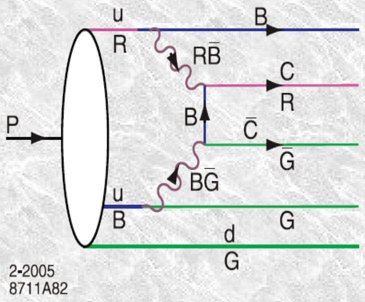
  - a c-cbar pair fluctuation already exists, peaked at large x~0.4
  - fully participates in DGLAP evolution
  - *c, cbar* asymmetry: small @ NLO (pQCD) or large (nonpert. models)

Indications from global fits

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

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

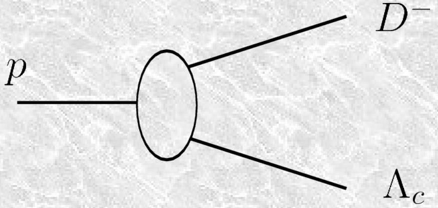
1) Brodsky-Hoyer-Peterson-Sakai [PLB 93 (80)]



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

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

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



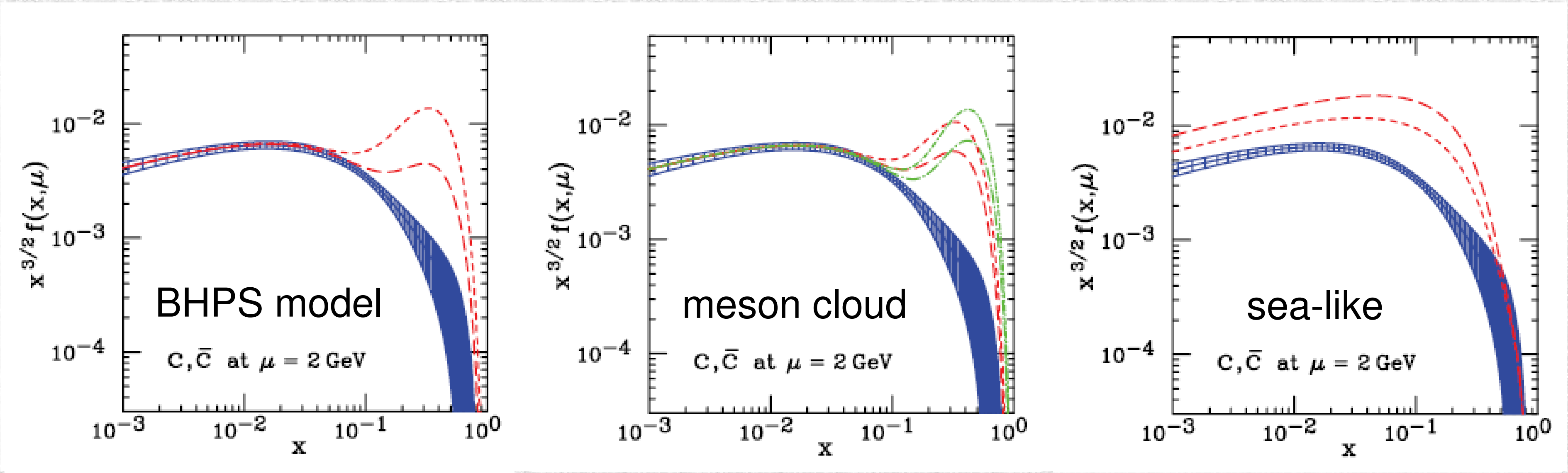
3) phenomenological "sea-like"

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

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*

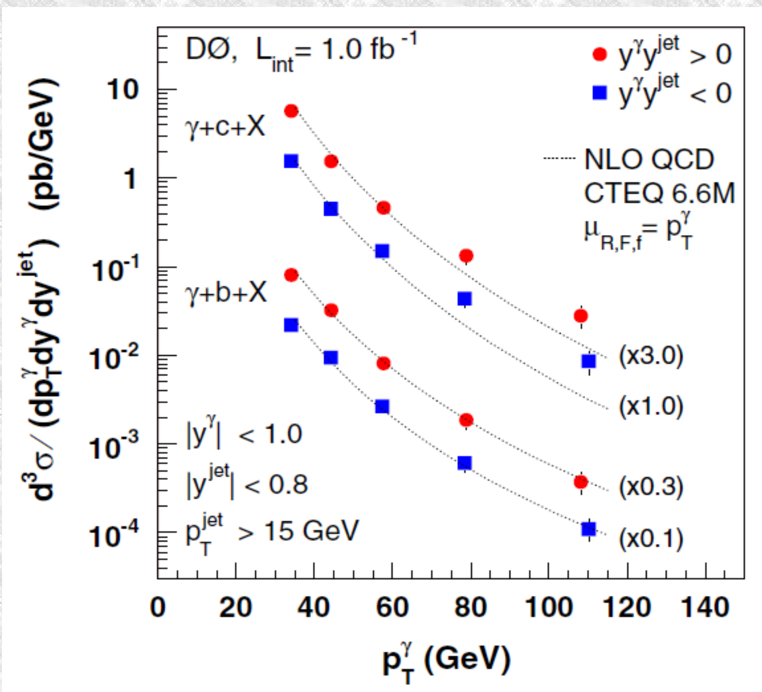


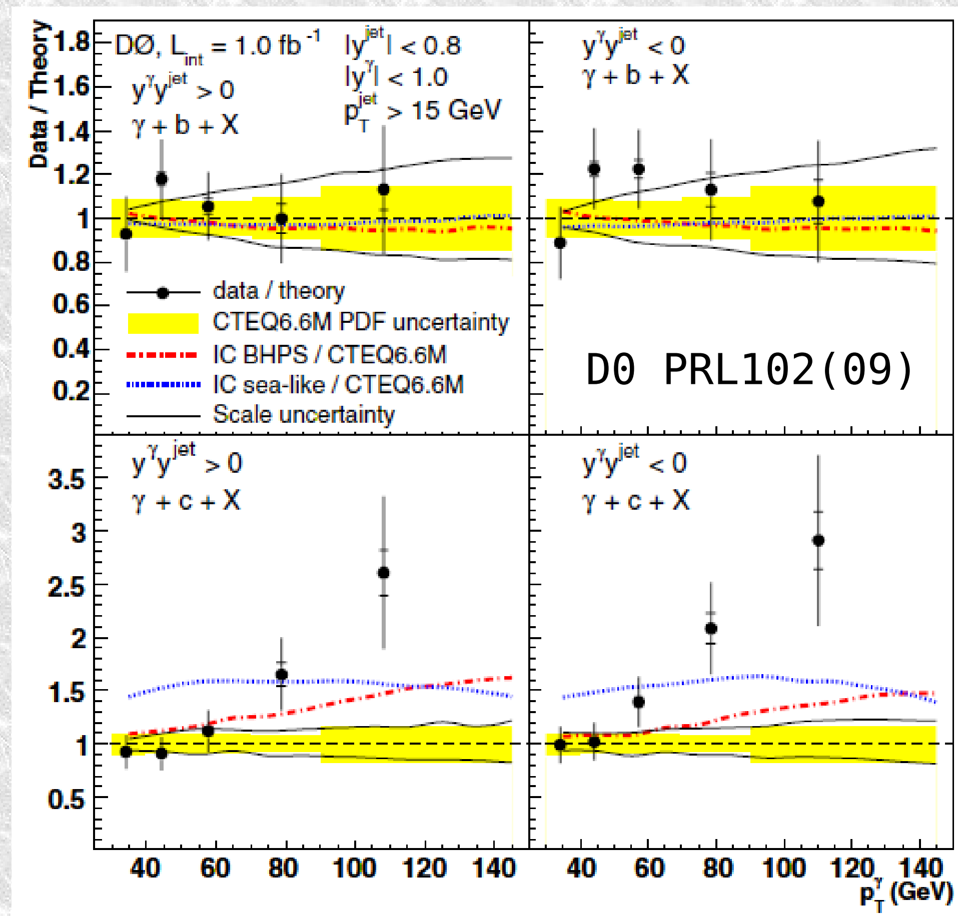
Experimental evidence - D0

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

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

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



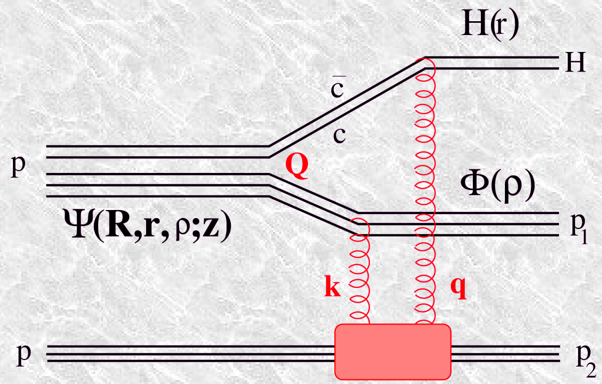


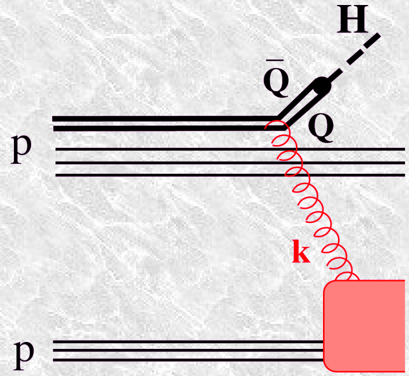
0.01<x<0.3 and 10^3<Q^2<10^4

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

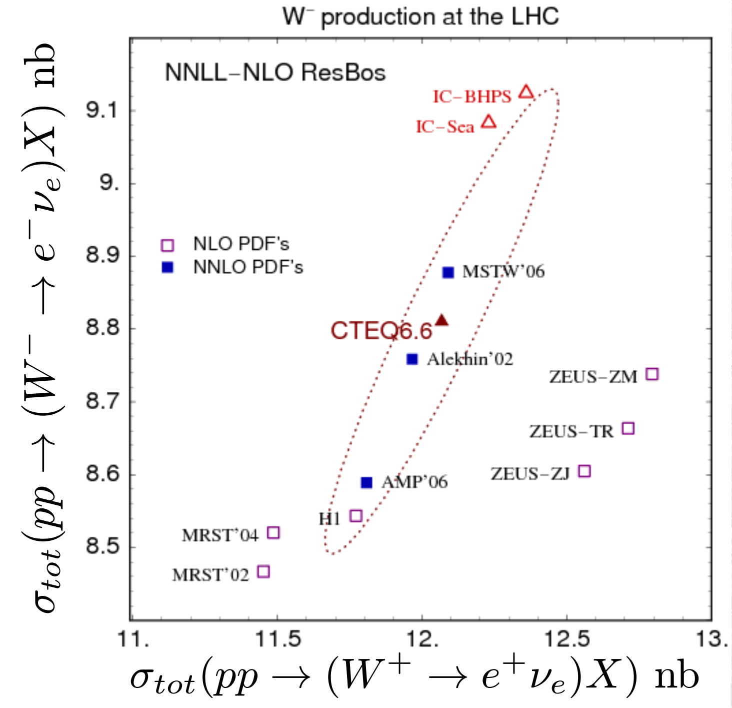
Phenomenological implications

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





  - W production [Nadolsky et al. PRD78(08)]



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***

- **F_L/F_2 ratio** [Ivanov, NPB814(09)]

- **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

Target and heavy-quark mass corrections

- DIS in collinear factorization: [Accardi, Qiu JHEP '08]

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

f parton mass — Nachtmann variable

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

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

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

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

Conclusions

- **Flavor separation at large *x* important**
  - to understand the nucleon structure
  - for phenomenological applications
- **but needs theoretical corrections**
  - target/quark mass, HT, nuclear corrections, ...
- **u, d quarks**
  - CTEQ6X reveals d-quark suppression compared to CTEQ / MRST fits
  - Essential to control nuclear corrections, or use free nucleon target
- **Gluons:** will be included in the CTEQ6X global fit
- **Intrinsic charm:** interesting direction for the future

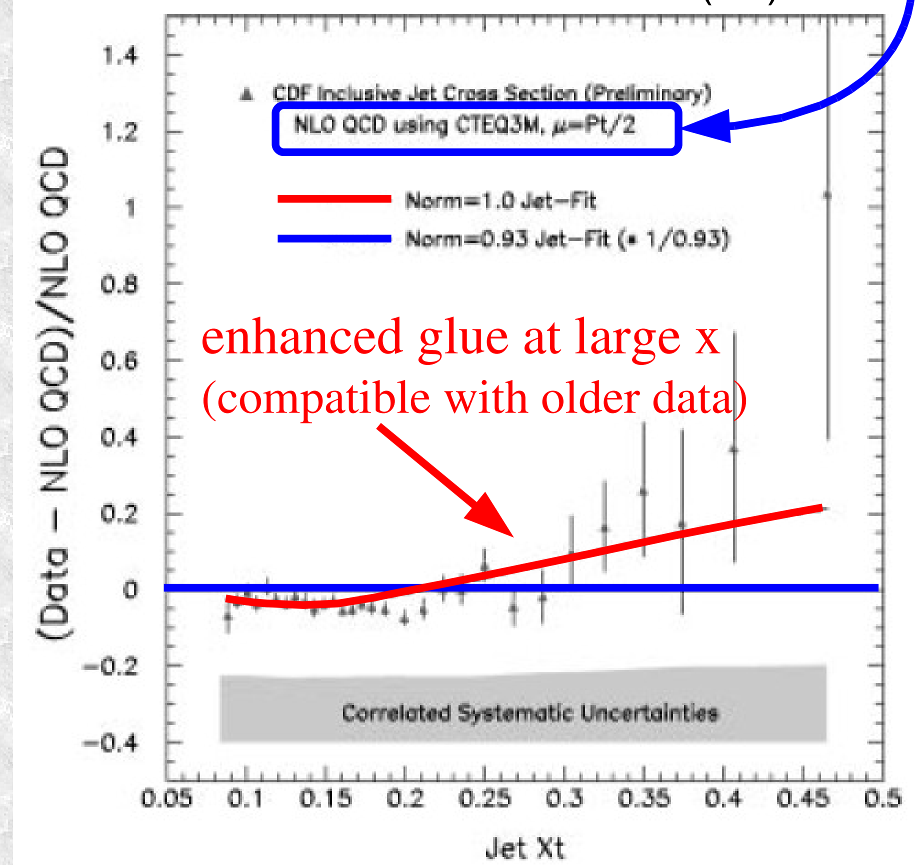
BACKUP SLIDES

Why large x_B and low Q^2 ?

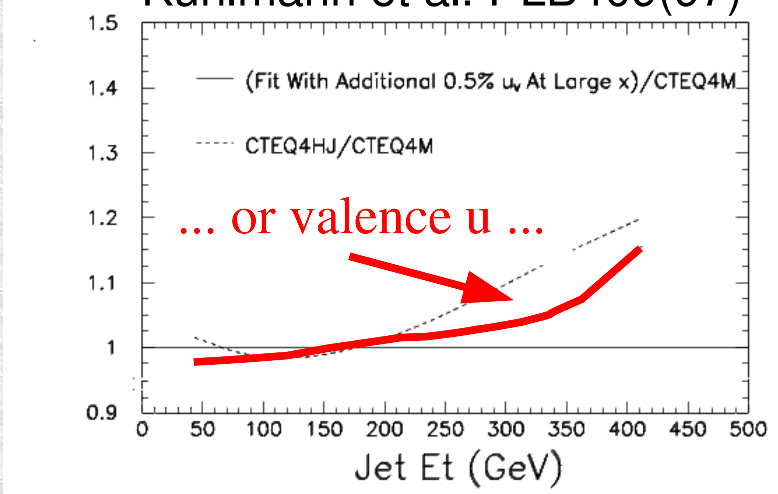
- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) New physics as excess in large-p_T spectra $\Leftrightarrow$ large x PDF
  - Example 2: 1996 CDF p_T excess

NLO state of the art at the time

Kuhlmann et al. PLB476(00)



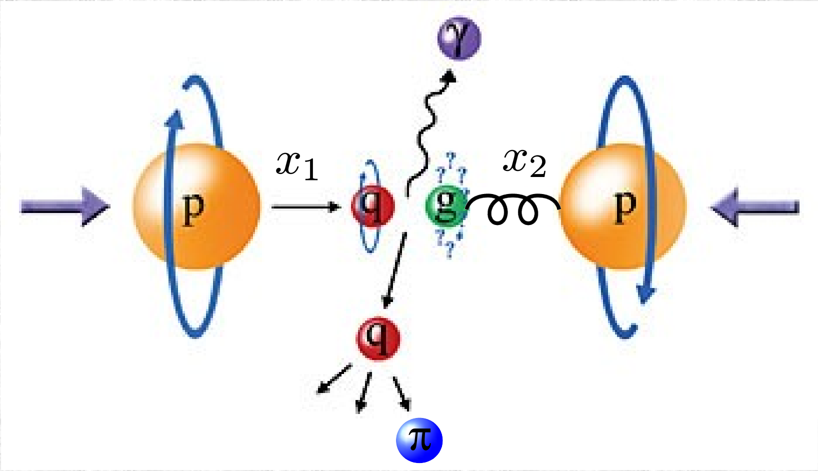
Kuhlmann et al. PLB409(97)



Why large x_B and low Q^2 ?

- 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 in large p_T spectra ⇔ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - non-perturbative nucleon structure
  - spin structure of the nucleon – most spin at large-x, but also, e.g.,

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



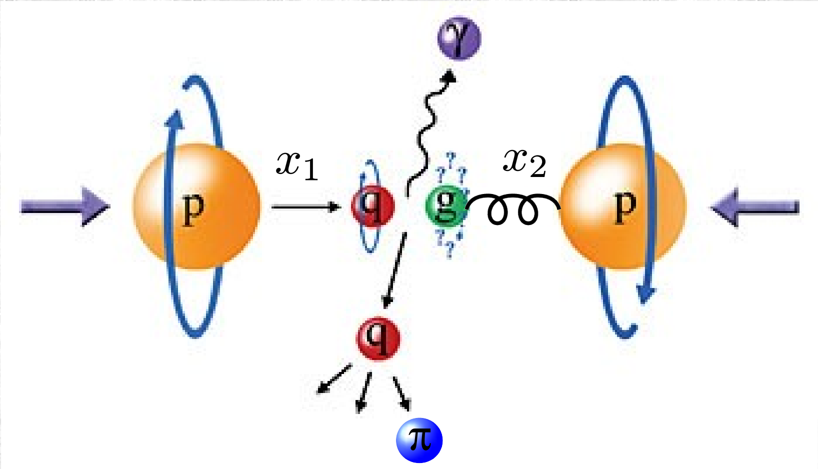
$$x_1 \sim \frac{p_T}{\sqrt{s}}e^{y}$$

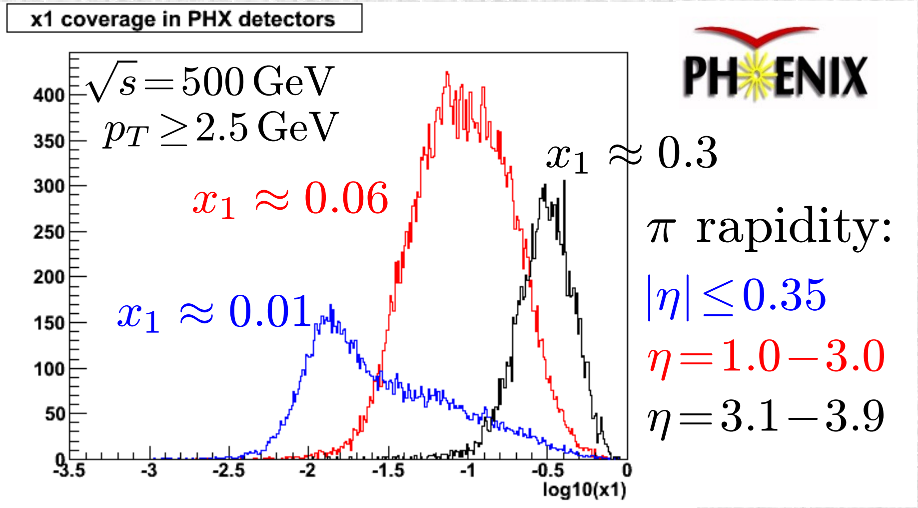
$$x_2 \sim \frac{p_T}{\sqrt{s}}e^{-y}$$

Why large x and low Q^2 ?

- 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 in large p_T spectra $\Leftrightarrow$ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - non-perturbative nucleon structure
  - spin structure at small x

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





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-scaling**, 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 $x_B > 1$ (!)

"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

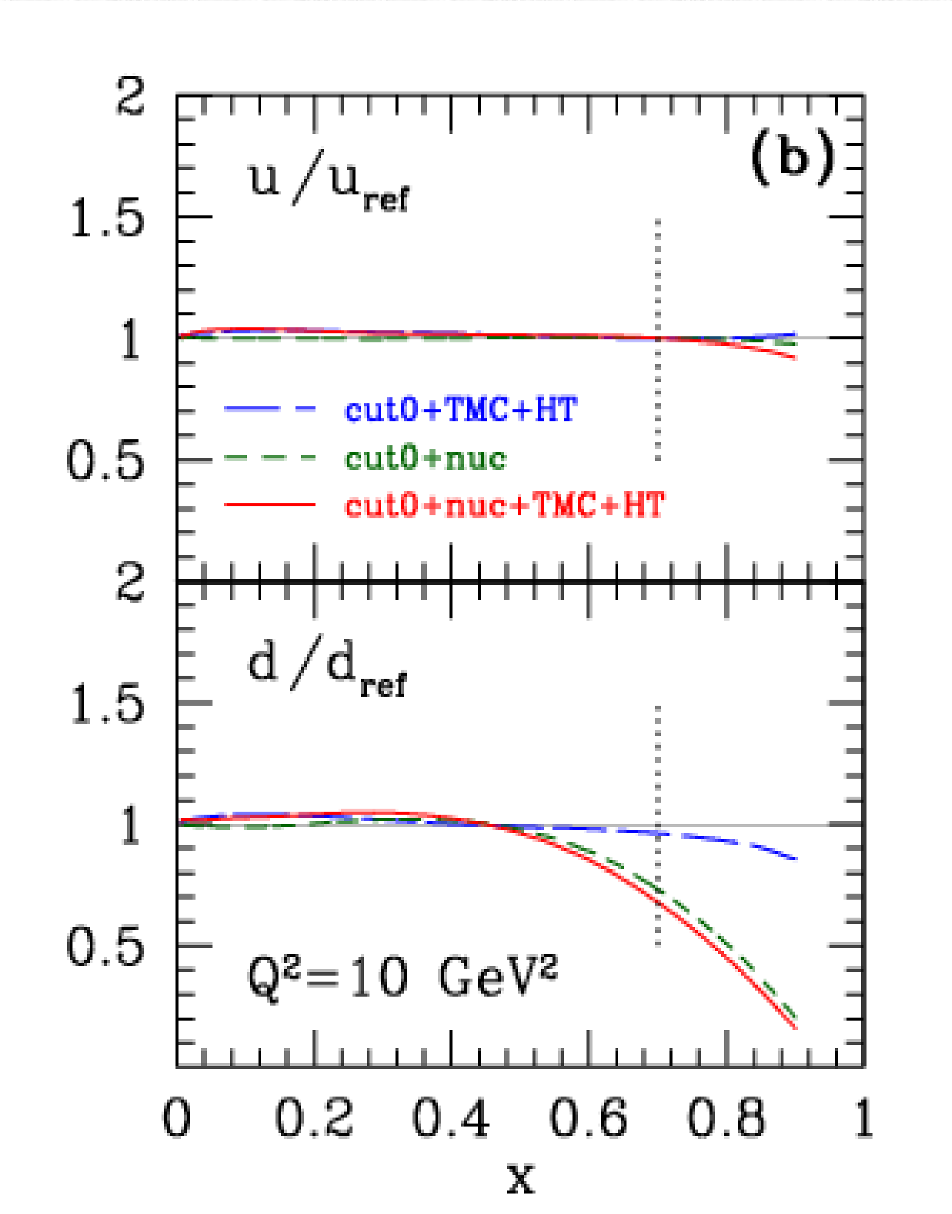
$$C(x_B) = a\,x^b\,(1 + c\,x)$$

  - parametrization is sufficiently flexible to give good fits to data
  - c parameter allows negative HT at small x_B

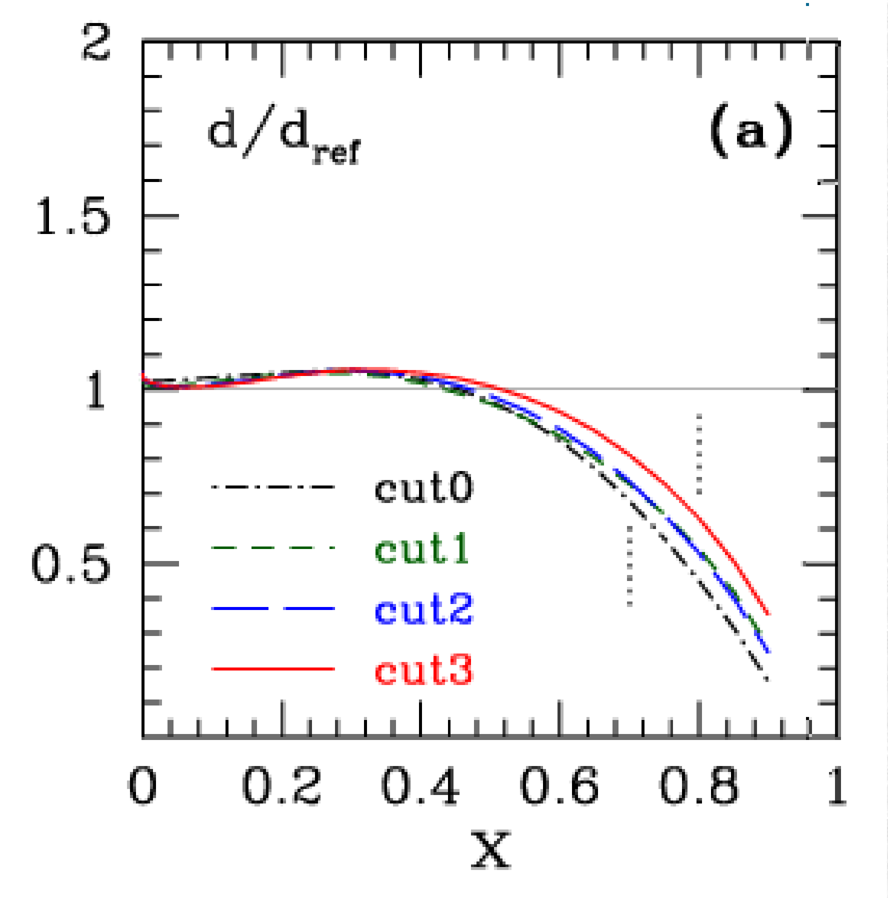
- **Important:** $C(x_B)$ includes
  - dynamical higher-twists (parton correlations)
  - all uncontrolled power corrections, e.g.,
    - √ TMC model uncertainty, Jet Mass Corrections
    - √ NNLO corrections (power-like at small Q)

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)

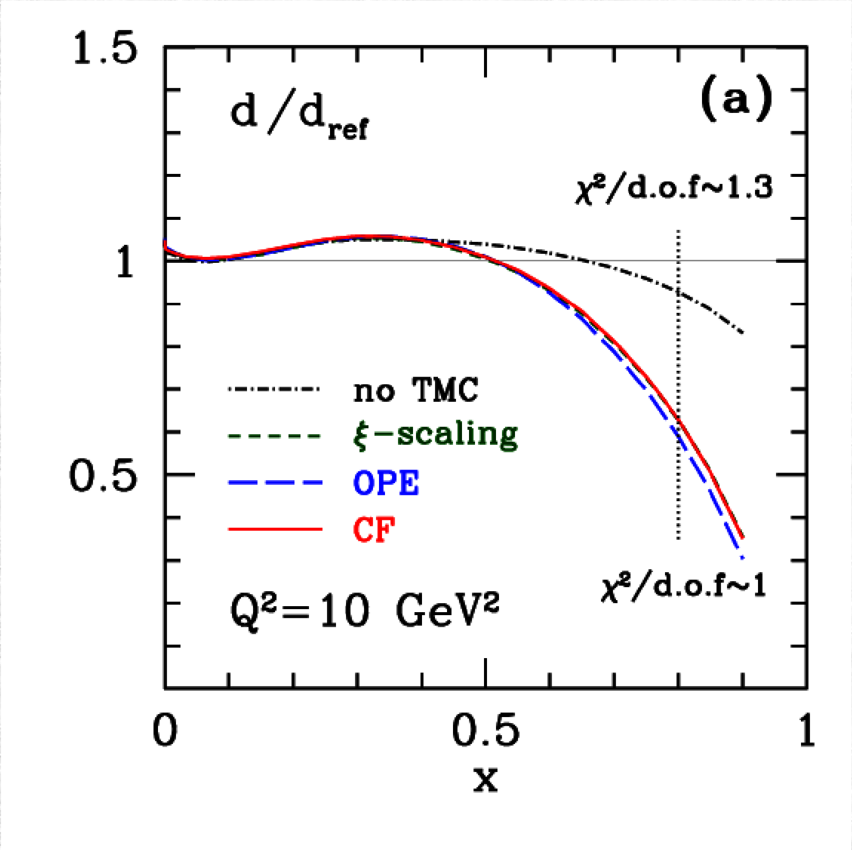


Stability of the d-quark fit



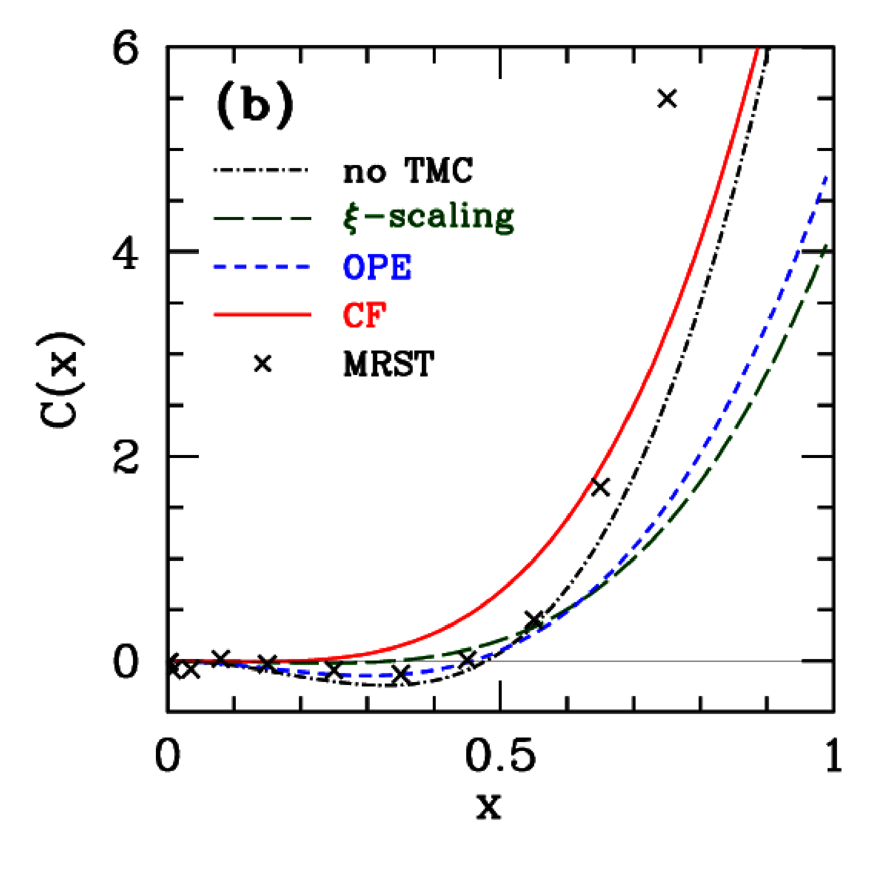
- **Relatively stable against kinematic cuts**, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at x=0.5–0.7 in the nominal range of validity of cut0

TMC vs HT



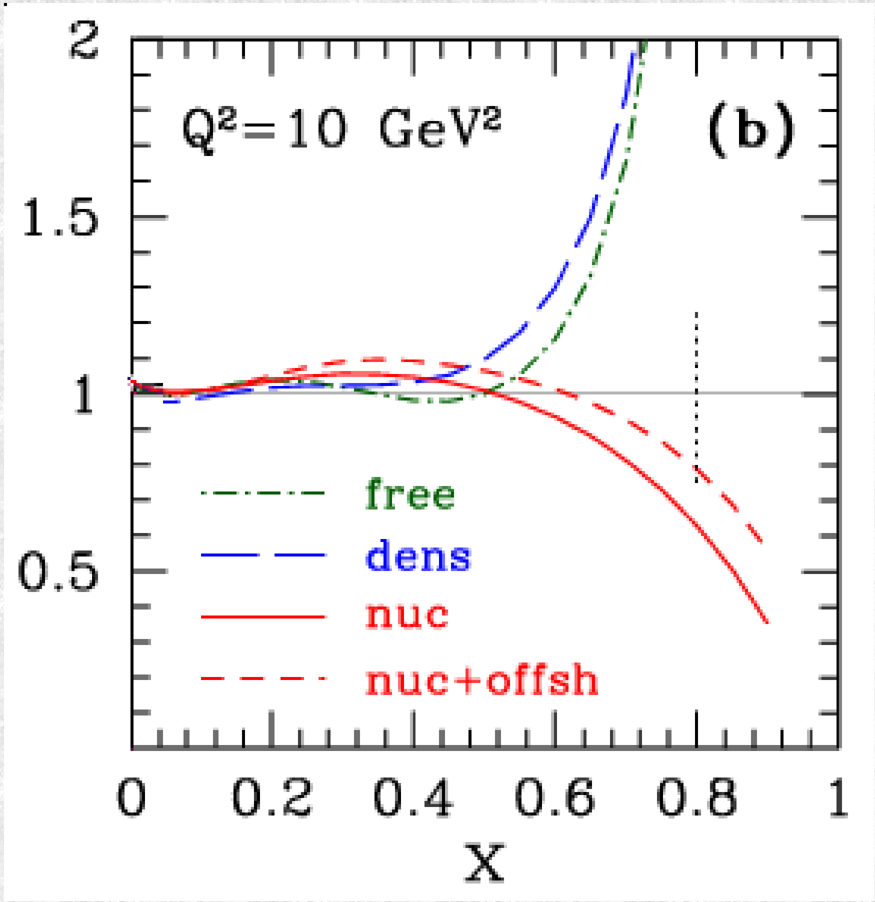
- **Extracted twist-2 PDF much less sensitive to choice of TMC**
  - fitted HT function compensates the TMC
  - except when no TMC is included
- **Inclusion of TMC allow for economical HT parametrization** (3 params)

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

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

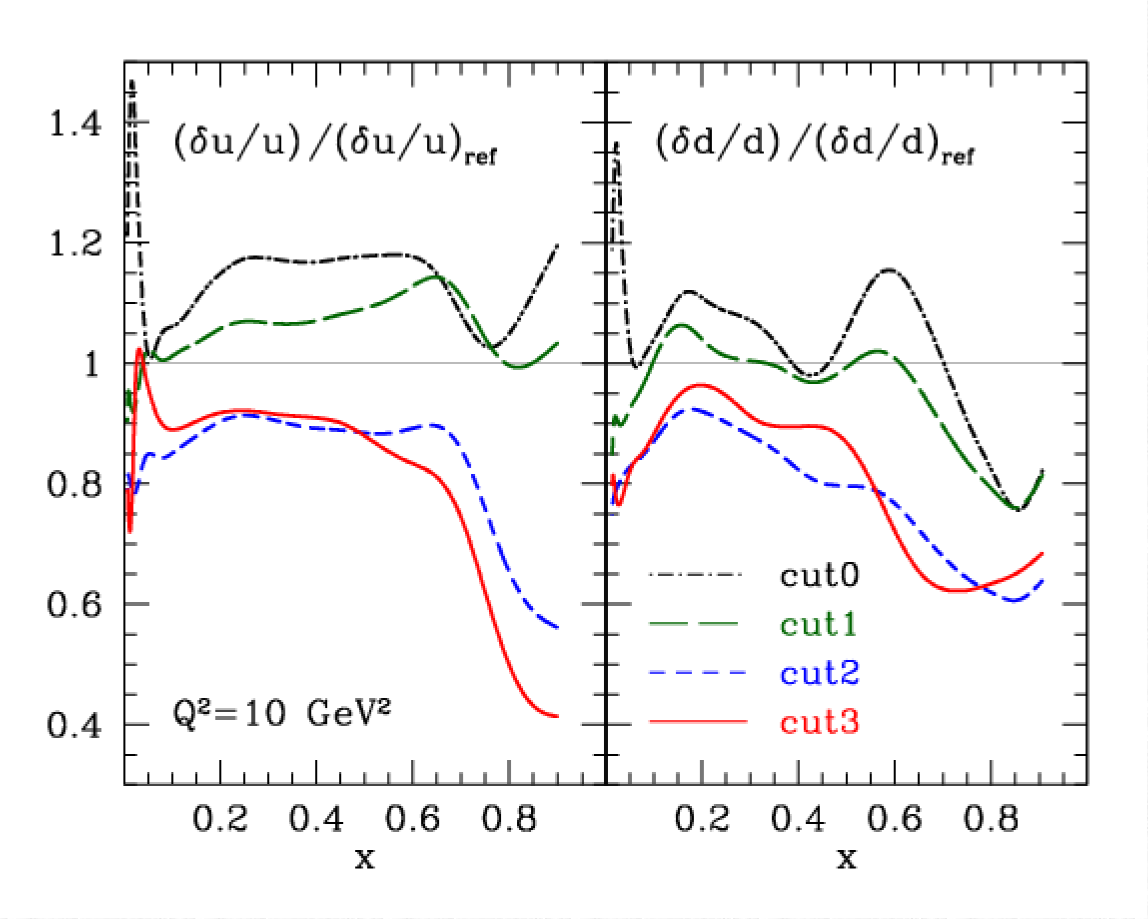
$$\frac{\delta d}{d} = \frac{4}{3}\frac{\delta F_2^d}{F_2^d}(1 + \frac{1}{d/u}).$$

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

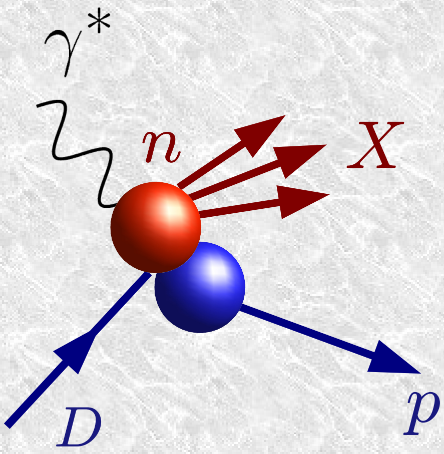
Experimental uncertainties: PDF errors

- **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 $p^2 \rightarrow {M_n}^2$

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