New global analysis of PDFs
- exploring the large-x domain

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“CTEQX”

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Outline

- Why is nucleon structure at large $x$ important?

- Navigating the large-$x$ landscape
  - nuclear corrections
  - target mass corrections & higher twists

- New global analysis (CTEQX)
  - first foray into high-$x$, low-$Q^2$ region
  - surprising new results for $d/u$

- Future experimental constraints
Why are PDFs at large $x$ interesting?

- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

→ most cleanly revealed at $x > 0.4$
Why are PDFs at large $x$ interesting?

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- Predictions for $x \to 1$ behavior of e.g. $d/u$ ratio
  - scalar diquark dominance: $d/u = 0$  
    - Feynman (1972)
  - hard gluon exchange: $d/u = 1/5$  
    - Farrar, Jackson (1975)
  - SU(6) symmetry: $d/u = 1/2$
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- Needed to understand backgrounds in searches for *new physics* beyond the Standard Model at LHC, $\nu$ oscillation experiments, astrophysics applications.

  - DGLAP evolution feeds low $x$, high $Q^2$ from high $x$, low $Q^2$.
At large $x$, valence $u$ and $d$ distributions extracted from $p$ and $n$ structure functions, e.g. at LO

\[ \frac{1}{x} F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v \]

\[ \frac{1}{x} F_2^n \approx \frac{4}{9} d_v + \frac{1}{9} u_v \]

- $u$ quark distribution well determined from proton
- $d$ quark distribution requires neutron structure function

\[ \frac{d}{u} \approx \frac{4 - F_2^n / F_2^p}{4F_2^n / F_2^p - 1} \]
No FREE neutron targets
(neutron half-life ~ 12 mins)

- use deuteron as “effective” neutron target

BUT deuteron is a nucleus

- \( F_2^d \neq F_2^p + F_2^n \)

- nuclear effects (nuclear binding, Fermi motion, shadowing) obscure neutron structure information

- need to correct for “nuclear EMC effect”

large uncertainty beyond \( x \sim 0.5 \)

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Large-\(x\) landscape:

\textit{nuclear effects in the deuteron}
nuclear “impulse approximation”

→ incoherent scattering from individual nucleons in \( d \)
  (good approx. at \( x \gg 0 \))

\[
F_2^d(x, Q^2) = \int \frac{dy}{x} f(y, \gamma) F_2^N(x/y, Q^2) + \delta^{(\text{off})} F_2^d
\]

nucleon momentum distribution in \( d \)
(“smearing function”)

\[
y = \frac{p \cdot q}{P \cdot q}
\]
light-cone momentum fraction of \( d \) carried by \( N \)

→ at finite \( Q^2 \), smearing function depends also on parameter

\[
\gamma = \frac{|q|}{q_0} = \sqrt{1 + 4M^2x^2/Q^2}
\]
N momentum distributions in $d$

- weak binding approximation (WBA):
  expand amplitudes to order $\vec{p}^2 / M^2$

$$f(y, \gamma) = \int \frac{d^3p}{(2\pi)^3} |\psi_d(p)|^2 \delta \left( y - 1 - \frac{\varepsilon + \gamma p_z}{M} \right)$$

$$\times \frac{1}{\gamma^2} \left[ 1 + \frac{\gamma^2 - 1}{y^2} \left( 1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2} (1 - 3\hat{p}_z^2) \right) \right]$$

- deuteron wave function $\psi_d(p)$
- deuteron separation energy $\varepsilon = \varepsilon_d - \frac{\vec{p}^2}{2M}$
- approaches usual nonrelativistic momentum distribution in $\gamma \rightarrow 1$ limit
$N$ momentum distributions in $d$

broader with increasing $\gamma$

$\gamma \lesssim 2$

Kahn, WM, Kulagin (2009)
Off-shell correction

\[ \delta^{(\text{off})} F_2^d \rightarrow \delta^{(\Psi)} F_2^d \] negative energy components of \( \psi_d \)

\[ \delta^{(p^2)} F_2^d \] off-shell \( N \) structure function

\[ \delta^{(\text{off})} F_2^d/F_2 \]

\[ \leq 1 - 2\% \] effect

WM, Schreiber, Thomas (1994)
EMC effect in deuteron

\[ Q^2 = 2 \text{ GeV}^2 \]

\[ F_2^d / F_2^N \]

\[ x \]

\[ x \sim 0.5 \text{–} 0.6 \]

\[ \sim 2\text{–}3\% \] reduction of \( d/N \) ratio at \( x \sim 0.5\text{–}0.6 \) with steep rise for \( x > 0.6 \)

\[ \rightarrow \] can significantly affect neutron extraction

# Frankfurt-Strikman “light-cone” model (no binding)
Large-$x$ landscape:

*target mass & higher twist corrections*
Target mass corrections

- Additional corrections from *kinematical* $Q^2/\nu^2$ effects

  $\rightarrow$ “target mass corrections” (TMC), since $x = Q^2/2M\nu$

- Important at large $x$ and low $Q^2$

  $\rightarrow$ new “Nachtmann” scaling variable

  $\xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}}$

  
  Baumik, Greenberg (1971)
  Nachtmann (1973)

  $\rightarrow$ but *not unique* – depends on formalism
  *(e.g. OPE, collinear factorization)*
Operator product expansion

$n$-th Cornwall-Norton moment of $F_2$ structure function

\[ M_2^n(Q^2) = \int dx \ x^{n-2} \ F_2(x, Q^2) = \sum_{j=0}^{\infty} \left( \frac{M^2}{Q^2} \right)^j \frac{(n+j)!}{j!(n-2)!} \frac{A_{n+2j}}{(n+2j)(n+2j-1)} \]

take inverse Mellin transform

\[ F_2^{\text{OPE}}(x, Q^2) = \frac{x^2}{\xi^2 \gamma^3} F_2^{(0)}(\xi, Q^2) + \frac{6M^2x^3}{Q^2 \gamma^4} \int_\xi^1 du \frac{F_2^{(0)}(u, Q^2)}{u^2} \]
\[ + \frac{12M^4x^4}{Q^4 \gamma^5} \int_\xi^1 dv(v - \xi) \frac{F_2^{(0)}(v, Q^2)}{v^2} \]

where $F_2^{(0)}$ is structure function in massless (Bjorken) limit

Georgi, Politzer (1976)
Target mass corrections

TMC important for verification of quark-hadron duality

Psaker, WM et al. (2008)
Target mass corrections

$TMC_{2}/F_2$

Accardi, Qiu (2008)

$TMC$ important at large $x$ even for large $Q^2$
**Collinear factorization**

- work directly in *momentum* space at partonic level (avoids need for Mellin transform)

- expand parton momentum $k$ around its *on-shell* and *collinear* component $(k^2 \perp \to 0)$

$$F_{T,L}(x, Q^2) = \sum_q \int_{\xi}^{\xi/x} \frac{dy}{y} \ C_{T,L}^q \left( \frac{\xi}{y}, Q^2 \right) q(y, Q^2)$$

(avoided unphysical $x > 1$ region)

- at leading order

$$F_{2\text{CF}}(x, Q^2) = \frac{x}{\xi \gamma^2} \ F_{2}^{(0)}(\xi, Q^2)$$

$$\approx \frac{\xi \gamma}{x} \ F_{2\text{OPE}}(x, Q^2)$$

*Ellis, Furmanski, Petronzio (1983)*

*Accardi, Qiu (2008)*

*Kretzer, Reno (2004)*
Higher twists

$\frac{1}{Q^2}$ expansion of structure function moments

$$M_n(Q^2) = \int_0^1 dx \, x^{n-2} \, F_2(x, Q^2) = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific “twist” (= dimension – spin)

$\rightarrow$ twist $> 2$ reveals long-range multi-parton correlations

$\rightarrow$ phenomenologically important wherever TMCs important

$\rightarrow$ parametrize $x$ dependence by

$$F_2(x, Q^2) = F_2^{LT}(x, Q^2) \left( 1 + \frac{C(x)}{Q^2} \right)$$
New global analysis ("CTEQX")
Next-to-leading order analysis of expanded set of proton and deuterium data, including large-$x$, low-$Q^2$ region

- Systematically study effects of $Q^2$ & $W$ cuts
  \[ \rightarrow \text{ as low as } Q \sim m_c \text{ and } W \sim 1.7 \text{ GeV} \]

- Include subleading $1/Q^2$ corrections
  \[ \rightarrow \text{ target mass corrections} \]
  \[ \rightarrow \text{ dynamical higher twists} \]

- Correct for nuclear effects in the deuteron
Kinematic cuts

\begin{align*}
cut0: \quad & Q^2 > 4 \text{ GeV}^2, \quad W^2 > 12.25 \text{ GeV}^2 \\
cut1: \quad & Q^2 > 3 \text{ GeV}^2, \quad W^2 > 8 \text{ GeV}^2 \\
cut2: \quad & Q^2 > 2 \text{ GeV}^2, \quad W^2 > 4 \text{ GeV}^2 \\
cut3: \quad & Q^2 > m_c^2, \quad W^2 > 3 \text{ GeV}^2
\end{align*}
**Data points**

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* only L−T separated data used at low $Q^2$
# new data sets in CTEQX fit

factor 2 increase from cut0 → cut3
Effect of new data on “standard” fits

- Extrapolation

- “cut0” (as in CTEQ6.1)

- No nuclear or $1/Q^2$ corrections

- No significant effect in measured region

- $u$ suppression at large $x$ due to E866 DY data
Effect on “reference” fit from $1/Q^2$ and nuclear corrections

- cut0 limits significant change to $u$ quark
- profound effect on $d$ quark from nuclear corrections in deuteron
- must include deuteron corrections for $x > 0.5$ even for standard cuts
Effect of $Q^2$ & $W$ cuts

- Systematically reduce $Q^2$ and $W$ cuts
- Fit includes TMCs (CF), HT term, nuclear corrections (WBA)

$d/d_{\text{ref}}$ for $Q^2=10$ GeV$^2$

- stable with respect to cut reduction
- $d$ quark suppressed by $\sim 50\%$ for $x > 0.5$
  (driven by nuclear corrections)
Nuclear corrections

\[ \frac{d}{d_{\text{ref}}} = F_{d}^{2} + F_{n}^{2} \]

- \textit{increased} \( d \) quark for no nuclear effects (or nuclear density model)
- \textit{decreased} \( d \) quark for nuclear smearing models
- Modest increase with off-shell correction (larger EMC effect)

* assumes \( F_{2}^{d} = F_{2}^{p} + F_{2}^{n} \) as in CTEQ6.1 and most other global fits
Nuclear corrections

\[ \frac{F_2^d}{F_2^N} - 1 \approx \frac{1}{4} \left( \frac{F_2^{Fe}}{F_2^d} - 1 \right) \]

*assumes EMC effect scales with density; extrapolated from Fe → deuterium

→ large differences with “free” for \( x > 0.6 \)

→ definition of density for deuteron is problematic
Effect of $1/Q^2$ corrections

1/$Q^2$ HT coefficient parametrized as $C(x) = c_1 x^{c_2} (1 + c_3 x)$

important interplay between TMCs and higher twist: HT alone cannot accommodate full $Q^2$ dependence

stable leading twist when both TMCs and HTs included
Consistency check of fit with $F_2^d/F_2^p$ ratio (not used in fit)

fits without nuclear smearing in deuteron overestimate data at intermediate $x$, do not reproduce rise at large $x$
Final PDF results

- $u/u_{\text{CTEQ6.1}}$
- $d/d_{\text{CTEQ6.1}}$

$Q^2 = 10 \text{ GeV}^2$

$\rightarrow$ full fits favors smaller $d/u$ ratio
Final PDF results

- full fits favors smaller $d/u$ ratio
- dominance of non-pQCD physics (cf. hard $g$ exchange)
Final PDF results

→ full fits favors smaller $d/u$ ratio

→ dominance of non-pQCD physics (cf. counting rules)

→ significantly reduced errors with weaker cuts
“Cleaner” methods of determining $d/u$

- $e \ d \rightarrow e \ p_{\text{spec}} \ X^*$
  - semi-inclusive DIS from $d$
  - $\rightarrow$ tag “spectator” protons

- $e \ ^3\text{He}(^3\text{H}) \rightarrow e \ X^*$
  - $^3\text{He}$-tritium mirror nuclei

- $e \ p \rightarrow e \ \pi^\pm \ X^*$
  - semi-inclusive DIS as flavor tag

- $e^\mp \ p \rightarrow \nu(\bar{\nu})X$
  - weak current as flavor probe

- $\nu(\bar{\nu}) \ p \rightarrow l^\mp \ X$

- $p \ p(\bar{p}) \rightarrow W^\pm \ X$

- $\bar{e}_L(\bar{e}_R) \ p \rightarrow e \ X^*$

*planned for JLab at 12 GeV
Summary & Outlook

- New global PDF analysis (CTEQX) including high-$x$, low-$Q^2$ data

- *Stable leading twist* PDFs obtained with TMC, higher twist and nuclear corrections (valid to $x \sim 0.8$)
  - opens door to study of nucleon structure over large kinematic domain

- Results suggest smaller $d/u$ ratio for $x > 0.6$

- *Future*: explore effects of
  - jet mass corrections, $W^2$ evolution, quark-hadron duality

- Extend analysis to *spin-dependent* PDFs ("SpinTEQ")
The End