Longitudinal structure of hadrons

Wally Melnitchouk
Outline

- **Spin-averaged nucleon structure**
  - $d/u$ ratio at large $x$, with *minimal* nuclear corrections
  - new global QCD analysis (“CTEQ6X”) with large-$x$ focus
    - importance of $1/Q^2$ corrections
  - resonance region structure / quark-hadron duality
    - recent first confirmation for neutron

- **Spin-dependent nucleon structure**
  - $A_1$ (or $\Delta u/u$, $\Delta d/d$) at large $x$
  - nuclear corrections for neutron extraction from $^3$He or $d$
  - finite $Q^2$ corrections / higher twist extraction
Nucleon structure at large $x$: spin-averaged
Why is nucleon structure 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 is nucleon structure at large $x$ interesting?

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

- Predictions for $x \to 1$ behavior of *e.g.* $d/u$ ratio
  - scalar diquark dominance: $d/u = 0$  \(\text{Feynman (1972)}\)
  - hard gluon exchange: $d/u = 1/5$  \(\text{Farrar, Jackson (1975)}\)
  - SU(6) symmetry: $d/u = 1/2$  \(\text{1960s}\)

- Needed to understand backgrounds in searches for *new physics* beyond the Standard Model at LHC or in $\nu$ oscillation experiments
  - DGLAP evolution feeds low-$x$, high-$Q^2$ from high-$x$, low-$Q^2$
At large $x$, valence $u$ and $d$ distributions determined 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 \( x \sim 0.5 \)
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”
**EMC effect in deuteron**

- **Incoherent scattering from individual nucleons in $d$**
  
  (good approx. at $x >> 0$)

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

**nucleon momentum distribution in $d$**

**“smearing function”**

- $y = p \cdot q / P \cdot q$ light-cone momentum fraction of $d$ carried by $N$

- at finite $Q^2$, smearing function depends also on parameter

\[
\gamma = |\mathbf{q}|/q_0 = \sqrt{1 + 4M^2x^2/Q^2}
\]
EMC effect in deuteron

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

- deuteron wave function \( \psi_d(p) \)
- deuteron separation energy
  \[ \varepsilon = \varepsilon_d - \frac{\vec{p}^2}{2M} \]
- effectively more smearing for larger \( x \) or lower \( Q^2 \)

Kulagin, Petti, NPA 765, 126 (2006)
Kahn et al., PRC 79, 035205 (2009)
using off-shell model, will get *larger* neutron
*cf. light-cone* model

but will get *smaller* neutron *cf. no nuclear effects or density* model
EMC effect in deuteron

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

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

→ \ ~ 2–3% reduction of \( \frac{F_2^d}{F_2^N} \) at \( x \sim 0.5–0.6 \) with steep rise for \( x > 0.6–0.7 \)

→ larger EMC effect at \( x \sim 0.5–0.6 \) with binding + off-shell corrections \( \text{cf.} \) light-cone
Finite-$Q^2$ corrections

- In OPE insertion of covariant derivatives in quark bilinears leads to terms $\sim Q^2/\nu^2 \sim M^2 x^2 / Q^2$

  $\rightarrow$ kinematical target mass corrections (formally leading twist)

  $\rightarrow$ gives rise to new “Nachtmann” scaling variable

$$\xi = \frac{2x}{1 + \gamma}, \quad \gamma^2 = 1 + Q^2/\nu^2$$

- Target mass corrected structure function (in OPE approach)

$$F_2(x, Q^2) = \frac{x^2}{\xi^2 \gamma^3} F_2^{(0)}(\xi, Q^2) + \frac{6M^2 x^3}{Q^2 \gamma^4} \int_{\xi}^{1} du \frac{F_2^{(0)}(u, Q^2)}{u^2}$$

$$+ \frac{12M^4 x^4}{Q^4 \gamma^5} \int_{\xi}^{1} dv(v - \xi) \frac{F_2^{(0)}(v, Q^2)}{v^2}$$

Georgi, Politzer (1976)
Finite-$Q^2$ corrections

$F_2$ vs. $x$

- **E94-110**
- Resonance Fit
- LT+TMC
- LT

$Q^2 = 1$

TMC important for verification of quark-hadron duality

WM, Ent, Keppel

* JLab Hall C
Finite-\(Q^2\) corrections

- **But** TMCs not unique: *e.g.* in collinear factorization
  
  - work directly in *momentum* space at partonic level
    (avoids Mellin transform; applicable also to non-DIS processes)
  
  - expand parton momentum \(k\) around its *on-shell* and *collinear* component \((k^2_\perp \to 0)\)

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

*Ellis, Furmanski, Petronzio (1983)*

- at leading order

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

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

*Accardi, Qiu (2008)*

*Kretzer, Reno (2004)*
Finite-$Q^2$ corrections

- **But** TMCs not unique: *e.g.* in collinear factorization

![Graph showing finite-$Q^2$ corrections](image)

- TMC important at large $x$ even for large $Q^2$

*Accardi, Qiu (2008)*
CTEQ6X global PDF fit

- New global QCD (next-to-leading order) analysis of expanded set of $p$ and $d$ data, including large-$x$, low-$Q^2$ region
  - joint JLab-CTEQ theory/experiment collaboration
    (with Hampton, FSU, FNAL, Duke)

- Systematically study effects of $Q^2$ & $W$ cuts
  - as low as $Q \sim m_c$ and $W \sim 1.7$ GeV

- Include large-$x$ corrections
  - TMCs & higher twists $F_2(x, Q^2) = F_2^{LT}(x, Q^2)(1 + C(x)/Q^2)$
  - realistic nuclear effects in deuteron (binding + off-shell)
    (most analyses use either no correction, or density model)
CTEQ6X – kinematic cuts

- cut0: \( Q^2 > 4 \text{ GeV}^2 \), \( W^2 > 12.25 \text{ GeV}^2 \)
- cut1: \( Q^2 > 3 \text{ GeV}^2 \), \( W^2 > 8 \text{ GeV}^2 \)
- cut2: \( Q^2 > 2 \text{ GeV}^2 \), \( W^2 > 4 \text{ GeV}^2 \)
- cut3: \( Q^2 > m_c^2 \), \( W^2 > 3 \text{ GeV}^2 \)

factor 2 increase in DIS data from cut0 \( \rightarrow \) cut3

- H1, ZEUS
- BCDMS
- NMC
- SLAC
- JLab

\( Q^2 \) (GeV\(^2\)) vs. \( x \)
Systematically reduce $Q^2$ and $W$ cuts, including TMC, HT & nuclear corrections

$\rightarrow$ stable with respect to cut reduction

$\rightarrow$ $d$ quark suppressed by $\sim 50\%$ for $x > 0.5$ (driven by nuclear corrections)

CTEQ6X – nuclear effects

→ *increased* $d$ quark for no nuclear effects
  (compensates for nuclear smearing in deuteron $\rightarrow$ increased $F_2^d$)

→ *decreased* $d$ quark for nuclear smearing models

$F_2^d/F_2^N > 1$ for $x \sim 0.6–0.8$
while $F_2^d/F_2^N < 1$ for “free” and “density” models

\[ F_2^d / F_2^N \uparrow \iff F_2^n / F_2^p \downarrow \iff d/u \downarrow \]

\* assumes $F_2^d = F_2^p + F_2^n$ as in CTEQ6.1 and most other global fits
CTEQ6X – $1/Q^2$ corrections

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

→ stable leading twist when both TMCs and HTs included
important interplay between TMCs and higher twist: HT alone cannot accommodate full $Q^2$ dependence

stable leading twist when both TMCs and HTs included

prescription dependence of TMCs may limit extraction of higher twist contributions

factor 2 at $x \sim 0.8$
CTEQ6X – final PDF results

\[ \frac{u}{u_{\text{CTEQ6.1}}} \]

\[ \frac{d}{d_{\text{CTEQ6.1}}} \]

\( Q^2 = 10 \text{ GeV}^2 \)

\[ x \]

→ full fits favors smaller \( d/u \) ratio

(CTEQ6.1 had no nuclear or TMC/HT corrections)
CTEQ6X – final PDF results

- full fits favors smaller $d/u$ ratio
  (CTEQ6.1 had no nuclear or TMC/HT corrections)

- up to 40-60% reduced errors with weaker cuts

CTEQ6X – implications

- **Stable leading twist PDFs for** \( W \gtrsim 1.7 \text{ GeV} \) & \( Q^2 \gtrsim 1.5 \text{ GeV}^2 \)
  - provided nuclear and subleading \( 1/Q^2 \) corrections included
  - advocates using (high statistics) low-\( W \) data to constrain large-\( x \) PDFs

- **Prescription dependence of TMCs limits extraction of higher twist matrix elements**
  - TMC / HT interplay needs to be better understood

- **Nuclear corrections in deuteron significant at for** \( x \gtrsim 0.6 \)
  - completely obscure \( d \) quark extraction at large-\( x \), require new methods free of nuclear uncertainties
New methods – spectator tagging ("BONUS")

\[ e \, d \rightarrow e \, p \, X \]

target \( d \)

recoil \( p \)

slow backward \( p \) (\( p < 100 \text{ MeV} \))

\( \rightarrow \) neutron nearly on-shell

\( \rightarrow \) minimize rescattering
New methods – DIS from $A=3$ (“MARATHON”)

- extract $n/p$ ratio from ratio of $A=3$ structure functions

\[
\frac{F_2^n}{F_2^p} = \frac{2R - F_2^{^3\text{He}} / F_2^{^3\text{H}}}{2F_2^{^3\text{He}} / F_2^{^3\text{H}} - R}
\]

→ ratio of $^3\text{He}$ to $^3\text{H}$
EMC ratios cancels to $\sim 1\%$ for $x < 0.85$
MARATHON

\begin{align*}
1 \lesssim Q^2 &\lesssim 13 \text{ GeV}^2 \\
4 \lesssim Q^2 &\lesssim 15 \text{ GeV}^2
\end{align*}

\begin{align*}
x &\leq 0.77 \ (0.83) \ [W \geq 2 \ (1.8) \text{ GeV}] \\
x &\leq 0.83 \ (0.87) \ [W \geq 2 \ (1.73) \text{ GeV}]
\end{align*}

- theoretical uncertainties similar to \(x \sim 0.85\)
- other: \(\pi\) structure function; \(3A(e,e'd)X\); (ideally) neutron tagging for cross-check!
- other: EMC effect in \(A=3\); isospin-dependence of nuclear corrections; SIDIS
Quark-hadron duality
Quark-hadron duality

- average over resonances
  (strongly $Q^2$ dependent)
  $\approx$ leading twist str. fn.
  ($\sim Q^2$ independent)

Niculescu et al., PRL 85, 1182 (2000)
Quark-hadron duality

- average over resonances
  (strongly $Q^2$ dependent)
  $\approx$ leading twist str. fn.
  ($\sim Q^2$ independent)

- duality violation for proton
  $\lesssim 10\%$, integrated over $x$

Malace et al., PRC 80, 035207 (2009)
Is duality in the proton a coincidence?

consider model with symmetric nucleon wave function

\[ \propto \sum_{i \neq j} e_i e_j \sim \left( \sum_i e_i \right)^2 - \sum_i e_i^2 \]

cat’s ears diagram (4-fermion higher twist \( \sim 1/Q^2 \))

coheren coherent

incoherent
Is duality in the proton a coincidence?

Consider model with symmetric nucleon wave function

cat's ears diagram \((4\text{-fermion higher twist } \sim 1/Q^2)\)

\[
\alpha \sum_{i \neq j} e_i e_j \sim \left( \sum_i e_i \right)^2 - \sum_i e_i^2
\]

coherent

incoherent

proton \(HT \sim 1 - \left( 2 \times \frac{4}{9} + \frac{1}{9} \right) = 0\)!

neutron \(HT \sim 0 - \left( \frac{4}{9} + 2 \times \frac{1}{9} \right) \neq 0\)

Brodsky, hep-ph/0006310

need to test duality in the neutron!
Quark-hadron duality

- average over resonances (strongly $Q^2$ dependent) 
  $\approx$ leading twist str. fn. ($\sim Q^2$ independent)

- duality violation for proton $\lesssim 10\%$, integrated over $x$

- recently confirmed also for neutron (from inclusive $p, d$ data) 
  $\rightarrow$ duality not accidental!

Malace et al., PRL 104, 102001 (2010)
Quark-hadron duality

- currently duality studies limited to $Q^2 \lesssim 6 \text{ GeV}^2$, beyond which no resonance data exist

- with 12 GeV will map out resonances to $Q^2 \sim 17 \text{ GeV}^2$

- high-precision low-$W$ data base will constrain PDFs at larger $x$ values

  → input into CTEQ6X-like global QCD fits
Semi-inclusive DIS
Semi-inclusive DIS at 12 GeV offers tremendous opportunity for determining

- flavor-spin decomposition of nucleon PDFs
  \( (e.g. \, d/u, \, \bar{d}/\bar{u}, \, \Delta \bar{d} - \Delta \bar{u}) \)

- new distributions, not accessible in inclusive DIS
  \( (e.g. \, \text{transversity, Sivers function, etc}) \)

- vital issue: does factorization of scattering & fragmentation processes (needed for pQCD treatment) hold at these energies?

  must establish *empirically* before method can be reliably utilized
6 GeV data hint at intriguing quark-hadron duality in SIDIS

Navasardyan et al., PRL 98, 022001 (2007)

→ trends consistent with resonance model predictions

Close, WM, PRC 79, 055202 (2009)
6 GeV data hint at intriguing quark-hadron duality in SIDIS

\[
\frac{D^-}{D^+} = \frac{4 - N_{\pi^+}^+/N_{\pi^-}^-}{4N_{\pi^+}^+/N_{\pi^-}^- - 1}
\]

resonance contributions to ratio cancel in quark model!

Navasardyan et al., PRL 98, 022001 (2007)

→ trends consistent with resonance model predictions

\[\sum_{1}^{N^* N^*_1} \frac{\gamma^*}{M} = \frac{\Sigma_{q, X}^N}{q} + X\]

Close, WM, PRC 79, 055202 (2009)
In parton model cross section has simple factorization:

\[
\frac{d\sigma}{dx \, dQ^2 \, dz_h} \sim \sum_q e_q^2 \, q(x, Q^2) \, D^h_q(z_h, Q^2)
\]

\[
z_h = \frac{p_h \cdot p}{q \cdot p} \rightarrow \frac{E_h}{\nu}
\]

At finite \(Q^2\) hadronic mass corrections (target & fragment):

\[
\frac{d\sigma}{dx \, dQ^2 \, dz_h} \sim \sum_q e_q^2 \, q(\xi_h, Q^2) \, D^h_q(\zeta_h, Q^2)
\]

\[
\xi_h = \xi \left(1 + \frac{m^2_{h}}{\zeta_h Q^2}\right) \quad \zeta_h = \frac{z_h \xi}{2x} \left(1 + \sqrt{1 - \frac{4x^2M^2m^2_{h}}{z^2_h Q^4}}\right)
\]

- Hadron mass dependence in quark distribution function
- Factorization breakdown (quantifiable!)
Ratio $\sigma / \sigma^{(0)}$ of corrected to uncorrected (massless limit) $\pi^+ + \pi^-$ cross sections

Hobbs, Accardi, WM, JHEP 11, 084 (2009)

- dramatic rise as $z_h \rightarrow 1$, more pronounced at low $Q^2$

- downward correction at small $z_h$ for heavier hadrons driven by suppression of PDF from $\left(1 + m^2_h / \zeta_h Q^2 \right)$ factor in $\xi_h \ (> \xi)$

- need to account for HMC at large $x$ or small $Q^2$ even at 12 GeV
Nucleon structure at large $x$: spin-dependent
Spin structure at large $x$

- Spin-dependent PDFs are even less well understood at large $x$ than spin-averaged PDFs

- Predictions for $x \to 1$ behavior:
  - scalar diquark dominance
    \[
    \frac{\Delta u}{u} \to 1, \quad \frac{\Delta d}{d} \to -\frac{1}{3}
    \]
    \[A_{1}^{p,n} \to 1\]
  - hard gluon exchange
    \[
    \frac{\Delta u}{u} \to 1, \quad \frac{\Delta d}{d} \to 1
    \]
    \[A_{1}^{p,n} \to 1\]
  - spin-flavor symmetry
    \[
    \frac{\Delta u}{u} = \frac{2}{3}, \quad \frac{\Delta d}{d} = -\frac{1}{3}
    \]
    \[A_{1}^{p} = \frac{5}{9}, \quad A_{1}^{n} = 0\]

- Spin PDFs almost completely unconstrained for $x \gtrsim 0.6$
Spin structure at large $x$

→ data consistent with SU(6) predictions (cf. unpolarized)

→ dramatic behavior expected in $\Delta d/d$ for $x \gtrsim 0.6$

reflects upturn in neutron asymmetry $A_1^n$
Spin structure at large $x$

---

**First evidence of rise above unity!**

**Dramatic behavior expected in** $\Delta d/d$ **for** $x \gtrsim 0.6$

---

**Reflects upturn in neutron asymmetry** $A_1^n$
E12-06-122 (Hall A)

\[ x \leq 0.71 \]

\[ 3.0 \lesssim Q^2 \lesssim 7.8 \text{ GeV}^2 \]

DIS kinematics

PR12-06-110 (Hall C)

\[ x \leq 0.77 \]

\[ 2.8 \lesssim Q^2 \lesssim 10.5 \text{ GeV}^2 \]

Flagship 12 GeV measurement!
Comprehensive program of inclusive and semi-inclusive measurements with CLAS12

- Reconstruct large-\(x\) \(\Delta u/u\) & \(\Delta d/d\) from any two of \(A_1^p, A_1^d, A_1^{3\text{He}}\) (and \(d/u\) ratio!)
Comprehensive program of *inclusive* and *semi-inclusive* measurements with CLAS12

Reconstruct large-$x$ $\Delta u/u$ & $\Delta d/d$ from any two of $A^p_1, A^d_1, A^{3\text{He}}_1$ (and $d/u$ ratio!)
Comprehensive program of inclusive and semi-inclusive measurements with CLAS12

- integrals over $x$ allow direct comparison with lattice QCD
- $Q^2$ dependence allows extraction of (leading & higher twist) matrix elements
Spin structure at large $x$ – nuclear effects

- Extracting neutron information from $^3$He or $d$ data requires subtraction of nuclear corrections

- Usual prescription accounts for effective polarizations of bound nucleons, assuming $x$ & $Q^2$ independent effects

$$ g_1^A = \langle \sigma_z \rangle^p g_1^p + \langle \sigma_z \rangle^n g_1^n $$

→ reasonable approximation for $x \lesssim 0.65$

→ breaks down for $x \gtrsim 0.7$

WM, Piller, Kulagin, Thomas, Weise (1995)
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→ finite-$Q^2$ corrections recently computed

Kulagin, WM, PRC 78, 065203 (2008)
Spin structure at large $x$ – nuclear effects

- Extracting neutron information from $^3\text{He}$ or $d$ data requires subtraction of nuclear corrections

- Usual prescription accounts for effective polarizations of bound nucleons, assuming $x$ & $Q^2$ independent effects

\[ g_1^A = \langle \sigma_z \rangle^p g_1^p + \langle \sigma_z \rangle^n g_1^n \]

→ reasonable approximation for $x \lessapprox 0.65$

→ breaks down for $x \gtrapprox 0.7$

→ finite-$Q^2$ corrections recently computed

→ especially egregious in resonance region

\[ ^3\text{He} \]

Kulagin, WM, PRC 78, 065203 (2008)
Spin structure at large $x$ – finite $Q^2$

- Limited $Q^2$ requires careful treatment of $1/Q^2$ corrections
- Prescription dependence of TMCs
- Expect cancellation with dynamical HTs for stable LTs (cf. CTEQX)

Accardi, WM, PLB 670, 114 (2008)
Spin structure at large $x$ – finite $Q^2$

- Limited $Q^2$ requires careful treatment of $1/Q^2$ corrections
  - Prescription dependence of TMCs
  - Expect cancellation with dynamical HTs for stable LTs (cf. CTEQX)

- Impact on extraction of higher twist matrix elements (e.g. color polarizabilities, E12-06-121) needs to be assessed

\[
\frac{\Gamma_{HT}^{1}}{Q^2} \propto \frac{a_{TMC}^2 + d_2 + f_2}{Q^2}
\]

\[
\chi_E = \frac{2}{3}(2d_2 + f_2)
\]

\[
\chi_B = \frac{1}{3}(4d_2 - f_2)
\]

Accardi, WM, PLB 670, 114 (2008)
Summary

- Measurement of structure functions at large $x$ at 12 GeV will resolve long-standing questions about $x \to 1$ behavior of PDFs
  - dramatic behavior for $x \gtrsim 0.6$ best revealed with highest possible $x$

- Need largest $Q^2$ range possible to constrain subleading $1/Q^2$ corrections
  - prescription dependence of TMCs needs to be better understood for unambiguous HT matrix element extraction

- Era of using effective polarization ansatz for nuclear corrections should end with end of 6 GeV program
  - both in the resonance & DIS regions
Summary

- Measurement of structure functions at large $x$ at 12 GeV will resolve long-standing questions about $x \rightarrow 1$ behavior of PDFs

  - dramatic behavior for $x \gtrsim 0.6$ best revealed with highest possible $x$

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  - both in the resonance & DIS regions

- Ongoing interest in & support for high $x$ physics
The End