What do we know and *don’t* know about parton distributions?

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CTEQ-Jefferson Lab collaboration
http://www.jlab.org/CJ

JLab Angular Momentum collaboration
http://www.jlab.org/JAM
Outline

- Are (collinear) PDFs relevant for TMDs & nucleon’s 3-D structure?
  → ~40% TMD talks!

- Unpolarized PDFs
  → valence, light antiquark, strange, charm, glue
    CJ15 global QCD analysis: Accardi, Brady, WM, Owens, Sato, PRD 93, 114017 (2016)

- Helicity-dependent PDFs
  → polarized valence, light antiquark, strange, glue
    JAM17 global QCD analysis: Ethier, Sato, WM, arXiv:1705.05889
    Sato et al., PRD 93, 074005 (2016)

- Scorecard…
Role of PDFs in 3-D structure

- Cross section and structure functions (SIDIS)

\[
\frac{d^5 \sigma(S_{\perp})}{dx_B dQ^2 dz_h d^2 P_{h\perp}} = \sigma_0 \left[ F_{UU} + \sin(\phi_h - \phi_s) \ F_{UT}^{\sin(\phi_h - \phi_s)} + \sin(\phi_h + \phi_s) \ \frac{2(1 - y)}{1 + (1 - y)^2} \ F_{UT}^{\sin(\phi_h + \phi_s)} + \ldots \right]
\]

- CSS formalism

\[
F_{UU} = H_{\text{SIDIS}} \frac{1}{z_h^2} \int_0^\infty \frac{db \ b}{(2\pi)} J_0(q_{h\perp} b) \tilde{W}_{UU}(b_*) + Y_{UU}
\]

\[
F_{UT}^{\sin(\phi_h - \phi_s)} = -H_{\text{SIDIS}} \frac{M_P}{z_h^2} \int_0^\infty \frac{db \ b^2}{(2\pi)} J_1(q_{h\perp} b) \tilde{W}_{UT}^{\sin(\phi_h - \phi_s)}(b_*) + Y_{UT}^{\sin(\phi_h - \phi_s)}
\]

\[
F_{UT}^{\sin(\phi_h + \phi_s)} = H_{\text{SIDIS}} \frac{M_h}{z_h^2} \int_0^\infty \frac{db \ b^2}{(2\pi)} J_1(q_{h\perp} b) \tilde{W}_{UT}^{\sin(\phi_h + \phi_s)}(b_*) + Y_{UT}^{\sin(\phi_h + \phi_s)}
\]

**“Y” term**

\[
b_* \rightarrow b, \quad b \ll b_{\text{max}}
\]

\[
b_* \rightarrow b_{\text{max}}, \quad b \gg b_{\text{max}}
\]

---

T. Rogers
Role of PDFs in 3-D structure

- **W term formulation in $b_T$ space**

$$\widetilde{W}_{UU}(b_*) \equiv e^{-S_{pert}(Q,b_*)-S_{NP}^f(Q,b)-S_{NP}^D(Q,b)} \, \widetilde{F}_{UU}(b_*)$$

$$\widetilde{W}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) \equiv e^{-S_{pert}(Q,b_*)-S_{NP}^{f_{1T}}(Q,b)-S_{NP}^D(Q,b)} \, \widetilde{F}_{UT}^{\sin(\phi_h-\phi_s)}(b_*)$$

$$\widetilde{W}_{UT}^{\sin(\phi_h+\phi_s)}(b_*) \equiv e^{-S_{pert}(Q,b_*)-S_{NP}^{h_1}(Q,b)-S_{NP}^{H_1}(Q,b)} \, \widetilde{F}_{UT}^{\sin(\phi_h+\phi_s)}(b_*)$$

- **Small-$b_T$ contribution**

$$\widetilde{F}_{UU}(b_*) = \sum_{q} e_q^2 \left( C_{q-1}^{f_1} \otimes f_1^i(x_B, \mu_B) \right) \left( \hat{C}^{D_1}_{j-q} \otimes D_{h/j}(z_h, \mu_B) \right)$$

$$\widetilde{F}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) = \sum_{q} e_q^2 \left( C_{q-1}^{f_{1T}} \otimes f_{1T}^{(1)i}(x_B, \mu_B) \right) \left( \hat{C}^{D_1}_{j-q} \otimes D_{h/j}(z_h, \mu_B) \right)$$

$$\widetilde{F}_{UT}^{\sin(\phi_h+\phi_s)}(b_*) = \sum_{q} e_q^2 \left( \delta C_{q-1}^{h_1} \otimes h_1^i(x_B, \mu_B) \right) \left( \delta \hat{C}^{H_{1}^\perp}_{j-q} \otimes \hat{H}_{1}^{(1)j}(z_h, \mu_B) \right)$$

collinear PDFs and FFs!
Unpolarized PDFs

excellent description over orders of magnitude in $x$ and $Q^2$
**Unpolarized PDFs**

- **Ubiquity of proton $F_2$ data** (SLAC, EMC, NMC, BCDMS, HERA, JLab, …) provides strong constraints on $u$-quark PDF over large $x$ range

\[ F_2^p \sim \frac{4}{9} x u + \frac{1}{9} x d + \cdots \]

- **Absence of free-neutron data and smaller $|e_q|$ of $d$ quarks limit precision of $d$-quark PDF, especially at high $x$**

→ nuclear effects in deuterium obscure free-neutron structure
**Valence quark PDFs**

- **Valence $d/u$ ratio at high $x$ of particular interest**
  - testing ground for nucleon models in $x \to 1$ limit
  - $d/u \to 1/2$
    - SU(6) symmetry
  - $d/u \to 0$
    - $S = 0$ $qq$ dominance (color-hyperfine interaction)
  - $d/u \to 1/5$
    - $S_z = 0$ $qq$ dominance (perturbative gluon exchange)
  - $d/u \to 0.18 - 0.28$
    - DSE with $qq$ correlations

  → considerable uncertainty at high $x$ from deuterium corrections (no free neutrons!)

\[
F_2^d(x, Q^2) = \int_x dy f(y, \gamma) F_2^N(x/y, Q^2)
\]

\[
f(y, \gamma) = \int \frac{d^3p}{(2\pi)^3} |\psi_d(p)|^2 \delta(y - 1 - \frac{e + \gamma p_z}{M}) \times \frac{1}{y^2} \left[ 1 + \frac{\gamma^2}{y^2} \left( 1 + \frac{2e}{M} + \frac{p^2}{2M^2} (1 - 3\beta^2) \right) \right]
\]
Valence quark PDFs

- **Valence** $d/u$ ratio at high $x$ of particular interest

  ➔ significant reduction of PDF errors with new JLab tagged neutron & FNAL $W$-asymmetry data

  ➔ extrapolated ratio at $x = 1$

  $d/u \rightarrow 0.09 \pm 0.03$

  does not match any model!

  ➔ upcoming experiments at JLab (MARATHON, BONuS, SoLID) will determine $d/u$ up to $x \sim 0.85$
Light quark sea

- $x$ dependence of $\bar{d} - \bar{u}$ asymmetry established in Fermilab E866 $pp/pd$ Drell-Yan experiment

\[ \frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2 q(x_1) \bar{q}(x_2) + (x_1 \leftrightarrow x_2) \]
\[ \frac{\sigma_{pd}}{\sigma_{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \]

→ suggested role of chiral symmetry and pion cloud

\[ (\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)(x) \]

splitting function

→ strong enhancement of $\bar{d}$ at $x \sim 0.1 - 0.2$, but intriguing behavior at large $x$ hinting at possible sign change of $\bar{d} - \bar{u}$
Light quark sea

- Rigorous connection with QCD established via chiral EFT

\[
\mathcal{L}_{\text{eff}} = \frac{g_A}{2f_\pi} \bar{\psi}_N \gamma^\mu \gamma_5 \vec{\tau} \cdot \partial_\mu \vec{\pi} \psi_N - \frac{1}{(2f_\pi)^2} \bar{\psi}_N \gamma^\mu \vec{\tau} \cdot (\vec{\pi} \times \partial_\mu \vec{\pi}) \psi_N
\]

Weinberg (1967)

- lowest order $\pi N$ interaction includes pion rainbow and tadpole contributions

- matching quark- and hadron-level operators

\[
\mathcal{O}^{\mu_1 \cdots \mu_n}_{q} = \sum_h c^{(n)}_{q/h} \mathcal{O}_{\mu_1 \cdots \mu_n}^h
\]
yields convolution representation

\[
q(x) = \sum_h \int_x^1 \frac{dy}{y} f_h(y) q^h_v(x/y)
\]

C Ji, WM, Thomas (2013)
E866 data have driven successful phenomenology through interplay of PDFs and chiral physics.

... but lingering question of possible sign change of $d - \bar{u}$ at high $x$

→ sign change cannot be accommodated within chiral EFT framework since (negative) $\Delta$ contribution << (positive) $N$ contribution

→ evidence for other mechanisms?
“Independent evidence for $\bar{d} - \bar{u}$ sign change at $x \sim 0.3$” from NMC Peng et al., PLB 736 (2014) 411

$$\bar{d} - \bar{u} \equiv \frac{1}{2} (u_v - d_v) - \frac{3}{2x} (F_2^p - F_2^n)$$

→ conclusions based on LO analysis … how robust?
Light quark sea

At higher order can easily generate zero crossing in
\[
\Delta \equiv \frac{1}{2} (u_v - d_v) - \frac{3}{2x} (F_2^p - F_2^n)
\]
with no $\bar{d} - \bar{u}$ asymmetry!

\[Q^2 = 4 \text{ GeV}^2\]

→ no evidence of sign change from DIS data!
At higher order can easily generate zero crossing in

$$\Delta \equiv \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

with no $\bar{d} - \bar{u}$ asymmetry!

$Q^2 = 54 \text{ GeV}^2$

no evidence of sign change from DIS data!
Preliminary data from SeaQuest (E906) Drell-Yan experiment at Fermilab shows no evidence for sign change.

SeaQuest data consistent with E866 data up to $x \sim 0.2$, remains above unity up to $x \sim 0.5$.

Results not significantly affected if include nuclear corrections.
Strange quarks

Strange quark PDFs most directly determined from dimuon production in (anti)neutrino-nucleus DIS ($W^+ s \rightarrow c / W^- \bar{s} \rightarrow \bar{c}$)

- but significant uncertainty from nuclear corrections and semileptonic branching ratio uncertainty

- tension with HERMES semi-inclusive $K$-production data?

$$\begin{align*}
\kappa &= \frac{s + \bar{s}}{u + \bar{d}} \\
&\sim 0.2 - 0.5
\end{align*}$$

... but uncertainty from $K$ fragmentation functions
Strange quarks

- Fragmentation functions (FFs) determined from single-inclusive meson production in $e^+e^-$ annihilation

  ➡️ new “iterative Monte Carlo” (IMC) global analysis suggests differences with previous extractions

![Graphs showing fragmentation functions](image)

- SIDIS data also constrain fragmentation functions, but require simultaneous PDF + FF fit

  ➡️ J. Ethier
Strange quarks

- Alternatively, probe strange PDF in $W/Z$ production at LHC
  
  $$pp \rightarrow W(Z) + X$$  free of nuclear effects

$$r_s = (s + \bar{s})/2\bar{d}$$

$$= 1.00^{+0.25}_{-0.28}$$

→ more recent reanalysis of neutrino DIS (CHORUS, NOMAD) and ATLAS data does not support enhanced strange PDF

Alekhin et al. (2015)
Strange quarks

Alternatively, probe strange PDF in $W/Z$ production at LHC

$$pp \rightarrow W(Z) + X \text{ free of nuclear effects}$$

$$r_s = \frac{\langle s + \bar{s} \rangle}{2\bar{d}} = 1.00^{+0.25}_{-0.28}$$

More recent reanalysis of neutrino DIS (CHORUS, NOMAD) and ATLAS data does not support enhanced strange PDF

effect could be related to underestimated $\bar{d}$ PDF from collider data
Strange quarks

Parity-violating DIS allows strange contribution to be isolated, when combined with e.m. $p$ and $n$ DIS data at low/intermediate $x$.

\[ F_2^{\gamma p} = \frac{4}{9} x(u + \bar{u}) + \frac{1}{9} x(d + \bar{d} + s + \bar{s}) + \cdots \]
\[ F_2^{\gamma n} = \frac{4}{9} x(d + \bar{d}) + \frac{1}{9} x(u + \bar{u} + s + \bar{s}) + \cdots \]
\[ F_2^{\gamma Z,p} = \left( \frac{1}{3} - \frac{8}{9} \sin^2 \theta_W \right) x(u + \bar{u}) + \left( \frac{1}{6} - \frac{2}{9} \sin^2 \theta_W \right) (d + \bar{d} + s + \bar{s}) + \cdots \]
\[ \approx \frac{1}{9} x(u + \bar{u} + d + \bar{d} + s + \bar{s}) + \cdots \quad \text{for } \sin^2 \theta_W \approx 1/4 \]

\[ F_3^{\gamma Z,p} = \frac{2}{3} (u - \bar{u}) + \frac{1}{3} (d - \bar{d} + s - \bar{s}) + \cdots \]

3 equations with 3 unknowns; order of magnitude greater sensitivity of $\gamma Z$ to strange PDF.

$V \times A$ term also sensitive to $s - \bar{s}$.
Strange quarks

Parity-violating DIS allows strange contribution to be isolated, when combined with e.m. $p$ and $n$ DIS data at low/intermediate $x$

→ PVDIS asymmetry

$$A_{PV} \propto g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + \frac{g_V^e}{2} Y_3 \frac{F_3^{\gamma Z}}{F_1^{\gamma}}$$

**M. Dalton et al.**

*JLab PAC45 proposal (2017)*
Charm in the nucleon

Is there a large “intrinsic charm” (IC) component in the nucleon?

- with standard fitting technology
  momentum carried by “IC”
  \( \langle x \rangle_{IC} < 0.1\% \text{ at } 5\sigma \text{ CL} \)

- difficult to accommodate both low-\( x \) and high-\( x \) EMC \( F_2^c \) data

Jimenez-Delgado et al. (2015)
Charm in the nucleon

Is there a large “intrinsic charm” (IC) component in the nucleon?

- with standard fitting technology
  - momentum carried by “IC”
  - $\langle x \rangle_{IC} < 0.1\%$ at $5\sigma$ CL

- recent “neural network” analysis
  - $\langle x \rangle_{IC} < 1\%$ at $1\sigma$ CL, but can go
    - $< 0$ at low $x$ to fit EMC $F_2^C$ data

→ no evidence for “large” IC, but exact limits subject to treatment of perturbative & nonperturbative QCD effects
Spin-dependent PDFs

- Polarized DIS data on protons similarly constrain $\Delta u$ PDF

$$g_1^p \sim \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \cdots$$

- Polarized deuterium & $^3$He data more sensitive to $\Delta d$ PDF

$\rightarrow$ uncertainties still larger because $|\Delta d| \ll |\Delta u|$
Spin-dependent PDFs

Impact of JLab 6 GeV data

\( g_1 = g_1^2(TMC) + g_1^3(TMC) + g_1^4 \)

\( g_2 = g_2^2(TMC) + g_2^3(TMC) \)

\( g_1^3 = (p^2 - 1) \left[ g_2^3 - 2 \int_0^1 \frac{dy}{y} g_2^3 \right] \)

\( D^3(x) = N x^a(1 - x)^b(1 + c x) \)

\( g_1^4 = N' x^{a'}(1 - x)^{b'}(1 + \gamma' x) \frac{1}{Q^2} \)

eg1-dvcs (CLAS) → signal for higher twist

twist-3 PDFs large, same sign as twist-2

twist-4 negligible
Spin-dependent PDFs

- Assuming SU(3) symmetry, can extract polarized strangeness from inclusive DIS analysis

\[ s\text{-quark polarization negative, } \Delta s \sim -0.1 \]

as in previous DIS fits…

what if relax SU(3) constraint?

\[ \Delta g \]

at intermediate \( x \)

- To distinguish between \( q \) and \( \bar{q} \), need SIDIS data

\[ \sim \sum_{q} e_{q}^{2} [\Delta q(x) D_{q}^{h}(z) + \Delta \bar{q}(x) D_{\bar{q}}^{h}(z)] \]

\[ \rightarrow \] need fragmentation functions…

\[ J. Ethier \]
Spin-dependent PDFs

- Polarized glue has most sensitivity in jet production in $\bar{p}p$ at RHIC

$\Delta g$ positive in measured region ($x \gtrsim 0.05$) but large uncertainty at smaller $x$

- do not know $x$-integrated value, or its uncertainty!

*STAR 2009 run (preliminary) | $|\eta| < 0.5$

$|\eta| < 1.0$

$A_{jet}^p$ vs $p_T [GeV]$ and $A_{jet}^{\perp L}$ vs $x\Delta g$

$Q^2 = 10 GeV^2$

$de$ $Florian$ $et$ $al.$, $PRL$ $113$, $012001$ $(2014)$
## Scorecard

<table>
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<th>$u_v$</th>
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→ stay tuned for rest of story…