Insights into nucleon structure from parton distributions

Wally Melnitchouk

Jefferson Lab
“Theoretical nuclear physics” — quest to understand nature in terms of fundamental building blocks — “atoms”

→ circa 5th century BC...

Leucippus

Democritus
“Experimental nuclear physics” — 23 centuries later, discovery of atomic nucleus

... followed by discoveries of proton (Rutherford, 1917) and neutron (Chadwick, 1932)
Almost 100 years later, what do we know about the nucleon?

→ they have finite size  

Hofstadter (1955)

elastic  \( e p \to e p \) 

scattering cross section

\[
\frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_{\text{point}} \times F^2(Q^2)
\]

form factor

→ from slope of form factor \( F(Q^2) \) vs. momentum transfer squared \( Q^2 \), obtained r.m.s. charge radius

\[
\sim 0.75 \times 10^{-15} \text{m}
\]

(within 10% of current best value!)

D. Dutta talk (Mon)
Almost 100 years later, what do we know about the nucleon?

→ remarkably, at higher $Q^2$ inelastic cross section exhibits point-like behaviour!

**Friedman, Kendall, Taylor** (1969)

deep-inelastic $ep \rightarrow eX$ scattering (DIS) cross section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{d^2\sigma}{d\Omega dE'} \bigg|_{\text{point}} \left(2F_1 \tan^2 \frac{\theta}{2} + F_2\right)$$

structure functions

→ how can nucleon have finite-size and point-like properties at the same time?
At high energies, scattering is point-like… but from *constituents* of nucleon


Measurement of structure functions in DIS reveals how nucleon is made up of quarks & gluons

→ in Feynman’s parton model, structure functions given by parton distribution functions (PDFs)

\[ F_2 = x \sum_q e_q^2 q(x) \]

\[ q(x) = \text{probability distribution to find quark } q \text{ in nucleon with momentum fraction } x \]
In QCD, parton distributions are universal functions which are process-independent

→ established formally through factorisation theorems (e.g. collinear, TMD, …)

\[ \text{Collins, Soper, Sterman ("CSS"), 1980s} \]

→ allows high-energy cross sections to be factorised into “hard scattering partonic cross sections” (calculated from QCD using perturbation theory), and “soft” matrix elements (parameterised via PDFs)
In QCD, parton distributions are universal functions which are process-independent

established formally through factorisation theorems

(e.g. collinear, TMD, …)

Collins, Soper, Sterman ("CSS"), 1980s

\[
\sigma_{AB \rightarrow CX}(p_A, p_B) = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, \mu) f_{b/B}(x_b, \mu) \times \hat{\sigma}_{ab \rightarrow CX}(x_a p_A, x_b p_B, Q/\mu)
\]
In QCD, parton distributions are universal functions which are process-independent

→ established formally through factorisation theorems

(e.g. collinear, TMD, …)

Collins, Soper, Sterman ("CSS"), 1980s

+ Jianwei Qiu — new JLab Theory Director

\[
\sigma_{AB \rightarrow CX}(p_A, p_B) = \sum_{a,b} \int d x_a \, d x_b \, f_{a/A}(x_a, \mu) \, f_{b/B}(x_b, \mu) \\
\times \hat{\sigma}_{ab \rightarrow CX}(x_a p_A, x_b p_B, Q/\mu)
\]
Universality of PDFs allows data from many different processes (DIS, SIDIS, weak boson/jet production in \(pp\), Drell-Yan …) to be analysed simultaneously

→ parameterisations of spin-averaged \((f = f^\uparrow + f^\downarrow)\)
and spin-dependent \((\Delta f = f^\uparrow - f^\downarrow)\) PDFs

→ e.g. CTEQ-JLab (CJ), JLab Angular Momentum (JAM), …

\[
Q^2 = 10 \text{ GeV}^2
\]

\(x\Delta u^+\)
\(x\Delta d^+\)
\(x\Delta s^+\)
\(x\Delta g\)

JAM (Sato, Ethier, WM…)

CTEQ-JLab (CJ) (Owens, Accardi, Keppel, WM…)

JAM (Sato, Ethier, WM…)

CJ15

\(x\)

\(1\)

\(0.8\)

\(0.6\)

\(0.4\)

\(0.2\)

\(0.1\)

\(0\)

\(10^{-4}\)

\(10^{-3}\)

\(10^{-2}\)

\(0.9\)

\(0.7\)

\(0.5\)

\(0.3\)

\(0.1\)

\(x\Delta u^+\)

\(x\Delta d^+\)

\(x\Delta s^+\)

\(x\Delta g\)
Universality of PDFs allows data from many different processes (DIS, SIDIS, weak boson/jet production in $pp$, Drell-Yan, …) to be analysed simultaneously

- parameterisations of spin-averaged ($f = f^\uparrow + f^\downarrow$) and spin-dependent ($\Delta f = f^\uparrow - f^\downarrow$) PDFs

Precision PDFs needed to
(1) understand basic structure of QCD bound states
(2) compute backgrounds in searches for BSM physics

- $Q^2$ evolution feeds
  low $x$, high $Q^2$ (“LHC”)
  from high $x$, low $Q^2$ (“JLab”)

![Diagram showing $Q^2$ and $x$ axes with collider and fixed-target labels]
Valence quarks & QCD models

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
      (colour-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!)

Roberts
Valence quarks & QCD models

Valence $d/u$ ratio at high $x$

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

extrapolated ratio at $x = 1$

$$\frac{d}{u} \rightarrow 0.09 \pm 0.03$$

does not match any model!

upcoming experiments at JLab will determine $d/u$ up to $x \sim 0.85$
Valence quarks & BSM searches

Observation of new physics signals requires accurate determination of QCD backgrounds, which depend on PDFs

→ e.g. heavy $W'$ boson production at LHC

- 3.4 $\sigma$ excess in $WZ$ diboson channel at $\sim 2$ TeV
- extended gauge model $W' \rightarrow WZ$ with $M < 1.5$ TeV excluded at 95% c.l.

→ for $W'^-$ production, parton luminosity is

$$\mathcal{L}_{W'^-} \sim d(x_1) \bar{u}(x_2) \quad \text{at large rapidity } y_{W'}$$

$x_{1,2} = \frac{M_{W'}}{\sqrt{s}} e^{\pm y_{W'}}$

uncertain at high $x_1$
Valence quarks & BSM searches

Observation of new physics signals requires accurate determination of QCD backgrounds, which depend on PDFs.

- Large-\(x\) uncertainties scale with mass.

PDF uncertainty small at low \(y_{W'}\), but rises dramatically at large \(y_{W'}\) for all \(M_{W'}\).

\[
\begin{align*}
M_{W'} &= 7 \text{ TeV} \\
&= 3.5 \text{ TeV} \\
&= 1.5 \text{ TeV} \\
&= 0.5 \text{ TeV} \\
&= 80 \text{ GeV}
\end{align*}
\]
Light quark sea

From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)

\[ \bar{d} \approx \bar{u} \]

In 1984 Thomas made audacious suggestion that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

\[ \bar{d} > \bar{u} \]
Light quark sea

From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)

\[ q \quad \rightarrow \quad \text{since } u \text{ and } d \text{ quarks nearly degenerate, expect flavour-symmetric light-quark sea} \quad \bar{d} \approx \bar{u} \]

In 1984 Thomas made audacious suggestion that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

\[ \pi^+ \quad \leftarrow \quad (u\bar{d}) \quad \rightarrow \quad \bar{d} > \bar{u} \]
Light quark sea

Asymmetry spectacularly confirmed (more than a decade later) in high-precision DIS and Drell-Yan experiments

firmly established role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

\[
\begin{align*}
\frac{d\sigma}{dx_1dx_2} &\sim \sum_q e_q^2 q(x_1) \bar{q}(x_2) + (x_1 \leftrightarrow x_2) \\
\frac{\sigma_{pd}}{\sigma_{pp}} &\approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \text{ for } x_1 \gg x_2
\end{align*}
\]

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

pion distribution in nucleon

pion PDF
Light quark sea

Asymmetry spectacularly confirmed (more than a decade later) in high-precision DIS and Drell-Yan experiments

No nuclear correction for deuterium

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

firmly established role of chiral symmetry and pion cloud as central to understanding of nucleon’s quark structure

\[ (\bar{d} - \bar{u})(x) = (f_{2\pi} \otimes \bar{q}_{2\pi})(x) \]

P. Reimer (2016)
Light quark sea

Early calculations used phenomenological models — more recently rigorous connection with QCD established via effective chiral field theory

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

Weinberg (1967)

→ lowest order \( \pi N \) interaction includes pion rainbow and tadpole contributions

→ matching quark- and hadron-level operators

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

yields convolution representation

\[ q(x) = \sum_h \int_x^1 \frac{dy}{y} f_h(y) q^h(x/y) \]
Light quark sea

Early calculations used phenomenological models — more recently rigorous connection with QCD established via effective chiral field theory

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

Weinberg (1967)

→ expanding PDF moments in powers of \( m_\pi \), coefficients of leading nonanalytic (LNA) terms are model-independent!

Thomas, WM, Steffens (2000)
Chueng Ji, WM, Thomas (2012)

nonanalytic behaviour vital for chiral extrapolation of lattice data on PDF moments

\[
\langle x \rangle_{u-d}^{\text{LNA}} \sim m_\pi^2 \log m_\pi^2
\]

Detmold et al. (2001)
Light quark sea

Drell-Yan $\bar{d} - \bar{u}$ data can be described using range of UV regulators (shapes of pion momentum distributions).

→ semi-inclusive production of "leading neutrons" at HERA can discriminate between different shapes

$$\frac{d^3\sigma^{\text{LN}}}{dx\,dQ^2\,dy} \sim F_2^{\text{LN}(3)}(x, Q^2, y) = f_\pi(y) F_2^{\pi}(x/y, Q^2)$$

→ best fit to combined ZEUS/H1 and DY data prefers $t$-dependent exponential regulator

McKenney et al. (2016)
Light quark sea

Drell-Yan $\bar{d} - \bar{u}$ data can be described using range of UV regulators (shapes of pion momentum distributions)

$\rightarrow$ semi-inclusive production of “leading neutrons” at HERA can discriminate between different shapes

$$\frac{d^3 \sigma_{\text{LN}}}{dx \, dQ^2 \, dy} \sim F_{2\, \text{LN}(3)}(x, Q^2, y) = f_\pi(y) \, F_2^\pi(x/y, Q^2)$$

$\rightarrow$ constrain shape of $F_2^\pi$ at $10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined HERA + Drell-Yan fit

McKenney, Sato, WM, Chueng Ji (2016)

$\rightarrow$ global analysis under way of HERA LN, Drell-Yan $\pi^0 N + pd/pp$ (+ future JLab TDIS data) to determine pion PDFs at all $x$

Barry, Chueng Ji, WM, Sato (2016)

Thia Keppel talk (Tue 16:05)
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, semileptonic branching ratio uncertainty

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

historically, strange to nonstrange ratio

$$\kappa = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

$$\sim 0.2 - 0.5$$

... 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

→ SIDIS data also constrain fragmentation functions, but require simultaneous PDF + FF fit (currently in progress)

Nobuo Sato et al.  
arXiv:1609.00899
Strange quarks

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

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

$\rightarrow$ surprisingly large strangeness

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

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

$\rightarrow$ 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

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

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

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

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

suggests effect related to underestimated $\bar{d}$ PDF from collider data

Alekhin et al. (2015)
Strange quarks

Some indication of strange–antistrange asymmetry from $\nu/\bar{\nu}$ DIS data

$$S^{-} = \int_{0}^{1} dx x(s - \bar{s}) = (2.0 \pm 1.4) \times 10^{-3}$$  \textit{NuTeV} (2007)

predicted from chiral SU(3) symmetry breaking via “kaon cloud”

$$K^{+} \leftarrow (u\bar{s})$$  \textit{Signal, Thomas} (1987)

$\Lambda$ ... but shape more difficult to constrain

Recent chiral effective theory analysis (including rainbow, tadpole & Kroll-Ruderman) favours small positive moment

$$S^{-} \lesssim 1 \times 10^{-3}$$

\textit{Xuangong Wang talk} (Mon)

\textit{X. Wang et al.} (2016)
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 \( F_c^2 \) data

→ no evidence for “large” IC, but exact limits subject to treatment of perturbative & nonperturbative QCD effects
Charm in the nucleon

Associated prompt photon + charm production

\[ pp \rightarrow \gamma + c/\bar{c} + X \]

may reveal “intrinsic” charm component

→ “smoking gun” would be observation of asymmetric distributions \( c(x) \neq \bar{c}(x) \)

→ arises naturally in hadronic models

with \( p \rightarrow \bar{D} + \Lambda_c \) dissociation

Paiva, Nielsen, Navarra, Duraes, Barz (1996)

WM, Thomas (1997)
Outlook and new directions

Study of PDFs has brought together essential elements of nuclear and high-energy physics

James Zanotti talk (Fri 10:30)
Outlook and new directions

New approach to global QCD analysis — “IMC”

→ minimise bias from choice of initial parameters

→ statistically rigorous PDF uncertainties, without assumptions about “tolerance” or Gaussianity

→ ultimate goal is simultaneous fit of unpolarised and polarised PDFs and fragmentation functions in sight (generalise to TMDs)

iterative Monte Carlo workflow

Nobuo Sato et al. (2016)
Outlook and new directions

New generation of experiments at JLab–12 GeV will map out difficult to explore large-\(x\) region

\[\rightarrow \text{MARATHON (}{^3\text{H}}-{^3\text{He DIS}), BONuS (tagged deuteron DIS), Solid (parity-violating DIS)} \rightarrow \text{A. Deshpande (Mon)}\]

\[\rightarrow \text{spin-dependent PDFs from polarised DIS and semi-inclusive DIS}\]

Drell-Yan data from SeaQuest at Fermilab will fix \(\bar{d}/\bar{u}\) at high \(x\)

Data from RHIC-spin to probe polarized glue \[\rightarrow \text{C. Gagliardi (Tue 14:10)}\]

LHC data on Drell-Yan, \(W\)-production … will continue to provide constraints on (unpolarised) PDFs

A future Electron-Ion Collider (EIC) would provide a new level of precision studies of unpolarised and polarised PDFs

\[\rightarrow \text{EIC session (Mon)}\]
Thank You!