Partonic Structure of Hadrons

Theory

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The International Conference on
Electromagnetic Interactions with Nucleons and Nuclei (EINN 2013)
October 28 – November 02, 2013, Pafos (Cyprus)
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

But, the Higgs mechanism generates
Too little to be relevant for
the mass of our world of visible matter!

\[ m_q \sim 10 \text{ MeV} \]
\[ m_N \sim 1000 \text{ MeV} \]
Why do we care about the structure?
  Structure leads to the revolution in knowledge

Nucleon is not point-like and has internal structure
  Birth of QCD, partons (quarks and gluons) and their dynamics

How to “see” hadron’s partonic internal structure?
  QCD factorization links hadron cross sections to parton structures

Hadron properties and partonic structures
  Proton spin, mass, radius (EM charge, color, quark, gluon), ...

Summary
Revolution in our view of atomic structure (100 years ago):

J.J. Thomson’s plum-pudding model

Rutherford’s planetary model

Modern model Quantum orbitals

Completely changed our view of the visible world:
- Mass by “tiny” nuclei – less than 1 trillionth in volume
- Motion by quantum probability – the quantum world!

Provided infinite opportunities to improve things around us:
- Nano materials, quantum computing, …
Nuclear structure and nuclear physics

- Since the Rutherford exp’t,

- Origin of nuclear force?
  
  *Nucleon-nucleon, multi-nucleon, …?*
Hadrons – building blocks

- Protons, neutrons, and pions:

\[
\begin{align*}
\text{Protons} & : & m &= 938.3 \text{ MeV} & S &= 1/2 & I_3 &= +1/2 \\
\text{Neutrons} & : & m &= 939.6 \text{ MeV} & S &= 1/2 & I_3 &= -1/2
\end{align*}
\]

- Pions:

\[
\begin{align*}
\text{Up} & : & m &= 139.6 \text{ MeV} & S &= 0 & I_3 &= \pm 1 \\
\text{Down} & : & m &= 135.0 \text{ MeV} & S &= 0 & I_3 &= 0
\end{align*}
\]

- Isospin doublet: \[
N = \begin{pmatrix} p \\ n \end{pmatrix}
\]
- Isospin triplet: \[
\pi = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}
\]

- “Historic” – \(\pi\) as \(NN\) bound state:

\[
\begin{align*}
\pi^+ &= (p\bar{n}), & \pi^- &= (n\bar{p}), & \pi^0 &= \frac{1}{\sqrt{2}}(p\bar{p} + n\bar{n})
\end{align*}
\]

Fermi and Yang, 1952; Nambu and Jona-Lasinio, 1960 (dynamics)
Yang-Mills theory, SU(2) Non-Abelian Gauge theory (1953)
Nucleon structure

- Nucleon is not elementary:
  - Magnetic moment: \( g_{\text{proton}} \neq 2 \), \( g_{\text{neutron}} \neq 0 \)

- The zoo of particles:

The Quark Model

Proton

Neutron

Nobel Prize, 1969
A complete example: Proton

- **Flavor-spin part:**

\[
|p \uparrow\rangle \equiv \psi_{\text{Flavor}} \times \psi_{\text{Spin}} = \frac{1}{\sqrt{2}} \left[(8_{M_S}, 2_{M_S}) + (8_{M_A}, 2_{M_A})\right]
\]

\[
= \frac{1}{\sqrt{18}} [uud(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2 \uparrow\uparrow\downarrow) + udu(\uparrow\uparrow\downarrow + \downarrow\uparrow\uparrow - 2 \downarrow\uparrow\uparrow)
\]

- **Normalization:**

\[
\langle p \uparrow | p \uparrow \rangle = \frac{1}{18}[(1 + 1 + (-2)^2) + (1 + 1 + (-2)^2) + (1 + 1 + (-2)^2)] = 1
\]

- **Charge:**

\[
\hat{Q} = \sum_{i=1}^{3} \hat{Q}_i
\]

\[
\langle p \uparrow | \hat{Q} | p \uparrow \rangle = \frac{1}{18}[(\frac{2}{3} + \frac{2}{3} - \frac{1}{3})(1 + 1 + (-2)^2) + (\frac{2}{3} - \frac{1}{3} + \frac{2}{3})(1 + 1 + (-2)^2)
\]

\[\quad + (-\frac{1}{3} + \frac{2}{3} + \frac{2}{3})(1 + 1 + (-2)^2)] = 1
\]

- **Spin:**

\[
\hat{S} = \sum_{i=1}^{3} \hat{s}_i
\]

\[
\langle p \uparrow | \hat{S} | p \uparrow \rangle = \frac{1}{18}\{[(\frac{1}{2} - \frac{i-1}{2} + \frac{1}{2}) + (-\frac{1}{2} + \frac{1}{2} + \frac{1}{2}) + 4(\frac{1}{2} + \frac{1}{2} - \frac{1}{2})]
\]

\[\quad + [\frac{1}{2} + \frac{1}{2} + 4\frac{1}{2}] + [\frac{1}{2} + \frac{1}{2} + 4\frac{1}{2}]\} = \frac{1}{2}
\]
Magnetic Moments

- **Quark’s magnetic moment:**
  
  Assumption: Constituent quark’s magnetic moment is the same as that of a point-like, structure-less, spin-\(\frac{1}{2}\) Dirac particle
  
  \[
  \hat{\mu}_i = \hat{Q}_i \left( \frac{e}{2m_i} \right) \quad \text{for flavor “}i\text{”}
  \]

- **Proton’s magnetic moment:**
  
  \[
  \mu_p = \langle p \uparrow | \sum_{i=1}^{3} \hat{\mu}_i (\hat{\sigma}_3)_i | p \uparrow \rangle \quad (\hat{\sigma}_3)_i \quad \text{for quark spin direction}
  \]
  
  \[
  = \frac{1}{3} [4\mu_u - \mu_d]
  \]

- **Neutron’s magnetic moment:**
  
  \[
  \mu_n = \langle n \uparrow | \sum_{i=1}^{3} \hat{\mu}_i (\hat{\sigma}_3)_i | n \uparrow \rangle = \frac{1}{3} [4\mu_d - \mu_n]
  \]

  If \(m_u = m_d\), \(\Rightarrow \ \frac{\mu_u}{\mu_d} = \frac{2/3}{-1/3} = -2 \Rightarrow \ \left( \frac{\mu_n}{\mu_p} \right)_\text{QM} = -\frac{2}{3}
  
  \[
  \left( \frac{\mu_n}{\mu_p} \right)_\text{Exp} = -0.68497945 \pm 0.00000058
  \]

  How to “see” nucleon’s structure?
Deep inelastic scattering (DIS)

- Discovery of spin $\frac{1}{2}$ quarks:
  - SLAC 1968

- The birth of QCD (1973)
  - Quark Model + Yang-Mill gauge theory

- Nucleon structure is complicate:
  - Color Confinement
    - 200 MeV (1 fm)
  - Asymptotic freedom
    - 2 GeV (1/10 fm)
  - Probing momentum

QCD Landscape of the nucleon and atomic nuclei?
Quantum Chromodynamics (QCD)

A quantum field theory of quarks and gluons

- **Fields:**
  - **Quark fields:** spin-½ Dirac fermion (like electron)
  - **Color triplet:** $i = 1, 2, 3 = N_c$
  - **Flavor:** $f = u, d, s, c, b, t$
  - **Gluon fields:** spin-1 vector field (like photon)
  - **Color octet:** $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**
  
  $$L_{QCD}(\psi, A) = \sum_f \bar{\psi}_i^f \left[ (i\partial_{\mu}\delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^{\mu} - m_f\delta_{ij} \right] \psi_j^f - \frac{1}{4} \left[ \partial_{\mu}A_{\nu,a} - \partial_{\nu}A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c} \right]^2 + \text{gauge fixing + ghost terms}$$

- **QED Lagrangian density – force to hold atoms together:**
  
  $$L_{QED}(\phi, A) = \sum_f \bar{\psi}^f \left[ (i\partial_{\mu} - eA_{\mu})\gamma^{\mu} - m_f \right] \psi^f - \frac{1}{4} \left[ \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu} \right]^2$$

**QCD is much richer in dynamics than QED**

- **Gluons are dark, but, interact with themselves, NO free quarks and gluons**
Role of QCD in the formation of hadronic matter

QCD influenced how the universe evolve
- the dynamics of early universe
- the emergence of nucleons, and nuclei

Accelerator technology allows us to:
- recreate the condition of early universe
- repeat the formation of hadronic matter

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>1.5 – 4.5 MeV</td>
</tr>
<tr>
<td>$d$</td>
<td>5.0 – 8.5 MeV</td>
</tr>
<tr>
<td>$s$</td>
<td>80 – 155 MeV</td>
</tr>
<tr>
<td>$c$</td>
<td>1.0 – 1.4 GeV</td>
</tr>
<tr>
<td>$b$</td>
<td>4.0 – 4.5 GeV</td>
</tr>
<tr>
<td>$t$</td>
<td>174.3 ± 5.1 GeV</td>
</tr>
</tbody>
</table>
QCD and hadron mass spectrum

- Lattice QCD calculation of hadron masses:

Hadrons are made of quarks and gluons bound together by QCD
Heavy flavors – new challenges

- Particles discovered in 1964 – Now:

- New X, Y, Z particles:

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$J^{PC}$</th>
<th>Decay Modes</th>
<th>Production Modes</th>
</tr>
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<tr>
<td>$Y_s(2175)$</td>
<td>2175 ± 8</td>
<td>58 ± 26</td>
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<td>$\phi f_0(980)$</td>
<td>$e^+e^-$ (ISR), $J/\psi$ decay</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>3871.4 ± 0.6</td>
<td>&lt; 2.3</td>
<td>1++</td>
<td>$\pi^+\pi^- J/\psi, \gamma J/\psi$</td>
<td>$B \rightarrow KX(3872), pp$</td>
</tr>
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<td>$X(3875)$</td>
<td>3875.5 ± 1.5</td>
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<tr>
<td>$Y(4008)$</td>
<td>4008±82</td>
<td>226±180</td>
<td>1--</td>
<td>$\pi^+\pi^- J/\psi$</td>
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<td>4156 ± 29</td>
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$D^0$ – $\bar{D}^0$ “molecule”
Heavy flavors – new challenges

- **Particles discovered in 1964 – Now:**
  - New X, Y, Z particles:

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**See talk by Yuan, …**
States outside Quark Model

- Charmonium quantum numbers: \[ P = -(-1)^L \quad C = (-1)^{L+S} \]
  
  \[ \begin{align*}
  L = 0 : & \quad J^{PC} = 0^{-+}, 1^{--} \\
  L = 1 : & \quad J^{PC} = 1^{+-}, 0^{++}, 1^{++}, 2^{++} \\
  L = 2 : & \quad J^{PC} = 2^{-+}, 1^{--}, 2^{--}, 3^{--}, \ldots
  \end{align*} \]

  The complete list of allowed \( q\bar{q} \) quantum numbers, \( J^{PC} \), has gaps!

- Exotic \( J^{PC} \): \( 0^{--}, 0^{+-}, 1^{--}, 2^{++}, \ldots \), etc

- Charmonium hybrids:
  - States with an excited gluonic degree of freedom

- If it exists,
  - Link QCD dynamics of quarks and gluons to hadrons beyond the Quark Model – new insight to the formation of hadrons
  - Why one “quasi-stable” gluon? What is the penalty to have more?
How to probe or “see” what is inside a hadron?

*Sub-femtometer scope?*

Need a well-controlled “tool” or ”probe” at sub-fermi scale!
QCD Asymptotic Freedom

\[ \Lambda_{QCD} \]:

\[ \alpha_s(\mu_2) = \frac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi} \alpha_s(\mu_1) \ln \left( \frac{\mu_2^2}{\mu_1^2} \right)} \equiv -\beta_1 \ln \left( \frac{\mu_2^2}{\Lambda_{QCD}^2} \right) \]

\[ \mu_2 \text{ and } \mu_1 \text{ not independent} \]

Asymptotic Freedom \( \Leftrightarrow \) antiscreening

QCD: \( \frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0 \)

Compare

QED: \( \frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0 \)


2004 Nobel Prize in Physics

Weak coupling \( \Leftrightarrow \) Reliable QCD perturbation theory (perturbative QCD)

Controllable QCD dynamics at short-distance (large momentum transfer)!
The challenges

- **BUT:**

  Detectors only see hadrons and leptons, not quarks and gluons!

  *How to probe quark-gluon structure of hadron without seeing them?*

- **Facts:**

  Hadronic scale $\sim 1/fm \sim \Lambda_{QCD}$ is non-perturbative

  Cross section involving identified hadron(s) is not infrared safe and is not perturbatively calculable!

- **Solution – QCD Factorization:**

  - Isolate the calculable dynamics of quarks and gluons
  - Connect quarks and gluons to hadrons via non-perturbative but universal distribution functions
    - provide information on the partonic structure of the hadron
Sub-femtometer “scope”

- New DIS “Rutherford” experiment:

  \[ Q^2 = 4EE' \sin^2(\theta/2), \quad x_B = \frac{Q^2}{2m_N \nu}, \quad \nu = E - E' \]

- QCD Factorization - theory development in last thirty years:

  - Sub-femtometer probe
  - The structure
  - Cross section
  - Asymptotic freedom
  - Parton in a hadron
  - Factorization (theoretical advances in recent years!)
An example: Inclusive DIS

- **Process:**
  \[ e(k) + N(p) \rightarrow e'(k') + X \]
  \[ Q^2 = 4E E' \sin^2(\theta/2), \quad x_B = \frac{Q^2}{2m_N \nu}, \quad \nu = E - E' \]

- **Spin-averaged cross section:**
  \[
  \frac{d^2 \sigma}{dx dQ^2} = \frac{4\pi \alpha^2}{x Q^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]
  
  F_L(x, Q^2) = F_2(x, Q^2) - 2x F_1(x, Q^2)
  
  F_2(x, Q^2) = x \sum e_q^2 \left[ q(x, Q^2) + \bar{q}(x, Q^2) \right]
  
  + \mathcal{O}(\alpha_s) + \mathcal{O}(1/Q^2)
  
  QCD Factorization!

- **Spin-averaged cross section:**
  \[
  \frac{1}{2} \left[ \frac{d^2 \sigma}{dx dQ^2} - \frac{d^2 \sigma}{dx dQ^2} \right] \approx \frac{4\pi \alpha^2}{Q^4} y (2 - y) g_1(x, Q^2)
  
  g_1(x, Q^2) = \frac{1}{2} \sum e_q^2 \left[ \Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) \right]
  
  QCD Factorization!

  Helicity PDFs

Cross section \rightarrow structure functions \rightarrow PDFs
A few steps of details (3 slides)

- **Scattering amplitude:**
  \[ M(\lambda, \lambda'; \sigma, q) = \bar{u}_{\lambda'}(k') \left[ -ie\gamma_\mu \right] u_\lambda(k) \]
  \* \[ \left( \frac{i}{q^2} \right) (-g^{\mu\mu'}) \]
  \* \[ \langle X | eJ^{em}_{\mu'}(0) | p, \sigma \rangle \]

- **Cross section:**
  \[ d\sigma^{DIS} = \frac{1}{2s} \left( \frac{1}{2} \right)^2 \sum_X \sum_{\lambda, \lambda', \sigma} |M(\lambda, \lambda'; \sigma, q)|^2 \left[ \prod_{i=1}^X \frac{d^3l_i}{(2\pi)^3 2E_i} \right] \frac{d^3k'}{(2\pi)^3 2E'} (2\pi)^4 \delta^4 \left( \sum_{i=1}^X l_i + k' - p - k \right) \]
  \[ \rightarrow \quad E' \frac{d\sigma^{DIS}}{d^3k'} = \frac{1}{2s} \left( \frac{1}{Q^2} \right)^2 L^{\mu\nu}(k, k') W_{\mu\nu}(q, p) \]

- **Leptonic tensor:**
  – known from QED
  \[ L^{\mu\nu}(k, k') = \frac{e^2}{2\pi^2} \left( k^\mu k'^\nu + k^\nu k'^\mu - k \cdot k' g^{\mu\nu} \right) \]
Hadronic tensor and structure functions

Hadronic tensor:

\[ W_{\mu\nu}(q, p, S) = \frac{1}{4\pi} \int d^4z \ e^{i q \cdot z} \langle p, S | J_{\mu}^\dagger(z) J_{\nu}(0) | p, S \rangle \]

Structure functions:

- Parity invariance (EM current) \( \rightarrow W_{\mu\nu} = W_{\nu\mu} \) symmetric for spin avg.
- Time-reversal invariance \( \rightarrow W_{\mu\nu} = W_{\mu\nu}^* \) real
- Current conservation \( \rightarrow q^\mu W_{\mu\nu} = q^\nu W_{\mu\nu} = 0 \)

\[ W_{\mu\nu} = - \left( g_{\mu\nu} - \frac{q_{\mu} q_{\nu}}{q^2} \right) F_1(x_B, Q^2) + \frac{1}{p \cdot q} \left( p_{\mu} - q_{\mu} \frac{p \cdot q}{q^2} \right) \left( p_{\nu} - q_{\nu} \frac{p \cdot q}{q^2} \right) F_2(x_B, Q^2) \]

\[ + i M_p \epsilon_{\mu\nu\rho\sigma} q_{\rho} \left[ \frac{S_{\sigma}}{p \cdot q} g_1(x_B, Q^2) + \frac{(p.q) S_{\sigma} - (S.q) p_{\sigma}}{(p.q)^2} g_2(x_B, Q^2) \right] \]

Spin and polarization:

Spin-avg: \( \sigma = \frac{1}{2} [\sigma(s) + \sigma(-s)] \) \quad Spin-dep: \( \Delta\sigma = \frac{1}{2} [\sigma(s) - \sigma(-s)] \)
Approximation and factorization

- Collinear approximation, if
  \[ Q \sim x p \cdot n \gg k_T, \sqrt{k^2} \]

- Lowest order:
  \[
  \int \frac{dx}{x} + O \left( \frac{k_T^2}{Q^2} \right) \otimes \left( \frac{\gamma \cdot n}{2p \cdot n} \delta \left( x - \frac{k \cdot n}{p \cdot n} \right) \frac{d^4k}{(2\pi)^4} \right)
  \]

  Scheme dependence

  \[
  \sum \frac{1}{2} \gamma \cdot (xp)
  \]

  Same as elastic x-section

Parton’s transverse momentum is integrated into parton distributions, and provides a scale of power corrections

- DIS limit: \( \nu, Q^2 \rightarrow \infty, \) while \( x_B \) fixed

  Feynman’s parton model and Bjorken scaling

  \[
  F_2(x_B, Q^2) = x_B \sum_f e_f^2 \varphi_f(x_B) + O(\alpha_s) + O \left( \frac{\Lambda_{QCD}^2}{Q^2} \right)
  \]
Factorization – two or more identified hadrons

- **One hadron:**
  \[ \ell + h(p) \rightarrow \ell' + X \]
  \[
  \sigma_{\text{DIS}}^{\text{tot}} = \Sigma \left( xP \rightarrow e^- e^+ q \right) + O\left( \frac{1}{QR} \right)
  \]
  Now
  Hard-part

- **Two hadrons:**
  \[ h(p) + h'(p') \rightarrow V(\gamma^*, Z^0, \ldots) + X \]
  \[
  \sigma_{\text{DY}}^{\text{tot}} = \Sigma \left( xP \rightarrow j(x) \right) + O\left( \frac{1}{QR} \right)
  \]

**Predictive power:** Universal Parton Distributions

[Diagram showing interactions and processes]
Parton distribution functions (PDFs)

- **Two parton correlations:**

\[
\langle p, s | \bar{\psi}_i(0) \Gamma_{ij} \psi_j(y^-) | p, s \rangle \\
\langle p, s | F^{+i}(0) F^{+j}(y^-) | p, s \rangle f_{ij}
\]

- **Cross section – Factorization:**

\[
\sigma(Q, s) \pm \sigma(Q, -s) \propto \langle p, s | O(\psi, A^\mu) | p, s \rangle \pm \langle p, -s | O(\psi, A^\mu) | p, -s \rangle
\]

Factorized partonic part is independent of hadron spin

- **Parity and time-reversal invariance:**

\[
\langle p, -s | O(\psi, A^\mu) | p, -s \rangle = \langle p, s | \mathcal{P} \mathcal{T} O^\dagger(\psi, A^\mu) T^{-1} \mathcal{P}^{-1} | p, s \rangle
\]

- **Good operators:**

\[
\langle p, s | \mathcal{P} \mathcal{T} O^\dagger(\psi, A^\mu) T^{-1} \mathcal{P}^{-1} | p, s \rangle = \pm \langle p, s | O(\psi, A^\mu) | p, s \rangle
\]

Operator gives “+”: contribute to spin-averaged cross section

Operator gives “−”: contribute to spin asymmetries
Collinear quark and gluon distributions

- **Quark distributions** – leading power spin projection:
  \[
  \mathcal{O}(\psi, A^\mu) = \overline{\psi}(0) \gamma^\pm \psi(y^-) \Rightarrow q(x) \quad \text{(Number density)}
  \]
  \[
  \mathcal{O}(\psi, A^\mu) = \overline{\psi}(0) \gamma^\mp \gamma_5 \psi(y^-) \Rightarrow \Delta q(x) \quad \text{(Net helicity)}
  \]
  \[
  \mathcal{O}(\psi, A^\mu) = \overline{\psi}(0) \gamma^\pm \gamma \cdot s_\perp \psi(y^-) \Rightarrow \delta q(x) \rightarrow h(x) \quad \text{(Transversity)}
  \]

- **Gluon distributions** – leading power spin projection:
  \[
  \mathcal{O}(\psi, A^\mu) = \frac{1}{xp^+} F^{+i}(0) \left[ \delta^{ij} \right] F^{+j}(y^-) \Rightarrow G(x) \quad \text{(Number density)}
  \]
  \[
  \mathcal{O}(\psi, A^\mu) = \frac{1}{xp^+} F^{+i}(0) \left[ i \epsilon^{ij} \right] F^{+j}(y^-) \Rightarrow \Delta G(x) \quad \text{(Net helicity)}
  \]

- **All operators for collinear PDFs are “local”**:
  \[
  U^+_-(\infty, 0) U^+_-(\infty, y^-) = \exp \left[ -ig \int_0^{y^-} dy' A^+(y') \right]
  \]

  All operators are localized to “1/xp ~ 1/Q” (Not true for TMDs!)
Physical cross sections should not depend on the factorization scale

\[ \mu_F^2 \frac{d}{d\mu_F^2} F_2(x_B, Q^2) = 0 \]

Evolution (differential-integral) equation for PDFs

\[ \sum_f \left[ \mu_F^2 \frac{d}{d\mu_F^2} C_f \left( \frac{x_B}{x}, \frac{Q^2}{\mu_F^2}, \alpha_s \right) \right] \otimes \varphi_f(x, \mu_F^2) + \sum_f C_f \left( \frac{x_B}{x}, \frac{Q^2}{\mu_F^2}, \alpha_s \right) \otimes \mu_F^2 \frac{d}{d\mu_F^2} \varphi_f(x, \mu_F^2) = 0 \]

PDFs and coefficient functions share the same logarithms

PDFs: \( \log \left( \frac{\mu_F^2}{\mu_0^2} \right) \) or \( \log \left( \frac{\mu_F^2}{\Lambda_{QCD}^2} \right) \)

Coefficient functions: \( \log \left( \frac{Q^2}{\mu_F^2} \right) \) or \( \log \left( \frac{Q^2}{\mu^2} \right) \)

DGLAP evolution equation:

\[ \mu_F^2 \frac{\partial}{\partial \mu_F^2} \varphi_i(x, \mu_F^2) = \sum_j P_{i/j} \left( \frac{x}{x'}, \alpha_s \right) \otimes \varphi_j(x', \mu_F^2) \]
Global QCD analysis – test of QCD

Input DPFs at $Q_0$

$\varphi_{f/h}(x, \{a_j\})$

DGLAP

$\varphi_{f/h}(x)$ at $Q > Q_0$

Minimize $\chi^2$

Vary $\{a_j\}$

QCD calculation

Comparison with Data at various $x$ and $Q$

Procedure: Iterate to find the best set of $\{a_j\}$ for the input DPFs
Successes of QCD factorization

Measure e-p at 0.3 TeV (HERA)

Universal PDFs

- Predict hadronic collisions at 0.2, 1.96, and 7 TeV:
Puzzles and new challenges

How to describe hadron properties in terms of parton dynamics?

How to explore hadron structure beyond 1-D parton distributions?
The hadron mass puzzle

- How does QCD generate energy for the proton’s mass?
  - $m_q \sim 10$ MeV
  - $m_N \sim 1000$ MeV
  - Quark mass $\sim 1\%$ proton’s mass
  - *Higgs mechanism is not enough***!!

- Generation of mass: from QCD dynamics?
  - BSE calculation results confirmed by lattice simulation
  - Light-quark mass comes from a cloud of soft gluons
  - Gluon is massless in UV, but “massive” in IR


$m_{G}^2(k^2) \approx m_G^4/(k^2+m_G^2)$

Qin et al., Phys. Rev. C 84 042202 (Rapid Comm.)
The hadron mass sum rule

QCD definition:

\[
M = \frac{\langle P | \int d^3x \ T^{00}(0, x) | P \rangle}{\langle P | P \rangle} \equiv \langle T^{00} \rangle
\]

QCD energy-momentum tensor:

\[
T^{\mu\nu} = \frac{1}{2} \overline{\psi} iD^{\mu\nu} \psi + \frac{1}{4} g^{\mu\nu} F^2 - F^\mu_{\alpha} F^\nu_{\alpha}
\]

\[H_{\text{QCD}} = \int d^3x \ T^{00}(0, x)\]

Decomposition:

\[H_{\text{QCD}} = H_q + H_m + H_G + H_a\]

<table>
<thead>
<tr>
<th>Mass type</th>
<th>(H_i)</th>
<th>(M_i)</th>
<th>(m_s \rightarrow 0) (MeV)</th>
<th>(m_s \rightarrow \infty) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark energy</td>
<td>(\psi^\dagger (-i \mathbf{D} \cdot \alpha) \psi)</td>
<td>(3(a - b)/4)</td>
<td>270</td>
<td>300</td>
</tr>
<tr>
<td>Quark mass</td>
<td>(\overline{\psi} m \psi)</td>
<td>(b)</td>
<td>160</td>
<td>110</td>
</tr>
<tr>
<td>Gluon energy</td>
<td>(\frac{1}{4} (\mathbf{E}^2 + \mathbf{B}^2))</td>
<td>(3(1 - a)/4)</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>Trace anomaly</td>
<td>(\frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2))</td>
<td>((1 - b)/4)</td>
<td>190</td>
<td>210</td>
</tr>
</tbody>
</table>

\[a(\mu^2) = \sum_f \int_0^1 x[q_f(x, \mu^2) + \overline{q}_f(x, \mu^2)] dx\]

\[bM = \langle P | m_u \overline{u} u + m_d \overline{d} d | P \rangle + \langle P | m_s \overline{s} s | P \rangle\]

✧ None of these terms is a “direct” physical measurable (e.g. cross section)!

Can we “measure” them with controllable approximation?

Can we “measure” them by lattice calculation, or other approaches?
The proton spin puzzle

- **Proton** – composite particle of quarks and gluons:
  
  Spin = intrinsic (parton spin) + motion (orbital angular momentum)

- **Proton spin sum rule:**

  \[
  S(\mu) = \frac{1}{2}
  \]

  \[
  S(\mu) = \sum_f \langle P, S| \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) = \frac{1}{2} \Delta \Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + L_g(\mu)
  \]

  Decomposition is useful if, only if, each term can be related to physical observables with controllable approximation

- **Over 20 years effort (following EMC discovery)**
  
  - **Quark (valence + sea) helicity:** \(~ 30\%\) of proton spin
  - **Gluon helicity (latest RHIC data):** \(~ 20\%\) from limited x range

  How to explore the “full” gluon and sea quark contribution?

  How to quantify the role of orbital motion?

  How to calculate them on the lattice?
The nucleon structure

- **A unified view – Wigner distributions:**

  - **5D**
    - $W(x,b_T,k_T)$
  
  - **3D**
    - $f(x,k_T)$
    - $f(x,b_T)$
    - $f(x)$

- **3D imaging of sea and gluons (EIC@US, no spin@LHeC):**
  
  - TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - GPDs – Spatial imaging of quarks and gluons (exclusive DIS)
Parton distributions

1-D HADRON STRUCTURE

QCD Collinear factorization for Cross sections with one large momentum transfer

HERA data alone leads to precise PDFs
Polarized EIC should pin down proton helicity distributions

See talks by Jansen, Lorce, Surrow, ...
Flavor structure of the proton sea

- The proton sea is not SU(3) symmetric!

Violation of Gottfried sum rule

\[ S_G = \int_0^1 \frac{1}{x} \frac{(F_2^p(x) - F_2^n(x))}{x} \, dx \]

\[ = \frac{1}{3} + \frac{2}{3} \int_0^1 (\bar{u}_p(x) - \bar{d}_p(x)) \, dx \]

\[ = \frac{1}{3} \quad (\text{if} \quad \bar{u}_p = \bar{d}_p) \quad \text{NMC:} \quad S_G = 0.235 \pm 0.026 \]

Confirmed by Drell-Yan exp’t

Why \( \bar{d}(x) \neq \bar{u}(x) \) ?

Why does \( \bar{d}(x) - \bar{u}(x) \) change sign?
Challenges for $\bar{d}(x) - \bar{u}(x)$

- All known models predict no sign change!

- Future experiments:
  - Meson cloud
  - Chiral-quark soliton model
  - Statistic model

Fermilab E906

Very important non-perturbative physics

What is the ratio as $x$ increases?
Asymmetry between strange and up/down sea?

- LO and NLO QCD global fitting to DIS data:
  \[ s(x) = \bar{s}(x) = \frac{\kappa(x)}{2} \left( \bar{u}(x) + \bar{d}(x) \right) \]
  with \( \kappa(x) \sim 0.5 \) for \( x > 0.1 \)

- New LHC data on W/Z data:
  \[ r_s = (s + \bar{s}) / 2\bar{d} = 1.00^{+0.09}_{-0.10} \]
  at \( x=0.023, Q^2 = 1.9 \text{ GeV}^2 \)

- HERMES data:
  Does not follow the shape of \( u(x) + d(x) \)?
  Why strange sea behave so different?
  Non-perturbative origin of \( \bar{s}(x) \) differing from \( s(x) \)?
TMDs

3-D HADRON STRUCTURE

QCD TMD factorization
for
Cross sections with one large and one small
momentum transfers

“Picture” of confined parton motion inside a hadron
Quantum correlation between hadron property and parton motion,
Parton properties influence hadronization

See talks by Jen-Chieh Peng, …
Transverse momentum dependent PDFs (TMDs)

- Two parton correlations – like PDFs:
  
  \[ f(x) = \int d^2k_\perp f(x, k_\perp) \]

  Without integrating over \( k_T \)

  Need two-scale observables – to be sensitive to \( k_T \)

- Averaged \( k_T \) effect – twist-3 correlation functions:
  
  \[ \sim \int d^2k_\perp k_\perp f(x, k_\perp) \]

  No probability interpretation - Quantum interference of single/double states

Sivers, Collins, Boer-Mulders, Ji-Ma-Yuan, ...

Efremov-Teryaev, Qiu-Sterman, Koike, Kang, Yuan,...
An example: Sivers effect

- Single-spin asymmetry: \( A(\ell, \vec{s}) \equiv \frac{\Delta \sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})} \)

  More sensitive to the role of quantum correlation!

- Consistently observed for almost 40 years – vanish without \( k_T \)!

- Quantum correlation between hadron spin and parton motion:

- Observed particle

- Sivers effect – Sivers function

  Hadron spin influences parton’s transverse motion
TMDs – Link hadron property to parton motion

- **TMDs - rich quantum correlations:**

<table>
<thead>
<tr>
<th>Quark Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-Polarized (U)</td>
</tr>
<tr>
<td>( f_1 = )</td>
</tr>
<tr>
<td>Nucleon Polarization</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>T</td>
</tr>
</tbody>
</table>

- **Similar for gluons**

- **DIS, naturally, has two scales and two planes:**
  - Two scales:
    - high \( Q \) - localized probe
    - Low \( p_T \) - sensitive to confining scale
  - Two planes:
    - angular modulation to separate TMDs

Hard to separate TMDs in hadronic collisions
Non-locality of TMD parton distributions

- **TMD distributions with non-local gauge links:**

  \[ f_{q/h}^\uparrow (x, k_\perp, \vec{S}) = \int \frac{dy^- d^2 y_\perp}{(2\pi)^3} e^{i p^+ y^- - i k_\perp \cdot y_\perp} \langle p, \vec{S} | \overline{\psi}(0^-, 0_\perp) \text{Gauge link} \frac{\gamma^+}{2} \psi(y^-, y_\perp) | p, \vec{S} \rangle \]

- **SIDIS:**

- **DY:**

  - For a fixed spin state:

  \[ f_{q/h}^{\text{SIDIS}} (x, k_\perp, \vec{S}) \neq f_{q/h}^{\text{DY}} (x, k_\perp, \vec{S}) \]

- **Parity + Time-reversal invariance:**

  \[ \mathcal{F}_{q/h}^{\text{SIDIS}} (x, k_T, s_T) = \mathcal{F}_{q/h}^{\text{DY}} (x, k_T, -s_T) \]

  \[ f_{q/h}^{\text{Sivers}} (x, k_\perp)^{\text{SIDIS}} = - f_{q/h}^{\text{Sivers}} (x, k_\perp)^{\text{DY}} \]

  **The sign change is a critical test of TMD factorization approach**
Extract Sivers function from SIDIS

- **SIDIS:** \( \ell + p^\uparrow \rightarrow \ell' + \pi(p_T) + X : p_T \ll Q \)

- **SIDIS and DY cover both double-scale and single-scale cases:**

- **Precise** \( p_T \)–dependence? – motion?

- **TMD**

- **Collinear Factorization**
Importance of the evolution

- Aybat, Prokudin, Rogers, 2012:

  ![Graph showing HERMES and COMPASS TMD evolution](image)

  **Huge Q dependence**

- Sun, Yuan, 2013:

  ![Graph showing Q dependence](image)

  **Smaller Q dependence**

  **No disagreement on evolution equations!**

**Issue:** Extrapolation to non-perturbative large b-region

**Choice of the Q-dependent “form factor”**
GPDs

1+2-D HADRON STRUCTURE

QCD collinear factorization for
Cross sections of exclusive processes with small t

EM charge radius
To
Proton’s quark radius, gluon radius
as a function of x!

See talks by Frank Sabatie, …
How is color distributed inside the proton?

- The “big” question:

  How color is distributed inside a hadron? (clue for color confinement?)

- Electric charge distribution:

  Elastic electric form factor \[\rightarrow\] Charge distributions

- But, NO color elastic nucleon form factor!

  Hadron is colorless and gluon carries color

  Parton density’s spatial distributions – a function of \(x\) as well (more “proton”-like than “neutron”-like)
Spatial imaging of quarks and gluons

- Partonic structure – spatial distributions of quarks and gluons:
  - Need a localized probe
  - Scan in transverse direction
  - Partonic structure

- Need exclusive processes – diffractive scattering

But, every parton can participate – need a “localized” probe! $Q \gg |t|$ !!!

No factorization for hadron-hadron diffractive scattering !

- Deep virtual Compton scattering (DVCS):

\[
\frac{d\sigma}{dx_B dQ^2 dt} = H_q(x, \xi, t, Q), E_q(x, \xi, t, Q), \ldots
\]

F.T. of t-dep

Quark spatial distributions

Proton’s “quark radius”
Proton’s “gluon radius”

- Exclusive vector meson production:
  \[ \frac{d\sigma}{dx_B dQ^2 dt} \]
  \( Q \)
  \( J/\psi, \Phi, \ldots \)
  - Fourier transform of the t-dep
  - Spatial imaging of glue density
  - Resolution \( \sim 1/Q \)

- Gluon imaging from simulation:
  Images of gluons from exclusive \( J/\psi \) production
  Proton’s “gluon radius”
  Natural of pion cloud?

Model dependence – parameterization?
Proposed (or talked about) Future EICs

Electron-Ion Colliders in the world:

<table>
<thead>
<tr>
<th></th>
<th>HERA@DESY</th>
<th>LHeC@CERN</th>
<th>eRHIC@BNL</th>
<th>MEIC@JLab</th>
<th>HIAF@CAS</th>
<th>ENC@GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$E_{CM}$ (GeV)</strong></td>
<td>320</td>
<td>800-1300</td>
<td>45-175</td>
<td>12-140</td>
<td>12 → 65</td>
<td>14</td>
</tr>
<tr>
<td><strong>proton $x_{min}$</strong></td>
<td>$1 \times 10^{-5}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$5 \times 10^{-5}$</td>
<td>$7 \times 10^{-3}$ → $3 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>ion</strong></td>
<td>p</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to $^{40}$Ca</td>
</tr>
<tr>
<td><strong>polarization</strong></td>
<td>-</td>
<td>-</td>
<td>p, $^3$He</td>
<td>p, d, $^3$He ($^6$Li)</td>
<td>p, d, $^3$He</td>
<td>p, d</td>
</tr>
<tr>
<td><strong>$L$ [cm$^{-2}$ s$^{-1}$]</strong></td>
<td>$2 \times 10^{31}$</td>
<td>$10^{33}$</td>
<td>$10^{33-34}$</td>
<td>$10^{33-34}$</td>
<td>$10^{32-33}$ → $10^{35}$</td>
<td>$10^{32}$</td>
</tr>
<tr>
<td><strong>IP</strong></td>
<td>2</td>
<td>1</td>
<td>2+</td>
<td>2+</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Year</strong></td>
<td>1992-2007</td>
<td>2022 (?)</td>
<td>2022</td>
<td>Post-12 GeV</td>
<td>2019 → 2030?</td>
<td>upgrade to FAIR</td>
</tr>
</tbody>
</table>

Common features (differences from HERA):

- High luminosity – sufficiently high energy (100-1000 x HERA)
- High energy polarized electron + polarized proton beam
- High energy heavy ion beams (large number of A’s)
Nuclear structure

Nuclear landscape $\equiv$ Superposition of nucleon landscape!

- Overlapping of pion cloud?
- Overlapping of sea quarks?
- Overlapping of soft gluons?

Nature of nuclear force?

See talks by Kawtar Hafidi, ...
An “easiest” measurement

- EMC effect, Shadowing and Saturation:

Questions:

Why nuclear structure function suppressed at small $x$?
Will the suppression/shadowing continue to fall as $x$ decreases?
An “easiest” measurement

- EMC effect, Shadowing and Saturation:

- Role of color in nuclear binding:
  - Immediate impact on our understanding of neutron stars
  - Colored metal/crystal or condensed “gas”
Summary

- QCD is very successful in the asymptotic regime (< 1/10 fm):
  But, we have learned very little about hadron structure and its formation

- Advances in QCD factorization in last 15 years,
  TMD factorization for two-scale observables,
  Collinear factorization for exclusive processes with a small t,
  Allow us to probe nucleon/nucleus structure beyond 1D PDFs

- Newly proposed EIC facilities would make it possible to “see”
  3D QCD landscape/structure of nucleon/nucleus

Advances of our knowledge in 3D structure of nucleon/nucleus might give us enough hints to explore the nature of confinement and dynamical chiral symmetry breaking, neither of which is apparent in QCD Lagrangian

Thanks!