Parton flavor separation at large fractional momentum

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Pavia U.
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Outline

- Introduction
  - Quark, gluons and nucleons
  - Parton distributions
  - Global fits

- Why large fractional momentum ($x$)

- Up and down: the CTEQ6X fit

- Gluons, intrinsic charm

- Outlook: the Electron-Ion Collider
Quarks, gluons and nucleons
Hadrons are made of quarks

- 6 flavors (and 3 colors):
  - up, down, strange – light
  - charm, bottom, top – heavy

- confined in colorless hadrons
  - mesons – 2 quarks
  - baryons – 3 quarks
  - tetraquarks (?)
  - pentaquarks (???)

nucleons

- Proton
- Anti-proton
- Neutron
- Lambda
- $\pi^+$
- $K^0$
- $\pi^0$
- $J/\psi$
Nucleons are made of 3 quarks...

Fractional momentum:

\[ x = \frac{p_{\text{parton}}^+}{p_{\text{nucleon}}^+} \]

\[ p^\pm = \frac{1}{\sqrt{2}}(p_0 \pm p_3) \]
Nucleons are made of 3 quarks...

Fractional momentum:

\[ x = \frac{p^+_{\text{parton}}}{p^+_{\text{nucleon}}} \]

\[ p^\pm = \frac{1}{\sqrt{2}} (p_0 \pm p_3) \]
Fractional momentum:

\[ x = \frac{p^+_{\text{parton}}}{p^+_{\text{nucleon}}} \]

\[ p^\pm = \frac{1}{\sqrt{2}}(p_0 \pm p_3) \]
... and gluons, sea quarks ...

Fractional momentum:

\[ x = \frac{p^+_{\text{parton}}}{p^+_{\text{nucleon}}} \]

\[ p^\pm = \frac{1}{\sqrt{2}} (p_0 \pm p_3) \]
... spinning and orbiting around!

... but this is another story ...
Probing the nucleon parton structure

- Need a large momentum transfer $Q^2=q_\mu q^\mu$ to resolve the parton structure

- Example 1: Deep Inelastic Scattering (DIS)

\[ Q^2 = p_{\gamma,Z}^2 \]
Probing the nucleon parton structure

- Need a large momentum transfer \( Q^2 = q_\mu q^\mu \) to resolve the parton structure

- Example 2: Drell-Yan lepton pair creation (DY)

\[
Q^2 = (p_\ell + p_{\bar{\ell}})^2
\]
Probing the nucleon parton structure

- Need a large momentum transfer $Q^2 = q_\mu q^\mu$ to resolve the parton structure

- Example 3: jet production in p+p collisions

\[ Q^2 = E_{jet}^2 \]
Factorization of hard scattering processes

- **p**erturbative QCD factorization of short and long distance physics

\[ d\sigma_{\text{hadron}} = \sum_{f_1, f_2, i, j} \phi_{f_1} \otimes \hat{\sigma}_{\text{parton}}^{f_1 f_2 \rightarrow ij} \otimes \phi_{f_2} \]

- **Universality**: PDF from DIS describe also DY, p+p→jets+X, ...

**Parton Distribution Fns** (from inclusive DIS)

**pQCD cross section**
Factorization of hard scattering processes

- Hard scattering, computable in pQCD – e.g., in DIS (at Leading Order)

\[ q^\mu \rightarrow (k+q) \rightarrow q^\nu \]

\[ = - \frac{1}{2} \left( g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) e_f^2 \delta \left( 1 + \frac{q^2}{2k \cdot q} \right) \]

\[ + \left( k_\mu - q_\mu \frac{k \cdot q}{q^2} \right) (\mu \leftrightarrow \nu) \frac{e_f^2}{k \cdot q} \delta \left( 1 + \frac{q^2}{2k \cdot q} \right) \]

- PDF – field theoretical definition (at Leading Order)

\[ \varphi_q(x) = \int \frac{dz^-}{2\pi} e^{i z^- k^+} \langle p | \bar{\psi}(z^- n) \frac{\gamma \cdot \bar{n}}{2} \psi(0) | p \rangle \]
Global PDF fits

Problem: we need a set of PDFs in order to calculate a particular hard-scattering process

Solution:

- Choose a data set for a choice of different hard scattering processes
- Generate PDFs using a parametrized functional form at initial scale $Q_0$; evolve them from $Q_0$ to any $Q$ using DGLAP evolution equations
- Use the PDF to compute the chosen hard scatterings
- Repeatedly vary the parameters and evolve the PDFs again
- Obtain an optimal fit to a set of data.

Examples: CTEQ6.6, MRST2008 for unpolarized protons
DSSV, LSS for polarized protons

For details, see J. Owens' lectures at the 2007 CTEQ summer school
Global PDF fits as a tool

- Test new theoretical ideas
  - *e.g.*, constrain amount of intrinsic charm

- Phenomenology explorations
  - *e.g.*, can CDF / HERA “excesses” be at all due to glue/quark underestimate at large $x$?

- Test / constrain models
  - *e.g.*, by extrapolating $d/u$ at $x=1$
  - Possibly, constrain nuclear corrections

- Limitations
  - existing data
  - experimental errors
  - theoretical errors
Why large $x$ ?
Why large $x$?

- Large uncertainties in quark and gluon PDF at $x > 0.4$ – e.g., CTEQ6.1

**PDF errors**
- propagation of exp. errors into the fit
- statistical interpretation
- reduced by enlarging the data set

**Theoretical errors**
- often poorly known
- difficult to quantify
- can be dominant
Why large $x$?

- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large $x$ are needed, e.g.,
  - at LHC, Tevatron
    1) QCD background in high-mass new physics searches
    2) Lumi monitoring at high mass ($Z,W$ cross-section)
- Example: $Z'$ production

\[ M_{Z'} \gtrsim 200 \text{ GeV} \quad x = \frac{m_T}{\sqrt{s}} e^y \]

$x \geq 0.02$ (LHC), $0.1$ (Tevatron)

but recent work raises the bar:
\[ M_{Z'} \gtrsim 900 \text{ MeV} \]
Why large $x$?

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- Example 2: 1996 CDF $p_T$ excess

Kuhlmann et al. PLB409(97)

… or valence $u$ …

NLO state of the art at the time

Kuhlmann et al. PLB476(00)

enhanced glue at large $x$
(compatible with older data)
Why large $x$?

- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large $x$ are needed, e.g.,
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    1) QCD background in high-mass new physics searches
    2) Luminosity monitoring at high-mass – $Z, W$ cross sections
- non-perturbative nucleon structure – e.g., $d/u$ at $x \rightarrow 1$

\[
\frac{F_2}{F_2^{\text{NN}}_p} \approx \frac{1 + 4d/u}{4 + d/u}
\]
Why large $x$?

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    2) Luminosity monitoring at high-mass – $Z, W$ cross sections
  - non-perturbative nucleon structure – e.g., $\Delta u/u, \Delta d/d$ at $x \to 1$
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- Precise PDF at large $x$ are needed, e.g.,
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    1) QCD background in high-mass new physics searches
    2) Luminosity monitoring at high-mass – $Z, W$ cross sections
  - non-perturbative nucleon structure
  - spin structure of the nucleon at small $x$

\[
\sigma(p\bar{p} \rightarrow \pi^0 X) \propto \Delta q(x_1) \Delta g(x_2) \hat{\sigma}^{qg\rightarrow qg} \otimes D_{q}^{\pi^0}(z)
\]

\[
x_1 \sim \frac{p_T}{\sqrt{s}} e^y
\]

\[
x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}
\]
Why large $x$?

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\[
\sigma(p\bar{p} \rightarrow \pi^0 X) \propto \Delta q(x_1) \Delta g(x_2) \delta^{gg \rightarrow qg} \otimes D^\pi_1 (z)
\]
Why large $x$?

- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large $x$ are needed, e.g.,
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    2) Luminosity monitoring at high-mass – $Z,W$ cross sections
  - non-perturbative nucleon structure
  - spin structure of the nucleon at small $x$
  - neutrino oscillations
Why large $x$ ... and low $Q^2$?

- JLab and SLAC have precision DIS data at large $x$, BUT low $Q^2$

- need of theoretical control over

1) higher twist $\propto \Lambda^2/Q^2$
2) target mass corrections (TMC) $\propto x_B^2 m_N^2/Q^2$
3) heavy-quark mass corrections $\propto m_Q^2/Q^2$
4) nuclear corrections

5) jet mass corrections (JMC) $\propto m_j^2/Q^2$
6) large-$x$ resummation
7) large-$x$ DGLAP evolution
8) quark-hadron duality
9) parton recombination at large $x$
10) perturbative stability at low-$Q^2$
11) ...

this talk

accardi@jlab.org  Pavia U., 13 Jul 2010
Up and down: the CTEQ6X fit

Accardi, Christy, Keppel, Melnitchouk, Monaghan, Morfín, Owens, Phys. Rev. D 81, 034016 (2010)
Collaboration and goals

JLab / Fermilab/ Florida State U. collaboration


Initial Goals:

- Extend PDF global fits to larger values of $x_B$ and lower values of $Q$
- Wealth of data from older SLAC experiments and newer Jlab, DY
- see if PDF errors can be reduced using new JLAB data
**CTEQ6X vs. CTEQ**

**CTEQ**
- \( Q^2 \geq 4 \text{ GeV}^2 \) \( W^2 \geq 12.25 \text{ GeV}^2 \)
- not so large \( x \), not too low \( Q^2 \)
- hope \( 1/Q^2 \) corrections not large

**CTEQ6X**
- TMC, HT, deuteron corrections
- Progressively lower the cuts:

<table>
<thead>
<tr>
<th>( Q^2 ) [GeV(^2)]</th>
<th>( W^2 ) [GeV(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTEQ = cut0</td>
<td>4</td>
</tr>
<tr>
<td>cut1</td>
<td>3</td>
</tr>
<tr>
<td>cut2</td>
<td>2</td>
</tr>
<tr>
<td>cut3</td>
<td>1.69</td>
</tr>
</tbody>
</table>

- Better large-\( x \), low-\( Q^2 \) coverage
CTEQ

\[ Q^2 \geq 4 \text{ GeV}^2 \quad W^2 \geq 12.25 \text{ GeV}^2 \]

- not so large \( x \), not too low \( Q^2 \)
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<tbody>
<tr>
<td>CTEQ</td>
<td>4</td>
<td>12.25</td>
</tr>
<tr>
<td>cut1</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>cut2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>cut3</td>
<td>1.69</td>
<td>3</td>
</tr>
</tbody>
</table>

- Better large-\( x \), low-\( Q^2 \) coverage
Target mass corrections

- Nachtmann variable: \( \xi = \frac{2x_B}{1 + \sqrt{1 + 4x_B^2 m_N^2/Q^2}} < 1 \) at \( x_B = 1 \)

- **Standard Georgi-Politzer (OPE)**
  [Georgi, Politzer 1976; see review by Schienbein et al. 2007]
  [see also Leader, d'Alesio, Murgia, 2009]
  - leads to non-zero structure functions at \( x_B > 1 \) (!)

- **Collinear factorization** [Accardi, Qiu, JHEP 2008; Accardi, Melnitchouk 2008]
  Structure fns as convolutions of parton level structure fns and PDF

\[
F_{T,L}(x_B, Q^2, m_N) = \sum_f \int_\xi \frac{\xi}{x_B} \frac{dx}{x} \, h_{T,L}^{f f}(\frac{\xi}{x}, Q^2) \varphi_f(x, Q^2)
\]

- respects kinematic boundaries

- **\( \xi \)-scaling**, uses CF with \( x_{\text{max}} = 1 \) [Aivazis et al '94; Kretzer, Reno '02]

\[
F_{T,L}^{nv}(x_B, Q^2, m_N) \equiv F_T^{(0)}(\xi, Q^2)
\]

- leads to non-zero structure functions at \( x_B > 0 \) (!)
“Higher-Twists” parametrization

Parametrize by a multiplicative factor (same for $p$ and $n$, for simplicity):

$$F_2(data) = F_2(TMC) \times \left(1 + \frac{C(x_B)}{Q^2}\right)$$

with

$$C(x_B) = a x^b (1 + c x)$$

Important: $C(x_B)$ includes

- dynamical higher-twists (parton correlations, e.g., $\langle p|\bar{\psi}D_AD_A\psi|p\rangle$)
- all uncontrolled power corrections:
  - TMC model uncertainty, Jet Mass Corrections
  - NNLO corrections (power-like at small $Q$)
  - large-x resummation
  - ...

Pavia U., 13 Jul 2010
Deuterium corrections

- nucleon Fermi motion and binding energy
- use non-relativistic deuteron wave-function
- finite-$Q^2$ corrections

\[ F_{2A}(x_B) = \int_{x_B}^{A} dy S_A(y, \gamma, x_B) F_{2}^{TMC+HT}(x_B/y, Q^2) \]

\[ \gamma = \sqrt{1 + 4x_B^2 m_N^2 / Q^2} \]

\[ \frac{x_B}{y} = -\frac{q^2}{2p_N \cdot q} \]

- off-shell effects can be included in $S_A$

Pavia U., 13 Jul 2010
Reference fit vs. CTEQ6.1

- **Reference fit:**
  - cut0, no corrections
  - PDF errors with $\Delta \chi = 1$

<table>
<thead>
<tr>
<th>data</th>
<th>CTEQ6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS (JLab)</td>
<td>NO</td>
</tr>
<tr>
<td>SLAC</td>
<td>NO</td>
</tr>
<tr>
<td>NMC</td>
<td>✓</td>
</tr>
<tr>
<td>BCDMS</td>
<td>✓</td>
</tr>
<tr>
<td>H1</td>
<td>✓</td>
</tr>
<tr>
<td>ZEUS</td>
<td>✓</td>
</tr>
<tr>
<td>DY E605</td>
<td>✓</td>
</tr>
<tr>
<td>DY E866</td>
<td>NO</td>
</tr>
<tr>
<td>W CDF ’98 (ℓ)</td>
<td>✓</td>
</tr>
<tr>
<td>W CDF ’05 (ℓ)</td>
<td>NO</td>
</tr>
<tr>
<td>W D0 ’08 (ℓ)</td>
<td>NO</td>
</tr>
<tr>
<td>W D0 ’08 (e)</td>
<td>NO</td>
</tr>
<tr>
<td>W CDF ’09 (W)</td>
<td>NO</td>
</tr>
<tr>
<td>jet CDF</td>
<td>✓</td>
</tr>
<tr>
<td>jet D0</td>
<td>✓</td>
</tr>
<tr>
<td>jet γ+jet       D0</td>
<td>NO</td>
</tr>
</tbody>
</table>
CTEQ6X vs CTEQ6.1

- CTEQ6X fit:
  - cut3, TMC+HT
  - deuteron corrections

- TMC, HT compensate each other

- u-quark:
  - almost unchanged

- d-quark suppressed
  - due to deuteron corrections

- Reduced PDF errors
  - about 30-50%

Q^2 = 10 GeV^2
CTEQ6X vs CTEQ6.1

CTEQ6X fit:
- cut3, TMC + HT
- deuteron corrections

TMC, HT compensate each other

u-quark:
- almost unchanged

d-quark suppressed
- due to deuteron corrections

Reduced PDF errors
- about 30-50%
Deuterium corrections

- $d$-quarks are very sensitive to deuterium corrections
- Off-shell corrections completely absorbed by the $d$-quark

free $\equiv$ free p+n
dens $\equiv$ density model corrections
nuc $\equiv$ WBA smearing model
offsh $\equiv$ off-shell corrections

[Melnitchouk et al., '94]
Impact on LHC

- Parton luminosities: \( L_{i,j}(M) = \frac{1}{S} \int_{M^2/s}^1 \frac{dx}{x} q_i(x, M^2) q_j(M^2/(xs), M^2) \)

- Nuclear model uncertainty \( \sim 10\% \) at large \( x \):
  - dominates \( Z \) cross-sections used as luminosity monitor

\[ L_{i,j}(M) = \frac{1}{S} \int_{M^2/s}^1 \frac{dx}{x} q_i(x, M^2) q_j(M^2/(xs), M^2) \]

- exp = experimental
- RS = renorm. scale
- MC = charm mass
- TS = charm threshold
- SS = strangeness suppr.
d-quarks at large $x$

- Large theoretical undertainties on $d$-quark at large $x$
  
  - coming from deuteron corrections
    
    (no deuteron $\Rightarrow$ $d$ unconstrained at large $x$)
  
  - unavoidable at the moment: model dependent

- How to progress?

  - Avoid them
    
    - Free nucleon targets $\Rightarrow$ not enough data so far
  
  - Constrain them
    
    - $Q^2$ dependence of $D/p$ ratios at large $x$ (maybe)
    
    - Use quasi-free nucleon targets
    
    - Use ratio of $^3\text{He}$ - $^3\text{H}$ mirror nuclei
Free nucleon targets

Constraints on large-\(x\) \(d\)-quarks from

\[ p + p(\bar{p}) : \text{DY at large } x_F \]

\[ p + p(\bar{p}) : \text{W-asymmetry at large rapidity} \]

\[ (D0 \text{ and CDF}) \]

\[ \nu + p \text{ and } \bar{\nu} - p \]

- **WA21 already has data**
  (but hard to reconstruct cross-sections from published “quark distributions”)

- **MINERvA with a hydrogen target**

- **Parity Violating DIS**

- **L/R electron asymmetry \(\Rightarrow \gamma/Z\) interference \(\propto d/u\)**

- **Charged current structure functions**
  [H1 and ZEUS]

\[ \bar{\nu}(\bar{\nu}) p \longrightarrow l^\pm X \]

\[ p p(\bar{p}) \longrightarrow \mu^+ \mu^- X \]

\[ p p(\bar{p}) \longrightarrow W^\pm X \]

\[ \bar{e}_L(e_R) p \longrightarrow e X \]

\[ e p \longrightarrow \nu X \]

*planned for Jlab at 12 GeV*

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HERA combined data

[JHEP 1001, 2010]

- H1 and ZEUS combined data on $e^+p$ and $e^-p$ collisions, NC & CC

Reaches into the critical $x$ range
Too limited $x$ coverage
These data alone insufficient for $d$-quark at large $x$
combine with deuterium data, cross check nuclear corrections
Constraining the nuclear corrections

- Quasi-free nucleon targets *
  [BONUS, E94-102 and EG6 at JLab 6 GeV]

\[ e \, A \rightarrow e \, (A - 1) \, X \]

- \(^3\)He - \(^3\)H mirror nuclei *

\[ \frac{^3H}{^3He} \approx \frac{n \, 2 + p/n}{p \, 2 + n/p} \]

* planned for Jlab at 12 GeV
Gluons
Observables for gluons

- Jets in $p+p$ collision – CT09
  - limited statistics
  - only very large $Q^2$, and smallish $x$

- $dF_2 / d(\ln Q^2)$
  - indirect
  - limited leverage at large $x$, large errors

- Longitudinal $F_L$
  - directly sensitive to gluons
  - so far not many data points
  - JLab / JLab12 will improve large-$x$ coverage, but low $Q^2$
HT for $F_L$ have little constraints from theory, some guidance from renormalon calculations

- Perturbatively unclear at large $x$
- When fitted, large at NLO, decrease at NNLO

“The high $x$ and low $Q^2$ domain is 'dangerous'. This is another reason, along with target mass, to avoid fitting data in this region”

[Martin, Stirling, Thorne, PLB635(06)]

Should we dare more?
[see e.g., Alekhin et al., arXiv:0710.0124]
Target Mass Corrections

- Difference between Coll. Fact. [Accardi, Qiu] and OPE [Georgi, Politzer] for $F_2$
- different slope in $Q^2 \Rightarrow$ different gluons from $dF_2/d(ln Q^2)$!

Accardi, Qiu JHEP '08

\[
\begin{align*}
F_2/F_2^{(0)} & \quad F_2^{CP}/F_2^{(0)} \\
F_n^{nv}/F_2^{(0)} & \quad Q^2 = 2 \text{ GeV}^2 \\
F_2/F_2^{(0)} & \quad Q^2 = 25 \text{ GeV}^2 \\
\end{align*}
\]

MRST2002

Accardi, Qiu JHEP '08

\[
\begin{align*}
F_2/F_2^{(0)} & \quad F_2^{CP}/F_2^{(0)} \\
F_n^{nv}/F_2^{(0)} & \quad x_B = 0.8 \\
F_2/F_2^{(0)} & \quad x_B = 0.4 \\
\end{align*}
\]

MRST2002
Target Mass Corrections

- Very different $F_L$ correction
- Can the differences be absorbed in HT terms?
- Play $F_L$ and $F_2$ off each other $\Rightarrow$ can differentiate TMC method??

Accardi, Qiu JHEP '08

\[ R = \frac{\sigma_L}{\sigma_T} \]

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

\[ Q^2 = 25 \text{ GeV}^2 \]

\[ x_B = 0.8 \]

\[ x_B = 0.4 \]
Intrinsic charm
Intrinsic vs. radiative charm

Usual assumption in global fits: at threshold

\[ c(x, Q_c \approx m_c) = 0 \]

charm generated during DGLAP evolution

but QCD predicts intrinsic charm

\[ a \bar{c} \text{ pair fluctuation already exists, peaked at large } x \sim 0.4 \]

\[ \text{fully participates in DGLAP evolution} \]

\[ c, \bar{c} \text{ asymmetry: small @ NLO (pQCD) or large (nonpert. models)} \]
Phenomenological implications

- SM and beyond at Tevatron and LHC
  - Higgs and single top production sensitive to heavy quarks
  - Novel Higgs production mechanisms at large $x_F \approx 0.7-0.9$
    [Brodsky et al. PRD73(06), NPB907(09)]

- W production
  [Nadolsky et al. PRD78(08)]
Indications from global fits

[see Pumplin PRD 73(06) for review of models]

1) Brodsky-Hoyer-Peterson-Sakai [PLB 93 (80)]
\[ c(x) = \bar{c}(x) = A x^2 [6x(1 + x) \ln x + (1 - x)(1 + 10x + x^2)] \]

2) meson-cloud model
[Navarre et al '96, '98; Melnitchouk, Steffens, Thomas '97, '99]
\[ c(x) = Ax^{1.897} (1 - x)^{6.095} \]
\[ \bar{c}(x) = \bar{A}x^{2.511} (1 - x)^{4.929} \]

3) phenomenological “sea-like”
\[ c(x) = \bar{c}(x) \propto \bar{d}(x) + \bar{u}(x) \]
Indications from global fits

All models allow $\text{IC} = 0\text{-}3\%$ intrinsic charm
- Evolution redistributes IC to lower $x$, but large-$x$ peak persists
- sea-like spread out over $x$
Experimental evidence - D0

D0 measured excess of $\gamma$+charm jets compared CTEQ6.6  [D0, PRL102(09)]

\[ g + Q \rightarrow \gamma/Z + Q \]
\[ q + \bar{q} \rightarrow \gamma/Z + g \rightarrow \gamma/Z + Q\bar{Q} \]

- Difference due to
  - intrinsic charm?
  - underestimate of $g \rightarrow c\bar{c}$?
How to measure hadronic collisions

\[ \gamma/Z + \text{charm jet} \]
- sensitive to \[ g + Q \rightarrow \gamma/Z + Q \] and \[ q + \bar{q} \rightarrow \gamma/Z + g \rightarrow \gamma/Z + Q\bar{Q} \]
- \( y_\gamma y_{jet} > 0 \) and \( y_\gamma y_{jet} < 0 \) sensitive to different \( x_1, x_2 \)
- allows constraints on \( Q, \bar{Q}, \) and gluons
- angular dependence to distinguish above sub-processes

Also,

- High \( x_F \) \( pp \rightarrow J/\psi X \)
- High \( x_F \) \( pp \rightarrow J/\psi J/\psi X \)
- High \( x_F \) \( pp \rightarrow \Lambda_c X \)
- High \( x_F \) \( pp \rightarrow \Lambda_b X \)
- High \( x_F \) \( pp \rightarrow \Xi(c\bar{c}d) X \) (SELEX)
How to measure – DIS

- HERA charm and bottom events
  - already included in the fits
  - most data at small $x$, where $\gamma g \rightarrow c\bar{c}$ dominates over $\gamma c \rightarrow c X$
  - needs larger $x$

- JLab 6/12
  - Ideally placed across the charm threshold
  - $D^+$ vs. $D^-$ sensitive to $c/c\bar{c}$ asymmetry

- EIC (LHeC ??)
  - jet measurements are possible
  - larger $Q^2$ range than Jlab, larger $x$ than HERA
Target and heavy-quark mass corrections

DIS in collinear factorization: [Accardi, Qiu JHEP '08]

Currently being revisited

\[ F_{T,L}(x_B, Q^2, m_N) = \sum_f \int_{x_f^{\text{min}}}^{x_f^{\text{max}}} \frac{dx}{x} h_{T,L}^{f} \left( \frac{\xi_f}{x}, Q^2 \right) \varphi_f(x, Q^2) \]

\[ \xi_f = \xi \left[ 1 - \frac{\xi^2 x^2 m_f^2}{Q^2} \right]^{-1} \quad m_f \to 0 \quad \xi \to x_B \]

\[ x_f^{\text{min}} = \xi \frac{Q^2 + (c - 1)m_f^2 + \Delta[m_f^2, -Q^2, cm_f^2]}{2Q^2} \quad m_f \to 0 \quad \xi \to x_B \]

\[ x_f^{\text{max}} = \xi \frac{Q^2/x_B + 3m_f^2 + \Delta[m_f^2, -Q^2, Q^2(1/x_B - 1)]}{2Q^2} \quad m_f \to 0 \quad \xi/x_B \to 1 \]

\[ \Delta[a, b, c] = \sqrt{a^2 + b^2 + c^2 - 2(ab + bc + ca)} \quad \xi = 2x_B/(1 + \sqrt{1 + 4x_B^2 M_N^2 / Q^2}) \]
Outlook: the Electron-Ion Collider
The EIC for dummies

- Future US-based e+p (e+A) collider – 2 designs:
  - **BNL – eRHIC:** \( E_e = 5-30 \text{ GeV} \quad E_p = 250 \text{ GeV} \quad \mathcal{L} \sim 10^{34} \text{ cm}^{-2}/\text{s}^{-1} \)
  - **Jlab – MEIC:** \( E_e = 3-11 \text{ GeV} \quad E_p = 60 \text{ GeV} \quad \mathcal{L} \sim 10^{34} \text{ cm}^{-2}/\text{s}^{-1} \)
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![Graph showing proton and deuteron data](image)

**MEIC** will probe lower x in the shadowing region, and higher $Q^2$ at large x.
Projected Results - $F_2^p$ Relative Uncertainty

- MEIC 4+60
- 1 year of running (26 weeks) at 50% efficiency, or $230 \text{ fb}^{-1}$

Solid lines are statistical errors, dotted lines are stat+syst in quadrature

For MeRHIC the luminosity is probably down by a factor of ~10, so these error bars will go up ~50%

Huge improvement in $Q^2$ coverage and uncertainty

Will, for instance, greatly aid global pdf fitting efforts

![Graph showing $Q^2$ vs. relative error for different $x_B$ values. The graph includes data points from JLab, SLAC, BCDMS, NMC, ZEUS, H1, and MEIC. The text indicates only statistical errors on projected results.](image)
**Projected Results - $F_2^d$ Relative Uncertainty**

- MEIC 4+30
- 1 year of running (26 weeks)
  at 50% efficiency, or 35 fb$^{-1}$

Even with a factor 10 less statistics for the deuteron the improvement compared to NMC is impressive

*EIC will have excellent kinematics to measure n/p at large x!*

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Projected Results - $F_2^d$ Relative Uncertainty

- Only stat. errors on projected results

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Accardi, Ent, in progress
Impact on global fits

Sensible reduction in PDF error, likely larger than shown if energy scan is performed.
Structure functions at the EIC

• Bread and butter: inclusive DIS
  o Detailed rates: $F_2$ and $F_L$, $p$ and $D$
  o charm and bottom str.fns.?
  o Impact on global fits: large-x, small-x and saturation

• Electroweak structure functions
  o flavor separation, charge symmetry violation, new spin str.fns.
  o requires high luminosity – needed rates under study

• Spectator tagging will open up an exciting physics program
  o Ongoing detector design – angular & momentum resolution
  o Rate estimates needed
  o $p$ vs. $n$ tagging:
    ✓ “effective” neutron target
    ✓ control nuclear effects on an “effective” proton
  o Tagging with $^4$He targets ???
    ✓ EMC effect

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Pavia U., 13 Jul 2010
Conclusions

✿ Flavor separation at large $x$ important
  → to understand the nucleon structure
  → for phenomenological applications

✿ but needs theoretical corrections
  → target/hadron/quark mass, HT, nuclear corrections, ...

✿ u, d quarks: ongoing CTEQ6X studies
✿ Gluons: will be included in the CTEQ6X global fit
✿ Intrinsic charm: interesting direction for the future

✿ Lots of progress available at the EIC

The future is bright ... and busy!
BACKUP SLIDES
Effects of corrections on reference fit

- Apply the theoretical corrections one at a time

- 2 important lessons:
  - **cut0 removes TMC+HT** (as desired)
  - **nuclear corrections are large starting from** \( x > 0.5 \) !! ("safe cuts" aren't safe everywhere)
Stability of the d-quark fit

- Relatively stable against kinematic cuts, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at $x=0.5–0.7$ in the nominal range of validity of cut0
Extracted twist-2 PDF much less sensitive to choice of TMC
- fitted HT function compensates the TMC
- except when no TMC is included
- Inclusion of TMC allow for economical HT parametrization (3 params)
Extracted higher-twist term depends on the type of TMC used

- $Q^2 > 1.69\text{ GeV}^2$ and $W^2 > 3\text{ GeV}^2$ (referred to as “cut03”)
- lower cuts $\Rightarrow x_B < 0.85$ compared to $x_B < 0.7$ in CTEQ/MRST
- No evidence for negative HT
**Off-shell corrections**

\[ F_2^p = \frac{4}{9} x u \left(1 + \frac{d}{4u}\right) \]  
no corrections

\[ F_2^d = \frac{5}{9} x u \left(1 + \frac{d}{u}\right) \]  
O.S. corrections

\[
\frac{\delta d}{d} = \frac{4}{3} \frac{\delta F_2^d}{F_2^d} \left(1 + \frac{1}{d/u}\right).
\]

1.5% on \( F_2^d \) \( \Rightarrow \) 40% on \( d \)-quark !!!

\[ \downarrow \text{d-quark is strongly correlated to choice of Off-Shell correction!} \]

\[ \downarrow \text{on-shell or mild off-shell correction} \Rightarrow \text{d-quark suppression} \]

\[ \downarrow \text{might as well be enhanced...} \]

\[ \downarrow \text{Need to constrain the models!} \quad \text{see later} \]
PDF errors at large $x$ are reduced by lowering the cuts

Note: these are exp. errors propagated in the fit

nuclear correction uncertainty for d-quarks likely larger than this!
Quasi-free nucleon targets

BONUS and E94-102 experiments at JLab

- DIS on deuterium with tagged proton
  - tagged proton momentum is measured
  - neutron off-shellness can be reconstructed

- Study the off-shell dependence of $F_2(n)$ and quark PDFs

$$q \equiv q_D(x, Q^2, p^2)$$

- Extrapolate to a free neutron target $p^2 \rightarrow M_n^2$
D/p ratios

- Strong $Q^2$ dependence of nuclear smearing
- use fixed $x_B$ data up to larger $Q^2$
- needs resonance region ⇒ quark-hadron duality
- off-shell corrections can't be constrained

![Graphs showing $D/p$ ratios at different $Q^2$ values.](image)
• $E_e = 4 \text{ GeV}, \ E_p = 60 \text{ GeV}$
  - larger $s$ (~4000 MeRHIC, or ~2500 MEIC) would cost luminosity
  - $0.004 < y < 0.8$
  - Luminosity $\sim 3 \times 10^{34}$
  - 1 year of running (26 weeks) at 50% efficiency, or $230 \text{ fb}^{-1}$
  - Somewhat smaller $Q^2$ reach and large luminosity is better choice at large $x$, $\sigma \sim (1-x)^3$

Projected Results IIa - $F_2^p$ with CTEQ6X PDFs

only stat. errors on projected results
Projected Results IIb - $F_2^d$

- $E_e = 8$ GeV, $E_N = 30$ GeV ($s = 1000$)
- Luminosity $\sim 3.5 \times 10^{33}$ (scales with synchrotron limit)
- Smaller neutron str. fn. + reduced luminosity = factor of 10 loss in rate.
- One year of running (26 wk) at 50% efficiency, or $35 \text{ fb}^{-1}$

Can tag spectator proton, measure neutron, concurrently

only stat. errors on projected results