100 Years Ago...

Scattering experiments provide insight into the matter structure

E. Rutherford, F.R.S.*
*Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

**The Scattering of α and β Particles by Matter and the Structure of the Atom**

Considering the evidence as a whole, it seems simplest to suppose that the atom contains a central charge distributed through a very small volume, and that the large single deflexions are due to the central charge as a whole, and not to its constituents.

*Philosophical Magazine* Series 6, vol. 21 May 1911, p. 669-688
Atom: Electrons + Nucleus

nucleons: protons, neutrons
mass $M_N \sim 1$ GeV
Atom: Electrons + Nucleus

Structure within the Atom

- **Nucleus**: Size $= 10^{-14}$ m
- **Quark**: Size $< 10^{-19}$ m
- **Atom**: Size $= 10^{-10}$ m

Partons (quarks & qluons)

- Valence quarks ($u, d$)
  - Most quantum properties

BUT:

- $M_u \approx 0.003 \, M_N$
- $M_d \approx 0.006 \, M_N$

Where does the mass of the nucleon come from?
Feynman’s Parton Model

• The nucleon is made up of point-like constituents (partons)
• Partons behave incoherently
• Probability $f(x)$ for a parton $f$ to carry the fraction $x$ of the nucleon momentum is an intrinsic property of the nucleon, i.e. process independent

Learn about the nucleon structure via lepton-nucleon scattering
Feynman’s Parton Model

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Learn about the nucleon structure via lepton-nucleon scattering

Electron-proton scattering in parton picture

Electron scatters off a charged constituent (parton) of the proton

Identify the charged partons with quarks
Hadron - Electron Ring Accelerator

World-only $ep$ collider

$E_p = 460-920$ GeV

$E_e = 27.6$ GeV

Unique tool to study proton structure

HERA: 6.3km circumference accelerator of electrons and protons.

End of running 30/6/07
HERA Collider Experiments

Collider experiments H1 & ZEUS
\[ \sqrt{s}_{\text{max}} = 318 \text{ GeV} \]

Integrated luminosity
\[ \sim 0.5 \text{ fb}^{-1} \] per experiment
Deep Inelastic Scattering

$e^\pm$ Scatter both electron/positrons

Neutral Current: $\gamma, Z^0$ exchange

Charged Current: $W^\pm$ exchange

$e^\pm, \bar{\nu}$
**ep Scattering at HERA**

**Deep Inelastic Scattering**

- Scatter both electron/positrons
- Neutral Current: $\gamma, Z^0$ exchange
- Charged Current: $W^\pm$ exchange

$\gamma, Z : \text{Neutral Current } \ ep \rightarrow e \ X$

Isolated energetic scattered $e^\pm$
**ep Scattering at HERA**

**Deep Inelastic Scattering**

\[ e^\pm, k \rightarrow e^\pm, k', \gamma, Z^0, W^\pm \]

\[ q = k - k' \]

\[ P_q = x P_p \]

Scatter both electron/positrons

Neutral Current: \( \gamma, Z^0 \) exchange

Charged Current: \( W^\pm \) exchange

\( \gamma, Z : \) Neutral Current \( ep \rightarrow e X \)

Isolated energetic scattered \( e^\pm \)

\( W^\pm : \) Charged Current \( ep \rightarrow \nu X \)

Large missing transverse momentum
Kinematics of $ep$ Scattering in Parton Model

$\gamma$ exchange

\[ x = -q^2 / 2p \cdot q \quad \text{Bjorken scaling} \]
Kinematics of $ep$ Scattering in Parton Model

**Infinite proton momentum frame:**

- Partons do not interact, move parallel to the proton, massless, no transverse momentum
- Parton $i$ carries fraction $x_i$ of $P_p$

**Kinematics:**

$$x = -\frac{q^2}{2p \cdot q} \quad \text{Bjorken scaling}$$
Kinematics of $ep$ Scattering in Parton Model

$\gamma$ exchange

$$x = -\frac{q^2}{2p \cdot q} \quad \text{Bjorken scaling}$$

$$Q^2 = -q^2 \quad \text{photon virtuality}$$
Kinematics of $ep$ Scattering in Parton Model

**Kinematics:**

$x = -q^2 / 2p \cdot q \quad \text{Bjorken scaling}$

$Q^2 = -q^2 \quad \text{photon virtuality}$

4-momentum transfer $Q^2$ defines distance scale $r$ at which proton is probed

$r \approx \frac{\hbar c}{Q} = 0.2 [\text{fm}] / Q [\text{GeV}]$
**Kinematics of $ep$ Scattering in Parton Model**

4-momentum transfer $Q^2$ defines distance scale $r$ at which proton is probed.

**HERA collider:** $r_{\text{min}} \approx R_p/1000$

**Kinematics:**

$x = -q^2 / 2p \cdot q$  \quad Bjorken scaling

$Q^2 = -q^2$  \quad photon virtuality
DIS Cross Section and Proton Structure

E.g. for Neutral Current: \( e^\pm p \rightarrow e^\pm X \)

\[
\frac{d^2 \sigma^{e^\pm p}}{dx dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} \left[ (1 + (1 - y)^2) F_2 - y^2 F_L \mp x F_3 \right]
\]

\( y \): transferred photon energy fraction

Quark-Parton Model: \( F_2 \propto x \sum_f q_f + \bar{q}_f \)

Parton Distribution Functions (PDFs):
probability to find a parton \( q \) in a proton carrying fraction \( x \) of it’s momentum

Bjorken scaling: if partons do not interact, \( q=q(x) \); \( F_2=F_2(x) \)
Quarks do interact via gluon exchange. Probability via splitting functions:

\[ F_2(x) \rightarrow F_2(x, Q^2), \quad q(x) \rightarrow q(x, Q^2) \]
Quark and gluon distributions coupled in DGLAP equations
Scaling Violations at Highest Precision

JHEP 01 (2010) 109: combined H1 and ZEUS data from HERA I, $\mathcal{L} \sim 115$ pb$^{-1}$

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)$$

H1 and ZEUS data averaged:

- global fit of 1402 measurements
- 110 sources of systematic errors
- account for systematic correlations (cross calibration of experiments)
- total uncertainty: 1-2% for $Q^2 < 500$ GeV$^2$
- covered kinematics:
  $$10^{-7} < x < 0.65$$
  $$0.05 < Q^2 < 30000$$ GeV$^2$

![Graph showing data points and fit for H1 and ZEUS combined data.]
Scaling Violations at Highest Precision

*JHEP 01 (2010) 109*: combined H1 and ZEUS data from HERA I, $L \sim 115 \text{ pb}^{-1}$

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)$$

Small $x$: $F_2$ rises with $Q^2$

- Gluon splits into quark pair

Large $x$: $F_2$ falls with $Q^2$

- Quarks radiate gluons
Determination of Parton Density Functions

Structure function factorization: for an exchange-Boson $V (\gamma, Z, W^\pm)$

$$F_2^V (x, Q^2) = \sum_{i=q, \bar{q}, g} \int_x^1 dz \times C_{2i}^V (\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i (z, \mu_F, \mu_R)$$

determined using measured cross sections

calculable in pQCD

PDF

$x$-dependence of PDFs is not calculable in perturbative QCD:

- parameterize at a starting scale $Q^2_0$: $f(x) = Ax^B (1-x)^C (1+Dx+Ex^2)$
- evolve these PDFs using DGLAP equations to $Q^2 > Q^2_0$
- construct structure functions from PDFs and coefficient functions: predictions for every data point in $(x, Q^2)$ – plane
- $\chi^2$- fit to the experimental data
PDFs determined from the QCD fit to the NC and CC cross sections

**HERAPDF1.5 (prel.)**

QCD@NLO DGLAP combined H1 and ZEUS data

**Heracles Structure Functions Working Group July 2010**

**H1 and ZEUS HERA I+II Combined PDF Fit**

- Experimental uncertainty
- Parametrization: shapes of PDF at starting scale $Q_0$
- Model assumptions: masses of $c, b$ - quarks, fraction of strange quarks, $\alpha_s(M_Z)$

Gluons and sea quarks: dominant partons at low $x$
QCD using HERAPDF describes HERA NC and CC data very well.
PDFs From HERA to Tevatron and the LHC

PDFs obtained from data of fixed target, HERA, Tevatron

HERA measurements: covers most of the \((x, Q^2)\) plane, best constrain at low, medium \(x\)
PDFs obtained from data of fixed target, HERA, Tevatron

**HERA measurements:** covers most of the \((x, Q^2)\) plane, best constrain at low, medium \(x\)

From HERA to kinematics of Tevatron, LHC:

- evolution in \(Q^2\) via DGLAP

**PDFs From HERA to Tevatron and the LHC**
HERAPDF vs Jets at Tevatron

Prediction based on HERAPDF in agreement with Tevatron

Tevatron Jet Cross Sections

\[ \frac{d^2\sigma}{dy^{\text{jet}} dp_T^{\text{jet}}} \] [nb/(Gev/c)]

- D0 RunII
- HERAPDF1.0

Cone R=0.7 - fastNLO (+ non-perturbative corr.)

<table>
<thead>
<tr>
<th></th>
<th>10^{-15}</th>
<th>10^{-12}</th>
<th>10^{-9}</th>
<th>10^{-6}</th>
<th>10^{-3}</th>
<th>10^{0}</th>
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<tbody>
<tr>
<td>0.4 \leq</td>
<td>y^{\text{jet}}</td>
<td>&lt; 0.4 (x 10^6)</td>
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<tr>
<td>0.8 \leq</td>
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<td>&lt; 0.8 (x 10^3)</td>
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<tr>
<td>1.2 \leq</td>
<td>y^{\text{jet}}</td>
<td>&lt; 1.2</td>
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<tr>
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<tr>
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\[ P_T^{\text{jet}} \text{ [Gev/c]} \]
Prediction based on HERAPDF agrees very well with Tevatron data.
Differences between the PDF groups:

- data used in the fit and estimation of uncertainties
- different treatment of heavy quarks
Heavy Quarks and PDF Fits

Factorization:  \[ F_2^V(x, Q^2) = \sum_{i=l, q, g} \int_x^1 dz \times C_2^{V,i} \left( \frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S \right) \times f_i(z, \mu_F, \mu_R) \]

\[ i \] - number of active flavours in the proton: defines the factorization (HQ) scheme
Heavy Quarks and PDF Fits

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\( i \) - number of active flavours in the proton: defines the factorization (HQ) scheme

- \( i \) fixed: Fixed Flavour Number Scheme (FFNS)
  - only light flavours in the proton: \( i = 3 \ (4) \)
  - \( c\)- (\( b\)-) quarks massive, produced in boson-gluon fusion

\( Q^2 \gg m_{HQ}^2 \): can be less precise, NLO coefficients contain terms \( \sim \ln \left( \frac{Q}{m_{HQ}} \right) \)
Heavy Quarks and PDF Fits

Factorization: \[ F_2^V(x, Q^2) = \sum_{i=1,\bar{q},g} \int_x^1 dz \times C^V_{2i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R) \]

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- \( i \) variable: Variable Flavour Number Scheme (VFNS)
  - Zero Mass VFNS: all flavours massless. Breaks down at \( Q^2 \sim m_{HQ}^2 \)
  - Generalized Mass VFNS: different implementations provided by PDF groups
    - smooth matching with FFNS for \( Q^2 \to m_{HQ}^2 \) must be assured
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QCD analysis of the proton structure: **treatment of heavy quarks essential**
Usually HQ coefficient functions use a pole mass definition.

BUT: pole mass defined for free quarks
Corrections due to loop integrals receive large contributions $\sim O(\Lambda_{\text{QCD}})$

Another way of defining quark mass: via renormalization

![Diagram showing electron, gamma, quark, and gluon interactions](image)
Heavy Quark Mass Definition in PDFs

Usually HQ coefficient functions use a **pole mass** definition.

**BUT:** pole mass defined for free quarks.
Corrections due to loop integrals receive large contributions $\sim O(\Lambda_{QCD})$.

Another way of defining quark mass: via renormalization.

- Large higher order corrections
- Bad convergence of perturbative series

**Running coupling**

**Running mass**
Massive HQ coefficient functions are calculated at NLO using pole mass

*Smith. et al NPB 395,162 (1993)*

Used by the global fit groups: MSTW, CTEQ, ABKM, GJR, HERAPDF

**ZMVFNS:** $m_{HQ}$ defines a threshold at which HQ appears as an active flavour

**GMVFNS:** $m_{HQ}$ is also used as a parameter at which FFNS turns into VFNS
Massive HQ coefficient functions are calculated at NLO using pole mass


Used by the global fit groups: MSTW, CTEQ, ABKM, GJR, HERAPDF

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<td>4.5</td>
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PDG values: $1.66\pm0.18 / 4.79$

PDF fits assume pole mass definition for heavy quarks

Values of $m_c$ as used by most PDF groups too low wrt. PDG
Heavy Quark Mass Values in PDFs

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**PDG values:** 1.66±0.18 / 4.79

PDF fits assume pole mass definition for heavy quarks

Values of $m_c$ as used by most PDF groups too low wrt. PDG

HQ treatment in PDF fits, meaning and values of HQ masses non trivial..

**Heavy quark data can help!**
Heavy Quark Production at HERA

Heavy quarks in $e p$ scattering produced in boson-gluon fusion

Contribution to total DIS cross section:
- charm: $\sim 30\%$ at large $Q^2$
- beauty: at most $1\%$

Gluon directly involved:
- cross-check of $g(x)$ from NC and CC DIS cross sections

HQ contributions to the proton structure function $F_2$: (e.g. charm)

$$\sigma^{cc} \propto F_2^{cc} (x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L^{cc} (x, Q^2)$$

Direct test of HQ schemes in PDF fits
Heavy Quark Tagging Methods at HERA

d* charmed mesons

H1 Preliminary
HERA II

\[ \text{fit} \]

\[ N(D^*) = 20803 \pm 282 \]

\[ \begin{align*}
5 < Q^2 < 100 \text{ GeV}^2 \\
0.02 < y < 0.7 \\
|\eta(D^*)| < 1.5 \\
p_{T}(D^*) > 1.5 \text{ GeV}
\end{align*} \]

Entries / 0.5 MeV

M(Kππ) - M(Kπ) [GeV]
Heavy Quark Tagging Methods at HERA

charmed mesons

+ vertex reconstruction
Heavy Quark Tagging Methods at HERA

charmed mesons

+ vertex reconstruction
Heavy Quark Tagging Methods at HERA

charmed mesons

properties of $c-, b$- hadrons:
- track multiplicity
- long lifetime

+ vertex reconstruction
Heavy Quark Tagging Methods at HERA

**charm mesons**

**track displacement significance**

+ vertex reconstruction

![H1 Preliminary HERA II K²+π⁺π⁻π⁻π⁻ fit, N(D⁺) = 20803 ± 202](image)

![ZEUS D± decay-length significance, S > 2](image)

![δ/σ(δ) vs. δ](image)
Heavy Quark Tagging Methods at HERA

charmed mesons

+ vertex reconstruction

track displacement

semi-leptonic decays of c and b

\[ D^* \]

\[ D^\pm \]
Heavy Quark Tagging Methods at HERA

**charmed mesons**

- $D^*$

**different tag methods**

- orthogonal systematics

**track displacement**

- $c$ and $b$ uds

**Combination of all measurements**

**D**

- vertex reconstruction

$\delta/\sigma(\delta)$

- $p_T^{rel}$ (GeV)

- $M(c\ell\nu)$

- $M(D^*)$

- $M(K\pi\pi)$
Understanding Beauty Production

Beauty production in DIS

H1 Beauty Jet Cross section

- H1 Data
- NLO $\mu = \sqrt{\frac{Q^2 + p_T^2 + m^2}{2}}$
- NLO $\mu = \sqrt{Q^2 + 4m^2}$

MSTW08FF3

Lifetime information

$d\sigma/dQ^2$ [pb/GeV$^2$]

$Q^2$ [GeV$^2$]
Understanding Beauty Production

Beauty production in DIS

![Graph showing beauty production in DIS](image)

**H1 Beauty Jet Cross section**

**ZEUS**

$\mu +$ Jet

- **$d\sigma/dQ^2$ [pb/GeV^2]**
- **$d\sigma/dp_T$ [pb/GeV]**
- **$d\sigma/dp_T$ [pb/GeV]**
- **$d\sigma/dp_T$ [pb/GeV]**

**Lifetime**

**Understanding Beauty Production**
Understanding Beauty Production

Beauty production in DIS

\[ \frac{d\sigma}{dQ^2} \left[ \text{pb/GeV}^2 \right] \]

H1 Beauty Jet Cross section

- H1 Data
- NLO \( \mu = \frac{(Q^2 + p^2 + m^2)/2}{\mu} \)
- NLO \( \mu = \frac{Q^2 + 4m^2}{\mu} \)
- MSTW08FF3

\[ \text{lifetime} \]

\[ \mu + \text{Jet} \]

ZEUS

- ZEUS (prel.) 354 pb\(^{-1}\)
- HVQDIS \(\otimes\) hadr \(\otimes\) rad
- Rappap x 1.6

\[ \text{ep} \rightarrow e' \bar{b} b X \rightarrow e' \text{jet} X' \]

\[ \frac{d\sigma}{dx} \left( \text{pp} \right) \]

- Lifetime information

\[ \frac{d\sigma}{dx} \left( \text{pp} \right) \]

- Lifetime information

\[ \frac{d\sigma}{dQ^2} \left[ \text{pb/GeV}^2 \right] \]

- Lifetime information

\[ \frac{d\sigma}{dQ^2} \left[ \text{pb/GeV}^2 \right] \]

- Lifetime information
Understanding Beauty Production

Beauty production in DIS

HERA measurements of beauty in DIS described well by NLO QCD
Beauty contribution $F^b_2$ to the proton structure function $F_2$:

- well described by NLO and NNLO using different HQ schemes
- large statistical uncertainties
Open charm production in DIS

D* production in DIS

- H1 data
- H1 data (prel.)
- HVQDIS (MRST2004FF3nlo)

$0.02 < y < 0.7$

$|\eta(D^*)| < 1.5$

$p_T(D^*) > 1.5$ GeV
Open charm production in DIS

Understanding of HQ Production Mechanism

D* production in DIS

\[ \frac{d\sigma}{dQ^2} \text{ [pb/GeV}^2\text{]} \]

\[ 0.02 < y < 0.7 \]
\[ |\eta(D^*)| < 1.5 \]
\[ p_T(D^*) > 1.5 \text{ GeV} \]

H1 data

\[ 0 < Q^2 < 10^3 \text{ [GeV}^2\text{]} \]

\[ 10^-3 < \frac{d\sigma}{dQ^2} < 10^3 \text{ [pb/GeV}^2\text{]} \]

H1 data (prel.)

HVQDIS (MRST2004FF3nlo)

\[ 0 < Q^2 < 10^3 \text{ [GeV}^2\text{]} \]

\[ 10^-1 < \frac{d\sigma}{dQ^2} < 10^1 \text{ [pb/GeV}^2\text{]} \]

\[ 0 < Q^2 < 10^3 \text{ [GeV}^2\text{]} \]

\[ 0 < y < 0.7 \]

\[ |\eta(D^*)| < 1.5 \]

\[ p_T(D^*) > 1.5 \text{ GeV} \]

\[ -1.5 < \eta(D^*) < 1.5 \]

\[ \frac{d\sigma}{d\eta} \text{ (nb)} \]

0.02 < y < 0.7

|\eta(D^*)| < 1.5

\[ p_T(D^*) > 1.5 \text{ GeV} \]

ZEU(h) D* (prel.) 323 pb^{-1}

\[ H1 \text{ data} \]

\[ H1 \text{ data (prel.)} \]

\[ HVQDIS \text{ (MRST2004FF3nlo)} \]

\[ ZEUS \text{ D}^+ \]

\[ ZEUS \text{ D}^+ 133.6 \text{ pb}^{-1} \]

\[ HVQDIS \]

\[ \eta(D^+) \]
Understanding of HQ Production Mechanism

Open charm production in DIS

$D^*$ production in DIS

$0.02 < y < 0.7$
$|\eta(D^0)| < 1.5$
$p_T(D^0) > 1.5 \text{ GeV}$

$\frac{d\sigma}{d Q^2} \text{ [pb/GeV}^2\text{]}$

$\frac{d\sigma}{d Q} \text{ (nb)}$

$\frac{d\sigma}{d Q} \text{ (nb/GeV}^2\text{)}$

$ep \rightarrow e + D^0/\overline{D^0} + X$

- ZEUS (133.6 pb$^{-1}$)
- NLO QCD (HVQDIS)

$R$

$Q^2 (\text{GeV}^2)$
Understanding of HQ Production Mechanism

Open charm production in DIS

H1 Charm Jet Cross section

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- NLO $\mu = (Q^2 + p_T^2 + m^2)/2$
- NLO $\mu = Q^2 + 4m^2$
- MSTW08FF3

D* production in DIS

$0.02 < y < 0.7$

$|D^*| < 1.5$

$|D^*| > 1.5$ GeV

$T_{p_{T}(D^*)}$

D0

$e^+ e^- \rightarrow D^0 \bar{D}^0 + X$

ZEUS (133.6 pb$^{-1}$)
Understanding of HQ Production Mechanism

Open charm production in DIS

H1 Charm Jet Cross section

HERA measurements of charm in DIS described well by NLO QCD
Massive or Massless Scheme?

$100 \text{GeV}^2 < Q^2 < 1000 \text{GeV}^2$

Charm at $Q^2 \gg m_c^2$: FFNS describes data well, ZMVFNNS does not

Open charm at high $Q^2$

vs

FFNS NLO

ZMVFNNS NLO

Charm at $Q^2 \gg m_c^2$: FFNS describes data well, ZMVFNNS does not
Charm Structure Function at HERA

HERA Charm Measurement:
H1 + ZEUS
9 measurements
different charm tag methods
51 systematic error sources
correlations accounted for
Combined Charm Data of HERA

HERA Charm Measurement:
H1 + ZEUS
9 measurements
different charm tag methods
51 systematic error sources
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Precision 5 - 10%

Very precise $F_2^{cc}$ measurement
Charm at HERA: Test HQ Schemes in PDFs

HERA Charm Measurement:
H1 + ZEUS
9 measurements
different charm tag methods
51 systematic error sources
correlations accounted for

Precision 5 - 10%

Different HQ schemes

Data help understanding differences in HQ schemes
Charm at HERA: Test Choice of $m_c$ in PDF

F$^c_2$ not included in HERAPDF1.0 but is well described.

charm quark mass value varied in the PDF Fit:

- $m_c = 1.4$ GeV
- $m_c = 1.35$ vs $1.65$ GeV

PDG pole mass

PDFs obtained from inclusive data sensitive to the choice of $m_c$
Charm Data in the PDF Fit

Charm production probes gluon directly. **Do charm data influence the gluon?**

Consider 2 values of $m_c$

$m_c = 1.65$ GeV: **better fit**

steeper gluon distribution

PDFs and PDF fit using charm data is sensitive to the value of $m_c$
Charm Mass as a Model Parameter in PDF

Study the sensitivity of the PDF fit to the value of $m_c$

PDF fit to inclusive DIS

$\chi^2$ / ndf

$F_2$

$m_c^{\text{model (opt)}} = 1.308 \pm 0.100$ GeV

H1 and ZEUS (prel.)

Herapdf1.0

RT standard

- flexible param
- standard param

Weak dependence on $m_c$
Charm Mass as a Model Parameter in PDF

Study the sensitivity of the PDF fit to the value of $m_c$

PDF fit to inclusive DIS

PDF fit to inclusive DIS + charm data

Weak dependence on $m_c$

Strong dependence on $m_c$
Different HQ Schemes in PDFs

Value of $m_c$: how different for various HQ schemes in PDF Fits?

Test different HQ schemes (used by different PDF groups)

![Graph showing $F_2 + F_c^2$ vs $m_c^{model}$ with different HQ schemes compared to H1 and ZEUS (prel.)]
Different HQ Schemes in PDFs

Value of $m_c$: how different for various HQ schemes in PDF Fits?

Test different HQ schemes
(used by different PDF groups)

RT: MSTW PDFs
ACOT: CTEQ PDFs
ZMVFNS: NNPDF

NB: ZMVFNS does not describe charm data even at $Q^2 >> m_c^2$
Different HQ Schemes in PDFs

Value of $m_c$: how different for various HQ schemes in PDF Fits?

Test different HQ schemes (used by different PDF groups)

Different HQ schemes prefer different optimal $m_c$
Different HQ Schemes in PDFs

Value of $m_c$: how different for various HQ schemes in PDF Fits?

Test different HQ schemes (used by different PDF groups)

Different HQ schemes prefer different optimal $m_c$ parameter of a specific HQ scheme in PDF fits
What is the Meaning of $m_c$ in PDF Fits?

Recent theory developments: (ABKM group, DESY, arXiv:1011.5790)
HQ coefficient functions provided in \(\overline{\text{MS}}\) scheme using running \(m_{HQ}\)

Perturbative series converge better
Consistent treatment of HQ in PDF fits
\(m_c(m_c)\) determined using DIS data

What happens if HERA charm data are included?

Work in progress…
Heavy Quarks in PDFs and W/Z at LHC

Prediction of $W^\pm$ cross section @ LHC: dominant uncertainty due to PDF

Prediction using $m_c = 1.4$ GeV

Error band: PDF uncertainty

Experimental error

Parametrization variation

Model assumptions including $m_c$ variation

$m_c$ variation in PDF: significant uncertainty on W@LHC in central region
Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions

Larger $m_c \rightarrow$ more gluons, less charm $\rightarrow$ more light quarks $\rightarrow$ larger $\sigma_W$
Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions

Only one HQ scheme

\[ W^+ (\sqrt{s} = 7 \text{ TeV}) \]

HERAPDF1.0 + \( F_2^{\text{prel.}} \)

\( m_c \) variation in PDF

1.4 < \( m_c < 1.65 \) GeV

3\% uncertainty on W prediction
Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions

$m_c$ variation in PDF

$1.4 < m_c < 1.65$ GeV

3% uncertainty on W prediction

Using different HQ schemes:

+ 7% uncertainty

Large uncertainty on $\sigma_W$ prediction due to HQ treatment in PDFs
Charm at HERA and W/Z at LHC

Use the optimal $m_c$ for HQ schemes in PDFs fixed by HERA charm data

★ Optimal $m_c$ using $F_2 + F_2^c$

ZMVFNS not considered

Uncertainty on $\sigma_W$ prediction due to HQ treatment in PDFs reduced to 1 %
HERAPDF vs first LHC Data

\[ W \rightarrow e\nu \]

\[ \int L \, dt = 315 \text{ nb}^{-1} \]

\[ W \rightarrow \mu\nu \]

\[ \int L \, dt = 310 \text{ nb}^{-1} \]
HERAPDF vs first LHC Data

  - $3.1 \pm 0.3 \text{ pb}^{-1}$ at $\sqrt{s}=7 \text{ TeV}$
So far the LHC data not very precise, but this will change very soon

⇒ best understanding of PDF is a must.
Summary

- Understanding of the LHC data demands precise PDFs
  - HERA DIS data provide highest precision
- Heavy quarks: important, but quite some issue in QCD analyses
  - HERA charm data provide severe constraints
  - Example: PDF uncertainties on predictions for W and Z at the LHC

PDFs from HERA to the LHC is a success
Common effort of experiments and theory needed
Back up
Ultimate precision DIS: combined HERA Data

Published in JHEP 01 (2010) 109 : complete HERA I data, $\mathcal{L} \sim 115 \text{ pb}^{-1}$

e.g. NC cross section vs $Q^2$: 6 bins in $x$

H1 and ZEUS data averaged:
- global fit of 1402 measurements
- 110 sources of systematic errors
- account for systematic correlations (cross-calibration of experiments)
- total uncertainty: 1-2% for $Q^2 < 500 \text{ GeV}^2$
- covered kinematics:
  
  $10^{-7} < x < 0.65$,
  
  $0.05 < Q^2 < 30000 \text{ GeV}^2$
Combination Procedure

Minimized value:

\[ \chi^2 (\vec{m}, \vec{b}) = \sum_i \frac{(m^i - \sum_j \gamma_j m^i b_j - \mu^i)^2}{(\delta_{i,\text{stat}} \mu^i)^2 + (\delta_{i,\text{unc}} m^i)^2} + \sum_j b_j \]

\(\mu^i\) measured value at point \(i\)

\(\delta_i\) statistical, uncorrelated systematic error

\(\gamma_j\) – correlated systematic error

\(b_j\) – shift of correlated systematic error sources

\(m^i\) – true value (corresponds to min \(\chi^2\))

Measurements performed sometimes in slightly different range of \((x, Q^2)\) swimming to the common \((x, Q^2)\) grid via NLO QCD in massive scheme
HERA Parton Density Functions

10 parameter fit, NLO DGLAP

Heavy quarks: massive

Variable Flavour Number Scheme

Scales: $\mu_r = \mu_f = Q^2$

Experimentally very precise

Parameterization at starting scale:

$$xg(x) = A_g x^B_g (1 - x)^{C_g}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} (1 + E_{u_v} x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1 - x)^{C_{d_v}}$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}}$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}}$$

Model assumptions:

$$Q_0^2 = 1.9 \text{ GeV}^2, \alpha_s(M_Z) = 0.1176$$

$$m_c = 1.4 \text{ GeV}; m_b = 4.75 \text{ GeV}; f_s(Q_0^2) = 0.31$$
Modern Understanding of the Proton

HERA PDF:
- use consistent data set: H1+ZEUS
- proper treatment of error correlations

Global PDF Fit Groups:
(ABKM, CTEQ, GJR, MSTW, NNPDF)
- use more data sets from different experiments
- error correlations sometimes unclear
- not all include combined HERA data
- all treat heavy quarks differently
HERA PDFs vs global QCD analysis

HERAPDF compared to one of the global PDF Fit results:

• much better precision in gluon and sea
• differences in valence
Think of scattering of longitudinal and transverse polarized photons: 

\( y \) (or \( Y = 1 \pm (1-y)^2 \)) related to photon polarization

cross section:

\[
\sigma \sim \sigma_T + \frac{2(1-y)}{Y} \sigma_L
\]

Kinematics:

\[ x = -\frac{q^2}{2p \cdot q} \quad \text{Bjorken scaling variable} \]
\[ Q^2 = -q^2 \quad \text{photon virtuality} \]
\[ y = \frac{p \cdot q}{p \cdot k} \quad \text{transferred } \gamma \text{ energy fraction} \]
**ep Scattering in Quark-Parton Picture**

Think of scattering of longitudinal and transverse polarized photons:  
\[ y \ (\text{or} \ Y_\pm = 1 \pm (1-y)^2) \]  
related to photon polarization

Cross section:
\[
\sigma \sim \sigma_T + \frac{2(1-y)}{Y_+} \sigma_L
\]

Parton Model: scattering off a quark \((s = \frac{1}{2})\):

**Kinematics:**
- \(x = -q^2 / 2p \cdot q\)  
  Bjorken scaling variable
- \(Q^2 = -q^2\)  
  photon virtuality
- \(y = p \cdot q / p \cdot k\)  
  transferred \(\gamma\) energy fraction

helicity conservation \(\Rightarrow \sigma_L = 0\)
Proton Structure Functions

Cross Section of ep scattering expressed via proton structure functions

\[
\frac{d^2 \sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ (1 + (1 - y)^2)F_2 - y^2 F_L \pm x F_3 \right]
\]

measured

Kinematics:

- \( x = -\frac{q^2}{2p \cdot q} \) \textit{Bjorken scaling variable}
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Proton Structure Functions

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\]

measured

Quark-Parton-Model:

\[
F_L \sim \sigma_L = 0
\]

\[
F_2 = \sum_q x e_q^2 (q(x) + \bar{q}(x))
\]

Parton Distribution Functions (PDFs): probability to find a quark in a proton carrying \(x\) fraction of its momentum

Kinematics:

\(x = -q^2 / 2p \cdot q\) Bjorken scaling variable
\(Q^2 = -q^2\) photon virtuality
\(y = p \cdot q / p \cdot k\) transferred \(\gamma\) energy fraction
Another way to access the gluon directly: $F_L$

Remind of photon-scattering: $F_2 \sim (\sigma_T + \sigma_L)$, $F_L \sim \sigma_L$

Angular momentum conservation: spin $\frac{1}{2}$ quark absorbs spin-1 photon

Quark helicity $\pm \frac{1}{2}$, $F_L = 0$

Off-shell quarks may absorb longitudinal photons

QCD:

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum_q e_q^2 (1 - \frac{x}{z}) zg(z) \right]$$

Quarks radiating a gluon

Gluons splitting into quarks
Extraction of $F_L$

measurements @ same $Q^2, x$

$E_p = 920$ GeV

$E_p = 575$ GeV

$E_p = 460$ GeV

Intercept: $F_2$

Slope: $F_L$
HERA PDF Fits at NNLO

QCD using NNLO PDF predicts different $F_L$ shape

First HERA PDF Fits at NNLO:
Lhapdf grids available  https://www.desy.de/h1zeus/combined_results/

NNLO has impact on $F_L$ at low $Q^2$
HQ Contribution to the Proton Structure

Can be determined experimentally: e.g. “charm structure function”:

\[ F_{2}^{cc} \propto \frac{Q^2}{m_c^2} \int \frac{dx}{x} \xi_c^2 g(x_g, Q^2) \times C(...) \]

- use and combine different charm tagging methods
- measure cross sections of charm and beauty production in DIS:
  \[ \sigma^{cc} \propto F_{2}^{cc} (x, Q^2) - \frac{y^2}{1 + (1 - y)} F_{L}^{cc} (x, Q^2) \]

- Direct test of different schemes of HQ treatment in PDF fits

- Can be included in the full QCD analysis of DIS cross sections
  additional constrain on the gluon density in the proton
  reduce parameterization uncertainty
PDFs From HERA to Tevatron and the LHC

Kinematics in pp collisions

Center-of-mass energy:

\[ s = 4 \cdot E_1 \cdot E_2 \]

2-parton interaction:

\[ \hat{s} = x_1 \cdot x_2 \cdot s \geq M \]

Energy scale \( M = Q \)

\[ x_{1,2} = \frac{M}{\sqrt{s}} \cdot \exp(\pm y) \]

HERA coverage in \( x \)
Proton collisions at the LHC

LHC: $p-p$ collisions at $\sqrt{s} = 7, 10, 14$ TeV

Goal @ LHC: Higgs and new physics

Main challenge: Background suppression

Main Background: QCD

Hard processes > 80% gluon-gluon fusion

Cross section $\sim |g(x)|^2$

*Precision of the gluon density essential!*

Luminosity: e.g. $ud \rightarrow W^+ \rightarrow l^+ \nu_l$

*Precision of light quark densities essential!*

Key issue: understanding of the proton
Proton-Proton Collisions at High Energies

Structure: $f_i(x, Q^2) = q_i(x, Q^2), g(x, Q^2)$, $f_i$ - beam parameters, process independent

Hard 2-parton interaction calculable in pQCD
Proton-Proton Collisions at High Energies

Structure: \( f_i(x, Q^2) = q_i(x, Q^2), \ g(x, Q^2), \)

\( f_i \) - beam parameters, **process independent**

Hard 2-parton interaction calculable in pQCD

\[
\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \hat{\sigma}_{ij}
\]

\[
\tau \cdot \frac{dL_{ij}}{d\tau} \propto \int_{0}^{1} dx_1 dx_2 (x_1 f_i(x_1, \mu_F^2) \cdot x_2 f_j(x_2, \mu_F^2)) + (1 \leftrightarrow 2) \delta(\tau - x_1 x_2)
\]
Proton-Proton Collisions at High Energies

Structure: $f_i(x, Q^2) = q_i(x, Q^2)$, $g(x, Q^2)$, $f_i$ - beam parameters, process independent

Hard 2-parton interaction calculable in pQCD

Factorization: PDF $\otimes$ hard sub-process ME

$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \hat{\sigma}_{ij}$$

$$\tau \cdot \frac{dL_{ij}}{d\tau} \propto \int_0^1 dx_1 dx_2 (x_1 f_i(x_1, \mu_F^2) \cdot x_2 f_j(x_2, \mu_F^2)) + (1 \leftrightarrow 2) \delta(\tau - x_1 x_2)$$

Precision of PDFs essential!
Predictions based on HERAPDF in agreement with TEVATRON data