Physics of gluons and heavy quarks from HERA to the LHC

Katerina Lipka, DESY

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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. \( u\bar{d} \rightarrow W^+ \rightarrow l^+n_l \)

*Precision of light quark densities essential!*
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Key issue: understanding of the proton
World-only $ep$ machine to study the proton structure

Till June 2007:
- collisions at $\sqrt{s} = 318$ GeV
- collider experiments
  - H1 and ZEUS
- integrated Luminosity
  - $\sim 0.5 \text{ fb}^{-1}$ experiment
World-only $ep$ machine to study the proton structure

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- collisions at $\sqrt{s} = 318$ GeV
- collider experiments H1 and ZEUS
- integrated Luminosity $\sim 0.5 \, fb^{-1}$/ experiment
Inclusive Deep Inelastic Scattering

DIS: tool to study the proton

Kinematics:

\[ Q^2 = -q^2 \quad \text{photon virtuality} \]
\[ x = \frac{-q^2}{2p \cdot q} \quad \text{Bjorken scaling variable} \]
\[ s = (k + p)^2 \quad \text{center of mass energy} \]
\[ y = \frac{p \cdot q}{p \cdot k} \quad \text{transferred energy fraction} \]
Inclusive Deep Inelastic Scattering

DIS: tool to study the proton

$\gamma, Z : \text{Neutral Current } e_p \rightarrow lX$

$W^\pm : \text{Charged Current } e_p \rightarrow \nu X$

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Deep Inelastic Scattering Cross Section

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

- **e^p** sensitive to \( u \) - valence
- **e^+p** sensitive to \( d \) - valence

**Neutral Current:**
- Low \( Q^2 \): \( \gamma \) exchange
- High \( Q^2 \): \( Z/\gamma \) interference

**Charged Current:**
- Lower at low \( Q^2 \)

Unification at \( M_W^2 \)
DIS cross section and proton structure

DIS cross sections connected to proton structure functions, e.g. NC:

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

- \( F_2(x, Q^2) \propto x \sum_f q_f(x, Q^2) + \bar{q}_f(x, Q^2) \) \quad Dominant contribution
- \( x F_3(x, Q^2) \propto x \sum_f q_f(x, Q^2) - \bar{q}_f(x, Q^2) \) \quad Z/γ interference
- \( F_L(x, Q^2) \propto x \alpha_s g(x, Q^2) \) \quad Directly sensitive to the gluon

\( q_i(x, Q^2), g(x, Q^2) \) - Parton Distribution Functions:

*probability density finding a parton carrying the momentum fraction \( x \) at \( Q^2 \)*

PDFs are determined via QCD fits to experimentally measured \( \sigma_{NC} \) and \( \sigma_{CC} \)

Covered kinematics range: \( 0.1 < Q^2 < 20000 \text{ GeV}^2 \) and \( 10^{-5} < x < 0.9 \)
PDFs determined from the QCD fit to the NC and CC cross sections

Gluon density determined from scaling violations

\[ \frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)xg(x, Q^2) \]
HERA PDFs using inclusive DIS

Gluons and sea quarks: dominant partons at low $x$

HERAPDF1.0 PDF set:
- use consistent data set H1+ZEUS
- proper treatment of error correlations

Global PDF Fit Groups (USA, UK):
- use more data sets from different experiments
- error correlations sometimes unclear
HERAPDF1.0 compared to one of the global Fit results:

- much better precision in gluon and sea
- differences in valence: has to be understood by both groups
Where PDF for LHC are coming from..

PDFs determined experimentally at HERA, Fixed Target Exp, Tevatron

HERA:
covers most of the kinematics plane,
Best PDF constrain at low and medium $x$
Where PDF for LHC are coming from..

PDFs determined experimentally are evolved to kinematics plane of the LHC.

PDFs from HERA to the LHC:
Evolution in $Q^2$ via DGLAP equations
Most precise PDF set on the market
Uncertainties on PDFs from inclusive DIS

- Experimental uncertainty small
- Dominant uncertainties:
  - parameterization:
    - assumption on gluon distribution
  - model:
    - assumptions on fractions of $s$ & $c$
    - assumptions on $c$, $b$- masses

Disadvantage of fit to inclusive data: due to correlations of gluon and sea quark distributions rely much on the parameterization of the QCD fit

Need additional constrain / cross-check from direct access to the gluon
Direct access to the gluon: heavy quarks

Dominated by Boson–Gluon Fusion (BGF)

- heavy quarks at HERA:
  - charm \((m_c \approx 1.65 \text{ GeV})\) and
  - beauty \((m_b \approx 4.75 \text{ GeV})\)
- HQ mass provides hard scale for pQCD
- contribution to the DIS cross section
  - charm up to 30% at high \(Q^2\)
  - beauty at most 1%

Factorization: heavy flavour production cross section =

\[
\text{Proton Structure} \otimes \text{Photon Structure} \otimes \text{Matrix Element}
\]

Gluon directly involved:

- constrain gluon density in proton/cross-check the inclusive PDF fits
HQ Contribution to the Proton Structure

QCD analysis of the proton structure: treatment of heavy quarks essential!

Direct test of different approaches of HQ treatment in PDF fits via extraction of HQ structure functions:

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

- Can be included in the full QCD analysis of DIS cross sections
- additional constrain on the gluon density in the proton
- reduce parameterization uncertainty

- Use and combine different charm tagging methods:
  - full reconstruction of charmed hadrons in the detector
  - use large mass and long lifetime of the heavy quarks
  - use semi-leptonic decays
Charm and Beauty Production: test pQCD

Charm from D*

H1 Preliminary HERA II

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

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

HQ from semi-leptonic decays

- H1 data (prelim)
- HVQDIS (MRST2004FF3nlo)

Charm: NLO QCD agrees with data

Beauty: NLO lower in normalization

Theory uncertainties: HQ masses, scales, fragmentation model
**Charm Structure Function**

- Large variety of measurements
- Nice agreement between methods
- Experimental precision of several measurements will further improve

**Combine different measurements**

- orthogonal systematic uncertainties
- treat systematic correlations properly
- win in precision
Averaged $F_2^{cc}$: HERA Combined Data

- **H1** (full HERA run statistics)
  - $F_2^{cc}$ extracted from $D^*$-meson cross sections
  - Charm tag via large Lifetime of heavy quarks

- **ZEUS** (only part of HERA data – significant improvement expected!)
  - $F_2^{cc}$ determined using semi-leptonic decays into muons
  - Full reconstruction of $D^*$, $D^0$, $D^\pm$ mesons

- Correlations of systematic uncertainties:
  - within single experiment
  - theory uncertainties correlated between H1 and ZEUS

- Precision of the combined result 5-10%, to be improved

(HERA inclusive $F_2$ precision 1-2%)
$F_2^{cc}$ vs most recent HERAPDF1.0

$F_2^{cc}$ measurement triggered an additional model uncertainty in the PDF fit to inclusive DIS

- $m_c = 1.4 \text{ GeV}$
- $m_c = 1.4$ vs $1.65 \text{ GeV}$
  (largest uncertainty part)

Inclusive data prefer low $m_c$

$F_2^{cc}$ data prefer higher $m_c$

Pole $m_c = 1.65 \pm 0.18 \text{ GeV}$
Test different HQ treatment schemes

Different approaches of HF treatment in global fits can be tested
What does value of $m_c$ mean for PDFs

HERA PDF: additional uncertainty due to variation of $1.4 < m_c < 1.65$ GeV

The choice of the $m_c$ influences
- the gluon PDF,
- most visible in charm PDF,
- consequences for light quarks
choice of $m_c=1.65$ raises $W/Z$ cross-section predictions at the LHC by $\sim 3\%$

Larger $m_c \rightarrow$ more gluons, less charm $\rightarrow$ more light quarks $\rightarrow$ larger $\sigma_W$

Does matter for the Luminosity measurement @ LHC!

$W/Z$ production @ LHC known to the precision of the PDFs
Summary

• Precise understanding of the proton structure crucial for the LHC physics
• Most precise PDFs are coming from DIS inclusive measurements at HERA
• These PDFs have small experimental but sizable model uncertainty
• Additional constrain to come from exclusive final states, like HQ production:
  - at HERA HQ born by gluons: direct test of gluon PDF from inclusive DIS
• Measurement of \( F_2^{cc} / F_2^{bb} \) is the mean to include HQ into the QCD Fits
• Charm measurements indicate steeper gluon wrt. inclusive data alone
• Choice of charm mass in the PDF does matter for the LHC cross sections
• More precise measurements are expected
• PDF fits using charm data are being tested at HERA

• \( W/Z \) production @ LHC known to the precision of the PDFs
Back up
HERAPDF1.0 vs other PDF set

\[ x_f \]

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

\[ x_f \]

\[ Q^2 = 10000 \text{ GeV}^2 \]

HERAPDF1.0 vs other PDF set
Charm contribution to $F_2(\mu, \text{lifetime})$

Quark fractions $\rho_c$, $\rho_b$, $\rho_{uds}$: from fit to observables sensitive to lifetime or heavy mass of charmed (beauty) hadrons using Monte Carlo templates

Normalization: inclusive reduced cross section $\sigma_{\text{red}}(x,Q^2)$

Bin center corrections $\delta_{\text{BCC}}$: via FFNS NLO calculation

$$\sigma_{\text{red}}^{c\bar{c}}(x,Q^2) = \sigma_{\text{red}}(x,Q^2) \cdot \frac{\rho_c \cdot N_{c}^{MC} + \rho_b \cdot N_{b}^{MC} + \rho_{uds} \cdot N_{uds}^{MC}}{\rho_c \cdot N_{c}^{MC} + \rho_b \cdot N_{b}^{MC} + \rho_{uds} \cdot N_{uds}^{MC}} \cdot \delta_{\text{BCC}}$$

Connection to $F_2^c$:

$$\sigma_{\text{red}}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{1 + (1 - y)^2} F_L^{c\bar{c}}$$
F2cc vs FFNS

HERA Heavy Flavour Working Group

October 2009

Q^2 = 2 GeV^2, Q^2 = 4 GeV^2, Q^2 = 6.5 GeV^2
Q^2 = 12 GeV^2, Q^2 = 20 GeV^2, Q^2 = 35 GeV^2
Q^2 = 60 GeV^2, Q^2 = 120 GeV^2, Q^2 = 200 GeV^2
Q^2 = 400 GeV^2, Q^2 = 1000 GeV^2

HERA (prel.)

GJR08 FFNS
ABKM FFNS NLO
ABKM FFNS NNLO
$F_2^{cc}$ vs GMVFNS

October 2009

HERA Heavy Flavour Working Group

HERA (prel.)

MSTW08 NNLO
MSTW08 NLO
CTEQ 6.6
ABKM BMSN

$x$ vs $Q^2$ for various values of $Q^2$
$F_{2cc}$ vs FFNS NLO
Perfect description of inclusive CC and NC data over the whole range
HERAPDF1.0 at high energies

Tevatron Jet Cross sections

W cross sections at the LHC@14 TeV

uncertainties on other PDFs not shown

HERAPDF does well for Tevatron

Predictions for LHC @ 7,10,14 TeV available with full uncertainty band
HERAPDF1.0: are we happy?

Advantage of HERA QCD analysis vs global analysis groups:

- Consistent treatment of systematic correlations in the data sets!

BUT same disadvantage: correlation of $g(x)$ and $s(x)$ in DGLAP formalism rely much on fit parameterization: need Tests!

Next Steps: inclusion of further data in the fit, extend the $Q^2$ and $x$ range

use the exclusive final states in the fit: Jets, HQ production

Heavy Quarks (charm, beauty): high contribution to total cross section

direct access to the gluon

different schemes of treatment in Fits
reduce parametrization uncertainty
HQ Contribution to the Proton Structure

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

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

- 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
Charm contribution to $F_2$ (charm via D)

$$F_2^{car{c}} \ (\text{exp}) = \frac{\sigma_{\text{vis}} \ (\text{exp})}{\sigma_{\text{vis}} \ (\text{theory})} F_2^{car{c}} \ (\text{theory})$$

Visible meson cross section:  $p_T(D^*) > 1.5$ GeV, $|\eta(D^*)| < 1.5$

Problem: detector sees only $\sim 30\%$ of the phase space for $c \rightarrow D$

$\rightarrow$ strong model dependence due to large extrapolation factors

Extrapolation uncertainties:  mass of charm quark, scales, fragmentation model (experimentally measurable)
Heavy Quarks and PDF Fits

QCD analysis of the proton structure: treatment of heavy quarks essential!

*Fixed Flavour Number Scheme:*

*charm (beauty)* quarks massive, produced in BGF

only light flavours in the proton: \( N_f = 3 \) (4)

Problem: expected to break down at \( Q^2 \gg m_{HQ}^2 \)

*Variable Flavour Number Scheme:*

- *Zero Mass*: all flavours massless, \( N_f \) variable. Breaks down at \( Q^2 \sim m_{HQ}^2 \)

- *Generalized Mass*: matched scheme, expect appropriate description at all \( Q^2 \), different implementations available

HQ measurements can decide on the appropriate treatment
Heavy quark tagging methods at HERA

Full reconstruction of charmed mesons: $D^*, D^\pm, D^0$ from decay particles in detector

Via reconstructed $D^* \rightarrow D^0 \pi \rightarrow K\pi\pi$

$$\Delta m(D^*) = M_{inv}(K\pi\pi) - M_{inv}(K\pi)$$

Signal obtained from the fit
Heavy quark tagging methods at HERA

Large mass, long lifetime of heavy hadrons: charm comes alone with beauty

- Semi-leptonic decays ($e, \mu$)
- Large mass: transverse momentum to Jet axis: muon $p_T^{rel}$
- Large lifetime: impact parameter $\delta$
Charm and Beauty Production: test pQCD

Direct test of Scheme: Charm data at high $Q^2$
- described well by Massive Scheme
- not described by Zero Mass Scheme

NLO in massive scheme used to extract $F_{2}^{cc}$
Combination Procedure

Minimized value:

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

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

\( \delta_i \) statistical, uncorrelated systematic error

\( \gamma_j^i \) – 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