Experimental tests of QCD

- Proton structure
- $\alpha_s$
- The real secrets of QCD:
  - Diffraction
  - Underlying event
  - Fragmentation
- Nucleon spin
Hard QCD machines

30.6.2007: HERA-shutdown – the end of a unique machine for DIS at the high energy frontier

HERA: $\sqrt{s} = 318$ GeV
~70 abstracts for HEP2007

TEVATRON: $\sqrt{s} = 2$ TeV
Run II: 3 fb$^{-1}$ so far, aim for 8 fb$^{-1}$ until 2009
~10 abstracts for HEP2007

LEP: $\sqrt{s} = 90-200$ GeV
~5 abstracts for HEP2007

LHC: $\sqrt{s} = 14$ TeV
Start May 2008
~5 abstracts for HEP2007
Deep inelastic scattering at HERA

$\gamma$-Resolution
$Q^2 = -q^2$

$\gamma$-Energy
$y = \frac{E_g}{E_{e|p-cms}}$

Relation: $Q^2 = S_{xy}$

Event in H1 detector:

$27.6 \text{ GeV}$

$920 \text{ GeV}$
The HERA proton handbook

Scaling violations \( \sim g(x, Q^2) \)

Bremsstrahlung of valence quarks

Using all info in an NLO QCD fit (DGLAP evolution):

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

\[ xu, \quad xd, \quad xS \times 0.05 \]
From HERA to LHC in a nutshell

\[ Q^2 = 6400 \text{ GeV}^2 \]

\[ Q^2 = 250 \text{ GeV}^2 \]

Gluons

\[ \nu l \]

\[ \text{HERA} \]

\[ x = 0.005 \]

\[ W \]

\[ \text{DGLAP} \]

\[ M = 10 \text{ TeV} \]

\[ M = 100 \text{ GeV} \]

\[ M = 10 \text{ GeV} \]

\[ x_{1,2} = (M/14 \text{ TeV}) \exp(\pm y) \]

\[ Q = M \]

\[ \text{fixed target} \]
HERA proton PDF --> LHC W production

'Lumi' process for LHC

\[ \text{Prediction using ZEUS-S-PDF} \]

\[ \text{\( W^+ \)} \]

\[ \text{\( \pm 3.5\% \) precision} \]

\[ \text{\( \Rightarrow \) HERA } u, d \text{ and gluon determine precision} \]

\[ \text{\( \Rightarrow \) how far can we improve this?} \]
Inclusive DIS at highest $E_\gamma$ (high $y$)

Helps to extrapolate to LHC and to understand $F_L$
Valence quarks: $xF_3$

$e^+ e^-$

$\gamma Z$ interference flips sign for $e^+ p \rightarrow e^- p$

$xF_3 \sim \sigma(e^- p) - \sigma(e^+ p) \sim 2u_v + d_v$

$\gamma Z$ interference flips sign for $e^+ p \rightarrow e^- p$

Valuable info on valence quarks at low $x<0.1$
The final word from HERA for low $Q^2 < 10 \text{ GeV}^2$

$\Rightarrow$ Mapping the transition to the soft QCD regime ($Q^2 < 1 \text{ GeV}^2$)

$\Rightarrow$ Up to 3% precision reached - provides unique data for models
Warning: Signs of Breakdown of DGLAP at small $x$

$Q^2 > 5 \text{ GeV}^2$

$x \sim 10^{-4}$

$\Rightarrow$ Strong hints for $k_T$ unordered gluon emissions, neglected in DGLAP
Gluon density determinations

Jet cross sections

\[
\frac{\partial F_2}{\partial \ln Q^2} \bigg|_x \propto \alpha_s(Q^2) x g(x, Q^2)
\]

Still most precise - to be improved soon with the available HERA data

Gluon

\[ F_{c\bar{c}}^c \]
\[ F_2 \]
\[ F_L \]
Gluon from jets @ HERA

\[ e^+ \gamma^* \rightarrow Q^2 \rightarrow p\]

Jet

\[ \sqrt{\alpha_s} \rightarrow g \]

Jet

Calibrate jet energy scale via pt balance with scattered e+

M. Cooper-Sakar: HERA-LHC workshop, 700 pb-1 HERA data simulation:

Wealth of new data to constrain g(x)

H1

DESY-06-020

High \( p_T \) Dijets in photoproduction

DESY-07-092

Inclusive jets at high \( E_T \) and \( Q^2 \)

DESY-07-073

Dijets at high \( E_T \) and \( Q^2 \)

DESY-06-241

+ more to come from both experiments

ZEUS

H1

DESY-07-092

Inclusive jets at high \( E_T \) and \( Q^2 \)

DESY-06-241

Dijets at high \( E_T \) and \( Q^2 \)
Gluon from jets at Tevatron

Can probe the ‘most violent’ gluons!

Deviation from NLO QCD could also signal new physics!

Hadronic energy scale dominates experimental uncertainty

Data can constrain $g(x)$ at high $x$
Gluon via charm @ HERA

\[ Q^2 \sim m_c^2 \]

**Massive c**

\[ Q^2 \gg m_c^2 \]

**Massless c**

\[ F_{2cc} = F_2|_{\text{charm in the final state}} \]

- **NLO QCD fit using H1** \( F_{2cc} \), fitting only gluon

\[ Q^2 = 4 \text{ GeV}^2 \]

- \( x_\text{g from F2c fit} \)
- \( x_\text{g from H1 fit} \)

\( F_2 \)

\[ Q^2 (\text{GeV}^2) \]

\( x \)

\[ 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \]

- H1 HERA I (D^0)
- ZEUS HERA I (D^0)
- H1 HERA I (VTX)
- ZEUS (prel.) HERA II:
- \( x = 0.00003 \times 4^{10} \)
- \( x = 0.00005 \times 4^{10} \)
- \( x = 0.00007 \times 4^{10} \)
- \( x = 0.00013 \times 4^{10} \)
- \( x = 0.00018 \times 4^{10} \)
- \( x = 0.0003 \times 4^{15} \)
- \( x = 0.00035 \times 4^{14} \)
- \( x = 0.0005 \times 4^{13} \)
- \( x = 0.0006 \times 4^{13} \)
- \( x = 0.0008 \times 4^{11} \)
- \( x = 0.001 \times 4^{10} \)
- \( x = 0.0012 \times 4^{9} \)
- \( x = 0.0015 \times 4^{8} \)
- \( x = 0.002 \times 4^{7} \)
- \( x = 0.003 \times 4^{6} \)
- \( x = 0.004 \times 4^{5} \)
- \( x = 0.006 \times 4^{4} \)
- \( x = 0.008 \times 4^{3} \)

- CTEQ5f3
- MRST2004FF3

\[ \Rightarrow F_{2cc} \text{ data can constrain the proton gluon density at small } x \]
HERA beauty density ... goes to LHC

'Beautyful' new HERA II data
Astonishing spread of model predictions!
Probe b PDF with Z+jet at Tevatron

Z+b jet. CDF RUN II Preliminary

CDF update with 5x higher statistics

Z+b-jet/Z+jet :

CDF: 2.35±0.36(stat) ±0.45(sys) %
D0: 2.1±0.4(stat) +0.3−0.2(sys) %
NLO: 1.8±0.4 % (CTEQ6)

⇒ More to come!
Gluon density via $F_L$ at HERA

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

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

Extract $F_L$ from $\sigma_r(x,Q^2)$ at different $y$

$\gamma = 0.4$

$Q^2 = 40 \text{ GeV}^2$

$x = 0.001$

$920 \text{ GeV}$

$\gamma = 0.8$

$Q^2 = 40 \text{ GeV}^2$

$x = 0.001$

$460 \text{ GeV}$

HERA: All runs

Last 3 HERA months

$\Rightarrow$ Nice low $E_p$ data on tape

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities

$\Rightarrow$ Simulation

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.4$

$x = 0.001$

$920 \text{ GeV}$

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.8$

$x = 0.001$

$460 \text{ GeV}$

$\Rightarrow$ Nice low $E_p$ data on tape

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.4$

$x = 0.001$

$920 \text{ GeV}$

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.8$

$x = 0.001$

$460 \text{ GeV}$

$\Rightarrow$ Nice low $E_p$ data on tape

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.4$

$x = 0.001$

$920 \text{ GeV}$

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.8$

$x = 0.001$

$460 \text{ GeV}$

$\Rightarrow$ Nice low $E_p$ data on tape

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.4$

$x = 0.001$

$920 \text{ GeV}$

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.8$

$x = 0.001$

$460 \text{ GeV}$

$\Rightarrow$ Nice low $E_p$ data on tape

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.4$

$x = 0.001$

$920 \text{ GeV}$

$27.6 \text{ GeV}$

$Q^2 = 40 \text{ GeV}^2$

$\gamma = 0.8$

$x = 0.001$

$460 \text{ GeV}$

$\Rightarrow$ Nice low $E_p$ data on tape

$\Rightarrow$ Final $F_L$ should separate extreme gluon densities
Prompt $\gamma$ - sensitive probe of QCD!

**HERA: ep**

- $Q^2 > 4 \text{ GeV}^2$
- $q \rightarrow \text{Jet}$

**HERA: $\gamma p$**

- $Q^2 \sim 0 \text{ GeV}^2$
- Resolved $\gamma$ contributions

**Tevatron: ppbar**

- $q \rightarrow \text{Jet}$

**Surprise:** NLO too low

**... too low at low $E_T^\gamma$**

**High sensitivity to proton gluon density**
Strong coupling $\alpha_s$

**OPAL:** $\sim 400$ k Four-jet events!

**HERA $\alpha_s$ from fit to incl. Jet data**

(H1: DESY-07-073, ZEUS: DESY-06-241)

$\alpha_s(m_Z) = 0.1198 \pm 0.0019$ (exp.) $\pm 0.0026$ (th.)

**More to come from HERA incl. DIS and jets (HERA II!)**
Diffraction: Intro

➔ Hadron-Hadron scattering dominated by soft elastic processes, called diffraction
➔ Question: partonic nature of this exchange?
Hard diffraction at HERA - a key to the partonic nature

Inclusive diffr.

\[ Q^2 > 8.5 \text{ GeV}^2 \]

New: add info from diffractive dijets

\[ Q^2 > 8.5 \text{ GeV}^2 \]

\[ x_{Fp} \]

\[ \beta \]

\[ \rho \]

\[ X \]

\[ p \]

Consistent picture, improved gluon density

\[ z_{\text{singlet}}(z) \]

\[ z_{\text{gluon}}(z) \]

\( \mu_f^2 = 25 \text{ GeV}^2 \)
Does QCD factorisation hold? $\sigma = \text{Diffr. PDF} \otimes \sigma_{\text{hard matrix el.}}$

**Tevatron**

- Rescatter with $p$?
- $g(x)$, jet
- $g(z_{ip})$, jet
- (gap)
- $p$, $\bar{p}$

**HERA photoproduction: $Q^2 \sim 0$**

- Rescatter with $p$?
- $g(x_c)$, $C$, jet
- $g(z_{ip})$, $\bar{C}$, jet
- $p$, $\bar{p}$

$\Rightarrow$ H1 sees global suppression by $\sim 0.5$

$\Rightarrow$ Similar ZEUS analysis: sees much smaller suppression (due to harder jet $p_T$ cuts?)

Frixione NLO

H1 Fit B
Elastic Vector meson production at HERA

$Q^2$ $\gamma$ $p$

$W_{\gamma p}$ $e$

$qq$-dipol $\rho$, $\phi$, $J/\psi$, $\Upsilon$

$\text{Obtain 3d-picture of proton}$
VM production: energy dependence

Soft QCD
Photoproduction: $Q^2 \sim 0$

Hard QCD

$\sigma_{tot}(\gamma p)$

$\sigma(\gamma p \rightarrow \omega p)$

$\sigma(\gamma p \rightarrow \phi p)$

$\sigma(\gamma p \rightarrow J/\psi p)$

$\sigma(\gamma p \rightarrow \psi(2S)p)$

$\sigma(\gamma p \rightarrow \tau(1S)p)$

$\sigma \sim W^\delta$

$W_{\gamma p}$

$Q^2$

$|g(x,\mu_f)|^2$

$\mu_f = 2$ GeV

$\mu_f = 5$ GeV

$\mu_f = 14$ GeV

H1 Collaboration

Gluon density

VM mass sets hard scale of interaction
VM production: energy dependence

\[ \sigma \sim W^\delta \]

DIS: \( Q^2 > 1 \text{ GeV}^2 \)

\[ W_{\gamma p} \]

\[ Q^2 \]

\[ g(x, \mu_f)^2 \]

\[ Q^2 + M^2 \text{(GeV}^2) \]


\[ \Rightarrow \text{VM mass and } Q^2 'set' \]

\[ \text{hard scale of interaction} \]
Vector meson production: $t$-slope vs $Q^2$

\[ d\sigma/dt \sim e^{-b|t|} \quad b \sim r_p^2 + r_{qq}^2 \]

\( Q^2_{\text{small}} \)

\( Q^2_{\text{large}} \)

Transverse extension of hard gluons in proton is \( \sim 0.6 \text{ fm} \), smaller than proton radius 0.8 fm!
Physics interest is in hard primary interaction: need to understand & correct underlying event
Underlying event: Z + jet at Tevatron

- Clean signal
- Well predictable

Jet energy density

- No UE
- Clean signal
- Well predictable

Energy flow

Run II Preliminary

CDF Run II Preliminary

Z → ee + jets
- $66 < M_{ee} < 116 \text{ GeV/c}^2$
- $E^e_T > 25 \text{ GeV}, |\eta^e| < 1$
- $|\eta^e| < 1 \parallel 1.2 < |\eta^\gamma| < 2.8$
- $p^e_T > 30 \text{ GeV/c}, |y^e| < 2.1$
- $\Delta R(e, jet) > 0.7$

Calorimeter towers with $|y| < 0.7$

$\Rightarrow$ UE effects clearly visible
$\Rightarrow$ PYTHIA Tune A
Underlying event at HERA

Highly improved description by models with multiple interactions

Three-jets

Four-jets

\[ Q^2 \approx 0 \]

Resolved photon

Jet

Jet

Jet

Jet

Proton remnant

Proton

MPI

MPI energy flow

\[ \gamma \text{ remnant} \]

\[ \gamma \]

\[ X_{\gamma} \]
Charged particle momenta in DIS

Breit frame

\[ \pi^\pm, K^\pm \]
\[ x_p = p/(Q/2) \]

\[ \rightarrow \]

Clear scaling violations
Rough agreement with e^+e^- data
Failure of NLO models

\[ Q^2 (\text{GeV}^2) \]
\[ 10^2, 10^3, 10^4 \]
\[ 10^{-2}, 10^{-1}, 10^0, 10^1, 10^2 \]

NLO models
- Kretzer
- AKK
- KKP

\[ x_p \text{ range} \]
- H1 44 pb^{-1}
- ZEUS (prel.) 0.5 fb^{-1}
- e^+e^-

\[ 0.0 - 0.02 (\times 30) \]
- 0.02 - 0.05 (\times 5)
- 0.05 - 0.1 (\times 2)
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 0.7
- 0.7 - 1.0
Nucleon Spin structure

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

DIS with pol. lepton beams on pol. targets

QCD analysis:
\[ \Delta \Sigma = 0.330 \pm 0.011 \text{(th.)} \pm 0.025 \text{(exp.)} \pm 0.028 \text{(evol.)} \]

HERMES: Precise measurements for \( x < 10^{-2} \)
Also brand-new results for Valence quark polarisation from Semi-incl. DIS

COMPASS: Precise measurements for \( x < 10^{-2} \)
Contributions from gluon?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

High pt Hadrons or charm tag

Use asymmetries between particle rates for nucleon target parallel and antiparallel polarised wrt beam polarisation

RHIC pp: Jets

Disfavour large \( \Delta G \), more data will come

\( \Delta g \) not yet well constrained

- Results for transverse polarised target: Non-zero Sivers amplitudes for \( \pi \rightarrow L_i \leftrightarrow 0 \)
- DVCS target spin asymmetry: \( J_u + J_d / 2.9 \approx 0.42 \)
- Much more precise DVCS results to be expected from last HERA data periods

\( \Delta G \approx 0.2 - 0.3 \)
Summary

➢ HERA:
  - 30.6.2007 - end of a unique machine for DIS at the high energy frontier, successor?
  - Many new results at HEP2007, improved precisions 'challenge' QCD at new level!
  - Refine calibrations to achieve final results with full HERA statistics:
    ✔ Proton content: gluon density (very important for LHC), charm & beauty
    ✔ High precision $\alpha_s$
    ✔ Diffraction (e.g. gain more insight on factorisation breaking)

➢ Tevatron:
  - Accumulating (happily!) more lumi than ever
  - Unique QCD lab, complementary to HERA:
    ✔ Proton content: access to the gluon density at highest x
    ✔ Reveal complicate structure of hadron hadron collisions: Underlying event, multiple interactions

➢ HERMES, COMPASS, RHIC: hunting the 'contributors' to the nuclear spin
  ✔ Nicely improving knowledge - but puzzle still not settled: gluons or orbital angular momentum?

Thanks to: H. Abramowicz,, C. Diaconu, D. Hasch, R. Lefevre, A. Levy and all speakers in the QCD session
Backup
HERA Gluondensity --> LHC

Proton $g(x)$

Proton $g(x)$

$t$

H

gg→ H prediction-uncertainty

$\sigma(gg \rightarrow H)$ [pb]

$\sqrt{s} = 14$ TeV

MRST
CTEQ
Alekhin

$M_H$ [GeV]

0.1 1 10 100 1000

0.95 0.9 0.95 1 1.1

0.1 1 10 100 1000

⇒ HERA Gluondensity determines precision! How far can we improve this???
QCD fit prospects

Assumptions:
- 700 pb\(^{-1}\) Lumi at HERA II \(\approx\) reached by combining H1+ZEUS
- Inclusive data: Only high \(Q^2>100\) GeV\(^2\) taken into account
- Only statistical improvements, no systematical

\(x\approx0.1\) still statistically limited

\(\Rightarrow\) Improvement of PDFs at high \(x\) reflected in jets cross sections at LHC

\(\Rightarrow\) more HERA statistics available (not taken into account here!)
CTEQ global PDF fits: Effect of proper charm mass treatment in CTEQ6.5M

CTEQ6.1M: charm mass neglected in the kinematics of the processes

Shift of PDFs from CTEQ6.1M to CTEQ6.5M

W. Tung, DIS2007
Corresponding effect on LHC predictions

W/Z Production xSec @ LHC

Correct charm mass treatment is crucial for accurate predictions of LHC xSecs!