Ultimi risultati di HERA e il loro impatto su LHC

Monica Turcato
Hamburg University

Incontri di Fisica delle Alte Energie
IFAE 2001
Perugia, 28 aprile 2011

Questa è per forza di cose una selezione limitata di risultati di HERA, che riflette il tempo limitato a disposizione e le preferenze personalissime dell’autore...
The HERA collider

HERA was an ep collider operating at a center of mass energy of 318 GeV.

Two collider experiments: H1 and ZEUS.

Data taking ended in June 07.

Collected luminosity: ~0.5 fb$^{-1}$ per experiment
DIS kinematic:

\[
\begin{align*}
  s &= (P + k)^2 \\
  Q^2 &= -q^2 = -(k - k')^2 \\
  x &= \frac{Q^2}{2P \cdot q} \\
  y &= \frac{P \cdot q}{P \cdot k} \approx \frac{Q^2}{sx} \\
  W^2 &= (P + q)^2 \approx Q^2 \frac{1 - x}{x} \\
  Y_{\pm} &= 1 \pm (1 - y)^2
\end{align*}
\]
The structure of the proton

The proton structure is a fundamental input for cross sections predictions at the LHC. Best determination from different inputs:

- inclusive NC and CC cross sections
- jet production
- heavy flavour production

Focus on the combination of the data of the H1 and ZEUS experiments.
HERA, Tevatron and the LHC

- $Q^2$: 'hardness' of the interaction
- $x$: momentum fraction of the parton

At LHC:

$$M \cong Q$$

$$x_{1,2} \cong \frac{M}{14 \text{ TeV}} e^{\pm y}$$
Evolution in $Q^2$ driven by the DGLAP equation, determines the PDFs for each $Q^2$ at a given $x$.

Using the HERA data and DGLAP evolution precise predictions can be made at the LHC for masses of $M\sim100$ GeV in the central rapidity region ($M=Q$).
H1 and ZEUS NC and CC cross sections

Tools to investigate QCD at HERA

NC, low $Q^2$ dominated by $\gamma$ exchange. High-$Q^2$, $Z/\gamma$ interference becomes important.

CC: smaller at low $Q^2$ (W exchange)

Unification at $Q^2 \sim M_W^2 \sim 10.000\ GeV^2$
The structure of the proton

- The ep NC cross section can be expressed in terms of the structure functions $F_2, F_3, F_L$.

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

where $Y_\pm = 1 \pm (1 - y)^2$

- These structure functions are related to the proton parton distribution functions:

  \[
  F_2 \sim x(q + \bar{q}) \quad xF_3 \sim x(q - \bar{q}) \quad F_L \sim x\alpha_s g
  \]

- Charged current is sensitive to the quark charges:

  \[
  \tilde{\sigma}(e^- p) \sim x(u + c + (1 - y)^2(\bar{d} + \bar{s})) \quad \tilde{\sigma}(e^+ p) \sim x(\bar{u} + \bar{c} + (1 - y)^2(d + s))
  \]
The $F_2$ structure function

- NC and CC cross sections from H1 and ZEUS combined
- Precision of 1-2% also due to different systematic uncertainties in the two experiments
- Gluon density from scaling violations
  \[
  \frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)xg(x, Q^2)
  \]
- DGLAP drives the evolution in $Q^2$ at fixed $x$

H1 and ZEUS

$F_2 \sim x(q+\bar{q})$
The combined HERA data have been used as the sole input for the extraction of the HERAPDF1.0.

Gluon (and sea) scaled down by a factor 20, dominate at low $x$. 

Precise picture of the proton
Test of the PDFs in the high $p_T$ kinematic region at the Tevatron.

HERAPDF1.0 able to describe Tevatron jets also at high $p_T$ (different kinematic region)

Consistent picture of QCD: extrapolation from HERA ($Q^2 \sim 1-10000$ GeV$^2$) to Tevatron (1TeV) works.

https://www.desy.de/h1zeus/combined_results/benchmark/tev.html
• Parton distribution functions are universal

• Standard 'candles' of the SM can be predicted using the HERAPDF1.0

• Here: W and Z at LHC

• Sensitivity to the $x \sim 10^{-3}$ region

Very good precision in the central rapidity region

Precise prediction of SM cross sections for LHC
Here for an Higgs mass of 120 GeV

https://www.desy.de/h1zeus/combined_results/benchmark/lhc.html
is that it?

H1 and ZEUS

- Precision is 2% for $3 < Q^2 < 500 \text{ GeV}^2$ and reaches 1% for $20 < Q^2 < 100 \text{ GeV}^2$
- At higher $Q^2$ the precision is lower
- HERAII data (~3 times the HERAI statistics, 10 times for $e^-p$ collisions) can significantly improve the picture
NC and CC in HERAII

ZEUS

ZEUS and H1 are finishing their analyses of NC and CC processes

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New ZEUS preliminary at DIS 2011

EPJ C70, 4 (2010) 945
Combination including the HERAII data

H1 and ZEUS

\[
\sigma_{+,-}^{\gamma p} (x, Q^2) = \frac{1}{2} \left[ \sigma_{+} (x, Q^2) + \sigma_{-} (x, Q^2) \right]
\]

HERA I NC e^+p

HERA I NC e^-p

HERAPDF1.0 e^+p

HERAPDF1.0 e^-p

\[
x = 0.02 \quad (x^{300.0})
\]
\[
x = 0.032 \quad (x^{170.0})
\]
\[
x = 0.05 \quad (x^{90.0})
\]
\[
x = 0.08 \quad (x^{50.0})
\]
\[
x = 0.13 \quad (x^{20.0})
\]
\[
x = 0.18 \quad (x^{8.0})
\]
\[
x = 0.25 \quad (x^{2.4})
\]
\[
x = 0.40 \quad (x^{0.7})
\]
\[
x = 0.65
\]

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


H1prelim-10-142, ZEUS-prel-10-018
**CC e⁻p and HERAPDF1.5**

**H1 and ZEUS**

![Graphs showing data points and curves for different Q^2 values](image)

Significant improvement on the precision, impact on the valence quark distributions

H1prelim-10-142, ZEUS-prel-10-018
Valence quark distributions

u-valence significantly improved in HERAPDF1.5

H1 and ZEUS HERA I Combined PDF Fit

H1 and ZEUS HERA I+II Combined PDF Fit

H1prelim-10-142, ZEUS-prel-10-018
HERAPDF1.5 and ATLAS jets

Good description of the ATLAS jet data from HERAPDF1.5
Jet cross sections

- Stringent test of perturbative QCD
- Sensitivity to the gluon in the proton, precise input to QCD fits.
- Extract $\alpha_s$ with high precision, check the scale dependence within a single experiment and in different regimes.
The PDF fit done with inclusive NC and CC cross sections is not sensitive to $\alpha_s$: $\alpha_s$ is fixed in the fit for HERAPDF1.0 and 1.5.

If $\alpha_s$ is set free, the uncertainty on the gluon becomes much bigger...
Inclusion of the jets allows a precise $\alpha_s$ determination in the PDF fit!

H1 and ZEUS (prel.)

HERAPDF1.6: HERA jets included

The uncertainty on the gluon is similar to that of HERAPDF1.5
Charm and beauty production

- Stringent test of perturbative QCD, sensitivity to the gluon in the proton.
- Multi-scale problem (mass, $p_T$, $Q^2$)
- Check of the QCD fits dependence on the heavy flavour treatment
Consistent picture among various analyses using different methods.

The secondary vertices analysis significantly improves the precision.

Figure showing data points and curves for different models and datasets, including ZEUS-S+HVQDIS, GJR08 NLO, ABKM NNLO, MSTW08 NLO, MSTW08 NNLO, and CTEQ6.6 NLO.
Test of the PDFs on a different final state at HERA (data are not in the HERAPDF1.0 fit).

Combination of ZEUS and H1 data brings the precision to 5-10% (to be improved)

Good description of the charm data.

Consistent picture of QCD
Test of the PDFs on a different final state at HERA (data are not in the HERAPDF1.0 fit).

Combination of ZEUS and H1 data brings the precision to 5-10% (to be improved)

Good description of the charm data.

Consistent picture of QCD
Values of the W and Z cross sections at the LHC depend significantly on the heavy quark treatment used and on the charm mass.

- But if the charm data are considered, an 'optimal' charm mass can be extracted for each scheme.

- W and Z cross section at this point do not depend on scheme or mass.
Impact of the charm data on the PDFs

Values of the $W$ and $Z$ cross sections at the LHC depend significantly on the heavy quark treatment used and on the charm mass.

- But if the charm data are considered, an 'optimal' charm mass can be extracted for each scheme.
- $W$ and $Z$ cross section at this point do not depend on scheme or mass.

HERA Inclusive Working Group         August 2010
H1prelim-10-143, ZEUS-prel-10-019

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Conclusions

The HERA experiments H1 and ZEUS are completing their analyses.

The focus is now on the combination of the data.

Precise inclusive cross section measurements have already provided important input for the determination of the proton structure.

Improvements on the precision and the understanding of the proton structure can come from jets and heavy flavour measurements.

The HERA legacy is an important input for the present LHC experiments!
The ZEUS and H1 detectors

Multi-purpose detectors, asymmetric in the proton beam (forward) direction due to the two different beam energies.

Combination of the data: motivation

- Basic assumption: the two experiments are measuring the same cross sections in the same kinematic points
- In the combination procedure the consistency of the data is studied. Different systematic uncertainties are reduced in the procedure.
- Combined cross sections are used as input to QCD fits to determine the proton PDF.
- The combination method uses an iterative $\chi^2$ minimization which include full error correlations.
- Code available, S. Glazov, DIS05 and HERA-LHC WS
Minimization is non-linear and use an iterative procedure

Convergence is usually after two iterations

⇒ Full $\chi^2$ is the sum over all $\chi^2_{\exp}$

$M^i$ measured central values

$M^{i,\text{true}}$ fitted combined H1 - ZEUS values

$\sigma_i$ statistical and uncorrelated systematic uncertainties

$\sigma_{\alpha_j}$ correlated systematic uncertainties

$\frac{\partial M^i}{\partial \alpha_j}$ sensitivity of datum i to systematic j

$\Delta \alpha_j$ fitted shift of correlated uncertainties
The $F_L$ structure function

- Vanishes at LO in QCD, direct sensitivity to the gluon.
- Can be measured as the slope of the reduced cross section vs $y$ straight line, when the reduced cross section is measured at the same $Q^2$ and $x$ but different $y$.
- Need to measure the reduced cross section at different centre of mass energies ($Q^2 = sxy$)

$$F_L \sim x\alpha_s g$$

ZEUS

![Graph showing $F_L$ measurements at different $Q^2$ and $x$]
The $F_L$ structure function

Direct $F_L$ measurement from three different centre of mass energies.

Directly sensitive to the gluon,

$$F_L \sim \alpha_s x g(x, Q^2)$$

Good understanding of the gluon content of the proton

H1prelim-10-043, ZEUS-prel-10-001
The $F_L$ structure function

Direct $F_L$ measurement from three different centre of mass energies.

Directly sensitive to the gluon,

$F_L \sim \alpha_s x g(x, Q^2)$

Good understanding of the gluon content of the proton

H1 Collaboration
CC cross sections vs polarization

\[ P_e = \frac{N_R - N_L}{N_R + N_L} \]

\[ \sigma_{e^{\pm}p}^{NC} = \sigma_{e^{\pm}p}^{NC, \text{unpol}} + P_e \sigma_{e^{\pm}p}^{NC, \text{pol}} \]

\[ \sigma_{e^{\pm}p}^{CC} = (1 \pm P_e) \sigma_{e^{\pm}p}^{CC, \text{unpol}} \]

HERA Charged Current \( e^+p \) Scattering

- \( e^+p \rightarrow \nu X \)
- H1 HERA I
- H1 HERA II (prel.)
- ZEUS 06-07
- ZEUS HERA I
- ZEUS 98-06

Q\(^2\) > 400 GeV\(^2\)

y < 0.9
Tevatron Jet Cross Sections

Going in more detail...

Ratio to HERAPDF1.0

Ratio to CTEQ 6.6

https://www.desy.de/h1zeus/combined_results/benchmark/tev.html
Gluon parameterisation is more flexible. Quality of the fit is similar at NLO and NNLO. Gluon distribution changes a bit.
Anti-\(k_T\) and SIScone jet algorithms

Reanalysis of inclusive jets in DIS

(k\(T\) used originally)

Data very well described by NLO and all the algorithms.

Similar precision (slightly worse for SIScone)

Ratios evaluated up to order \(\alpha_s^3\)

First publication on data, now prel. also for PHP
Inclusive jets and dijets in NC DIS

Kinematic range $Q^2 > 125 \text{ GeV}^2$. Good agreement with QCD at NLO.
Inclusive jets in PHP

\[ Q^2 < 1 \text{ GeV}^2, \ 0.2 < y < 0.85 \]

At least one jet with 
\[ E_{T}^{\text{jet}} > 17 \text{ GeV}, \ -1 < \eta_{\text{jet}} < 2.5 \]

\[ \alpha_s \] extracted from the dependence of the cross section on \( E_T \). Jets in PHP gave the most precise \( \alpha_s \) measurement at ZEUS, now extended to HERAII.

Test of the running of \( \alpha_s \).
Running of the coupling constant with the scale tested from the low to the high $Q^2$ regime.

New precise $\alpha_s$ measurements from DIS and PHP in agreement with the world average.
Beauty in DIS with electrons

Signal determined from a likelihood function involving electron and beauty variables.

\[ N_{\text{Cand}} = 363 \text{ pb}^{-1} \]

\[ C_{\text{e}} = 10^{-1} \]

\[ C_{\text{BE}} = 10^{-1} \]

\[ C_{\text{NOE}} = 10^{-1} \]

\[ C_{\text{ZEUS}} = 10^{-1} \]

\[ L = 363 \text{ pb}^{-1} \]

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

\[ \frac{d\sigma}{dx}(\text{pb}) \]
Beauty in DIS

Beauty reconstructed from jets with secondary vertices.

5.0 GeV² < Q² < 1000.0 GeV², 0.02 < y < 0.7
E_T(Jet) > 5.0 GeV, -1.6 < η(Jet) < 2.2

90000 beauty events available

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Beauty in DIS

Beauty reconstructed from jets with secondary vertices.

\[5.0 \text{GeV}^2 < Q^2 < 1000.0 \text{GeV}^2, 0.02 < y < 0.7\]

\[E_T(Jet) > 5.0 \text{GeV}, -1.6 < \eta(Jet) < 2.2\]

90 000 beauty events available

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D\(^+\) in DIS

D\(^+\) reconstructed using lifetime information. L=323 pb\(^{-1}\).

\[
5 < Q^2_{DA} < 1000 \text{ GeV}^2 \\
0.02 < y_{DA} < 0.7 \\
1.5 < p_T(D^+) < 15 \text{ GeV} \\
|\eta(D^+)| < 1.6
\]

\[
d\sigma/dQ^2 (\text{nb/GeV}^2) \\
d\sigma/dp_T (D^+) (\text{nb/GeV})
\]

~ 7200 D\(^+\) events available

Precision comparable to D\(^*\) in HERAI
Beauty and charm in photoproduction

Latest measurement based on inclusive secondary vertices.

Significant improvement in precision for beauty.

Good agreement with NLO.
Latest measurement based on inclusive secondary vertices.

Significant improvement in precision for beauty.

Good agreement with NLO.
Latest measurement based on inclusive secondary vertices.

Significant improvement in precision for beauty.

Good agreement with NLO, also at threshold.
Inelastic J/ψ production

Graph showing the distribution of ZEUS and H1 data with theoretical predictions for different regions of z.

- ZEUS 468 pb⁻¹
- ZEUS (prel.) 468 pb⁻¹
- H1 165 pb⁻¹
- QCD kₜ factorisation

Theoretical predictions for different regions of z:
- 0.1 < z < 0.3, x 1E+4
- 0.3 < z < 0.45, x 1E+3
- 0.45 < z < 0.6, x 1E+2
- 0.6 < z < 0.75, x 1E+1
- 0.75 < z < 0.9, x 1E+0

The plots indicate the comparison between experimental data and theoretical models for the inelastic J/ψ production.
NC cross sections at high $x$

$Q^2 = 575$ GeV$^2$

$Q^2 = 725$ GeV$^2$

$Q^2 = 875$ GeV$^2$

$Q^2 = 1025$ GeV$^2$

$Q^2 = 1200$ GeV$^2$

$Q^2 = 1400$ GeV$^2$

$Q^2 = 1650$ GeV$^2$

$Q^2 = 1950$ GeV$^2$

$Q^2 = 2250$ GeV$^2$

$Q^2 = 2600$ GeV$^2$

$Q^2 = 3000$ GeV$^2$

$Q^2 = 3500$ GeV$^2$

$Q^2 = 4150$ GeV$^2$

$Q^2 = 4850$ GeV$^2$

$Q^2 = 5600$ GeV$^2$

$Q^2 = 7000$ GeV$^2$

$Q^2 = 9500$ GeV$^2$

$Q^2 = 15500$ GeV$^2$

ZEUS (prel.) $e^+ p$ 142 pb$^{-1}$

HERAPDF 1.5

ZEUS (prel.) $e^+ p$ 187 pb$^{-1}$

HERAPDF 1.5
High, medium and low energy cross section at high $y$

HERA NC cross sections from data collected at $E_p=920$, 460 and 575 GeV for the $F_L$ determination used in PDF fits. ZEUS extends its $Q^2$ region for all energies, down to 5 GeV$^2$ for HER also using shifted vertex data.
The $F_3$ structure function

$xf_3 \sim x(2u_v + d_v)$

Good understanding of the quark content of the proton
\[ \chi^2 \text{ Definition} \]

\[
\chi^2_{\text{exp}}(M^{i,\text{true}}, \Delta \alpha_j) = \sum_i \frac{[M^{i,\text{true}} - (M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j} \Delta \alpha_j)]^2}{\sigma_i^2} + \sum_j \frac{(\Delta \alpha_j)^2}{\sigma_{\alpha_j}^2}
\]

for a single data set

\( M^i \) measured central values

\( M^{i,\text{true}} \) fitted combined H1 - ZEUS values

\( \sigma_i \) statistical and uncorrelated systematic uncertainties

\( \sigma_{\alpha_j} \) correlated systematic uncertainties

\( \frac{\partial M^i}{\partial \alpha_j} \) sensitivity of datum i to systematic j

\( \Delta \alpha_j \) fitted shift of correlated uncertainties

Cross calibration of the correlated systematics between different data sets

If all \( \Delta \alpha_j = 0 \rightarrow \) standard weighted average

\[ \Rightarrow \text{Full } \chi^2 \text{ is the sum over all } \chi^2_{\text{exp}} \]