Combination and QCD Analysis of the HERA Inclusive Cross Sections

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Outline:

• H1 and ZEUS at the HERA collider
• Data Combination
• QCD Analysis
• Results and Comparisons
• Summary
HERA at DESY

- HERA is world’s only $e^\pm p$ collider
  - Located at DESY, Hamburg - Germany
  - In operation for 15 years (1992-2007)
  - H1 and ZEUS collider experiments
    - General purpose detectors

HERA-I 1992-2000  $E_p=820,920$ GeV
HERA-II 2003-2007  $E_p=920, 460,575$ GeV

Registered $\sim 1 fb^{-1}$ of integrated luminosity of physics data.
HERA provides unique opportunity to study the structure of proton:

- Kinematic variables:
  - Virtuality of exchanged boson:
    \[ Q^2 = -q^2 = -(k - k')^2 \]
  - Bjorken scaling variable:
    \[ x = \frac{Q^2}{2p \cdot q} \]

H1 and ZEUS kinematics span over 6 orders of magnitude in x and Q²!
Combination of the H1 and ZEUS Measurements

• Ultimate precision is obtained by combining the H1 and ZEUS measurements

• The combination procedure is performed before QCD analysis:
  ▪ The combination of data is performed using the $\chi^2$ minimisation procedure

  1402 of HERA I H1 and ZEUS measurements were combined into 741 unique cross section points with 113 correlated systematic sources.

  ➢ Improvement on Statistical precision:
    – H1 and ZEUS collected similar amounts of physics data.
  ➢ Improvement of Systematic precision:
    – H1 and ZEUS are different detectors and use different analysis techniques;
    – The H1 and ZEUS cross sections have different sensitivities to similar sources of correlated systematic uncertainty.
Results of Combining H1 and ZEUS Data

The combination procedure yields a consistent data set:

- $\chi^2$/dof = 637/656
- Before combination, the systematic errors are ~3 times larger than statistical for $Q^2 < 100$ GeV$^2$
- After combination, the systematic errors are of same precision as the statistical errors, reaching 1% total precision!
QCD Analysis Framework

- **Data Sets:**
  - HERA I combined data [JHEP01 (2010) 109]
    - NC e⁻, CC e⁻, CC e⁺ (Q²>100 GeV²)
    - NC e⁺ (Q²>0.045 GeV²)
  - Combined HERA II Low Energy Data Set of Ep=460, 575 GeV [prelim.]
    - Q²>2.5 GeV²
  - Combined HERA I+high Q² HERA II data [prelim.]

- **QCD Fit settings:**
  - NLO (and NNLO) DGLAP evolution equations
  - RT-VFNS (as for MSTW08)
    - Other schemes were investigated as well: RT (optimal), ACOT (full and χ), FFNS
  - PDF parametrised at the starting scale Q₀²:
    \[ G, u_{val}, d_{val}, U = u( +c), D = d + s( +b) \]
    \[ x_f(x, Q_0^2) = A x^B (1-x)^C (1+D x+E x^2) \]
    - Apply quark number and momentum sum rules
    - The optimum number of parameters chosen by saturation of the χ²
      - central fit with 10 free parameters
      - χ²/dof=574/582

<table>
<thead>
<tr>
<th>Scheme</th>
<th>TRVFNS</th>
</tr>
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<tbody>
<tr>
<td>Evolution</td>
<td>QCDNUM17.02</td>
</tr>
<tr>
<td>Order</td>
<td>NLO</td>
</tr>
<tr>
<td>Q₀²</td>
<td>1.9 GeV²</td>
</tr>
<tr>
<td>fₛ = s/D</td>
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<tr>
<td>Renorm. scale</td>
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</tr>
<tr>
<td>Factor. scale</td>
<td>3.5 GeV²</td>
</tr>
<tr>
<td>Qₘᵦ²</td>
<td>0.1176</td>
</tr>
<tr>
<td>αₛ(M_Z)</td>
<td>1.4 GeV</td>
</tr>
<tr>
<td>M_c</td>
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<tr>
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    - NC $e^-$, CC $e^-$, CC $e^+$ ($Q^2 > 100$ GeV$^2$)
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    \[
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    \]
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Sources of PDF uncertainties at HERA

• **Experimental Uncertainties:**
  - Consistent data sets ➔ use $\Delta \chi^2 = 1$

• **Model Uncertainties:**
  - following variations have been considered

<table>
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<tr>
<th>Variation</th>
<th>Standard Value</th>
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<th>Upper Limit</th>
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<td>$f_s$</td>
<td>0.31</td>
<td>0.23</td>
<td>0.38</td>
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<td>$m_c$ [GeV]</td>
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<td>4.75</td>
<td>4.3</td>
<td>5.0</td>
</tr>
<tr>
<td>$Q^2_{min}$ [GeV$^2$]</td>
<td>3.5</td>
<td>2.5</td>
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• **Parametrisation Uncertainties:**
  - An envelope formed from PDF fits using other variants of parametrisation form at the starting scale:
    - Scanning of 11 parameter space
    - $Q^2_0$ variation and negative gluon parametrisation
    - Relaxing assumptions used for central fit
• Starting Scale

10 GeV²

- Observe valence like shape of the gluon at the starting scale.
- Parametrisation uncertainty dominates.

• HERAPDF1.0 set available in LHAPDF since v5.8.1 (Dec 2009)
Plots show the extended kinematic range of the HERA I data as compared to the fixed target measurements:

- Data points include experimental errors
- Fit line includes total error

HERAPDF1.0 fit describes our data well!

Extrapolation of the HERAPDF1.0 fit agrees well with fixed target data (SLAC and BCDMS)!
Hence, there is a universal description of partonic processes and all can be described with: HERA input, SM couplings and pQCD evolution!

- Predictions for high-\(E_T\) jet cross-sections with full uncertainties compared to the D0 data
- DIS data from HERA predicts Tevatron jets production from ppbar process.
- Z and W at Tevatron are well predicted by HERAPDF1.0
Hence, there is a universal description of partonic processes and all can be described with: HERA input, SM couplings and pQCD evolution!
LHC predictions based on HERAPDF1.0

- Predictions using HERAPDF1.0 for W, Z cross sections.

- Predictions using HERAPDF1.0 for Higgs cross sections.

- Predictions using HERAPDF1.0 for top cross sections.

Uncertainties:

- Experimental
- Model
- Parametrisation
- $\alpha_S$ variation

Exciting new times ahead to actually compare the predictions to real measurements from the LHC!
Fits performed to HERA I data (as used for HERAPDF1.0) at NNLO using RT-VFNS:

- $\alpha_s(M_Z)$ at NLO = 0.1176
- $\alpha_s(M_Z)$ at NNLO = 0.1145

NNLO fits are slightly worse than NLO

Note: Plots at NNLO are compared to HERAPDF1.0 (NLO) only illustratively $\rightarrow$ expect to be different!
**HERAPDF including Low Energy data**

- Preliminary HERA Combined Low Energy data available!

- New accurate measurement in $Q^2 > 2.5$ GeV$^2$ range, sensitive to structure function $F_L$ are included in the QCD analysis on top of the HERA I data

- PDFs from the new fit agree very well with HERAPDF1.0

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<th>Data sets</th>
<th>HERAPDF1.0</th>
<th>+ Low Energy data</th>
</tr>
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<tbody>
<tr>
<td>Total $\chi^2$/dof</td>
<td>574/582</td>
<td>818/806</td>
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 HERA Inclusive Working Group

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voica@mail.desy.de
• Preliminary HERA Combined Low Energy data available!

• New accurate measurement in $Q^2 > 2.5$ GeV$^2$ range, sensitive to structure function $F_L$ are included in the QCD analysis on top of the HERA I data.

• However, The $Q^2 \geq 5$ GeV$^2$ cut brings large improvement in $\chi^2$ [$818/806 \rightarrow 698/771$] and it yields different shapes for gluon and sea PDFs.
  - for HERAPDF1.0, $Q^2$ cut variation is included in the model uncertainty, but it had smaller effect.
The lines are $F_L$ predictions using combined HERA I and low energy data.

Low $Q^2$ region remains very interesting for further QCD tests!
Combining HERA I and II Inclusive data

- New HERA II preliminary data available!
  - More precise measurements in the high $Q^2$ and high $x$ regions (especially NC $e^-p$ and CC $e^\pm p$)
  ➔ could constrain better PDFs at high $x$
- HERA I and HERA II are combined using same averaging procedure as described before:
  - 674 unique cross sections points with 134 sources of systematic uncertainties

**Without HERA II**

**With HERA II**

Much more precise CC measurements after including new high $Q^2$ HERA II set!
Propagate new data through QCD fit analysis to produce a new set of HERAPDFs: HERAPDF1.5

- For preliminary studies use same settings as for HERAPDF1.0
- Parametrisation uncertainty will be further investigated for final release.
HERAPDF1.5 vs HERAPDF1.0

- $x_g, x_{u_v}, x_{d_v}, x_{\text{Sea}}$ ($x_{\text{Sea}}=x_U+x_D$) at the scale $Q_0^2=10$ GeV$^2$

- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high $x$ region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0
Summary

- HERA provides accurate determinations of the proton structure and can predict related Standard Model processes!

- New preliminary measurements from HERA II time period are available in the HERA QCD analyses!

- Using HERA information, we have precise predictions for the LHC and the time has come to confront them with the data!