Symposium in honour of Robert Roosen
“A deeper look into matter”

19th of Oct 2012 - 14h-16h
Promotiezaal VUB - D2.01
Campus Oefenplein, Brussel

“Robert Roosen at the IIHE”
Prof. Catherine De Clercq

“Charm & Beauty experiments”
Prof. em. Stefaan Tavernier

“The H1 experiment at HERA”
Prof. Eckhard Elsen (DESY)

“The legacy of HERA”
Dr. Sergey Levonian (DESY)

Reception from 16h – at the IIHE
In the beginning the was the Idea...
...then a lot of Hard Work...
...and finally...

The Legacy of HERA

S. Levonian (DESY)
HERA: The World’s Only $e^p$ Collider

- **1998** $E_p$ upgrade: 820 $\Rightarrow$ 920 GeV
  
  \[ \sqrt{s} : 301 \Rightarrow 319 \text{ GeV} \]

- **2001** HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised $e^+/e^-$
  
  \[ \langle P \rangle = 40\% \]

**HERA-1** (1993-2000) $\approx 120 \text{ pb}^{-1}$

**HERA-2** (2003-2007) $\approx 380 \text{ pb}^{-1}$

**Final Data samples**

H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$
Deep-Inelastic Scattering at HERA

Neutral Current DIS: \( ep \rightarrow e'X \)

charged current DIS: \( ep \rightarrow \nu X \)

Kinematics:
- Momentum transfer: \( Q^2 = -q^2 \)
- Bjorken \( x \): \( x = Q^2/(2p \cdot q) \)
- Inelasticity: \( y = (p \cdot q)/(p \cdot l) \)
Physics landscape at HERA

• HERA as Super-microscope
  ▶ Proton structure at high resolution
  ▶ Impact for LHC
Physics landscape at HERA

- **HERA as Super-microscope**
  - Proton structure at high resolution
  - Impact for LHC

- **HERA as Energy frontier machine**
  - Electroweak unification at work
  - Anything beyond the Standard Model?
Physics landscape at HERA

- **HERA as Super-microscope**
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  - Impact for LHC

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- **HERA as QCD laboratory**
  - Putting QCD in stringent tests with:
    - Jets (parton evolution schemes, NLO QCD, $\alpha_s$)
    - Heavy flavor sector (multiscale problem: $Q^2$, $M_Q$, $E_t$)
    - Diffraction (interplay of soft and hard physics)
  - HERA specifics: lox $x$ physics

- **Search for Novel Phenomena**
- **Precision Measurements**
Unpolarized DIS cross sections

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

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

\[ \sigma_{\text{CC}}^{\text{pol}} \]

**Electro-Weak Unification**

No \(W\) coupling to \(e_R\) and \(e_L\)
So far all NC and CC HERA data were in good agreement with the SM. Try to look more carefully at the tails, using two strategies:

1. Specific BSM signals search (LQ, LFV, SUSY, ...) – guided by theory

2. Model independent generic search (data vs SM) – guided by data
Leptoquarks?

1994-97: High $Q^2$ events.
Rate in excess of Standard Model!
Leptoquarks?

1994-97: High $Q^2$ events.
Rate in excess of Standard Model!

2011: Final status

H1 Search for First Generation Leptoquarks

H1 Search for First Generation Scalar Leptoquarks
Model independent search for New Phenomena

- Identify isolated objects: \(e, \mu, \gamma, j, \nu\)

- Select events, having at least two objects with high \(P_T > 20\text{GeV}\)

- Classify into exclusive channels containing from 2 to 5 objects

- Compare with SM predictions \(\Rightarrow\) good overall agreement

- Find interesting regions with greatest deviations from SM in kin. distributions \((M_{\text{all}}, \Sigma P_T)\)

\(\Rightarrow\) Combine H1 and ZEUS data
Model independent search for New Phenomena

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  $\Rightarrow$ Combine H1 and ZEUS data

H1+ZEUS, 0.59 fb$^{-1}$

- Largest observed deviations from the SM at HERA
  JHEP 0910:013 (2009)
  JHEP 1003:035 (2010)
HERA as a Super-microscope

Dotted lines show the spread in predictions prior to HERA startup (1992)
HERA as a Super-microscope

- Precision of $(1 - 2)\%$ in the bulk region
- Perfect description of the data by NLO QCD over many orders in $x$ and $Q^2$
- Universal PDFs determined with error bands

Any substructures at $10^{-18}m$?
HERA as a Super-microscope

• Precision of $(1 - 2)\%$ in the bulk region

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• Universal PDFs determined with error bands

Any substructures at $10^{-18}$m?

No. Quarks are still pointlike

Upper limit: $R_q < 0.65 \cdot 10^{-3}$ fm
**HERAPDF for LHC**

Knowledge of gluon without HERA data.

Knowledge of gluon with HERA

Cooper-Sarkar et al.: HERA-LHC workshop 2009

Tevatron Jet Cross Sections

CDF Data (Run II)

Herapdf for LHC

\[ \text{Cross section} \]

\[ |y_{\text{jet}}| < 1.6 \times 10^{-6} \]

\[ |y_{\text{jet}}| < 1.1 \times 10^{-3} \]

\[ |y_{\text{jet}}| < 0.7 \times 10^{3} \]

\[ |y_{\text{jet}}| < 0.1 \times 10^{6} \]

**CDF Data (Run II)**

**LHC Data**

2011
HERA as QCD factory

H1 Preliminary

Forward Photons

1 central jet + 1 forward jet

ZEUS

H1 and ZEUS

H1 Data

SIBYLL 2.1

EPOS 1.99

RAPGAP (default PYTHIA hadronisation)

ZEUS 6 pb

ZEUS 40 pb

ZEUS 60 pb

ZEUS 80 pb

ZEUS 100 pb

ZEUS 120 pb

σ = 11.1 ± 2.8 MeV

M_t = 2.281 ± 0.003 GeV

H1 Data

CTEQ 6.6

CTEQ 6.6

CTEQ 6.6

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CTEQ 6.6

CTEQ 6.6

CTEQ 6.6

CTEQ 6.6
Jets at HERA

Precision QCD

$\alpha_s$ from Jet Cross Sections in DIS

$\alpha_s$ from Jet Cross Sections in DIS

H1 data for $S < Q^2 < 100 \text{ GeV}^2$
H1 data for $Q^2 > 150 \text{ GeV}^2$
Fit from $Q^2 > 150 \text{ GeV}^2$ [arXiv:0904.3870]

$\alpha_s = 0.1168 \pm 0.0007 \text{(exp.)} \pm 0.0016 \text{(PDF)}$

Central value and exp. unc.
Theory/PDF unc.
Precision QCD

New dynamics? look at different topologies especially with forward jets

NLO DGLAP insufficient at low $x$

jets at HERA
**Diffraction at HERA**

- **Fundamental aim:** understand high energy limit of QCD (gluodynamics; CGC ?)
- **Novelty:** for the first time probe partonic structure of diffractive exchange
- **Practical motivations:** study factorisation properties of diffraction; try to transport to $hh$ scattering (e.g. predict diffractive Higgs production at LHC)

\[
x_{IP} = \xi = \frac{Q^2 + M_y^2}{Q^2 + W^2}
\]

(momentum fraction of colour singlet exchange)

\[
\beta = \frac{Q^2}{Q^2 + M_x^2} = x_{q/IP} = \frac{x}{x_{IP}}
\]

(fraction of exchange momentum, coupling to $\gamma^*$)

\[
t = (p - p')^2
\]

(4-momentum transfer squared)

**Experimental methods:**
1) selecting LRG events
2) detecting $p$ in Roman Pots

**FPS, VFPS**
<table>
<thead>
<tr>
<th>RFT: soft $hh$ scattering</th>
<th>vs</th>
<th>QCD: deep inelastic $ep$ scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Hadronic degrees of freedom</td>
<td>• Partonic degrees of freedom</td>
<td></td>
</tr>
<tr>
<td>• Validity: large $s \gg t$</td>
<td>• Low $x$: $W^2 \gg Q^2$, $t (Q^2/W^2 \simeq x \ll 1)$</td>
<td></td>
</tr>
<tr>
<td>• $IP$ dominates: $\alpha_{IP}(0) &gt; \alpha_{IR}(0)$</td>
<td>• gluons dominate: $xg(x) \gg xq_{val}(x)$</td>
<td></td>
</tr>
<tr>
<td>$\rightarrow \sigma_{tot} \propto s^{\alpha_{IP}(0)-1}$</td>
<td>$F_2(x, Q^2) \propto xg(x) \sim x^{-\lambda}$</td>
<td></td>
</tr>
<tr>
<td>• Unitarity corrections unavoidable</td>
<td>• Saturation of the $xg(x)$</td>
<td></td>
</tr>
<tr>
<td>($\sigma_{tot} \leq \ln^2(s/s_0)$ at $s \rightarrow \infty$)</td>
<td>(non-linear effects, shadowing, ...)</td>
<td></td>
</tr>
<tr>
<td>• When? $s_{sat} = ?$</td>
<td>• $x_{sat}(Q_{sat}) = ?$</td>
<td></td>
</tr>
<tr>
<td>• First to be seen in diffraction: $\sigma_D \propto s^{2(\alpha-1)}$</td>
<td>• First to be seen in diffraction: $\sigma_D \propto</td>
<td>xg(x)</td>
</tr>
</tbody>
</table>

$\Rightarrow$ Diffraction $\equiv$ Physics of the Pomeron,
the essence of strong interactions

$\Rightarrow$ Diffraction $\equiv$ Gluodynamics,
the essence of QCD

(in high energy limit)
First observation of diffraction in DIS
1992 data, 24.7 nb$^{-1}$
Inclusive Diffraction in DIS

First observation of diffraction in DIS
1992 data, 24.7 nb⁻¹

- Compelling confirmation of the NLO QCD picture of diffraction over a wide kinematic range. Clear candidate for the textbook!
Exclusive Diffraction at HERA

Since its advent HERA radically changed landscape in this field:

Development of colour dipole approach from VM production to DIS (Nikolaev, Zakharov, Bjorken,...)
Collinear factorisation framework ⇒ access to GPDs and parton correlations in the proton
Relation to $F_2$ and $\sigma_{tot}$ via Optical Theorem
Universal Pomeron vs perturbative gluons, interplay of soft and hard physics
Multi-scale problem: $Q^2$, $t$, Mass - what is the relevant scale here?

Check Regge factorisation hypothesis at the proton vertex
Since $\gamma$ and VM are spin=1 particles ⇒ sensitivity to helicity properties of diffractive scattering

⇒ Rich physics program
Diffractive electroproduction of $\rho$ and $\phi$ mesons at HERA

Editors: X. Janssen, P. Marage

Volume: 111 pages, 48 figures, 53 tables
Diffractive electroproduction of $\rho$ and $\phi$ mesons at HERA

$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} \cdot t$

$\sim$ transverse size

Transition from soft to hard behavior at $\mu^2 \simeq 4 - 5 \text{ GeV}^2$
Further Diffractive Topics

- Jets in diffraction

- Investigation of QCD factorization breaking ($\gamma p$ vs DIS)

- Extracting DPDFs using global QCD fit of all available HERA data
Ongoing Diffractive Analyses

- Jets in diffraction
- Investigation of QCD factorization breaking ($\gamma p$ vs DIS)
- Extracting DPDFs using global QCD fit of all available HERA data

In all these analyses activity and great expertise of Belgium groups is absolutely valuable. Using now HERA results and experience for low $x$ physics and diffraction at LHC
Summary

- Standard Model survived 1 fb$^{-1}$ of HERA data and is still in a good shape. Next challenge is now coming from the LHC - stay tuned!

- Combining H1 and ZEUS data allowed proton structure to be measured with unprecedented precision

- NLO DGLAP is surprisingly successful down to low $Q^2$ and low $x$ in describing bulk of HERA data. However, some room for parton evolution beyond DGLAP is found at specific phase space corners ⇒ important message for LHC

- Gained new insights into high energy diffraction: Pomeron under the HERA microscope shows complicated interplay of soft and hard phenomena. Understanding colour singlet exchange remains a major challenge in QCD

- There is a wealth of unique data from HERA. All efforts are taken to save them for possible future analysis, MC models tuning and outreach purposes
More heritage from HERA

★ Unique experience how to build and run such a complicated asymmetric collider (SC magnet technology, beam diagnostics, specific background problems etc.) Invaluable for any future $ep$ machine (eRHIC, LHeC, ...)

★ HERAFitter – A platform originally developed at HERA and now evolved into an open source project including also LHC experiments and theory groups

★ Data Preservation Project – Another DESY initiative started in 2008 which by now includes all major HEP experiments and recognized at high international level
HERAFitter: Proton Structure from HERA to LHC

- Open access QCD/PDF infrastructure based on collaborative approach of HERAPDF
- Exploit DESY expertise in the field of Proton Structure
- Promote the HERA Physics at LHC:
  - Endorsed by H1, ZEUS, ATLAS, CMS
- Project discussed with and supported by the PRC
- First LHC publications based on HERAFitter

**Data:**
- HERA, Tevatron, LHC fixed target experiments
- Inclusive DIS, Jets, Diffraction, Drell-Yan, Top, W, Z prod.

**Theory:**
- Different HF schemes,
- Different evolution codes,
- FastNLO, Applgrid, Hathor,
- NNPDF reweighting,
- Dipol model

http://projects.hepforge.org/herafitter
DPHEP Project

- All major HEP experiments and organisations involved
- Several models adopted for preservation strategy, including data integrity checks and automated s/w validation.
- Non-digital Documentation, Education and Outreach

- 5 Workshops held in 2009-2012
- Important milestone reached with recent publication
- DPHEP is now moving to a new phase
- Funding is needed, from within HEP, or from EU (FP8)
- Next Workshop is in Marseille, 19-21 November 2012

The project is endorsed by ICFA and is in full swing
1992 - Startup; 2007 - End of Data taking; 2012 - Finalizing Analyses

These were two extremely exciting decades!
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Sad ?
1992 - Startup; 2007 - End of Data taking; 2012 - Finalizing Analyses

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Sad?

No! Deeply thinking...