HERA and the LHC

2nd workshop on the implication of HERA for LHC physics

- Selected Highlights of the First Workshop
- Goals for the 2nd Workshop
- Few Organizational Matters

A De Roeck (CERN) and H. Jung (DESY)
06/06/06
Why HERA and the LHC?

**electron proton collider HERA**
\[ \sqrt{s} = 320 \text{ GeV} \]

**proton proton collider LHC**
\[ \sqrt{s} = 14 \text{ TeV} \]

**HERA: QCD**
structure of the proton

**LHC: Higgs, SUSY etc,**
but mostly QCD...

\[ \sqrt{\frac{Q^2}{s}} \sim 0.01 \]

**typical range**

\[ \sqrt{\frac{Q^2}{s}} \sim 0.01 \text{ for } Q^2 \sim 10 \text{ GeV}^2 \]

\[ \sqrt{\frac{M^2}{s}} \sim 0.01 \text{ for } M \sim 140 \text{ GeV} \]
Examples: HERA $\rightarrow$ LHC

Structure functions and parton distributions
LHC: cross sections/precision

B-production: B quark
PDFs of the proton

Underlying event: tunable elementarity of one beam particle
$\gamma p \leftrightarrow \gamma^* p$ collisions

LHC: event complexity

Diffraction
LHC: diffractive scalar production

Diffraction
LHC: cross sections/precision

H1 Preliminary
Workshop Aims

- To identify and prioritize those measurements to be made at HERA which have an impact on the physics reach of the LHC.
- To encourage and stimulate transfer of knowledge between the HERA and LHC communities and establish an ongoing interaction.
- To encourage and stimulate theory and phenomenological efforts related to the above goals.
- To examine and improve theoretical and experimental tools related to the above goals.
- To increase the quantitative understanding of the implication of HERA measurements on LHC physics.

⇒ Five Working Groups
- Parton density functions
- Multi-jet final states
- Heavy quarks (charm and beauty)
- Diffraction
- MC-tools

6 major meetings in 12 months

Workshop Chairs
H. Jung, ADR
Many thanks to all conveners and authors!

- Phase I of this workshop concluded with the proceedings
- However an important link between communities has been established.
- March 05': We should not just let it fade away, but strongly exploit it, to the benefit of both communities.
- Therefore keep momentum with one HERA/LHC meeting per year

2006 CERN: 6-9 June
2007 DESY date to be determined
2008 CERN (first LHC physics?)

- Keep also good contacts with TeV4LHC workshop activities (started Sept.2004)
HERA Impact on the LHC

- W prod. at LHC without HERA:
  - $0.0001 < x < 0.1$

- W prod. at LHC including HERA:
  - $0.0001 < x < 0.1$

PDFs without HERA:
- ~ 16 %

PDFs including HERA:
- ~ 3.5 %
Precise PDFs for the LHC

**inclusive jet xsection**

CTEQ6 uncertainties

- 0<y<1
- 1<y<2
- 2<y<3

**Signature for new physics**

➔ jet x-section

Discovery potential depends on precise PDFs

Extra Dimensions?

Precision determination of PDFs needed ... understanding QCD is the key to new physics

Supersymmetry?

D.Stump et al hep-ph/0303013

CTEQ6.1
Impact of Future HERA Data

- Improvement in PDF precision with projected 700 fb$^{-1}$ of data in HERA-II
- Includes jets in DIS and $\gamma p$
- Note only HERA (ZEUS) data are used in the fits

<table>
<thead>
<tr>
<th>data sample</th>
<th>kinematic coverage</th>
<th>HERA-I $\mathcal{L}$ (pb$^{-1}$)</th>
<th>HERA-II $\mathcal{L}$ (pb$^{-1}$) (assumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96-97 NC $e^+p$ [7]</td>
<td>$2.7 &lt; Q^2 &lt; 30000$ GeV$^2$; $6.3 \cdot 10^{-5} &lt; x &lt; 0.65$</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>94-97 CC $e^+p$ [10]</td>
<td>$280 &lt; Q^2 &lt; 17000$ GeV$^2$; $6.3 \cdot 10^{-5} &lt; x &lt; 0.65$</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>98-99 NC $e^-p$ [8]</td>
<td>$200 &lt; Q^2 &lt; 30000$ GeV$^2$; $0.005 &lt; x &lt; 0.65$</td>
<td>16</td>
<td>350</td>
</tr>
<tr>
<td>98-99 CC $e^-p$ [11]</td>
<td>$280 &lt; Q^2 &lt; 17000$ GeV$^2$; $0.015 &lt; x &lt; 0.42$</td>
<td>16</td>
<td>350</td>
</tr>
<tr>
<td>99-00 NC $e^+p$ [9]</td>
<td>$200 &lt; Q^2 &lt; 30000$ GeV$^2$; $0.005 &lt; x &lt; 0.65$</td>
<td>63</td>
<td>350</td>
</tr>
<tr>
<td>99-00 CC $e^+p$ [12]</td>
<td>$280 &lt; Q^2 &lt; 17000$ GeV$^2$; $0.008 &lt; x &lt; 0.42$</td>
<td>61</td>
<td>350</td>
</tr>
<tr>
<td>96-97 inc. DIS jets [13]</td>
<td>$125 &lt; Q^2 &lt; 30000$ GeV$^2$; $E_T^{Breit} &gt; 8$ GeV</td>
<td>37</td>
<td>500</td>
</tr>
<tr>
<td>96-97 dijets in $\gamma p$ [14]</td>
<td>$Q^2 \lesssim 1$ GeV$^2$; $E_T^{jet,1,2} &gt; 14, 11$ GeV</td>
<td>37</td>
<td>500</td>
</tr>
<tr>
<td>optimised jets [17]</td>
<td>$Q^2 \lesssim 1$ GeV$^2$; $E_T^{jet,1,2} &gt; 20, 15$ GeV</td>
<td>-</td>
<td>500</td>
</tr>
</tbody>
</table>

Gwenlan Cooper-Sarkar Targett-Adams hep-ph/0509220
Using jets together with $F_2$ (at large $Q^2$) quark and gluon uncertainties

from C. Gwenlan, A. Cooper-Sarkar, C. Targett-Adams

high statistics from HERA II is important (assumed 700 pb$^{-1}$)

Error on LHC jet xsection reduced !!!
Average HERA data

From M. Cooper-Sakar, C. Gwenlan and S. Glazov

- Average H1&ZEUS data sets
- Combined PDF fit to H1& ZEUS

Much reduced uncertainties ....
Model independent analysis of data desirable
get THE HERA – PDF !!!!!
LHC Kinematics/QCD evolution

Evolution of PDFs to high $Q^2$ & low $x$ important at the LHC
Precision? Level of approximation? CCFM/BFKL? , non-linear effects?
Impact of the measurement of $F_L$

$F_L$ could referee the gluon distribution!

$F_L$ is like $F_2$: little theoretical ambiguity (compared to e.g. $F_2^C$)

$$\sigma_r = F_2 - y^2 / [1 + (1 - y)^2] \cdot F_L = F_2(x, Q^2) - f(y) \cdot F_L(x, Q^2)$$

Need to lower the energy of proton or electron beam for this measurement
Measuring $F_L$

Detailed study for H1, with 2 lower proton beam energy settings

Feltesse/Klein et al

$F_L$ can referee between MRST and CTEQ gluons

$F_L$ is gluon driven

Looks like $F_L$ may happen in 2007!
What is the underlying event (UE), multiple parton interactions (MI)?

- Everything, except the LO process we're currently interested in
  - parton showers
  - additional remnant - remnant interactions

- NOT pile-up events (luminosity dependent)
Effect of underlying event on central jet veto in VBF Higgs

Rapidity of the central jet in Higgs events; CMS; full simulation, $L=2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$

Uncertainty of the central jet veto efficiency due to UE model; ATLAS.

“bkg. like” behaviour for soft jets; fake jets: pile up+UE+detector
Initial $k_T$ at HERA and LHC

Initial $k_T$ in the hard scattering

$\langle k_T \rangle$ large $\Rightarrow$ unintegrated parton PDFs will be needed

Test predictions at HERA Large $k_T$ effects affect Higgs searches

Measure unintegrated PDFs $f(x,Q^2,k_T^2)$ at HERA via final states
**Deviations: non-linear effects in QCD evolution?**

Gribov-Levin-Ryskin-Mueller-Qiu equation:

\[
\frac{\partial xg(x, Q^2)}{\partial \log Q^2} = \left. \frac{\partial xg(x, Q^2)}{\partial \log Q^2} \right|_{\text{DGLAP}} - \frac{9\pi\alpha_s^2}{2Q^2} \int_x^1 \frac{dy}{y} y^2 G^{(2)}(y, Q^2)
\]

\[
x^2 G^{(2)}(x, Q^2) = \frac{1}{\pi R^2} (xg(x, Q^2))^2
\]

- non-linear (quadratic) correction
  - has "–" sign
  - Q^2 evolution is **slower**
  - refit HERA F_2 data, reduces F_2^{DGLAP} at low x and moderate Q^2
  - xg(x, Q^2) at low Q^2 (<10 GeV^2) and x (<10^{-3}) is larger than in DGLAP

\[\text{Get these non-linear effects better understood from HERA!} \]
\[\text{Precise HERA data important!!!} \]
\[\text{connection to MI, diffraction ...} \]
**Non-linear effects at LHC**

**Nonlinear evolution equation for uPDF:**

(Balitsky-Kovchegov equation)

\[
f(x, k^2) = \tilde{f}^{(0)}(x, k^2) + K^1 \otimes f - K^2 \otimes f^2
\]

\[
\tilde{f}^{(0)}(x, k^2) \rightarrow \text{input}
\]

\[
K^1 \otimes f \rightarrow \text{BFKL}
\]

\[
K^2 \otimes f^2 = \left(1 - k^2 \frac{d}{dk^2}\right)^2 R^2
\]

\[
\int_x^1 \frac{dz}{z} \left[ \int_{k^2}^{\infty} \frac{dk'^2}{k'^4} \alpha_s(k'^2) \ln \left( \frac{k'^2}{k^2} \right) f(z, k'^2) \right]^2
\]

Bottom suppression due to non-linear effects in BK

- Significant effects...
- up to factor of 2 in hot spot scenario
- factorization still ok?
**HERA II** analysis (expect factor 10 more), larger kinematic range, both exp. with CST/MVD

→ **Understand** $b$-production mechanism (...remember $b$-puzzle at the TeVatron...)

→ **NOTE:** gluon drives heavy quark PDFs .... transverse momenta ????

From O.Behnke, A. Geiser, A. Meyer, M. Wing
Exclusive Higgs Production

Exclusive diffractive Higgs production $pp \rightarrow p + H + p$ : $2-10$ fb

Cross section ‘stabelized’ during the previous workshop

Advantages Exclusive:
- $Jz=0$ suppression of $gg \rightarrow bb$ background
- Mass measurement via missing mass

$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$

$\Delta M = O(1.0 - 2.0)$ GeV

E.g. V. Khoze et al
M. Boonekamp et al.
B. Cox et al. ...
 Measurement of exclusive Higgs

• goal: mass resolution 1 GeV for Higgs with
• 420 m stations are needed for low mass Higgs
• other issues:
  - triggers
  - gap-survival rates

B. Cox, M Grothe, H. Kowalski et al.

- Detector stations at 220 m and 420 m from Interaction point
- 420 m station is in cold region.... - Hamburg pipe
Here is something missing

**Ideas for upgrading forward region**

from V. Andreev, A. Buniatian, L. Lytkine, M. Kapishin, HJU

- important for UHECR (hadron showers at $E \sim 10^{17}$ eV)
- important region for small $x$ QCD: MI - saturation - diffraction - gap-survival
- possibilities:
  - small angle tagging: micro-stations
  - calorimetry

$\eta$-7-10
$E=2-7$ TeV

$21.5$ m
$85$ m $95$ m $135$ m
MC and other Tools

- Parton distribution library:
  - LHAPDF now official carrier of the PDFs
    - Used by LHC experiments in generators
    - HERA pdfs have been added
    - Allows error uncertainty estimates
    - Pion and photon added, particularly for HERA. F2D next?
- NLOLIB framework for NLO QCD programs
  - Uniform user interface/interface to HZTOOL
  - e+e-/ep included, pp can be added
- HZTOOL/JetWeb/RunMC/Cedar(?) for tuning
  - All HERA results to be included, some e+e-. Include more pp?
- RAPGAP, Cascade Monte Carlos for inclusive and diffractive pp
- Plenty of exchange on other MC tools, leading to new MC tools and comparisons with ep where possible
- Continuation of the MC@LHC 2003 workshop, concerning validation
  ⇒ A new MC@LHC workshop this summer 2006: June 17-26
Nutshell: Results for the LHC

- Parton Distribution Functions
  - Dialogue/discussion between PDF fitters and community that delivers the data.
  - Combined data (H1/Zeus Datasets for F2, F2D), other data (e.g. TeV. jets)?
  - Discrepancies between PDFs will be ironed out, eg via new measurements. Fits with 1-σ bands available.
  - Quantitative estimates for low-x/large-x resummation available
  - Timescale for the full program 1-2 years, i.e. just in time for the LHC
doione more precise PDFs: maybe factor 2? (personal guess/hope)

- Diffraction
  - Improved understanding on the DPE/Higgs production and cross section

- Final states
  - Lots of work/progress on underlying events (tuning), gap survival

- Heavy quarks
  - Saturation effects measurable at low pt
  - Heavy quark parton distributions eg. for Higgs cross section calculations.

- Tools
  - Tool development ongoing strongly...
Goals and suggestions for 2nd workshop

- precision determination of PDFs, including uPDFS and generalised PDFs
  - what precision can be expected in 2007/2008 from the HERA and perhaps combined with other data and with the improvements in theory? This was started in the first workshop but is it the final word for LHC preparation
  - how does it affect LHC measurements quantitatively
  - combined H1/ZEUS parton data sets (started at the previous)
  - can we judge which PDF is preferred (MRST/CTEQ...) in 2007/2008 eg. from FL or LHC measurements?

- MI/underlying events/jets
  - uncertainties for top/Higgs production
  - underlying event tuning at HERA (as for the Tevatron data)
    - testing new underlying event models with data
    - new advised parameter set for underlying events
  - Quantative uPDFs and MI influence for SUSYHiggs discoveries
  - Understanding MI interactions with HERA data (AGK,...)
  - uncertainties for gap-survival probabilities for the LHC
  - Test HO/resummed jet predictions at HERA
Goals and suggestions for 2nd workshop

- **Heavy Quarks: details of production mechanisms**
  - beauty at HERA -> top at LHC ?
  - higher orders
  - small x/ large x resummations
  - saturation effects
  - Include HERA charm data for gluon constraints in fits (like the jets)

- **diffraction and small x**
  - saturation and non-linear effects:
  - what is the saturation scale, where HERA can help
  - is saturation relevant for LHC, and where ?
  - physics of the forward region
  - elastic protons
  - jets in 6 < eta < 11
  - what can be learned from total xsection sigma_tot for ptcut in multiple scatterings ?
  - How to relate diffraction with multiple scatterings
  - continuing studies on the exclusive Higgs production and detection
Goals and suggestions for 2nd workshop

**MC & Tools**
- HZTool -> relevanca also for MC@NLO
- benchmarking of xsections for HERA and LHC: jets, W/Z, Higgs, HQ, diffraction
- Tools for pdf fits including proper treatment of alphas, different evolution (DGLAP LO/NLO/NNLO, CCFM/BFKL) proper treatment of data uncertainties extraction of PDFs, uPDFs, generalised PDFs
- NLO programs and libraries
- SCET type of QCD generators for multi-jet production?

Keywords: tools, phenomenological progress, and quantitative estimate for the impact of HERA on LHC measurements
Final words: Organization this week

- **Rooms**
  - Plenary sessions are Main Auditorium (Tue/Thu) and 40-S2-A01 (Fri)
  - All parallel sessions in B40 and council chamber (WG3/Friday)
- **Buffet Dinner on Thursday**: location: B501 (restaurant-1/glass box)
  - Buy your ticket with at the secretariat: 20 CHF
- **Secretariat**: here (coffee break) and B40-5-B02

Have a good workshop
Backup
Physics at the LHC: pp @ 14 TeV

Higgs!

Supersymmetry?

Extra Dimensions?

CP triangle!

QGP?

Precision measurements e.g top!

Split SUSY?

But also QCD, diffraction, b & c physics,... especially in the early phase
These need to be understood for precision measurements, bkg understanding etc
Important role for HERA data & HERA expertise  This workshop
Physics at the LHC: other examples

High energy hadron showers

Color glass Condensate

Multi Jet event: Is it Multiple Interaction or Black hole production

LHC

UHE CR

QCD @ LHC in its own!!!
High scale QCD, jets, UHECR, smallest x, parton saturation - new phase in QCD - non-linear phenomena
Multiple Interactions at LHC

Charged multiplicities in transverse region

Models tuned to Tevatron data
- give HUGE differences at LHC ...
- better understand multiple interactions ...

C. Buttar et al

![Graphs showing charged multiplicities vs. Pt leading jet (GeV)]
Towards understanding of MI

- Cutting rules (AGK) extended to QCD
- Relate diffraction, saturation and multiple scatterings
- All from the same amplitude, but different factors:
  - +1 Diffraction
  - -4 Saturation
  - +2 Multiple Interactions
- Extended now also to pp !!!
  - further work needed ...

→ HERA is the place to understand MI ！！！
  (TeVatron to tune MC ！！！)
→ Towards the description of "everything" ！！！！
Multiple Interactions and top mass

- Multiple Interactions
- Jet fragmentation properties, jet profiles
- Final state QCD radiation
- B-fragmentation

Significant effects on top mass determination
Better understand them !!!

from M. Mangano

hep-ex/04003021

Are we sure ?
Simple spread of existing PDFs gives up to 10% uncertainty on Higgs cross section
\( \Rightarrow \) we have to do better than that!
At the LHC: momentum fractions $x_1$ and $x_2$ determined by mass and rapidity of $X$

HERA measurements do not cover the LHC region, e.g. for central Higgs production
⇒PDFs evolved via DGLAP equations from $(x,Q^2_0)$ to $(x,Q^2)$

Note: $W,Z$, Higgs production needs PDFs from the $x$ range $10^{-4}$ - $10^{-1}$

Is it safe?

Q. is NLO (or NNLO) DGLAP sufficient at small $x$? Are higher-orders $\sim \alpha_s^n \log^m x$ important? CCFM? BFKL? Non-linear effects? Saturation?

E.g. R. Thorne: yes low-$x$ resummations are important and can lead to >10% differences