LHeC
Large Hadron electron Collider project

Anna Staśto
Penn State & BNL & INP Krakow

http://www.cern.ch/lhec

CERN, 8 February 2013
Project Development

2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept

2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)

2009: 2nd CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

2010: Report to CERN SPC (June)
      3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
      NuPECC puts LHeC to its Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11) refereed and being updated

2012: Discussion of LHeC at LHC Machine Workshop (Chamonix)
      Publication of CDR – European Strategy
      New workshop (June 14-15, 2012)

LHeC has some history already ..
LHeC Study Group


193 authors
631 pages
947 references
5 chapters
14 sections
Organisation for CDR

Scientific Advisory Committee

Guido Altarelli (Roma)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell (MPI Muenchen) - Chair
Swapan Chattopadhyay (Cockcroft Institute)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (NWO)
Joel Feltesse (Saclay)
Roland Garoby (CERN)
Rolf Heuer (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Lev Lipatov (St. Petersburg)
Kartheinz Meier (Heidelberg)
Richard Milner (MIT)
Joachim Mnich (DESY)
Steve Myers (CERN)
Guenther Rosner (Glasgow)
Alexander N. Skrinsky (INP Novosibirsk)
Anthony Thomas (JLab)
Steve Vigdor (Brookhaven)
Ferdinand Willeke (Brookhaven)
Frank Wilczek (MIT)

Working Group Convenors

Accelerator Design
Oliver Bruening (CERN)
John Dainton (Liverpool)

Interaction Region
Bernhard Holzer (CERN)
Uwe Schmelling (DESY)
Pierre van Mechelen (Antwerpen)

Detector Design
Peter Costka (DESY)
Alessandro Polini (Bologna)
Reiner Wallny (Zurich)

New Physics at Large Scales
Georges Azuelos (Montreal)
Emmanuelle Perez (CERN)
Georg Weiglein (Hamburg)

Precision QCD and Electroweak
Olaf Behnke (DESY)
Paolo Gambino (Torino)
Thomas Gehrmann (Zurich)
Claire Gwilliam (Oxford)

Physics at High Parton Densities
Néstor Armesto (Santiago de Compostela)
Brian A. Cole (Columbia)
Paul R. Newman (Birmingham)
Anna M. Stasto (PennState)

CERN Referees

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kazuo Yokoya (KEK)
Energy Recovery
Georg Hofstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzel (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconeia (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)
LHeC is the latest & most promising idea to take ep physics to the TeV centre-of-mass scale ... ... at high luminosity

Outline of the talk:

- Physics motivation
- Accelerator and detector design
- Physics possibilities
- Timeline and outlook
Deep inelastic electron-proton collider

HERA Hamburg 1992-2007

Equivalent to a 50 TeV beam on a fixed target proton ~2500 times more than SLAC!

Around 500 pb⁻¹ per experiment

HERA (1992-2007) … the only ever collider of electron beams with proton beams

ZEUS

HERA Luminosity 2002 - 2007

P (920 GeV)
e (27.5 GeV)
**Results from HERA**

HERA established detailed proton structure: parton density functions.

Increasing role of gluons at small $x$. Proton structure is highly complex due to the QCD radiation (evolution).

Other results: measurement of coupling constant, jets, photon structure, diffractive processes, charm and bottom structure functions, limits for new physics (leptoquarks).
Limitations of HERA

- Low luminosity for high precision (large $x$)
- No deuterons
- No heavy nuclei
- Low $x$ saturation ? (too small $s$)
- Precision measurement of $\alpha_s$ (overall not precise enough)
- ...

**HERA in one box**

the first ep collider

$E_p \times E_e = 920 \times 27.6 \text{GeV}^2$

$\sqrt{s} = 2 \sqrt{E_e E_p} = 320 \text{ GeV}$

$L = 1 \ldots 4 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$

$\rightarrow \Sigma L = 0.5 \text{fb}^{-1}$


$Q^2 = [0.1 - 3 \times 10^4] \text{GeV}^2$

-4-momentum transfer$^2$

$x = Q^2/(sy) \approx 10^{-4} \ldots 0.7$

Bjorken $x$

$y = 0.005 \ldots 0.9$

inelasticity

**HEP needs a TeV energy scale machine with 100 times higher luminosity than HERA to develop DIS physics further and to complement the physics at the LHC. The Large Hadron Collider $p$ and $A$ beams offer a unique opportunity to build a second ep and first eA collider at the energy frontier.**
Physics motivation for ep/eA in TeV range

• Details of parton structure of the nucleon (from ep, ed/eA), full unfolding of PDFs. Measurement of GPDs and unintegrated PDFs.

• Mapping the gluon field down to very low x. Saturation physics.

• Heavy quarks, factorization, diffraction, electroweak processes.

• Properties of Higgs. Very good sensitivity to: H to bbar, H to WW coupling in the 120-130 GeV mass range.

• Searches and understanding of new physics. Very precise measurement of the coupling constant. Leptoquarks, excited leptons...

• Deep inelastic scattering off nuclei. Nuclear parton distributions. Pinning down the initial state for heavy ion collisions.
Accelerator design in linac-ring option

500 MeV injection
3 turns
2 linacs, 10 GeV energy recovery
90% polarisation

\[ L = 10^{33} \text{ cm}^{-2} \text{s}^{-1} \]

Higher energy:
140 GeV linac
ILC type
31.5 MV/m
without energy recovery
lower luminosity
### Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>$e$, $p$, $^{208}\text{Pb}^{82+}$</td>
</tr>
<tr>
<td>beam energy (/nucleon) [GeV]</td>
<td>60, 7000, 2760</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25, 100, 25, 100</td>
</tr>
<tr>
<td>bunch intensity (nucleon) [$10^{10}$]</td>
<td>0.1 (0.2), 0.4, 17 (22), 2.5</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>6.4 (12.8), 860 (1110), 6</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>0.6, 75.5</td>
</tr>
<tr>
<td>polarization [%]</td>
<td>90 ($e^+$ none), none, none</td>
</tr>
<tr>
<td>normalized rms emittance [$\mu m$]</td>
<td>50, 3.75 (2.0), 1.5</td>
</tr>
<tr>
<td>geometric rms emittance [nm]</td>
<td>0.43, 0.50 (0.31)</td>
</tr>
<tr>
<td>IP beta function $\beta^*_{x,y}$ [m]</td>
<td>0.12 (0.032), 0.1 (0.05)</td>
</tr>
<tr>
<td>IP spot size [$\mu m$]</td>
<td>7.2 (3.7), 7.2 (3.7)</td>
</tr>
<tr>
<td>synchrotron tune $Q_s$</td>
<td>—, $1.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>hadron beam-beam parameter</td>
<td>0.0001 (0.0002)</td>
</tr>
<tr>
<td>lepton disruption parameter $D$</td>
<td>6 (30)</td>
</tr>
<tr>
<td>crossing angle</td>
<td>0 (detector-integrated dipole)</td>
</tr>
<tr>
<td>hourglass reduction factor $H_{hg}$</td>
<td>0.91 (0.67)</td>
</tr>
<tr>
<td>pinch enhancement factor $H_D$</td>
<td>1.35 (0.3 for $e^+$)</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>1.3, 0.81</td>
</tr>
<tr>
<td>luminosity / nucleon [$10^{33}$ cm$^{-2}$s$^{-1}$]</td>
<td>1 (10), 0.2</td>
</tr>
</tbody>
</table>

Designed for **synchronous ep and pp operation** during the HL-LHC phase.
Figure 1: Schematic view on the LHeC racetrack configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the collision point with three passes through the opposite linear structures of 60 cavity-cryo modules each. The arc radius is about 1 km, mainly determined by the synchrotron radiation loss of the 60 GeV beam which is returned from the IP and decelerated for recovering the beam power. Comprehensive design studies of the lattice, optics, beam (beam) dynamics, dump, IR and return arc magnets, as well as auxiliary systems such as RF, cryogenics or spin rotators are contained in the CDR [1], which as for physics and detector had been reviewed by 24 referees appointed by CERN.

Ring-Ring option as fall back;
Access to $Q^2=1$ GeV$^2$ in ep mode for all $x > 5 \times 10^{-7}$ requires scattered electron acceptance to $179^\circ$

Similarly, need $1^\circ$ acceptance in outgoing proton direction to contain hadrons at high $x$ (essential for good kinematic reconstruction)
**LHeC kinematics**

**ep/eA collisions**

\[ E_p = 7 \text{ TeV} \]
\[ E_A = 2.75 \text{ TeV/nucleon} \]
\[ E_e = 50 - 150 \text{ GeV} \]
\[ \sqrt{s} \simeq 1 - 2 \text{ TeV} \]

- **Requirements:**
  - Luminosity \( \sim 10^{33} \text{ cm}^{-2}\text{s}^{-1} \). \( eA \): \( L_{en} \sim 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
  - Acceptance: 1-179 degrees (low-x ep/eA).
  - Tracking to 1 mrad.
  - EMCAL calibration to 0.1 %.
  - HCAL calibration to 0.5 %.
  - Luminosity determination to 1 %.
  - Compatible with LHC operation.
Figure 13.52: Acceptance for $J/\psi$ with $E_e = 50$ GeV as a function of $W$, the center of mass energy of the $\gamma p$ system. A detector with larger coverage both in the forward and in the rear region allows for measurements on a much wider $W$ range.

Figure 13.53: A full view of the baseline detector in the r-z plane with all components shown. The detector dimensions are $\approx 14$ m in $z$ with a diameter of $\approx 9$ m.

Detector design

Forward/backward asymmetry in energy deposited and thus in geometry and technology

Present dimensions: $L \times D = 14 \times 9$ m$^2$ [CMS 21 x 15 m$^2$, ATLAS 45 x 25 m$^2$]
Taggers at -62 m (e), 100 m (γ,LR), -22.4 m (γ,RR), +100 m (n), +420 m (p)
Beyond Standard Model

- Leptoquarks
- Contact Interactions
- Excited Fermions
- Higgs in MSSM
- Heavy Leptons
- 4th generation quarks
- Z'
- SUSY
- ???

QCD and EW precision physics

- Structure functions
- Quark distributions from direct measurements
- Strong coupling constant to high accuracy
- Higgs in SM
- Gluon distribution in extended x range to unprecedented accuracy
- Single top and anti-top production
- Electroweak couplings
- Heavy quark fragmentation functions
- Heavy flavor production with high accuracy
- Jets and QCD in photoproduction
- Partonic structure of the photon
- ...

Small x and high parton densities

- New regime at low x
- Saturation
- Diffraction
- Vector Mesons
- Deeply Virtual Compton Scattering
- Forward jets and parton dynamics
- DIS on nuclei
- Generalized/unintegrated parton distribution functions
## 3 Precision QCD and Electroweak Physics

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Inclusive deep inelastic scattering</td>
<td>35</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Cross sections and structure functions</td>
<td>35</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Neutral current</td>
<td>35</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Charged current</td>
<td>37</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Cross section simulation and uncertainties</td>
<td>39</td>
</tr>
<tr>
<td>3.1.5</td>
<td>Longitudinal structure function $F_L$</td>
<td>41</td>
</tr>
<tr>
<td>3.2</td>
<td>Determination of parton distributions</td>
<td>47</td>
</tr>
<tr>
<td>3.2.1</td>
<td>QCD fit ansatz</td>
<td>48</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Valence quarks</td>
<td>49</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Probing $q \neq \bar{q}$ and $u^p \neq d^n$</td>
<td>52</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Strange quarks</td>
<td>54</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Releasing PDF constraints</td>
<td>54</td>
</tr>
<tr>
<td>3.2.6</td>
<td>Top quarks</td>
<td>55</td>
</tr>
<tr>
<td>3.3</td>
<td>Gluon distribution</td>
<td>58</td>
</tr>
<tr>
<td>3.4</td>
<td>Prospects to measure the strong coupling constant</td>
<td>61</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Status of the DIS measurements of $\alpha_s$</td>
<td>62</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Simulation of $\alpha_s$ determination</td>
<td>63</td>
</tr>
<tr>
<td>3.5</td>
<td>Electron-deuteron scattering</td>
<td>65</td>
</tr>
<tr>
<td>3.6</td>
<td>Charm and beauty production</td>
<td>68</td>
</tr>
<tr>
<td>3.6.1</td>
<td>Introduction and overview of expected highlights</td>
<td>68</td>
</tr>
<tr>
<td>3.6.2</td>
<td>Total production cross sections for charm, beauty and top quarks</td>
<td>71</td>
</tr>
<tr>
<td>3.6.3</td>
<td>Charm and beauty production in DIS</td>
<td>72</td>
</tr>
<tr>
<td>3.6.4</td>
<td>Determination of the charm mass parameter in VFN schemes</td>
<td>76</td>
</tr>
<tr>
<td>3.6.5</td>
<td>Intrinsic heavy flavour</td>
<td>77</td>
</tr>
<tr>
<td>3.6.6</td>
<td>$D^*$ meson photoproduction study</td>
<td>78</td>
</tr>
<tr>
<td>3.7</td>
<td>High $p_T$ jets</td>
<td>81</td>
</tr>
<tr>
<td>3.7.1</td>
<td>Jets in $ep$</td>
<td>81</td>
</tr>
<tr>
<td>3.7.2</td>
<td>Jets in $\gamma A$</td>
<td>87</td>
</tr>
<tr>
<td>3.8</td>
<td>Total photoproduction cross section</td>
<td>89</td>
</tr>
<tr>
<td>3.9</td>
<td>Electroweak physics</td>
<td>90</td>
</tr>
<tr>
<td>3.9.1</td>
<td>Context</td>
<td>91</td>
</tr>
<tr>
<td>3.9.2</td>
<td>Light quark weak neutral current couplings</td>
<td>92</td>
</tr>
<tr>
<td>3.9.3</td>
<td>Determination of the weak mixing angle</td>
<td>93</td>
</tr>
</tbody>
</table>
Reduced cross section: huge kinematic range and excellent accuracy

Longitudinal structure function: lowering electron energy
Figure 3.6: Reduced charged current cross sections with statistical uncertainties corresponding to 1 fb$^{-1}$ electron (top data points, red) and positron (lower data points, blue) proton scattering at the LHeC. The curves are determined by the dominant valence quark distributions, $u_v$ for $e^-p$ and $d_v$ for $e^+p$. In the simulation the lepton polarisation is taken to be zero. The valence-quark approximation of the reduced cross section is seen to hold at $x \geq 0.3$. A precise determination of the $u/d$ ratio up to large $x$ appears to be feasible at very high $Q^2$. 
Constraining the pdfs

Gluon at small $x$: large uncertainties

Constraints by including LHeC simulated data

Constraints on valence at large $x$

Constraints of strange quark density through charm tagging
Mapping the Gluon Distribution

QCD fit analysis (default: NC, CC, LHeC only, following HERAPDF) with full experimental errors

The gluon is unknown at low $x$ and high $x$ – QCD: non-linear evolution, resummation. BSM: hi M – HL-LHC!
Valence Quarks

Down valence distribution at $Q^2 = 1.9$ GeV$^2$

Up valence distribution at $Q^2 = 1.9$ GeV$^2$

Long time to understand d/u. LHeC: free of higher twist
More on valence quarks: $x F_3^\gamma Z$

Figure 3.11: Simulation of the LHeC measurement of the interference structure function $x F_3^\gamma Z$ from unpolarised $e^\pm p$ scattering with 10 fb$^{-1}$ luminosity per beam (blue, closed points) compared with the HERA II data as obtained by H1 (preliminary, green triangles) and by ZEUS (red squares) with about 0.15 fb$^{-1}$ luminosity per beam charge. The H1 $x$ values are enlarged by 10% of their given values for clarity. It should be noted that any significant deviation of sea from anti-quarks, see Eq. 3.27, would cause $x F_3^\gamma Z$ at low $x$ to not tend to zero. The top plot shows an average of $x F_3^\gamma Z$ over $Q^2$ projected to a chosen $Q^2$ value of 1500 GeV$^2$ exploiting the fact that the valence quarks are approximately independent of $Q^2$. The lower plot is a zoom into the high $x$ region.
Luminosity $10 \, fb^{-1}$

**LHeC is a flavor factory!**

**Total cross sections in ep collisions**

- Charm $\gamma p$
- Charm DIS
- Beauty $\gamma p$
- Beauty DIS
- $cc$
- $sW \rightarrow c$
- $sW \rightarrow \bar{c}$
- $bW \rightarrow t$
- $bW \rightarrow \bar{t}$
- $tt$ $\gamma p$
- $tt$ DIS

Events per $10 \, fb^{-1}$

- $10^{-3}$
- $10^{-2}$
- $10^{-1}$
- $1$ $10^0$
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
- $10^7$
- $10^8$
- $10^9$
- $10^{10}$

$LHeC$
Flavor decomposition

- **$F^b_2$ (beauty)**
  - High precision c,b measurements
  - Possible s (and sbar) from charged current
  - b is a small x observable
  - Also possible $Wb \rightarrow t$

- **$F^c_2$ (charm)**
  - Systematic error dominates (so far 3%)
  - Precise measurement near threshold and up to $10^6$ GeV^2
  - $F^c_2$ will become precision testing ground for QCD and proton structure

- **$F^s_2$ (strange)**
  - Open: 10°
  - Closed: 10°
  - Box: 1 TeV
Flavor decomposition

Charm

LHeC $F_{2cc}$ (RAPGAP MC, 7 TeV x 100 GeV, 10 fb$^{-1}$, $\varepsilon_c=0.1$)

<table>
<thead>
<tr>
<th>$Q^2$ in GeV$^2$</th>
<th>$j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>7</td>
</tr>
<tr>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>1000</td>
<td>9</td>
</tr>
<tr>
<td>5000</td>
<td>10</td>
</tr>
</tbody>
</table>

$\triangle$ HERA combined data

- LHeC $\theta_c > 0^\circ$
- LHeC $\theta_c > 2^\circ$
- LHeC $\theta_c > 10^\circ$

Beauty

LHeC $F_{2bb}$ (RAPGAP MC, 7 TeV x 100 GeV, 10 fb$^{-1}$, $\varepsilon_b=0.5$)

<table>
<thead>
<tr>
<th>$Q^2$ in GeV$^2$</th>
<th>$j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
</tr>
<tr>
<td>250</td>
<td>7</td>
</tr>
<tr>
<td>650</td>
<td>8</td>
</tr>
<tr>
<td>1200</td>
<td>9</td>
</tr>
<tr>
<td>2500</td>
<td>10</td>
</tr>
<tr>
<td>10000</td>
<td>11</td>
</tr>
</tbody>
</table>

$\triangle$ H1 vtx DATA

- LHeC $\theta_b > 0^\circ$
- LHeC $\theta_b > 2^\circ$
- LHeC $\theta_b > 10^\circ$
Strange quark distributions: results from LHC

Previous MSTW, NNPDF analysis indicated strangeness suppression. ATLAS points to SU(3) symmetry with 0.5(sbar+s)/d-bar ratio

Trend confirmed in NNPDF collider only fit
Strange pdf from LHeC

Figure 3.13: Simulated measurement of the anti-strange quark density in CC $e^-p$ scattering with charm tagging at the LHeC, for a luminosity of $10^{13}$ fb$^{-1}$. Closed points: tagging acceptance down to 10 degrees. The charm quark tagging efficiency is assumed to be $\epsilon_c = 0.1$ and the efficiency to keep light quark background $\text{bgd}_q = 0.01$. High lumi, High $Q^2$, Charm tagging efficiency 10%, Closed points acceptance to 10 degrees, Open points acceptance to 1 degree.
Why deuteron?

- Deuteron as effective neutron beam
- Quark flavor decomposition
  \[ F_2(p) \propto 4u + d \]
  \[ F_2(n) \propto u + 4d \]
- Particularly important at large $x$
  - Large $d$-quark uncertainty
  - $d/u$ ratio at $x \to 1$ probes non perturbative proton structure
    Accardi et al. [CTEQ-JLab collab.] PRD84(2011)
- At $x \lesssim 10^{-2}$ sea quarks dominate, expect $F_2(p) \approx F_2(n)$
Deutrons: constraints on light quark sea asymmetry

Deuterons crucial for:
- neutron structure
- flavor separation

Tests of charge symmetry using electrons and positrons

$$R^- = 2 \frac{W_2^{-D} - W_2^{+D}}{W_2^{-p} + W_2^{+p}}$$
Complementarity of LHeC to LHC

Searching for High Mass SUSY

With high energy and luminosity, the LHC search range will be extended to high masses, up to \( \sim 5 \) TeV in pair production, and PDF uncertainties come in \( \sim 1/(1-x) \).
Gluon-Gluon Luminosity

NNLO gg luminosity at LHC ($\sqrt{s} = 14$ TeV)

Ratio to MSTW 2008 (68% C.L.)

- MSTW08
- CT10
- NNPDF2.3
- ABM11
- JR09
- HERAPDF1.5

G. Watt (July 2012)
Monica d’Onofrio talk at Chavannes-de-Bogis

What the LHeC can do

- M. Kramer and R. Klees working on impact of improved PDF fits on theoretical predictions for SUSY process:
  - Example: gl-gl production (assuming m_gl = m_sq)
  - without (blue, CTEQ6) and with (green) LHeC PDF

Preliminary

![PDF Errors Graph]

PDF-Errors for pp -> gluino + gluino + X

- Improve of factor of 2-3 @ 2 TeV
- Factor of 10 at 3.5 TeV
Using ZEUS fitting code, HERA + LHeC data ... EW couplings free

$E_e = 100 \text{ GeV}, L = 10^{+5} \text{ fb}^{-1}, P = +/- 0.9$

Also measurement of weak mixing angle below and above $M_z$ (scale variation)
Higgs at the LHeC

**Signal**

CC: $H \rightarrow b\bar{b}$ (BR $\sim 0.7$ at $M_H=120$ GeV)

![Graph showing CC Higgs production cross-section](image1)

- $\sigma \sim 0.16$ pb at $\sqrt{s}=2.05$ TeV

**Higgs production cross-section**

at $\sqrt{s} = 1.98$ TeV ($E_e=140$ GeV, $E_p=7$ TeV)

![Graph showing Higgs production cross-section](image2)

**CC Higgs production cross-section** ($M_H = 120$ GeV)

<table>
<thead>
<tr>
<th>Electron beam energy (GeV)</th>
<th>50 GeV</th>
<th>100 GeV</th>
<th>150 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross-section (fb)</td>
<td>81</td>
<td>165</td>
<td>239</td>
</tr>
</tbody>
</table>

Higgs can be studied at the LHeC.
- High rates in CC interactions.
- $b\bar{b}$ channel cleaner at the LHeC.
- Precision measurements of WW and ZZ couplings. CP properties.

![Graph showing Higgs production cross-section as a function of $m_H$](image3)
Higgs at the LHeC

Signal and background cut flow

- Beam energy:
  - Electron beam: 150 GeV
  - Proton beam: 7 TeV

- SM Higgs mass: 120 GeV

- Luminosity: 10 fb⁻¹

<table>
<thead>
<tr>
<th>Cut Condition</th>
<th>H→bb</th>
<th>CC DIS</th>
<th>NC bbj</th>
<th>S/N</th>
<th>S/√N</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC rejection</td>
<td>816</td>
<td>123000</td>
<td>4630</td>
<td>6.38×10⁻³</td>
<td>2.28</td>
</tr>
<tr>
<td>+ b-tag requirement + Higgs invariant mass</td>
<td>178</td>
<td>1620</td>
<td>179</td>
<td>9.92×10⁻²</td>
<td>4.21</td>
</tr>
<tr>
<td>All cuts</td>
<td>84.6</td>
<td>29.1</td>
<td>18.3</td>
<td>1.79</td>
<td>12.3</td>
</tr>
</tbody>
</table>

- Comparison with 60 GeV option

<table>
<thead>
<tr>
<th>Beam energy:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam: 150 GeV ⇒ 60 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut Condition</th>
<th>H→bb (10 fb⁻¹)</th>
<th>H→bb (100 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→bb signal</td>
<td>84.6</td>
<td>248</td>
</tr>
<tr>
<td>S/N</td>
<td>1.79</td>
<td>1.05</td>
</tr>
<tr>
<td>S/√N</td>
<td>12.3</td>
<td>16.1</td>
</tr>
</tbody>
</table>

- We can explore other channels
  - NC Higgs production in ZZ fusion
  - Other light Higgs decay channels
Measurement of strong coupling

Strong coupling is least known of all couplings
Grand unification predictions suffer from uncertainty
DIS tends to be lower than the world average
LHeC: per mille accuracy (now percent accuracy)

A dedicated study was performed to determine the accuracy of alphas from the LHeC was performed using for the central values the SM prediction smeared within its uncertainties assuming Gauss distribution and taking into account correlations

<table>
<thead>
<tr>
<th>case</th>
<th>cut $[Q^2 \text{ (GeV}^2)]$</th>
<th>$\alpha_S$</th>
<th>uncertainty</th>
<th>relative precision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA only (14p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.11529</td>
<td>0.002238</td>
<td>1.94</td>
</tr>
<tr>
<td>HERA+jets (14p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.12023</td>
<td>0.000995</td>
<td>0.82</td>
</tr>
<tr>
<td>LHeC only (14p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.11680</td>
<td>0.000180</td>
<td>0.15</td>
</tr>
<tr>
<td>LHeC only (10p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.11796</td>
<td>0.000199</td>
<td>0.17</td>
</tr>
<tr>
<td>LHeC only (14p)</td>
<td>$Q^2 &gt; 20.$</td>
<td>0.11602</td>
<td>0.000292</td>
<td>0.25</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>$Q^2 &gt; 3.5$</td>
<td>0.11769</td>
<td>0.000132</td>
<td>0.11</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>$Q^2 &gt; 7.0$</td>
<td>0.11831</td>
<td>0.000238</td>
<td>0.20</td>
</tr>
<tr>
<td>LHeC+HERA (10p)</td>
<td>$Q^2 &gt; 10.$</td>
<td>0.11839</td>
<td>0.000304</td>
<td>0.26</td>
</tr>
</tbody>
</table>
4 Physics at High Parton Densities

4.1 Physics at small $x$ .................................................. 101
  4.1.1 High energy and density regime of QCD ..................... 101
  4.1.2 Status following HERA data .................................. 109
  4.1.3 Low-$x$ physics perspectives at the LHC .................... 116
  4.1.4 Nuclear targets ................................................... 119

4.2 Prospects at the LHeC .............................................. 124
  4.2.1 Strategy: decreasing $x$ and increasing $A$ ................ 124
  4.2.2 Inclusive measurements ....................................... 124
  4.2.3 Exclusive production .......................................... 132
  4.2.4 Inclusive diffraction .......................................... 152
  4.2.5 Jet and multi-jet observables, parton dynamics and fragmentation . 166
  4.2.6 Implications for ultra-high energy neutrino interactions and detection 178
HERA established strong growth of the gluon density towards small $x$.

Parton saturation: recombination of gluons at sufficiently high densities leading to nonlinear modification of the evolution equations.

Emergence of a dynamical scale: saturation scale dependent on energy.

What we learned from HERA about saturation?

Linear DGLAP evolution works well at HERA.

Hints of saturation at low $Q$ and low $x$: deterioration of the global fit in that region.

Large diffractive component.

Success of the dipole models in the description of the data.

The models point at the low value of the saturation scale $LHeC$ would provide an access to a kinematic regime where the saturation scale is perturbative.
LHeC would deliver a two-pronged approach:

1. Probing lower $x$ in ep. Evolution of a single source
2. Increasing target matter in eA (overlapping many sources at fixed kinematics, density $\sim A^{1/3} \sim 6$ for Pb, worth 2 orders of magnitude in $x$)

Precision measurements of structure functions at very low $x$: test DGLAP, small $x$, saturation inspired approaches.

Interestingly, rather small band of uncertainties for models based on saturation as compared with the calculations based on the linear evolution. Possible cause: the nonlinear evolution washes out any uncertainties due to the initial conditions, or too constrained parametrization used within the similar framework.

approx. 2% error on the $F_2$ pseudodata, and 8% on the $F_L$ pseudodata, should be able to distinguish between some of the scenarios.
Heavy Ion Physics

Initial conditions of QGP

Hadronization in Media

Nuclear Parton Distributions

Black body limit

Saturation in ep AND in eA?

Diffraction in eA scattering

**Deuterons**: tag $p$ in $en$ to beat Fermi motion and exploit diffraction-shadowing relation …

LHeC eA is natural continuation of (part of) the heavy ion physics of the LHC ($AA$ and $pA$, forward)

EIC programme:
see recent workshop arXiv:1108.1713 [nucl-th]
Nuclear ratio for structure function or a parton density:

\[ R^A_f(x, Q^2) = \frac{f^A(x, Q^2)}{A \times f^N(x, Q^2)} \]

Nuclear effects \[ R^A \neq 1 \]

LHeC potential: precisely measure partonic structure of the nuclei at small \( x \).

Nuclear structure functions measured with very high accuracy.
Nuclear parton distributions

Current status: nuclear parton distribution functions are poorly known at small $x$. Especially gluon density, below $x=0.01$ can be anything between 0 and 1....
Nuclear parton distributions at LHeC

Global NLO fit with the LHeC pseudodata included

Much smaller uncertainties.

Very large constraint on the low $x$ gluons and sea quarks with the LHeC pseudodata.
Diffraction

\[ x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2} \]

\[ \beta = \frac{Q^2}{Q^2 + M_X^2 - t} \]

\[ x_{Bj} = x_{IP} \beta \]

Methods: Leading proton tagging, large rapidity gap selection

Diffractive Kinematics at \( x_{IP} = 0.01 \)

Diffractive Kinematics at \( x_{IP} = 0.0001 \)

\( \eta_{\text{max}} \) from LRG selection ...
Diffractive mass distribution

New domain of diffractive masses.
$M_X$ can include $W/Z$/beauty
Inclusive diffraction in eA

Diffractive structure function for Pb

Diffractive to inclusive ratio for protons and Pb

Enhanced diffraction in the nuclear case

Study of diffractive dijets, heavy quarks for the factorization tests
Exclusive diffraction

- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude and GPDs.
- Suitable process for estimating the 'blackness' of the interaction.
- $t$-dependence provides an information about the impact parameter profile of the amplitude.

Large momentum transfer $t$ probes small impact parameter where the density of interaction region is most dense.

Unitarity limit: $N(x,r,b) = 1$
Exclusive diffraction: predictions

\[ \sigma \gamma p \rightarrow J/\Psi + p (W) \]

- b-Sat dipole model \( \text{[Golec-Biernat, Wuesthoff, Bartels, Motyka, Kowalski, Watt]} \)
- eikonalised: with saturation
- 1-Pomeron: no saturation

\[ \gamma p \rightarrow J/\psi + p \]

LHeC central values from extrapolating HERA data:
\[ \sigma(\gamma p) = (2.96 \text{ nb})(W/\text{GeV})^{0.721} \]

Large effects even for the t-integrated observable.

Different \( W \) behavior depending whether saturation is included or not.

Simulated data are from extrapolated fit to HERA data

LHeC can distinguish between the different scenarios.
**Exclusive diffraction: \( t \)-dependence**

\[
\gamma p \rightarrow J/\psi + p
\]

Photoproduction in bins of \( W \) and \( t \).

Already for small values of \( t \) and smallest energies large discrepancies between the models. LHeC can discriminate.

Large values of \( t \): increased sensitivity to small impact parameters.

Amplitude as a function of the impact parameter.
Possible nuclear resonances at small $t$?

Challenges: need to distinguish between coherent and incoherent diffraction. Need dedicated instrumentation, zero degree calorimeter.

Energy dependence for different targets.

$t$-dependence: characteristic dips.
LHeC has an unprecedented potential as a high luminosity, high energy DIS machine. Offering a unique window for small x physics and high parton density regime.

Precision DIS measurements: constraining and unfolding PDFs, heavy flavor physics, precision strong coupling, precision electroweak measurements. Higgs properties.

eA at high energy essential to untangle the complex nuclear structure at low x and constrain the initial conditions for AA at the LHC. Complementary to pp/pA/AA.

CDR for the project is complete: arXiv:1206.2913

Next steps in the near future:

• Reorganization of the working groups. Forming a collaboration.

• Detailed evaluation of the relation of ep/eA program to LHC (esp. pp and pA) is needed.

• First steps towards Technical Design Report.

http://cern.ch/lhec
backup
Explore dual nature of the photon: pointlike interactions or hadronic behavior.

Tests of universality of hadronic cross sections, unitarity, transition between perturbative and nonperturbative regimes.

Dedicated detectors for small angle scattered electrons at 62m from the interaction point.

Kinematics of events:
\[ Q^2 \sim 0.01 \]
\[ y \sim 0.3 \]

Systematics is the limiting factor here. Assumed 7% for the simulated data as in H1 and ZEUS.
Diffraction and saturation

Dipole model at high energy: photon fluctuates into $q\bar{q}$ pair and undergoes an interaction with the target

$$\sigma_{T,L}(x, Q^2) = \int d^2r \int_0^1 dz \sum_f |\Psi_{T,L}^f(r, z, Q^2)|^2 \hat{\sigma}(x, r).$$

Inclusive: dominated by relatively hard component

Diffraction: dominated by the semi-hard momenta

Overlap function in the dipole model

Typical dipole sizes involved in the process

Diffraction is a collective phenomenon. Explore relation with saturation.
LHeC layout: ring-ring option

Figure 7.1: Schematic Layout of the LHeC: In grey the LEP tunnel now used for the LHC, in red the LHC. 

Table 7t34: Main parameters for the LHeC RR injector

- Electron beam energy: 3.73 GeV
- Proton energy: 200 MeV
- Extremes. The two LHeC bypasses are shown in blue. The RF is installed in the central straight section.

Figure 7t6z: Recirculator using 4 ILC modules.
Accelerator design

Multi-lab involvement: CERN, BNL, Novosibirsk, Cockroft, Cornell, DESY, EPFL Lausanne, JLab, KEK, Liverpool, SLAC, TAC Turkey, NTFU Norway, INFN, ...

Design constraint: power consumption < 100 MW. Electron energy 60 GeV in ring-ring mode

Installation 1m above LHC and 60cm to the inside. By-passes of existing experiments. Challenging, but possible.
5 New Physics at High Energy

5.1 New physics in inclusive DIS at high $Q^2$ .................................................. 182
  5.1.1 Quark substructure ................................................................. 183
  5.1.2 Contact interactions ............................................................... 184
  5.1.3 Kaluza-Klein gravitons in extra-dimensions ................................. 186

5.2 Leptoquarks and leptogluons ............................................................... 188
  5.2.1 Phenomenology of leptoquarks in $ep$ collisions ............................ 188
  5.2.2 The Buchmüller-Rückl-Wyler Model ........................................... 189
  5.2.3 Phenomenology of leptoquarks in $pp$ collisions .......................... 189
  5.2.4 Contact term approach ............................................................ 191
  5.2.5 Current status of leptoquark searches ....................................... 191
  5.2.6 Sensitivity on leptoquarks at LHC and at LHeC ............................ 192
  5.2.7 Determination of LQ properties ................................................ 192
  5.2.8 Leptoquarks as R-parity violating squarks ................................ 198
  5.2.9 Leptogluons ........................................................................... 200

5.3 Excited leptons and other new heavy leptons ....................................... 200
  5.3.1 Excited fermion models ............................................................ 201
  5.3.2 Simulation and results .............................................................. 202

5.4 New physics in boson-quark interactions ............................................. 205
  5.4.1 An LHeC-based $\gamma p$ collider ............................................... 205
  5.4.2 Anomalous single top production at a $\gamma p$ collider .................... 205
  5.4.3 Excited quarks in $\gamma p$ collisions at the LHeC ......................... 208
  5.4.4 Quarks from a fourth generation at LHeC ................................ 209
  5.4.5 Diquarks at LHeC ................................................................... 209
  5.4.6 Quarks from a fourth generation in $Wq$ interactions .................... 210

5.5 Sensitivity to a Higgs boson ............................................................... 210
  5.5.1 Introductory remarks ............................................................... 211
  5.5.2 Higgs production at the LHeC .................................................. 213
  5.5.3 Observability of the signal ....................................................... 214
  5.5.4 Probing anomalous $HWW$ couplings at the LHeC ..................... 220
Leptoquarks appear in many extensions of the SM.

May help explain remarkable symmetry between lepton and quark sectors.

Produced via fusion of electron with the quark (antiquark) from the proton.

In pp leptoquarks mainly produced in pairs. Single production in ep. Better suited for studies of properties (quantum numbers etc.)

Mass sensitivity to 1.0-1.5 TeV. Comparable with LHC, much cleaner!
Leptoquark properties

- Quantum numbers and couplings:
  - F: fermion number can be obtained from asymmetry in single LQ production, since $q$ have higher $x$ than $\bar{q}$

$$A = \frac{\sigma_e^- - \sigma_e^+}{\sigma_e^- + \sigma_e^+} \begin{cases} > 0 & \text{for } F=2 \\ < 0 & \text{for } F=0 \end{cases}$$
Excited leptons


![Graph showing excited leptons](image)

![Graph comparing production cross sections](image)
Monica d’Onofrio talk at Chavannes-de-Bogis

- **SUSY @ LHeC**
  - Possible searches in R-parity violation SUSY scenarios
  - Complementarities with LHC:
    - Implication of LHC findings for LHeC reach
    - Implication of LHeC PDF constraints on SUSY for the LHC
    - New uncharted scenarios

**Strong production**

- Cross section $\sim 2.5$ pb for $m = 1000$ GeV, $\sim 0.01$ pb for $m$ (squark, gluino) = 2 TeV → clearly, high stats samples are needed.

**mSUGRA reference point:**
- $m_0=650$, $m_{1/2}=975$, $xs = 1.1E-05$ nb

Decay chain might be complex, including Z or Higgs
**Monica d’Onofrio talk at Chavannes-de-Bogis**

**Importance of PDF**

- If we see deviations from SM, will be important to characterize the physics underneath
- The case of strong production:

  - Driven by gluon pdf at large $x$
  - Sizeable uncertainty $\approx \pm 25\%$ for $m \approx 1$ TeV

  - Driven by valence quark pdfs at large $x$
  - Small uncertainty $\approx \pm 5\%$ for $m \approx 1$ TeV

Monica D’Onofrio, LHeC Workshop 6/15/2012