Higgs physics
at a high luminosity LHeC

Uta Klein
in cooperation with
the LHeC study group

Seminar, RHUL, November 13th, 2013
**DIS : Some basics**

**HERA** : Only ep collider so far!
c.m.s. energy of 320 GeV using
\( E_e = 27.6 \text{ GeV} \)
\( E_p = 0.92 \text{ TeV} \) [like Tevatron protons]

**Neutral Current DIS event with H1**

\[
q = (k - k'), q^2 = -Q^2 \\
s = (k + P)^2 \\
(xP + q)^2 = m^2, P^2 = M_p^2 \\
\text{if} \ (Q^2 \gg x^2 M_p^2, m^2):
\]
\[
q^2 + 2xPq = 0 \\
x = \frac{Q^2}{2Pq} \\
Q^2 = sxy
\]

\[
\frac{d^2\sigma}{d\Omega dq^2} = \frac{e^4}{4E^2\sin^4 (\theta/2)} \left[ W_2(q^2, W) + 2W_1(q^2, W) \tan^2 (\theta/2) \right]
\]

@SLAC: **birth of DIS, 45 years ago.**
A Large Hadron Electron Collider at CERN

CDR: About 200 experimentalists and theorists from 69 institutes working for 5 years based on series of yearly workshops since 2008

E.g. recent contributions at EPS2013:
http://indico.cern.ch/conferenceDisplay.py?confId=218030

An energy recovery electron accelerator for DIS at the LHC by Daniel Schulte
The LHeC as a Higgs facility by Uta Klein
High Precision DIS with the LHeC by Amanda Cooper-Sarkar
The LHeC as an energy frontier eA collider by Max Klein
A new detector for deep inelastic physics by Peter Kostka et al.
New Physics with the LHeC by Monica d’Onofrio et al.

http://cern.ch/lhec

Supported by CERN, ECFA, NuPECC
Physics at a glance

LHeC: up to 100 to 1000 times HERA luminosity! (no pile-up)
High precision proton PDFs, also for LHC searches
High precision $\alpha_s$ to 0.1%
challenging lattice QCD
Higgs@HERA $\sigma \sim 0.5$ fb ...
Higgs@LHeC with $\sigma \sim 200$ fb

$\sqrt{s} = 1.3$ TeV
Light SM Higgs production in $e p$

**CC**

**LO SM Higgs Production**

- $e^- u \rightarrow ve h d$
  - around 90-80%
- $e^- d^{\sim} \rightarrow ve h u^{\sim}$
  - around 10-20%

**NC**

**LO SM Higgs Production**

- $e^- d \rightarrow e^- h d$
  - around 1/3
- $e^- u \rightarrow e^- h u$
  - around 1/3

RHUL, Uta Klein, Higgs@LHeC
Light SM Higgs production in ep

Electron beam energy

<table>
<thead>
<tr>
<th>Electron beam energy</th>
<th>CC $e^-p$</th>
<th>CC $e^+p$</th>
<th>NC $e^-p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section [fb]</td>
<td>109</td>
<td>58</td>
<td>20</td>
</tr>
<tr>
<td>Polarised cross section [fb] $P=-80%$</td>
<td>196</td>
<td>N.A.</td>
<td>25</td>
</tr>
</tbody>
</table>

$E_e=60$ GeV : $\sqrt{s}=1.3$ TeV

- Scale dependencies of the LO calculations are in the range of 5-10%.
- NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.

Total CC $e^-p$ Higgs production cross section using design LHC protons of 7 TeV
SM Higgs with $M_H = 120$ GeV

<table>
<thead>
<tr>
<th>Electron beam energy</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 at ~125 GeV: dominant decay to $b\bar{b}$ (58%)
**H → bb study: Analysis framework**

- Calculate cross section with tree-level Feynman diagrams (PDF CTEQ6L1) using partonic c.m.s.
- Generate final state of outgoing particles
  - standard DIS HERA tools couldn’t be used!

Input parameters for initial studies (CC e⁻p) for the CDR (*before* Higgs discovery):
- 150 GeV electron beam
  - [60 GeV configuration as comparison]
- 7 TeV proton beam
- 120 GeV SM Higgs boson mass

**Generator level cuts**
- \( p_T > 5 \text{ GeV} \) (for partons besides \( b \))
- \( |\eta| < 5.0 \)
- For NC: Number of \( b \) quarks \( \geq 2 \)

---

Event generation
- SM Higgs production
- CC & NC background
  - by MadGraph/MadEvent

- Fragmentation
- Hadronization
  - by PYTHIA (modified for ep)

Fast detector simulation
- by PGS (LHC-style detector)

**H → bb selection**

RHUL, Uta Klein, Higgs@LHeC
Examples: Generated samples

Signal

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

\[
\begin{array}{c}
u \\
W \\
\hbar \\
W \\
ed \\
\end{array}
\begin{array}{c}
d \\
b \\
b \\
ev \\
\end{array}
\]

\( \sigma \sim 0.16 \text{ pb} \)

at \( \sqrt{s}=2.05\text{TeV} \)

generate \( p e^- \rightarrow h \nu l j, h \rightarrow b b^\star \)

Background (examples)

CC: 3 jets (\( \sim 57 \text{ pb} \))

CC: single top production (\( \sim 4.1 \text{ pb} \))

CC: Z production (\( \sim 0.11 \text{ pb} \))

NC: b pair production (\( \sim 1.1 \text{ nb} \))

NOTE: Background sample cross sections are after pre-selection in generator and for \( E=150 \text{ GeV} \)

Graphs by MadGraph
NC DIS rejection
- Exclude electron-tagged events
- $E_{T,\text{miss}} > 20$ GeV
- $N_{\text{jet}} (p_T > 20$ GeV $) \geq 3$
- $E_{T,\text{total}} > 100$ GeV
- $y_{JB} < 0.9$, $Q_{JB}^2 > 400$ GeV$^2$

b-tag requirement
- $N_{b\text{-jet}} (p_T > 20$ GeV $) \geq 2$

Higgs invariant mass
- $90 < M_H < 120$ GeV

$\Rightarrow$ 44% of remaining BG is single-top...

Single top rejection
- $M_{jjj,\text{top}} > 250$ GeV
- $M_{jj,\text{W}} > 130$ GeV

$\Rightarrow$ 10% mis-ID
CDR : H → bb results

- **Forward jet tagging**
  - $\eta_{\text{jet}} > 2$ (lowest $\eta$ jet excluding b-tagged jets)
  - Coordinate: Fwd: +z-axis along proton beam

- **Higgs invariant mass after all selection**
  - $E_e = 150$ GeV

**[M_H=120 GeV, E_p=7 TeV]**

Clear signal obtained with just cut based analysis already!

RHUL, Uta Klein, Higgs@LHeC
Case study for electron beam energy of 60 GeV using same analysis strategy
- luminosity values of 100 fb\(^{-1}\) → with high luminosity LHeC 100 fb\(^{-1}\)/year would be feasible!

- Linac with high electron polarisation of about 90% → enhancement by factor 1.9 feasible, i.e. around 500 Higgs candidates for \(E_e=60\) GeV allowing to measure Hbb coupling with 4% statistical precision, based on 100 fb\(^{-1}\)

Conservative estimate of S/N → more detailed study using OWN detector required.

*Note: A parton-level study delivered S/N of 4.7.
Measure CP properties of Higgs

- Higgs couplings with a pair of gauge bosons (WW/ZZ) and a pair of heavy fermions (t/b/τ) are largest.

- Higgs@LHeC allows uniquely to access HWW vertex \( \rightarrow \) explore the CP properties of HVV couplings: BSM will modify CP-even (\( \lambda \)) and CP-odd (\( \lambda' \)) states differently

\[
\Gamma_{(SM)}^{\mu\nu}(p, q) = g M_W g^{\mu\nu}
\]

\[
\Gamma_{(BSM)}^{\mu\nu}(p, q) = \frac{-g}{M_W} [\lambda (p.q g_{\mu\nu} - p_{\nu} q_\mu) + i \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma]
\]

- Study **shape changes** in DIS normalised CC Higgs \( \rightarrow \) bb cross section versus the azimuthal angle, \( \Delta\phi_{MET,J} \), between \( E_{T,\text{miss}} \) and forward jet.

In ep, full \( \Delta\phi \) range can be explored, here not shown yet.
**Kinematic distributions**

\[ M_H = 120 \text{ GeV}, \ E_e = 150 \text{ GeV}, \ E_p = 7 \text{ TeV} \]

a-b) Kinematic distributions of generated Higgs
c-d) Reconstructed \( y_{J_B} \) and \( Q^2_{J_B} \)

Generated events passed to Pythia and to generic LHC-style detector:

- **Coverage:**
  - Tracking: \(|\eta| < 3\)
  - Calorimeter: \(|\eta| < 5\)
- **Calorimeter resolution**
  - EM: \(1\% \oplus 5\%/\sqrt{E}\)
  - Hadron: \(60%/\sqrt{E}\)
  - Cell size: \((\Delta\eta,\Delta\phi) = (0.03, 0.03)\)
- **Jet reconstructed** (cone \( \Delta R = 0.7 \))
- **b-tag performance**
  - Flat efficiency for \(|\eta| < 3\)
  - Efficiency/mis-ID
    - b-jet: 60%
    - c-jet: 10%
    - Other jets: 1%
Master thesis by Sergio Mandelli, Liverpool 2013: $M_H=125$ GeV

- Lowering of electron beam energy (more cost efficient) will challenge more detector design: worse separation between higgs and forward jet ($\Delta \eta$ shrinks) and b-quarks from Higgs decay are more forward.
- Supports $E_e=60$ GeV: $S/B \approx 1$ confirmed for $H \to bb$ with this $M_H=125$ GeV study.
- High acceptance Silicon Tracking System  $\sim 1^\circ$ (high tagging capabilities)
- Liquid Argon EM Calorimeter
- Iron-Scintillator Hadronic Calorimeter
- Forward Backward Calorimeters: Si/W Si/Cu

RHUL, Uta Klein, Higgs@LHeC
... as a Higgs “Facility” @ 1 ab⁻¹

→ for first time a realistic option of an 1 ab⁻¹ ep collider (stronger e-source, stronger focussing magnets) and excellent performance of LHC (higher brightness of proton beam); ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel  [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

<table>
<thead>
<tr>
<th>LHeC Higgs</th>
<th>CC (e⁻p)</th>
<th>NC (e⁻p)</th>
<th>CC (e⁺p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation</td>
<td>-0.8</td>
<td>-0.8</td>
<td>0</td>
</tr>
<tr>
<td>Luminosity [ab⁻¹]</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cross Section [fb]</td>
<td>196</td>
<td>25</td>
<td>58</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay</th>
<th>BrFraction</th>
<th>N_{CC}^H (e⁻p)</th>
<th>N_{NC}^H (e⁻p)</th>
<th>N_{CC}^H (e⁺p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → b̅b</td>
<td>0.577</td>
<td>113 100</td>
<td>13 900</td>
<td>3 350</td>
</tr>
<tr>
<td>H → c̅c</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
<td>170</td>
</tr>
<tr>
<td>H → τ⁺τ⁻</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
<td>370</td>
</tr>
<tr>
<td>H → μμ</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>H → 4l</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>H → 2l2ν</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>H → gg</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
<td>500</td>
</tr>
<tr>
<td>H → WW</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
<td>1 250</td>
</tr>
<tr>
<td>H → ZZ</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
<td>150</td>
</tr>
<tr>
<td>H → γγ</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>H → Zγ</td>
<td>0.00154</td>
<td>300</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

Ultimate e and p beams, 10 years of operation
E_e=60 GeV
E_p=7000 GeV

→ other BR’s started to be explored, e.g. ττ and more rare decyas
Steps towards an LHeC ERL Test Facility at CERN

STRAWMAN OPTICS DESIGN FOR THE LHeC ERL TEST FACILITY

A. Valloni, O. Bruning, R. Calaga, E. Jensen, M. Klein, R. Tomas, F. Zimmermann,
CERN, Geneva, Switzerland
A. Bogacz, D. Douglas, Jefferson Lab, Newport News Virginia

Figure 2: Consequent upgrade to LHeC pre-accelerator. By modifying the machine backleg to include a second full cryomodule, the recirculator can deliver higher beam energy of 600 MeV.

Table 3: Future ERLs for electron-hadron colliders

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JLab MEIC</th>
<th>BNL eRHIC</th>
<th>CERN LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>5-10</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>750</td>
<td>704</td>
<td>$n \times 40$</td>
</tr>
<tr>
<td># of passes</td>
<td>-</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Current/pass [mA]</td>
<td>3</td>
<td>50</td>
<td>6.6</td>
</tr>
<tr>
<td>Charge [nC]</td>
<td>4</td>
<td>3.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Bunch Length [mm]</td>
<td>7.5</td>
<td>2.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Current Test Facility Design (Final Stage)

Daresbury workshop: January 2013: 802 MHz, basic parameters reviewed

Strong international interest in collaborating:
AsTEC, IHEP Beijing, BINP Novosibirsk, BNL, Cornell, Jefferson Lab, U Mainz..

First step endorsed last week: Development of 2 cavity cryo modules by 2016 and design of the test facility by 2014 (“CDR”) and 2016 (“TDR”)
**Baseline: Energy Recovery Linac**

- Design constraint: power consumption < 100 MW \( \rightarrow E_e = 60 \text{ GeV} \)

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures

<table>
<thead>
<tr>
<th>Luminosity ( [10^{33}\text{cm}^{-2}\text{s}^{-1}] )</th>
<th>1-10**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector acceptance [deg]</td>
<td>1</td>
</tr>
<tr>
<td>Polarization [%]</td>
<td>90</td>
</tr>
<tr>
<td>IP beam sizes [( \mu \text{m} )]</td>
<td>7</td>
</tr>
<tr>
<td>Crossing angle [mrad]</td>
<td>0</td>
</tr>
<tr>
<td>e- ( L^* ) [m]</td>
<td>30</td>
</tr>
<tr>
<td>Proton ( L^* ) [m]</td>
<td>15</td>
</tr>
<tr>
<td>e- beta( ^*_{x,y} ) [m]</td>
<td>0.12</td>
</tr>
<tr>
<td>Proton beta( ^*_{x,y} ) [m]</td>
<td>0.1</td>
</tr>
<tr>
<td>Synchrotron power [kW]</td>
<td>10</td>
</tr>
</tbody>
</table>

- ep Lumi \( 10^{33} - 10^{34} \text{ cm} \text{s}^{-2} \text{s}^{-1} \) **
- 10 - 100 fb\(^{-1}\) per year
- 100 fb\(^{-1}\) – 1 ab\(^{-1}\) total
- eD and eA collisions have always been integral to programme
- e-nucleon Lumi estimates \( \sim 10^{31} (10^{32} ) \text{ cm} \text{s}^{-2} \text{s}^{-1} \) for eD (ePb) \( \rightarrow \) similar (more) than HERA ep luminosity

** based on existing high luminosity proposal
Two 1km long LINACs connected at CERN territory
Arcs of 1km radius: ~9km tunnel
3 passages with energy recovery
STATUS OF THE EXPLORATION OF AN ALTERNATIVE CLIC FIRST ENERGY STAGE BASED ON KLYSTRONS

D. Schulte, A. Grudiev, Ph. Lehruhn, G. McMoneagle, I. Syratchev, W. Volosyak, CERN, Geneva, Switzerland

PRELIMINARY DESIGN OF A HIGGS FACTORY \( \mu^+\mu^- \) STORAGE RING*

A.V. Zlobin*, Y.I. Alexahin, V.V. Kapin, V.V. Kashikhin, N.V. Mokhov, I.S. Tropin, FNAL, Batavia, IL 60510, U.S.A.

THE LHeC AS A HIGGS BOSON FACTORY

F. Zimmermann, O. Brüning, CERN, Geneva, Switzerland; M. Klein, DESY, Hamburg, Germany

TLEP: A HIGH-PERFORMANCE CIRCULAR e+e- COLLIDER TO STUDY THE HIGGS BOSON

M. Koratzinos, A.P. Bloudel, U. Geneva, Switzerland; R. Aleksan, CEA/Saclay, France; O. Brunner, A. Butterworth, P. Janot, E. Jensen, J. Osborne, F. Zimmermann, CERN, Geneva, Switzerland; J. R. Ellis, King’s College, London; M. Zanetti, MIT, Cambridge, USA

DESIGN OF A TeV BEAM DRIVEN PLASMA WAKEFIELD LINEAR COLLIDER*

E. Adli†, University of Oslo, Norway

J.P. Delahaye, S.J. Gessner, M.J. Hogan, T. Raubenheimer, SLAC, Stanford, USA

W. An, W. Mori, C. Joshi, UCLA, Los Angeles, USA, P. Muggli, MPP, Munich, Germany

Some IPAC2013 Papers

A MUON COLLIDER AS A HIGGS FACTORY*

D. Neuffer*, M. Palmer, Y. Alexahin, Fermilab, Batavia IL 60510, USA, C. Ankenbrandt, Muons, Inc., Batavia IL 60510, USA, J. P. Delahaye, SLAC, Menlo Park, CA 94025 USA

OPTIMIZATION PARAMETER DESIGN OF A CIRCULAR e+e- HIGGS FACTORY*

D. Wang*, J. Gao, M. Xiao, H. Geng, S. Xu, Y. Guo, N. Wang, Y. An, Q. Qin, G. Xu, S. Wang, IHEP, Beijing, 100049, China

CONSIDERATIONS FOR A HIGGS FACILITY BASED ON LASER WAKEFIELD ACCELERATION

S. Hillenbrand, KIT, Karlsruhe, Germany and CERN, Geneva, Switzerland

A.-S. Müller, KIT, Karlsruhe, Germany

Assmann*, D. Schulte, CERN, Geneva, Switzerland

SIMULATED BEAM-BEAM LIMIT FOR CIRCULAR HIGGS FACTORIES

K. Ohmi, KEK-ACCL, 1-1 Oho, Tsukuba, 305-0801, Japan

F. Zimmermann, CERN-ABP, Geneva, CH-1211, Switzerland
Lepton collider options beyond LHC

- SPS
- LEP/LHC

Distance in km:
-25 -20 -15 -10 -5 0 5 10 15 20 25
Lepton collider options beyond LHC

- **ILC** (phase 1 to full, up to 1 TeV c.m.)
- **CLIC** (similar footprint for up to 3 TeV c.m.)

TDR's published
Lepton collider options beyond LHC

- **ILC** (phase 1 to full, up to 1 TeV c.m.)
- **CLIC** (similar footprint for up to 3 TeV c.m.)
- **SPS**
- **LEP/LHC**
- **LHeC** (e-p, ERL)

TDR's published
Lepton collider options beyond LHC

**TDR’s published**

**After EPS**: FCC group formed for pp, ee, ep

**New compact accelerators**

- $\mu^+\mu^-$ collider
- Plasma Linear Collider
  - R&D on feasibility ongoing

**ILC** (phase 1 to full, up to 1 TeV c.m.)

**CLIC** (similar footprint for up to 3 TeV c.m.)

**SPS** (injector to TLEP?)

**LEP/LHC** (injector to TLEP?)

**LHeC** (e-p, ERL)

**TLEP** (up to 0.35 TeV c.m.)

**VHE-LHC** (100 km version)

TDR to be worked out
Future Circular Colliders at CERN

100 km with 20 T magnets provides 50 TeV per proton beam.

80 km may not be feasible due to Saleve, if placed below Lac Leman → 100 km?

New tunnel may host a ‘complete’ Higgs facility → FCC design study kick-off chaired by Michael Benedikt

LHeC to run synchronously with HL-LHC and later with VHE-LHC

*) “Civil Engineering Feasibility Studies for Future Ring Colliders at CERN”, Contributed by O.Brüning, M.Klein, S.Myers, J.Osborne, L.Rossi, C.Waaijer, F.Zimmerman to IPAC13 Shanghai
Using LHeC input: experimental uncertainty of predicted LHC Higgs cross section is strongly reduced to 0.4% due to PDFs and $\alpha_s$ high precision results.}

- clear Higgs mass sensitivity in cross section predictions.

- Higgs@LHC with $\sigma(H) \sim 50$ pb

- HL-LHC + ep Higgs potential and PDFs and $\alpha_s$ : transform the LHC facility into a genuine Higgs factory
Searches for Supersymmetry

Direct searches for Supersymmetry at the LHeC can be performed in the context of R-parity conserving or violating scenarios:

- R-parity = (-1)^{3(B-L)+2s} (R = 1 for SM particles, -1 for MSSM partners)

• Sensitivity for selectron-squark production for m(\text{select}) = 500 GeV

• Exclusion limits set by the LHC depend on the SUSY mass hierarchy. If no evidence for RPC SUSY is found in Run II, SUSY particles may be out of reach for LHC interplay in terms of PDF fundamental for HL-LHC

• If violated, various terms arising from superpotential

• Reach up to 1 TeV squark masses

• Feasibility of these searches will depend on LHC findings

Strong impact of improved PDF fits on the theoretical predictions for SUSY process at high sparticle masses. Ex.:

- gluino pair production (m_{\tilde{g}} = m_{\tilde{sq}})

Dependency on discovery potential and exclusion limits at 300 and 3000 /d for 14 TeV c.o.m. at the LHC

CT10 up ABKM09 down MSTW08 (equivalent to LHeC PDF)

Effect up to 1 TeV (plot to be replaced)

ATLAS-PUB-2012-001
With high energy and luminosity, the LHC search range will be extended to high masses, up to 5 TeV in pair production. At correspondingly high $x (> 0.5)$ the PDFs are unknown to a considerable extent → PDF uncertainties easily $> 100\%$ for high mass searches ➔ gluon density from LHeC (10% at $x=0.6, \sim 4$TeV)]

The HL-LHC (search) programme requires a much more precise understanding of QCD, which the LHeC provides (strong coupling, gluon, valence, factorisation, saturation, diffraction... ).

RHUL, Uta Klein, Higgs@LHeC
LHeC, in ep(A) collisions **synchronous** with pp (AA) HL-LHC running, could deliver fundamentally new insights on the structure of the proton (and nucleus) and the strong coupling $\alpha_s$ with high precision $\Rightarrow$ thus strengthen enormously the HL/HE-LHC physics case for searches [“On the Relation of the LHeC and the LHC”, arXiv:1211.5102]

Sensitivity to H→bb is estimated by an initial simulation study: LHeC has the potential to measure H → bb coupling with an S/N of $\sim$1 and to 1% (4%) accuracy with 60 GeV electron beam based on a luminosity of $10^{34}$ ($10^{33}$) cm$^{-2}$ s$^{-1}$.

At LHeC, various Higgs boson decays and Higgs CP eigenstates could be accessed via WW and ZZ fusion at c.m.s. energies of **1.3 TeV** and with **1 ab$^{-1}$** – fully complementary to LHC experiments.

**New high luminosity prospects in ep have just started to be explored and open exciting new potential for complementary, precision Higgs physics at the LHC facility $\Rightarrow$ brilliant opportunities for very nice BSc and Master theses, and PostDoc work**
For an overview:


Web page http://cern.ch/lhec  ➡️ New web and communication page coming

LHeC Meetings: http://indico.cern.ch/categoryDisplay.py?categId=1874

A recent brief overview paper: Oliver Bruening and Max Klein, arXiv:1305.2090

Conferences in 2013: LPCC (April), DIS Marseille, IPAC Shanghai, EPS Stockholm

Next workshop January 21/22 Chavannes - near CERN (no fee)
Please register if you are interested:
https://indico.cern.ch/conferenceDisplay.py?confId=278903
Two sessions: Detector+Physics and Testfacility+Accelerator

For the TDR phase: International Advisory Committee is being formed, chaired by emeritus CERN DG Herwig Schopper
Additional material
Analysis framework updated

- Calculate cross section with tree-level Feynman diagrams, e.g. PDF CTEQ6L1, using pT of scattered quark as scale for high scale ep processes like single t, Z, W, H productions
- CDR Higgs study : Madgraph 4 and DIS-customized Pythia
- **NEW:** full update for Madgraph5 v1.5.13
- Higgs mass 125 GeV as default → changes done in `models/sm` : masses and widths in restrict*py files and in `parameters.py`
- MG5 and Pythia now fully interfaced to most modern LHAPDF → test of LHeC PDFs
- code on lxplus: `/afs/.cern.ch/project/lhec/software/MadGraph`

**Caveat :** only valid for ep

eA needs modelling of nuclear evaporation and fragmentation
‘Detector’ based on ATLAS PGS

LHeC ! parameter set name
320 ! eta cells in calorimeter
200 ! phi cells in calorimeter
0.0314159 ! eta width of calorimeter cells  |eta| < 5
0.0314159 ! phi width of calorimeter cells
0.01 ! electromagnetic calorimeter resolution const
0.1 ! electromagnetic calorimeter resolution * sqrt(E)
0.4 ! hadronical calorimeter resolution * sqrt(E)
0.2 ! MET resolution
0.01 ! calorimeter cell edge crack fraction
cone ! jet finding algorithm (cone or ktjet) jets: cone<0.7 → change to anti-kt
5.0 ! calorimeter trigger cluster finding seed threshold (GeV)
1.0 ! calorimeter trigger cluster finding shoulder threshold (GeV)
0.5 ! calorimeter kt cluster finder cone size (delta R)
2.0 ! outer radius of tracker (m)
4.0 ! magnetic field (T)
0.000013 ! sagitta resolution (m)
0.98 ! track finding efficiency
1.00 ! minimum track pt (GeV/c)
3.0 ! tracking eta coverage
3.0 ! e/gamma eta coverage
2.5 ! muon eta coverage
2.0 ! tau eta coverage

Disclaimer:
PGS of LHC detector
+ flat b-tagging
in the full tracking range of |
\eta |<3.0
b: 60%, c: 10%, udsg: 1%
CAL coverage until |
\eta |<5.0
NC DY : current PDF uncertainties

14 TeV, VRAP L.Dixon et al, U.Klein
• high luminosity option using $L=10^{34}$ cm$^{-2}$s$^{-1}$ (LHeC) and $L=5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (HL-LHC) with 150 pile-up events (25 ns) [calculations by M. Klein]

⇒ Pile-up events expected for LHeC $< \sim 0.1$

Using pp LHC pile-up estimates

$$N(ep) = N(pp) \times \frac{s(yp)}{s(pp)} \times \frac{L(ep)}{L(pp)}$$

$$= 150 \times 0.003 \times 0.2$$

$$= 0.1$$

Direct calculation using total gamma-proton cross section of 300 μb

$$N(ep) = 300 \times 10^{-6} \times 10^{-24} \text{ cm}^2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \times 25 \times 10^{-9} \text{s}$$

$$= 0.075$$
$\alpha_s$

Per mille precision
NNNLO PDFs
Heavy quarks $\rightarrow$
Full set of PDFs

<table>
<thead>
<tr>
<th>Data input</th>
<th>Experimental uncertainty on $m_c$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA: NC+CC</td>
<td>100</td>
</tr>
<tr>
<td>HERA: NC+CC+ $F_2^{cc}$</td>
<td>60</td>
</tr>
<tr>
<td>LHeC: NC+CC</td>
<td>25</td>
</tr>
<tr>
<td>LHeC: NC+CC+ $F_2^{cc}$</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>case</th>
<th>$Q^2$ cut (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>0.12203</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>

From LHeC CDR
### Table 3.1: Assumptions used in the simulation of the NC cross sections on the size of uncertainties from various sources.

These assumptions correspond to typical best values achieved in the H1 experiment. Note that in the cross section measurement, the energy scale and angular uncertainties are relative to the Monte Carlo and not to be confused with resolution effects which determine the purity and stability of binned cross sections. The total cross section error due to these uncertainties, e.g. for $Q^2 = 100 \text{ GeV}^2$, is about 1.2, 0.7 and 2.0% for $y = 0.84$, 0.1, 0.004.

<table>
<thead>
<tr>
<th>source of uncertainty</th>
<th>error on the source or cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>scattered electron energy scale $\Delta E'_e/E'_e$</td>
<td>0.1 %</td>
</tr>
<tr>
<td>scattered electron polar angle</td>
<td>0.1 mrad</td>
</tr>
<tr>
<td>hadronic energy scale $\Delta E_h/E_h$</td>
<td>0.5 %</td>
</tr>
<tr>
<td>calorimeter noise (only $y &lt; 0.01$)</td>
<td>1-3 %</td>
</tr>
<tr>
<td>radiative corrections</td>
<td>0.5%</td>
</tr>
<tr>
<td>photoproduction background (only $y &gt; 0.5$)</td>
<td>1%</td>
</tr>
<tr>
<td>global efficiency error</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – checked against H1 MC
Case Study for $M_H=120$ GeV

- Measure deviation of the Higgs production with respect to the SM using the absolute rate of events.
- The ratio of the number of events in region B to that of region A in the $\Delta\phi_{\text{MET,J}}$ spectrum.

Assume Gaussian errors and the following systematics:
- 10% on the background rate
- 5% on the shape of the $\Delta\phi_{\text{MET,J}}$ in background
- 5% on the rate of the SM Higgs
- Evaluating theoretical error on $\Delta\phi_{\text{MET,J}}$ shape