Prospects for Higgs Physics at LHeC

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ICHEP 2012, Melbourne, July 7th, 2012
A Large Hadron Electron Collider at CERN


LHeC Study Group

CDR: About 200 experimentalists and theorists from 69 institutes

Further LHeC talks at ICHEP2012:
- QCD studies, jets and $\alpha_s$ by Claudia Glasman
- Low-x and eA physics by Paul Newman
- Detector design by Alessandro Polini
- Accelerator overview by Max Klein

http://cern.ch/lhec

Supported by
CERN, ECFA, NuPECC
Higgs at ~126 GeV: dominant decay to bb

LoSM Higgs Production

\[ \sqrt{s} = 1 - 2 \text{ TeV} : \]

- LHeC: up to 100 times HERA luminosity! (no pile-up)
- CC: \( \sigma \sim 200 \text{ fb} \) (@HERA \( \sim 0.5 \text{ fb} \))
- NC: \( \sigma \sim 50 \text{ fb} \) (Z heavier than W and couplings to fermions smaller)
Light SM Higgs production in ep

Higgs at ~126 GeV: dominant decay to bb

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ICHEP2012, Uta Klein, Higgs@LHeC

In ep, direction of quark (FS) is well defined.
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>

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

**Analysis framework**

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

- **Fragmentation**
- **Hadronization**
  - by PHSYTHIA (modified for ep)

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

- **H → bb selection**

- **Calculate cross section with tree-level Feynman diagrams (PDF CTEQ6L1)**

- **Generate final state of outgoing particles**

**Input parameters for initial studies (CC e⁻p):**
- 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 \( \geq 2 \)
Background (examples)

CC: H → b̅b (BR ~ 0.7 at M_H=120GeV)

σ~ 0.16 pb

at √s=2.05TeV

NOTE: Background sample numbers are after pre-selection in generator

Background (examples)

CC: 3 jets (~57 pb)

CC: single top production (~4.1 pb)

CC: Z production (~0.11 pb)

NC: b pair production (~1.1 nb)
Kinematic distributions

[M_H=120 GeV, E_e=150 GeV, E_p=7 TeV]

a-b) Kinematic distributions of generated Higgs

c-d) Reconstructed $y_{JB}$ and $Q^2_{JB}$

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%
Selection of $H \rightarrow b\bar{b}$

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

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

- **Higgs invariant mass**
  - $90 < M_H < 120 \text{ GeV}$
  - $\Rightarrow 44\%$ of remaining BG is single-top...

- **Single top rejection**
  - $M_{jjj,\text{top}} > 250 \text{ GeV}$
  - $M_{jj,W} > 130 \text{ GeV}$
  - $\Rightarrow 10\%$ mis-ID
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

Clear signal obtained with just cut based analysis already!
Case study for electron beam energy of 60 GeV using same analysis strategy
- luminosity values of 100 fb\(^{-1}\) (10 fb\(^{-1}\)/year) are feasible

- Linac with high electron polarisation of about 90% \(\Rightarrow\) enhancement by factor 1.9 feasible, i.e. around 500 Higgs candidates for \(E_e=60\) GeV allowing to measure H\(\rightarrow\)bb coupling with 4% statistical precision.

- Conservative estimate of S/N \(\Rightarrow\) more detailed study using OWN detector required.

Note: A parton-level study delivered S/N of 4.7.
• In SM, the only fundamental neutral scalar is a $J^{PC} = 0^{++}$.

• Various extensions of the SM can have several Higgs bosons with different $CP$ properties: e.g. MSSM has two $CP$-even and one $CP$-odd states.

• Therefore, should a neutral spin-0 particle be detected, a study of its $CP$-properties would be essential to establish it as the SM Higgs boson.

• To study the effects beyond SM, we need to establish the $CP$ eigenvalues for the Higgs states if $CP$ is conserved, and measure the mixing between $CP$-even and $CP$-odd states if it is not.
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

\[
\Gamma^{\mu \nu}_{(SM)}(p, q) = g M_W g^{\mu \nu} \quad \Rightarrow \quad \Gamma^{(BSM)}_{\mu \nu}(p, q) = \frac{-g}{M_W} [\lambda (p \cdot q g_{\mu \nu} - p_{\nu} q_\mu) + i \lambda' \epsilon_{\mu \nu \rho \sigma} p^\rho q^\sigma]
\]

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

In \( ep \), full \( \Delta \phi \) range can be explored, here not shown yet.
• Limits on effective coupling strengths of CP-even and CP-odd couplings are correlated.

• At LHeC, with 5-10 fb⁻¹, $|\lambda|$ values up to 0.2 to 0.4 can be uniquely probed for both the CP-even and CP-odd states of a light SM Higgs for electron beam energies in the range of 50 to 150 GeV.

$M_H = 120$ GeV
**Summary**

- **LHeC**, in ep(A) collisions synchronous with pp running, could deliver fundamentally new insights on the structure of the proton (and nucleus) with high precision.

- At LHeC, a light Higgs boson and its CP eigenstates could be uniquely accessed via WW and ZZ fusion - complementary to LHC experiments.

- Sensitivity to H → bb is estimated by an initial simulation study: LHeC has the potential to measure H → bb coupling to ~4% accuracy with 60 GeV electron beam. Other production and decay channels have to be explored still using dedicated LHeC detector simulation, instead of the PGS used so far.

- With the isolation of the H→bb signal at the LHeC, a window of opportunity opens for the exploration of the CP properties of the HVV vertex: LHeC offers a number of advantages
  - Clear separation of HWW and HZZ couplings
  - Very good signal to background ratio
  - Identification of backward forward directions (and full azimuthal coverage)

- Detector design is crucial for an efficient H→ bbar signal selection and CC/NC multi-jet background rejection. **Prospects have just started to be explored.**
SM Higgs cross section predictions [fb] for various electron beam energies

<table>
<thead>
<tr>
<th></th>
<th>100 GeV</th>
<th>120 GeV</th>
<th>160 GeV</th>
<th>200 GeV</th>
<th>240 GeV</th>
<th>280 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>E=50 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>102.4</td>
<td>80.6</td>
<td>50.3</td>
<td>31.6</td>
<td>19.9</td>
<td>12.5</td>
</tr>
<tr>
<td>E=100 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>201.3</td>
<td>165.3</td>
<td>113.2</td>
<td>78.6</td>
<td>55.2</td>
<td>39.1</td>
</tr>
<tr>
<td>E=150 GeV</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>286.3</td>
<td>239.5</td>
<td>170.4</td>
<td>123.3</td>
<td>90.5</td>
<td>67.1</td>
</tr>
</tbody>
</table>
LHC ! 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
0.2 ! electromagnetic calorimeter resolution * sqrt(E) 20% → 5%
0.8 ! hadronic calorimeter resolution * sqrt(E) 80% → 60%
0.2 ! MET resolution
0.01 ! calorimeter cell edge crack fraction
cone ! jet finding algorithm (cone or ktjet) jets: cone<0.7
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
2.4 ! muon eta coverage
2.0 ! tau eta coverage

Disclaimer:
PGS of LHC detector + flat b-tagging
in the full tracking range of |
η|<3.0
b: 60%, c: 10%, udsg: 1%
CAL coverage until |
η|<5.0
Anti-top selection

- \( M_{jj,W} > 130 \text{ GeV} \)
Experimental cuts will not change the basic picture of the $\Delta\phi_{\text{MET},J}$ dependence of normalised DIS CC Higgs cross section.

1. All 3 jets have $p_T > 30$ GeV.
2. b-tagged jets must have $|\eta| < 2.5$
3. remaining jet must have $1 < |\eta| < 5$
4. inv. mass of remaining jet and reconstructed Higgs > 250 GeV (at parton level, just the 3-jet invariant mass)
5. MET > 25 GeV
6. $\Delta\phi$ between reconstructed MET and each jets > 0.2.
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