Light SM Higgs in ep-collisions at the TeV scale

• Motivation
• Methodology
• Results for CC e-p
• Outlook

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DIS 2010, April 21st 2010
Motivation

- SM mass generation mechanism needs the Higgs boson
- LHC and Tevatron experiments will have the capability to observe or exclude the Higgs
- EW precision data and direct searches suggest a mass range $m_H \geq 114$ GeV, see e.g. recent review by J.Ellis [arXiv:1004.0648]

$$m_h = 116.4^{+15.6}_{-1.3} \text{ GeV}$$

LHC projections @ 14 TeV

$162 \text{ GeV} < m_h < 166 \text{ GeV}$
Higgs Boson Couplings

Higgs couplings to both gauge bosons and fermions determine the Higgs production cross sections.

→ Measurements of those provide crucial tests of the mass generation mechanism realised in nature!

→ If a Higgs with mass < 200 GeV is discovered at LHC, Higgs boson couplings and the total width may be extracted after several years of running, see e.g. M. Duhrssen et al. [hep-ph/0406323]

→ However, even then will be a measurement of the bottom Yukawa coupling extremely challenging since the $H \rightarrow bb$ dominant at $m_H \leq 130$ GeV is overwhelmed by QCD backgrounds for b-jets.

LHeC is an LHC upgrade proposal focusing on precision measurements of the partonic substructure of the proton and the strong coupling at $\sqrt{s}$ of 1 to 2 TeV.

An ep collider can add on valuable information w.r.t. LHC measurements in particular if a light SM Higgs was discovered and some knowledge on the total width and some boson couplings are known.
SM Higgs Production Examples

pp

\[ g \rightarrow t H \sim 10 \text{pb} \]
\[ g \rightarrow W H \sim 1 \text{pb} \]
\[ W \rightarrow W W \sim 1 - 0.1 \text{pb} \]

→ at LHC typically \( \sim 10^{-12} \)
of the total cross section

e^+e^-

250 \times 250 \text{ GeV}^2

\[ \sim 60 \text{ fb} \]
\[ + \ldots \sim 6 \text{ fb} \]
\[ + \sim 0.2 \text{ fb} \]

Decay depends strongly on \( m_H \)
- low masses : bbar, but also \( \gamma\gamma, \tau^+\tau^- \)
- high masses : WW, ZZ ... ttbar

Variety of search topologies with different S/B
SM Higgs Branching Fractions (HDECAY 2.0)

Branching fraction

$H \to b\bar{b}$

$H$ mass (GeV)

$H \to b\bar{b}$

Branching fraction

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$1$
Methodology

MadGraph: tree level calculations of various processes
SM parameters can be steered via SM parameter calculator (change $m_H$)
Beam energy, phase space cuts, PDF, scales etc. via steering card
Madgraph produced all Feynman diagrams shown in this talk.

Use version 4.4.17 including pythia-pgs interface modified for DIS
$\rightarrow$ Higgs decay is done via Pythia
PDF: CTEQ6L1 (LO PDF and LO $\alpha_S=0.13$)
Factorisation and renormalisations scales set to partonic c.m.s.
$\rightarrow$ Generator and detector-level Higgs search studies done by
M.Ishitsuka, K.Kimura, M Kuze, J. Maeda [Tokyo Institute of Technology]
and U.Klein, C.Hengler [University of Liverpool]

Higgs decay modes can be considered (package DECAY).
$\rightarrow$ Generator based studies using 4-vector smearing for detector by T. Han
and B. Mellado [arxiv:0909.2460] using Madgraph but fixed
renormalisation and factorisation scales.
$\rightarrow$ investigated Higgs searches at LHEC assuming Higgs mass is known
CC : LO SM Higgs Production

de-p (swap charges for e+p)

e- u -> ve h d

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

\[ \sim 200 \text{ fb} \]

(Z heavier than W and couplings to fermions smaller)

NC : LO SM Higgs Production

e-p (swap charges for e+p)

e- d -> e- h d

\[ \sim 50 \text{ fb} \]

around 90-80%

around 10-20%

around 1/3
Total LO Higgs Cross Sections vs $M_H$
140 GeV x 7000 GeV
Detector design will be crucial for signal detection and background rejection efficiency.
# Total CC e-p Higgs Cross Sections (fb) versus Electron Beam Energy

<table>
<thead>
<tr>
<th>Energy (GeV)</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>50 GeV</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>100 GeV</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>150 GeV</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>

- 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%.

Higgs Kinematics in e⁻p CC

- 50 k Higgs events, $m_H = 120$ GeV, $150$ GeV x $7000$ GeV
- Higgs decay via Pythia:
  ~68% into bbar + other decay modes
  ...somewhat lower than expected, similar number via DECAY in Madgraph (~72%)

Higgs rapidity in central to forward region

Higgs rapidity in central to forward region
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>parameter set name</td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>! eta cells in calorimeter</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>! phi cells in calorimeter</td>
<td></td>
</tr>
<tr>
<td>0.0314159</td>
<td>! eta width of calorimeter cells $</td>
<td>\eta</td>
</tr>
<tr>
<td>0.0314159</td>
<td>! phi width of calorimeter cells</td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>! electromagnetic calorimeter resolution const</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>! electromagnetic calorimeter resolution $\sqrt{E}$</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>! hadronic calorimeter resolution $\sqrt{E}$</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>! MET resolution</td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>! calorimeter cell edge crack fraction</td>
<td></td>
</tr>
<tr>
<td>cone</td>
<td>! jet finding algorithm (cone or ktjet)</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>! calorimeter trigger cluster finding seed threshold (GeV)</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>! calorimeter trigger cluster finding shoulder threshold (GeV)</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>! calorimeter kt cluster finder cone size (delta R)</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>! outer radius of tracker (m)</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>! magnetic field (T)</td>
<td></td>
</tr>
<tr>
<td>0.000013</td>
<td>! sagitta resolution (m)</td>
<td></td>
</tr>
<tr>
<td>0.98</td>
<td>! track finding efficiency</td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>! minimum track pt (GeV/c)</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>! tracking eta coverage</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>! e/gamma eta coverage</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>! muon eta coverage</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>! tau eta coverage</td>
<td></td>
</tr>
</tbody>
</table>

**Disclaimer:**

PGS of LHC detector + CDF type b-tagging will be replaced by LHeC detector!

(work is ongoing, possible values given in green)
Inclusive Kinematics (rec=Jaquet-Blondel)

- **gen y**
- **Pythia y**
- **rec y_{JB}**

- **gen Q^2**
- **Pythia Q^2**
- **rec Q^2_{JB}**

- $y_{JB} < 0.9$
- $Q^2 > 400$
Search for Higgs: Invariant Dijet Mass

\[ Q^2 > 400 \text{ GeV}^2, \gamma_{JB} < 0.9, E_{\text{jet}}^T > 20 \text{ GeV}, E_{\text{miss}}^T > 20 \text{ GeV}, \]
\[ \theta_{\text{jet}} > 1^\circ \text{ (CAL)}, \text{ NO b-tagging (!)}, \text{ no Higgs mass constraint (!)} \]

RED: 2 jets with lowest rapidity & \( E_{\text{total}}^T > 100 \text{ GeV} \)
BLUE: 2 jets with highest \( p_T \)

\( M_{jj} / \text{GeV} \)

209 fb\(^{-1}\)

Jets with lowest rapidity (red selection)

\( \eta = 4 \Rightarrow 2.1^\circ \)
Background

~100 k CC dijet+spectator events, $E_{\text{jet}}>5$ GeV, $\theta_{\text{jet}}>0.5$ deg, $M_{\text{jj}}>30$ GeV
58.8 pb (LO cross section, scale uncertainty expected to be 50-100%)
MadGraph generated 542 diagrams including higgs, single top, single W
→ After ‘simple’ dijet-selection: BG ~100 times larger than Higgs signal!
Remaining Background after kinematic and b-tagging cuts

- Higgs events
- CC 3jet BG
- CC $b\bar{b}j$
- CC $b\bar{c}s$

80 GeV < $M_H$ < 125 GeV (10 fb$^{-1}$)

Higgs / CC 3jets BG $\frac{S}{S+N} = 46.9 / 229 = 0.20$

- dominant CC 3-jets bgd due bcs processes (c-jet had high b-tag efficiency)
- 95% of bcs processes from single-top events
  $\rightarrow$ reject single top events using

$$N_{\text{Jet}} \geq 3, M_{\text{top}} > 200 \text{ GeV}, M_W > 130 \text{ GeV}$$
Background and Hadronic Energy Resolution after kinematic, b-tagging & single top cuts

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Higgs event</th>
<th>CC 3jet BG (Z → bb!)</th>
<th>S/(S+N)</th>
<th>S/V(S+N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 %</td>
<td>20.0</td>
<td>12.5</td>
<td>1.60</td>
<td>5.67</td>
</tr>
<tr>
<td>60 %</td>
<td>20.5</td>
<td>10.1</td>
<td>2.02</td>
<td>6.43</td>
</tr>
<tr>
<td>40 %</td>
<td>20.2</td>
<td>7.64</td>
<td>2.62</td>
<td>7.24</td>
</tr>
</tbody>
</table>
**B-Tagging in PGS $f_b(E_T, \eta)$**

Original based on CDF Run II

- stops mainly at $\eta \sim 1$

Change $\eta$ scale ($\times 2.5$)

- more LHeC-like $b$-tagging up to $\eta \sim 2.5$
# Higgs Search at LHeC for 10 fb⁻¹

<table>
<thead>
<tr>
<th>Cut</th>
<th>$b\bar{b}$ decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>no cut</td>
<td>1690</td>
</tr>
<tr>
<td>$Q^2 &gt; 400\text{GeV}^2$ &amp; $\gamma &lt; 0.9$</td>
<td>1520</td>
</tr>
<tr>
<td>$E_{T,\text{miss}} &gt; 20\text{ GeV}$</td>
<td>1390</td>
</tr>
<tr>
<td>$N_{\text{trk,electron}} = 0$</td>
<td>1370</td>
</tr>
<tr>
<td>$E_{T,\text{total}} &gt; 100\text{GeV}$</td>
<td>1060</td>
</tr>
<tr>
<td>$N_{\text{jet}} \geq 2$</td>
<td>1030</td>
</tr>
<tr>
<td>$N_{b\text{jet}} \geq 2$</td>
<td>328</td>
</tr>
<tr>
<td>$N_{\text{jet}} \geq 3$</td>
<td>256</td>
</tr>
</tbody>
</table>

$M_W > 130\text{GeV}$ & $M_{\text{top}} > 200\text{GeV}$ | 111 |

$90 < M_H < 120$

- Extended b-tagging improves signal extraction by more than factor 3.
- Work is ongoing!

→ Light SM Higgs could be (re)discovered in Hbb-channel at LHeC ...
**Another Promising Study**

- $m_H = 120$ GeV, $e^p$: 140 GeV X 7000 GeV using Madgraph and DECAY
- generated parton energies and angles smeared by resolutions, e.g. $\delta E_{\text{had}} = 60\%$ yields $\delta m_H = 7\%$ (w/o angular smearing)
- $60\%$ b-tagging efficiency applied on b-quarks and rejection factors of 10 and 100 for c and light quarks, resp., for $|\eta| < 2.5$
- require mass of 2 b-partons to be within $120 \pm 10$ GeV (assume known $m_H$)
- tag the forward spectator parton within $1 < \eta < 5$ and $p_T > 30$ GeV
- high invariant mass of H-candidate and spectator jet, $M_{HJ} > 250$ GeV

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**forward jet tagging**

inspired from VBF@LHC: Phys. Lett. B611(2005)60

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S: $12/\text{fb}^{-1}$
S/N = 4.7

[arxiv:0909.2460]
Outlook

- A first look to CC e-p higgs production confirms the early LEP+LHC studies on dominant dijet+spectator jet background and the importance of the b-tagging, hadronic energy resolution and forward jet tagging. → first results are very encouraging! It is all work in progress!

- Full MadGraph + Pythia + PGS chain is working for DIS and Pythia-Madevent files can be read in into detector simulation tools → Higgs channel can be used to optimise LHeC detector!

- More detailed background sources for CC e-p higgs has to be studied in particular beauty in photoproduction, but we need our own detector simulation for realistic estimates of rejection factors or tagging possibilities.

- Study also NC Higgs searches which is an important benchmark process for understanding the HZZ coupling.

- Study the extraction of Hbb coupling using LHeC Higgs cross sections in NC and CC in combination with LHC Higgs signal projections!
Special thanks to


for contributions and fruitful discussions.
Material

1\textsuperscript{st} LHeC workshop, 1\textsuperscript{st} - 3\textsuperscript{rd} September 2008, Divonne.
http://indico.cern.ch/conferenceDisplay.py?confId=31463
Talks by E.Perez and G.Weiglein; M.Kuze et al.; U.Klein

LHeC pre Meeting at DIS 2009, 25\textsuperscript{th} April 2009, Madrid.
http://indico.cern.ch/conferenceOtherViews.py?
  view=cdsagenda&confId=55684
Talks by M.Ishitsuka et al.; U.Klein

2\textsuperscript{nd} LHeC workshop, 1\textsuperscript{st} - 3\textsuperscript{rd} September 2009, Divonne.
http://indico.cern.ch/conferenceDisplay.py?confId=59304
Talks by M.Kuze et al.; B.Mellado and T.Han; U.Klein

LHeC Mini\_workshop, 8\textsuperscript{th} April 2010, Hamburg.
http://indico.cern.ch/conferenceDisplay.py?confId=83882
Talk by K.Kimura et al.

More material on the LHeC project can be found here:
http://www.ep.ph.bham.ac.uk/exp/LHeC/
Some inspiring previous studies

**Searching for the Higgs in e p collisions at LEP / LHC.**

**Standard-model Higgs boson production at HERA.**
Bernd A. Kniehl
Additional Slides
Large cross-section of $\bar{b}\bar{c}s$ or $\bar{b}\bar{u}d$ 3 Jets events.
95% of these processes was single-top production $\bar{t} \rightarrow W\bar{b} \rightarrow (\bar{c}s \text{ or } \bar{u}d) \bar{b}$
They were suspected 3Jets background for Higgs discovery.