Potential of Higgs and BSM Physics at the LHeC

Uta Klein
on behalf of
the LHeC/FCC-eh Study Group
Design constraint: power consumption < 100 MW : $E_e = 60 \text{ GeV}$ using energy recovery: ‘green’ technology

- **high electron polarisation of 80-90%**

Installation decoupled from LHC!
Concurrent ep and pp operation!

- ep Lumi $10^{34}$ cm s$^{-2}$ s$^{-1}$ **
- 100 fb$^{-1}$ per year
- $L= 1000$ fb$^{-1}$ total collected in 10 years
- eA luminosity estimates $\sim 10^{33}$ cm s$^{-2}$ s$^{-1}$ eA

** based on existing HL-LHC proposal

LHeC CDR: arXiv:1206.2913, see also recent LheC/FCC-eh WS@CERN
**VBF Higgs Production in ep** (top) and pp (bottom)

**ep**: Higgs production in ep comes uniquely from either CC or NC DIS

Clean bb final state, S/B $\gg 1$

**e-h Cross Calibration for Precision ep**

Clean, precise reconstruction and easy distinction of ZZH and WWH

**without pile-up**:

$< 0.1$@LHeC up to $1$@FCCeh events

**VBF: Small theoretical uncertainties!**

**pp**: Higgs production in pp comes predominantly from $gg \rightarrow H$:

high rates crucial for rare decays

VBF cross section about 200 fb

(about as large as at the LHeC).

Pile-up in pp at $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ is $150@25$ns

S/B very small for bb

**Final Precision in pp needs accurate N$^3$LO PDFs & $\alpha_S$**
SM Higgs in ep

U. Klein, @DIS2015

unpolarised electrons

$\sqrt{s}=3.5$ TeV

<table>
<thead>
<tr>
<th>$\sqrt{s}=1.3$ TeV</th>
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<tbody>
<tr>
<td>FCC-eh</td>
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<tr>
<td>LheC</td>
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$\sigma_h$ (fb)

<table>
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<tr>
<th>$\sigma$ [fb]</th>
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<tbody>
<tr>
<td>1.3 TeV</td>
</tr>
<tr>
<td>P=0</td>
</tr>
<tr>
<td>NC DIS</td>
</tr>
<tr>
<td>21</td>
</tr>
<tr>
<td>EIC</td>
</tr>
<tr>
<td>109</td>
</tr>
<tr>
<td>P=-0.8</td>
</tr>
<tr>
<td>CC DIS</td>
</tr>
<tr>
<td>196</td>
</tr>
</tbody>
</table>

HERA (L=0.5 fb⁻¹)

US-EIC

$\sigma$ @ EIC: 7 orders of magnitude lower

$\sqrt{s}=1.3$ TeV

LHeC / FCC-eh: Sizeable Higgs rates in charged current (CC) DIS for $L=100-1000$ fb⁻¹
**LHeC: Higgs “Facility” @ 1 ab⁻¹**

**Post-CDR:** 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)

⇒ full MG5 + Pythia + Delphes feasibility studies

<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>$N_H^{CC}_{e^-p}$</th>
<th>$N_H^{NC}_{e^-p}$</th>
<th>$N_H^{CC}_{e^+p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>0.577</td>
<td>113 100</td>
<td>13 900</td>
<td>3 350</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>0.029</td>
<td>5 700</td>
<td>700</td>
<td>170</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>0.063</td>
<td>12 350</td>
<td>1 600</td>
<td>370</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>0.00022</td>
<td>50</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow 4l$</td>
<td>0.00013</td>
<td>30</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow 2l2\nu$</td>
<td>0.0106</td>
<td>2 080</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>0.086</td>
<td>16 850</td>
<td>2 050</td>
<td>500</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>0.215</td>
<td>42 100</td>
<td>5 150</td>
<td>1 250</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>0.0264</td>
<td>5 200</td>
<td>600</td>
<td>150</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.00228</td>
<td>450</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>0.00154</td>
<td>300</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

⇒ Decay to bb is dominating decay mode: 58%

**LHC:** perfect Higgs factory for gluon-induced rare decays

Ultimate polarised e-beam of 60 GeV and LHC 7 TeV p-beams, 10 years of operation

Higgs decay to charm is factor 20 less likely than Hbb

$\sqrt{s} = 1.3$ TeV
Dijet Mass Candidates  

\[ \text{HFL untagged} \]

Delphes detector level

\[ \times 10^3 \]

- **Step 1**
  - Basic kinematic cuts and loose selection \((p_T > 15 \text{ GeV})\)

  - **Worst** case scenario plot: Photoproduction background (PHP) is assumed to be 100%!
  - However, addition of small angle electron taggers will reduce PHP to \(~1\%-2\%\)

- **Step 2**
  - HFL tagging

  - Generator cut of 60 GeV

- **Step 3**
  - BDT in Search Window

  - Before topmass cuts

- **BDT:** U Klein; Cut-based: M Kuze, M Tanaka

- **100 fb^{-1}**
  - 1 year of data

\( \text{M}_{jj} \)
realistic HFL tagging & BDT

LHeC @ L=1000 fb⁻¹

Hbb

10% PHP and 100% other bgd

$\kappa(\text{Hbb}) = 0.5\%$

remaining Hbb

Hcc

2% Hbb and 2% other bgd

$\kappa(\text{Hcc}) = 4\%$

Hbb signal with BDT>0

Hcc signal with BDT>0
LHC: First 3σ Hbb Evidence!

ATLAS, Aug 2017, sub. to JHEP

https://arxiv.org/abs/1708.03299

- use Higgs→bb in associated production with a W or Z boson
- explore various final states (e.g. Z→vv, W→lν, Z→ll categories)
- Run-I and II combined, S/B-weighted categories: μ=0.9±0.28(stat+syst)

Example:

- Encouraging result for HL-LHC prospects
- Very encouraging for prospects in ep that we can handle S/B ~10⁻³ processes with sophisticated analysis techniques

Hbb expectation @ LHeC for 36 fb⁻¹ (½ year data): δμ~7-8% with significance of ~14
SM Higgs into HFL Summary

- Assume a 60 GeV polarized electron beam and 1000 fb\(^{-1}\) (~10 years running)
- Expected number of signal events and error of coupling constant from BDT results.
- Background assumed to be known to ~2%

Expected number of signal events
(E\(_{e}\) = 60 GeV)

- FCC ep (~85,000 H\(\rightarrow\)bb events)
- DLHC (~35,000 H\(\rightarrow\)bb events)
- LHeC (~15,000 H\(\rightarrow\)bb events)

<table>
<thead>
<tr>
<th></th>
<th>LHeC (\sqrt{s} \sim 1.3) TeV</th>
<th>DLHC (\sqrt{s} \sim 1.8) TeV</th>
<th>FCC ep (\sqrt{s} \sim 3.5) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\kappa) (Hbb)</td>
<td>0.5%</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>(\kappa) (Hcc)</td>
<td>4%</td>
<td>2.8%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>
Using LHeC input: experimental uncertainty of predicted LHC Higgs cross section due to PDFs and $\alpha_s$ is strongly reduced to $<\sim 0.5$

theoretically clean path to determine $N^3$LO PDFs using ep DIS

ALL those ‘benefits’ for pp within the first few years, using $\sim 100$ fb$^{-1}$ ep data

NNLO pp–Higgs Cross Sections at 14 TeV

precision from LHeC can add a very significant constraint on the Higgs mass and challenge Lattice QCD calculations for $\alpha_s$:
Higgs Couplings at pp + ep
After HL-LHC and LHeC running concurrently for 10 years

\[ y_{V_i} = \sqrt{\frac{g_{V_i}}{2v}} = \sqrt{\frac{m_{V_i}}{v}} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

- \[ \int L dt = 300 \text{ fb}^{-1} \]
- \[ \int L dt = 3000 \text{ fb}^{-1} \]

ATLAS Simulation Preliminary

For pp:

- PDF+\(\alpha_s\) errors
  - 0.5% with new ep input!

- LHeC @1ab^{-1}
  - with much more Higgs results in 2038 ...

- \(\delta m_b\) to 10 MeV;
- \(\delta m_{\text{charm}}\) to 3 MeV

Uncertainty on pp Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..
Direct Measurement of $|V_{tb}|$

$1$ including top-quark mass uncertainty
$2$ $\sigma_{\text{theo}}$: NLO PDF4LHC11 NPPS205 (2010) 10, CPC191 (2015) 74
$3$ including beam energy uncertainty

$\frac{1}{12} > 1.000 \pm 0.005$ (expected)

$syst$ of 1-10%

Plot by O. Cakir et al.

ATLAS+CMS Preliminary

May 2017

$|f_{LV}V_{tb}| \pm ($meas$) \pm$ (theo)

$1.02 \pm 0.06 \pm 0.02$

$1.028 \pm 0.042 \pm 0.024$

$1.020 \pm 0.046 \pm 0.017$

$0.979 \pm 0.045 \pm 0.016$

$0.998 \pm 0.038 \pm 0.016$

$1.03 \pm 0.07 \pm 0.02$

$1.07 \pm 0.09 \pm 0.02$

$1.03 \pm 0.16 \pm 0.03$

$1.04 \pm 0.15 \pm 0.03$

$0.97 \pm 0.10 \pm 0.03$

$1.03 \pm 0.12 \pm 0.04$

$1.02 \pm 0.08 \pm 0.04$

$1.14 \pm 0.24 \pm 0.04$

$0.93 \pm 0.18 \pm 0.04$

$LHeC, 100 \text{ fb}^{-1}$

$1.000\pm0.005$

(expected)

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

$e$ beam: 60 GeV

$|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cd}|$, $|V_{cs}|$, $|V_{cb}|$, $|V_{td}|$, $|V_{ts}|$, $|V_{tb}|$

HAD: $N_t = 22000$, S/B=1.2

LEP: $N_t = 11000$, S/B=11

$\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$

$t$-channel:

ATLAS 7 TeV
PRD 90 (2014) 112006 (4.59 fb$^{-1}$)

ATLAS 8 TeV
arXiv:1702.02859 (20.2 fb$^{-1}$)

CMS 7 TeV
JHEP 12 (2012) 035 (1.17 - 1.56 fb$^{-1}$)

CMS 8 TeV
JHEP 06 (2014) 090 (19.7 fb$^{-1}$)

CMS combined 7+8 TeV
JHEP 06 (2014) 090

CMS 13 TeV
arXiv:1610.00678 (2.3 fb$^{-1}$)

ATLAS 13 TeV
JHEP 04 (2017) 086 (3.2 fb$^{-1}$)

$W_t$:

ATLAS 7 TeV
PLB 716 (2012) 142 (2.05 fb$^{-1}$)

CMS 7 TeV
PRL 110 (2013) 022003 (4.9 fb$^{-1}$)

ATLAS 8 TeV
JHEP 01 (2016) 064 (20.3 fb$^{-1}$)

CMS 8 TeV
PRL 112 (2014) 231802 (12.2 fb$^{-1}$)

LHC combined 8 TeV
ATLAS-CONF-2016-023, CMS-PAS-TOP-15-019

ATLAS 13 TeV
arXiv:1612.07231 (3.2 fb$^{-1}$)

$s$-channel:

ATLAS 8 TeV
PLB 756 (2016) 228 (20.3 fb$^{-1}$)
Exploring SM EFT & New Physics

In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.

What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:

Four fermion operators with leptons and quark fields:

- 59 operators or 2499 parameters experimentally to constraint!
- where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks
- ep potential for general BSM searches ‘that look like hadronic noise’ in pp
## BSM: LHeC-LHC complementarity

| Compositeness | • 4-fermion EFT: Lepton-quark compositeness scale  
• Quark radius |
| Leptoquarks and RPV squark decay | • Accessible range largely excluded, but not completely  
• Better measure of LQ characteristics, if they exist |
| Anomalous Triple Gauge Couplings | • Comparable to LHC |
| Top FCNC couplings | • couplings – great potential wrt HL-LHC |
| Vector-like leptons, heavy/excited leptons, bileptons, higher isospin lepton multiplets | • No constraints on VLL, so far, at LHC  
• Extend sensitivity to for lower masses |
| Heavy neutrinos, Majorana neutrinos, sterile neutrinos | • Symmetry-protected see-saw model  
• LHeC reach similar or better than HL-LHC |
| SUSY EW: compressed scenario, Higgsino, (dark sector) | • Long-lived neutral particles  
• Disappearing tracks – low background, compensate the low signal production rate |
| Anomalous Quartic Gauge Couplings | • Better control on background:  
no gluon exchange diagrams (mostly FCC?) |
| extended Higgs sector: higher isospin multiplet | • Singly- and doubly- charged higgs by VBF  
(mostly FCC) |


**FCNC Branching Ratios at Colliders**

- **improve limits on BR(t→γu), BR(t→Hu) considerably**

\[ E_e = 60 \text{ GeV} \]
\[ 1000 \text{ fb}^{-1} \]

**MVA**

- LHeC
- FCC-ep
- LHeC

**cut-based**

**Plot by C Schwanenberger**

- **ATLAS+CMS Preliminary**
- **LHCtopWG**
- November 2016

**BR(t→ Hu)**

- Each limit assumes that all other processes are zero

- **BR(t→ γu)**

- **95% CL**

- **test SUSY, little Higgs, technicolor...**
Sterile Neutrinos

\[ \mathcal{L}_N = - (Y_\nu)_{i\alpha} \bar{\nu}_R^i \Phi^\dagger \mathbf{L}^\alpha - \frac{1}{2} \bar{\nu}_R^i M_{ij} (\nu_R^j)^c + \text{H.c.} \]

\( \nu \) Yukawa matrix

sterile \( \nu \) mass matrix

\( X \quad Y \)

\( W \)

\( \ell_e \quad \theta_c \quad N \)

Non-unitarity parameters:

\[ \varepsilon_{\alpha\alpha} = - \theta_{\alpha}^* \theta_{\alpha} \]

Parton-level studies: For HL-LHC and LHeC, the vertex displacements between 1 mm and 1 m are assumed as background-free & 100% signal efficiency

\( \Rightarrow \) very good potentials

\( \Rightarrow \) however, studies need certainly more realism
e-p collider can definitely ‘win’ when the signal is too heavy for ee, and “impossible” at pp colliders.

→ LHeC and HL-LHC have similar mass reach, \( c\tau \) can be measured in ep (in pp: only MET measured)
Introduce phase dependent top Yukawa coupling

\[ \mathcal{L} = -i \frac{m_t}{v} \bar{t} [\cos \zeta_t + i \gamma_5 \sin \zeta_t] t h \]

Enhancement of the cross-section as a function of phase

Observe/exclude non-zero phase to better than 4\sigma \Rightarrow \text{With Zero Phase: Measure } ttH \text{ coupling with 17% accuracy} \Rightarrow \text{work ongoing on HE-LHeC & FCC-eh prospects}
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 → explore the CP properties of HVV couplings: BSM will modify CP-even (λ) and CP-odd (λ’) states differently

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

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

CDR initial study of HWW vertex:
CP couplings probed to
\( \lambda \sim 0.05 \)
\( \lambda' \sim 0.2 \)
based on 50 fb\(^{-1}\)
Double Higgs Production in ep

**FCC-eh 5% systematatic uncertainty included**

1σ for SM hhh for $E_e$ 60 (120)GeV and $10 \text{ab}^{-1}$

$$g_{hhh}^{(1)} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

Probing anomalous couplings: limits are obtained by scanning one of the non-BSM coupling while keeping other couplings to their SM values.

Explore LHeC and HE-LHeC potential!

Here $g_{...}^{(i)}, i = 1, 2$, and $\tilde{g}_{...}$ are real coefficients corresponding to the CP-even and CP-odd couplings respectively, of the $hhh$, $hWW$ and $hhWW$ anomalous vertices.
Invisible Higgs@LHeC
relating the Higgs and ‘dark’ matter

HL-LHC @ 3 ab^{-1} [arXiv:1411.7699]
Br(h \rightarrow E_T) < 3.5\% @95\% C.L., MVA based
For LHeC, assume: 1ab^{-1}, P_e=-0.9, cut based
Br(h \rightarrow E_T) < 6\% @ 95 \% C.L.

\[ C_{MET}^2 = \kappa_Z^2 \times Br(h \rightarrow E_T) \]

\( \kappa_Z \): BSM w.r.t. SM HZZ coupling

Colours: expected statistical significance

\( \rightarrow \) potential much enhanced for HE-LHeC @ 1.8 TeV & FCC-eh @ 3.5 TeV
\( \rightarrow \) NEW studies performed on Delphes detector-level using our Madevent framework
Branching for invisible Higgs

Results for full MG5+Delphes analyses look very encouraging for a measurement of the branching of Higgs to invisible in ep down to 2%. For 2 different detector options we get similar results.

We also checked LHeC ↔ FCC-eh scaling with the corresponding cross sections (* results in table): Downscaling FCC-eh simulation results to LHeC would give 4.5%, while up-scaling of LHeC simulation to FCC-eh would result in 2.1% — all well within uncertainties of projections.

- employ further synergies within LHC community and HL-LHC&FCC study group
  - further detector and analysis details have certainly an impact on results
Exotic Higgs at LHeC@1ab⁻¹

[arXiv:1608.08458]

Btag scenarios

(A) \( \epsilon_b = 70\%, \epsilon_c = 10\% \), \( \epsilon_{g,u,d,s} = 1\% \)
(B) \( \epsilon_b = 70\%, \epsilon_c = 20\% \), \( \epsilon_{g,u,d,s} = 1\% \)
(C) \( \epsilon_b = 60\%, \epsilon_c = 10\% \), \( \epsilon_{g,u,d,s} = 1\% \)
(D) \( \epsilon_b = 60\%, \epsilon_c = 20\% \), \( \epsilon_{g,u,d,s} = 1\% \)

95\% C.L. for \( m_\phi \) of 20, 40, 60 GeV for

\[
C_{4b}^2 = \kappa_V^2 \times \text{Br}(h \to \phi\phi) \times \text{Br}^2(\phi \to b\bar{b})
\]

is 0.3\%, 0.2\% and 0.1\%
Impact of PDFs @ High x

- Large uncertainties in high x PDFs limit searches for new physics at high scales. Many interesting processes at LHC are gluon-gluon initiated: top, Higgs, … and BSM processes, such as gluino pair production.

- For HL-LHC → studied in detail impact of LHeC precision partons.

- Studies updated with modern PDF sets
  - $M(\text{squark}) = M(\text{gluino}) = \mu_R = \mu_F$
  - LHeC PDF uncertainty attached to MMHT14

High-x parton density are small and highly uncertain → negative x-section at high masses for NNPDF30nlo → x-section calculation unstable → exclude replica.

Christoph Borschensky
Michael Kramer
LHC (14 TeV)

$M_{\tilde{g}} = M_{\tilde{q}}[\text{TeV}]$

arXiv:1211.5102
... to take home

- The LHC is fantastic – let’s use it as best as we can!
- An ep@LHC collider – dubbed LHeC - could be build as an O(10%) cost upgrade to HL-LHC: ep running concurrently with HL-LHC pp (from 2028-2038).
- LHeC would complement the pp program by providing invaluable DIS data and high precision PDF, $\alpha_S$ and $N^3LO \rightarrow$ turn HL-LHC into a powerful Higgs factory

- LHeC is surprisingly good at probing Higgs couplings - comparable to lepton colliders e.g. for Hbb.
- BSM sensitivity of ep shown by selected topics like sterile neutrinos, FCNC and Higgsino
- HL-LHC and LHeC are unique ‘add-ons’ \rightarrow deserves further dedicated joint studies.
Additional Sources & Thanks to

• Much more material can be found here: LHeC and FCC-eh Workshop, September 2017, CERN
  https://indico.cern.ch/event/639067/

• The LHeC/FCC-eh study group, http://cern.ch/lhec.

• “On the Relation of the LHeC and the LHC” [arXiv:1211.5102]

• 1st FCC Physics Workshop, 16.1.-20.1.2017, CERN
  https://indico.cern.ch/event/550509/

Special thanks to my colleagues in the LHeC/FCC-eh Higgs group, the project leader Max Klein, our detector expert Peter Kostka, and our bi-weekly Higgs-top working group discussions.
The ep Landscape: Luminosity vs $\sqrt{s}$

China
CEIC1 = Chinese version of Electron-Ion Collider ("A dilution-free mini-COMPASS")

U.S.
MEIC1 = EIC@Jlab
MEIC2 = EIC@BNL

Europe
LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

future extensions

http://cerncourier.com/cws/article/cern/57304
LHC: Total Higgs Cross Sections @ N^3LO

PDF + ALPHAS UNCERTAINTY

48.58 pb = 16.00 pb (+32.9%) (LO, rEFT)
  + 20.84 pb (+42.9%) (NLO, rEFT)
  - 2.05 pb (-4.2%) ((t, b, c), exact NLO)
  + 9.56 pb (+19.7%) (NNLO, rEFT)
  + 0.34 pb (+0.2%) (NNLO, 1/m_t)
  + 2.40 pb (+4.9%) (EW, QCD-EW)
  + 1.49 pb (+3.1%) (N^3LO, rEFT)

DIFERENT VALUES FOR ABM PDFS

Falko Dulat for the N^3LO team.
CERN seminar 11.12.2015 https://indico.cern.ch/event/462111/
Tensions: $\alpha_s$ and $\sigma_{\text{Higgs}}^{\text{tot}}$ at 13 TeV

C. Anastasiou et al, arXiv: 1602.00695

Recommendation using PDF4LHC and 68% CL

$$\sigma = 48.58 \text{ pb}^{+2.22 \text{ pb}(+4.56\%)}_{-3.27 \text{ pb}(-6.72\%)} \text{ (theory)} \pm 1.56 \text{ pb} (3.20\%) \text{ (PDF} + \alpha_s\text{).}$$

ABM prediction

$$\sigma_{\text{ABM12}} = 45.07 \text{ pb}^{+2.00 \text{ pb}(+4.43\%)}_{-2.88 \text{ pb}(-6.39\%)} \text{ (theory)} \pm 0.52 \text{ pb} (1.17\%) \text{ (PDF} + \alpha_s\text{).} \quad (8.3)$$

The significantly lower central value is mostly due to the smaller value of $\alpha_s$, which however is also smaller than the world average.
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations): top quark expected to be most sensitive to BSM physics, due to large mass

- high precision measurements of $V_{tb}$ and search for anomalous $W_{tb}$ couplings
- direct measurement of top quark charge and search for anomalous $t\bar{t}b\gamma$ couplings (e.g. EDM, MDM)
- measurement of top isospin and search for anomalous $t\bar{t}bZ$ couplings (e.g. EDM, MDM)
- sensitive search for FCNC couplings will constrain BSM models that predict FCNC (e.g. SUSY, little Higgs, technicolour)
Cut-based Results for Hbb @ LHeC

Masahiro Tanaka, Masahiro Kuze

Various studies pursued since the LHeC CDR [before the Higgs discovery, see http://cern.ch/lhec] focusing on SM 125 GeV Higgs decay into b-quarks

- Assumed 1000 fb\(^{-1}\) of statistics. (~10 years running for LHeC.)
- Veto efficiency of 90% for photo-production background is assumed, using forward electron tagging.

Precision of coupling constant (Statistics error only)

\[ \kappa = \frac{\sqrt{N_s + N_b}}{2N_s} \]

Signal: 3600
Bkg: 1250
\( \kappa \) (Hbb) \sim 0.97%
Analysis Framework

- Calculate cross section with tree-level Feynman diagrams (any UFO) using $p_T$ of scattered quark as scale (CDR ̄s) for ep processes with MadGraph5
- Standard HERA tools can NOT to be used!
- Higgs mass 125 GeV as default
- Fragmentation & hadronisation uses ep-customised Pythia.

- Delphes ‘detector’ → displaced vertices and signed impact parameter distributions → studied for LHeC, and used for FCC-eh SM Higgs extrapolations
  - powerful method to optimise detector tuning and S/N for various Higgs, top and BSM decays
  - Ongoing: Integration of eh into FCC simulation framework
SM Higgs Production in ep

σ (LO QCD CTEQ6L1 $M_H=125$ GeV)

<table>
<thead>
<tr>
<th>c.m.s. energy</th>
<th>1.3 TeV @LHC</th>
<th>3.5 TeV @FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross section [fb]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC DIS</td>
<td>21</td>
<td>127</td>
</tr>
<tr>
<td>CC DIS</td>
<td>109</td>
<td>560</td>
</tr>
<tr>
<td>CC DIS polarised cross section [fb]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P=-80%</td>
<td>196</td>
<td>1008</td>
</tr>
</tbody>
</table>

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

• 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%.

→ Realistic and conservative HFL tagging within Delphes realised, and dependence on vertex resolution (nominal 10 μm) and anti-kt jet radius studied
→ Light jet rejection very conservative, i.e. factor 10 worse than ATLAS
→ used in full LHeC analysis and for FCC-eh extrapolations
**Hbb**: Using same background assumptions as for cut-based analysis, we get factor 5 more Hbb candidates (~15000) and a coupling error of 0.6%.

**Hcc**: High sensitivity to vertex resolution (Half res= 5 μm best) and jet radius (R=0.5 best) → expect about 500-600 Hcc candidates
LHeC: BDT Result for $H \rightarrow cc$

NEW: Using $R = 0.5$ anti-kt jets and ATLAS IBL vertex resolution (5 $\mu$m)

$\rightarrow$ Hbb and Hcc candidates increased by factor $\sim 4$ w.r.t. anti-kt $R=0.9$ jets

$\rightarrow$ Further BDT optimisation for Hcc

For $L=1000 \text{ fb}^{-1}$: All background cross sections assumed to 2% after 10 years of running; $\sim 15000$ Hbb evts means $\delta \mu(Hbb) \leq 1 \ldots 2 \%$
Double Higgs Production at FCC-eh


\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^{(3)}_{h_h h_h} + \mathcal{L}^{(3)}_{h_W W} + \mathcal{L}^{(4)}_{h_h h_W W}. \]

\[ \mathcal{L}^{(3)}_{h_h h_h} = \frac{m_h^2}{2v} (1 - g^{(1)}_{hhh}) h^3 + \frac{1}{2v} g^{(2)}_{hhh} h \partial_\mu h \partial^\mu h, \] (2)

\[ \mathcal{L}^{(3)}_{h_W W} = -g \left[ \frac{g^{(1)}_{h_W W}}{2m_W} W^{\mu \nu} W^\dagger_{\mu \nu} h + \frac{g^{(2)}_{h_W W}}{m_W} (W^\nu \partial^\mu W^\dagger_{\mu \nu} h + h.c) \right. \]
\[ \left. + \frac{g^{(3)}_{h_W W}}{2m_W} W^{\mu \nu} \tilde{W}^\dagger_{\mu \nu} h \right], \] (3)

\[ \mathcal{L}^{(4)}_{h_h h_W W} = -g^2 \left[ \frac{g^{(1)}_{h_h h_W W}}{4m_W^2} W^{\mu \nu} W^\dagger_{\mu \nu} h^2 + \frac{g^{(2)}_{h_h h_W W}}{2m_W^2} (W^\nu \partial^\mu W^\dagger_{\mu \nu} h^2 + h.c) \right. \]
\[ \left. + \frac{g^{(3)}_{h_h h_W W}}{4m_W^2} W^{\mu \nu} \tilde{W}^\dagger_{\mu \nu} h^2 \right]. \] (4)

FCC-eh
SM(P=-0.8)
\( \sigma(HH)=430 \text{ ab} \)
in VBF!

→ All other g coefficients are anomalous couplings to the hhh, hWW and hhWW anomalous vertices
→ those are 0 in SM
Invisible Higgs Decay in $e^p$

CC production of an invisible Higgs

\[ e^- \rightarrow W^\pm \rightarrow h \rightarrow \chi^0 \]

\[ u \rightarrow W^\pm \rightarrow h \rightarrow \chi^0 \]

NC production of an invisible Higgs

\[ e^- \rightarrow Z \rightarrow h \rightarrow \chi^0 \]

\[ u \rightarrow Z \rightarrow h \rightarrow \chi^0 \]

→ We focus currently on NC DIS channel: employ that kinematic is over constrained using jet and electron information in the final state

→ We use the idea from C. Zhang and Y.-L. Tang: We emulate Higgs to invisible by assuming a branching of 100% for $H \rightarrow ZZ \rightarrow 4\nu$

→ We started to study signals and backgrounds using CMS-style and FCC-eh-style ‘Delphes’ detectors, using same analysis strategies as developed for LHeC (C. Zhang and BSc thesis S. Kawaguchi)
Selection Requirements

Basic cuts (Cut 0)

- $N(\text{jets})$ for the jet and the electron
- $p_T$ for the leading jet and the leading electron
- for the leading jet and the leading electron
- for the leading jet and the leading electron

Cut 1: $|\Delta \phi_{\text{jet},E_{\text{miss}}}| > 1 \text{ rad}$
Cut 2: $E_{\text{miss}} > 50 \text{ GeV}$
Cut 3: $\eta_{\text{jet}} - \eta_e > 3$
Cut 4: $\phi_{\text{jet}} - \phi_e < 2.4$
Cut 5: $-1.3 < \eta_e < 1.1$
Cut 6: $0.08 < y_e < 0.55$
Cut 7: require 1 electron, 1 jet, and veto tau’s and muons
Results for FCC-eh - Using BDT

MVA using samples with 1 jet and 1e- with high pT, and other variables as a BDT input.

<table>
<thead>
<tr>
<th>BDT &gt;</th>
<th>Signal</th>
<th>Z[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>31961</td>
<td>3.25</td>
</tr>
<tr>
<td>0.05</td>
<td>29932</td>
<td>2.81</td>
</tr>
<tr>
<td>0.1</td>
<td>25686</td>
<td>2.40</td>
</tr>
<tr>
<td>0.15</td>
<td>19898</td>
<td>2.08</td>
</tr>
<tr>
<td>0.2</td>
<td>13020</td>
<td>1.93</td>
</tr>
<tr>
<td>0.25</td>
<td>6998</td>
<td>2.04</td>
</tr>
<tr>
<td>0.3</td>
<td>2320</td>
<td>2.82</td>
</tr>
</tbody>
</table>

Branching ratio calculated by $\frac{S}{\sqrt{S+B}}$:

$Z = \frac{13020 \times Br(h \rightarrow E \downarrow T)}{\sqrt{13020 \times Br(h \rightarrow E \downarrow T) + 15562}}$

In the case of $2\sigma$, $Br(h \rightarrow E \downarrow T) \sim 1.93\%$
for faking our signal feature:
one electron, one jet, and missing transverse energy ($E_{T\text{miss}}$)
$W^+j\nu$ and $W^-j\nu$ backgrounds and

\[ p + e^- \rightarrow W^- + j + \nu_e \]
\[ W^- \rightarrow e^- + \nu_e \]

$W_j\nu$ background

\[ p + e^- \rightarrow Z + j + e^- \]
\[ Z \rightarrow \nu + \bar{\nu} \]

$Z_j\nu$ background
Exotic Higgs Decays

\[ h \rightarrow \phi\phi \rightarrow 4b \]

\( \phi \): a spin-0 particle from new physics.

\[ e q \rightarrow \nu_e h q' \rightarrow \nu_e \phi \phi q' \rightarrow \nu_e b\bar{b} b b q' \]

\[ \mathcal{L}_{\text{eff}} = \lambda_h v h \phi^2 + \lambda_b \phi \bar{b} b + \mathcal{L}_\phi \text{decay, other} \]

- Well motivated signature in extended Higgs sector.
- Difficult to probe at hadron colliders.
- LHeC signal: here using CC channel.
- Backgrounds: CC multijet, CC t/h/W/Z+jets, PHP multijet.
- PHP backgrounds assumed to be negligible after MET requirements and electron tagging.
- Current analysis is done at parton level.

@LHeC: 95% C.L. for \( m_\phi \) of 20, 40, 60 GeV is 0.3%, 0.2% and 0.1% for \( C_{4b}^2 \)