Precision Higgs Physics at the FCC-eh

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on behalf of

the LHeC/FCC-eh Study Group

3rd FCC Physics and Experiments Workshop, January 16th, 2020
Two 802 MHz Electron LINACs + 2x3 return arcs: using energy recovery in same structure: sustainable technology with power consumption < 100 MW instead of 1 GW for a conventional LINAC.

- Beam dump: no radioactive waste!
- High electron polarisation of 80-90%

Concurrent eh and hh operation with same running time!

Genuine Twin Collider idea holds for FCC-hh and LHC.

Ep peak lumi $10^{34}$ cm$^{-2}$ s$^{-1}$ (based on existing HL-LHC design)

- ‘No’ pile-up: <0.1@LHeC; ~1@FCCeh

Scale dependencies of the LO calculations are in the range of 5-10%. Tests done with MG5 and Comp Hep.

NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to 5%.

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NLO QCD corrections are small, but shape distortions of kinematic distributions up to 20%. QED corrections up to 5%.


Total cross section [fb]
(LO QCD CTEQ6L1 $M_H=125$ GeV)

<table>
<thead>
<tr>
<th>c.m.s. energy</th>
<th>1.3 TeV LHeC</th>
<th>3.5 TeV FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC DIS</td>
<td>109</td>
<td>560</td>
</tr>
<tr>
<td>NC DIS</td>
<td>21</td>
<td>127</td>
</tr>
</tbody>
</table>

$P=\sim-80\%$
| CC DIS | 196   | 1008 |
| NC DIS | 25    | 148  |

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

Theory well under control in ep! LHeC will deliver $N^3$LO PDFs, $m_c$ to 3 MeV, $m_b$ to 10 MeV and $\alpha_s$ to $\sim0.1-0.2\%$
Analysis Framework and Detector

- Calculate cross section with tree-level Feynman diagrams (any UFO) using $p_T$ of scattered quark as scale (CDR $\hat{s}$) for ep processes with MadGraph5; parton-level x-check CompHep

- Fragmentation & hadronisation uses ep-customised Pythia.

- **Delphes ‘detector’**
  - displaced vertices and signed impact parameter distributions studied for LHeC and FCC-eh SM Higgs; and for extrapolations [PGS for CDR and until 2014]
  - ‘Standard’ GPD LHC-style detectors used and further studied based on optimising Higgs measurements, i.e. vertex resolution a la ATLAS IBL, excellent hadronic and elmag resolutions using ‘best’ state-of-the-art detector technologies (no R&D ‘needed’)

- Analysis requirements fed back to ep detector design


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**Event generation**
- SM or BSM production
- CC & NC DIS background
  - by MadGraph5/MadEvent

**Fast detector simulation**
- by Delphes
  - test of LHeC detector

**S/B analysis**
- cuts or BDT

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- **Event generation**
  - by MadGraph5/MadEvent
  - Fragmentation
  - Hadronization
  - by PYTHIA (modified for ep)*

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DIS Kinematics at FCC-\(\text{e}\text{e}\) @ \(\sqrt{s}=3.5\) TeV

\[
q = (k - k'), q^2 = -Q^2 \\
s = (k + P)^2 \\
(xP + q)^2 = m^2, P^2 = M_p^2 \\
\text{if } (Q^2 \gg x^2 M_p^2, m^2): \\
q^2 + 2xPq = 0 \\
x = \frac{Q^2}{2Pq} \\
x_{1,2} = (M/\sqrt{s}) \exp(\pm y) \\
Q^2 \sim M^2
\]
Higgs decay particles (here to $W^*W$), struck quark and scattered lepton are well separated in detector acceptance.
Rates and Geometric acceptances

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fraction</th>
<th>Events in CC</th>
<th>Events in NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>0.581</td>
<td>1 208 000</td>
<td>175 000</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>0.215</td>
<td>447 000</td>
<td>64 000</td>
</tr>
<tr>
<td>$gg$</td>
<td>0.082</td>
<td>171 000</td>
<td>25 000</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.063</td>
<td>131 000</td>
<td>20 000</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>0.029</td>
<td>60 000</td>
<td>9 000</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.026</td>
<td>54 000</td>
<td>7 900</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.0023</td>
<td>5 000</td>
<td>700</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>0.0015</td>
<td>3 000</td>
<td>450</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>0.0002</td>
<td>400</td>
<td>70</td>
</tr>
</tbody>
</table>

- Large acceptance for jets up to $\eta=6$ for FCC-eh to cover forward scattered jet
- Tracking acceptance up to $\eta=3.5$ for Higgs decay products to ensure high acceptances of 57% at FCC-eh [70% at LHeC] for dominant decays
- Acceptance of muon spectrometer up to $\eta=4$ opens prospect to measure $H \rightarrow \mu\mu$ signal strength to ~6% at FCC-eh
Higgs in eh: **cut** based results

Example of samples:

<table>
<thead>
<tr>
<th></th>
<th>Unpolarised (P=0) samples $E_e=60$ GeV</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_p=7$ TeV</td>
<td>$E_p=50$ TeV</td>
<td>FCC</td>
</tr>
<tr>
<td></td>
<td>LHeC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal CC:H→bb</td>
<td>0.113 (pb) 0.2M</td>
<td>0.467 (pb) 0.15M</td>
<td></td>
</tr>
<tr>
<td>CC jij no top</td>
<td>4.5</td>
<td>21.2</td>
<td></td>
</tr>
<tr>
<td>CC single top</td>
<td>0.77</td>
<td>9.75</td>
<td></td>
</tr>
<tr>
<td>CC Z</td>
<td>0.52</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>NC Z</td>
<td>0.13</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>PA jij</td>
<td>41</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nsample</td>
<td>N/ $\sigma$ (fb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1760</td>
<td>321</td>
<td></td>
</tr>
<tr>
<td></td>
<td>570</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1160</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1140</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>455</td>
<td></td>
</tr>
</tbody>
</table>

Delphes ep-style detector + flat parton-level b-tagging for $|\eta|<3.0$

- conservative HFL tagging:
  - $b$: 60%, $c$: 10%, udsg: 1%
  - CAL coverage $|\eta|<5$ LHeC [<6 FCC-eh]

**Mass of 2 b-jets after event selection**

H→bb: S/N>1 using *conservative* light misID and *simple* cuts

→ confirmed earlier & post CDR studies

100 fb$^{-1}$

~ 1 year of data

Higgs@LHeC: see also CDR & PRD.D82:016009,2010

Note: plenty of single Z, W and top in ep
Hunting for Precision Hbb

Dijet Mass Candidates \textit{HFL untagged} at Delphes detector level

\begin{itemize}
  \item \textbf{Step 1}
    \begin{itemize}
      \item Basic kinematic cuts and loose selection ($p_T > 15$ GeV)
    \end{itemize}

  \item \textbf{Step 2}
    \begin{itemize}
      \item HFL tagging
    \end{itemize}

  \item \textbf{Step 3}
    \begin{itemize}
      \item BDT in Search Window
    \end{itemize}
\end{itemize}

\textbf{‘Worst’ case scenario plot}: Photoproduction background (PHP) is assumed to be 100%!

PHP update: Modelled via Weiszaecker-Williams and cross-checked with Pythia.

\rightarrow addition of small angle electron taggers will reduce PHP to \sim 1-2%
BDT Results for Higgs @ LHeC
using realistic HFL tagging at Delphes detector level

Hbb: Clear sensitivity to chosen jet radius; rather robust w.r.t. vertex resolution in range of 5 to 20 μm for 0.5<pT<5 GeV

Hcc: High sensitivity to vertex resolution (nominal 10 μm) and jet radius choice → expect about 400-600 Hcc candidates

[similar event numbers for ILC Zqq-Hcc study arXiv: 0909.1052]
Higgs in ep – clean S/B, no pile-up

→ further improvements using BDT

realistic HFL tagging & BDT

LHeC @ L=1000 fb⁻¹

μ=σ/σ_{SM}

δμ/μ(Hbb) = 0.8%

Assuming background in control regions understood to 2% and negligible MC statistics for background in signal region; SM Higgs bb contribution in cc controlled by genuine Hbb measurement and b and c-jet correlation, see e.g. methodology ILC Hcc study arXiv: 0909.1052

[ILC Zqq-Hcc study got 8.8% for Hcc signal strength for M_{H}=120 GeV σ_{pol}(Hcc)=6.9 fb with similar Hcc, Hbb event numbers but factor 6.8 higher SM background than LHeC]
SM Higgs Signal Strengths in \( ep \)

\[ \delta \mu / \mu \text{ [%]} \]

HWW and HZZ signal strengths measured at once in DIS via selection of the final state (e or \( \nu \))

\[ \begin{align*}
\text{WW} \rightarrow H & \quad \text{LHeC 200 fb} \\
& \quad \text{FCC-eh 1 pb}
\end{align*} \]

\[ \begin{align*}
\text{ZZ} \rightarrow H & \quad \text{LHeC 25 fb} \\
& \quad \text{FCC-eh 148 fb}
\end{align*} \]

\( E_e = 60 \text{ GeV} \)

\( E_e = 60 \text{ GeV} \quad \text{LHeC} \ E_p = 7 \text{ TeV} \ L=1ab^{-1} \quad \text{HE-LHC} \ E_p = 14 \text{ TeV} \ L=2ab^{-1} \quad \text{FCC} : E_p = 50 \text{ TeV} \ L=2ab^{-1} \)

\( \rightarrow \text{NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.} \)
... and Consistency Checks of EW Theory

→ similar tests possible using various cms energy CLIC machines, see e.g. [arXiv:1608.07538], however, in ep, we could perform them with one machine

\[
\frac{\sigma_{WW \rightarrow H \rightarrow ii}}{\sigma_{ZZ \rightarrow H \rightarrow ii}} = \frac{\kappa_W^2}{\kappa_Z^2}
\]

\[
\frac{\kappa_W}{\kappa_Z} = \cos^2 \theta_W = 1 - \sin^2 \theta_W
\]

→ Dominated by H→bb decay channel precision

➢ Very interesting consistency check of EW theory

➢ Values for \(\cos^2 \Theta\) given here are the PDG value as central value 0.777 and uncertainty from ep Higgs measurement prospects

LHeC: ± 0.010
HE-LHeC ± 0.006
FCC-eh ± 0.004

→ Another nice test: How does the Higgs couple to 3\textsuperscript{rd} and 2\textsuperscript{nd} generation quark?

b is down-type and c is up-type
**WW to Higgs to W*W to 4 jets**

- CC DIS Higgs production and decay to W*W gives direct access to $g_{HWW}^4$ assuming no NP in production and decay

→ important process: allows *nearly direct* access to $g_{HWW}$ and $\delta g_{HWW} = 1/4 \delta \mu/\mu (H \rightarrow W^*W)$

**New study** for FCC-eh (at 3.5 TeV): Signal and Background generated by usual MG5+Pythia framework using $\text{BR}(H \rightarrow WW)=21.5\%$ and 67\% for $W \rightarrow jj$ decay: $\sigma=100 \text{ fb} \sim 45\%$ of $\sigma(HWW)$

→ passed thru FCC-eh Delphes detector
→ background processes dominated by CC multijets, top and single H,W, Z + jets ($4^{\text{th}}$ + more jets from shower)

→ various anti-kt R choices studied for the resolved case (all 4 jets reconstructed)
→ optimal choice $R=0.7$

→ more event categories and decay modes could be added a la LHC-style studies
H → WW* analysis strategy & results

Reconstructed W*, W and Higgs, after jet combinatorics based on selecting at least 5 jets with $p_T > 6$ GeV and finding the higgs candidate which has two jet pairs with min $\Delta \eta$, and max $\Delta \eta$ between Higgs and fwd jet, and max $\Delta \phi$ between Higgs and ETmiss or Higgs and fwd jet passed to BDT

→ Acceptance X efficiency of 20% and purity of 68% that true forward jet is identified for pre-selected events
→ HWW signal strengths of 1.9 to 2.5% reached depending on background assumptions and pre-selection & BDT details
→ very nice results expected for $\delta_{\text{HWW}}$ of 0.5 to 0.6% from this channel only

At Delphes detector level

NO mass requirements in combinatorics!
Stand-alone ep $\kappa$ Coupling Fits

Assuming SM branching fractions weighted by the measured $\kappa$ values, and $\Gamma_{md}$ (c.f. CLIC model-dependent method)

see e.g. [arXiv:1608.07538]

Note: also $H$ in $ePb$

Very high precision due to CC+NC DIS in clean environment in luminous, energy frontier $ep$ scattering
**Higgs @ HL-LHC, ee and FCC-eh**

within kappa framework; statistical errors only

... to explore the synergy fully

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC(_{250})</th>
<th>CLIC(_{380})</th>
<th>FCC-ee 5 @ 240 GeV</th>
<th>FCC-ee +1.5 @ 365 GeV</th>
<th>FCC-ee HL-LHC</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (ab(^{-1}))</td>
<td>3</td>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>+4</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>Years</td>
<td>25</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>+4</td>
<td>—</td>
<td>20</td>
</tr>
<tr>
<td>(\delta \Gamma_H/\Gamma_H) (%)</td>
<td>SM</td>
<td>3.8</td>
<td>6.3</td>
<td>2.7</td>
<td>1.3</td>
<td>1.1</td>
<td>SM</td>
</tr>
<tr>
<td>(\delta g_{HZZ}/g_{HZZ}) (%)</td>
<td>1.3</td>
<td>0.35</td>
<td>0.80</td>
<td>0.2</td>
<td>0.17</td>
<td>0.16</td>
<td>0.43</td>
</tr>
<tr>
<td>(\delta g_{HWW}/g_{HWW}) (%)</td>
<td>1.4</td>
<td>1.7</td>
<td>1.3</td>
<td>1.3</td>
<td>0.43</td>
<td>0.40</td>
<td>0.26</td>
</tr>
<tr>
<td>(\delta g_{Hbb}/g_{Hbb}) (%)</td>
<td>2.9</td>
<td>1.8</td>
<td>2.8</td>
<td>1.3</td>
<td>0.61</td>
<td>0.55</td>
<td>0.74</td>
</tr>
<tr>
<td>(\delta g_{Hcc}/g_{Hcc}) (%)</td>
<td>SM</td>
<td>2.3</td>
<td>6.8</td>
<td>1.7</td>
<td>1.21</td>
<td>1.18</td>
<td>1.35</td>
</tr>
<tr>
<td>(\delta g_{Hgg}/g_{Hgg}) (%)</td>
<td>1.8</td>
<td>2.2</td>
<td>3.8</td>
<td>1.6</td>
<td>1.01</td>
<td>0.83</td>
<td>1.17</td>
</tr>
<tr>
<td>(\delta g_{H\tau\tau}/g_{H\tau\tau}) (%)</td>
<td>1.7</td>
<td>1.9</td>
<td>4.2</td>
<td>1.4</td>
<td>0.74</td>
<td>0.64</td>
<td>1.10</td>
</tr>
<tr>
<td>(\delta g_{H\mu\mu}/g_{H\mu\mu}) (%)</td>
<td>4.4</td>
<td>13</td>
<td>n.a.</td>
<td>10.1</td>
<td>9.0</td>
<td>3.9</td>
<td>n.a.</td>
</tr>
<tr>
<td>(\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}) (%)</td>
<td>1.6</td>
<td>6.4</td>
<td>n.a.</td>
<td>4.8</td>
<td>3.9</td>
<td>1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>(\delta g_{Htt}/g_{Htt}) (%)</td>
<td>2.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2.4</td>
<td>ttH 1.7</td>
</tr>
<tr>
<td>(BR_{EXO}) (%)</td>
<td>SM</td>
<td>&lt; 1.8</td>
<td>&lt; 3.0</td>
<td>&lt; 1.2</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

→ Combine the complementary measurements for best physics outcome!
→ FCC-hh will be the machine to pin down HH and all rare decays!

Higgs-inv.: 1.2%
HH ~20%
Higgs Boson studies at future particle colliders

Table 3. Expected relative precision (%) of the $\kappa$ parameters in the kappa-0 scenario described in Section 2 for future accelerators. Colliders are considered independently, not in combination with the HL-LHC. No BSM width is allowed in the fit: both $\text{BR}_{\text{unt}}$ and $\text{BR}_{\text{inv}}$ are set to 0, and therefore $\kappa_V$ is not constrained. Cases in which a particular parameter has been fixed to the SM value due to lack of sensitivity are shown with a dash (-). A star (*) indicates the cases in which a parameter has been left free in the fit due to lack of input in the reference documentation. The integrated luminosity and running conditions considered for each collider in this comparison are described in Table 1. FCC-ee/eh/hh corresponds to the combined performance of FCC-ee_{240}+FCC-ee_{365}, FCC-eh and FCC-hh. In the case of HE-LHC, two theoretical uncertainty scenarios (S2 and S2’) [13] are given for comparison.

<table>
<thead>
<tr>
<th>kappa-0</th>
<th>HL-LHC</th>
<th>LHeC</th>
<th>HE-LHC S2</th>
<th>S2’</th>
<th>ILC 250</th>
<th>ILC 500</th>
<th>ILC 1000</th>
<th>CLIC 380</th>
<th>CLIC 15000</th>
<th>CLIC 3000</th>
<th>CEPC 240</th>
<th>FCC-ee ee_{240}</th>
<th>FCC-ee ee_{365}</th>
<th>FCC-ee/eh/hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W$ [%]</td>
<td>1.7</td>
<td>0.75</td>
<td>1.4</td>
<td>0.98</td>
<td>1.8</td>
<td>0.29</td>
<td>0.24</td>
<td>0.86</td>
<td>0.16</td>
<td>0.11</td>
<td>1.3</td>
<td>1.3</td>
<td>0.43</td>
<td>0.14</td>
</tr>
<tr>
<td>$\kappa_Z$ [%]</td>
<td>1.5</td>
<td>1.2</td>
<td>1.3</td>
<td>0.9</td>
<td>0.29</td>
<td>0.23</td>
<td>0.22</td>
<td>0.5</td>
<td>0.26</td>
<td>0.23</td>
<td>0.14</td>
<td>0.20</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>$\kappa_g$ [%]</td>
<td>2.3</td>
<td>3.6</td>
<td>1.9</td>
<td>1.2</td>
<td>2.3</td>
<td>0.97</td>
<td>0.66</td>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>1.5</td>
<td>1.7</td>
<td>1.0</td>
<td>0.49</td>
</tr>
<tr>
<td>$\kappa_{\gamma}$ [%]</td>
<td>1.9</td>
<td>7.6</td>
<td>1.6</td>
<td>1.2</td>
<td>6.7</td>
<td>3.4</td>
<td>1.9</td>
<td>98*</td>
<td>5.0</td>
<td>2.2</td>
<td>3.7</td>
<td>4.7</td>
<td>3.9</td>
<td>0.29</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$ [%]</td>
<td>10.</td>
<td>–</td>
<td>5.7</td>
<td>3.8</td>
<td>99*</td>
<td>86*</td>
<td>85*</td>
<td>120*</td>
<td>15</td>
<td>6.9</td>
<td>8.2</td>
<td>81*</td>
<td>75*</td>
<td>0.69</td>
</tr>
<tr>
<td>$\kappa_{C}$ [%]</td>
<td>–</td>
<td>4.1</td>
<td>–</td>
<td>–</td>
<td>2.5</td>
<td>1.3</td>
<td>0.9</td>
<td>4.3</td>
<td>1.8</td>
<td>1.4</td>
<td>2.2</td>
<td>1.8</td>
<td>1.3</td>
<td>0.95</td>
</tr>
<tr>
<td>$\kappa_{\ell}$ [%]</td>
<td>3.3</td>
<td>–</td>
<td>2.8</td>
<td>1.7</td>
<td>–</td>
<td>6.9</td>
<td>1.6</td>
<td>–</td>
<td>–</td>
<td>2.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>$\kappa_{b}$ [%]</td>
<td>3.6</td>
<td>2.1</td>
<td>3.2</td>
<td>2.3</td>
<td>1.8</td>
<td>0.58</td>
<td>0.48</td>
<td>1.9</td>
<td>0.46</td>
<td>0.37</td>
<td>1.2</td>
<td>1.3</td>
<td>0.67</td>
<td>0.43</td>
</tr>
<tr>
<td>$\kappa_{\mu}$ [%]</td>
<td>4.6</td>
<td>–</td>
<td>2.5</td>
<td>1.7</td>
<td>15</td>
<td>9.4</td>
<td>6.2</td>
<td>320*</td>
<td>13</td>
<td>5.8</td>
<td>8.9</td>
<td>10</td>
<td>8.9</td>
<td>0.41</td>
</tr>
<tr>
<td>$\kappa_{\tau}$ [%]</td>
<td>1.9</td>
<td>3.3</td>
<td>1.5</td>
<td>1.1</td>
<td>1.9</td>
<td>0.70</td>
<td>0.57</td>
<td>3.0</td>
<td>1.3</td>
<td>0.88</td>
<td>1.3</td>
<td>1.4</td>
<td>0.73</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**FCC-ee/eh/hh**

... gives the complete picture

$\Rightarrow$ check consistency at sub-percent level of different Higgs production & background compositions!
eh resolves HWW-HZZ correlation, see line marked with X on left plot, and reduces further correlations X

Higgs production in the three collider modes ee, ep, pp are also important for theory development
For the near future: SM Higgs Couplings & $\delta\sigma_{\text{Higgs}}(pp)$

Update of LHeC ES submission CERN-ACC-2018-0084

Figure 4: PRELIMINARY Uncertainties of coupling constant determinations using the kappa framework at the LHC in the six most frequent decay channels from the combination of ATLAS and CMS prospects at HL-LHC (blue, 3 ab$^{-1}$), the LHeC (gold, 1 ab$^{-1}$) and the combination of $pp$ and $ee$ (dark blue).

LHeC adds charm

NEW. preliminary Paper soon

HL-LH(e)C ensures centre of Higgs physics stays at CERN in the thirties. High precision needs $e+e^-$ for total width. H-HH at HL-LHC!

What are the true PDF errors in $pp$?

Plot from M Klein, DIS2019, and see talks at this WS

with LHeC input: $\delta\sigma = [0.3 \text{ (pdf)} + 0.2 (\alpha_s)]\%$
Wrap Up

- **FCC-eh** could measure the dominant Higgs couplings, including $ttH$, to 0.26-1.7% precision [CC+NC DIS, no pile-up, clean final state..]

- **LHeC would add charm to HL-LHC**

- Striking synergy of $ep (>\sim 1\,\text{TeV})$ and $ee (250-350\,\text{GeV})$ and $pp$ for Higgs coupling measurements, also to remove HZZ and HWW and further correlations!

- $ep$ would empower the physics potential of $pp$ (non-resonant searches, EW, Higgs..) through high precision QCD measurements: flavour separated PDFs at $N^3\text{LO}$, $\alpha_s$ to per mille ...

- **Higgs measurements in ep are self consistent experimentally and theoretically based on DIS cross sections with very small systematic uncertainties**

- **Combining pp with ep, a very powerful Higgs facility can be established at the HL-LHC already in the 30ties or later at the FCC-hh.**
50 journal papers on BSM with LHeC/Fcc-eh in recent years.
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://lhec.web.cern.ch

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


• Update used from April 2018 https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR

• FCC Week 2018, Amsterdam, https://indico.cern.ch/event/656491/

• FCC to EU Strategy CERN-ACC-2018-0056

• LHeC to EU Strategy CERN-ACC-2018-0084

Special thanks to my colleagues in the LHeC/FCC-eh study group and to Jorge de Blas for the discussion of model-dependent coupling fits.
Additional material
Top Yukawa Coupling @ LHeC

B.Coleppa, M.Kumar, S.Kumar, B.Mellado, PLB770 (2017) 335

SM:
\[ \mathcal{L}_{\text{Yukawa}} = -\frac{m_t}{v} \bar{t} t h - \frac{m_b}{v} \bar{b} b h. \]

BSM: Introduce phases of top-Higgs and bottom-Higgs couplings
\[ \mathcal{L} = -\frac{m_t}{v} [\kappa \cos \zeta_t + i \gamma_5 \sin \zeta_t] t h \]
\[ -\frac{m_b}{v} [\cos \zeta_b + i \gamma_5 \sin \zeta_b] \bar{b} h. \]

Enhancement of the DIS cross-section as a function of phase

Observe/Exclude non-zero phase to better than 4σ
⇒ With Zero Phase: Measure ttH coupling with 17% accuracy at LHeC ⇒ extrapolation to FCC-eh: ttH to 1.7%
Branching for invisible Higgs

Values given in case of $2\sigma$ and $L=1\text{ ab}^{-1}$

<table>
<thead>
<tr>
<th>Detectors</th>
<th>LHeC 1.3 [1.8 TeV]</th>
<th>HE-LHeC [1.8 TeV]</th>
<th>FCC-eh 3.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC-style</td>
<td>4.7% [3.2%]</td>
<td></td>
<td>1.9%</td>
</tr>
<tr>
<td>First ‘ep-style’</td>
<td>5.7%</td>
<td></td>
<td>2.6%</td>
</tr>
<tr>
<td>+BDT Optimisation</td>
<td>5.5% (4.5%*)</td>
<td>1.7% (2.1%*)</td>
<td></td>
</tr>
</tbody>
</table>

**LHeC parton-level, cut based**: <6% [Y.-L.Tang et al. arXiv: 1508.01095]

- Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques*
- Full MG5+Delphes analyses, done for 3 c.m.s. energies $\rightarrow$ very encouraging for a measurement of the branching of Higgs to invisible in ep down to 5% [1.2%] for 1 [2] ab$^{-1}$ for LHeC [FCC-eh]
- A lot of checks done: We also checked LHeC $\leftrightarrow$ FCC-he scaling with the corresponding cross sections (* results in table): Downscaling FCC-he simulation results to LHeC would give 4.5%, while up-scaling of LHeC simulation to FCC-he would result in 2.1% $\rightarrow$ all well within uncertainties of projections of ~25%

- Further detector and analysis details have certainly an impact on results $\rightarrow$ enhance potential further

PORTAL to Dark Matter?
Double Higgs Production

Encouraging FCC-eh cut-based study; full Delphes-detector simulation; conservative HFL tagging

<table>
<thead>
<tr>
<th>Integrated Luminosity (fb⁻¹)</th>
<th>Limits of couplings at 95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>g⁽¹⁾<em>{hhh} + g⁽²⁾</em>{hhh} × 5</td>
</tr>
<tr>
<td>1000</td>
<td>g⁽¹⁾<em>{hWW} + g⁽²⁾</em>{hWW} + g⁽³⁾_{hWW}</td>
</tr>
<tr>
<td>10000</td>
<td></td>
</tr>
</tbody>
</table>

5% systematic uncertainty on S and B included

1σ for SM hhh for Eₑ 60 (120)GeV and 10ab⁻¹

FCC-eh g⁽¹⁾_{hhh} ~ 20% in ep

1σ for SM hhh for Eₑ 60 (120)GeV and 10ab⁻¹

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

Here g⁽ⁿ⁾_{(i...j)} are real coefficients corresponding to the CP-even and CP-odd couplings respectively, of the hhh, hWW and hhWW anomalous vertices.

Bands show the still allowed regions.
**SM Higgs in ep**

Unpolarised electrons

$\sqrt{s} = 3.5$ TeV

$\sqrt{s} = 1.3$ TeV

**Higgs in eA @FCC-ePb**

$\sigma_{\text{Higgs}}$ [fb]

Eff. ‘Ep’ = 19.7 TeV

<table>
<thead>
<tr>
<th>$E_e$ [GeV]</th>
<th>$P_e = 0$</th>
<th>-0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>105</td>
<td>190</td>
</tr>
<tr>
<td>30</td>
<td>153</td>
<td>276</td>
</tr>
<tr>
<td>50</td>
<td>242</td>
<td>436</td>
</tr>
<tr>
<td>60</td>
<td>282</td>
<td>507</td>
</tr>
</tbody>
</table>

LHeC / FCC-eh: Sizeable Higgs rates in charged current (CC) DIS for $L = 100-1000$ fb$^{-1}$
Length x Diameter: LHeC (13.3 x 9 m²)  HE-LHC (15.6 x 10.4)  FCCeh (19 x 12) m²
ATLAS (45 x 25)  CMS (21 x 15):  [LHeC < CMS, FCC-eh ~ CMS size]

If CERN decides that the HE LHC comes, the LHeC detector should anticipate that...
Higgs in **ee vs ep**

**ee** Dominant Higgs productions:
- **ep**: CC DIS WW Fusion
- **ep**: NC DIS ZZ Fusion

**ep vs ee** - Higgs cross sections

- **ep**: CC DIS WW Fusion
- **ep**: NC DIS ZZ Fusion

---

**CLIC** 350 GeV

**1.4 TeV**

**3 TeV**

**3.5 TeV**

---

**ep**: HWW

**HZZ** 148 fb

**HWW** 1 pb

---

**ILC/FCCee**

**HZZ**

**tth**

**ZH**

**ZHH**

---

**FCC-eh**

---

**arXiv:1608.07538**
VBF Higgs Production in ep (top) and pp (bottom)

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

Clean bb final state, S/B >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

**pp**: Higgs production in pp comes predominantly (~80%) from gg → H:
High rates crucial for rare decays

Pile-up in pp at 5 × 10^{-34} cm^2 s^{-1} is 150@25ns
FCC-hh: pile-up 500-1000 (!)
S/B very small for bb
Final precision in pp needs accurate N^3LO PDFs & α_s
Further Estimates of Higgs Prospects

- Use LO Higgs cross sections $\sigma_H$ for $M_H=125$ GeV, in [fb], and branching fractions $BR(H \rightarrow XX)$ from Higgs Cross Section Handbook
- Apply further branching, $BR(X \rightarrow FS)$ in case e.g. of $W \rightarrow 2$ jets and use acceptance (Acc) estimates based on MG5, for further decay
- Use reconstruction efficiencies, $\varepsilon$, achieved at LHC Run-1, see e.g. prospect calculations explored in arXiv:1511.05170
- Use fully simulated LHeC BDT $H \rightarrow bb$ and $H \rightarrow cc$ & FCC-eh $H \rightarrow WW^*$ and exotic Higgs search results as baseline for S/B ranges; use fully simulated cut-based FCC-eh & LHeC $H \rightarrow bb$ results for further bench-marking
- Use fully simulated Higgs to invisible for 3 c.m.s. scenarios as guidance for extrapolation uncertainty
- Estimate Higgs events per decay channel for certain Luminosity in [fb^{-1}] and cross section in [fb]

$$N = \sigma_H \cdot BR(H \rightarrow XX) \cdot BR(X \rightarrow FS) \cdot L$$

- Calculate uncertainties of signal strengths w.r.t. SM expectation

$$\frac{\delta \mu}{\mu} = \frac{1}{\sqrt{N}} \cdot f \quad \text{with} \quad f = \sqrt{\frac{1 + 1/(S/B)}{Acc \cdot \varepsilon}}$$

$$\mu = \frac{\sigma}{\sigma_{SM}}$$
Electroweak precision observables at FCC eh

- Electroweak precision measurements at FCC-eh

**Precision measurements of couplings to light quark families**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Uncertainty</th>
<th>(Relative uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g^e_\gamma$</td>
<td>0.0022</td>
<td>(1.1%)</td>
</tr>
<tr>
<td>$g^\tau_\tau$</td>
<td>0.0031</td>
<td>(0.6%)</td>
</tr>
<tr>
<td>$g^e_\mu$</td>
<td>0.0049</td>
<td>(1.4%)</td>
</tr>
<tr>
<td>$g^\tau_\mu$</td>
<td>0.0049</td>
<td>(0.97%)</td>
</tr>
</tbody>
</table>

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh

**NEW**

$ee + ep$

Talk by J deBlas
FCC Week 2018

No Fermion flavour universality assumed

Independent info about all 3 SM fermion families
Double Higgs Production at FCC-eh

“Probing anomalous couplings using di-Higgs production in electron-proton collisions” by Mukesh Kumar, Xifeng Ruan, Rashidul Islam, Alan S. Cornell, Max Klein, Uta Klein, Bruce Mellado,


\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{h\ell h}^{(3)} + \mathcal{L}_{hWW}^{(3)} + \mathcal{L}_{hhWW}^{(4)}. \]

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

\[ \mathcal{L}_{hWW}^{(3)} = -g \left[ \frac{g_{hWW}^{(1)}}{2m_W} W^{\mu\nu} W^{\mu\nu}_\ell h + \frac{g_{hWW}^{(2)}}{m_W} (W^{\nu} \partial_\mu W^{\mu\nu}_\ell h + h.c) \right. \]

\[ \left. + \frac{\tilde{g}_{hWW}}{2m_W} W^{\mu\nu} \tilde{W}^{\mu\nu}_\ell h \right], \]

\[ \mathcal{L}_{hhWW}^{(4)} = -g^2 \left[ \frac{g_{hhWW}^{(1)}}{4m_W^2} W^{\mu\nu} W^{\mu\nu}_\ell h^2 + \frac{g_{hhWW}^{(2)}}{2m_W^2} (W^{\nu} \partial_\mu W^{\mu\nu}_\ell h^2 + h.c) \right. \]

\[ \left. + \frac{\tilde{g}_{hhWW}}{4m_W^2} W^{\mu\nu} \tilde{W}^{\mu\nu}_\ell h^2 \right]. \]

⇒ All other g coefficients are anomalous couplings to the $hhh$, $hWW$ and $hhWW$ anomalous vertices ⇒ those are 0 in SM

FCC-eh

$SM(P=-0.8)$

$\sigma(HH)=430 \, \text{ab}$ in VBF!
Effective Vertices

\[\Gamma_{hhh} = -6\lambda v \left[ g_{hhh}^{(1)} + \frac{g_{hhh}^{(2)}}{3m_h^2} (p_1 \cdot p_2 + p_2 \cdot p_3 + p_3 \cdot p_1) \right], \quad (6)\]

\[\Gamma_{hW-W+} = g m_W \left\{ 1 + \frac{g_{hWW}^{(1)}}{m_W^2} p_2 \cdot p_3 + \frac{g_{hWW}^{(2)}}{m_W^2} (p_2^2 + p_3^2) \right\} \eta^\mu_2 \eta^\mu_3 \]
\[\quad - \frac{g_{hWW}^{(1)}}{m_W^2} p_2^\mu_3 p_3^\mu_2 - \frac{g_{hWW}^{(2)}}{m_W^2} (p_2 \eta_2 p_3^\mu_3 + p_3 \eta_3 p_2^\mu_2) \]
\[\quad - i \frac{\tilde{g}_{hWW}}{m_W^2} \epsilon_{\mu_2 \mu_3 \mu_4 \nu} p_2^\mu_2 p_3^\nu \right\}, \quad (7)\]

\[\Gamma_{hhW-W+} = g^2 \left\{ \left( \frac{1}{2} + \frac{g_{hhWW}^{(1)}}{m_W^2} p_3 \cdot p_4 + \frac{g_{hhWW}^{(2)}}{m_W^2} (p_3^2 + p_4^2) \right) \eta^\mu_3 \eta^\mu_4 \right\}
\[\quad - \frac{g_{hhWW}^{(1)}}{m_W^2} p_3^\mu_4 p_4^\mu_3 - \frac{g_{hhWW}^{(2)}}{m_W^2} (p_3 \eta_3 p_4^\nu + p_4 \eta_4 p_3^\nu) \]
\[\quad - i \frac{\tilde{g}_{hhWW}}{m_W^2} \epsilon_{\mu_3 \mu_4 \mu_5 \nu} p_3^\mu_3 p_4^\nu \right\}. \quad (8)\]

Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.
HH@FCC-eh: Azimuthal Angle Distributions

→ $\Delta \Phi_{E_t \text{miss}, \text{jet}}$ between missing transverse energy and forward jet, at Delphes detector-level, including background: $b\bar{b}bj$, $bbjj$, $Z(bb)h(bb)j$, $ttj$, $h(bb)bbj$
→ Signal: $hh \rightarrow bbbb$ decays motivated by $h \rightarrow bb$ studies.

→ Normalised DIS cross sections are sensitive to non-BSM vertices
→ Initial study published for this novel $\Delta \Phi_{E_t \text{miss}, \text{jet}}$ variable
→ Potential for a deeper analysis and interpretation
Event Selection using $h \rightarrow bb$

$P_e = -0.8$, Anti-kt jets R=0.4, Etmiss>40 GeV, $\eta$(fwd jet)>5,
$90 < m_{bb}(1) , m_{bb}(2) < 125$ GeV, $m(4b)>290$ GeV
$b$-tagging for $|\eta|<5$ assumed to be 70% with misidentifications of 10% for charm and 1% for light quarks /gluons

<table>
<thead>
<tr>
<th>Cuts / Samples</th>
<th>Signal</th>
<th>4b+jets</th>
<th>2b+jets</th>
<th>Top</th>
<th>ZZ</th>
<th>$bbH$</th>
<th>ZH</th>
<th>Total Bkg</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>$2.00 \times 10^3$</td>
<td>$3.21 \times 10^7$</td>
<td>$2.32 \times 10^9$</td>
<td>$7.42 \times 10^6$</td>
<td>$7.70 \times 10^3$</td>
<td>$1.94 \times 10^4$</td>
<td>$6.97 \times 10^3$</td>
<td>$2.36 \times 10^9$</td>
<td>0.04</td>
</tr>
<tr>
<td>At least 4b + 1 $j$</td>
<td>$3.11 \times 10^2$</td>
<td>$7.08 \times 10^4$</td>
<td>$2.56 \times 10^4$</td>
<td>$9.87 \times 10^3$</td>
<td>$7.00 \times 10^2$</td>
<td>$6.32 \times 10^2$</td>
<td>$7.23 \times 10^2$</td>
<td>$1.08 \times 10^5$</td>
<td>0.94</td>
</tr>
<tr>
<td>Lepton rejection $p_T &gt; 10$ GeV</td>
<td>$3.11 \times 10^2$</td>
<td>$5.95 \times 10^4$</td>
<td>$9.94 \times 10^3$</td>
<td>$6.44 \times 10^3$</td>
<td>$6.92 \times 10^2$</td>
<td>$2.26 \times 10^2$</td>
<td>$7.16 \times 10^2$</td>
<td>$7.75 \times 10^4$</td>
<td>1.12</td>
</tr>
<tr>
<td>Forward jet $\eta_j &gt; 4.0$</td>
<td>233</td>
<td>13007.30</td>
<td>2151.15</td>
<td>307.67</td>
<td>381.04</td>
<td>46.82</td>
<td>503.22</td>
<td>16397.19</td>
<td>1.82</td>
</tr>
<tr>
<td>$E_T &gt; 40$ GeV</td>
<td>155</td>
<td>963.20</td>
<td>129.38</td>
<td>85.81</td>
<td>342.18</td>
<td>19.11</td>
<td>388.25</td>
<td>1927.93</td>
<td>3.48</td>
</tr>
<tr>
<td>$\Delta \phi_{ET &gt; 0.4}$</td>
<td>133</td>
<td>439.79</td>
<td>61.80</td>
<td>63.99</td>
<td>287.10</td>
<td>14.53</td>
<td>337.14</td>
<td>1204.35</td>
<td>3.76</td>
</tr>
<tr>
<td>$m_{bb} \in [95, 125], m_{bb}^2 \in [90, 125]$</td>
<td>54.5</td>
<td>28.69</td>
<td>5.89</td>
<td>6.68</td>
<td>5.14</td>
<td>1.42</td>
<td>17.41</td>
<td>65.23</td>
<td>6.04</td>
</tr>
<tr>
<td>$m_{4b} &gt; 290$ GeV</td>
<td>49.2</td>
<td>16.98</td>
<td>1.74</td>
<td>2.90</td>
<td>1.39</td>
<td>1.21</td>
<td>11.01</td>
<td>29.23</td>
<td>7.51</td>
</tr>
</tbody>
</table>

Table 2: A summary table of event selections to optimise the signal with respect to the backgrounds in terms of the weights at 10 ab$^{-1}$. In the first column the selection criteria are given as described in the text. The second column contains the weights of the signal process $p e^- \rightarrow hh j \nu_e$, where both the Higgs bosons decay to $bb$ pair. In the next columns the sum of weights of all individual prominent backgrounds in charged current, neutral current and photo-production are given with each selection, whereas in the penultimate column all backgrounds’ weights are added. The significance is calculated at each stage of the optimised selection criteria using the formula $S = \sqrt{2[(S + B) \log(1 + S/B) - S]}$, where $S$ and $B$ are the expected signal and background yields at a luminosity of 10 ab$^{-1}$ respectively. This optimisation has been performed for $E_e = 60$ GeV and $E_{\nu} = 50$ TeV.
Exotic Higgs Searches in $ep$

Values for $P_e=0$

→ reflecting coupling of new scalar to 125 GeV Higgs

Uta Klein & Michael O’Keefe
MPHYS 2017

MG5 UFO [arXiv:1608.08458]
η Distributions at FCC-eh

Scale: $p_T$ of leading jet

Exotic Higgs decay particles (2 light scalars of 20 GeV), struck quark and scattered lepton are well separated in detector acceptance.
Exotic Higgs @ FCC-eh

Example: \( h \rightarrow \phi \phi \rightarrow 4b \)

- \( m_\phi = 20 \text{ GeV} \)
- \( \text{BR}=10\% \)

\[ Z = \sqrt{2 \left( S + B \right) \ln \left( 1 + \frac{S}{B} \right) - S} \]

\( M_\phi \) vs. \( M_{2b} \) [GeV]

\( M_h \) vs. \( M_{2b} \) [GeV]

<table>
<thead>
<tr>
<th>BR (%)</th>
<th>( \sigma ) (fb)</th>
<th>( \Delta \sigma ) (fb)</th>
<th>( Z )</th>
<th>( \sigma ) (fb)</th>
<th>( \Delta \sigma ) (fb)</th>
<th>( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.03</td>
<td>0.02</td>
<td>1.14</td>
<td>0.03</td>
<td>0.03</td>
<td>1.17</td>
</tr>
<tr>
<td>0.4</td>
<td>0.05</td>
<td>0.02</td>
<td>2.27</td>
<td>0.07</td>
<td>0.03</td>
<td>2.33</td>
</tr>
<tr>
<td>0.6</td>
<td>0.08</td>
<td>0.02</td>
<td>3.37</td>
<td>0.10</td>
<td>0.03</td>
<td>3.47</td>
</tr>
<tr>
<td>0.8</td>
<td>0.10</td>
<td>0.02</td>
<td>4.46</td>
<td>0.13</td>
<td>0.03</td>
<td>4.59</td>
</tr>
</tbody>
</table>

Very promising first results to discover an exotic Higgs decay into two new light scalars at FCC-eh down to a BR of 1% for 1 ab\(^{-1}\).

A BR of 10% could be discovered within 1 year (100 fb\(^{-1}\)).
BDT Analysis @ BR=10%

Delphes-detector level with b-tag |η|<2.5

$\Phi = 20$ GeV

$\Phi = 60$ GeV

$L = 100 \text{ fb}^{-1}$

$P_e = -80\%$