Prospects for Higgs Physics with Electron-Proton Colliders

Max Klein

on behalf of
the LHeC/FCC-eh Higgs Group

Based on Uta Klein,
Talk at FCC CDR
4.3.2019 at CERN
and Higgs in ep paper, in preparation

DIS19, Torino, April 11th, 2019
Physics with Energy Frontier DIS

Raison(s) d’etre of the LHeC

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

Discovery (top, H, heavy ν’s..)

Beyond the Standard Model

A Unique Nuclear Physics Facility
International Advisory Committee with CERN mandate to provide “Direction for ep/eA both at LHC+FCC”

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS)

Coordination Group

Accelerator+Detector+Physics

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5(11) are members of the FCC coordination team

OB+MK: FCC-eh coordinators
FCC IAC: Guenter Dissertori +

Working Groups

PDFs, QCD
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eA Physics
Nestor Armesto
Small x
Paul Newman, Anna Stasto
Detector
Alessandro Polini
Peter Kostka
Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
$10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity and factor of 15/120 (LHC/FCCeh) extension of $Q^2$, 1/x reach
1000 times HERA luminosity. It therefore extends up to $x \sim 1$.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.
Future ep Colliders at CERN with electron ERL

LHC (HL and HE)

1.2-1.3 TeV cms energy
$10^{34}$ luminosity: 1 ab$^{-1}$ in 10 years.
2 ab$^{-1}$ with HE LHC [interesting ERL Programme standalone in transition!]
WW$\rightarrow$H Cross section similar to $Z^* \rightarrow ZH$
Note: gg$\rightarrow$H is about 50 pb at LHC

FCC

3.5 TeV cms energy
1.5 $10^{34}$ luminosity: 2-3 ab$^{-1}$ in 20 years
CC Higgs cross section $\sim$ 1 pb
This is 4 times higher than FCC-ee
Expect similar precision for both ee and ee
HERA’s legacy: the gluon dominated proton

Rapidity plateau at $x = M_H / 2E_p = 0.01$: Precise knowledge of $xg$ is a base for LHC Higgs physics

Prospect: very high precision PDFs and coupling from LHeC: to $N^3LO \rightarrow$ precision in pp (+ep)
SM Higgs Production in $ep$ well understood

\[ \begin{array}{c}
\text{CC : LO SM Higgs Production} \\
\text{FCC protons} \rightarrow \text{Fwd jet} \\
\text{ERL electrons} \rightarrow \text{ET}_{\text{miss}} \\
\text{WWH}
\end{array} \]

\[ \begin{array}{c}
\text{NC : LO SM Higgs Production} \\
\text{FCC protons} \rightarrow \text{Fwd jet} \\
\text{ERL electrons} \rightarrow \text{FS electron} \\
\text{ZZH}
\end{array} \]

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-he</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>
<tr>
<td>P=-80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC DIS</td>
<td>196</td>
<td>1008</td>
</tr>
<tr>
<td>NC DIS</td>
<td>25</td>
<td>148</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%. Tests done with MG5 and CompHep.
  - **NLO QCD corrections are small**, but shape distortions of kinematic distributions up to 20%. QED corrections up to -5%.

DIS Kinematics at FCC-eh @ $\sqrt{s}=3.5$ TeV

MadGraph scale: $p_T$ of leading jet

Parton-level

DIS kinematics very well behaved

[btw also at HERA, but the cross section was 0.7 (0.1) fb in CC (NC) while H1 and ZEUS each collected only about 0.5 fb$^{-1}$ of luminosity. LHeC: cross section 200 times larger and luminosity 500 times larger: ⇒ ep becomes a Higgs laboratory]
Higgs decay particles (here to WW), struck quark and scattered lepton are well separated in polar angle and in detector acceptance. Very fwd jet at FCC.
VBF Higgs Production and experimental conditions

**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
- pile-up in ep: $<0.1@LHeC$ up to $1@FCCeh$ events

**pp:** Higgs production in pp comes predominantly (~80%) from $gg \rightarrow H$:
- high rates crucial for rare decays

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

**FCC-hh:** pile-up 500-1000 (!)
- S/B very small for bb, too harsh for cc
- Final precision in pp needs accurate $N^3\text{LO}$ PDFs & $\alpha_S$
Rates of Higgs production at LHeC

<table>
<thead>
<tr>
<th>LHeC Higgs</th>
<th>CC ($e^-p$)</th>
<th>NC ($e^-p$)</th>
<th>CC ($e^+p$)</th>
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<tbody>
<tr>
<td>Polarisation</td>
<td>-0.8</td>
<td>-0.8</td>
<td>0</td>
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<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>

Approximately

x4 at HE LHC

x10 at FCC-eh

a million bb..

Due to longer operation, higher luminosity and higher cross sections
Analysis Framework and ‘Detector’

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

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

• Fragmentation
• Hadronization by PYTHIA (modified for ep)

Fast detector simulation by Delphes → test of LHeC detector

S/B analysis → cuts or BDT
Branching for invisible Higgs

Values given in case of 2σ and L=1 ab\(^{-1}\)

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

LHeC parton-level, cut based <6% [arXiv: 1508.01095]
HL-LHC @ 3 ab\(^{-1}\) < 3.5% [arXiv:1411. 7699]

- Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using standard cut/BDT analysis techniques
- Results for 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 1.2% (1.7%) for 2 (1) ab\(^{-1}\)

- 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 \(~25%\)

\(\rightarrow\) further detector and analysis details have certainly an impact on results
CDR Updates: Two independent analyses

[after Higgs discovery $M_H=125$ GeV, $E_p=7$ TeV, $E_e=60$ GeV; cut-based & conservative]

$\sqrt{s}=1.3$ TeV

ICHEP 2014
Master Thesis Ellis Kay, Liverpool 2014, PGS “detector” ATLAS-style and & modeling of PHP background using low $Q^2$ NC DIS

Confirmed CDR: $S/N>1$ using conservative light misID and cut-based $\delta\mu=2\%$ for 1 ab$^{-1}$

Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

PGS of LHC detector + flat parton-level b-tagging for $|\eta|<3.0$

$b$: 60%, $c$: 10%, $\text{udsg}$: 1%

CAL coverage $|\eta|<5.0$

$100$ fb$^{-1}$

1 year of data
Hunting for Precision Hbb

Dijet Mass Candidates $HFL$ untagged at detector level

Step 1
Basic kinematic cuts and loose selection ($p_T > 15$ GeV)

'Worst' case scenario plot: Photoproduction background (PHP) is assumed to be 100%!

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

→ addition of small angle electron taggers will reduce PHP to ~1-2%

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

Step 2
HFL tagging

Step 3
BDT in Search Window
Top: Mass of three highest $p_T$ Jets

- **HFL untagged**

- **Single top candidates!**

- **Cut-based** analysis: usual cut to accept Higgs candidates on cost of signal efficiency
Realistic and conservative HFL tagging (a la Tevatron) within Delphes realised and dependence on vertex resolution (nominal 10 μm) and anti-kt jet radius studied

Light jet misID efficiency very conservative, worse than ATLAS-BDT-based

used in full LHeC analysis and for FCC-eh extrapolations
Hbb: Clear sensitivity to chosen jet radius; rather robust w.r.t. vertex resolution in range of 5 to 20 μm.

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

BDT Results for Higgs @ LHeC using realistic HFL tagging at Delphes detector level

Daniel Hampson, MPHYS 2016
**Higgs in ep - clean S/B, no pile-up**

**realistic HFL tagging & BDT**

LHeC @ $L=1000$ fb$^{-1}$

- **Hbb**
  - $2\%$ PHP and $2\%$ other bgd

$$\text{Events} \times 10^3$$

- **Hcc**
  - $2\%$ Hbb and $2\%$ other bgd

$$\text{Events}$$

- **Hbb signal with BDT>0**
  - $\mu = \sigma / \sigma_{SM}$
  - $\delta \mu / \mu(\text{Hbb}) = 0.8\%$

- **Hcc signal with BDT>0**
  - $\delta \mu / \mu(\text{Hcc}) = 7.4\%$

*Assuming ATLAS light jet misID efficiencies*

*Main systematic checks: variations of background contribution and tagging efficiencies*

Uta Klein & Daniel Hampson

& Izzy Harris

BSc 2017
Further Estimates of Higgs Prospects

• Use LO Higgs cross sections $\sigma_H$ for $M_H=125$ GeV, in [fb], and branching fractions $\text{BR}(H \rightarrow XX)$ from Higgs Cross Section Handbook (c.f. appendix)
• Apply further branching, $\text{BR}(X \rightarrow FS)$ in case e.g. of $W \rightarrow 2 \text{ jets}$ 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 Hbb and Hcc results as baseline for S/B ranges
• Use fully simulated Higgs to invisible for 3 ep c.m.s. scenarios as guidance for extrapolation uncertainty (~25%)
• Estimate Higgs events per decay channel for certain Luminosity in [fb$^{-1}$]

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

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

$$\frac{\Delta \mu}{\mu} = \frac{1}{\sqrt{N}} \cdot f$$

with

$$f = \sqrt{\frac{1 + 1/(S/B)}{\text{Acc} \cdot \varepsilon}}$$

$$\mu = \frac{\sigma}{\sigma_{SM}}$$
HWW and HZZ signal strengths measured at once in DIS via selection of the final state (e or $\nu$)

$\delta \mu/\mu$ [%]

<table>
<thead>
<tr>
<th>Process</th>
<th>LHeC</th>
<th>FCC-eh</th>
<th>HE LHeC</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW→H</td>
<td>200 fb</td>
<td>1 pb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ→H</td>
<td>25 fb</td>
<td>150 fb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$E_e = 60$ GeV

Charged Currents: ep → vHX
Neutral Currents: ep → eHX

$\rightarrow$ NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.

$E_e = 60$ GeV $LHeC E_p = 7$ TeV $L=1ab^{-1}$ HE-LHC $E_p = 14$ TeV $L=2ab^{-1}$ FCC: $E_p = 50$ TeV $L=2ab^{-1}$
Systematic errors of $\mu$ for $bb$

Systematic errors of $\mu$ for $bb$

\begin{align*}
\delta \mu / \mu &= (0.80 \pm 0.12) \% \quad [\text{preliminary}]
\end{align*}

- Dominant HFL tagging: light jet misID [ATLAS vs 3 ATLAS]
- Photoproduction: reduced down to 10% vs 2%
- Acceptance x Efficiency: $\pm 5\%$
  \[ \rightarrow \text{Estimated effects on } f \]

- Variation of hadronic energy resolution
  (M Tanaka, 2017): 7% on cross section
- Luminosity 0.5 to 1%: negligible

- Prediction of $ep$ CC SM $H \rightarrow bb$ cross section: 2%
- Based on LHeC measurements and PDFs

\[ \rightarrow \delta \kappa (bb) = (1.40 \pm 0.03)\% \]
\[ \rightarrow \delta \kappa (WW) = (0.54 \pm 0.03)\% \]

Note:
Doubling the WW signal strength uncertainty increases $\delta \kappa (bb)$ from 1.4 to 1.9% and $\delta \kappa (WW)$ from 0.54 to 0.74%
κ Coupling Fit Comparison

So far we considered 7 most abundant SM Higgs decay channels, \( i=1..7 \)
✧ \( bb, WW, gg, \tau\tau, cc, ZZ, \gamma\gamma \)
✧ \( ttH \) may be added. (ep: 1.3 TeV cms!)
→ eight measurements of \( \kappa_W \) and \( \kappa_Z \)
→ two simultaneous measurements of the other couplings (in CC and NC)

For LHeC nominal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>xww</th>
<th>1.054536E-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>0) Parameter &quot;Kw&quot;</td>
<td>1 +- 0.0054</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Parameter &quot;Kz&quot;</td>
<td>1 +- 0.012</td>
<td>xzz</td>
<td>1.011857E-01</td>
</tr>
<tr>
<td>2) Parameter &quot;Kg&quot;</td>
<td>1 +- 0.030</td>
<td>xgg</td>
<td>1.030503E-01</td>
</tr>
<tr>
<td>3) Parameter &quot;Kga&quot;</td>
<td>1 +- 0.072</td>
<td>xyy</td>
<td>1.072375E-01</td>
</tr>
<tr>
<td>4) Parameter &quot;Kc&quot;</td>
<td>1 +- 0.037</td>
<td>xcc</td>
<td>1.037344E-01</td>
</tr>
<tr>
<td>5) Parameter &quot;Kb&quot;</td>
<td>1 +- 0.014</td>
<td>xbb</td>
<td>1.013978E-01</td>
</tr>
<tr>
<td>6) Parameter &quot;Ktau&quot;</td>
<td>1 +- 0.028</td>
<td>xttau</td>
<td>1.028223E-01</td>
</tr>
</tbody>
</table>

J de Blas                      M Klein

Two independent fit programs: results are in very good agreement.
→ Assuming SM branching fractions weighted by the measured \( \kappa \) values, and \( \Gamma_{md} \) (c.f. CLIC model-dependent method)

\[ \frac{\delta \kappa}{\kappa} \text{ [\%]} \]

Preliminary

<table>
<thead>
<tr>
<th>( \delta \kappa/\kappa \text{ [%]} )</th>
<th>HE LHeC</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>WW</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>gg</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>( \tau \tau )</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>cc</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>ZZ</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>( \gamma \gamma )</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>( \Upsilon \Upsilon )</td>
<td>&lt;1 %</td>
<td>&lt;1 %</td>
</tr>
</tbody>
</table>

\( \delta \kappa/\kappa \text{ [\%]} \)

M+U.Klein, 5.4.18
NC+CC Analysis using overconstrained system of couplings

\( E_\rho = 60 \text{ GeV} \quad L=2ab^{-1} \quad \text{HE-LHC} \quad E_\rho = 14 \text{ TeV} \quad \text{FCC: } E_\rho = 50 \text{ TeV} \)

See also talk by Jorge de Blas@FCC-Week2018 for further fits and ep+ee combinations.
similar tests possible using various cms energy CLIC machines, however, in ep, we could perform them with one machine

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

Dominated by $H\rightarrow bb$ 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: $\pm 0.010$

HE-LHeC $\pm 0.006$

FCC-he $\pm 0.004$

Another nice test: **How does the Higgs couple to 3rd and 2nd generation quark?**

$b$ is down-type and $c$ is up-type
LHeC and HL-LHC Higgs Prospects

Hcc@pp: ~2.0-5.5 $\sigma_{\text{SM}}$@HL-LHC

[HL-LHC Oct 2017]

submitted to ECFA:

Amazing prospect for measuring fundamental Higgs couplings to high precision (dark blue) at LHC with pp + ep using SM assumptions.

HL-LHC prospects using new CMS projections (3ab$^{-1}$) with two scenarios, S1 and S2, in a SM coupling fit
4.2. Determination of Higgs Couplings in pp and ep

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!

NEW.
preliminary
Paper soon

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).
Higgs precision observables at FCC ee and eh

- Fit to modified Higgs couplings (assuming no extra invisible decays)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>FCC-ee Relative precision</th>
<th>Coupling</th>
<th>FCC-eh Relative precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_b$</td>
<td>0.58%</td>
<td>$\kappa_b$</td>
<td>0.74%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>-</td>
<td>$\kappa_t$</td>
<td>-</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>0.78%</td>
<td>$\kappa_\tau$</td>
<td>1.10%</td>
</tr>
<tr>
<td>$\kappa_c$</td>
<td>1.05%</td>
<td>$\kappa_c$</td>
<td>1.35%</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>9.6%</td>
<td>$\kappa_\mu$</td>
<td>-</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.16%</td>
<td>$\kappa_Z$</td>
<td>0.43%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>0.41%</td>
<td>$\kappa_W$</td>
<td>0.26%</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>1.23%</td>
<td>$\kappa_g$</td>
<td>1.17%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>2.18%</td>
<td>$\kappa_\gamma$</td>
<td>2.35%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>-</td>
<td>$\kappa_{Z\gamma}$</td>
<td>-</td>
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$k_i \equiv g_{hi}/g_{hi}^{SM}$

Published in book 1 of FCC
## Higgs coupling prospects in kappa framework

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<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC_250</th>
<th>CLIC_380</th>
<th>FCC-ee @ 240 GeV</th>
<th>FCC-ee @ 365 GeV</th>
<th>FCC-ee @ HL-LHC</th>
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<td>2</td>
<td>0.5</td>
<td>5 +1.5 @ 240 GeV</td>
<td>+1.5 @ 365 GeV</td>
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<td>2</td>
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<td>Years</td>
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<td>15</td>
<td>8</td>
<td>3 +4</td>
<td>—</td>
<td>20</td>
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<tr>
<td>(\delta \Gamma_H/\Gamma_H) (%)</td>
<td>SM</td>
<td>3.6</td>
<td>4.7</td>
<td>2.7</td>
<td>1.3</td>
<td>1.1</td>
<td>SM</td>
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<tr>
<td>(\delta g_{HZZ}/g_{HZZ}) (%)</td>
<td>1.5</td>
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<td>0.2</td>
<td>0.17</td>
<td>0.16</td>
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<td>1.0</td>
<td>1.3</td>
<td>0.43</td>
<td>0.40</td>
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<td>(\delta g_{Hbb}/g_{Hbb}) (%)</td>
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<td>1.21</td>
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<tr>
<td>(\delta g_{Htt}/g_{Htt}) (%)</td>
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<td>1.7</td>
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<tr>
<td>BR(_{EXO}) (%)</td>
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<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>

Table from Book1 of FCC. (w/o LHeC and CepC)

Synergetic evaluation under way by ECFA Higgs working group → preparation for Granada.
Note: rare channels are for pp. Muon has 0.02% branching fraction – 10% error in e+e-
Higgs complementarities: Global fit to Higgs couplings at FCC

- All single Higgs couplings can be determined below the 1%

**FCC-ee/FCC-eh**
Precise determinations for the leading couplings

**HZZ**
Crucial for normalization of FCC-hh results

**FCC-hh**
Completes the picture with precise determinations of Top and coupling associated to rare decays

**NOT MODEL-INDEPENDENT:**
Results assume that, if there is New physics, it can only be in the Higgs couplings

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Relative precision</th>
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<td>$\kappa_b$</td>
<td>0.38%</td>
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<tr>
<td>$\kappa_t$</td>
<td>0.51%</td>
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<tr>
<td>$\kappa_\tau$</td>
<td>0.58%</td>
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<tr>
<td>$\kappa_c$</td>
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<td>$\kappa_\mu$</td>
<td>0.42%</td>
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<tr>
<td>$\kappa_Z$</td>
<td>0.14%</td>
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<tr>
<td>$\kappa_W$</td>
<td>0.17%</td>
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<tr>
<td>$\kappa_g$</td>
<td>0.74%</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>0.40%</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>0.52%</td>
</tr>
</tbody>
</table>

$$\kappa_i \equiv \frac{g_{hi}}{g_{hi}^{SM}}$$
It is not enough to celebrate super-high precision, and it will be very hard to indeed achieve that
Exotic Higgs Decays

$h \rightarrow \phi\phi \rightarrow 4b$

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

\[ L_{\text{eff}} = \lambda h v h \phi^2 + \lambda_b \phi \bar{b}b + L_{\phi \text{ decay,other}} \]

- S. Liu, Y. L. Tang, C. Zhang, S. Zhu, 1608.08458

- Well motivated signature in extended Higgs sector.

- Difficult to probe at hadron colliders.

- LHeC signal: here using CC channel.

- Backgrounds: CC multijet, CC \(t/h/W/Z+\text{jets, PHP multijet.}\)

- 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 \(C_{4b}^2\)
Very promising first results to discover an exotic Higgs decay into two new light scalars at FCC-he down to a BR of 1% for 1 ab\(^{-1}\). A BR of 10% could be discovered within 1 year (100 fb\(^{-1}\)).
Full simulation of DIS \([EM,\text{had calibration, tracking, backgrounds, ...}]\)

\[
\frac{\partial F_2(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_1^x dz \left[ F_2(z) P_{qq}(z) + 2 \sum_{i=1}^{N_f} e_i^2 \cdot G(z) P_{qG}(z) \right]
\]

LHeC

Unravelling proton structure needs cleanest DIS constraints, proton cf Claire Gwenlan, at this workshop

High precision \(F_L\) from variation of \(E_e\) independently of LHC/FCC

High precision \(F_2(x, Q^2)\) from few days of nominal ep running. Needs large \(Q^2\) and low \(x \sim 1/s\): Impossible at EIC

Full set of PDFs and strong coupling: self consistent system!

Discovery of Saturation @ low \(x\); Test of Factorisation; high \(x\)

LHeC CDR: 1206.2913 J Phys G

MK: 1802.04317
Cross section to N^3LO needs PDFs to N^3LO and strong coupling to per mile precision.

LHeC with 50fb^{-1}

ep Higgs paper, to appear.
Precision Higgs Physics at High-Energy Electron-Proton Colliders

LHeC Higgs Study Group


Tentative authorlist - TO BE UPDATED

Abstract. The Higgs boson and its physics have become a central topic of modern particle physics and a key parameter in the evaluation of future high energy collider projects. This paper provides a summary and overview on the potential of future luminous, energy frontier electron-proton colliders, especially the LHeC, the HE-LHC and the FCC-eh, for precision Standard Model measurements of the properties of the Higgs boson in deep inelastic scattering. Detailed analyses are presented on the prospects for accurate measurements of the Higgs boson decays into pairs of bottom and charm quarks. An extended study is performed for estimating the precision on the Higgs couplings in the most abundant decay channels, based on measurements in the charged and weak neutral current DIS reactions. The addition of $ep$ information to the expected HL-LHC Higgs coupling measurements is demonstrated to lead to major improvements on the Higgs results one can expect to come from the LHC facility at large.
We hope to see $H \rightarrow bb$ in the LHeC Detector

P. Kostka et al., Orsay WS 2018
LHeC (FCC-he) could measure the dominant Higgs couplings, including $ttH$, to 0.6-17% (0.2-2%) precision [CC+NC DIS, no pile-up, clean final state..]

Striking synergy of $ep (>\sim 1\ TeV)$ and $ee (250-350\ GeV)$ and $pp$ for Higgs coupling measurements!

$ep$ would empower the physics potential of $pp$ (non-resonant searches, EW, Higgs..) through high precision QCD measurements: flavour separated PDFs at $N^3LO$, $\alpha_s$ 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 LHC and subsequently at higher energy hadron colliders.
Additional material
Thanks to Hao Sun

50 journal papers on BSM with LHeC in recent years
## LHeC / HE-LHeC / FCCeh Calorimeter Characteristic

<table>
<thead>
<tr>
<th></th>
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<td>$\eta_{\text{max/min}}$</td>
<td>5.2</td>
<td>5.1</td>
<td>2.7/-2.1</td>
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<td>$\sigma_E/E$ [%]</td>
<td>1) 13.5 1.7</td>
<td>2) 31.8 2.4</td>
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<td></td>
<td></td>
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<td>$E/\sqrt{E} \oplus b$</td>
<td>1) 1.7</td>
<td>2)</td>
<td></td>
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<tr>
<td>E-Flow</td>
<td>$\sigma_{E_{\text{jet}}}/E_{\text{jet}} = 0.03$ (at lower energies 25%/\sqrt{E} ; sampling ~50 ; $\sigma_{\text{jet}} \sim 3%$)</td>
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<tr>
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<td>$X_0 \geq 28$</td>
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<td>17.0 0.8</td>
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<td>1) 1.8</td>
<td>2)</td>
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<td>E-Flow</td>
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1) GEANT4 stimulation based fits; 2) DDG4 stimulation based fits
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<td>15.8</td>
<td></td>
<td>7.7</td>
<td>5.5</td>
</tr>
</tbody>
</table>
LHeC Detector for the HL/HE-LHC

Length x Diameter: LHeC (13.3 x 9 m²)  HE-LHC (15.6 x 10.4)  FCCeh (19 x 12)  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...
Couplings of the dominant Higgs decays could be measured to few percent precision at ep@HL-LHC.

Impressive complementarity of ee and ep→ to get model independent couplings, use absolute HZZ cross section from ee.
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](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/](https://indico.cern.ch/event/550509/)


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

• FCC Week 2018, Amsterdam, [https://indico.cern.ch/event/656491/](https://indico.cern.ch/event/656491/)

Special thanks to my colleagues in the LHeC/FCC-he Higgs group and to Jorge de Blas for the discussion of model-dependent coupling fits.
Double Higgs Production

FCC-eh cut-based study

95% C.L. Exclusion Limits from $\sigma_{\text{fiducial}}$

Limits of couplings at 95% C.L.

- $g_{\text{hhh}}^{(1)}$
- $g_{\text{hhh}}^{(2)} \times 5$
- $g_{\text{hhWW}}^{(2)} \times 10$
- $g_{\text{hhWW}}^{(1)}$
- $\tilde{g}_{\text{hhWW}}$

Integrated Luminosity [fb$^{-1}$]

100 1000 10000

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

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

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

⇒ explore He-LHeC/LHeC ep prospects!

Here $g_{\text{hhh}}^{(i)}, i = 1, 2$, and $\tilde{g}(...)$ are real coefficients corresponding to the CP-even and CP-odd couplings respectively, of the $hhh$, $hWW$ and $hhWW$ anomalous vertices.
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,

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

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

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

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

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
Effective Vertices

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

\[ \Gamma_{hW^-W^+} = g m_W \left\{ 1 + \frac{g^{(1)}_{hWW}}{m_W^2} p_2 \cdot p_3 + \frac{g^{(2)}_{hWW}}{m_W^2} (p_2^2 + p_3^2) \right\} \eta^{\mu_2 \mu_3} \]

\[ - \frac{g^{(1)}_{hWW}}{m_W^2} p_2^\mu \, p_3^\mu \, - \frac{g^{(2}_{hWW}}{m_W^2} (p_2^\mu \, p_3^\mu + p_3^\mu \, p_2^\mu) \]

\[ - i \frac{\tilde{g}^{(1)}_{hWW}}{m_W^2} \epsilon_{\mu_2 \mu_3 \nu \lambda} p_2^\mu \, p_3^\nu \right\}, \quad (7) \]

\[ \Gamma_{hhW^-W^+} = g^2 \left\{ \frac{1}{2} + \frac{g^{(1)}_{hhWW}}{m_W^2} p_3 \cdot p_4 + \frac{g^{(2)}_{hhWW}}{m_W^2} (p_3^2 + p_4^2) \right\} \eta^{\mu_3 \mu_4} \]

\[ - \frac{g^{(1)}_{hhWW}}{m_W^2} p_3^\mu \, p_4^\mu \, - \frac{g^{(2)}_{hhWW}}{m_W^2} (p_3^\mu \, p_4^\mu + p_4^\mu \, p_3^\mu) \]

\[ - i \frac{\tilde{g}^{(1)}_{hhWW}}{m_W^2} \epsilon_{\mu_3 \mu_4 \nu \lambda} p_3^\mu \, p_4^\nu \right\}. \quad (8) \]

Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.
**SM Higgs in ep**

Unpolarised electrons

\( \sqrt{s} = 3.5 \) TeV

\( \sqrt{s} = 1.3 \) TeV

\( \sigma_{\text{eff. }} = 19.7 \text{ TeV} \)

Higgs in eA @ FCC-ePb

\( \sigma_{\text{Higgs}} [\text{fb}] \)

**US-EIC**

\( \sigma \) @ EIC: 7 orders of magnitude lower

**LHeC / FCC-eh**: Sizeable Higgs rates in charged current (CC) DIS for \( L = 100-1000 \) fb\(^{-1} \)

**FCC-eh**

**LheC**

**HERA (L = 0.5 fb\(^{-1}\))**

**σ @ EIC**: 7 orders of magnitude lower

<table>
<thead>
<tr>
<th>( E_p [\text{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>
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<tr>
<td>50</td>
<td>242</td>
<td>436</td>
</tr>
<tr>
<td>60</td>
<td>282</td>
<td>507</td>
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</tbody>
</table>
FCC-eh cut based results

- unpolarised samples using $E_e=60$ GeV and $E_p$ of 7 and 50 TeV

<table>
<thead>
<tr>
<th></th>
<th>LHeC</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal CC:H-&gt;bb</td>
<td>0.113</td>
<td>$0.467$</td>
</tr>
<tr>
<td>CCjj no top</td>
<td>4.5</td>
<td>$21.2$</td>
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<tr>
<td>CC single top</td>
<td>0.77</td>
<td>$9.75$</td>
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<tr>
<td>CC Z</td>
<td>0.52</td>
<td>$1.6$</td>
</tr>
<tr>
<td>NC Z</td>
<td>0.13</td>
<td>$0.33$</td>
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<tr>
<td>PAjj</td>
<td>41</td>
<td>$262$</td>
</tr>
</tbody>
</table>

Mass of 2 b-jets after event selection

**FCC**

100 fb$^{-1}$

**LHeC (PK)**

100 fb$^{-1}$
Higgs in $ee$ vs $ep$

$ee$: Dominant Higgs productions

$pe$ vs $e^+e^-$ Higgs cross sections

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

CLIC 350
1.4 TeV

HLHC

HWW 1 pb
HZZ 148 fb
between missing transverse energy and forward jet, at Delphes detector-level, including background: bbbbj, bbjjj, Z(bb)h(bb)j, ttj, h(bb)bbj
→ For signal, we consider hh→ bbbbj decays motivated by h→bb studies.

→ normalised DIS cross sections are sensitive to non-BSM vertices
→ initial study published for this novel variable
→ potential for a deeper analysis and interpretation
### CC DIS WWH $\rightarrow$ H

<table>
<thead>
<tr>
<th></th>
<th>bb</th>
<th>WW</th>
<th>gg</th>
<th>$\tau\tau$</th>
<th>cc</th>
<th>ZZ</th>
<th>$\gamma\gamma$</th>
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<tbody>
<tr>
<td><strong>BR</strong></td>
<td>0.577</td>
<td>0.215</td>
<td>0.086</td>
<td>0.0632</td>
<td>0.0291</td>
<td>0.0264</td>
<td>0.00228</td>
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<tr>
<td>$\delta BR_{\text{theory}}$</td>
<td>3.2%</td>
<td>4.2%</td>
<td>10.1%</td>
<td>5.7%</td>
<td>12.2%</td>
<td>4.2%</td>
<td>5.0%</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>$1.15 \times 10^6$</td>
<td>$4.3 \times 10^5$</td>
<td>$1.72 \times 10^5$</td>
<td>$1.26 \times 10^5$</td>
<td>$5.8 \times 10^4$</td>
<td>$5.2 \times 10^4$</td>
<td>4600</td>
</tr>
<tr>
<td>$f$</td>
<td>2.86 $_{\text{BDT}}$</td>
<td>16</td>
<td>7.4</td>
<td>5.9</td>
<td>5.6 $_{\text{BDT}}$</td>
<td>8.9</td>
<td>3.23</td>
</tr>
<tr>
<td>$\delta \mu/\mu$ [%]</td>
<td>0.27</td>
<td>2.45</td>
<td>1.78</td>
<td>1.65</td>
<td>2.36</td>
<td>3.94</td>
<td>3.23</td>
</tr>
</tbody>
</table>

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

$\rightarrow$ Sum of first 6 branching fractions that could be measured

LHeC : 0.9964 +/- 0.02

**FCC-eh**: 0.9964 +/- 0.01