QCD uncertainties on Higgs and EWK measurable

Fabrizio Caola
Rudolf Peierls Centre for Theoretical Physics & Wadham College
Topics covered and input summarised

- How well can the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?

- What are the theoretical developments in QCD and EWK needed to fully capitalize on the experimental data?

Main documents covered:

- Higgs Boson studies at future particle colliders $[arXiv:1905.03764]$  
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders  
- Precision calculations for high-energy collider processes  
- Monte Carlo event generators for high energy particle physics event simulation  
- Quantum Chromodynamics: Theory - Input for the European Particle Physics Strategy Update  
- collider specific reports / studies

Many thanks to S. Forte, K. Melnikov, G. Salam and PPG conveners for discussions
A snapshot: \textit{EWPO}

<table>
<thead>
<tr>
<th>(\delta \Gamma_Z ) [MeV]</th>
<th>(\delta R_t [10^{-4}])</th>
<th>(\delta R_b [10^{-5}])</th>
<th>(\delta \sin^2 \theta_{\text{eff}}^{\ell} [10^{-6}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present EWPO theoretical uncertainties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXP-2018</td>
<td>2.3</td>
<td>250</td>
<td>66</td>
</tr>
<tr>
<td>TH-2018</td>
<td>0.4</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>EXP-FCC-ee</td>
<td>0.1</td>
<td>10</td>
<td>(\frac{2}{6})</td>
</tr>
<tr>
<td>TH-FCC-ee</td>
<td>0.07</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

EWPO theoretical uncertainties when FCC-ee will start

Z\bar{\ell}f vertex, dominant 3-loop EW, dominant 4-loop mixed QCD-EW

\(\delta \alpha_s = 0.00015\)

see S. Dittmaier’s talk
Higgs: parametric uncertainties

<table>
<thead>
<tr>
<th>Decay</th>
<th>Partial width [keV]</th>
<th>current unc. $\Delta\Gamma/\Gamma$ [%]</th>
<th>future unc. $\Delta\Gamma/\Gamma$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta\Gamma_{\text{Intr}}$</td>
<td>$\Delta\Gamma_{\text{Par}}(m_q)$</td>
<td>$\Delta\Gamma_{\text{Par}}(\alpha_s)$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>2379</td>
<td>&lt; 0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>256</td>
<td>&lt; 0.3</td>
<td>–</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>118</td>
<td>&lt; 0.4</td>
<td>4.0</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>0.89</td>
<td>&lt; 0.3</td>
<td>–</td>
</tr>
<tr>
<td>$H \rightarrow W^+W^-$</td>
<td>883</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>335</td>
<td>3.2</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>108</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>9.3</td>
<td>&lt; 1.0</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>6.3</td>
<td>5.0</td>
<td>–</td>
</tr>
</tbody>
</table>

$\delta\alpha_s = 0.0002$
$\delta m_t = 50$ MeV
$\delta m_b = 13$ MeV
$\delta m_c = 7$ MeV
$\delta m_H = 10$ MeV

see S. Dittmaier’s talk

HXSWG, extrapolation of current ggF uncertainties to high energy pp colliders
A snapshot: Higgs

Figure 2. Expected relative precision (%) of the $\kappa$ parameters in the kappa-3 scenario described in Section 2. For details, see Tables 4 and 5.

QCD uncertainty on overall rates/Br:
• HL-LHC S2 \(\approx\)today/2
• future colliders: \(~\approx\)today/2 for Br, 1% at HE, 0.5% at LHeC, 1% total FCC-hh
A snapshot: Higgs

QCD uncertainty on overall rates/Br:
- HL-LHC S2 [=today/2]
- future colliders: ~today/2 for Br, 1% at HE, 0.5% at LHeC, 1% total FCC-hh
Some words of caution

1. TH uncertainties under SM assumptions. Both intrinsic and parametric uncertainties can change in BSM scenarios.

2. No correlations among theory uncertainties
   - Currently, we did not study the problem in enough detail to have a foolproof recipe for theory uncertainty correlations [my personal opinion].
   - Theories uncertainties are not exactly random variables...
   - It is becoming an important issues for many LHC physics. Examples:
     * Higgs combinations/STXS
     * PDFs theory uncertainties
     * Complicated background & interplay with MVAs, e.g. $\bar{t}H$ vs $\bar{t}\bar{b}\bar{b}$
   - Important to understand for a coherent treatment of uncertainties, a lot of effort going on right now → no longer a neglected issue, expect progress.
Parameters: $\alpha_s$

$\delta \alpha_s = 0.0002$

Very Challenging

Current status

Prospects

- $e^+e^-$, hadronic decays, global fits $\rightarrow$ potential to reach 0.15%. QCD-robust, but sensitive to new physics contaminations
- $e^+e^-$, event shapes/jet rates $\rightarrow$ good potential, but remember the LEP lesson
- Thrust, C parameter: 0.113, 1%
- Jet rates: 0.119, 1%
- Must understand better underlying theory (NP corrections, formally subleading terms…)
- Hadron collider observables / PDF fits $\rightarrow$ very high accuracy, but same problems as PDF fits (low Q contamination, theory uncertainties, correlations with PDFs)
- Lattice very robust. Most robust determination $\rightarrow$ new approach. Assuming computer improvements $\rightarrow$ 0.3%, promising

Projections: see D. d’Enterria contribution in [arXiv:1512.05194]
Parameters: masses

1. Bottom, charm $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV

2. Top mass: $\delta m_t = 50$ MeV

- Hadron colliders: with the current level of understanding of QCD $\rightarrow$ unlikely to control better than $\sim \Lambda_{QCD}$. Progress at this stage almost impossible to predict (if no breakthrough, could be very limited)

- High precision: $e^+e^-$ threshold scan, can reach 50 MeV for short-distance masses. Very well-developed theory
Parameters: PDFs

Required improvements

- Theoretical uncertainties → first results appearing very soon
  Framework to investigate th. uncertainty, correlations available ~now
- High precision in the evolution → N³LO splitting function. Massive calculations, but reasonable to expect it in the not far future
- Better understanding of specific kinematic regions (nuclear corrections, higher twist, saturation…). With extended dataset: can afford to discard "problematic" data (low $Q^2$…)

Juan Rojo, SM@LHC 2019
Intrinsic uncertainties reduction

Highest precision: clean environment, simple observable \(\rightarrow\) EWPO
  - Mostly from \(Z\bar{f}f\) vertex
  - pQCD works very well, but precision requires many QCD/EW loops

Results required:
  - Leading 3-loop \(Z\bar{f}f\): \(\alpha \alpha_s^2, n_f \alpha^2 \alpha_s, n_f^2 \alpha^3\)
  - Also 4-loop QCD may be required
  - Full 2-loop completed recently

Typical problem: many loops, few legs
  - Well-established framework, massively difficult technical problems
  - A remarkable amount of progress recently \(\rightarrow\) expect new results
  - No kinematics dependence \(\rightarrow\) numerical approach

Also in this case, may need to consider more "realistic" scenario
  - \(e^+e^- \rightarrow f\bar{f}\), at 2-loops
  - Non-trivial kinematics, but 2-loop
Intrinsic uncertainties reduction

Highest precision: clean environment, simple observable → EWPO
  • mostly from Zf̄f vertex
  • pQCD works very well, but precision requires many QCD/EW loops

Results required:
  • leading 3-loop Zf̄f: ααs^2, n_f α^2 αs, n_f^2 α^3
  • also 4-loop QCD may be required
  • full 2-loop completed recently

Typical problem:
  • many loops, few legs
    • well-established framework, massively difficult technical problems
    • a remarkable amount of progress recently → expect new results
    • no kinematics dependence → numerical approach

Also in this case, may need to consider more "realistic" scenario
  • e^+e^- → f̄f, at 2-loops
  • non-trivial kinematics, but 2-loop
Intrinsic uncertainties reduction

Higher statistics/energy: *can explore a broad range of interesting processes/observables*

- A very rich physics potential
- Would require less precision than EWPO, but more complex processes (many legs, non-trivial kinematics, much more involved phenomenological studies)
- High precision for H, V, top, jets. Already now very good control. Improvements non-trivial

In this situation, *QCD TH improvements along a single direction won’t do*, concerted effort is required

- higher order QCD/EW calculations
- all-order resummation
- better parton showers
- better control over NP effects
- new pheno idea to maximise potential/stay away from "dangerous" regions
Intrinsic uncertainties reduction

Example: vector boson $p_T$, where we are and how to improve

Summary

- Measurements of gauge boson $p_T$ at the LHC require us to push theory predictions to the limits of perturbation theory and beyond

- Pattern of QCD (massless, except for thresholds in PDFs) corrections well understood, with residual errors at the 3-5% level across most of the spectrum

- Beyond this point, several effects become relevant:
  - higher order QCD corrections to the differential spectrum (i.e. $N^4LL+N^3LO$)
  - PDF errors at the 1-3% level: How to combine with the remaining perturbative error? Are differences between sets really understood? Theory uncertainties in PDFs?
  - NP corrections expected to be as large as 1-2%, small-mass Drell-Yan could be exploited to constrain these in a data driven manner (high TH+EXP precision required, challenging for TMD PDFs)
  - QED corrections at the ~1-2% level, uncertainties can be potentially reduced
  - bottom-quark mass corrections at the ~1-2% level, calculation at small $p_T$ feasible
  - parametric uncertainties, e.g. strong coupling at the ~1% level, currently hard to improve further
Intrinsic uncertainties reduction

Example: “Higgs at the HL/HE-LHC” LHCHXSWG report

\(ggF\): many small sources of uncertainties that add up

Improving substantially on any of the current sources of uncertainty represents a major theoretical challenge that should be met in accordance with our ability to utilise said precision and with experimental capabilities.

It is obvious that the future precision of experimental measurement of Higgs boson properties will challenge the theoretical community. Achieving a significant improvement of our current theoretical understanding of the Higgs boson and its interactions will inspire us to push the boundaries of our capabilities to predict and extract information.

+ extreme kinematics [boosted, off-shell…]

- **VBF**: NNLO beyond DIS, NNLOPS, control over MPI (+had)
- **VH**: \(gg\to ZZ\), realistic final states \((H\to b\bar{b})\), PS
- **ttH**: NNLO, precision in \(t\bar{t}b\bar{b}\) (higher orders, shower, connection with MVA…)
**Path towards precision: QCD**

1. **Within perturbation theory**
   - **Fixed-order**: NNLO for $2\to3$ reactions, $N^3$LO for standard candles, EFTs
     - non-trivial improvement over current technology (multi-loop amplitudes, IR subtraction schemes, efficient NLO $2\to4$, extreme regions…)
     - may require going beyond "standard" approach to perturbative calculations.
     - $\bar{t}@N^3$LO: $\delta\sigma \neq R+V$, non-analytic $|\alpha_s|$ terms [see M. Beneke, Ruiz-Fermienia 1606.02434, Melnikov, Vainshtein, Voloshin 1402.5690]
     - Jets: factorisation violation [see e.g. Catani, de Florian, Rodrigo 1112.4405]
   - **All-order**
     - High accuracy, more exclusive/combined resummation. Understanding subleading terms
     - Better parton showers
       - Generic fixed-order/PS merging at high formal accuracy
     - Beyond (N)LL shower
     - Beyond leading color [genuinely new conceptual development required]
Path towards precision: QCD

2. Beyond perturbation theory
   • Better control/understanding over (some) NP effects
     • eventually, limiting factor for many analysis (e.g. now: $m_t$)
     • NP $\sim 1/\Lambda^k$. Very little known.
     • $k=1,2$ massively different in practice $\rightarrow$ systematic understanding of scaling would be already useful
     • At least to some extent, can be done from first principles
   • Beyond first principles
     • NP aspects in the shower: hadronization models etc…

3. Pheno studies
   • How to maximise physics potential
   • Stay away from problematic regions
   • Identify new observables/fiducial regions
   • Study correlations, connections with MVAs…
Path towards precision: QCD

Would require both significant improvement over current state-of-the-art

• Technically very challenging, but judging from progress in the last 10 years not unreasonable
• Would require focus, dedication and support

Would also require genuinely new conceptual breakthrough in QCD → much more difficult to predict

• Going from 20% to 10% qualitatively different than going from 10-5% to \( \neq 1\% \)
• Significant development beyond current standard framework will be required

[Sociological issues (large groups, very long projects, more and more technical…) → see also QCD session tomorrow]
Thank you very much
Back-up
Table 1. Values for the instantaneous luminosity are given; these are before and after a luminosity upgrade planned. The last column gives the abbreviation used in this report in the following sections. When the entire programme is discussed, the highest energy corresponds to 75% of that. The values for production can be measured without the decay of the Higgs. For HL-LHC this is also the case while for HE-LHC and FCC

| Collider   | Type | $\sqrt{s}$ | $P$ [\%] $|e^-/e^+$] | N(Det.) | $L_{\text{inst}}$ $[10^{34} \text{cm}^{-2} \text{s}^{-1}]$ | $L$ $[\text{ab}^{-1}]$ | Time [years] | Refs. | Abbreviation |
|------------|------|------------|---------------------|---------|-------------------------------------------|-----------------|-------------|-------|-------------|
| HL-LHC     | $pp$ | 14 TeV     | -                   | 2       | 5                                         | 6.0             | 12          | [10]  | HL-LHC      |
| FCC-hh     | $pp$ | 100 TeV    | -                   | 2       | 30                                        | 30.0            | 25          | [1]   | FCC-hh      |
| FCC-ee     | $ee$ | $M_Z$      | 0/0                 | 2       | 100/200                                   | 150             | 4           | [1]   | FCC-ee$_{240}$ |
|            |      | $2M_W$     | 0/0                 | 2       | 25                                        | 10              | 1-2         |       | FCC-ee$_{365}$ |
|            |      | 240 GeV    | 0/0                 | 2       | 7                                         | 5               | 3           |       | (1 y SD before $2m_{top}$ run) |
|            |      | $2m_{top}$ | 0/0                 | 2       | 0.8/1.4                                   | 1.5             | 5           | (+1)  | |
| ILC        | $ee$ | 250 GeV    | ±80/±30             | 1       | 1.35/2.7                                  | 2.0             | 11.5        | [3, 11]| ILC$_{250}$ |
|            |      | 350 GeV    | ±80/±30             | 1       | 1.6                                       | 0.2             | 1           |       | ILC$_{350}$ |
|            |      | 500 GeV    | ±80/±30             | 1       | 1.8/3.6                                   | 4.0             | 8.5         |       | ILC$_{500}$ |
|            |      |            |                     |         |                                           |                 |             |       | (1 y SD after 250 GeV run) |
| CEPC       | $ee$ | $M_Z$      | 0/0                 | 2       | 17/32                                     | 16              | 2           | [2]   | CEPC       |
|            |      | $2M_W$     | 0/0                 | 2       | 10                                        | 2.6             | 1           |       |             |
|            |      | 240 GeV    | 0/0                 | 2       | 3                                         | 5.6             | 7           |       |             |
| CLIC       | $ee$ | 380 GeV    | ±80/0               | 1       | 1.5                                       | 1.0             | 8           | [12]  | CLIC$_{380}$ |
|            |      | 1.5 TeV    | ±80/0               | 1       | 3.7                                       | 2.5             | 7           |       | CLIC$_{1500}$ |
|            |      | 3.0 TeV    | ±80/0               | 1       | 6.0                                       | 5.0             | 8           |       | CLIC$_{3000}$ |
|            |      |            |                     |         |                                           |                 |             |       | (2 y SDs between energy stages) |
| LHeC       | $ep$ | 1.3 TeV    | -                   | 1       | 0.8                                       | 1.0             | 15          | [9]   | LHeC       |
| HE-LHeC    | $ep$ | 2.6 TeV    | -                   | 1       | 1.5                                       | 2.0             | 20          | [1]   | HE-LHeC    |
| FCC-eh     | $ep$ | 3.5 TeV    | -                   | 1       | 1.5                                       | 2.0             | 25          | [1]   | FCC-eh     |
PDFs: HL-LHC

PDFs at the HL-LHC (Q = 10 GeV)

PDFs at the HL-LHC (Q = 10 GeV)

PDFs at the HL-LHC (Q = 10 GeV)

PDFs at the HL-LHC (Q = 10 GeV)
PDFs: LHeC
Theoretical Cross Sections and Partial Width Uncertainties

Table 1. Cross sections for the main production channels expected for Higgs boson production at the different types of colliders (as defined in Table 1).

<table>
<thead>
<tr>
<th>pp collider</th>
<th>Total</th>
<th>$ggH$</th>
<th>VBF</th>
<th>$WH$</th>
<th>$ZH$</th>
<th>$t\bar{t}H$</th>
<th>$tH$</th>
<th>$ggHH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC (13 TeV)</td>
<td>56</td>
<td>48.6</td>
<td>3.77</td>
<td>1.36</td>
<td>0.88</td>
<td>0.510</td>
<td>0.074</td>
<td>0.031</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>62</td>
<td>54.7</td>
<td>4.26</td>
<td>1.50</td>
<td>0.99</td>
<td>0.613</td>
<td>0.090</td>
<td>0.037</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>168</td>
<td>147</td>
<td>11.8</td>
<td>3.40</td>
<td>2.47</td>
<td>2.86</td>
<td>0.418</td>
<td>0.140</td>
</tr>
<tr>
<td>FCC$_{hh}$</td>
<td>936</td>
<td>802</td>
<td>69</td>
<td>15.7</td>
<td>11.4</td>
<td>32.1</td>
<td>4.70</td>
<td>1.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$e^+e^-$ collider ($\mathcal{P}<em>{e^-} / \mathcal{P}</em>{e^+}$)</th>
<th>Total</th>
<th>$VBF$</th>
<th>$ZH$</th>
<th>$t\bar{t}H$</th>
<th>$ZHH$ (CC VBF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPC</td>
<td>199</td>
<td>6.19/0.28</td>
<td></td>
<td></td>
<td>192.6</td>
</tr>
<tr>
<td>FCC$_{ee}$</td>
<td>199</td>
<td>6.19/0.28</td>
<td></td>
<td></td>
<td>192.6</td>
</tr>
<tr>
<td>ILC$_{250}$ (-80/30)</td>
<td>313</td>
<td>15.4/0.70</td>
<td>297</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILC$_{500}$ (-80/30)</td>
<td>262</td>
<td>158/7.8</td>
<td>96</td>
<td>0.41</td>
<td>0.2</td>
</tr>
<tr>
<td>CLIC$_{380}$ (0/0)</td>
<td>160</td>
<td>40/7.4</td>
<td>113</td>
<td>–</td>
<td>0.029 (0.0020)</td>
</tr>
<tr>
<td>CLIC$_{1500}$ (0/0)</td>
<td>329</td>
<td>290/30</td>
<td>7.5</td>
<td>1.3</td>
<td>0.082 (0.207)</td>
</tr>
<tr>
<td>CLIC$_{3000}$ (0/0)</td>
<td>532</td>
<td>480/49</td>
<td>2</td>
<td>0.48</td>
<td>0.037 (0.77)</td>
</tr>
<tr>
<td>CLIC$_{380}$ (-80/0)</td>
<td>209</td>
<td>68/8.7</td>
<td>133</td>
<td>–</td>
<td>0.034 (0.0024)</td>
</tr>
<tr>
<td>CLIC$_{1500}$ (-80/0)</td>
<td>574</td>
<td>528/35</td>
<td>8.8</td>
<td>1.70</td>
<td>0.97 (0.37)</td>
</tr>
<tr>
<td>CLIC$_{3000}$ (-80/0)</td>
<td>921</td>
<td>860/57</td>
<td>2.4</td>
<td>0.61</td>
<td>0.043 (1.38)</td>
</tr>
<tr>
<td>CLIC$_{380}$ (+80/0)</td>
<td>112</td>
<td>13/6.0</td>
<td>93</td>
<td>–</td>
<td>0.024 (0.0016)</td>
</tr>
<tr>
<td>CLIC$_{1500}$ (+80/0)</td>
<td>91</td>
<td>59/24</td>
<td>6.2</td>
<td>0.89</td>
<td>0.068 (0.045)</td>
</tr>
<tr>
<td>CLIC$_{3000}$ (+80/0)</td>
<td>138</td>
<td>96/40</td>
<td>1.7</td>
<td>0.34</td>
<td>0.30 (1.56)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$e^- p$ collider ($\mathcal{P}_{e^-}$)</th>
<th>Total</th>
<th>$VBF$</th>
<th>$tH$</th>
<th>$HH$ (CC VBF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC (0)</td>
<td>130</td>
<td>110/20</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>HE-LHeC (0)</td>
<td>247</td>
<td>206/41</td>
<td>0.37</td>
<td>0.04</td>
</tr>
<tr>
<td>FCC$_{eh}$ (0)</td>
<td>674</td>
<td>547/127</td>
<td>4.2</td>
<td>0.26</td>
</tr>
<tr>
<td>LHeC (-80)</td>
<td>221</td>
<td>197/24</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>HE-LHeC (-80)</td>
<td>420</td>
<td>372/48</td>
<td>0.67</td>
<td>0.07</td>
</tr>
<tr>
<td>FCC$_{eh}$ (-80)</td>
<td>1189</td>
<td>1040/149</td>
<td>7.6</td>
<td>0.47</td>
</tr>
</tbody>
</table>