Higher-order corrections for HZ production and related techniques

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What is a Higgs Boson?

The elusive Higgs boson, if found, would complete the Standard Model of physics. It is thought that matter obtains mass by interacting with the Higgs field. If Higgs did not exist, according to this model, everything in the universe would be massless.

The "cocktail party" analogy

Imagine a party where guests are evenly spaced around the room. The river of guests represents the Higgs field, which is everywhere in the universe. Moving a slightly heavier guest inside the room makes it seem a bit heavier to those nearby, but none notice the difference until they are stuck in their own living room.

As the celebrity passes through the room, the concerted stamp of guests surrounding her gives the group a bit of extra attention. The stamp is harder to stop once the same scene is repeated, and so we can say that the stamp has captured mass.

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**ATLAS and CMS**

**LHC Run 1**

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS + CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
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<td>$H \rightarrow ZZ \rightarrow 4l$</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td>$126.02 \pm 0.51 (\pm 0.43 \pm 0.27)$ GeV</td>
<td>$124.70 \pm 0.34 (\pm 0.31 \pm 0.15)$ GeV</td>
<td>$125.07 \pm 0.29 (\pm 0.25 \pm 0.14)$ GeV</td>
</tr>
<tr>
<td><strong>Stat.</strong></td>
<td>$124.51 \pm 0.52 (\pm 0.52 \pm 0.04)$ GeV</td>
<td>$125.59 \pm 0.45 (\pm 0.42 \pm 0.17)$ GeV</td>
<td>$125.15 \pm 0.40 (\pm 0.37 \pm 0.15)$ GeV</td>
</tr>
<tr>
<td><strong>Syst.</strong></td>
<td>$124.51 \pm 0.52 (\pm 0.52 \pm 0.04)$ GeV</td>
<td>$125.59 \pm 0.45 (\pm 0.42 \pm 0.17)$ GeV</td>
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$m_H$ [GeV]
Next Generation $e^+e^-$ Collider (Higgs Factory)

- ILC (Japan)
- CEPC (China)
- FCC-ee (Europe)

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section</th>
<th>Events in 5.6 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow ZH$</td>
<td>196.2</td>
<td>$1.10 \times 10^6$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \nu_e\bar{\nu}_e H$</td>
<td>6.19</td>
<td>$3.47 \times 10^4$</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow e^+e^- H$</td>
<td>0.28</td>
<td>$1.57 \times 10^3$</td>
</tr>
<tr>
<td>Total</td>
<td>203.7</td>
<td>$1.14 \times 10^6$</td>
</tr>
</tbody>
</table>
**Total Xsection of** $e^+ e^- \rightarrow HZ$

- The relative precision of $\sigma(ZH)$ can be 0.5% ($\mathcal{L} = 5.6 \text{ ab}^{-1}$)

- Model independent analysis gives $\delta\kappa_Z = 0.25\%$, which however did not include theoretical uncertainty.

- EW NLO $\mathcal{O}(\alpha)$ (>2% uncert.) & EW+QCD mixed NNLO $\mathcal{O}(\alpha\alpha_s)$ (>1% uncert.) by including scale uncert. and scheme uncert.


- Precision of $\delta\kappa_Z$ can affect the studies of EW phase transition.


- Precision measurement on $\sigma(ZH)$ may shed light on new physics search, e.g.


- Therefore, NNLO EW correction must be included for future physics analysis.
Difficulties on NNLO EW correction

• Virtual correction:

1. Multi-scale two-loop Feynman diagrams, esp. non-planar double-box
   ⇒ reduction of amplitude, reduction to master integrals, calculation of
   master integrals

2. 25377 Feynman diagrams (Feynman gauge), where only 2250 diagrams
   are very challenging, i.e. with 7 denominators.

• Real correction:

3. double QED radiation should be handled easily (Abelian case compared
   to well studied QCD radiation)
Choices for amplitude reduction

• Projection method

• IBP method

• Series representation method
Choices for reduction to master integrals

• IBP reduction

• Series representation method
Calculation of master integrals

• Analytical method:
  Most conventional approach, but one may confront difficult integrals, e.g. elliptic integral, in the complicated amplitudes.

• Numerical method:
  1. Sector decomposition
  
  2. Mellin-Barnes

  3. Series representation

• Semi-numerical method
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Finally

• NNLO EW correction to $e^+e^- \rightarrow HZ$ must be done to match the precision of experiment data.

• The complete solution will take years.

• Call for international collaboration or working group for this big project.
  ✦ Ayres Freitas group @ University of Pittsburgh
  ✦ Zhao Li group @ IHEP-CAS
  ✦ Hua-Xing Zhu group @ Zhejiang University