Higher-order corrections for HZ production and related techniques

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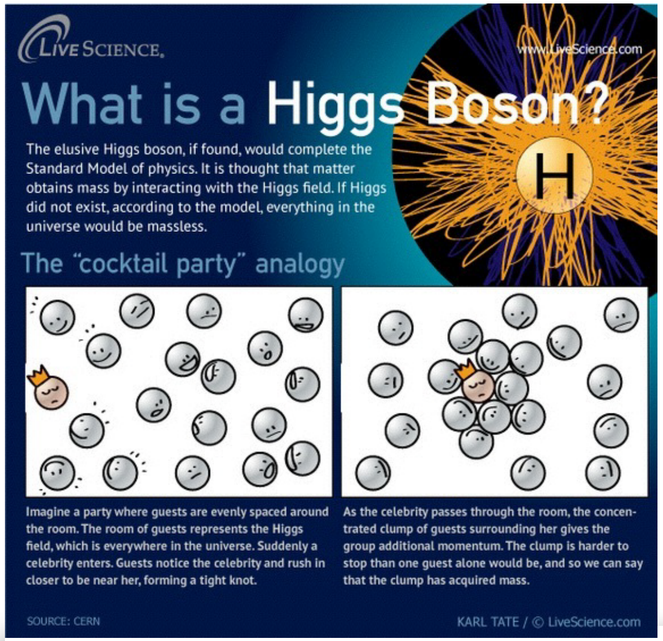
Snowmass Community Planning Meeting

“From Amplitudes to Precision Theory for Future Colliders” Oct 6th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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 the model, everything in the universe would be massless.
H
The "cocktail party" analogy
Imagine a party where guests are evenly spaced around the room. The room of guests represents the Higgs field, which is everywhere in the universe. Suddenly a celebrity enters. Guests notice the celebrity and rush in closer to be near her, forming a tight knot.
As the celebrity passes through the room, the concentrated clump of guests surrounding her gives the group additional momentum. The clump is harder to stop than one guest alone would be, and so we can say that the clump has acquired mass.
SOURCE: CERN
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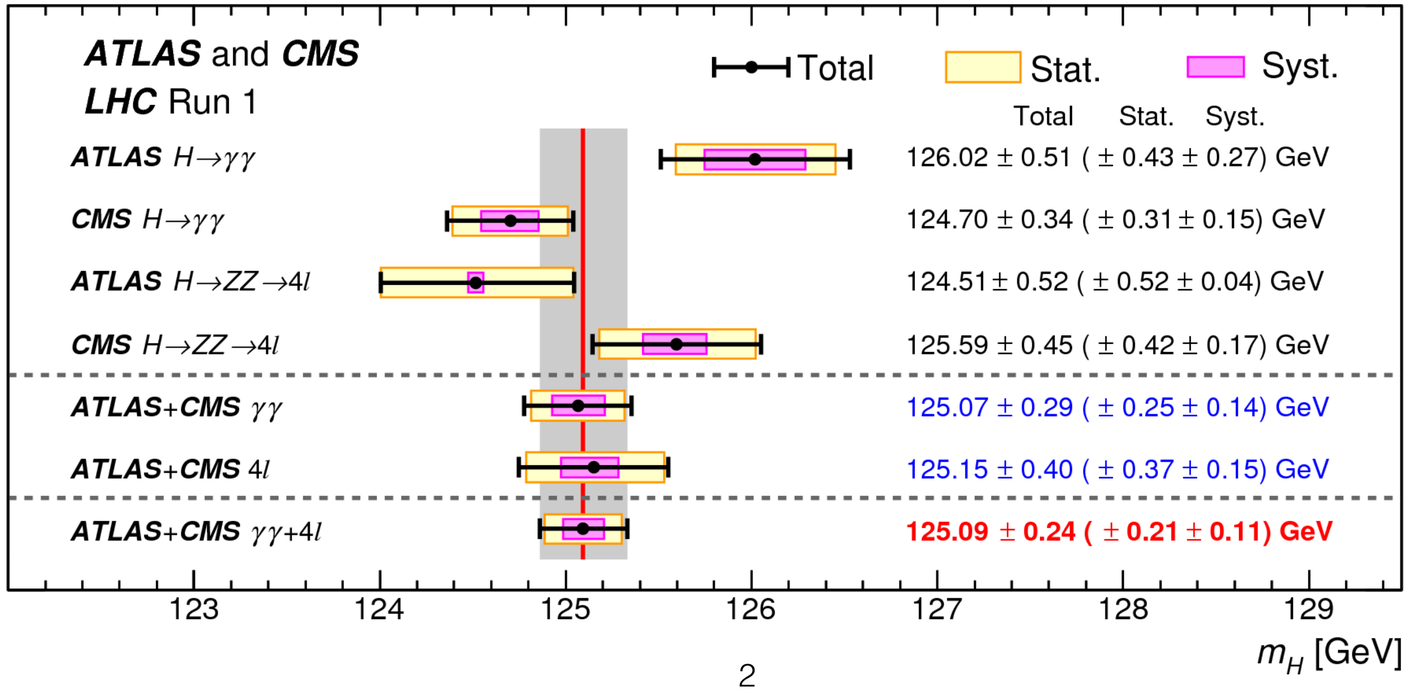
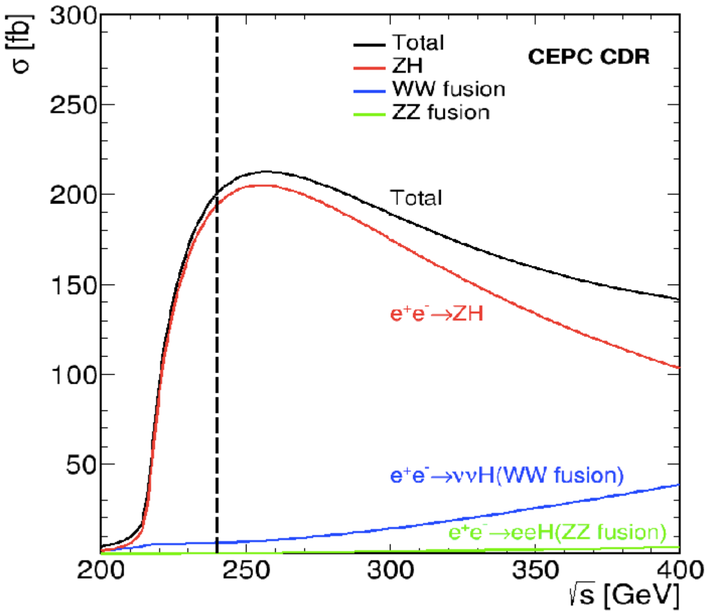
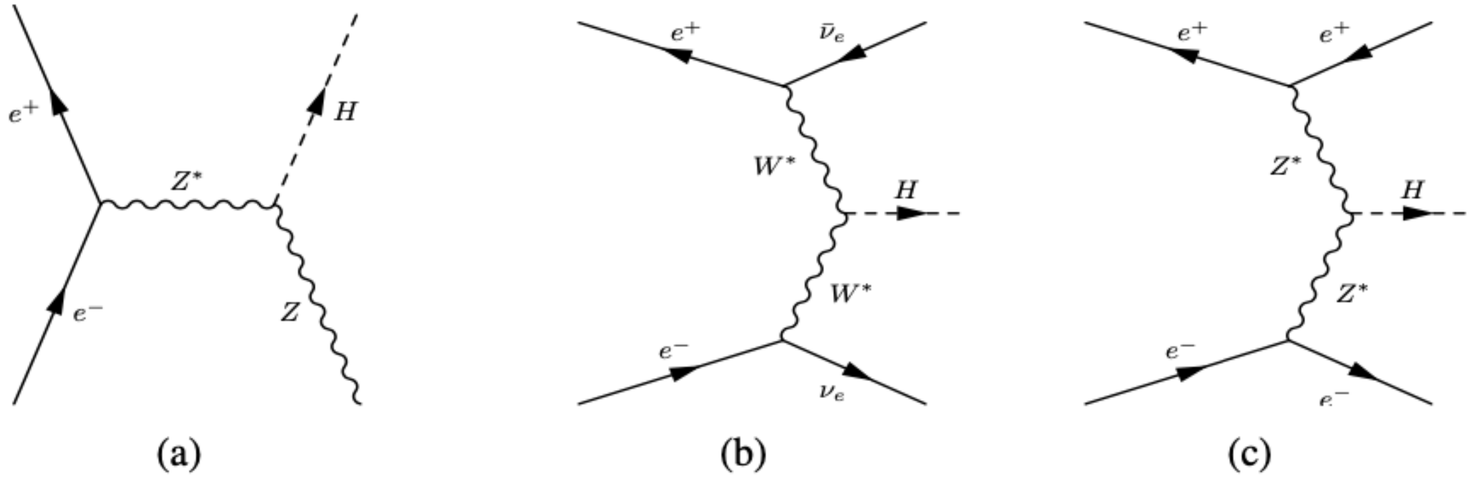

ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ 126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ 124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l 124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l 125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ 125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l 125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l 125.09 ± 0.24 (± 0.21 ± 0.11) GeV
123
124
125
126
127
128
129
m_H [GeV]

Next Generation e^+e^- Collider (Higgs Factory)

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





Process	Cross section	Events in $5.6\,\mathrm{ab}^{-1}$
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to e^+e^- H$	0.28	1.57×10^3
Total	203.7	1.14×10^6

Total Xsection of $e^+e^- \to HZ$

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

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

- 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.
  Nucl. Phys. B 216, 469 (1983); Z. Phys. C 55, 605 (1992); Phys. Rev. D 95, 093003 (2017); Phys. Rev. D 96, 051301 (2017)

- Precision of $\delta\kappa_Z$ can affect the studies of EW phase transition.
  Phys. Lett. B 317, 385 (1993); Phys. Lett. B 323, 339 (1994); JHEP 08, 010 (2007)

- Precision measurement on $\sigma(ZH)$ may shed light on new physics search, e.g.
  JHEP 1503 (2015) 146; Phys.Rept. 496 (2010) 1-77; JHEP 08 (2015) 152

- 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
     $\Rightarrow$ 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
  JHEP, 05: 060 (2002); JHEP, 04: 021 (2004)
- IBP method
  Int. J. Mod. Phys., A15: 5087–5159 (2000)
- Series representation method
  Phys. Rev., D99(7): 071501 (2019); Phys.Rev.D 101 (2020) 7, 076023

Choices for reduction to master integrals

- IBP reduction
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- Series representation method
  Phys. Rev., D99(7): 071501 (2019)

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
     Nucl. Phys. B585 (2000) 741; Int.J.Mod.Phys.A 23 (2008) 1457-1486; etc.

  2. Mellin-Barnes
     Phys. Lett. B460 (1999) 397; Phys.Lett.B469 (1999) 225; etc.

  3. Series representation
     Phys. Rev., D99(7): 071501 (2019)

- Semi-numerical method
  JHEP 11 (2006) 048

Finally

- NNLO EW correction to $e^+e^- \to HZ$ 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