Mixed electroweak-QCD corrections to $e^+e^- \to HZ$ at Higgs factories

Department of modern physics
University of Science and Technology of China

Qingfeng SUN

2016/11/30 (Beijing)

arXiv:1609.03995
In collaboration with Feng Feng(CUMT), Yu Jia(IHEP), Wen-long Sang(SWU)

Outline

1. Motivations
2. Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$
3. Our recent NNLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha\alpha_s)$
4. Detailed techniques and results
5. Summary and outlook

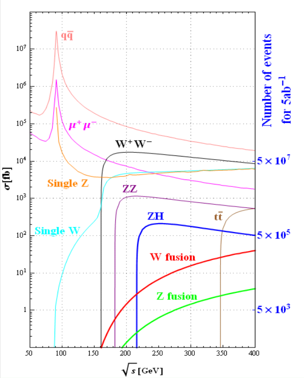
Outline

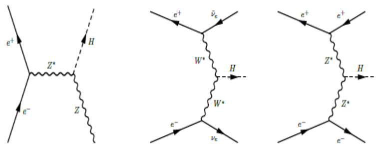
1. Motivations
2. Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$
3. Our recent NNLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha\alpha_s)$
4. Detailed techniques and results
5. Summary and outlook

Motivations

- The e^+e^- Higgs factory is an ideal place to test the property of Higgs Boson in Standard Model and to seek the hint of new physics.
- Three next-generation e^+e^- colliders have been proposed to serve as Higgs factory: International Linear Collider (ILC), Future Circular Collider (FCC-ee), and Circular Electron-Positron Collider (CEPC).
- CEPC can measure production cross section for σ(ZH) to very high precision.
- Knowing the NLO electroweak correction (a few percent) to $e^+e^- \to HZ$ is not sufficient to meet experimental precision.
- NNLO corrections to $e^+e^- \to HZ$ should be considered, which include $\mathcal{O}(\alpha^2)$ and $\mathcal{O}(\alpha\alpha_s)$. The latter is obviously dominant, so we will calculate it.

- Various Higgs production mechanism at lepton colliders.





As is seen, the Higgsstrahlung process $e^+e^- \to HZ$ is dominant in e^+e^- colliders at low energy. Its contribution is much more important than that of WW and ZZ fusion mechanism.

Outline

1. Motivations
2. Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$
3. Our recent NNLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha\alpha_s)$
4. Detailed techniques and results
5. Summary and outlook

Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$

The $\mathcal{O}(\alpha)$ corrections to $e^+e^- \to HZ$ have been calculated independently by three groups:

- J. Fleischer and F. Jegerlehner, Nucl. Phys. B 216 (1983) 469.
- B. A. Kniehl, Z. Phys. C 55 (1992) 605.
- A. Denner, J. Kublbeck, R. Mertig and M. Bohm, Z. Phys. C 56 (1992) 261.

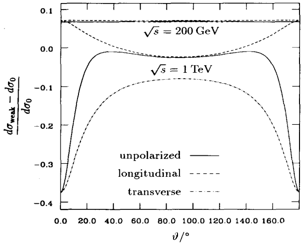


Fig. 15. The relative corrections to the differential cross section for different polarizations of the Z-boson and different CMS energies

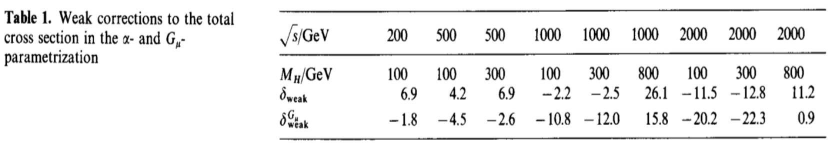


Table 1. Weak corrections to the total cross section in the α- and G_μ-parametrization

$\sqrt{s}$/GeV	200	500	500	1000	1000	1000	2000	2000	2000
M_H/GeV	100	100	300	100	300	800	100	300	800
δ_{weak}	6.9	4.2	6.9	−2.2	−2.5	26.1	−11.5	−12.8	11.2
$\delta_{\text{weak}}^{G_\mu}$	−1.8	−4.5	−2.6	−10.8	−12.0	15.8	−20.2	−22.3	0.9

Outline

1. Motivations

2. Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$

3. Our recent NNLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha\alpha_s)$

4. Detailed techniques and results

5. Summary and outlook

Typical higher order Feynman diagrams to Higgsstrahlung

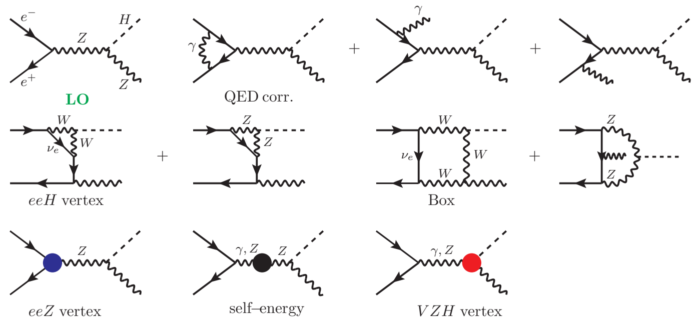
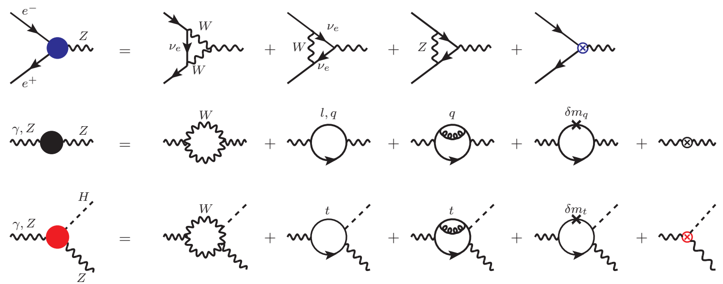


图: LO diagram for $e^+e^- \to HZ$, together with some representative higher-order diagrams.



Representative diagrams for the radiative corrections to the renormalized eeZ vertex, γ/Z self-energy, and $ZZH/\gamma ZH$ vertex, through $\mathcal{O}(\alpha\alpha_s)$. The cross represents the quark mass counterterm in QCD, cap denotes the electroweak counterterm in on-shell scheme.

At $\mathcal{O}(\alpha\alpha_s)$ 2-loop level, there are totally 47 master integrals.

Outline

1. Motivations
2. Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$
3. Our recent NNLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha\alpha_s)$
4. Detailed techniques and results
5. Summary and outlook

Techniques

We renormalize the UV divergences with on-mass-shell scheme. Related references:

- A. Sirlin, Phys. Rev. D 22, 971 (1980).
- A. Denner, Fortsch. Phys. 41, 307 (1993).

The top quark mass appears in internal top quark propagators and the $Ht\bar{t}$ Yukawa vertex, which is renormalized in on-shell scheme as:

$$\delta m_t = -m_t \Gamma(1+\epsilon) \left(\frac{4\pi\mu^2}{m_t^2} \right)^{\epsilon} \frac{C_F}{4} \frac{\alpha_s}{\pi} \frac{3-2\epsilon}{\epsilon(1-2\epsilon)}.$$

Related counterterms at $\mathcal{O}(\alpha\alpha_s)$:

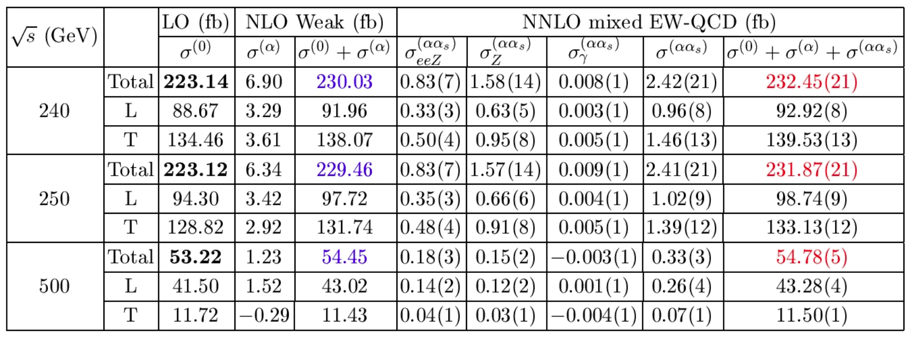
δZ_e, δM_Z^2, δM_W^2, δM_H^2, δZ_{ZZ}, $\delta Z_{\gamma Z}$ and δZ_H

We adopt the so-called $\alpha(0)$ scheme where $\alpha(0) = 1/137.035999$. The charge renormalization constant Z_e(defined by $e^0 = Z_e e$) in $\alpha(0)$ scheme is expressed as:

$$\begin{aligned}\delta Z_e\Big|_{\alpha(0)} =& \frac{1}{2}\Pi^{\gamma\gamma}(0) - \frac{s_W}{c_W}\frac{\Sigma_T^{\gamma Z}(0)}{M_Z^2} \\ =& \frac{1}{2}\Delta\alpha_{had}^{(5)}\left(M_Z^2\right) + \frac{1}{2}Re\Pi^{\gamma\gamma(5)}\left(M_Z^2\right) + \frac{1}{2}\Pi_{rem}^{\gamma\gamma}(0) - \frac{s_W}{c_W}\frac{\Sigma_T^{\gamma Z}(0)}{M_Z^2},\end{aligned}$$

where $\Delta\alpha_{had}^{(5)}(M_Z^2) = 0.02771$ represents the non-perturbative hadronic contributions to the running effect of the electroweak coupling and $\Pi_{rem}^{\gamma\gamma(5)}(0)$ is the remaining possible photon vacuum polarizations from other charged SM particles.

Numeric Results in $\alpha(0)$ scheme



$\sqrt{s}$ (GeV)		LO (fb)	NLO Weak (fb)		NNLO mixed EW-QCD (fb)				
		$\sigma^{(0)}$	$\sigma^{(\alpha)}$	$\sigma^{(0)}+\sigma^{(\alpha)}$	$\sigma_{eeZ}^{(\alpha\alpha_s)}$	$\sigma_{Z}^{(\alpha\alpha_s)}$	$\sigma_{\gamma}^{(\alpha\alpha_s)}$	$\sigma^{(\alpha\alpha_s)}$	$\sigma^{(0)}+\sigma^{(\alpha)}+\sigma^{(\alpha\alpha_s)}$
240	Total	**223.14**	6.90	230.03	0.83(7)	1.58(14)	0.008(1)	2.42(21)	232.45(21)
	L	88.67	3.29	91.96	0.33(3)	0.63(5)	0.003(1)	0.96(8)	92.92(8)
	T	134.46	3.61	138.07	0.50(4)	0.95(8)	0.005(1)	1.46(13)	139.53(13)
250	Total	**223.12**	6.34	229.46	0.83(7)	1.57(14)	0.009(1)	2.41(21)	231.87(21)
	L	94.30	3.42	97.72	0.35(3)	0.66(6)	0.004(1)	1.02(9)	98.74(9)
	T	128.82	2.92	131.74	0.48(4)	0.91(8)	0.005(1)	1.39(12)	133.13(12)
500	Total	**53.22**	1.23	54.45	0.18(3)	0.15(2)	−0.003(1)	0.33(3)	54.78(5)
	L	41.50	1.52	43.02	0.14(2)	0.12(2)	0.001(1)	0.26(4)	43.28(4)
	T	11.72	−0.29	11.43	0.04(1)	0.03(1)	−0.004(1)	0.07(1)	11.50(1)

The (un)polarized Higgsstrahlung cross sections at $\sqrt{s} = 240$ GeV, 250 GeV and 500 GeV. We enumerate the NLO weak corrections, together with the NNLO electroweak-QCD $\mathcal{O}(\alpha\alpha_s)$ corrections.

From $\alpha(0)$ to $\alpha(M_Z^2)$ scheme

Replacements:

$$\delta Z_e\Big|_{\alpha(M_Z^2)} = \delta Z_e\Big|_{\alpha(0)} - \frac{1}{2}\Delta\alpha(M_Z^2).$$

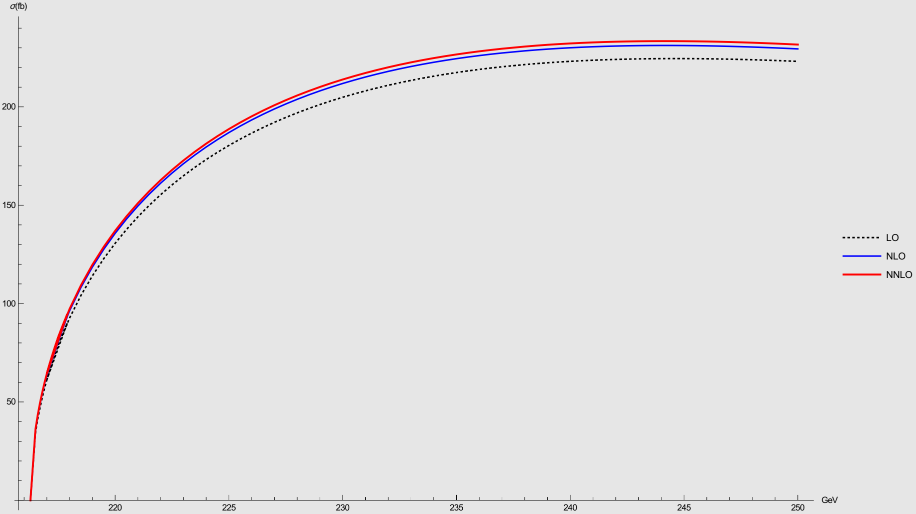
$$\alpha(M_Z^2) = \alpha(0)\left[1 + \Delta\alpha(M_Z^2)\big|_{\text{fermionic}} + \dots\right] = \frac{\alpha(0)}{1 - \Delta\alpha(M_Z^2)\big|_{\text{fermionic}}}.$$

with $\alpha(0) = 1/137.035999$
$\alpha(M_Z^2) = 1/128.933$
$\Delta\alpha(M_Z^2)\big|_{\text{fermionic}} = \Delta\alpha_{had}^{(5)}(M_Z^2) + \Delta\alpha(M_Z^2)\big|_{\text{lepton}} = 0.05913.$
The $\Delta\alpha(M_Z^2)\big|_{\text{fermionic}}$ above represents the fermionic contribution to the running effect of the α.

Numeric Results in $\alpha(M_Z^2)$ scheme

	LO	NLO	NNLO
240 GeV	**252.07**	228.67	231.56
250 GeV	**252.04**	227.97	230.87
500 GeV	**60.12**	54.04	54.44

表: Numeric Results in $\alpha(M_Z^2)$ scheme at various energy.



Total cross section with the center-of-mass energy ranging from threshold(216.28 GeV) to 250 GeV. The maximum of the cross section is around 244∼245 GeV

Polarized differential cross sections:

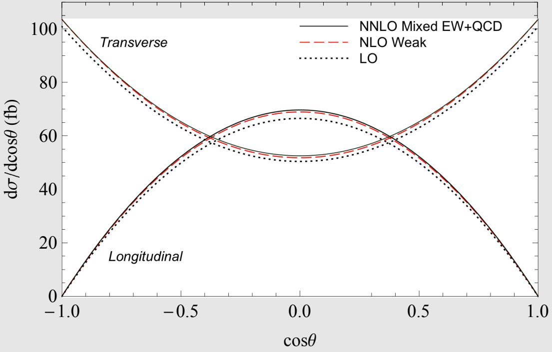


图: Differential polarized cross sections for Higgsstrahlung at $\sqrt{s} = 240$ GeV at various level of perturbative accuracy. The green band indicates the QCD uncertainty due to varying the renormalization scale from M_Z to $\sqrt{s}$.

Unpolarized differential cross sections:

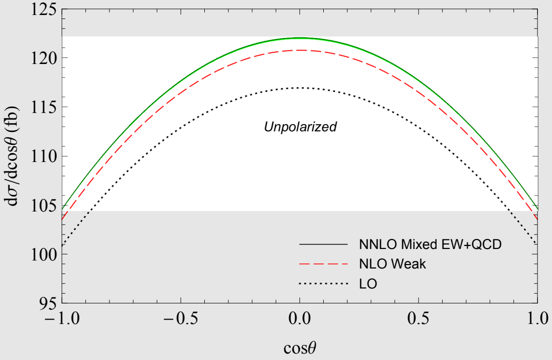


图: Differential unpolarized cross sections for Higgsstrahlung at $\sqrt{s} = 240$ GeV at various level of perturbative accuracy. The green band indicates the QCD uncertainty due to varying the renormalization scale from M_Z to $\sqrt{s}$.

Outline

1. Motivations
2. Previous NLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha)$
3. Our recent NNLO work on $e^+e^- \to HZ$ at $\mathcal{O}(\alpha\alpha_s)$
4. Detailed techniques and results
5. Summary and outlook

Summary and outlook I

- We revisit the $\mathcal{O}(\alpha)$ NLO correction with modern accuately measured parameters and and find the NLO correction is about 3.1% at 240 GeV.
- We calculate the $\mathcal{O}(\alpha\alpha_s)$ NNLO corrections and find the NNLO corrections sizable, about 1.1% at 240 GeV, well above the projected experimental sub-percent accuracy for the $\sigma(ZH)$ measurement.
- To meet such an exquisite experimental precision, it might even be relevant to further address the two-loop $\mathcal{O}(\alpha^2)$ NNLO corrections or even the three-loop $\mathcal{O}(\alpha\alpha_s^2)$ NNNLO corrections.
- The ISR(Initial State Radiation) effects have to be considered carefully to meet the experimental requirements.

Summary and outlook II

- More detailed error estimation

  From the updated data of review of particle physics:

  $M_W = 80.385 \pm 0.015$

  $M_t = 173.21 \pm 0.51 \pm 0.71$

  $M_H = 125.09 \pm 0.21 \pm 0.11$

  $\Delta\alpha^{(5)}_{had}(M_Z^2) = 0.02764 \pm 0.00013$

  etc...

  the uncertainty of the mass of Higgs boson will affect theoretical prediction because its mass will appear in the two-body phase space factor.

Thanks for your attention!