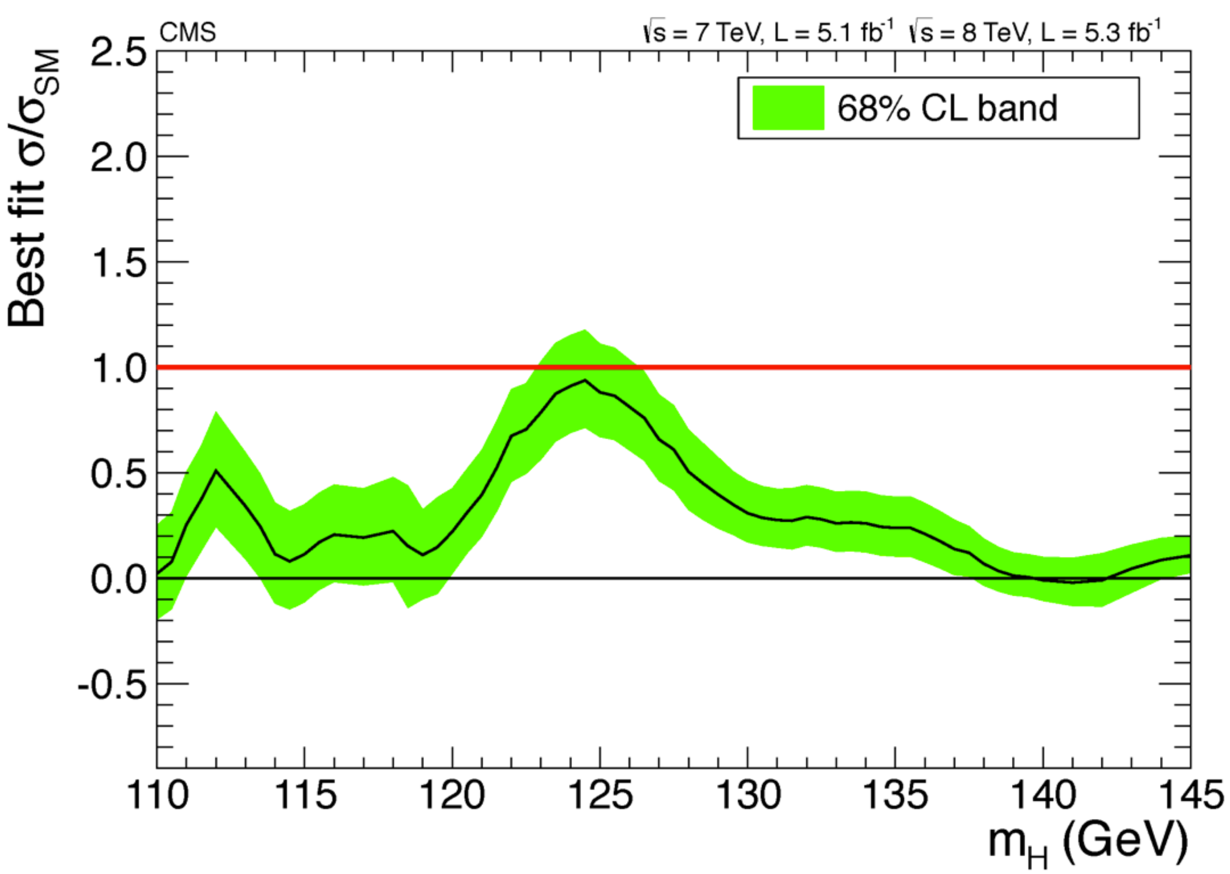
High Precision Higgs Production at CEPC

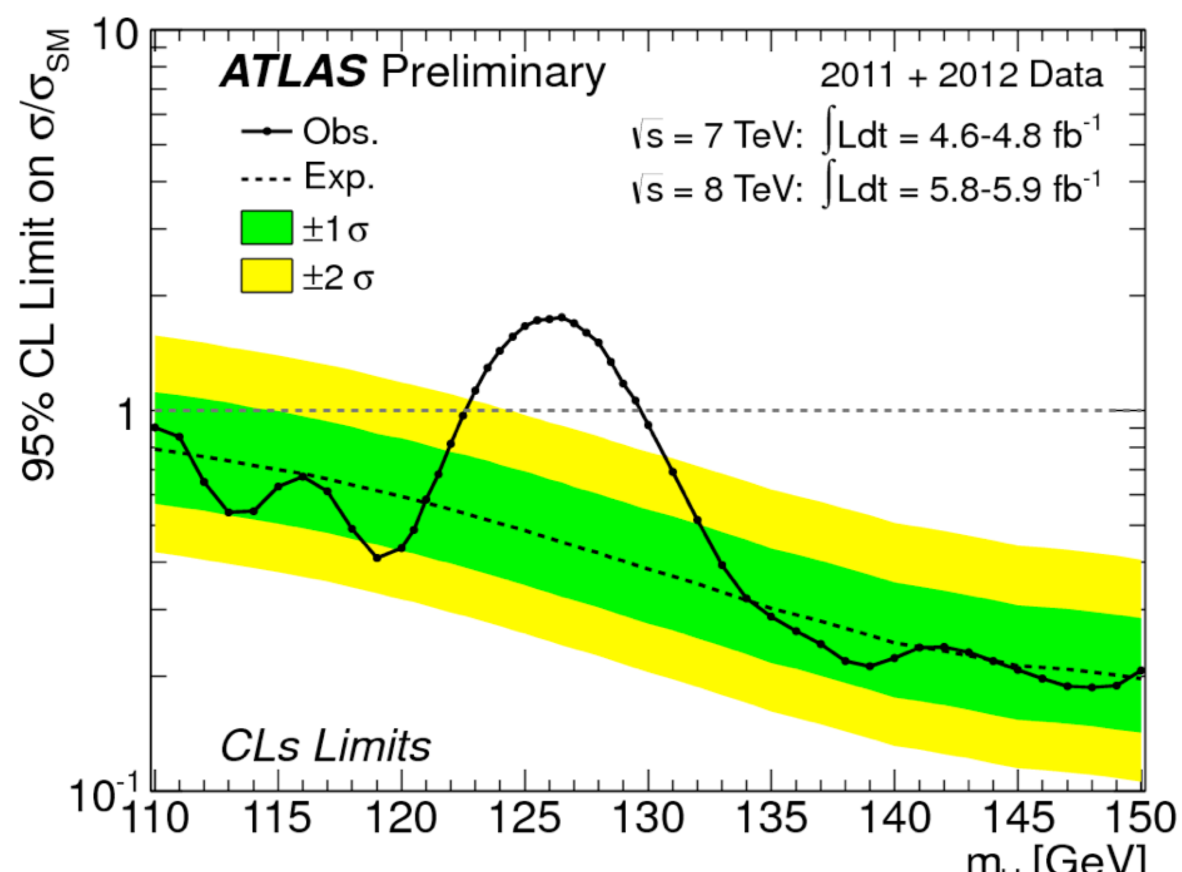
Zhao Li

IHEP-CAS

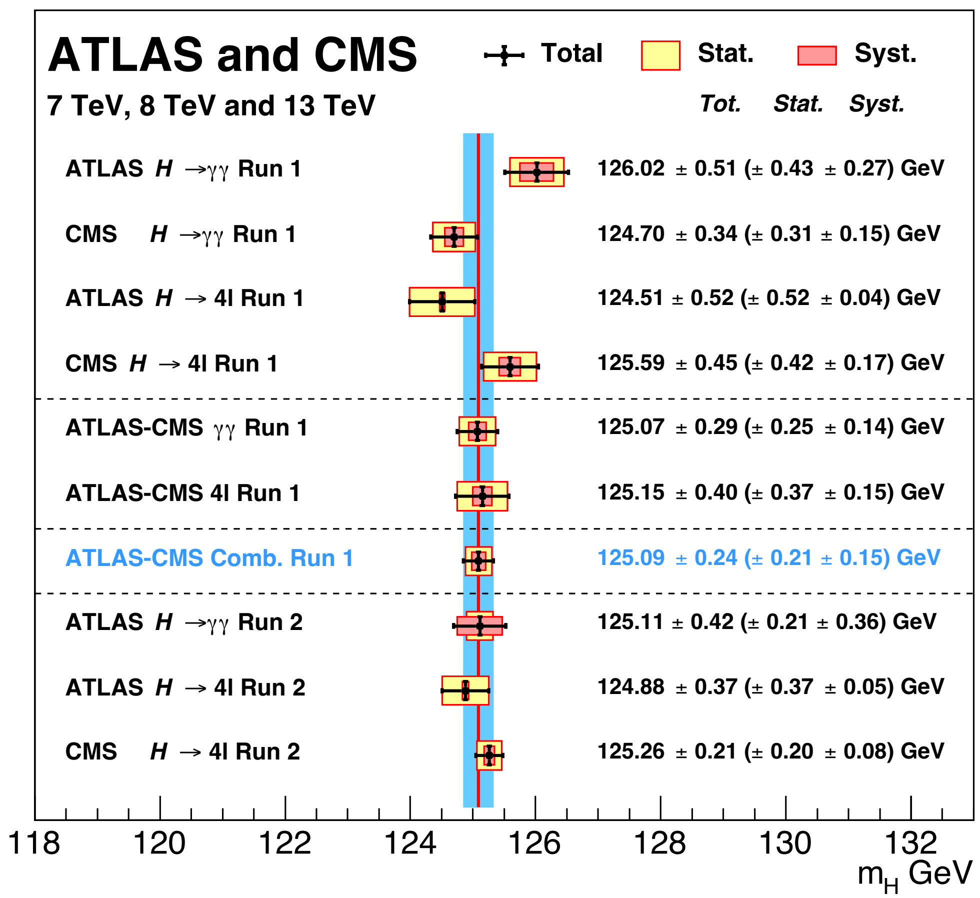
The 2023 International Workshop on Circular Electron Positron Collider

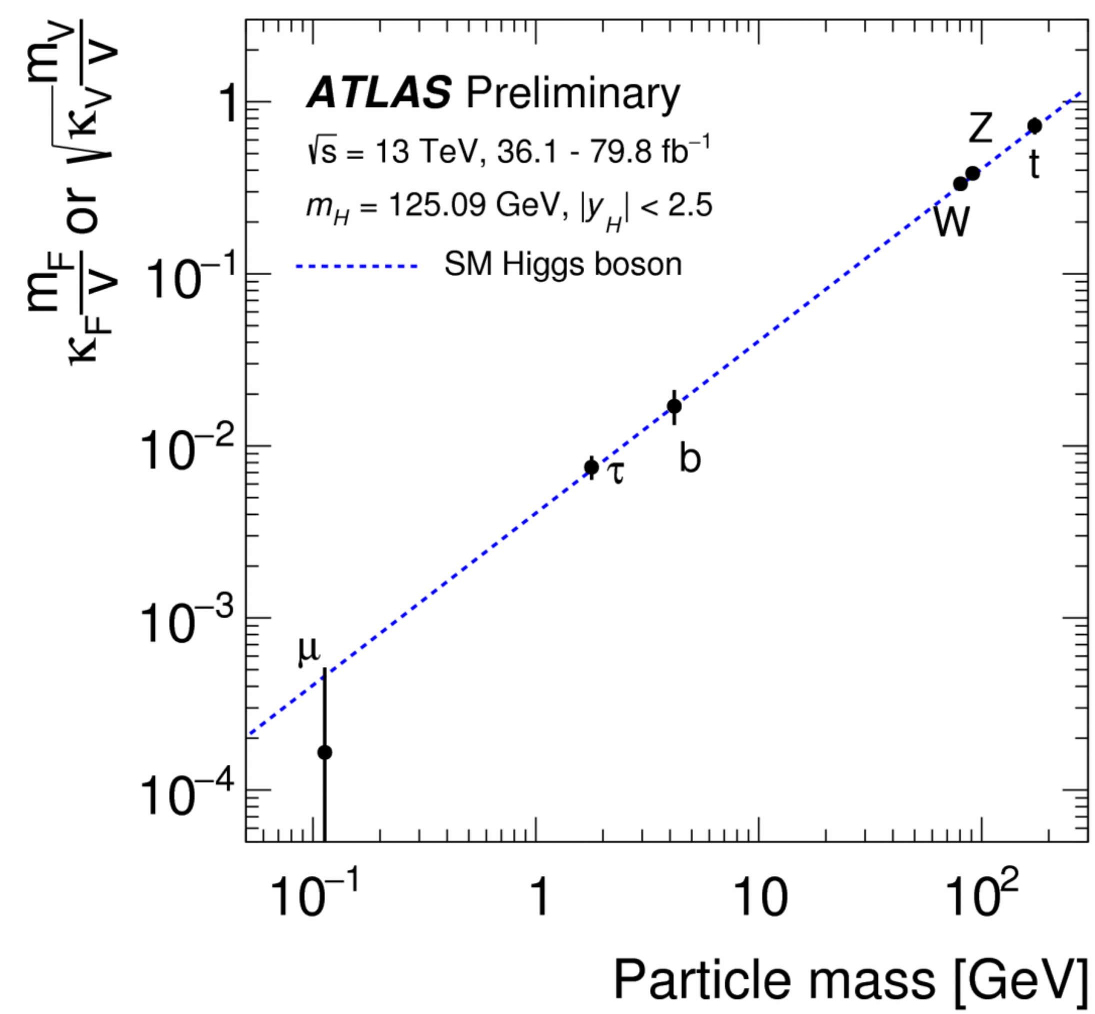

LHCb
ATLAS
CMS
ALICE

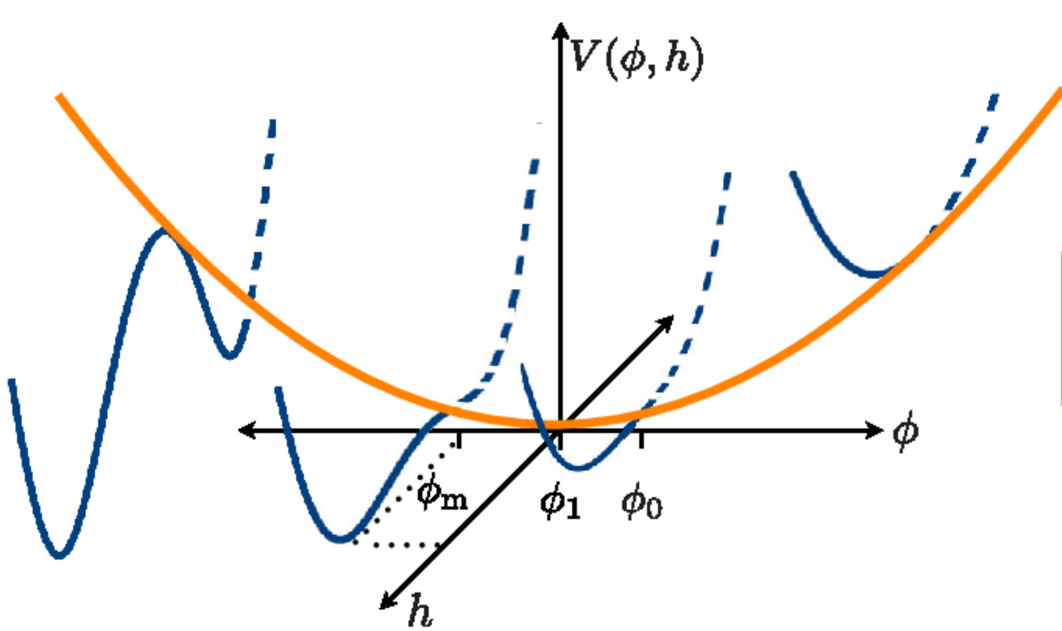

CMS
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
68% CL band
Best fit σ/σ_{SM}
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
110
115
120
125
130
135
140
145
m_H (GeV)

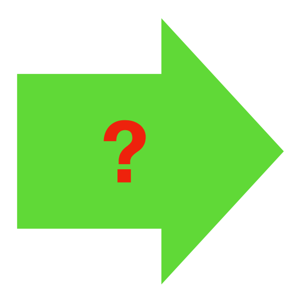

ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
$\pm 1\ \sigma$
$\pm 2\ \sigma$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8-5.9 fb^{-1}
CLs Limits
95% CL Limit on σ/σ_{SM}
10
1
10^{-1}
110
115
120
125
130
135
140
145
150
m_H [GeV]

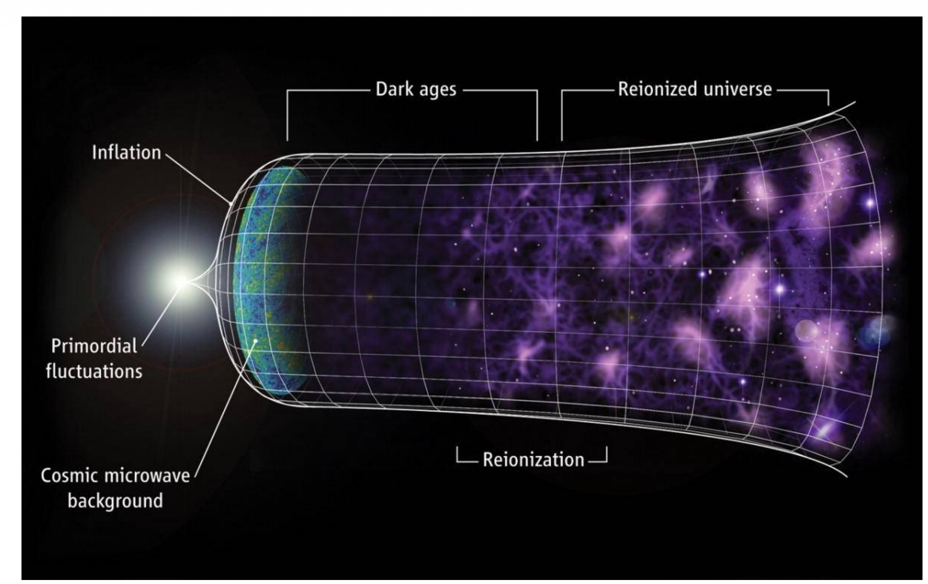
Precise Measurement on Higgs boson











CEPC
ILC
FCC-ee

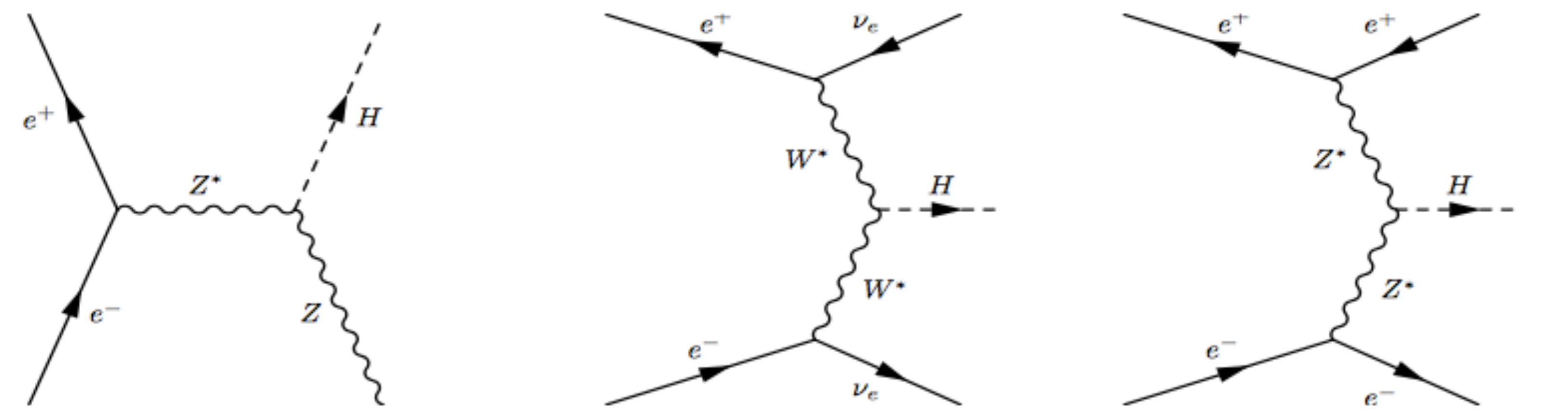
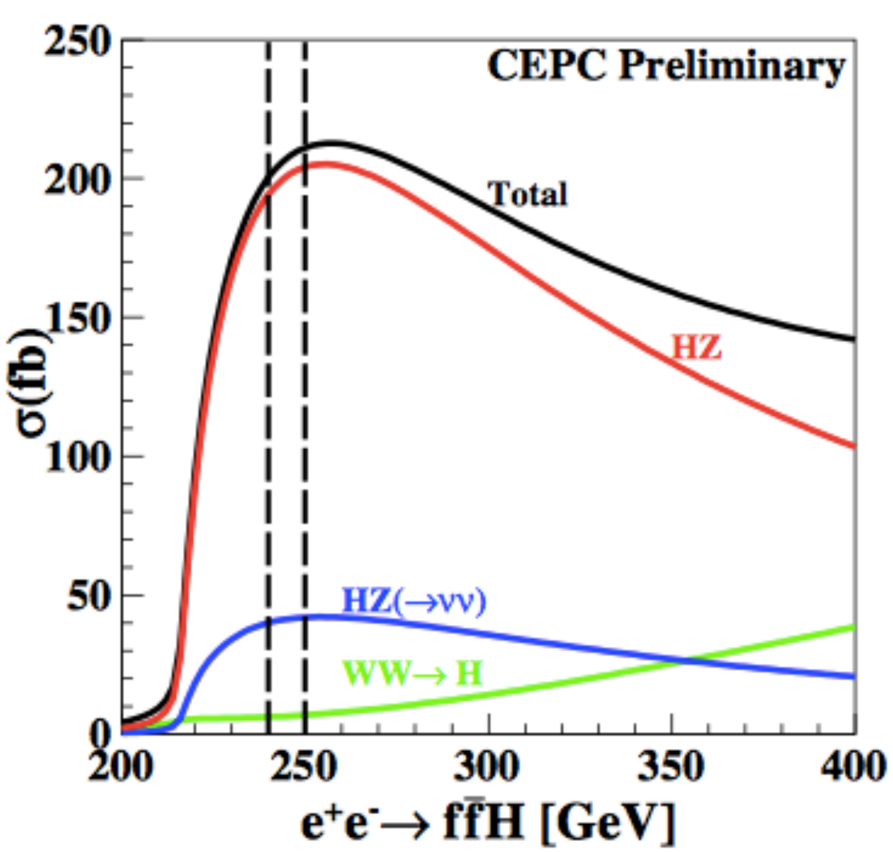
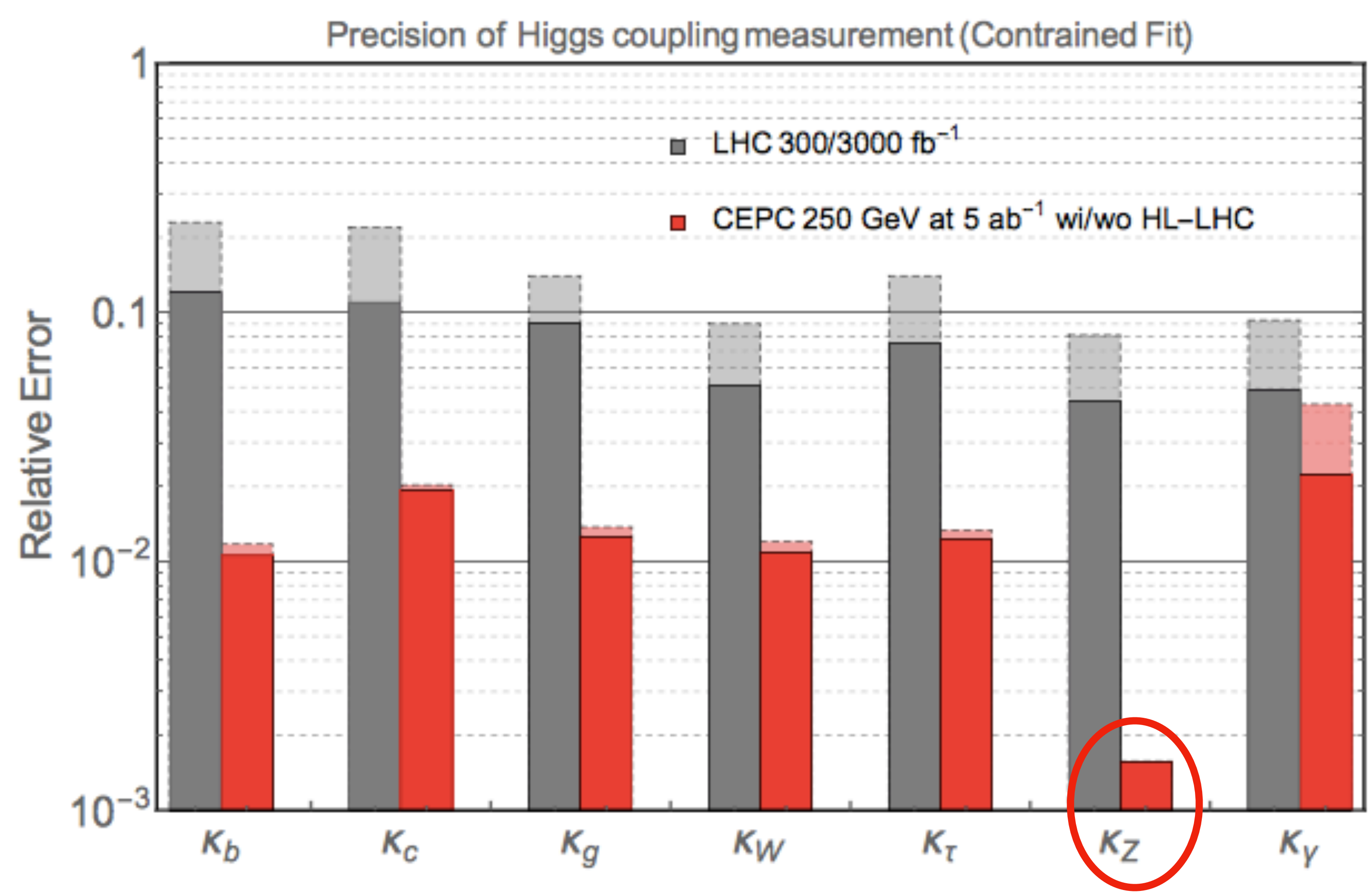


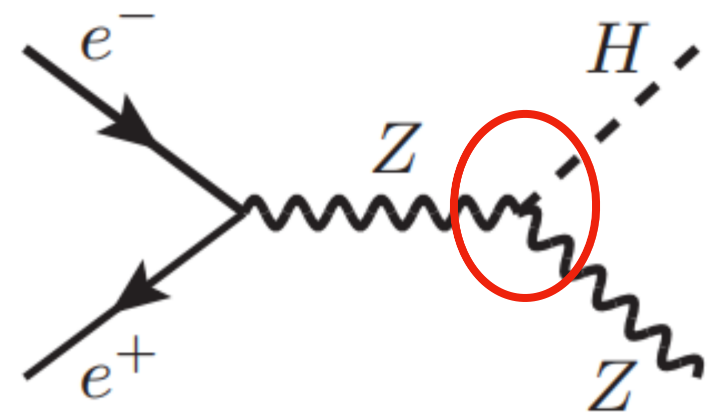
Figure 3.6 Feynman diagrams of the $e^+e^- \to ZH$, $e^+e^- \to \nu\bar{\nu}H$ and $e^+e^- \to e^+e^-H$ processes.





Challenges at next generation colliders

NLO: **Nucl.Phys.B 216 (1983) 469-492;**
Z.Phys.C 55 (1992) 605-618;
Z.Phys.C 56 (1992) 261-272

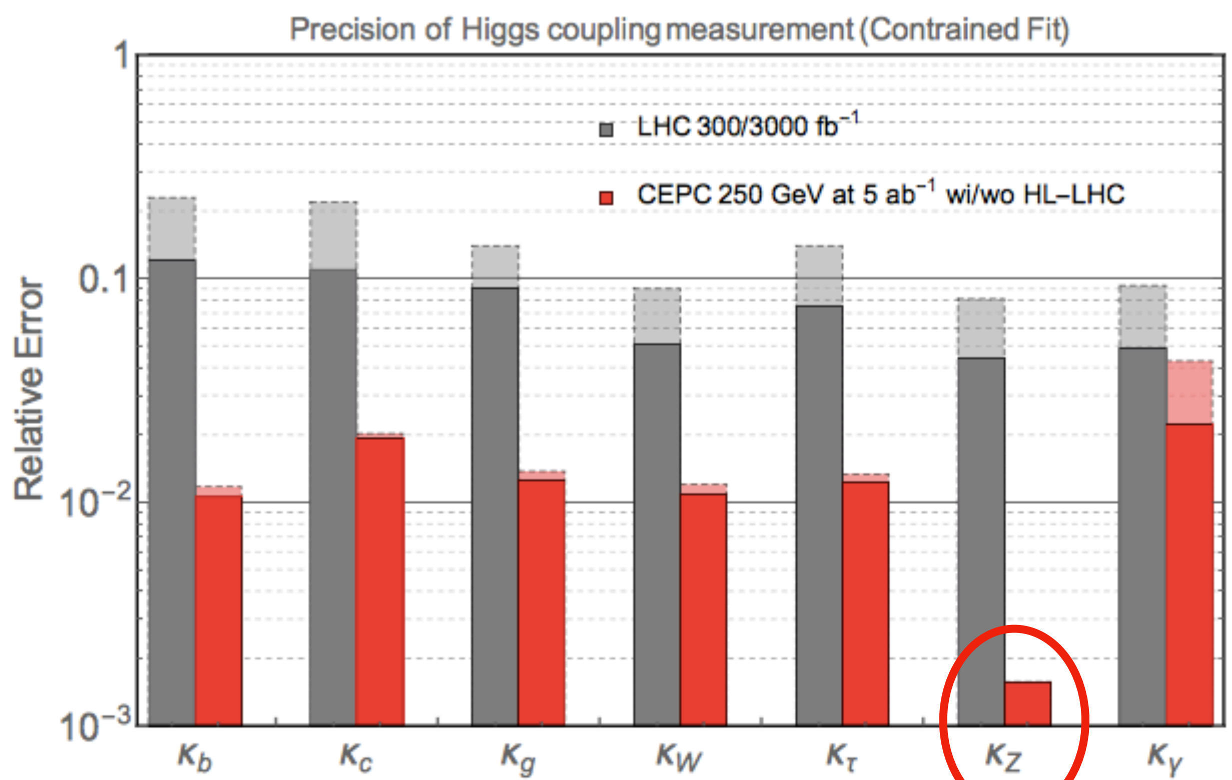


$\delta\sigma_{HZ}$ **< 0.5% with millions of Higgs bosons**

NLO-EW corr. err. ~ 6%

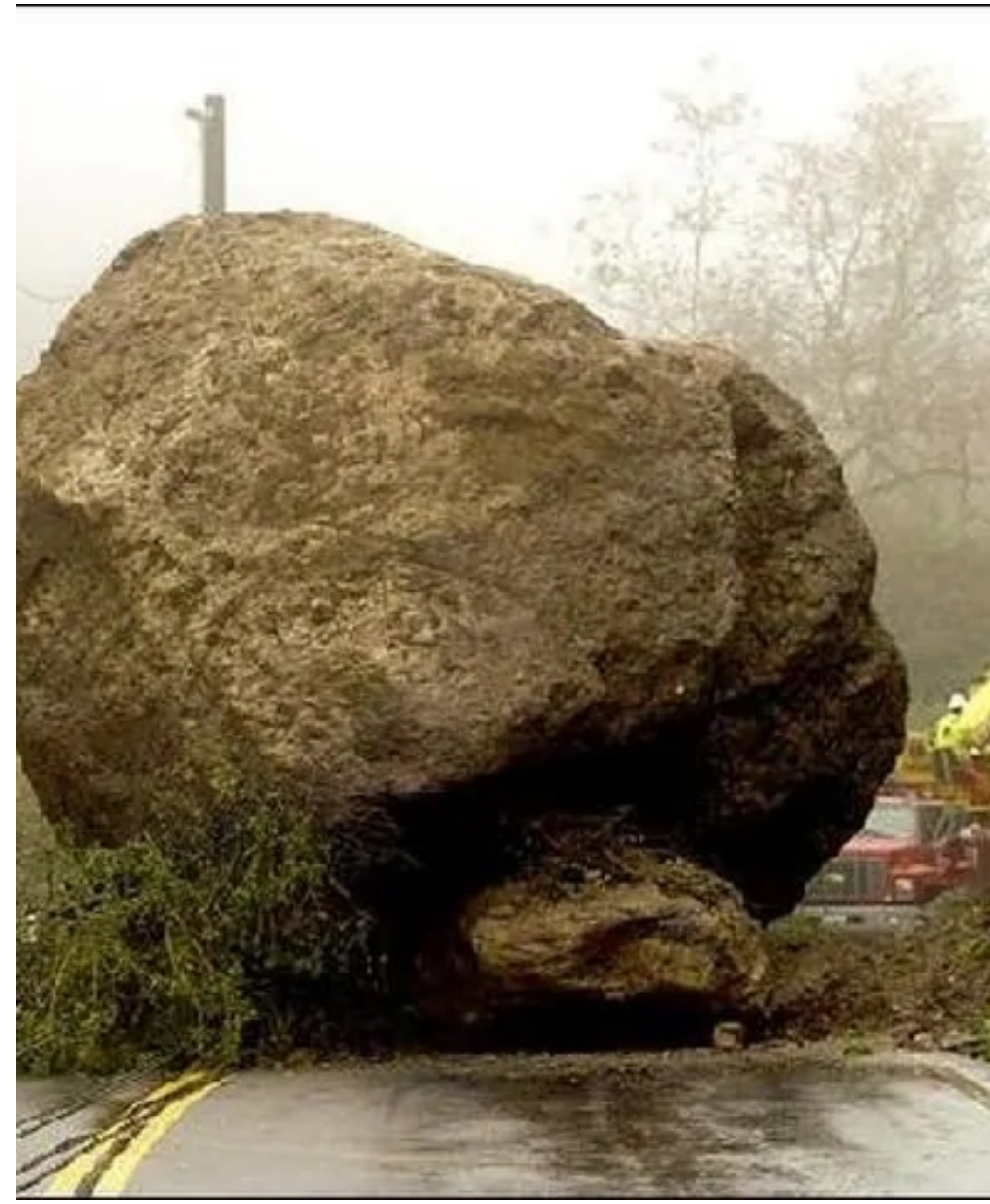
$\delta\kappa_Z$ **~ 3%**

Go beyond NLO!



Rocks on the road to higher orders

- Multi-loop multi-scale Feynman integrals: analytic evaluation? numerical evaluation?
- Exponentially increasing of calculation cost, even worse.
- Long road thereafter: event generation, matching to parton shower, etc.

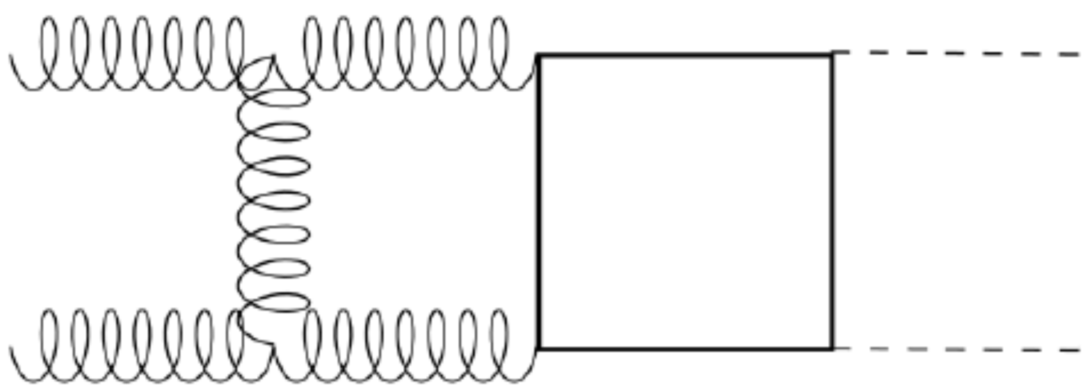


Improvement on numerical evaluation

Efficient numerical evaluation of Feynman integrals *

Zhao Li(李钊)[1,2;1)] Jian Wang(王健)[3;2)] Qi-Shu Yan(晏启树)[4,5;3)] Xiaoran Zhao(赵笑然)[1,4;4)]

Chinese Physics C Vol. 40, No. 3 (2016) 033103



$$I_C = e^{-2\epsilon\gamma_E} s^{-3-2\epsilon} \sum_{i=0}^{i=2} \frac{P_i}{\epsilon^i}.$$

	Vegas/CPU	QMC/GPU
P_2	$-7.959 \pm 0.009 - 10.586i \pm 0.009i$	$-7.949 \pm 0.003 - 10.585i \pm 0.005i$
P_1	$3.9 \pm 0.1 - 28.1i \pm 0.1i$	$3.831 \pm 0.005 - 28.022i \pm 0.005i$
P_0	$-3.9 \pm 0.8 + 92.3i \pm 0.8i$	$-4.63 \pm 0.07 + 92.13i \pm 0.07i$
Integration Time	45540s	19s

Mixed QCD-EW corrections

PHYSICAL REVIEW D **95,** 093003 (2017)

Mixed QCD-electroweak corrections for Higgs boson production at e^+e^- colliders

Yinqiang Gong,[1,*] Zhao Li,[2,†] Xiaofeng Xu,[1,‡] Li Lin Yang,[1,3,4,§] and Xiaoran Zhao[5,∥]

PHYSICAL REVIEW D **96,** 051301(R) (2017)

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

Qing-Feng Sun,[1,2] Feng Feng,[3,2] Yu Jia,[2,4,5] and Wen-Long Sang[6,*]

$\sqrt{s}$	Schemes	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)
240	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$
250	$\alpha(0)$	223.12 ± 0.47	229.20 ± 0.77	$231.63^{+0.75+0.12}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.01 ± 0.60	$227.67^{+0.82}_{-0.81}$	$230.58^{+0.80+0.14}_{-0.79-0.25}$
	G_μ	239.62 ± 0.06	231.82 ± 0.07	$232.65^{+0.07+0.04}_{-0.07-0.07}$

$\delta\sigma_{HZ}^{\rm mixed} > 1\%$

Production + Decay

Chinese Physics C Vol. 43, No. 1 (2019) 013108

Mixed electroweak-QCD corrections to $e^+e^-\to\mu^+\mu^-H$ at CEPC with finite-width effect*

Wen Chen(陈文)[1,2,3] Feng Feng(冯锋)[1,4] Yu Jia(贾宇)[1,2] Wen-Long Sang(桑文龙)[5;1)]

JHEP09(2021)114

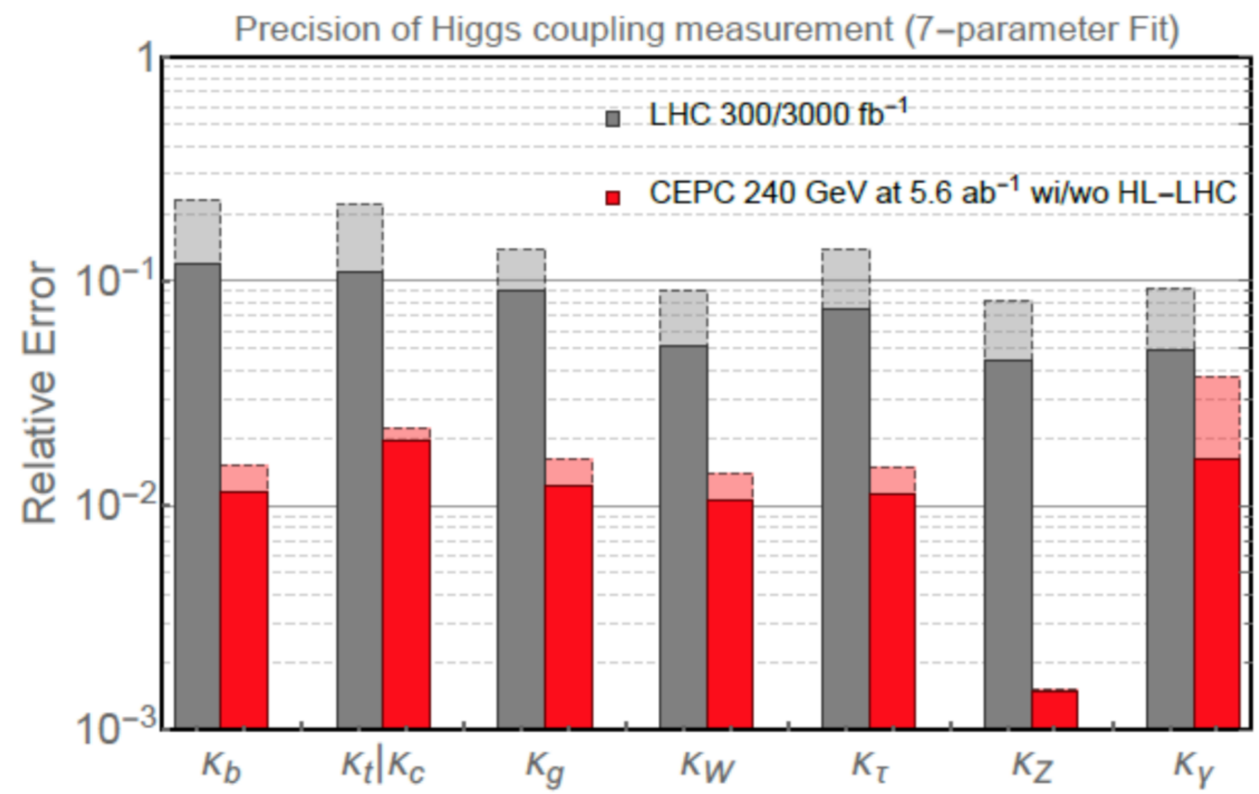
Mixed QCD-EW corrections for Higgs leptonic decay via HW^+W^- vertex

Chichuan Ma,[a] Yuxuan Wang,[a] Xiaofeng Xu,[b] Li Lin Yang[c] and Bin Zhou[a]

Table 3. Compare the full and NWA predictions to the cross sections at $\sqrt{s}$=240 GeV, at various levels of perturbative accuracy.

	LO	NLO	NNLO
σ/fb	6.983	7.385	7.488
$\sigma\|_{\rm NWA}$/fb	7.241	7.657	7.760

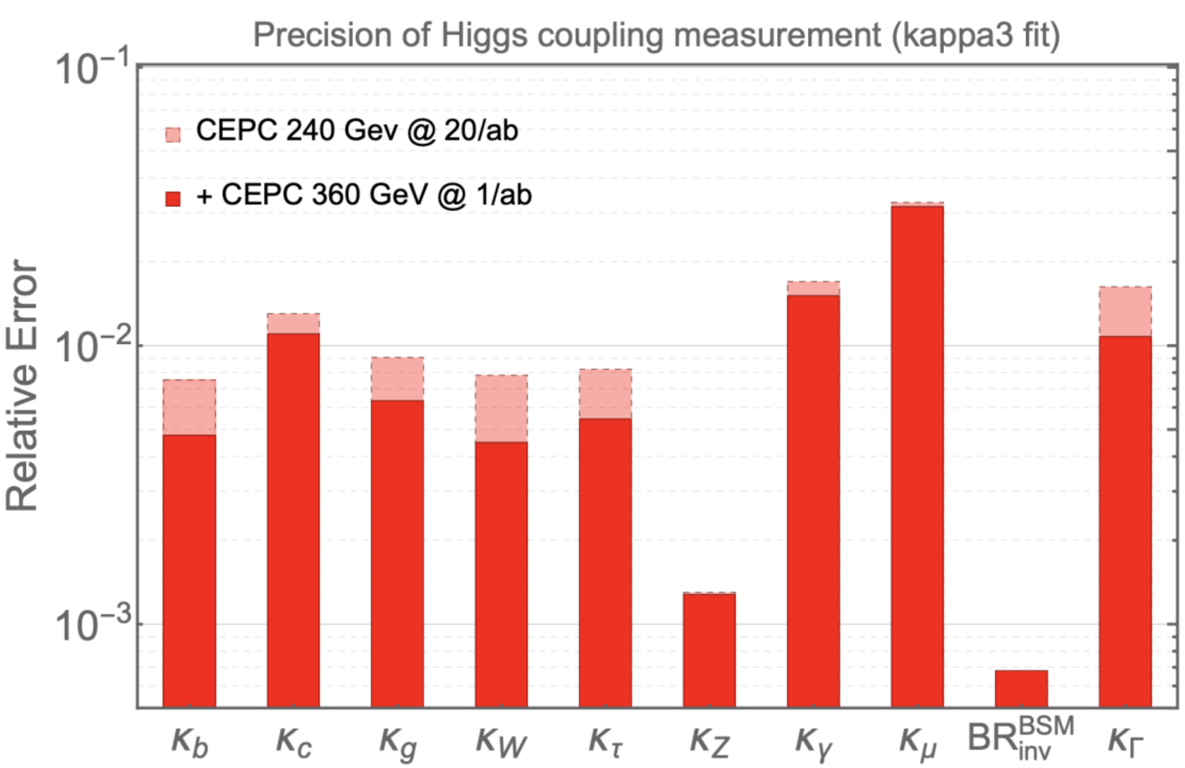
Investigate Decays



H→bb,cc, gg: CPC Vol. 44, No.1 (2020)013001
H →ZZ :EPJC 81, 879 (2021)
H→invisible: CPC Vol. 44, No.1 (2020)123001
H→ττ:Euro. Phys. J. C(2020) 80:7
H→μμ: Accepted by CPC
Higgs Global Analysis: ArXiv:2105.14997
Higgs CP: ArXiv: 2203.11707
H→γγ: ArXiv:2205.13269
Update on H→bb,cc, gg: ArXiv:2203.01469

Investigate Decays

Operation mode		ZH	Z	W^+W^-	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7/10	2	1	~5
CDR	*L* / IP [$\times10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\, dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	*L* / IP [$\times10^{34}$ cm^{-2}s^{-1}]	8.3	191.7	26.6	0.83
	$\int L\, dt$ [ab^{-1}, 2 IPs]	20	100	6.0	1.0
	Event yields [2 IPs]	4×10^6	3×10^{12}	1×10^8	5×10^5



May 2022

The Physics potential of the CEPC

Prepared for the US Snowmass Community Planning Exercise

(Snowmass 2021)

CEPC Physics Study Group

ArXiv: 2205.08553

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**20%**	**21%**	
$H\to\tau\tau$	**0.42%**		**2.10%**	**4.20%**	**7.50%**
$H\to\gamma\gamma$	**3.02%**		**11%**	**16%**	
$H\to\mu\mu$	**6.36%**		**41%**	**57%**	
$H\to Z\gamma$	**8.50%**		**35%**		
$\mathrm{Br}_{upper}(H\to inv.)$	**0.07%**				
Γ_H	**1.65%**		**1.10%**		

Higher orders are still needed

$\delta\sigma_{HZ}$ < 0.5% with millions of Higgs bosons

$\delta\sigma_{HZ}^{\text{mixed}}$ > 1%

$\delta\kappa_Z$ > 0.5%
Need NNLO EW?!

Theory precision

Categorization of two-loop Feynman diagrams in the $\mathcal{O}(\alpha^2)$ correction to $e^+e^- \to ZH$ *

Zhao Li [1,2,3] Yefan Wang[1,2] Quan-feng Wu [1,2]

Chinese Physics C Vol. 45, No. 5 (2021) 053102

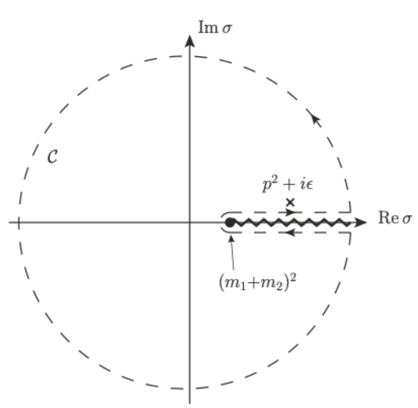
NNLO EW: 25377 diagrams

Seminumerical approach

On the evaluation of two-loop electroweak box diagrams for $e^+e^- \to HZ$ production

Qian Song and Ayres Freitas

JHEP04(2021)179



$$I_{\text{plan}} = -\int dx\, dy \left\{ \int_{\sigma_0}^{\infty} d\sigma\, \partial^2_{m'} \Delta B_0(\sigma, m'^2, m^2_{q'}) \times \left[D_0(p_1^2, p_2^2, k_2'^2, k_1'^2, s, t', m^2_{V_1}, m^2_{f'}, m^2_{V_2}, \sigma) - \frac{\sigma_0}{\sigma} D_0(p_1^2, p_2^2, k_2'^2, k_1'^2, s, t', m^2_{V_1}, m^2_{f'}, m^2_{V_2}, \sigma_0) \right] + \sigma_0\, \partial^2_{m'} B_0(0, m'^2, m^2_{q'})\, D_0(p_1^2, p_2^2, k_2'^2, k_1'^2, s, t', m^2_{V_1}, m^2_{f'}, m^2_{V_2}, \sigma_0) \right\}, \tag{2.9}$$

Two-Loop Electroweak Corrections with Fermion Loops to $e^+e^- \to ZH$

Ayres Freitas[*] and Qian Song[†]

PHYSICAL REVIEW LETTERS **130,** 031801 (2023)

Auxiliary Mass Flow

A systematic and efficient method to compute multi-loop master integrals

Xiao Liu [a], Yan-Qing Ma [a,b,c,*], Chen-Yu Wang [a]

Physics Letters B 779 (2018) 353–357

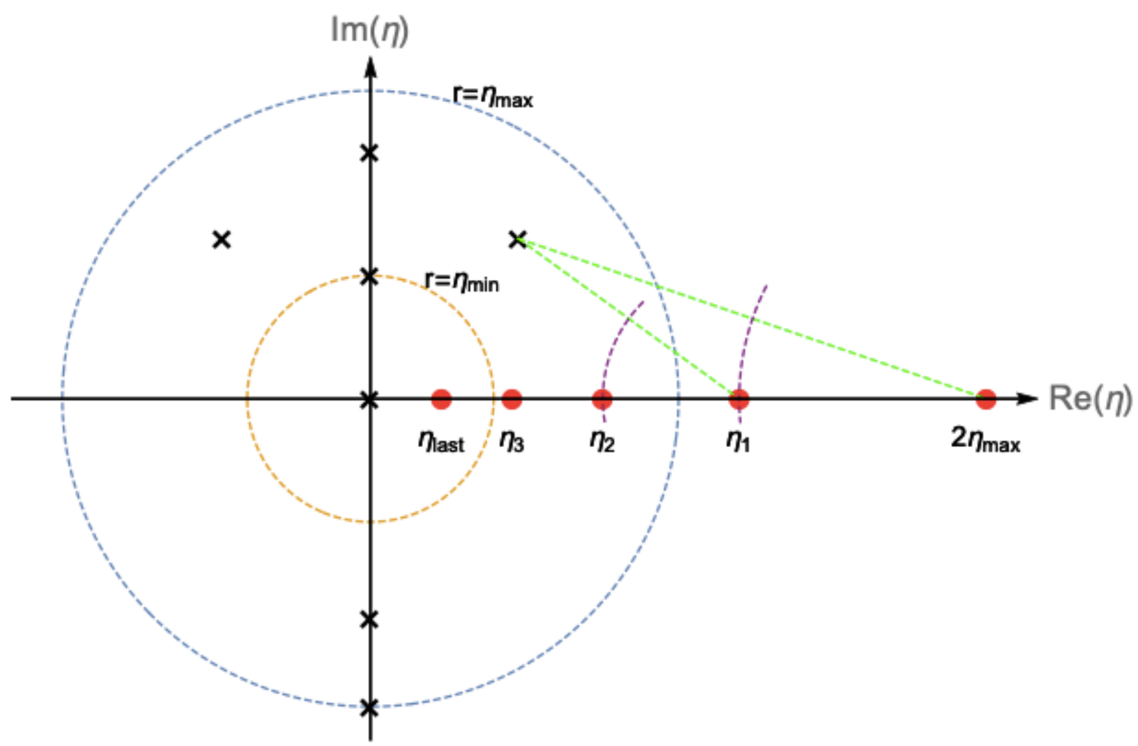
Determining arbitrary Feynman integrals by vacuum integrals

Xiao Liu[1,*] and Yan-Qing Ma[1,2,3,†]

PHYSICAL REVIEW D **99,** 071501(R) (2019)

$$I(D;\{\nu_\alpha\};\eta) \equiv \int \prod_{i=1}^{L} \frac{\mathrm{d}^D \ell_i}{\mathrm{i}\pi^{D/2}} \prod_{\alpha=1}^{N} \frac{1}{(\mathcal{D}_\alpha + \mathrm{i}\eta)^{\nu_\alpha}}$$

$$I(D;\{\nu_\alpha\};0) \equiv \lim_{\eta\to 0^+} I(D;\{\nu_\alpha\};\eta),$$



$$\frac{\partial}{\partial\eta}\vec{I}(\eta) = A(\eta)\vec{I}(\eta)\,,$$

AMFlow

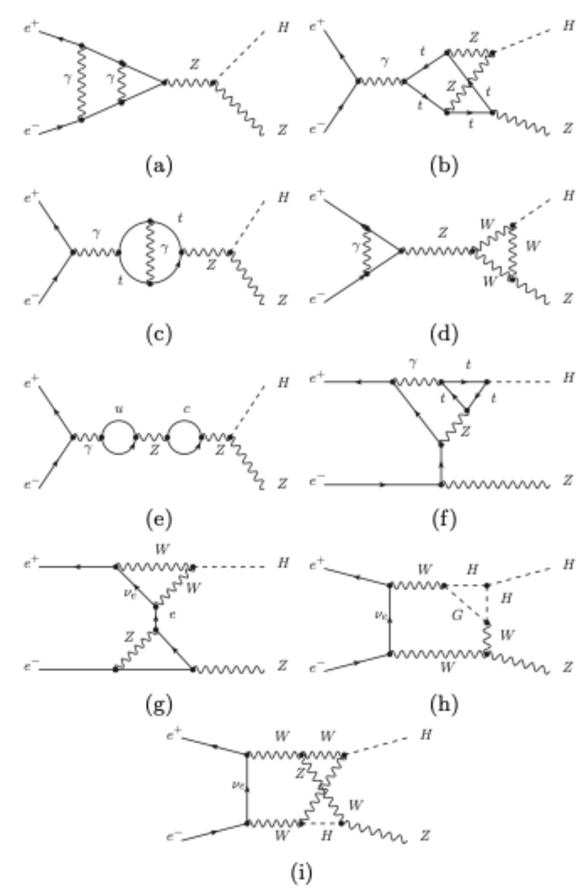
NNLO-EW for $e^+e^- \to HZ$

Complete two-loop electroweak corrections to $e^+e^- \to HZ$

Xiang Chen,[1,*] Xin Guan,[1,†] Chuan-Qi He,[1,‡] Zhao Li,[2,3,4,§] Xiao Liu,[5,¶] and Yan-Qing Ma[1,4,**]

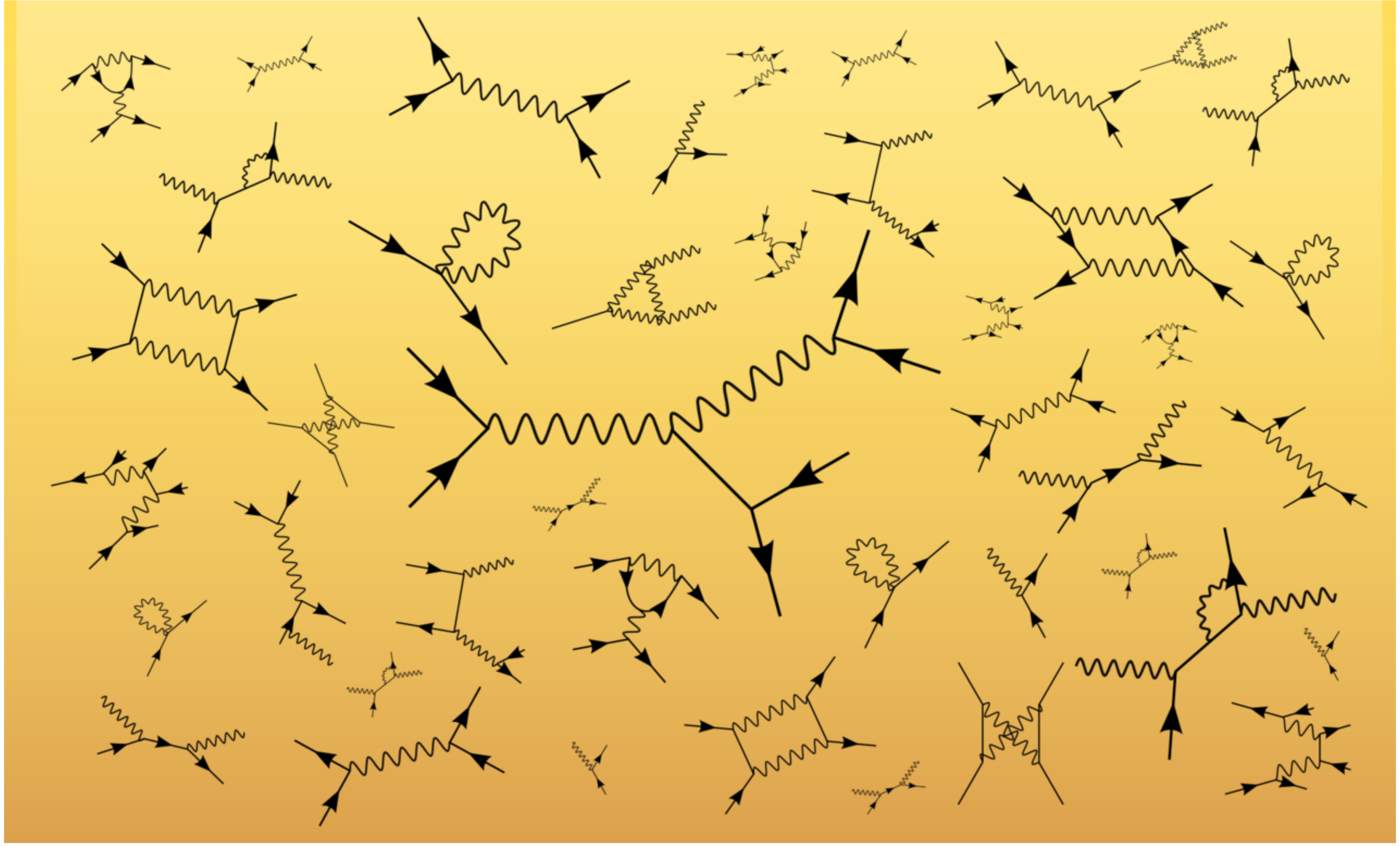
arXiv:2209.14953v1 [hep-ph]

$$\mathcal{A}^{(2)} = \alpha^4 (75548.083\epsilon^{-4} -3.1962821 \times 10^6 \epsilon^{-3} +1.1548893 \times 10^7 \epsilon^{-2} +2.6990603 \times 10^8 \epsilon^{-1} +1.5608903 \times 10^9 + \mathcal{O}(\epsilon)),$$



Prospects

- CEPC (ILC & FCC-ee) is indeed extraordinary Higgs factory.
- Most difficult calculations on NNLO EW correction has been accomplished.
- QED resummation effect could be important.
- QCD resummation effect based on QCD-EW mixed correction could also be important.
- Further matching to parton shower, event generator etc. will be needed.



Thank you!