Constraining the Higgs potential at e^+e^- colliders

Xiaoran Zhao[1]
In collaboration with
Fabio Maltoni(CP3), Davide Pagani(TUM)

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[1]Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain, Belgium

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The Higgs boson

- Discovered at LHC, 4th July, 2012.
- Properties measured at LHC.
- Next step: measuring Higgs self-couplings to probe the Higgs potential.

e^+e^- colliders are better.

The Higgs potential in SM

The SM Higgs potential is fixed by gauge symmetry and renormalisability:

$$V^{\mathrm{SM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \tag{1}$$

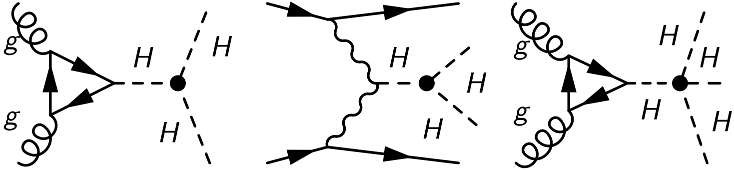
After electroweak symmetry breaking:

$$V^{\mathrm{SM}}(\Phi) = \frac{1}{2}m_H^2 H^2 + \lambda_3^{\mathrm{SM}} H^3 + \frac{\lambda_4^{\mathrm{SM}}}{4} H^4 \tag{2}$$

where $\lambda_3^{\mathrm{SM}} = \lambda_4^{\mathrm{SM}} = \lambda = \frac{m_H^2}{2v^2}$, fully determined in SM!
Various new physics models lead to non-SM values of λ_3 and/or λ_4.
Measuring λ_3 and λ_4: the main targets of the current and future colliders!

Direct measurement

- Directly measuring λ_3: double Higgs production. Loose bound at LHC, good precision at future e^+e^- and hadron colliders.

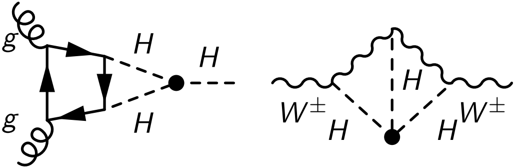


- Directly measuring λ_4: triple Higgs production. Only loose bounds at 100TeV pp collider, e.g. $\lambda_4/\lambda_4^{\mathrm{SM}} \in [-20, 30]$ [Chen et.al. '15]
  $\mathcal{O}(1)$ab at e^+e^-, too tiny for measurements, but sensitive on λ_4!

Indirectly probe

- λ_3: single Higgs at one-loop
  Attract lots of attention recently!

McCullough '14 Gorbahn and Haisch '16 Degrassi et.al. '16 Bizon et.al. '16 Di Vita et.al. '17 Maltoni et.al. '17



- Two-loop effects in electroweak precision measurement:

Degrassi et.al. '17 Kribs et.al. '17

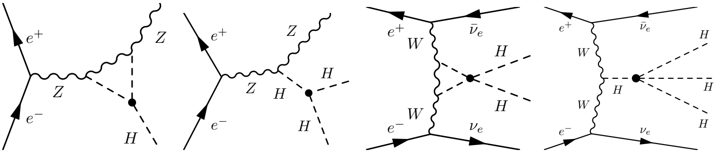
How about λ_4? Double Higgs production at one-loop!

Higgs self-couplings at e^+e^- colliders

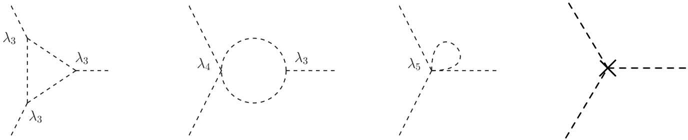
Previously only λ_3 at tree-level of double Higgs and one-loop level of single Higgs are studied.

	λ_3	λ_4
Single Higgs	one-loop	(two-loop)
Double Higgs	tree-level	one-loop
Triple Higgs	tree-level	tree-level

We extend to one-loop level of double Higgs, which is sensitive on λ_4. We also examine triple Higgs, where λ_3 and λ_4 appear at tree-level.



EFT parametrization and Renormalization



UV Divergent⇒ EFT for renormalization.

$$V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \boxed{\sum_{n=3} \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{1}{2}v^2)^2} \tag{3}$$

To vary λ_3 and λ_4 independently, we need both c_6 and c_8.

$$\kappa_3 = \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}} = 1 + \frac{c_6 v^2}{\Lambda^2} = 1 + \bar{c}_6 \tag{4}$$

$$\kappa_4 = \frac{\lambda_4}{\lambda_4^{\mathrm{SM}}} = 1 + \frac{6c_6 v^2}{\Lambda^2} + \frac{c_8 v^4}{\Lambda^4} = 1 + 6\bar{c}_6 + \bar{c}_8 \tag{5}$$

Bounding the Higgs potential: setup

Two production mechanisms

- Z boson associated production: ZH^n
- W boson fusion(WBF).

Colliders:

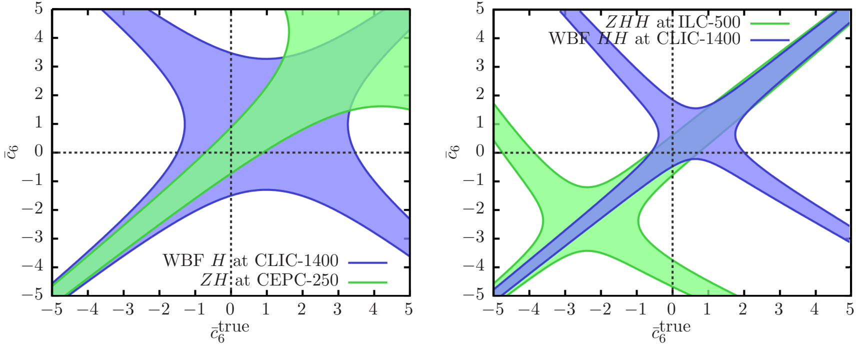
- Circular colliders: CEPC and FCC-ee. Only single Higgs is available.
- Linear colliders: ILC and CLIC. All processes are available.

Scenarios:

- Scenario 1: $\bar{c}_8$ effects are negligible.
- Scenario 2: $\bar{c}_8$ effects are non-negligible.

Scenario 1: single and double Higgs

$\bar{c}_8$ effects are negligible, we only have $\bar{c}_6$.



Left:Single Higgs

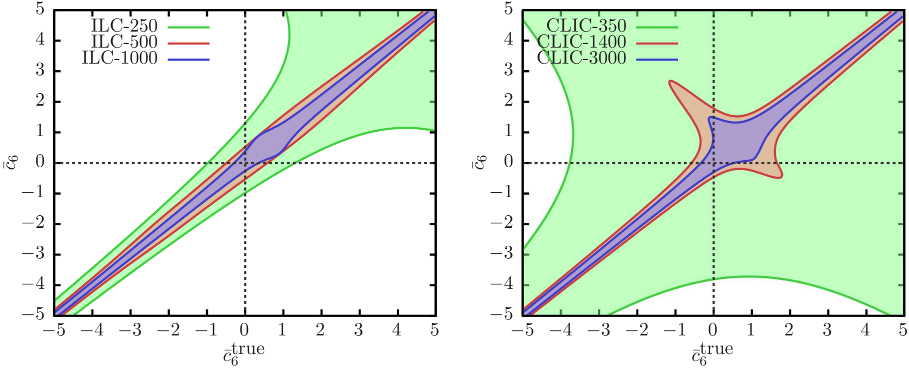
Right:Double Higgs

"X"-shape band, different center point⇒ complementary.

The band for double Higgs is thinner than single Higgs.

Scenario 1: combined

$\bar{c}_8$ effects are negligible, we only have $\bar{c}_6$.



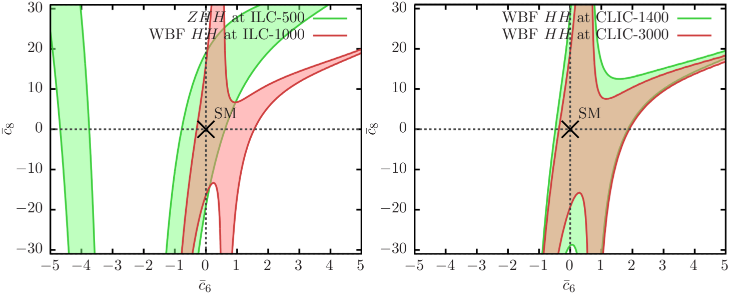
Left: ILC

Right: CLIC

- A good constraint over all region can be obtained at ILC.
- CLIC cannot resolve degeneracy around $\bar{c}_6 = 0.5$.

Scenario 2: double Higgs

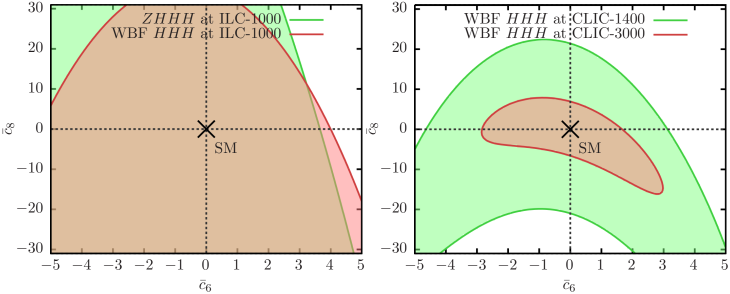
Non-negligible $\bar{c}_8$, assuming SM cross sections:



Combining *ZHH* and WBF *HH* yields better bounds.

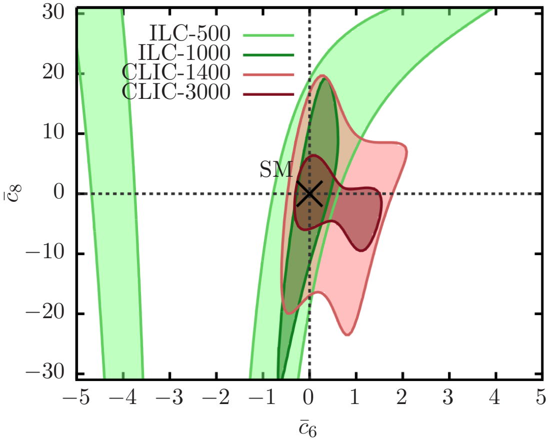
Scenario 2: triple Higgs

Tiny cross section⇒ zero events once SM is assumed.



- Useless at ILC.
- WBF *HHH* is important at CLIC, especially at 3TeV.

Scenario 2: combined



ILC is better on $\bar{c}_6$

CLIC is better on $\bar{c}_8$

Conclusion

- e^+e^- colliders
- One-loop for single and double Higgs
- tree-level for triple Higgs
- $(\bar{c}_6, \bar{c}_8)$: EFT description to cancel UV divergence
- WBF HH and ZHH are complementary
- Strong dependence on $\bar{c}_8$ for triple Higgs
- $\bar{c}_8$, comparable or even better than 100TeV.

Backup slides

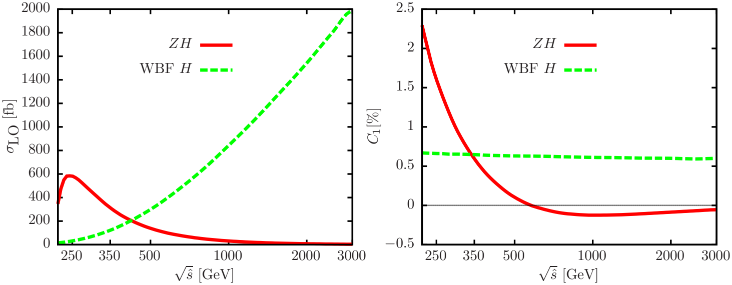
Counter term

$$\begin{aligned}\delta c_6 =& \frac{\Delta}{16\pi^2}\left[c_6\left(54\lambda - 9\frac{m_Z^2+2m_W^2}{v^2}+6\frac{N_c m_t^2}{v^2}\right)\right.\\ &+\frac{c_8 v^2}{\Lambda^2}\left(64\lambda - 6\frac{m_Z^2+2m_W^2}{v^2}+4\frac{N_c m_t^2}{v^2}\right)+\frac{45 c_6^2 v^2}{\Lambda^2}\\ &\left.+\frac{20 c_{10}\lambda v^4}{\Lambda^4}+\frac{36 c_6 c_8 v^4}{\Lambda^4}\right]\end{aligned}$$

where $\Delta = \frac{1}{\epsilon} - \log(4\pi) + \gamma_E$ is the divergence in $\overline{\mathrm{MS}}$ convention.

Results for single Higgs

$$\begin{aligned}
\sigma_{\mathrm{NLO}} &= \sigma_{\mathrm{LO}} + \sigma_{1-\mathrm{loop}}, \quad \sigma_{\mathrm{LO}} = \sigma_{\mathrm{LO}}^{\mathrm{SM}} && (6)\\
\sigma_{1-\mathrm{loop}} &= \sigma_0 + \sigma_1 \bar{c}_6 + \sigma_2 \bar{c}_6^2 && (7)\\
\sigma_{\mathrm{NLO}}^{\mathrm{pheno}} &= \sigma_{\mathrm{LO}} + \sigma_1 \bar{c}_6 + \sigma_2 \bar{c}_6^2 && (8)\\
&= \sigma^{\mathrm{LO}}(1 + (\kappa_3 - 1)C_1 + (\kappa_3^2 - 1)C_2) && (9)\\
C_2 &= \delta Z_H^{\mathrm{SM},\lambda} \approx -0.00154 && (10)
\end{aligned}$$



Results for double Higgs

$$\sigma_{\mathrm{LO}} = \sigma_0 + \sigma_1 \bar{c}_6 + \sigma_2 \bar{c}_6^2 \tag{11}$$

$$\sigma_{\mathrm{NLO}} = \sigma_{\mathrm{LO}} + \sigma_{1-\mathrm{loop}} \tag{12}$$

$$\sigma_{1-\mathrm{loop}} = \sigma_{00} + \sigma_{10} \bar{c}_6 + \sigma_{20} \bar{c}_6^2 + \sigma_{30} \bar{c}_6^3 + \sigma_{40} \bar{c}_6^4 \tag{13}$$

$$+ \bar{c}_8(\sigma_{01} + \sigma_{11} \bar{c}_6 + \sigma_{21} \bar{c}_6^2) + \bar{c}_{10}(\sigma_{001} + \sigma_{101} \bar{c}_6) \tag{14}$$

$\bar{c}_{10}$ contribution can be written as a kinematically independent shift to $\bar{c}_6$:

$$\bar{c}_6 \to \bar{c}_6 + \frac{5\lambda \bar{c}_{10}}{4\pi^2}(1 - \log \frac{m_H^2}{\mu_r^2}) \tag{15}$$

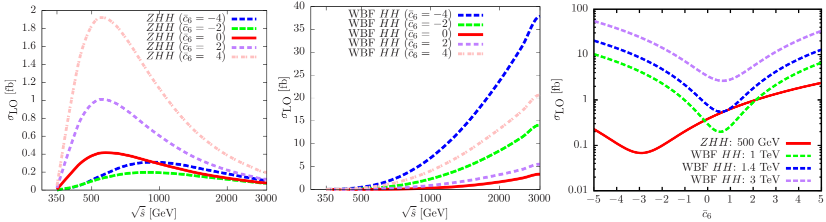
$$\sigma_{\mathrm{NLO}}^{\mathrm{pheno}} = \sigma^{\mathrm{LO}} + \Delta_{\bar{c}_6} + \Delta_{\bar{c}_8} \tag{16}$$

$$\Delta_{\bar{c}_6} = \sigma_{30} \bar{c}_6^3 + \sigma_{40} \bar{c}_6^4 \tag{17}$$

$$\Delta_{\bar{c}_8} = \bar{c}_8(\sigma_{01} + \sigma_{11} \bar{c}_6 + \sigma_{21} \bar{c}_6^2) \tag{18}$$

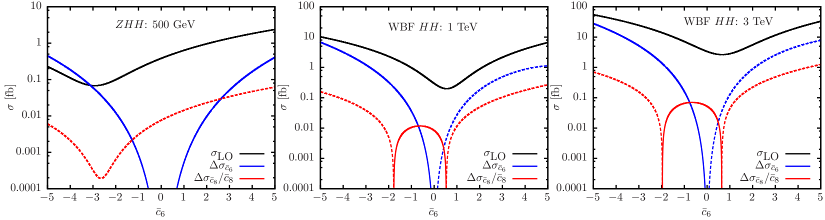
Results for double Higgs

LO cross sections:



Results for double Higgs

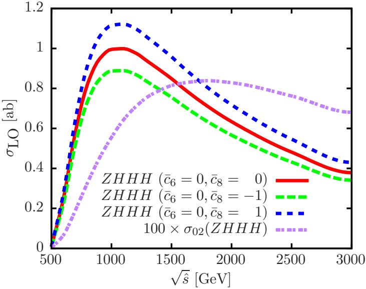
The one-loop contributions:

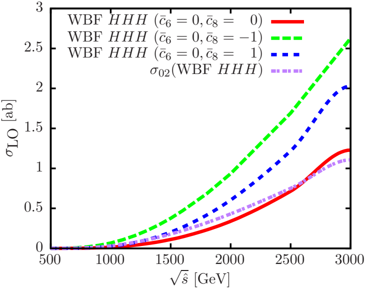


Sensitivity on $\bar{c}_8$ depends on value of $\bar{c}_6$

Results for Triple Higgs

$$\sigma_{\mathrm{LO}} = \sigma_{00} + \sum_{1 \le i+2j \le 4} \sigma_{ij} \bar{c}_6^i \bar{c}_8^j \tag{19}$$

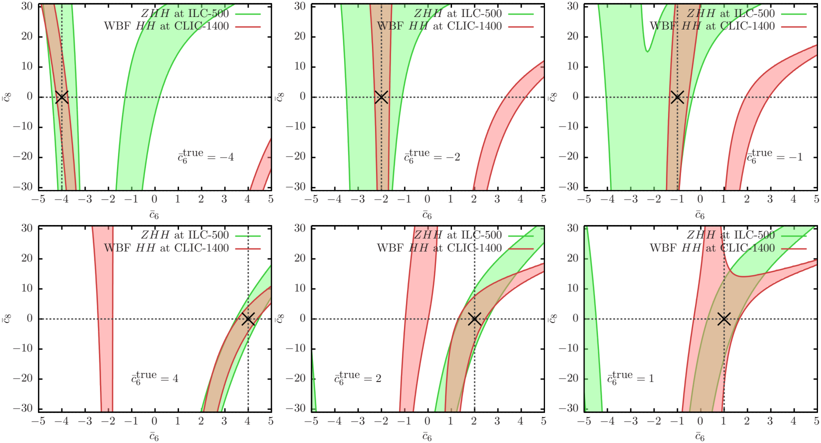




Although $\sigma_{\mathrm{SM}} = \sigma_{00}$ is tiny, for WBF *HHH* the cross section strongly depends on $(\bar{c}_6, \bar{c}_8)$: large $\bar{c}_8 \Rightarrow \sigma_{\mathrm{LO}} \approx \bar{c}_8^2 \sigma_{02} \approx \bar{c}_8^2 \sigma_{00}$.

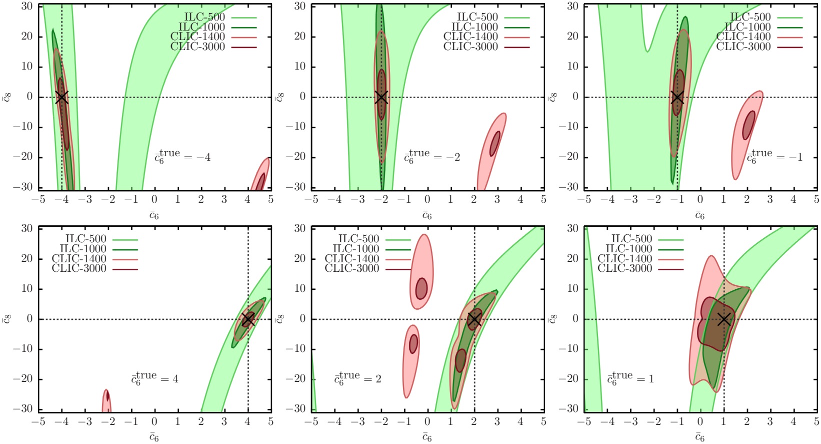
Bounding the Higgs potential: double Higgs

Scenario 2: non-negligible $\bar{c}_8$, BSM cases:



Bounding the Higgs potential: combined

Scenario 2: assuming BSM cases:



Bounding the Higgs potential: scenarios

	$\sqrt{\hat{s}}$ [GeV]	$P(e^-, e^+)$	Luminosity [ab^{-1}]	Relevant final states
CEPC	250	(0.0,0.0)	5.0	ZH, WBF H
FCC-ee	240	(0.0,0.0)	10.0	ZH, WBF H
	350	(0.0,0.0)	2.6	ZH, WBF H
ILC	250	(-0.8,0.3)	2.0	ZH, WBF H
	500	(-0.8,0.3)	4.0	ZHH, WBF H
	1000	(-0.8,0.2)	2.0	$ZHHH$, WBF $H(H(H))$
CLIC	350	(-0.8,0.0)	0.5	ZH, WBF H
	1400	(-0.8,0.0)	1.5	$ZHHH$, WBF $H(H(H))$
	3000	(-0.8,0.0)	2.0	WBF $H(H(H))$

- Scenario 1: $\bar{c}_8$ effects are negligible. Single, double and triple Higgs are considered. We allow both $\bar{c}_6 = 0$(SM-like) and $\bar{c}_6 \neq 0$(BSM case)
- Scenario 2: $\bar{c}_8$ effects are non-negligible. Here only double and triple Higgs are considered, since two-loop for single Higgs are not available. We explore how well we can constrain $\bar{c}_8$ and how much $\bar{c}_8$ can affect the measurement of $\bar{c}_6$.