Institute of High Energy Physics
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Probing Quartic Higgs Boson Self-Interactions at Future Colliders

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Based on Tao Liu, Kun-Feng Lyu, Jing Ren, Hua Xing Zhu arXiv: 1803.04359

Outline

Brief review on Higgs self-couplings measurement

Probing quartic Higgs self-couplings via dihiggs production

- Features of NLO corrections of quartic Higgs coupling
- Sensitivities to Higgs self-couplings on future lepton colliders

Why Higgs self-couplings interesting?

Higgs is the only SM particle that interact with itself

Higgs is quite SM-like, but less is known about the Higgs potential

SM: $\lambda_{3,\mathrm{SM}} = \frac{3m_h^2}{v}, \quad \lambda_{4,\mathrm{SM}} = \frac{3m_h^2}{v^2}.$

General: $V_{\mathrm{self}} = \frac{1}{3!}\lambda_{3,\mathrm{SM}}(1+\kappa_3)h^3 + \frac{1}{4!}\lambda_{4,\mathrm{SM}}(1+\kappa_4)h^4$

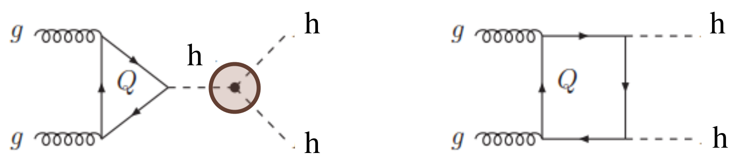
Higgs self-interactions deeply connected with great puzzles

- Electroweak baryogengesis: strong 1st order EWPT ⟶ large modification of Higgs self-interactions
- Higgs gravitational interaction $H^\dagger HR$: new derivative Higgs self-couplings
- …

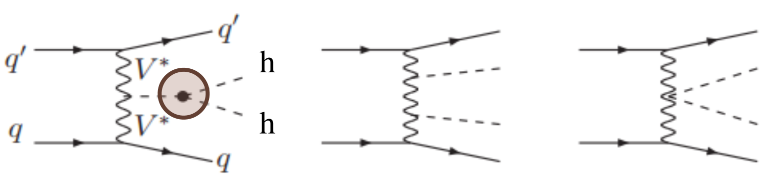
Cubic Higgs coupling: dihiggs production

Hadron collider: three main production channels

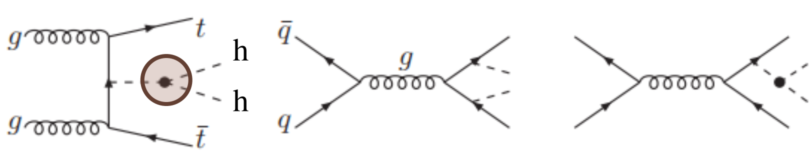
- Gluon fusion production

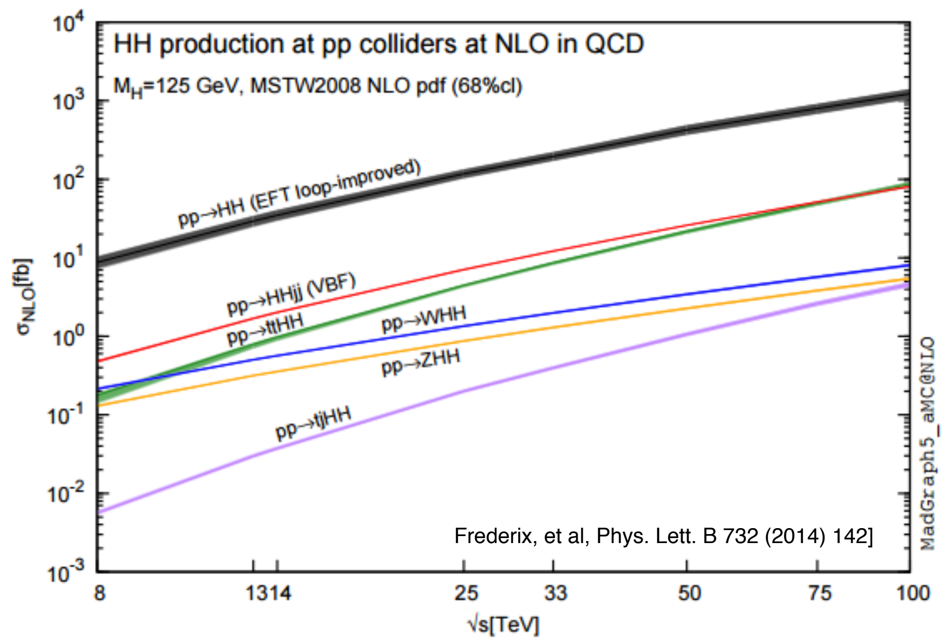


- Vector boson fusion production



- Top-pair associated production





Most promising channel $gg \to hh \to b\bar{b}\gamma\gamma$

HE-LHC, 27TeV, 15/fb: $\Delta\kappa_3 \approx 15\%$

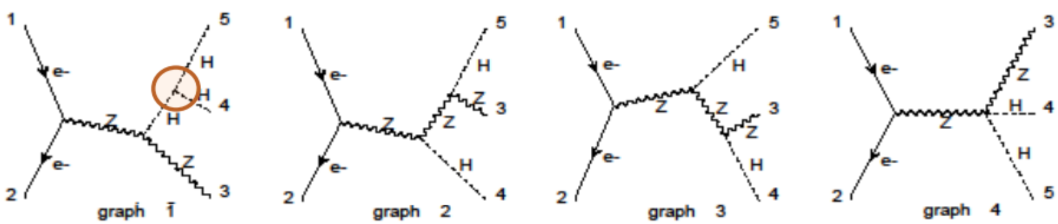
100TeV, 30/fb: $\Delta\kappa_3 \approx 5\%$

Gonçalves, Han, Kling, Plehn, Takeuchi, PRD 97, no. 11, 113004 (2018)

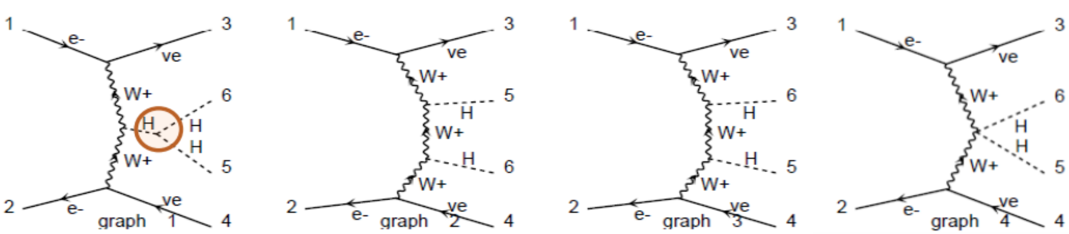
Cubic Higgs coupling: dihiggs production

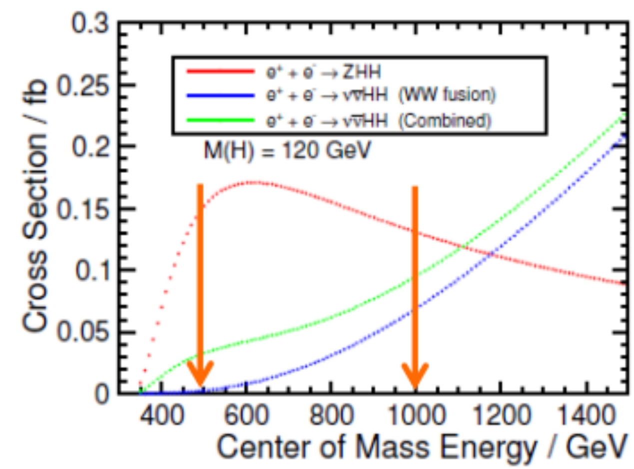
Lepton collider: two main production channels

- Z-boson associated production



- Vector boson fusion production





Two processes are studied on ILC and CLIC (at different E_{cm}) in great details

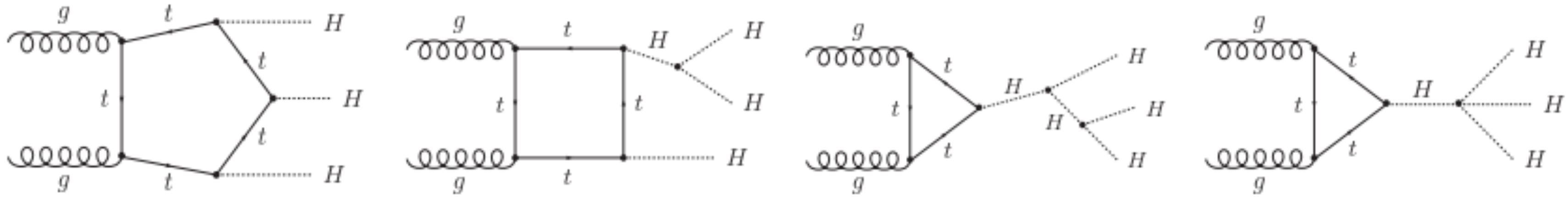
ILC sensitivity

Zhh, 500GeV, 4/ab: $\Delta\kappa_3 \approx 27\%$

vvhh, 1TeV, 2.5/ab: $\Delta\kappa_3 \approx 14\%$

Kurata et al, LCWS15, 2015

Quartic Higgs coupling: trihiggs production

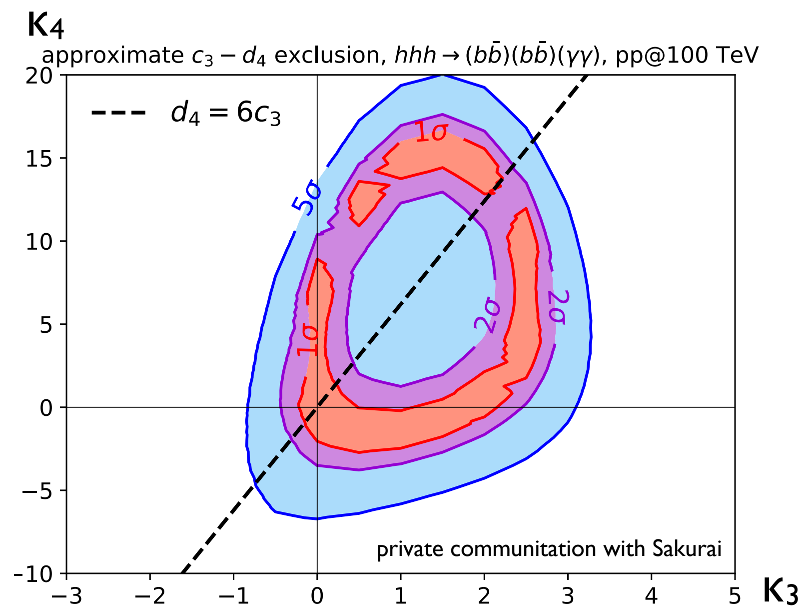


Plehn and Rauch, PRD 72, 053008 (2005)

- Production cross section quite small, ~5fb @ 100TeV
- Cross section depend on both cubic, quartic couplings, but the dependence on quartic couplings is much weaker
- Study of $hhh \to b\bar{b}b\bar{b}\gamma\gamma$ @ 100TeV

Papaefstathiou, Sakurai, JHEP 1602, 006 (2016)
Chen, Yan, Zhao, Zhong, Zhao, PRD 93, 013007 (2016)

κ_4 sensitivity depends strongly on κ_3.
For SM, κ_4 sensitivity is of *O(10)*



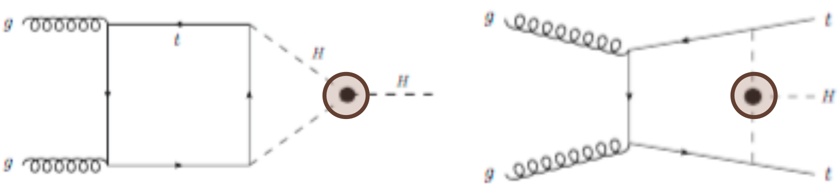
Still quite challenging!

“Indirect” probe of cubic Higgs coupling

Precise measurement of cubic Higgs coupling NLO corrections to single Higgs production

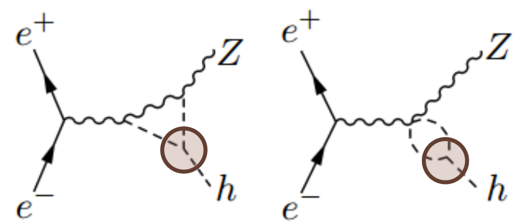
Hadron collider

Degrassi, Giardino, Maltoni, Pagani, arXiv:1607.04251 [hep-ph].



Lepton collider

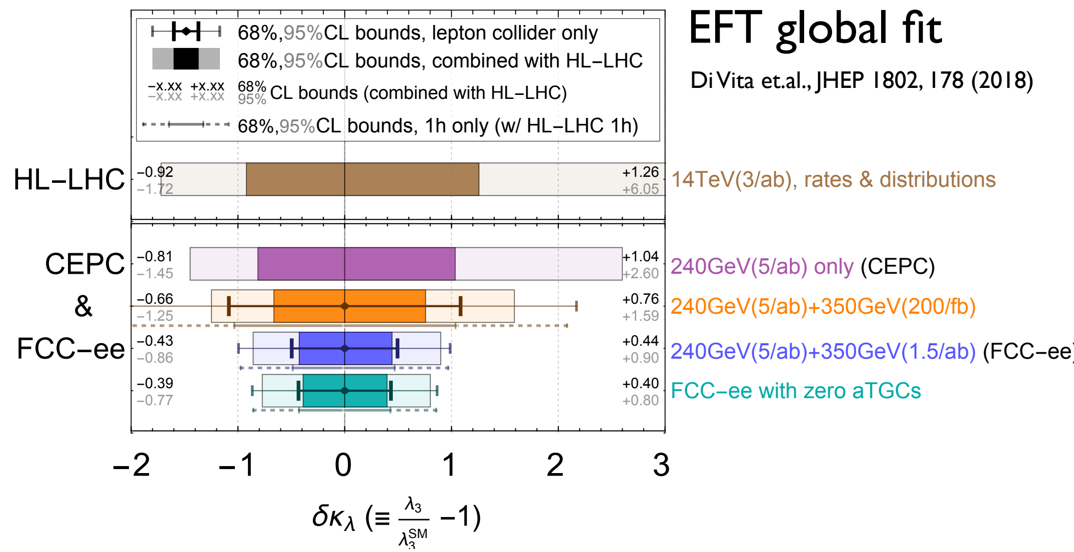
McCullough, PRD 90, no. 1, 015001 (2014); PRD 92, no. 3, 039903 (2015)



- Finite contribution to the form factor of relevant vertices
  (log-divergent corrections to Higgs two-point function absorbed into Higgs mass)
- Complimentary to dihiggs production measurement

EFT global fit

Di Vita et.al., JHEP 1802, 178 (2018)



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Formalism for dihiggs production at NLO

Need to embed the κ scheme (κ_3,κ_4) into an EFT

Brivio and Trott, Physics Reports, arXiv:1706.08945

- SMEFT: Higgs in $SU(2)_L$ doublet (decoupled NP)

$$V = F(H^\dagger H),$$

If there are more than one new operators

$$\Gamma(hhh), \Gamma(\pi\pi hh) \colon \kappa_3 \equiv v^2 F_v'''/3F_v''$$

$$\Gamma(hhhh) \colon \kappa_4 \equiv 2v^2 F_v'''/F_v'' + v^4 F_v^{(4)}/3F_v''$$

- HEFT: Higgs the EW singlet (composite Higgs models)

$$V(h) = \sum_n a_n (h/v)^n$$

more general parameterization

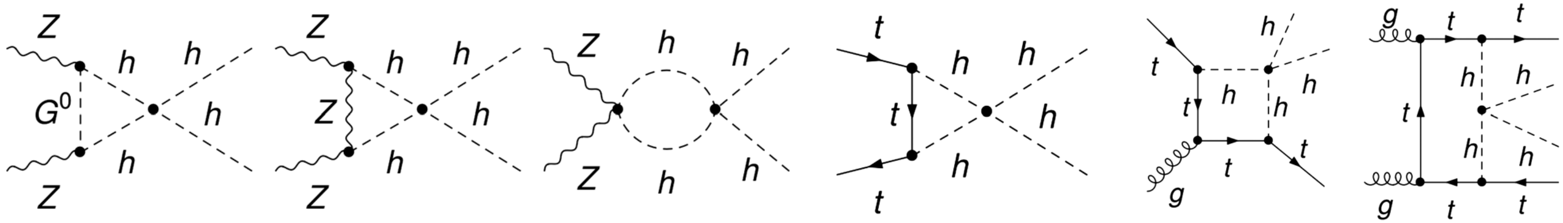
* Here we ignore loop contribution from h^5, which amounts to a redefinition of κ_3

- Quartic Higgs coupling decouples from other couplings that contribute to the dihiggs production
- Consistent to discuss NLO corrections of quartic coupling by κ_i

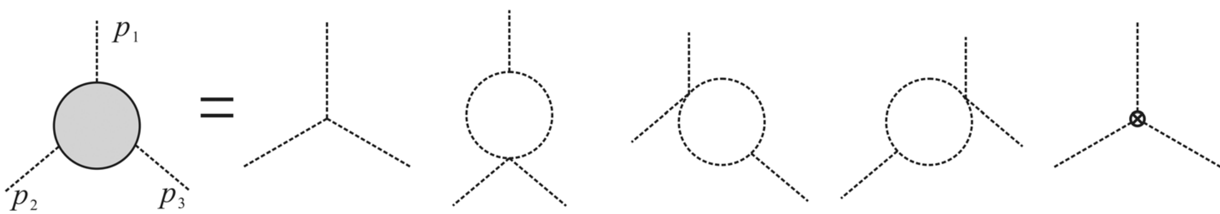
NLO correction of quartic Higgs coupling

Two type of NLO corrections from κ4

- Corrections to form factor of relevant vertices: finite (process dep)



- Renormalization of cubic Higgs coupling: log divergent (universal)



counter term
(i.e. $(H^\dagger H)^3$, h^3)

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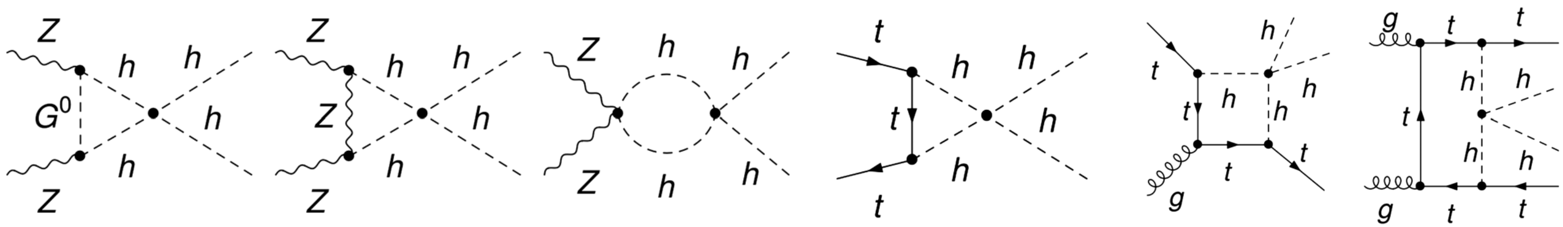

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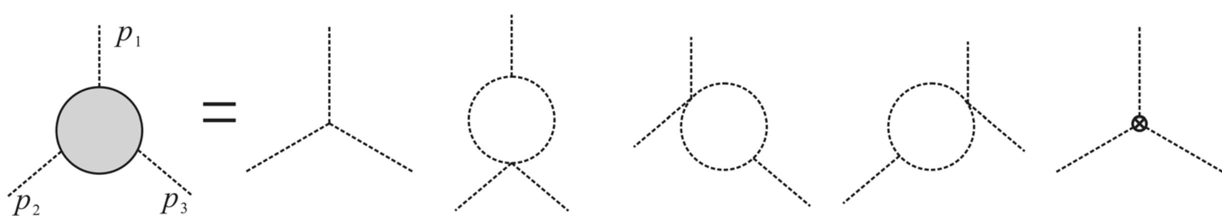

counter term
(i.e. $(H^\dagger H)^3$, h^3)

Difference: renormalization scheme dependence for κ_4 sensitivity

Dihiggs production cross section

Assuming no other NP (or constrained by EW and Higgs precision measurement), focus on corrections from Higgs self-couplings

$$\frac{\delta\sigma}{\sigma_0} \equiv \frac{\sigma - \sigma_0}{\sigma_0} = C_{31}\kappa_3 + C_{32}\kappa_3^2 + \kappa_4(C_{41} + C_{42}\kappa_3 + C_{43}\kappa_3^2)$$

- κ_3 denotes renormalized cubic Higgs coupling; coefficients C_{4i} depend on the renormalization scheme (ignore NLO corrections from κ_3)

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- κ_3 sensitivity scheme dependent, while for κ_4 it can be largely suppressed by marginalization of κ_3 in χ^2 analysis with $N \geq 2$ physical observables

Considering only linear terms: $O_i = C_{31}^{(i)}\kappa_3 + C_{41}^{(i)}\kappa_4$ (with measurement uncertainty σ_i)

$$\Delta\kappa_4 = \sqrt{\left[\sum_{k=1}^{N} \frac{a_k^2}{\sigma_k^2}\right] \left[\frac{1}{2}\sum_{i,j=1}^{N} \frac{a_i^2}{\sigma_i^2}\frac{a_j^2}{\sigma_j^2}\left(\frac{b_i}{a_i} - \frac{b_j}{a_j}\right)^2\right]^{-1}} \rightarrow \Delta C_{ij} = \frac{C_{41}^{(i)}}{C_{31}^{(i)}} - \frac{C_{41}^{(j)}}{C_{31}^{(j)}}$$

scheme independent at LO

$$(a_i, b_i) \rightarrow (C_{31}^{(i)}, C_{41}^{(i)})$$

Dihiggs production on lepton colliders

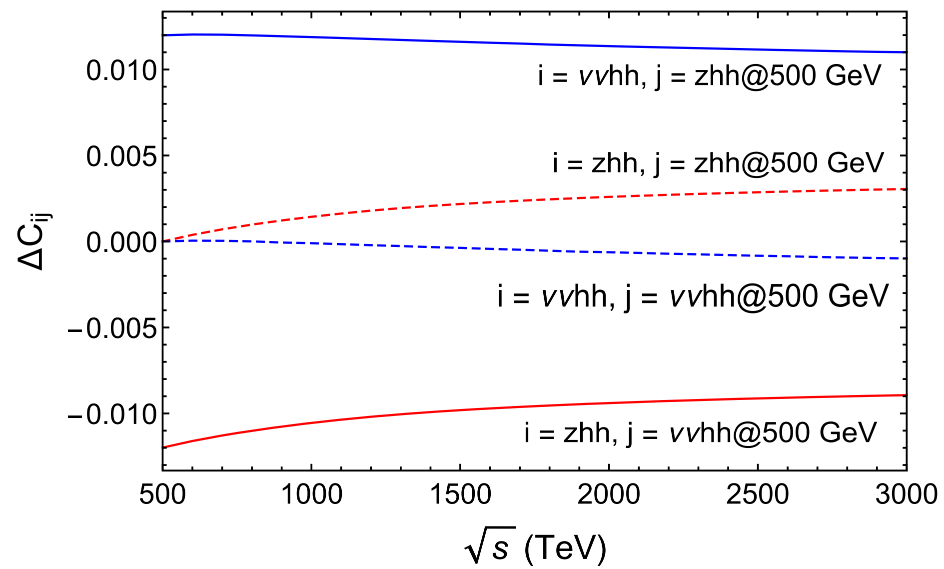
Focus on *Zhh* and *vvhh* production channels. Use FeynArt, FormCalc to calculate cross sections and fit coefficients C_{ij}

$$\delta\sigma/\sigma_0 = C_{31}\kappa_3 + C_{32}\kappa_3^2 + \kappa_4(C_{41} + C_{42}\kappa_3 + C_{43}\kappa_3^2)$$

$$\mathbf{\Delta C_{ij} = C_{41}^{(i)}/C_{31}^{(i)} - C_{41}^{(j)}/C_{31}^{(j)}}$$

- ΔC_{ij} quite insensitive to *s*
- Combining *Zhh* and *vvhh* leads to a larger $|\Delta C_{ij}| \sim O(10^{-2})$, a better sensitivity on κ_4

$$\Delta\kappa_4 = \frac{\sqrt{(\sigma_i/C_{31}^{(i)})^2 + (\sigma_j/C_{31}^{(j)})^2}}{|\Delta C_{ij}|}$$

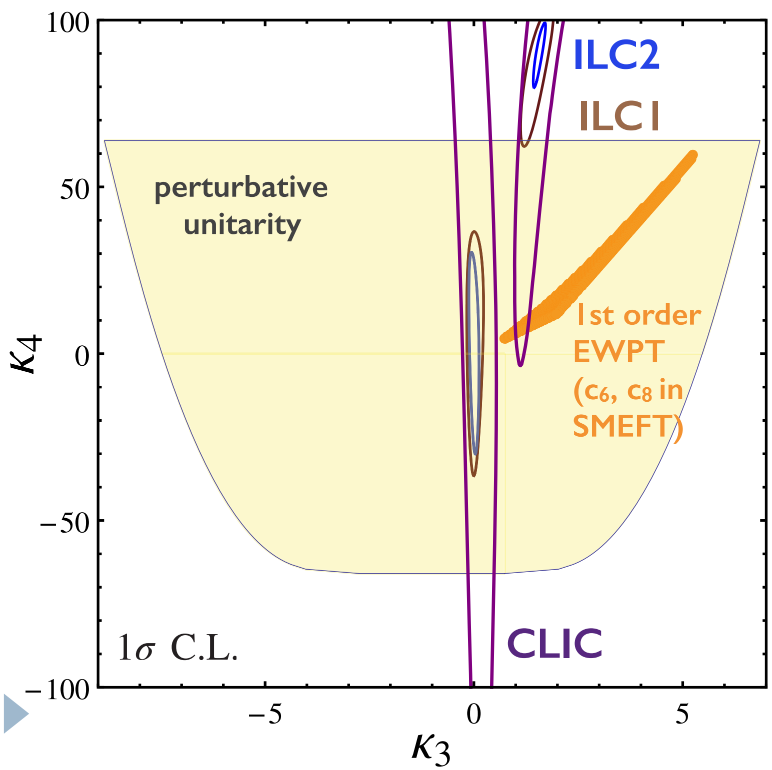


O_j is the reference observable; *s* varied for O_i

Lepton colliders sensitivities

ILC and CLIC in different operating scenarios

$\delta\sigma/\sigma_{SM}$	ILC			CLIC	
Operating scenarios	500 GeV, 4 ab^{-1}	1 TeV, 2.5 ab^{-1} [13]	1 TeV, 8 ab^{-1} [37]	1.4 TeV, 1.5 ab^{-1}	3TeV, 3 ab^{-1} [38]
Zhh	15% [13]	22.5% [13]	12.6% [13]	30% [13]	…
$\nu\nu hh$	…	16.8% [13]	9.4% [13]	44% [14]	16.3% [14]



(i) ILC1 = ILC (500 GeV, 4 ab^{-1} + 1 TeV, 2.5 ab^{-1})

(ii) ILC2 = ILC (500 GeV, 4 ab^{-1} + 1 TeV, 8 ab^{-1})

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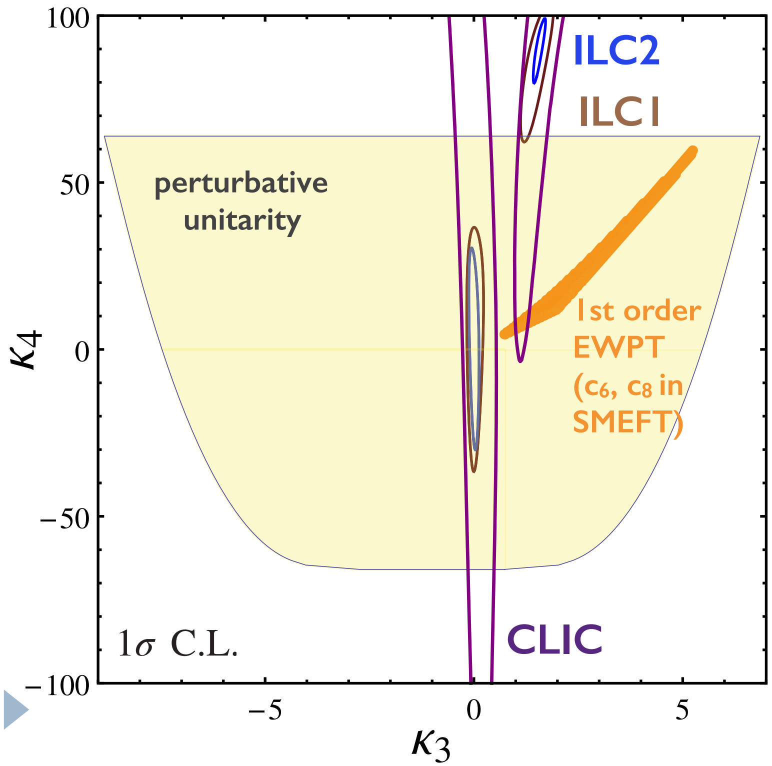


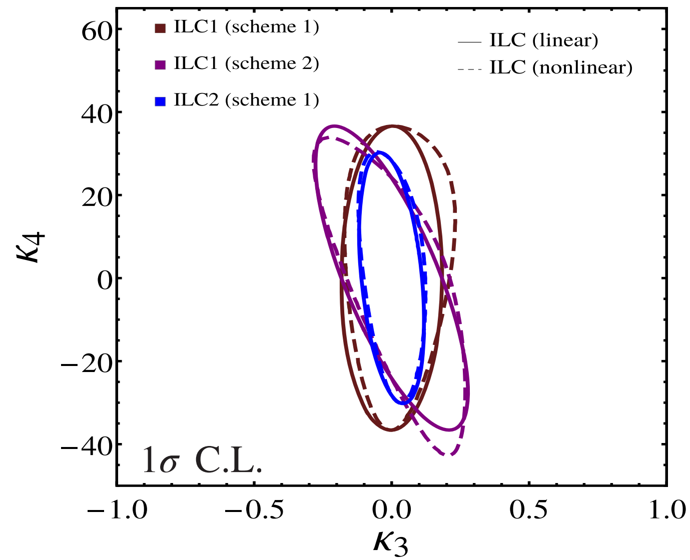
(i) ILC1 = ILC (500 GeV, 4 ab^{-1} + 1 TeV, 2.5 ab^{-1})

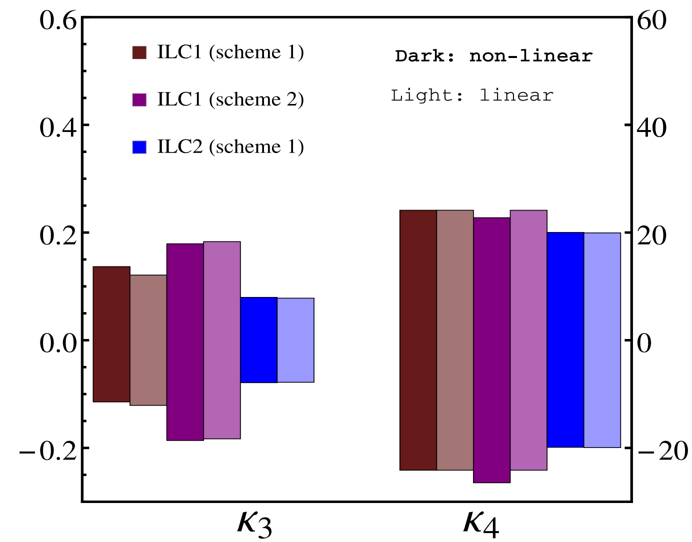
(ii) ILC2 = ILC (500 GeV, 4 ab^{-1} + 1 TeV, 8 ab^{-1})

- The sensitivity of κ_4 is much better on ILC than CLIC
- ILC can measure both *Zhh* and *vvhh* to a good precison, combination of which gives large $|\Delta C_{ij}|$

ILC Sensitivities and scheme dependence

- Scheme change leads to a rotation of sensitivity contour on κ_3-κ_4 plane; marginal $\Delta\kappa_3$ depends strongly on scheme

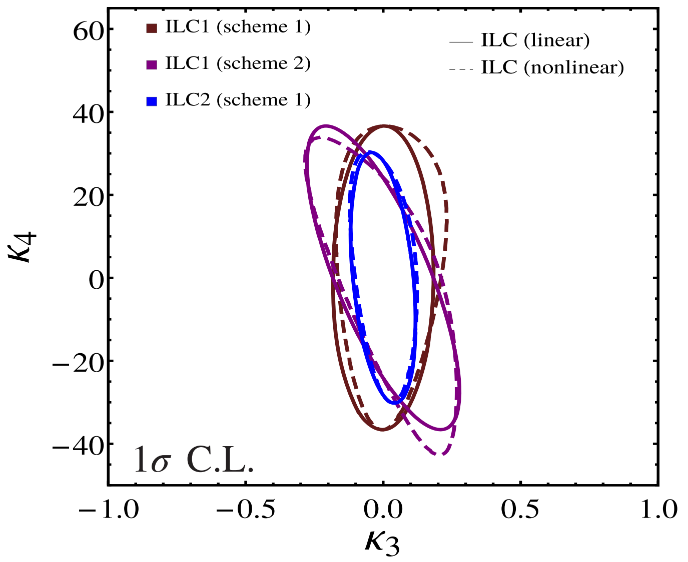


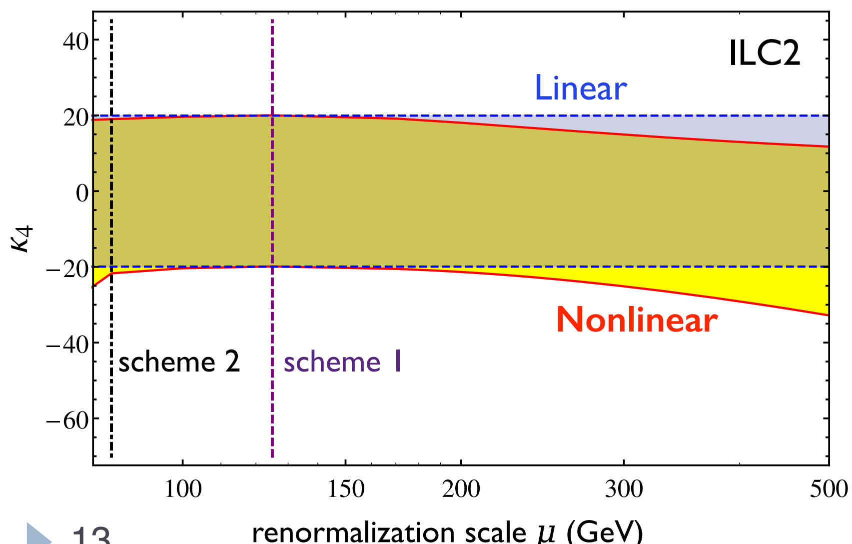


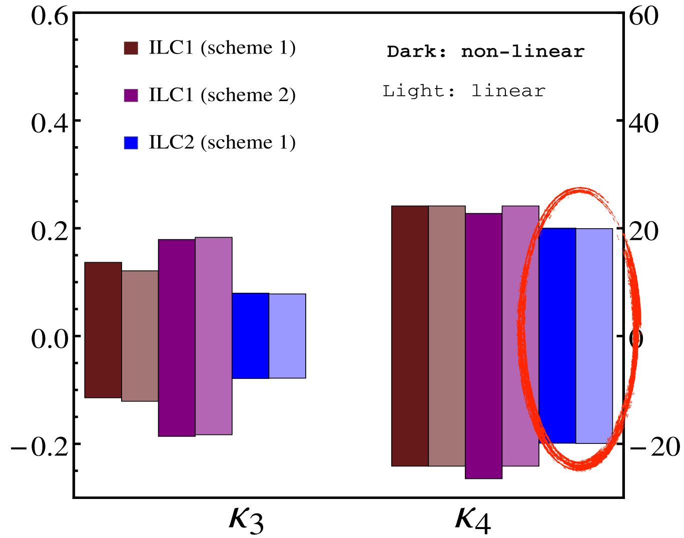
marginal sensitivities

ILC Sensitivities and scheme dependence

- Scheme change leads to a rotation of sensitivity contour on κ_3-κ_4 plane; marginal $\Delta\kappa_3$ depends strongly on scheme
- ILC2: marginal $\Delta\kappa_4 \sim \pm 20$ nearly scheme independent (some dep) at linear (nonlinear) level







marginalized sensitivities

Summary

- Dihiggs production can be used to indirectly probe quartic Higgs coupling. Need to consider renormalization scheme dependence in the interpretation of sensitivity
- Combining *Zhh* and *vvhh* channels on lepton colliders leads to $\Delta\kappa_4 \sim \pm 20$ in the optimal scenario, same order as the "direct" probe by trihiggs production at 100TeV pp collider
- Future study:
  - Utilize dihiggs invariant mass distribution
  - Study "indirect" probe on hadron colliders, i.e. gluon fusion; search for different dihiggs channels for a larger $|\Delta C_{ij}|$
  - Combine "indirect probe" by dihiggs production and "direct probe" by trihiggs production

Thank You!

Cross section fit formula

Vector boson-associated production and vector boson-fusion production on both lepton and hadron colliders ($\mu = m_h$)

$$\delta\sigma/\sigma_0 = C_{31}\kappa_3 + C_{32}\kappa_3^2 + \kappa_4(C_{41} + C_{42}\kappa_3 + C_{43}\kappa_3^2)$$

Lepton collider		σ_0 (fb)	C_{31}	C_{32}	C_{41}	C_{42}	C_{43}
ILC	Zhh (500 GeV)	0.232	0.564	0.0965	−0.00517	−0.00390	−0.000810
	Zhh (1 TeV)	0.166	0.350	0.0913	−0.00271	−0.00181	−0.000541
	$\nu\nu hh$ (1 TeV)	0.159	−1.20	1.10	−0.00327	0.00790	−0.00750
CLIC	Zhh (1.4 TeV)	0.0833	0.263	0.0827	−0.00186	−0.00122	−0.000422
	$\nu\nu hh$ (1.4 TeV)	0.191	−0.965	0.819	−0.0024	0.00541	−0.00505
	$\nu\nu hh$ (3 TeV)	0.825	−0.645	0.488	−0.00119	0.00251	−0.00247

Hadron collider		σ_0 (fb)	C_{31}	C_{32}	C_{41}	C_{42}	C_{43}
14 TeV	$jjhh$	1.26	−0.781	0.688	−0.00233	−0.00466	−0.00426
	Zhh	0.274	0.496	0.0954	−0.00441	−0.00327	−0.000738
	Whh	0.268	0.521	0.109	−0.0041	−0.00331	−0.000807
100 TeV	$jjhh$	59.3	−0.537	0.411	−0.00123	0.00238	−0.00220
	Zhh	2.95	0.454	0.091	−0.00416	−0.00293	−0.000677
	Whh	2.49	0.483	0.105	−0.00386	−0.003	−0.00075

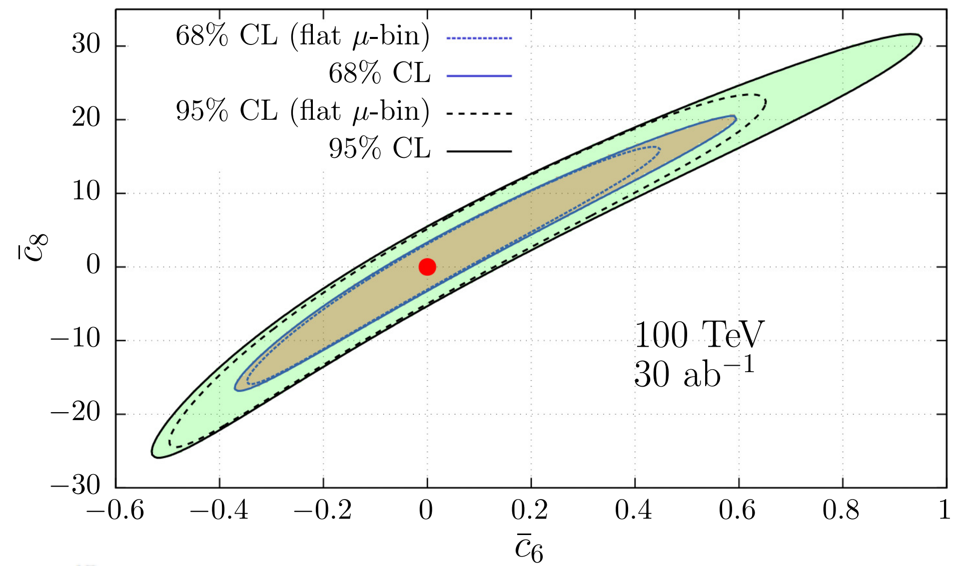
κ_4 sensitivity from gluon fusion production

Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao, arXiv:1811.12366 [hep-ph]

Consider NLO corrections of κ_4 at two loops

$$\kappa_3 = \bar{c}_6 \qquad \kappa_4 = 6\bar{c}_6 + \bar{c}_8$$

Results from cross section fit with renormalization scale $\mu = 2m_h$



Comparison with sensitivities from trihiggs production $hhh \to \bar{b}b\bar{b}b\gamma\gamma$ (depend strongly on b-tagging efficiency): quite different shapes