A global view on the Higgs self-coupling at lepton colliders

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Jornadas de la red española de futuros colisionadores
IFIC Valencia — 21/3/2018

based on S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. P., M. Riembau and T. Vantalon '17

The Higgs self-interaction

Measuring the **Higgs self-interactions** is an essential step to understand the structure of the **Higgs potential**

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4 \qquad \kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}$$

- distortions expected in many BSM scenarios
- related to order of EW phase transition (relevant for cosmology)
- limited precision at LHC due to small statistics $\lambda_3 \in [0, 2]$ at $1\,\sigma$

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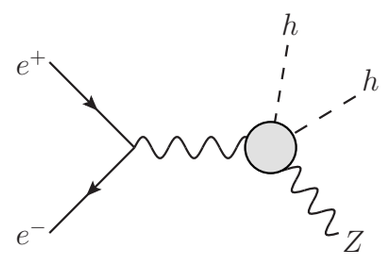
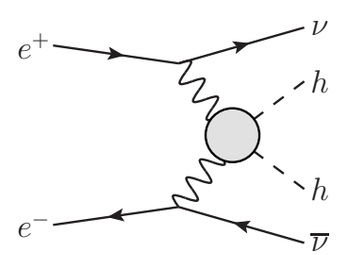
- limited precision at LHC due to small statistics $\lambda_3 \in [0, 2]$ at $1\,\sigma$

- ✦ at high-energy lepton machines accessible mainly in **HH production**
- ✦ additional bonus: test **strength of Higgs couplings** at high energy (VVhh coupling)

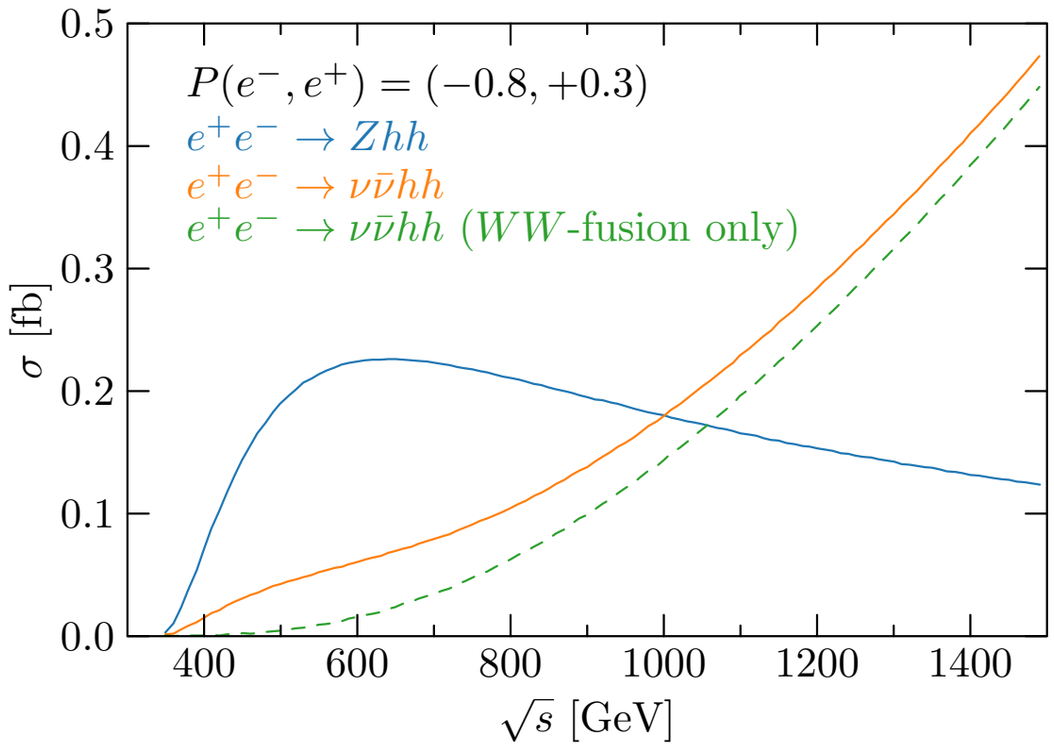




Main double-Higgs channels

Two main channels

Zhh and $\nu\bar{\nu}$hh



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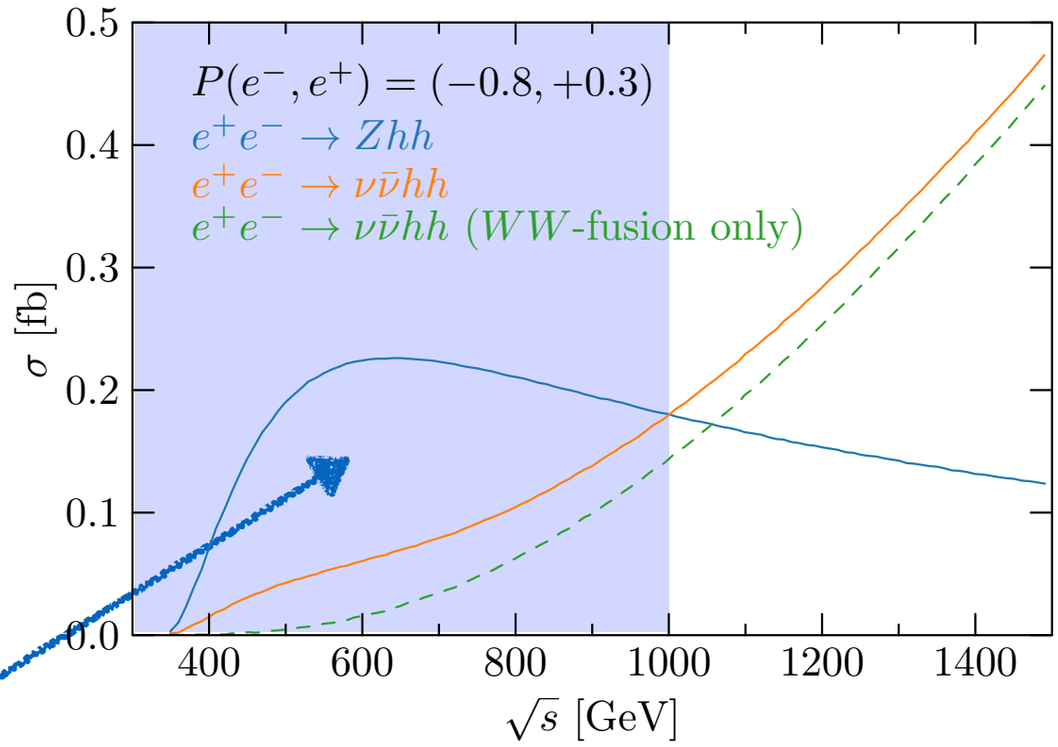
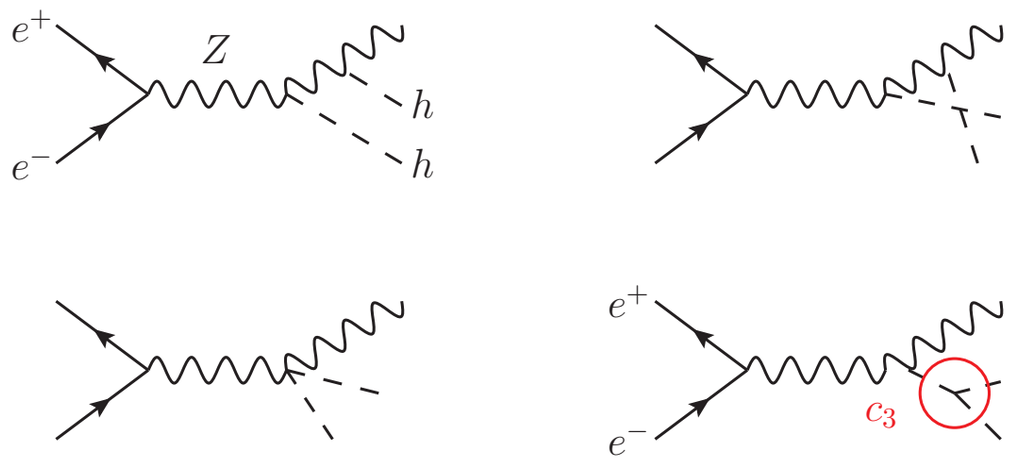


Double Higgs-strahlung (DHS)

dominant below 1 TeV



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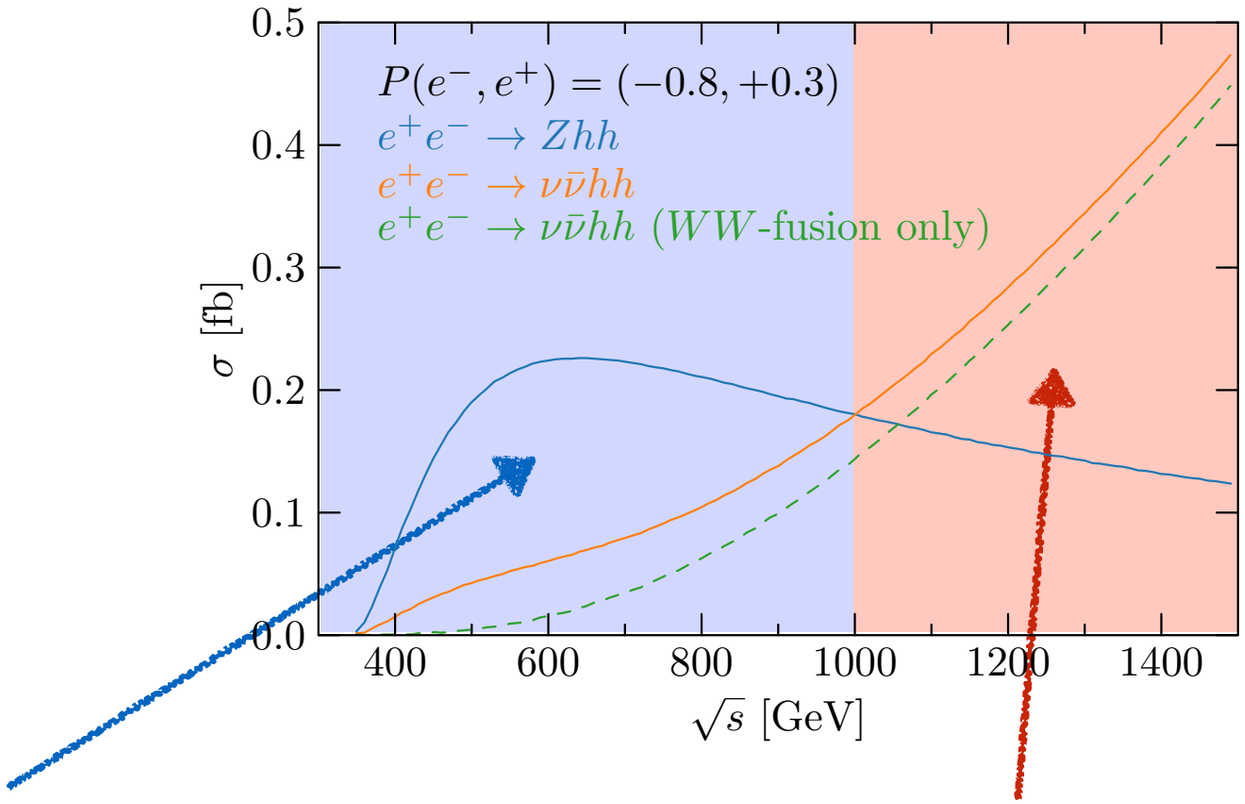

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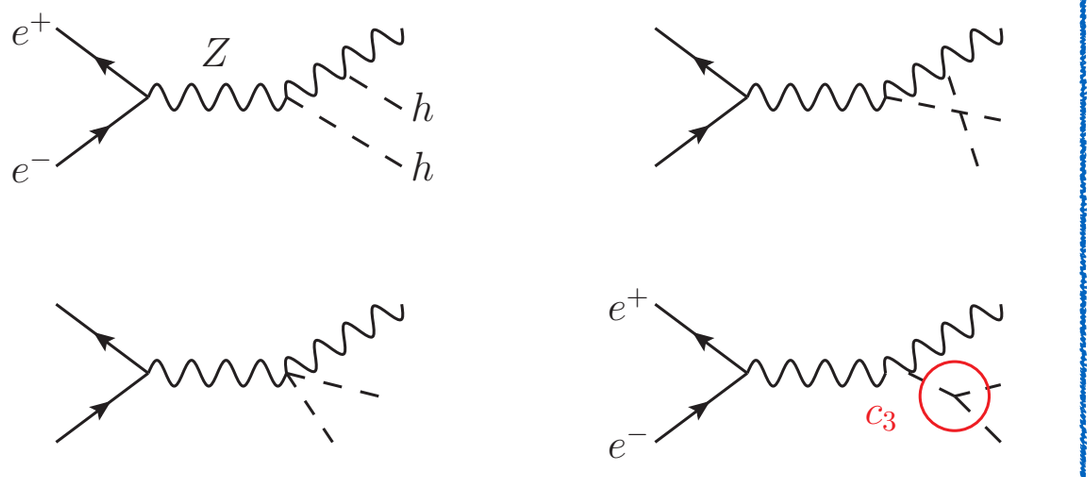
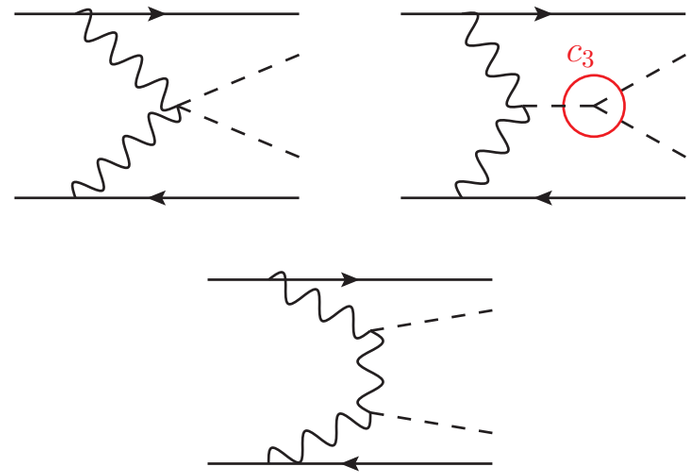


Vector Boson Fusion (VBF)

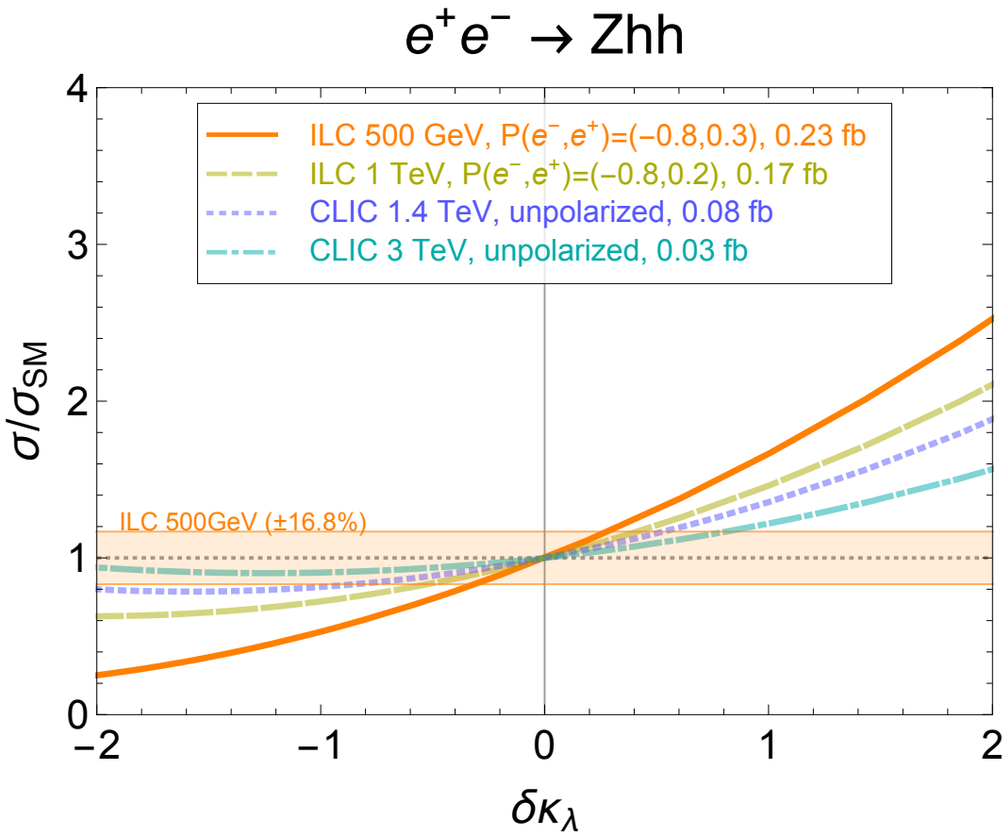
dominant above 1 TeV

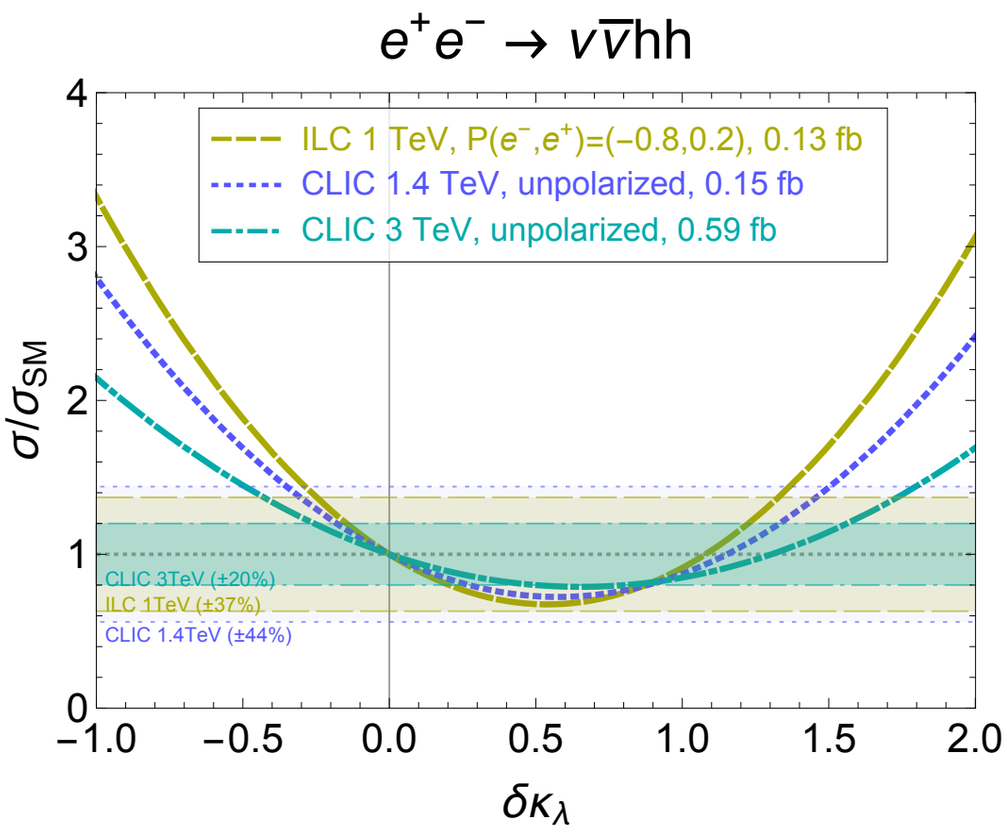


Sensitivity to Higgs self-coupling

The two channels provide complementary information

- Zhh gives stronger constraints on $\delta\lambda_3 > 0$
- $\nu\bar{\nu}$hh gives stronger constraints on $\delta\lambda_3 < 0$





- dependence on $\delta\lambda_3$ stronger at lower COM energy, optimal choices 500 GeV and 1 TeV

Precision reach at ILC

ILC 500 GeV ($4\ \mathrm{ab}^{-1}$, $P = (\pm 0.8, \mp 0.3)$) + 1 TeV ($2\ \mathrm{ab}^{-1}$, $P = (-0.8, +0.2)$)		
bounds on $\delta\kappa_\lambda$	68% CL	95% CL
ILC 500 GeV $(e^+e^- \to Zhh)$	$[-0.31, 0.28]$	$[-0.67, 0.54]$
ILC 1 TeV $(e^+e^- \to \nu\bar{\nu}hh)$	$[-0.25, 1.33]$	$[-0.44, 1.52]$
ILC combined	$[-0.20, 0.23]$	$[-0.37, 0.49]$

Precision at ILC **~20% at 68% CL** (combining 500 GeV and 1 TeV runs)

- combination of Zhh and $\nu\bar{\nu}$hh allows to exclude large positive corrections not testable at LHC (eg. $\delta\lambda_3 \sim 1$)

Precision reach at CLIC

CLIC 1.4 TeV ($1.5\ \mathrm{ab}^{-1}$) + 3 TeV ($2\ \mathrm{ab}^{-1}$), unpolarized beams, $e^+e^- \to \nu\bar{\nu}hh$		
bounds on $\delta\kappa_\lambda$	68% CL	95% CL
CLIC 1.4 TeV	$[-0.35, 1.51]$	$[-0.60, 1.76]$
CLIC 3 TeV	$[-0.26, 0.50] \cup [0.81, 1.56]$	$[-0.46, 1.76]$
CLIC combined	$[-0.22, 0.36] \cup [0.90, 1.46]$	$[-0.39, 1.63]$
$+Zhh$	$[-0.22, 0.34] \cup [1.07, 1.28]$	$[-0.39, 1.56]$

Precision at CLIC **~25% at 68% CL** (combining 1.4 TeV and 3 TeV runs)

… but inclusive measurements at CLIC can not resolve the **additional minimum** at $\delta\lambda_3 \sim 1$

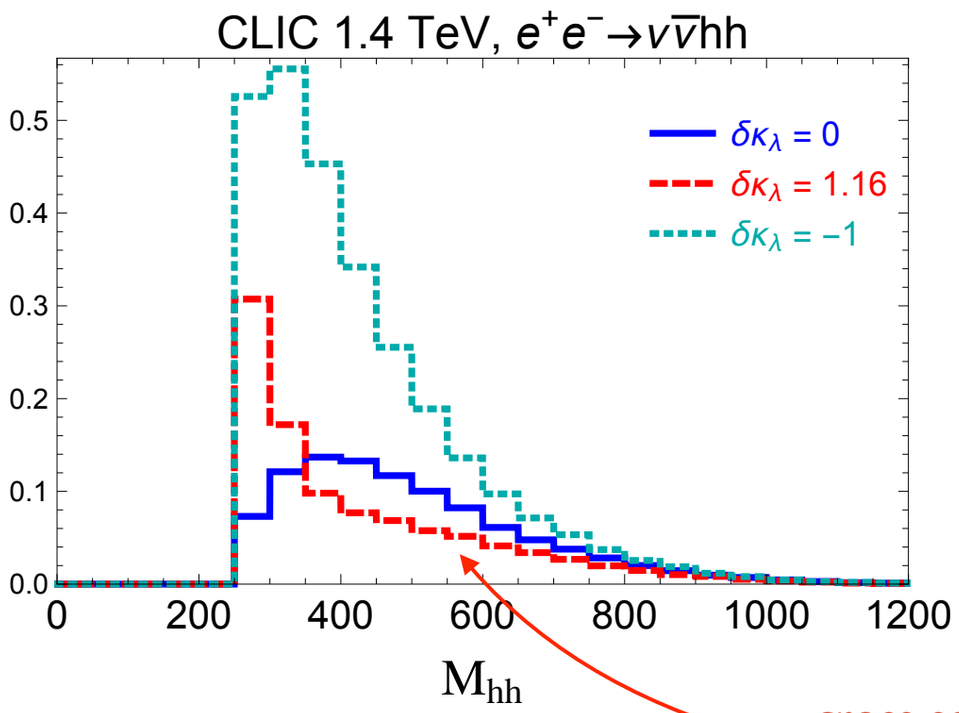
- Zhh helps to test the second minimum, but has limited impact
  (due to small cross section)

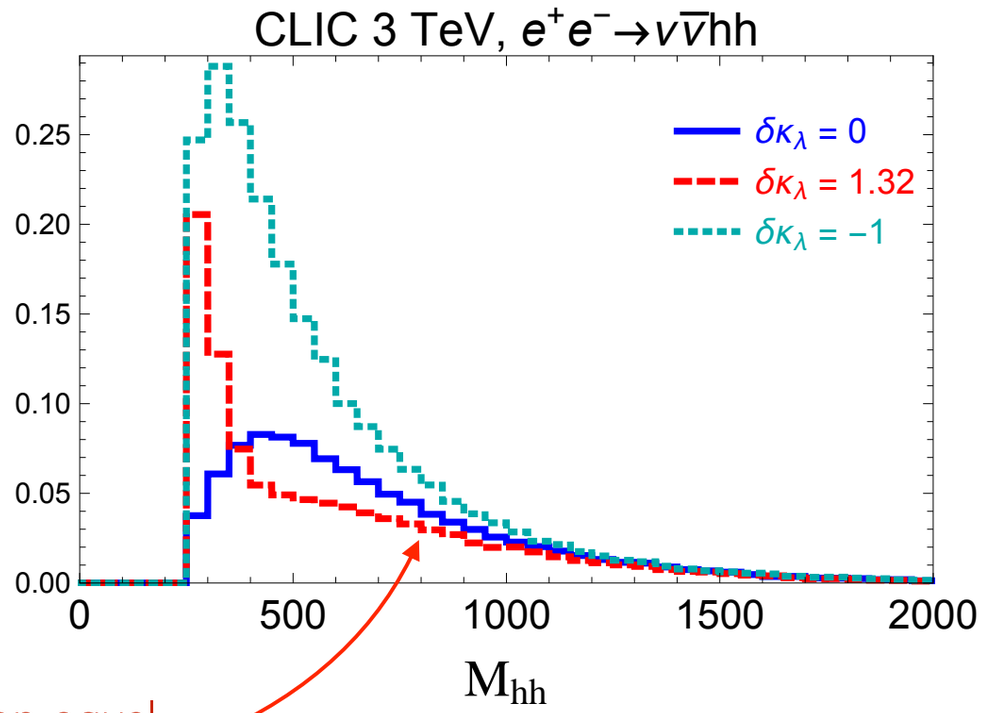
Additional improvement:

- consider **differential distributions**

Differential HH distributions

The Higgs trilinear coupling strongly modifies the distributions





cross section equal to SM one

	signal ev.	bkg. ev.
CLIC 1.4 TeV	~ 20	~ 40
CLIC 3 TeV	~ 60	~ 100

- differential analysis can exclude the second minimum

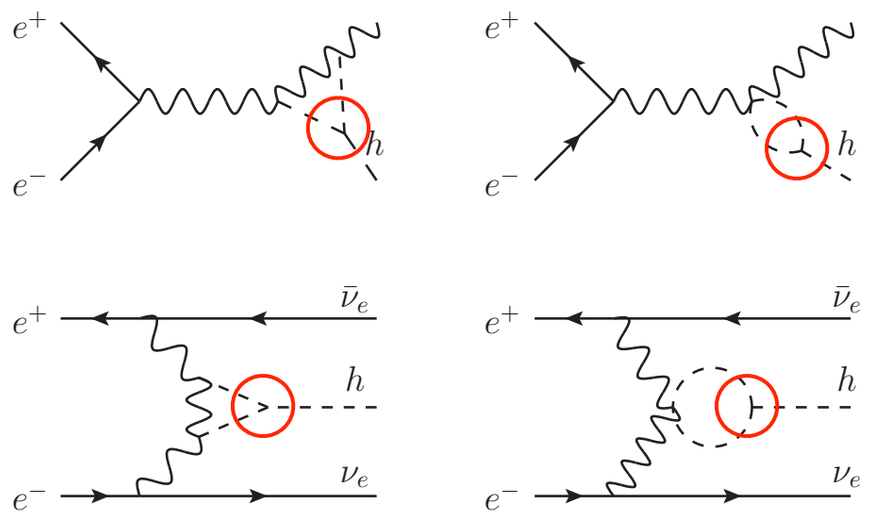
bounds on $\delta\kappa_\lambda$	68% CL	95% CL
CLIC inclusive	$[-0.22, 0.34] \cup [1.07, 1.28]$	$[-0.39, 1.56]$
2 bins in $\nu\bar{\nu}hh$	$[-0.19, 0.31]$	$[-0.33, 1.23]$
4 bins in $\nu\bar{\nu}hh$	$[-0.18, 0.30]$	$[-0.33, 1.11]$

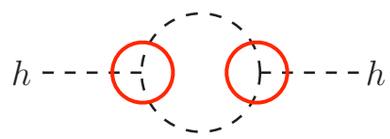
Help from Single Higgs?

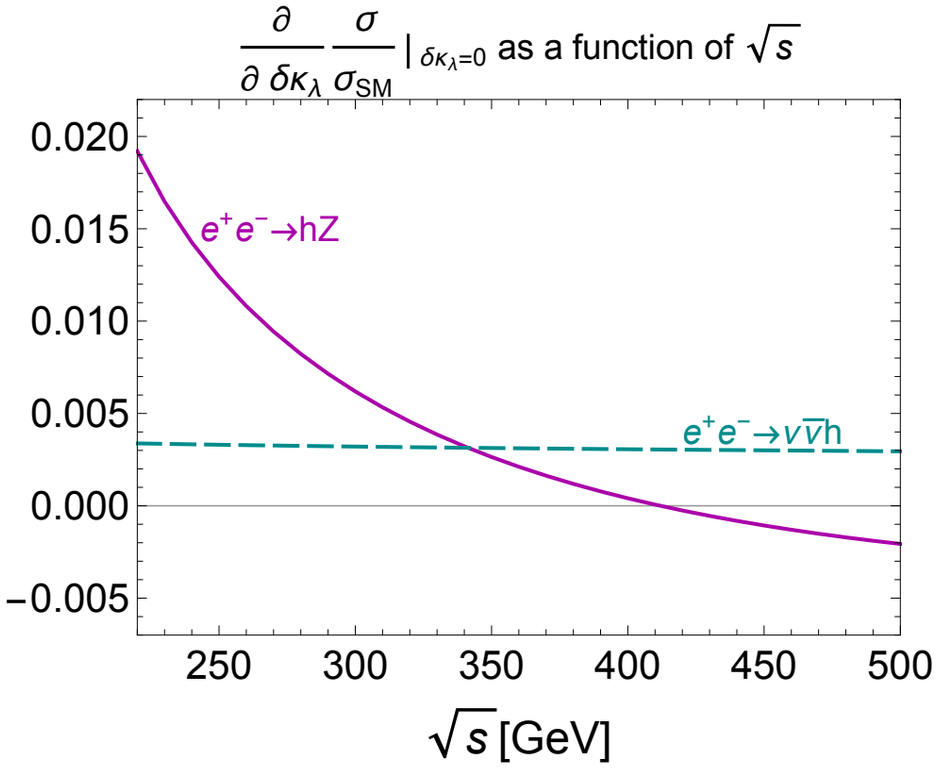
Self-Interaction from Single Higgs

Higgs self-interaction can be also probed indirectly through single-Higgs processes

[McCullough '13]







Good sensitivity at low energy in Zh (and $\nu\bar{\nu}$h) channels

- eg. exclusive analysis at TLEP 240 GeV:

$$|\delta\lambda_3| \lesssim 28\%$$

Single Higgs global analysis

Corrections to Higgs trilinear are usually **not alone:** accompanied by modifications of single Higgs couplings

global analysis is needed!

Several couplings can affect single-Higgs production

Minimal set in the Warsaw basis: 12 operators

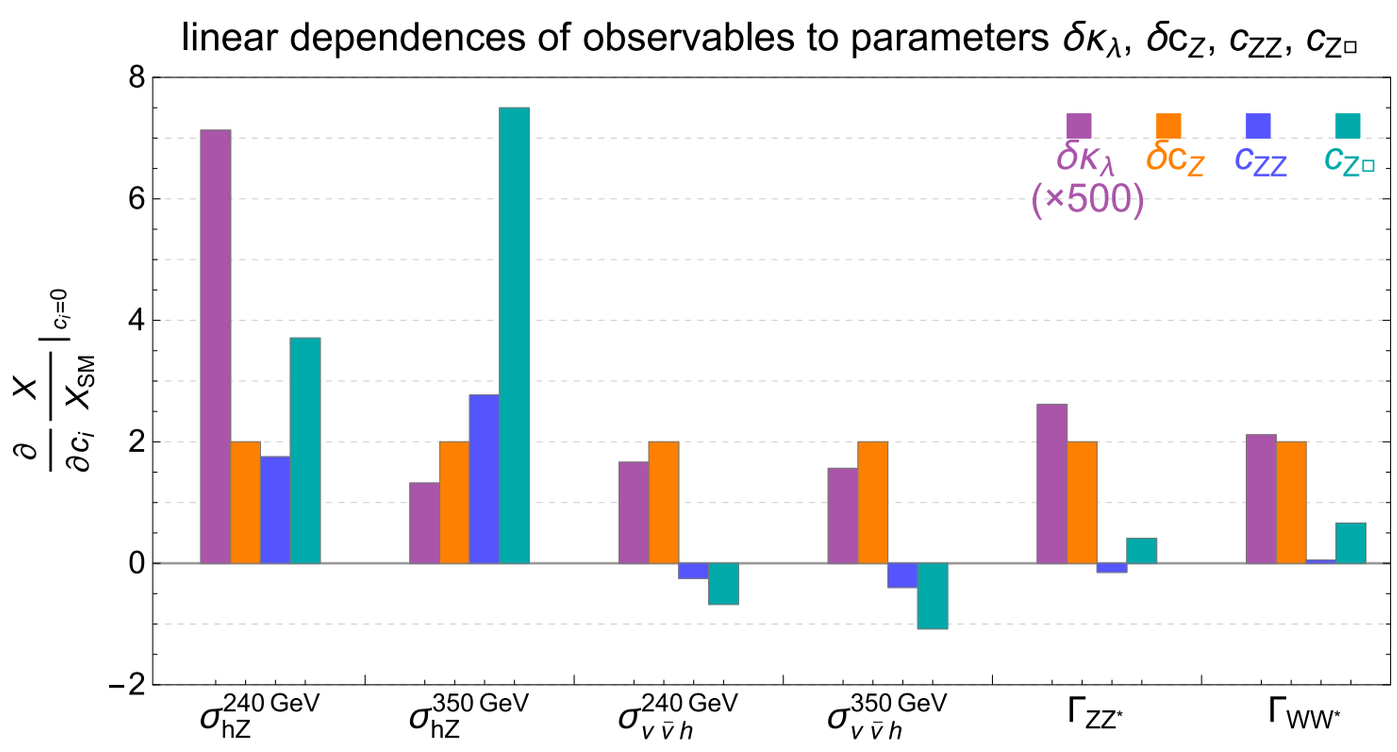
- Higgs couplings to gauge bosons $\delta c_z,\ c_{zz},\ c_{z\Box},\ c_{z_\gamma},\ c_{\gamma\gamma},\ c_{gg}$
- Yukawa's $\delta y_t,\ \delta y_b,\ \delta y_c\, \delta y_\tau,\ \delta y_\mu$
- triple gauge couplings λ_z

Single Higgs global analysis

All the 12 operators can be well constrained by a global fit

Higgs self interaction can also be added to the list: 12+1 operators

- can be distinguished thanks to different impact on various processes



Higgs trilinear from low-energy ILC

- global fit from single-Higgs channels can provide a first "precision" determination of Higgs trilinear coupling, improving HL-LHC reach

eg. combination of 250 GeV and 350 GeV can lead to ~50% precision on Higgs trilinear

Further improvement from combination with HL-LHC
(helps to lift additional HL-LHC minimum at $\delta\lambda_3 \sim 5$)

	lepton collider alone		lepton collider + HL-LHC	
	non-zero aTGCs	zero aTGCs	non-zero aTGCs	zero aTGCs
HL-LHC alone			$[-0.92, +1.26]$	$[-0.90, +1.24]$
ILC 250 GeV ($2\,\text{ab}^{-1}$)	$[-5.72, +5.87]$	$[-5.39, +5.62]$	$[-0.85, +1.13]$	$[-0.85, +1.12]$
+350 GeV ($200\,\text{fb}^{-1}$)	$[-1.26, +1.26]$	$[-1.18, +1.18]$	$[-0.72, +0.83]$	$[-0.71, +0.80]$
+350 GeV ($1.5\,\text{ab}^{-1}$)	$[-0.64, +0.64]$	$[-0.56, +0.56]$	$[-0.52, +0.54]$	$[-0.48, +0.50]$

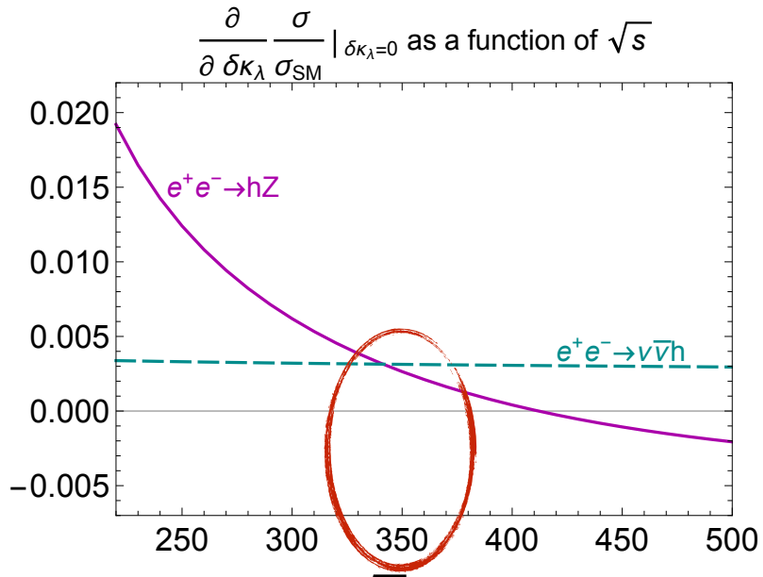
global fit with anomalous TGCs

no anomalous TGCs

Single Higgs global analysis

… but single-Higgs channels have a **small impact once high-energy colliders** can access double-Higgs production

- marginal improvement at ILC
- almost no change for CLIC
  (due to small dependence on Higgs trilinear at a 350 GeV run)



global fit including single- and double-Higgs channels

	68 %CL	95%CL
ILC up to 500 GeV	$[-0.27,\ 0.25]$	$[-0.55,\ 0.49]$
ILC up to 1 TeV	$[-0.18,\ 0.20]$	$[-0.35,\ 0.43]$
CLIC	$[-0.22,\ 0.36] \cup [0.91,\ 1.45]$	$[-0.39,\ 1.63]$
$+Zhh$	$[-0.22,\ 0.35] \cup [1.07,\ 1.27]$	$[-0.39,\ 1.56]$
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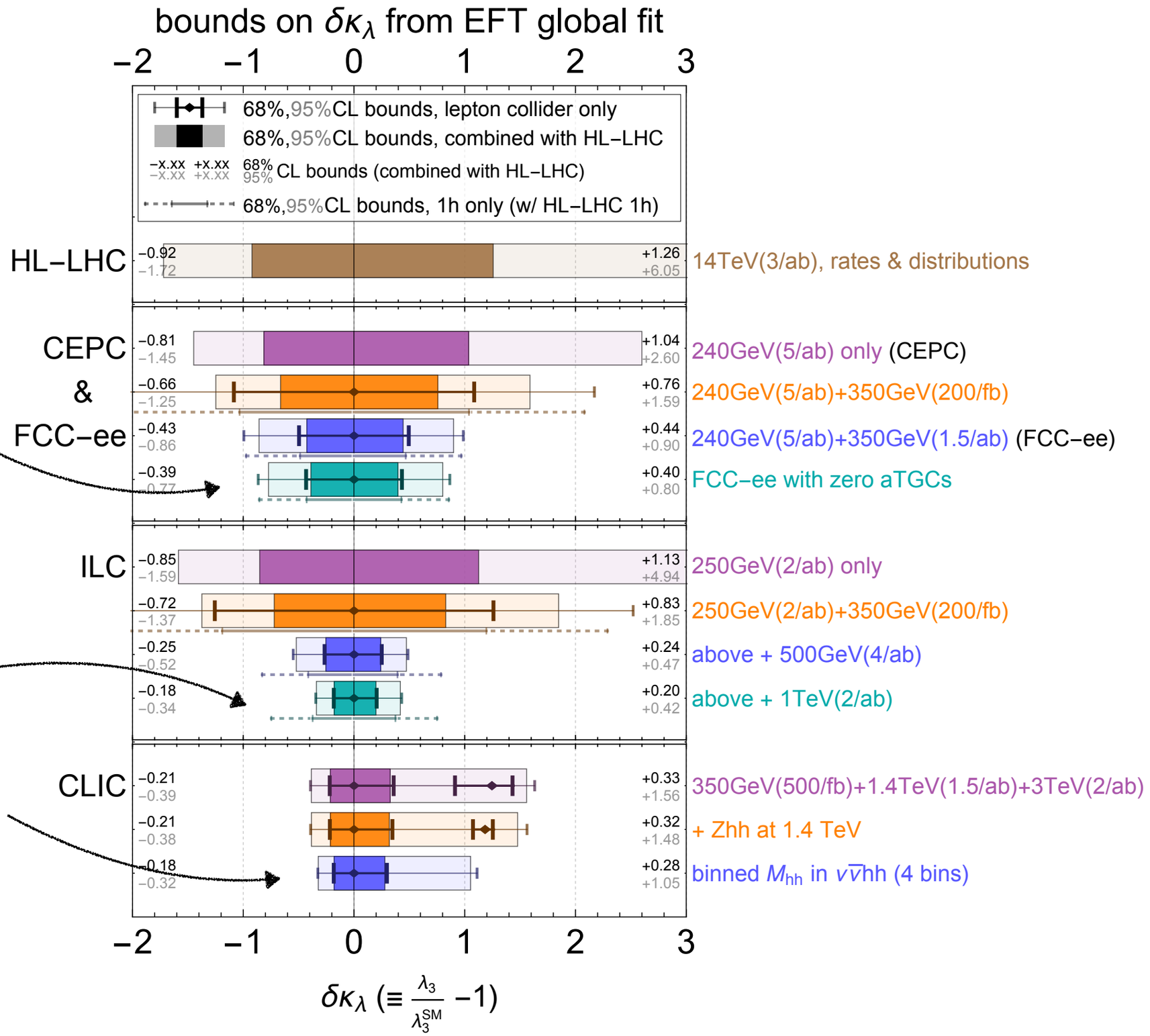
Comparison of different colliders

Reach at different colliders

CEPC and **FCC-ee**
can reach **~40%** precision

Combined global fit
at **ILC** or **CLIC**
can reach **~20%** precision
and select "correct" minimum



Conclusions

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High-energy **lepton colliders** can provide access the **Higgs trilinear self-coupling**

- allow for the first "precision" determination (only O(1) possible at HL-LHC)

- single-Higgs production at ILC can provide a ~50% determination

- two main channels at high-energy: Zhh and $\nu\bar{\nu}$hh

  - CLIC could reach a ~25% precision at 68% CL
    (exploiting invariant mass distribution to probe large positive corrections)

  - ILC could reach a ~20% precision at 68% CL