Higgs Trilinear: Reach and Implications

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mainly based on   De Blas et al. “The CLIC Potential for New Physics” 1812.02093

The Higgs self-interaction

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

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

- distortions expected in many BSM scenarios
- related to order of EW phase transition (relevant for cosmology)
- limited precision at LHC due to small statistics

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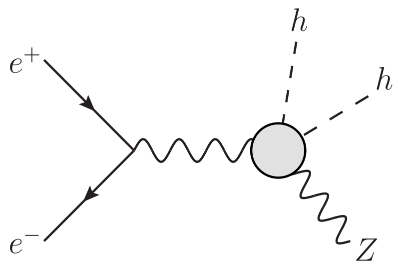
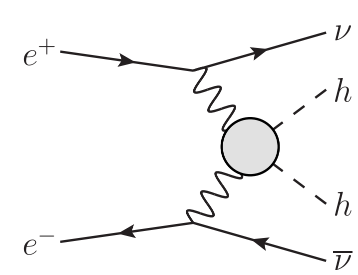
- limited precision at LHC due to small statistics

✦ at high-energy lepton machines accessible mainly in **HH production**



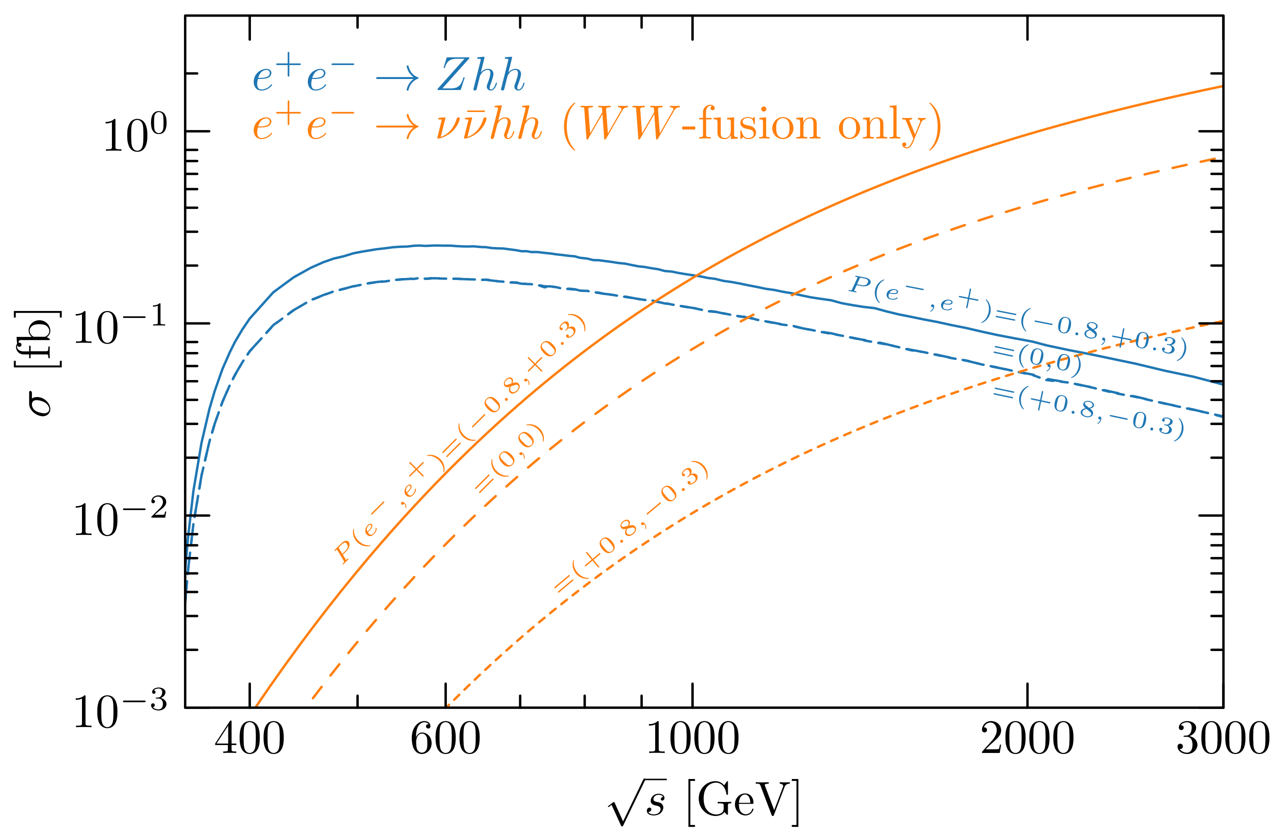
✦ additional bonus: test **strength of Higgs couplings** at high energy (VVHH coupling)



Main double-Higgs channels

Two main channels

ZHH and $\nu\bar{\nu}HH$



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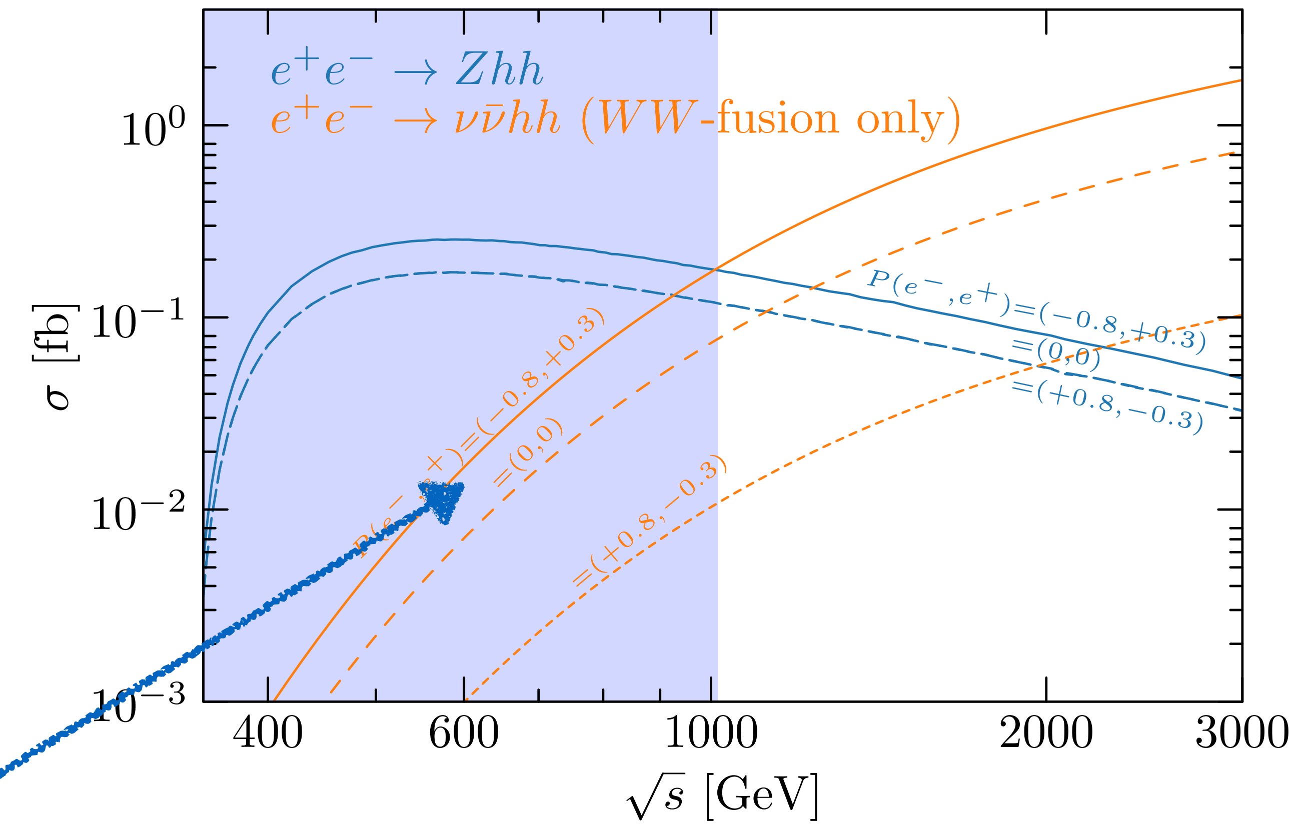
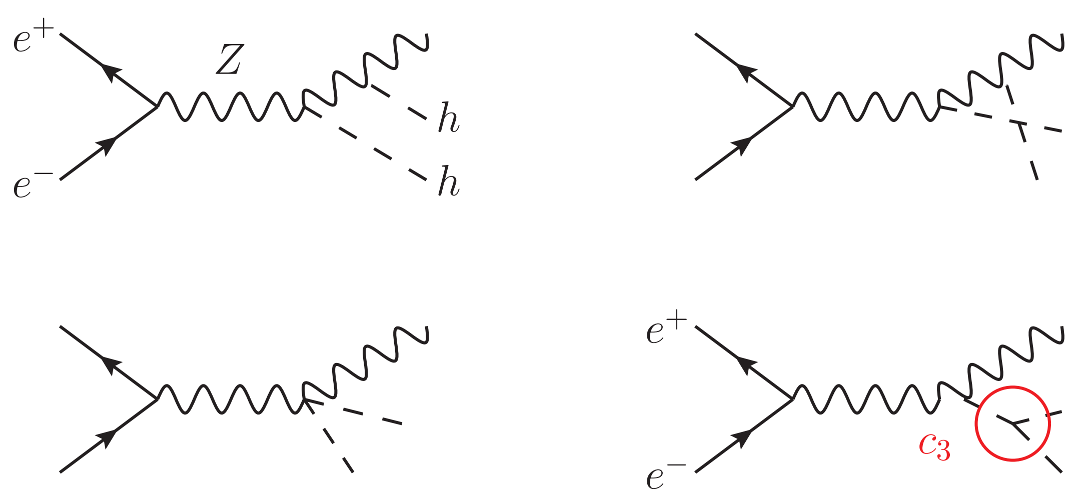


Double Higgs-strahlung (DHS)

dominant below 1 TeV



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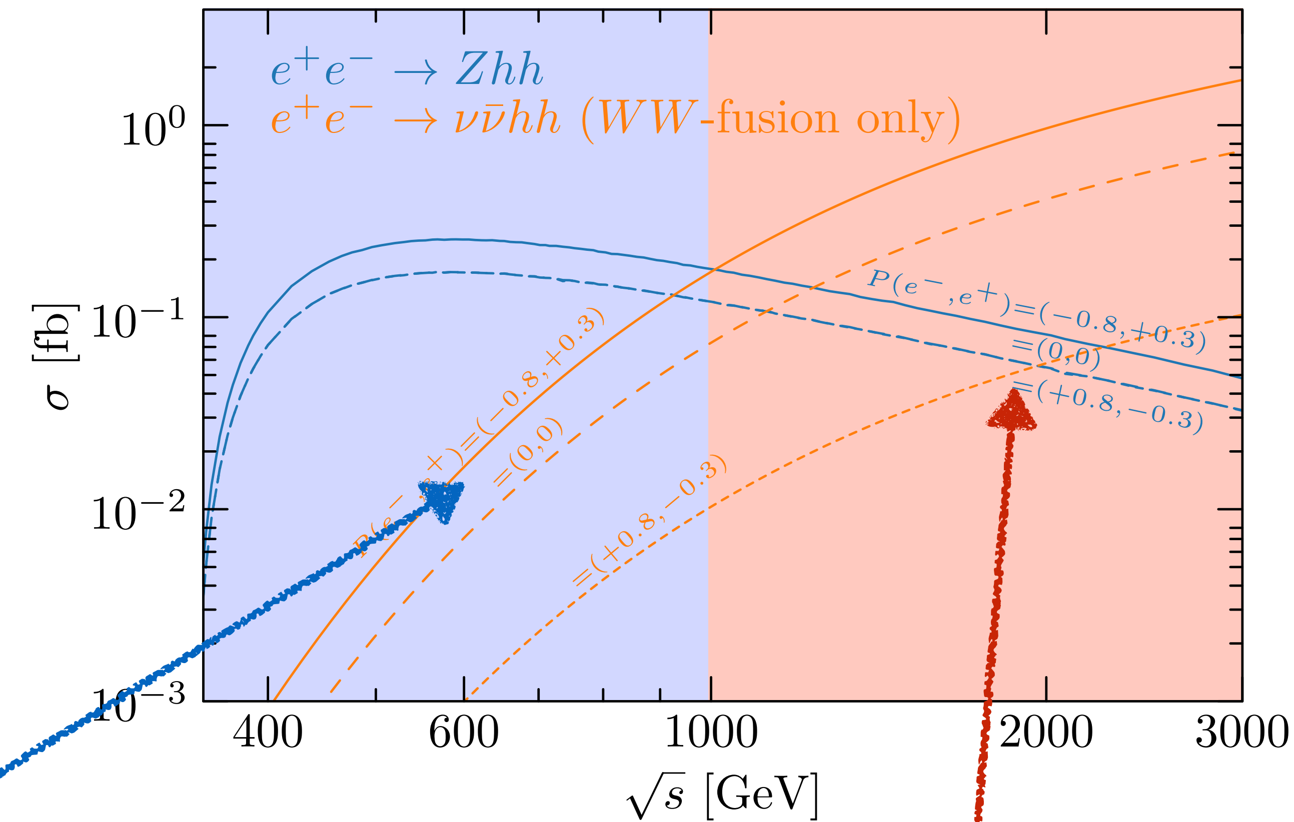

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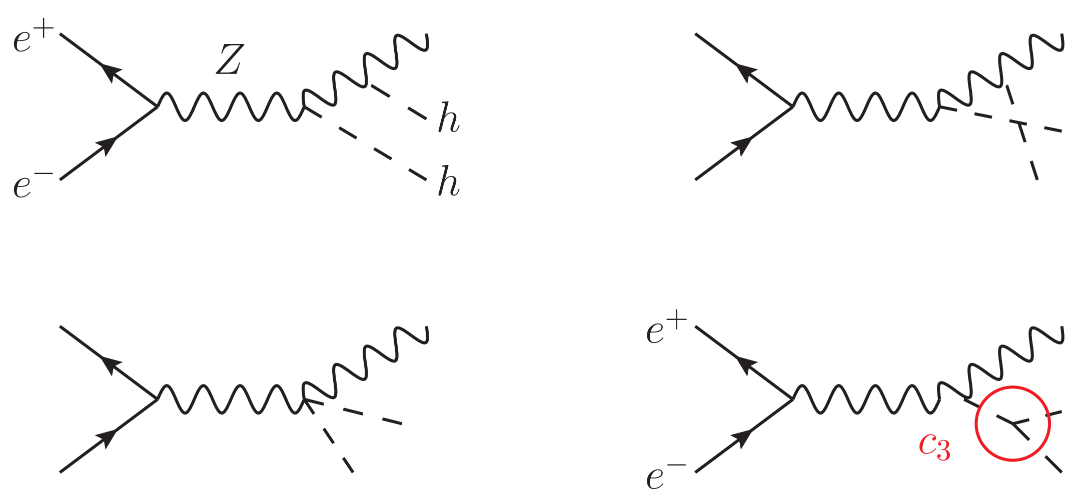
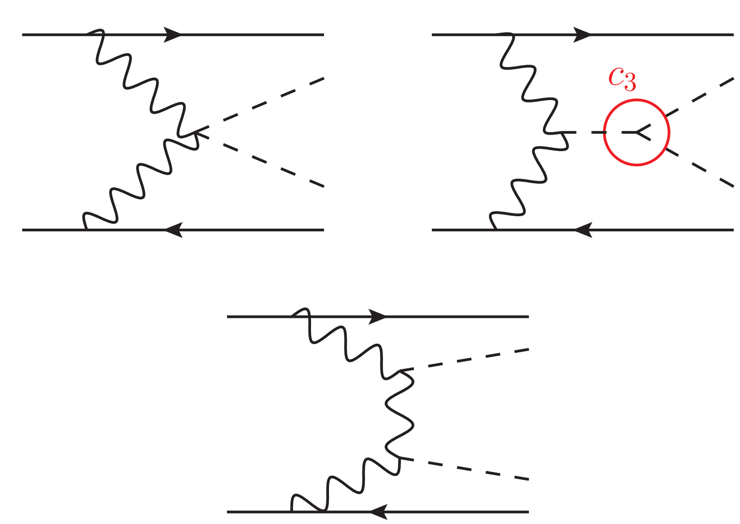


Vector Boson Fusion (VBF)

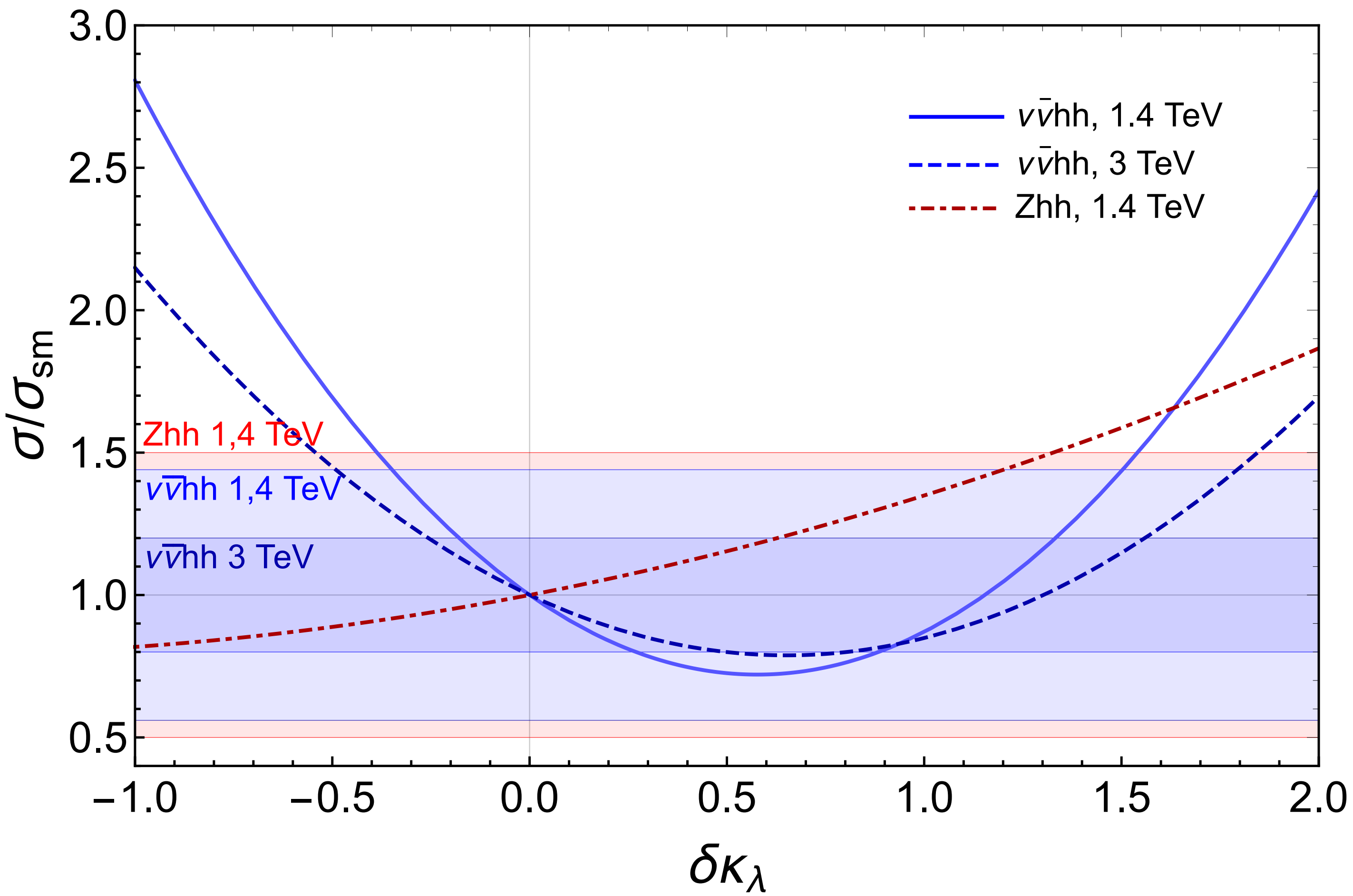
dominant above 1 TeV



Sensitivity to Higgs self-coupling

The two channels provide complementary information

- ZHH gives stronger constraints on $\delta\kappa_\lambda > 0$
- $\nu\bar{\nu}HH$ gives stronger constraints on $\delta\kappa_\lambda < 0$



- dependence on $\delta\kappa_\lambda$ decreases with energy in $\nu\bar{\nu}HH$, but compensated by large increase in cross section

Precision reach at CLIC

	$\Delta\chi^2 = 1$	$\Delta\chi^2 = 4$
CLIC Stage 2	$[-0.22,\ 0.48]$	$[-0.40,\ 1.05]$
CLIC Stage 3	$[-0.13,\ 0.16] \cup [1.13,\ 1.42]$	$[-0.24,\ 0.42] \cup [0.87,\ 1.53]$
CLIC Stage 2+3	$[-0.12,\ 0.14]$	$[-0.21,\ 0.35]$
5 bins in $\nu\bar{\nu}hh$	$[-0.11,\ 0.13]$	$[-0.21,\ 0.29]$

[Results from theory study,
see later for experimental study]

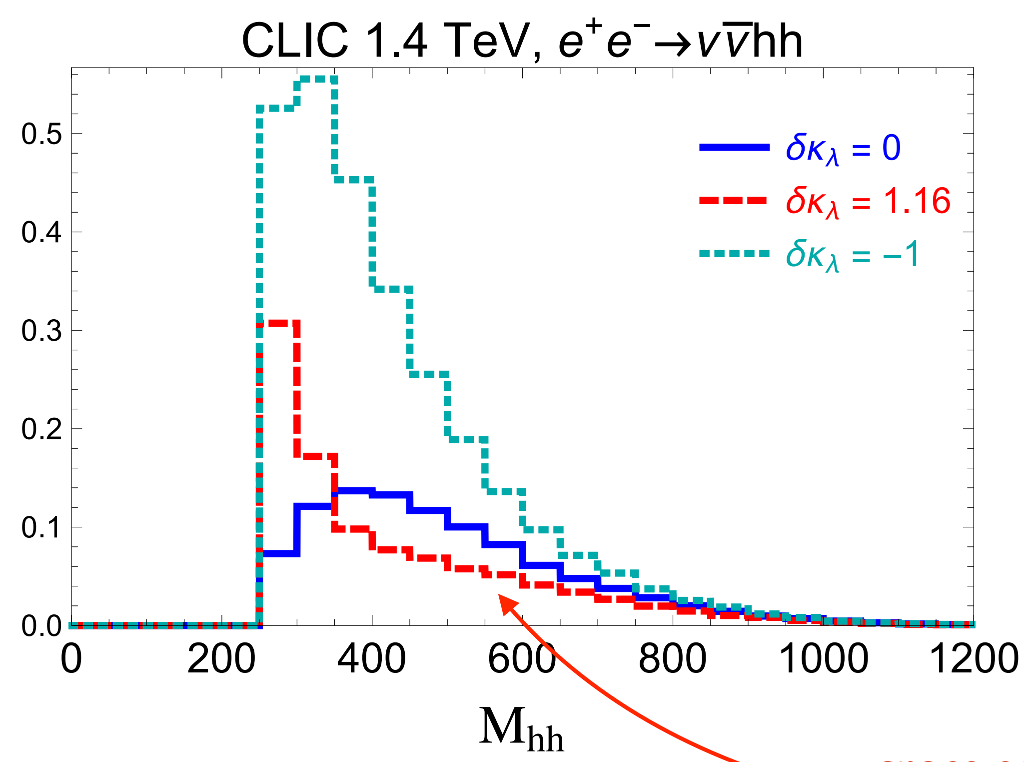
Precision at CLIC **~10% at 68% CL** (combining 1.4 TeV and 3 TeV runs)

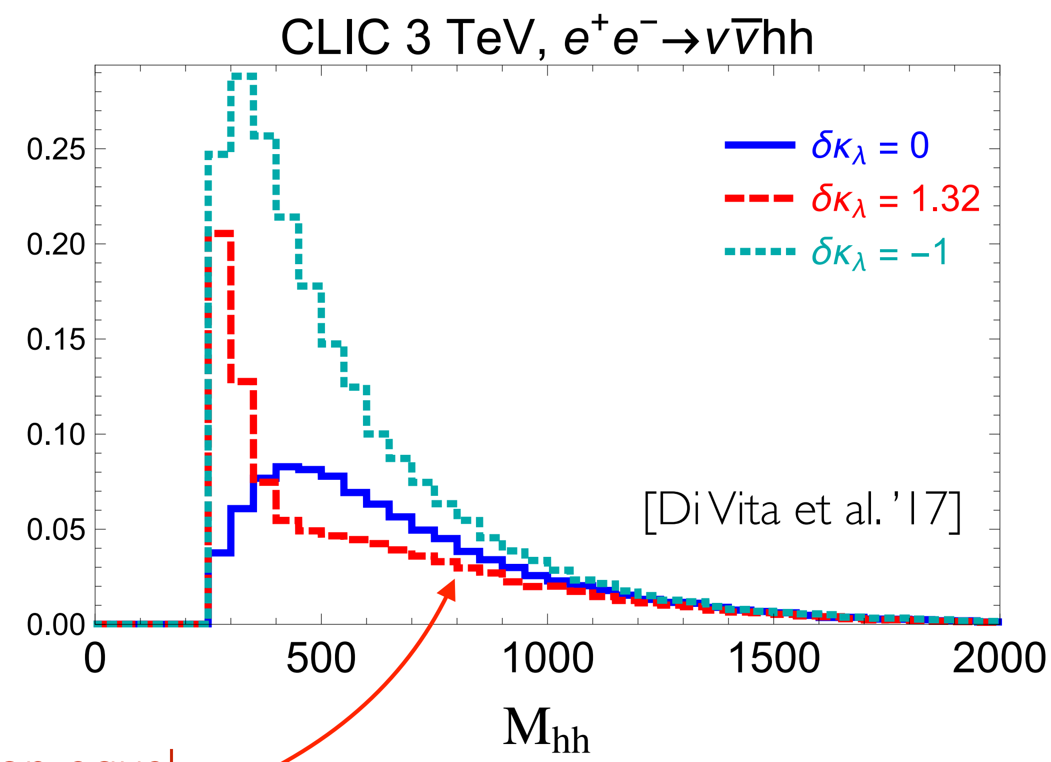
- Interplay between $\nu\bar{\nu}HH$ and ZHH has a strong impact on the reach, excluding the region at $\delta\kappa_\lambda \sim 1.2$

- Additional improvement from differential distribution in $\nu\bar{\nu}HH$

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 $\nu\bar{\nu}hh$	$[-0.18, 0.30]$	$[-0.33, 1.11]$

Precision reach at CLIC

More detailed analysis confirms previous discussion

Constraints for $\delta\kappa_\lambda$ based on	$\Delta\chi^2 = 1$
$hh\nu\bar{\nu}$ cross section only (3 TeV)	$[-0.10, +0.12] \cup [1.40, 1.61]$
$hh\nu\bar{\nu}$ (3 TeV) and Zhh (1.4 TeV) cross section	$[-0.10, +0.11]$
$hh\nu\bar{\nu}$ differential (3 TeV)	$[-0.07, +0.12]$
$hh\nu\bar{\nu}$ differential (3 TeV) and Zhh cross section (1.4 TeV)	$[-0.07, +0.11]$

[See talk by U. Schnoor for details]

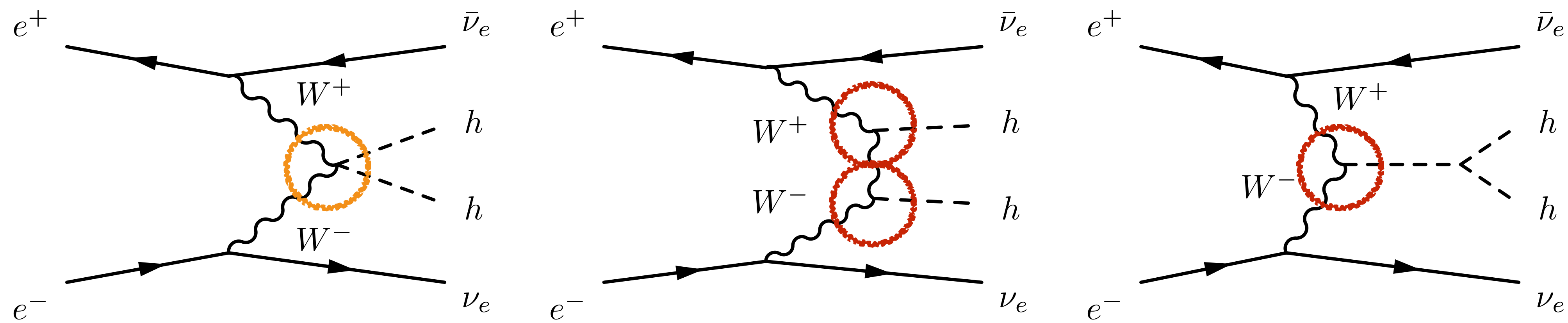
- Differential analysis of $\nu\bar{\nu}HH$ at 3 TeV is almost saturates the whole precision

Impact of Global Fit

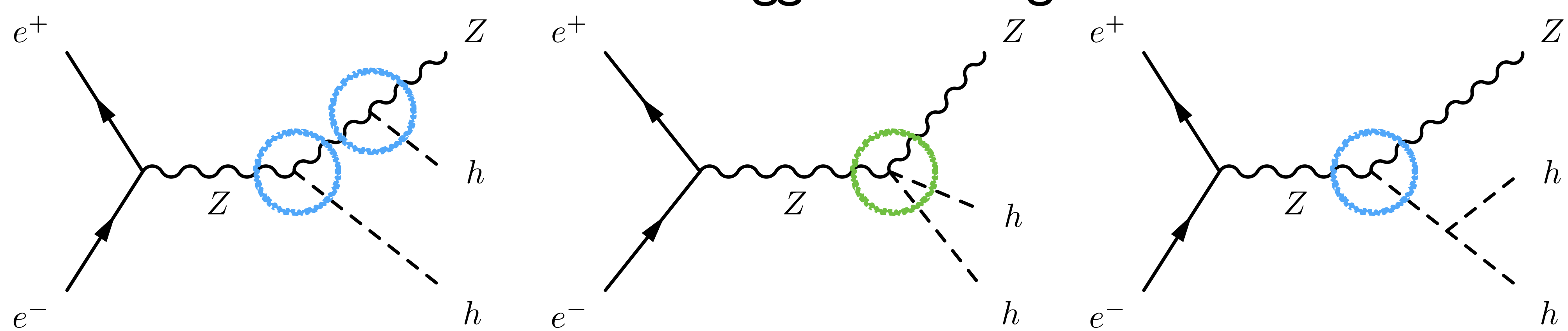
Single Higgs couplings

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

Vector Boson Fusion



Double Higgs-strahlung



- Several couplings can affect single-Higgs production (and Higgs decays)

Single Higgs couplings

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

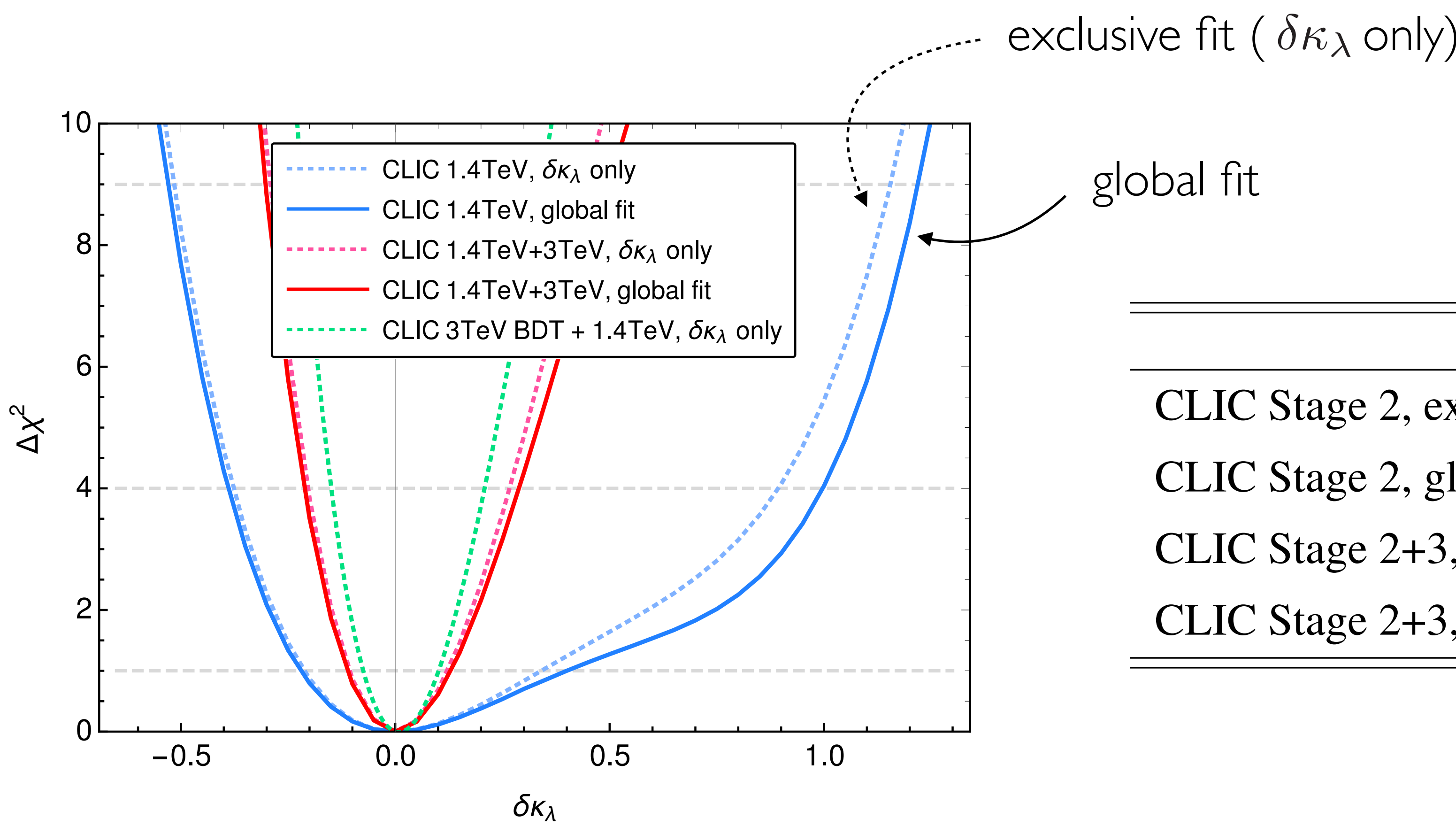
↓

global analysis is needed!

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

Impact of global fit



	68 %C.L.	95%C.L.
CLIC Stage 2, exclusive	$[-0.21,\ 0.34]$	$[-0.38,\ 0.89]$
CLIC Stage 2, global	$[-0.22,\ 0.40]$	$[-0.39,\ 1.00]$
CLIC Stage 2+3, exclusive	$[-0.11,\ 0.12]$	$[-0.20,\ 0.27]$
CLIC Stage 2+3, global	$[-0.11,\ 0.13]$	$[-0.21,\ 0.29]$

- ✦ Single Higgs measurements are precise enough to make deviations in single Higgs couplings subdominant in Higgs pair production

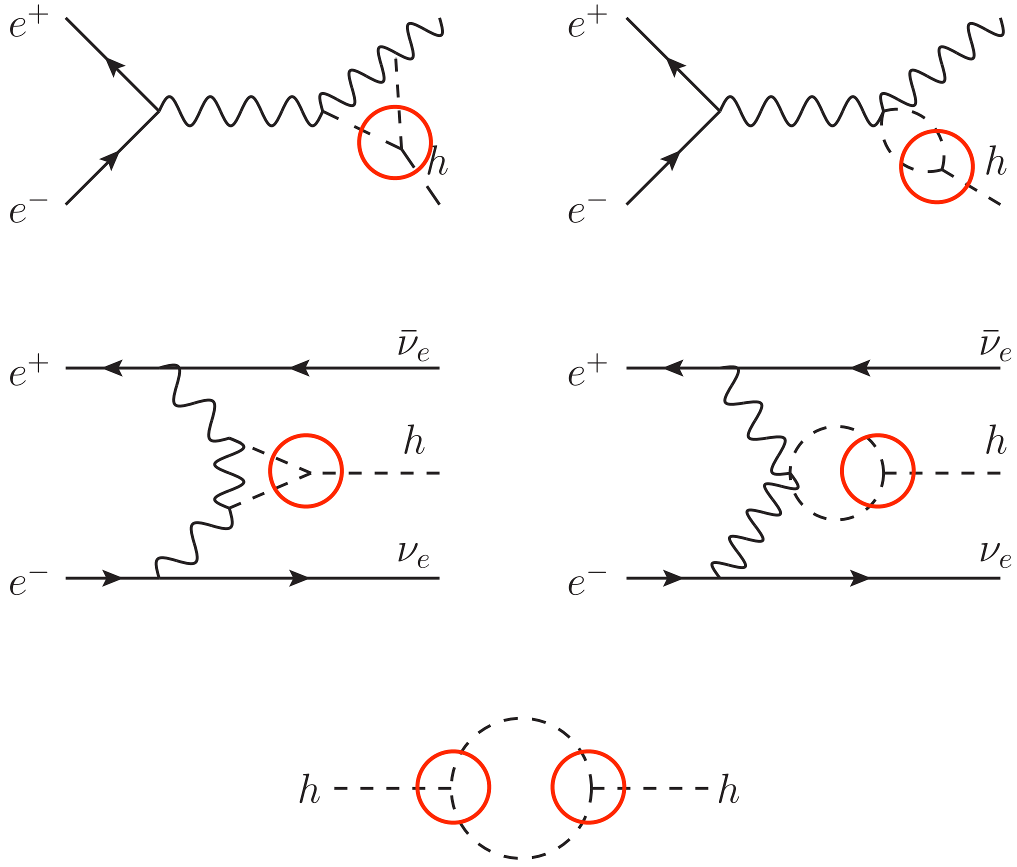
- ‣ Stage 2 fit is affected at the 10-20% level (especially the upper bound on $\delta\kappa_\lambda$)
- ‣ Stage 3 fit is nearly unchanged (modifications < 10%)

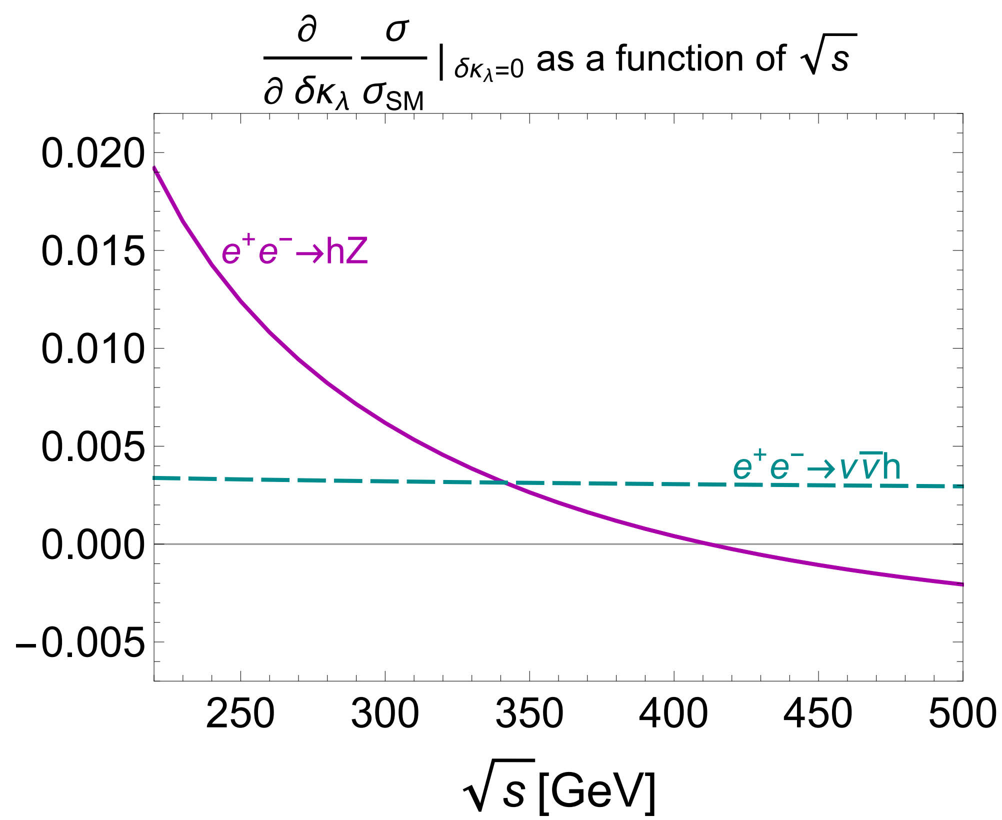
Higgs trilinear at CLIC Stage 1

Self-Interaction from Single Higgs

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

[McCullough '13]

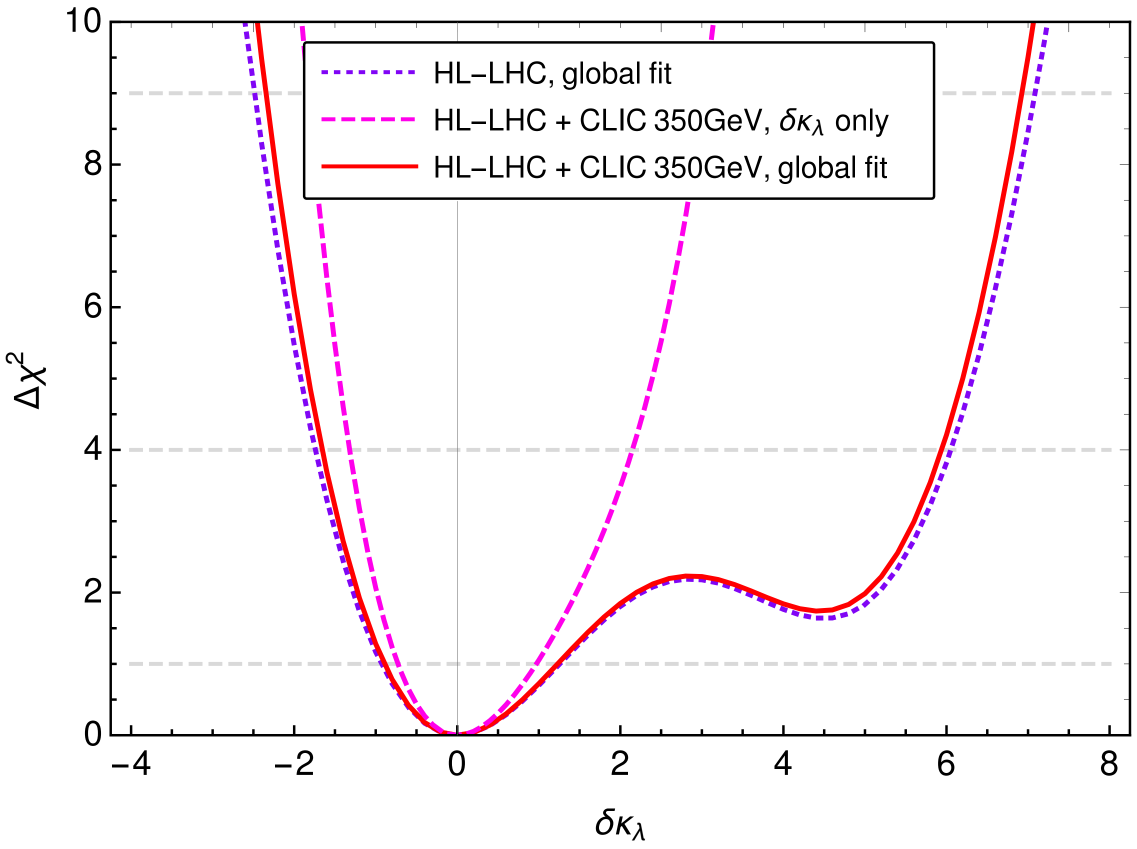




Good sensitivity at low energy in HZ (and $\nu\bar{\nu}H$) channels

Higgs trilinear at CLIC stage 1

✦ exclusive analysis can surpass HL-LHC sensitivity



Higgs trilinear at CLIC stage 1

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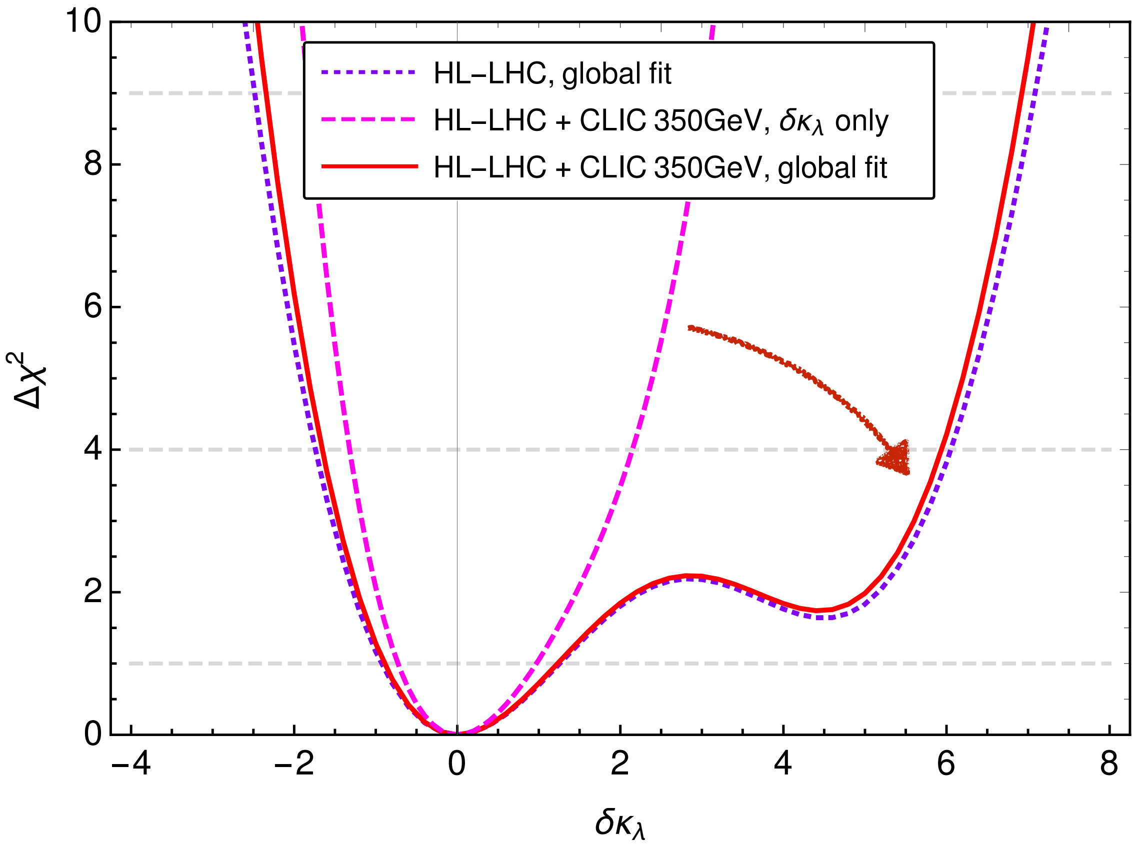


✦ but a global fit spoils the sensitivity

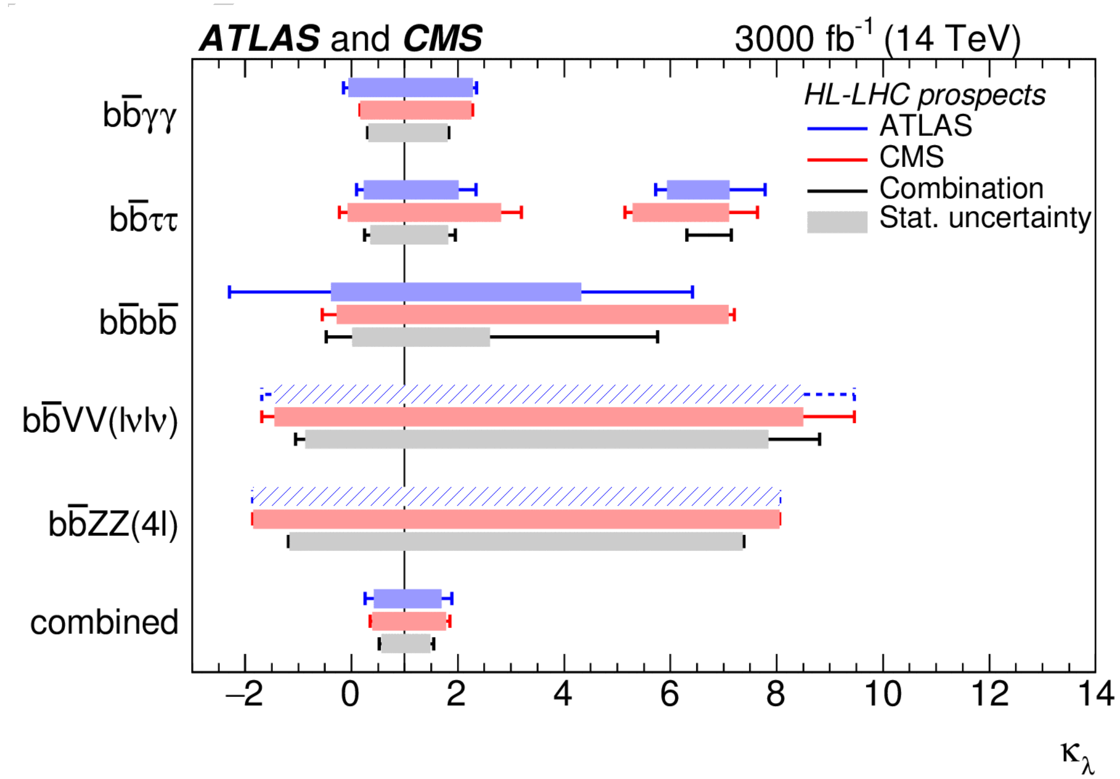
‣ strong correlation between $\delta\kappa_\lambda$ and modifications to the hZZ coupling

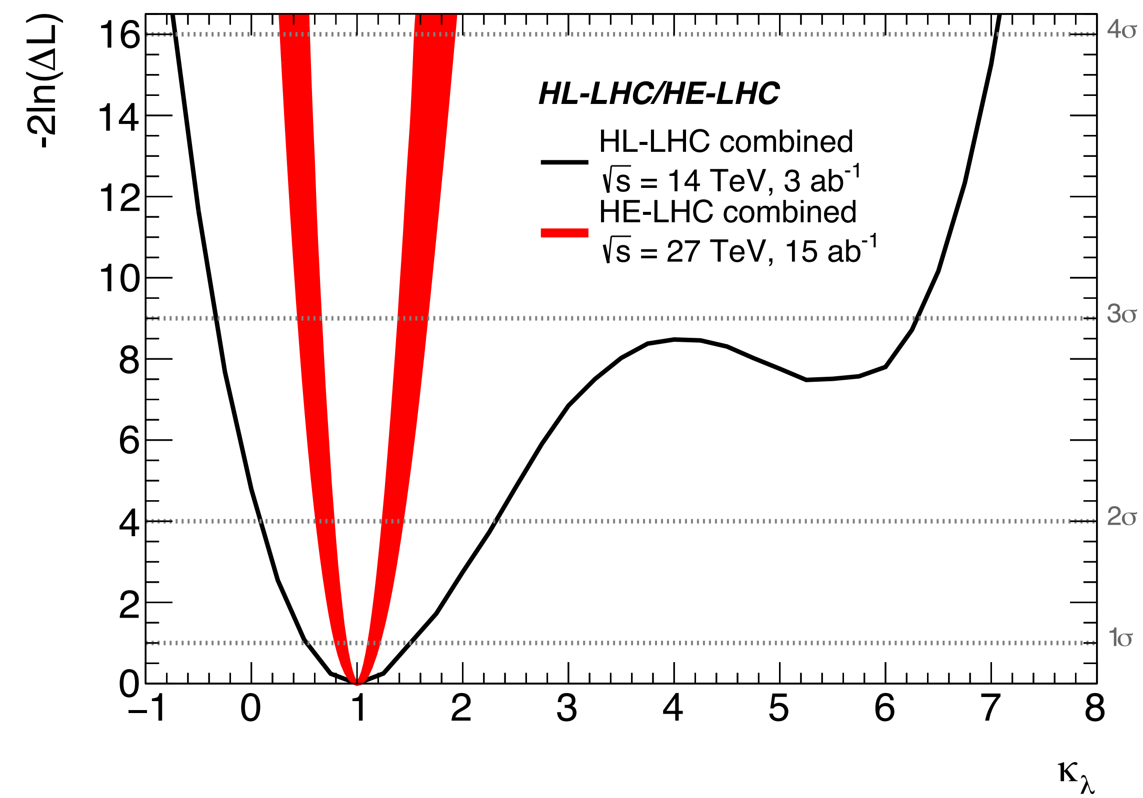
★ single Higgs channels basically insensitive to $\delta\kappa_\lambda$ at stage 2 and stage 3

Comparison with other colliders

HL and HE LHC

[Higgs Physics at the HL-LHC and HE-LHC report, to appear]



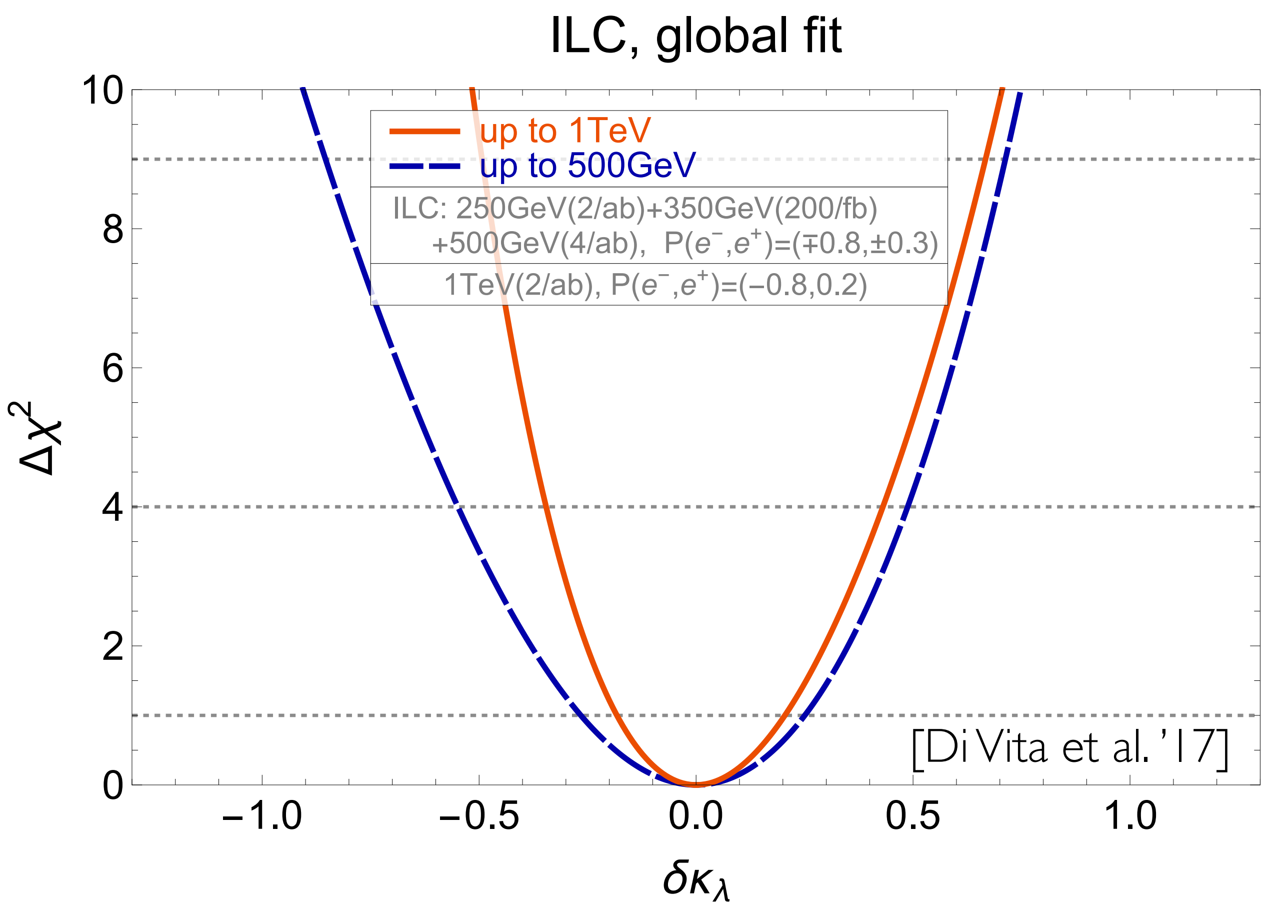


✦ HL-LHC can test the Higgs trilinear with O(50%) precision

$$-0.43 \leq \delta\kappa_\lambda \leq 0.5 \qquad \text{at} \quad 68\% \quad \text{C.L.}$$

✦ HE-LHC could test the Higgs trilinear with O(15-30%) precision
(projections vary significantly between different analyses)

ILC



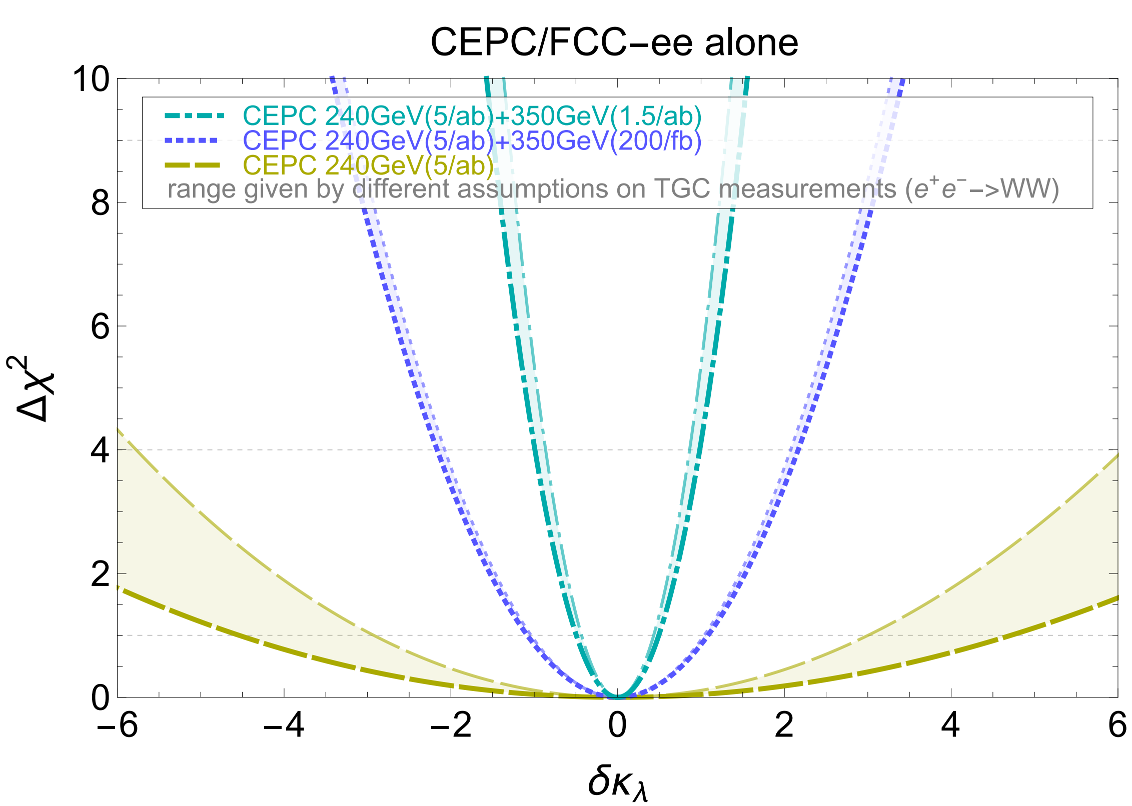
✦ ILC could test the Higgs trilinear with O(20%) precision

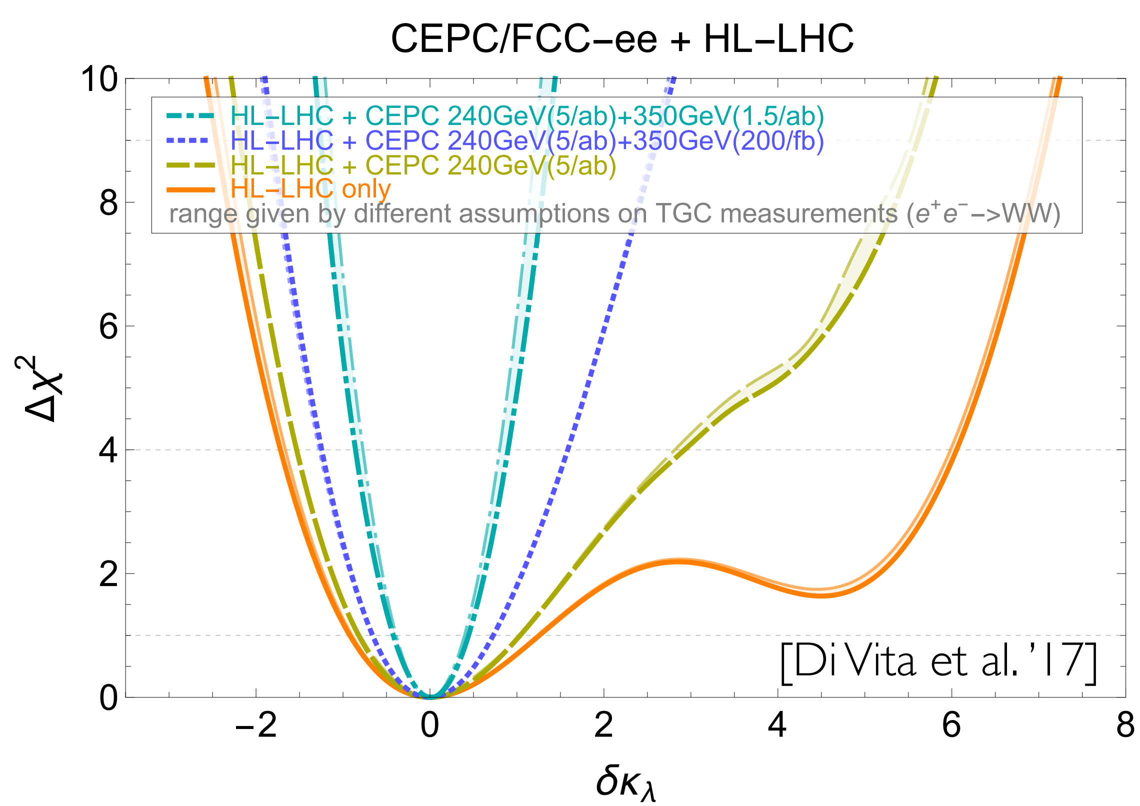
	68 %CL	95%CL
ILC up to 500 GeV	$[-0.27,\ 0.25]$	$[-0.55,\ 0.49]$
ILC up to 1 TeV	$[-0.18,\ 0.20]$	$[-0.35,\ 0.43]$

Low-energy Lepton Colliders

Single-Higgs channels can test the Higgs self-coupling provided that runs at different energies are performed (eg. 240 GeV and 350 GeV)

- combination of runs remove blind direction in the fit
- precision of order 30-40%





FCC-hh

Exclusive fit on $\delta\kappa_\lambda$

$\delta\kappa_\lambda$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

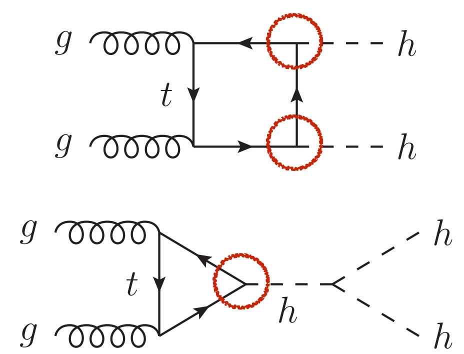
theory error: uncertainty on signal rate

$$\Delta_S = \frac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$$

overall rescaling of bkg rate $n_B \to r_B \times n_B$

[Contino et al. Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies '16]

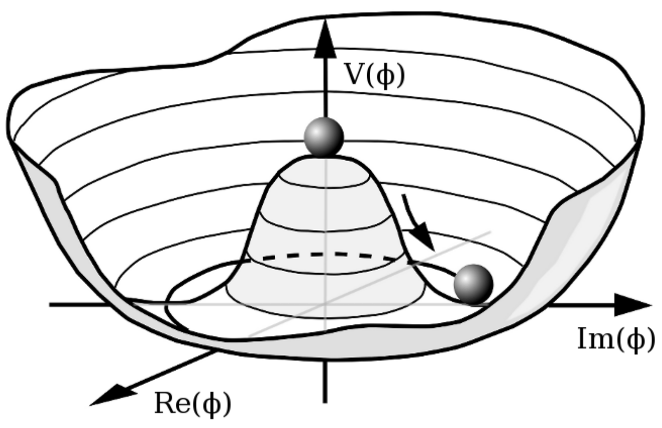
- precision likely to be limited by systematics
  (theory systematics dominant for $\Delta_S \gtrsim 2.5\%$, leading to $\delta\kappa_\lambda \simeq 2\Delta_S$)
- ultimate FCC-hh reach in the 4 - 6 % range
- global fit could significantly affect the prediction
  (strong dependence on top Yukawa coupling)



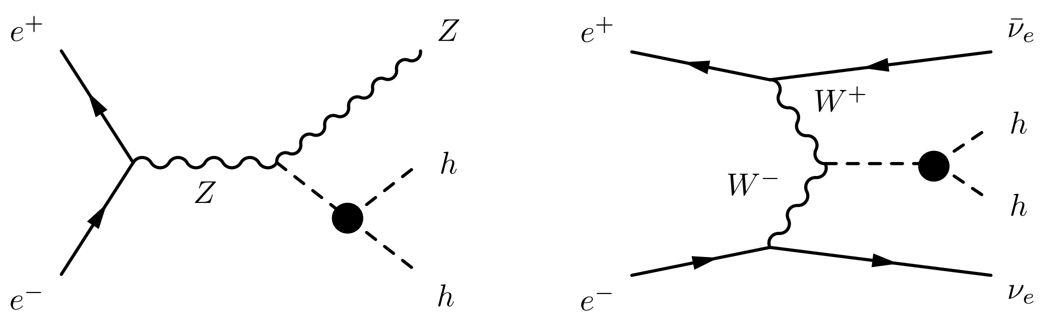
Theoretical implications

Theoretical implications

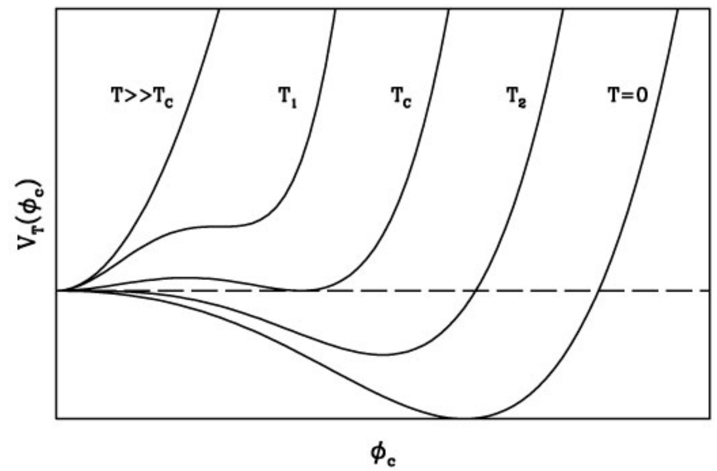
- Direct test of the structure of the Higgs potential
  (so far only Higgs mass term tested directly, but no interaction)



- Test of New-Physics models



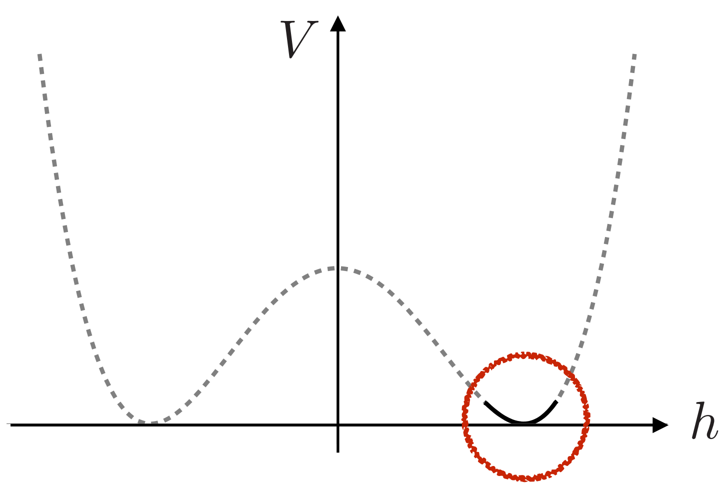
- Determine properties of EW phase transition
  (possible connection to cosmology, in particular baryogenesis)



Testing the Higgs potential

- Current measurements only tested locally the minimum of the Higgs potential
  (Higgs mass and VEV, i.e. quadratic approximation of the potential)

$$V(H) = \lambda_4 \left(|H|^2 - v^2\right)^2$$



- Directly measuring the Higgs self-interactions gives us direct evidence of the full structure of the Higgs potential

Deviations in Higgs couplings

Deviations in Higgs couplings are often present in BSM models

Generic new physics tends to give deviations of the same size in many Higgs interactions

eg. **minimal composite Higgs** models (SILH counting) $\xi = \frac{v^2}{f^2} \ll 1$

$$\mathcal{O}_H \sim \frac{1}{f^2}(\partial_\mu |H|^2)^2 \longrightarrow \kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \xi$$

$$\mathcal{O}_6 \sim \frac{\lambda_4}{f^2}|H|^6 \longrightarrow \kappa_\lambda \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \xi$$

$$\longrightarrow \delta\kappa_V \sim \delta\kappa_\lambda$$

- easier to test in single Higgs couplings

Deviations in Higgs couplings

Specific classes of models can however have enhanced deviations in Higgs self couplings

eg. **Higgs portal** models

new scalar singlet coupled to the Higgs

$$\mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_* \varphi / m_*)$$

g_* typical coupling

m_* mass scale of the singlet

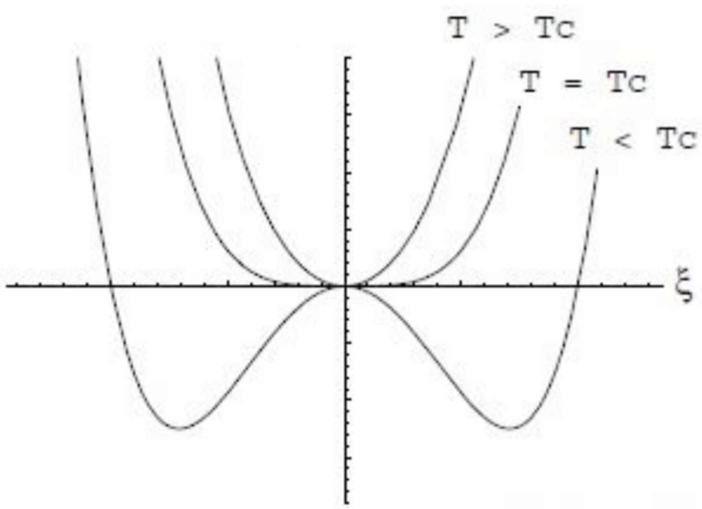
$$\delta\kappa_\lambda \sim \frac{\theta g_*^2}{\lambda_3^{\rm SM}} \theta^2 g_*^2 \frac{v^2}{m_*^2} \quad \gg \quad \delta\kappa_V \sim \theta^2 g_*^2 \frac{v^2}{m_*^2}$$

- deviations in Higgs self couplings can be much larger than deviations in single Higgs couplings

$$\theta \simeq 1 \quad g_* \simeq 3 \quad m_* \simeq 20\,\mathrm{TeV} \quad \longrightarrow \quad \delta\kappa_\lambda \sim 0.1 \quad \gg \quad \delta\kappa_V \sim 1.3 \times 10^{-3}$$

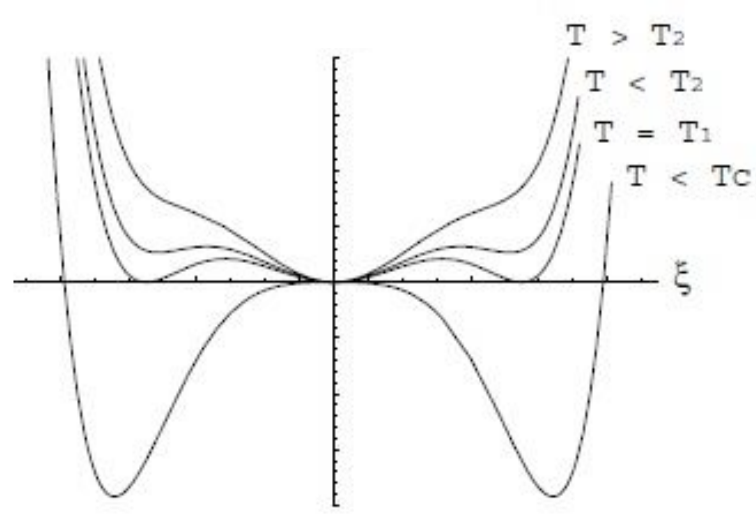
EW phase transition and baryogenesis

✦ The EW phase transition in the SM is very weak (actually a cross over for $m_h \gtrsim 80\,\mathrm{GeV}$)



- not suitable for baryogenesys which requires strong first order transition

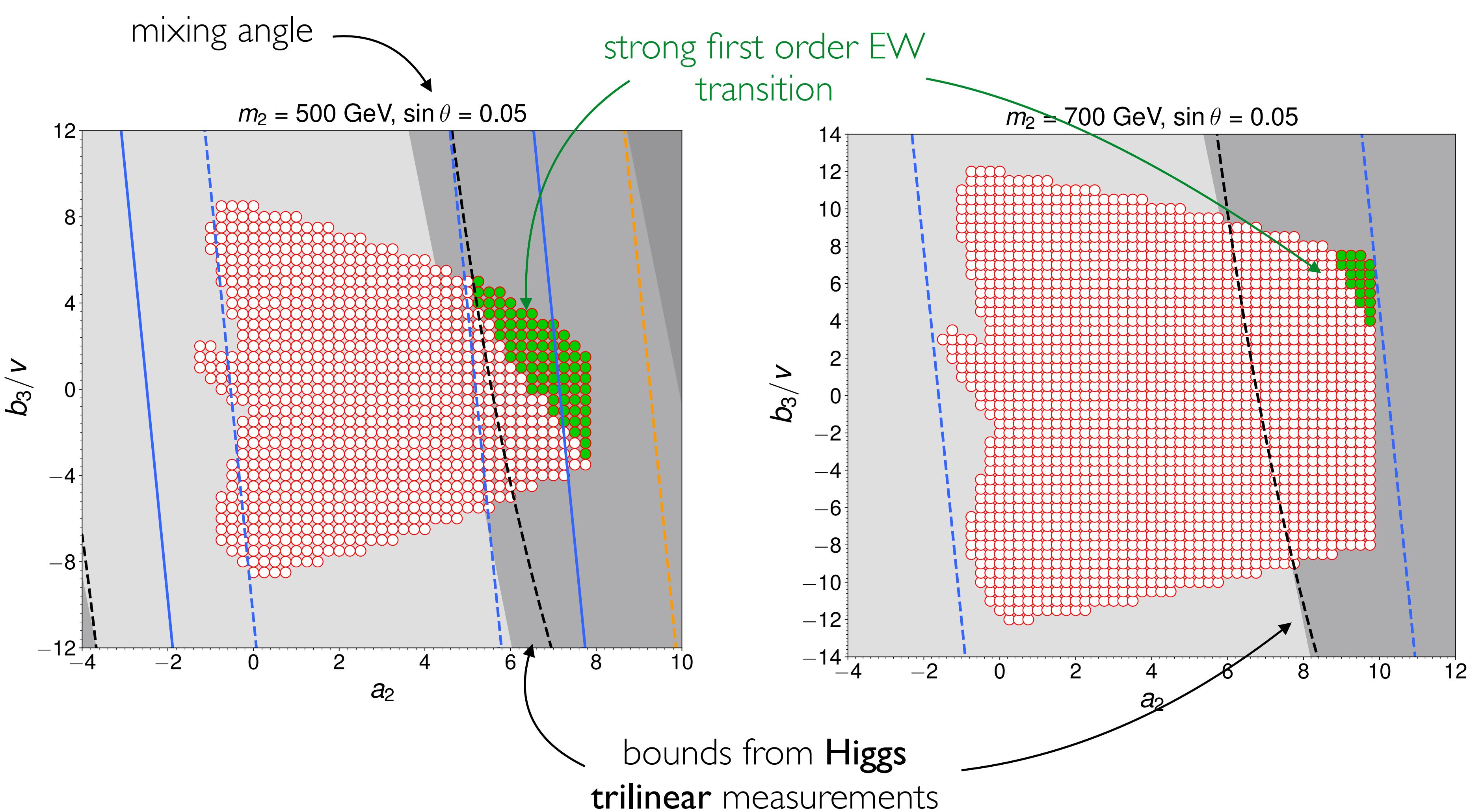
✦ a sizable modification of the Higgs self-couplings can turn the EW transition into strong first-order suitable for baryogenesis



Models for baryogenesis

Viable models for EW baryogenesis can be constructed by enlarging the Higgs sector with an extra (heavy) singlet

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - a_S S|H|^2 - \frac{1}{2}\lambda_{HS} S^2|H|^2 - V_S(S)$$



- grey regions tested by **single-Higgs coupling** measurements (stage I, II and III)
- blue (orange) lines from **resonant di-Higgs production** at 3 TeV (1.4 TeV)

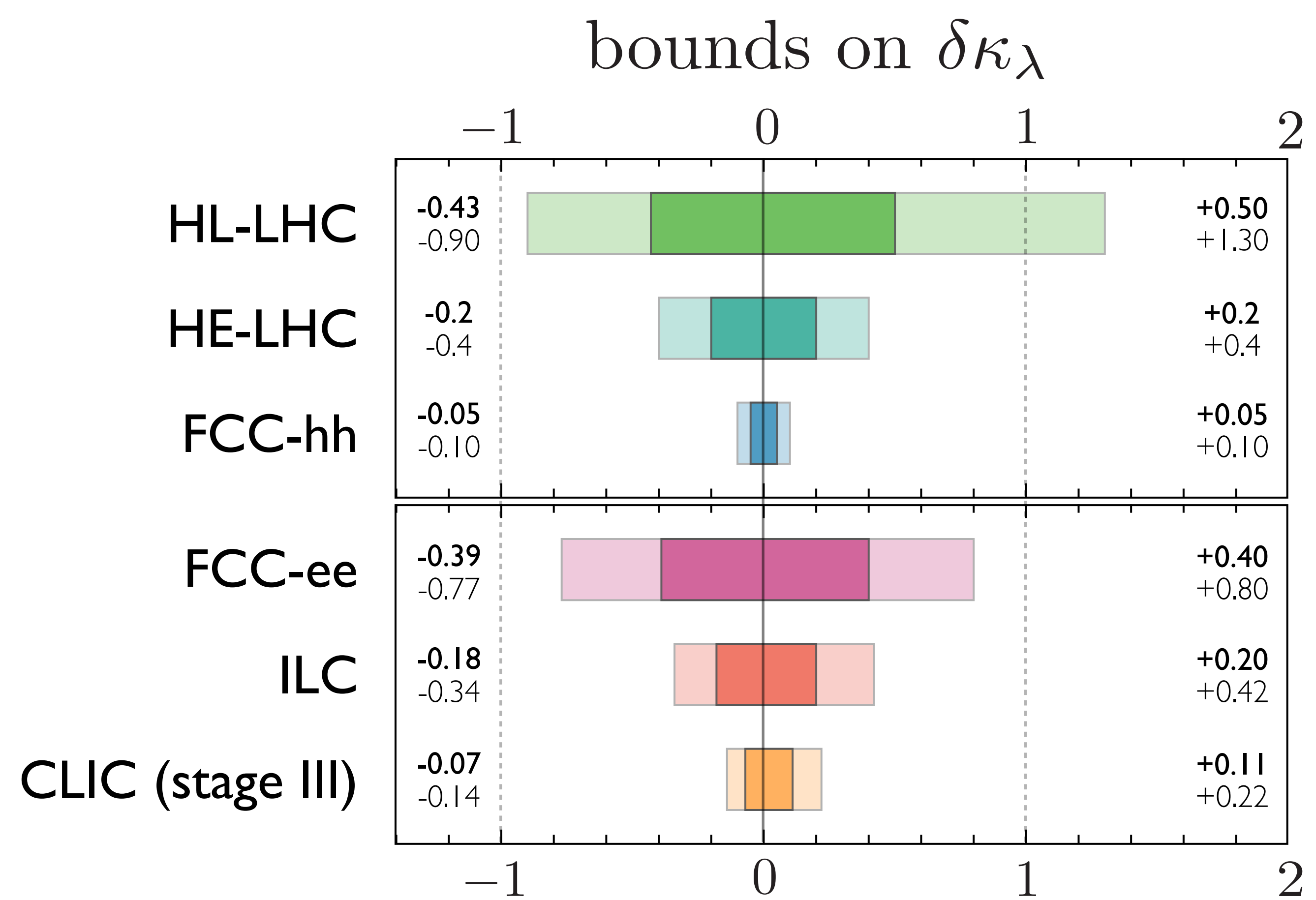
‣ Higgs trilinear measurements complementary to single-Higgs

Conclusions

Conclusions

CLIC allows to measure the **Higgs trilinear self-coupling**

- VBF and DHS main channels at stage II and stage III
  (possible exploitation of differential distribution in VBF)
- first precision determination (only O(50%) possible at HL-LHC)
- ultimate CLIC precision **~10%** at 68% CL
- only FCC-hh can compete in sensitivity



Conclusions

Higgs self-coupling measurement has several important theoretical implications

- Direct test of the structure of the **Higgs potential**
- Test of **New-Physics** scenarios (eg. Higgs portal models)
- Determination of the properties of the **EW phase transition**