Higgs Physics Beyond the LHC Era

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Fundamental physics at colliders

The main goal of the collider program is to deepen our knowledge of fundamental physics

In practical terms, this means **testing the SM**

looking for its possible **failures** → evidence of **New Physics** (BSM)

Testing the SM

Complementarity

devising different strategies to test the SM predictions
and to cover different types of new physics

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The **Higgs** plays a major role in testing the SM
and looking for new physics

Higgs properties

Higgs "pole" measurements

- Mass, width
- Spin / CP properties
- Yukawas, couplings to gauge bosons

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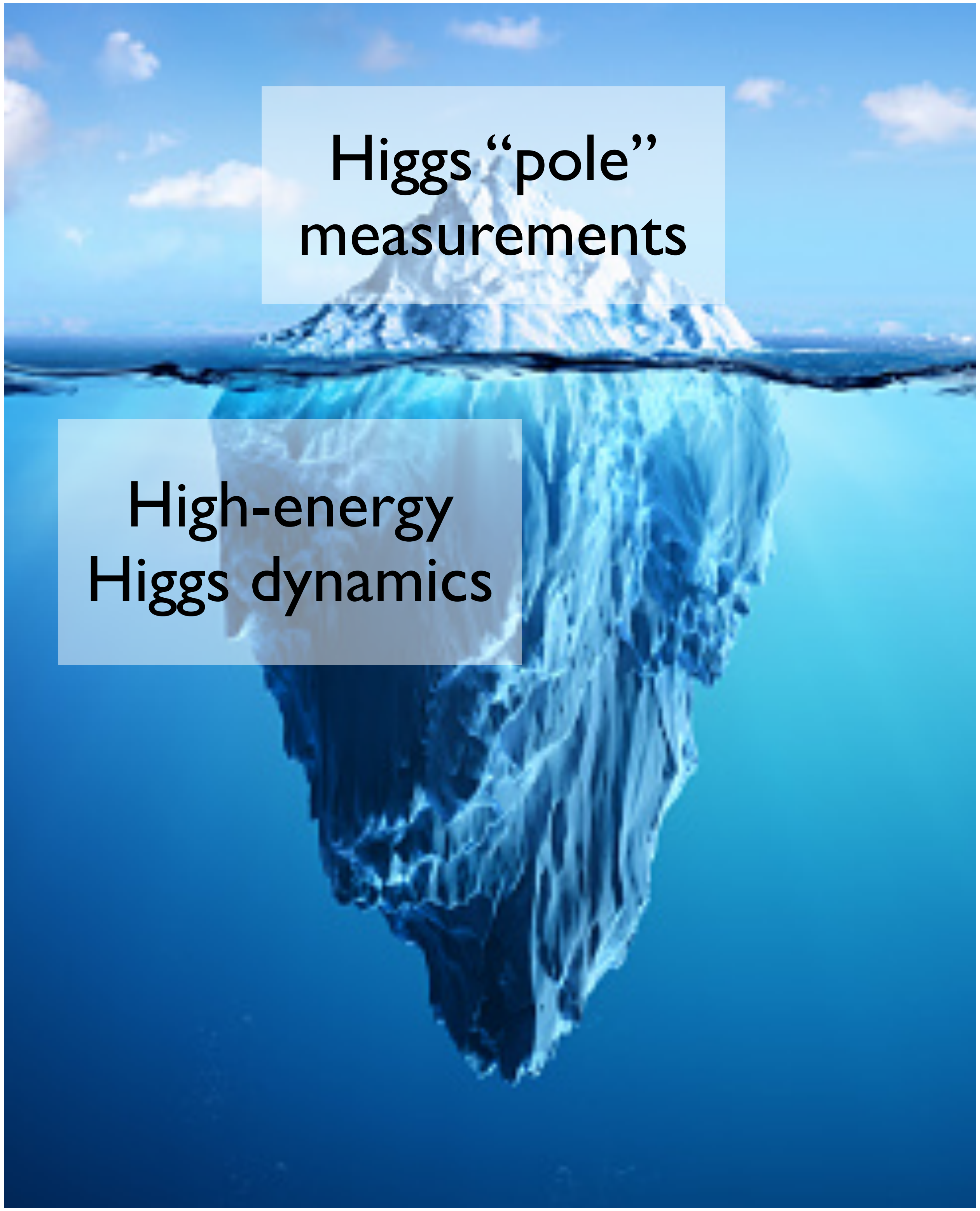
High-energy Higgs dynamics

- Restoration of EW symmetry / Goldstone equivalence theorem
- Non-linear couplings



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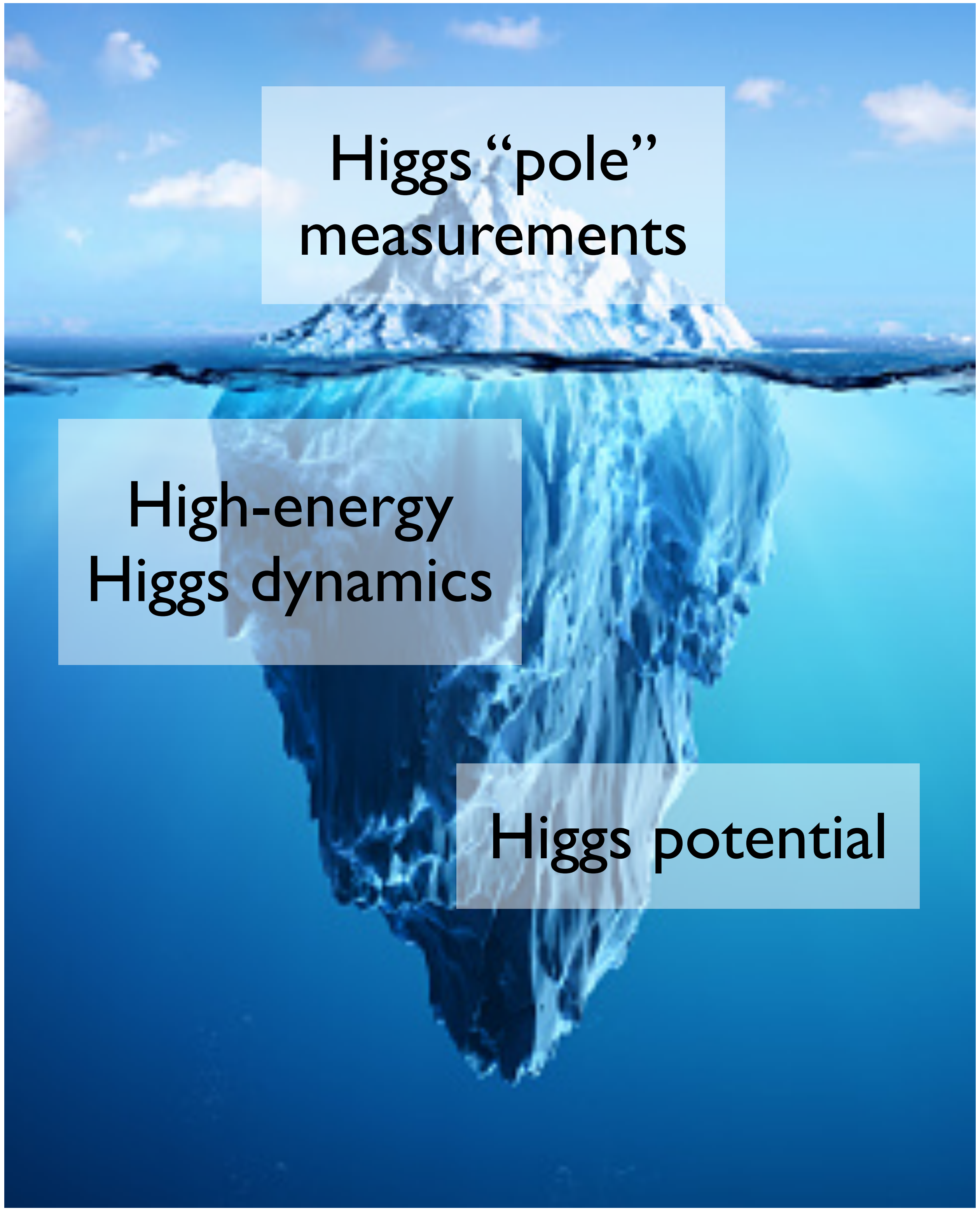
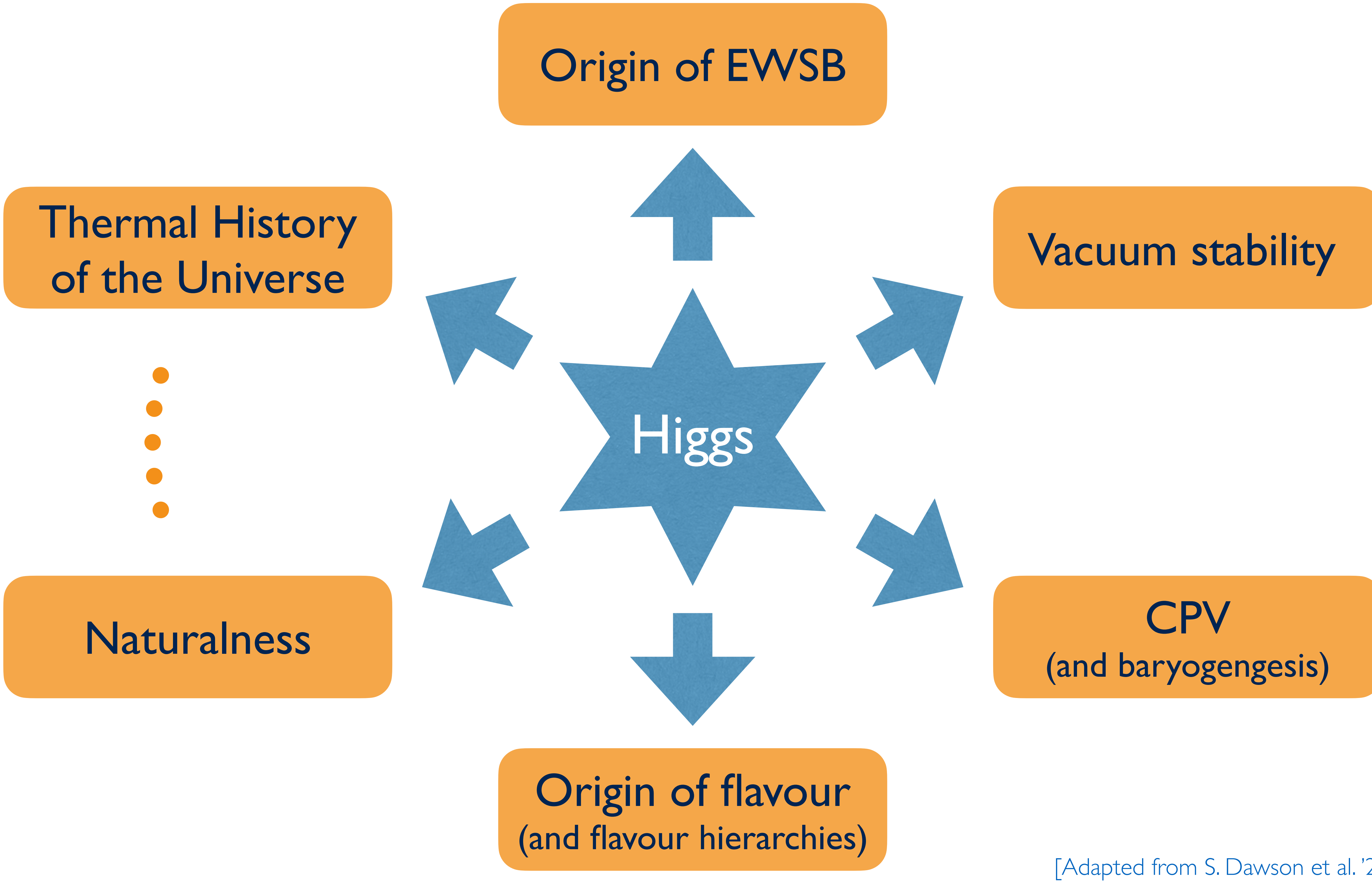
Higgs potential

- Higgs self-couplings



Relevance of Higgs properties

The Higgs is connected to the **most fundamental** aspects of the SM



[Adapted from S. Dawson et al. '22]

Relevance of Higgs couplings

EWSB

$$\mathcal{L} \supset D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 - y_{ij} \overline{\psi}_i \Phi \psi_j + \text{h.c.}$$

naturalness

vacuum stability

flavor structure and hierarchies, CP violation

How to describe new physics?

Various approaches can be used to describe the effect of new physics on the Higgs dynamics

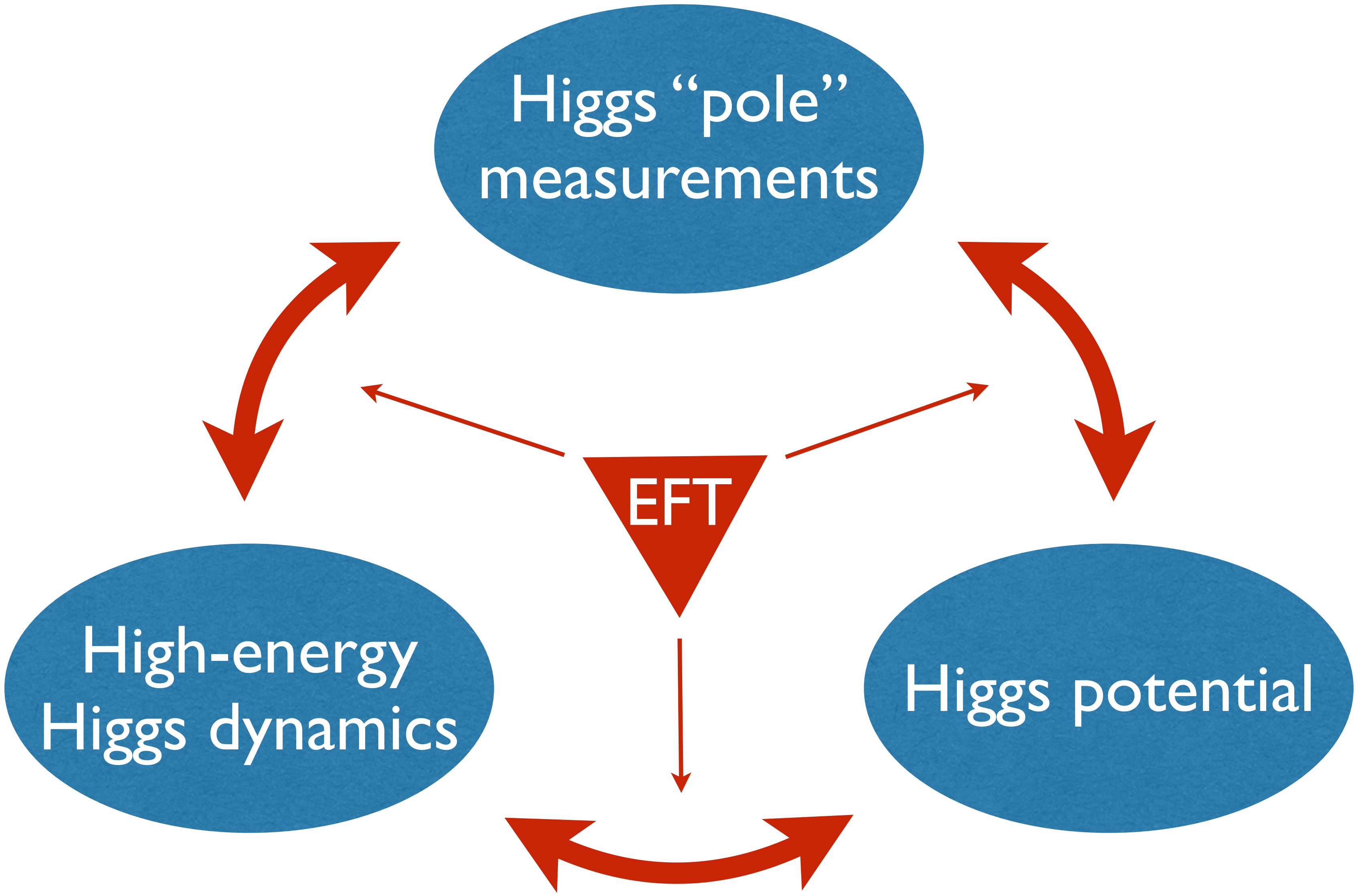
- ✦ Deviations in single couplings
  (i.e. κ -framework)
- ✦ EFT parametrization
- ✦ Explicit new-physics models
  (eg. Higgs portal models, extended Higgs sectors …)

↑ model independence

↓ stronger correlations

Correlations in Higgs couplings

The EFT approach (and also explicit new-physics models) predicts correlations between different Higgs couplings



Higgs “pole” measurements

Low-energy e⁺e⁻ colliders

Low-energy e⁺e⁻ colliders can test several Higgs "pole" properties

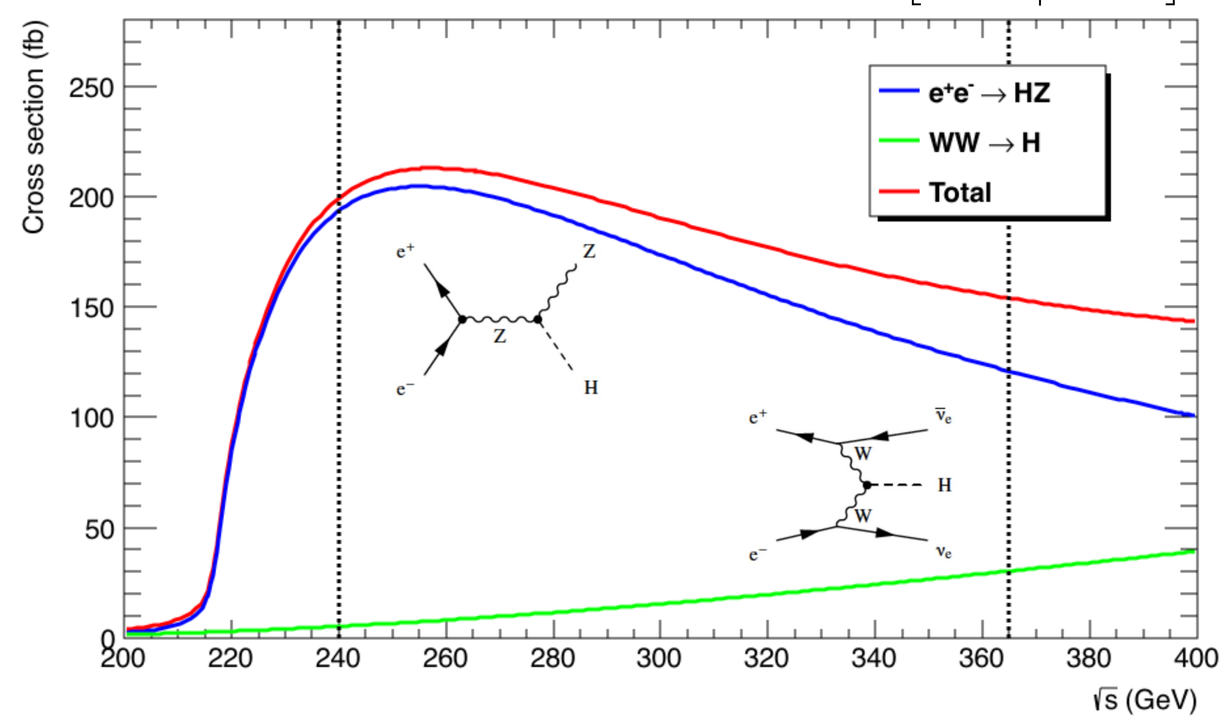
- determination of **absolute normalization of couplings** (via recoil method $HZ(\to \ell^+\ell^-)$)
- sensitivity to **invisible decays**
- measurement of Higgs **width**

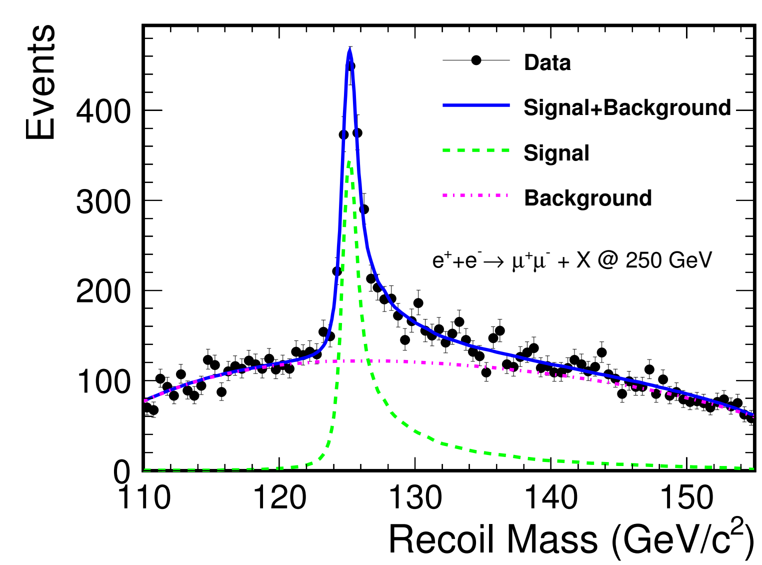
$$\delta\Gamma_H \sim 1\%$$

- measurement of Higgs **mass**

$$\delta m_H \sim 3\,\mathrm{MeV}$$

[FCC report '18]





Low-energy e^+e^- colliders

Higgs coupling sensitivity

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

[Table from mid-term report, from C. Grojean, Corfu '24]

- Model-independent measurement of linear Higgs couplings
- Significant improvement with respect to HL-LHC in

$$g^{eff}_{HZZ},\quad g^{eff}_{HWW},\quad g^{eff}_{Hgg},\quad g^{eff}_{Hbb},\quad g^{eff}_{Hcc},\quad g^{eff}_{H\tau\tau}$$

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- **Exception**: decay channels with low BR

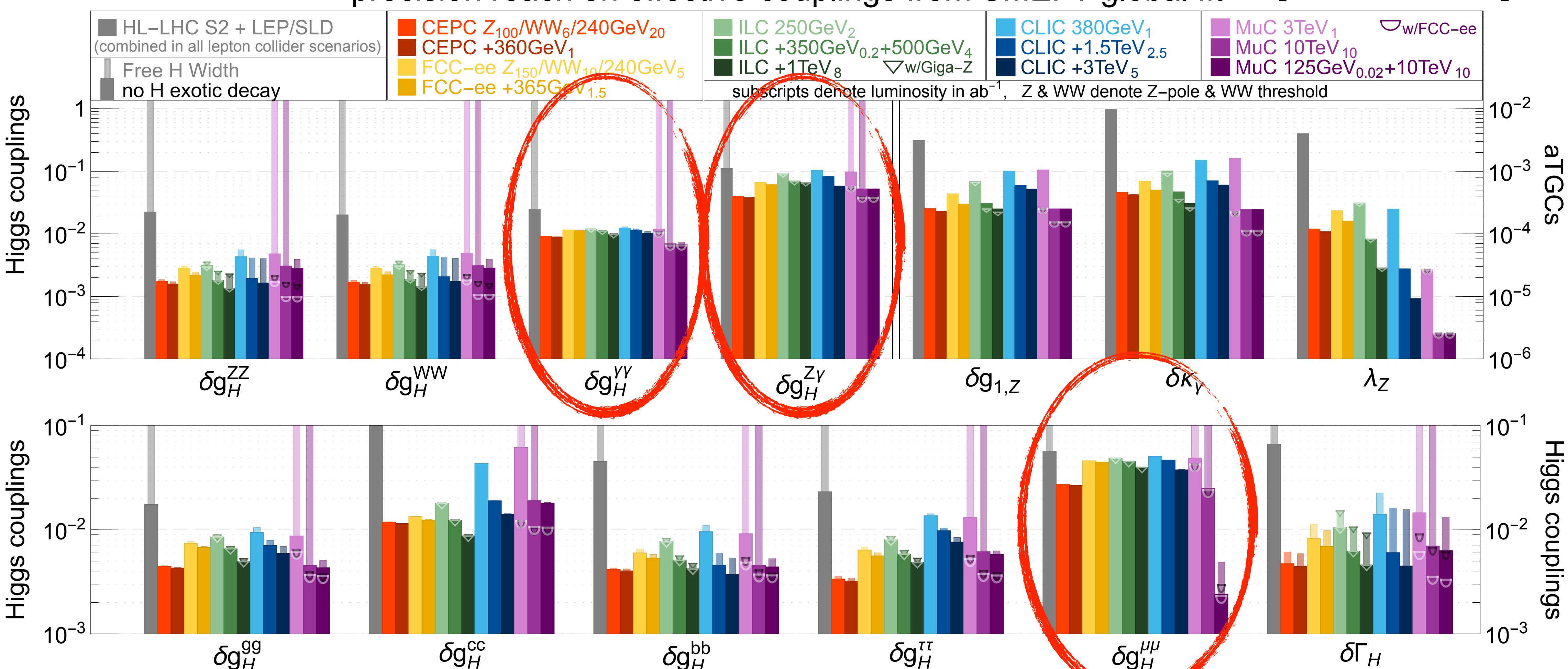
$$g^{eff}_{H\gamma\gamma},\quad g^{eff}_{H\mu\mu},\quad g^{eff}_{HZ\gamma}$$

Muon collider

A muon collider can improve the determination of some couplings

- improvement in $g^{eff}_{H\gamma\gamma}$ (and $g^{eff}_{HZ\gamma}$) with 10 TeV (and 125GeV) run
- improvement in $g^{eff}_{H\mu\mu}$ with 10 TeV run; excellent determination with 125GeV run

precision reach on effective couplings from SMEFT global fit [De Blas et al. '22]



High-energy hadron collider

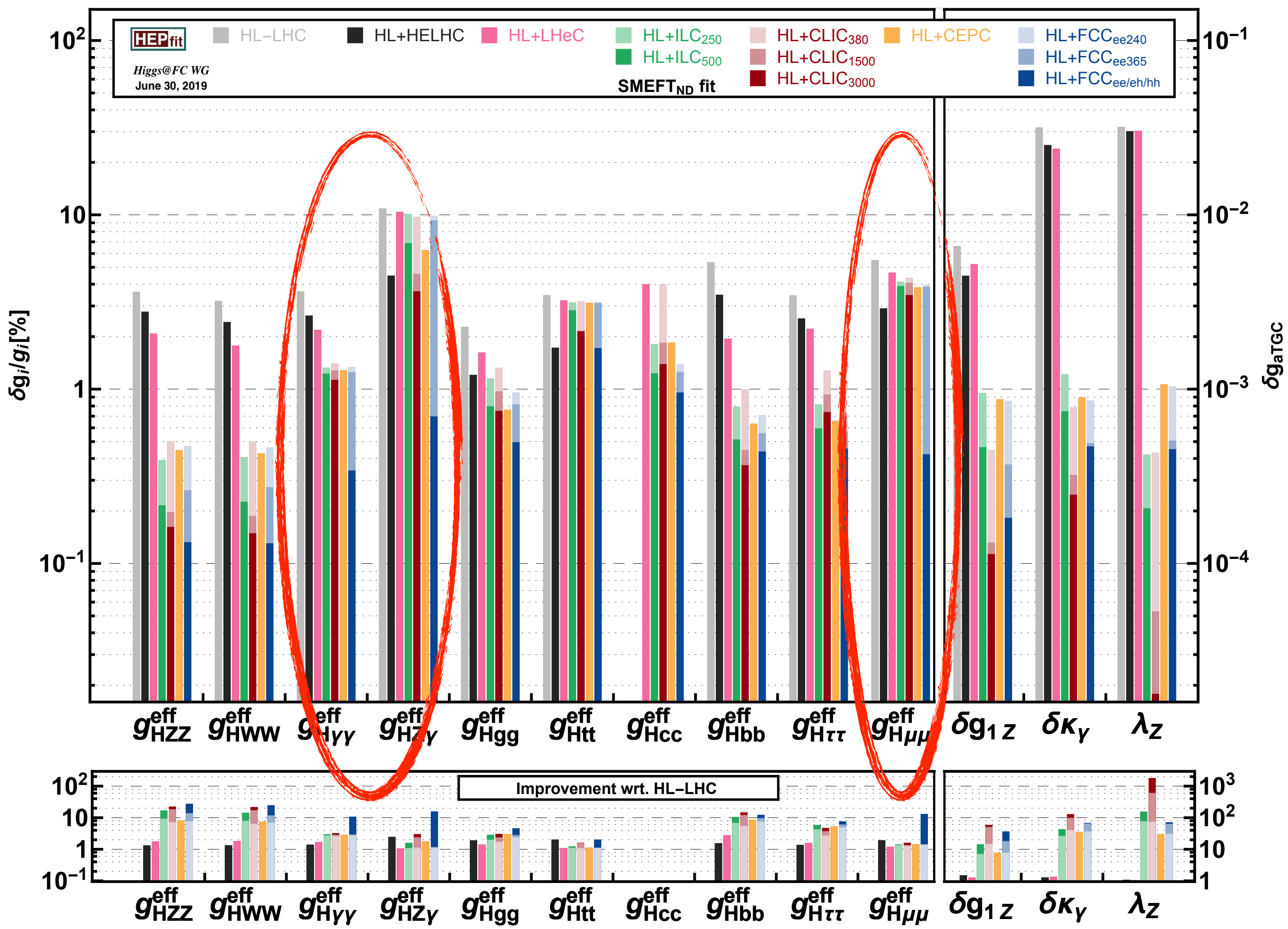
FCC-hh can test $g^{eff}_{H\gamma\gamma}, g^{eff}_{H\mu\mu}, g^{eff}_{HZ\gamma}$ with high precision

$g^{eff}_{H\gamma\gamma} \longrightarrow 0.4\%$

$g^{eff}_{H\mu\mu} \longrightarrow 0.7\%$

$g^{eff}_{HZ\gamma} \longrightarrow 0.9\%$

[De Blas et al. '22]



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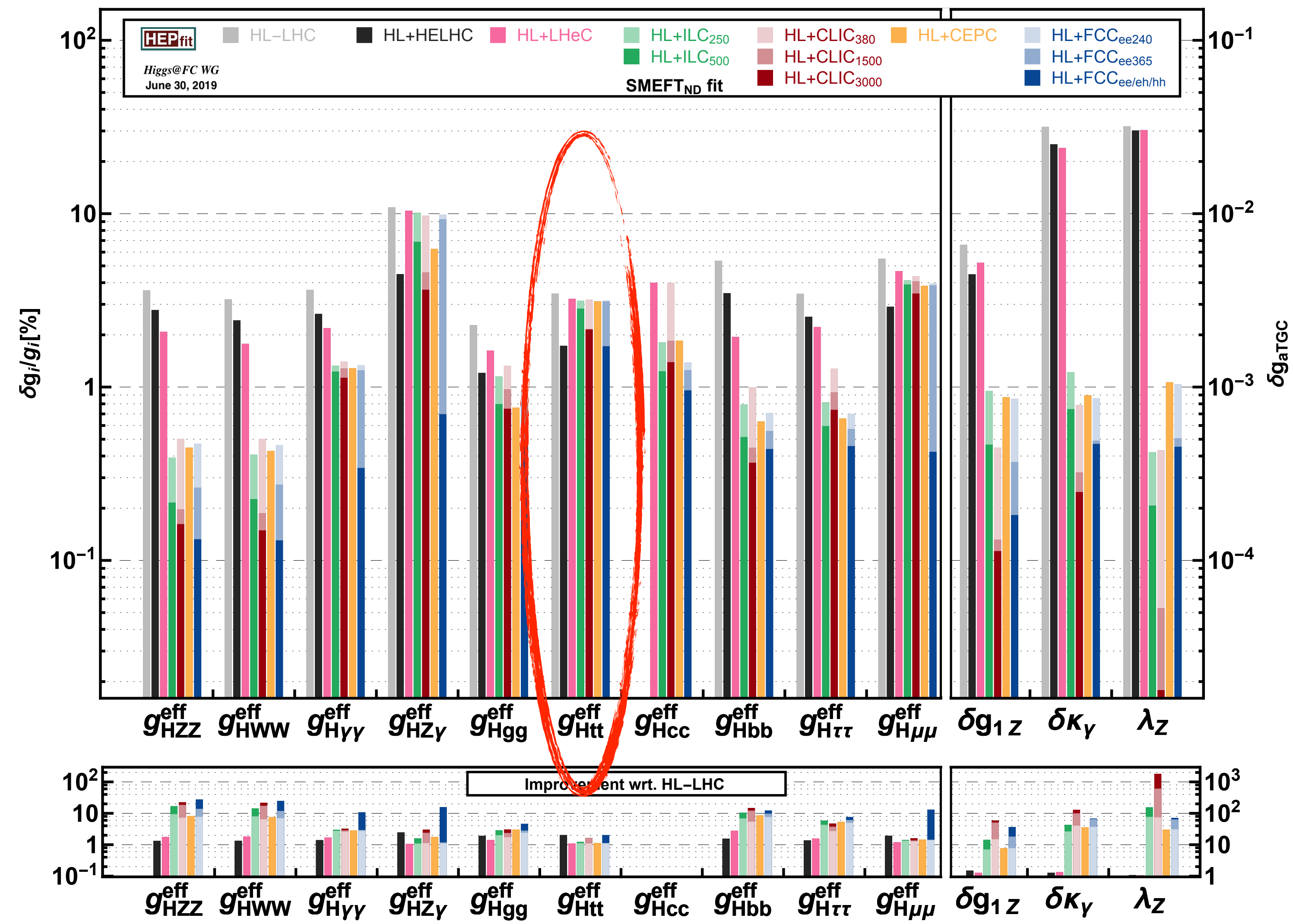
FCC-hh can improve the measurement of the top Yukawa

$$g^{eff}_{Htt} \longrightarrow 1\%$$

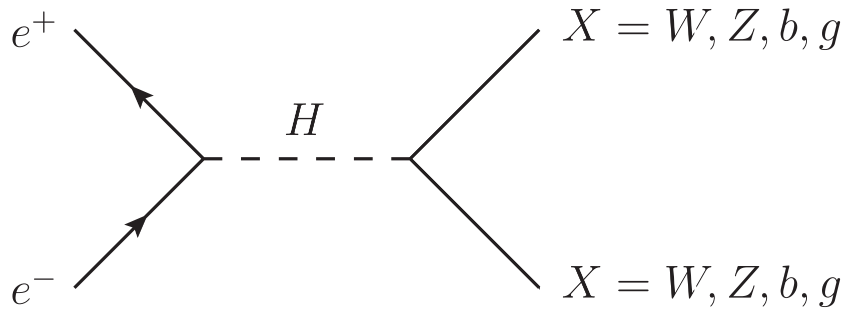
(improvement also possible at HE-LHC and CLIC 3TeV)

[De Blas et al. '22]

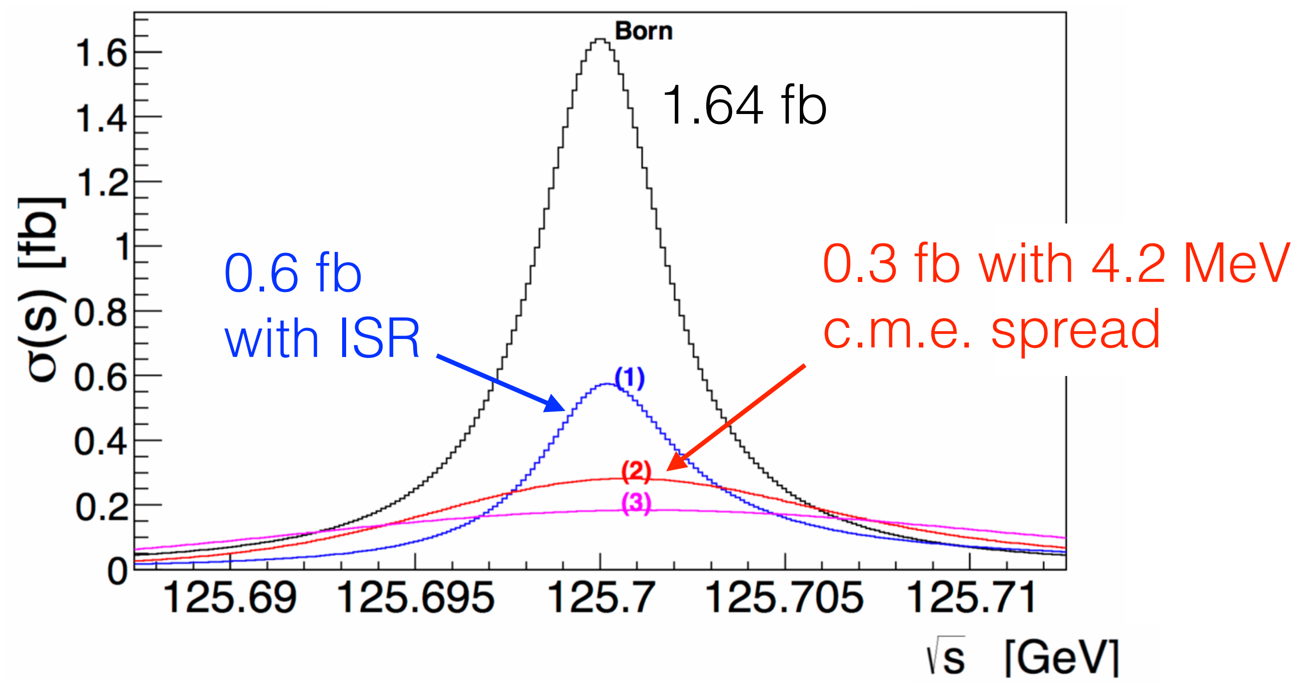


The electron Yukawa

Low-energy e^+e^- colliders could also access the **electron Yukawa** with a dedicated run at 125 GeV



[Jadach, Kycia '15]



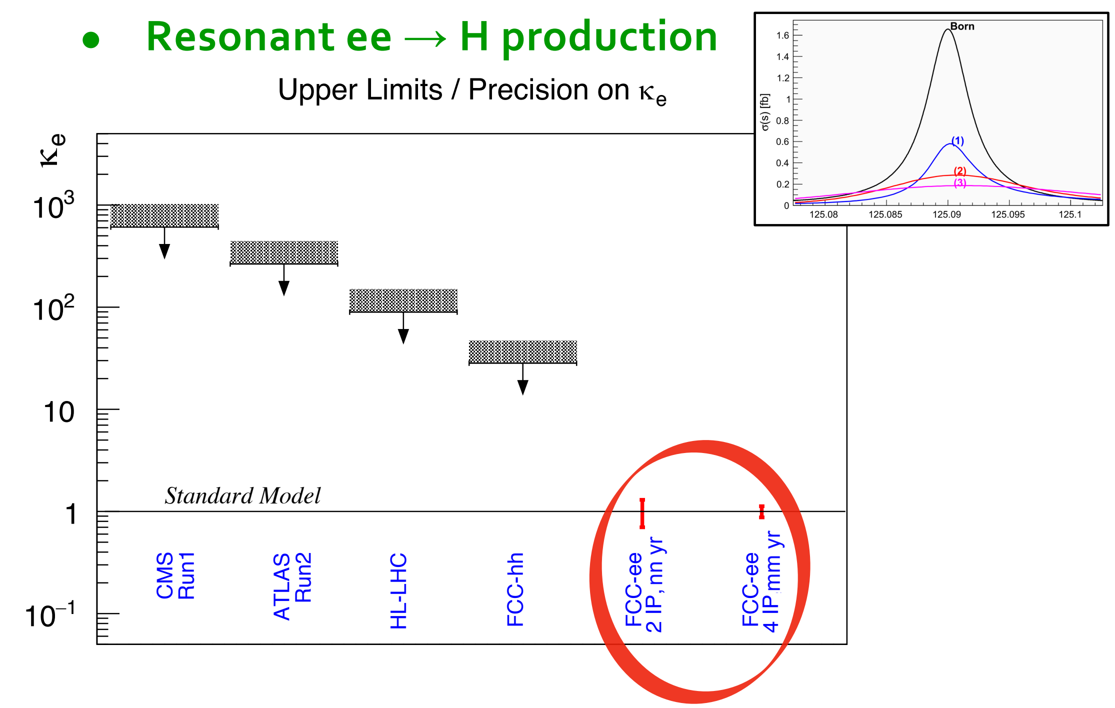
- peak cross section $\sigma \simeq 1.64\,\mathrm{fb}$
- significant reduction due to IRS and beam energy spread $\sigma \simeq 0.3\,\mathrm{fb}$

The electron Yukawa

Low-energy e^+e^- colliders could also access the **electron Yukawa** with a dedicated run at 125 GeV

- precision ~1-2σ could be reached with ~5 years of data

- **20 ab^{-1} / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim$ 1-2 × $\Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**



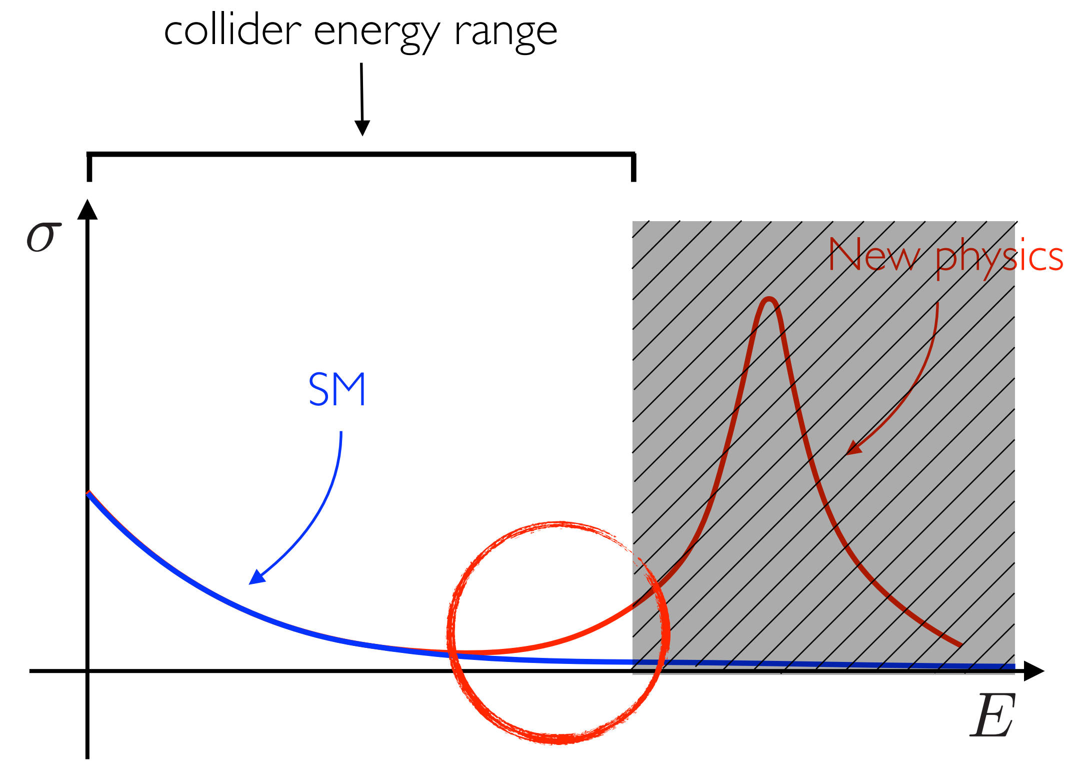
[from C. Grojean, Corfu '24]

High-energy Higgs dynamics

High-energy Higgs probes

Looking for the tail: Indirect searches

even if we can not directly produce
the new particles,
we can test their **indirect effects**



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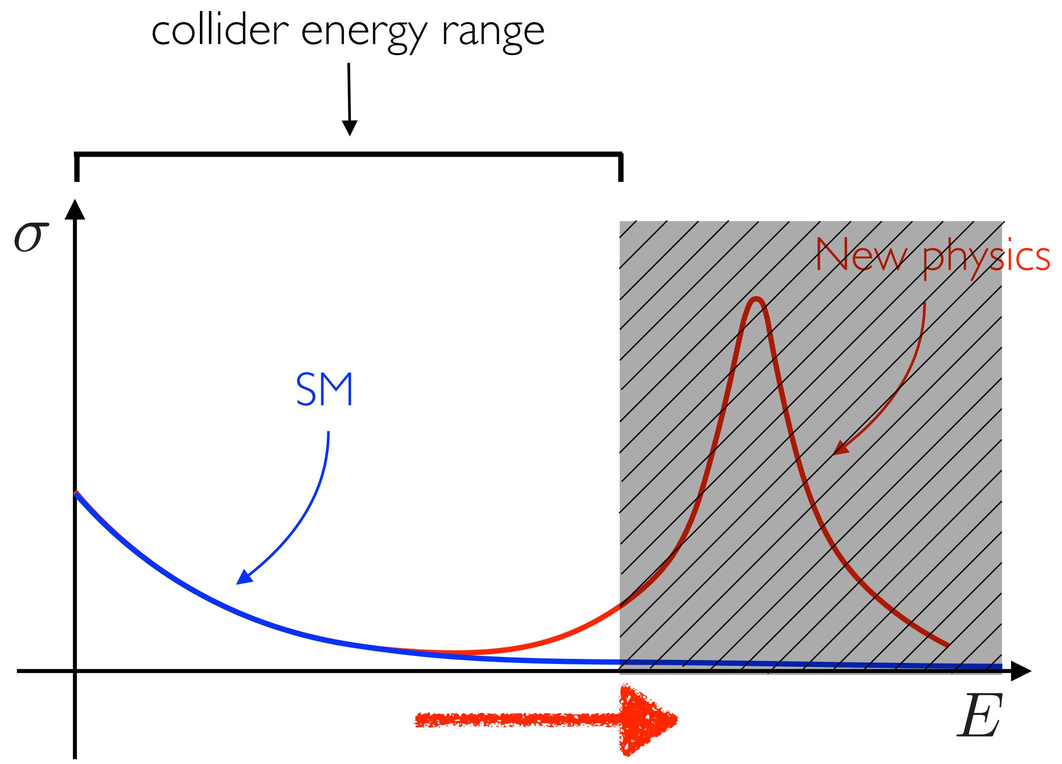
- new-physics effects tend to grow with energy
["energy helps accuracy", Farina et al. '16]



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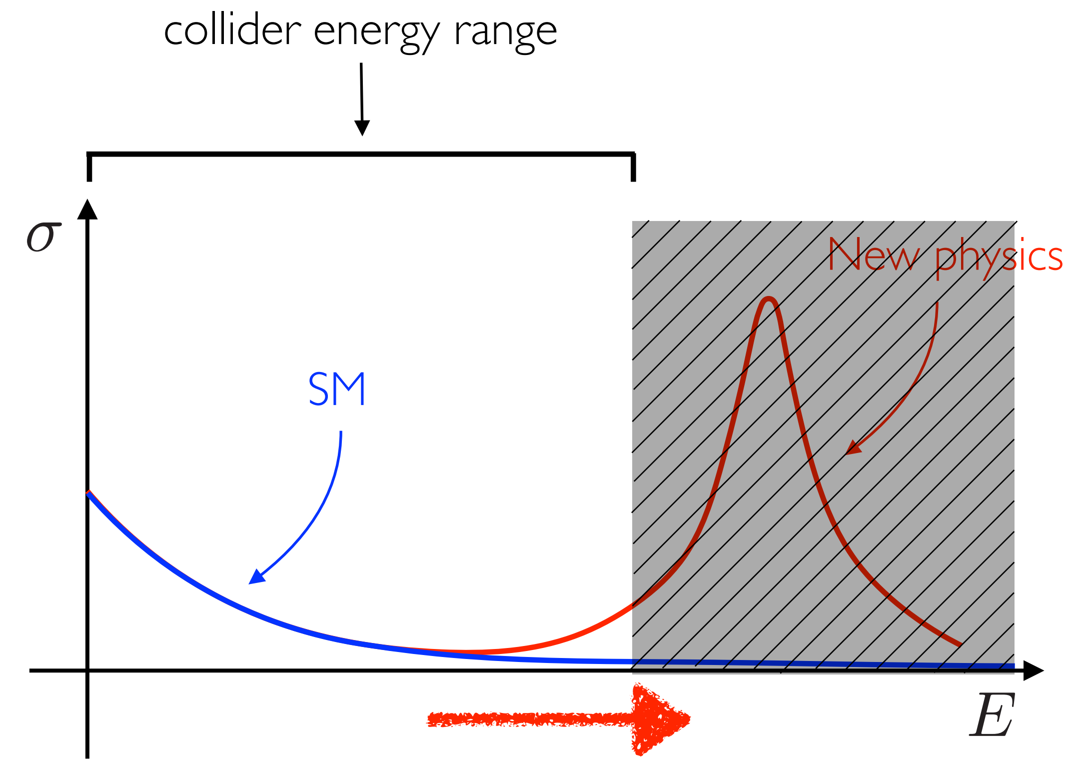


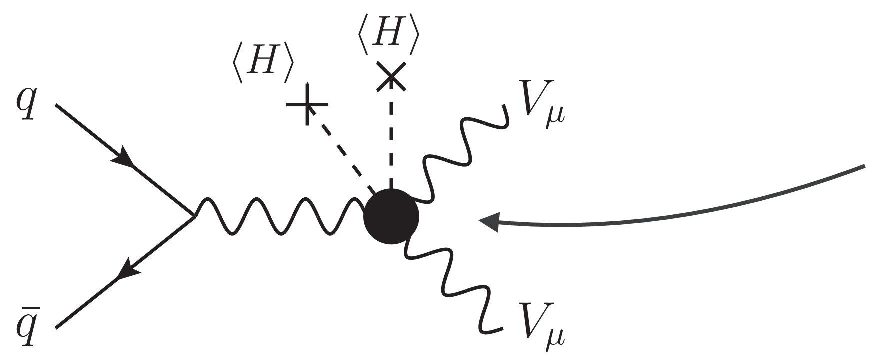
- new-physics effects tend to grow with energy
  [“energy helps accuracy”, Farina et al. ’16]

- deviations are “universal”
  - limited number of behaviors dictated by symmetry
  - can be parametrised by EFT
  - can test large set of BSM scenarios

Testing the Higgs dynamics

Di-boson production is a golden channel test
the high-energy Higgs dynamics

✦ can probe deviations in non-linear Higgs couplings



$$\mathcal{O}_W = (H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(D^\nu W_{\mu\nu})^i$$

$$\mathcal{O}_{HW} = (D_\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

Challenging analysis

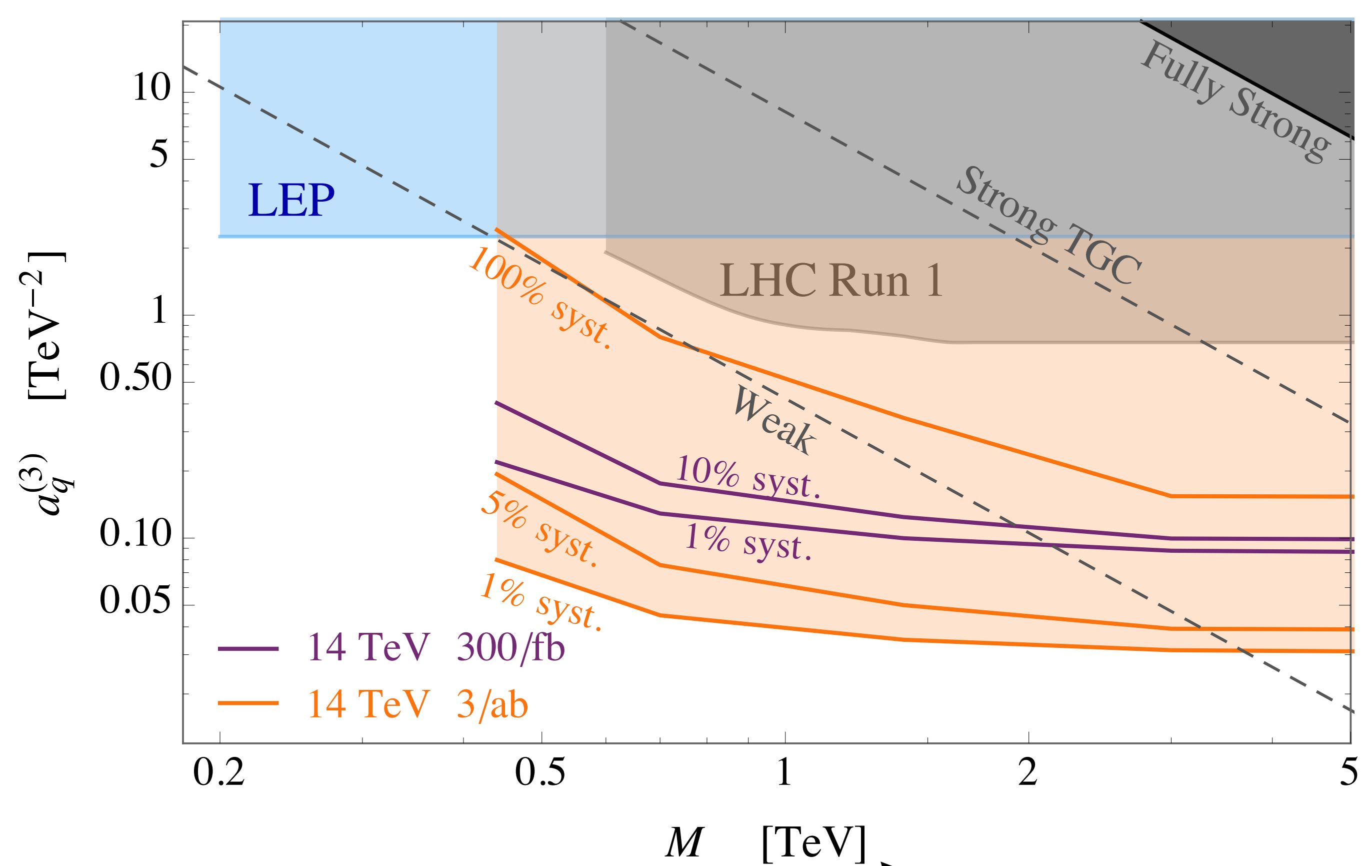
- energy-growing new physics effects confined to subleading helicity channels (longitudinal) (➔ **interference resurrection** via differential measurements)
- non-trivial complex final states

… but **very interesting** ➔ can be used to test a large set of BSM theories

WZ production: LHC

Estimate of the bounds on $a_q^{(3)}(\overline{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$

[Franceschini, GP, Pomarol, Riva, Wulzer '17]



~ mass of new states

- Non-trivial analysis: longitudinal channels small → exploit transverse zeroes
- Big improvement with respect to LEP

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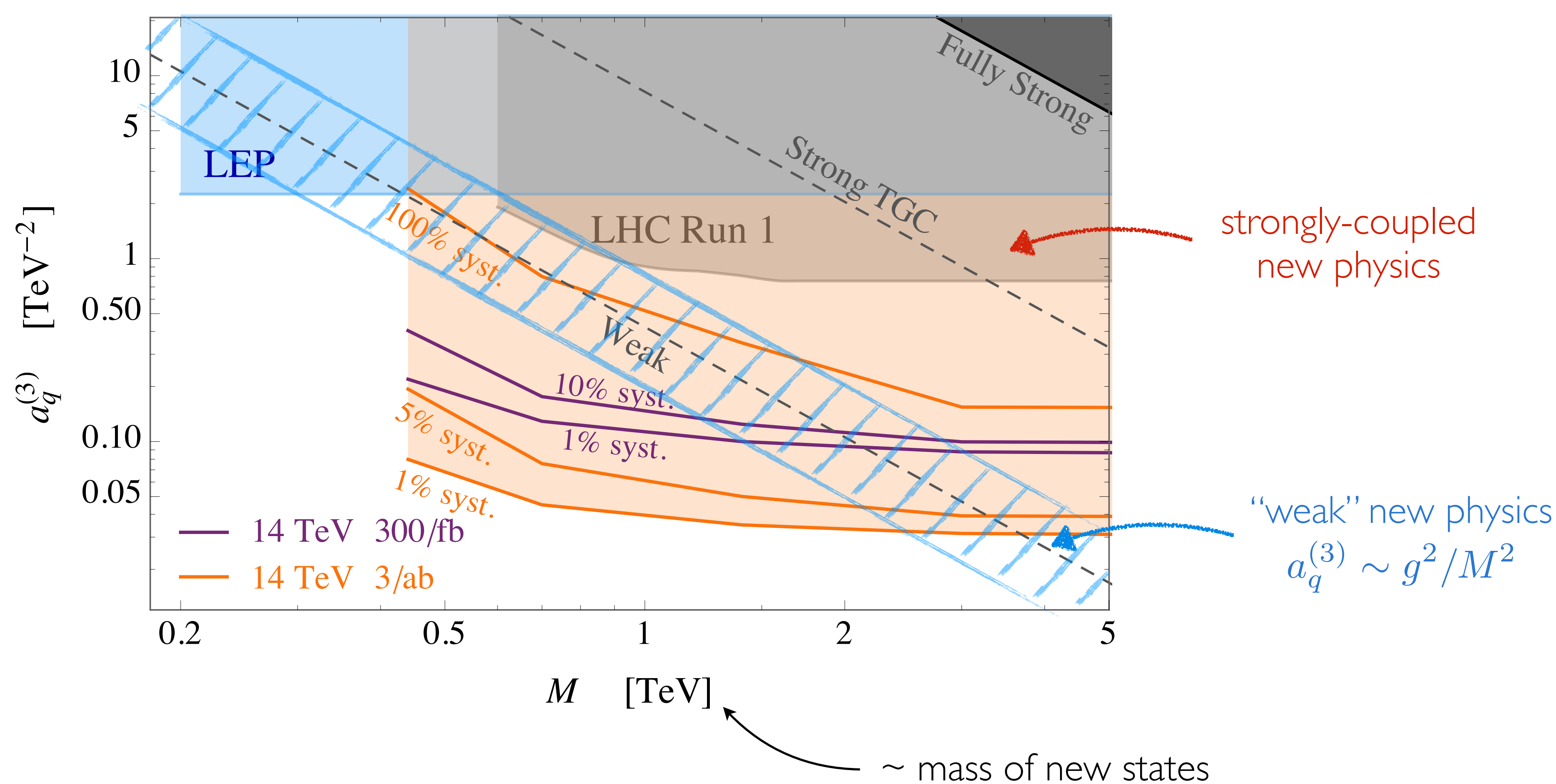
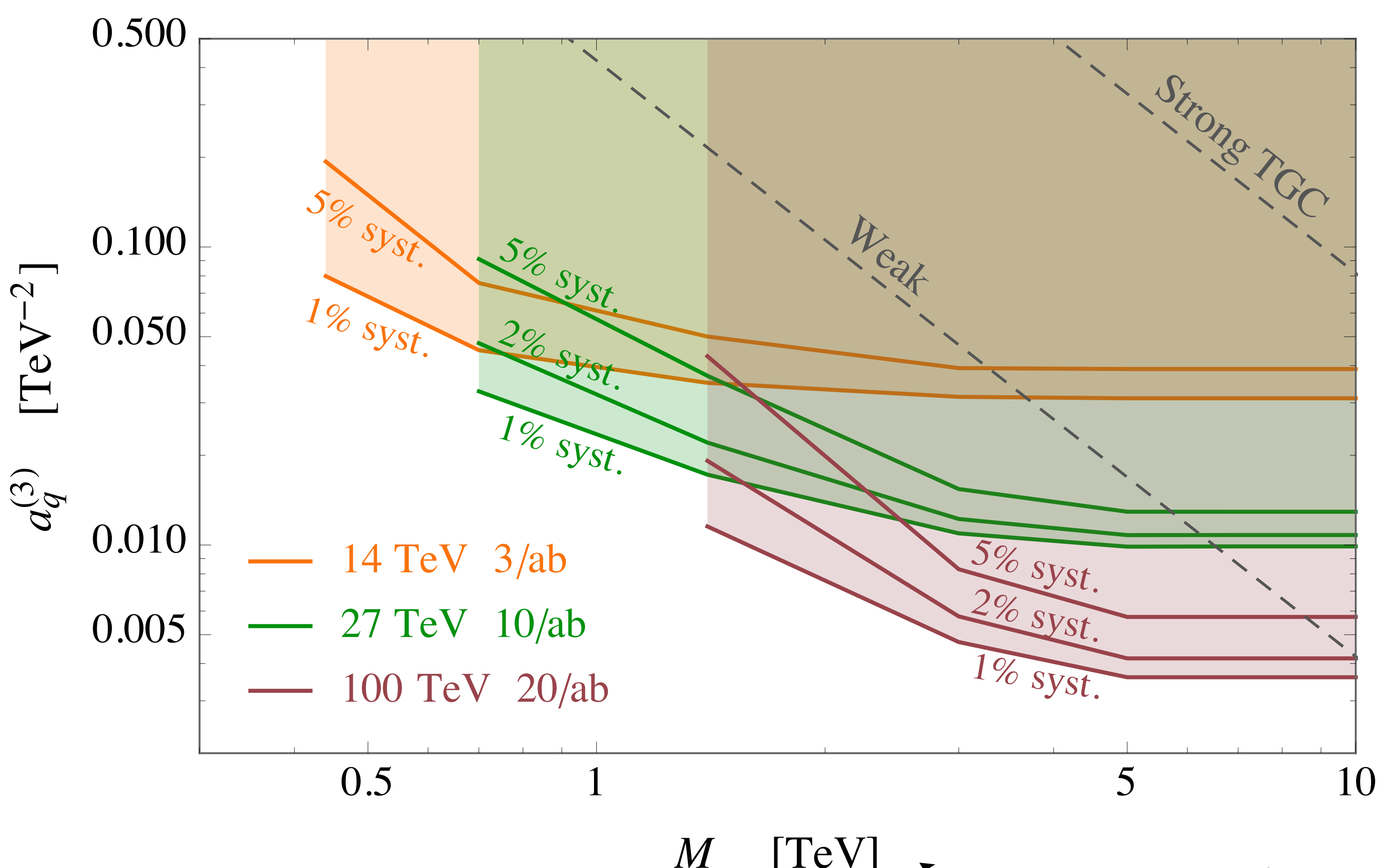


- ✦ Non-trivial analysis: longitudinal channels small ➔ exploit transverse zeroes
- ✦ Big improvement with respect to LEP
- ✦ **Accuracy** plays an important role for the BSM reach
  - weakly coupled new physics only accessible with low systematics ($\ll$100%)

WZ production: Future colliders

Estimate of the bounds on $a_q^{(3)}(\overline{q}_L\sigma^a\gamma^\mu q_L)(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)$

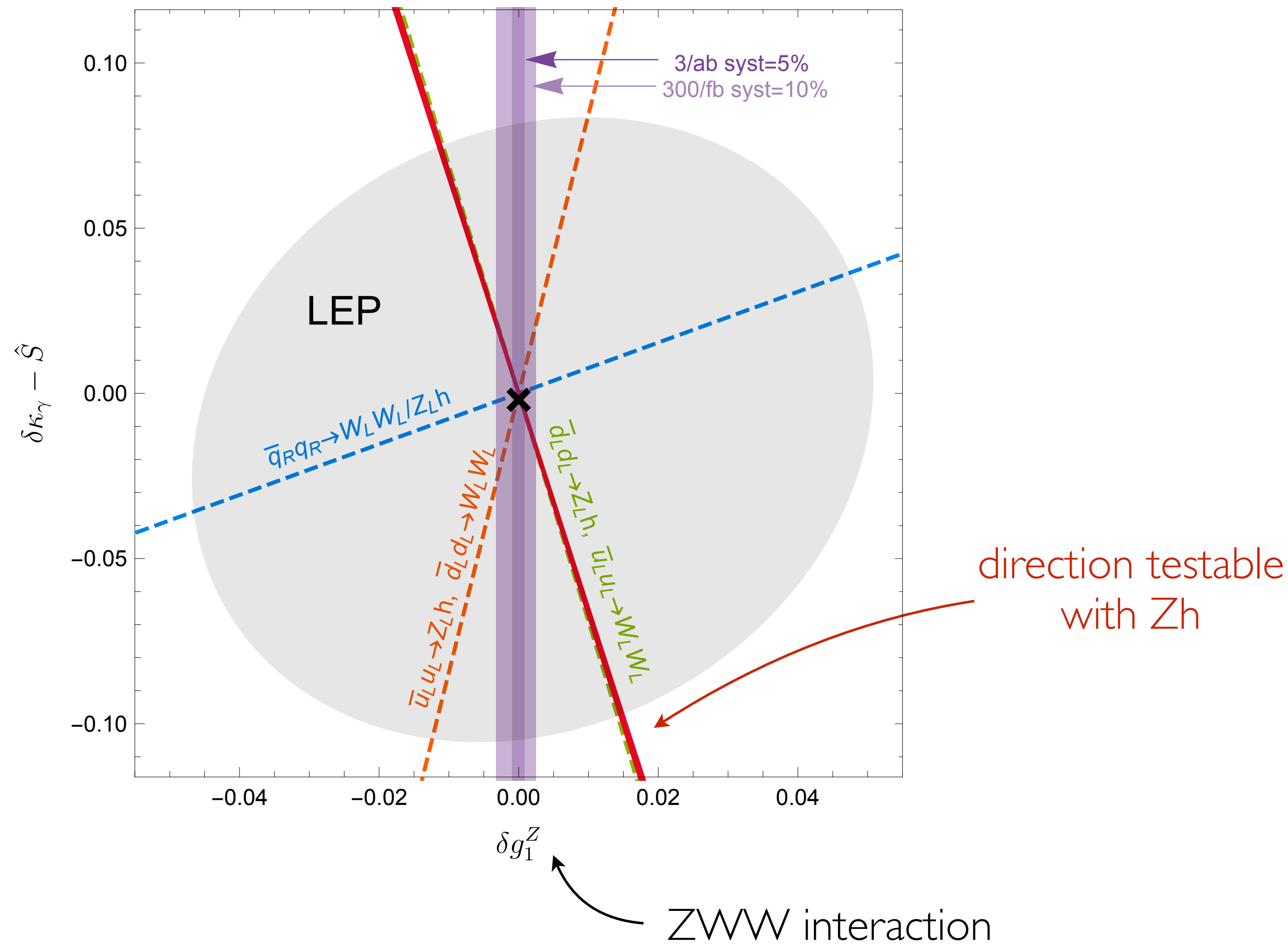


~ mass of new states

- ✦ additional improvement possible at future colliders
- ✦ reach at FCC-hh comparable with CLIC see [Ellis, Roloff, Sanz, You '17]

WZ Production and Universal Theories

Test universal theories in **WZ production channel** [Franceschini, GP, Pomarol, Riva, Wulzer '17]



- better determination on trilinear gauge couplings (δg_1^Z) with respect to global fit at LEP

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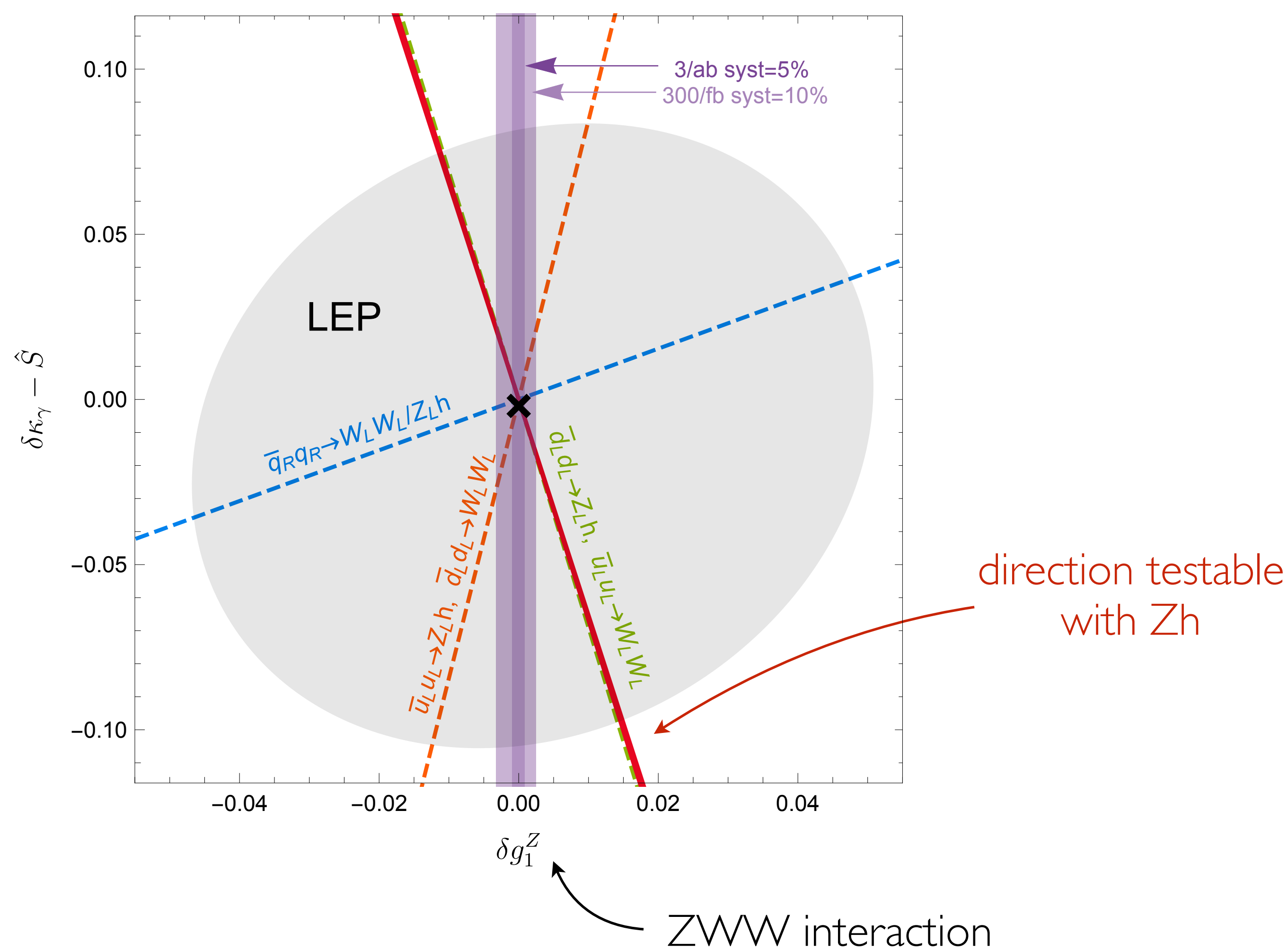
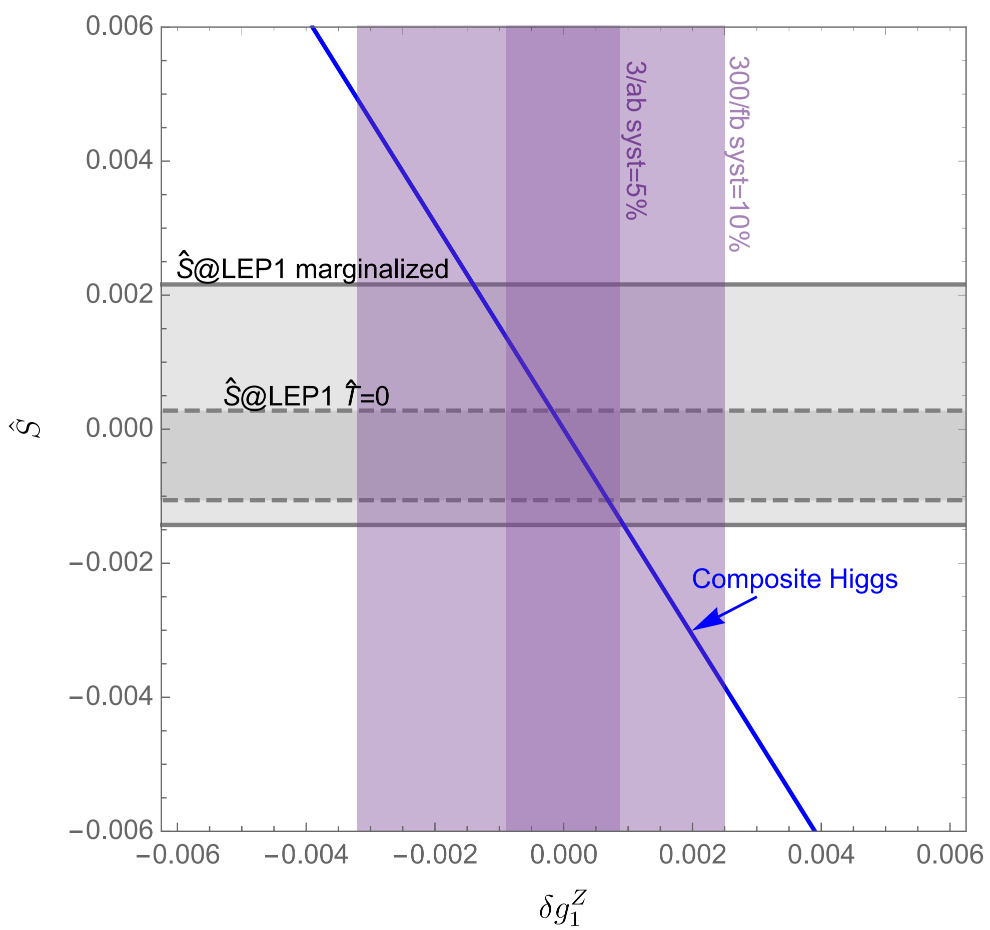




- better determination on trilinear gauge couplings (δg_1^Z) with respect to global fit at LEP

- LHC and LEP probe **independent operators**
  - correlations can exist in specific theories (eg. composite Higgs $\widehat{S} \simeq -\delta g_1^Z$)

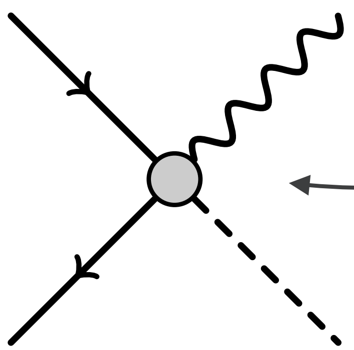
High luminosity and rare channels

High integrated luminosity → **very rare** but **very clean** channels

High luminosity and rare channels

High integrated luminosity ⟶ **very rare** but **very clean** channels

Example: **VH production**



$$a_q^{(3)}(\overline{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$$

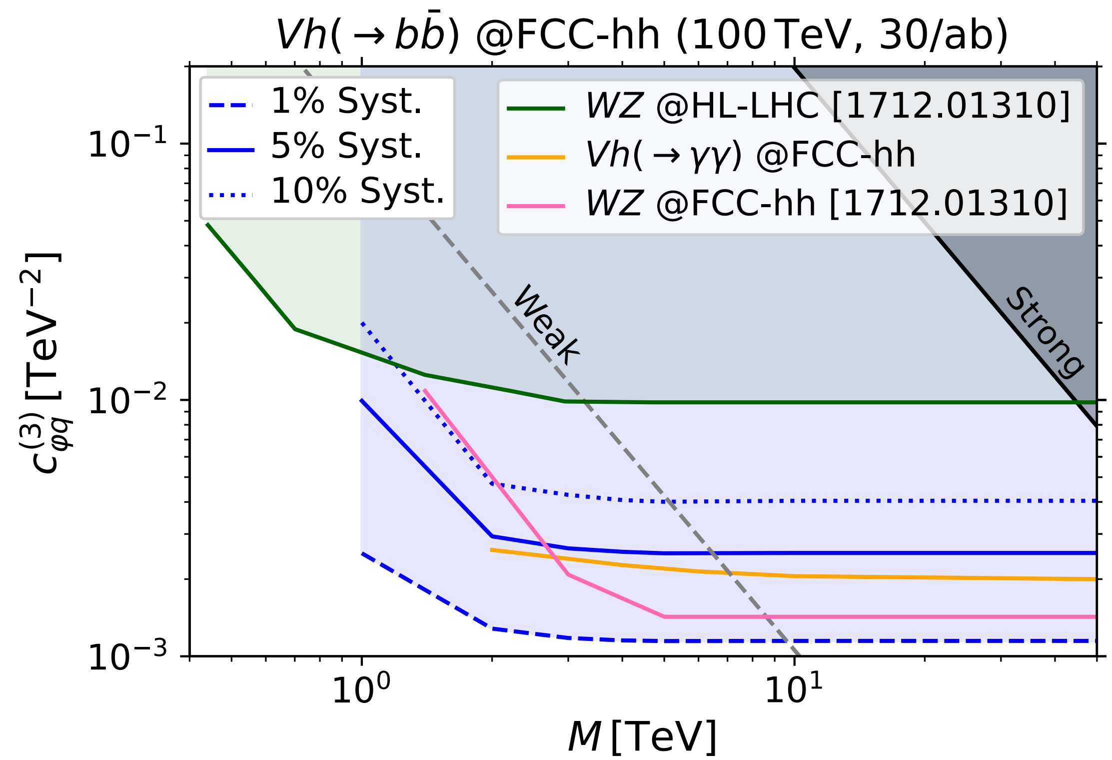
Different decay channels:

- $H \to bb$ ⟶ large cross section, but sizeable background
- $H \to \gamma\gamma$ ⟶ tiny cross section (only accessible at FCC-hh), but very clean

VH at FCC-hh

[Bishara, Englert et al. '22]

- ✦ $VH(\to bb)$ and $VH(\to \gamma\gamma)$ provide similar sensitivity
- ✦ Bounds competitive with WZ



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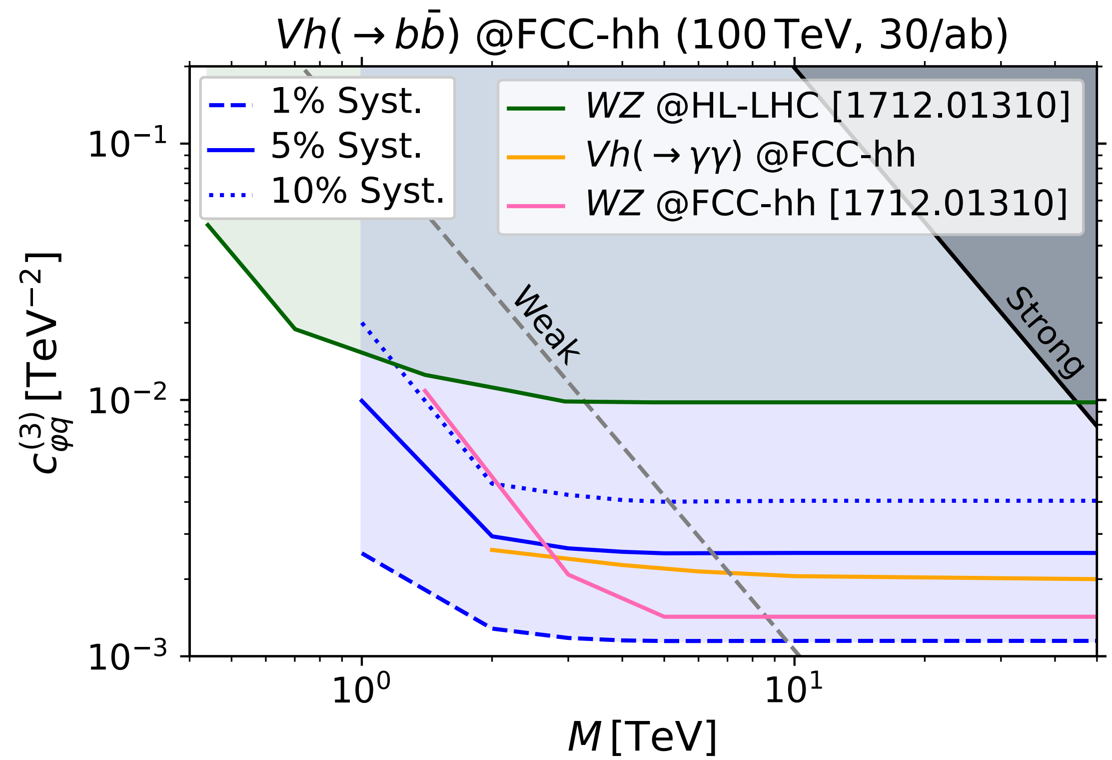
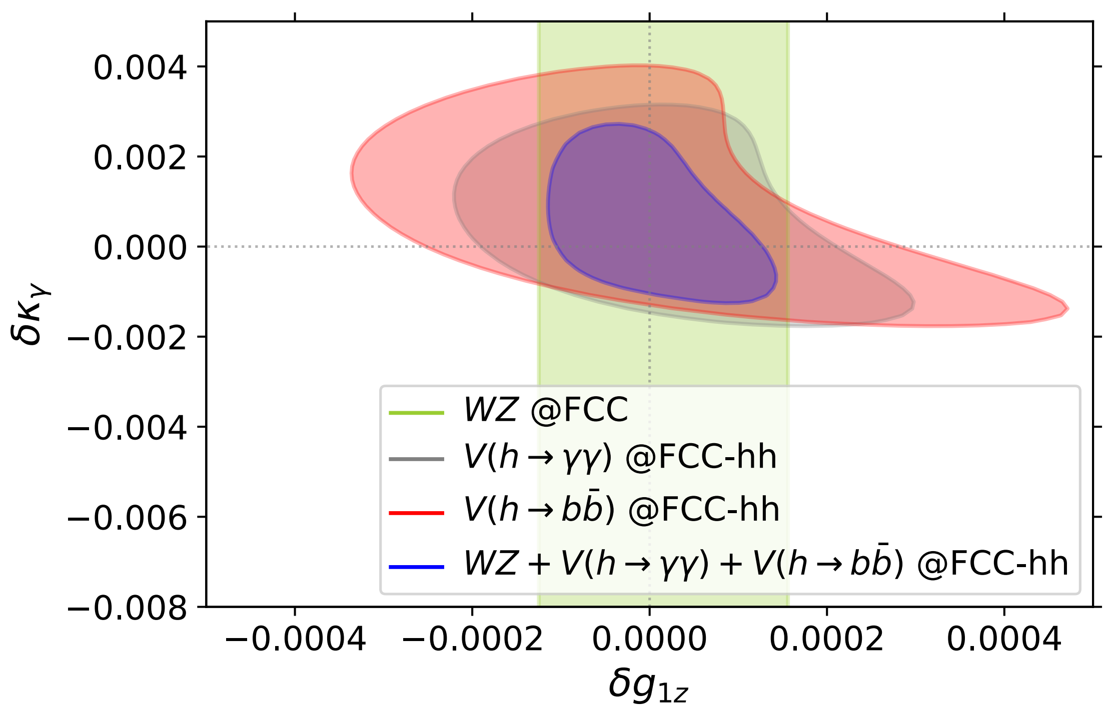
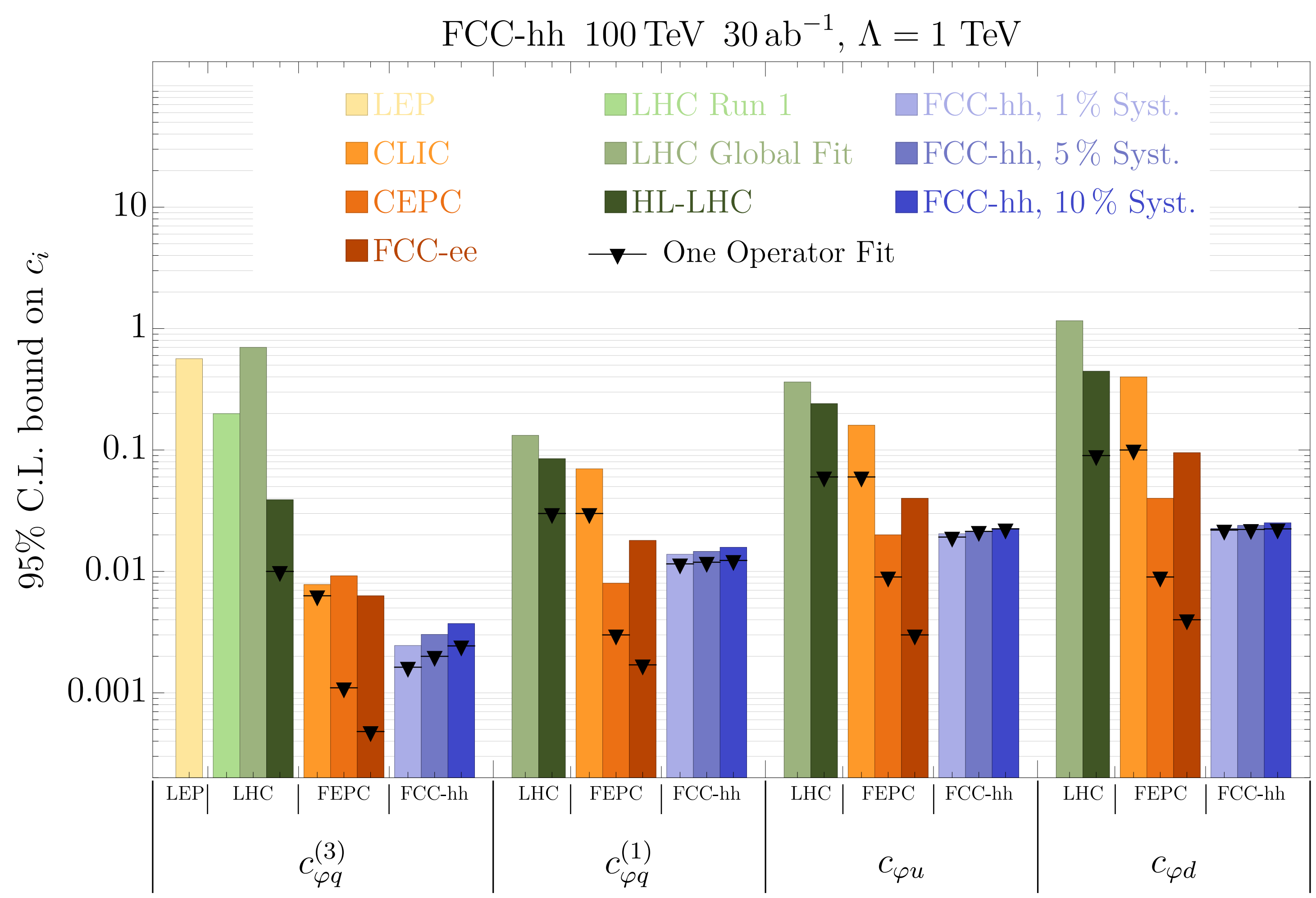


- Combination of the two channels can significantly improve the bounds



VH at FCC-hh

[Bishara, De Curtis et al. '20]



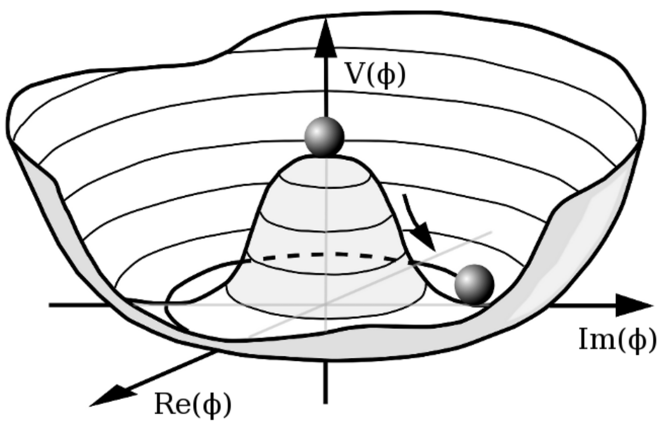
FCC-hh can match (or surpass) sensitivity at e^+e^- colliders

Higgs trilinear coupling

Theoretical Motivations

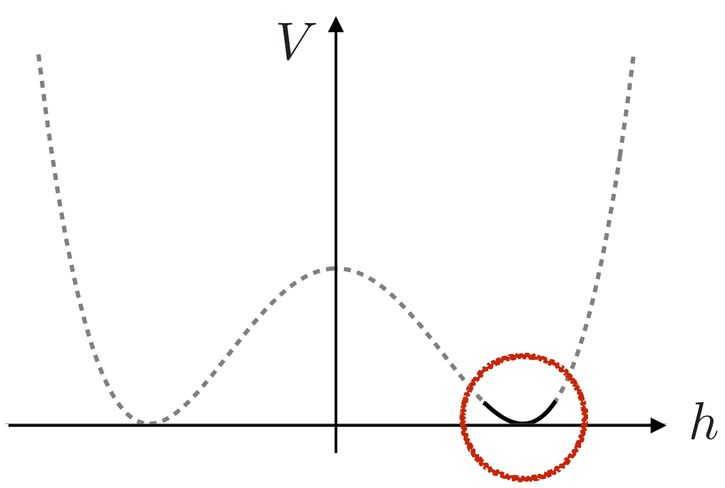
Measuring the **Higgs self-couplings**
is essential to understand the structure
of the **Higgs potential**

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$



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

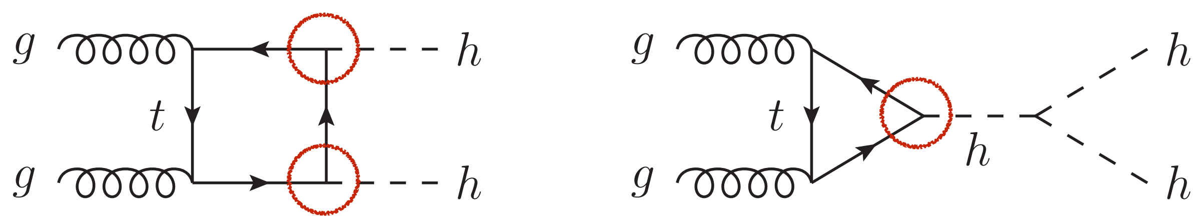
$$V(H) = \lambda_4 \left(|H|^2 - v^2\right)^2$$

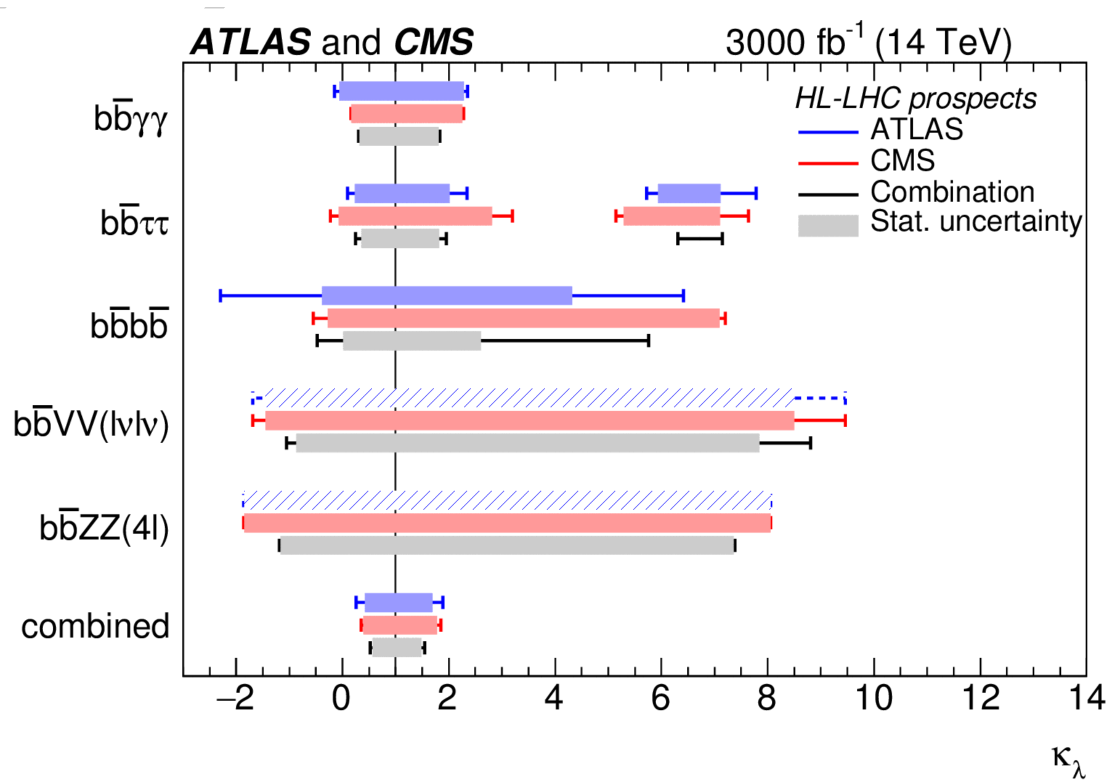


- Directly measuring the Higgs self-interactions gives us direct evidence of the full structure of the Higgs potential

High-luminosity LHC

Main sensitivity from gg → HH





combination of several decay channels

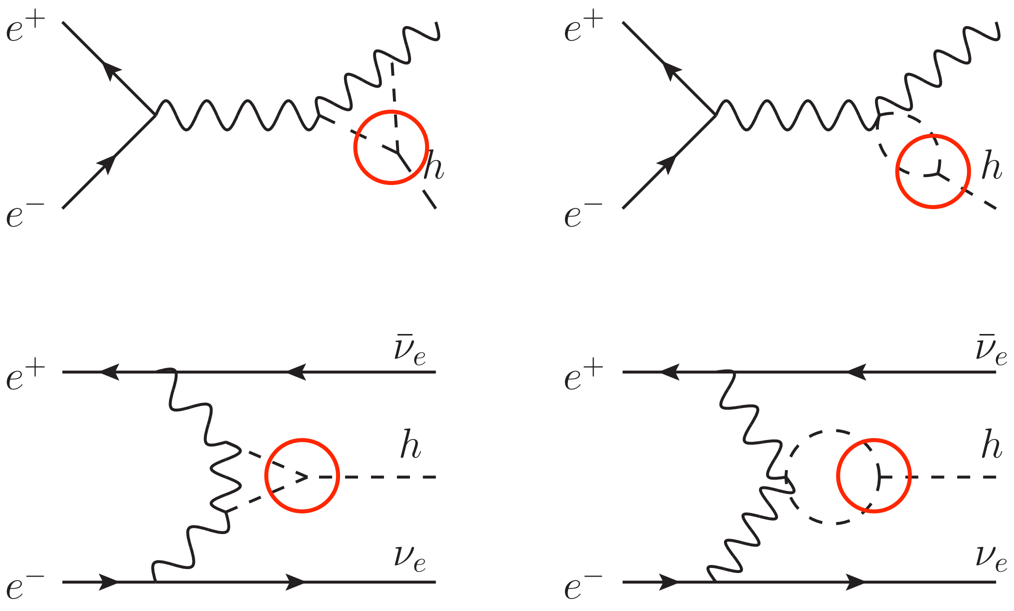
✦ HL-LHC can test the Higgs trilinear with O(50%) precision [See Di Micco et al. '19]

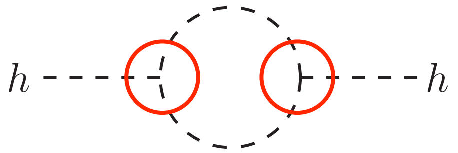
$$-0.43 \leq \delta\kappa_\lambda \leq 0.5 \quad \text{at} \quad 68\% \text{ C.L.}$$

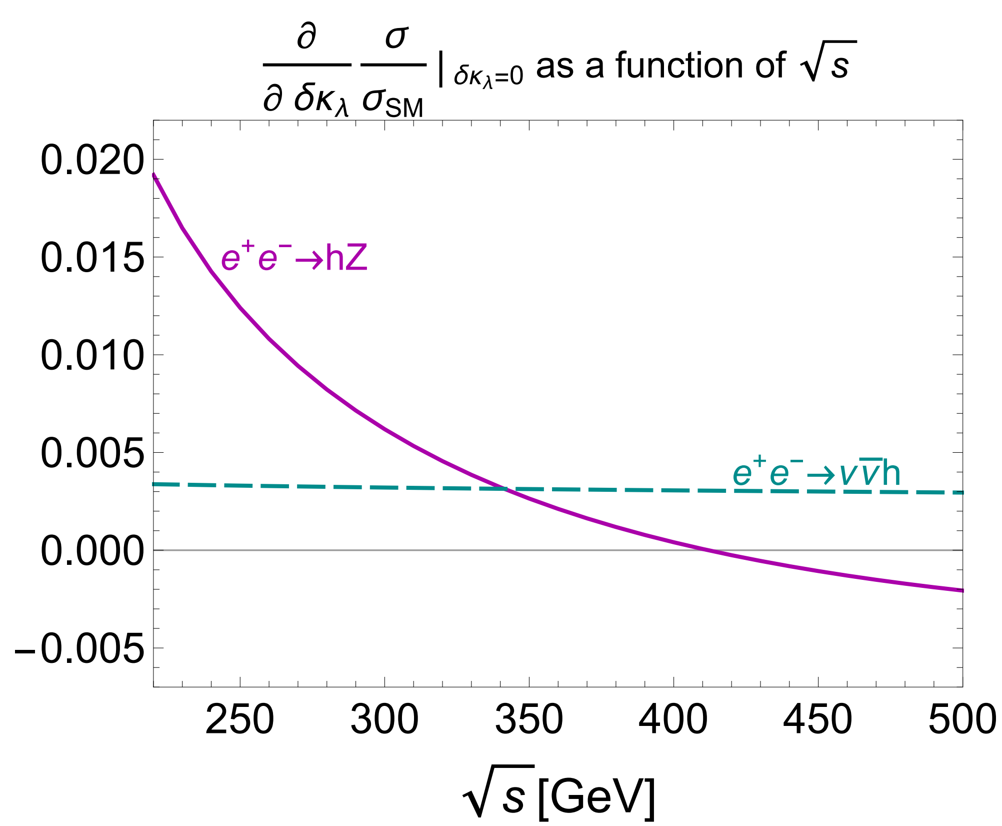
Low-energy e⁺e⁻ colliders

Higgs self-interaction can be probed indirectly through one-loop corrections to **single-Higgs processes**

[McCullough '13]







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

Low-energy e^+e^- colliders

Expected precision from 1-parameter fit (1σ bounds)

collider	1-parameter
CEPC 240	18%
FCC-ee 240	21%
FCC-ee 240/365	21%
FCC-ee (4IP)	15%
ILC 250	36%
ILC 250/500	32%
ILC 250/500/1000	29%
CLIC 380	117%
CLIC 380/1500	72%
CLIC 380/1500/3000	49%

[Di Micco et al. '19]

CECP and FCC-ee provide fair sensitivity

collider	Full $\mathcal{L}$ [ab^{-1}]
CECP 240	5.6
FCC-ee 240	5.0
FCC-ee 365	1.5
FCC-ee (4IP)	12.0 + 5.5
ILC 250	2.0
ILC 500	4.0
ILC 1000	8.0
CLIC 380	1.0
CLIC 1500	2.5
CLIC 3000	5.0

Low-energy e^+e^- colliders

Expected precision from global fit (1σ bounds)

collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

runs at single energy do not provide significant bounds

[Di Micco et al. '19]

collider	Full $\mathcal{L}$ [ab^{-1}]
CECP 240	5.6
FCC-ee 240	5.0
FCC-ee 365	1.5
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CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-

[Di Micco et al. '19]

runs at single energy do not provide significant bounds

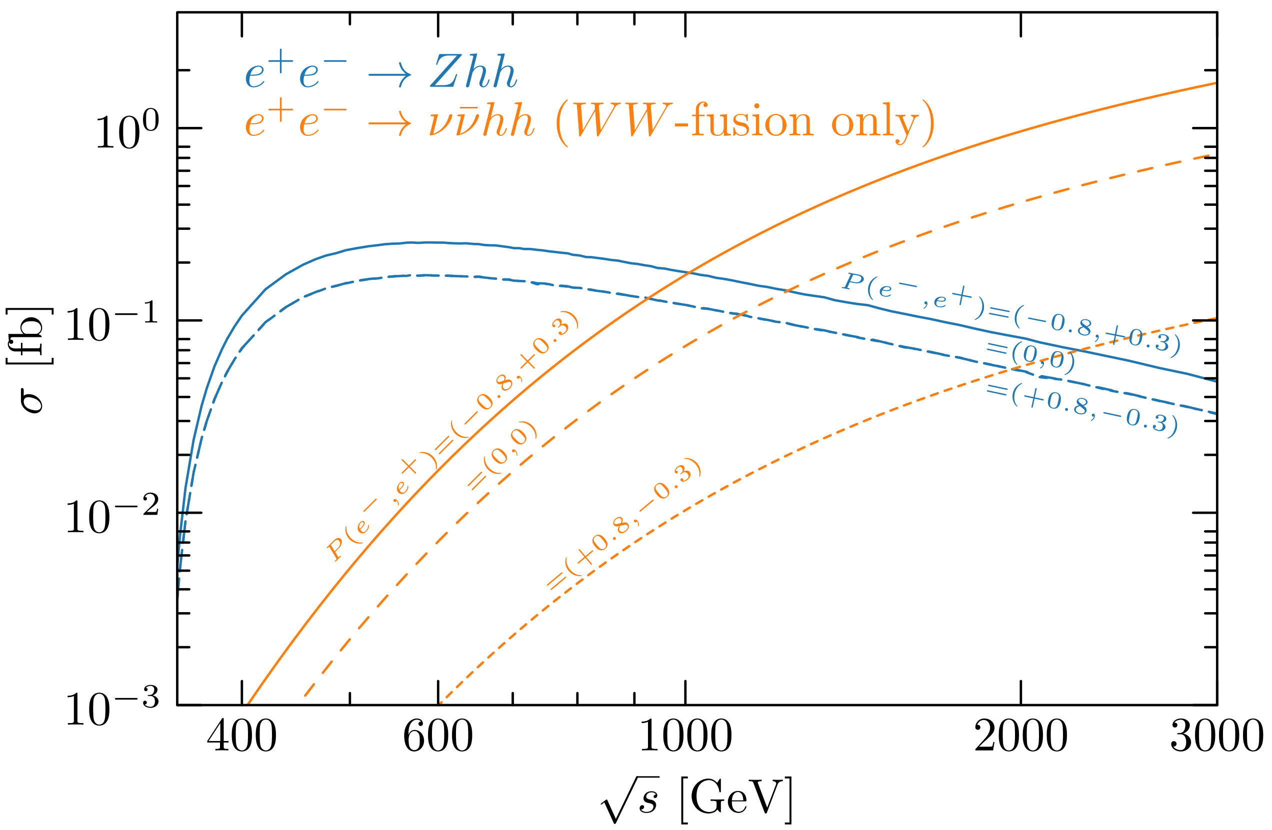
determination can reach 27% at FCC-ee with 4 interaction points

collider	Full $\mathcal{L}$ [ab^{-1}]
CECP 240	5.6
FCC-ee 240	5.0
FCC-ee 365	1.5
FCC-ee (4IP)	12.0 + 5.5
ILC 250	2.0
ILC 500	4.0
ILC 1000	8.0
CLIC 380	1.0
CLIC 1500	2.5
CLIC 3000	5.0

High-energy e^+e^- colliders

Two main channels

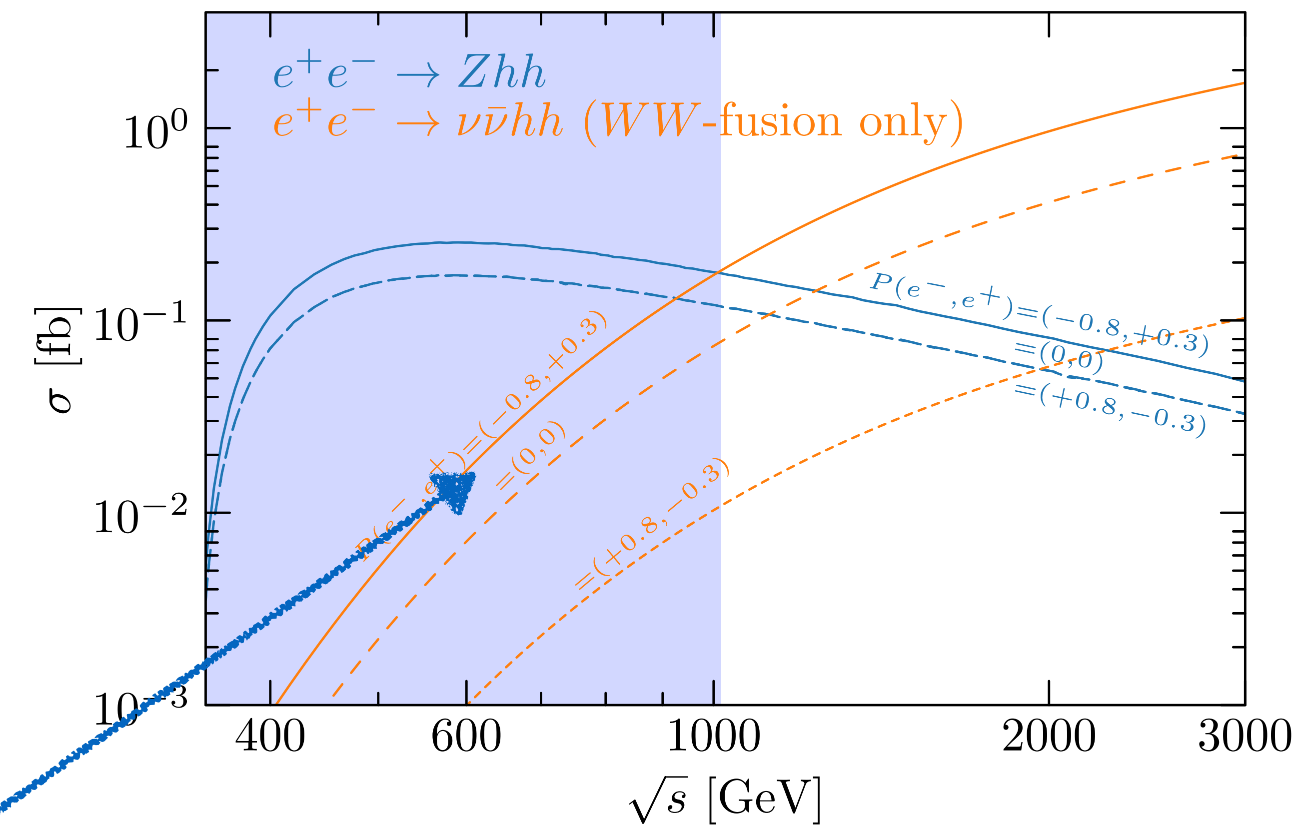
ZHH and $\nu\bar{\nu}HH$



High-energy e⁺e⁻ colliders

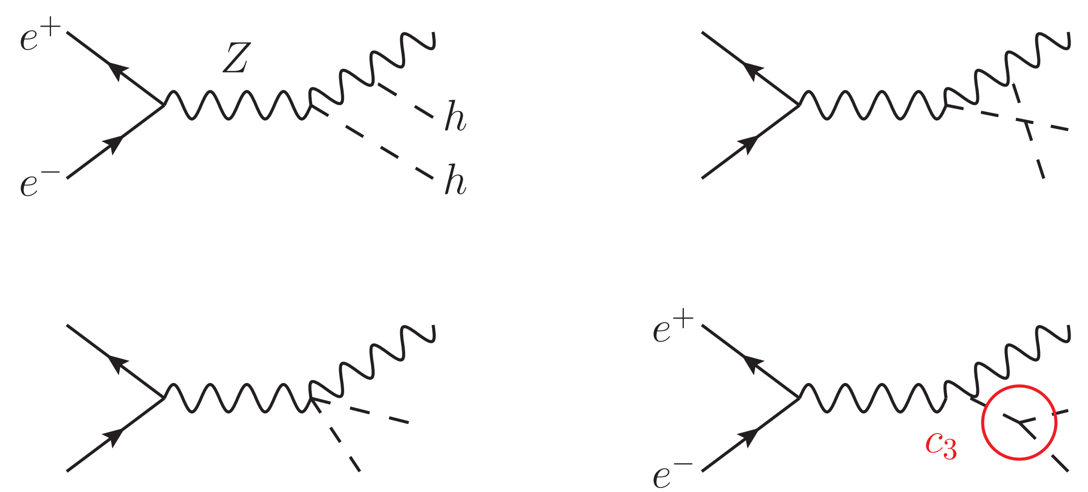
Two main channels

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



Double Higgs-strahlung (DHS)

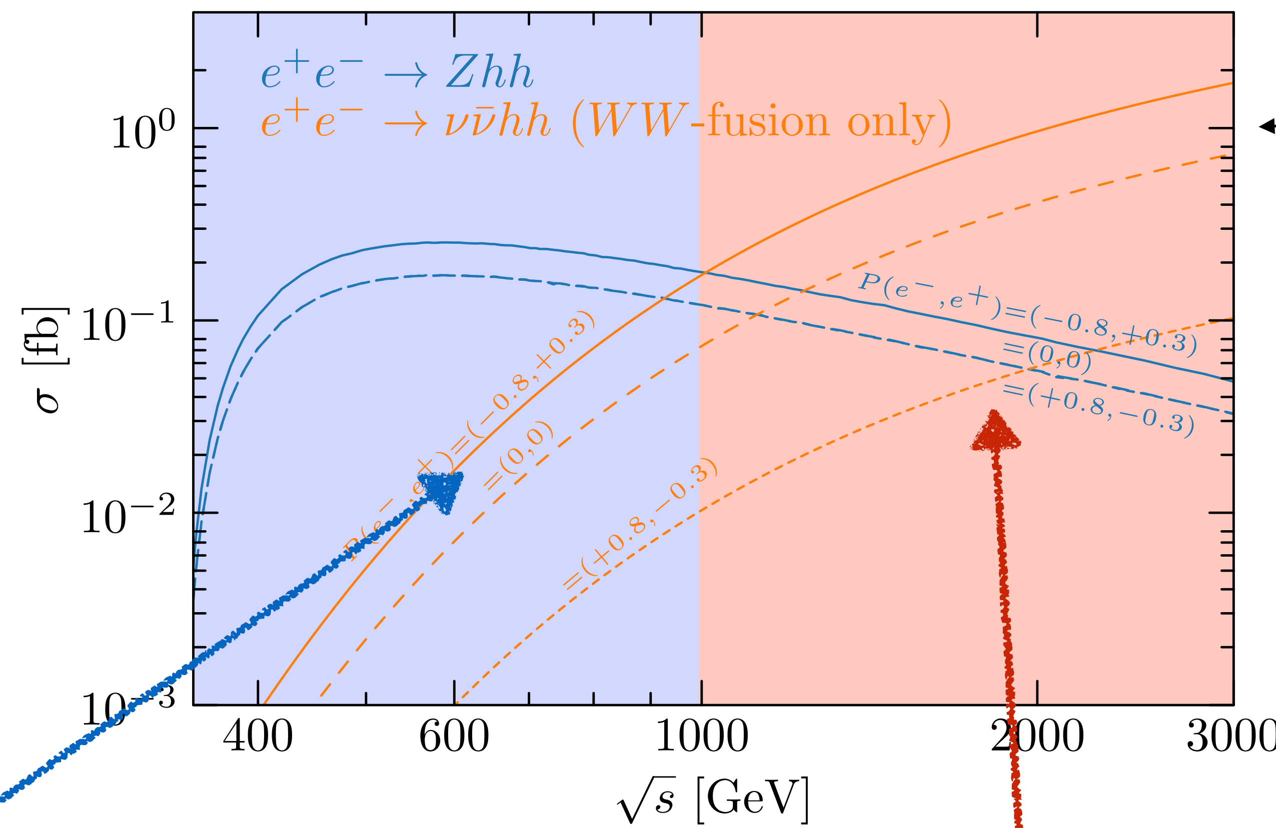
dominant below 1 TeV



High-energy e⁺e⁻ colliders

Two main channels

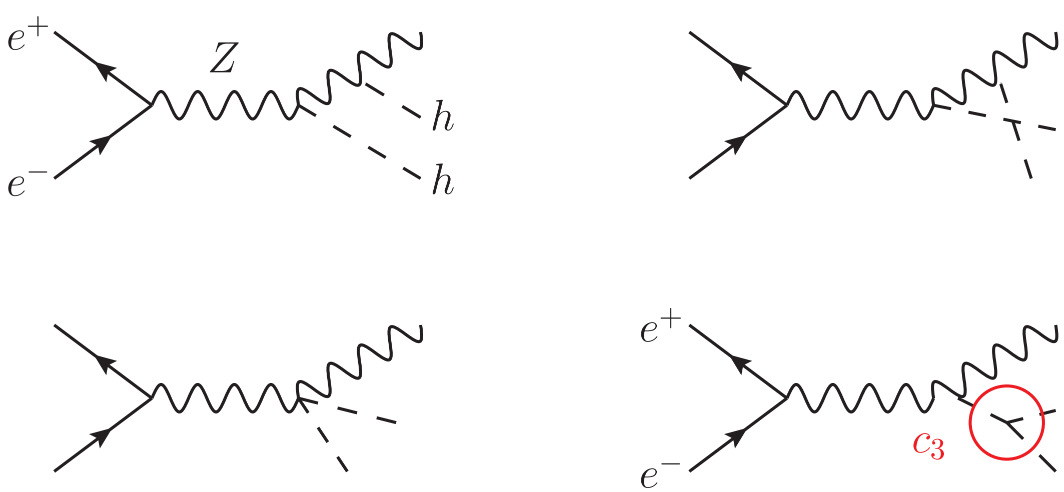
ZHH and $\nu\bar{\nu}HH$



beam polarization can enhance cross-section

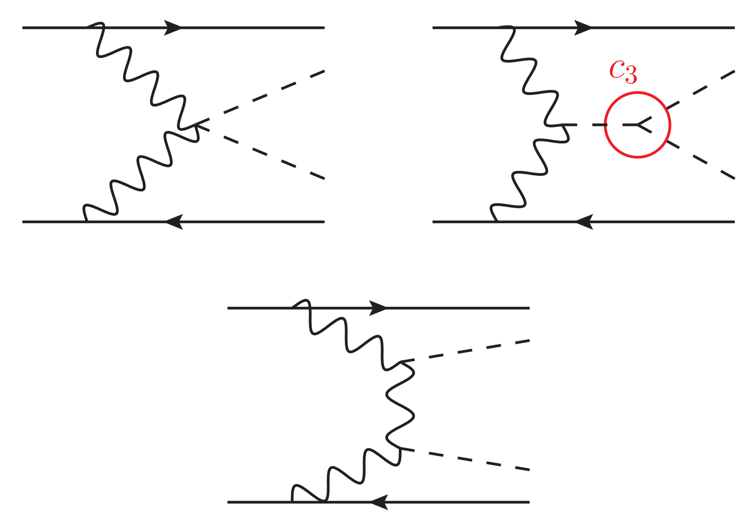
Double Higgs-strahlung (DHS)

dominant below 1 TeV



Vector Boson Fusion (VBF)

dominant above 1 TeV



Precision reach at ILC and CLIC

Expected precision from HH production channels
(1σ bounds)

collider	excl. from HH
HL-LHC	50%
ILC 500	27%
ILC 1000	10%
CLIC 1500	36%
CLIC 3000	[-7%, 11%]

Can reach the 10% threshold

FCC-hh

Exclusive fit on $\delta\kappa_\lambda$

$\sqrt{s} = 100$ TeV $\mathcal{L} = 30$ ab^{-1}

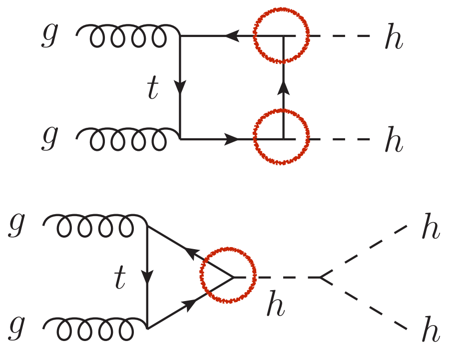
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}ZZ^*$ (4ℓ)	$b\bar{b}WW^*$ ($2j\ell\nu$)	$b\bar{b}b\bar{b}$ +jet
$\delta\kappa_\lambda$	6%	8%	14%	40%	30%

[Di Micco et al. '19]

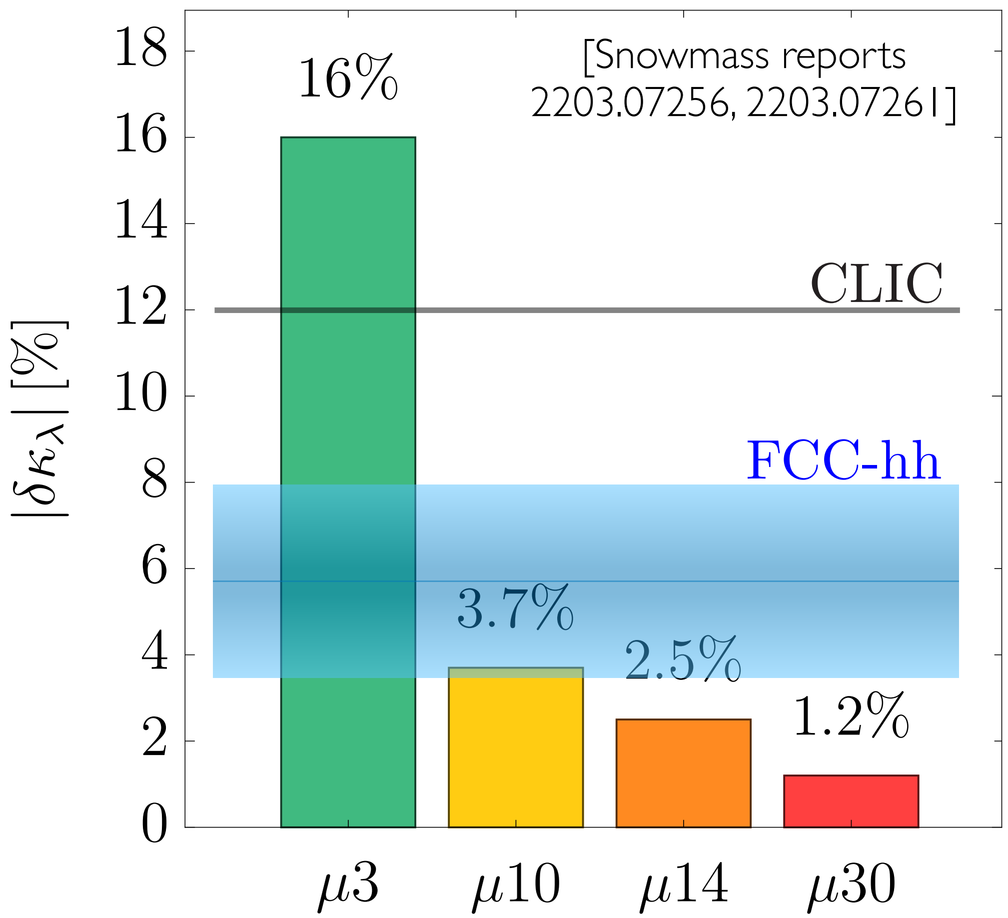
- precision likely to be limited by systematics
  (theory systematics dominant for $\Delta_S \gtrsim 2.5\%$, leading to $\delta\kappa_\lambda \simeq 2\Delta_S$)

- ultimate FCC-hh reach in the 3.4 - 7.8% range [Mangano et al. 2004.03505]

- global fit could affect the prediction
  (strong dependence on top Yukawa coupling)



Muon collider



energy	Full $\mathcal{L}$ [ab^{-1}]
3 TeV	≈ 2
10 TeV	10
14 TeV	≈ 20
30 TeV	90

- High-energy muon collider can be competitive with FCC-hh

Conclusions

Conclusions

Future colliders can provide **big quantitative and qualitative improvements** in our understanding of the Higgs boson

Important to exploit **complementarity** of different machines

<u>low-energy lepton colliders</u>

- "pole" properties (mass, width, ...)
- (most) linear Higgs couplings

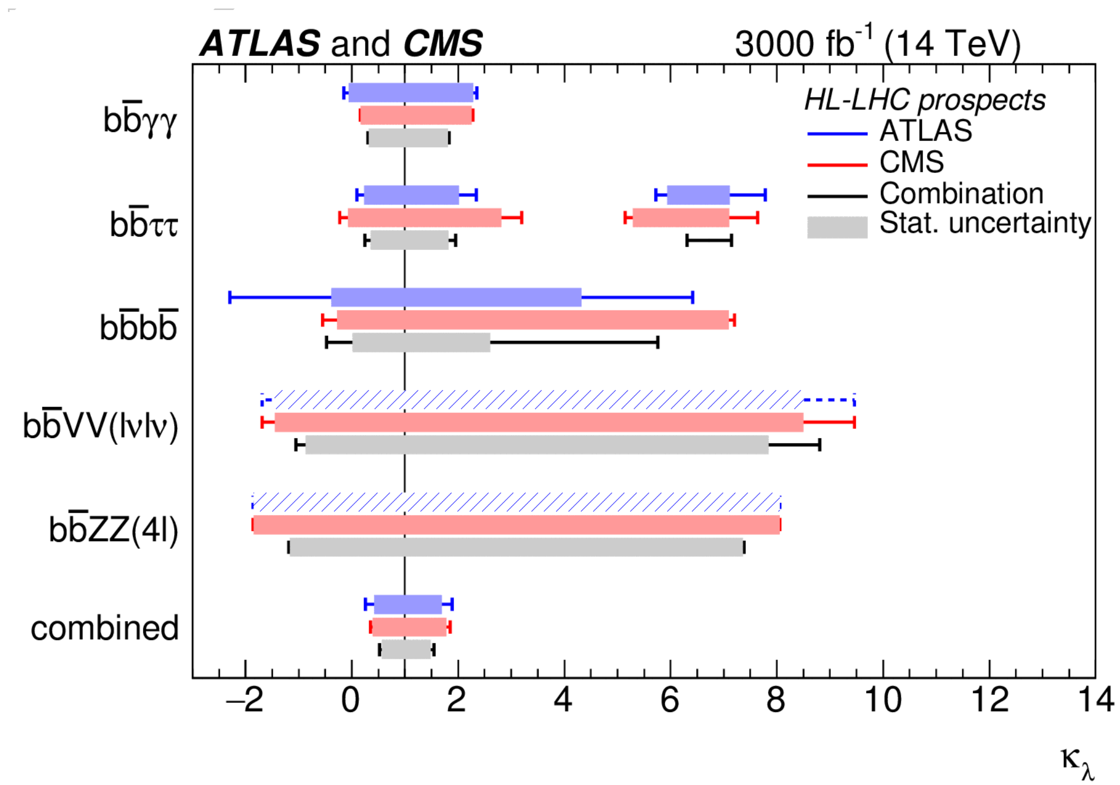
<u>high-energy lepton/hadron colliders</u>

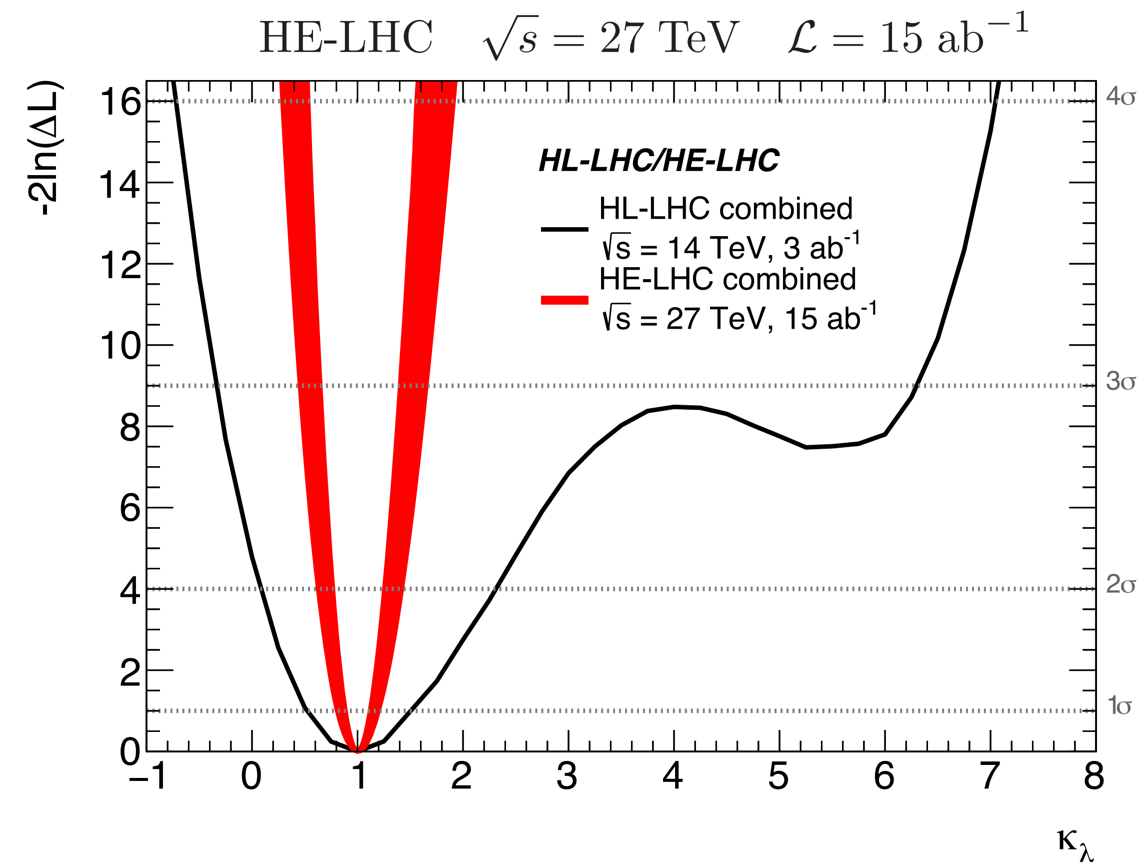
- top Yukawa, effective coupling to photon and Z
- non-linear couplings (+ Goldstone equivalence)
- Higgs potential

Backup

HL and HE LHC

[See Di Micco et al. '19]





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

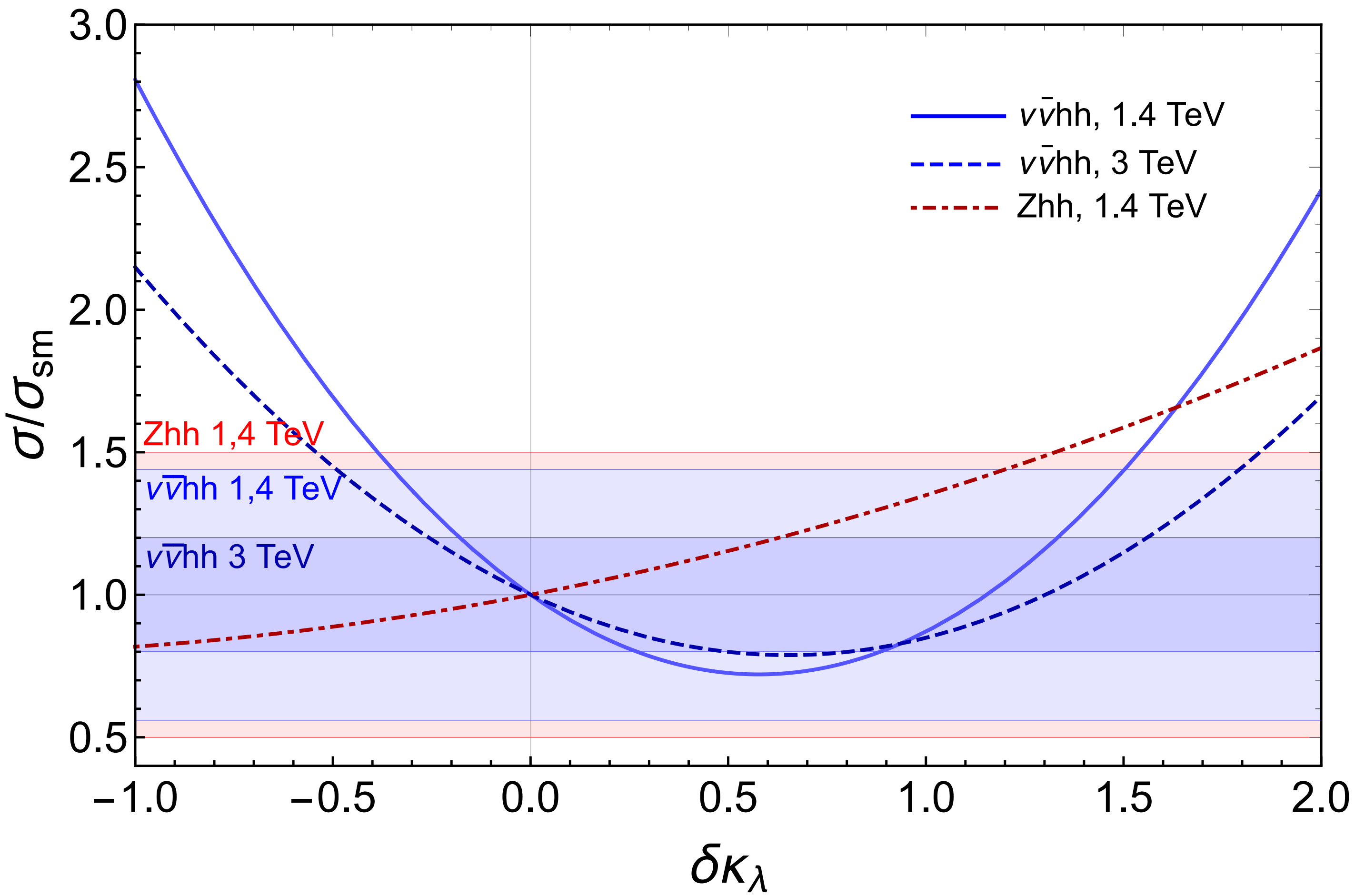
$$-0.43 \leq \delta\kappa_\lambda \leq 0.5 \quad \text{at} \quad 68\% \quad \text{C.L.}$$

- ✦ HE-LHC could test the Higgs trilinear with O(10-20%) precision (depending on systematics)

Sensitivity to Higgs self-coupling

The two channels provide complementary information

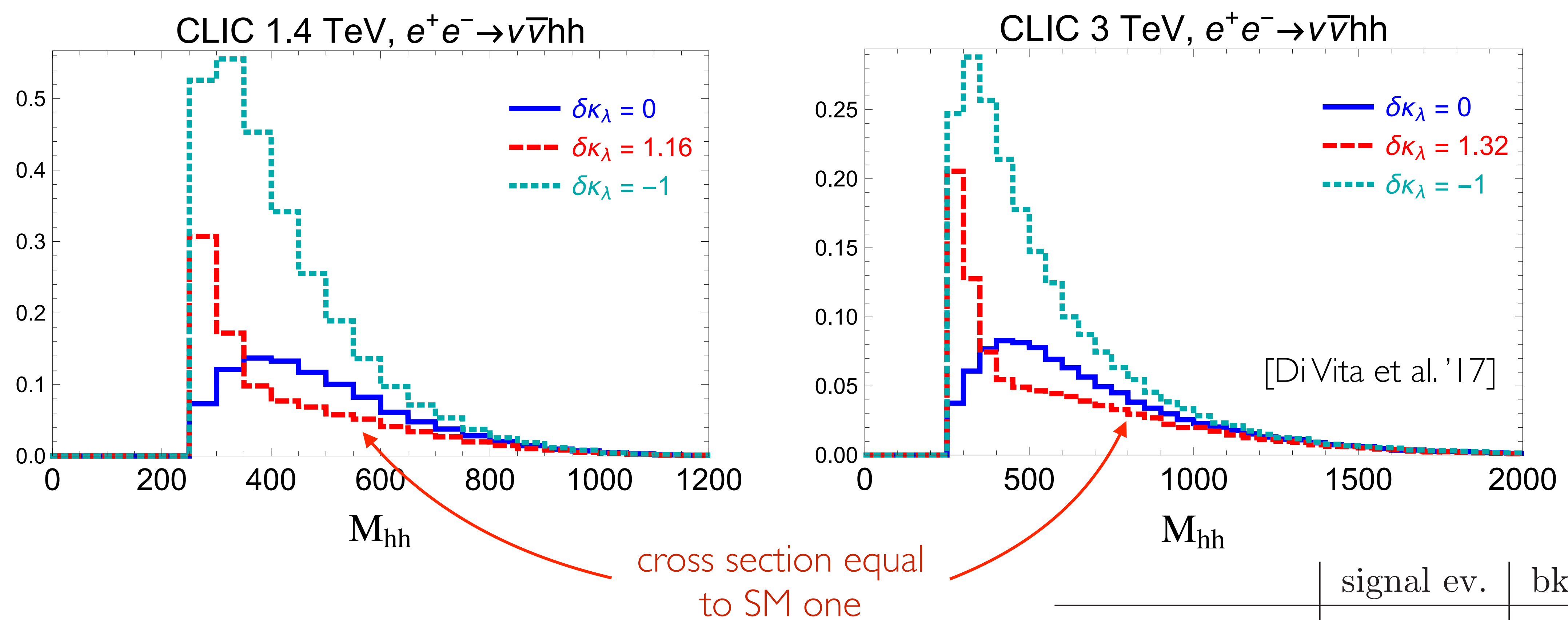
- ✦ ZHH gives stronger constraints on $\delta\kappa_\lambda > 0$
- ✦ $\nu\bar{\nu}HH$ gives stronger constraints on $\delta\kappa_\lambda < 0$



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

Help from differential distributions

The Higgs trilinear coupling strongly modifies the distributions



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

- differential analysis can help to exclude large deviations form the SM