2020 IAS program on High Energy physics

Higgs self-coupling prospect

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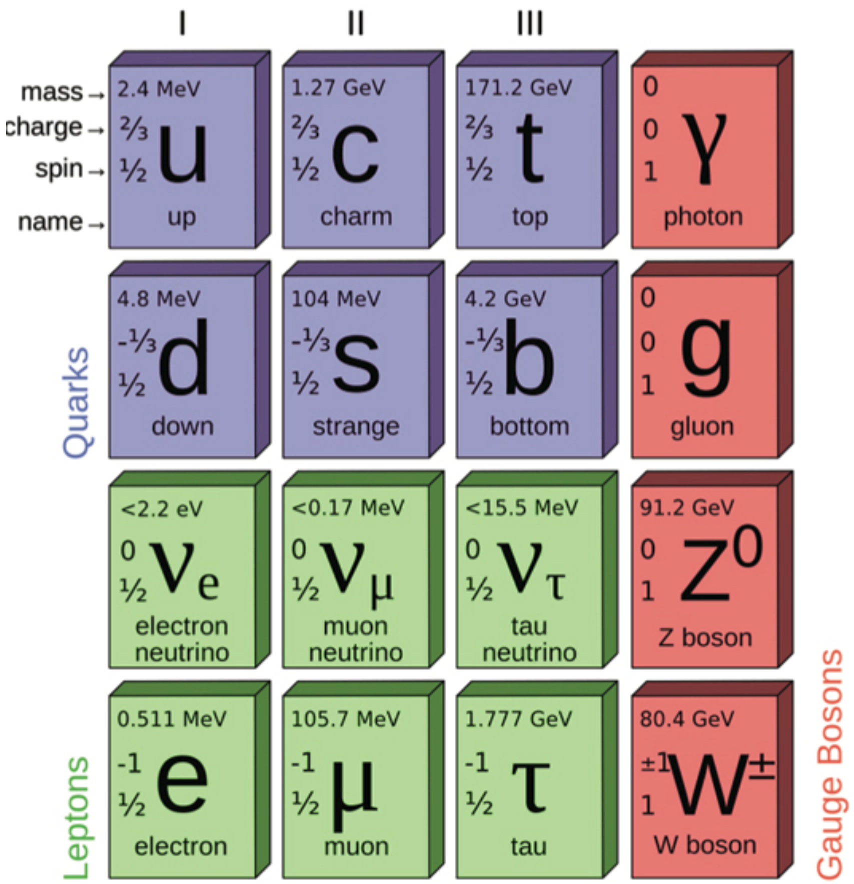
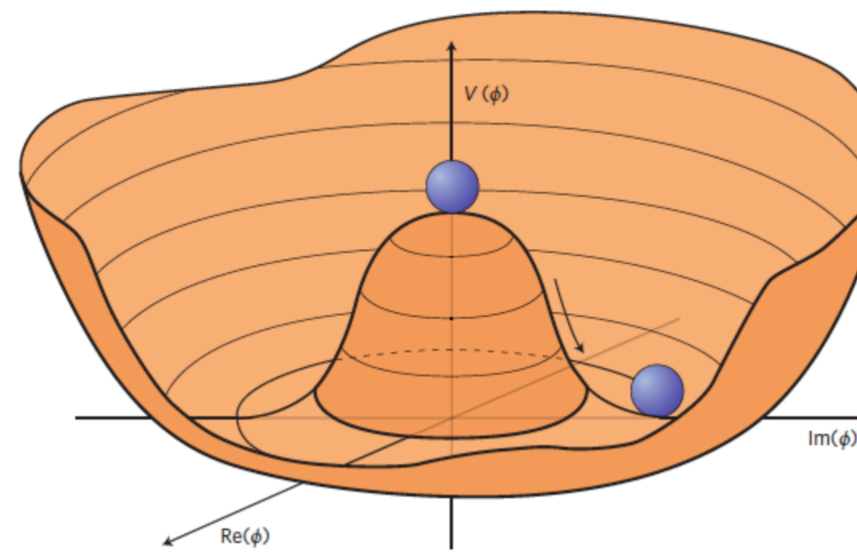
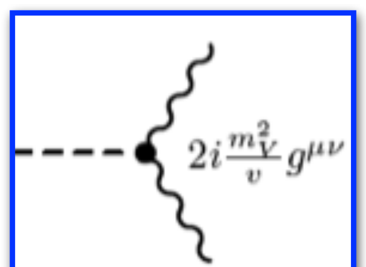
Introduction

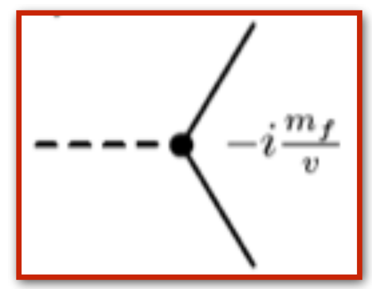
- **The Higgs particle is responsible for the masses of elementary particles.**



$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + \boxed{D_\mu\Phi^\dagger D^\mu\Phi} - V(\Phi) \\ & + \boxed{\bar{\Psi}_L\hat{Y}\Phi\Psi_R} + h.c.\end{aligned}$$







Gauge coupling **Yukawa coupling**

- **Higgs potential approximation:**

$$V(h) = \frac{1}{2}m_H^2h^2 + \boxed{\lambda_3 vh^3 + \frac{1}{4}\lambda_4 h^4} \quad \text{with} \quad \lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

Self-coupling

$$\kappa_\lambda = \kappa_3 = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

The measurement of Higgs self-coupling is a high priority goal for all the future colliders

How to measure the tri-linear self-coupling

Timeline of various collider projects

	T_0	+5	+10	+15	+20	...	+26
ILC	0.5/ab 250 GeV		1.5/ab 250 GeV		1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV	
CEPC	5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$		SppC =>			
CLIC	1.0/ab 380 GeV		2.5/ab 1.5 TeV		5.0/ab => until +28 3.0 TeV			
FCC	150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV		1.7/ab ee, $2m_{top}$		hh,eh =>	
LHeC	0.06/ab		0.2/ab		0.72/ab			
HE-LHC	10/ab per experiment in 20y							
FCC eh/hh	20/ab per experiment in 25y							

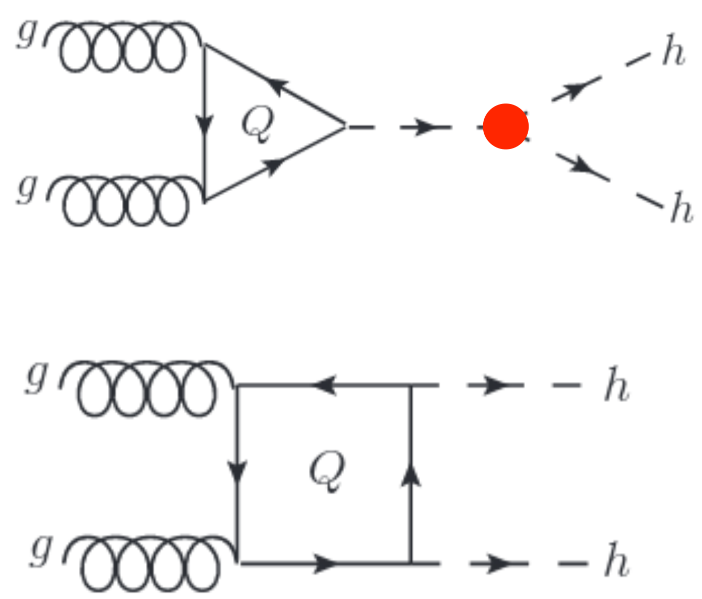
- **Hadron colliders**: **double Higgs production**, **Single Higgs production with NLO-EW correction**

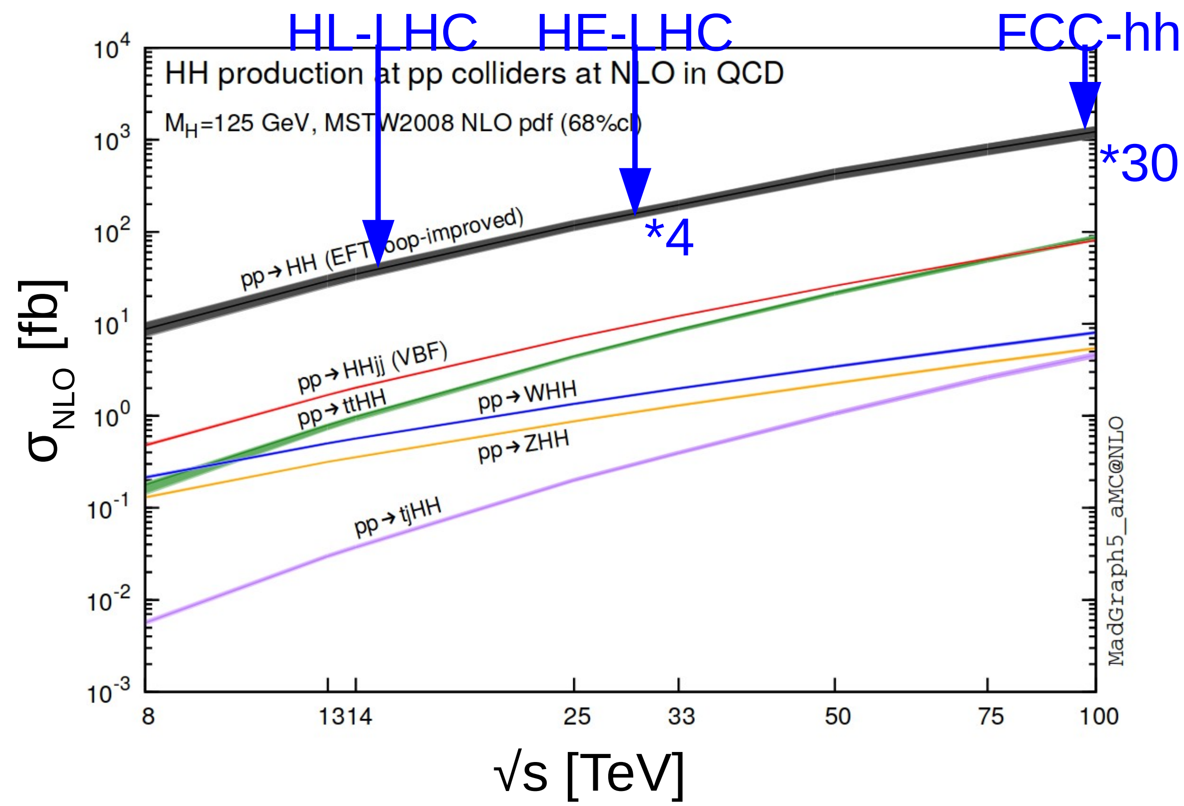
- **Low-energy lepton colliders**: **Single Higgs production with NLO-EW correction**

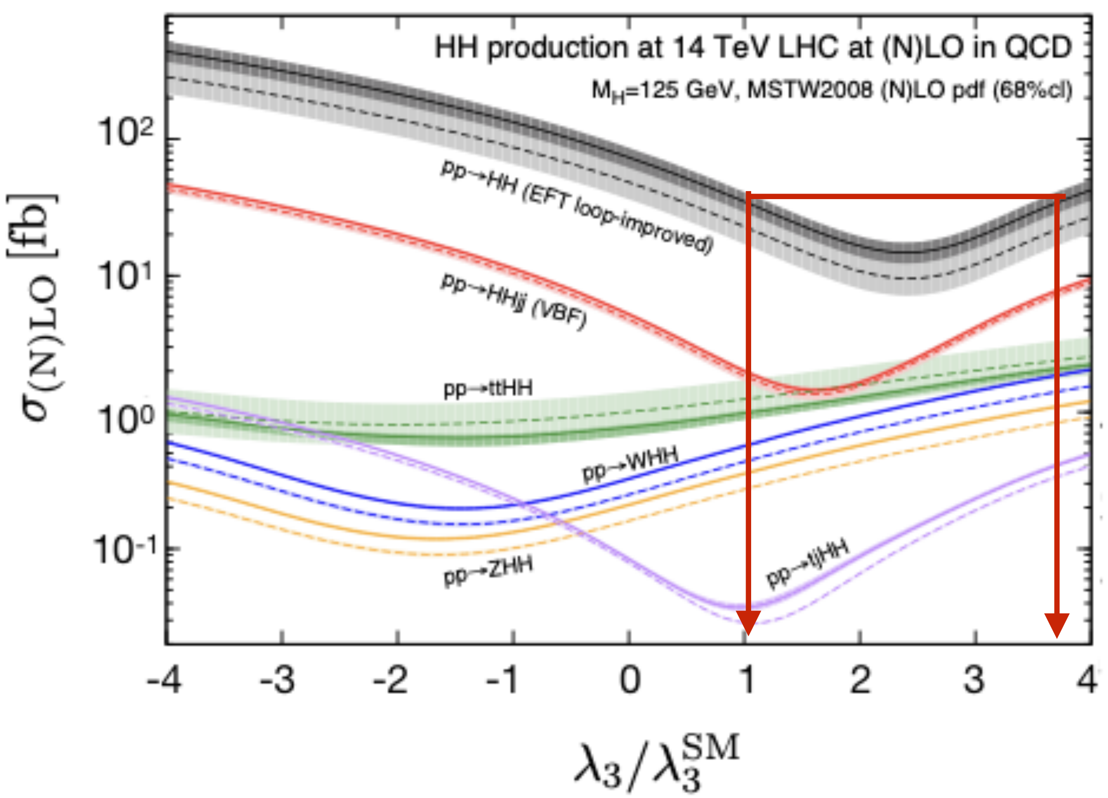
- **High-energy lepton colliders**: **double Higgs-strahlung, vector boson fusion**

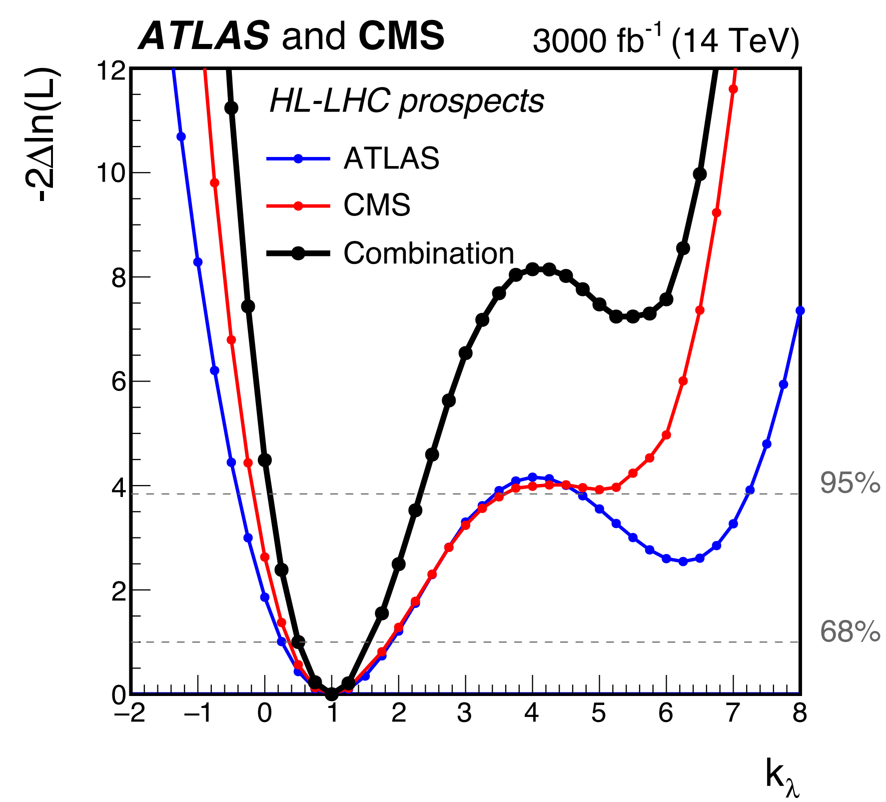
Hadron collider: Di-Higgs production

Destructive interference between triangle- and box- diagrams (σ(HH)/σ(H)=0.1%)



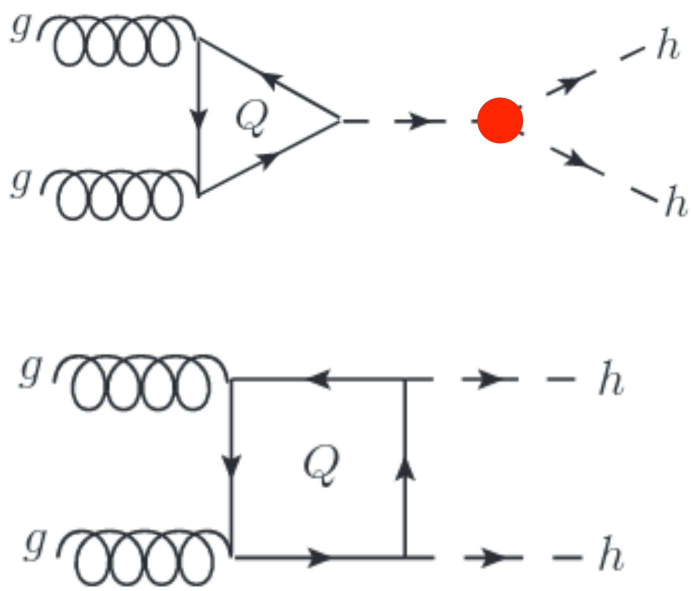


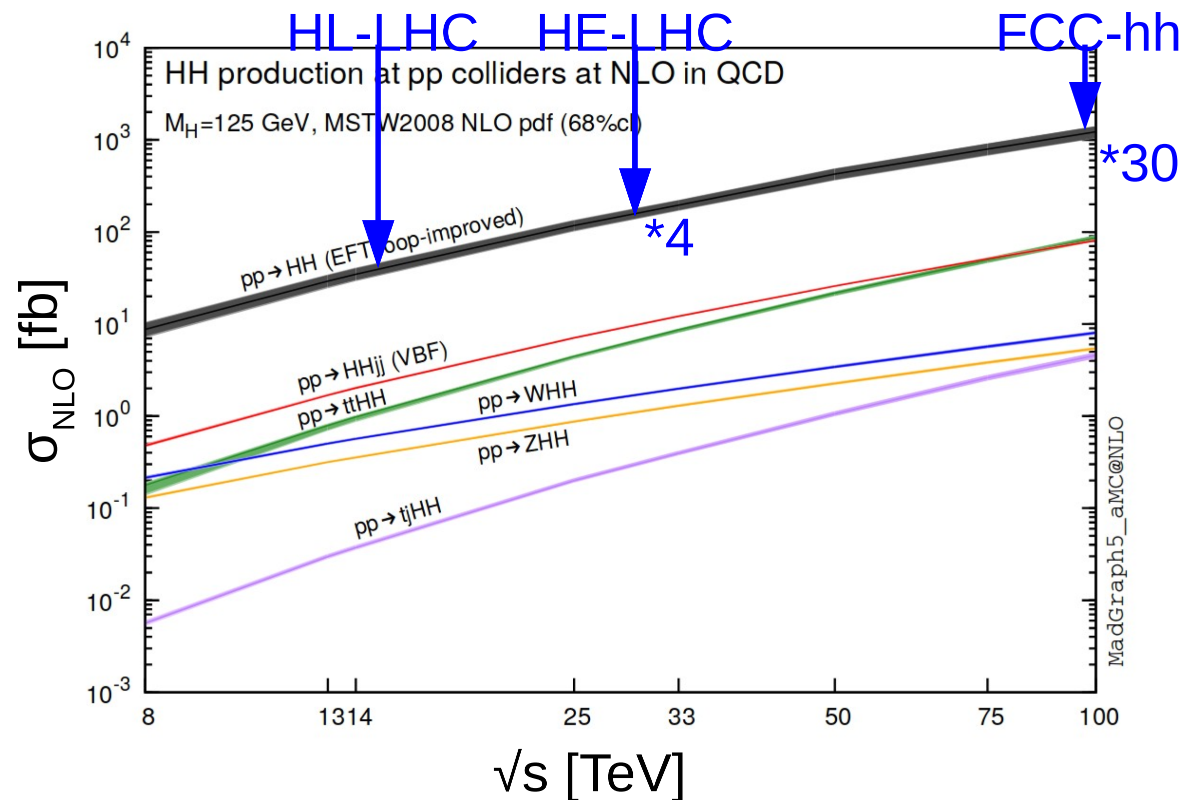


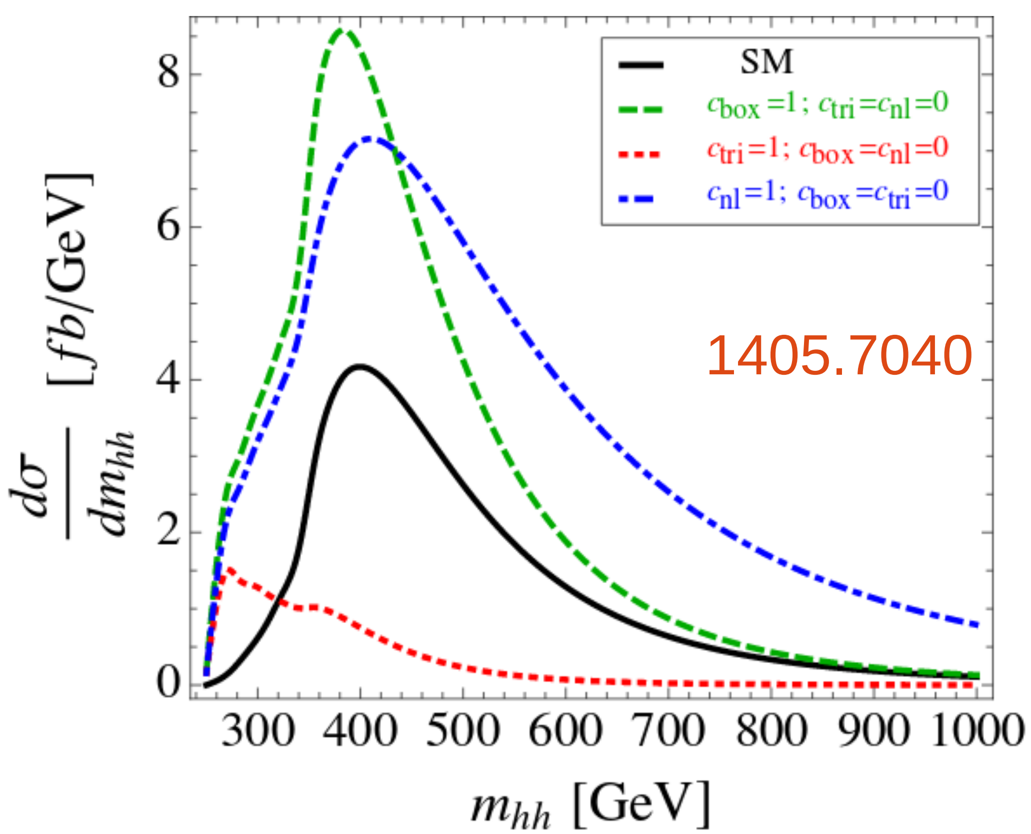


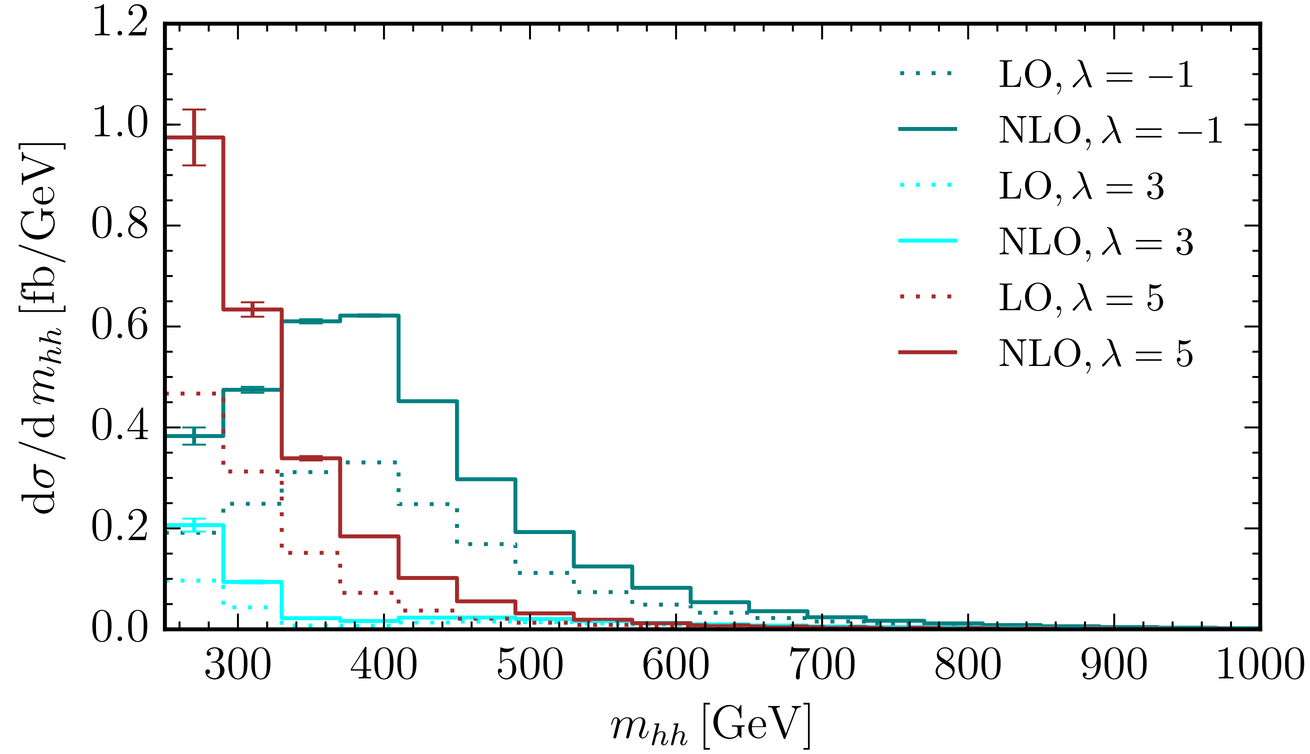
Hadron collider: Di-Higgs production

Destructive interference between triangle- and box- diagrams (σ(HH)/σ(H)=0.1%)



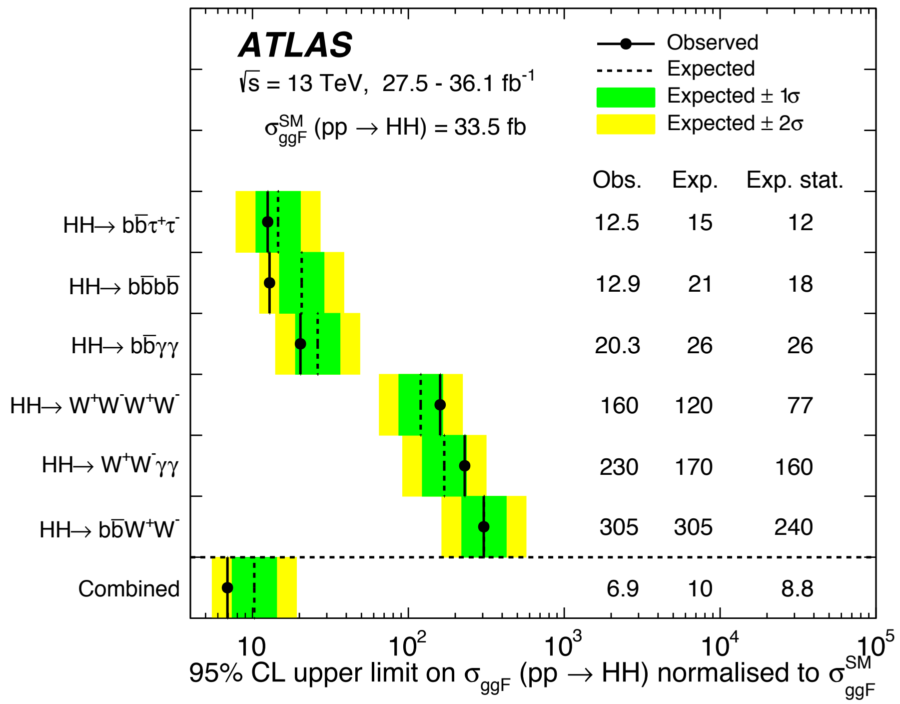


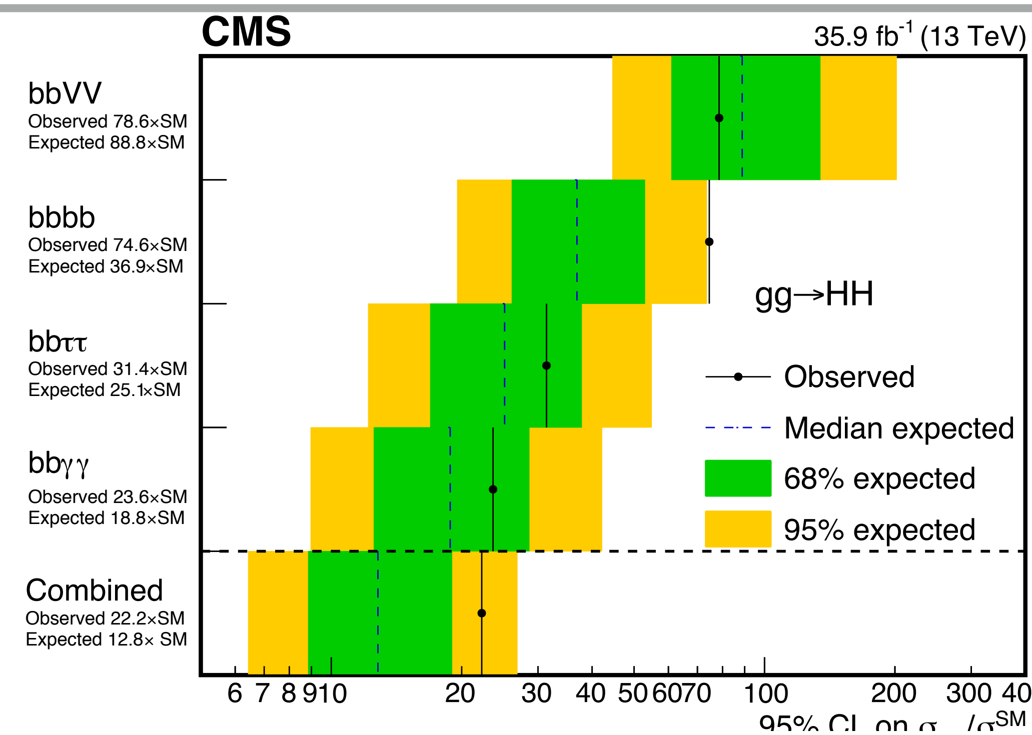


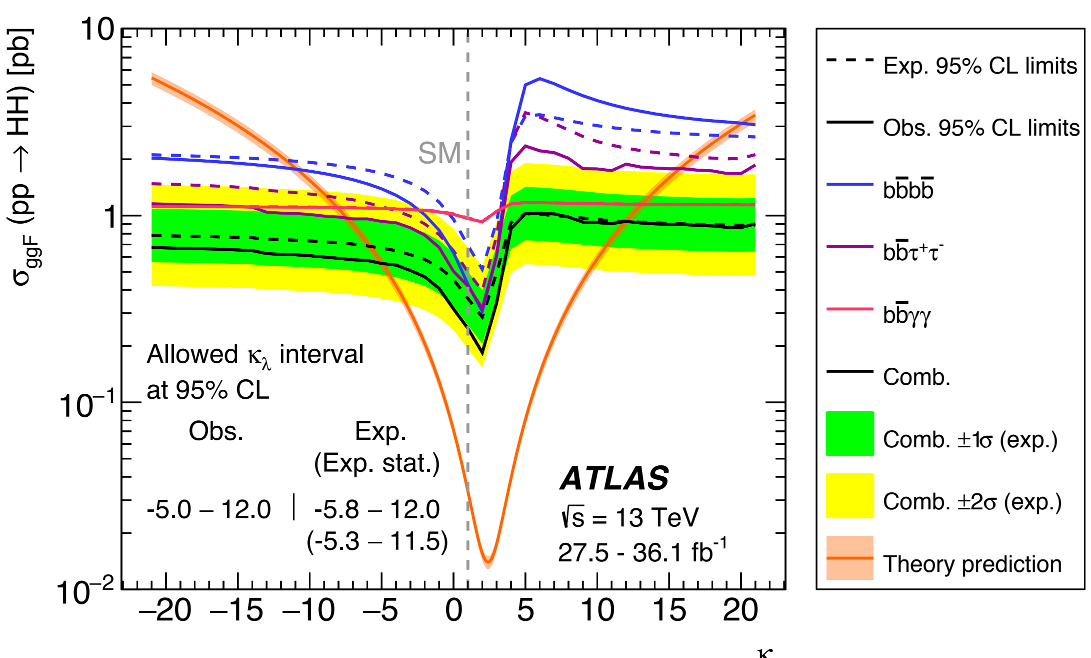


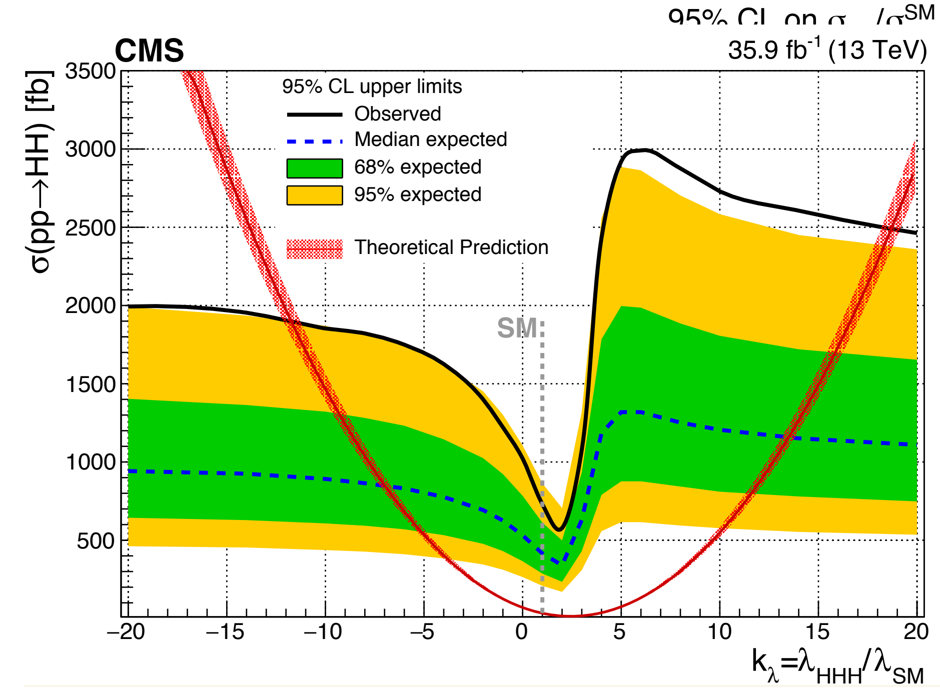
Current measurement

Assume all kinematic properties of HH pair are same as SM prediction, and only ggF XS can deviate from SM (the cross section uncertainty ~10% was not included in the fitting.)





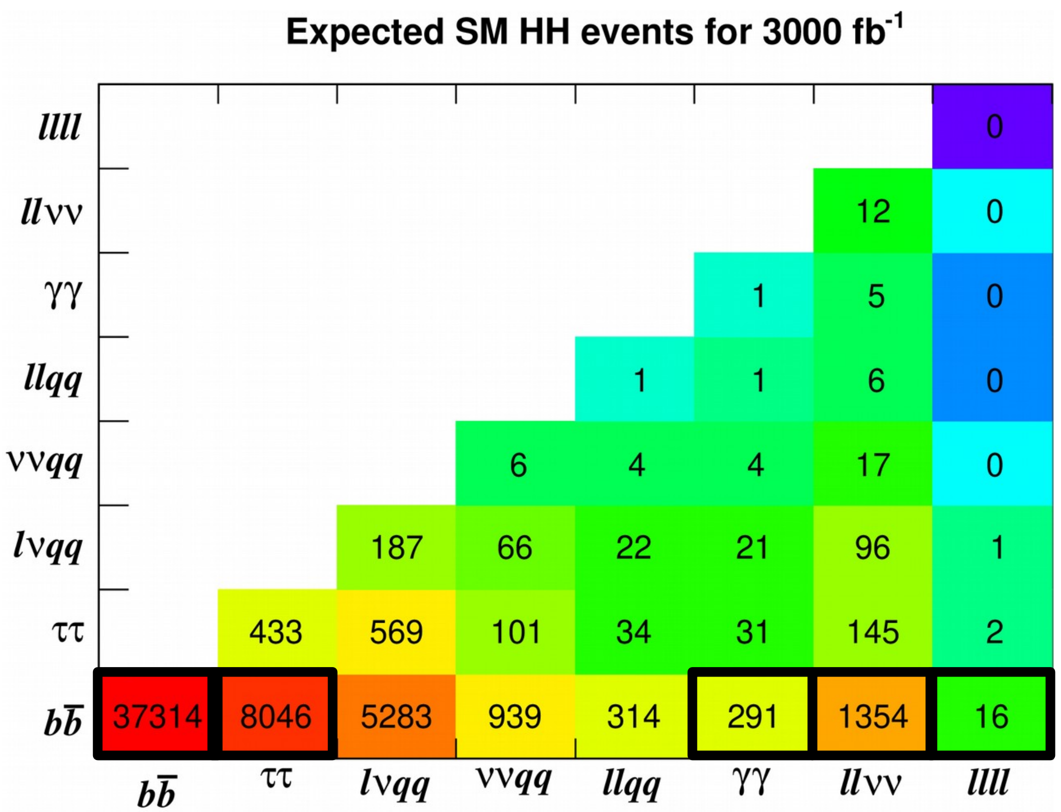




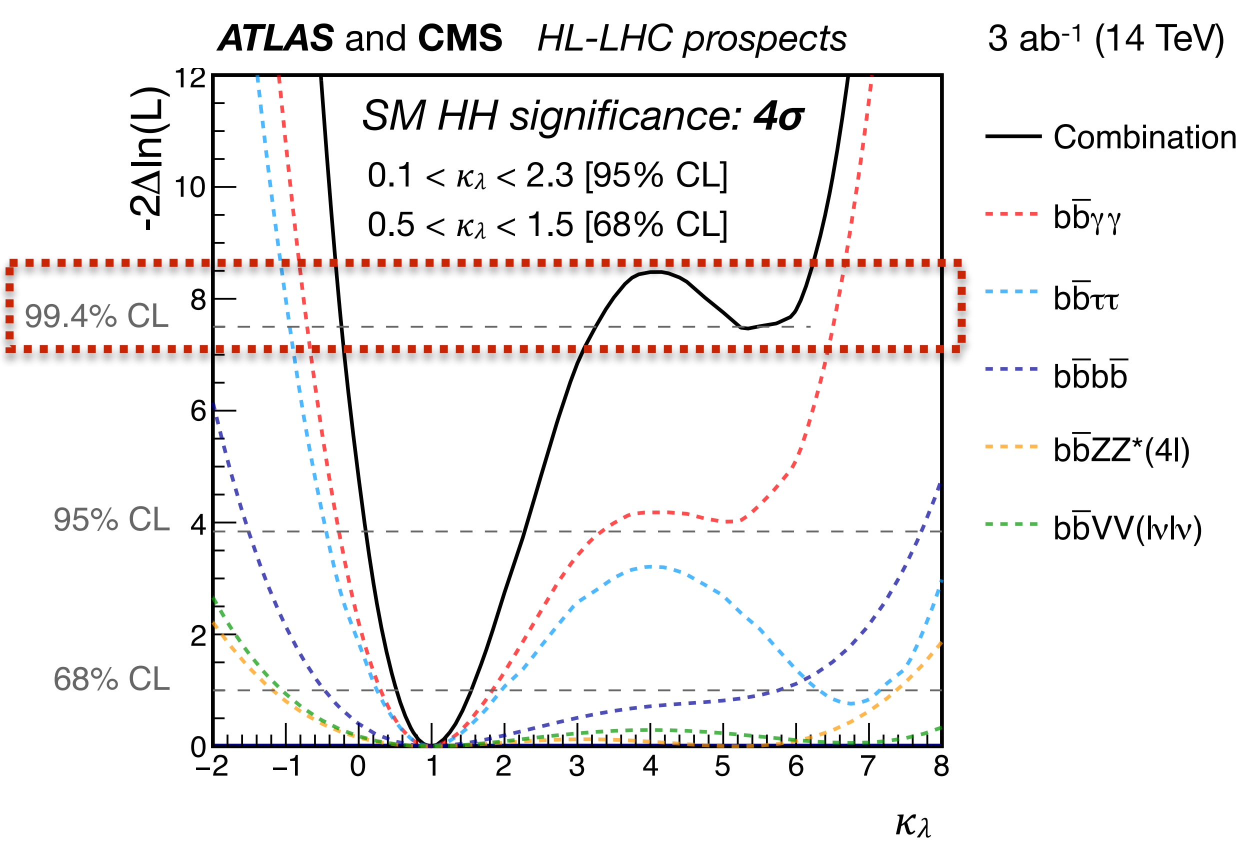
Getting close to **10*SM rate** for Di-Higgs production

Obs (Exp) κ_λ @ 95% CL: [-5.0,12.0] ([-5.8, 12.0]) for ATLAS , [-11.8, 18.8](-7.1, 13.6) for CMS

Prospect @ HL-LHC



	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

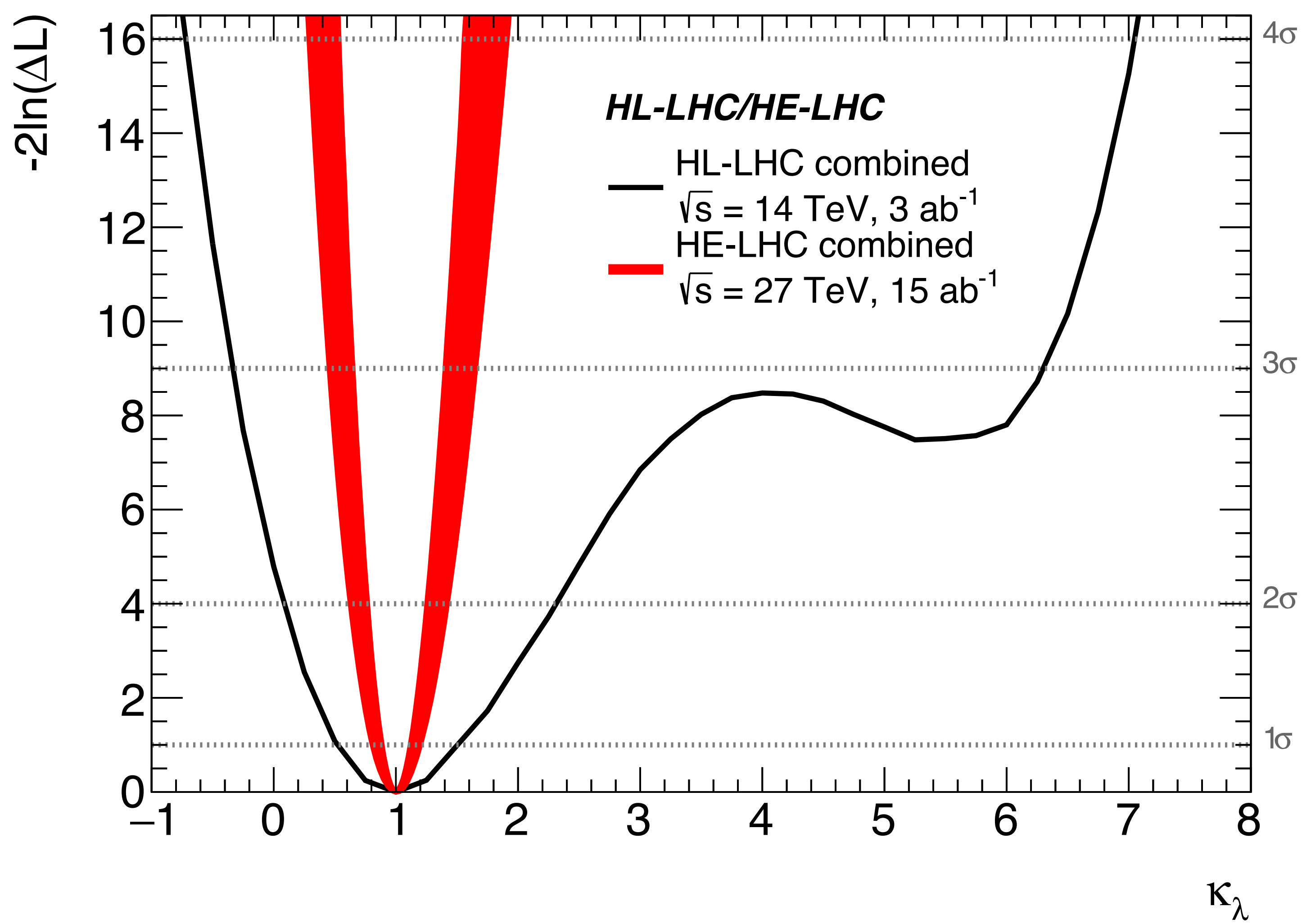


	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

Room with the exploration of the dependence on κλ

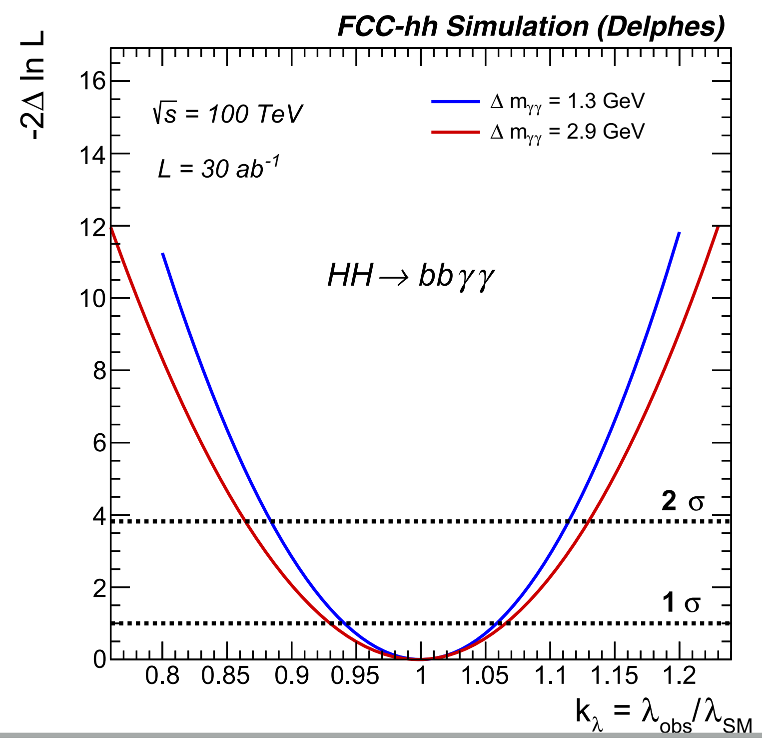
Prospect @ HE-LHC

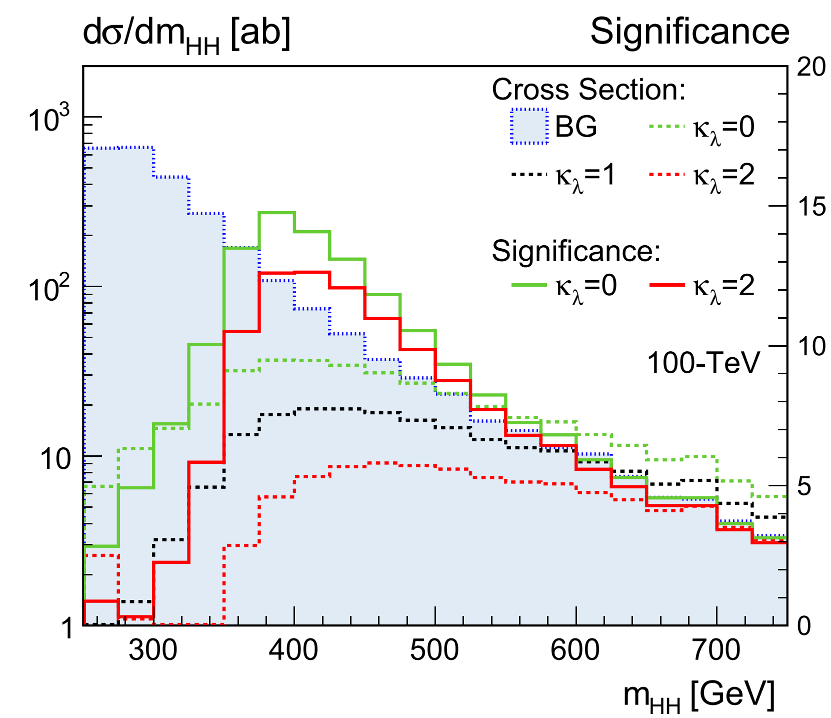
- Extrapolate ATLAS HL-LHC results to HE-LHC:
  - scale **cross-section (*4)** from 14TeV to 27TeV and **luminosity (*5)** to 15ab-1
  - **bbγγ**： 7.1σ with the precison on κ_λ of ~20%
  - **bbττ:** 10.7σ with the precision on κ_λ of ~40%
  - **Combination:** the precision on κ_λ of 10-20%



Prospect @ FCC-hh

	σ[100 TeV](fb)	σ[27 TeV](fb)
$gg \to HH$	$1.22 \times 10^{3}\,{}^{+0.9\%}_{-3.2\%} \pm 2.4\% \pm 4.5\%_{m_t}$	$140\,{}^{+1.3\%}_{-3.9\%} \pm 2.5\% \pm 3.4\%_{m_t}$
HHjj	$80.5 \pm 0.5\% \pm 1.8\%$	$1.95 \pm 2\% \pm 2.4\%$
$W^{+}HH$	$4.7 \pm 1\% \pm 1.8\%$	$0.37 \pm 0.4\% \pm 2.1\%$
$W^{-}HH$	$3.3 \pm 4\% \pm 1.9\%$	$0.20 \pm 1.3\% \pm 2.7\%$
ZHH	$8.2 \pm 5\% \pm 1.7\%$	$0.41 \pm 3\% \pm 1.8\%$
$t\bar{t}HH$	$82.1 \pm 8\% \pm 1.6\%$	$0.95\,{}^{+1.7\%}_{-4.5\%} \pm 3.1\%$



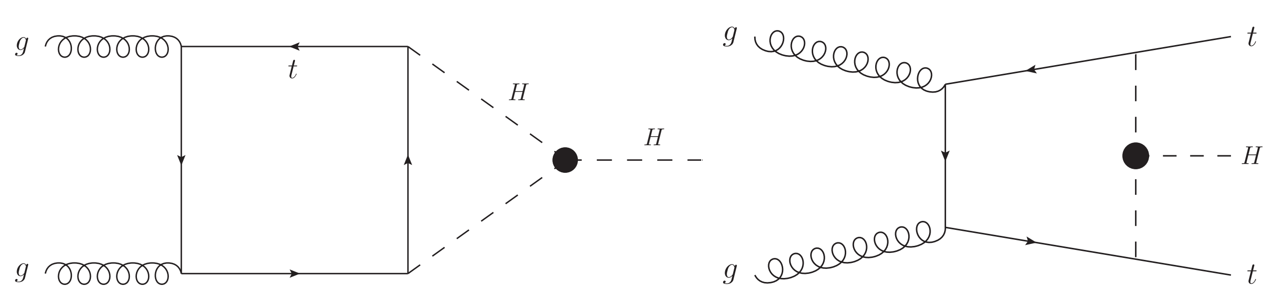


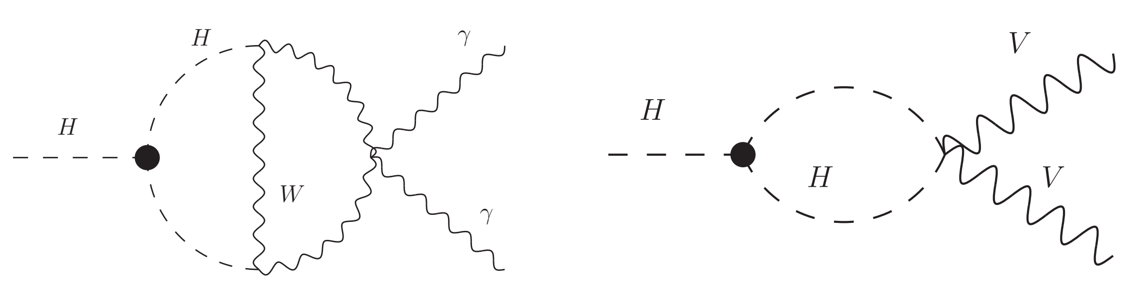
- Most sensitivity from bbγγ channel： different variation scenarios on photon efficiency, resolution, background level etc—> 5-7% uncertainty on κ_λ.
- More sensitivity can be achieved via kinematic exploration: mHH, Higgs pT and various angular correlation

	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^{*}[\to 4\ell]$	$b\bar{b}WW^{*}[\to 2j\ell\nu]$	$4b + \text{jet}$
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

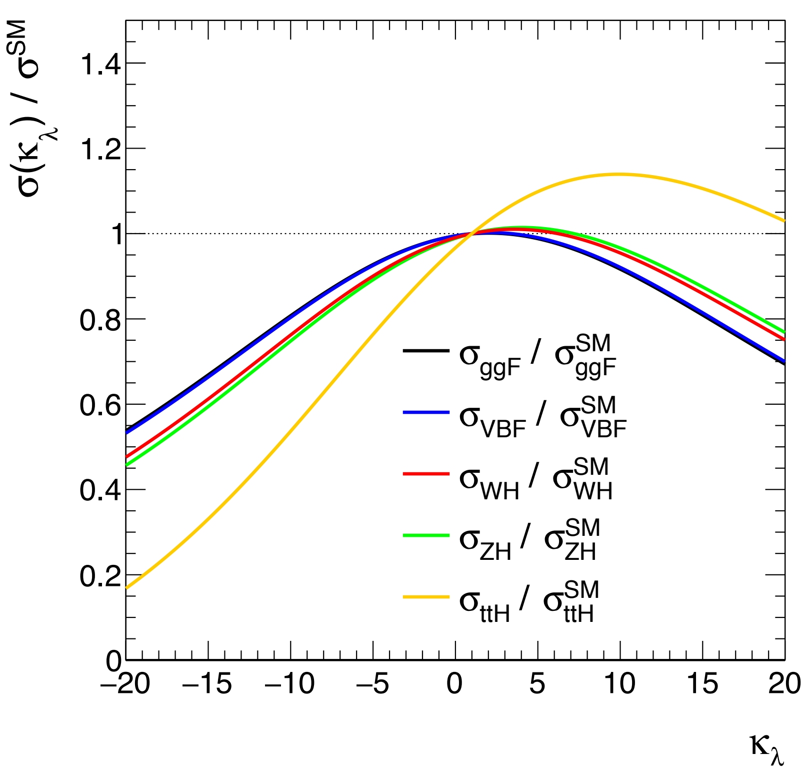
Indirect measurement from single Higgs processes

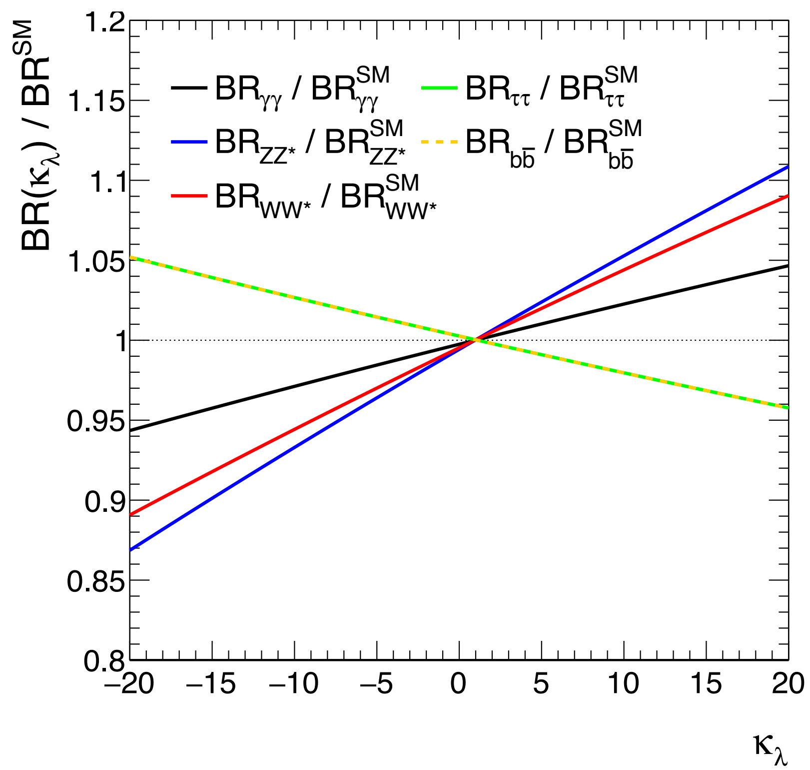
All the single Higgs production and decay processes are affected by an anomalous trilinear (**<u>not quartic</u>**) Higgs self coupling, parametrized by κ_λ.





All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.





$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = Z_H^{\rm BSM}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right]$$

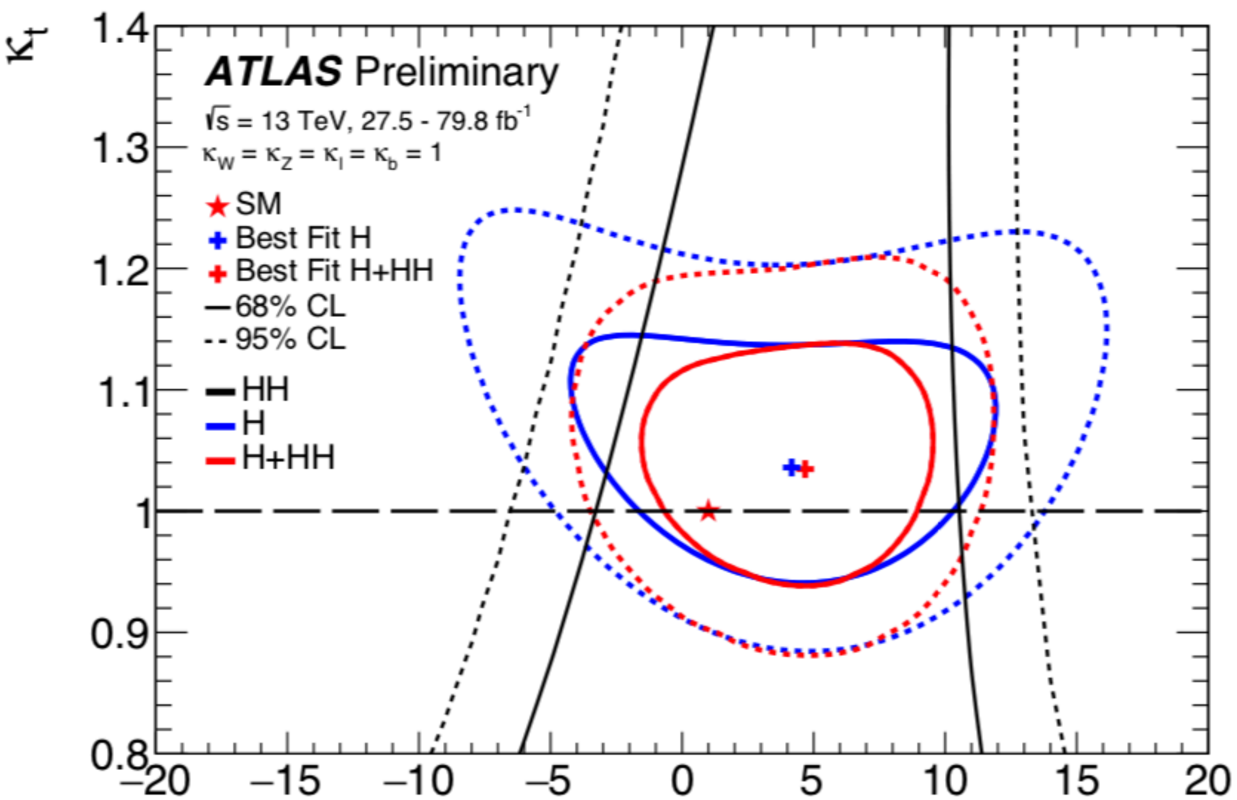
production mode	ggF	VBF	ZH	WH	$t\bar{t}H$
$C_1^i \times 100$	0.66	0.63	1.19	1.03	3.52
$K_{\rm EW}^i$	1.049	0.932	0.947	0.93	1.014
κ_i^2	κ_F^2	κ_V^2	κ_V^2	κ_V^2	κ_F^2

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{{\rm BR}_f^{\rm BSM}}{{\rm BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j {\rm BR}_j^{\rm SM}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

Constraint Higgs trilinear self-coupling

- Using STXS framework, constrain Higgs boson self-coupling using NLO EW corrections on the single Higgs boson production and decay.
- Complement direct measurement from HH channels and provide more stringent constraint.



ATLAS-CONF-2019-049

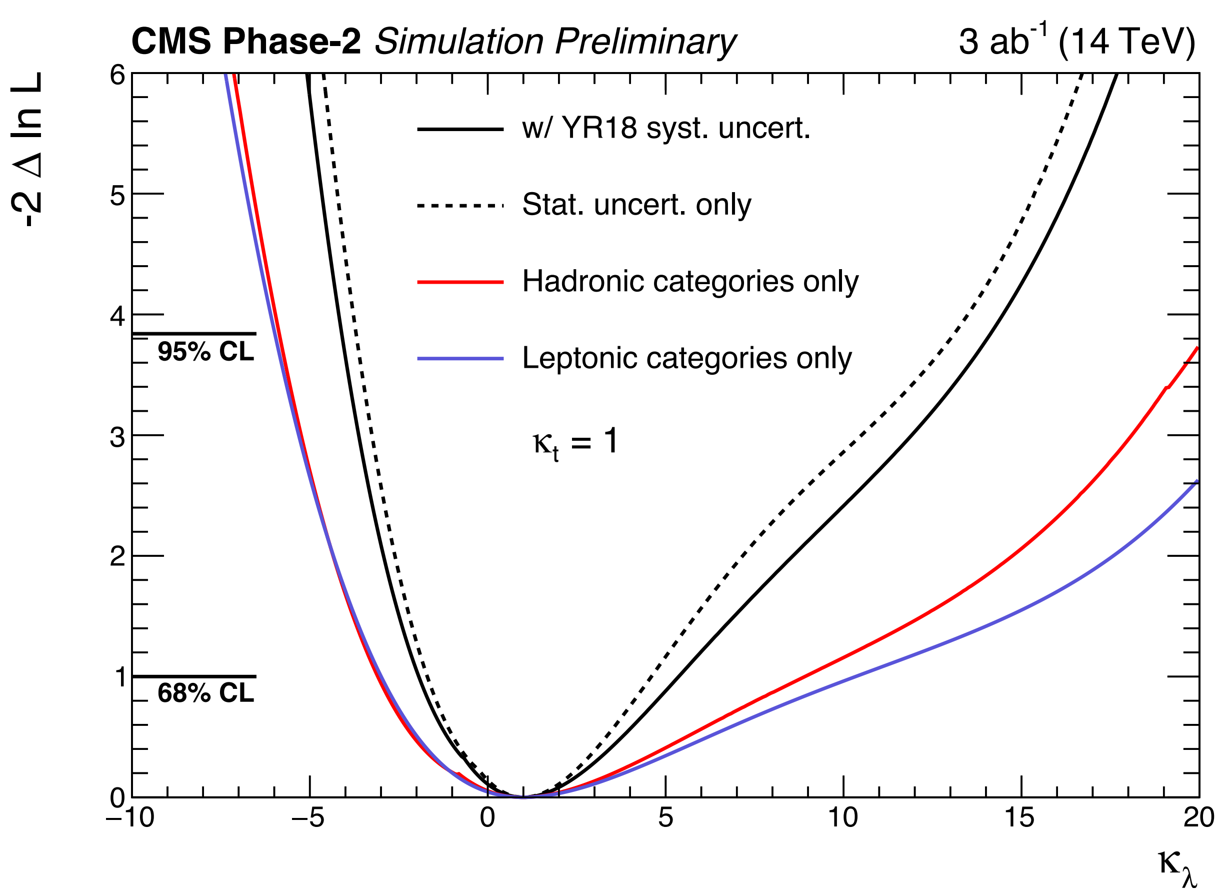
Constraint on **self-coupling (obs/expected) @ 95% CL:**

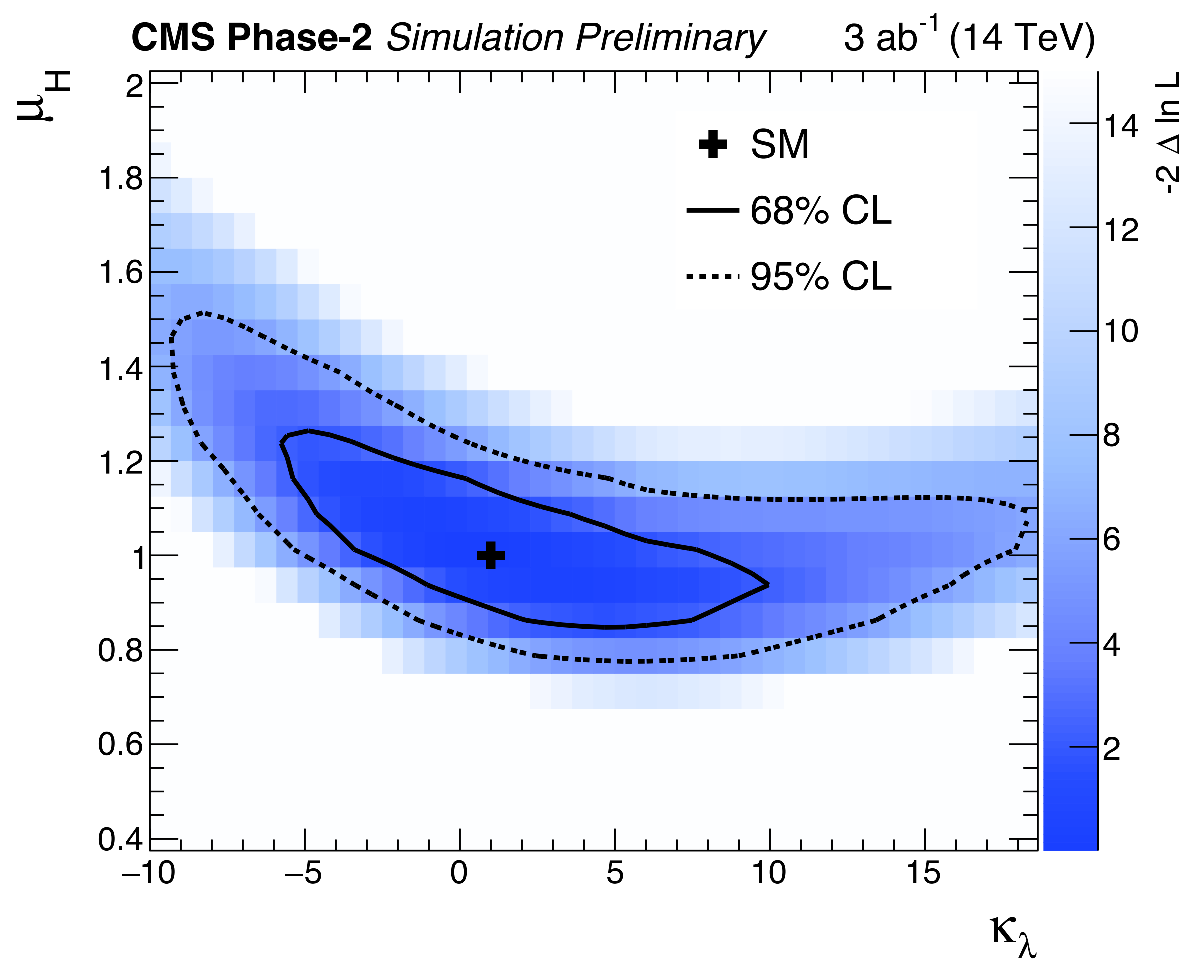
- **ATLAS (H):** **$-3.2<\kappa_\lambda<11.9$ / $-6.2<\kappa_\lambda<14.4$**
- **ATLAS (HH):** $-5.0<\kappa_\lambda<12.0$ / $-5.8<\kappa_\lambda<12.0$
- **ATLAS (H+HH):** **$-2.3<\kappa_\lambda<10.3$ / $-5.1<\kappa_\lambda<11.2$**
- **CMS(HH):** $-5.8<\kappa_\lambda<12.0$ / $-5<\kappa_\lambda<12.1$

- **Limited access to possible BSM effect**
  - No consideration of the kinematic dependence on kλ in the single Higgs process
  - No consistent EFT predicts only SM coupling variation without new contact interactions.
  - Combine LO and NLO effects in the two measurements with a k-framework

Indirect probes through differential distributions of single Higgs processes

$p_T(H)$ [GeV]	$[0, 45]$	$[45, 80]$	$[80, 120]$	$[120, 200]$	$[200, 350]$	> 350
ttH	5.31	4.73	3.92	2.79	1.42	0.42
tH	1.32	1.19	1.00	0.75	0.40	0.06
VH	1.66	1.23	0.77	0.35	0.02	-0.09





Constraint on **self-coupling (exp) @ 95% CL:**

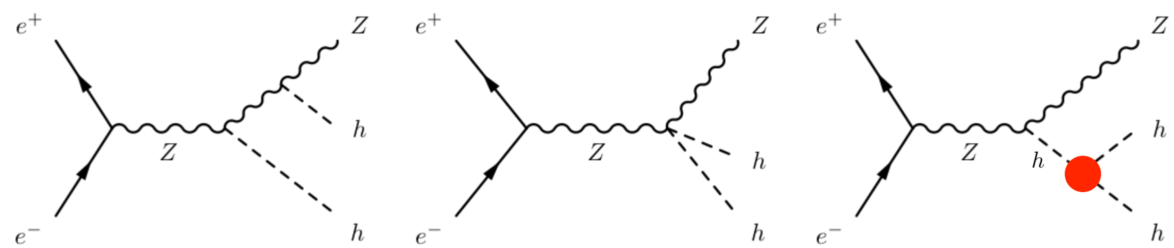
- **$-4.1<\kappa_\lambda<14.1$**

Constraint on **self-coupling (exp) @ 95% CL:**

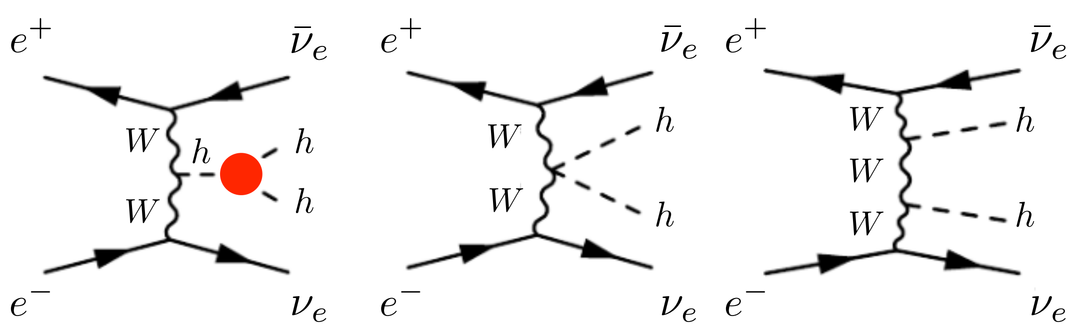
- **$-7.1<\kappa_\lambda<14.1$**

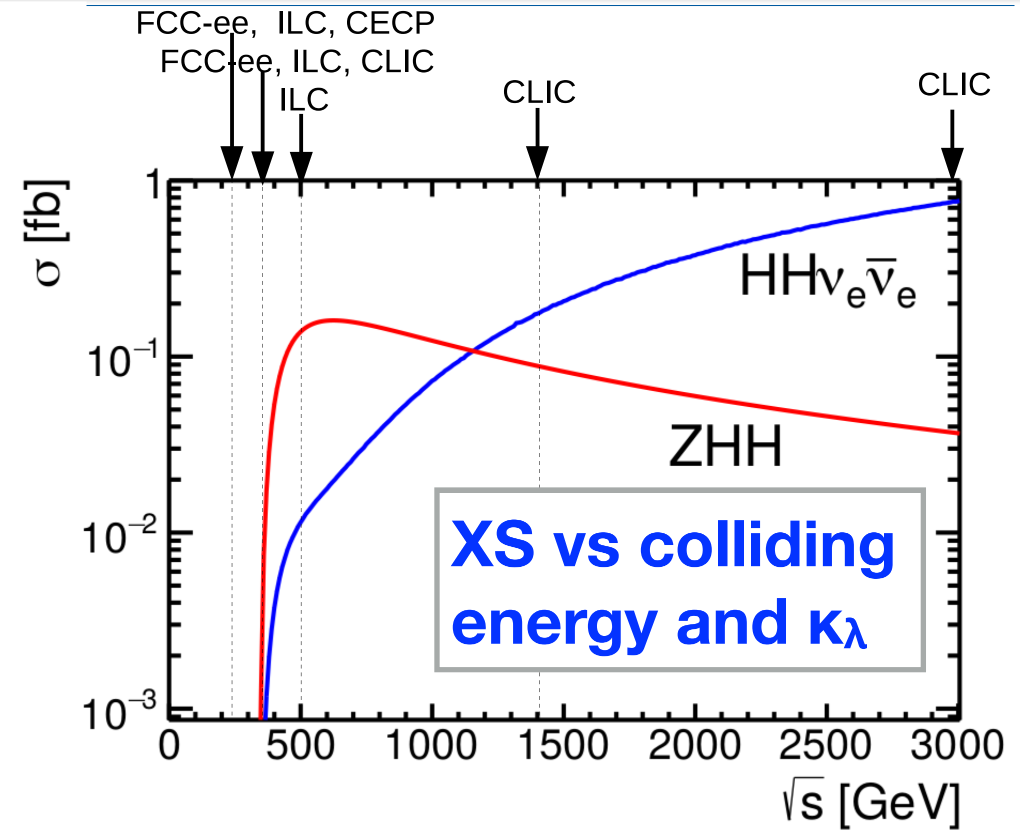
Lepton collider: Di-Higgs production

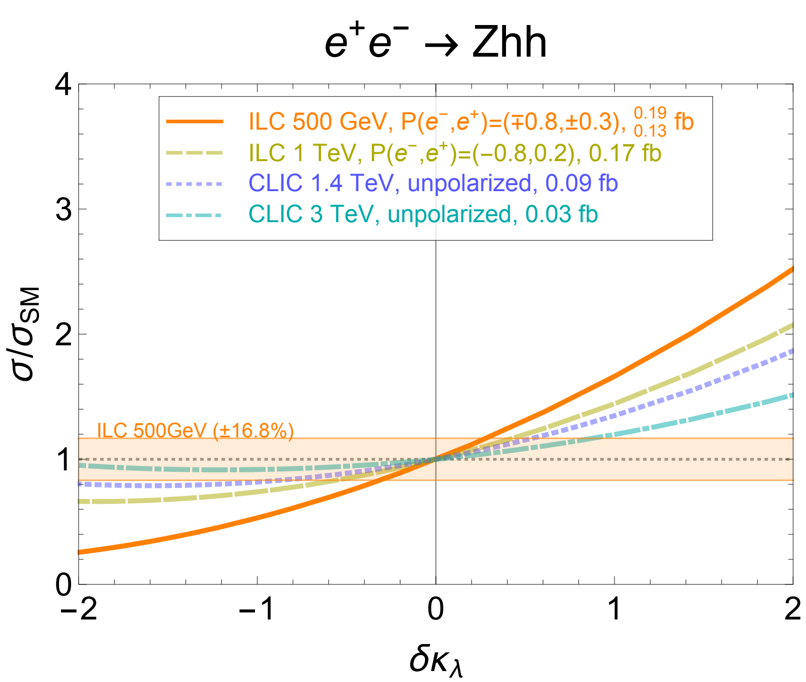
- Higgs-strahlung: ee→ZHH

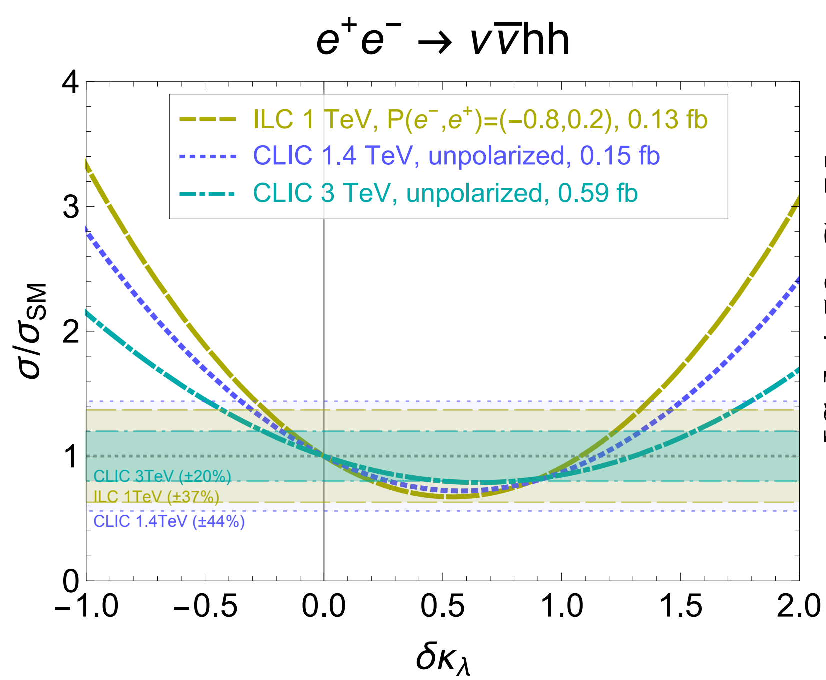


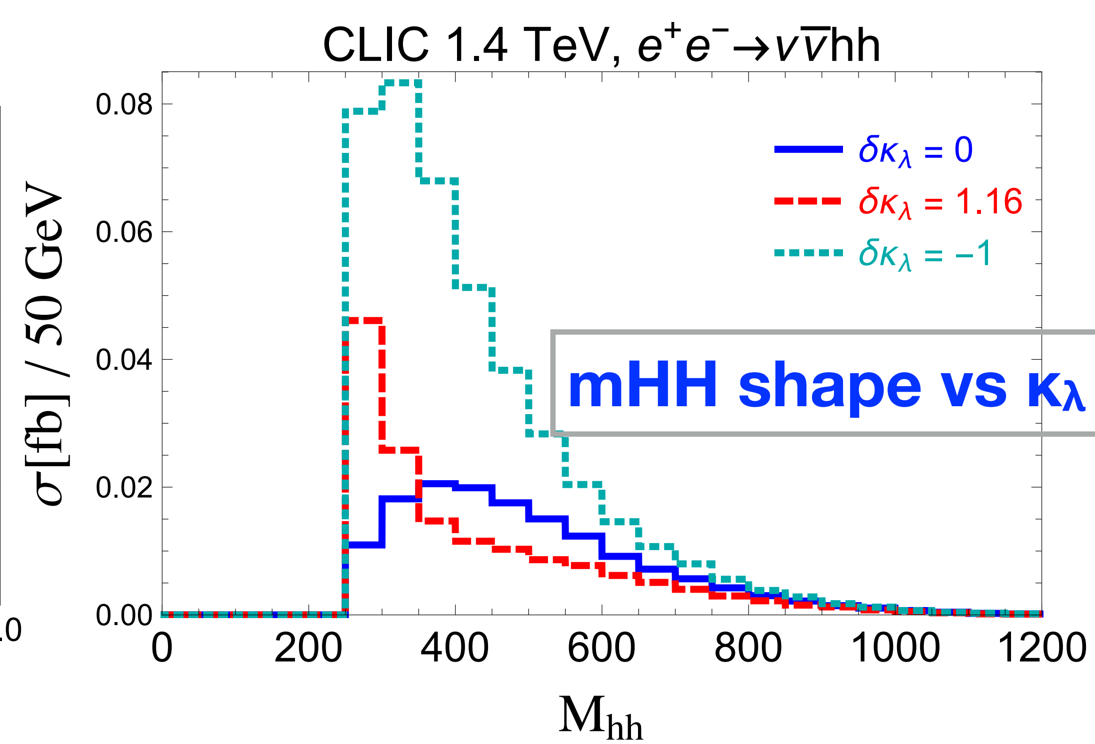
- VBF: ee→vvHH



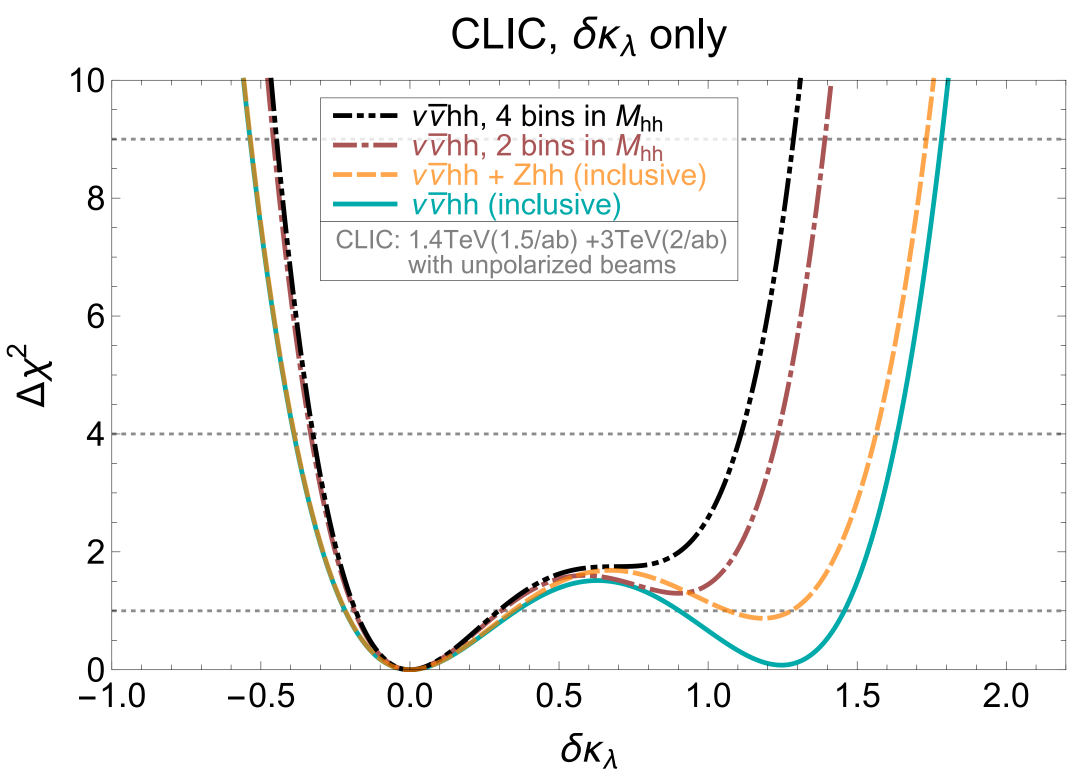


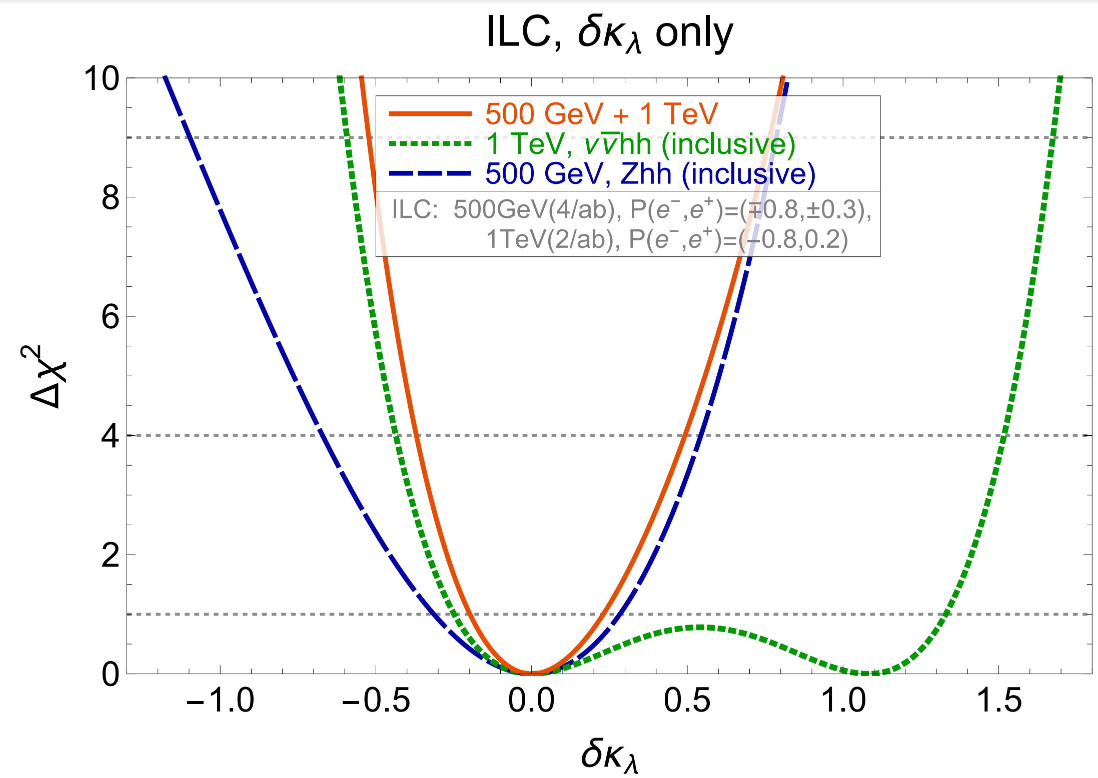






Exclusive measurement for high-energy lepton colliders



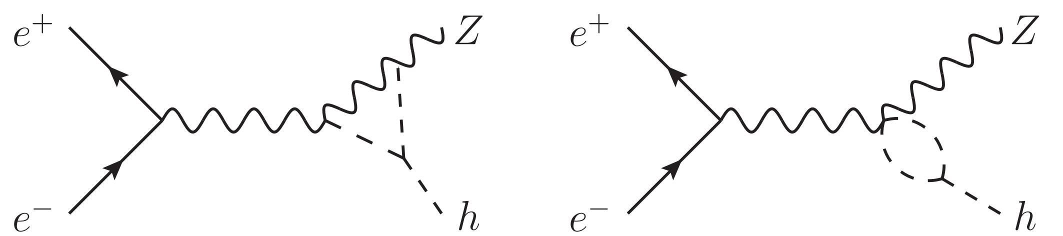


	68 %CL	95%CL
ILC 500 GeV	$[-0.31,\ 0.28]$	$[-0.67,\ 0.54]$
ILC 1 TeV	$[-0.25,\ 1.33]$	$[-0.44,\ 1.52]$
ILC combined	$[-0.20,\ 0.23]$	$[-0.37,\ 0.49]$
CLIC 1.4 TeV	$[-0.35,\ 1.51]$	$[-0.60,\ 1.76]$
CLIC 3 TeV	$[-0.26,\ 0.50] \cup [0.81,\ 1.56]$	$[-0.46,\ 1.76]$
CLIC combined	$[-0.22,\ 0.36] \cup [0.90,\ 1.46]$	$[-0.39,\ 1.63]$
$+Zhh$	$[-0.22,\ 0.34] \cup [1.07,\ 1.28]$	$[-0.39,\ 1.56]$
2 bins in $\nu\bar{\nu}hh$	$[-0.19,\ 0.31]$	$[-0.33,\ 1.23]$
4 bins in $\nu\bar{\nu}hh$	$[-0.18,\ 0.30]$	$[-0.33,\ 1.11]$

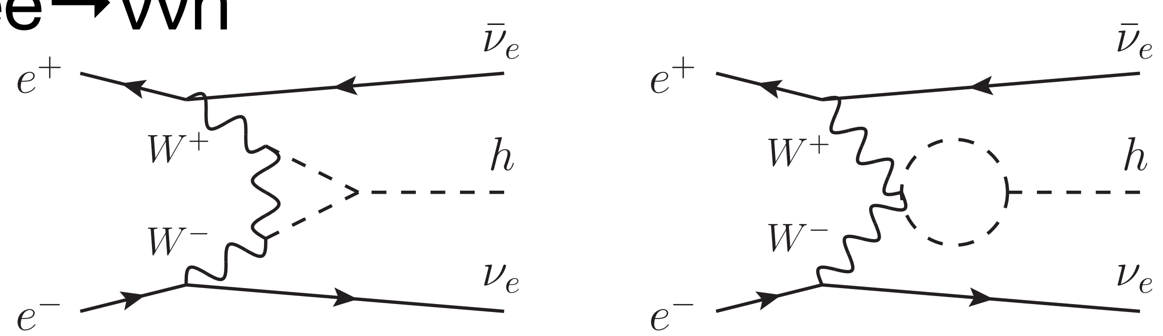
- Secondary solution @ $\delta\kappa_\lambda$~1 for the vvHH process
- m_{HH} differential analysis can help for the exclusion of the secondary solution
- Zhh is useful to enhance the precision

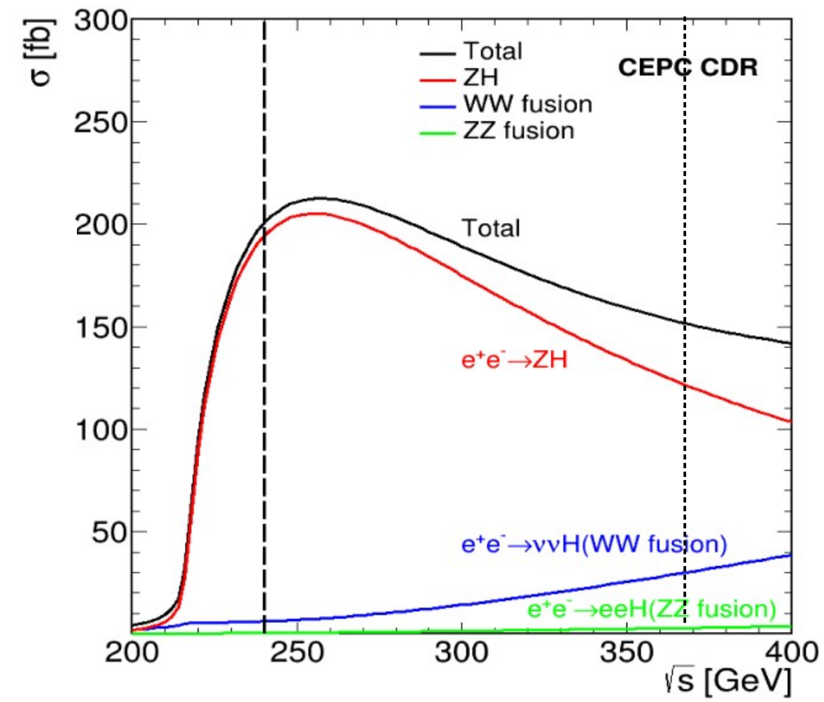
Indirect measurement from single Higgs processes

- ee→hZ



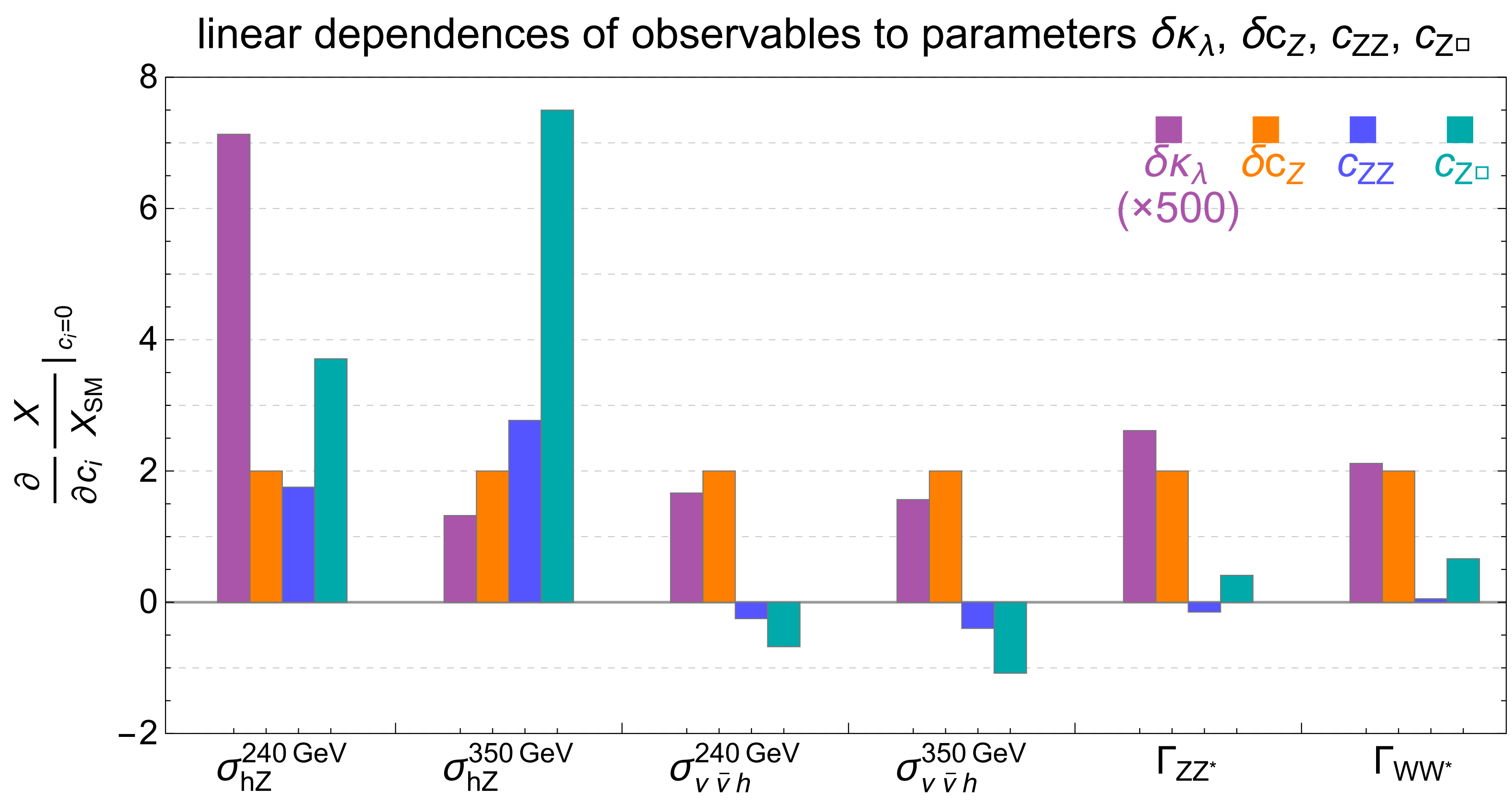
- ee→vvh

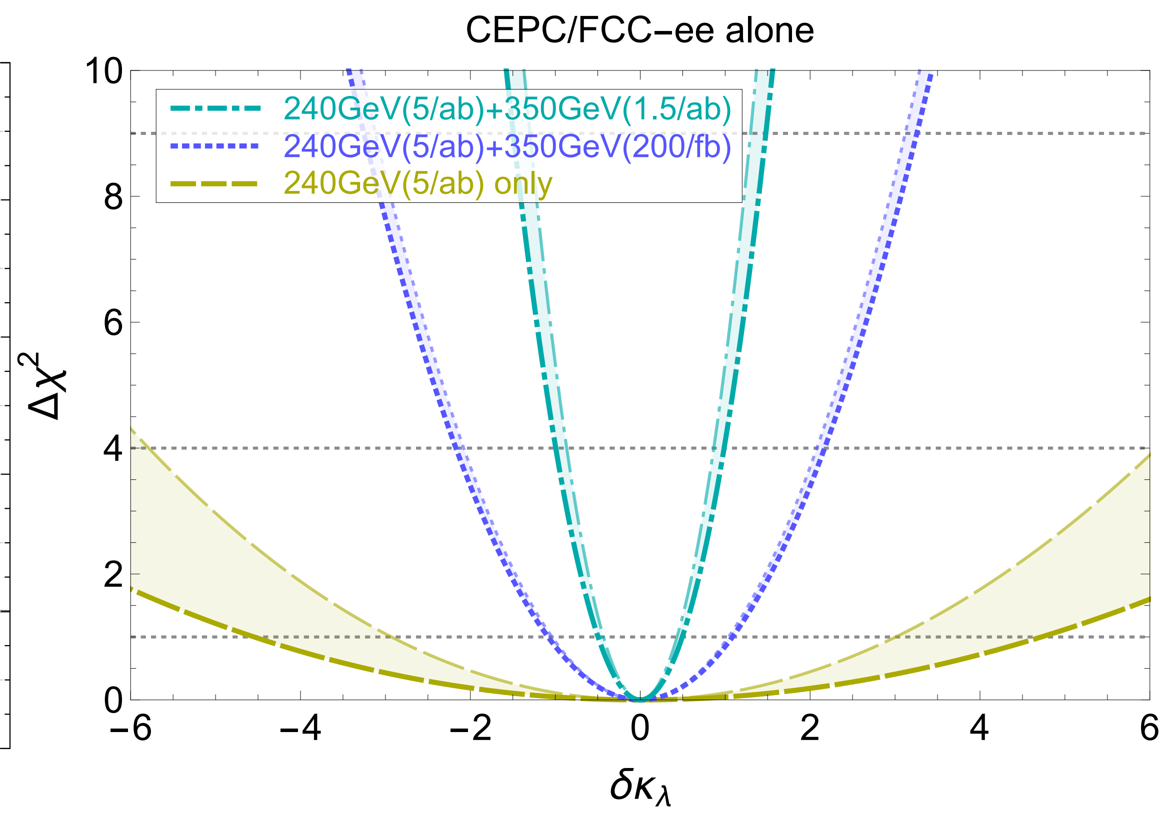




- **Processes for the global fit :**
  - **Higgsstrahlung production: ee→hZ**
  - **WW-funsion production: ee→vvh**
  - **Weak boson pair production: ee→WW**
- **Parameter list with new physics parametrization** through dimension-6 operators with EFT framework and simplicity assumption (CP-conserving, theory uncertainty etc.)
  - **Higgs couplings to the gauge bosons:** $\delta c_Z,\ c_{ZZ},\ c_{Z\Box},\ c_{\gamma\gamma},\ c_{Z\gamma},\ c_{gg}$
  - **Yukawa couplings:** $\delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu$
  - **Trilinear gauge couplings:** λ_Z
  - **Trilinear Higgs self-coupling:** $\delta\kappa_\lambda$

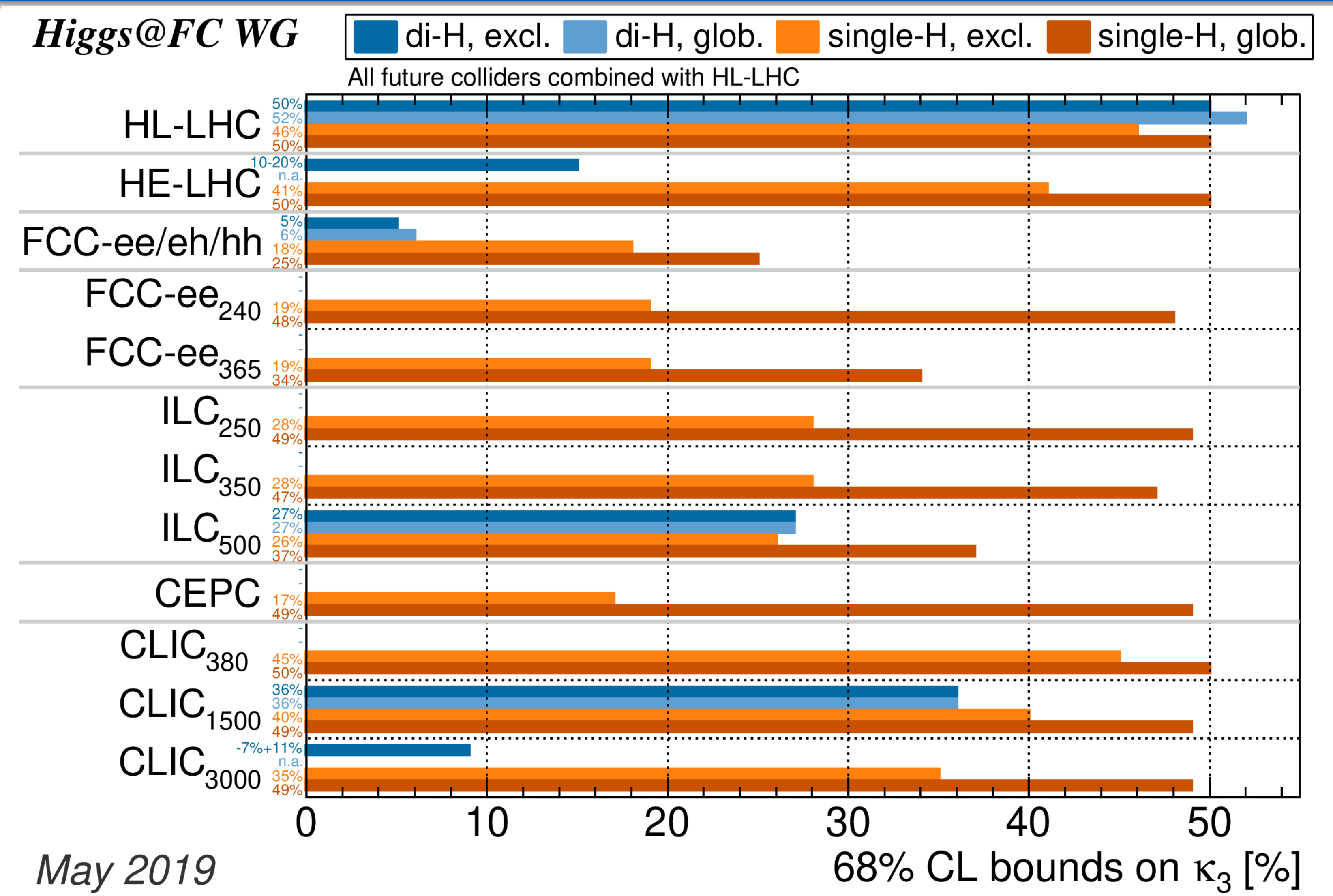
Indirect measurement from single Higgs processes





- Based on very **good precision on cross section** eg CEPC / FCC-ee:
  - σ(ZH) :~ 0.5% , σ(vvH) : 2-3%
  - The potential of constraining κλ with a precision better than O(1)

Comparison



- Constraint set by the HH production has a small impact from global analysis
- Single Higgs analysis can complement the results from HH analysis and global analysis is important to get robust results
- FCC-ee / CEPC can reach a sensitivity of ~20%, CLIC3000 / FCC-hh can reach a sensitivity of ~10%/5%.

Summary

- Prospective measurement of the tri-linear coupling at Future Colliders through the HH and single-Higgs production

- HL-LHC: 4σ evidence of the HH process with ATLAS and CMS combination. More room for the further improvement by exploring the kinematic dependence on κ_λ

- Sensitivity from Future colliders and combination with HL-LHC: 40% for CEPC/FCC-ee, further improvement to ~20% with the increasing of the collider energy, 2-5% for FCC-hh.