Higgs boson self-coupling measurements and extended Higgs boson sector

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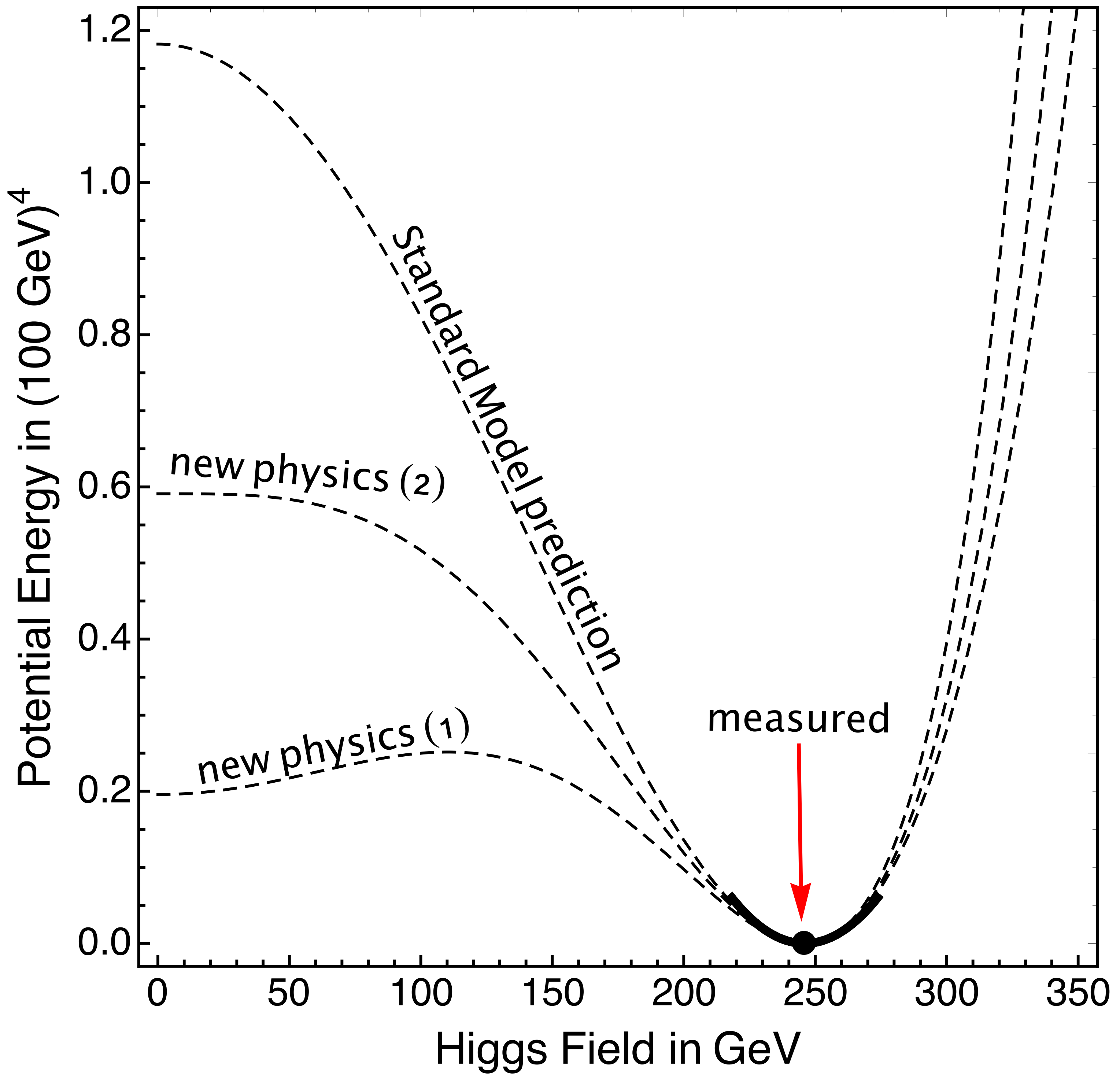
arXiv:1112.3022

Why λ_{HHH} is so important ?

The shape of the scalar potential is linked to many open questions of particle physics and cosmology

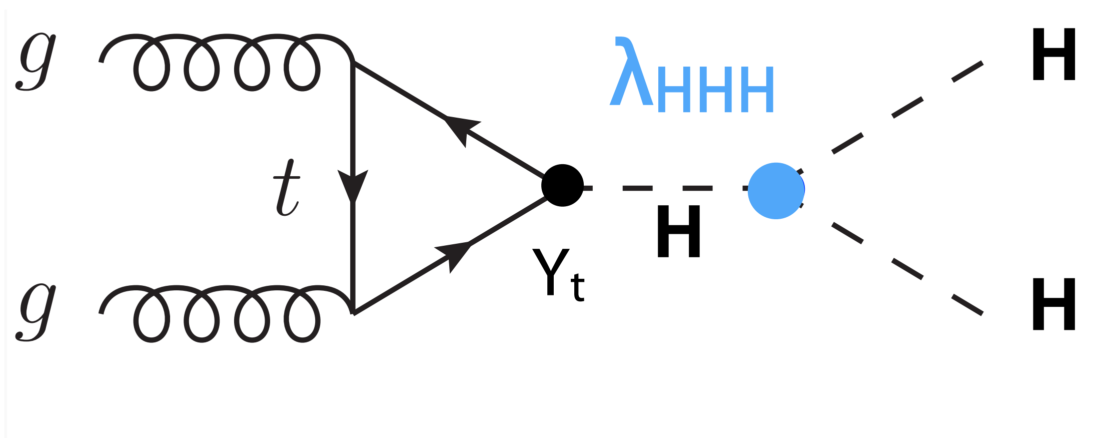


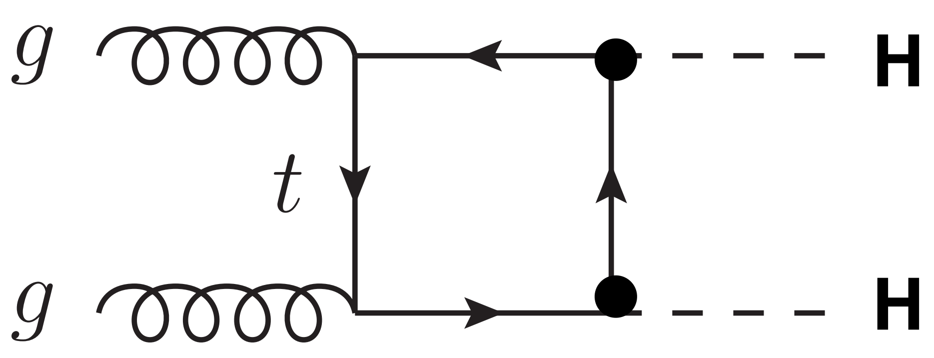
➔ The modification of the scalar potential at high scales makes the EW vacuum metastable

➔ The stability of the potential at high mass has an impact of the possible role of the Higgs boson as the inflaton in the primordial Universe

The HL-LHC λ_{HHH} "legacy"

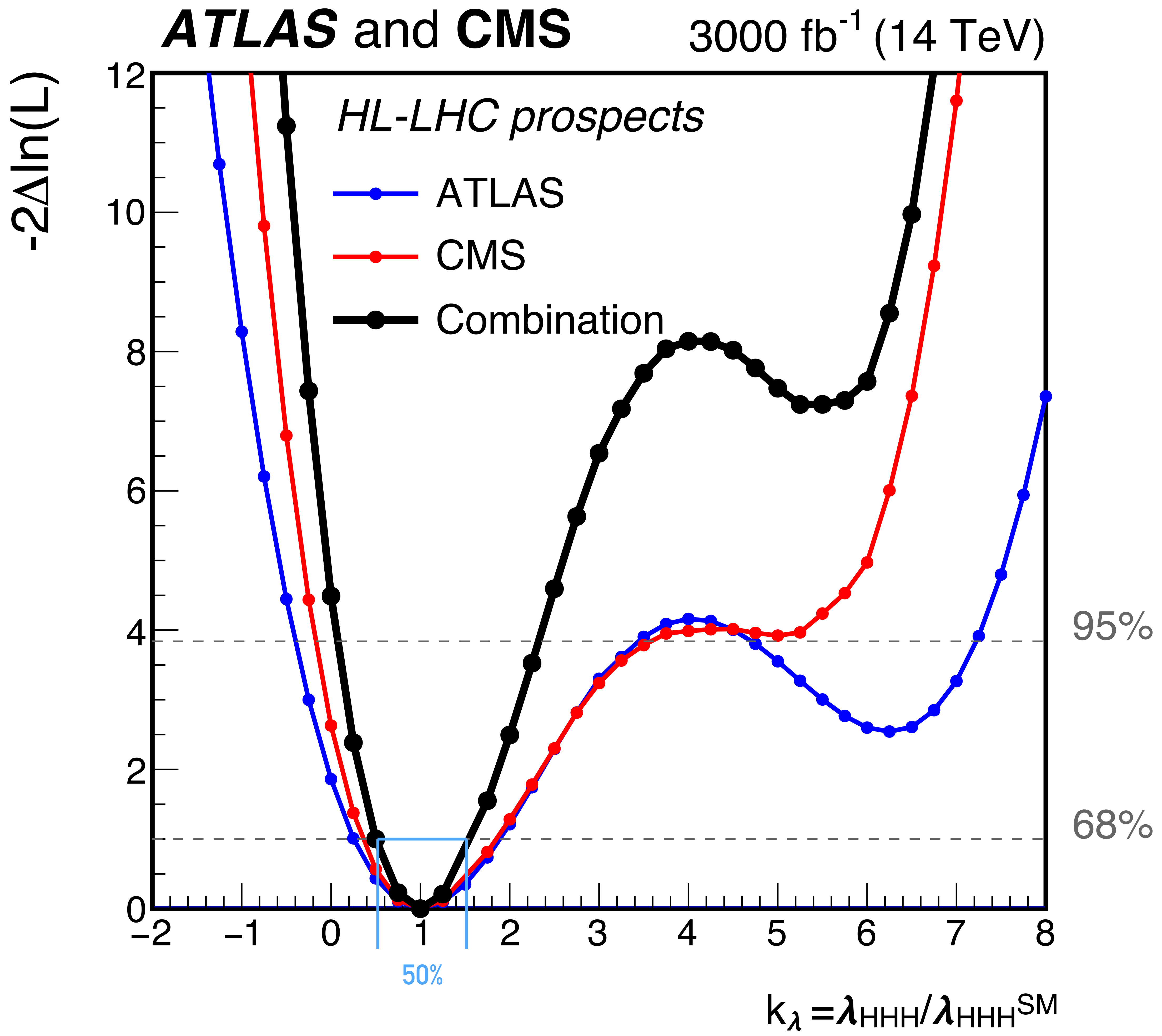
Measured in double Higgs boson production





Significance of HH production

	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	



➔ Constraint on the Higgs self-coupling of $0.5 < k_\lambda < 1.5$ at the 68% CL (e.g. 50% precision)

➔ The secondary minimum in the likelihood lineshape (due the degeneracy in the total number of HH signal events) excluded at 99.4%CL

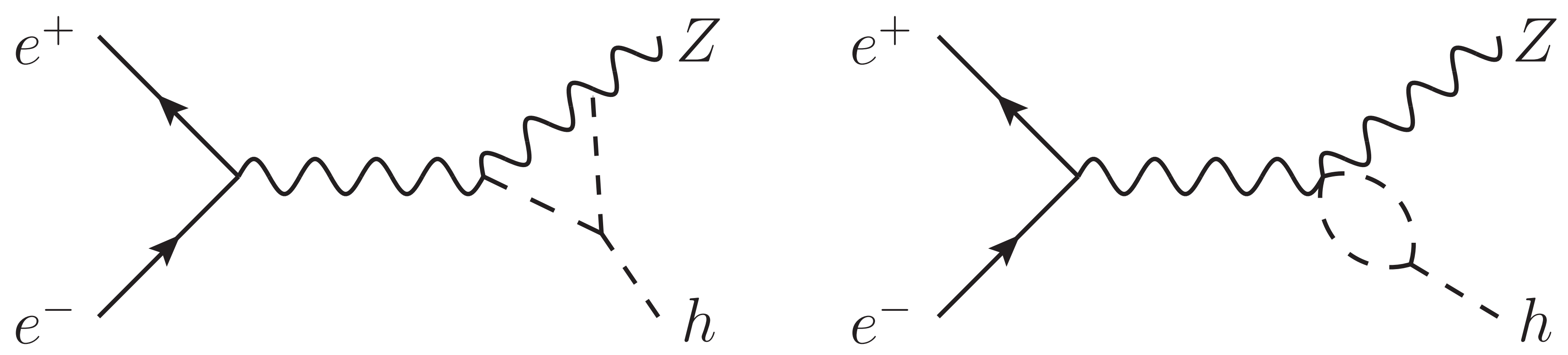
λ_{HHH} @ FCC-ee

Higher-order corrections to single-Higgs processes

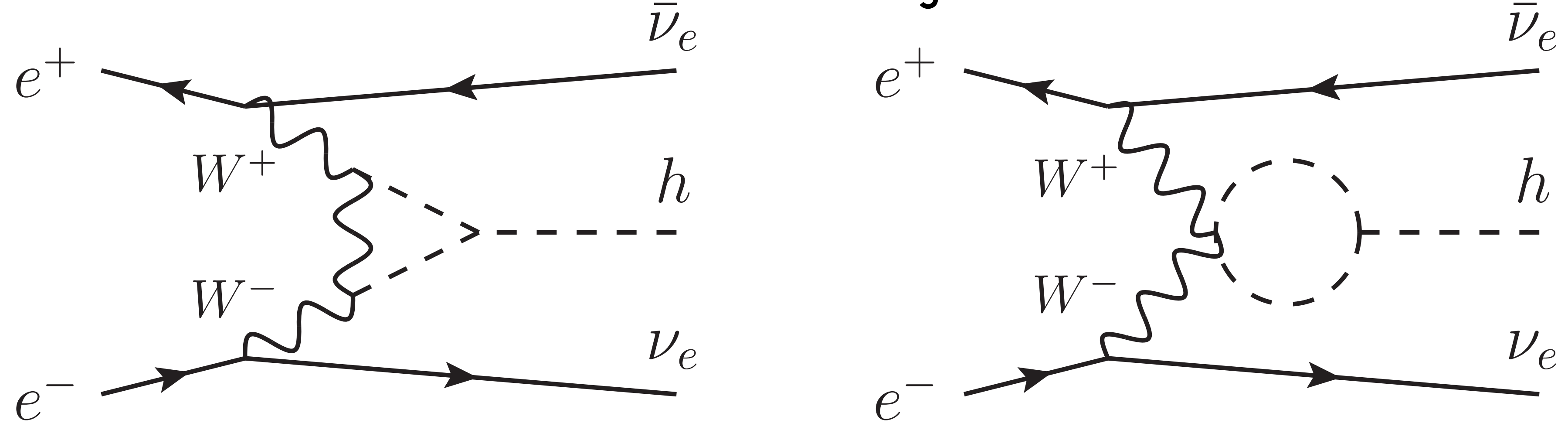
λ_{HHH} does not enter single-Higgs processes at LO but it affects both Higgs production and decay at NLO.

Linear correction to the vertex

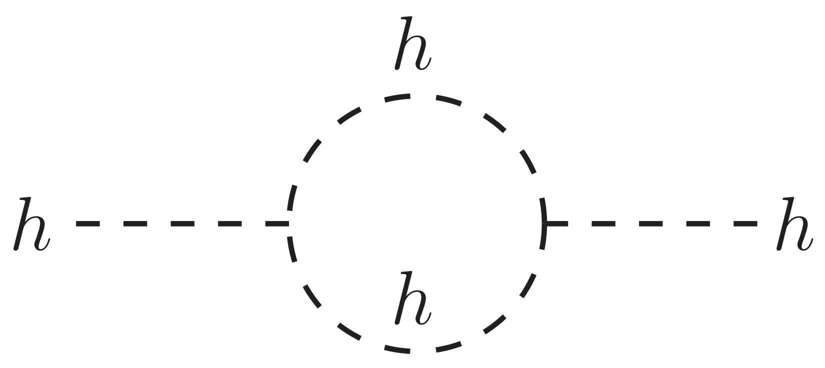
ZH Higgsstrahlung

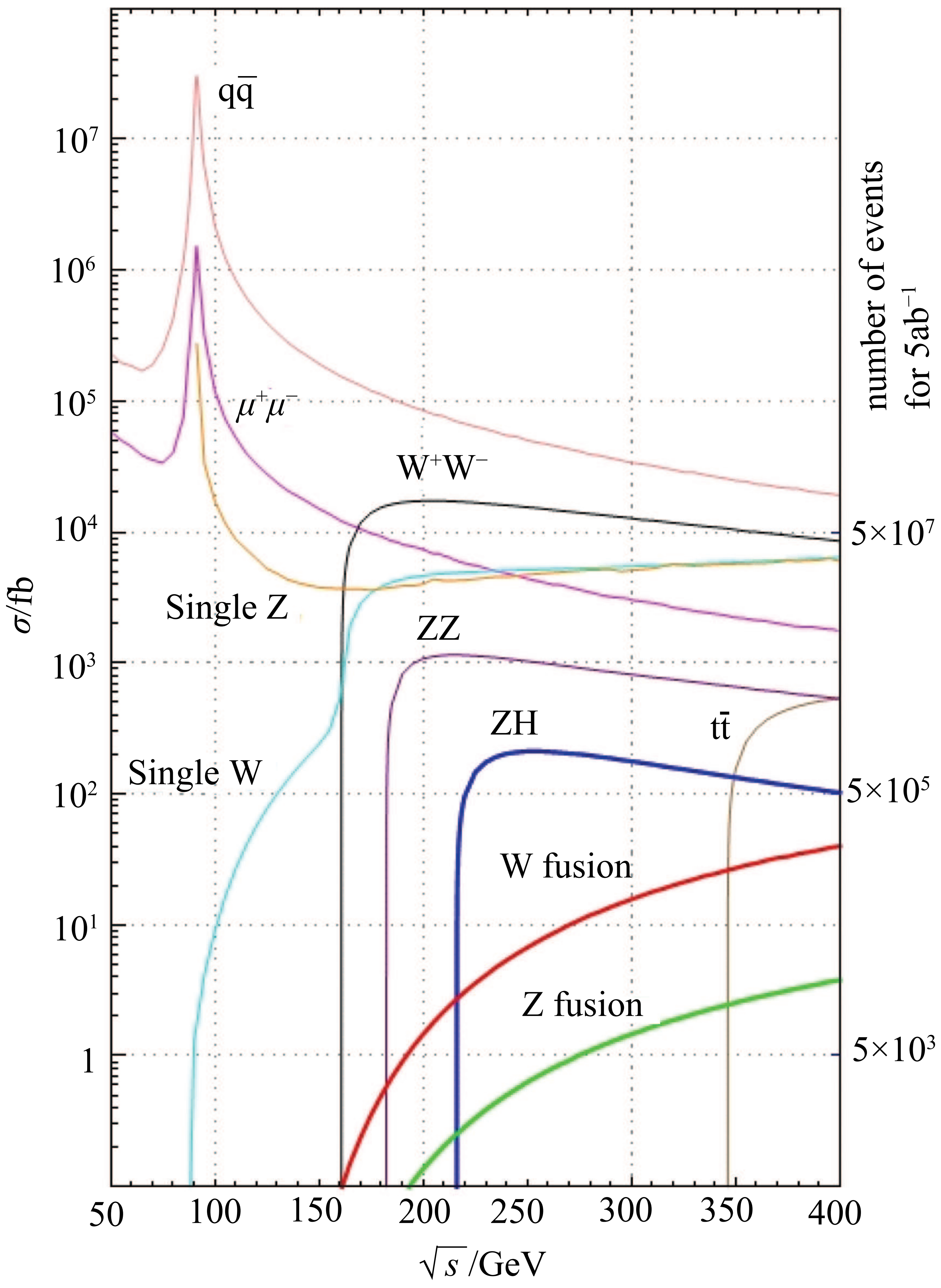


VBF processes
Both CC/NC diagrams



Quadratic corrections
(wave function renormalisation)





λ_{HHH} effect

arXiv:1711.03978

The NLO corrections to an observable Σ (e.g. σ(HZ))

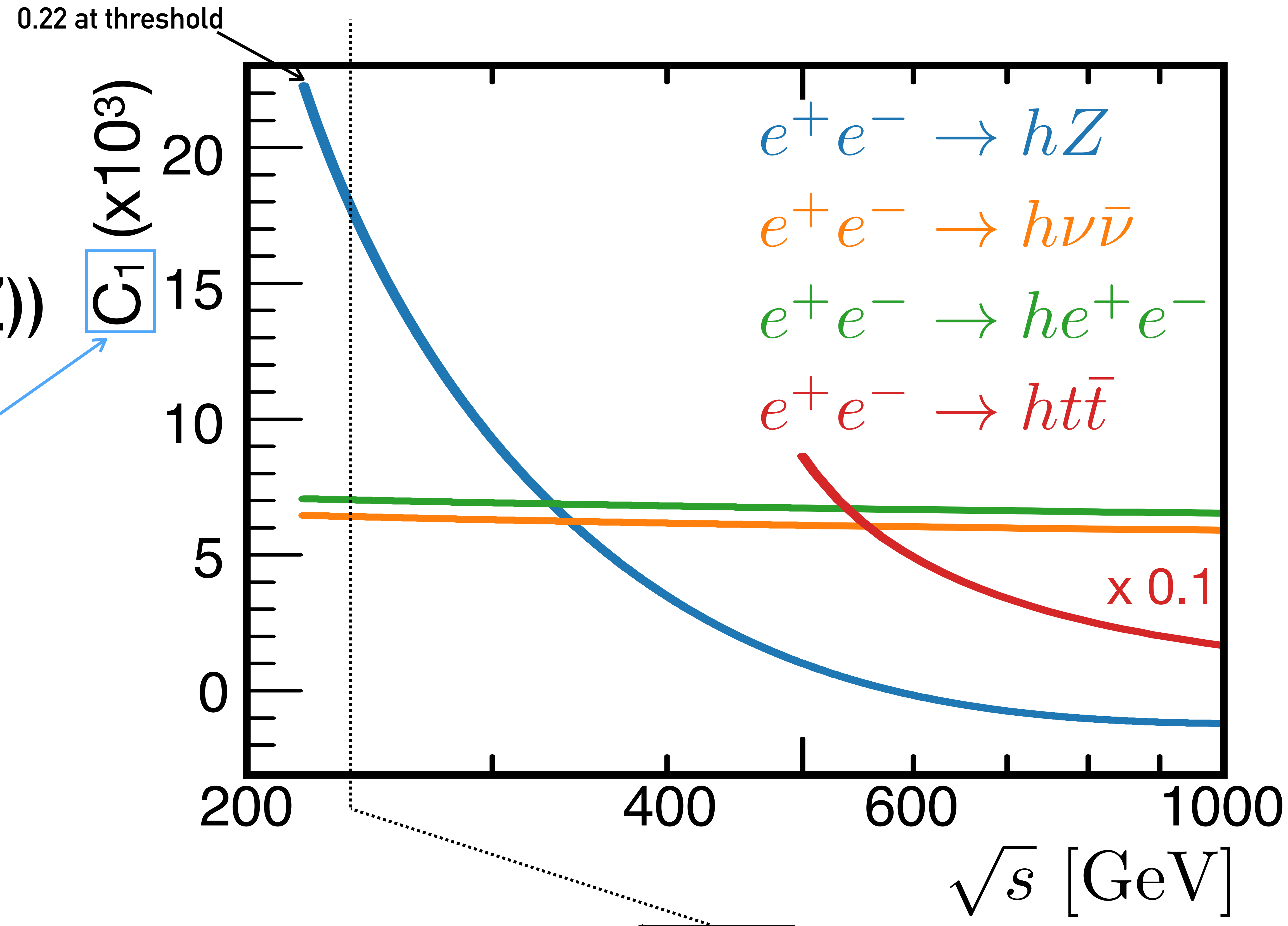
$$\Sigma_{\rm NLO} = \boxed{Z_H}\Sigma_{\rm LO}(1+\kappa_\lambda \boxed{C_1})$$

Universal coefficient — Process dependent coefficient

The impact of a deviation $\delta\kappa_\lambda$ from the SM value

$$\delta\Sigma \equiv \frac{\Sigma_{\rm NLO}}{\Sigma_{\rm NLO}(\kappa_\lambda=1)} - 1 \simeq (C_1 + 2\boxed{\delta Z_H})\delta\kappa_\lambda + \boxed{\delta Z_H}\delta\kappa_\lambda^2$$

$\delta Z_H \sim -0.00154$



C_1	**240**	350	500
$e^+e^- \to hZ$	0.017	0.0057	0.00099
$e^+e^- \to h\nu\bar{\nu}$	0.0064	0.0062	0.0061
$e^+e^- \to he^+e^-$	0.0070	0.0069	0.0067
$e^+e^- \to ht\bar{t}$			0.086

RULE OF THUMB: ‰ σ(HZ) measurement implies a few 10% constraint !

The 2 ways to perform λ_{HHH} measurement

below the double Higgs boson production threshold

1. an exclusive analysis of single Higgs processes at higher order, considering only deformation of the Higgs cubic coupling → a one-dimensional EFT fit

2. a global analysis of single Higgs processes at higher order, considering also all possible deformations of the single Higgs couplings → a multi-parameter EFT fit

→ Robust bounds can be obtained

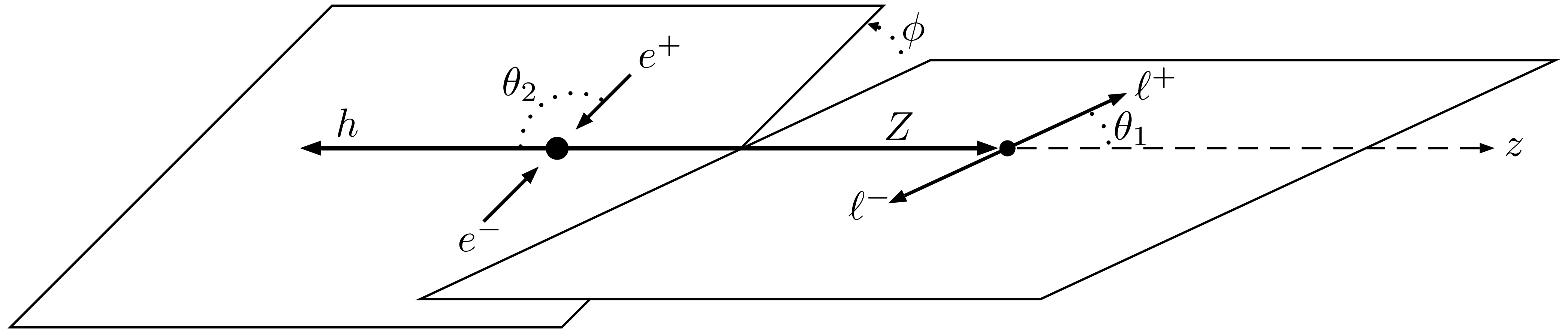
In the $SMEFT_{EWPO}$ mostly used in the following, the perfect EW constraints(*) are assumed and 12+1 parameters are fitted:

- (6) corrections to the Higgs boson couplings to the gauge bosons
- (5) corrections to the Yukawa couplings
- (1) correction to trilinear gauge couplings
- (1) correction to the trilinear Higgs boson self-coupling

(*) any new physics contributions to the EW precision observables are bounded to be exactly zero, after running at FCC-ee(Z), this assumption is *almost* verified

The optimal set of variables

- The ZH Higgsstrahlung rate
- The VBF rate
- The full angular distributions
  - 3 angles and 2 masses fully characterise ee→ZH→Hff
- The decay modes: ZZ,WW, γγ, Zγ, ττ, bb, gg, cc, μμ
  - H→Zγ decay, not very constraining for the SM hZγ coupling, but resolve the degeneracies of EFT parameters in the production processes
- Weak boson rate and distributions



Kappa-0 scenario	FCCee 240	FCCee 240+365	HL-LHC + FCCee 240	HL-LHC + FCCee 240+365
κ_W [%]	1.3	0.43	0.86	0.38
κ_Z [%]	0.20	0.17	0.15	0.14
κ_g [%]	1.7	1.0	1.1	0.88
κ_γ [%]	4.7	3.9	1.3	1.2
$\kappa_{Z\gamma}$ [%]	81⋆	75⋆	10.	10.
κ_c [%]	1.8	1.3	1.5	1.3
κ_t [%]	—	—	3.1	3.1
κ_b [%]	1.3	0.67	0.94	0.59
κ_μ [%]	10	8.9	4.	3.9
κ_τ [%]	1.4	0.73	0.9	0.61

Scenario	BR_{inv}	BR_{unt}
kappa-0	fixed at 0	fixed at 0
kappa-1	measured	fixed at 0
kappa-2	measured	measured
kappa-3	measured	measured

Not all of them used yet in all the projections

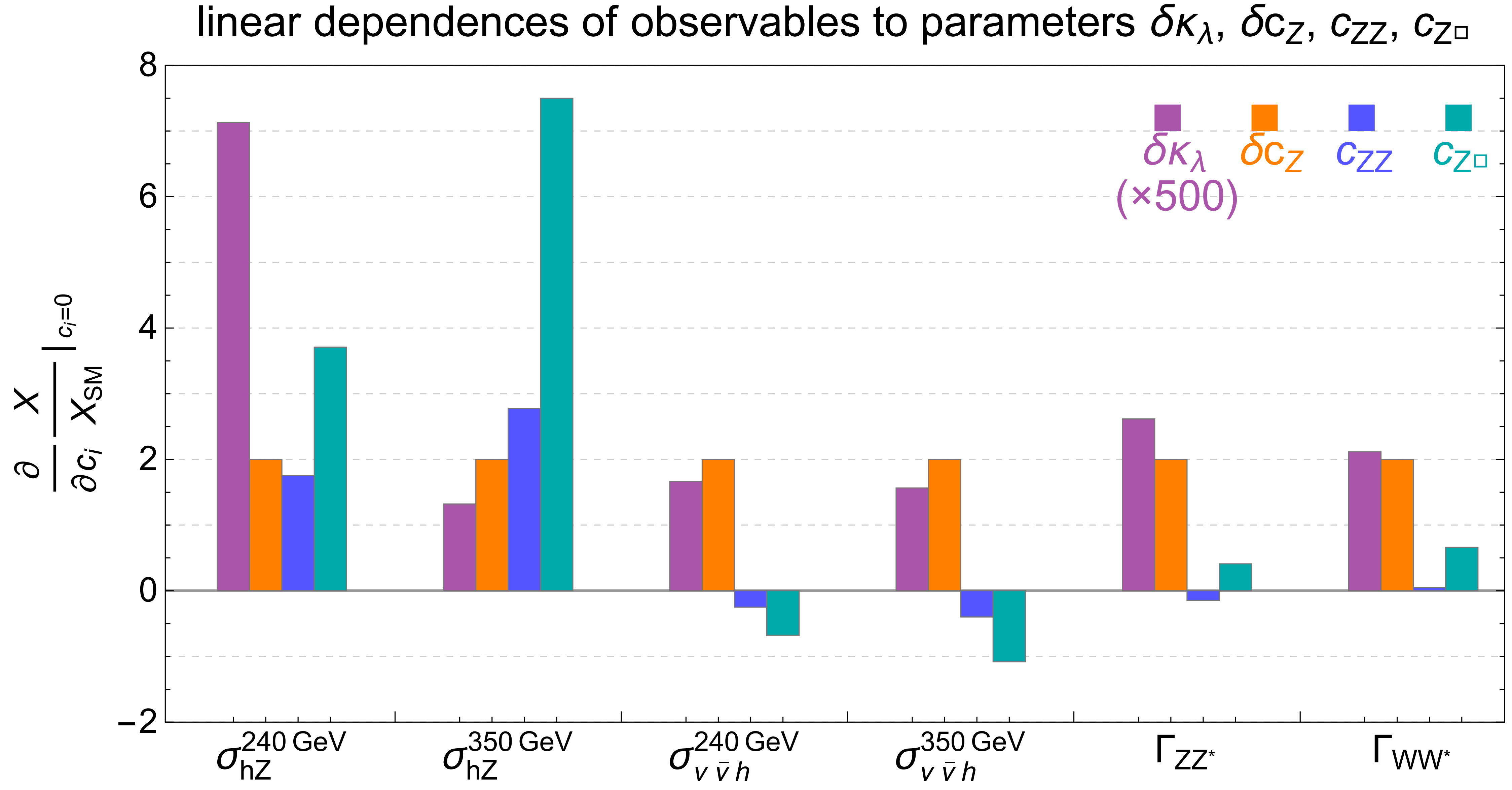
Two energy points, at least

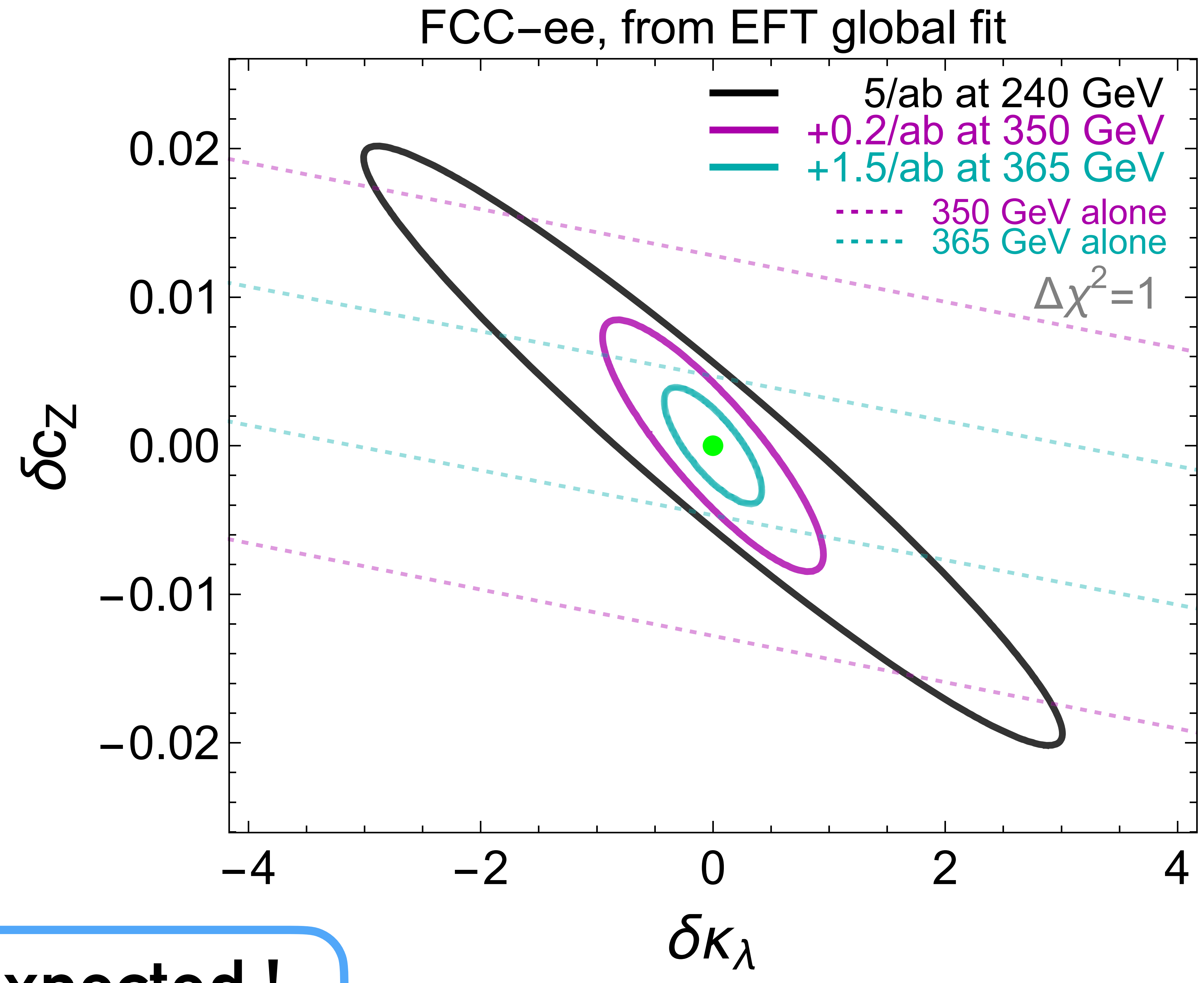
Disentangle a variation due to a modified Higgs boson self-coupling from variations due to another deformation of the SM

Having two energy points :

→ reduce the uncertainty on all the EFT parameters

→ lift off the degeneracy between δc_Z and $\delta\kappa_\lambda$ deviations





No flat directions are expected !

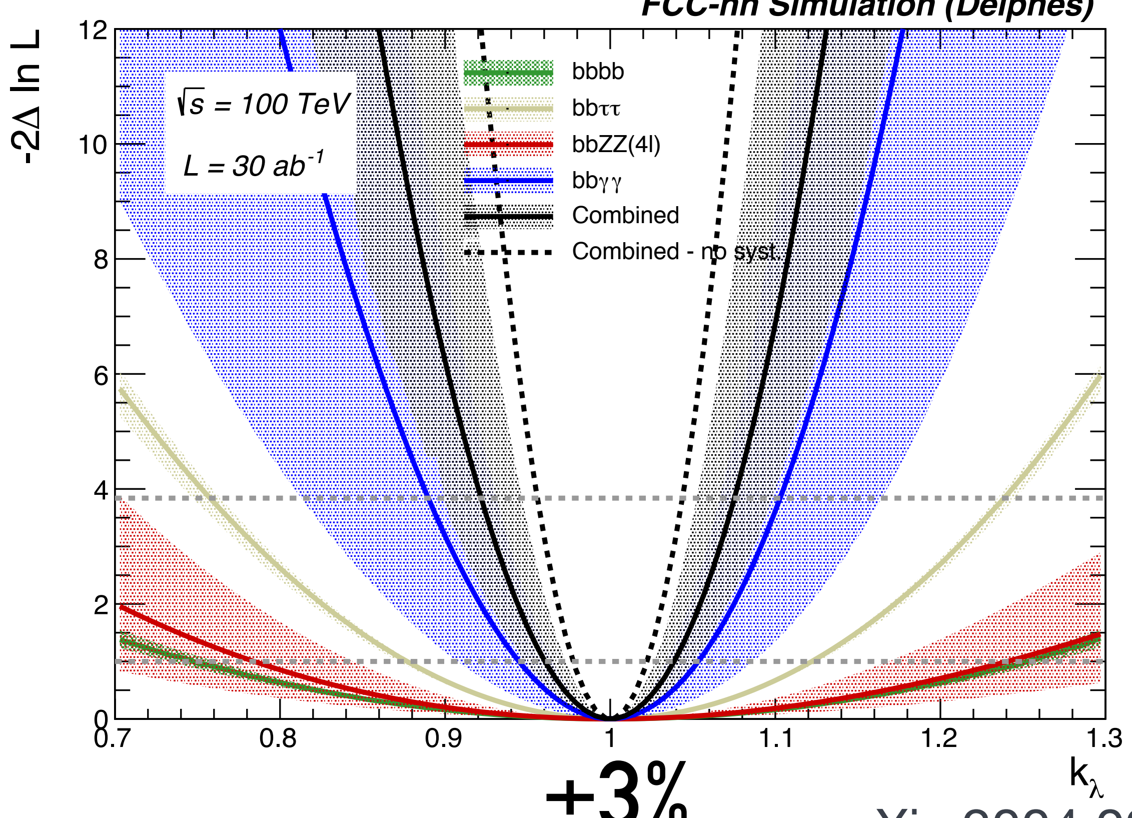
fitting only Higgs-related operators

arXiv:1905.03764

Main results

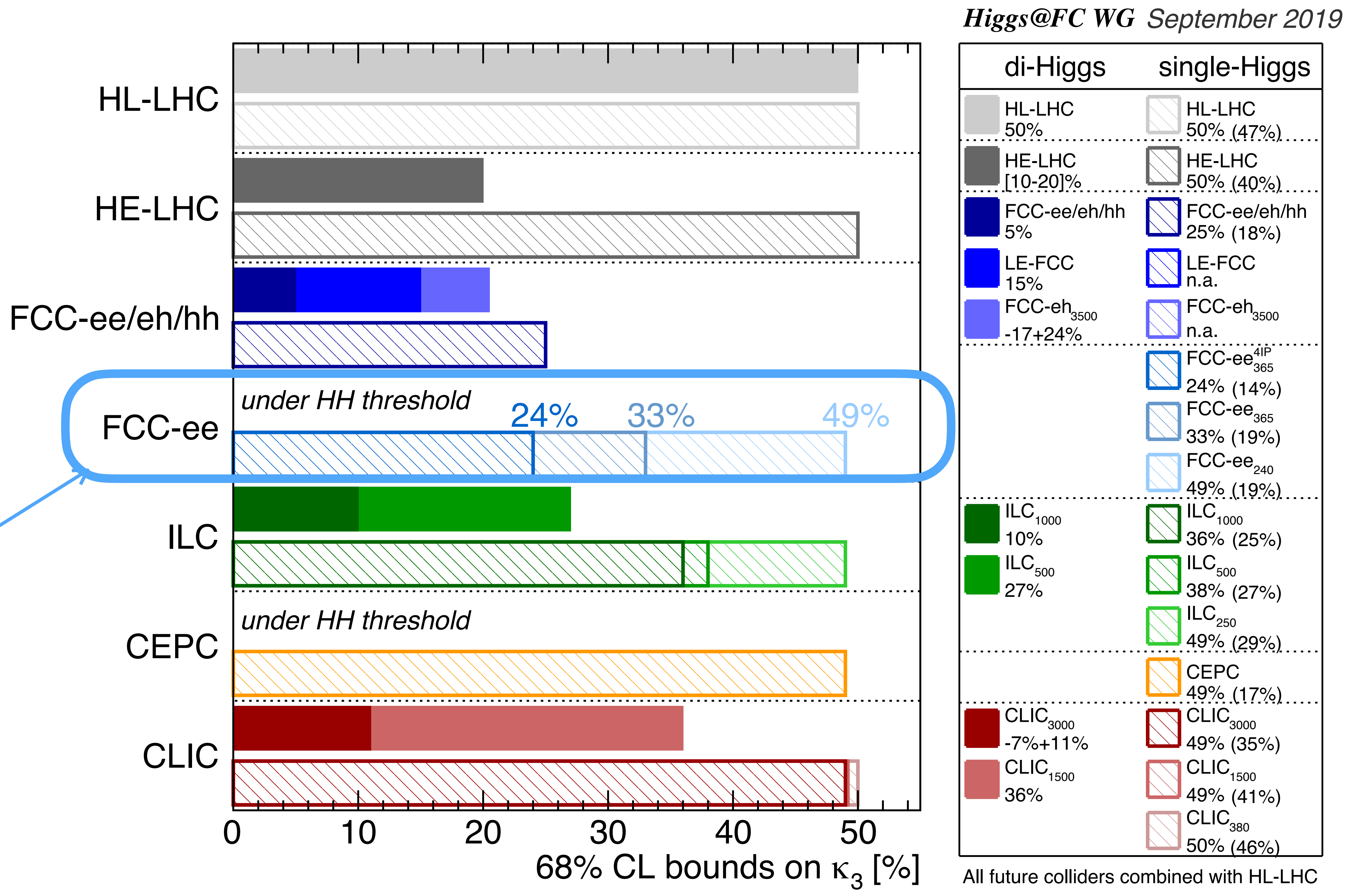
collider	(1) di-H excl.	(2.a) di-H glob.	(3) single-H excl. with HL-LHC	(3) single-H excl. w/o HL-LHC	(4) single-H glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%	47%	125%	50%
HE-LHC	10-20% (n.a.)	n.a.	40%	90%	50%
ILC_{250}	–	–	29%	126%	49%
ILC_{350}	–	–	28%	37%	46%
ILC_{500}	27% (27%)	27%	27%	32%	38%
ILC_{1000}	10% (n.a.)	10%	25%	n.a.	36%
$CLIC_{380}$	–	–	46%	120%	50%
$CLIC_{1500}$	36% (36%)	36%	41%	80%	49%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.	35%	65%	49%
FCC-ee_{240}	–	–	19%	21%	49%
FCC-ee_{365}	–	–	19%	21%	33%
FCC-ee^{4IP}_{365}	–	–	14%	n.a.	24%
FCC-eh	17-24% (n.a.)	n.a.	n.a.	n.a.	n.a.
FCC-ee/eh/hh	5% (5%)	6%	18%	19%	25%
LE-FCC	15% (n.a)	n.a	n.a.	n.a.	n.a.
CEPC	–	–	17%	n.a.	49%

FCC-hh updated result



±3%

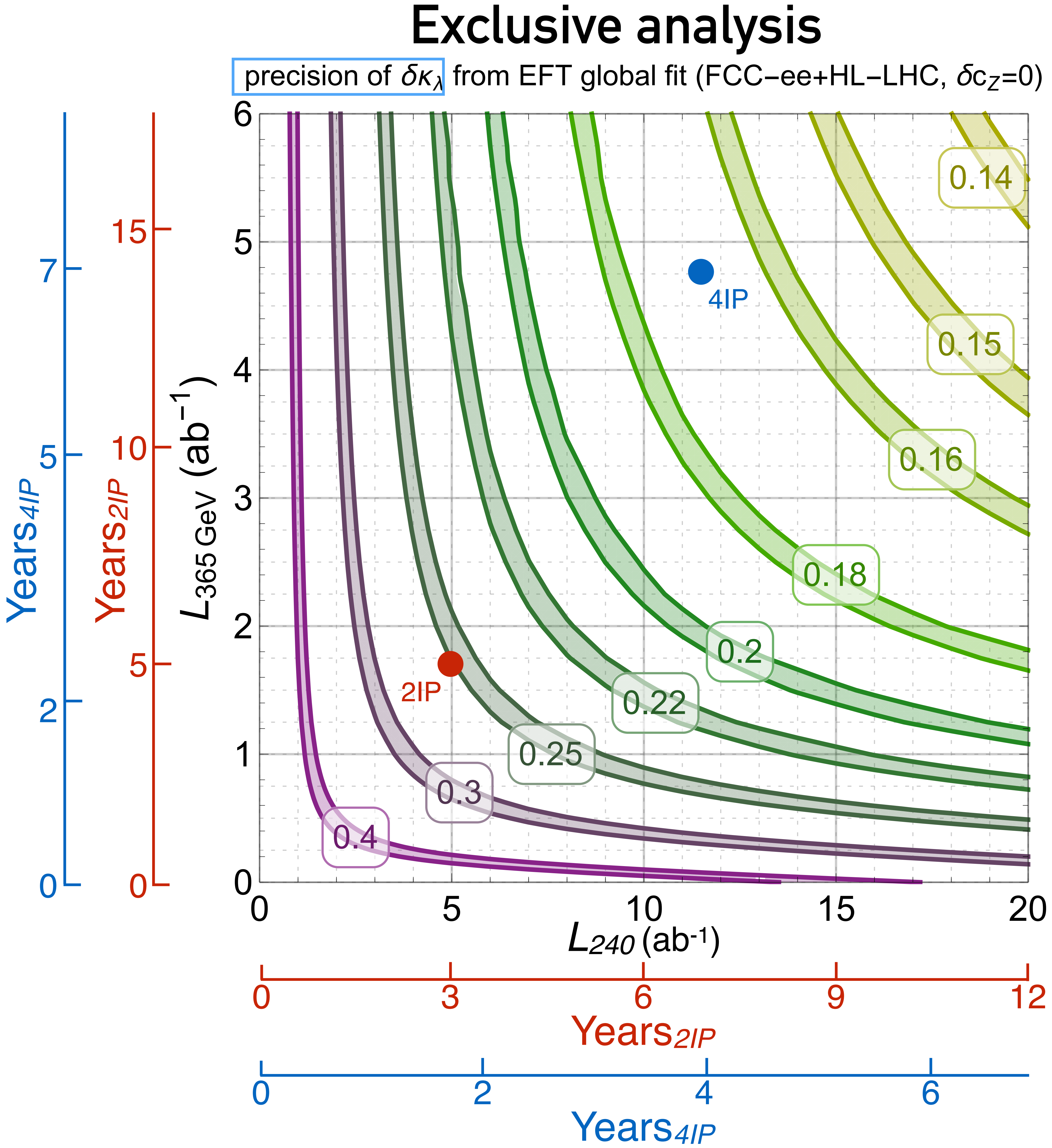
arXiv:2004.03505

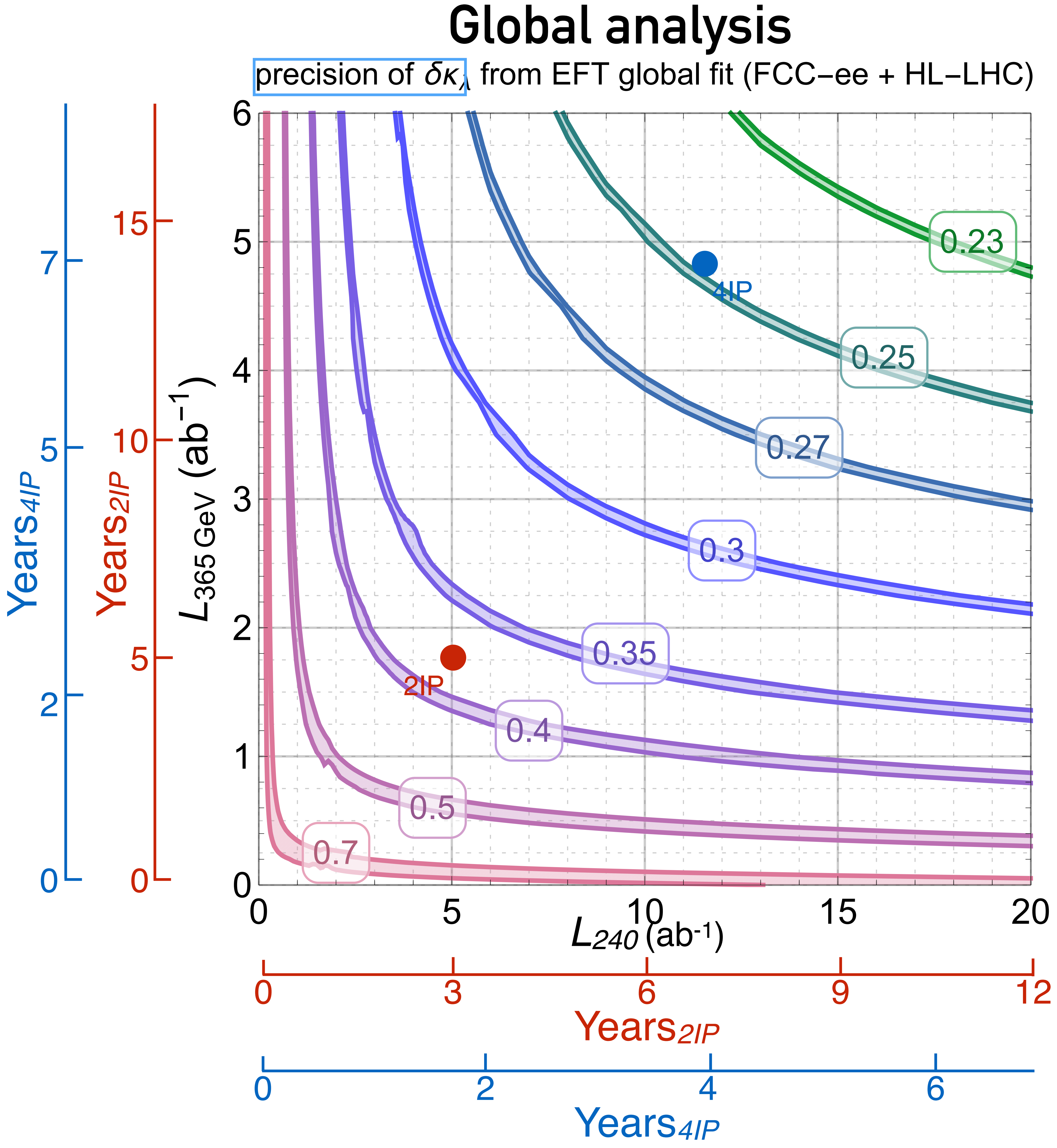


Simplified combination with HL-LHC

Statistics are of essence for this measurement, as for all other Higgs boson measurements

Evolution with integrated luminosities





- ➔ a loss of 15% luminosity per IP when going from 2IP to 4IP
- ➔ 3 years saved from the shorter Z pole and WW threshold runs

SMEFT fit

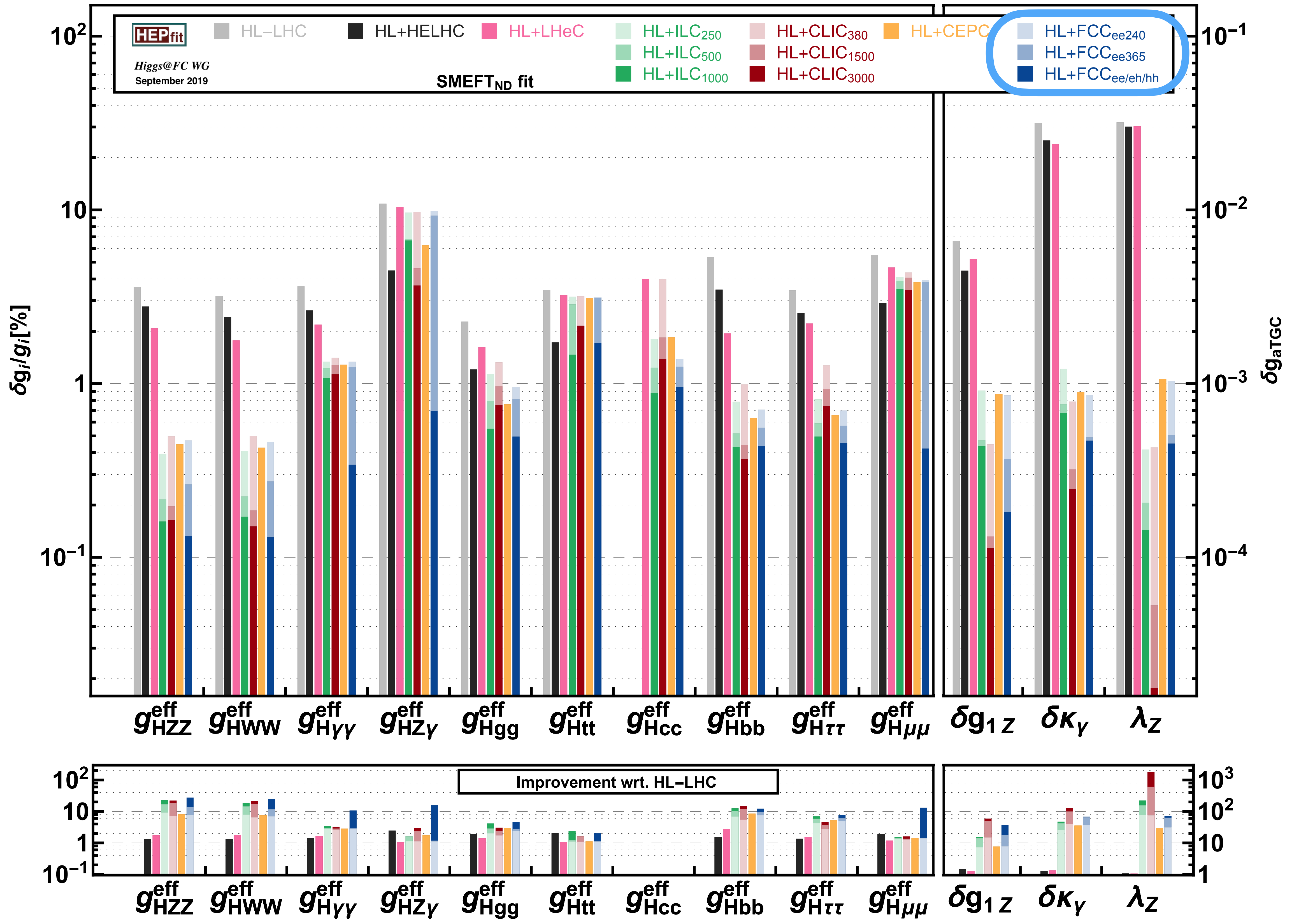
Results in the more general benchmark $SMEFT_{ND}$

ND = Neutral Diagonality, relaxed assumptions on 3rd gen. quarks and on leptons

Effective Higgs couplings and aTGC

13 independent coefficients

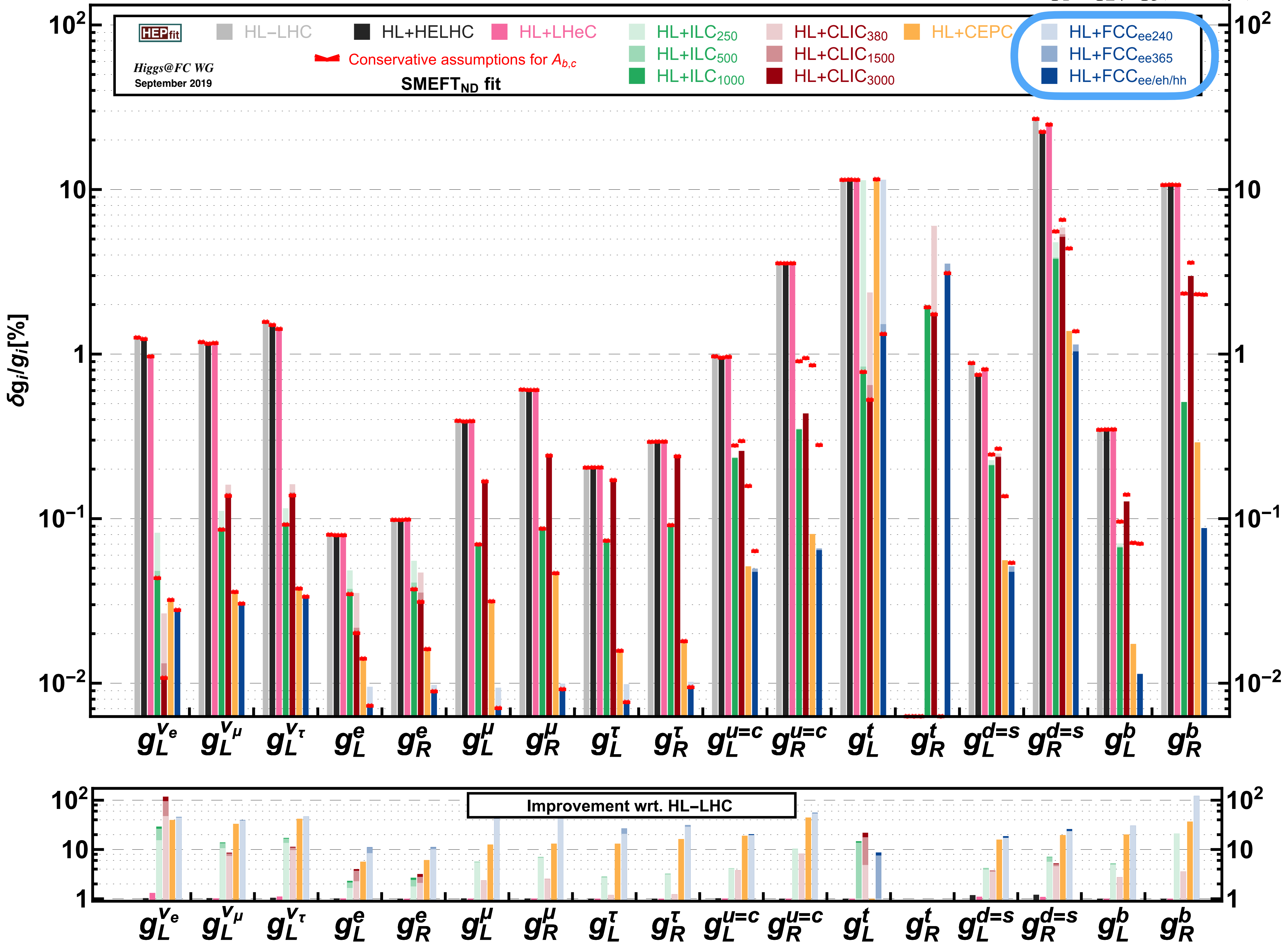
$$\{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\}$$



Effective EW couplings

17 independent coefficients

$$\left\{(\delta g_L^{Zu})_{q_i},(\delta g_L^{Zd})_{q_i},(\delta g_L^{Z\nu})_{\ell},(\delta g_L^{Ze})_{\ell},(\delta g_R^{Zu})_{q_i},(\delta g_R^{Zd})_{q_i},(\delta g_R^{Ze})_{\ell}\right\}_{q_1=q_2\neq q_3,\ \ell=e,\mu,\tau}.$$

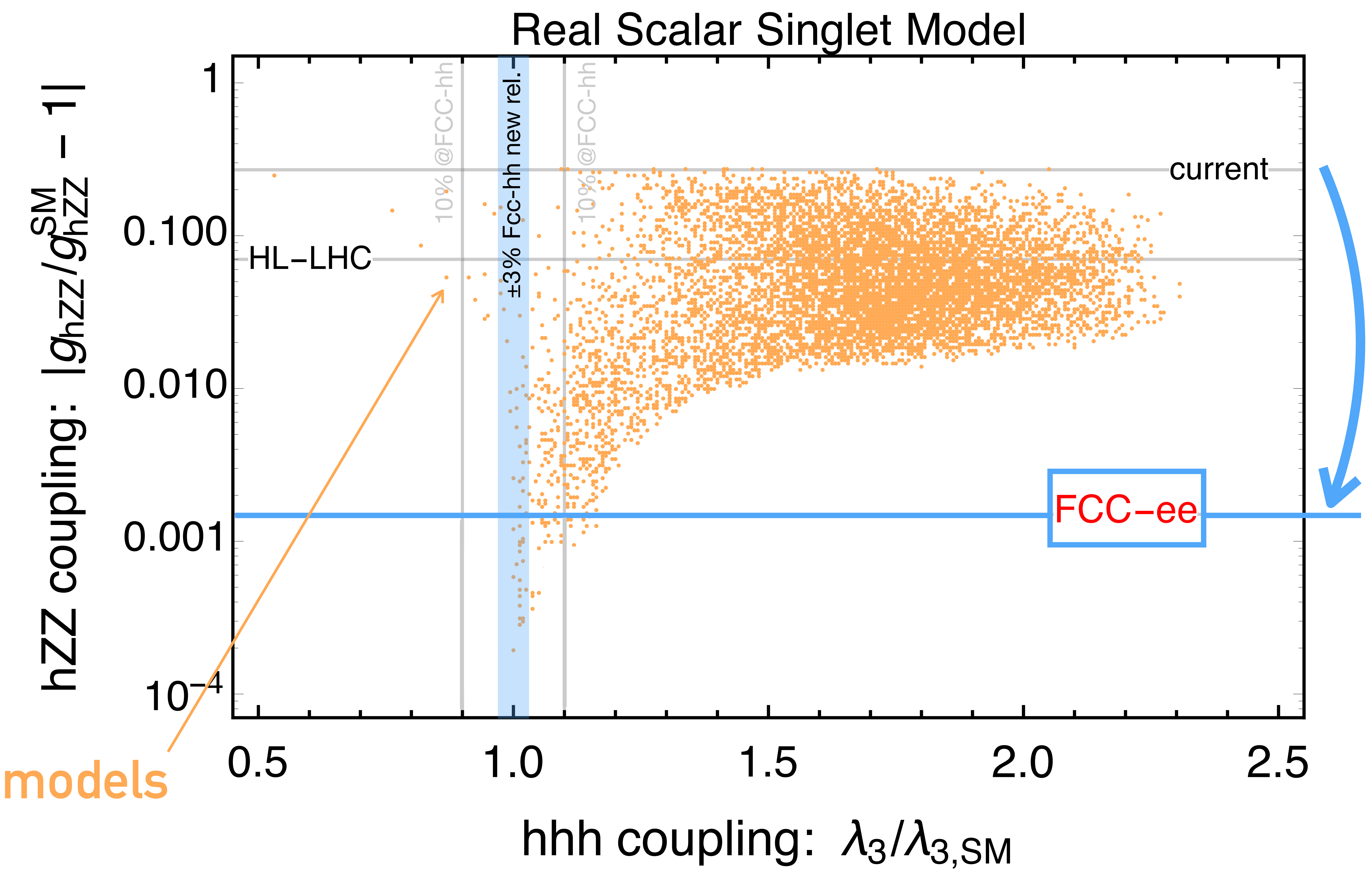


arXiv:1608.06619

Probing the Electroweak Phase Transition

Minimal extension of the Standard Model with a real, scalar singlet field S

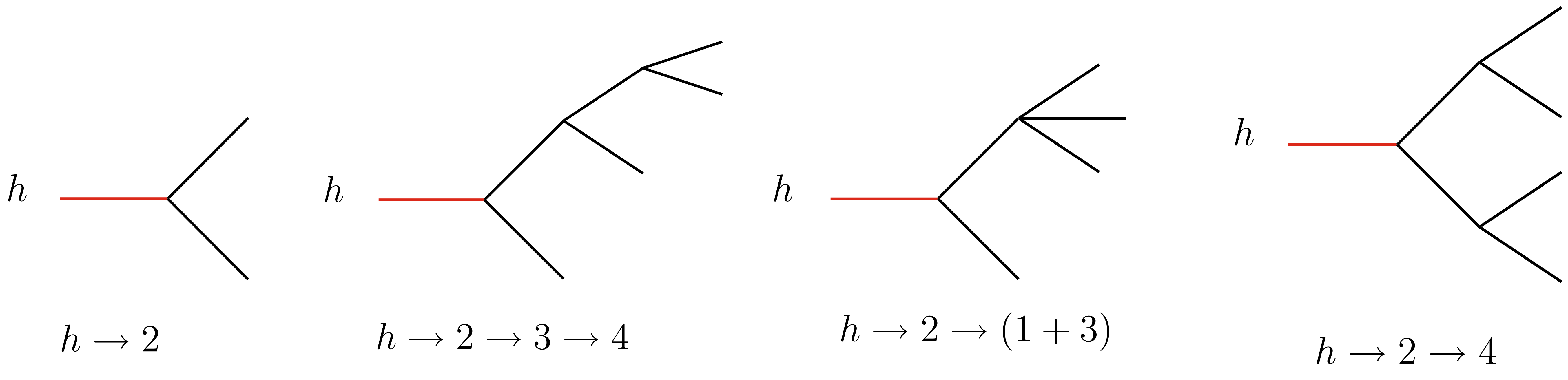
Due to the the Higgs-singlet mixing
→ HZZ coupling is suppressed compared to the SM prediction
→ λ_{HHH} coupling deviates from the SM prediction

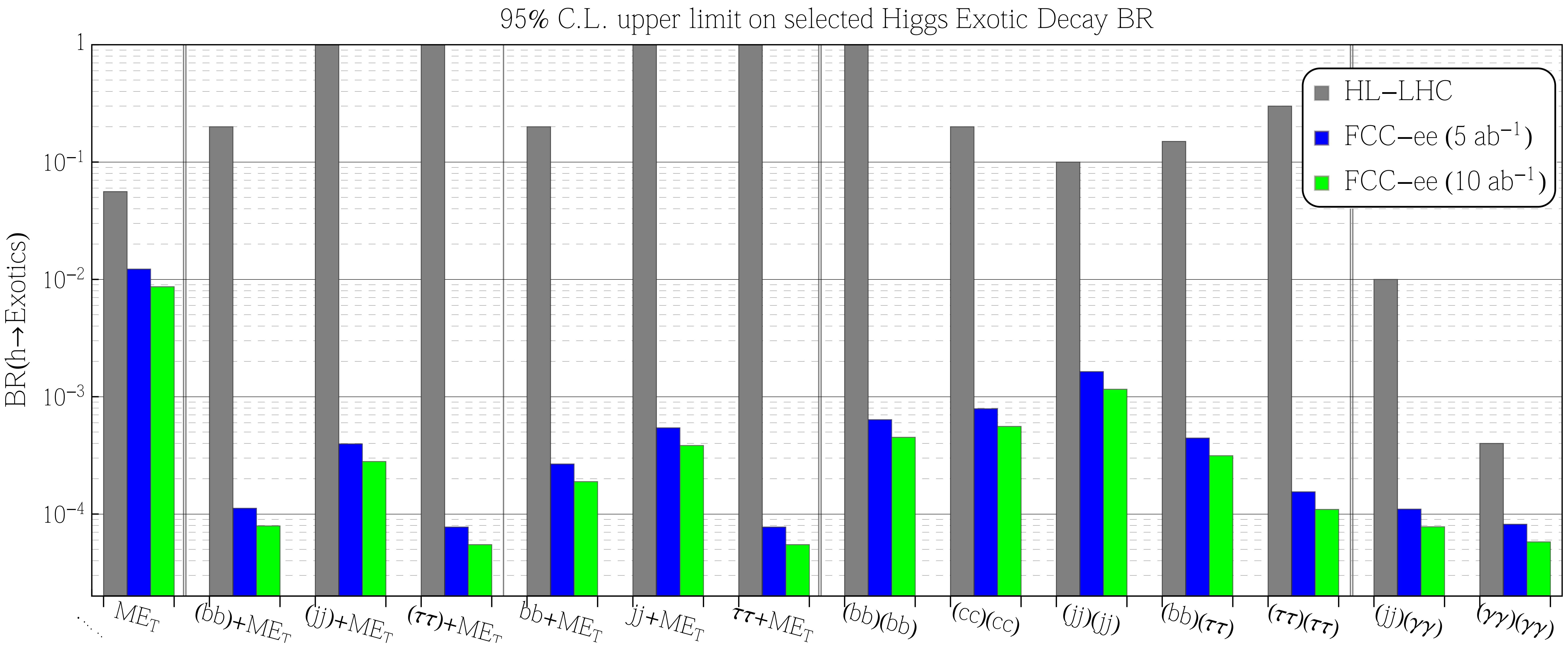


Deviations within the sensitivity reach of FCC cross-correlation between direct discovery (either S→HH or H→SS) and the Higgs property measurements

Higgs boson exotic decays

Exotic Higgs Boson decay into hidden sector steps which subsequently decay back into SM states





Conclusions

- ➔ The Higgs boson self-coupling (λ_{HHH}) is at the root of EW symmetry breaking
  - ➔ no need to reach double Higgs production threshold to have access to it!

- ➔ The FCCee/hh performance is superior
- ➔ At FCCee we could go down to 33%(24%) precision on λ_{HHH} with 2IP(4IP)
  - ➔ statistic and different energies are the keys
- ➔ Room to improve/refine the analyses
  - ➔ $\sqrt{s}$ optimisation at FCC-ee
  - ➔ better measurement of the rates
  - ➔ angular variables

- ➔ Statistic is as well the key to reduce the allow phase space for BSM Higgs boson models (towards discovery?)

- ➔ The way forward: design the detector, full simulation, …