Higgs physics (LHC, HL-LHC, ILC, FCC…)

Elisabeth Petit
on behalf of the contributors

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Séminaire Thématique GT01 "Physique des particules"
12-13 mars 2020

What do we learn from the Higgs boson?

Question	κ_V	κ_3	κ_g	κ_γ	λ_{hhh}	σ_{hZ}	$\mathrm{BR_{inv}}$	$\mathrm{BR_{und}}$	κ_ℓ	μ_{4f}	$\mathrm{BR}_{\tau\mu}$	Γ_h
Is h Alone?	+	+			+	+				+		+
Is h elementary?	+	+	+	+		+						
Why $m_h^2 \ll m_{\mathrm{Pl}}^2$?	+	+					+	+		+		+
1st order EWPT?			+	+	+	+				+		
CPV?		+(CP)										
Light singlets?							+	+	+	+		+
Flavor puzzles?		+							+		+	

BH, Y. Nir, arXiv:1905.00382

Many problems of particle physics today relate to Higgs observables

References and comments

- Contributions to the EPPSU:

  #152: HL-LHC #29: CEPC

  #160: HE-LHC #145: CLIC

  #135: FCC-hh #77: ILC

  #89: FCC-ee

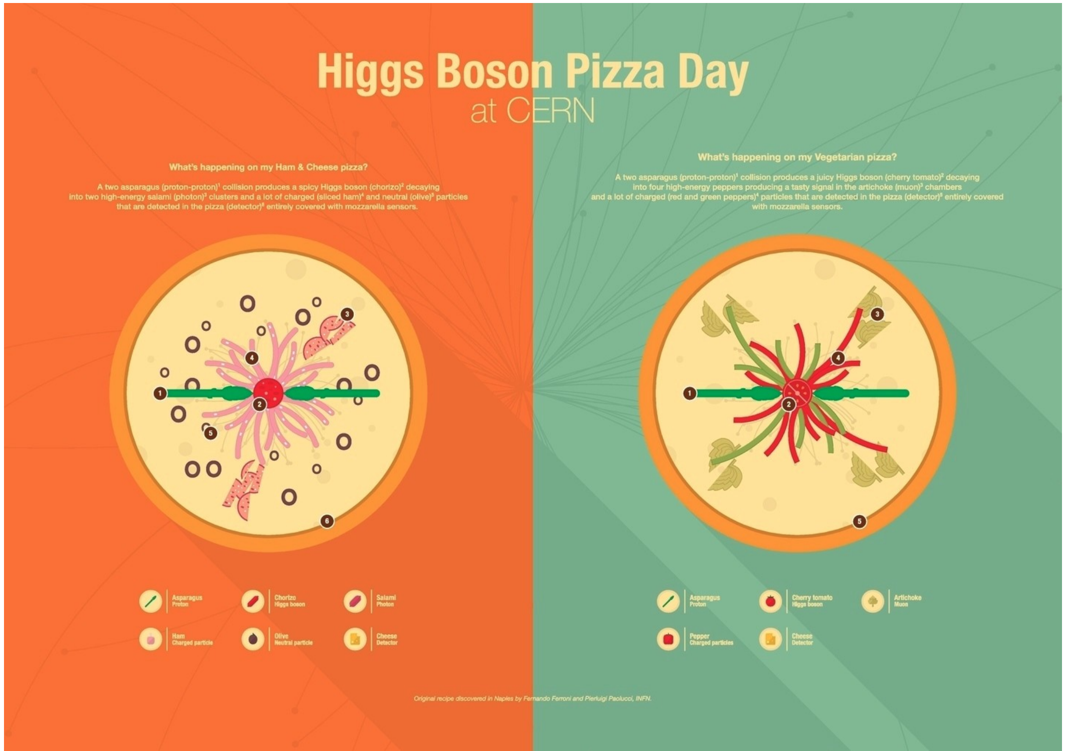
  - Briefing Book
  - Higgs Boson studies at future particle colliders
- Different simulation/analysis program for each proposal, varying from full simulation to parametric modelling (GUINEAPIG, CLICdet, WHIZARD, DELPHES)
- Generally assumed progress in systematic uncertainties over the next decades (experimental and theoretical)
- We should not over-interpret 20% differences between projected sensitivities. In many cases these are likely not significant
- Contributions to the GT01:
  - Physics opportunities at a future linear e+e− collider
  - Di-Higgs production and Higgs boson self-coupling at the HL-LHC with the ATLAS detector
  - LPNHE scientific perspectives for the European Strategy for Particle Physics

Outline

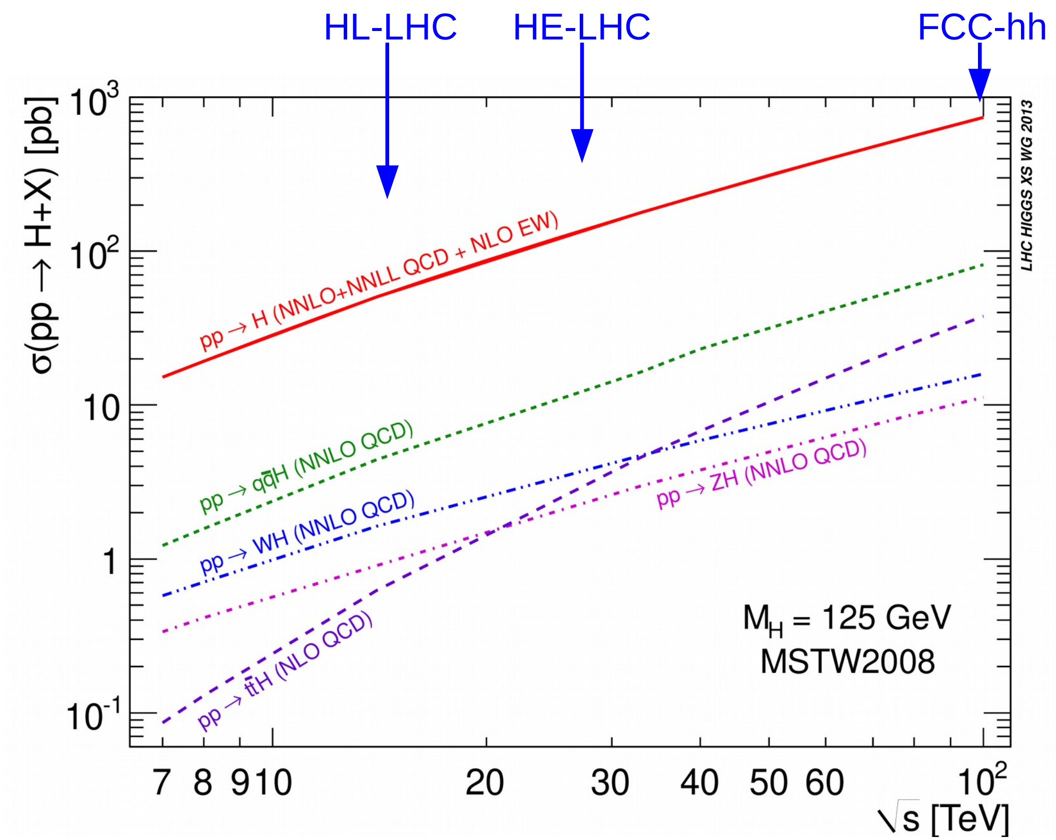
- Higgs couplings and properties
- Higgs self-coupling
- BSM Higgs

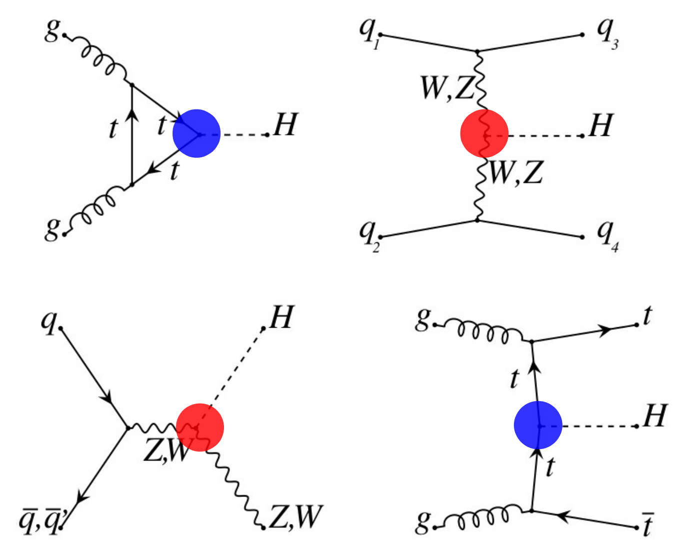
Collider	Type	$\sqrt{s}$	$\mathcal{P}$ [%]	N(Det.)	$\mathcal{L}_{\text{inst}}$ [10^{34}]	$\mathcal{L}$	Time	Refs.	Abbreviation
			[e^-/e^+]		$\text{cm}^{-2}\text{s}^{-1}$	[ab^{-1}]	[years]		
HL-LHC	pp	14 TeV	—	2	5	6.0	12	[13]	HL-LHC
HE-LHC	pp	27 TeV	—	2	16	15.0	20	[13]	HE-LHC
FCC-hh$^{(*)}$	pp	100 TeV	—	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1–2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{\text{top}}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{\text{top}}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC$_{1000}$
							(+1-2)		(1–2y SD after 500 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[15]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	—	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	ep	1.8 TeV	—	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	—	1	1.5	2.0	25	[1]	FCC-eh

Higgs couplings and properties



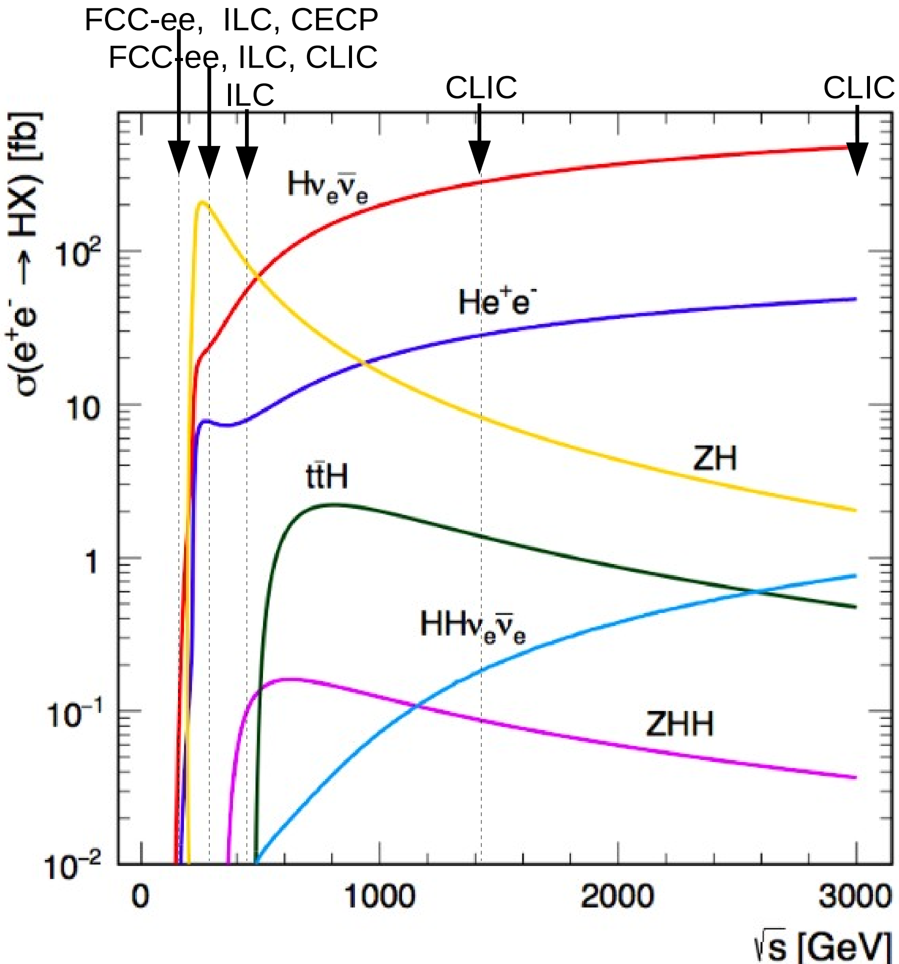
Higgs boson production at pp colliders

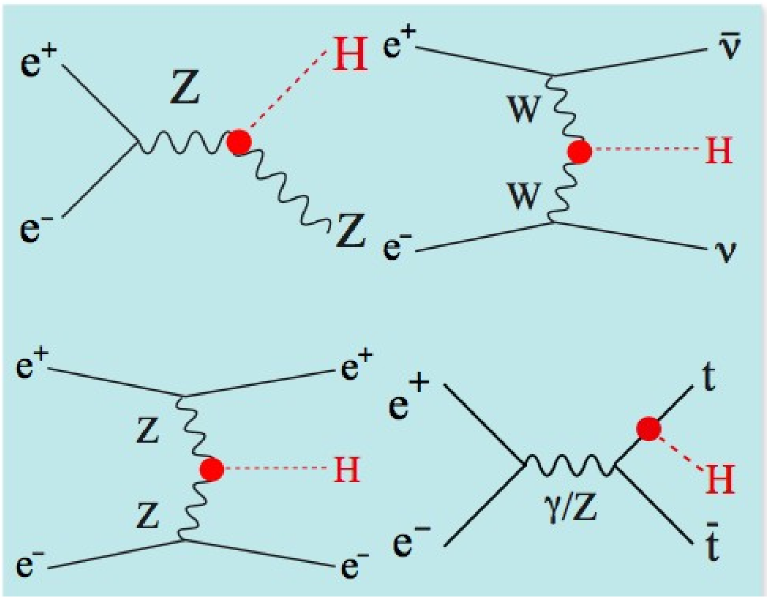




- High cross-section and luminosity
  - from 2.10^7 (LHC) to 3.10^{10} (FCC-hh) produced Higgs bosons
- Probing the Higgs boson at high pT enhances the sensitivity to new physics (not captured in the analyses presented here)

Higgs boson production at ee colliders





- Two important thresholds: √s ~250 GeV for ZH, 500 GeV for ttH
- Recoil mass method to obtain a precise ZH cross section measurement in a model independent way, regardless of the decay
  - $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$
- Circular colliders: precision EWK program at MZ and MW
- Linear colliders: polarized beams and potential to go to higher energies

κ and EFT Frameworks

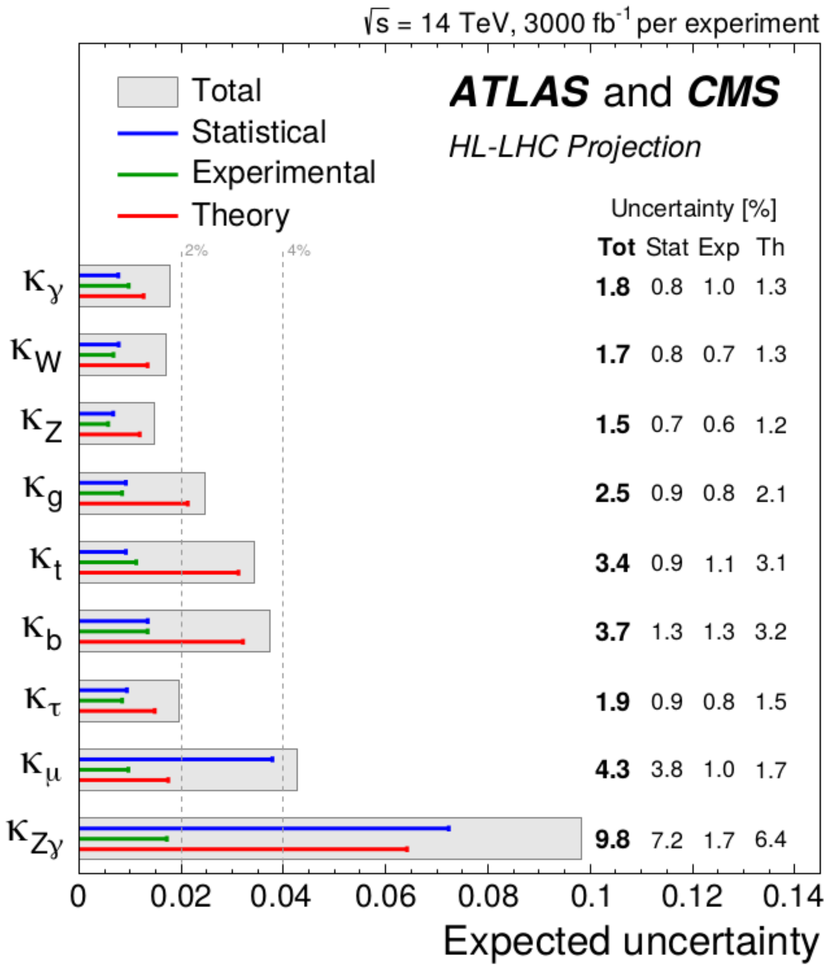
- κappa framework:
  - Higgs coupling properties in terms of a series of strength modifier parameters κ_i

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

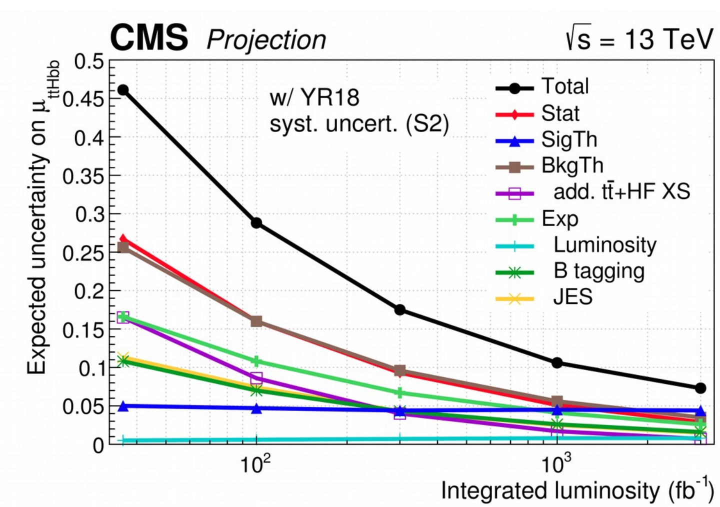
  - implies that Higgs coupling in production and decay are identical
  - no new operators
  - Pros
    - compact parameterization
    - does not require any BSM calculation per se
  - Cons
    - does not distinguish the source of NP
    - only for total rates, no kinematics, no polarisation
- EFT framework:
  - global fit, including not only Higgs but also di-boson and EWK precision observables
  - introducing set of SU(2)xU(1) compatible operators
  - breaks simple relation between Higgs production and decay
  - total width and Higgs to invisible as free parameters

Higgs couplings at HL-LHC

- Couplings based on projections of the current Run 2 analyses ($36 fb^{-1}$)
- Two scenarios for systematic uncertainties
  - S1: same as Run 2
  - S2: theoretical uncertainties /2, estimate ultimate performance of the experimental uncertainties

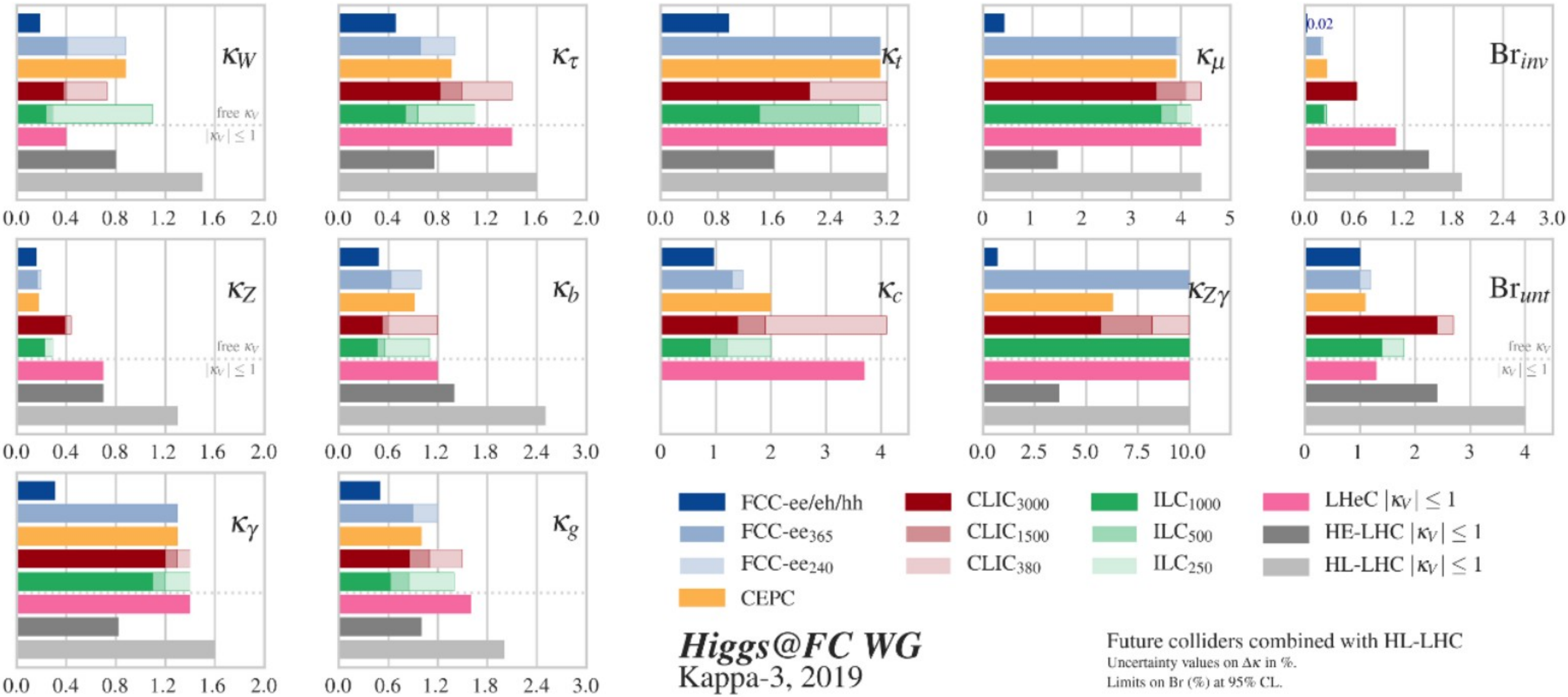


- O(few%) measurements of couplings
- Systematic errors dominate in general, large effect of theoretical uncertainties (production&decay) even in S2



Higgs couplings at Future Colliders

- All results combined with HL-LHC



- Sensitivities of ee colliders in their initial stages are rather comparable
- The most precise coupling measurements (to Z and W bosons), are measured to 0.2-0.3%

Improvements wrt HL-LHC

- κ framework

	LHeC *	HE-LHC S2′ *	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	3.8	1.9	1.4	5.2	6.2	2.1	3.8	3.9	1.7	1.7	3.7	7.9
κ_Z *	1.9	1.9	4.5	5.9	5.7	3.0	3.2	3.3	7.2	6.5	7.6	8.1
κ_g	1.2	2.0	1.4	2.4	3.2	1.3	1.8	2.3	2.0	1.7	2.2	4.0
κ_γ	1.1	2.0	1.1	1.3	1.5	1.1	1.2	1.3	1.2	1.2	1.2	5.2
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	2.0	1.0	1.1	2.3	1.0	1.5	1.5	1.0	1.0	1.0	3.3
κ_b	2.1	1.8	2.3	4.5	5.3	2.1	4.1	4.7	2.7	2.5	3.9	5.2
κ_μ	1.0	2.9	1.0	1.1	1.2	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.1	2.1	1.5	2.5	3.0	1.1	1.6	2.0	1.8	1.7	2.4	3.5
Br_{inv}	1.7	1.3	7.3	8.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.1	1.7	2.2	2.9	2.9	1.5	1.7	1.7	3.6	3.3	4.0	4.0
Br_{unt} **		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HLLHC

- EFT framework

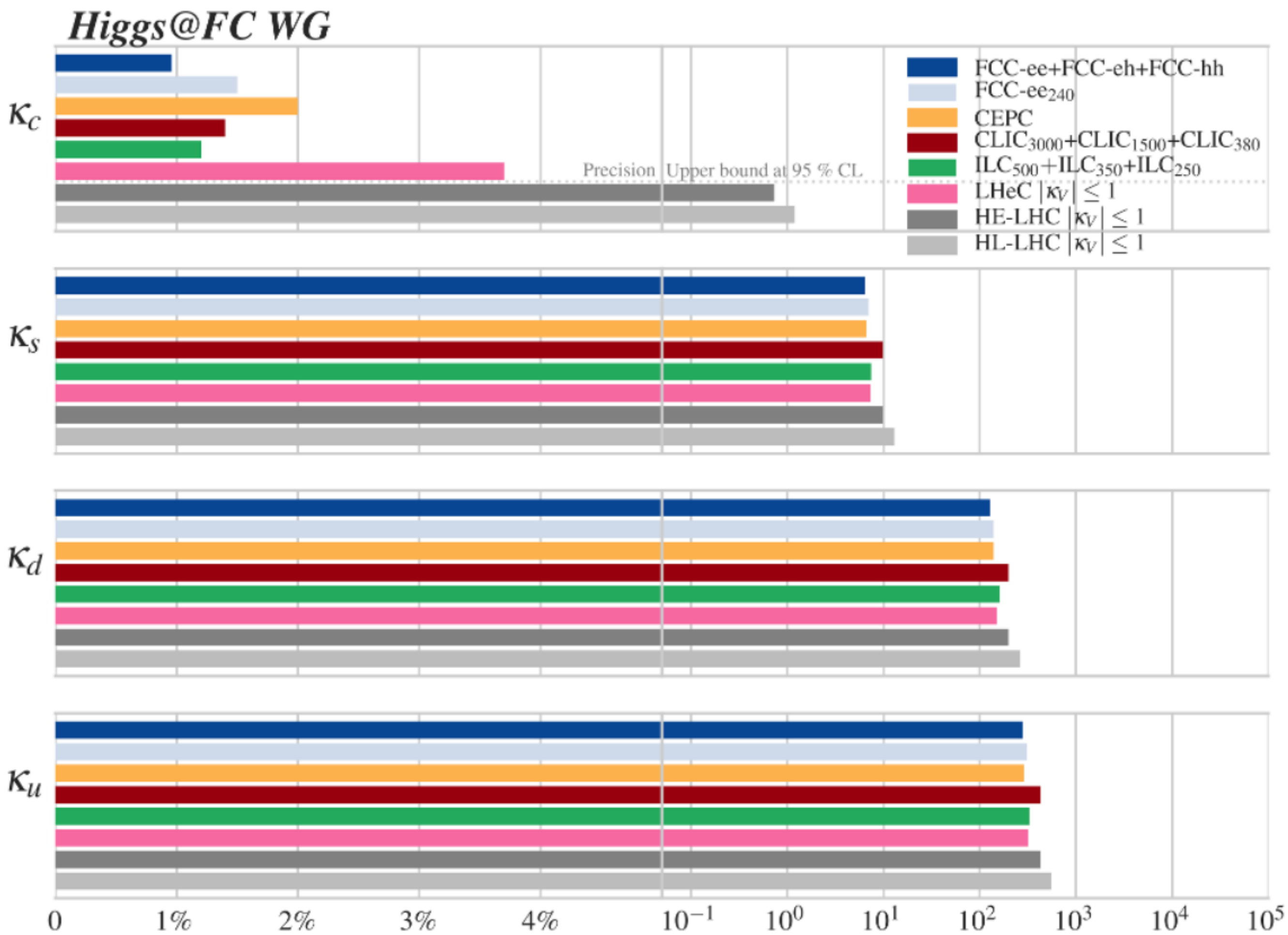
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{eff}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{eff}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

- Remark: no use of differential distributions ⇒ underestimate of power

Rare decays: light quarks

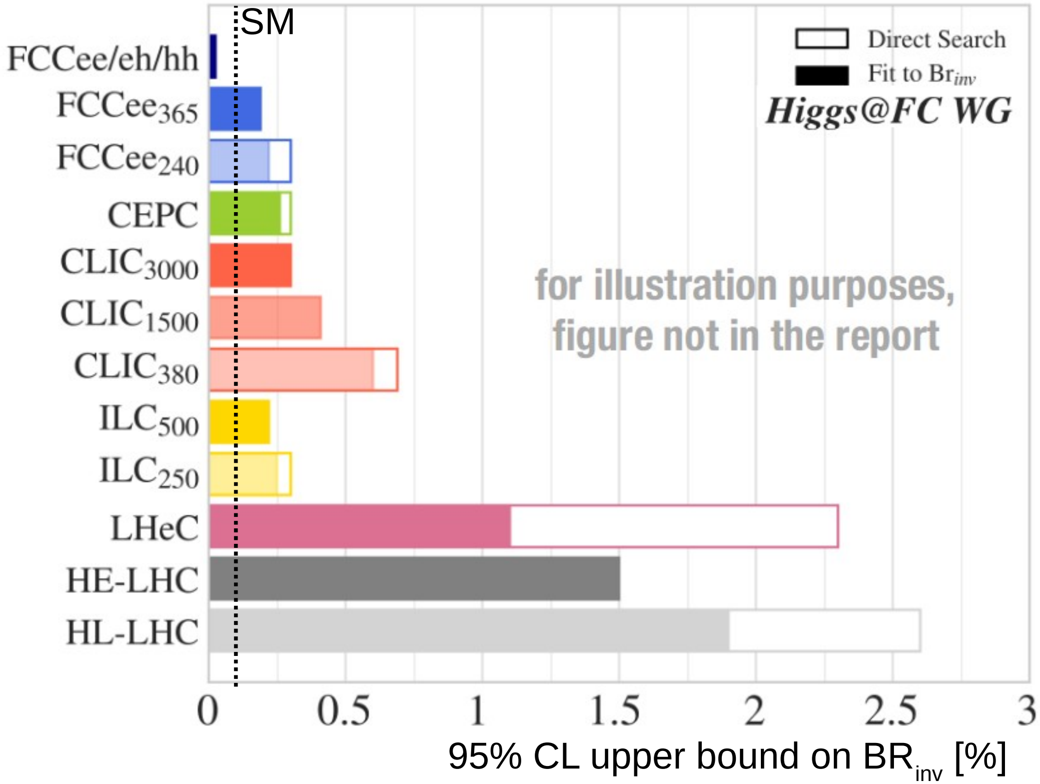
- Constraints on light Yukawa obtained from the upper limits on $BR_{untagged}$



- Hee: very challenging
  - FCC-ee: SM sensitivity could be reached in a five year run with a dedicated run at $\sqrt{s}=m_H$

Invisible width

- Connection between the Higgs boson and dark matter searches
- In the SM, $BR_{SM, inv}$ = BR(H→4ν) = 0.11%
- Current LHC limits ~ 15-20% @ 95%CL
- Direct searches for invisible width: fundamentally different in a hadron collider (ETmiss uncertainties) and a lepton collider (Z recoil)
  - Lepton colliders would improve upon HL-LHC limits by an order of magnitude
  - FCC-hh : another order of magnitude → values below the SM



Higgs boson CP

$$\delta\mathcal{L}_{\rm CPV}^{hVV} = \frac{h}{v}\left[\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \tilde{c}_{aa}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{za}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}\right]$$

$$\mathcal{L}_{\rm CPV}^{hff} = -\bar{\kappa}_f m_f \frac{h}{v}\bar{\psi}_f(\cos\alpha + i\gamma_5\sin\alpha)\psi_f$$

- Sensitivity to the CP-odd hVV weak operators: studies both at the level of rates/distributions and via CP-sensitive observables

- CP violation in fermionic Higgs decays: ττ decay channel → measurement of the linear polarisations of both taus and the azimuthal angle between them

- CP violation in the top quark interactions: ttH and tH (rates and distributions):
  - HL-LHC: CP-odd Higgs excluded with 200fb^{-1}
  - CLIC 1.5 TeV : α_t (ttH) better than 15°
  - LHeC: Higgs interacting with the top quarks with CP-odd coupling excluded at 3σ with 3 ab^{-1}
  - FCC-eh: precision of 1.9% on α_t
  - current indirect limits from EDM bounds stronger than direct (though comparable for tau)

Name	α_τ	$\tilde{c}_{zz}$
HL-LHC	8°	0.45 (0.13)
HE-LHC	—	0.18
CEPC	—	0.11
FCC-ee$_{240}$	10°	—
ILC$_{250}$	4°	0.014

Higgs boson width

- Three methods explored for HL-LHC
  - diphoton interference can only provide constraints ~8-22*SM
  - fits in the kappa framework: subjected to theoretical constraints (eg $|\kappa_V|<1$ and $B_{unt}=0$)
  - HZZ on-shell and off-shell: 20% precision, but very model-dependent
- Measurements in lepton colliders
  - mass recoil: measure the inclusive cross-section of ZH without assumption on the Higgs BR
  - mild model dependence $$\frac{\sigma(ee\to ZH)}{BR(H\to ZZ^*)}=\frac{\sigma(ee\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H}\simeq\left[\frac{\sigma(ee\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{SM}\times\Gamma_H$$

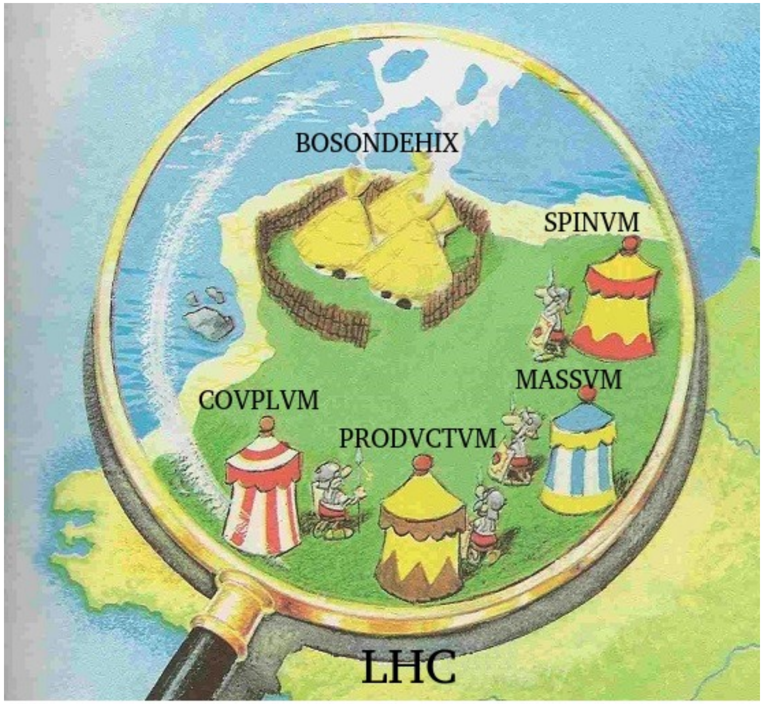
Collider	$\delta\Gamma_H$ [%] from ref.	Extraction technique for standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC_{250}	2.3	EFT fit [3, 4]	2.2
ILC_{500}	1.6	EFT fit [3, 4, 14]	1.1
ILC_{1000}	1.4	EFT fit [4]	1.0
$CLIC_{380}$	4.7	κ-framework [98]	2.5
$CLIC_{1500}$	2.6	κ-framework [98]	1.7
$CLIC_{3000}$	2.5	κ-framework [98]	1.6
CEPC	2.8	κ-framework [103, 104]	1.7
FCC-ee_{240}	2.7	κ-framework [1]	1.8
FCC-ee_{365}	1.3	κ-framework [1]	1.1

Higgs boson mass

- Current experimental precision ~0.1% (160 MeV)
- In lepton colliders m_H needs to be improved to around 10 MeV to avoid any limitation on ZZ/WW couplings
  - HL-LHC reach dependent on muon p_T calibration with high statistics: 10-20 MeV plausible (no formal study yet)
  - ZH recoil at lepton colliders: statistically limited

Collider	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ [%]
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[96]	1.9
HL-LHC	$m(ZZ)$	10-20	[13]	0.12-0.24
ILC_{250}	ZH recoil	14	[3]	0.17
$CLIC_{380}$	ZH recoil	78	[98]	0.94
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[20]	[98]	0.36
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23	[98]	0.28
FCC-ee	ZH recoil	11	[99]	0.13
CEPC	ZH recoil	5.9	[2]	0.07

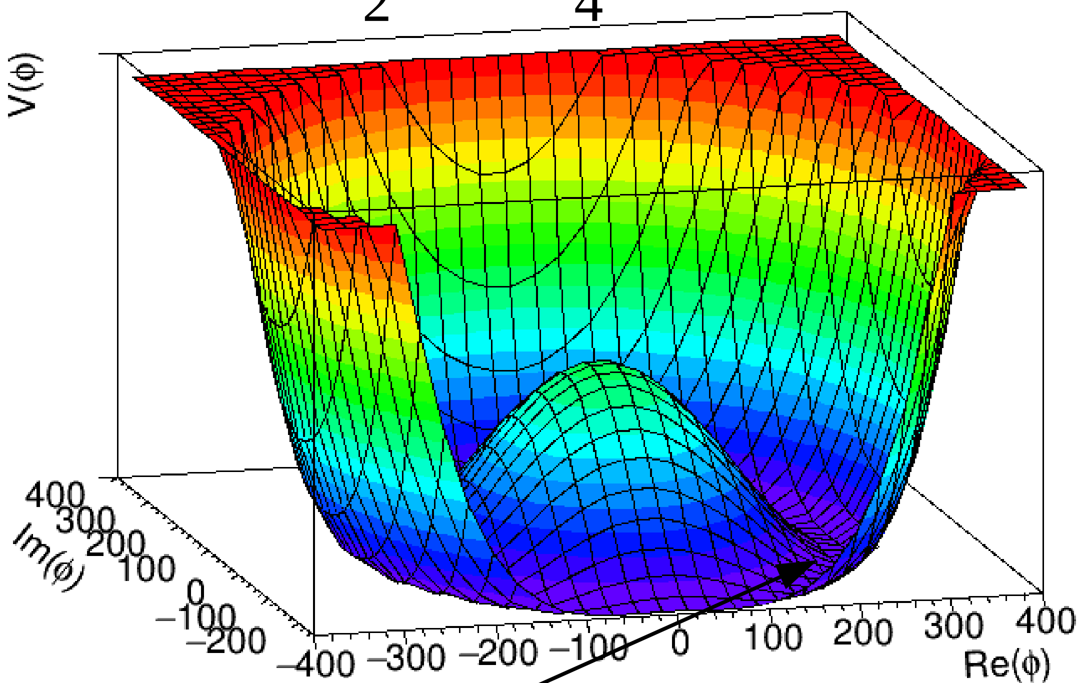
Higgs self-coupling



Nous sommes en l'an VII après la découverte du boson de Higgs. Toutes ses propriétés ont été mesurées. Toutes ? Non ! Un petit couplage, le tri-linéaire, résiste encore et toujours aux physiciens. Et la vie n'est pas facile pour les chercheurs des camps retranchés d'ATLAS et CMS.

Introduction

- Higgs potential: $V(\Phi)=\frac{1}{2}\mu^2\Phi^2+\frac{1}{4}\lambda\Phi^4$



- Approximation around the v.e.v:

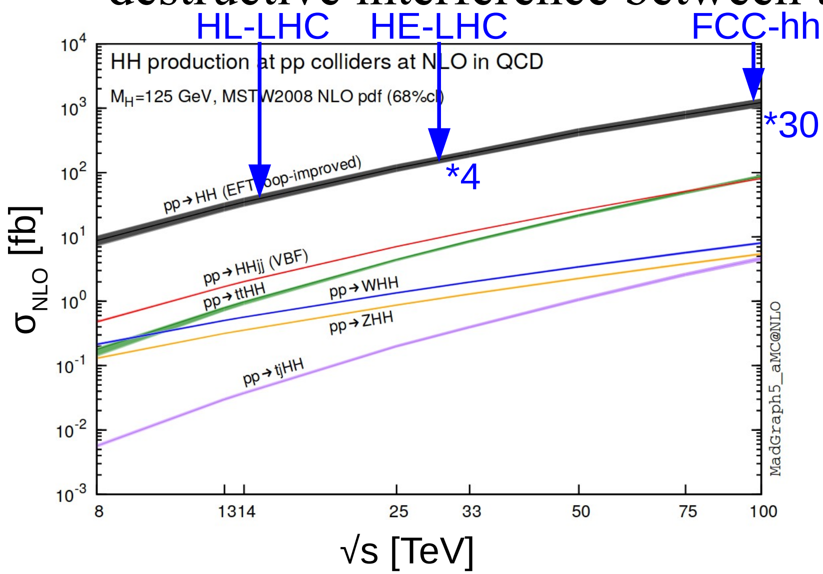
$$V(\Phi)\approx\underbrace{\lambda v^2 h^2}_{\text{mass term}}+\underbrace{\lambda v h^3+\frac{1}{4}\lambda h^4}_{\text{self-coupling terms}}$$

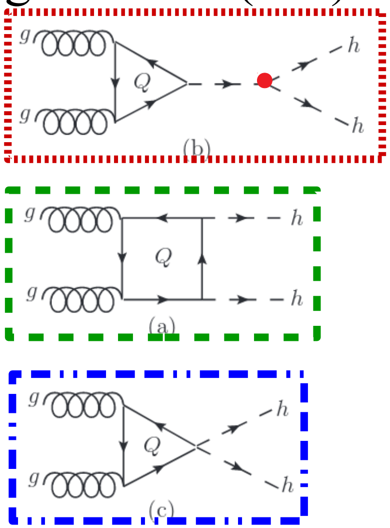
- λ known from v.e.v and Higgs mass: $\lambda=\frac{m_H^2}{2\cdot v^2}\approx 0.13$

- BSM effects could change λ ⇒ define deviation of tri-linear term: $\kappa_\lambda=\kappa_3=\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  - no quartic terms considered here

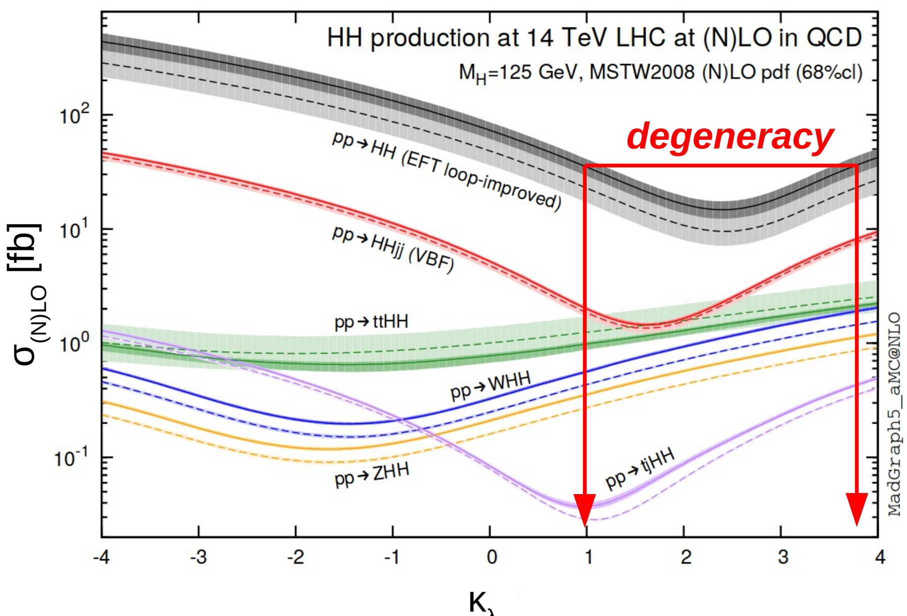
Di-Higgs production: pp colliders

- Main production mode: ggF
  - destructive interference between triangle and box diagrams ⇒ σ(HH)/σ(H) = 0.1%

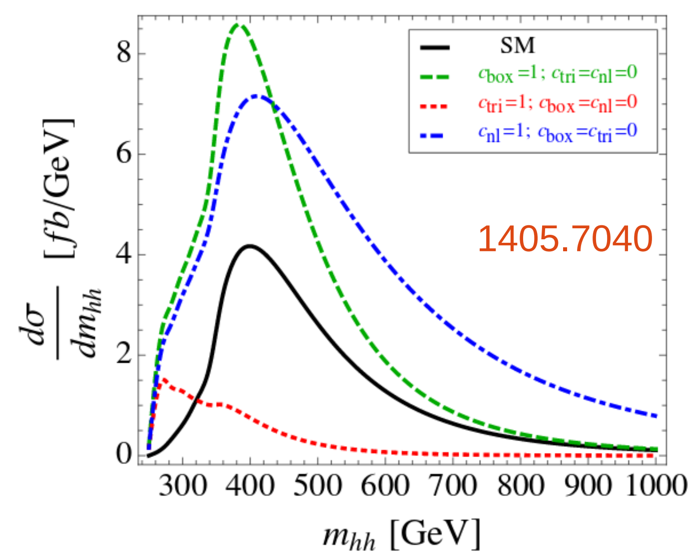




- Self-couplings through total HH cross section, and diff. cross section $d\sigma/dm_{HH}$:

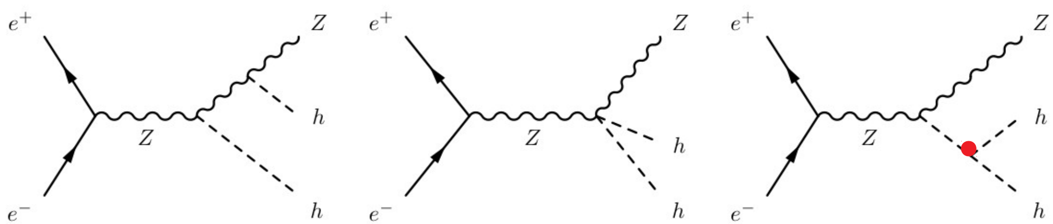


⊗

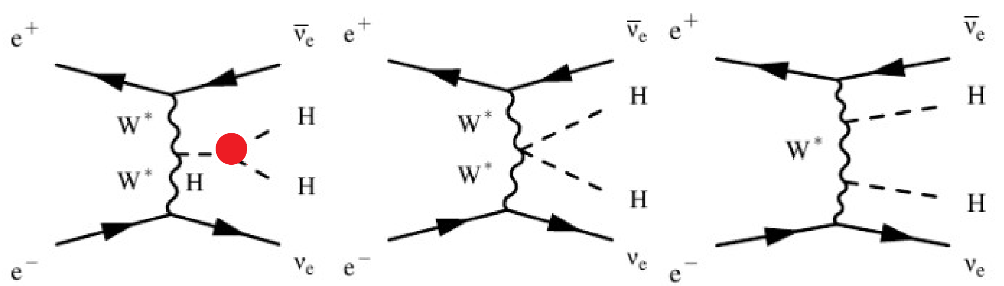


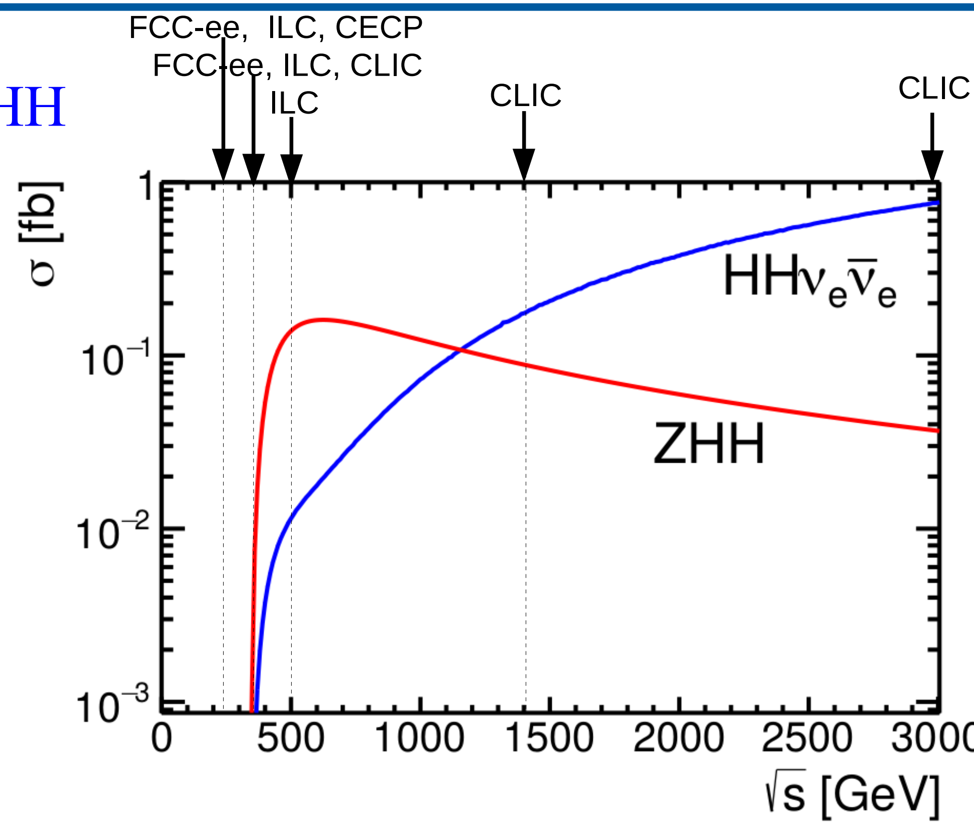
Di-Higgs production: ee colliders

- Main production modes: ZHH and $\nu\bar{\nu}HH$
  - ZHH

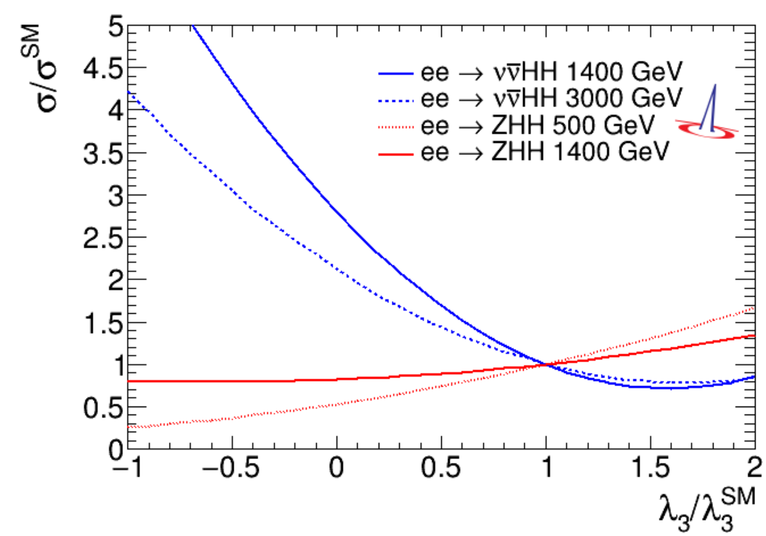


  - VBF $\nu\bar{\nu}HH$



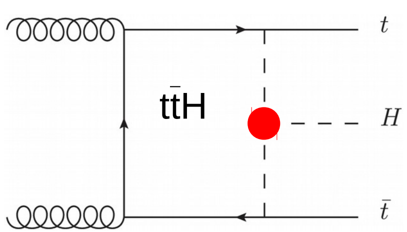


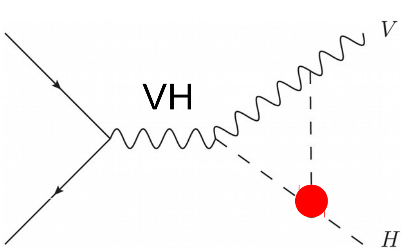
- Self-couplings through HH cross-section at different $\sqrt{s}$ + production modes + m_{HH}
  - ZHH stronger constraints for $\kappa_\lambda > 1$
  - $\nu\bar{\nu}HH$ stronger constraints for $\kappa_\lambda < 1$

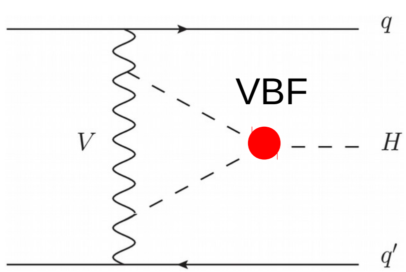


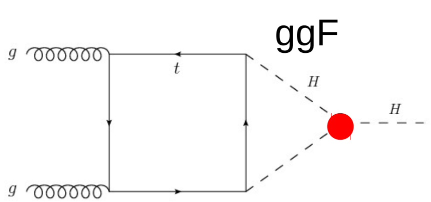
Self-coupling via single-Higgs couplings

- Higgs self-interaction via one-loop corrections of the single-Higgs production
  - κ_λ-dependent corrections to the tree-level cross-sections
- pp colliders:

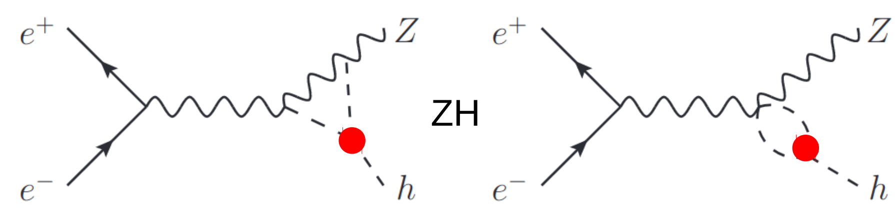


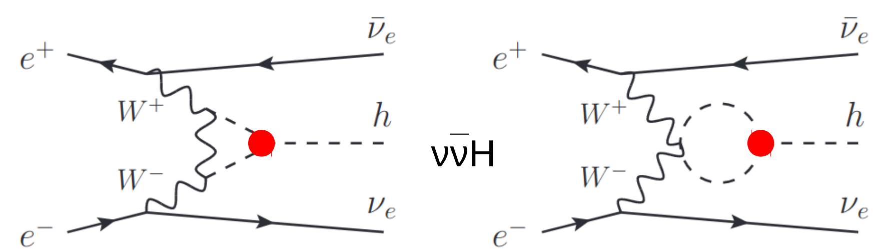






- ee colliders:



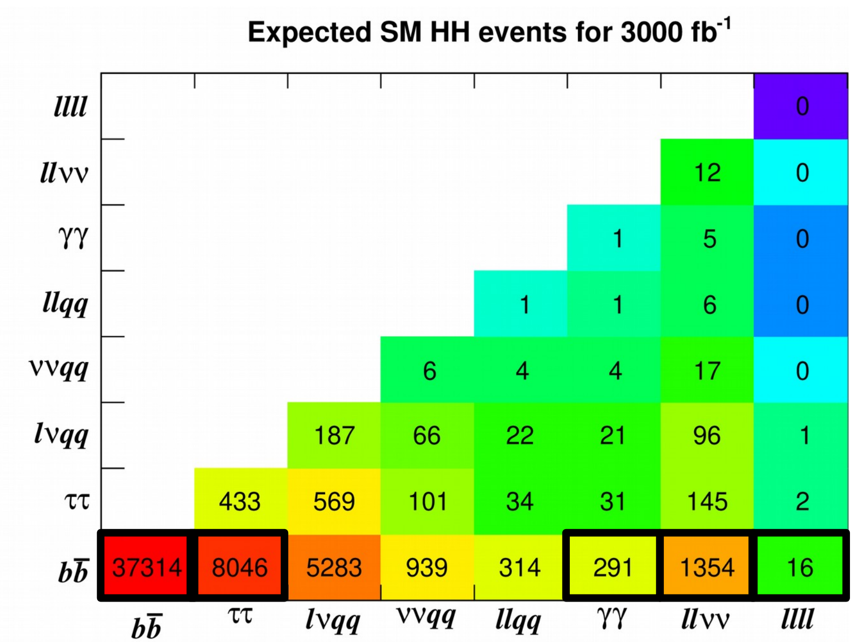


  - important when √s below HH threshold

- ex. for $\kappa_\lambda = 2$:
  - $\sigma(pp \rightarrow t\bar{t}H)$ modified by 3%
  - $\sigma(ee \rightarrow ZH)$ modified by 1%

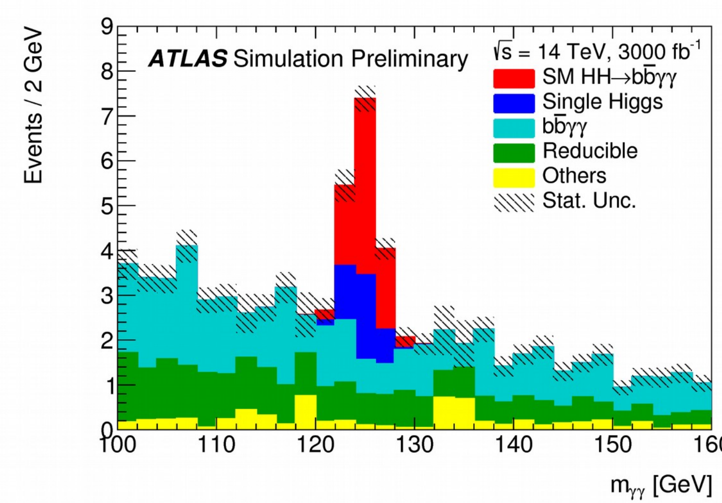
HH measurements at HL-LHC (1)

- Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200



	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 ☺

- General analysis strategy:
  - multivariate methods trained for observation of SM di-Higgs production
  - require candidate masses consistent with SM Higgs boson
  - use m_{HH} distribution when possible



HH measurements at HL-LHC (2)

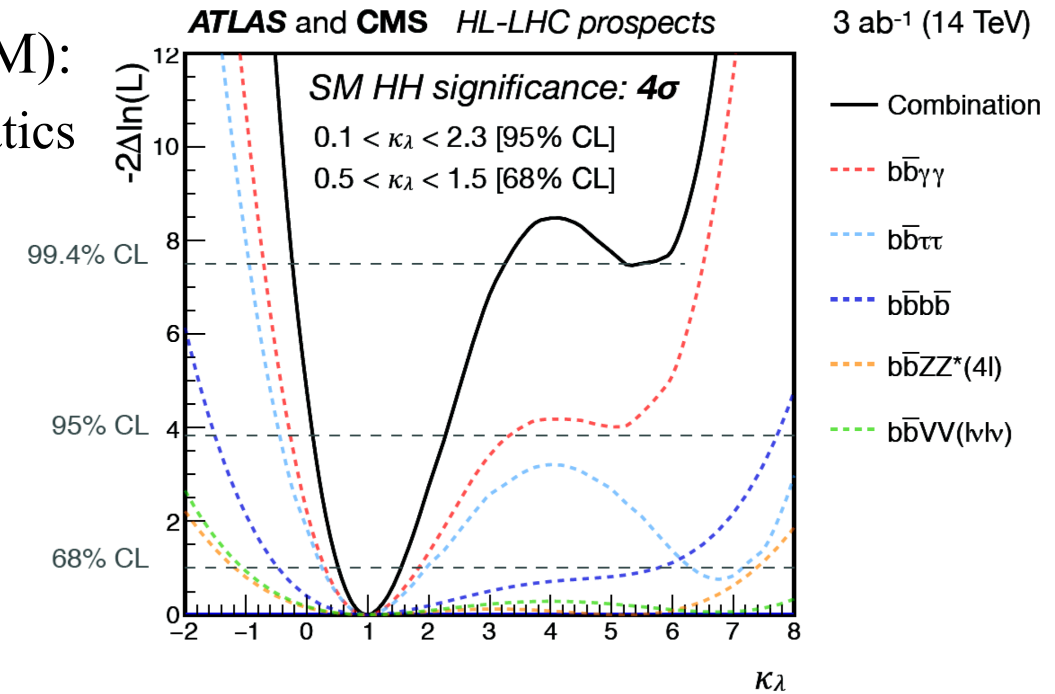
- Expected significance (SM) with and without systematics at HL-LHC

	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	

4σ expected with ATLAS+CMS!

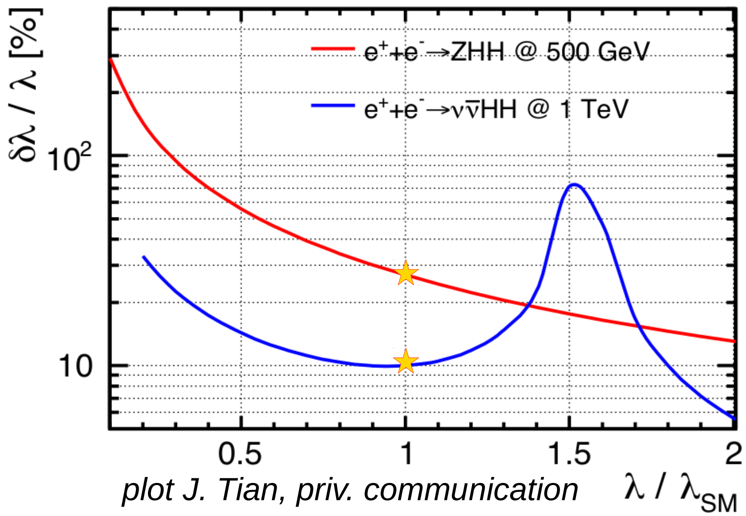
- Measurement of signal strength μ (SM):
  - ~25% (30%) without (with) systematics
  - μ = 0 (no SM HH signal) excluded at 95% CL

- Measurement of κ_λ:
  - 68% CI of 50%
  - 2nd minimum excluded at 99.4% CL thanks to the m_{HH} shape information



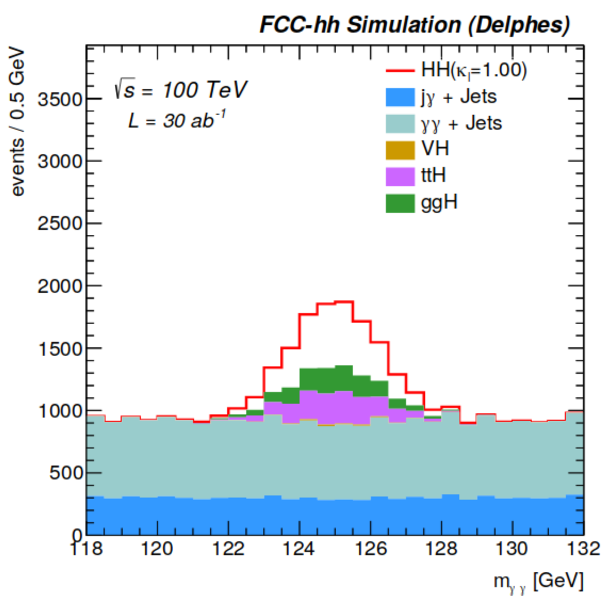
Self-coupling at Future Colliders

- di-Higgs:
  - ILC and CLIC: $\nu\bar{\nu}HH$ and ZHH

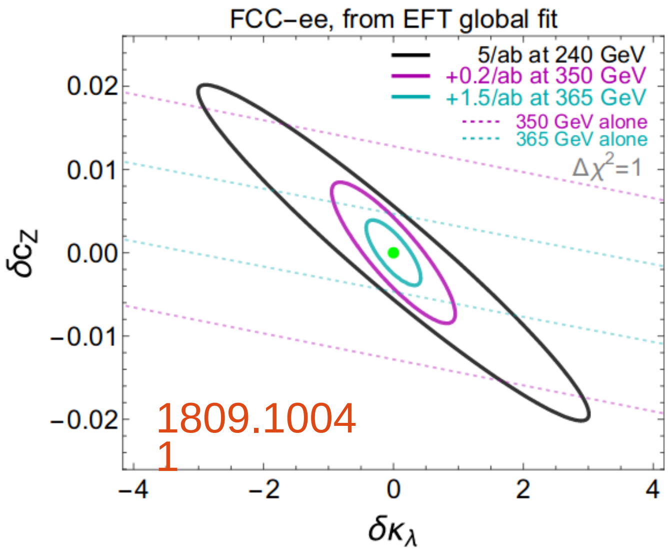


plot J. Tian, priv. communication

  - FCC-hh: main channel $b\bar{b}\gamma\gamma$

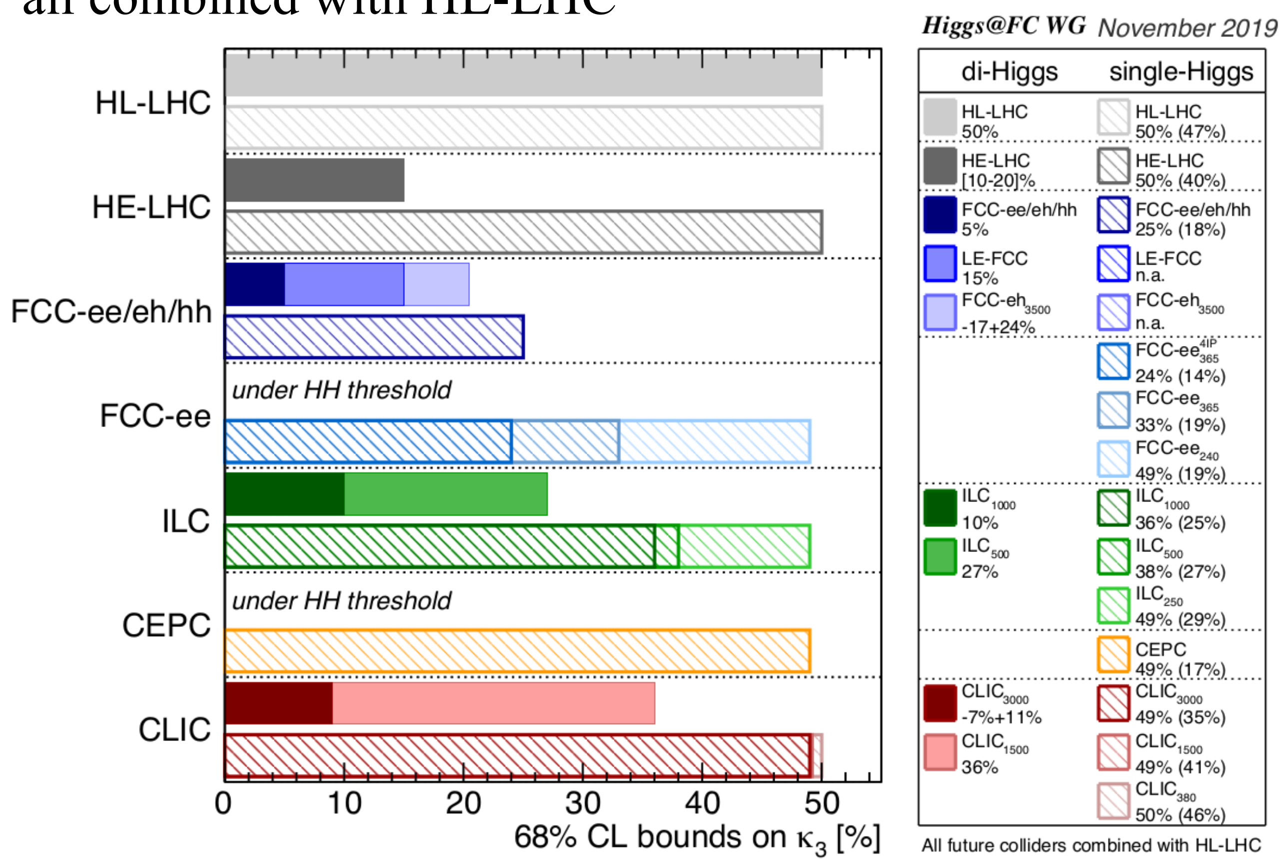


- Single-Higgs:
  - CEPC, FCC-ee, ILC, CLIC
- Based on very good precision on cross-section, eg CEPC and FCC-ee240:
  - $\sigma(ZH)$: 0.5%
  - $\sigma(\nu\bar{\nu}H)$: 2-3%
- Additional sensitivity from combining different $\sqrt{s}$
  - reduction of the uncertainty on other EFT parameters, removing correlations in the global fit



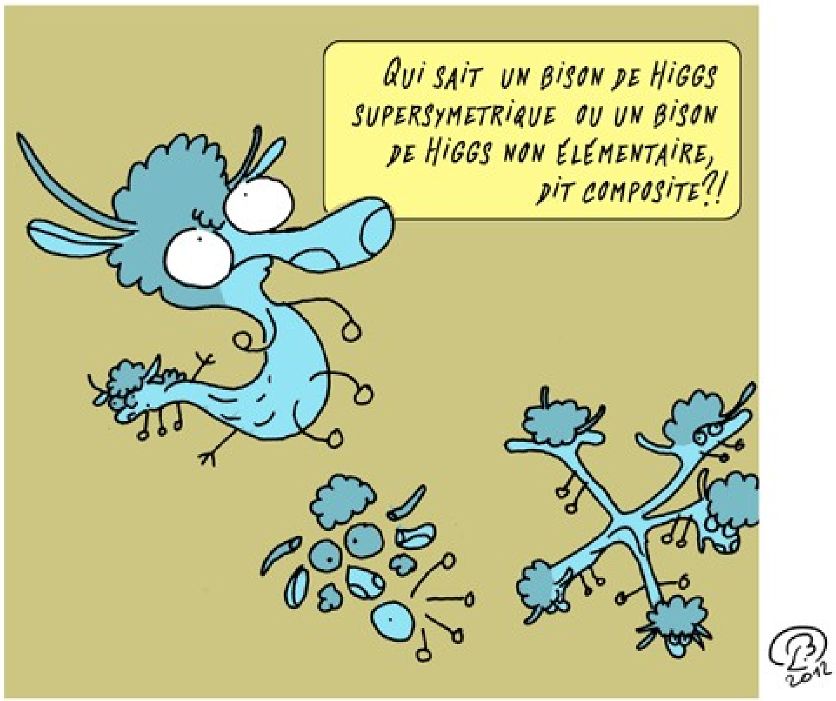
Results

- 68% CL uncertainties on κ_λ with di-Higgs and single-Higgs:
  - all combined with HL-LHC



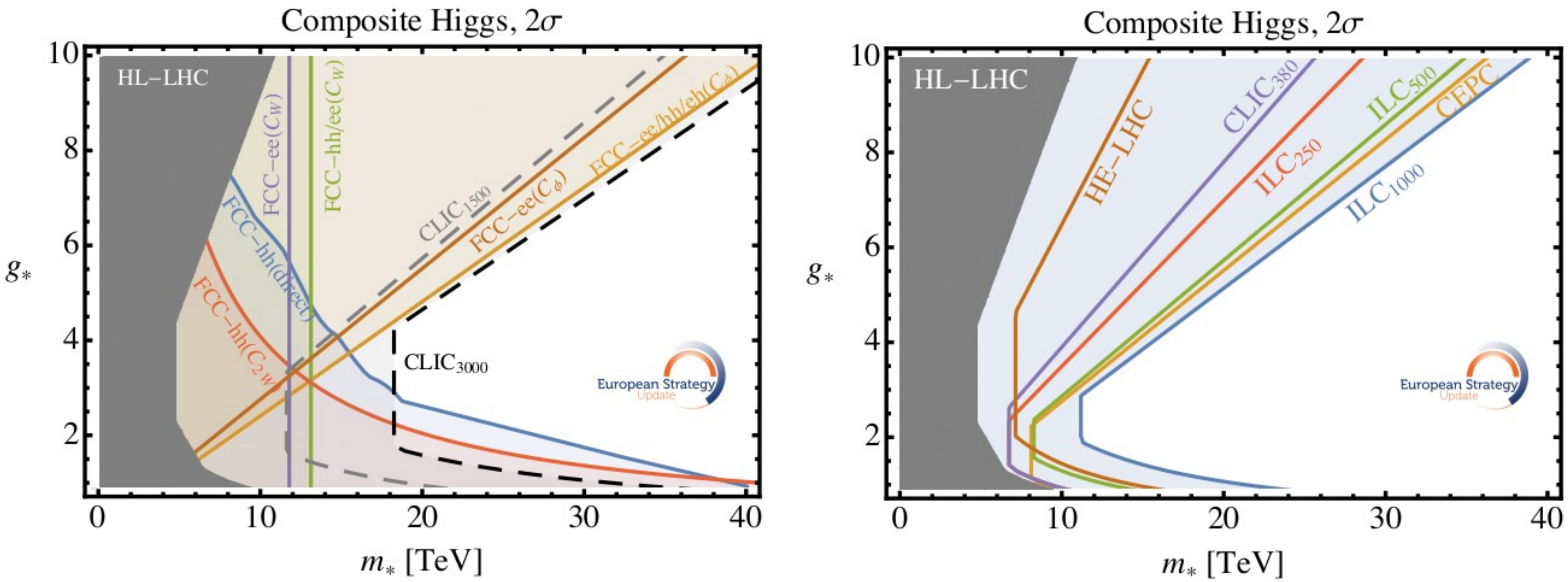
- HL-LHC will exclude the absence of the Higgs self-interaction at 95%CL
- Several of the proposed FCs will reach a sensitivity of ~20%
  ⇒ establish the existence of the self-interaction at 5σ
- CLIC3000/FCC-hh can reach a sensitivity of ~10%/5% ⇒ can start probing the size of the quantum corrections to the Higgs potential directly

BSM Higgs studies



Composite Higgs scenario

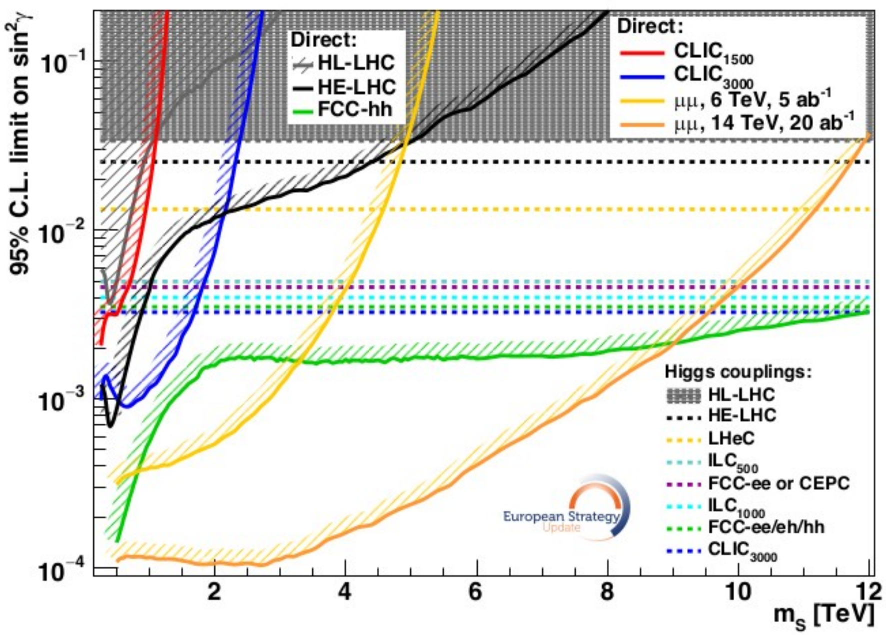
- Central idea: the Higgs emerges as a bound state of a new strongly-interacting confining Composite Sector, analogue to QCD but with a much higher confinement scale
- Two parameters: the mass scale m* and the coupling g*
  - m*: confinement scale, analogue to Λ_{QCD}. Its inverse can be interpreted as the geometric size of the Higgs, lH = 1/m∗ (=0 if Higgs elementary)
  - g*: interaction strength among particles originating from the Composite Sector

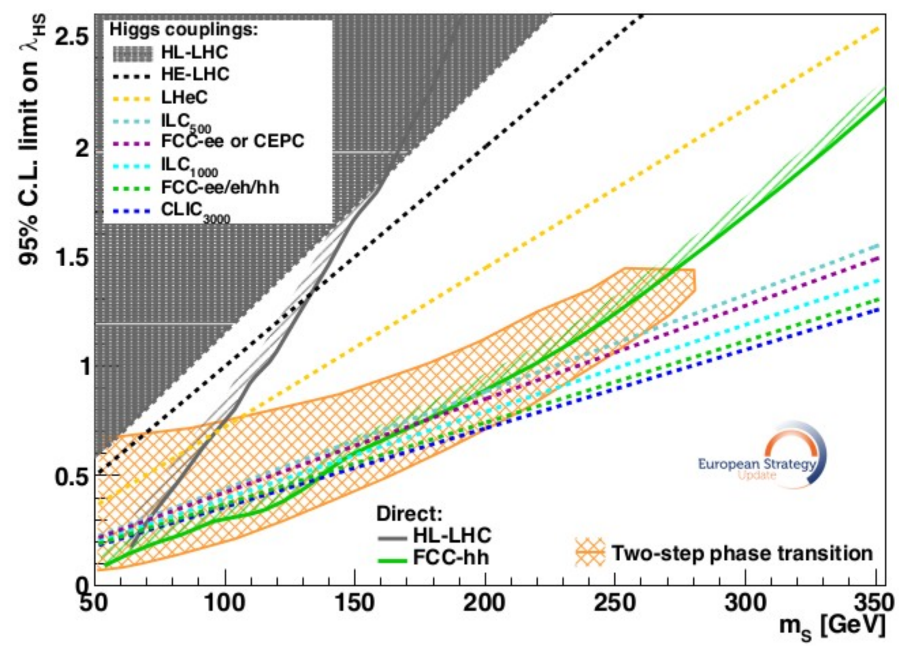


- The discovery reach of these particles at HL-LHC, HE-LHC and FCC-hh are of 1.5, 2 and 4.7 TeV, respectively

Extended Higgs sectors (1)

- Simple possibility is the extension of the SM scalar potential by a singlet massive scalar field S with interactions $V = \lambda_S S^4/4 + \lambda_{HS}|H|^2 S^2$
  - Mixing case: heavy singlet mixes with the SM Higgs boson (mixing parameter $\sin\gamma$)
  - Non-mixing case: S does not acquire a vacuum expectation value and the Z_2 symmetry remains unbroken, the new scalar is stable and escapes undetected

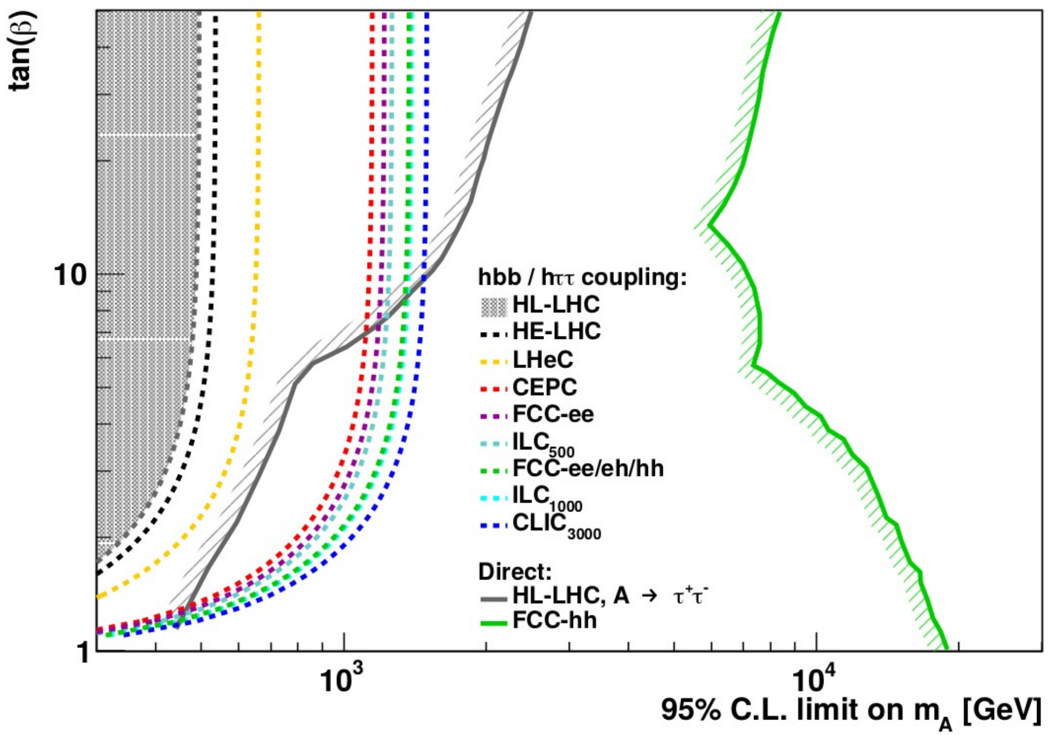




- NB: a large fraction of the region compatible with a first-order phase transition could be probed by the full CLIC or FCC programmes

Extended Higgs sectors (2)

- Addition of a second SU(2) doublet
  - naturally appears in supersymmetric extensions of the Higgs sector or in models with a non-minimal pattern of symmetry breaking
  - the scalar sector contains two CP-even scalars h and H, one CP-odd scalar A and a charged scalar H±
- Most sensitive channel: hττ at pp colliders, hbb at ee colliders



Conclusion

- Huge program for Higgs physics ahead of us
- Strong implications and recognised expertise of IN2P3 teams at LHC: many channels covered ($\gamma\gamma$, 4l, bb, ttH)

- HL-LHC: O(few%) measurement of couplings and 50% measurement of self-coupling
  - most measurements dominated by systematics → implication on detector upgrades and object performance
- Future Colliders:
  - most precise coupling measurements (Z and W bosons) measured to 0.2-0.3%
  - Higgs decays to invisible particles (e.g. dark matter candidates) can be constrained to values much better than 1%
  - measurement of the total width to within a few percent, possible at e^+e^- colliders, will provide an important constraint on many new physics scenarios
  - self-couplings: 5-10% could be reached at FCC-hh at 100 TeV, CLIC at 3 TeV or ILC at 1 TeV

- More on GT01 contributions in back-up

Back-up slides

Higgs physics at ILC: Plans groups IN2P3

- Extraction of the Higgs coupling to the Z boson from a simple countin of relying on the momentum resolution of the tracking chambers.
  - The efficiency is extracted from a 'Reference Sample' created by $e^+e^- \rightarrow$ HZ reco into a muon pair. From this the efficiency for the reconstruction of Higgs signal applied to channels in which the Z boson decays to particles other than a muon p the analysis is the number of final state hadrons

- Study of Higgs production in $e^+e^- \rightarrow Z(q\bar{q})H$
  - The analyses of hadronic final states of the process $e^+e^- \rightarrow$ HZ by IN2P3 groups intense development of a new generation of highly granular calorimeters (SiW ECAL and SDHCAL) and the realisation of the first technological prototype
    - Result will benefit from the development by the IN2P3 groups of a new PFA alg

HH physics: IN2P3/ATLAS plans

- Concentrate on bbγγ channel (already important contribution) + start bbττ channel
- Plans for Run-3 (2021-2023)
  - refinement of analyses
  - SM measurements:
    - diphoton + two (b-)jets: flavour composition + description of kinematic variables
    - Z(→bb)H(→γγ/ττ) and ggF+2 b-jets: could reach 2σ at the end of Run 3
  - preparation of detector and performance

- Plans for Run-4 (2027-2030)
  - commisioning of detectors and objects (eg new tracking stategies)
  - towards the ultimate performance of the detector and di-Higgs observation

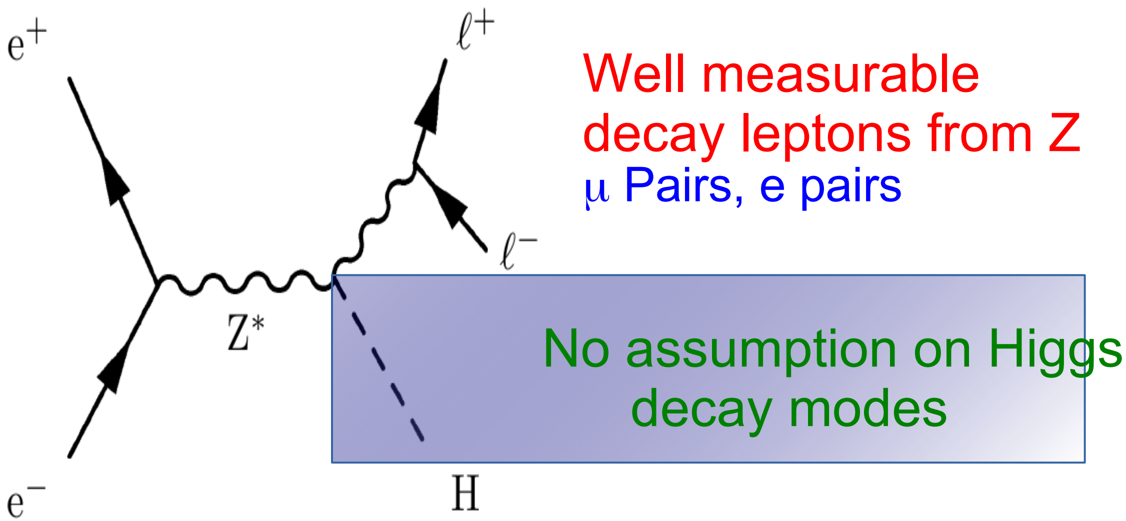
Run-3 (2021-2023)	LS 3 (2024-2025)	HL-LHC (2026-2037)	
HH → $b\bar{b}\gamma\gamma$ analysis			
HH → $b\bar{b}\tau\tau$ analysis			
SM background measurements			
Z(→bb)H(→γγ or →ττ) measurement			
egamma: preparation		egamma: commissioning	egamma: performance
b-tagging: preparation		b-tagging: commissioning	b-tagging: performance
τ-tagging: preparation		τ-tagging: commissioning	τ-tagging: performance

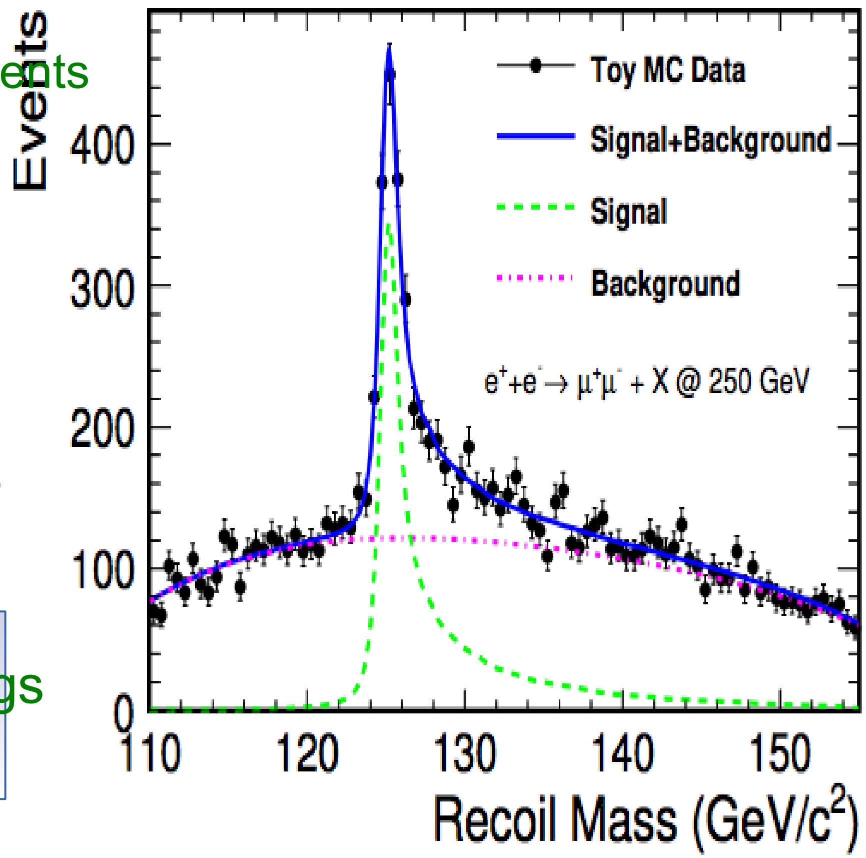
LPNHE scientific perspectives

- Plans through Run 3 of the LHC (ending 2023) and into the HL-LHC period which will begin around 2026
  - The LPHNE-ATLAS team is commited to two already approved Phase-II upgrade projects: ITk and HGTD.
  - The group expertise in tracking detectors and jets and photons performance will be essential to exploit the physics potential of HL-LHC.

- The FCC program (ee then pp) appears to us as the most promising future path to reach deeper understanding of elementary particle physics, while other collider and non-collider future facilities would also be very rewarding.

- Powerful channel for unbiased tagging of Higgs Events
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays





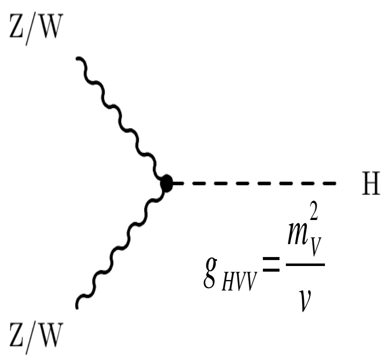
Higgs Recoil Mass:

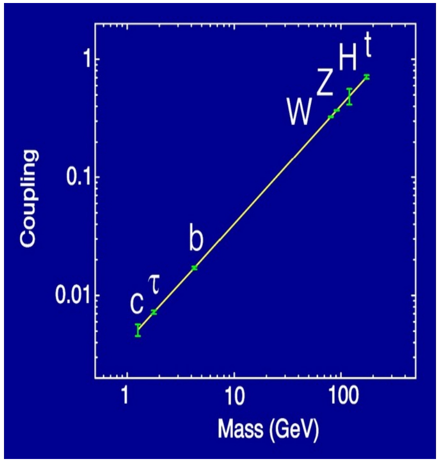
$M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2 E_Z \sqrt{s}$

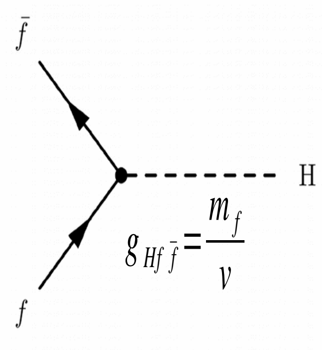
- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

Fitting Higgs Couplings – Kappa and EFT

Couplings to Higgs Boson in Standard Model







Analysis using Kappa-fit:

$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2\ , \quad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

- Simple scaling of SM-couplings
- Implies that Higgs coupling to Z in production and decay are identical
- No new operators

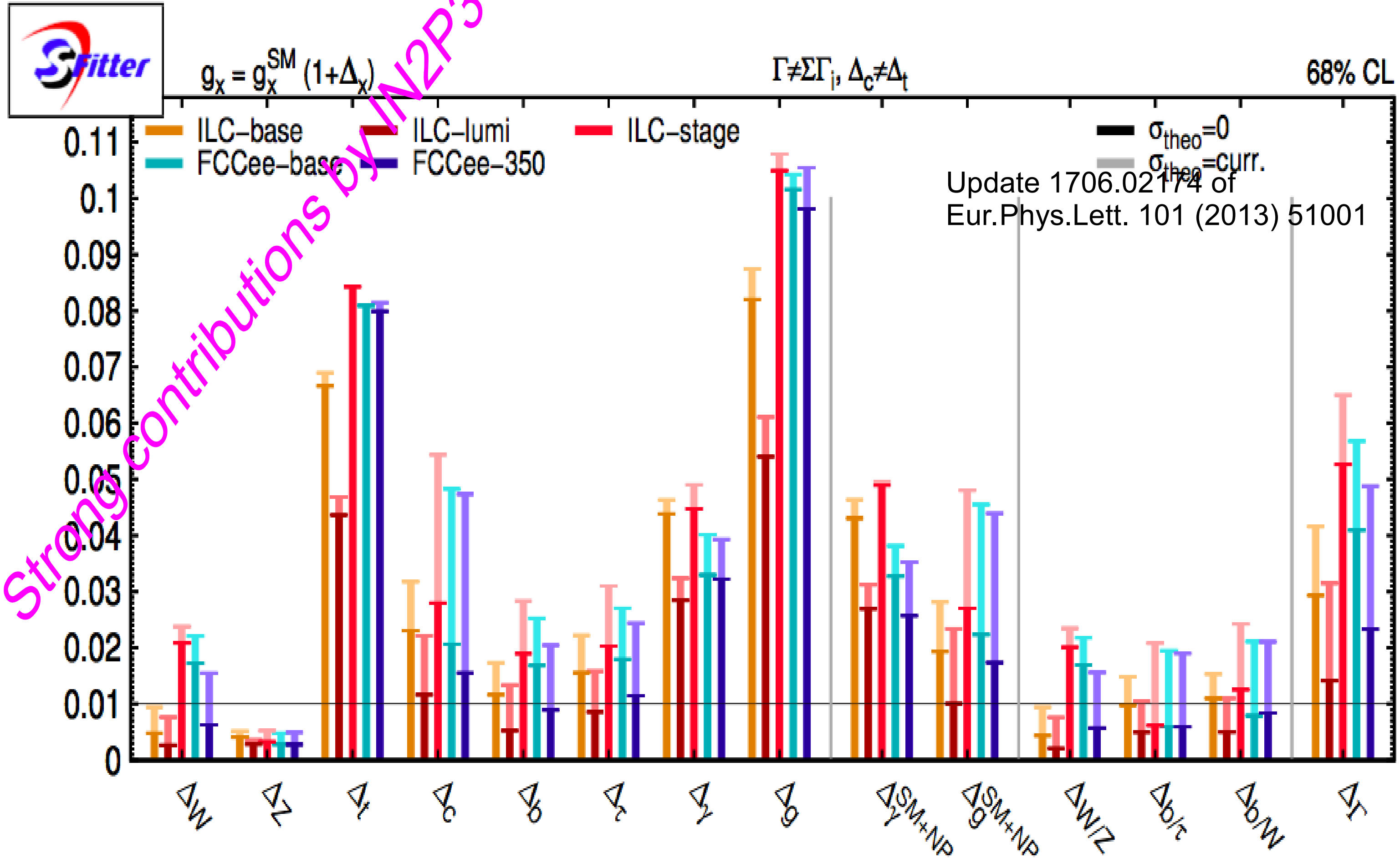
Analysis using EFT-fit:

$$\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$$
$$\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)$$

- Introducing set of SU(2)xU(1) compatible operators
- e.g. breaks simple relation between Higgs production and decay
- Total width and Higgs to invisible as free parameters
- Receives additional input from e.g. ee->WW and EWPO

Precision on Higgs Physics – Kappa framework

Strong contributions by IN2P3 Groups



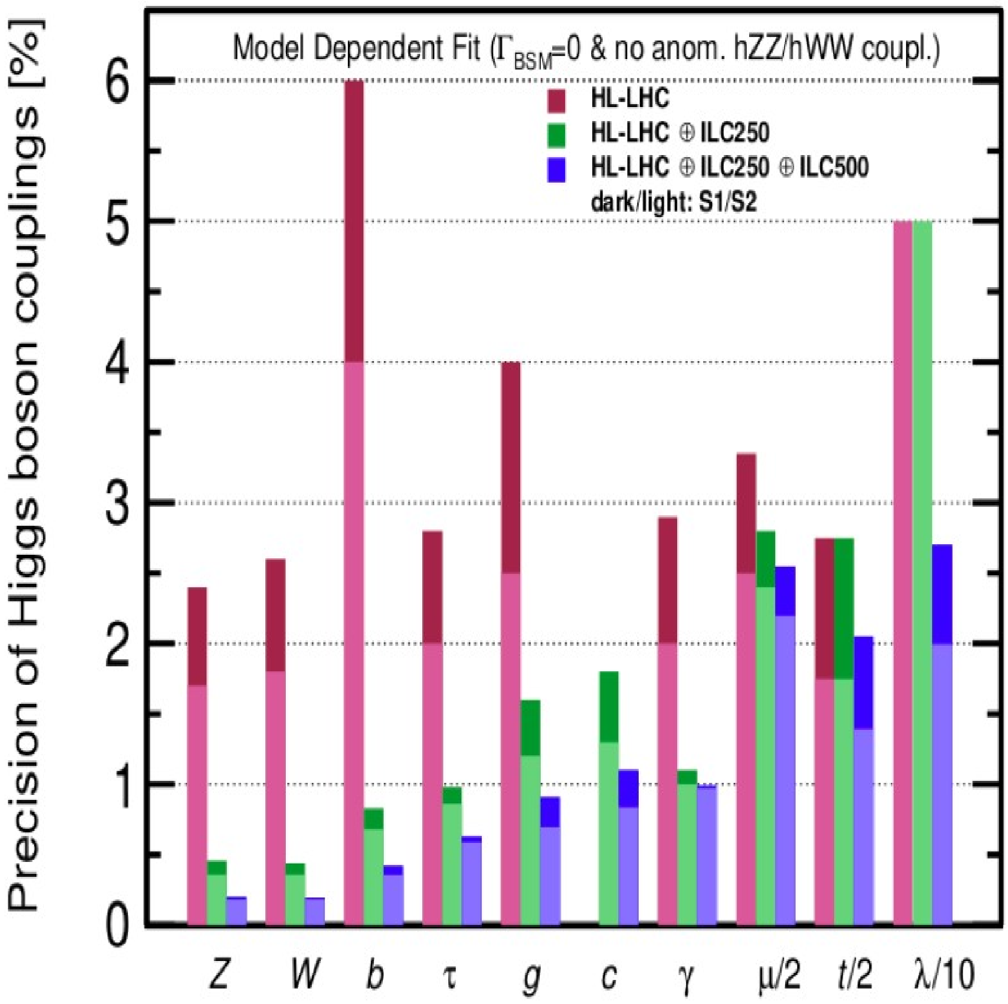
- Latest results from SFITTER group
  Assumption: HL-LHC basically completed before e+e- machine starts

- ILC250 already powerful program (needs however e.g. top-Yukawa as input)

- Higher energies beneficial for total width
and top-Yukawa couplings (fit constraints and H->γγ)

Precision on Higgs couplings – Model dependent fit

LCC physics working group

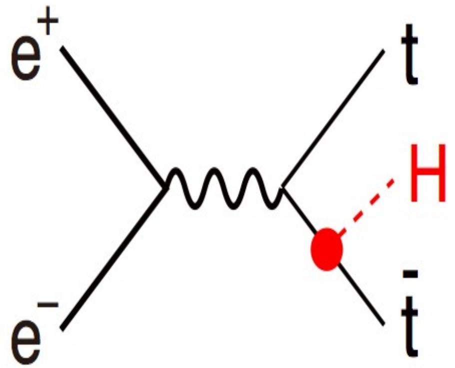


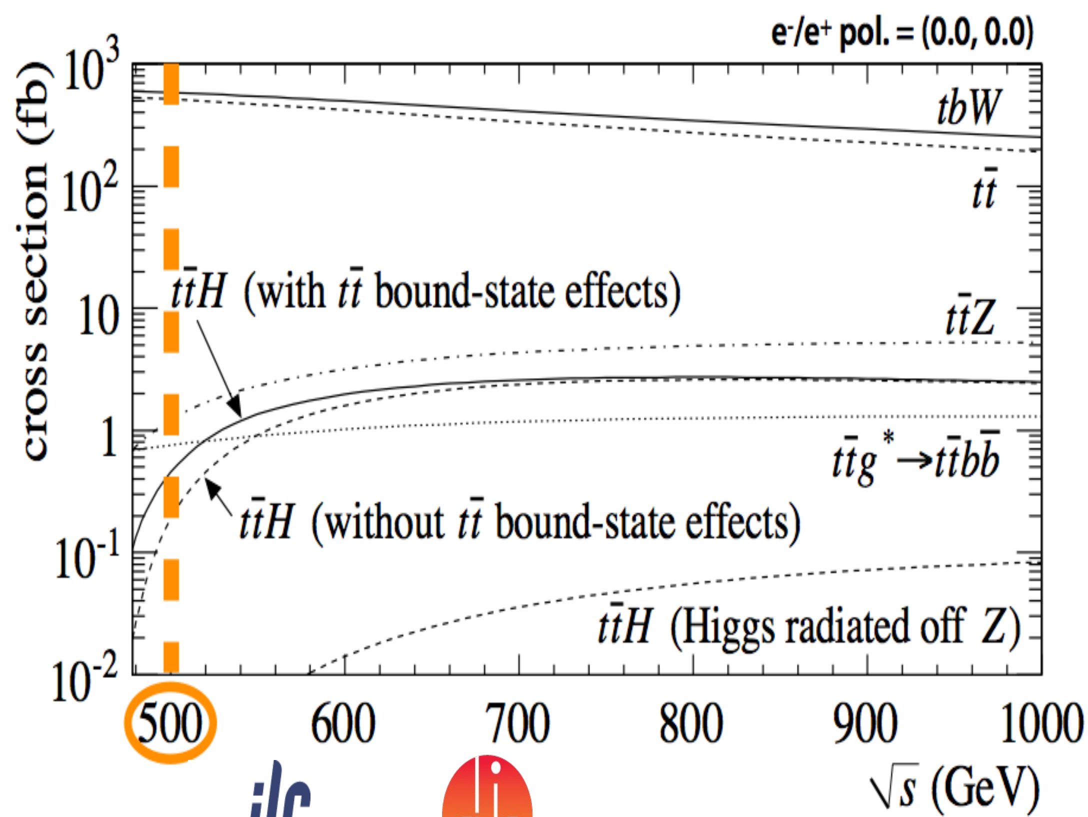
- Much higher precision at ILC for Higgs couplings
General observation for e+e- colliders

- Comparison to projected LHC results require
model dependent assumptions

- Precision on couplings benefit from higher energies

Top Yukawa Coupling





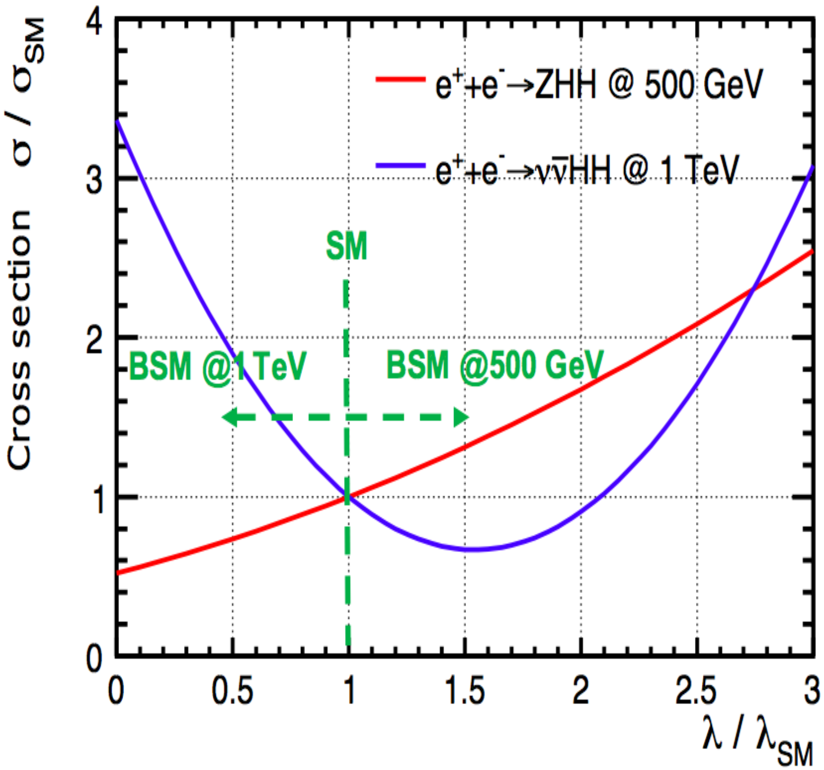
- Coupling of Higgs to heaviest particle known

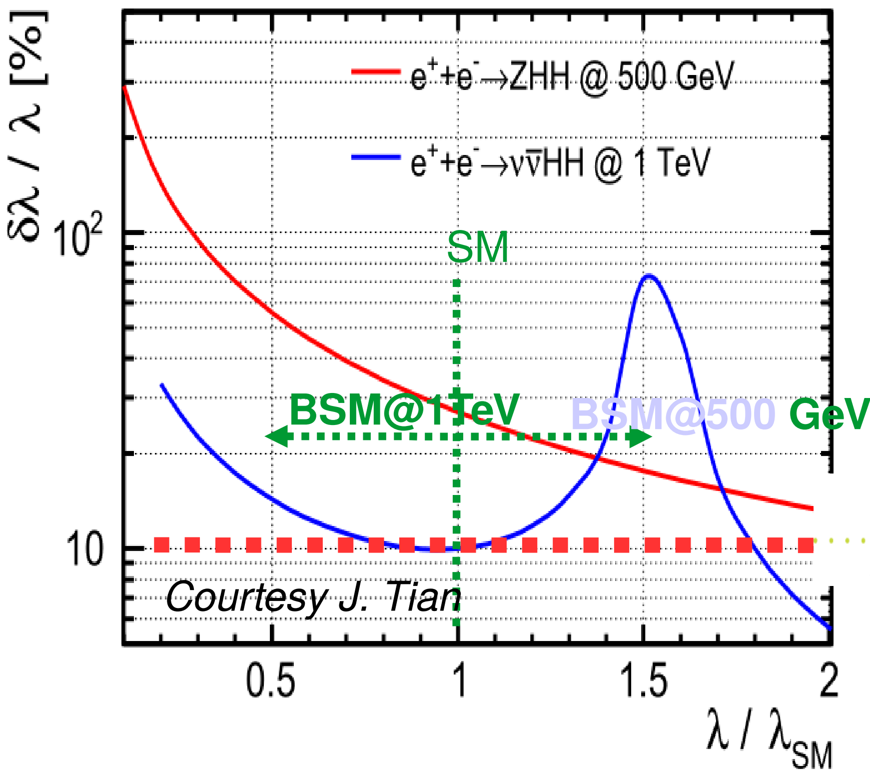
- Up to eight final state jet

√s[GeV]	550	1000	1400
L[ab-1]	4	8	2
δyt/yt[%]	2.8	2.0	2.7

Higgs self-coupling and new physics

Manifestation of new physics in observables and extracted results?





- Remarkable sensitivity of 500 GeV machine in case of large upward deviati
- 1 TeV machine superior for large upward and downward deviations

T. Tanabe, Higgs Coupling 2016

Higgs couplings: κ scenarios

- κ framework:

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

$$\kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

- Extension to allow for the possibility of Higgs boson decays to invisible or untagged BSM particles:

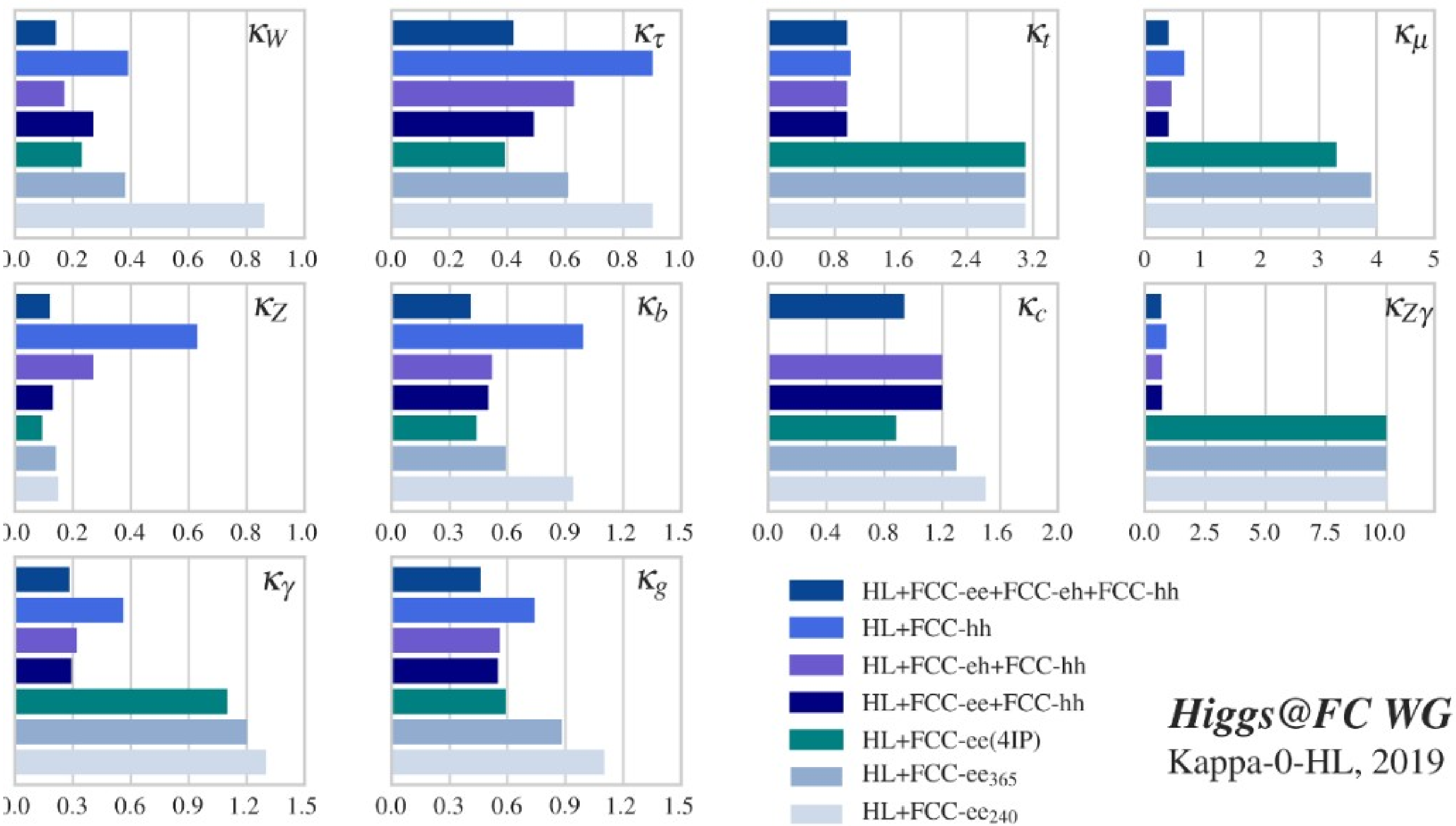
$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{\mathrm{inv}} + BR_{\mathrm{unt}})}$$

- Different fitting scenarios:

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-0	fixed at 0	fixed at 0	no
kappa-1	measured	fixed at 0	no
kappa-2	measured	measured	no
kappa-3	measured	measured	yes

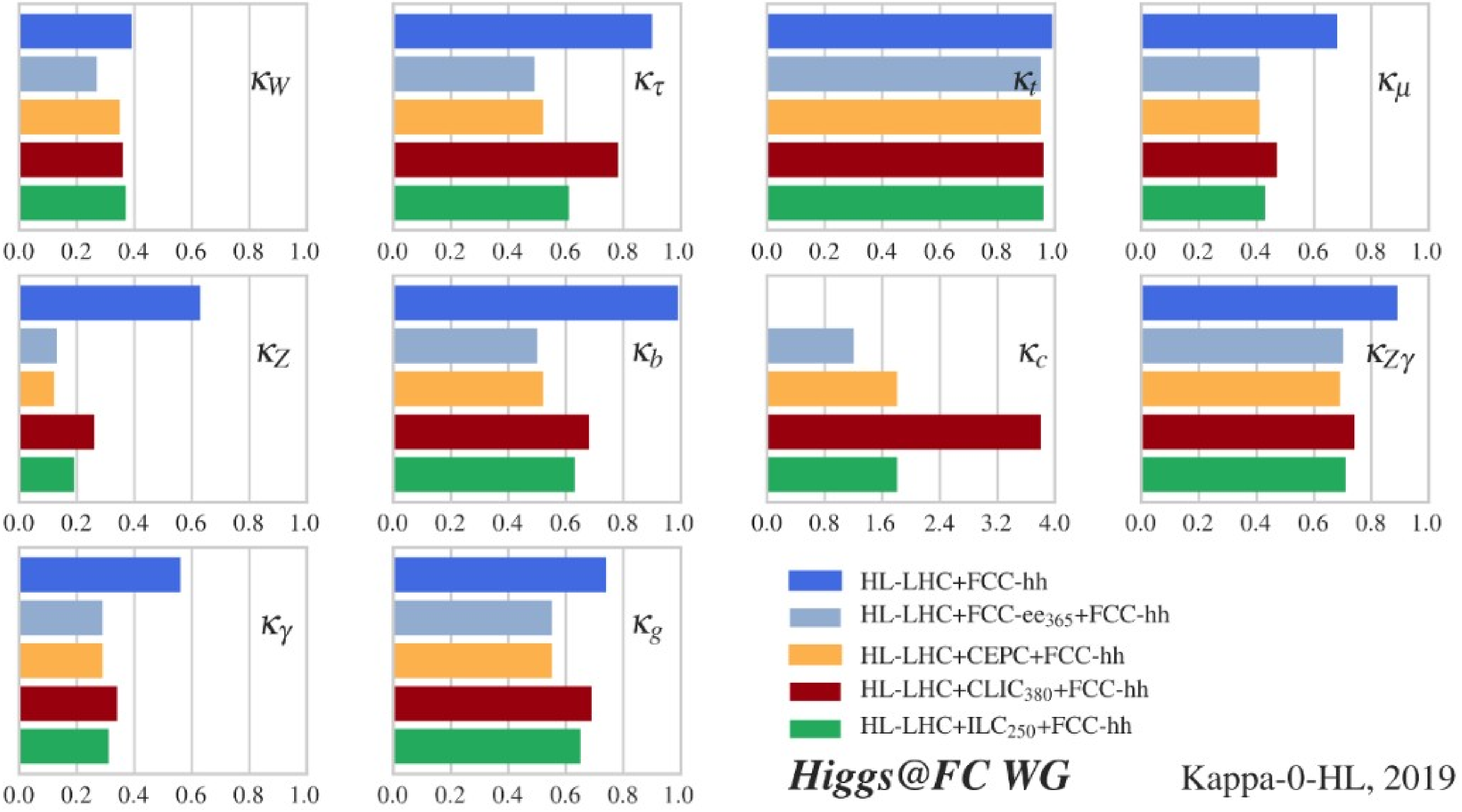
Higgs couplings: additional scenarios (1)

- Comparison of the different FCC scenarios in the kappa-0-HL scenario (similar to kappa-0 in that it does not allow any BSM decay, but including HL-LHC data)



Higgs couplings: additional scenarios (2)

- Combination of the different future ee colliders with FCC-hh and HL-LHC, in an extension of the kappa-0-HL scenario. Note that ILC 250 and CLIC 380 (first stages) are shown in comparison with CEPC (240) and FCC-ee 365



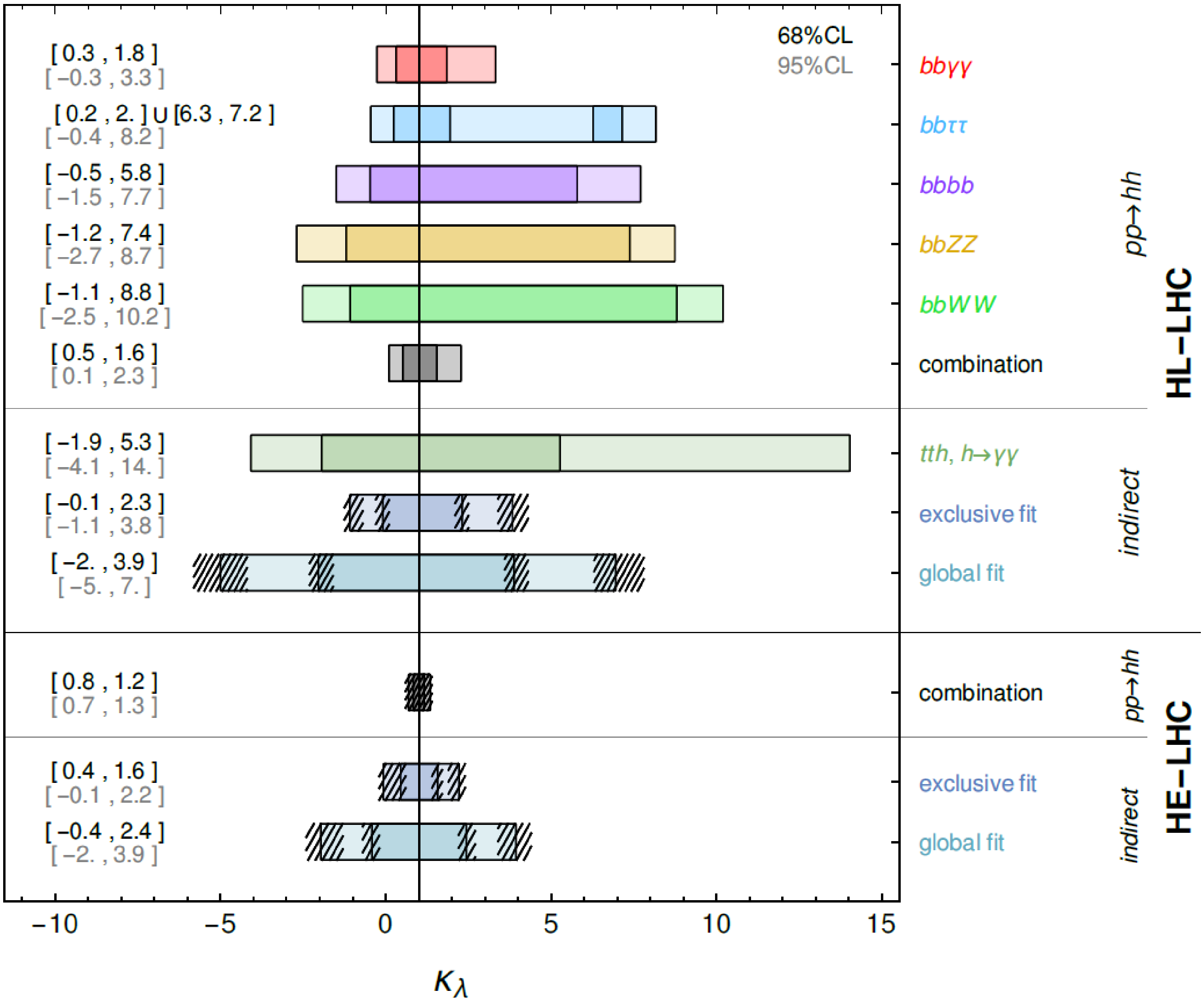
Higgs couplings: additional scenarios (3)

- Expected relative precision (%) of the κ parameters in the kappa-0-HL scenario for future lepton colliders combined with the HL-LHC and the FCC-hh 37.5, and with HL-LHC and FCC-hh. No BSM width is allowed in the fit: both BR_{unt} and BR_{inv} are set to 0.

kappa-0-HL	HL-LHC+FCC-hh$_{37.5}$+			
	ILC$_{250}$	CLIC$_{380}$	CEPC	FCC-ee$_{365}$
κ_W [%]	0.94	0.62	0.81	0.38
κ_Z [%]	0.21	0.33	0.13	0.14
κ_g [%]	1.3	1.3	0.97	0.87
κ_γ [%]	0.64	0.68	0.62	0.62
$\kappa_{Z\gamma}$ [%]	3.	3.1	2.8	3.
κ_c [%]	1.9	3.9	1.9	1.3
κ_t [%]	1.9	1.9	1.9	1.9
κ_b [%]	0.99	0.94	0.81	0.58
κ_μ [%]	1.	1.1	1.	1.
κ_τ [%]	0.96	1.2	0.83	0.6

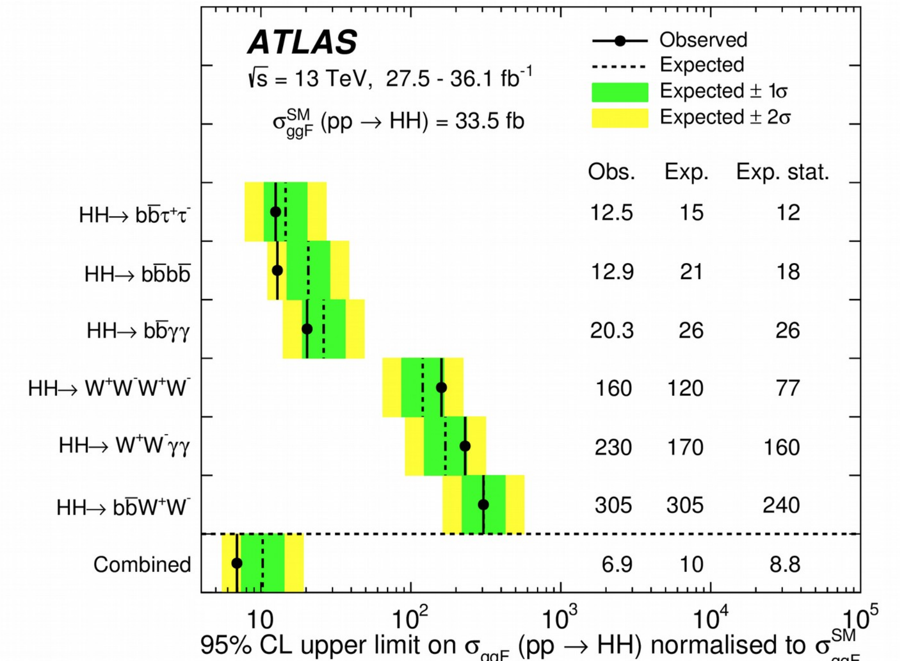
kappa-0-HL	HL-LHC+FCC-hh+			
	ILC$_{250}$	CLIC$_{380}$	CEPC	FCC-ee$_{365}$
κ_W [%]	0.37	0.36	0.35	0.27
κ_Z [%]	0.19	0.26	0.12	0.13
κ_g [%]	0.65	0.69	0.55	0.55
κ_γ [%]	0.31	0.34	0.29	0.29
$\kappa_{Z\gamma}$ [%]	0.71	0.74	0.69	0.7
κ_c [%]	1.8	3.8	1.8	1.2
κ_t [%]	0.96	0.96	0.95	0.95
κ_b [%]	0.63	0.68	0.52	0.5
κ_μ [%]	0.43	0.47	0.41	0.41
κ_τ [%]	0.61	0.78	0.52	0.49
Γ_H [%]	0.90	0.98	0.74	0.67

Summary of HL(HE)-LHC prospects

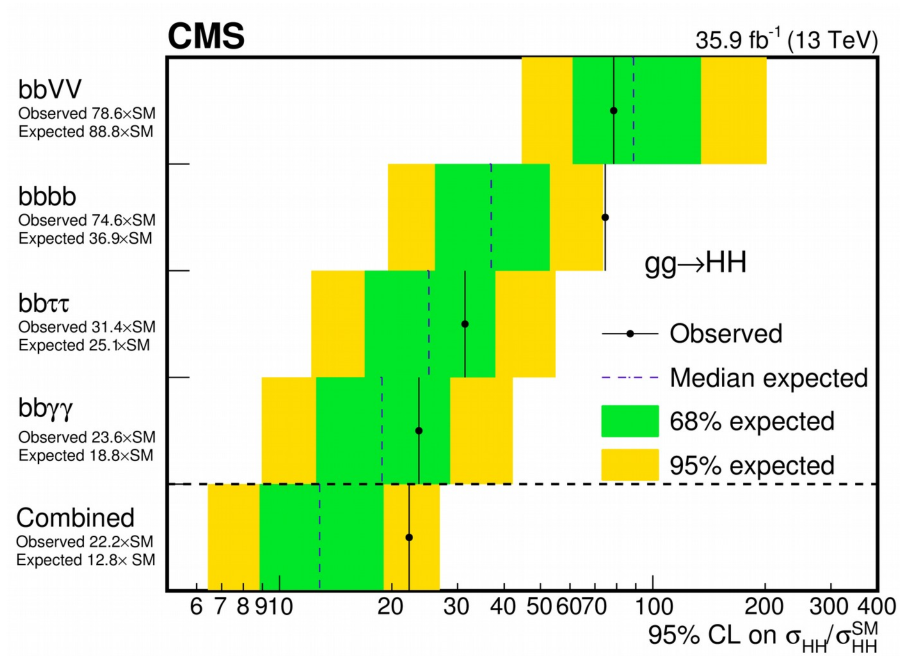
- 

Run-2 results

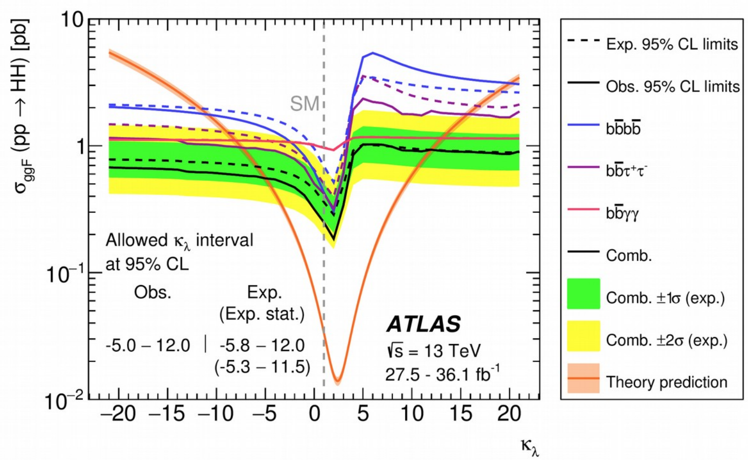
- ATLAS



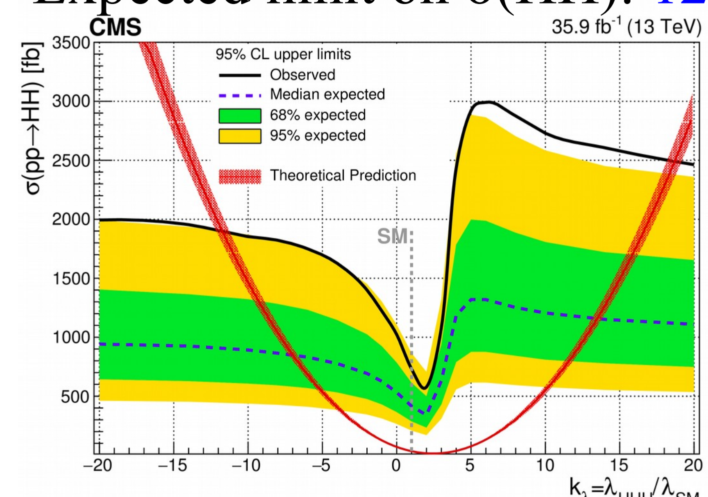
- CMS



- Expected limit on σ(HH): 10*SM



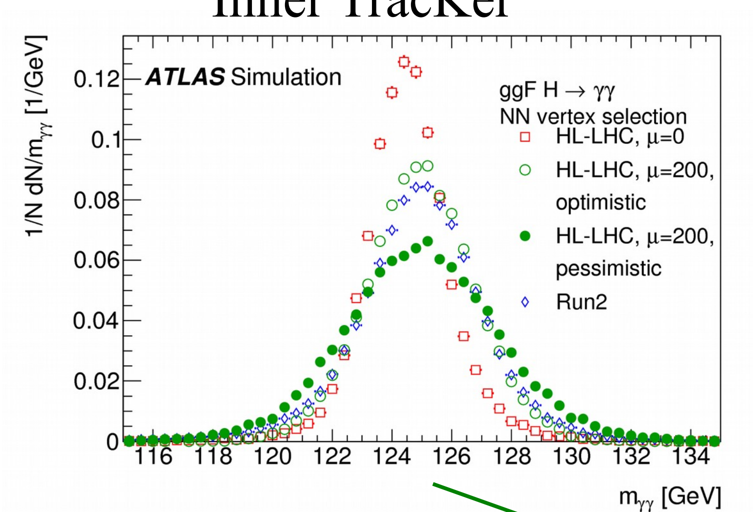
- Expected limit on σ(HH): 12.8*SM

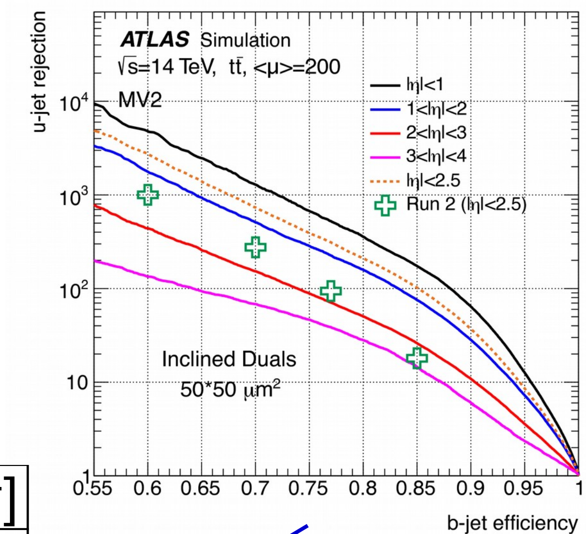


- $-5.0 < \kappa_\lambda < 12.0$ at 95% CL
- $-7.1 < \kappa_\lambda < 13.6$ at 95% CL

Detector performance at HL-LHC (2)

- Outcome of TDRs: current resolutions/efficiencies could be kept at HL-LHC!
- Example for ATLAS HH → $b\bar{b}\gamma\gamma$ analysis
  - Electromagnetic calorimeter
  - Inner TracKer

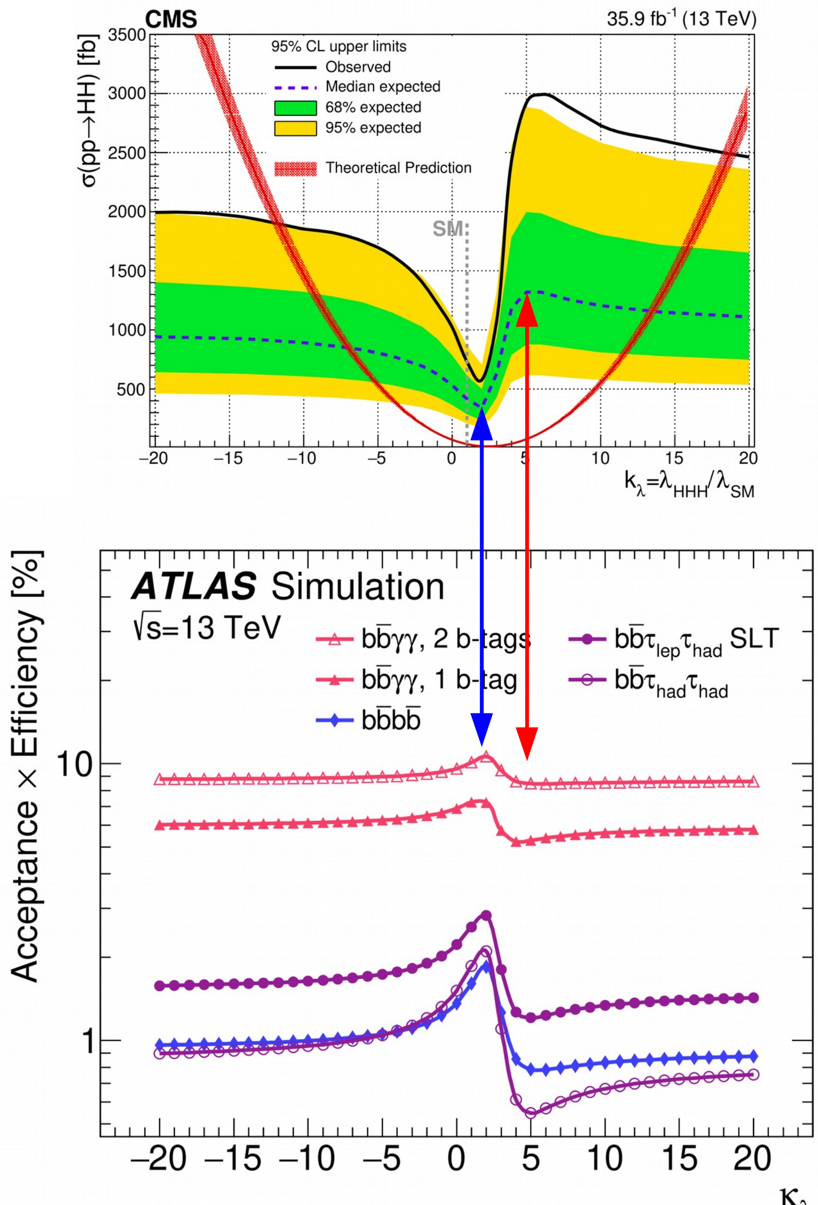




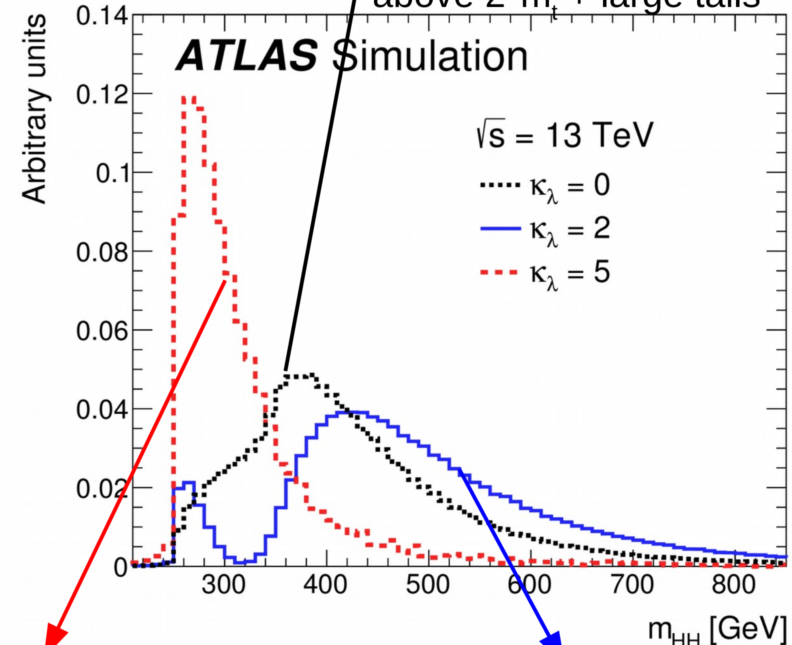
	significance [σ]
Strip TDR	1.05
LAr TDR	1.29
Pixel TDR	1.51

- Systematic uncertainties: common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC stat uncertainties neglected

- Sensitivity to κ_λ directly related to the acceptance, so to the m_{HH} shape



κ_λ=0: no triangle ⇒ increase of cross-section above 2*m_t + large tails



κ_λ=5: interference at high m_{HH} ⇒ soft spectrum

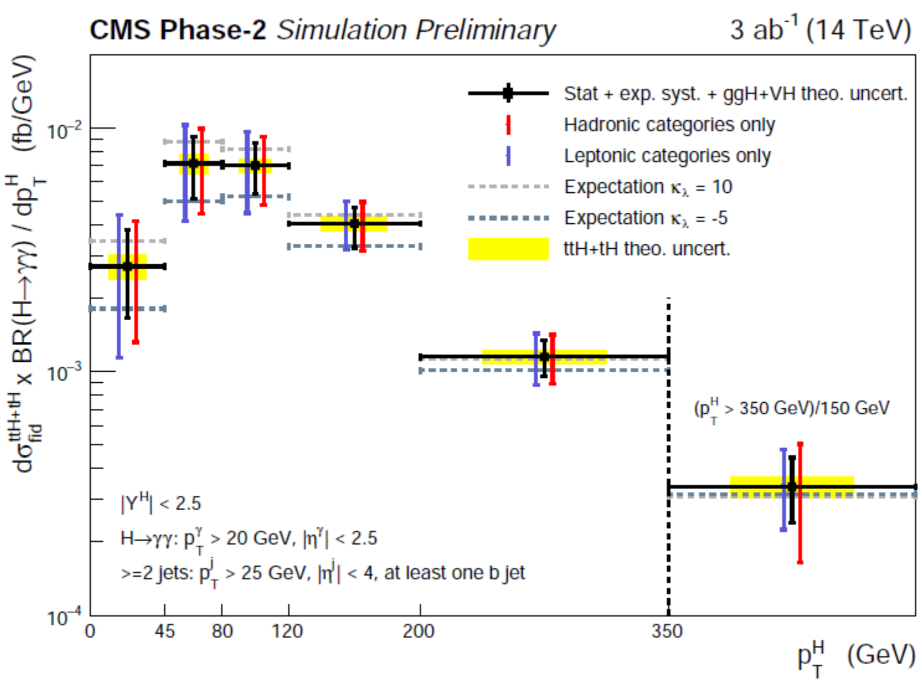
κ_λ=2: max interference ⇒ deficit between 2*m_H and 2*m_t + large tails

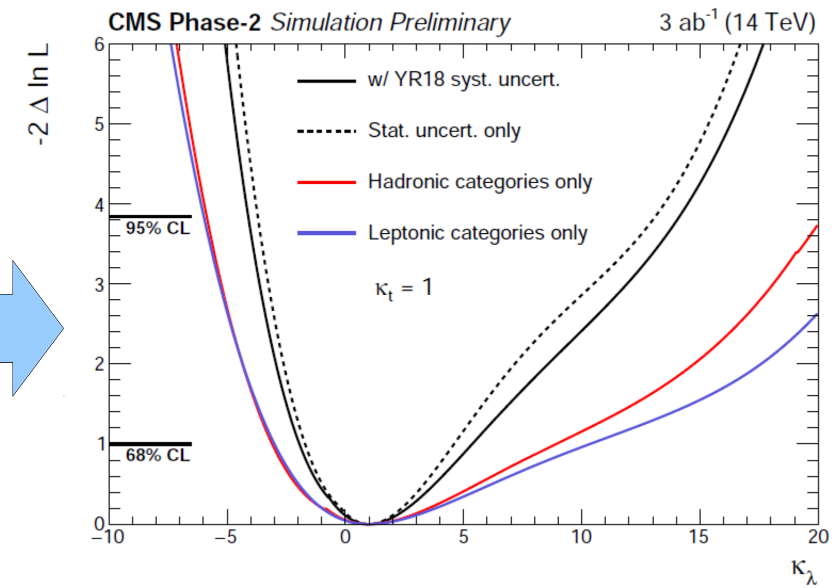
|κ_λ|>10: trilinear dominant ⇒ peaks at 2*m_H

- NB: most analyses optimised for κ_λ=1

Single-Higgs at HL-LHC (1)

- Method applied to $t\bar{t}H(\rightarrow\gamma\gamma)$ differential cross-section measurement:





- 68% CI: $-1.9 < \kappa_\lambda < 5.3$ if only κ_λ varied
- First test with experimental "data", more channels to be added

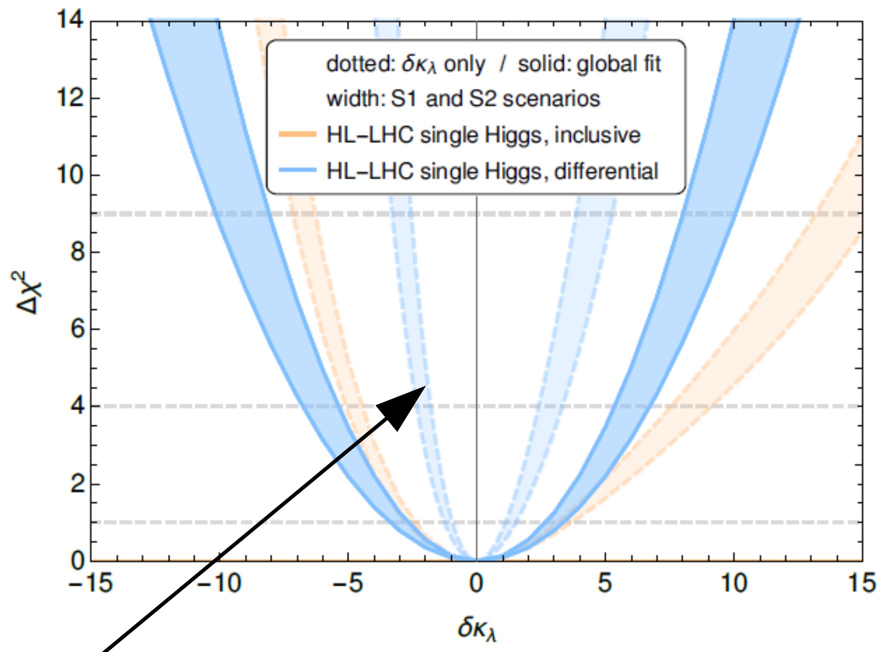
Single-Higgs at HL-LHC (2)

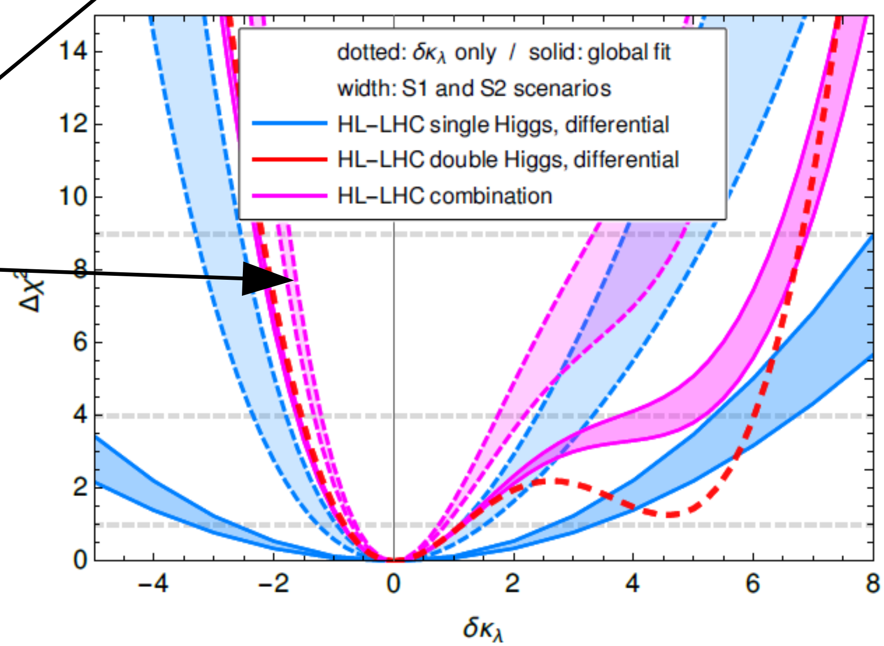
- Global fits of single-Higgs inclusive couplings and $t\bar{t}H$ differential measurements
  - for HL-LHC and HE-LHC

- Different BSM scenarios
  - only κ_λ can be varied (dotted line)
  - EFT framework (solid line)
- Different scenarios for systematics (bands)

- Biggest impact from diff. cross-section
- Improvement of di-Higgs direct measurements for variations of κ_λ only

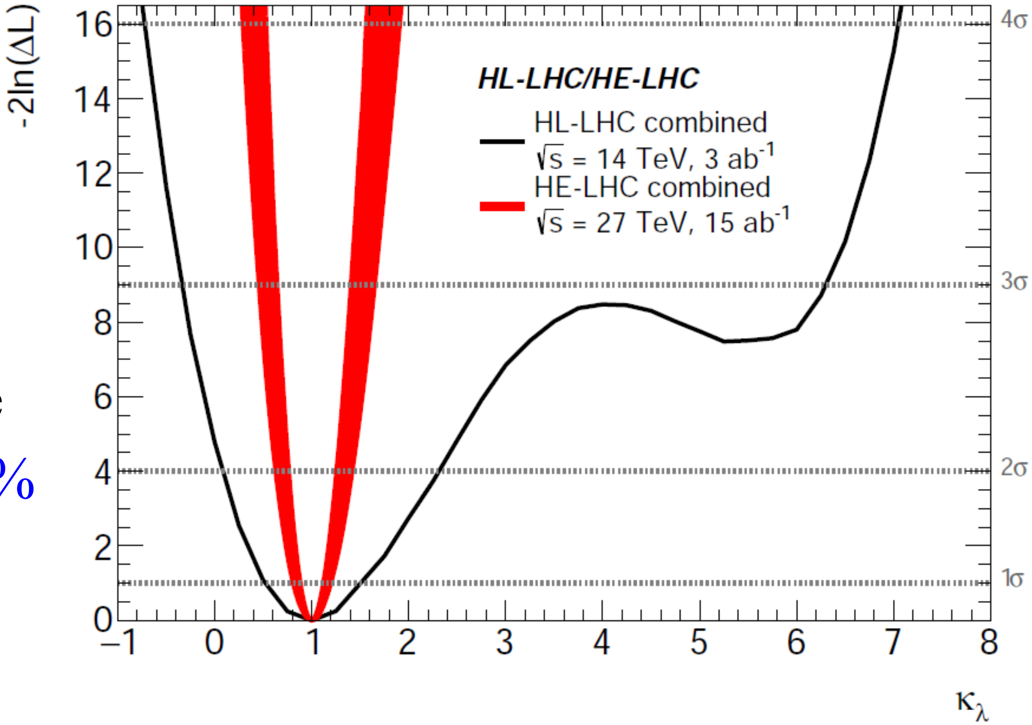
- HL-LHC: 68% CI (optimistic systematics):
  - $-0.1 < \kappa_\lambda < 2.3$ if only κ_λ varied
  - $-2 < \kappa_\lambda < 3.9$ for global fit





HE-LHC, HH measurements

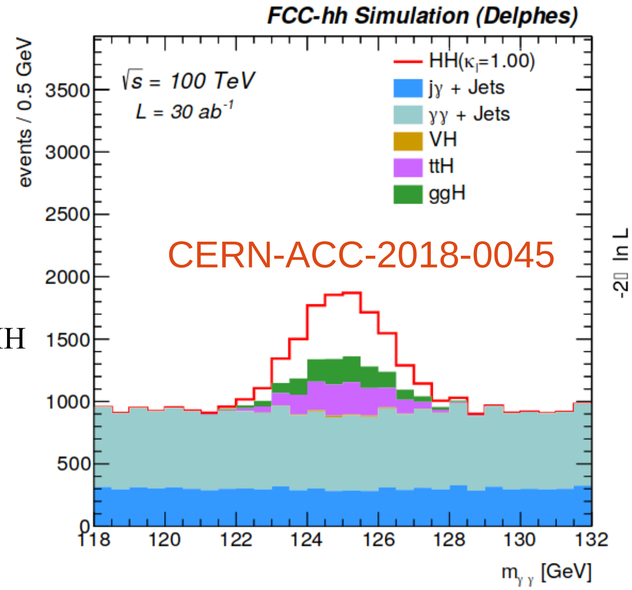
- Extrapolation of ATLAS HL-LHC results to HE-LHC: method 1
  - scale cross-section to 27 TeV (*4) and luminosity to 15 ab^{-1} (*5), no systematic uncertainties
  - $b\bar{b}\tau\tau$ channel: significance: 10.7σ, precision on κ_λ: 20%
  - $b\bar{b}\gamma\gamma$ channel: significance: 7.1σ, precision on κ_λ: 40%
    - pessimistic because analysis not optimised for measurement of κ_λ
- Phenomenology study for $b\bar{b}\gamma\gamma$: 15% precision on κ_λ
    - realistic detector performance
    - no pile-up considered (μ=800-1000)
- Combination of channels: κ_λ could be measured with a 68% CI of 10 to 20 %

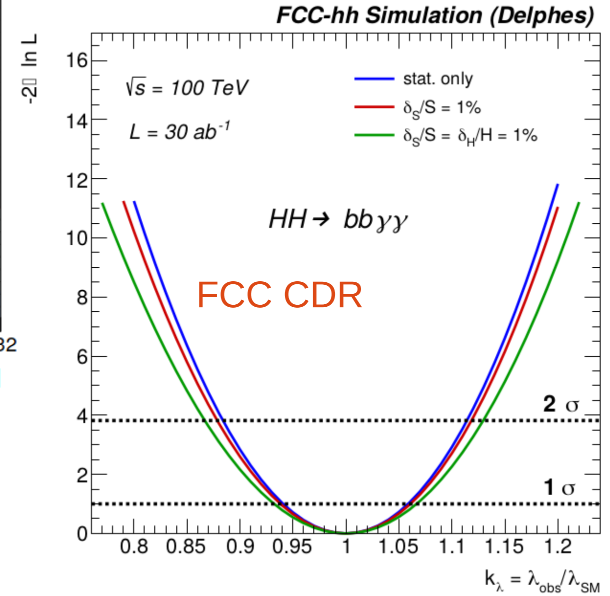


FCC-hh, HH measurement

- Method (1)
- Main channel : $b\bar{b}\gamma\gamma$
  - Delphes simulation
  - 2D likelihood fit of $m_{\gamma\gamma}$ vs m_{HH}
  - scenarios with varying
    - photon efficiency
    - $m_{\gamma\gamma}$ resolution
    - background level
    - small effect (1-2%)

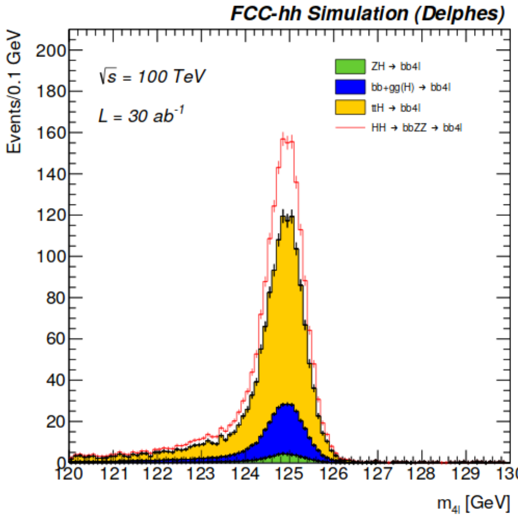
  ⇒ 5-7% uncertainty on κ_λ





- Other channels:

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

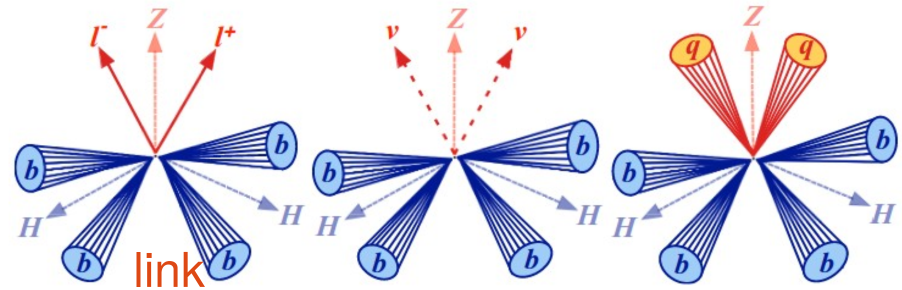


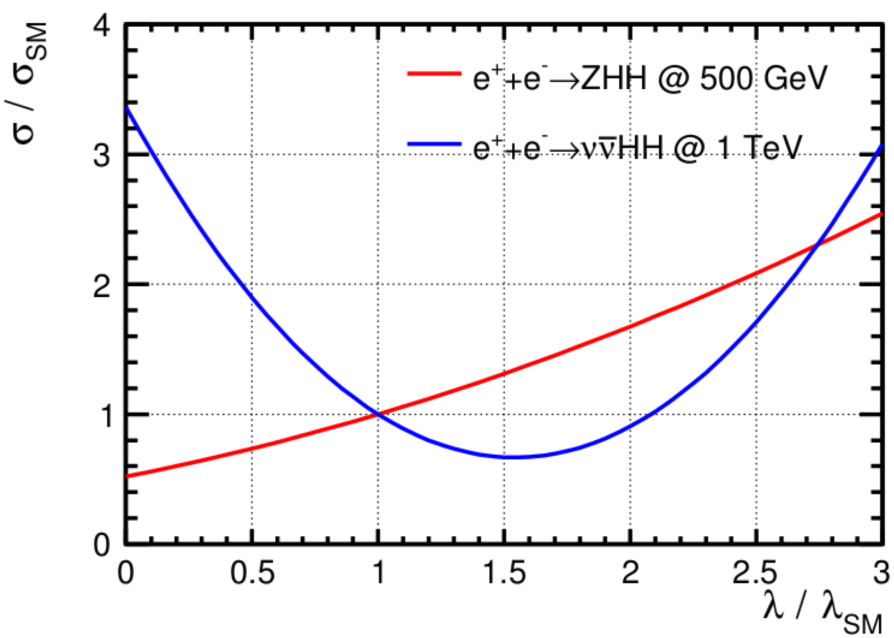
- Determination of κ_λ at the level of O(5%) expected to be within the FCC reach

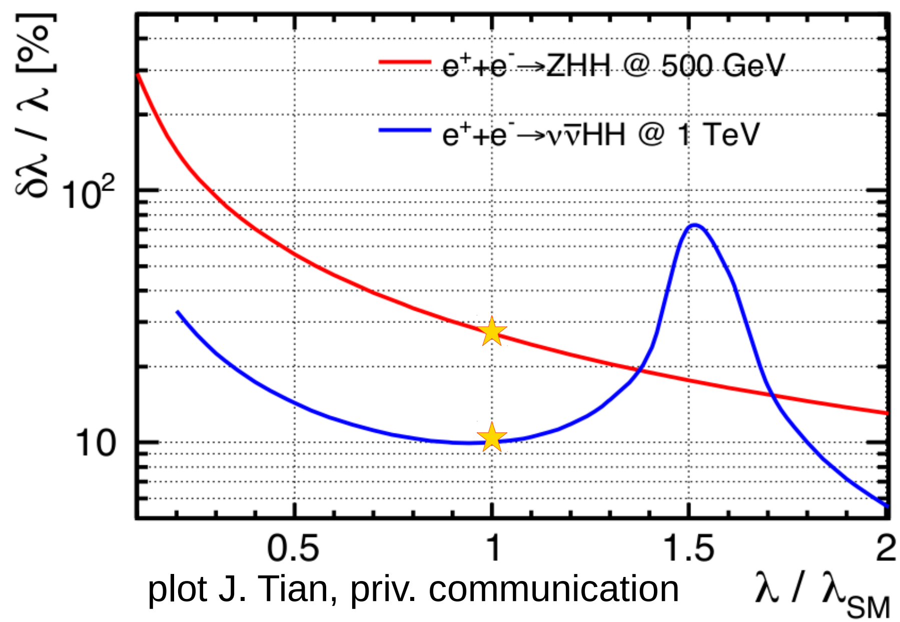
ILC, HH measurement

- Method (1)

- ZHH @500 GeV
  - $Z \to l^+l^-/\nu\bar{\nu}/q\bar{q}$ and $HH \to b\bar{b}b\bar{b}/b\bar{b}WW$
  - precision of 16.8% on the total cross section for $e^+ e^- \to ZHH$
  - 27% uncertainty on κ_λ



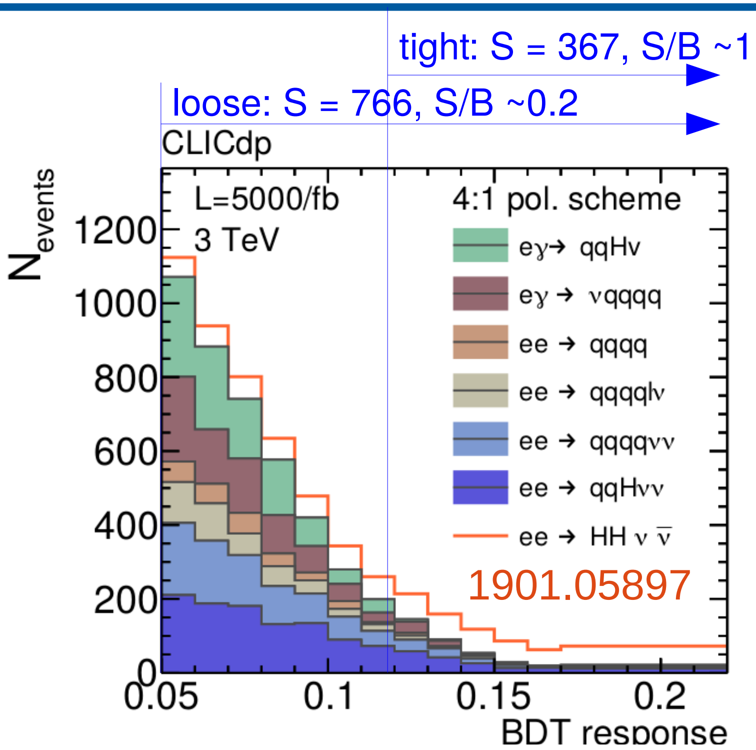


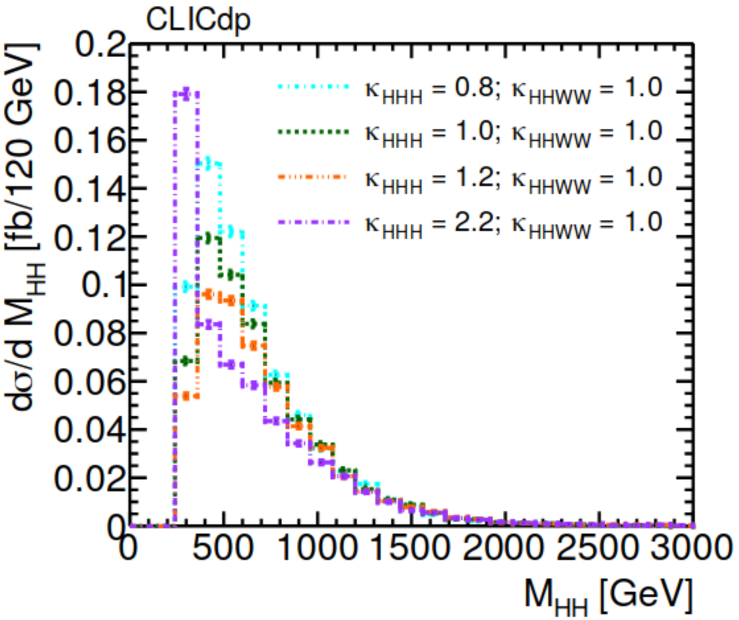


- Also studies of $\nu\bar{\nu}HH$ @1 TeV → 10% uncertainty

CLIC, HH measurement

- Method (1)
- $\nu\bar{\nu}$HH @1.4 and 3 TeV
  - full-simulation + BDT selection
  - Significance:
    - 1.4 TeV: 3.6σ
    - 3 TeV: ~14σ
- ZHH @ 1.4 TeV
  - extrapolation of 380 GeV full-sim performance
  - no background
- Uncertainty on κ_λ:
  - m_{HH} or ZHH cross-section to lift the degeneracy

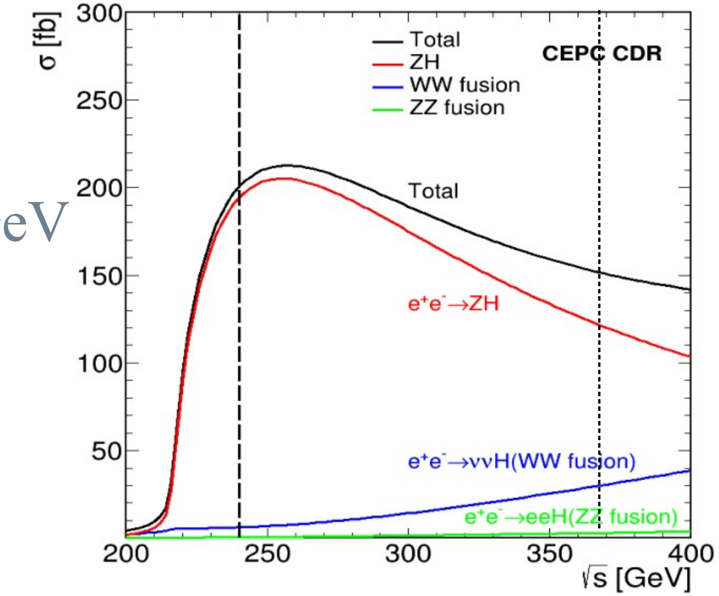




Constraints for κ_{HHH} based on	$\Delta\chi^2 = 1$
HH$\nu\bar{\nu}$ cross section only (3 TeV)	[0.90, 1.12] ∪ [2.40, 2.61]
HH$\nu\bar{\nu}$ (3 TeV) and ZHH (1.4 TeV) cross section	[0.90, 1.11]
HH$\nu\bar{\nu}$ differential (3 TeV)	[0.93, 1.12]
HH$\nu\bar{\nu}$ differential (3 TeV) and ZHH cross section (1.4 TeV)	[0.93, 1.11]

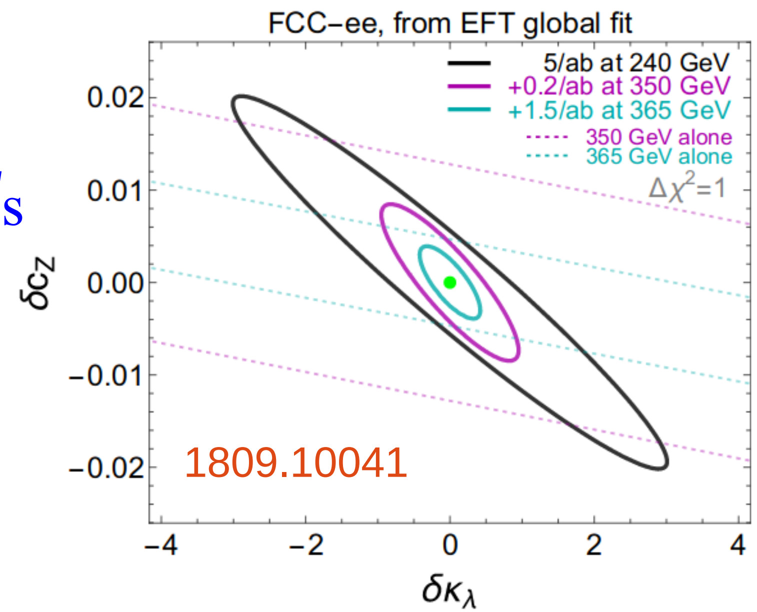
ee colliders below the HH threshold: CEPC, FCC-ee

- Methods (3) and (4) only
- CEPC, FCC-ee@240 GeV, ILC@250 GeV
- FCC-ee@365 GeV, ILC@350 GeV, CLIC@380 GeV



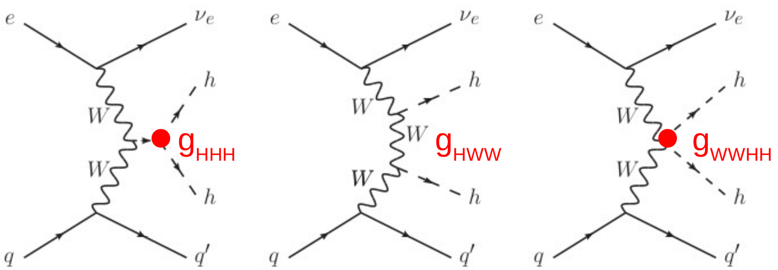
- Based on very good precision on cross-section, eg CEPC and FCC-ee240:
  - $\sigma(ZH)$: 0.5%
  - $\sigma(\nu\bar{\nu}H)$: 2-3%
  - ex.: $\sigma(ZH)$ modified by 1% for $\kappa_\lambda=2$ $\Rightarrow$ 2σ sensitivity

- Additional sensitivity from combining different $\sqrt{s}$
  - allows for a reduction of the uncertainty on other EFT parameters, removing correlations in the global fit



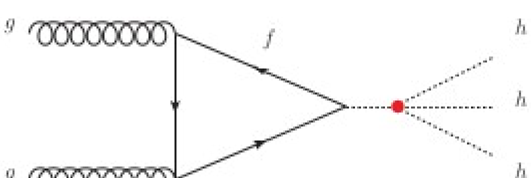
Additional inputs

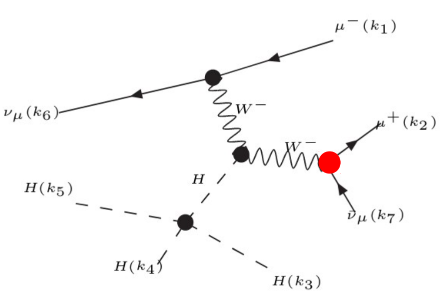
- ♦ electron-proton colliders: LHeC and FCC-eh
  - – FCC-eh di-Higgs:
    - $0.83 < \kappa_\lambda < 1.24$ @3.5 TeV
    - $0.88 < \kappa_\lambda < 1.14$ @5 TeV
  - – FCC-eh single-Higgs: missing the 1-loop dependence on k_λ
    ⇒ can't apply Methods (3) and (4)



1509.04016

- ♦ muon colliders 1901.06150
  - – preliminary projections
  - – $\sqrt{s}$ = 10, 14, 30 TeV
  - – HH → 4b: measurement of $\kappa_{\lambda 3}$: 3% at 10 TeV, 1% at 30 TeV

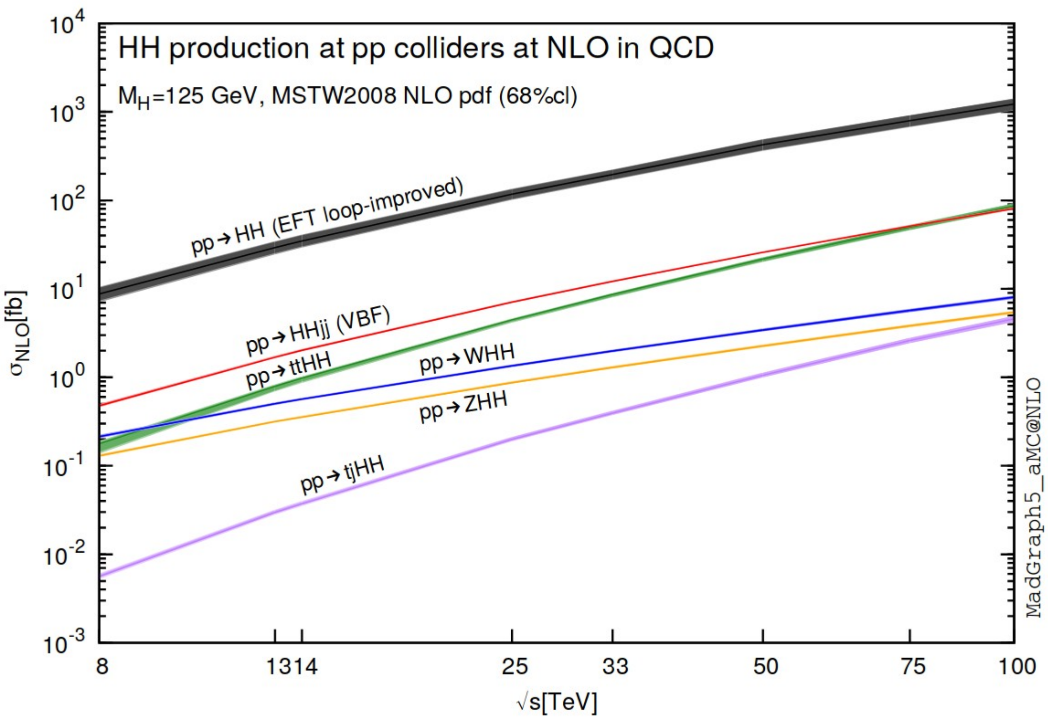


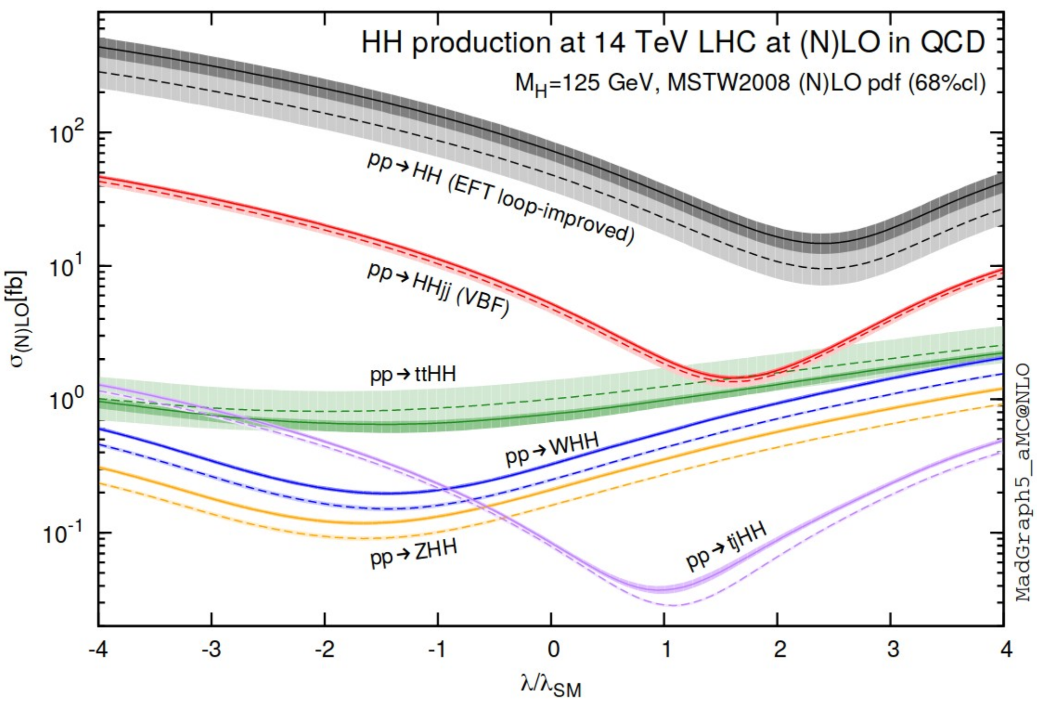


- ♦ Quartic term λ_4
  - – 2σ at FCC-hh, $\kappa_{\lambda 4}$ in [-4; +16] at 95% CL
  - – muon collider @ 30 TeV: $0.8 < \kappa_{\lambda 4} < 1.5$ at 68% CL (if $\kappa_{\lambda 3} = 1$)

Di-Higgs production

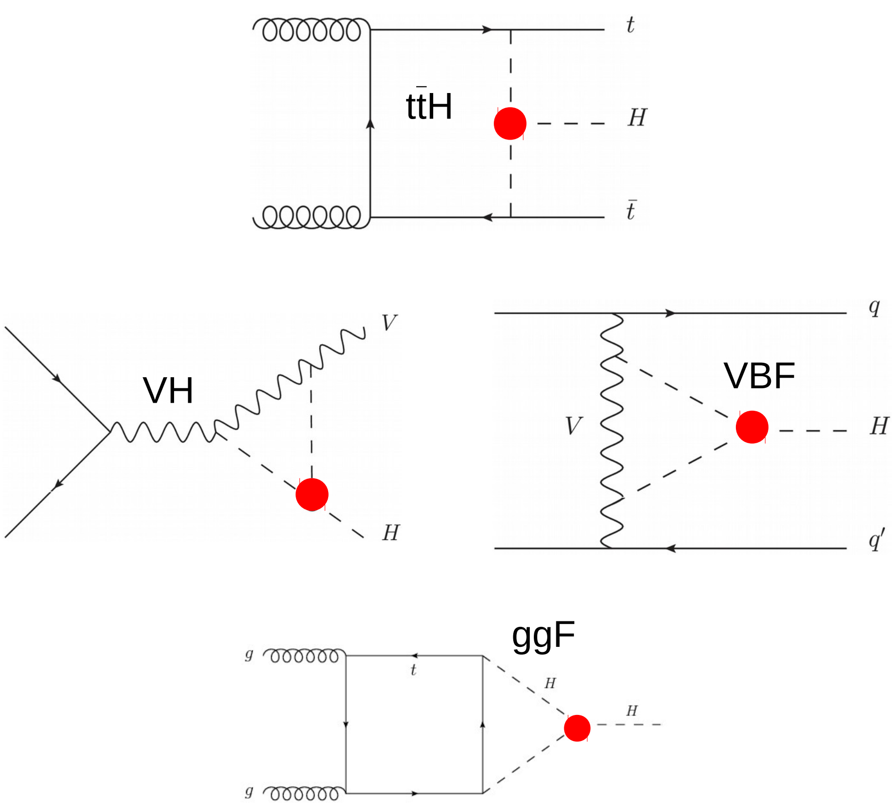
- Only ggF production considered at present



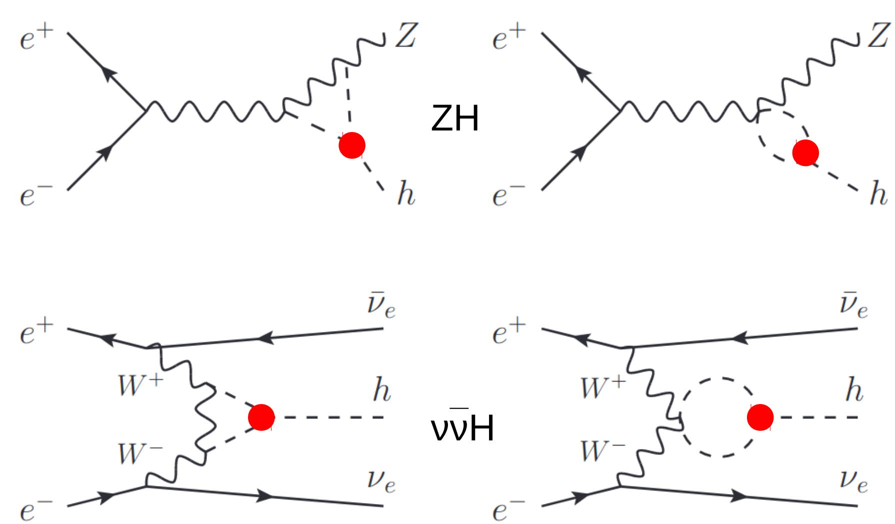


Single-Higgs couplings (1)

- Higgs self-interaction via one-loop corrections of the single-Higgs production
  - κ_λ-dependent corrections to the tree-level cross-sections
- pp colliders:



- ee colliders:



- ex. for $\kappa_\lambda = 2$:
  - $\sigma(pp \to t\bar{t}H)$ modified by 3%
  - $\sigma(ee \to ZH)$ modified by 1%

Single-Higgs couplings (2)

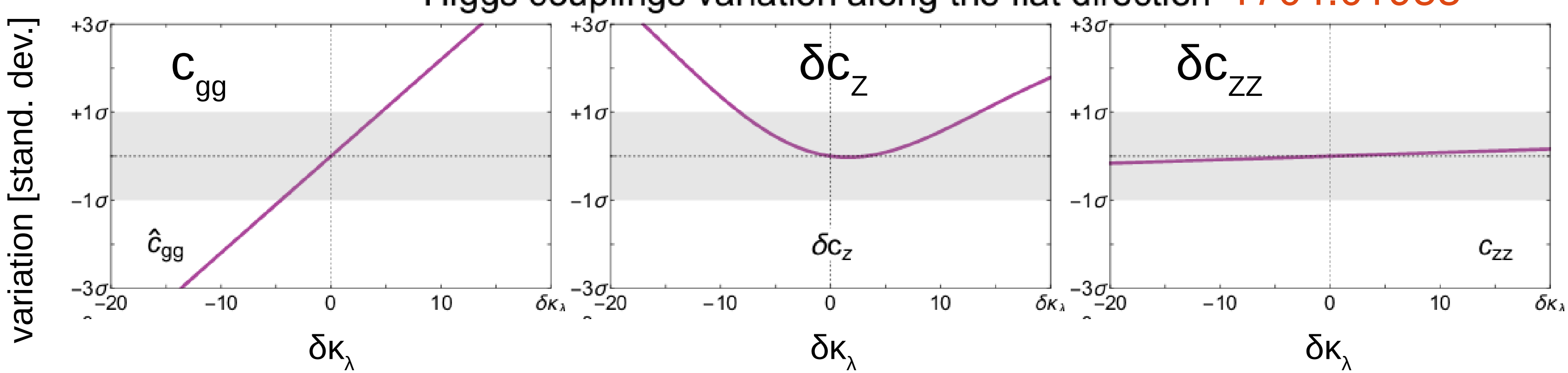
- More global view: $\mathrm{SMEFT}_{\mathrm{ND}}$
- Deformation of the single-Higgs + EW processes:

$$\mathrm{SMEFT_{ND}} \equiv \{\delta m,\, c_{gg},\, \delta c_z,\, c_{\gamma\gamma},\, c_{z\gamma},\, c_{zz},\, c_{z\Box},\, \delta y_t,\, \delta y_c,\, \delta y_b,\, \delta y_\tau,\, \delta y_\mu,\, \lambda_z\} + \left\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_\ell, (\delta g_L^{Ze})_\ell, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_\ell\right\}_{q_1=q_2\neq q_3,\ \ell=e,\mu,\tau}$$

+ correction to the trilinear Higgs self-coupling: $\delta\kappa_\lambda = \kappa_\lambda - 1$

- Can also consider the effect of $\delta\kappa_\lambda$ on the other parameters
  - a few examples:

Higgs couplings variation along the flat direction 1704.01953



  - could also affect EW precision observables at NNLO

How to measure deviations of λ_3

- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

Higgs self-coupling: summary of measurements

- Summary of inputs:

		√s	HH measurements	single-Higgs couplings
pp	HL-LHC	14 TeV	✔	✔
	HE-LHC	27 TeV	✔	✔
	FCC-hh/eh/ee	100 TeV	✔	✔
ee	CEPC	240 GeV		✔
	ILC250	250 GeV		✔
	ILC350	250 + 350 GeV		✔
	ILC500	250 + 350 + 500 GeV	✔	✔
	CLIC380	380 GeV		✔
	CLIC1500	380 GeV + 1.5 TeV	✔	✔
	CLIC3000	380 GeV + 1.5+3 TeV	✔	✔
	FCC-ee240	240 GeV		✔
	FCC-ee365	240 + 365 GeV		✔

- Combine FC results with HL-LHC (50% uncertainty on κ_λ)

HOW TO APPROACH SYSTEMATICS

* The large HL-LHC dataset will enable accurate measurements and unprecedented sensitivity to very rare phenomena
* In several analyses **systematic uncertainties will become a limiting factor**
* Several sources of systematics to consider:

Detector driven

Luminosity

Data statistics in control regions

Method uncertainties

Theory normalization and modeling

MC statistics

* Synergy of ATLAS and CMS in many physics projections and complexity of the problem required development of a **common set of guidelines**
    * Focus on experimental systematics that are most important for the projection studies we need (can't be comprehensive!)
        * Jet Energy Scale/Resolution, MET, B-tagging, Tau-ID, and many more…
    * Evaluation of theory uncertainties improvement

7 COMMON GUIDING PRINCIPLES FOR YR18

- Statistics-driven sources: data → $\sqrt{L}$, simulation → 0
  - account for larger data sample statistics available
  - to better understand full potential of HL-LHC
- Theory uncertainties typically halved
  - applies to both normalization (x-sec) and modeling
  - due to higher-order calculation and PDF improvements
- Uncertainties on methods kept as latest published results
  - Trigger thresholds same or better(lower) than current
  - assumption that pile-up effects are compensated by detector upgrades improvement and algorithmic developments
- Intrinsic detector limitations stay ~constant
  - usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
  - detector understanding and operational experience may compensate for e.g. detector aging
  - harmonized definition of « floor » values for experimantal systematics
- Luminosity uncertainty 1%

MORE DETAILS ON PROCEDURE

- Whenever feasible present results as

value ± stat ± syst_exp ± syst_theory [± syst_lumi]

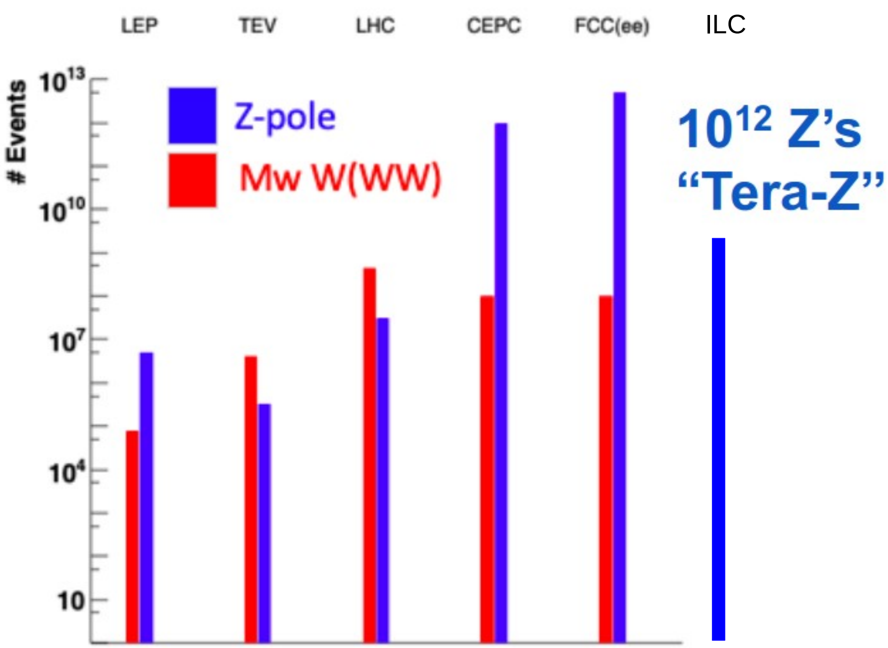
- Baseline scenario defined as:
  - **YR18(S2):** based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

Summary (simplified) table of some values of experimental systematics harmonized between ATLAS & CMS

Object	WP	Value
Muons	reco+ID(+ISO)	0.1%(0.5%)
Electrons	reco+ID+ISO	0,5%
Taus	reco+ID+ISO	5%(as in Run2)
B-jet tag	30<pt<300GeV (pt>300GeV)	~1%(2-6%)
c-jet tag		~2%
Light jets	L/M/T WP	5/10/15%
JES	abs/rel scale	0.1-0.2%(0.1-0.5%)
JEC	Pile-Up	0-2%
JEC	Flavor	0,75%
Integrated Luminosity		1%

Electroweak observables

- Decicated program at FCC-ee (and CEPC to some extend)



M. Lancaster

ILC:

- "Giga-Z" running not part of baseline but maybe later

Precision EWK Observables

Submission Inputs: 29, 145, 101, 132, 135

EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\rm eff}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

LHeC can measure $\sin^2\theta_W$ as f(E).

LHeC : Mw to 10 MeV but can measure PDFs allowing HL-LHC to half PDF uncertainty and achieve O(5 MeV) Mw.
ILC/CLIC : Mw to 5 MeV similar to HL-LHC/TeV average.

16 14/05/19 Mark Lancaster I Electroweak Precision Measurements European Strategy Update

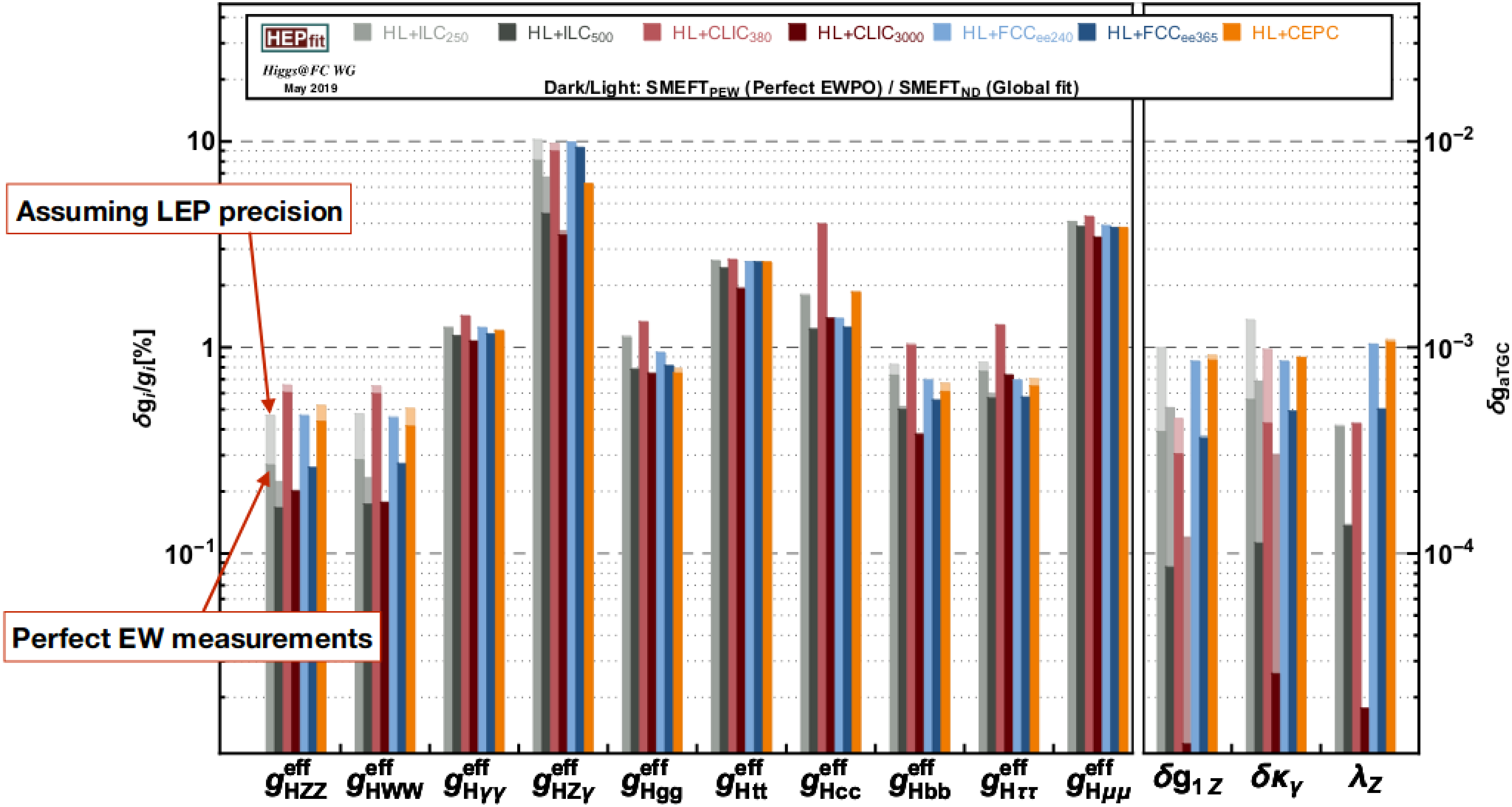
- ILC:
  - studies of radiative return to the Z at 250 GeV
  - possibility of a 1-year run at the Z pole (3 x 10^9 Z's)

EWPO: improvement wrt HL-LHC

	gZveveL	gZvmuvmuL	gZvtavtaL	gZeeL	gZeeR	gZmumuL	gZmumuR	gZtataL	gZtataR	gZuuL	gZuuR	gZccL	gZccR	gZttL	gZttR	gZddL	gZddR	gZssL	gZssR	gZbbL	gZbbR
ILC_{250}	≥ 10	1.2	1.5	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	1.0		1.2	1.5	1.2	1.5	1.0	1.0
ILC_{500}	≥ 10	1.2	1.6	1.3	1.8	1.0	1.0	1.0	1.0	1.1	1.0	1.1	1.0	≥ 10	⋆	1.2	1.5	1.2	1.5	1.0	1.0
$CLIC_{380}$	≥ 10	5.1	9.6	1.7	1.4	1.1	1.1	1.0	1.0	1.1	1.0	1.1	1.0	1.0		1.2	1.6	1.2	1.6	1.0	1.0
$CLIC_{1500}$	≥ 10	5.3	≥ 10	2.7	1.9	1.1	1.1	1.0	1.0	1.1	1.1	1.1	1.1	≥ 10	⋆	1.3	1.6	1.3	1.6	1.0	1.0
$CLIC_{3000}$	$\geq 10^2$	5.4	≥ 10	3.1	2.4	1.1	1.1	1.0	1.0	1.1	1.1	1.1	1.1	≥ 10	⋆	1.3	1.6	1.3	1.6	1.0	1.0
CEPC	1.0	1.0	1.0	1.8	2.0	≥ 10	≥ 10	1.1	1.0	1.1	1.0	1.1	1.0	1.0		1.2	1.5	1.2	1.5	≥ 10	≥ 10
$FCCee_{240}$	≥ 10	≥ 10	≥ 10	7.9	9.2	≥ 10	≥ 10	≥ 10	≥ 10	4.2	2.9	4.2	2.9	1.0		4.6	4.4	4.6	4.4	4.6	4.4
$FCCee_{365}$	≥ 10	≥ 10	≥ 10	9.9	10.0	≥ 10	≥ 10	≥ 10	≥ 10	4.2	2.9	4.2	2.9	7.5	⋆	4.6	4.4	4.6	4.4	4.6	4.4
FCCee/eh/hh	≥ 10	≥ 10	≥ 10	9.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	9.1	⋆	≥ 10	≥ 10	≥ 10	≥ 10	4.6	4.4

- Trilinear gauge couplings
  - will achieve precision 10^{-3}-10^{-4}
  - about 2-3 orders of magnitude better than LEP

Impact of EWPO (Z pole meas.) on Higgs couplings



Difference due to absence of precise enough EWPO at LC (no Z pole run)

Can be mitigated by using: (1) High-energies (2) EWPO from radiative return