Path towards measuring the Higgs potential

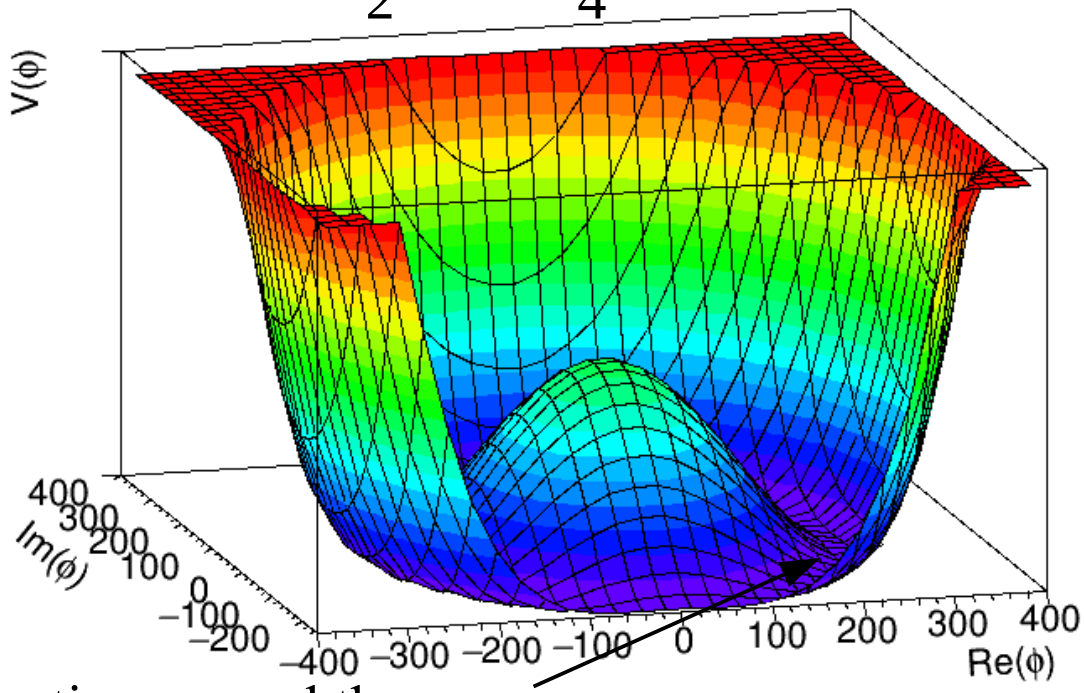
Elisabeth Petit (CPPM, AMU/CNRS/IN2P3)
on behalf of the *Higgs@FutureColliders* working group

Open Symposium - Update of the European Strategy for Particle Physics

14th of May 2019

Introduction

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



more details on the motivations in the talk by G. Servant

- Approximation around the v.e.v:

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

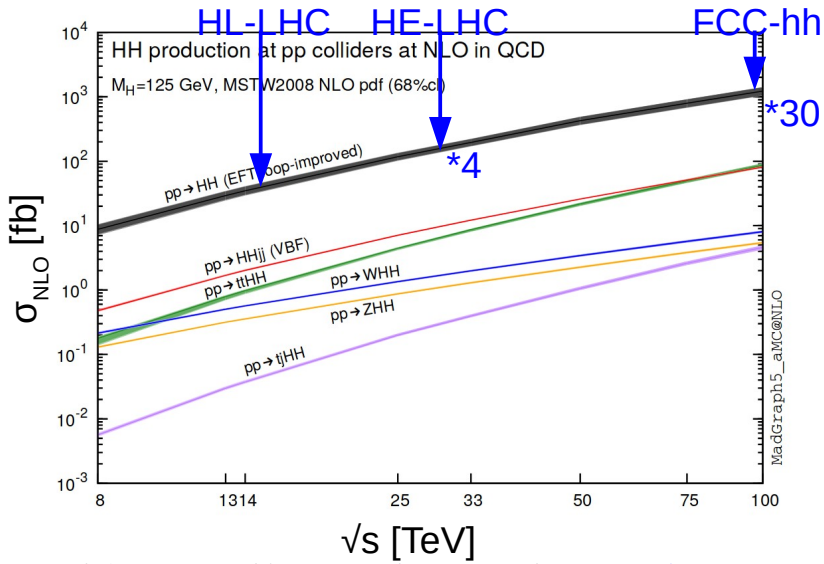
- λ known from v.e.v and Higgs mass: $\lambda=\frac{m_H^2}{2\cdot v^2}\approx 0.13$

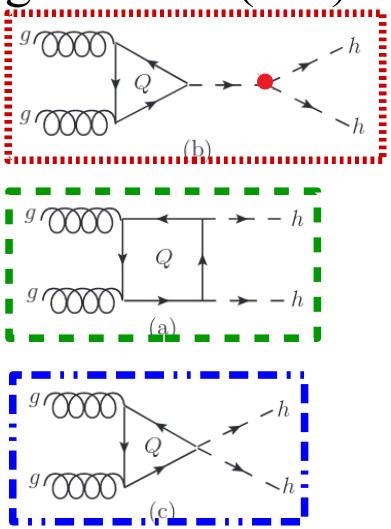
- BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda=\kappa_3=\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  - no quartic terms considered here

How to measure the tri-linear self-coupling

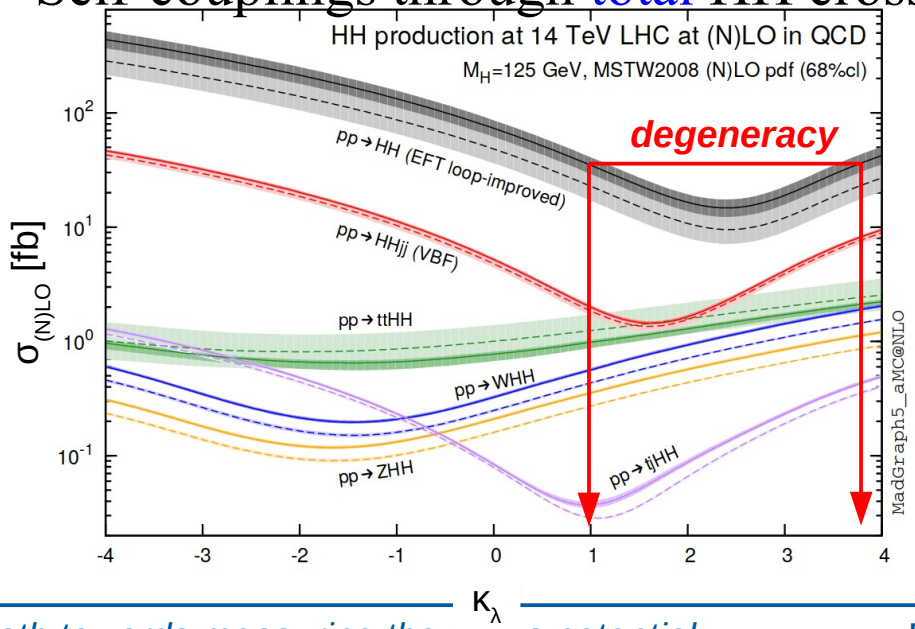
Di-Higgs production: pp colliders

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

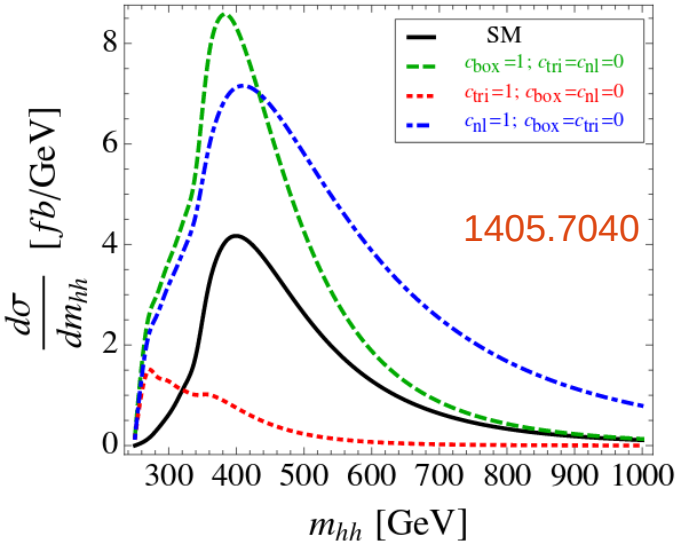




- Self-couplings through total HH cross section, and diff. cross section $d\sigma/dm_{HH}$:

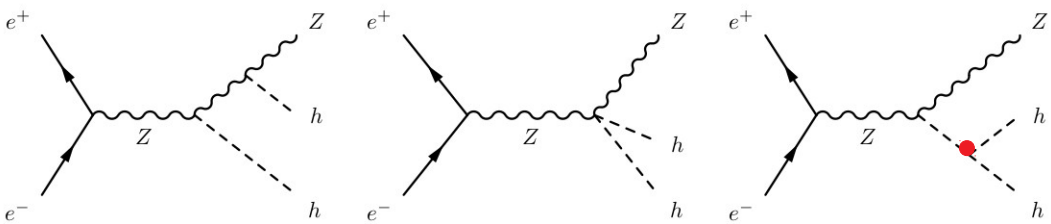


⊗

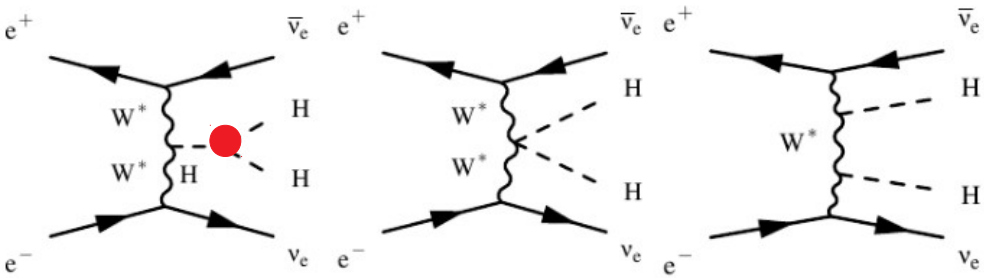


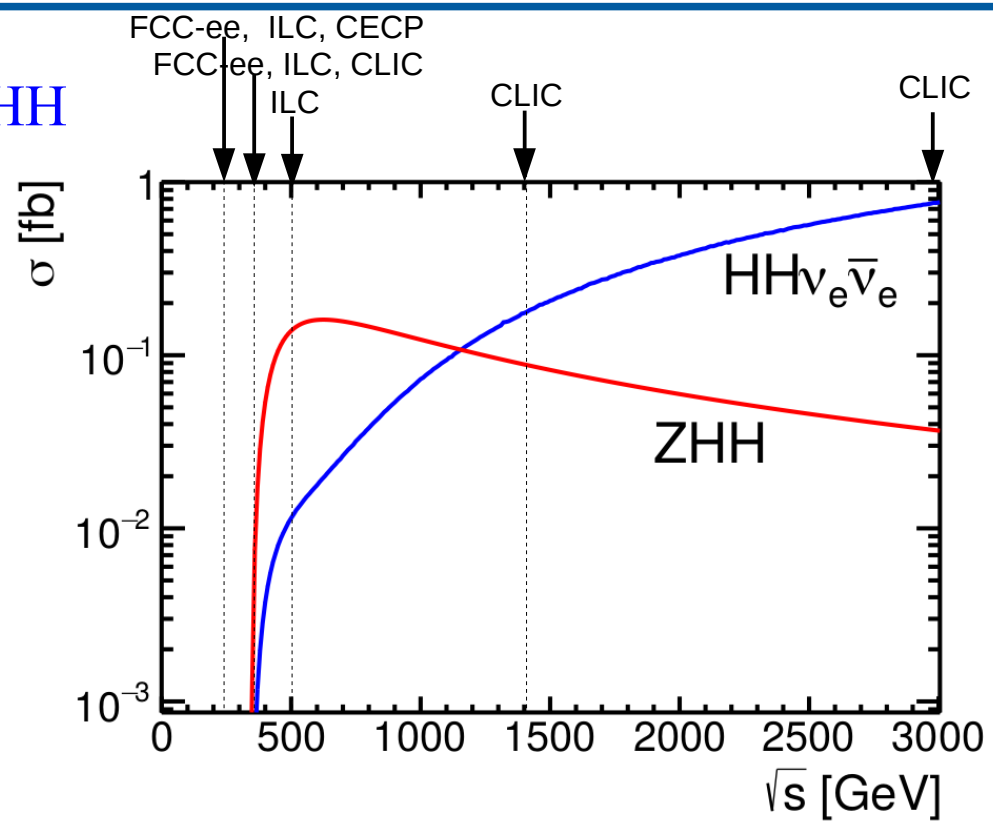
Di-Higgs production: ee colliders

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

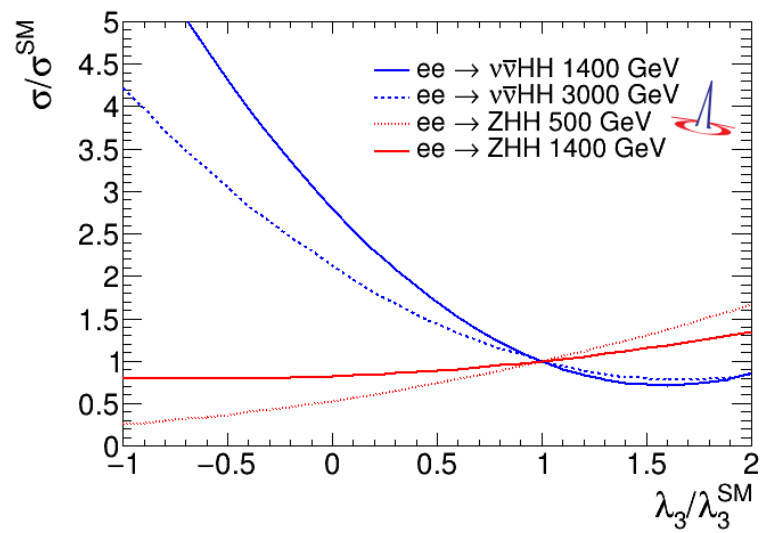


  - VBF $\nu\bar{\nu}$HH



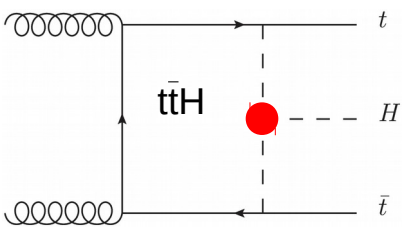


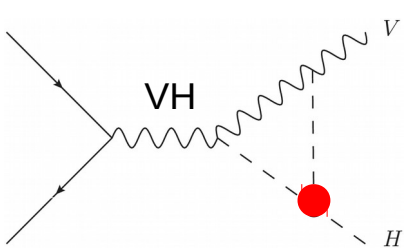
- Self-couplings through HH cross-section at different $\sqrt{s}$ + production modes + m_{HH}
  - ZHH stronger constraints for $\kappa_\lambda > 1$
  - $\nu\bar{\nu}$HH stronger constraints for $\kappa_\lambda < 1$

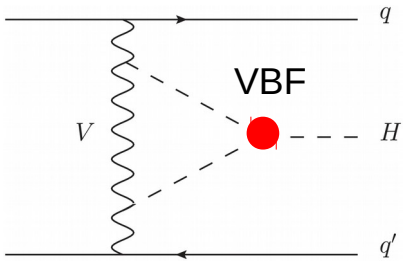


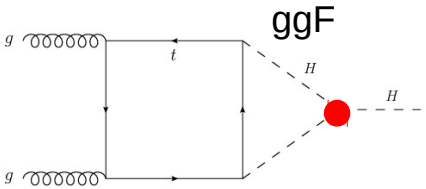
Single-Higgs couplings (1)

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

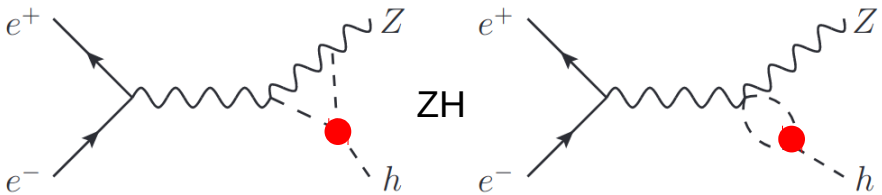


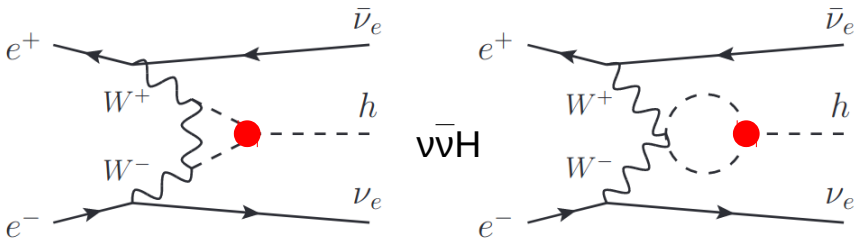






- ee colliders:





- 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)

all details in the talk by J. de Blas

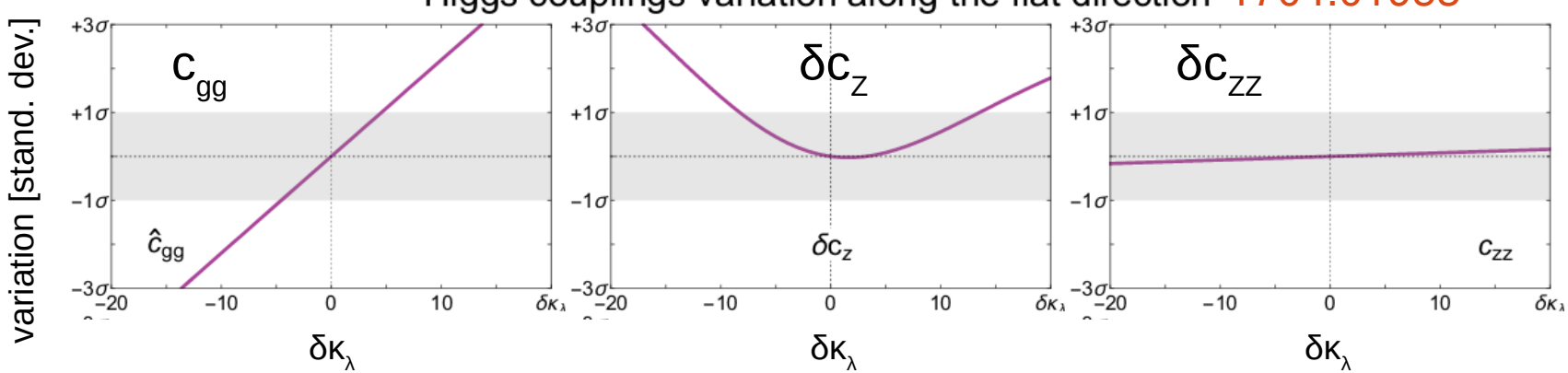
- More global view: $SMEFT_{ND}$
- Deformation of the single-Higgs + EW processes:

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

+ 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

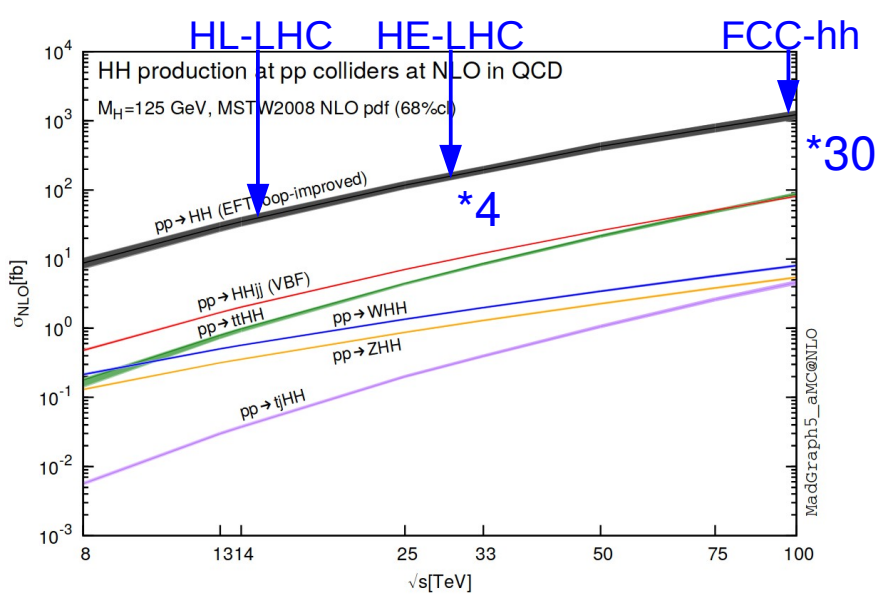
- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

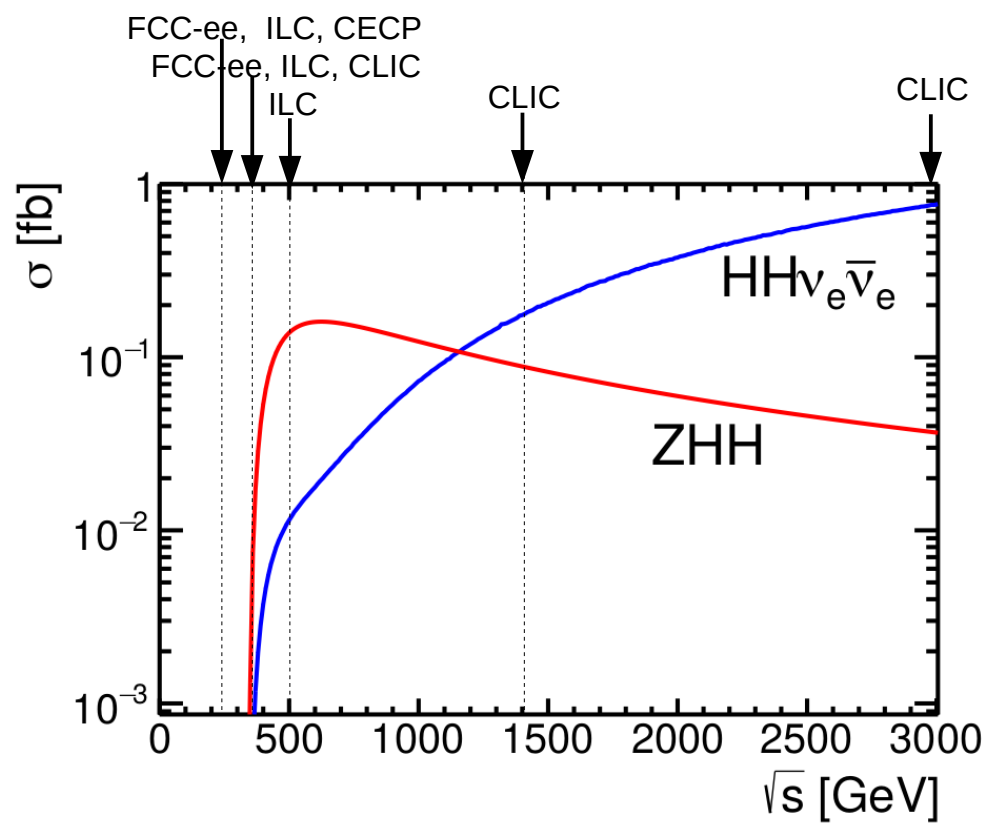
	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher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

#152: HL-LHC
#160: HE-LHC
#135: FCC-hh

#29: CEPC
#145: CLIC
#77: ILC
#89 : FCC-ee

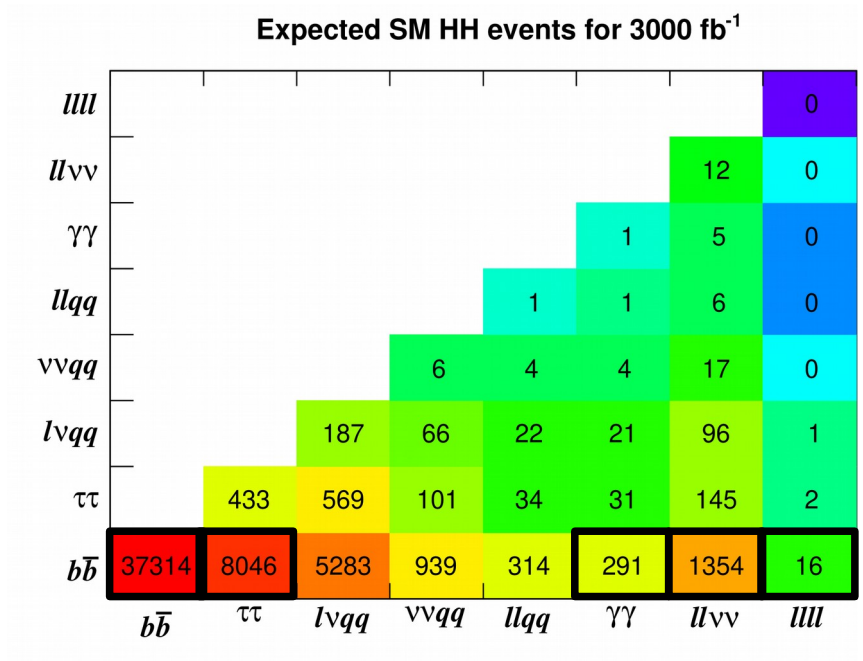
Inputs from Future Colliders





HL-LHC, HH measurements (1)

- Measure κ_λ through HH: method 1
- Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200



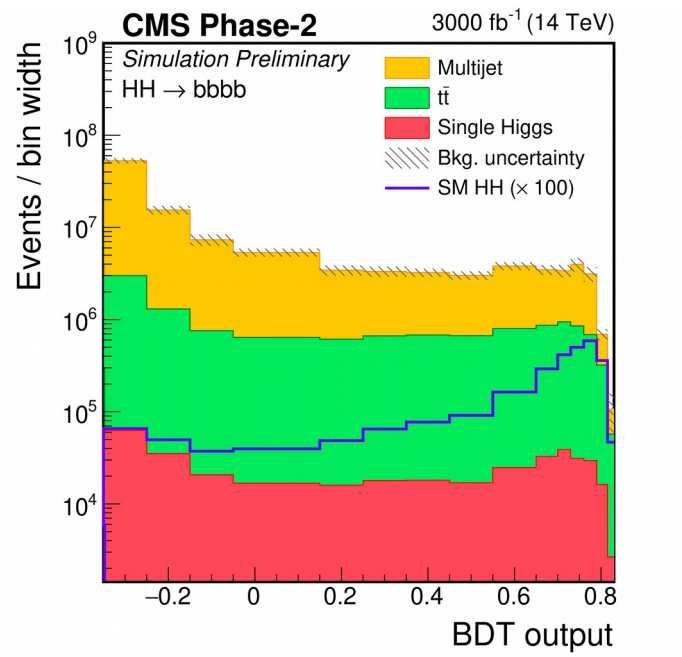
	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric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

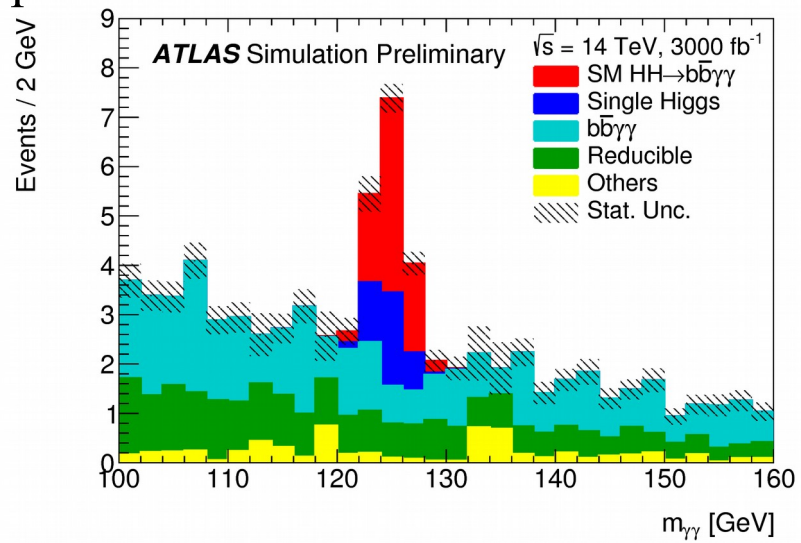
- Systematic uncertainties: common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties scaled by 0.5

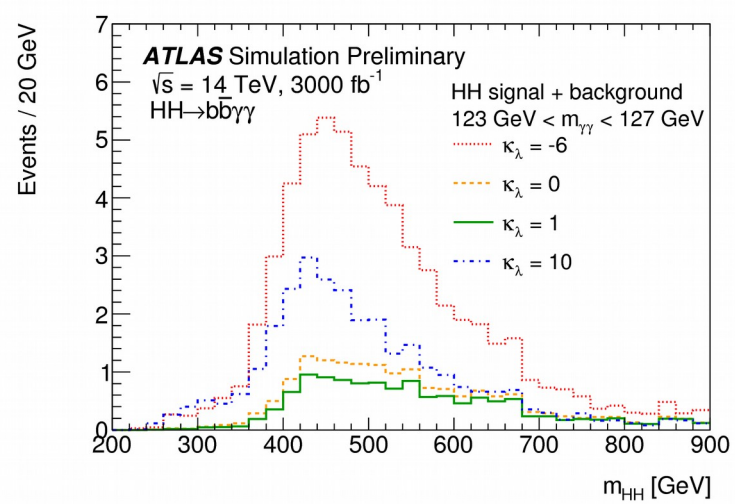
more details in the talk by P. Azzi

HL-LHC, HH measurements (2)

- 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







- NB: some inputs or systematics little known
  - multijet bkg modelling for HH→$b\bar{b}b\bar{b}$
  - τ fake-rate
  - …

⇒ room for improvement

HL-LHC, HH results

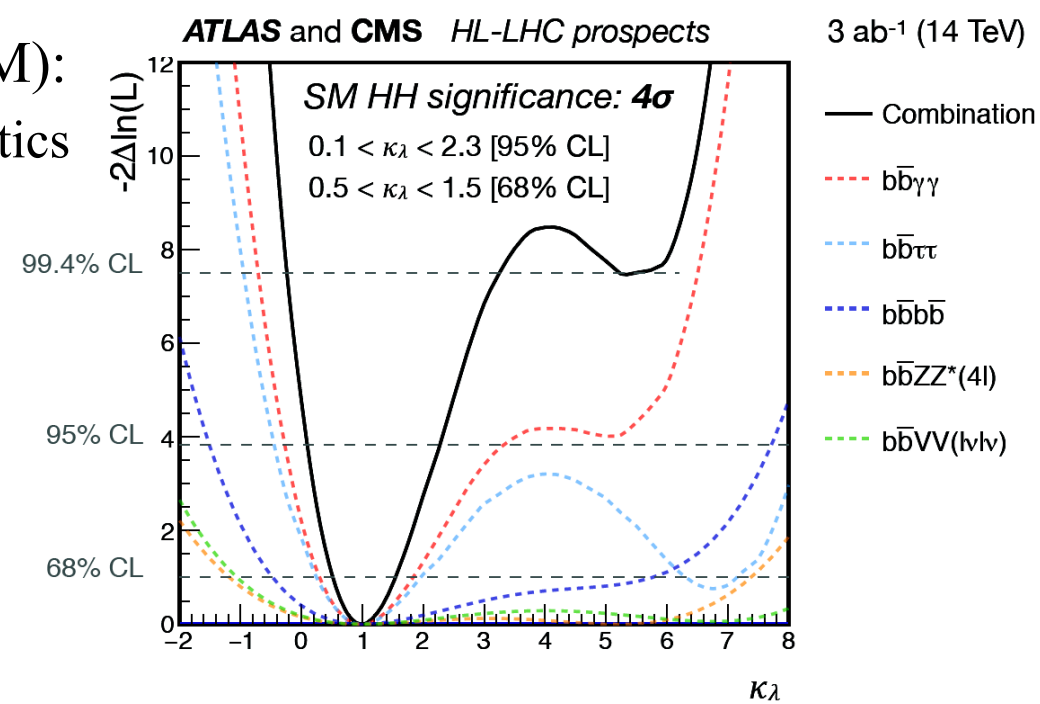
- Expected significance (SM) with and without systematics at HL-LHC

	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		Combined	
	4.5		4.0	

4σ expected with ATLAS+CMS!

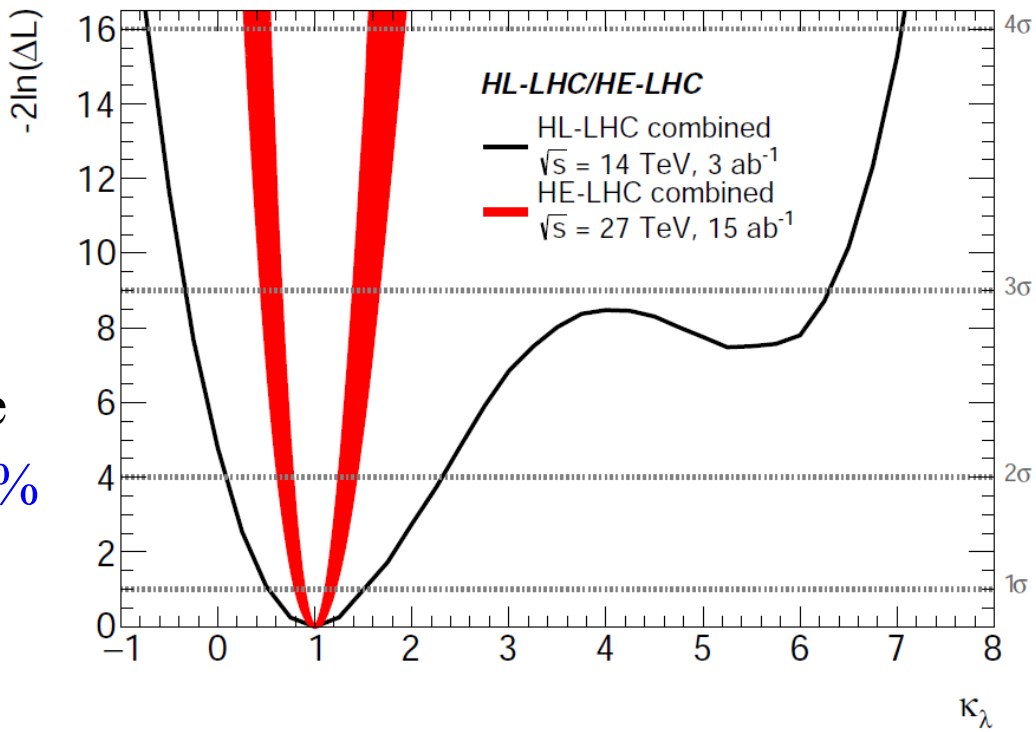
- Measurement of signal strength μ (SM):
  - ~25% (30%) without (with) systematics
  - μ = 0 (no SM HH signal) excluded at 95% CL

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



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)

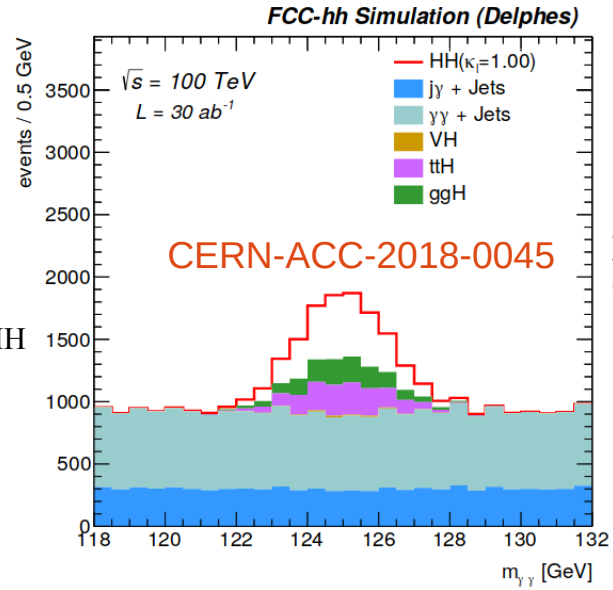


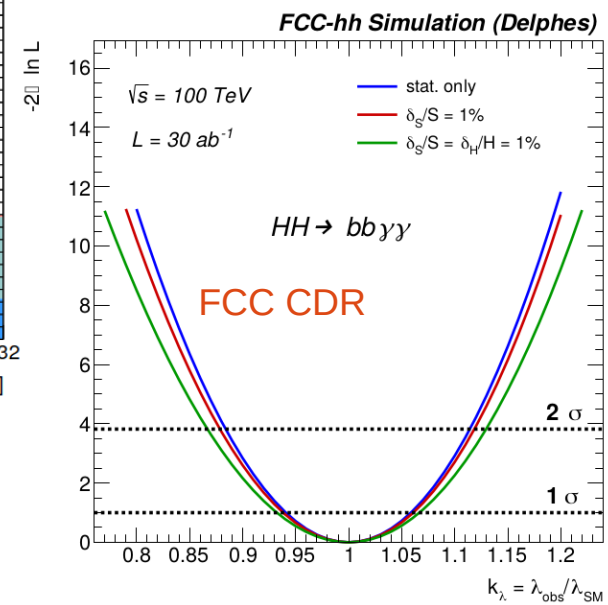
- Combination of channels: κ_λ could be measured with a 68% CI of 10 to 20 %

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%)

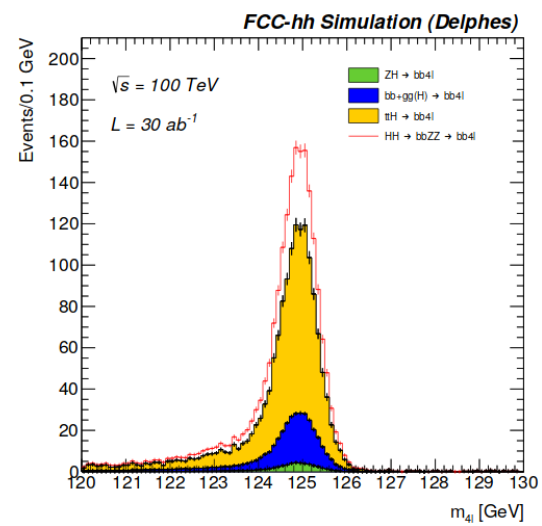
    ⇒ 5-7% uncertainty on κ_λ





- Other channels:

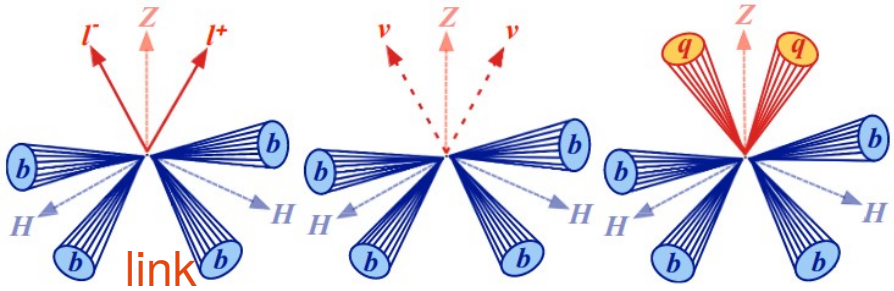
	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\rightarrow 4\ell]$	$b\bar{b}WW^*[\rightarrow 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%



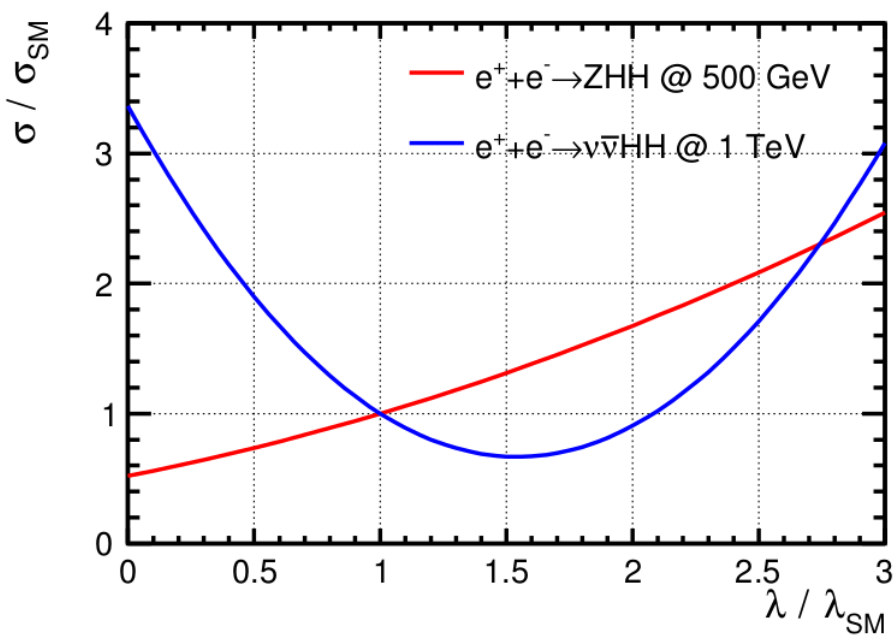
- Determination of κ_λ at the level of O(5%) expected to be within the FCC reach

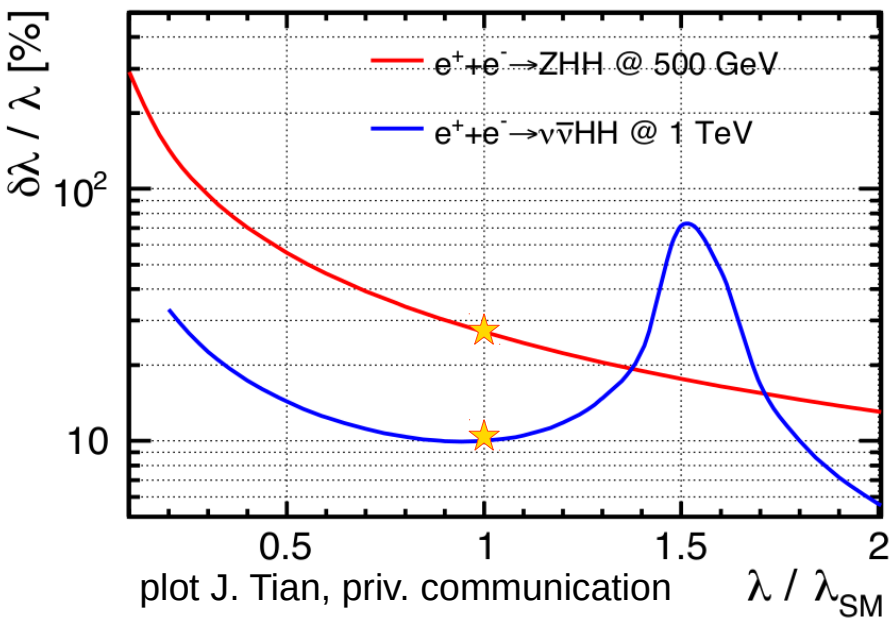
ILC, HH measurement

- Method (1)



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

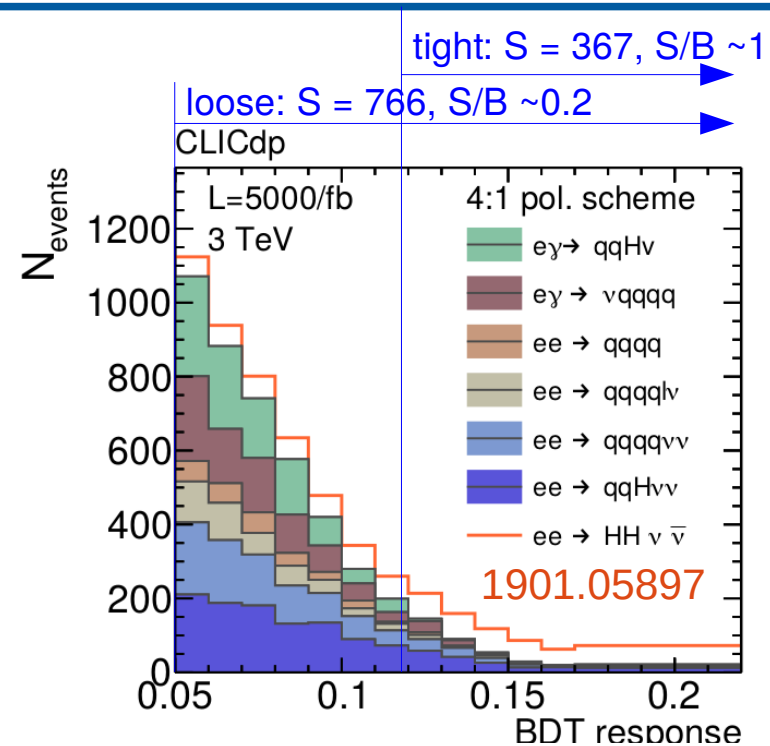


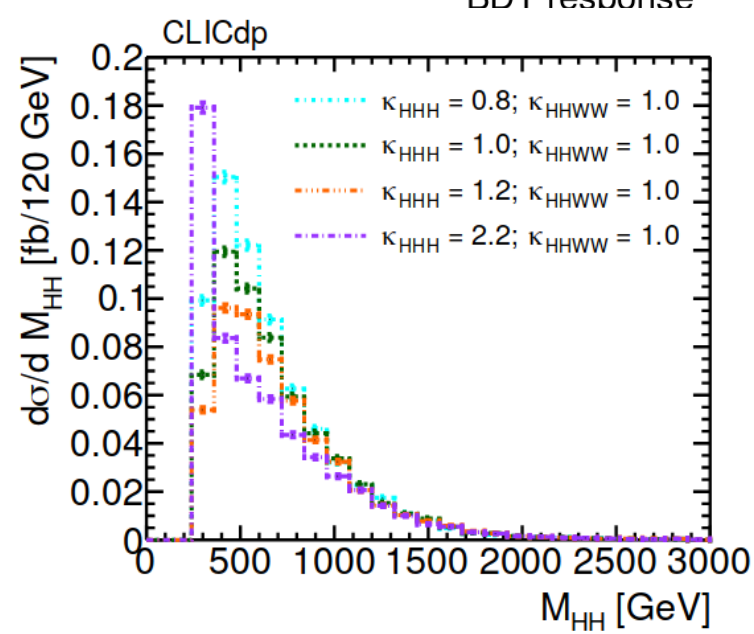


- Also studies of $\nu\bar{\nu}HH$ @1 TeV → 10% uncertainty

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

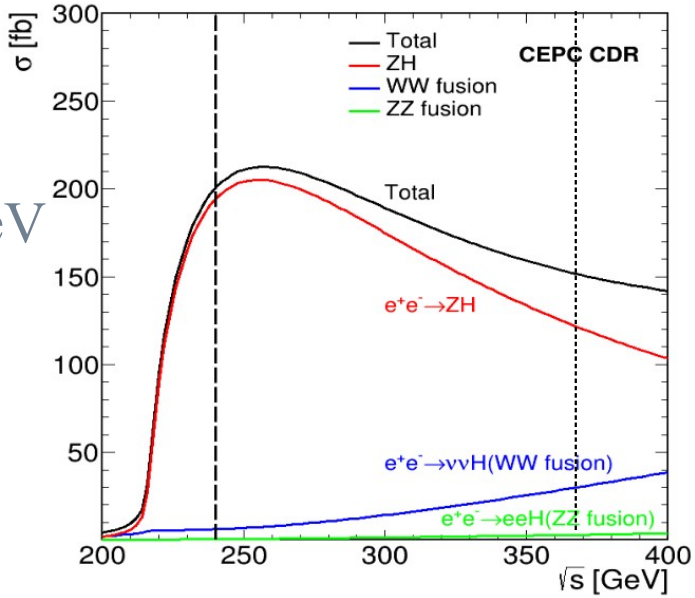




Constraints for κ_{HHH} based on	$\Delta\chi^2 = 1$
HH$\nu\bar{\nu}$ cross section only (3 TeV)	$[0.90, 1.12] \cup [2.40, 2.61]$
HH$\nu\bar{\nu}$ (3 TeV) and ZHH (1.4 TeV) cross section	$[0.90, 1.11]$
HH$\nu\bar{\nu}$ differential (3 TeV)	$[0.93, 1.12]$
HH$\nu\bar{\nu}$ differential (3 TeV) and ZHH cross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

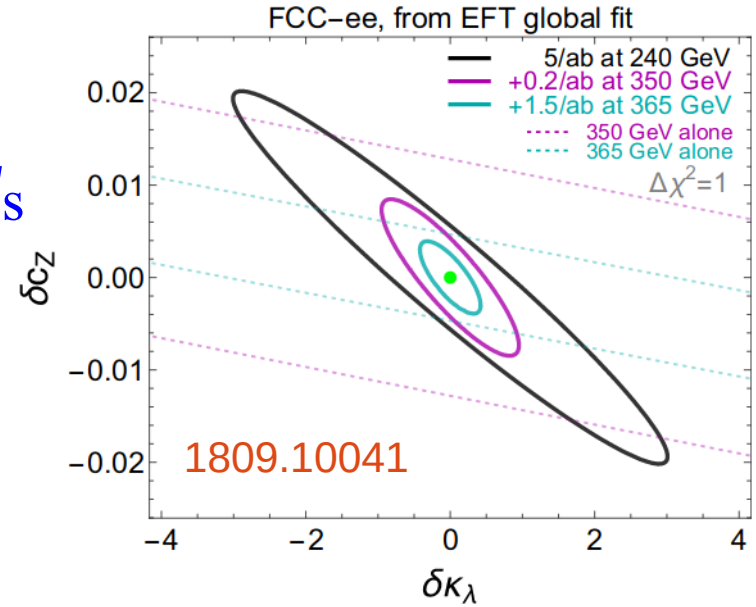
ee colliders below the HH threshold: CEPC, FCC-ee

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



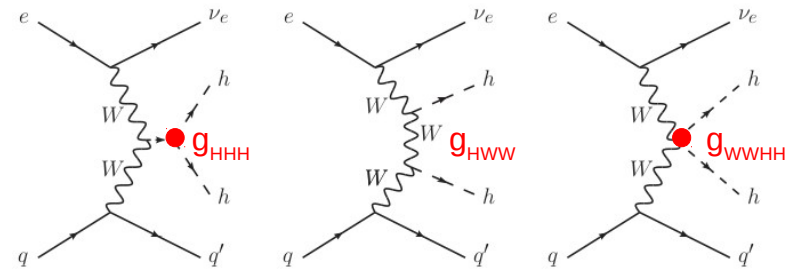
- Based on very good precision on cross-section, eg CEPC and FCC-ee240:
  - σ(ZH): 0.5%
  - σ($\nu\bar{\nu}$H): 2-3%
  - ex.: σ(ZH) modified by 1% for κ_λ=2
    ⇒ 2σ sensitivity

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



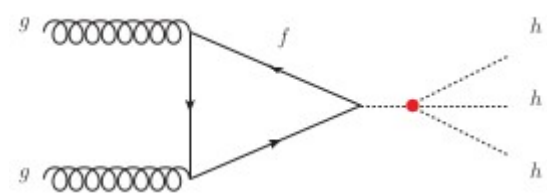
Additional inputs (not in the report)

- 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)

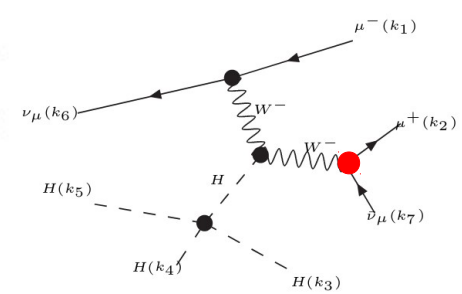


1509.04016

- 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 $\kappa_{\lambda 3} = 1$)



Comparisons and combination by the Higgs@FC working group

Inputs and methodology

	di-Higgs	single-H
exclusive	1. di-H, excl.	3. single-H, excl.
global	2. di-H, glob.	4. single-H, glob.

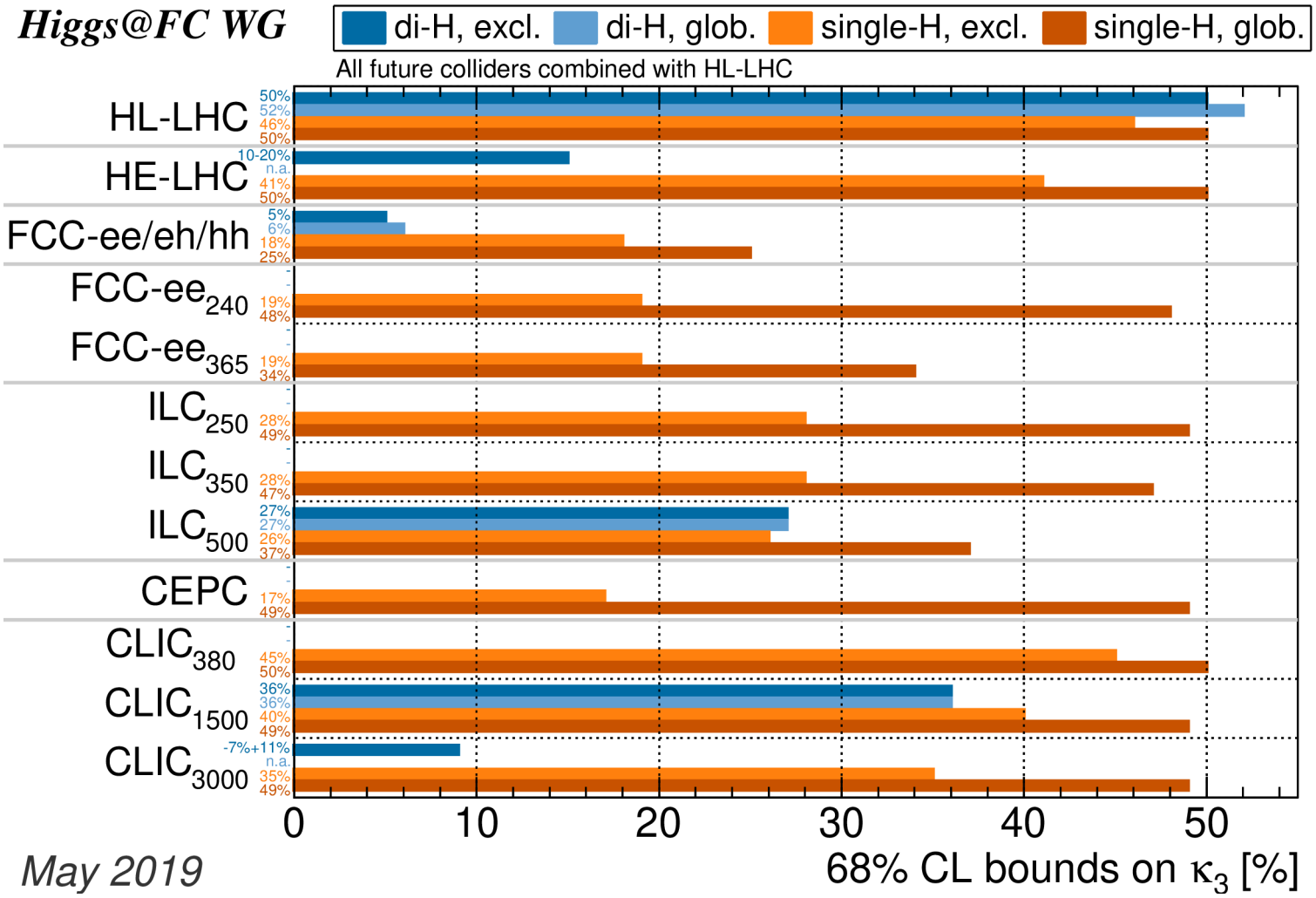
- Summary of inputs:

		√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		✔

- Compute the uncertainty on κ_λ using the four methods:
  - Method (1) : recomputed to validate the method, good agreement
  - Method (2) : combination of HH inputs and single-Higgs couplings with SMEFT (when possible)
  - Methods (3) and (4) : single-Higgs couplings (SMEFT) + combination with HL-LHC HH results (50% uncertainty)

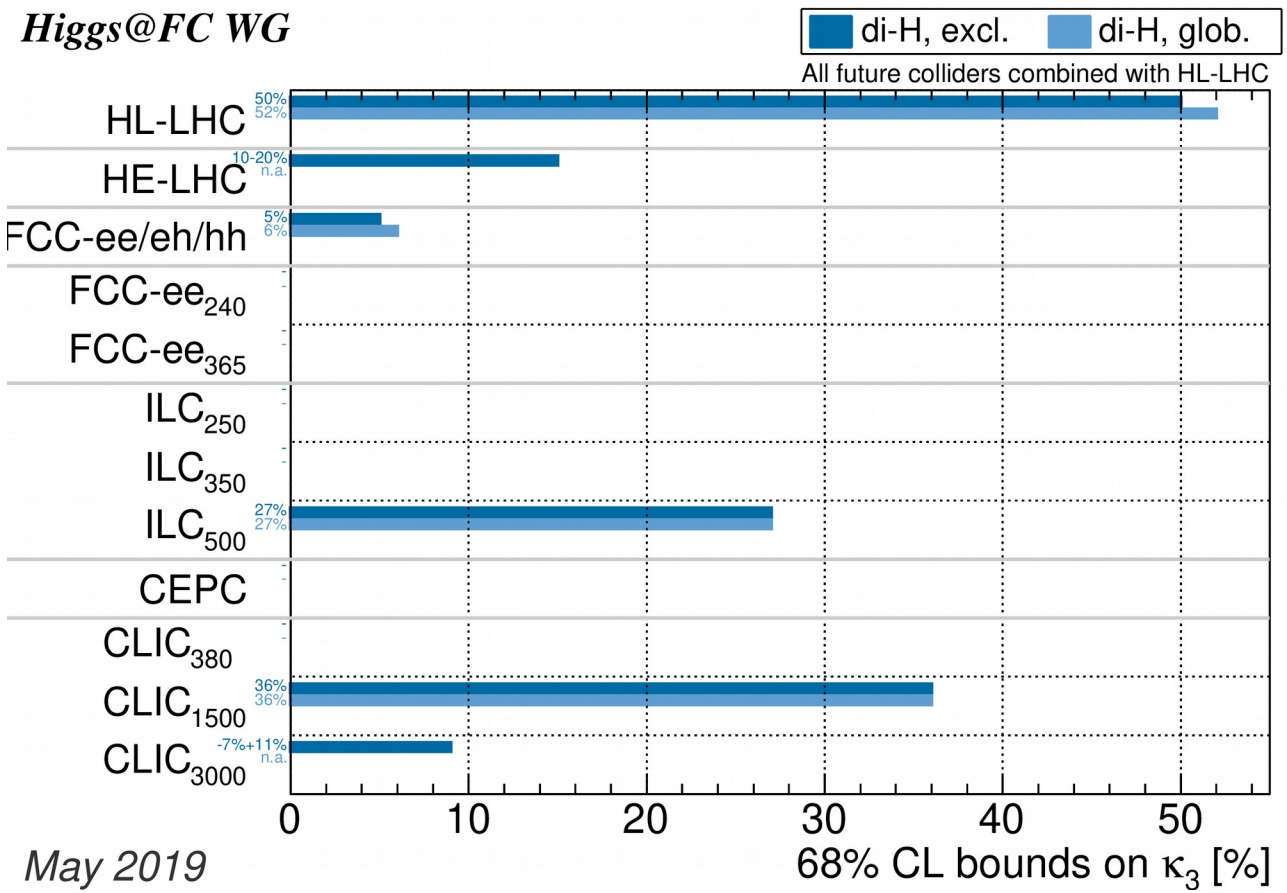
Results: global view

- 68% CL uncertainties on κ_λ with the four methods:



Results: using di-Higgs production

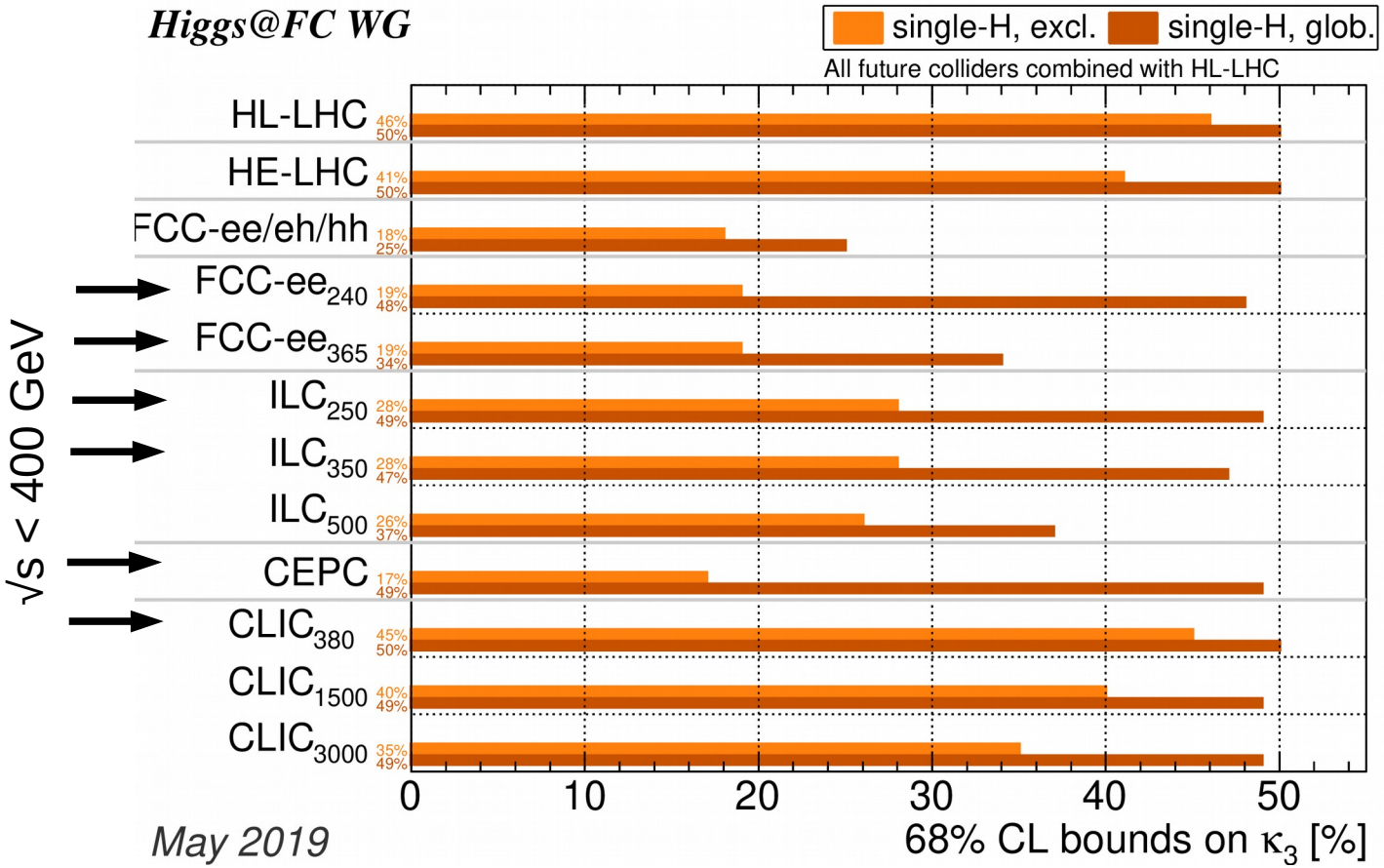
- 68% CL uncertainties on κ_λ:



- Constraints set by the HH production (method (1)) strong enough that small impact of a global analysis (method (2))
  - FCC-hh: 1% uncertainty on the top Yukawa coupling ⇒ deviation of HH rate at a level comparable to the uncertainty on κ_λ

Results: using single-Higgs measurements

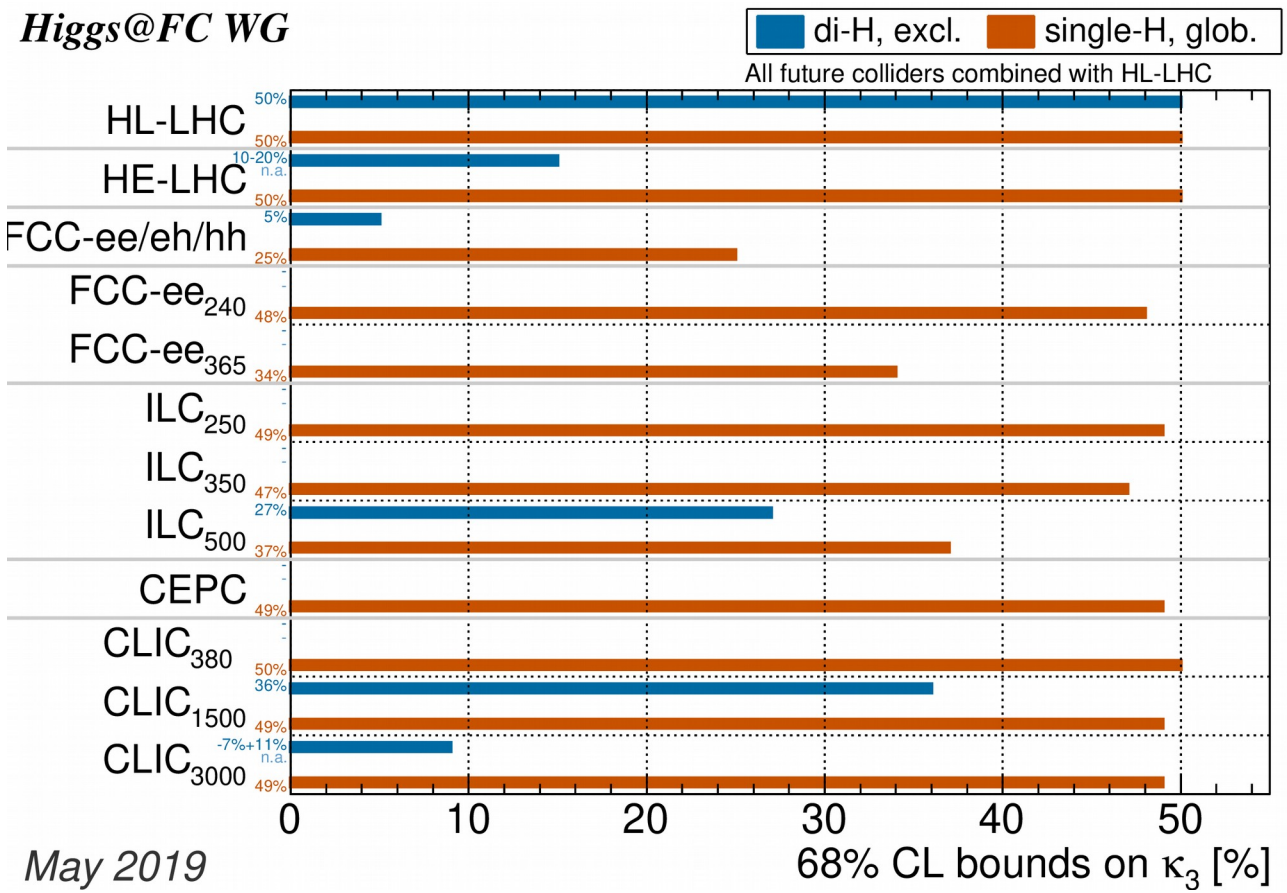
- 68% CL uncertainties on κ_λ:



- Methods (3) and (4) particularly relevant for low-energy colliders below the HH production threshold
  - above this, can still be relevant to complement results from the HH analysis: lift degeneracy + improve 95% CL limit
- Importance of global analysis, ie Method (4), to get robust results

Results: comparison of results

- 68% CL uncertainties on κ_λ with Methods (1) and (4):



- 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

Conclusion

- State of the art 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 + 50% uncertainty on κ_λ

- Sensitivity from Future Colliders and combination with HL-LHC
  - possible to establish the existence of the self-coupling at 5σ for several FCs

- Complementary of Methods to understand possible deviations from the SM

- Report from the *Higgs@FC* working group on arxiv: 1905.03764

Back-up

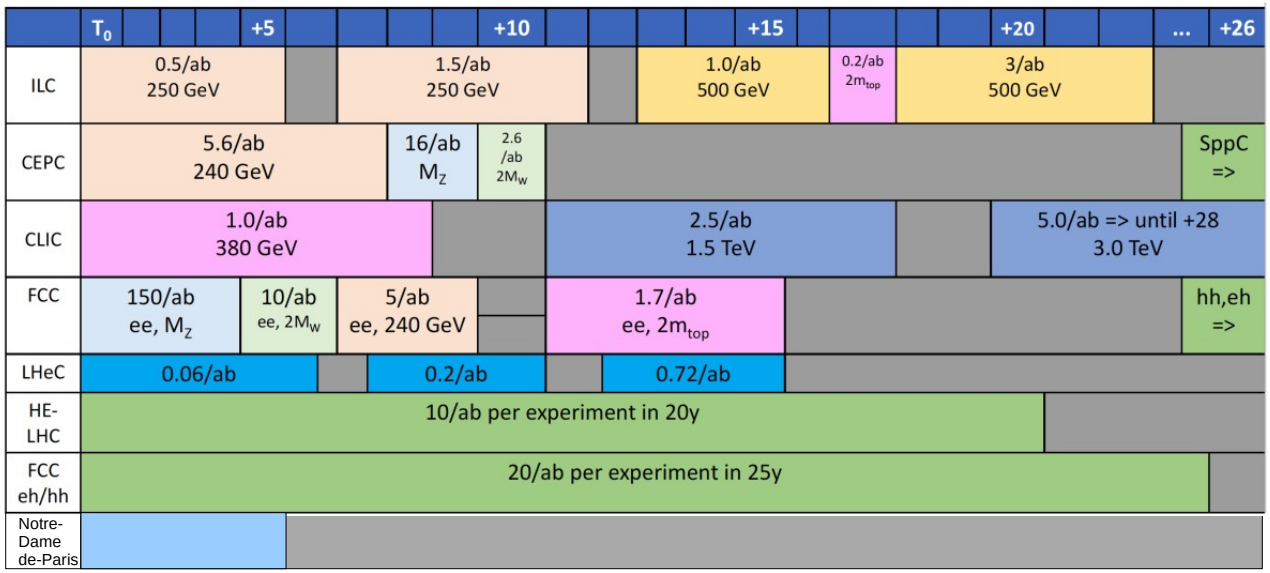
Results

collider	(1) di-H excl.	(2.a) di-H glob.	(3) single-H excl.	(4) single-H glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%	46%	50%
HE-LHC	10-20% (n.a.)	n.a.	41%	50%
ILC_{250}	–	–	28%	49%
ILC_{350}	–	–	28%	47%
ILC_{500}	27% (27%)	27%	26%	37%
$CLIC_{380}$	–	–	45%	50%
$CLIC_{1500}$	36% (36%)	36%	40%	49%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.	35%	49%
FCC-ee_{240}	–	–	19%	48%
FCC-ee_{365}	–	–	19%	34%
FCC-ee/eh/hh	5% (5%)	6%	18%	25%
CEPC	–	–	17%	49%

Table 11. Sensitivity at 68% probability on the Higgs cubic self-coupling at the various FCs. All the numbers reported correspond to a simplified combination of the considered collider with HL-LHC which is approximated by a 50% constraint on κ_3. The numbers in the first column (i.e. "di-H excl." or Method (1)) correspond to the results given by the future collider collaborations and in parenthesis, we report our derived estimate obtained in the binned analysis described in the text. In the three last columns, i.e. Methods (2a), (3) and (4), we report the results computed by the Higgs@FC working group. For the leptonic colliders, the runs are considered in sequence. For the colliders with $\sqrt{s} \lesssim 400$ GeV, Methods (1) and (2.a) cannot be used, hence the dash signs in the corresponding cells. No sensitivity was computed along Method (2.a) for HE-LHC and $CLIC_{3000}$ but our initial checks do not show any difference with the sensitivity obtained for Method (1). Due to the lack of results available for the ep cross section in SMEFT, we do not present any result for LHeC nor HE-LHeC.

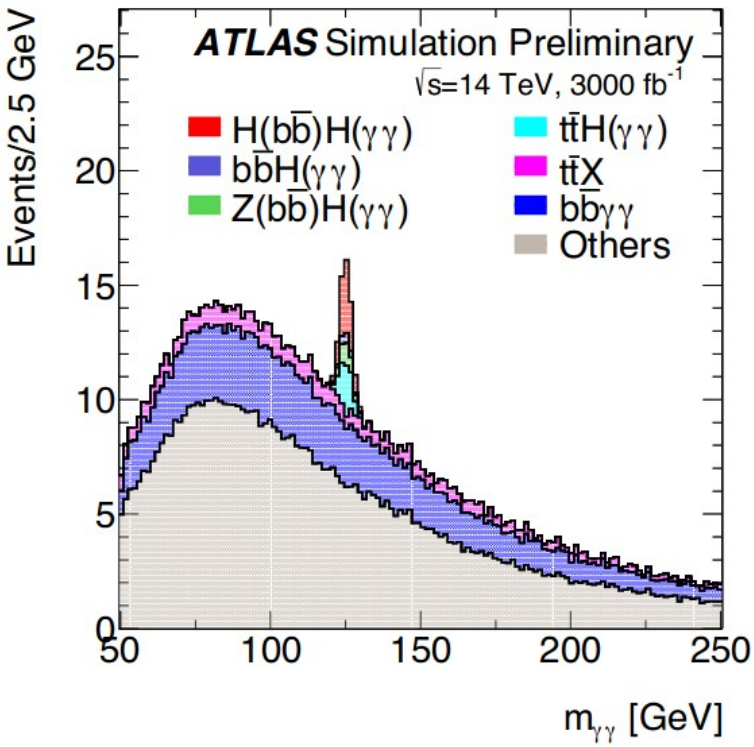
Future colliders

Collider	type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{inst}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	time [years]	Refs	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	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$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)	(1y SD before $2m_{top}$ run)	
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	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)	
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	[12]	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	[9]	LHeC
HE-LHeC	ep	2.6 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



Comparison to HL-LHC 2014 results

- ECFA High Luminosity LHC Experiments Workshop in 2014
- ggF cross-section: 40.2 fb [NNLO] → 36.69 fb [NNLO calculation with finite m_t effects at NLO]
- $b\bar{b}\gamma\gamma$ and $b\bar{b}WW$, no $b\bar{b}\tau\tau$ nor $b\bar{b}bb$
- Expected significance:
  - ~1.3σ for $bb\gamma\gamma$
  -



- Since then:
  - TDR of the Phase-II upgrades: improvement of performance
    - particle identification, energy resolution, trigger, …
  - large use of MVA selection
  - better understanding of extrapolation of uncertainties

HL-LHC prospects before the YR

Expected HH results at HL-LHC

HH final state	ATLAS Significance Coupling limit (95 % C.L.)	CMS Significance
HH → bbγγ	1.05 σ $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$	1.43 σ
HH →bbττ	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$	0.39 σ
HH →bbbb	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$	0.39 σ
HH →bbVV		0.45 σ
ttHH, HH-> bbbb	0.35 σ	

2018 Yellow Report:

Improved results already in the pipeline (especially for HL-LHC TDRs)

S. Jézéquel, HL-LHC/HE-LHC Workshop 2017 27

How to measure λ_3

- The sensitivity of the various future colliders to the Higgs cubic coupling can be obtained using four different methods:
  - 1. an exclusive analysis of HH production, i.e., a fit of the double Higgs cross section considering only deformation of the Higgs cubic coupling;
  - 2. a global analysis of HH production, i.e., a fit of of the double Higgs cross section considering also all possible deformations of the single Higgs couplings that are already constrained by single Higgs processes;
    - (a) the global fit does not consider the effects at higher order of the modified Higgs cubic coupling to single Higgs production and to Higgs decays;
    - (b) these higher order effects are included;
  - 3. an exclusive analysis of single Higgs processes at higher order, i.e., considering only deformation of the Higgs cubic coupling;
  - 4. a global analysis of single Higgs processes at higher order, i.e., considering also all possible deformations of the single Higgs couplings

	single-H	HH
global	4	2
exclusive	3	1

Mandate of the Higgs@FC working group

ECFA
European Committee for Future Accelerators

Mandate agreed by RECFA in consultation with the PPG
"Higgs physics with future colliders in parallel and beyond the HL-LHC"

- In the context of exploring the Higgs sector, provide a coherent comparison of the reach with all future collider programmes proposed for the European Strategy update, and to project the information on a timeline.
- For the benefit of the comparison, motivate the choice for an adequate interpretation framework (e.g. EFT, κ, …) and apply it, and map the potential prerequisites related to the validity and use of such framework(s).
- For at least the following aspects, where achievable, comparisons should be aim for:
  - Precision on couplings and self-couplings (through direct and indirect methods)
  - Sensitivities to anomalous and rare Higgs decays (SM and BSM), and precision on total width
  - Sensitivity to new high-scale physics through loop corrections
  - Sensitivities to flavor violation and CP violating effects
- In all cases the future collider information is to be combined with the expected HL-LHC reach, and the combined extended reach is to be compared with the baseline reach of the HL-LHC.
- In April 2019, provide a comprehensive and public report to inform the community.

December 19th, 2018 Higgs@FutureColliders 6

h the PPG
yond the HL-LHC"

y process, especially for the

- Towards the Open Symposium the working group will work together with the PPG and provide a comprehensive and public report to inform the community, i.e. this is not an ECFA report
- The working group has a scientific nature, i.e. not a strategic nature, it uses the input submitted to the Strategy process to map the landscape of Higgs physics at future colliders
- The "convenors" in the PPG who are connected to this specific topic (Beate Heinemann and Keith Ellis) and the ECFA chair (Jorgen D'Hondt) will be included as ex-officio observers, i.e. included in the working group communications and discussions

December 19th, 2018 Higgs@FutureColliders 7

SMEFT$_{ND}$ framework

- Effective lagrangian: $\mathscr{L}_{\rm Eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 + \frac{1}{\Lambda^4}\mathscr{L}_8 + \cdots, \qquad \mathscr{L}_d = \sum_i c_i^{(d)} \mathscr{O}_i^{(d)}.$
  - terms in *Higgs basis*
- Higgs couplings to vector bosons:
  - only c_{gg}, δc_Z, $c_{\gamma\gamma}$, $c_{Z\gamma}$, C_{ZZ}, $c_{Z\Box}$ independent parameters

$$\begin{aligned}\Delta\mathscr{L}_6^{\rm hVV} = \frac{h}{v}\Big[&2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu \\ &+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\ &+ c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z_{\mu\nu} \\ &+ c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}\Big],\end{aligned}$$

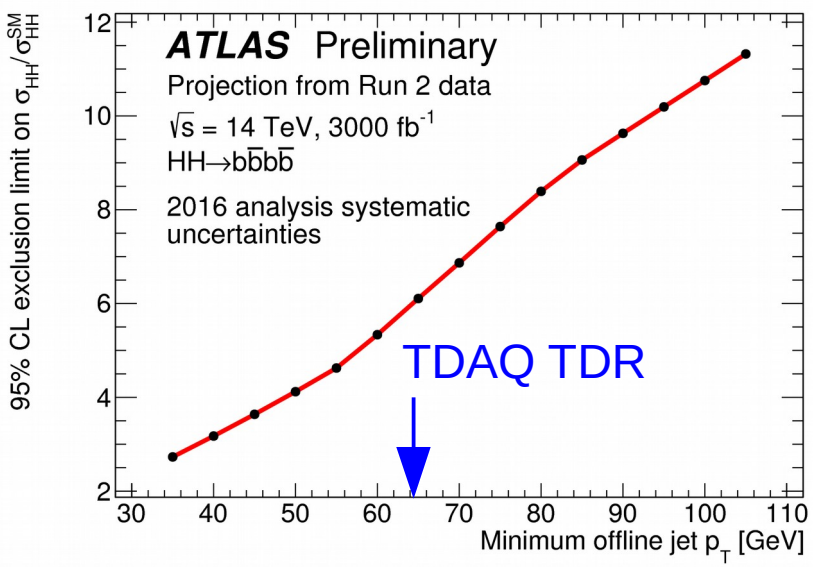
- Tri-linear gauge couplings:

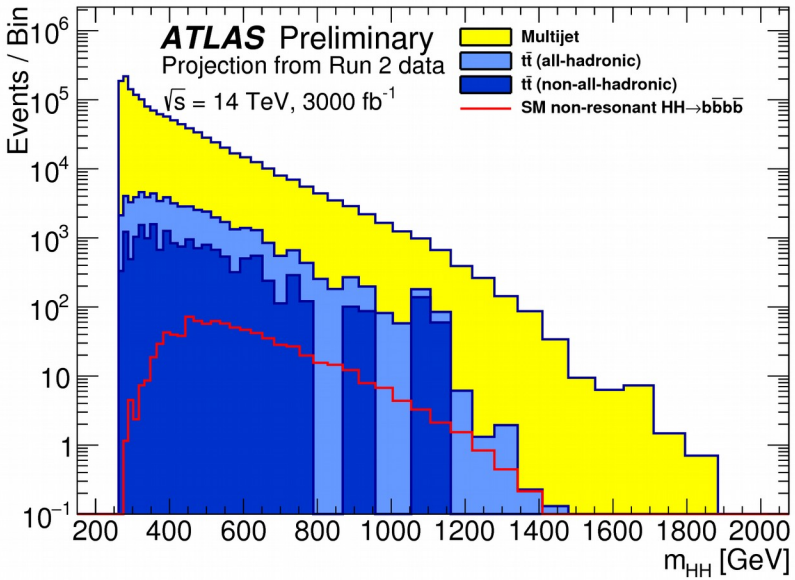
$$\begin{aligned}\Delta\mathscr{L}^{\rm aTGC} = &\; ie\delta\kappa_\gamma A^{\mu\nu} W_\mu^+ W_\nu^- + ig\cos\theta_w \left[\delta g_{1Z}(W_{\mu\nu}^+ W^{-\mu} - W_{\mu\nu}^- W^{+\mu}) Z^\nu + (\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma) Z^{\mu\nu} W_\mu^+ W_\nu^-\right] \\ &+ \frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W_\mu^{+\nu} W_\nu^{-\rho} A_\rho^\mu + \cos\theta_w W_\mu^{+\nu} W_\nu^{-\rho} Z_\rho^\mu\right),\end{aligned}$$

- Yukawa couplings: $\Delta\mathscr{L}_6^{\rm hff} = -\frac{h}{v}\sum_{f\in u,d,e} \hat{\delta} y_f m_f \bar{f} f + \text{h.c.}.$
- Neutral diagonality.

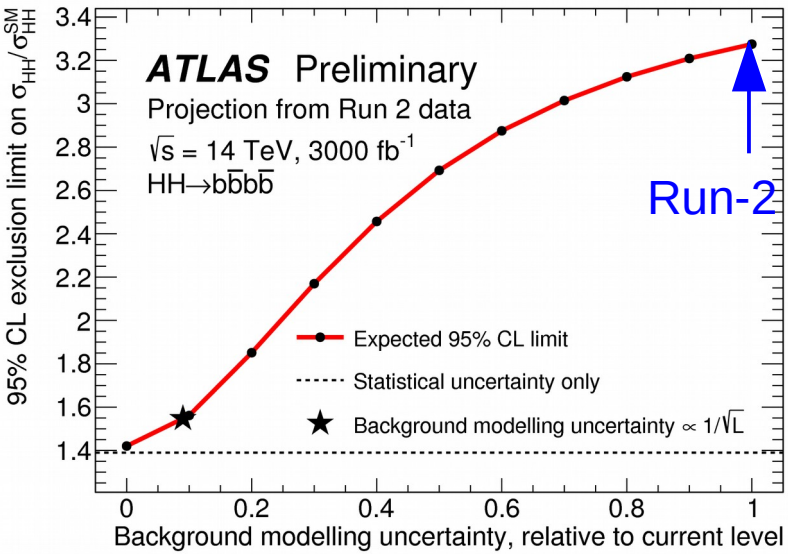
HH→$b\bar{b}b\bar{b}$ (ATLAS)

- Extrapolation from Run-2 analysis
  - fit of m_{4j} distribution
  - $p_T^{jet} > 40$ GeV, different thresholds tested





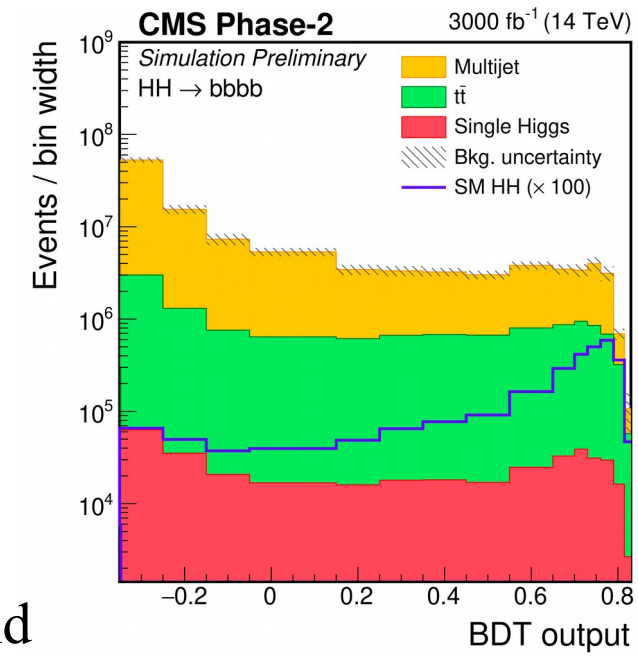
- Systematics
  - dominated by multijet data-driven model
  - conservative assumption:
    Run-2 systematics used



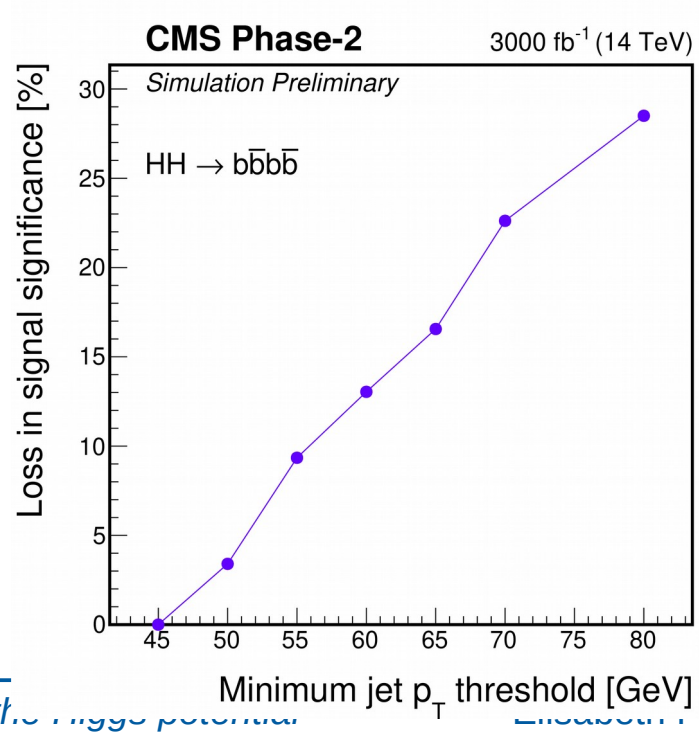
- Significance:
  1.4/0.61σ without/with syst

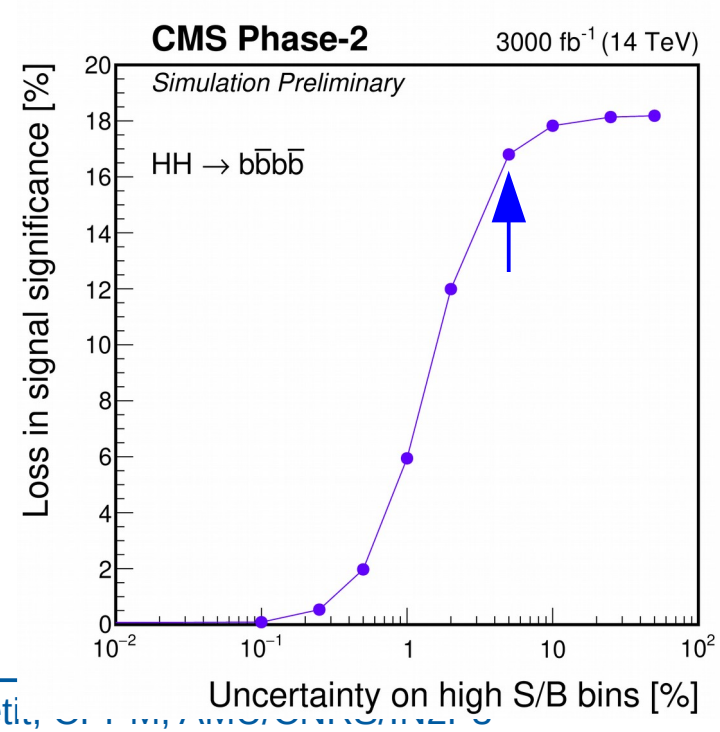
HH→$b\bar{b}b\bar{b}$ (CMS)

- SM sigmal + BSM benchmark points
- Resolved and boosted b-jets
  - boosted topologies more sensitive to BSM scenarios where high m_{HH} is enhanced
- Resolved:
  - p_T > 45 GeV, different thresholds tested
  - BDT against multijet bkg + $t\bar{t}$ and single-Higgs
- Small uncertainty considered for multijet background



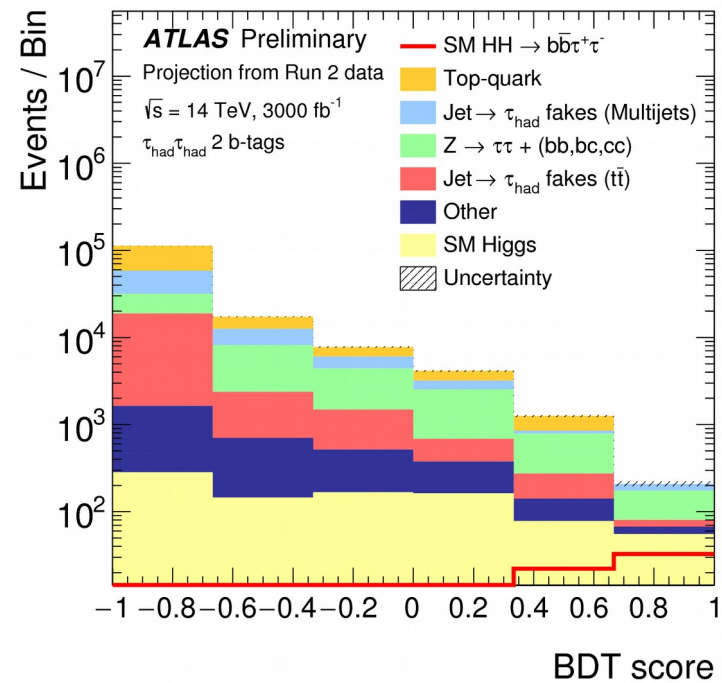
- Significance:
  1.2σ wo/syst
  0.95σ w/ syst

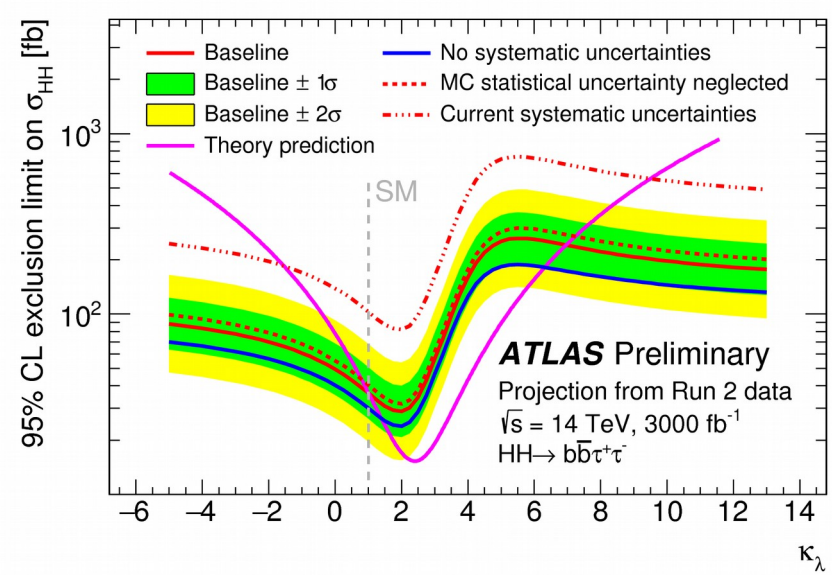




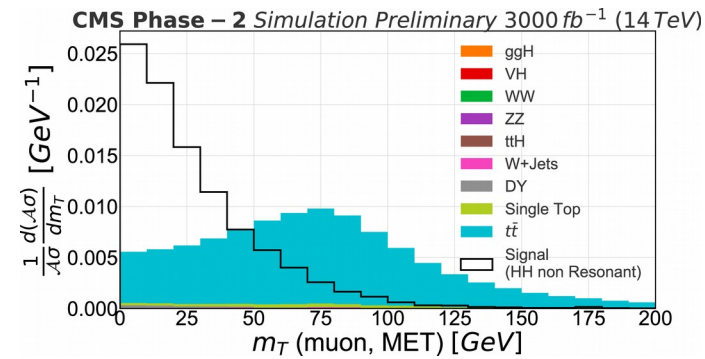
HH→$b\bar{b}\tau\tau$ (ATLAS)

- Extrapolation from Run-2 analysis
- Three signal regions:
  - $\tau_{lep}\tau_{had}$ (Single Lepton Trigger)
  - $\tau_{lep}\tau_{had}$ (Lepton Tau Trigger)
  - $\tau_{had}\tau_{had}$ (Single Tau Trigger and Di-Tau Trigger)
- BDT output used as final discriminant
  - binning adapted to higher statistics
- Limit on κ_λ: LTT category not included and dedicated BDT trained on $\kappa_\lambda = 20$
- Different assumptions for systematics
- Significance: 2.5/2.1σ without/with syst



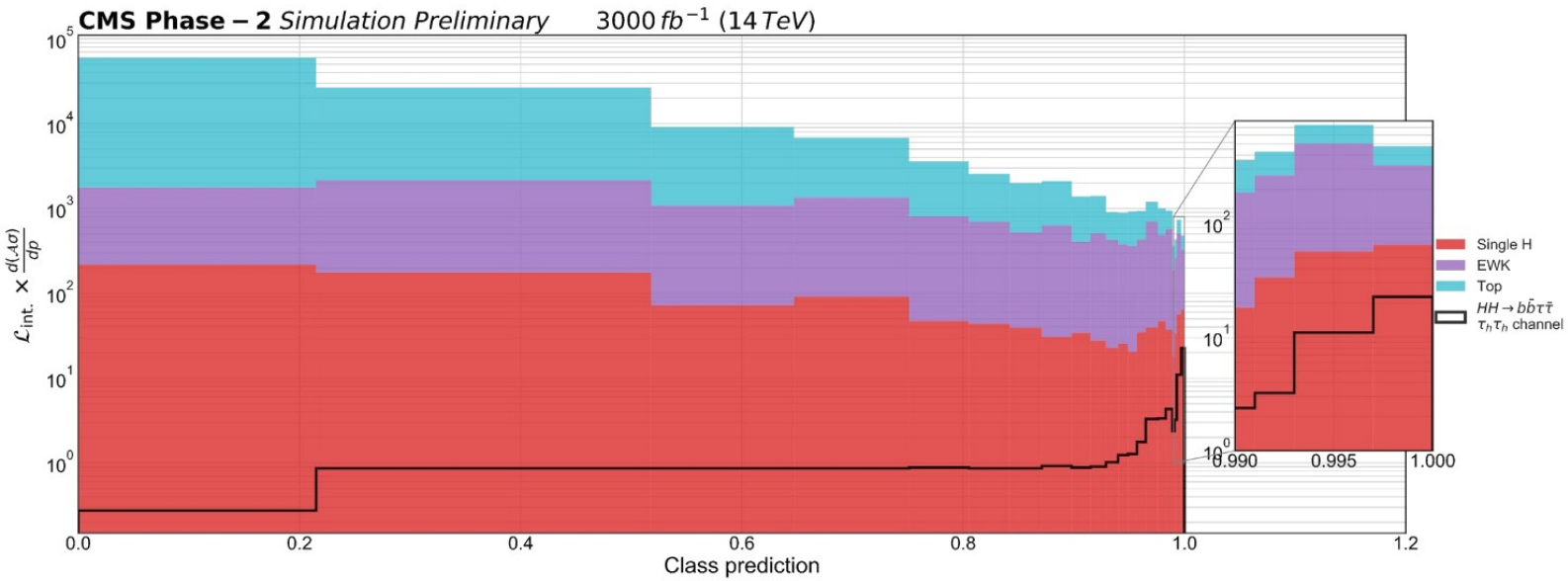


HH→$b\bar{b}\tau\tau$ (CMS)



- 3 categories: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$

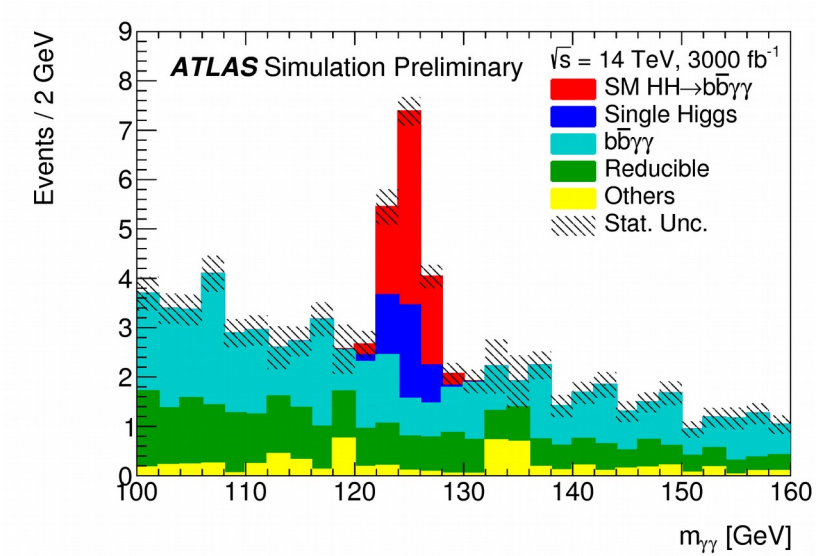
- Use of a neural network
  - 27 basic + 21 reconstructed + 4 global features
  - deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

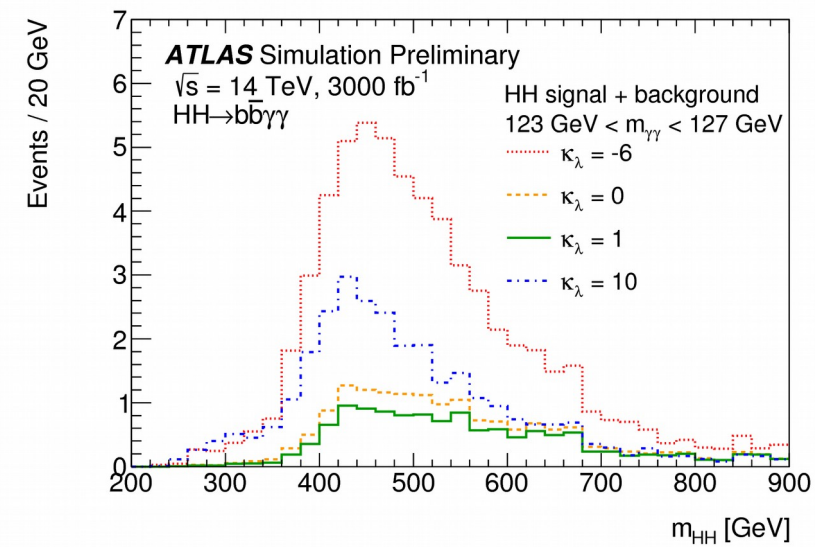


- Simultaneous fit of the NN output for the 3 decay channels
  - discriminant binned per decay channel via adaptive binning
- Significance: 1.6/1.4σ without/with syst

HH→$b\bar{b}\gamma\gamma$ (ATLAS)

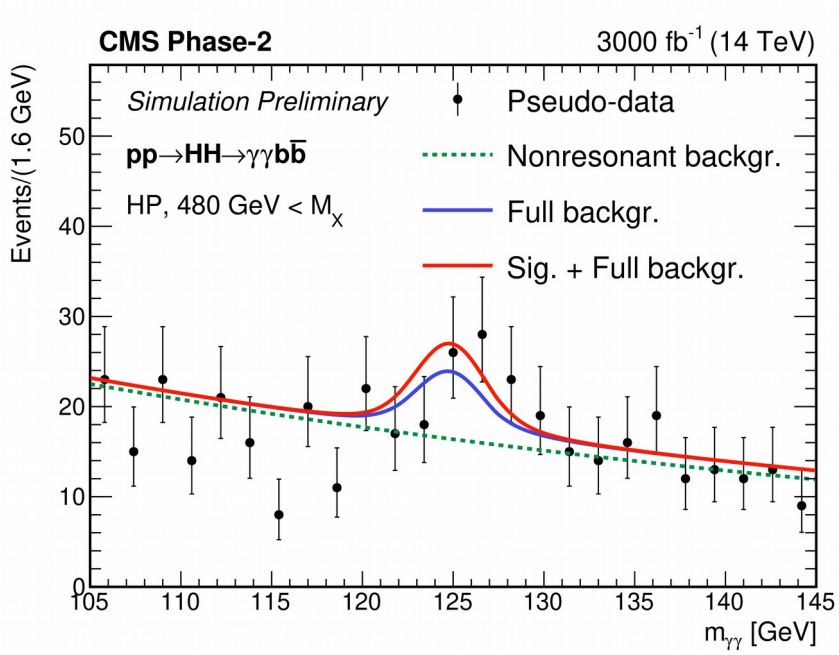
- Dedicated analysis with smearing functions: upgraded detector geometry and performance functions
  - $m_{\gamma\gamma}$ resolution ~ 1.6 GeV
- Dedicated BDT trained to remove continuum background and main single-Higgs background ($t\bar{t}H$)
- Limit on κ_λ: use of the $m_{b\bar{b}\gamma\gamma}$ distribution for events with $123 < m_{\gamma\gamma} < 127$ GeV
- Systematics: very small impact in general
- Significance: 2.1/2.0σ without/with syst

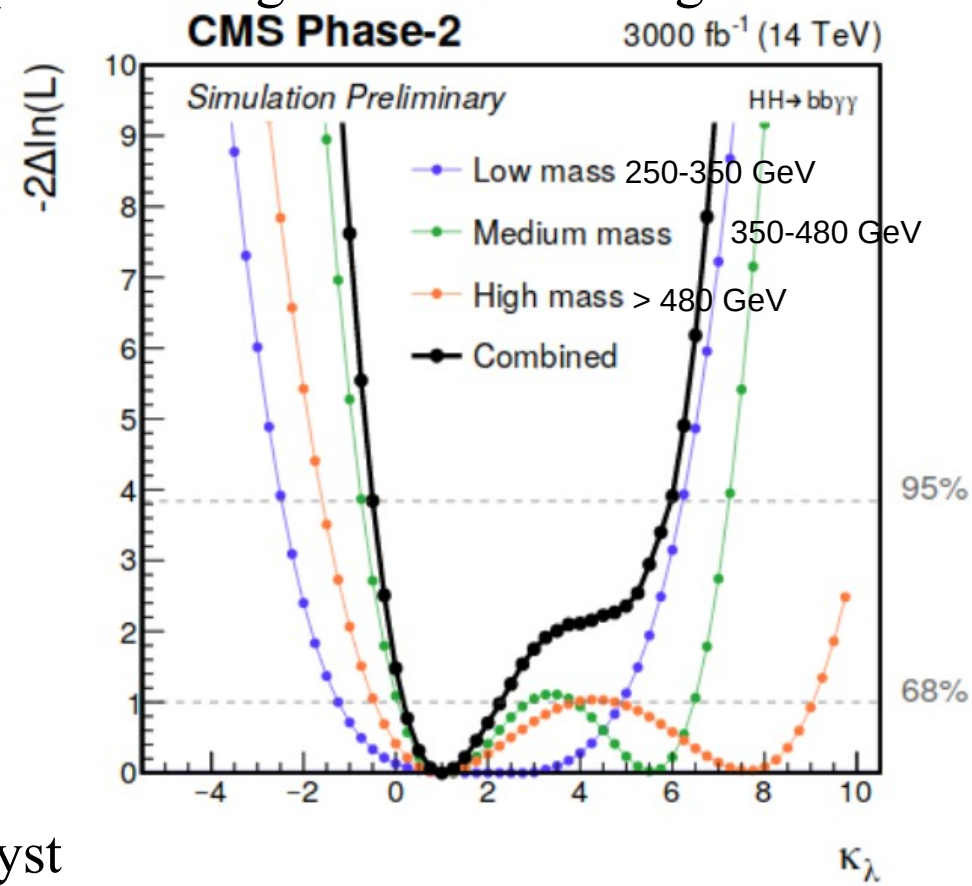




HH→$b\bar{b}\gamma\gamma$ (CMS)

- Dedicated BDT to reject $t\bar{t}H$
  - 75% reduction for 90% signal efficiency
- Classification of events based on $M_X = m_{jj\gamma\gamma} - m_{\gamma\gamma} - m_{jj} + 250$ GeV into low and high mass categories
- MVA event categorisation BDT to separate background and HH signal into medium (MP) and high (HP) purity
- Fit of $m_{\gamma\gamma}$ x m_{jj}

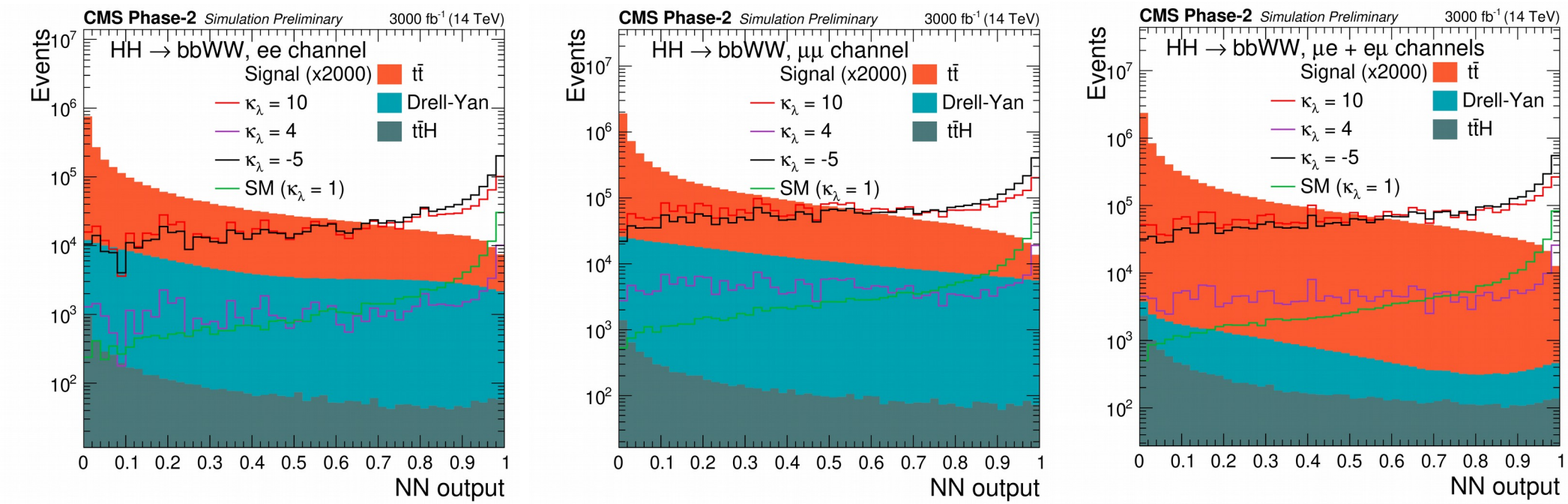




- Significance: 1.8/1.8σ without/with syst
  - difference with ATLAS partly due to $m_{\gamma\gamma}$ resolution

HH→$b\bar{b}$VV(lvlv), CMS only

- Optimised on WW, but ZZ signal included for the results
- Large irreducible backgrounds: $t\bar{t}$, DY
- Neural Network discriminant
  - 9 input angular and mass variables
  - signal extracted from the NN ouput (3 categories ee, μμ, eμ)

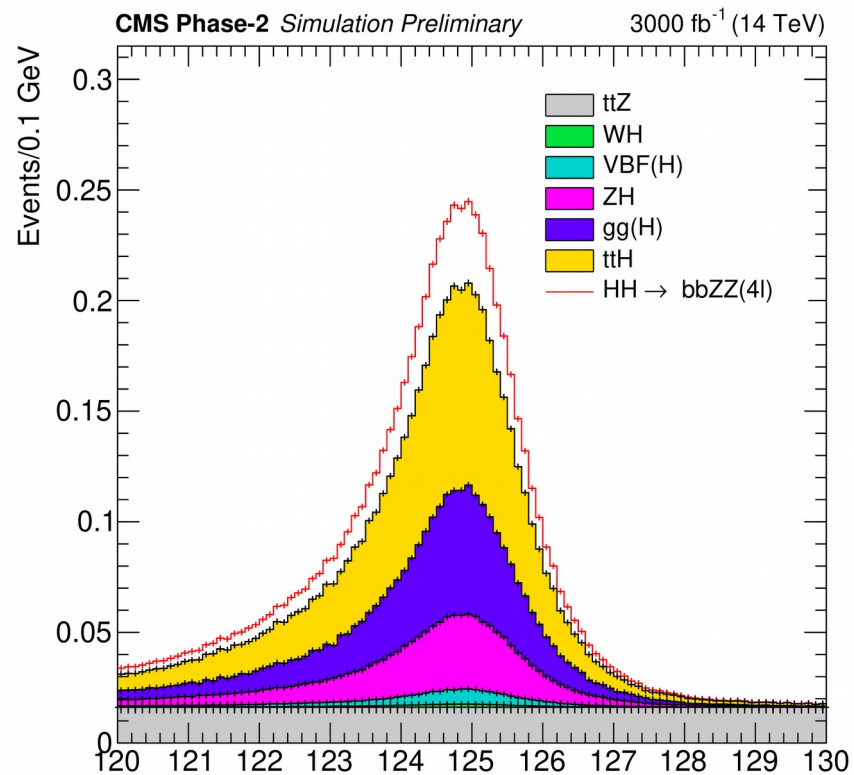


- Results: 0.6σ significance

HH→$b\bar{b}$ZZ(4l), CMS only

- Very rare but clean final state, yet unexplored at the LHC
- Powerful H→4ℓ signature ⇒ single Higgs dominant background
- Select events with m4ℓ compatible with m_H
- Counting experiment with events around m_H

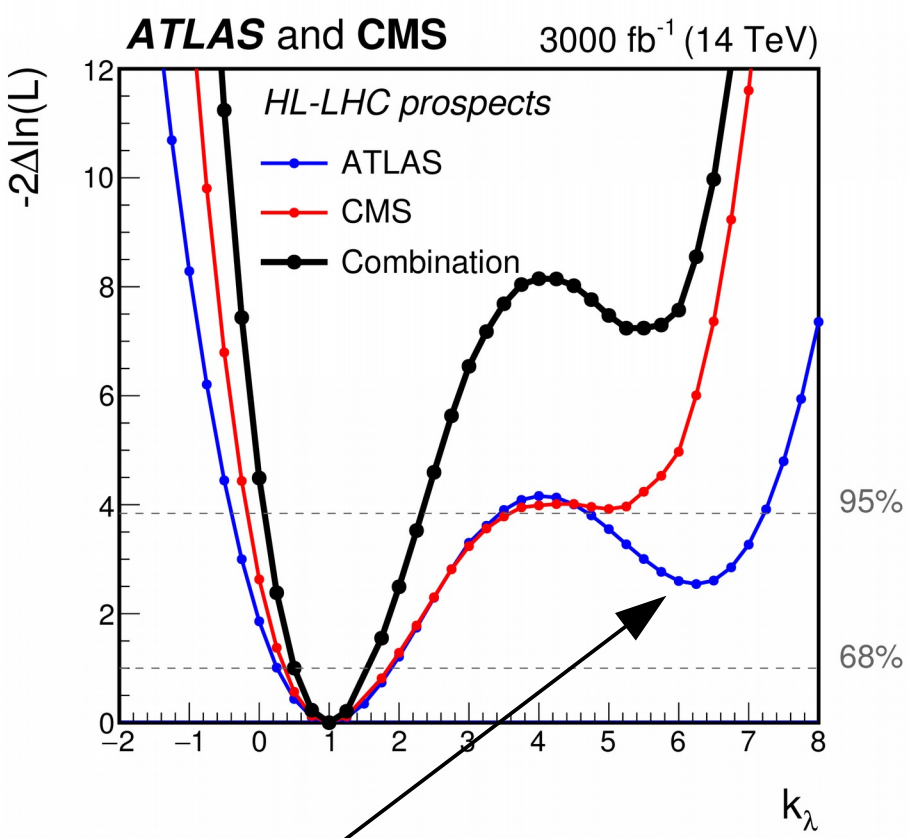
- ~1 signal event after selection
  - S/B ~0.1

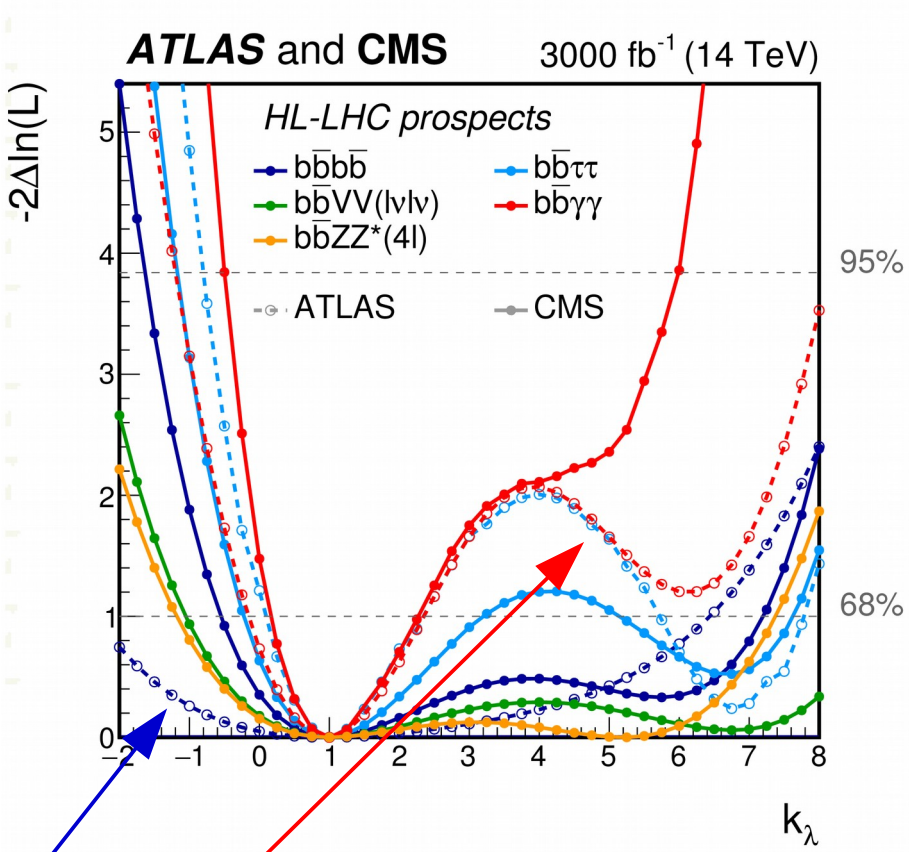


- Results: 0.4σ significance

Combined results (ATLAS+CMS)

- Comparison of negative log-likelihood ratios:

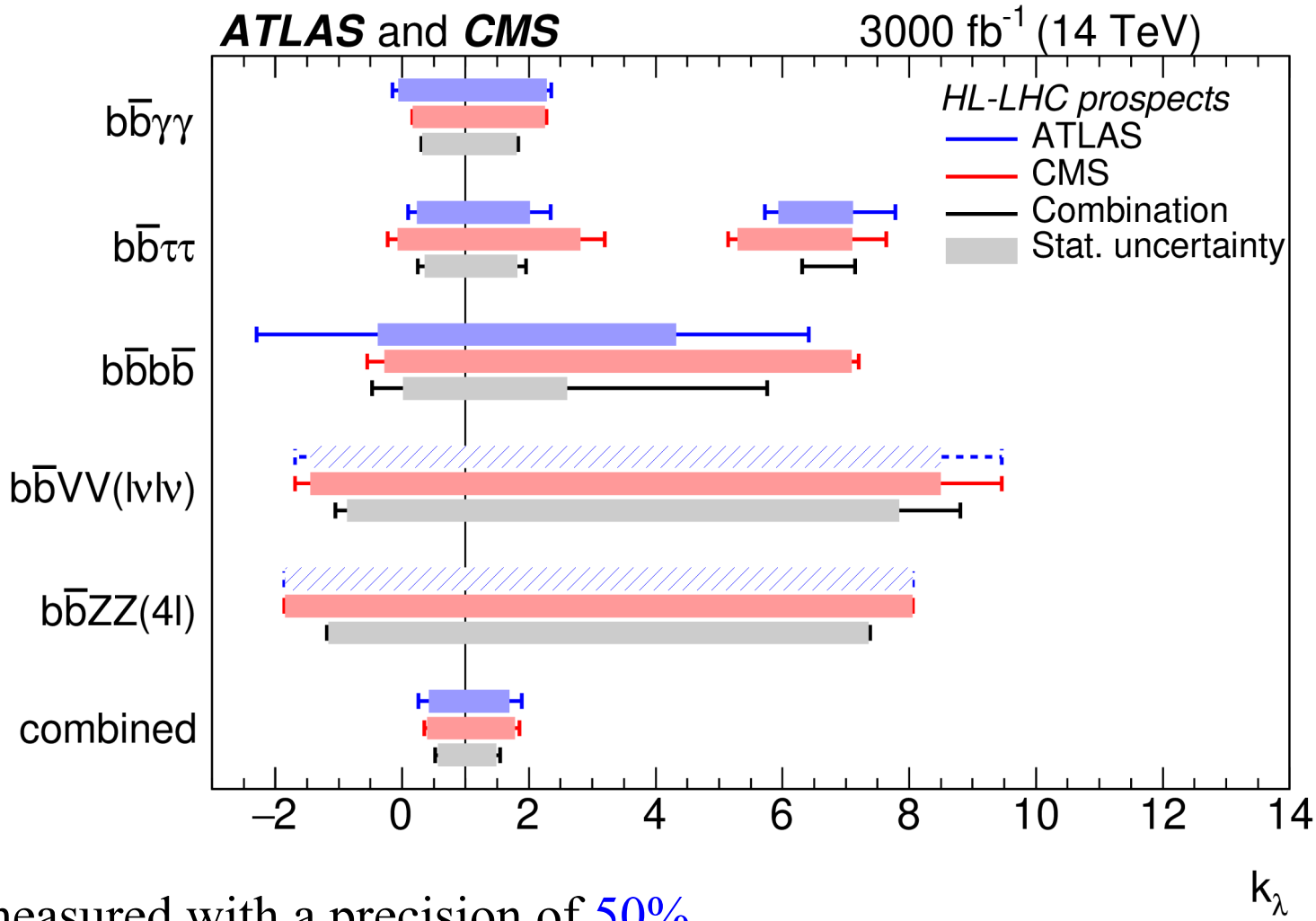




- Difference on 2nd minimum mainly from the $b\bar{b}\gamma\gamma$ channel: 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6 (while this low-m_{HH} category has no effect around 1)
- CMS slightly better below 1: $b\bar{b}b\bar{b}$ + other smaller channels

Combined results (ATLAS+CMS)

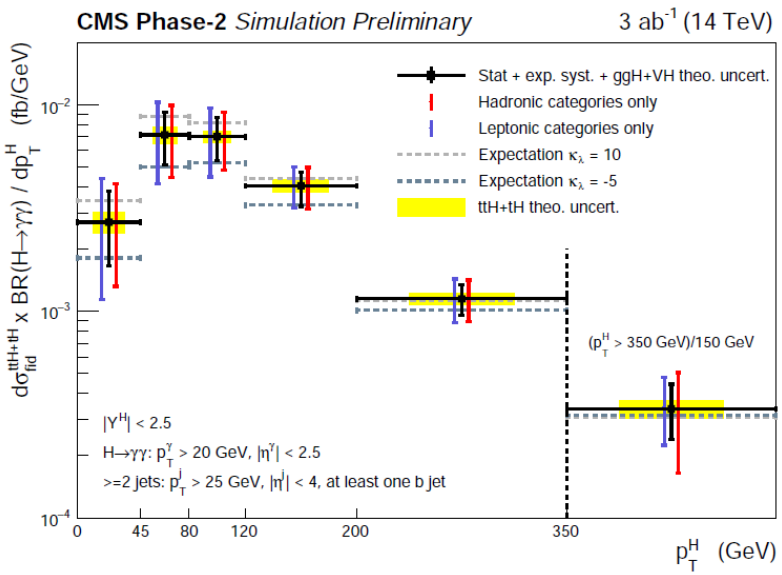
- 68% CI, channel by channel
- Dashed line = no ATLAS analysis, using value from CMS (as for Higgs couplings)



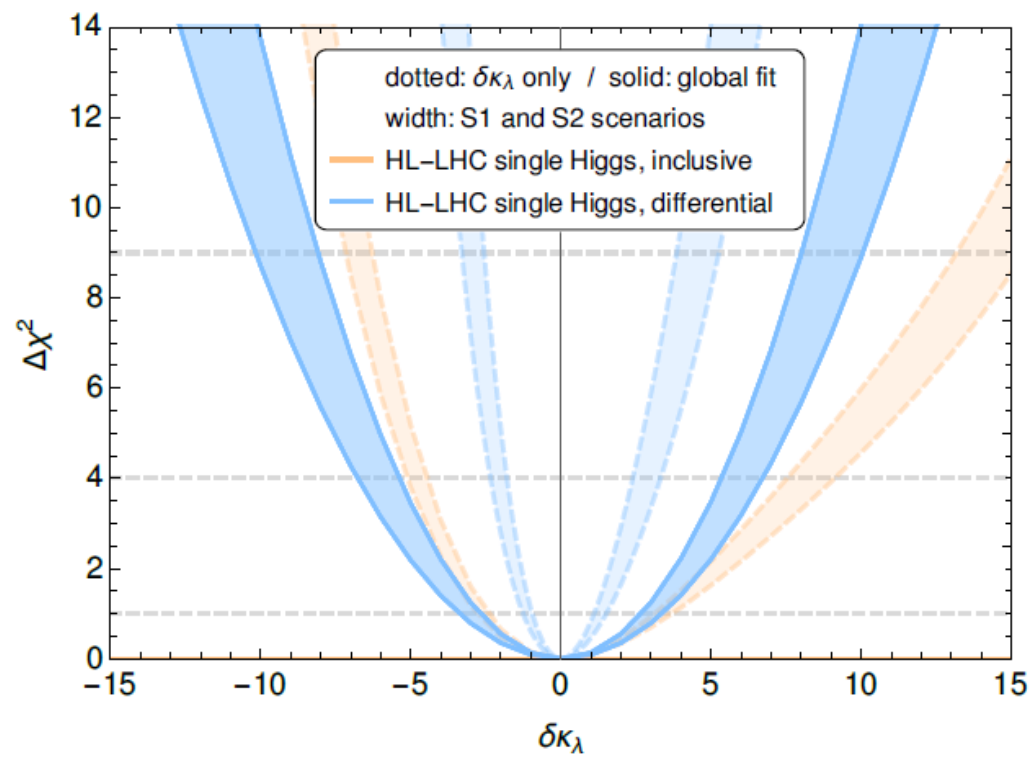
- κ_λ measured with a precision of 50%

HL-LHC, via single-Higgs

- Inputs:
  - production modes → using projections of couplings measurements
  - kinematics properties of the event, here p_T^{Higgs} in the $t\bar{t}H(\rightarrow\gamma\gamma)$ channel

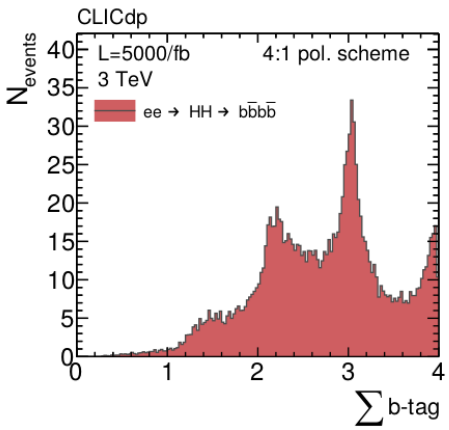


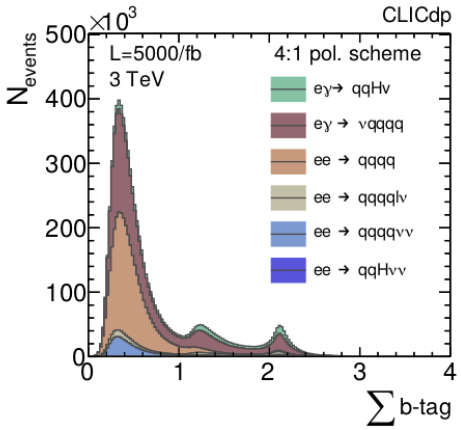
- Results:
  - dotted = method 3
  - solid = method 4
  - band = scenarios for systematics

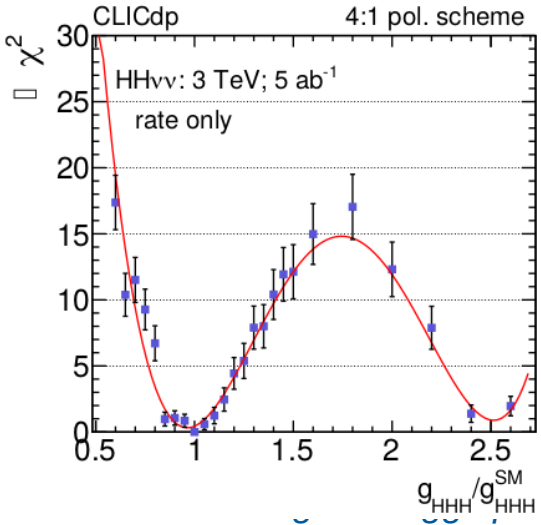


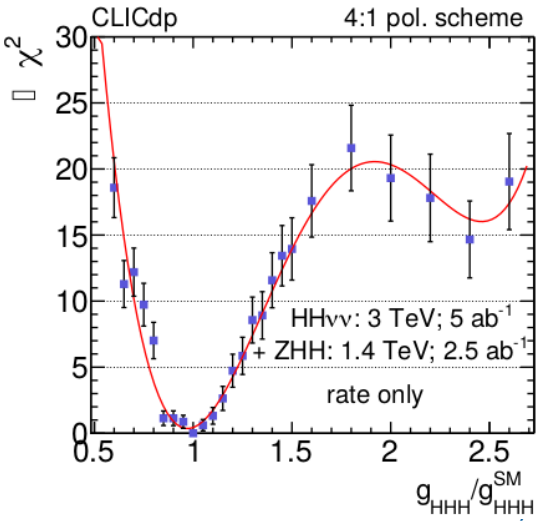
CLIC HH measurements, more information

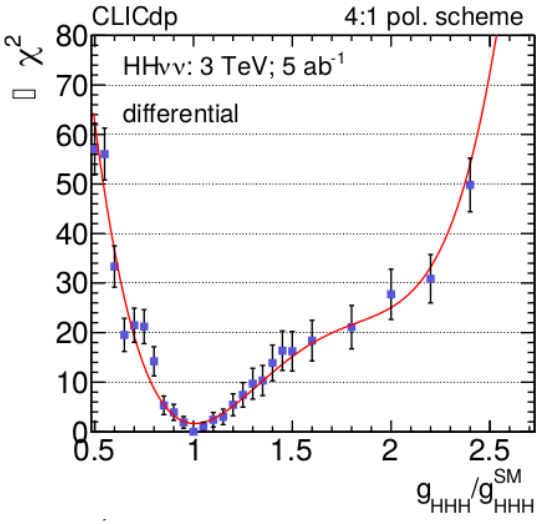
- Channels: $HH \rightarrow b\bar{b}b\bar{b}$ and $HH \rightarrow b\bar{b}WW(\rightarrow q\bar{q}q\bar{q})$, second almost no effect
- BDT observables
  - angular distance and invariant mass of the Higgs candidates
  - flavour-tagging information
  - m_{HH}
  - E_T^{miss}, $N_{photons}$, max (η_{jets})
- Significance:
  - 1.4 TeV: 3.6σ, 28% uncertainty
  - 3 TeV: ~14σ, 7.3% uncertainty
- Effect of systematics negligible





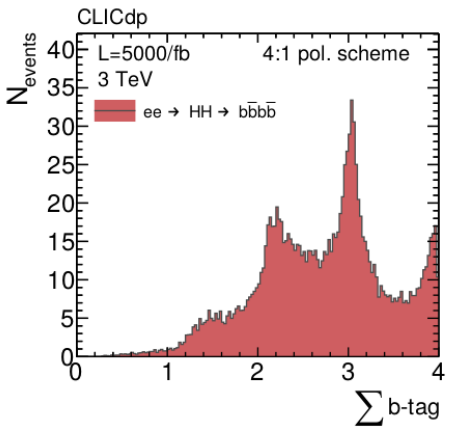


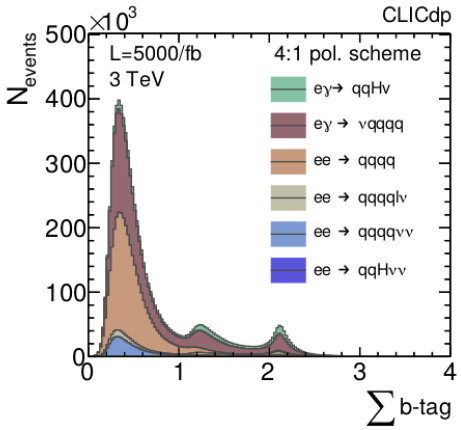


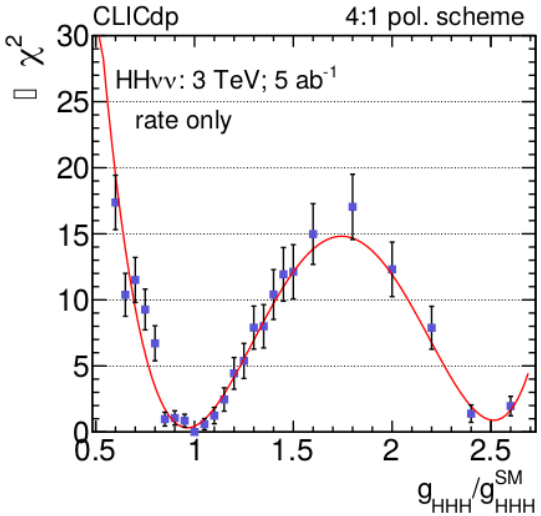


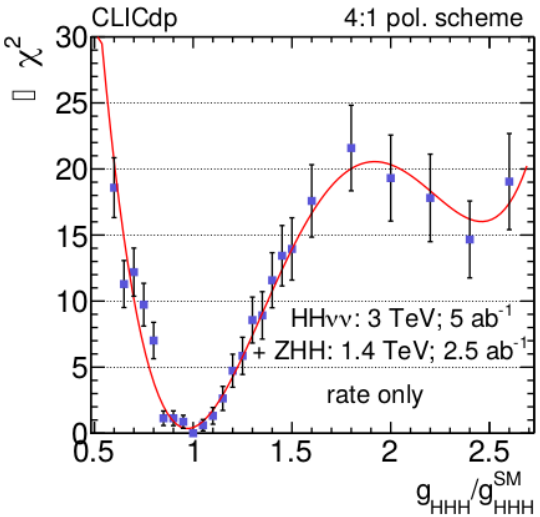
CLIC, more info

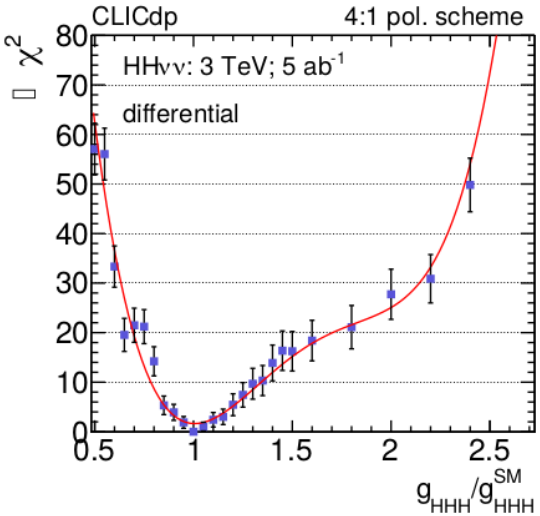
- Channels: $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}WW(\to q\bar{q}q\bar{q})$, second almost no effect
- BDT observables
  - angular distance and invariant mass of the Higgs candidates
  - flavour-tagging information
  - m_{HH}
  - E_T^{miss}, $N_{photons}$, max (η_{jets})
- Significance:
  - 1.4 TeV: 3.6σ, 28% uncertainty
  - 3 TeV: ~14σ, 7.3% uncertainty
- Effect of systematics negligible





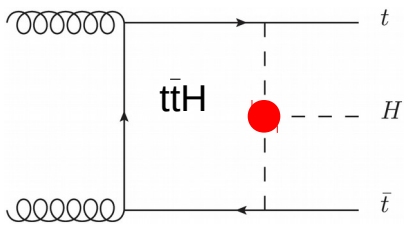


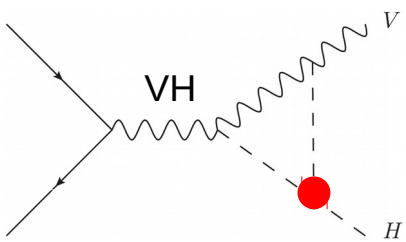


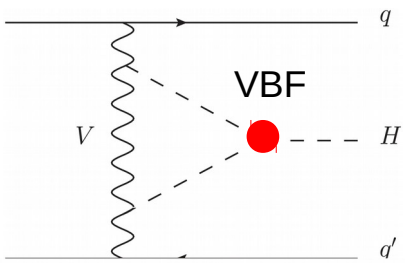


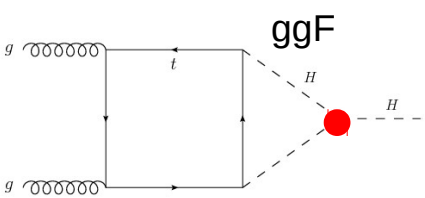
Single-Higgs couplings (1)

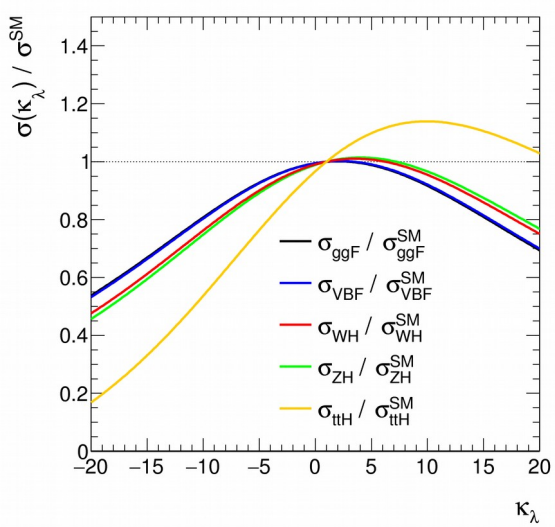
- Higgs self-interaction via one-loop corrections of the single-Higgs production
  - κ_λ-dependent corrections to the tree-level cross-sections
- pp colliders



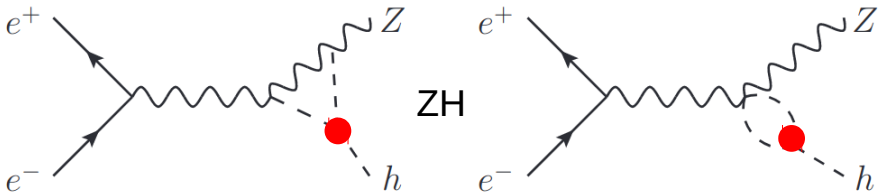


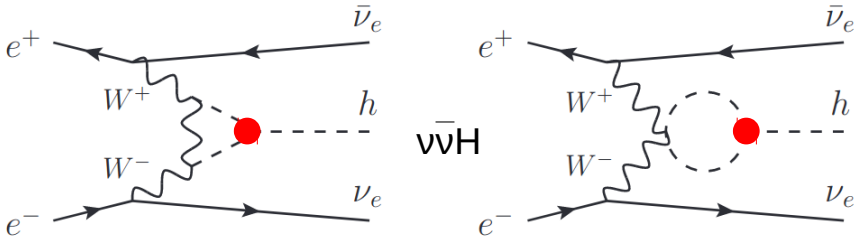


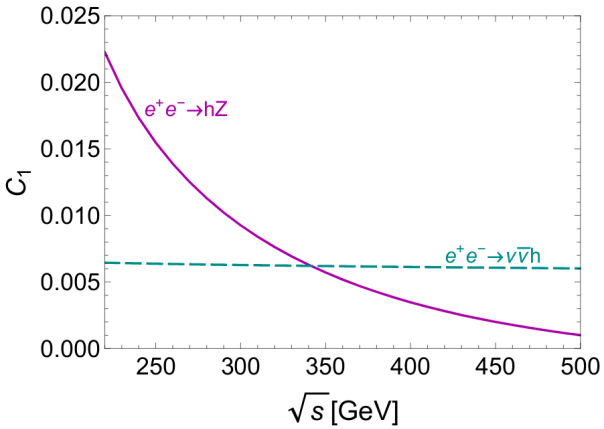




- ee colliders

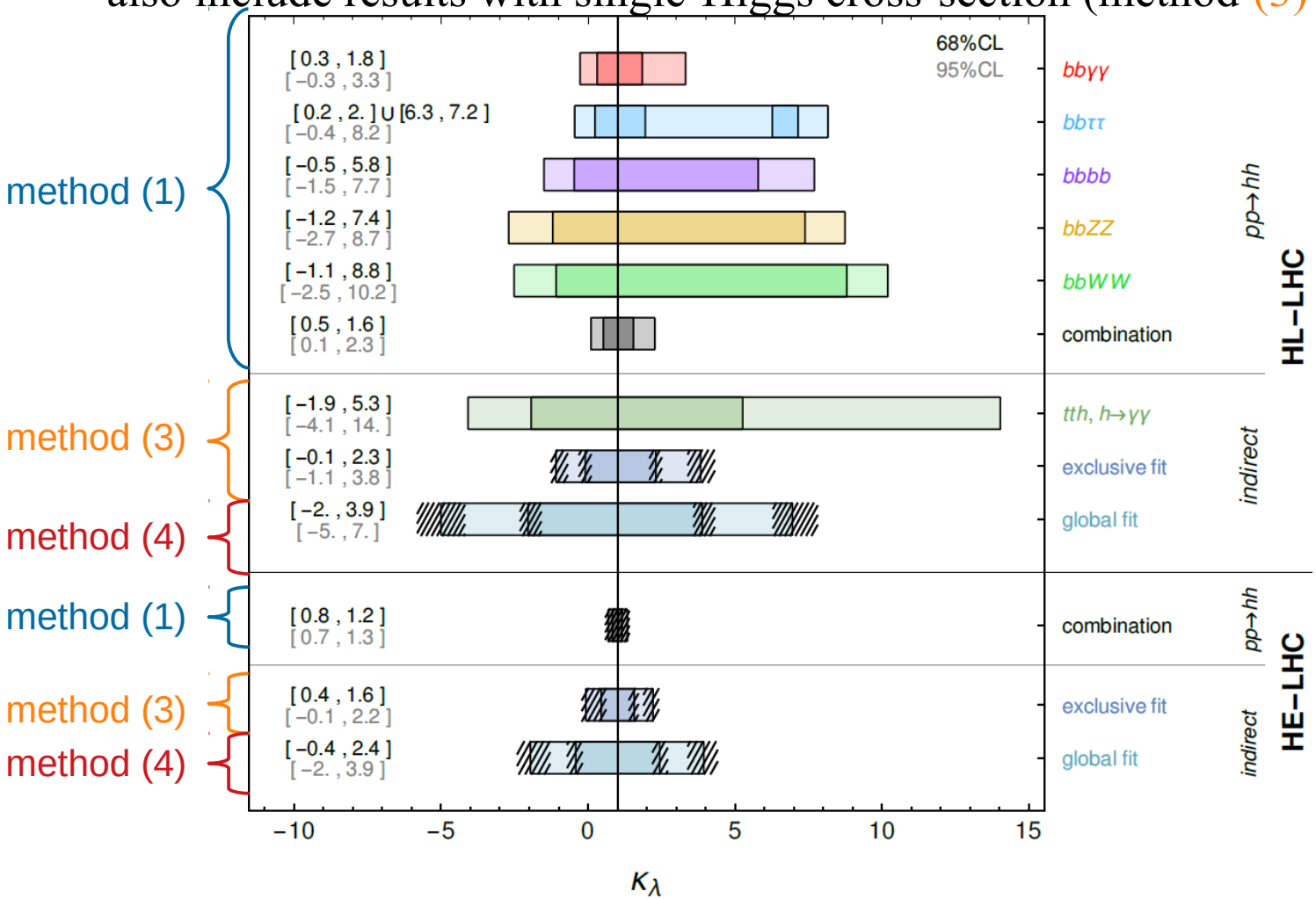






HL(HE)-LHC, summary

- 68% and 95% CI on the measurement of κ_λ:
  - also include results with single-Higgs cross-section (method (3) and (4))



- The 50% uncertainty from HL-LHC method (1) baseline for combination with other Future Colliders

Inputs to the European strategy update

- #152: The physics potential of HL-LHC
- #160: The physics potential of HE-LHC
- #135: Future Circular Collider - The Integrated Programme (FCC-int)
- #29: CEPC Input to the ESPP 2018 - Physics and Detector
- #145: The Compact Linear e+e− Collider (CLIC): Physics Potential
- #77: The International Linear Collider. A Global Project