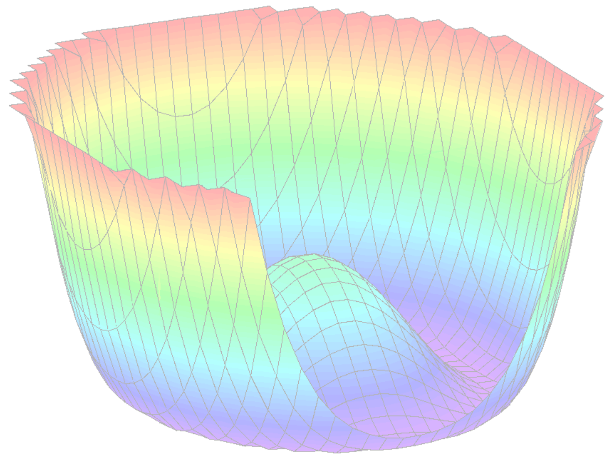


Experimental prospects on di-Higgs measurements

Elisabeth Petit (CPPM)
on behalf of the ATLAS, CMS and theory communities

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

CMS

ATLAS EXPERIMENT

IRN Terascale@Annecy
22nd of May 2019

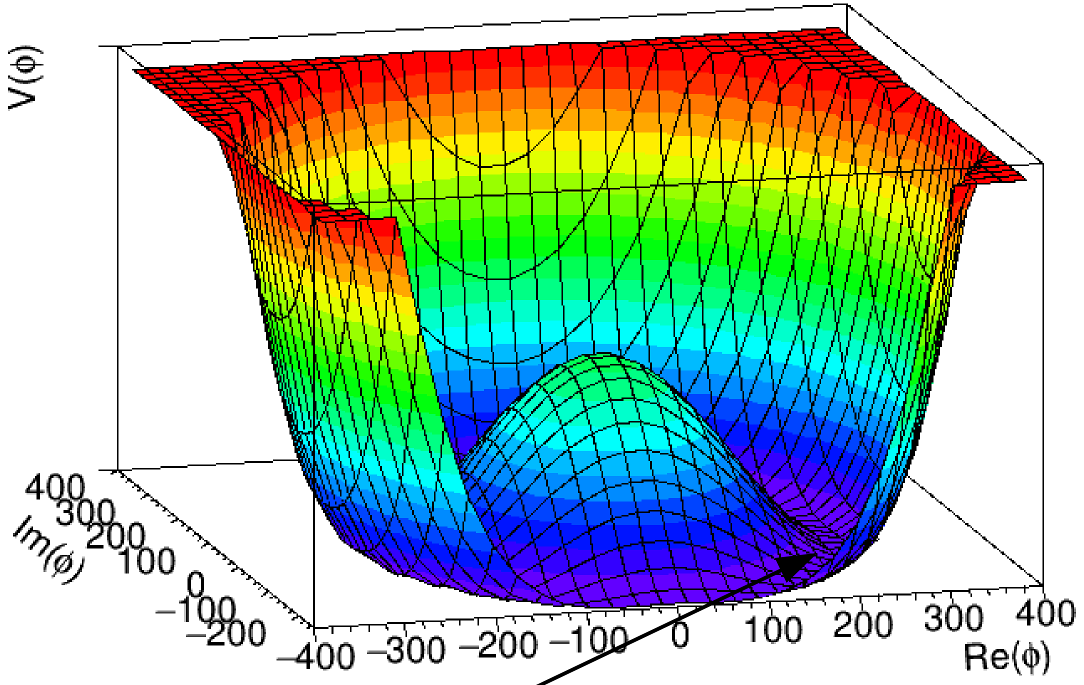
Introduction

- The Higgs self-coupling plays important roles
  - linked to naturalness/hierarchy problem
  - controls the stability of the EW vacuum (... like many other BSM parameters)
  - dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter imbalance via EW baryogenesis
- Does it need to be measured with high accuracy?
  - a few new physics scenarios would be revealed in the measurements of h3
  - only way to understand the dynamics of EWSB (Cooper pair or elementary scalar?)

- Latest results on di-Higgs production and Higgs self-couplings at HL-LHC
  - Yellow Report with CMS and theorists released at the end of 2018 as an input to the European strategy (1902.00134)
  - presented at CERN in March (link)
- Measurement of Higgs self-couplings with Future Colliders (FC)
  - within the Higgs@FC working group mandated by ECFA for the European Strategy Update (1905.03764)
  - presented at Granada last week (link)

Higgs potential

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



- Approximation around the v.e.v:

$$V(\Phi)\approx\lambda v^2 h^2+\lambda v h^3+\frac{1}{4}\lambda h^4$$

mass term self-coupling terms

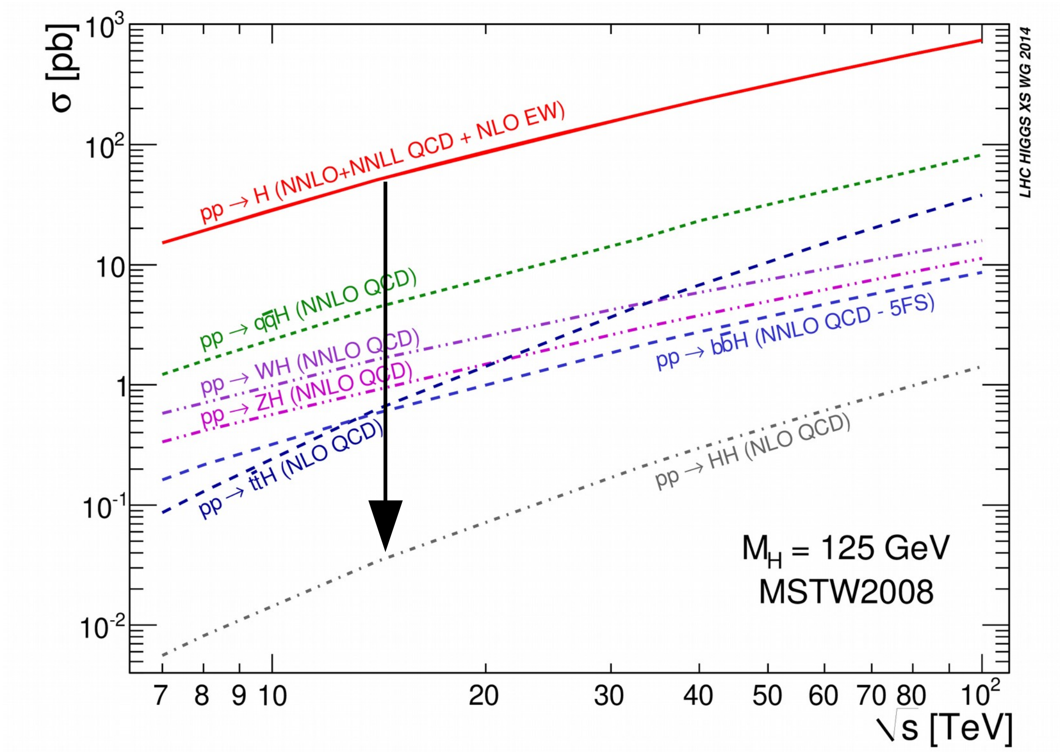
- λ known from v.e.v and Higgs mass: $\lambda=\frac{m_H^2}{2\cdot v^2}\approx 0.13$

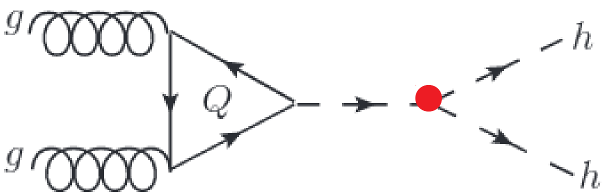
- BSM effect could change λ ⇒ define $\kappa_\lambda=\kappa_3=\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

HL-LHC propects

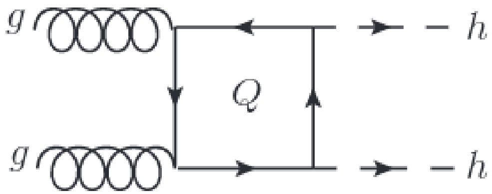
Di-Higgs production at pp colliders (1)

- Main production mode: ggF
  - σ = 36.69 fb NNLO/NNLL with finite top mass effects included at NLO in QCD
  - destructive interference between triangle and box diagrams ⇒ σ(HH)/σ(H) = 0.1%





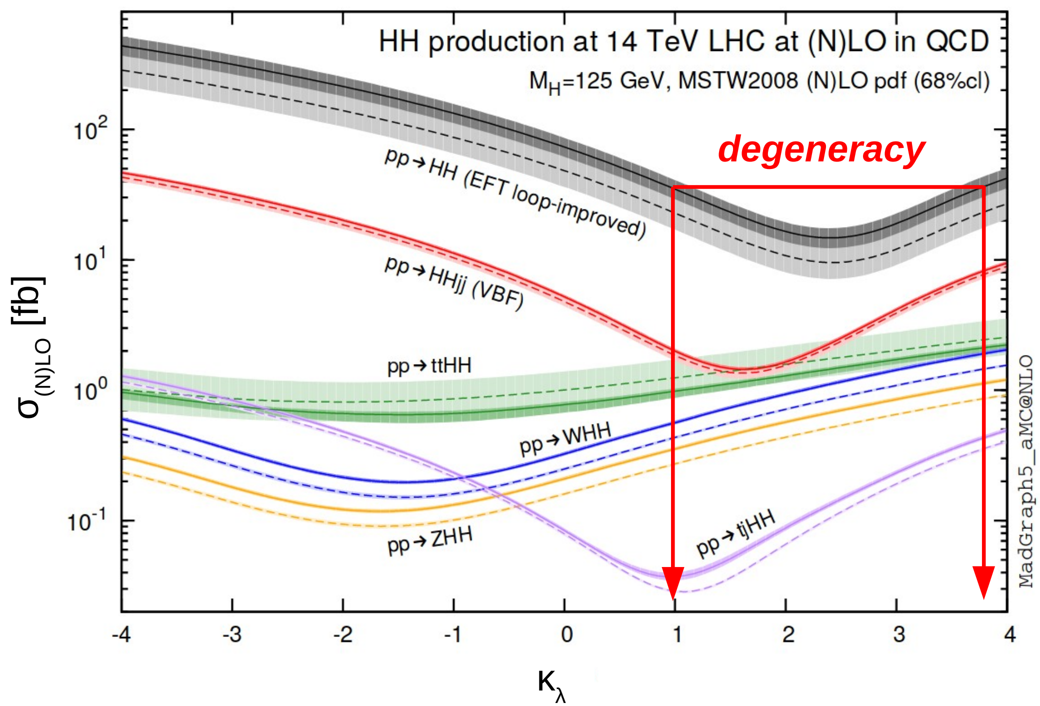
(b)



(a)

Di-Higgs production at pp colliders (2)

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



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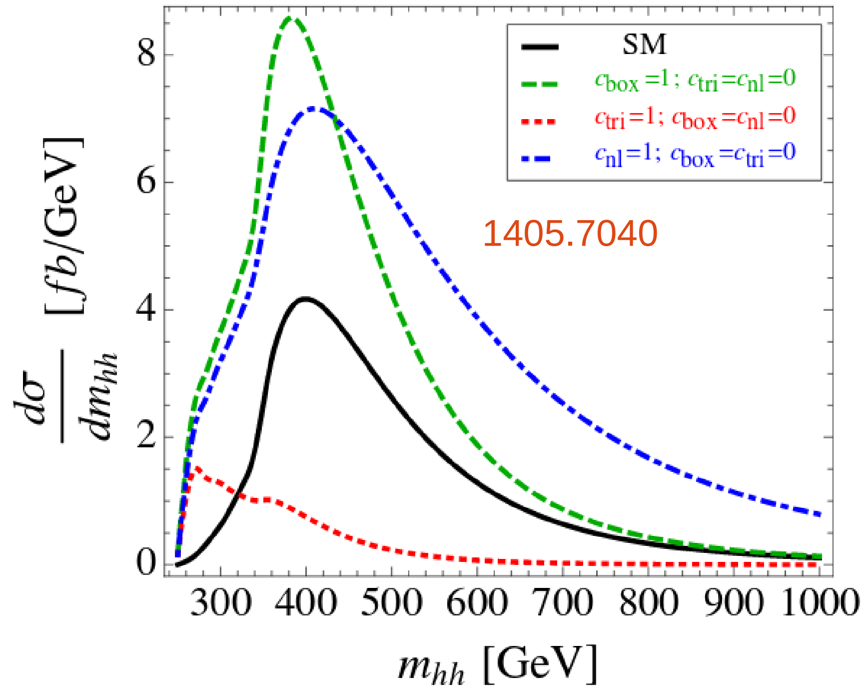
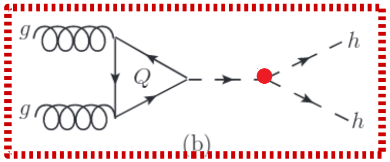
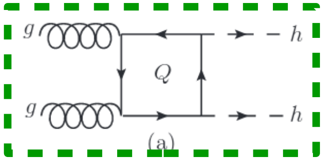
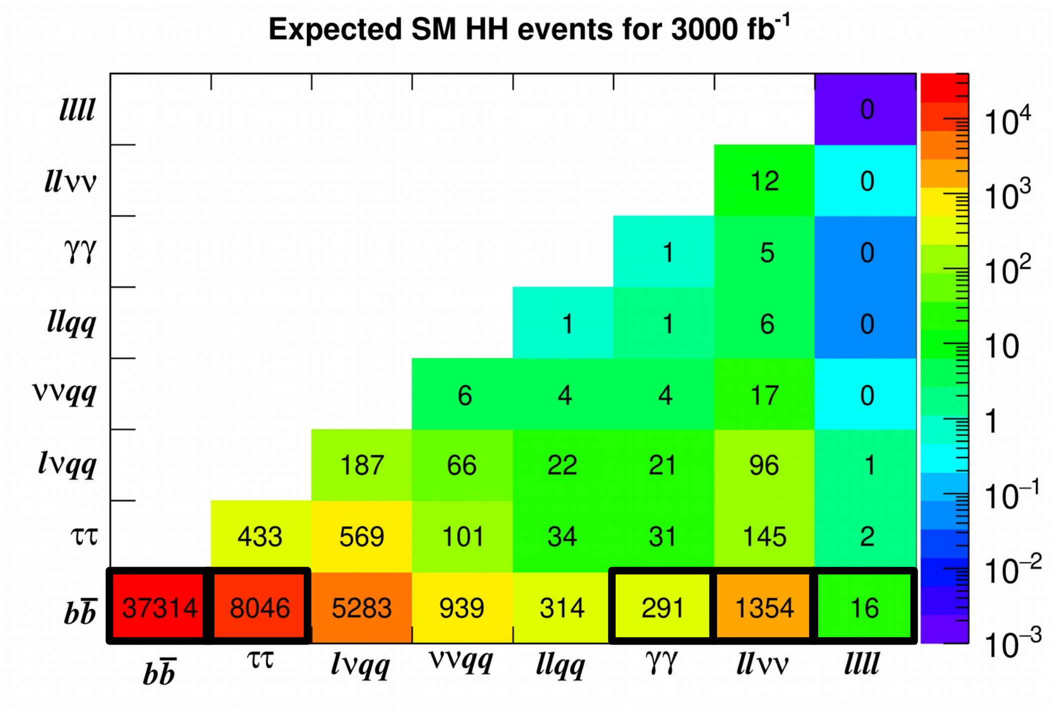






HH decays



	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 ☺

Methodology

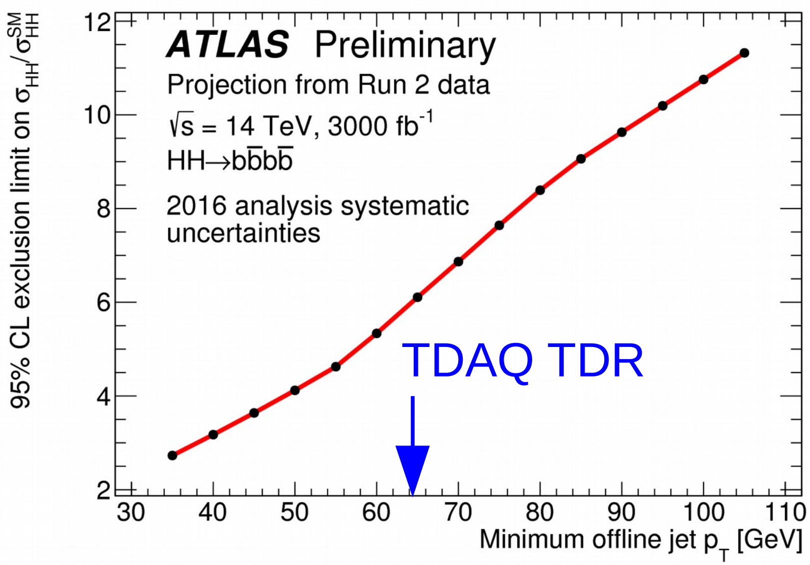
- Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200
  - improvements from the ATLAS and CMS TDRs in the past years

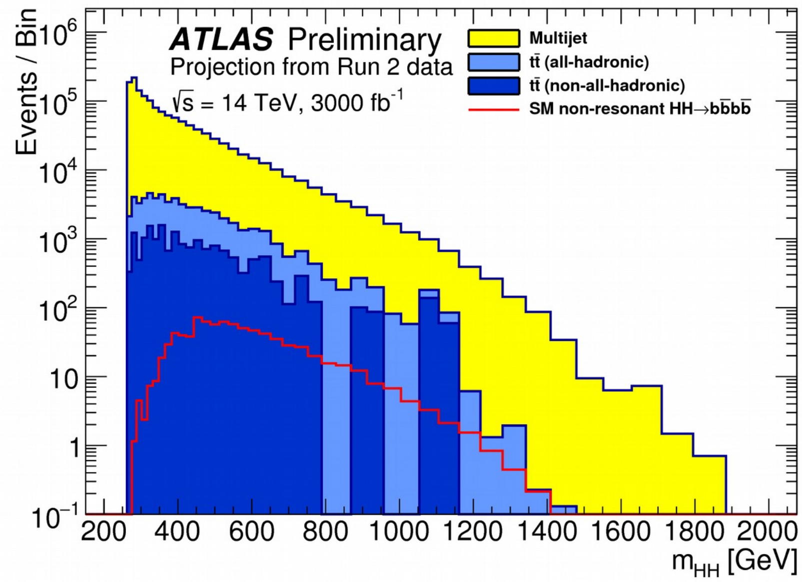
- General analysis strategy:
  - candidate mass consistent with SM Higgs boson
  - multivariate methods to reject background
  - use m_{HH} when possible
- Systematic uncertainties: common agreement between ATLAS and CMS
  - performance uncertainties scaled by 0.5 to 1
  - theoretical uncertainties divided by 2
  - MC stat uncertainties neglected
- NB: some inputs or systematics with large unknowns
  - multijet bkg modelling for $HH \to b\bar{b}b\bar{b}$
  - τ fake-rate
  - …

  ⇒ room for improvement

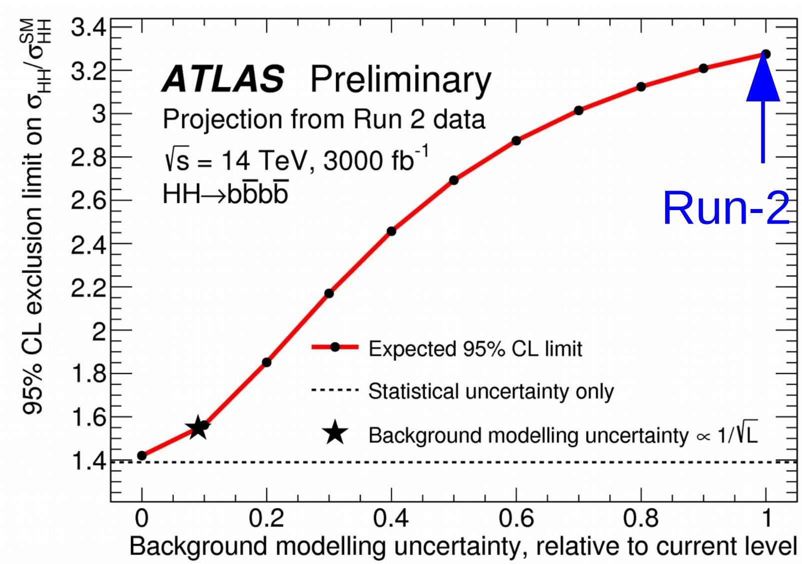
HH→$b\bar{b}b\bar{b}$ (ATLAS)

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





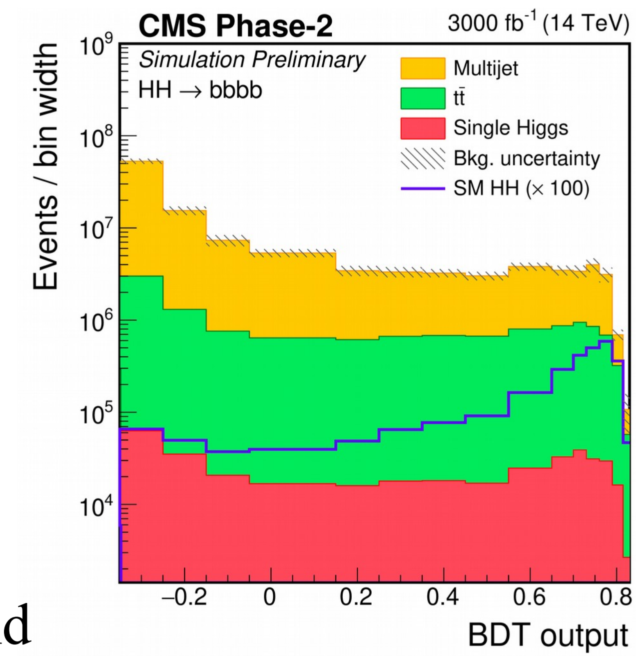
- Systematics
  - dominated by multijet data-driven model
  - conservative assumption: Run-2 systematics used



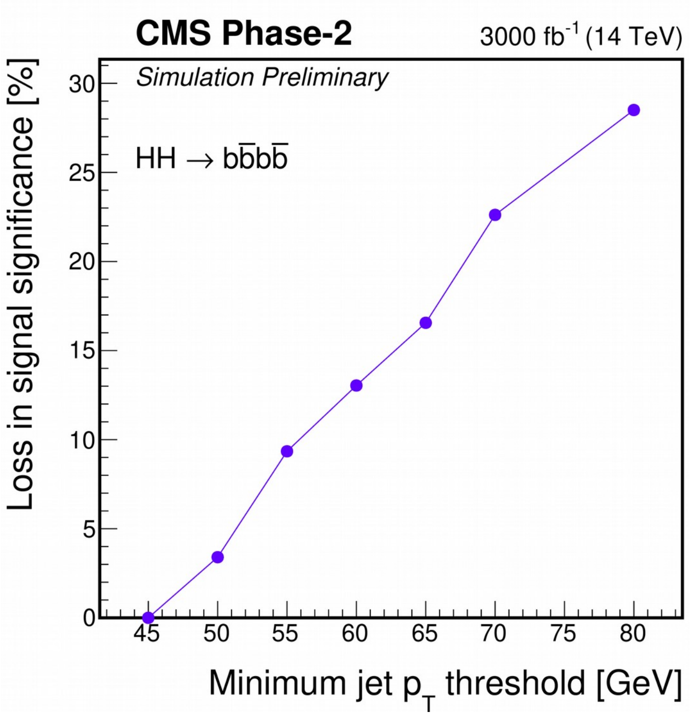
- Significance:
  1.4/0.61σ without/with syst

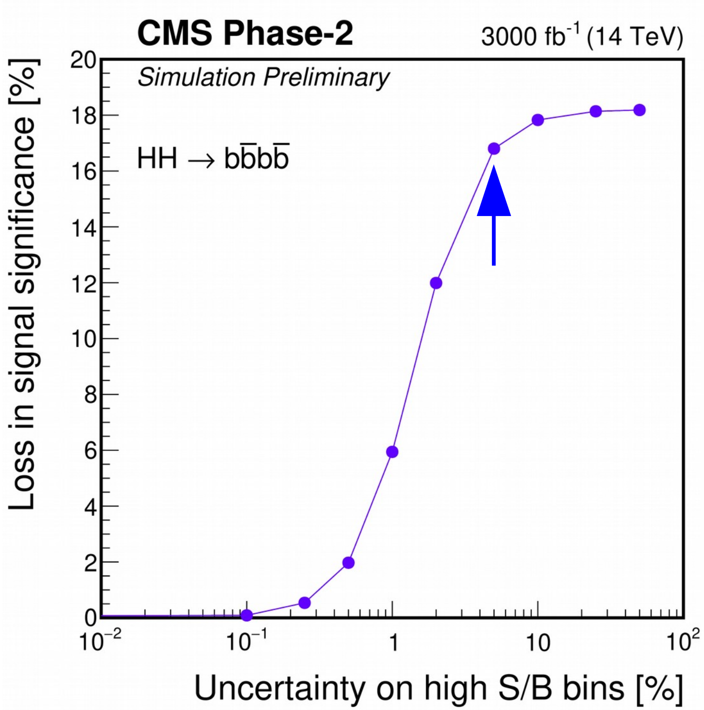
HH→$b\bar{b}b\bar{b}$ (CMS)

- 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



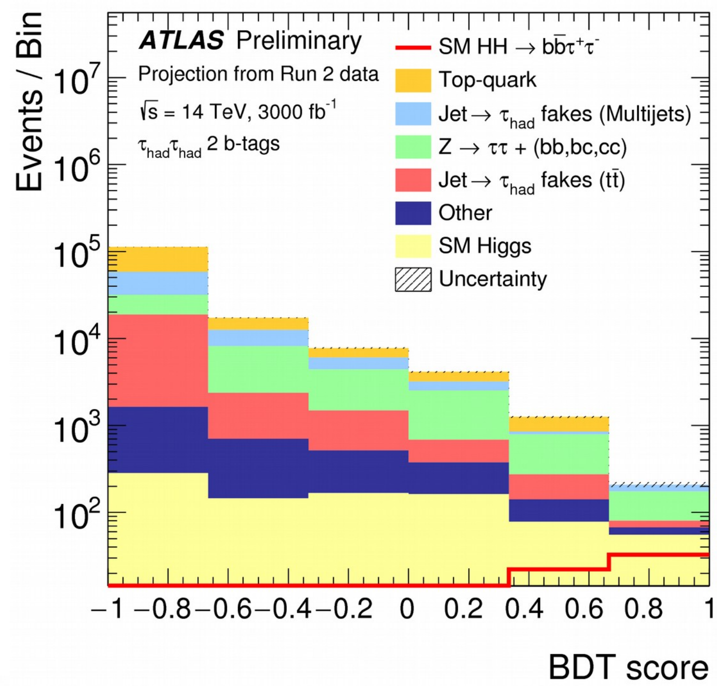
- Significance:
  1.2σ wo/syst
  0.95σ w/ syst

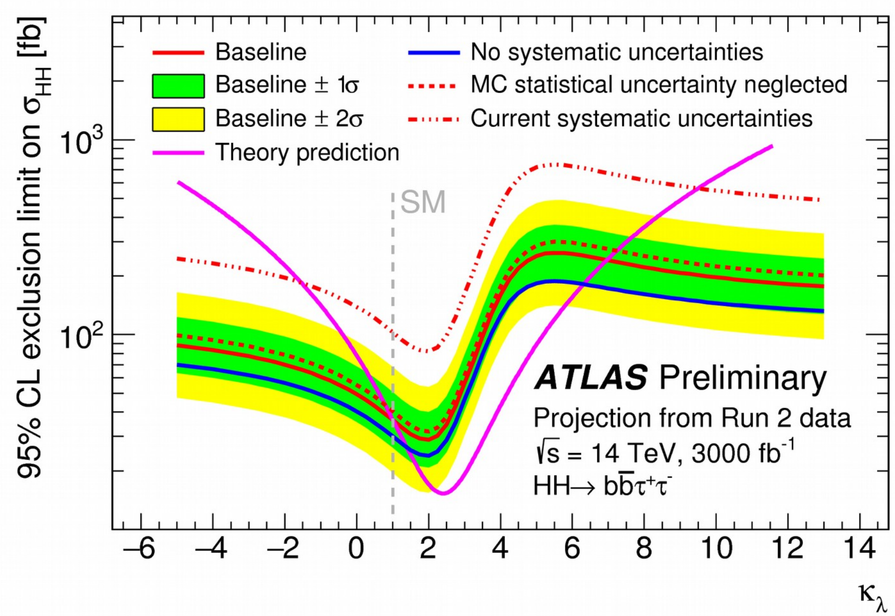




HH→$b\bar{b}\tau\tau$ (ATLAS)

- 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

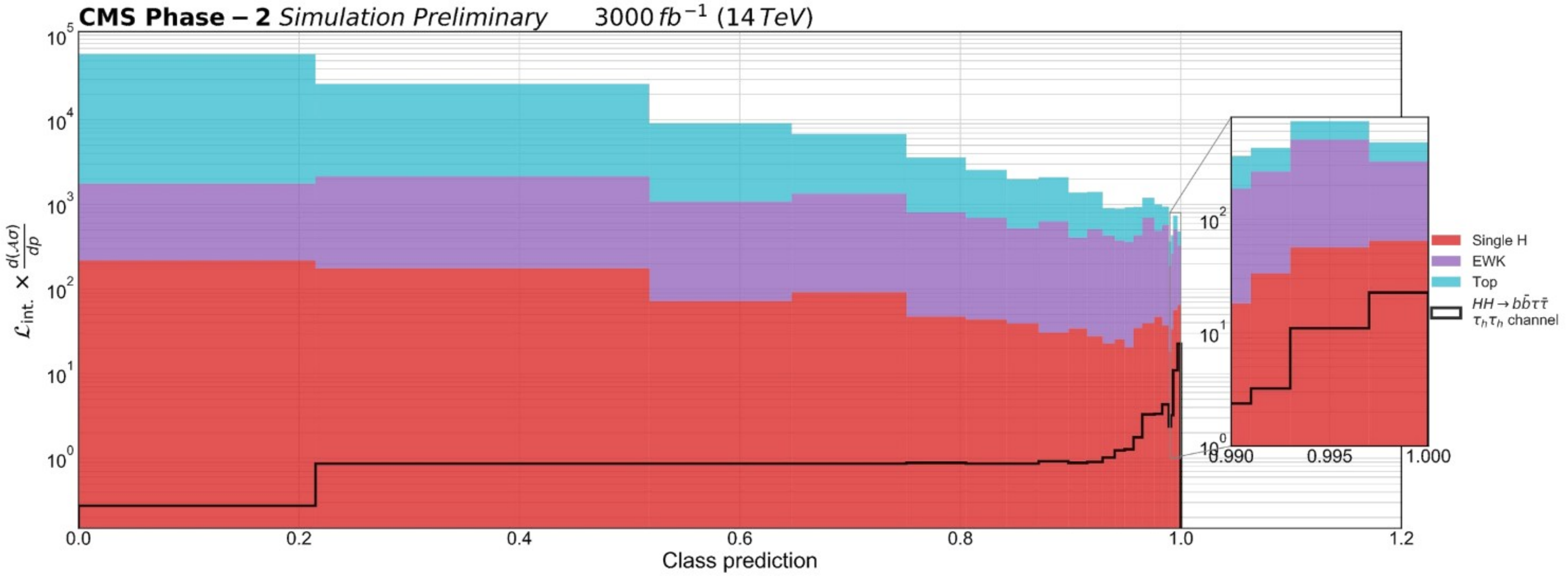




- Significance:
  2.5/2.1σ without/with syst

$HH \to b\bar{b}\tau\tau$ (CMS)

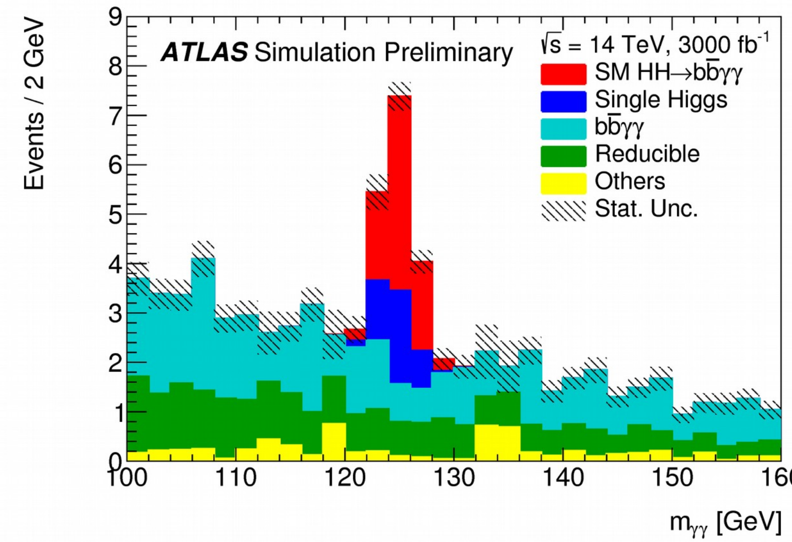
- 3 categories: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$
- Use of a neural network
  - 27 basic + 21 reconstructed + 4 global features
  - deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

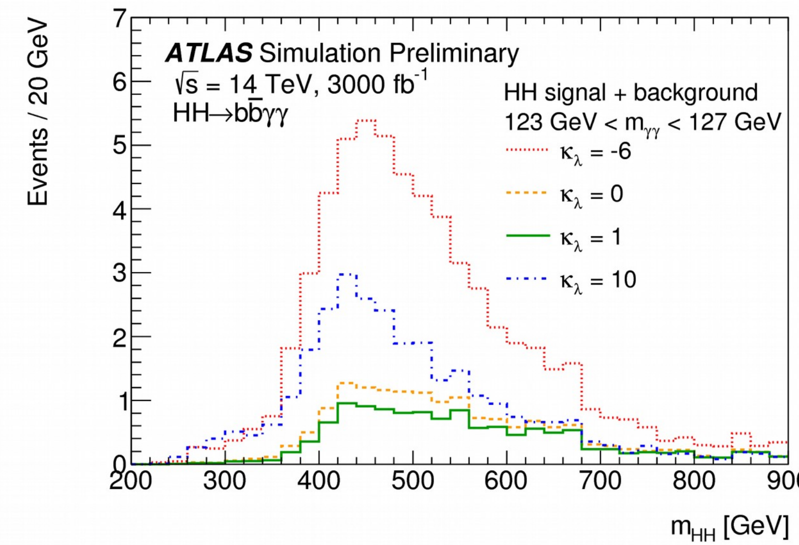


- Simultaneous fit of the NN output for the 3 decay channels
  - discriminant binned per decay channel via adaptive binning
- Significance: 1.6/1.4σ without/with syst

HH→b$\bar{b}$γγ (ATLAS)

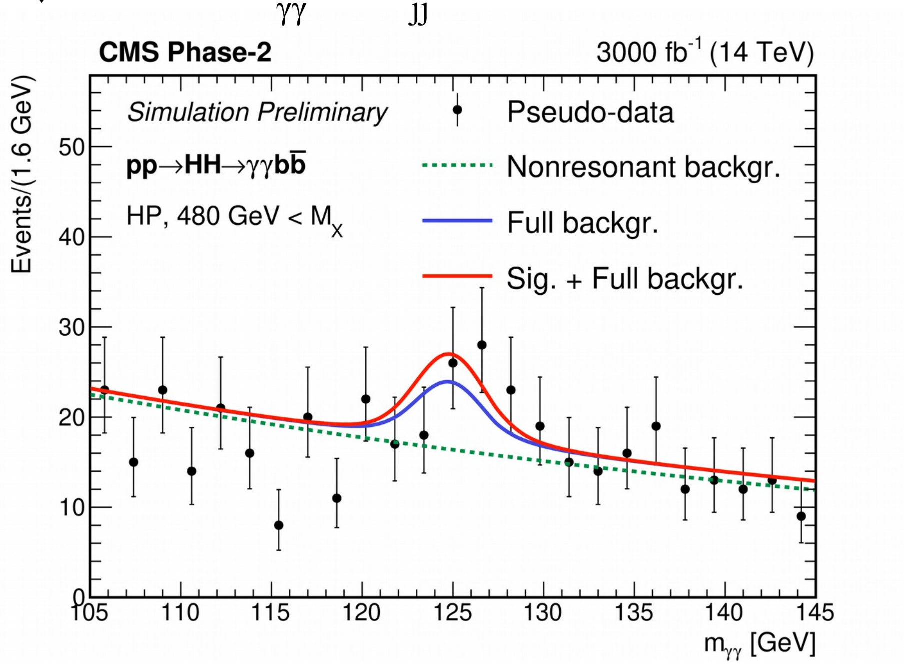
- Dedicated analysis with smearing functions: upgraded detector geometry and performance functions
  - $m_{\gamma\gamma}$ resolution ~ 1.6 GeV
- Dedicated BDT trained to remove continuum background and main single-Higgs background ($t\bar{t}H$)
- Limit on κ_λ: use of the $m_{b\bar{b}\gamma\gamma}$ distribution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

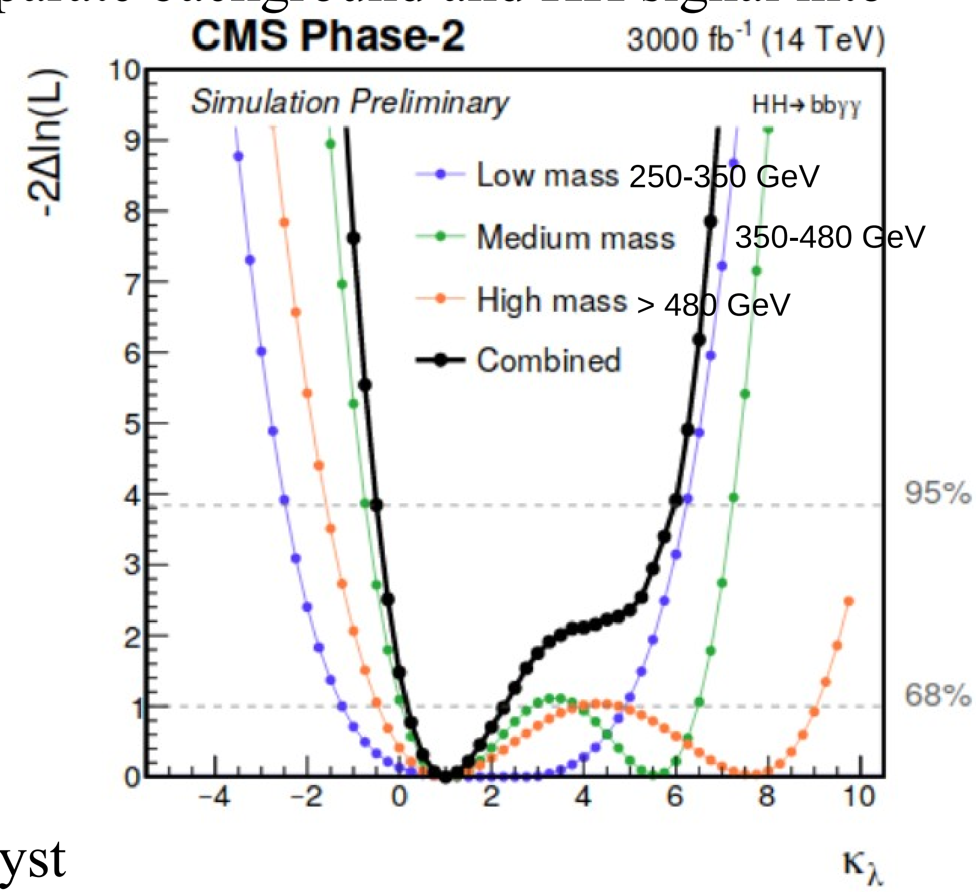




HH→$b\bar{b}\gamma\gamma$ (CMS)

- 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}

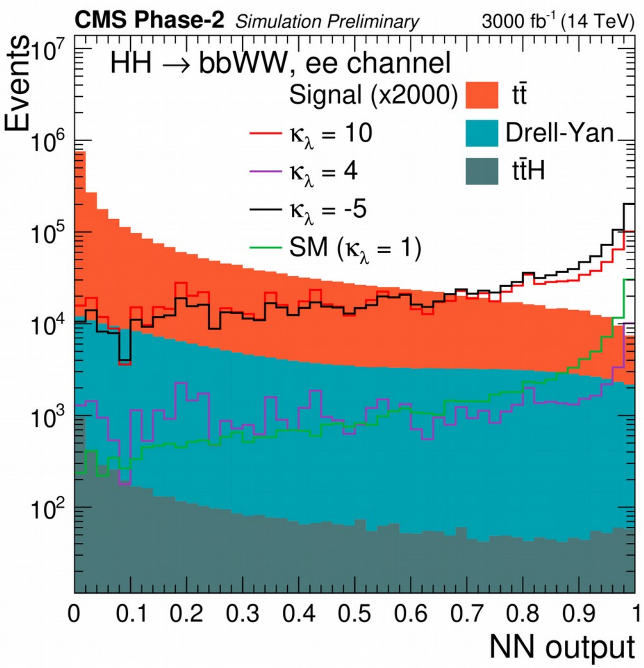


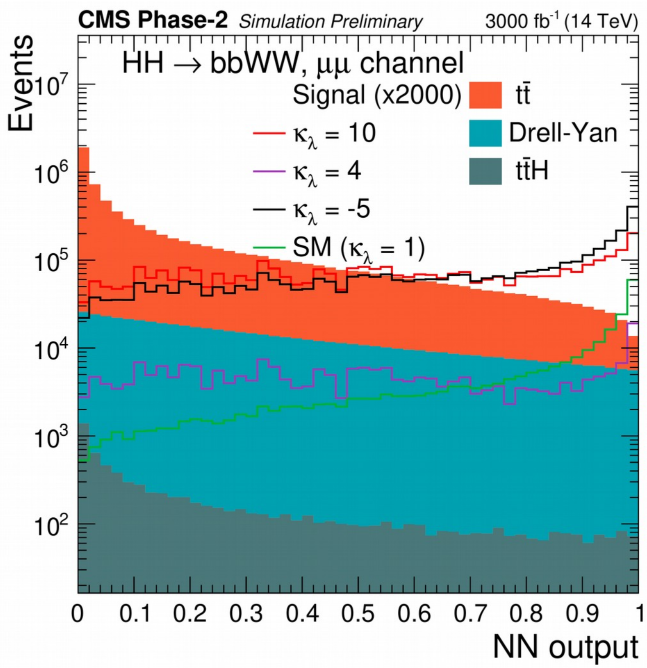


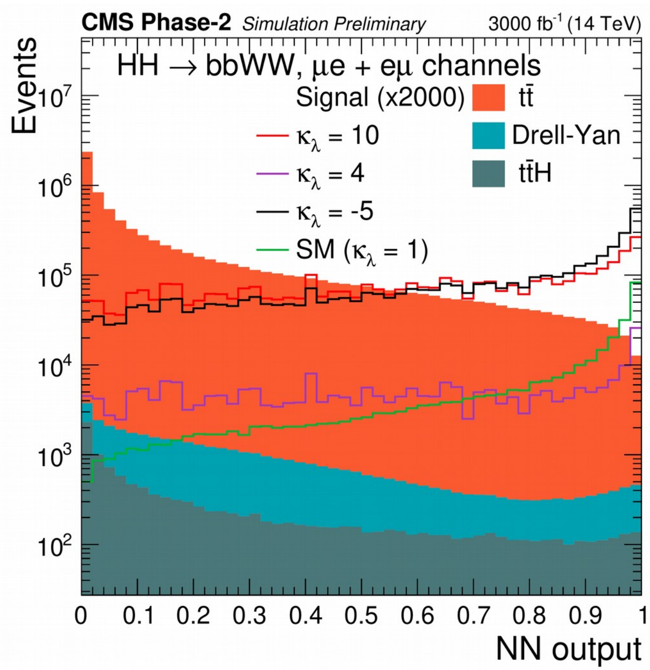
- Significance: 1.8/1.8σ without/with syst
  - difference with ATLAS partly due to $m_{\gamma\gamma}$ resolution

HH→b$\bar{b}$VV(lνlν), 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)



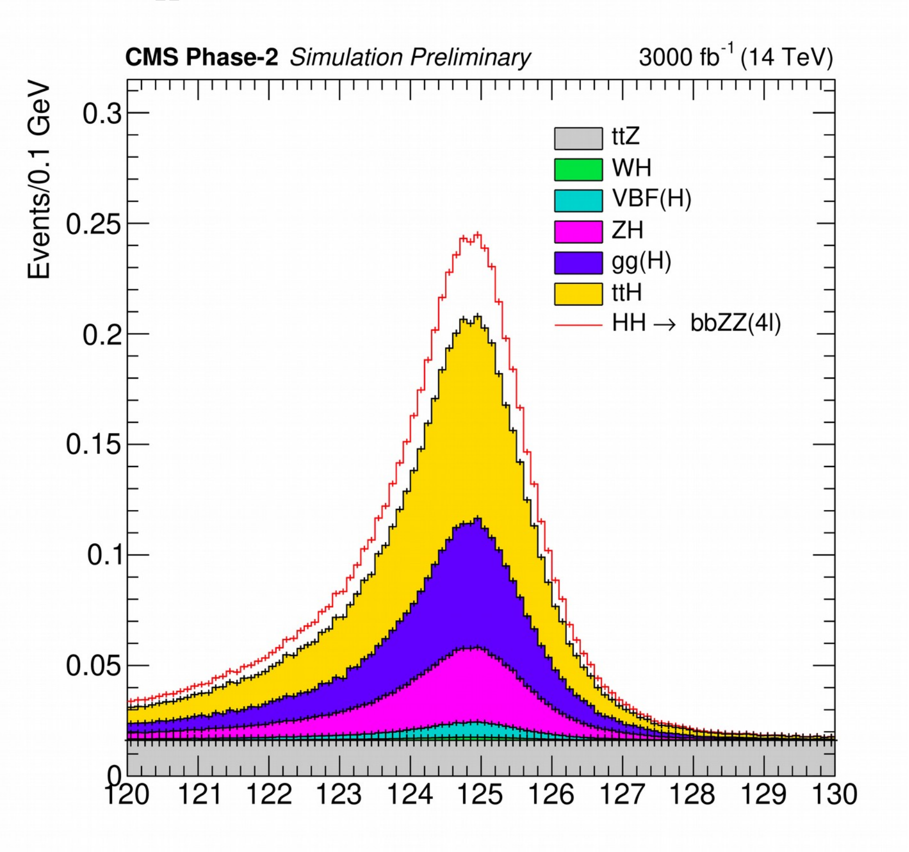




- Results: 0.6σ significance

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 $m_{4\ell}$ compatible with m_H
- Counting experiment with events around m_H

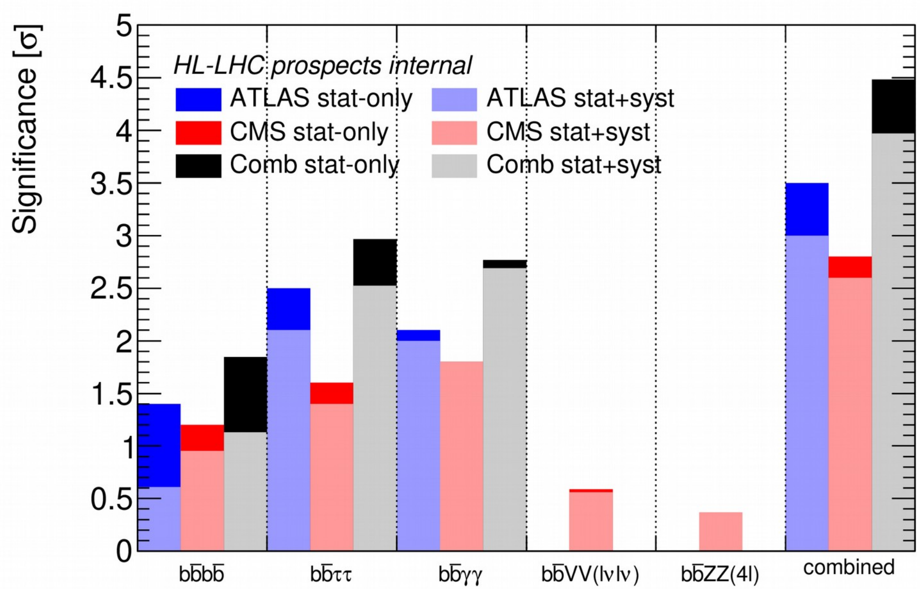


- ~1 signal event after selection
  - S/B ~0.1
- Results: 0.4σ significance

HL-LHC results (1)

- Combined values channel-by-channel
  - no correlation considered (shown to have negligible impact)
  - systematic uncertainties included
  - $b\bar{b}VV(l\nu l\nu)$ and $b\bar{b}ZZ(4l)$ are CMS only ⇒ scaled to 6000 fb^{-1}
- 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!

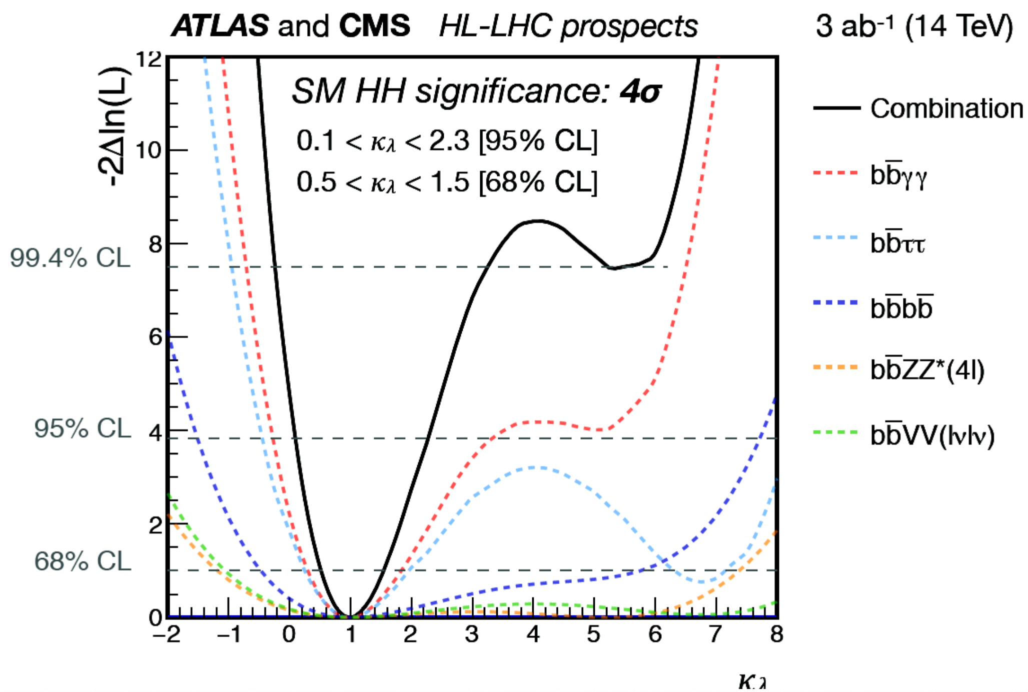
- Measurement of μ (SM signal injected):
  - ~25% (30%) without (with) systematics
  - μ = 0 (no SM HH signal) excluded at 95% CL

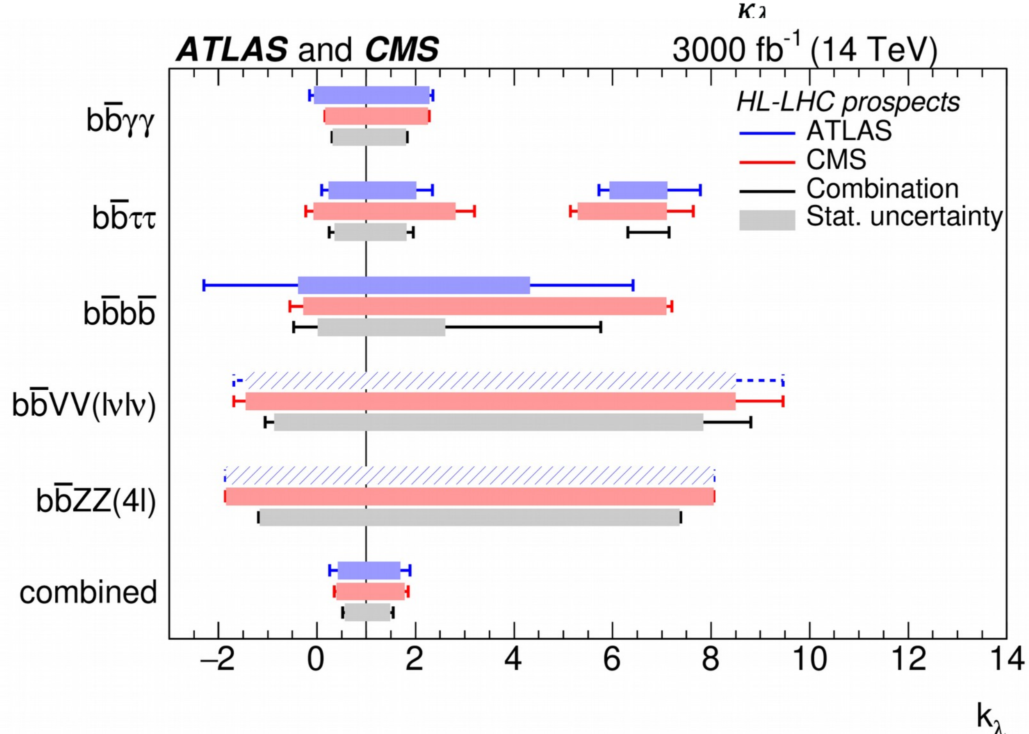
HL-LHC results (2)

- Measurement of κ_λ:

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

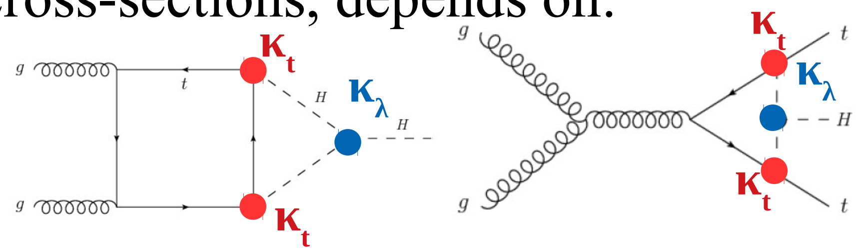
- Summary/channel:



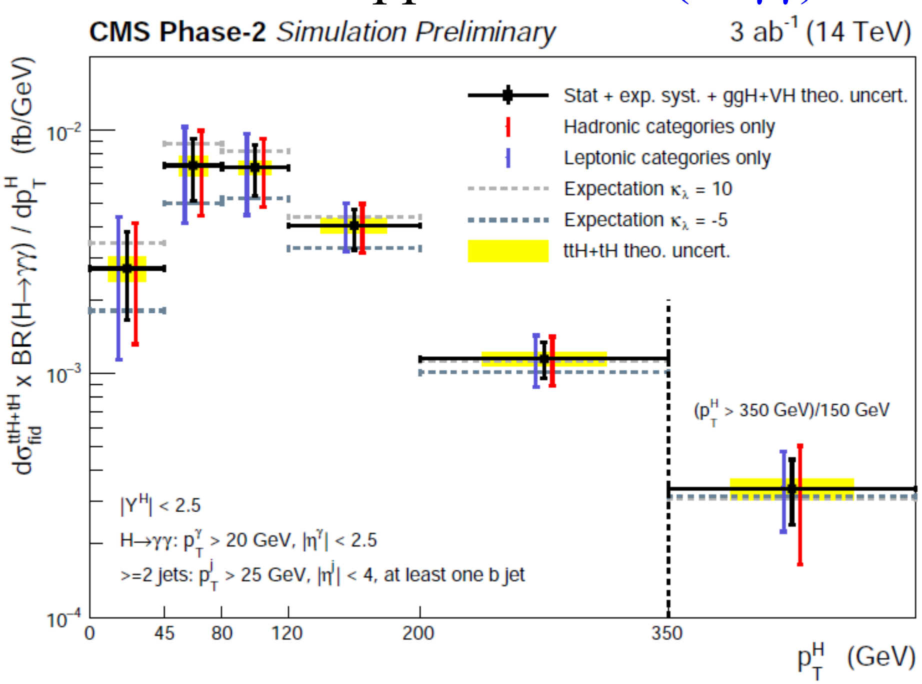


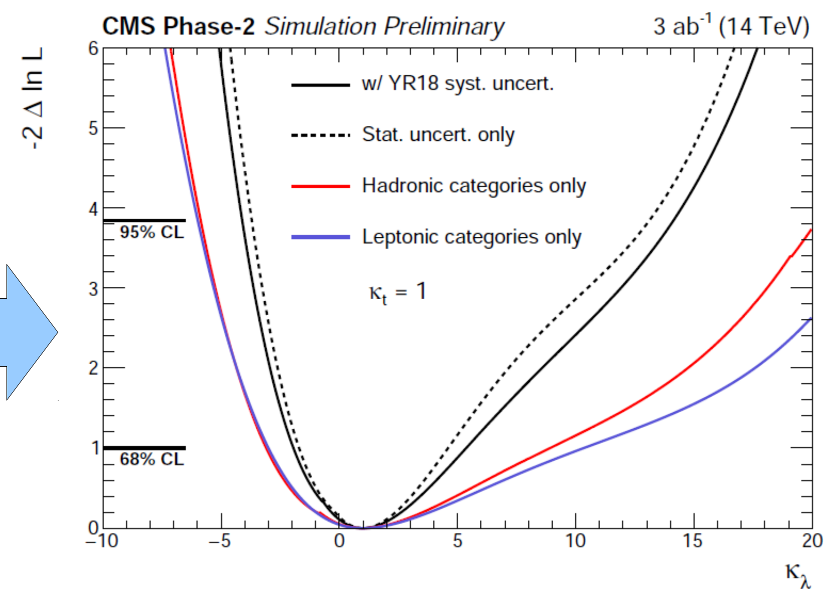
Indirect probes via single-Higgs (1)

- Single-Higgs production: Higgs self-interaction only via one-loop corrections (ie two loop-level for ggF)
- κ_λ-dependent corrections to the tree-level cross-sections, depends on:
  - production mode → mainly $t\bar{t}H$, tH, VH
  - kinematic properties of the event



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

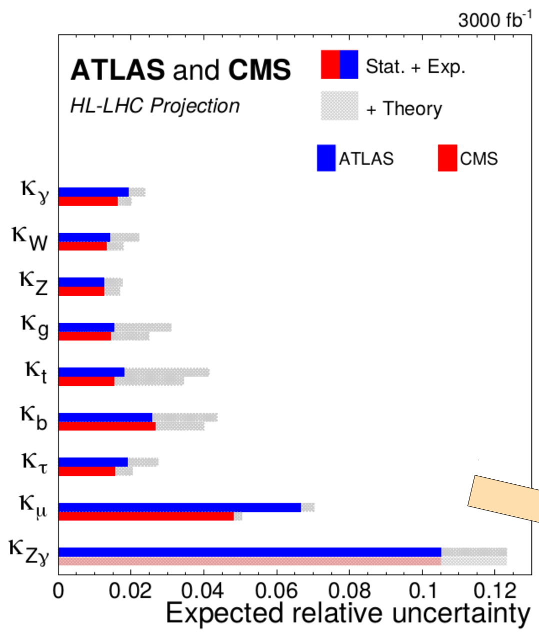


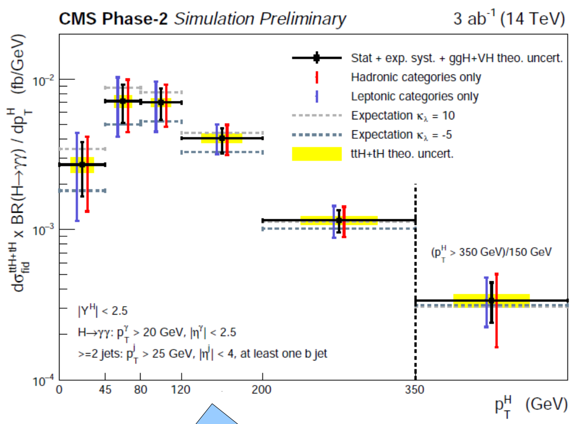


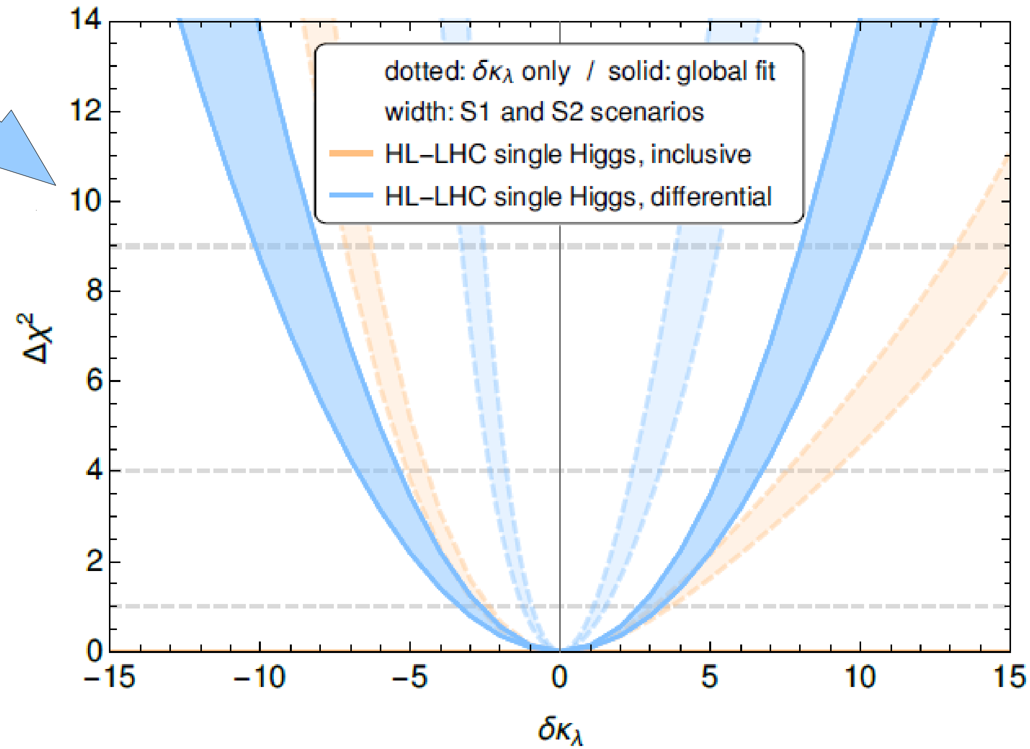
- First test with experimental “data”, more channels to be added

Indirect probes via single-Higgs (2)

- Global fit of $t\bar{t}H$ differential distribution + single-Higgs couplings



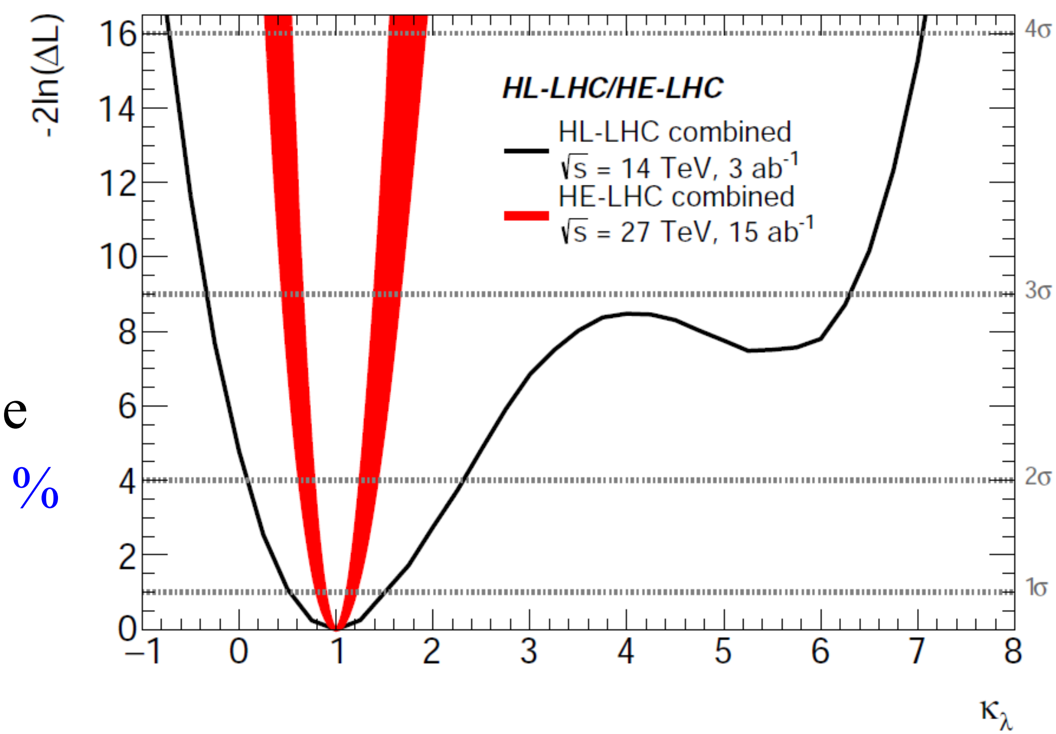




- Results:
  - dotted = only κ_λ varied
  - solid = global fit (EFT framework)
  - band = scenarios for systematics

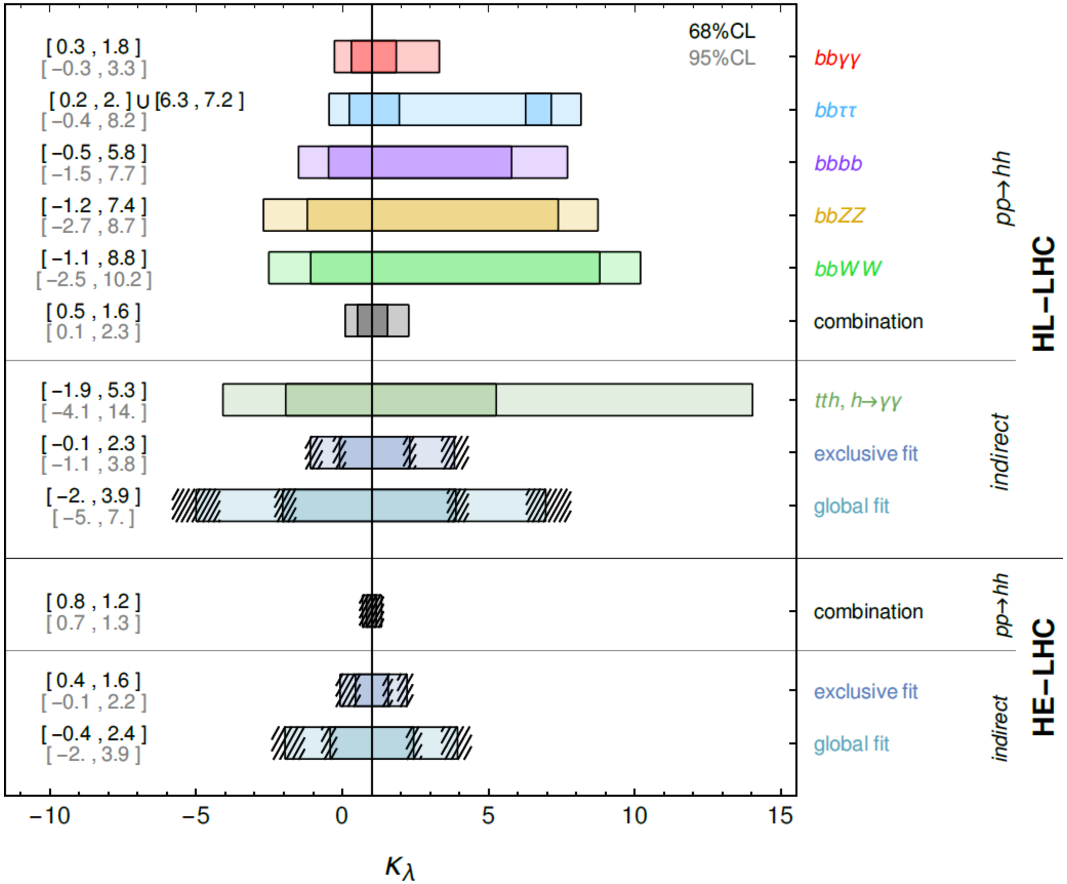
HE-LHC, HH measurements

- Extrapolation of ATLAS HL-LHC results to HE-LHC
  - 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 %



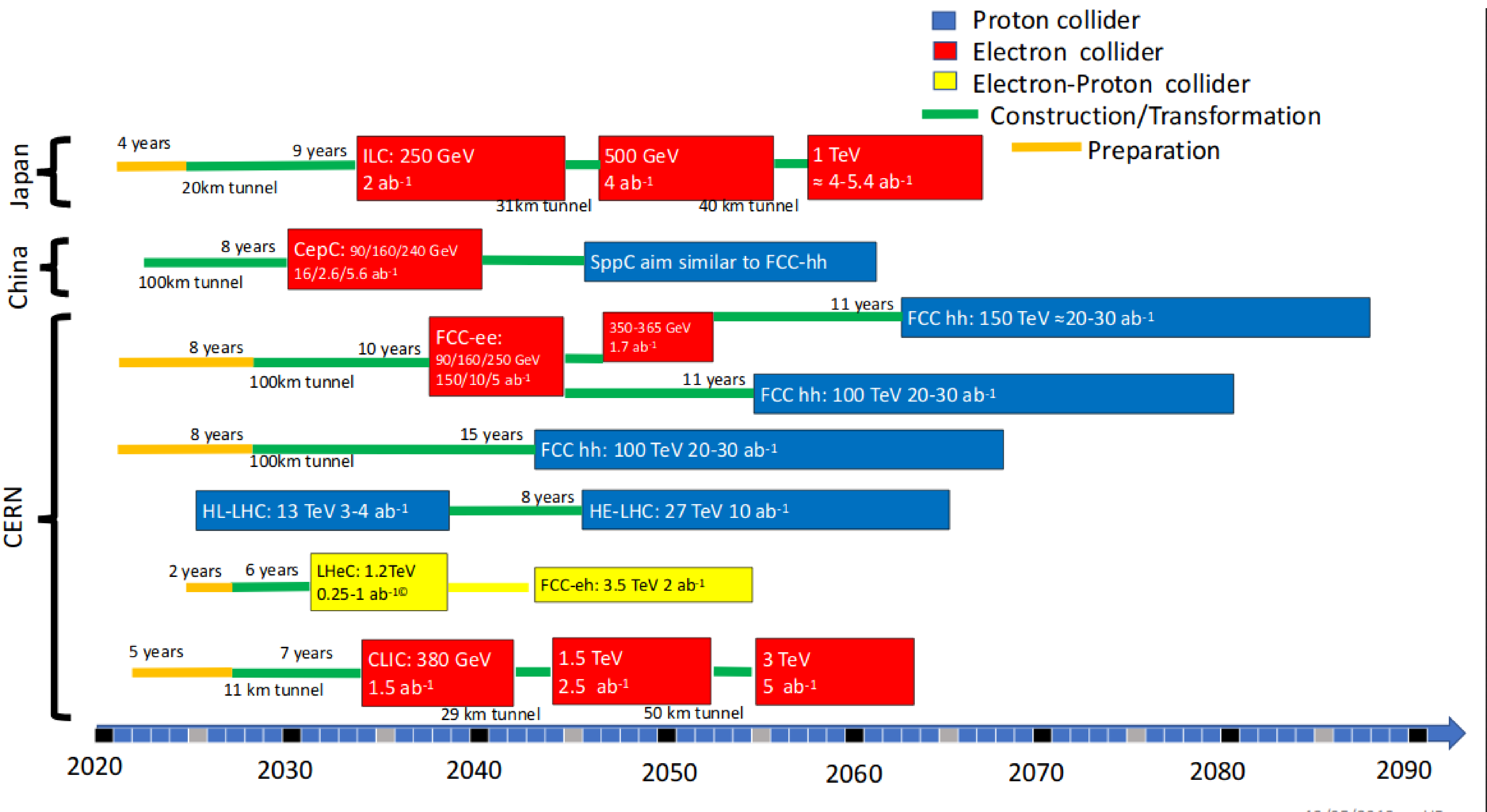
Conclusions for HL-LHC

- State-of-the-art computations of the cross-sections and m_{HH} available
- State-of-the art experimental studies on direct measurements
  - coherent results by ATLAS and CMS
  - went from ~2σ last year to a combined significance of 4σ!
    - first real measurements possible, eg precision on κ_λ: 50%
  - much room for improvement
- Nice developments on indirect constrains
  - single-Higgs differential cross-sections, global fits
- Estimates of sensitivity at HE-LHC
- YR on arxiv: 1902.00134



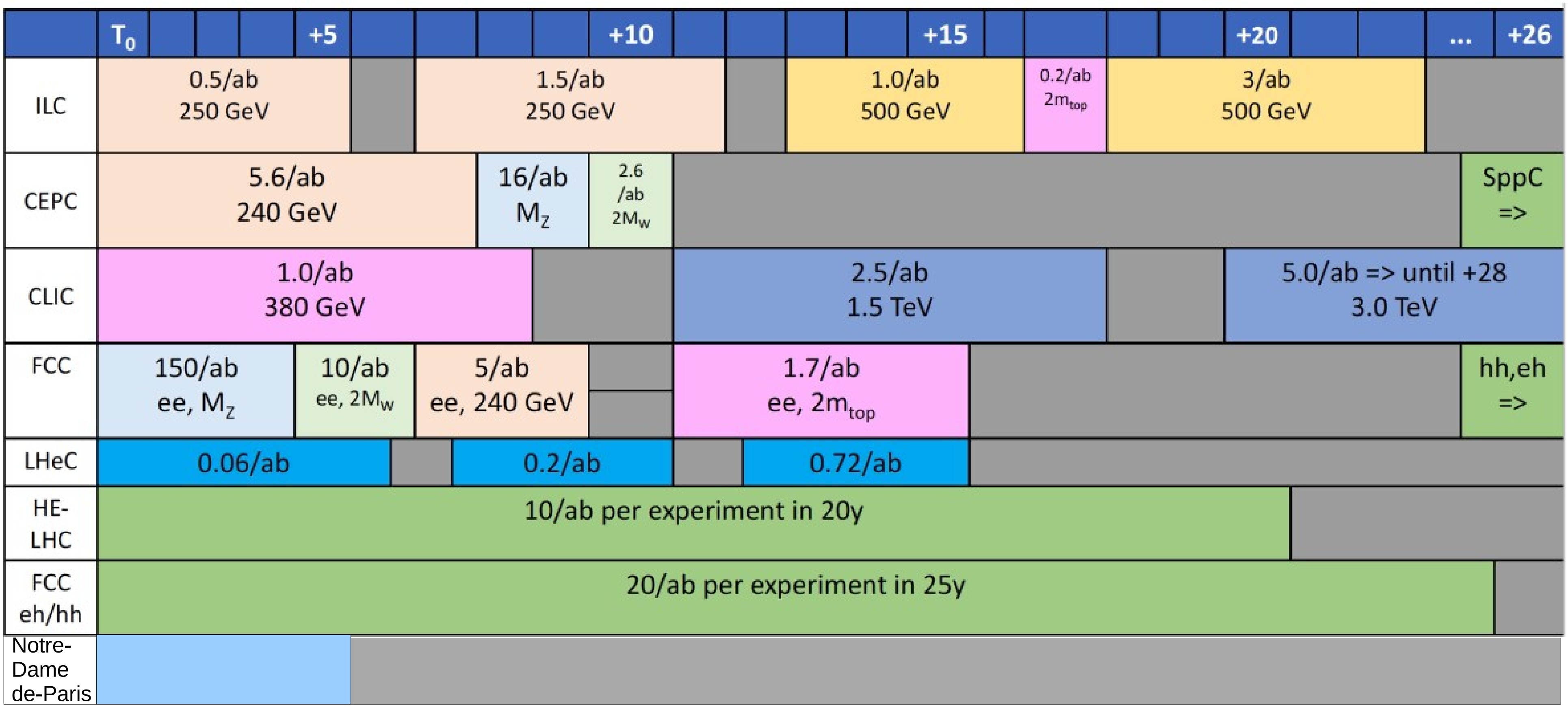
Future colliders propects

Possible scenarios for Future Colliders



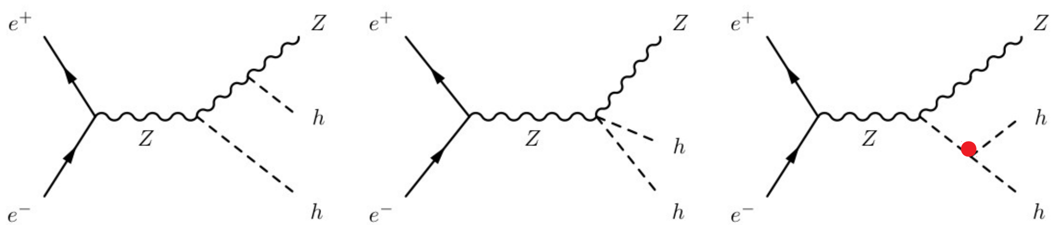
Timeline for Future Colliders

- Centre-of-mass energy and integrated luminosity:

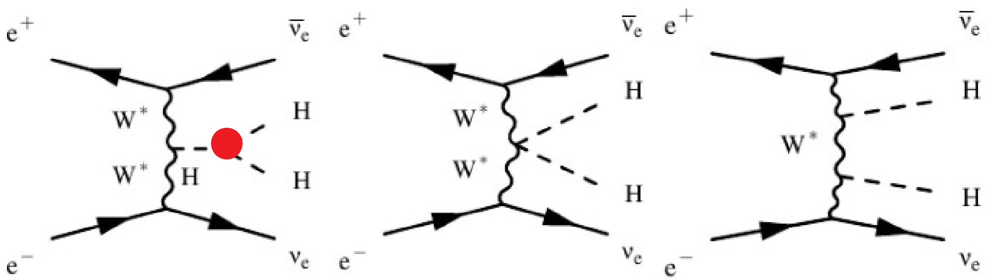


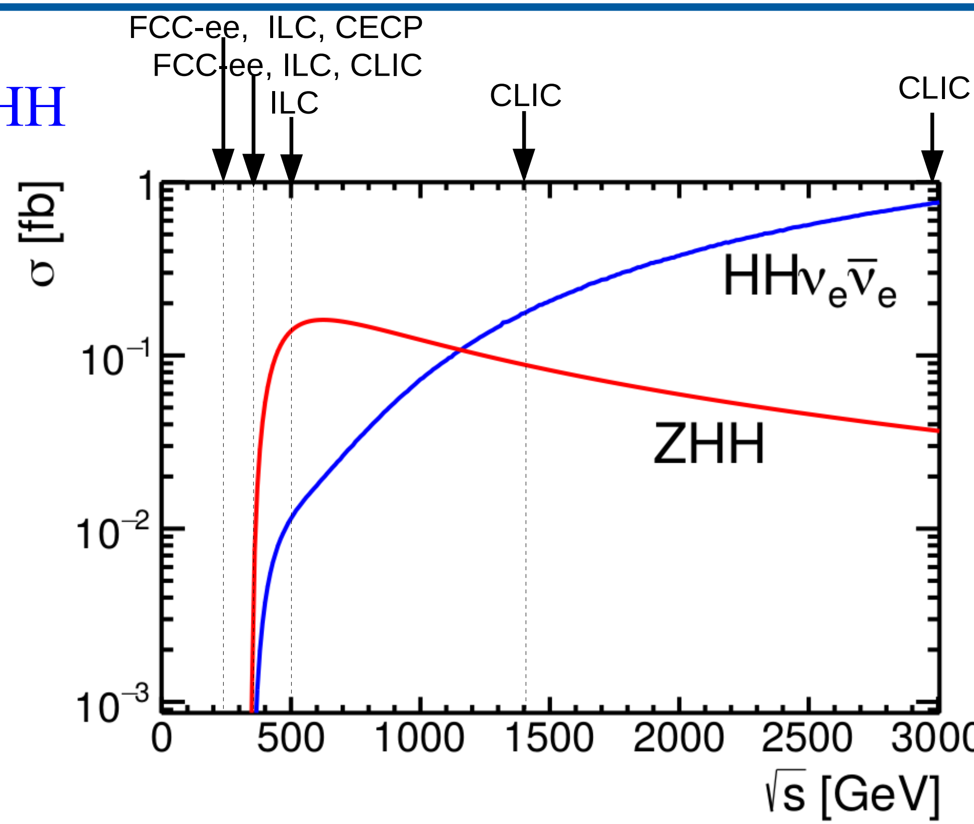
Di-Higgs production: ee colliders

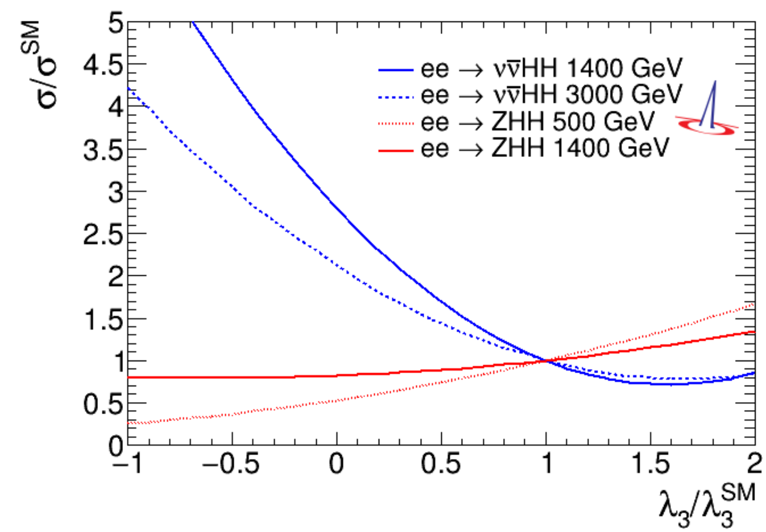
- Main production modes: ZHH and $\nu\bar{\nu}$HH
  - ZHH



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



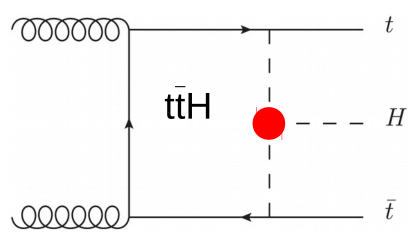


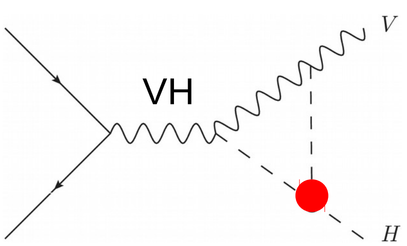


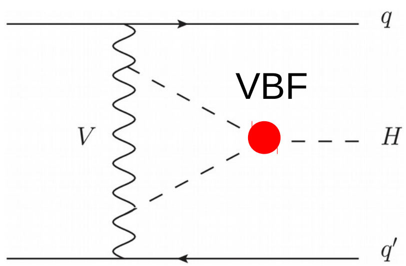
- Self-couplings through HH cross-section at different $\sqrt{s}$ + production modes + m_{HH}
- ZHH stronger constraints for $\kappa_\lambda > 1$
- $\nu\bar{\nu}$HH stronger constraints for $\kappa_\lambda < 1$

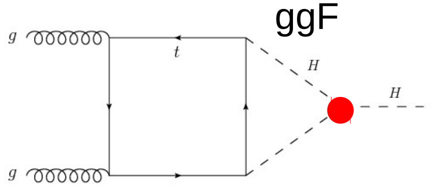
Single-Higgs couplings

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

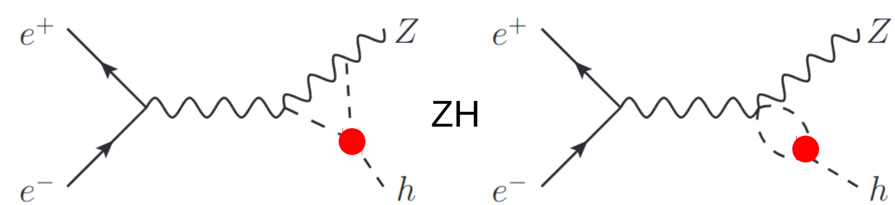


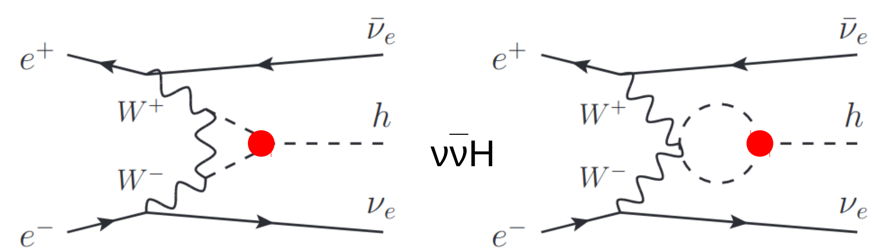






- ee colliders:
  - important for FC below HH production threshold (~400 GeV)





- ex. for $\kappa_\lambda = 2$:
  - $\sigma(pp \to t\bar{t}H)$ modified by 3%
  - $\sigma(ee \to ZH)$ modified by 1%
- More global view: effective field theory ($SMEFT_{ND}$)

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

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.

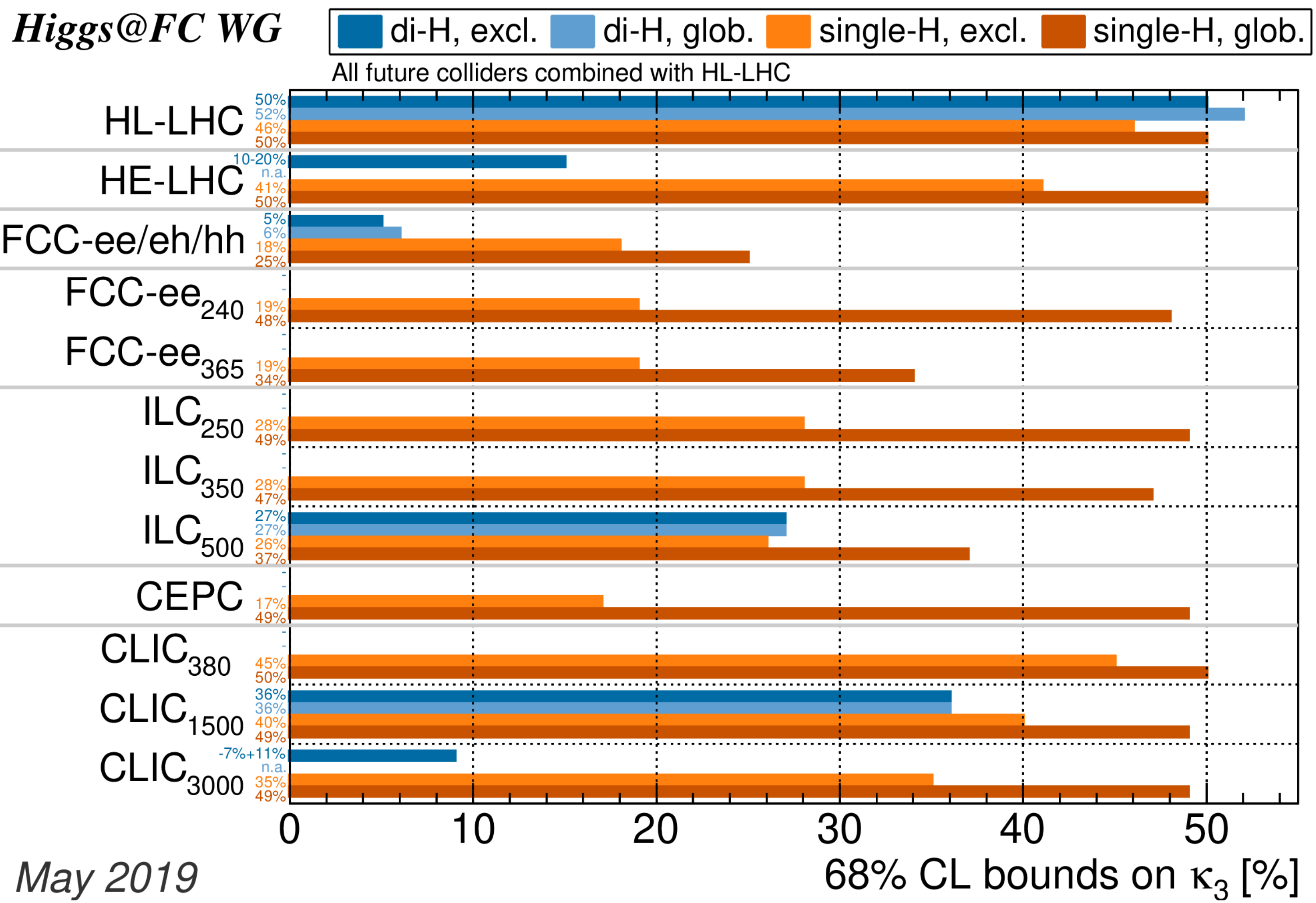
- Summary of inputs:

		√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)

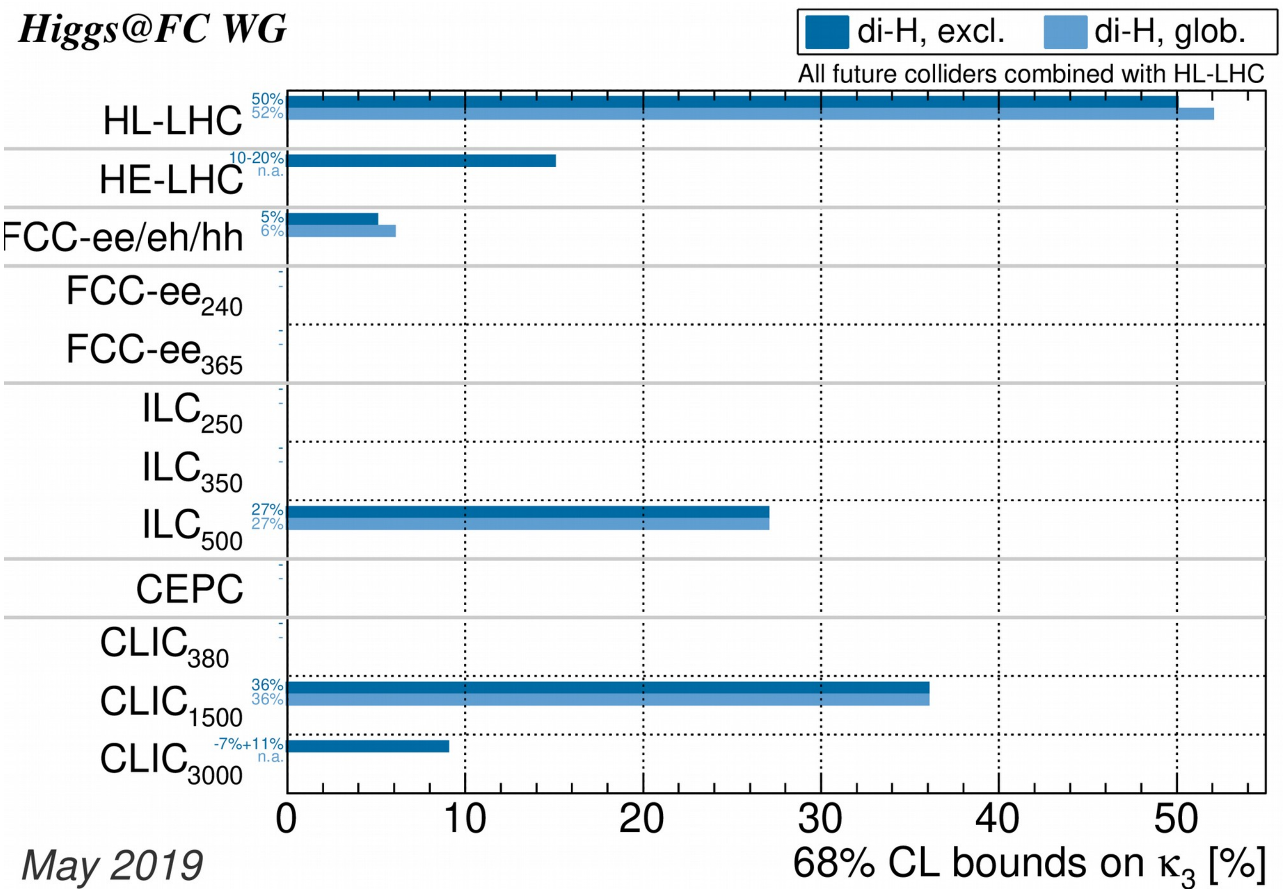
Results: global view

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



Results: using di-Higgs production

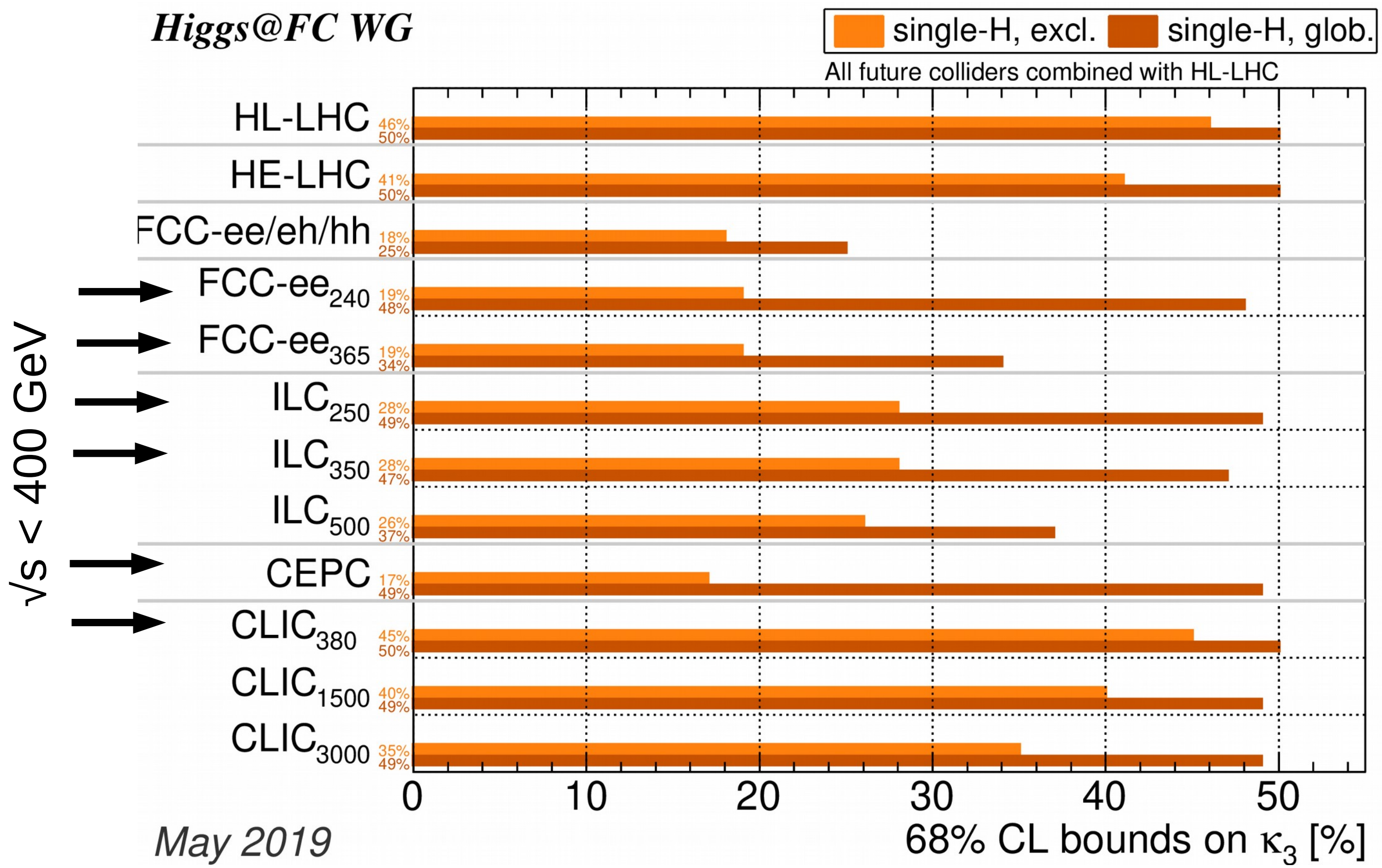
- 68% CL uncertainties on κ_λ:



- 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

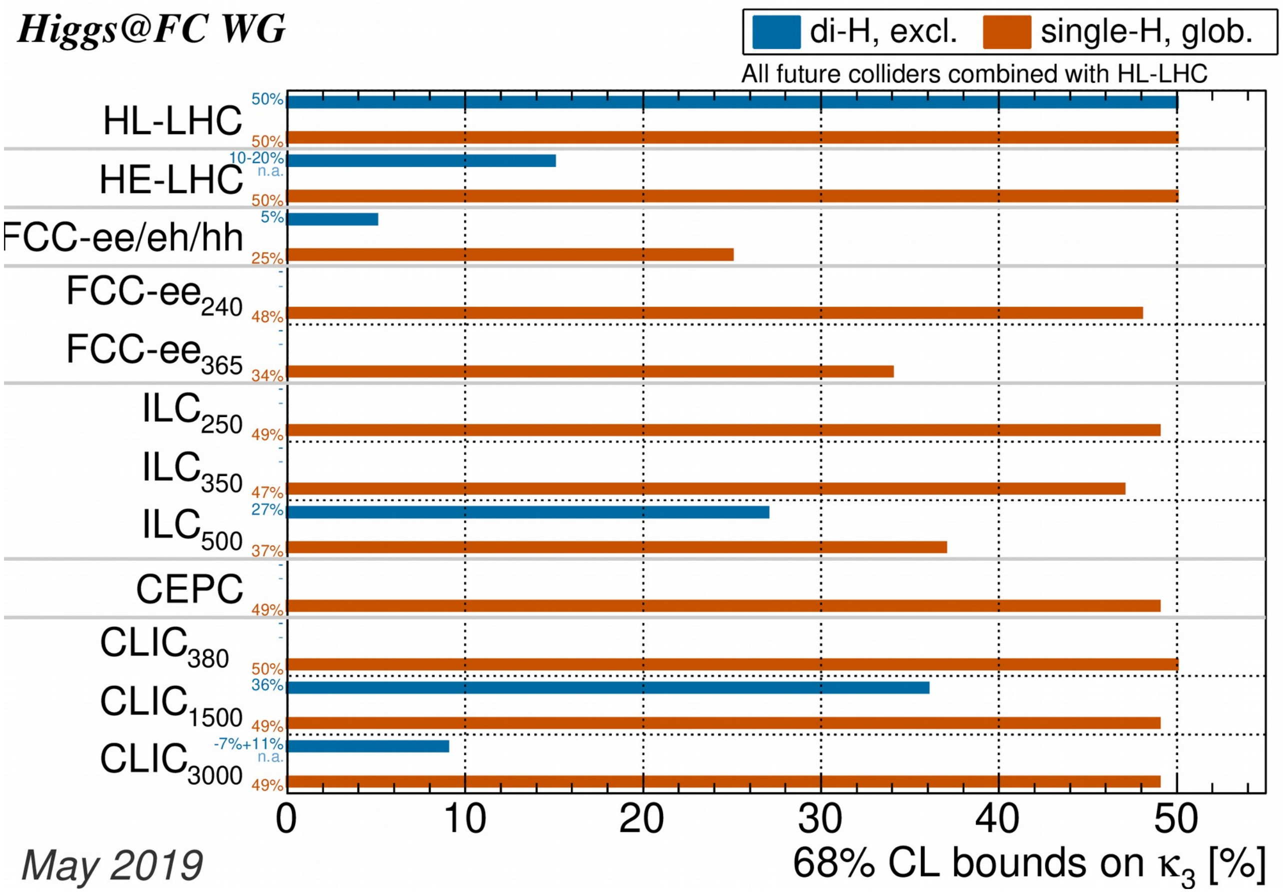
- 68% CL uncertainties on κ_λ:



- 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 for Future Colliders

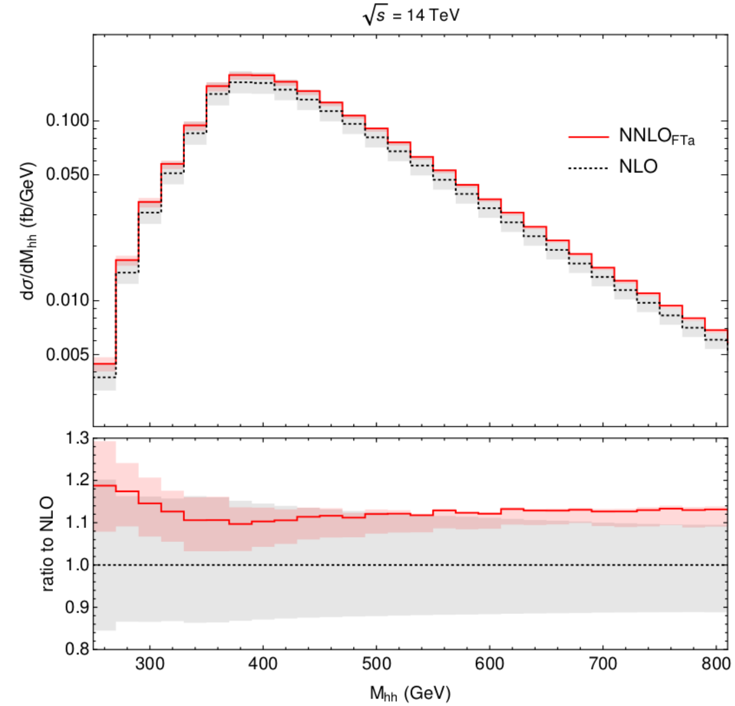
- State of the art prospective measurement of the tri-linear coupling at Future Colliders through the HH and single-Higgs production
- HL-LHC: 4σ evidence of the HH process + 50% uncertainty on κ_λ
- Sensitivity from Future Colliders and combination with HL-LHC
  - possible to establish the existence 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

HH production cross-section (1)

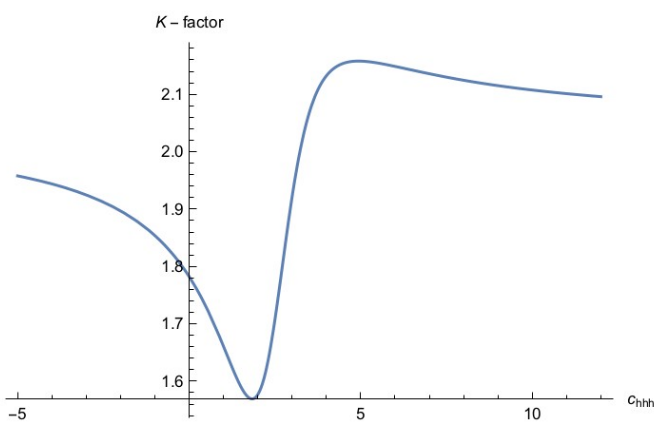
$\sqrt{s}$ [TeV]	NNLO_{FTa} [fb]	m_t unc.	PDF unc.	α_S unc.	PDF+α_S unc.
14	$36.69^{+2.1\%}_{-4.9\%}$	$\pm 2.7\%$	$\pm 2.1\%$	$\pm 2.1\%$	$\pm 3.0\%$
27	$139.9^{+1.3\%}_{-3.9\%}$	$\pm 3.4\%$	$\pm 1.7\%$	$\pm 1.8\%$	$\pm 2.5\%$

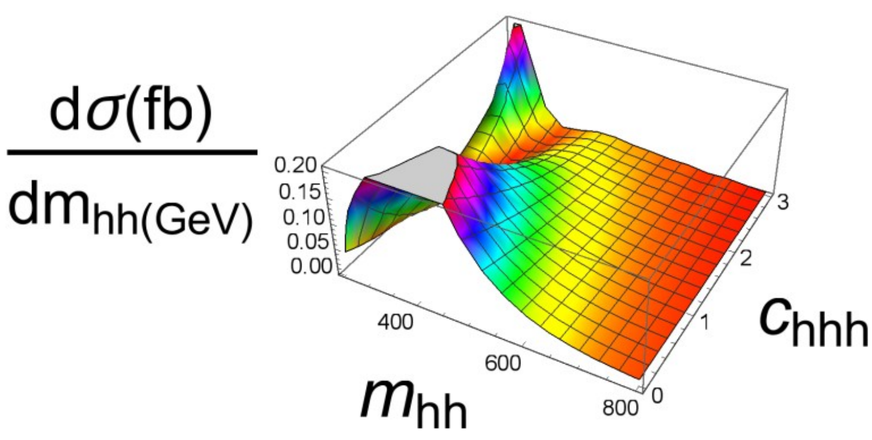
- SM calculation
  - ggF: state of the art NNLO calculation with finite m_t effects at NLO
    - -8% wrt YR4, used in previous projections
  - other production modes: NLO with full m_t-dependence



$\sqrt{s}$ (TeV)	ZHH	WHH	VBF HH	$ttHH$	$tjHH$
14	$0.359^{+1.9\%}_{-1.3\%} \pm 1.7\%$	$0.573^{+2.0\%}_{-1.4\%} \pm 1.9\%$	$1.95^{+1.1\%}_{-1.5\%} \pm 2.0\%$	$0.948^{+3.9\%}_{-13.5\%} \pm 3.2\%$	$0.0383^{+5.2\%}_{-3.3\%} \pm 4.7\%$
27	$0.963^{+2.1\%}_{-2.3\%} \pm 1.5\%$	$1.48^{+2.3\%}_{-2.5\%} \pm 1.7\%$	$8.21^{+1.1\%}_{-0.7\%} \pm 1.8\%$	$5.27^{+2.0\%}_{-3.7\%} \pm 2.5\%$	$0.254^{+3.8\%}_{-2.8\%} \pm 3.6\%$

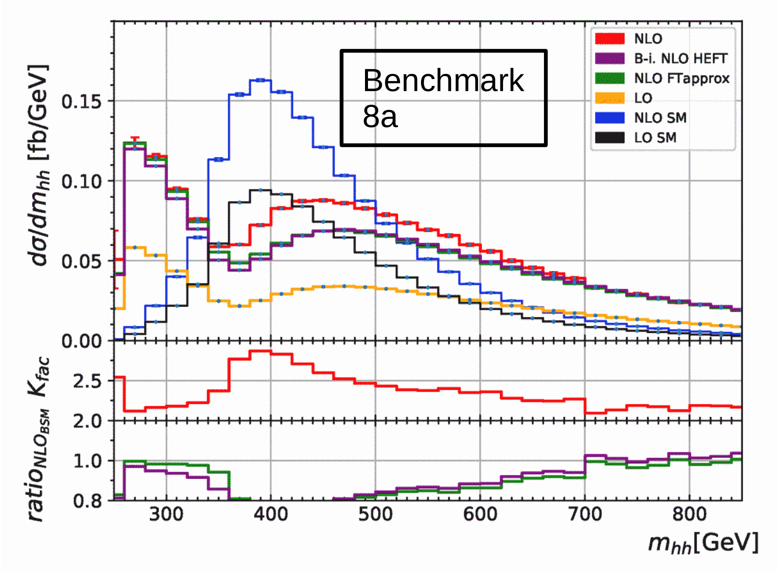
- Higgs self-coupling variations with full m_t-dependence at NLO
  - LO to NLO K-factors vary from 1.6 to 2.2!
  - m_{HH} differential cross-sections

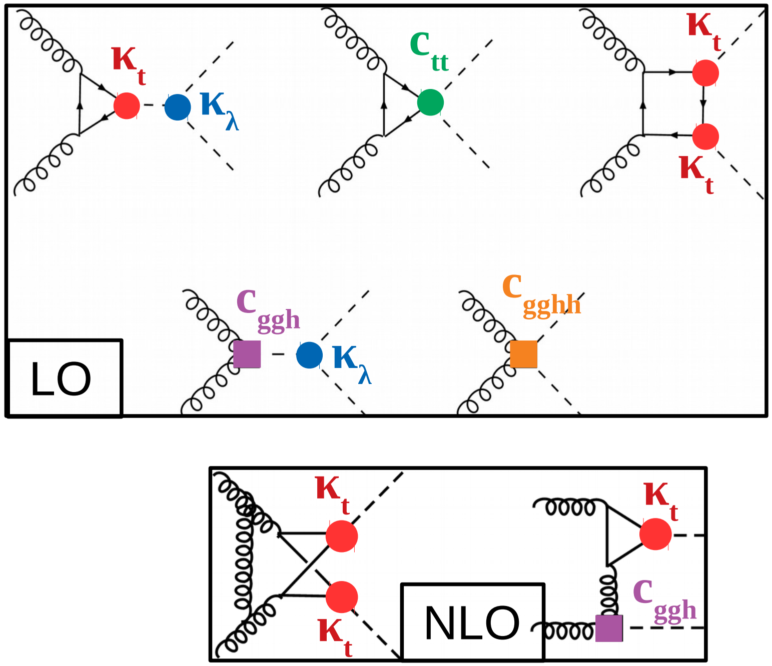




HH production cross-section (2)

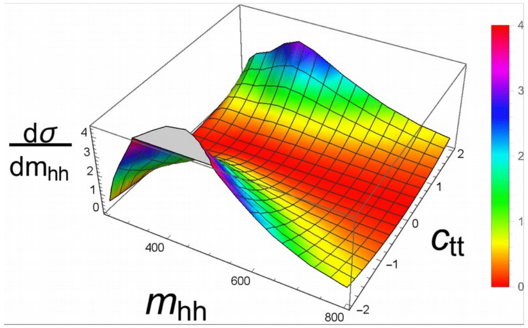
- BSM model: Non-linear EFT
- Cross-sections and m_{HH} at NLO QCD for some selected benchmark points





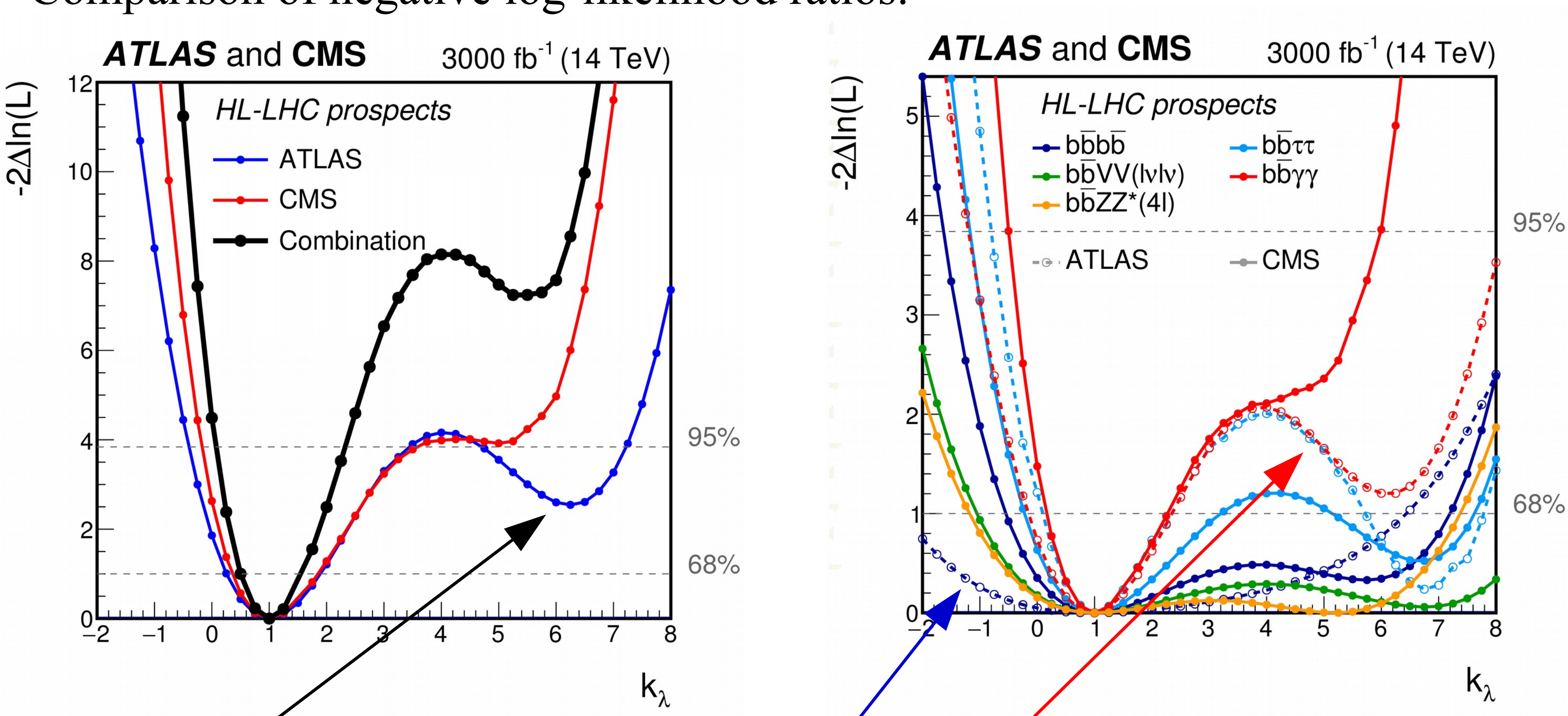
Benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
5a	1	1	0	2/15	4/15
6	2.4	1	0	2/15	1/15
7	5	1	0	2/15	1/15
8a	1	1	1/2	4/15	0
SM	1	1	0	0	0

- Available data files to reconstruct the full NLO result for any values of the 5 modifying parameters



Combined results (ATLAS+CMS)

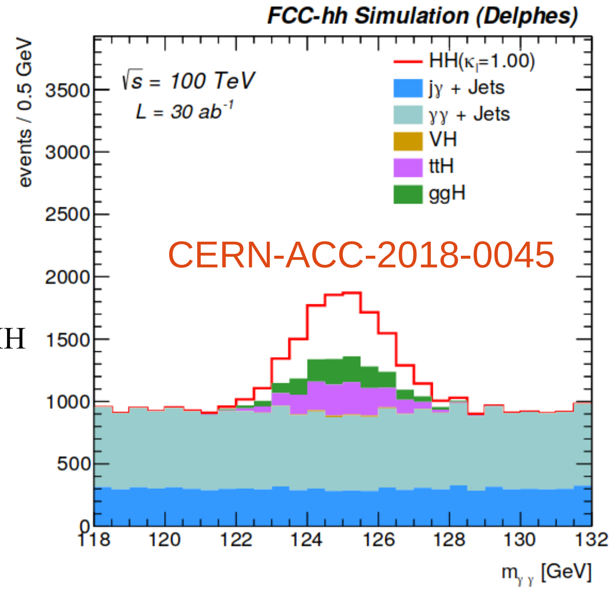
- Comparison of negative log-likelihood ratios:

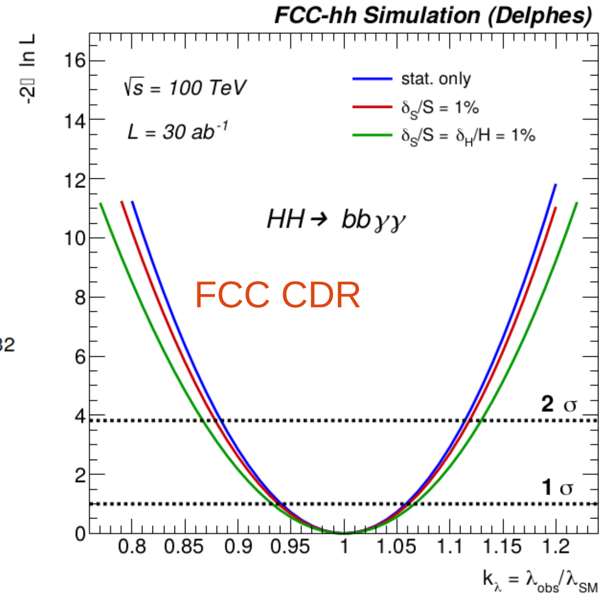


- Difference on 2nd minimum mainly from the $b\bar{b}\gamma\gamma$ channel: 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6 (while this low-m_{HH} category has no effect around 1)
- CMS slightly better below 1: $b\bar{b}b\bar{b}$ + other smaller channels

FCC-hh, HH measurement

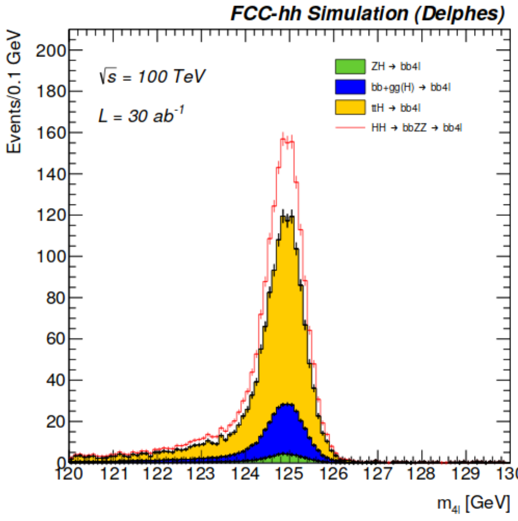
- Method (1)
- Main channel : $b\bar{b}\gamma\gamma$
  - Delphes simulation
  - 2D likelihood fit of $m_{\gamma\gamma}$ vs m_{HH}
  - scenarios with varying
    - photon efficiency
    - $m_{\gamma\gamma}$ resolution
    - background level
    - small effect (1-2%)
  - ⇒ 5-7% uncertainty on κ_λ





- Other channels:

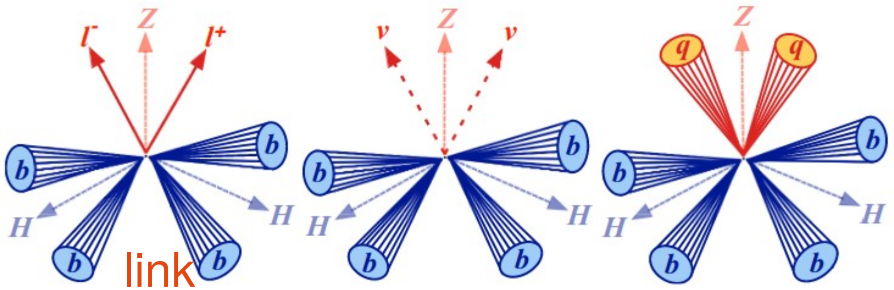
	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\to 4\ell]$	$b\bar{b}WW^*[\to 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

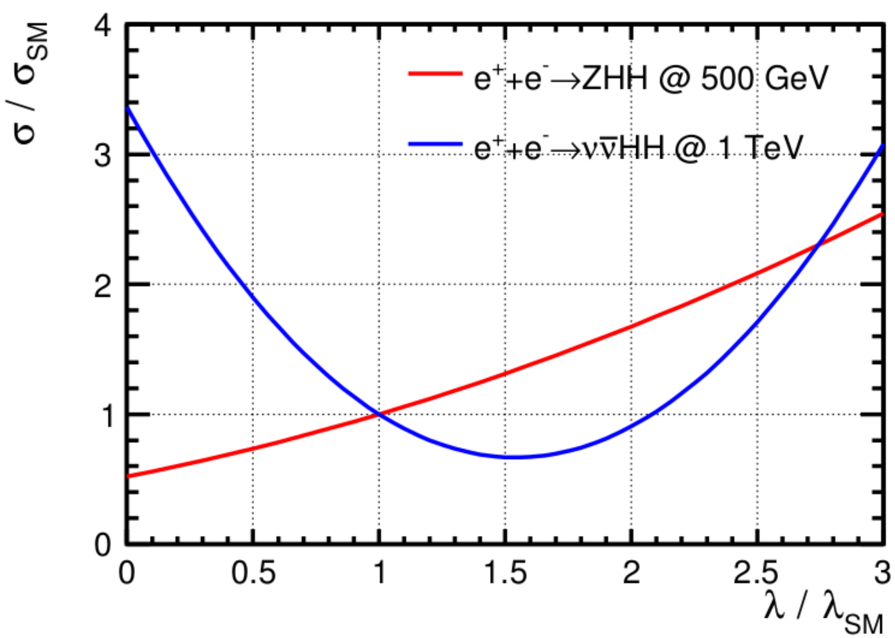


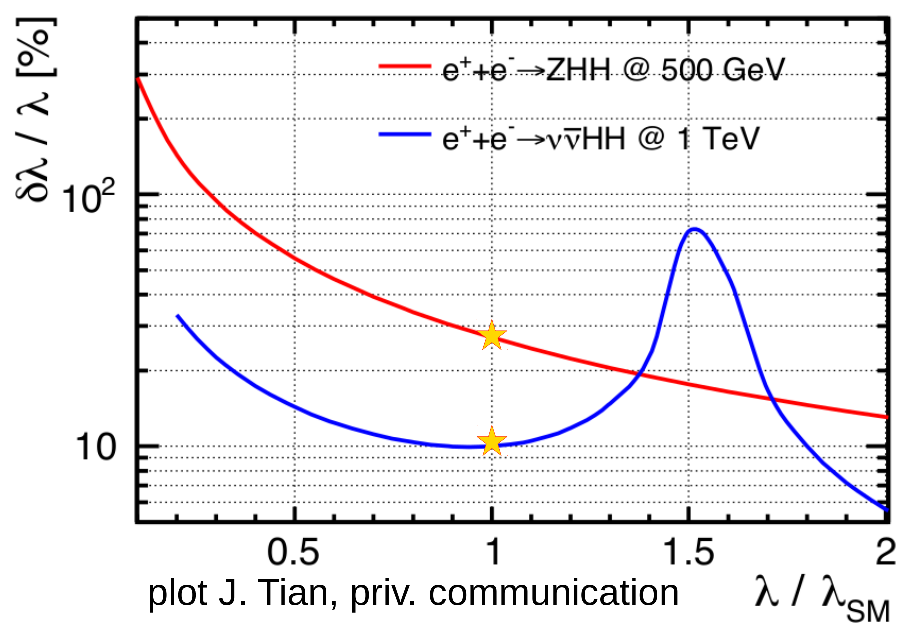
- Determination of κ_λ at the level of O(5%) expected to be within the FCC reach

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





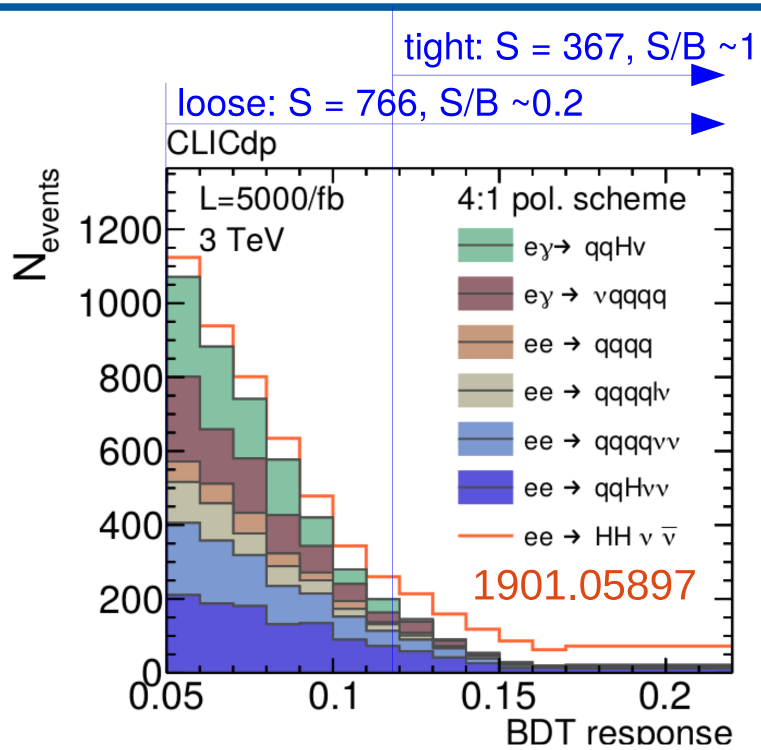


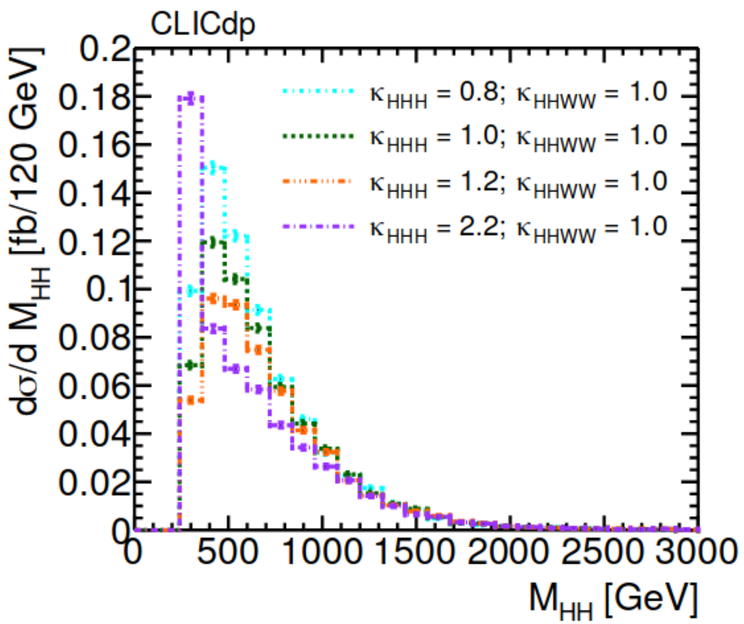
- Also studies of $\nu\bar{\nu}HH$ @1 TeV → 10% uncertainty

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

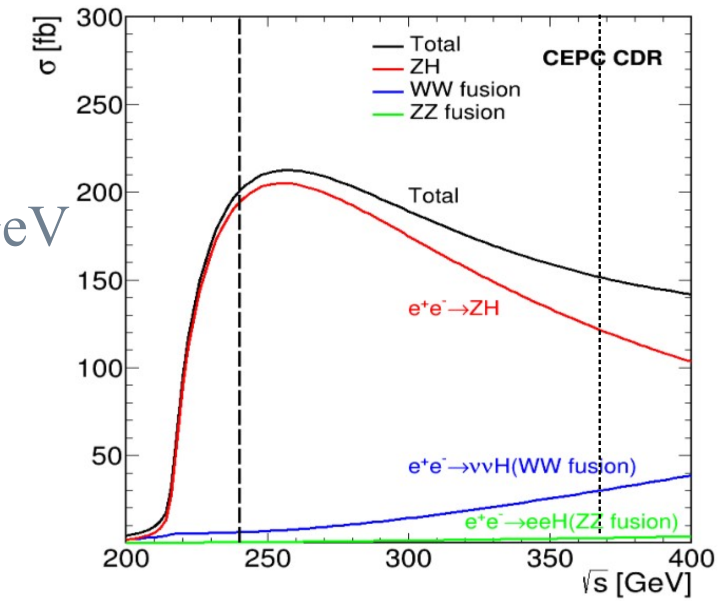
Constraints for κ_{HHH} based on	$\Delta\chi^2 = 1$
$HH\nu\bar{\nu}$ cross section only (3 TeV)	[0.90, 1.12] ∪ [2.40, 2.61]
$HH\nu\bar{\nu}$ (3 TeV) and ZHH (1.4 TeV) cross section	[0.90, 1.11]
$HH\nu\bar{\nu}$ differential (3 TeV)	[0.93, 1.12]
$HH\nu\bar{\nu}$ differential (3 TeV) and ZHH cross section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





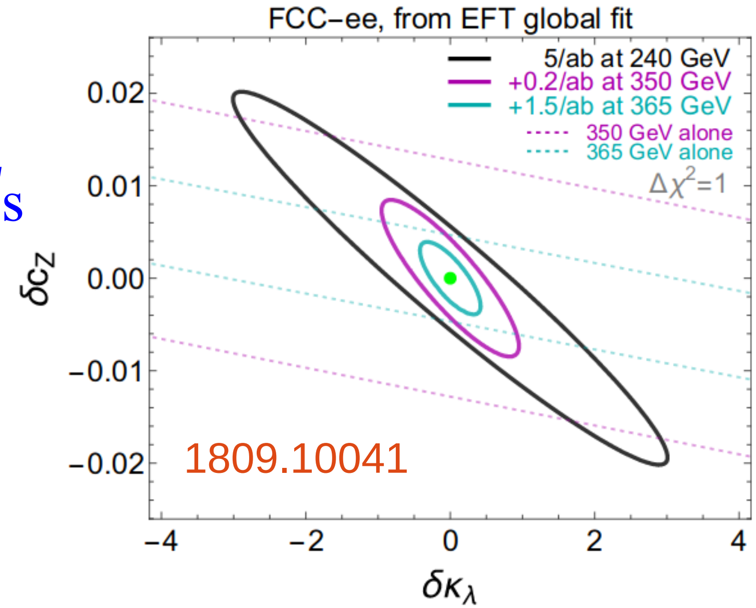
ee colliders below the HH threshold: CEPC, FCC-ee

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

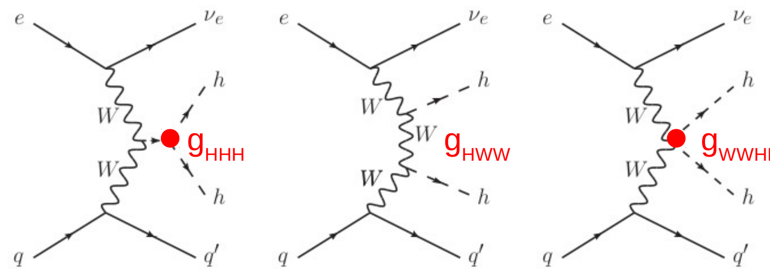


- Based on very good precision on cross-section, eg CEPC and FCC-ee240:
  - $\sigma(ZH)$: 0.5%
  - $\sigma(\nu\bar{\nu}H)$: 2-3%
  - ex.: $\sigma(ZH)$ modified by 1% for $\kappa_\lambda=2$ $\Rightarrow 2\sigma$ sensitivity

- 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 (not in the report)



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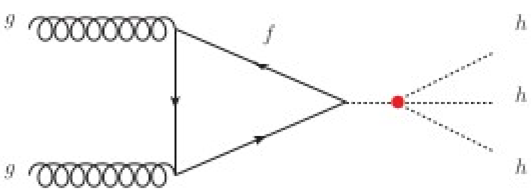
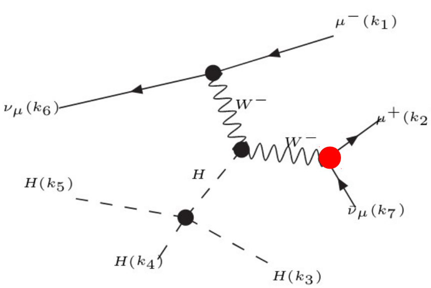
- ♦ electron-proton colliders: LHeC and FCC-eh
  - FCC-eh di-Higgs:
    - $0.83 < \kappa_\lambda < 1.24$ @3.5 TeV
    - $0.88 < \kappa_\lambda < 1.14$ @5 TeV
  - FCC-eh single-Higgs: missing the 1-loop dependence on k_λ ⇒ can't apply Methods (3) and (4)

- ♦ 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 $\kappa_{\lambda 3} = 1$)

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.

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h the PPG
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/ 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

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SMEFT$_{\text{ND}}$ framework

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

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

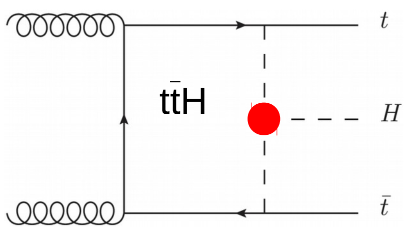
- Tri-linear gauge couplings:

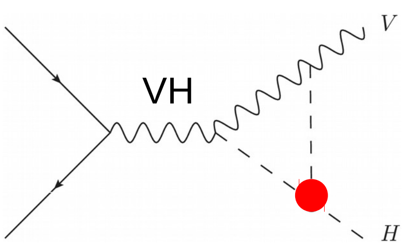
$$\begin{aligned}
\Delta\mathscr{L}^{\text{aTGC}} = \; & ie\,\delta\kappa_\gamma A^{\mu\nu} W_\mu^+ W_\nu^- + ig\cos\theta_w \Big[\delta g_{1Z}(W_{\mu\nu}^+ W^{-\mu} - W_{\mu\nu}^- W^{+\mu})Z^\nu + (\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma) Z^{\mu\nu} W_\mu^+ W_\nu^-\Big] \\
& + \frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w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

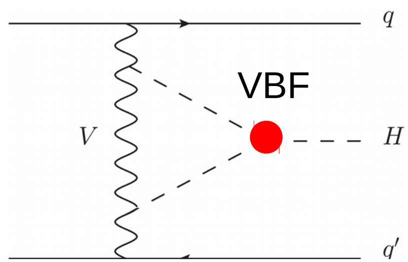
- Yukawa couplings: $\Delta\mathscr{L}_6^{\text{hff}} = -\frac{h}{v}\sum_{f\in u,d,e} \hat{\delta} y_f\, m_f \bar{f} f + \text{h.c.}.$
- Neutral diagonality.

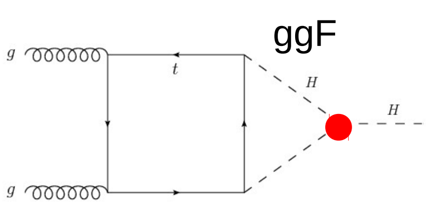
Single-Higgs couplings

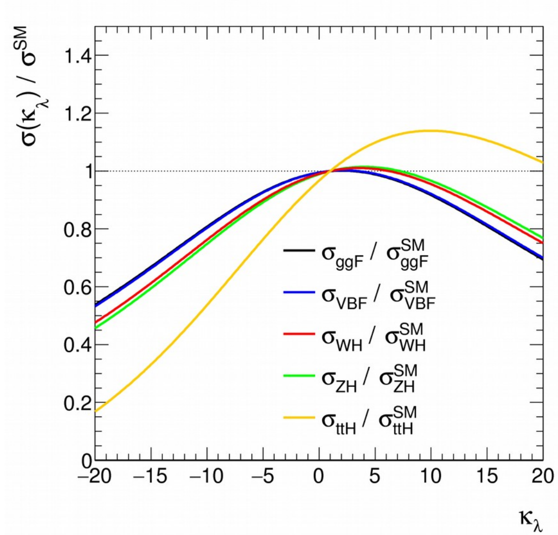
- Higgs self-interaction via one-loop corrections of the single-Higgs production
  - κ_λ-dependent corrections to the tree-level cross-sections
- pp colliders



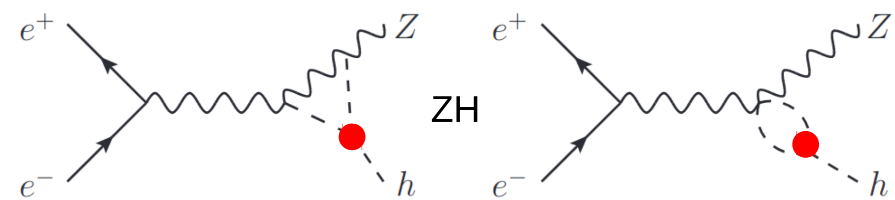


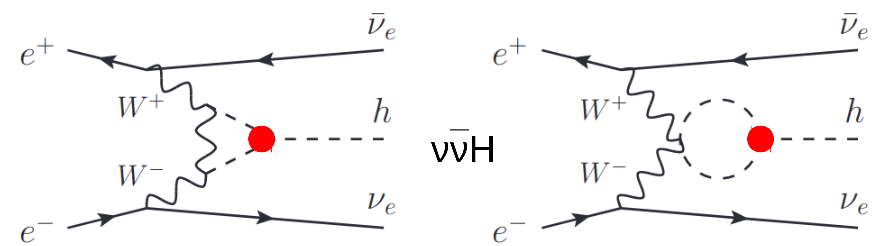


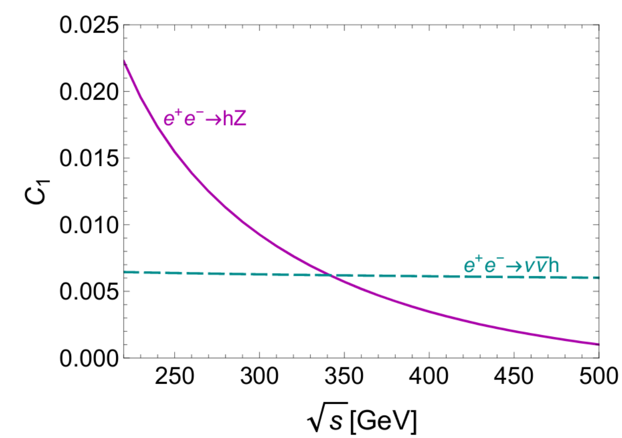




- ee colliders

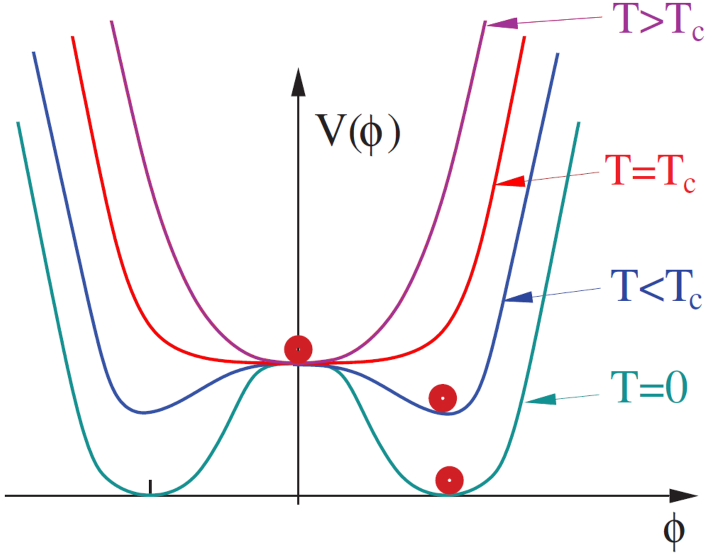


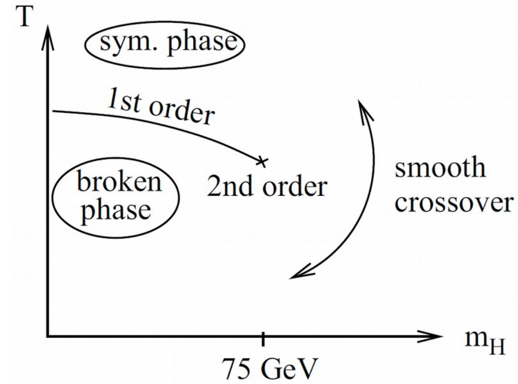




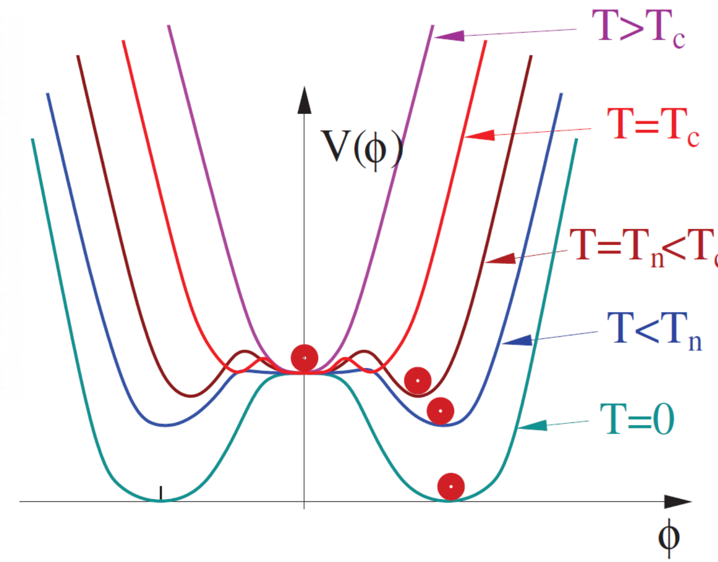
Higgs potential and electroweak phase transition

- Second order phase transition





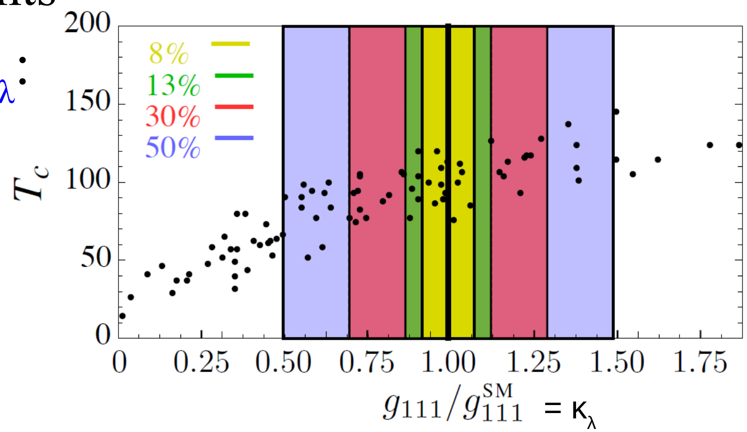
- First order phase transition

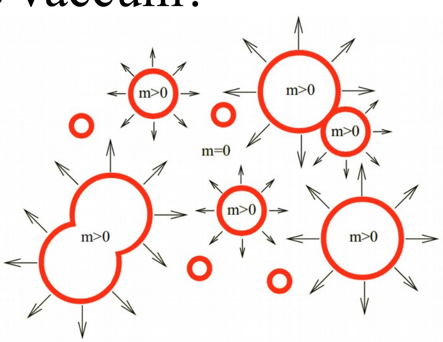


- – constantly at thermal equilibrium
- – not so interesting for cosmology
- – preferred option with the current measurements

- – matter-antimatter asymmetry?
- – domain walls?
- – gravitational waves created by bubbles of the vaccum?

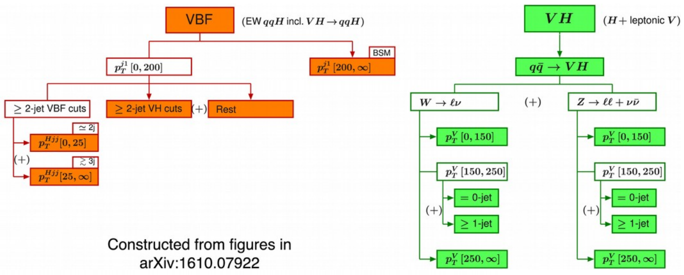
- T_C related to κ_λ:





LHC Run-2 single-Higgs exclusive

- Using results from the couplings measurements with ATLAS Run-2 data (36-80 fb^{-1})
  - simplified template cross-section categories
  - no categories for ttH



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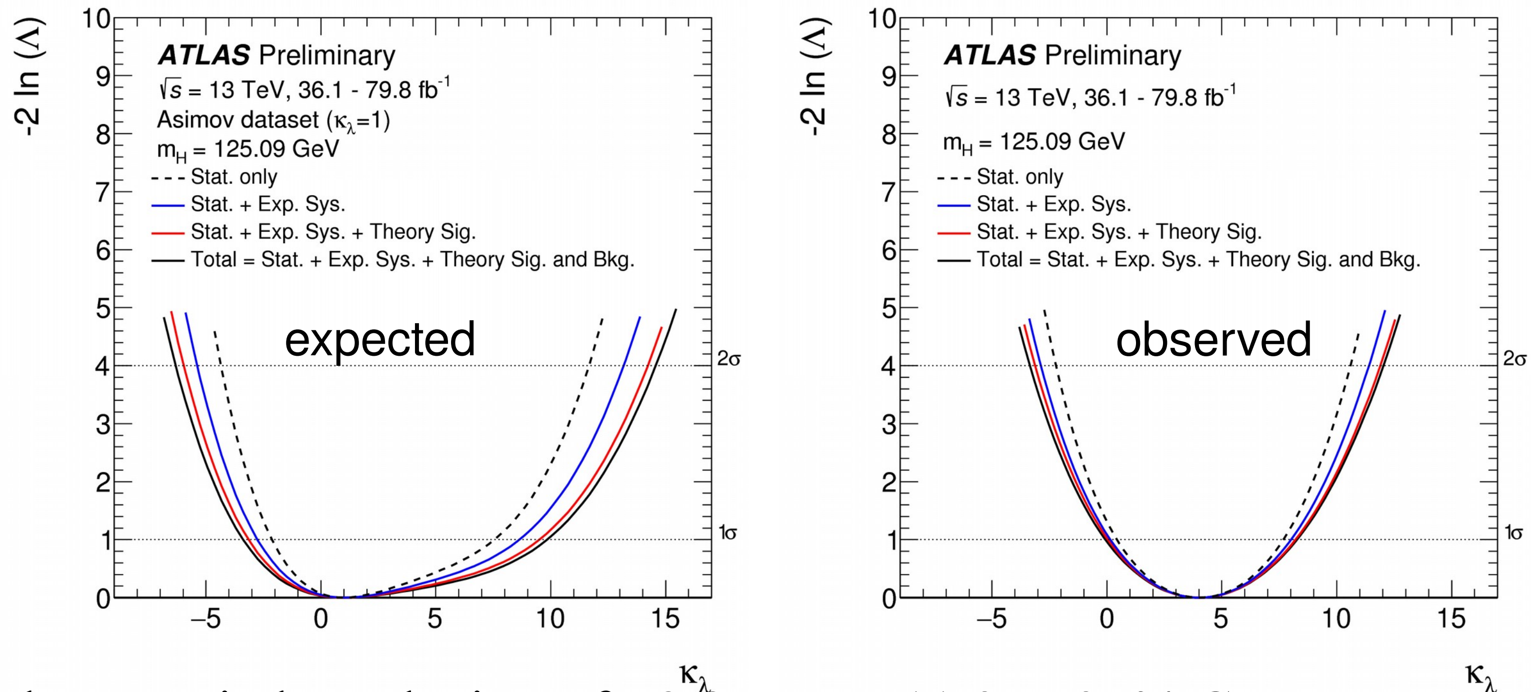

- If only κ_λ varied: exclusion of $-3.2 < \kappa_\lambda < 11.9$ at 95% CL
  - limit from direct measurement (36 fb^{-1}): $-5.0 < \kappa_\lambda < 12.1$ at 95% CL
  - at 68% CL: $\kappa_\lambda = 4.0^{+4.3}_{-4.1} = 4.0^{+3.7}_{-3.6}\,(\text{stat.})\,^{+1.6}_{-1.5}\,(\text{exp.})\,^{+1.3}_{-0.9}\,(\text{sig. th.})\,^{+0.8}_{-0.9}\,(\text{bkg. th.})$
  - will quickly be limited by systematics