Higgs self coupling and Higgs rare decays at FCC-hh

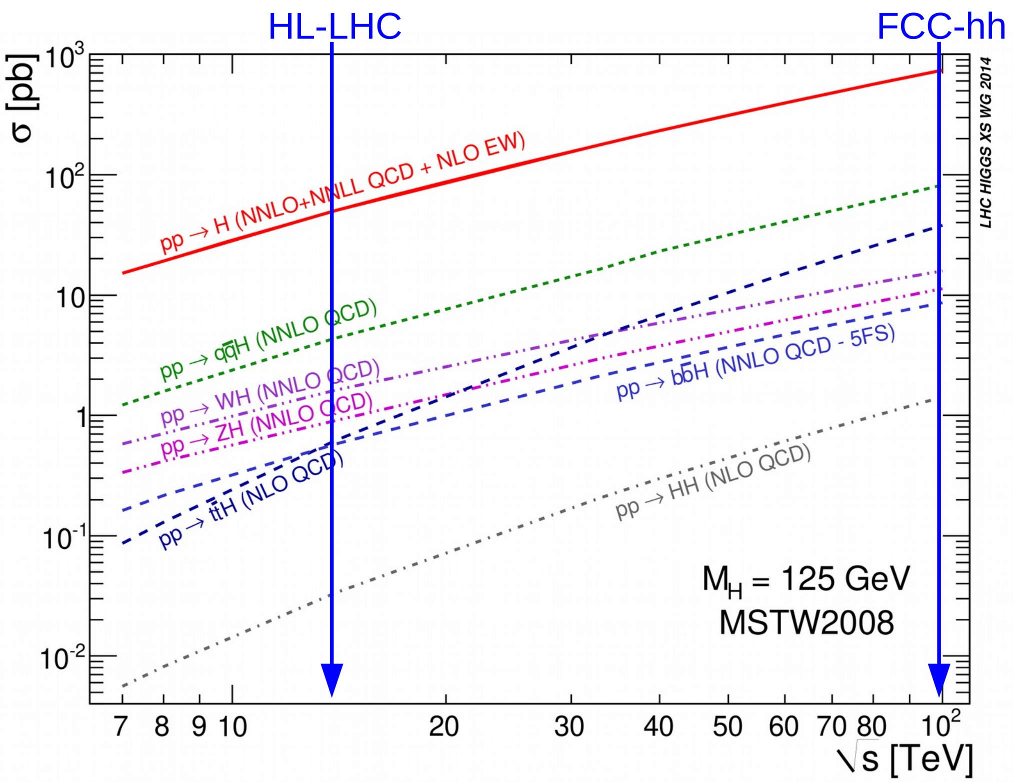
Elisabeth Petit
CPPM

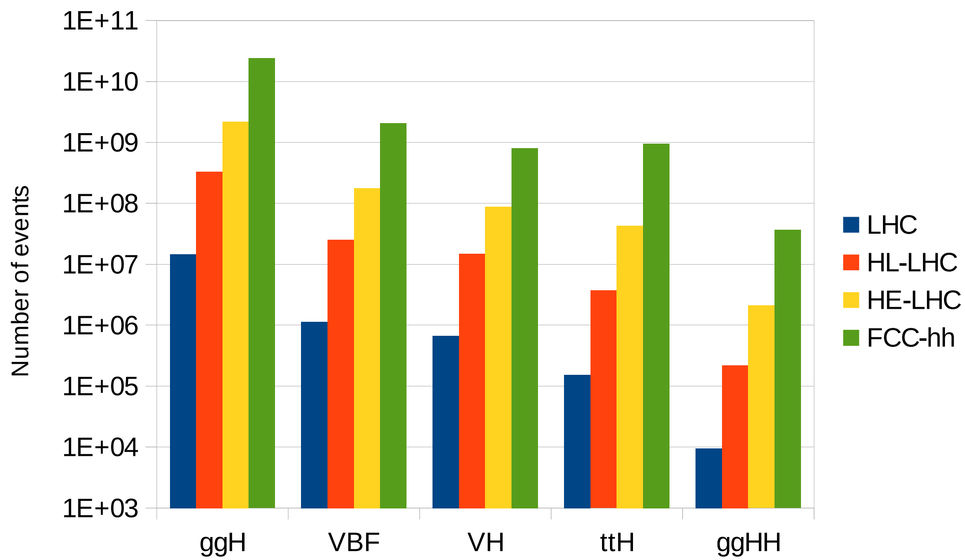
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Workshop FCC-France
15th of May 2020

Introduction

- O(100) more Higgs produced at FCC-hh (100 TeV, 30 ab^{-1}) than at HL-LHC (14 TeV, 6 ab^{-1})





- High precision measurements of the Higgs boson couplings: from a few % precision to <1% precision
- Opening measurements to rare processes:
  - HH(H) production
  - rare decays: Zγ, μμ, light quarks, invisible

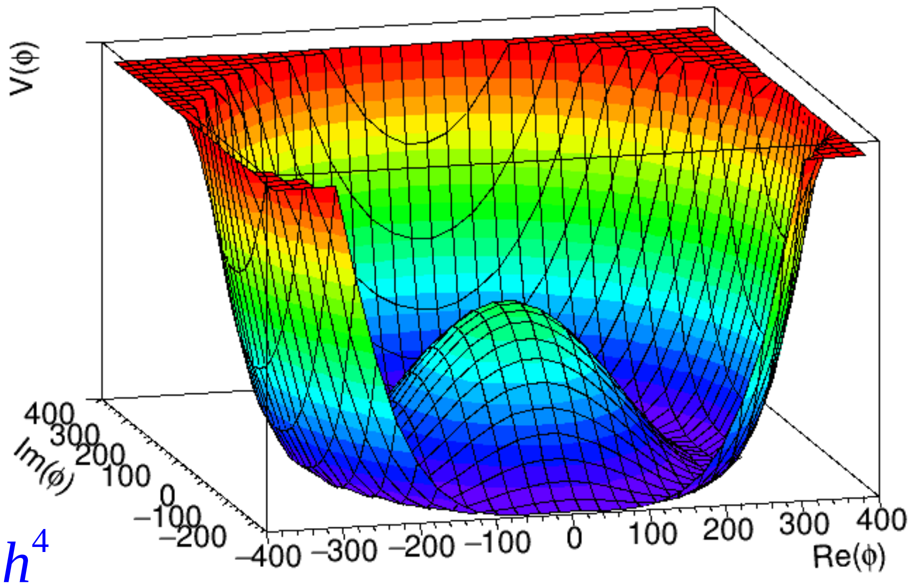
Main references

- Higgs and Electro-weak symmetry breaking at the FCC-hh (CERN-ACC-2018-0045)
- FCC Physics Opportunities - Future Circular Collider Conceptual Design Report Volume 1 (Eur. Phys. J. C (2019) 79:474)
- Future Circular Collider – European Strategy Update Documents (CERN-ACC-2019-0007)
- Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV p-p collider (arxiv:2004.03505)
- Higgs Boson studies at future particle colliders (JHEP01 (2020) 139)
- Higgs Physics at the HL-LHC and HE-LHC (CERN-LPCC-2018-04)

Higgs self-coupling

Self-couplings, introduction

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



- Approximation around the v.e.v:

$$V(h)\approx \underbrace{m_h^2 h^2}_{\text{mass term}}+\underbrace{(1+\kappa_3)\lambda_{hhh}^{SM} v h^3+\frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4}_{\text{self-coupling cubic and quartic terms}}$$

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

- BSM effects could change λ ⇒ define deviations of tri-linear and quartic terms

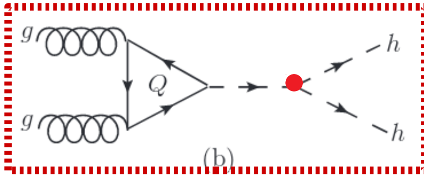
- Concentrate mainly on tri-linear coupling: $\kappa_\lambda=\kappa_3=\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  – what we can deduce from precision on κ_λ:

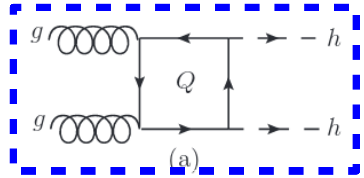
50% sensitivity: establish that $h^3\neq 0$ at 95%CL
20% sensitivity: 5σ discovery of the SM h^3 coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

C. Grojean

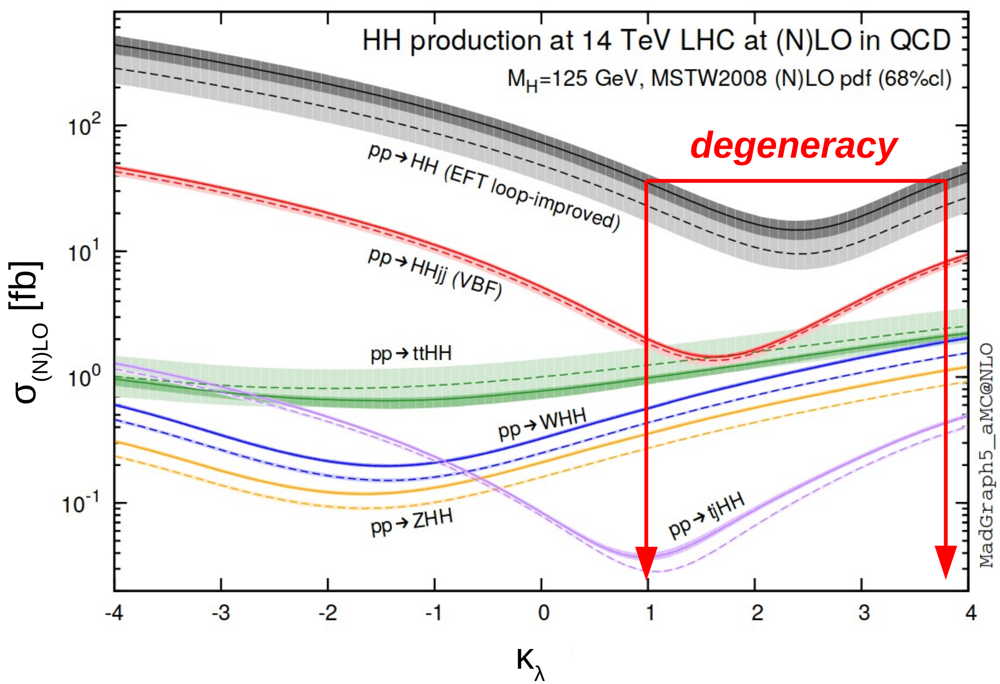
Di-Higgs production: pp colliders

- Main production mode: ggF
  - cross-section *30 between HL-LHC and FCC-hh
  - destructive interference between triangle and box diagrams ⇒ σ(HH)/σ(H) = 0.1%

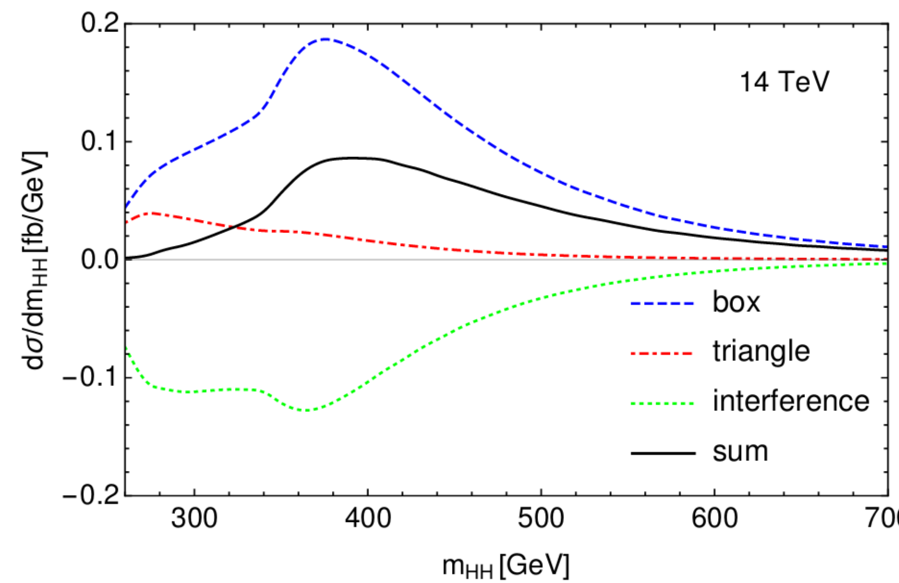




- Self-couplings through
  - total HH cross section
  - diff. cross section $d\sigma/dm_{HH}$:

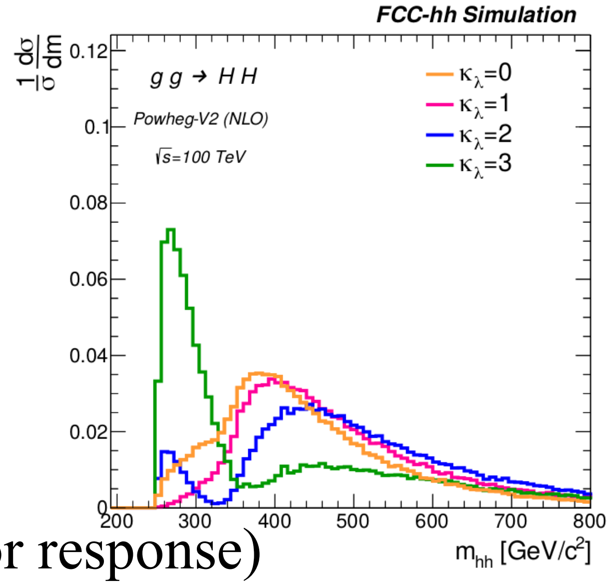


⊗



LHCHXSWG-2019-005

General strategy



- New result presented recently 2004.03505
- Main channels: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$
- Maximise the cross-section precision and use of variables sensitive to κ_λ
  - heavy use of BDT selections
- Use of Delphes simulation tool (parameterised detector response)
  - object efficiencies extrapolated from HL-LHC
  - pile-up = 1000 (not simulated but assume new techniques to cope with it)
- Several systematic uncertainty scenarios:

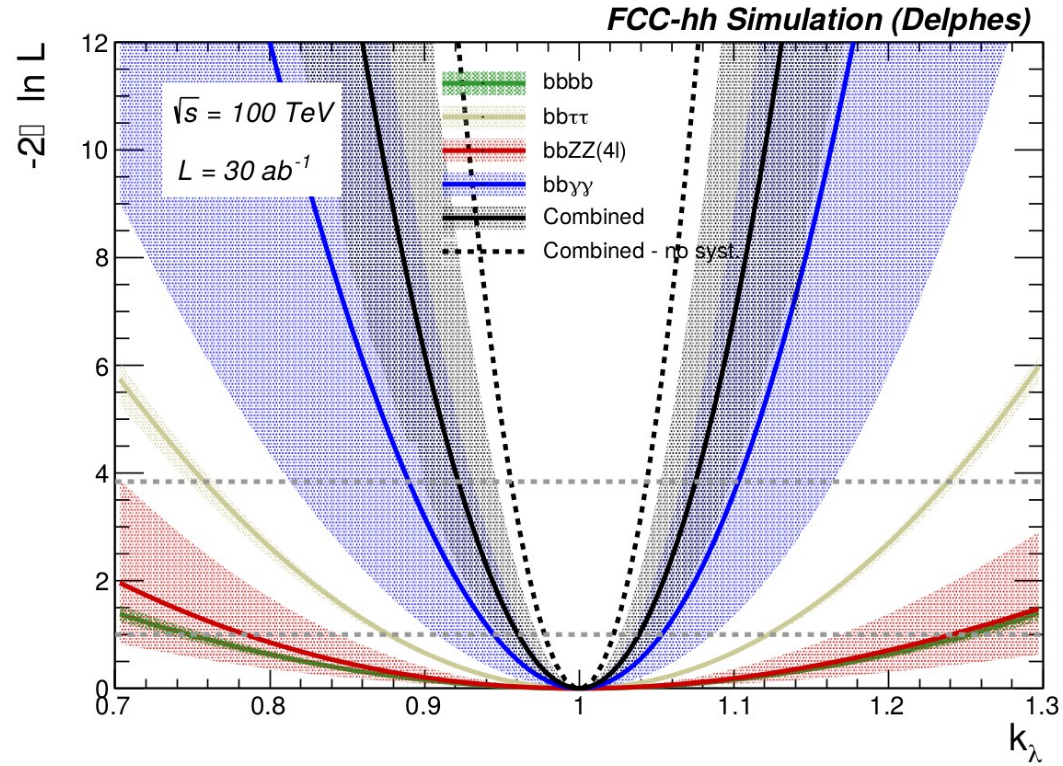
Uncertainty source	syst. I	syst. II	syst. III	Processes	HL-LHC (S2)
b-jet ID eff. /b-jet	0.5%	1%	2%	single H, HH, $t\bar{t}$	1%
τ-jet ID eff. /τ	1%	2.5%	5%	single H, HH, $t\bar{t}$	5%
γ ID eff. /γ	0.5%	1%	2%	single H, HH	2%
$\ell = e$-μ ID efficiency	0.5%	1%	2%	single H, HH, single V, VV, $t\bar{t}$V, $t\bar{t}$VV	0.5%
single H cross section	0.5%	1%	1.5%	H	~2%
$t\bar{t}$ cross section	0.5%	1%	1.5%	H	
luminosity	0.5%	1%	2%	single H, HH, single V, VV, $t\bar{t}$, $t\bar{t}$V, $t\bar{t}$VV	~1%
HH cross section	0.5%	1%	1.5%	HH	~2-3%

HH combined results

- 1D maximum likelihood fits of the BDT discriminants
- 68% CL uncertainty on κ_λ:

bbγγ	bbττ	bbbb	combined
3.5-8.5%	12-13%	24-26%	2.9-5.5%

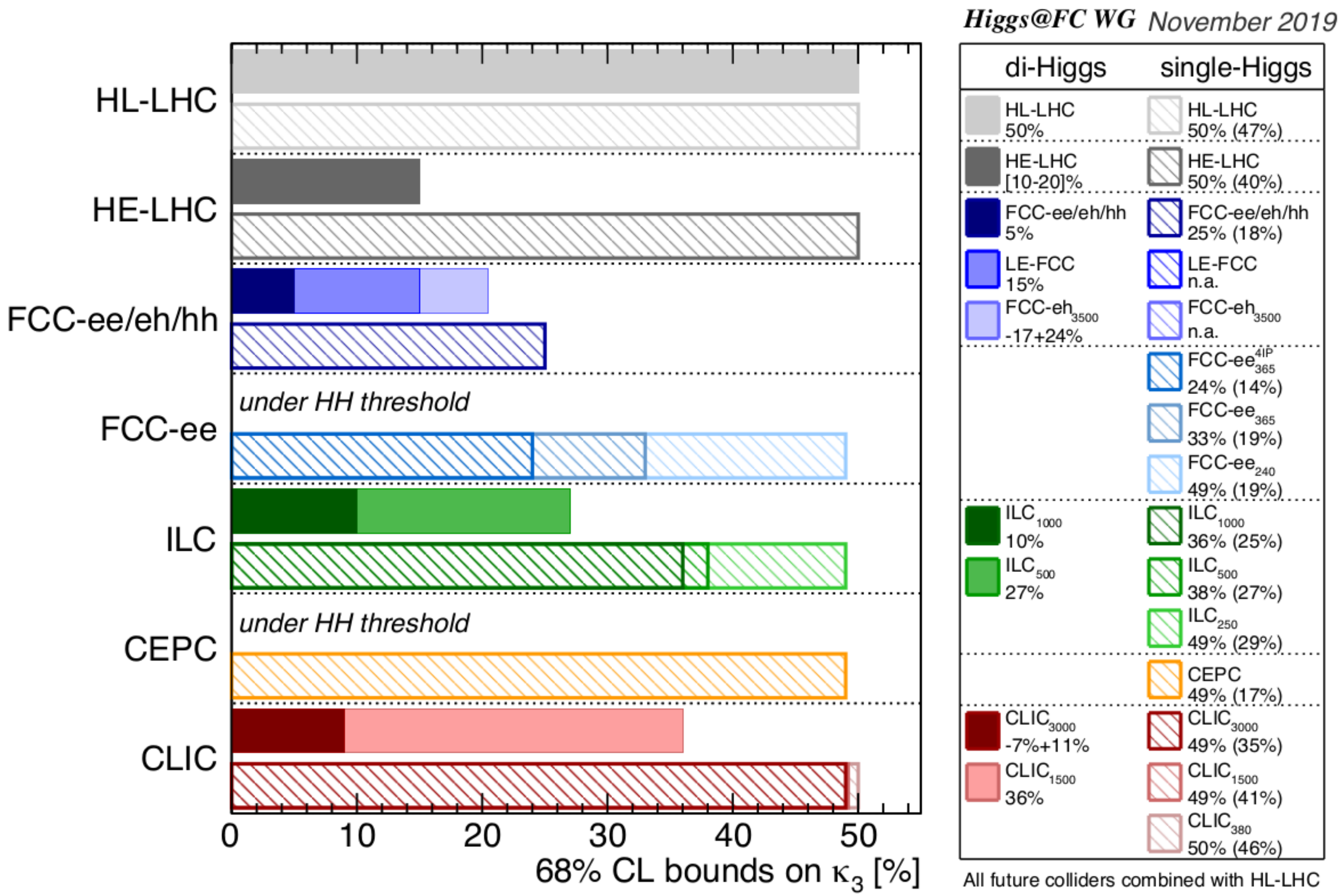
  - driven by the $b\bar{b}\gamma\gamma$ channel, limited by systematics



- A few remarks:
  - small impact of (eg QCD) background relies on the fact that the data will help to constrain the normalisations
  - precision achievable only if good measurements of other couplings: 1% uncertainty on $y_t \Rightarrow$ 5% uncertainty on κ_λ
  - uncertainty on σ_{HH}: 0.5%-1.5% (~5% today): needs at least one order beyond NLO with full top-mass dependence, possibly beyond N³LO in the infinite top-mass limit
- Evolution with luminosity:
  - 10% precision achievable with 3 ab^{-1} of data, ie a 3-5 year early run

Comparison of Future Colliders

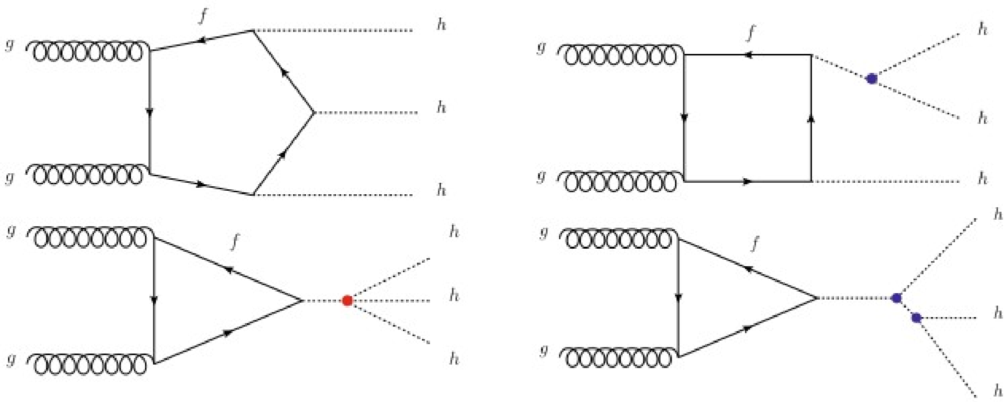
- 68% CL uncertainties on κ_λ with di-Higgs and single-Higgs:
  - all combined with HL-LHC



Quartic couplings

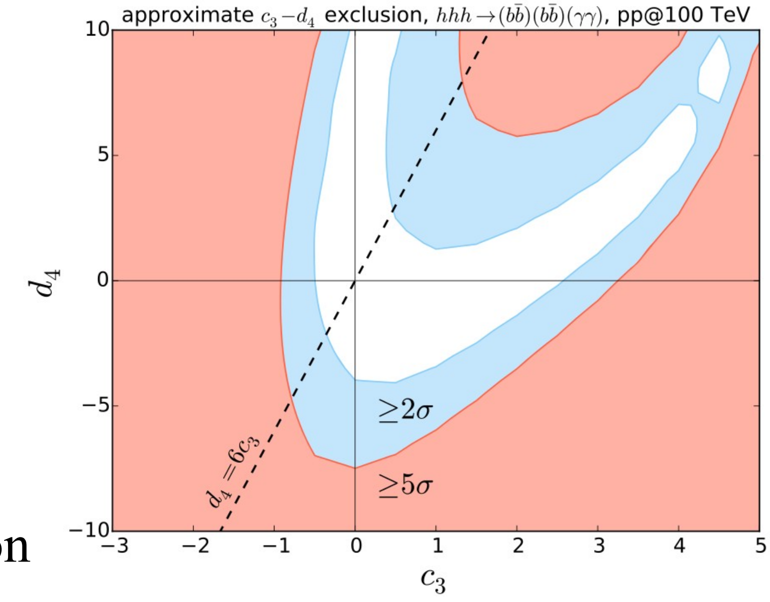
$$V(h) \approx m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4$$

- Beyond reach of most Future Colliders
  - still challenging at FCC-hh: $\sigma_{HHH} \sim 5$fb
- Quartic coupling via HHH production
  - cubic coupling also involved:

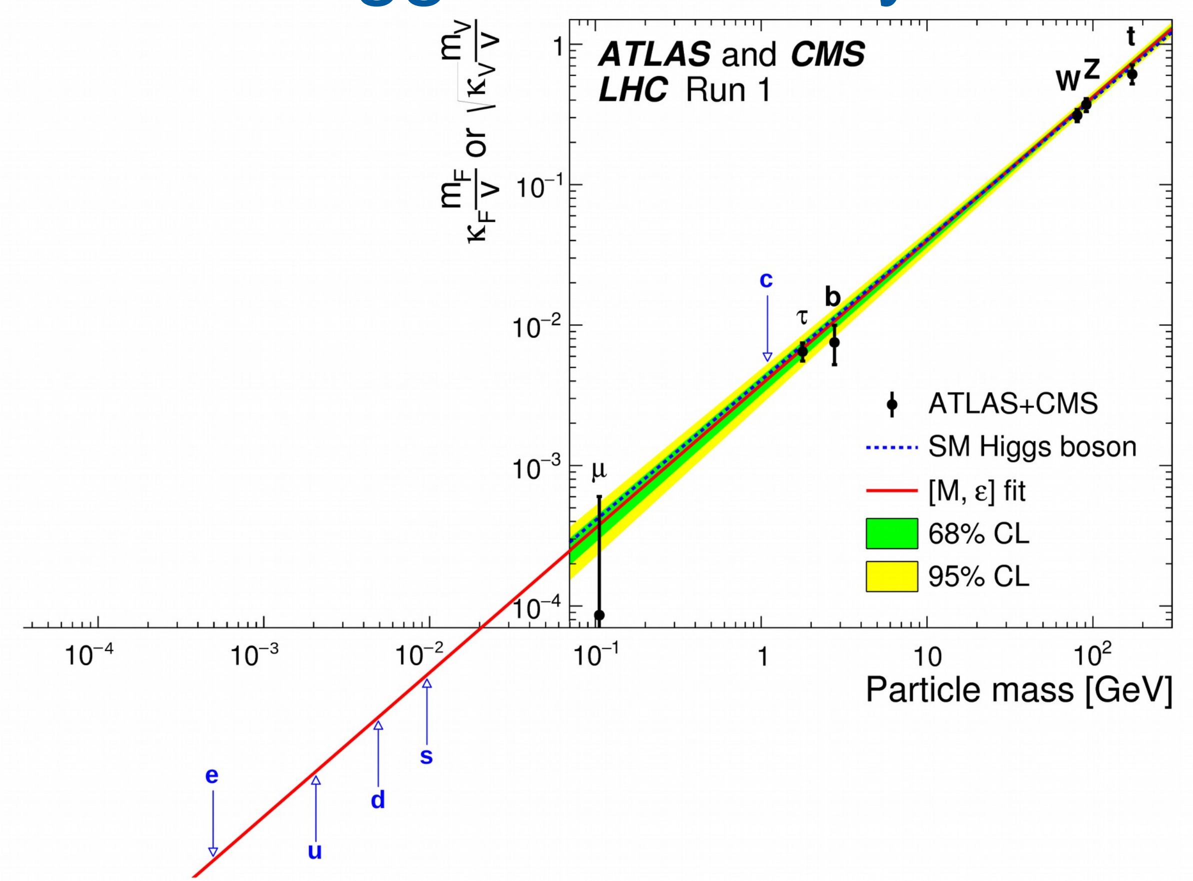


  - mild dependence of σ_{HHH} with κ_4
- Studies with
  - $b\bar{b}b\bar{b}\tau\tau$ 1704.04298
    - expect 3 signal and 14 bkg events
  - $b\bar{b}b\bar{b}\gamma\gamma$ 1508.06524
    - expect 10 signal and 31 bkg events
  - could reach 2σ significance and set exclusion limits in the κ_3-κ_4 plane

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\text{ab}^{-1}}$
$(bb)(bb)(bb)$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125

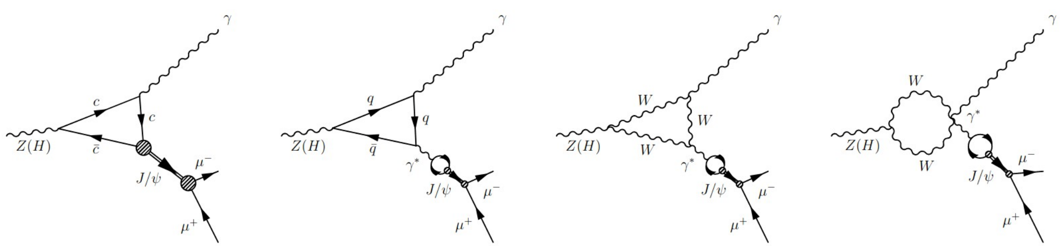


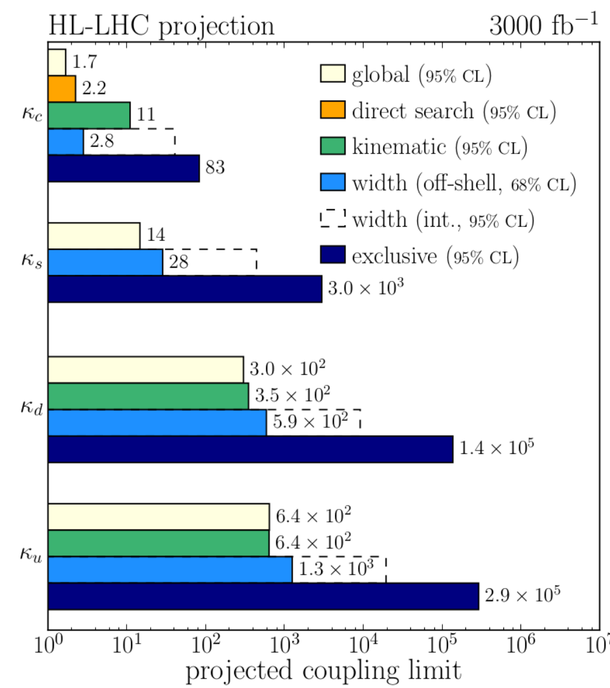
Higgs rare decays



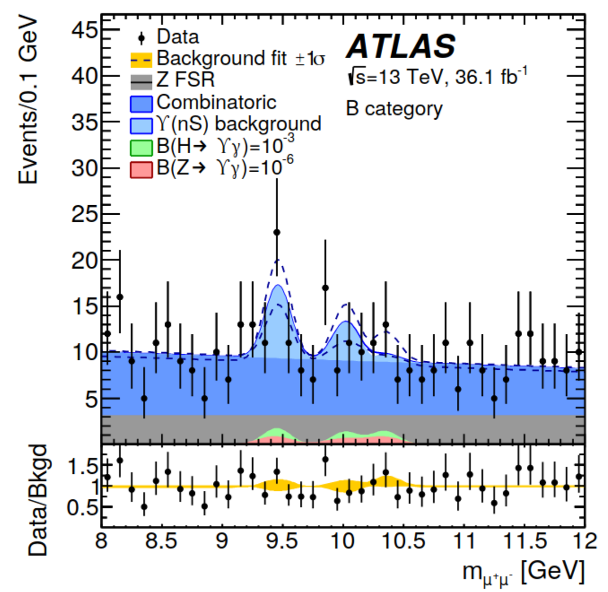
Yukawa coupling to 1st and 2nd generation fermions

- Mostly unreachable at HL-LHC
- Different methods:
- Indirect: fits of diff. cross-sections, total Higgs width, global fit of production cross-sections
- Direct inclusive decays ($H \rightarrow \mu\mu$, $H \rightarrow c\bar{c}$)
- Direct exclusive decays ($H \rightarrow$ meson + γ)





Light quark	Higgs decay	BR	Meson decay	N HL-LHC	N FCC-hh
u, d	H → ρ(770)γ	2E-05	π+π-	278	469438
s	H → Φγ	2E-06	K+K-	38	64548
c	H → J/μγ	3E-06	μμ	49	83549
c	H → ψ(2S)γ	1E-06	μμ	17	28781
c	H → Υ(nS)γ	1E-09	μμ	0	28

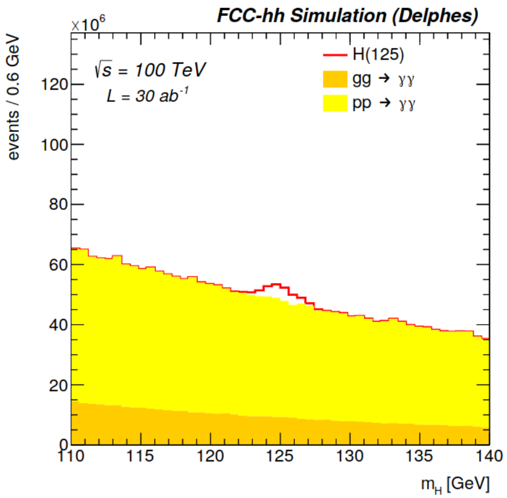


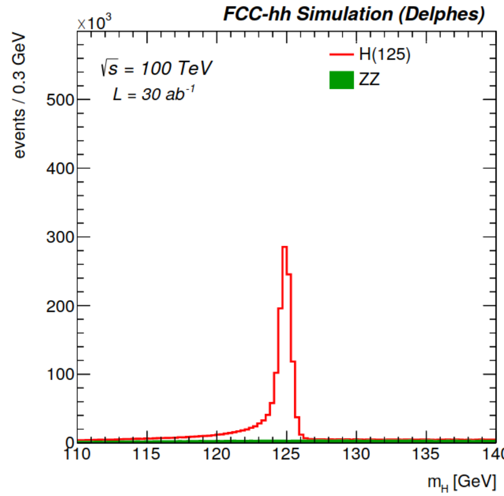
- first studies at LHC (ATLAS, CMS, LHCb)
- could benefit from high-statistics of FCC-hh

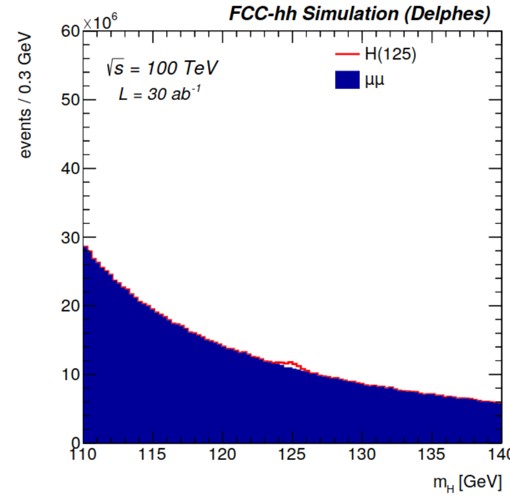
Direct inclusive rare decays

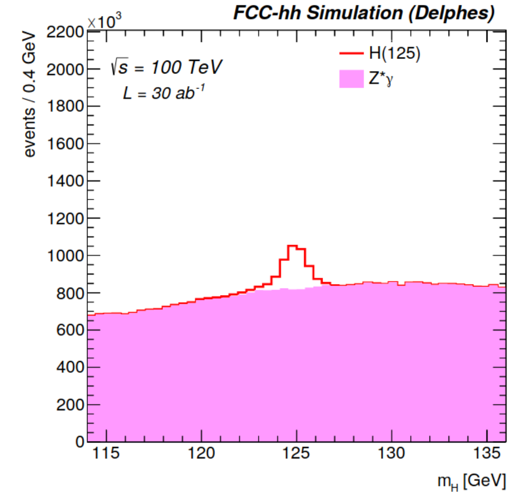
CERN-ACC-2018-0045

- Complementary measurements of $H\to\gamma\gamma$, $H\to ZZ\to 4\ell$, $H\to\mu\mu$, $H\to Z\gamma\to\ell\ell\gamma$

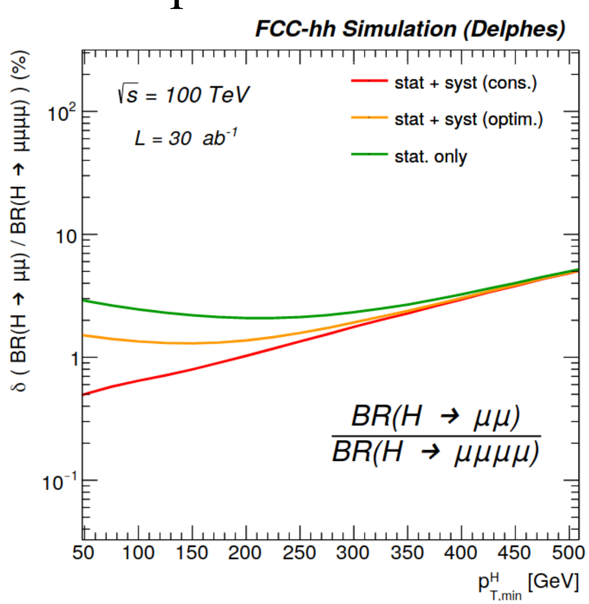








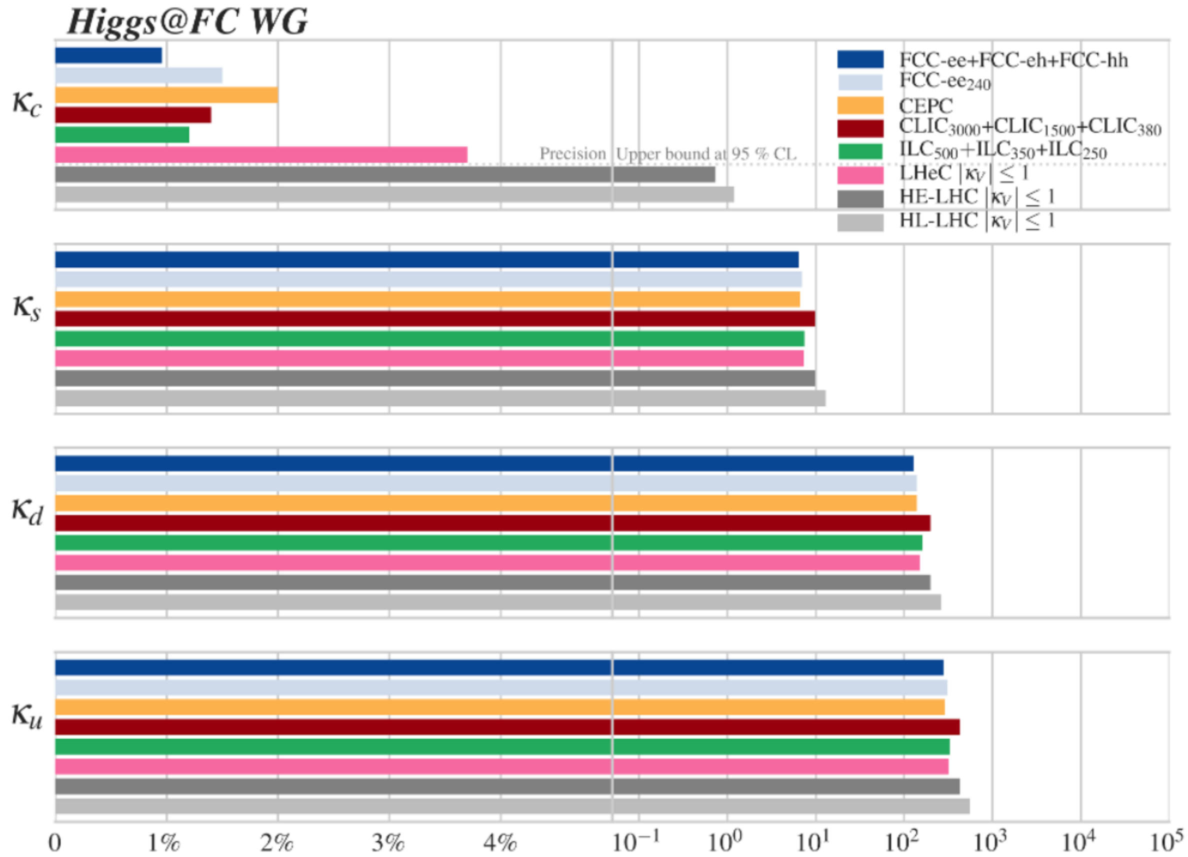
- Individual precision on BR: 1-2%
  - specific ratios of BR allow for cancellation of some uncertainties



Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to\gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.5%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta\mu/\mu$	0.28%	1.2%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.9%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H}\to\gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.6%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.4%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta R/R$	0.58%	1.8%

Light quarks through indirect measurements

- Constraints on light Yukawa obtained from the upper limits on BR to all untagged particles, using global fits in κ framework

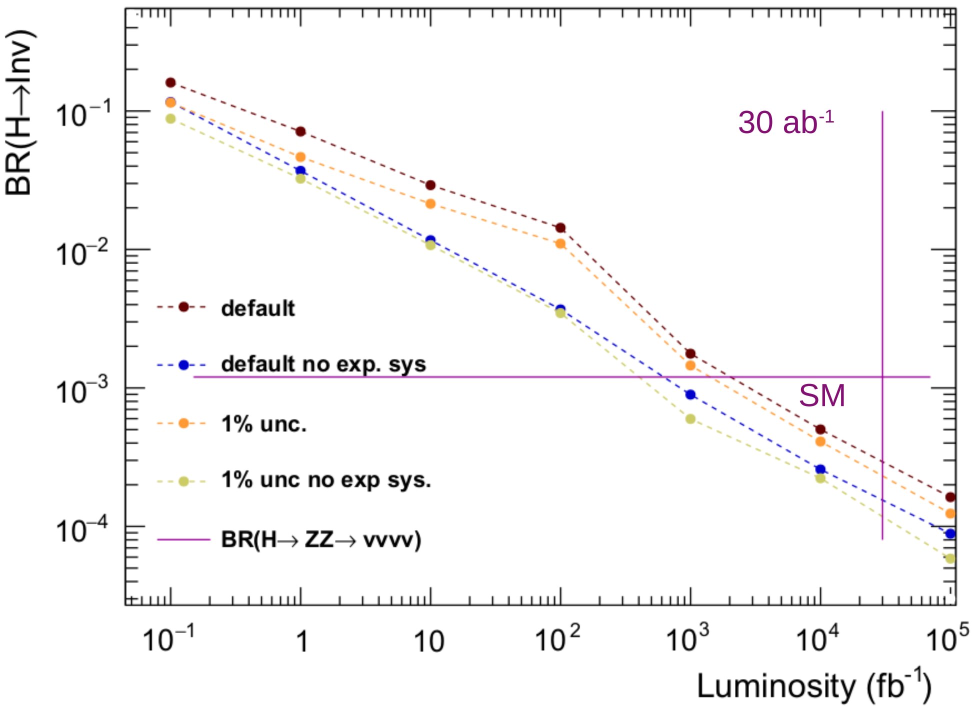


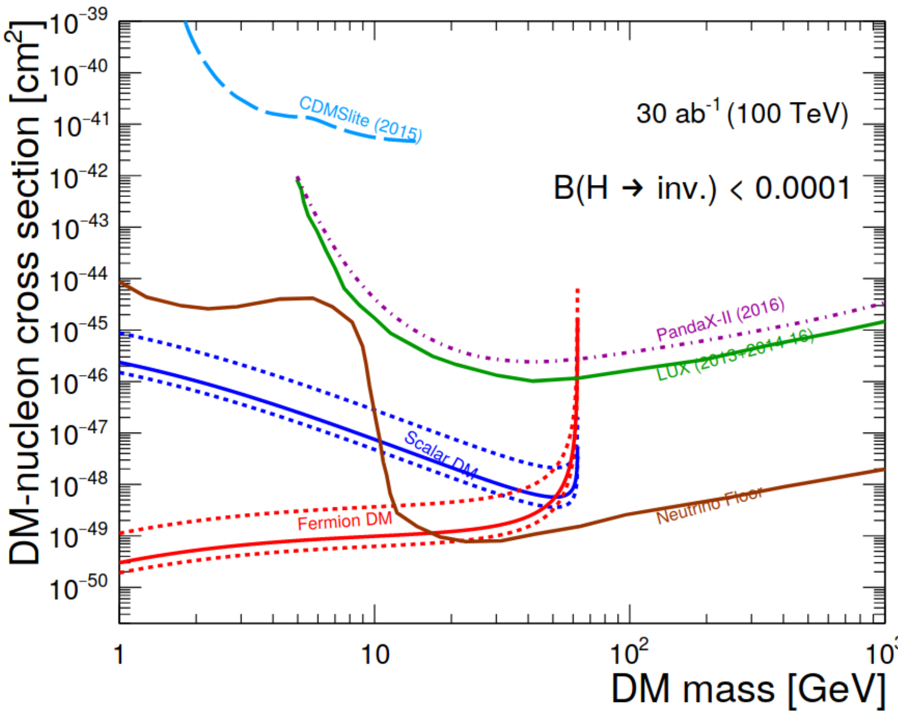
- FCC-ee+eh+hh:
  - first generation: 95% CL limits $\kappa_u < 280$, $\kappa_d < 130$
  - second generation: 95% CL limit $\kappa_s < 6.4$, κ_c measured with precision of <1%

Invisible width

CERN-ACC-2018-0045

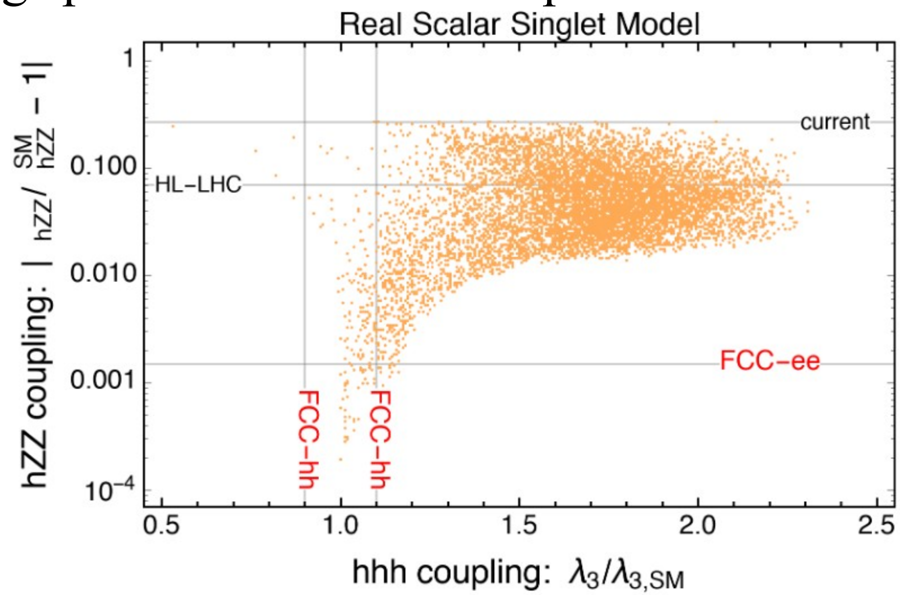
- Connection between the Higgs boson and Dark Matter searches
- Measurement from H + large E_T^{miss}
  - BR(H→inv) from precise fit the E_T^{miss} spectrum
  - background p_T spectrum from Z→νν constrained to the % level from data-driven measurements
  - ultimate precision: BR(H→inv) < 2.5 10^{-4}
    - SM (BR(H→4ν) = 0.11%) reached with ~1 ab^{-1}





Conclusion

- Ten billion Higgs bosons will be produced at FCC-hh
  - opening measurements to rare phase-spaces and decays
- The Higgs trilinear self-coupling will be measured with a precision of a few %
  - sensitive to quantum corrections of the Higgs potential and 1st order phase transitions
- First limits on the Higgs quartic self-coupling could be set

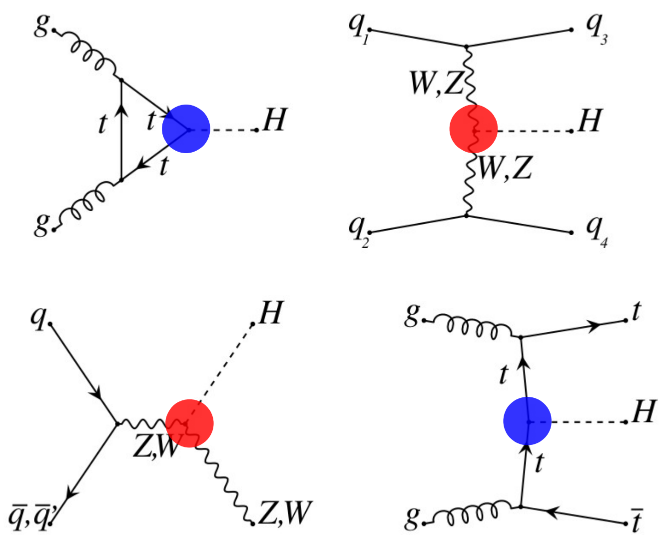


- Precise measurements of couplings to 2nd generation of fermions (μ, c) will be achievable
- Measurement of the Higgs invisible decays below the SM expectation → portal to Dark Matter

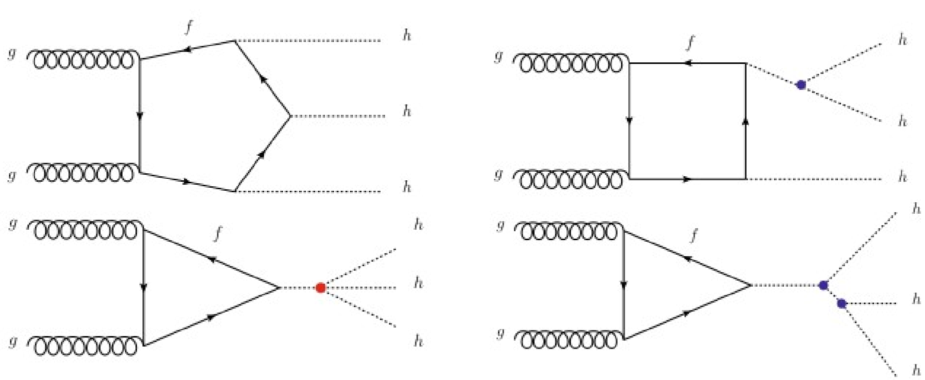
Back-up

Higgs boson production

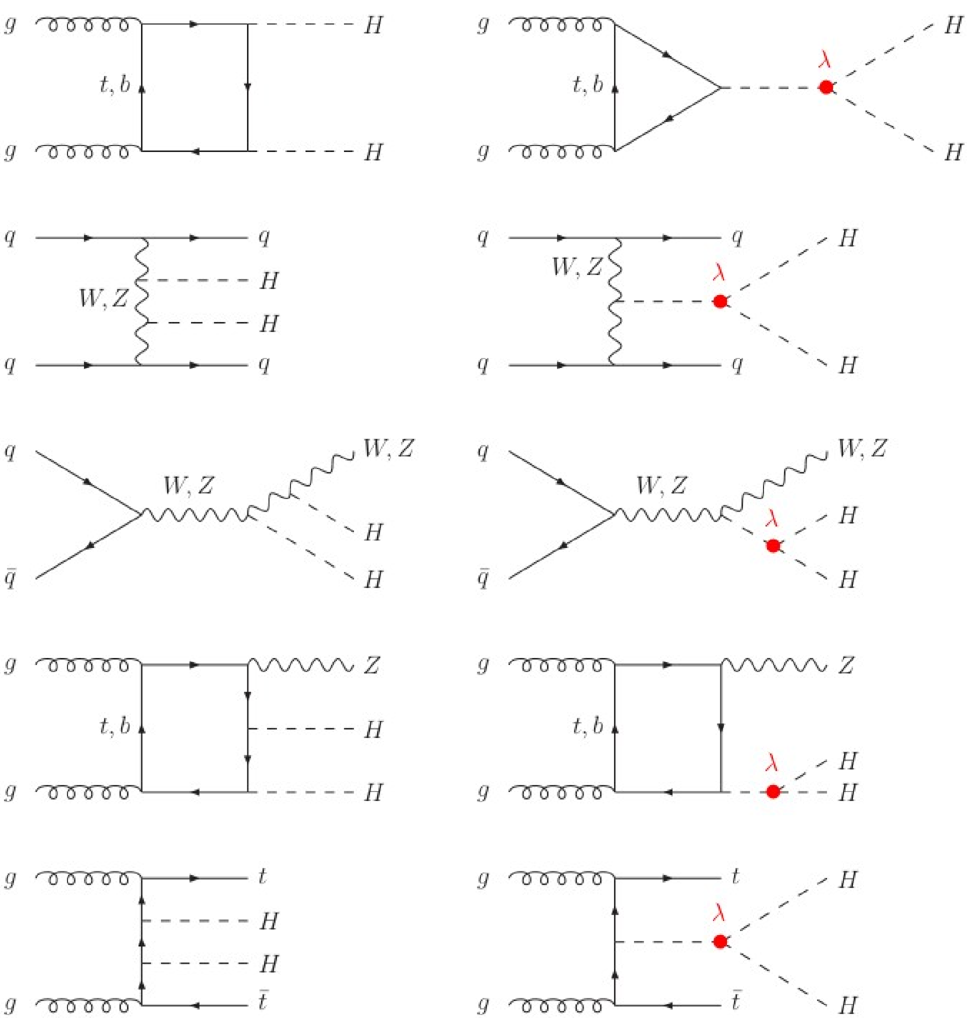
- Single-Higgs:



- Triple-Higgs (gluon fusion):

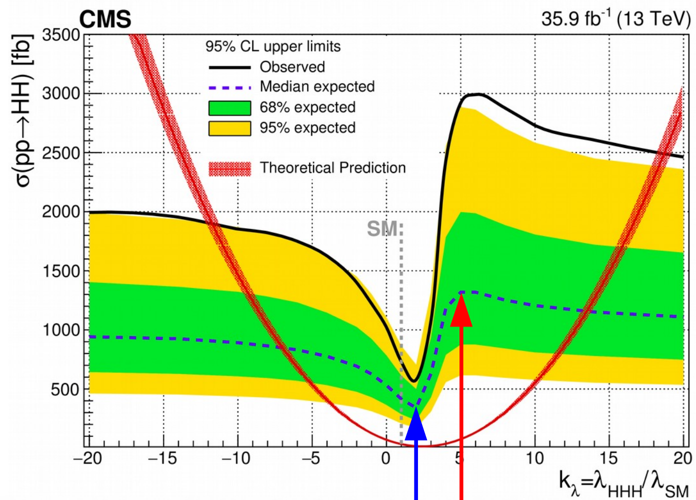


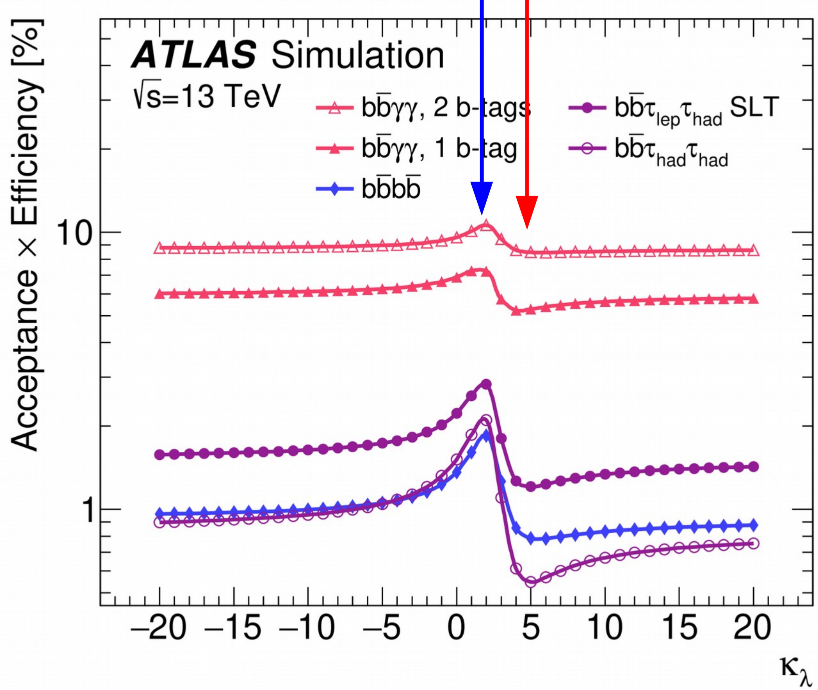
- Di-Higgs:

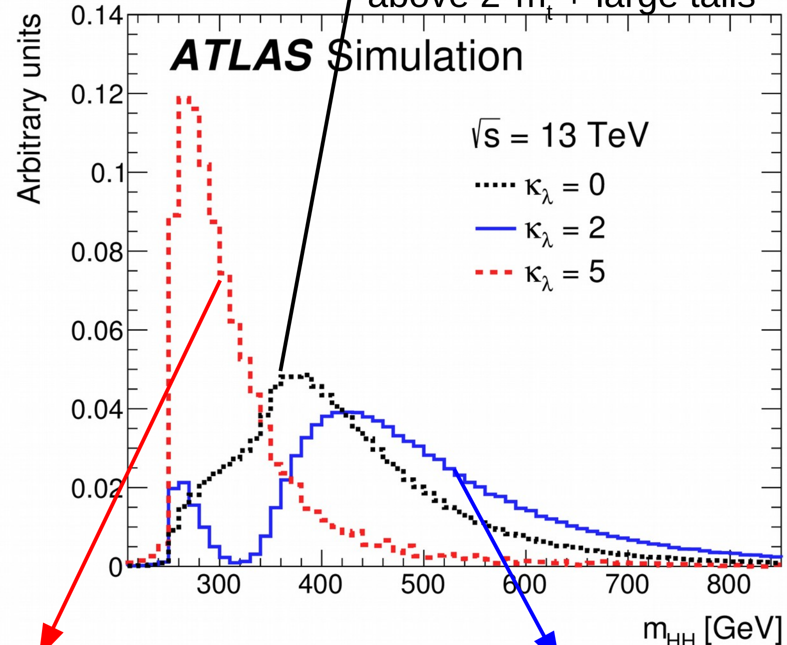


Di-Higgs production at hadronic colliders

- 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

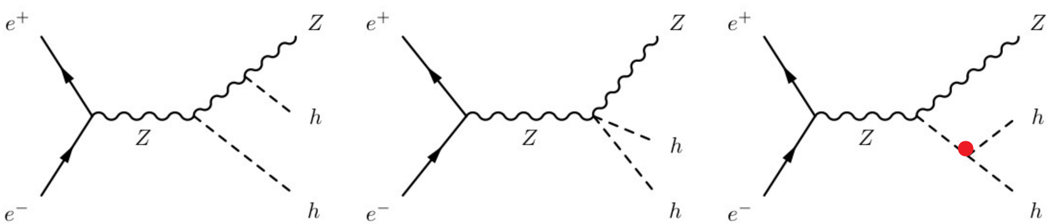
κ_λ=2: max interference ⇒ deficit between 2*m_H and 2*m_t + large tails

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

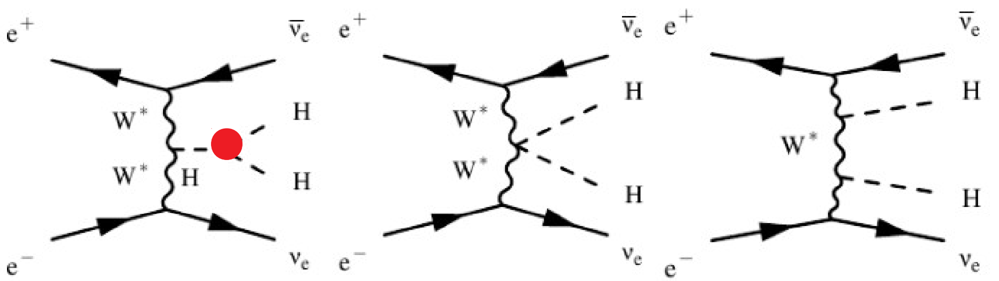
- NB: most analyses optimised for κ_λ=1

Di-Higgs production: ee colliders

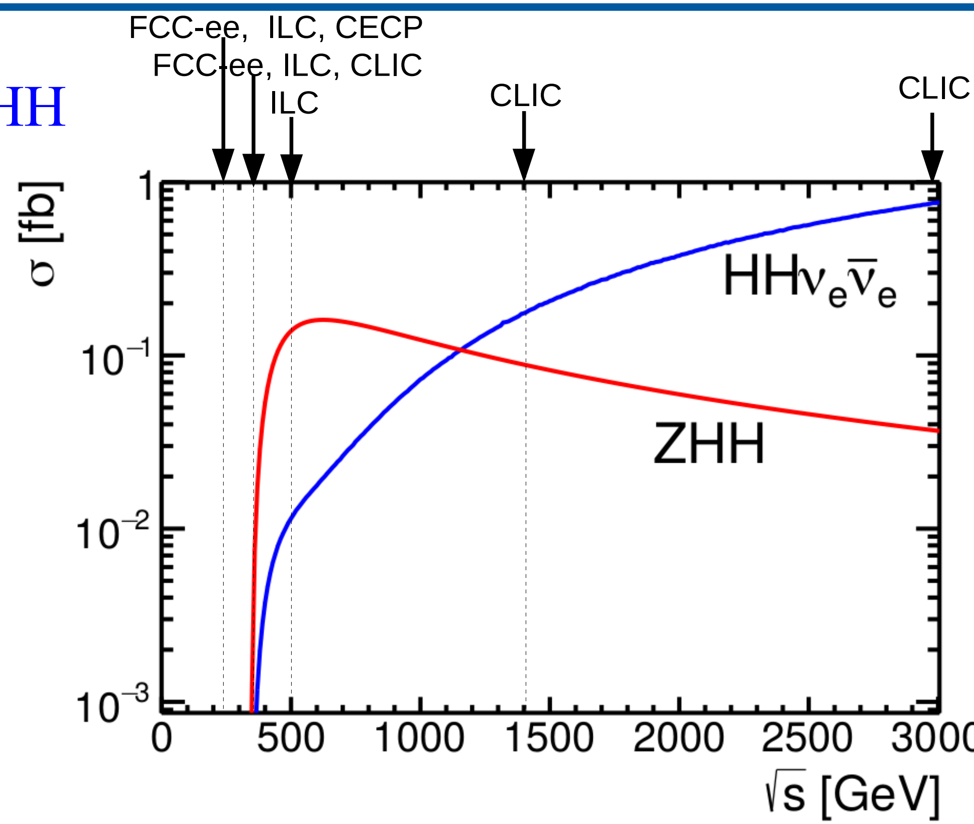
- Main production modes: ZHH and $\nu\bar{\nu}HH$
  - ZHH

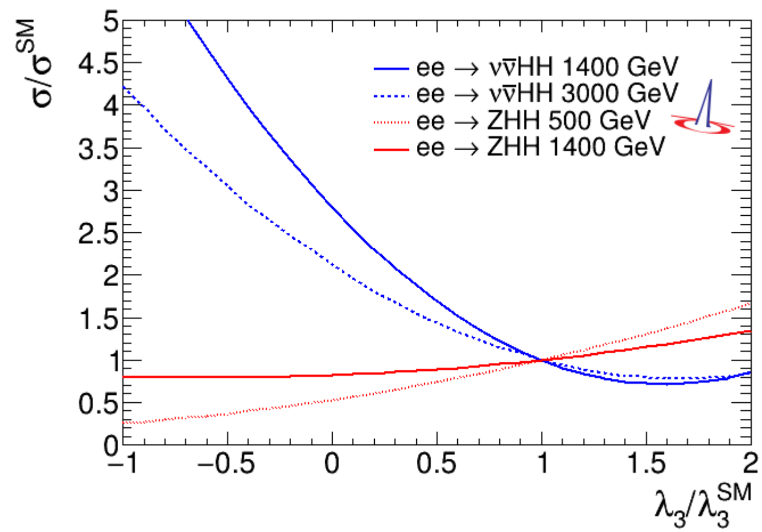


  - VBF $\nu\bar{\nu}HH$



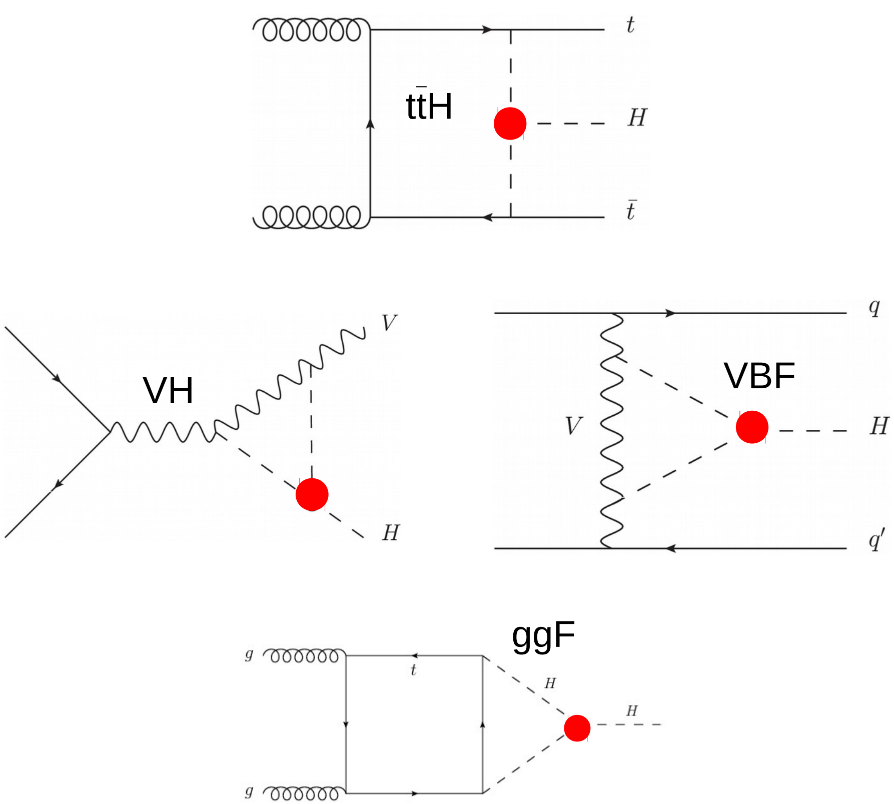
- Self-couplings through HH cross-section at different $\sqrt{s}$ + production modes + m_{HH}
  - ZHH stronger constraints for $\kappa_\lambda > 1$
  - $\nu\bar{\nu}HH$ stronger constraints for $\kappa_\lambda < 1$



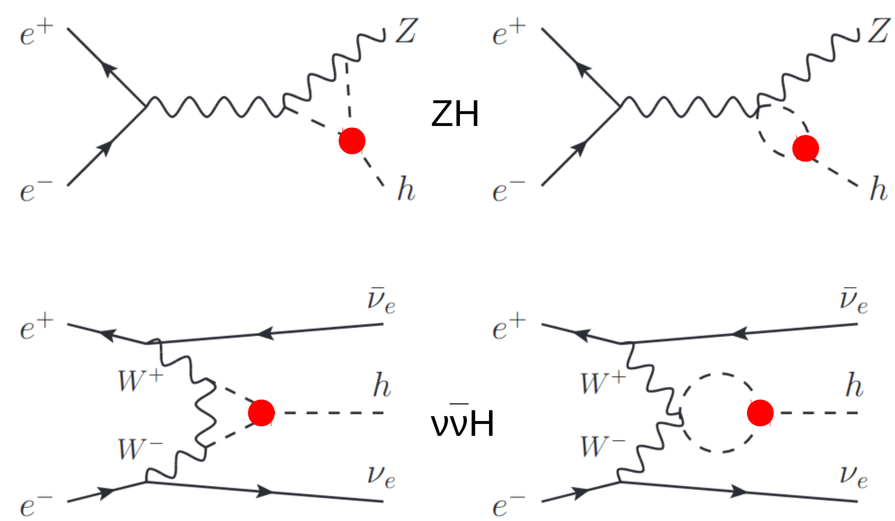


Self-coupling via single-Higgs couplings

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



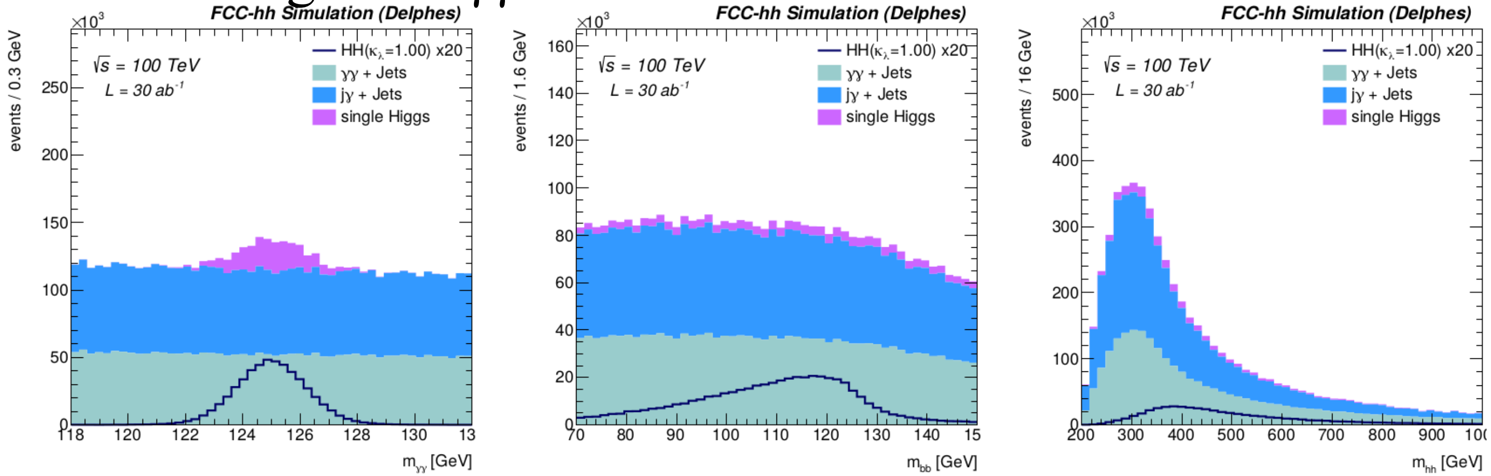
- ee colliders:



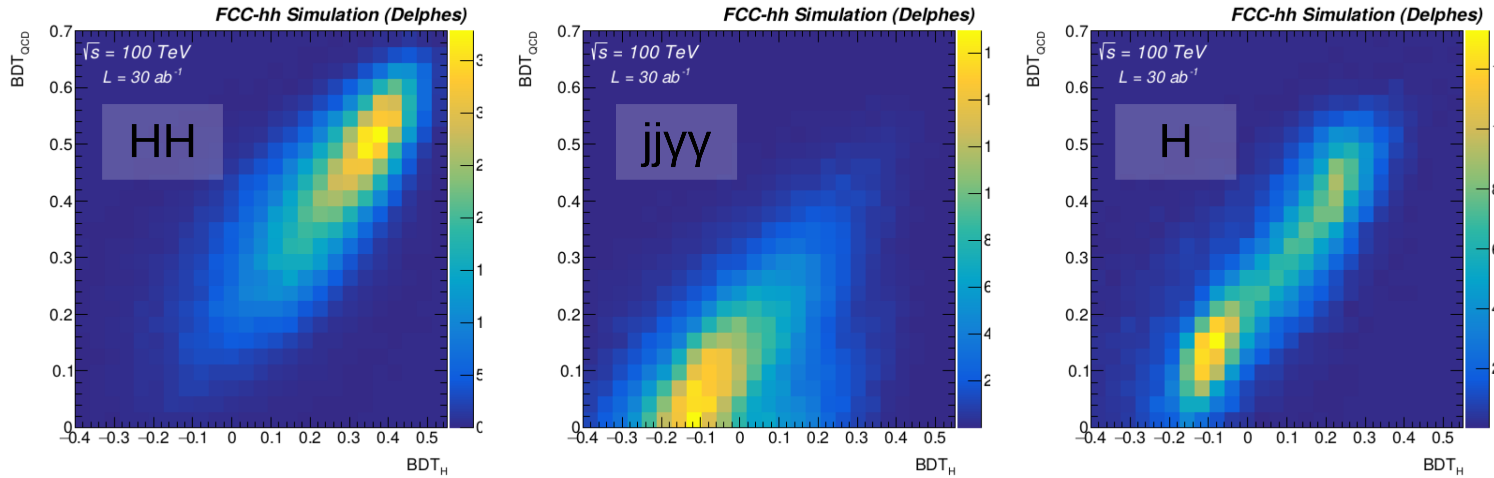
  - important when √s below HH threshold
- ex. for $\kappa_\lambda = 2$:
  - $\sigma(pp \to t\bar{t}H)$ modified by 3%
  - $\sigma(ee \to ZH)$ modified by 1%

FCC-hh HH → $b\bar{b}\gamma\gamma$ (1)

- Object efficiency:
  - $\varepsilon_\gamma = 85\%$ (p_T=50 GeV, η=0), $f_{j\to\gamma} = 0.002.e^{-pT/30GeV}$
  - $\varepsilon b = 85\%$, $f_{l\to b} = 1\%$, $f_{c\to b} = 5\%$ (p_T=50 GeV, η=0)
- Benefit from good mγγ resolution:

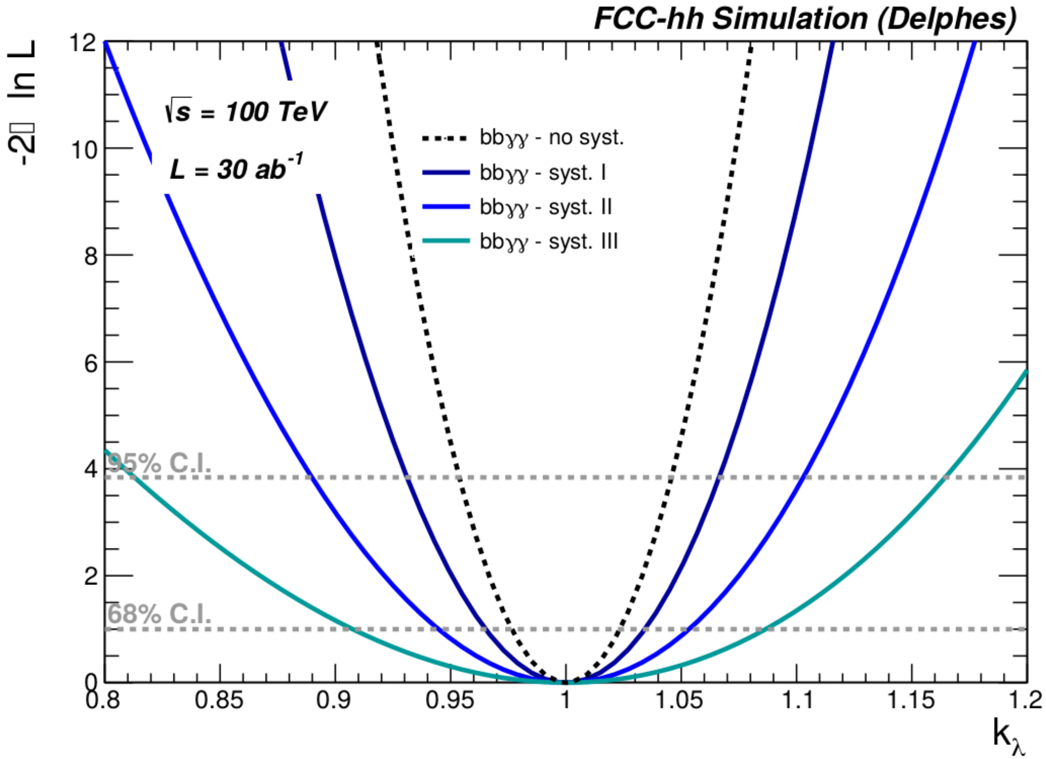


- BDT selection against QCD background and single-Higgs:



FCC-hh HH → $b\bar{b}\gamma\gamma$ (2)

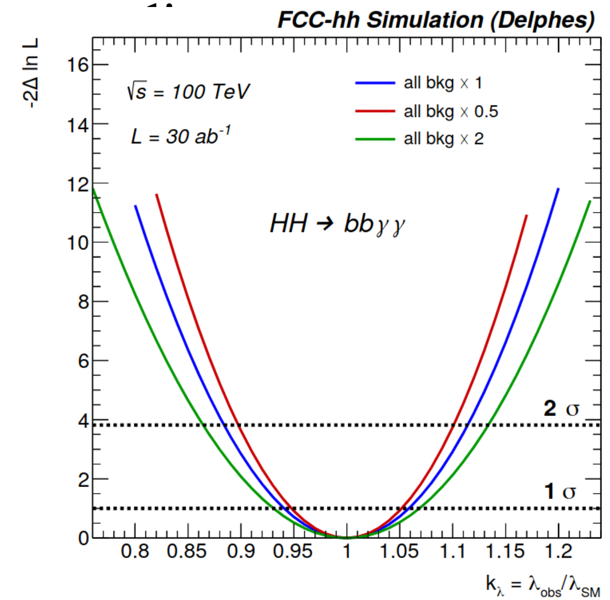
- Improved result wrt previous study
  - stat-only 68% CL: 5% → 2.5%

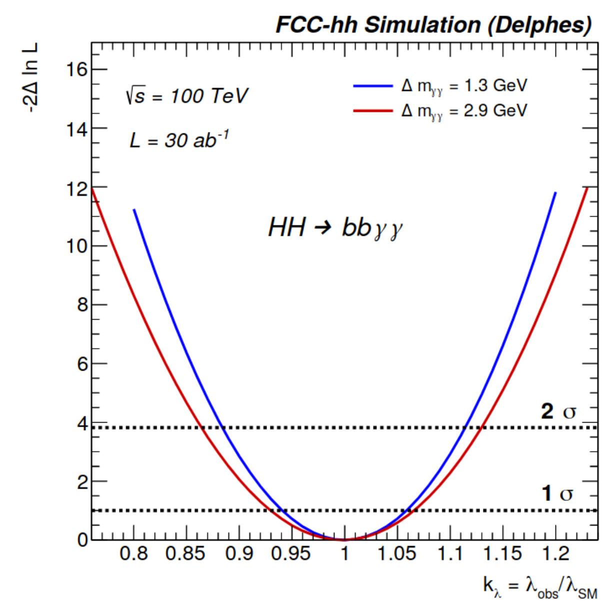


- Result limited by systematic uncertainties

$\delta_{\kappa_\lambda}(\%)$	no syst.	syst. I	syst. II	syst. III
68% CL	2.5%	3.5%	5.5%	8.5%
95% CL	4.5%	6.9%	10.5%	17.0%

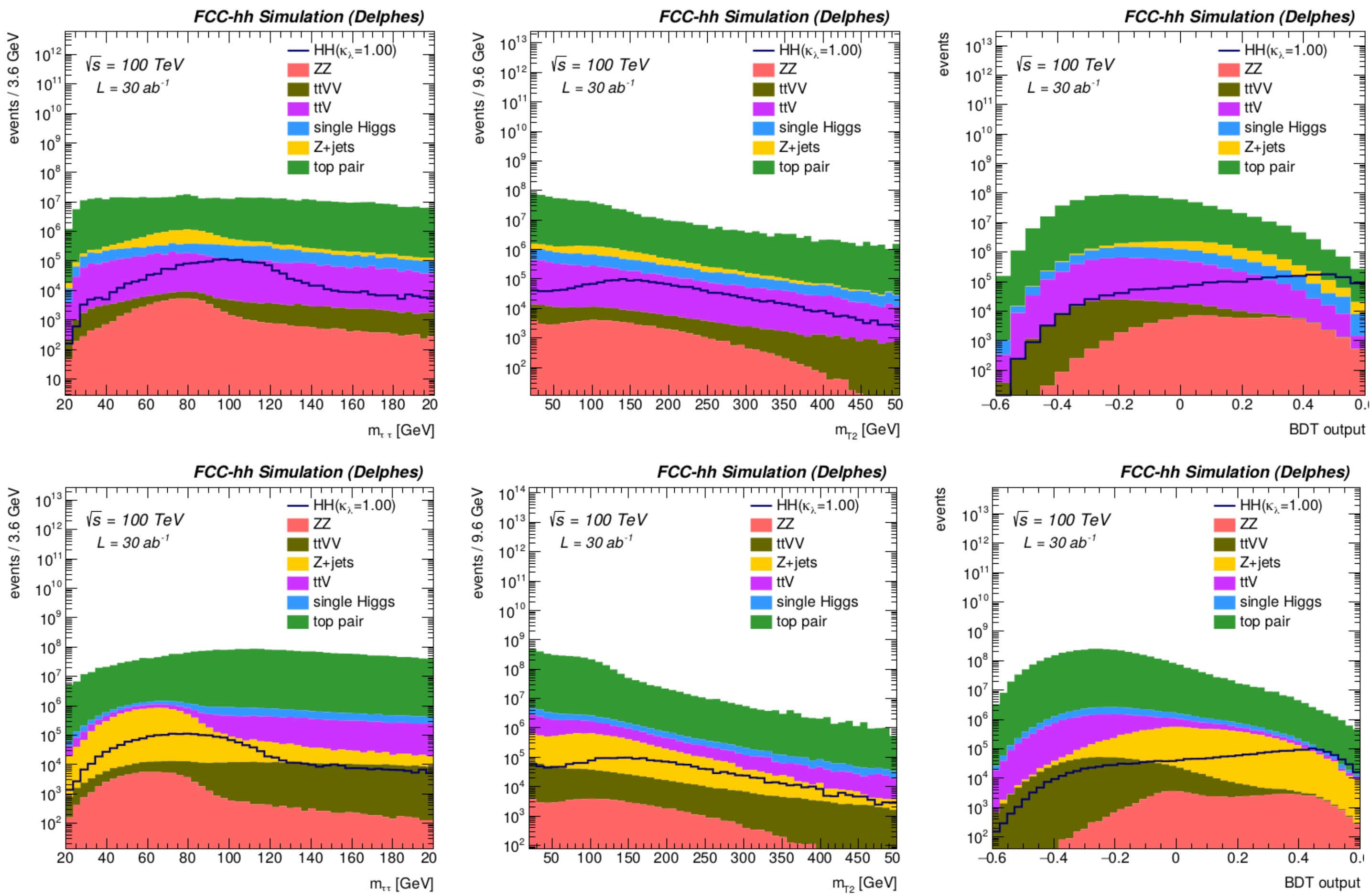
- Dependence on syst. uncertainties in previous





FCC-hh HH → $b\bar{b}\tau\tau$ (1)

- Two channels: $b\bar{b}\tau_h\tau_h$ and $b\bar{b}\tau_h\tau_l$
  - assume ε_{τ_h} = 80% and $f_{l\rightarrow\tau_h}$ = 1%
  - assume that QCD background could be constrained enough to be neglected
  - main backgrounds: Z+jets, single-Higgs, $t\bar{t}V$, $t\bar{t}VV$
- BDT selection:

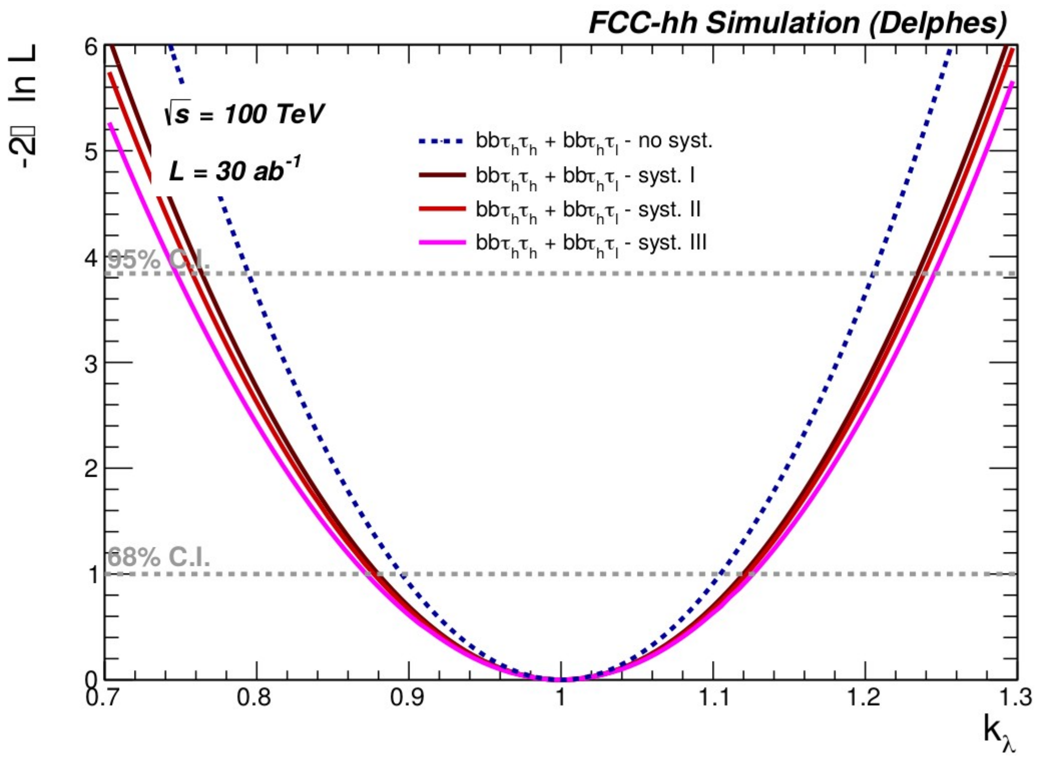


fully-hadronic

semi-leptonic

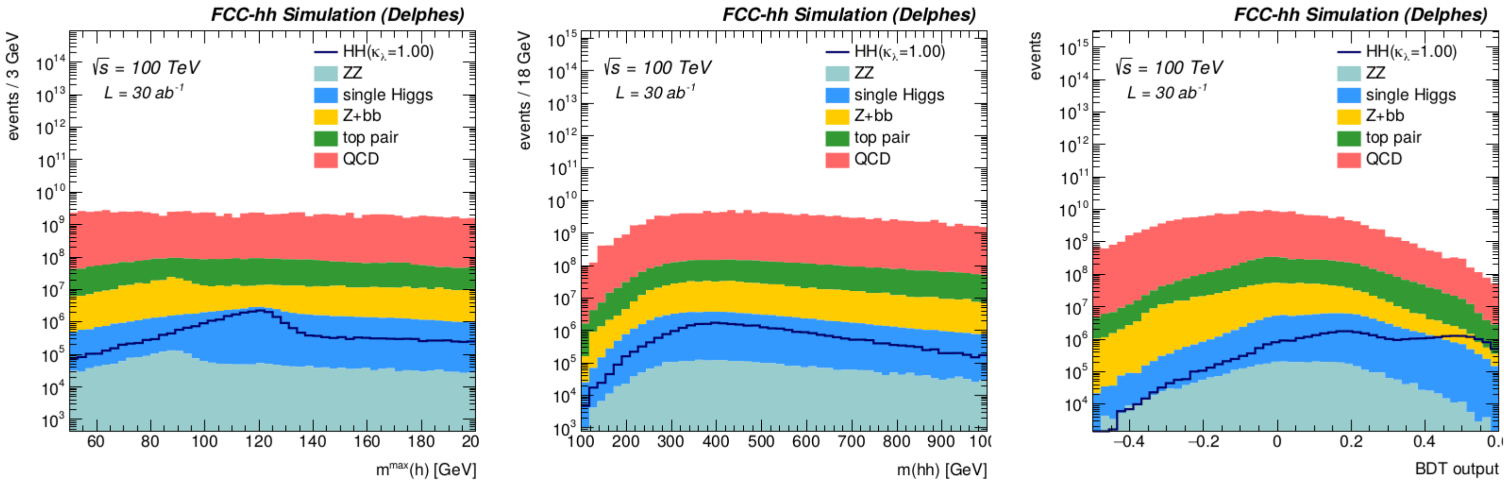
FCC-hh HH → $b\bar{b}\tau\tau$ (2)

- Expected 68% CL uncertainty on κλ: 12-13%
  - dominated by statistical uncertainty

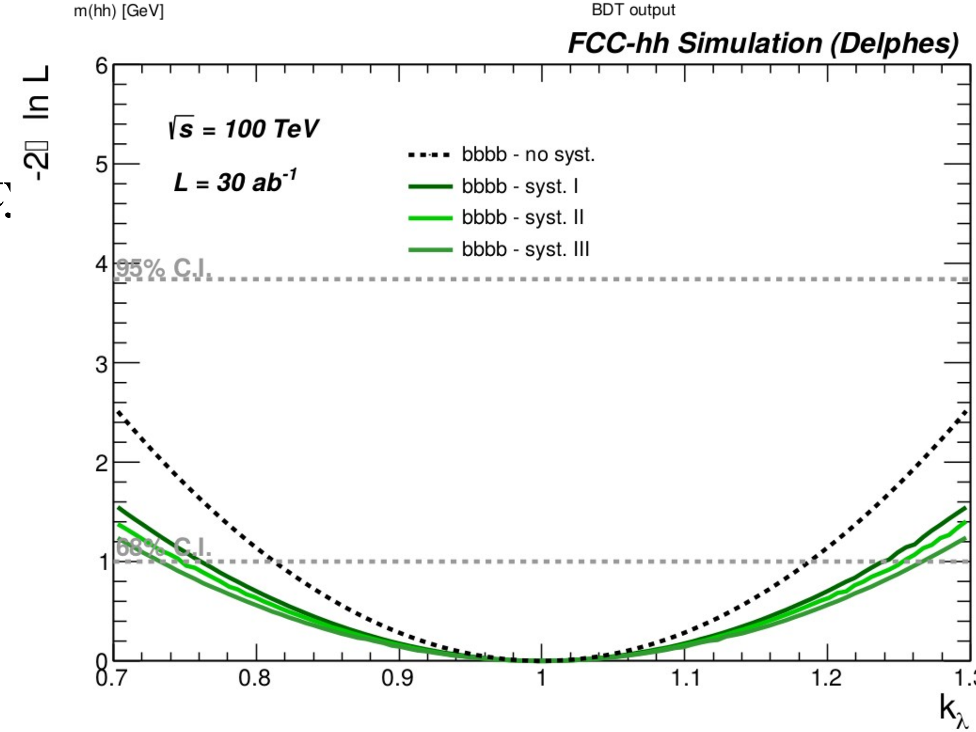


FCC-hh HH → $b\bar{b}b\bar{b}$

- Main background: QCD
  - BDT against it

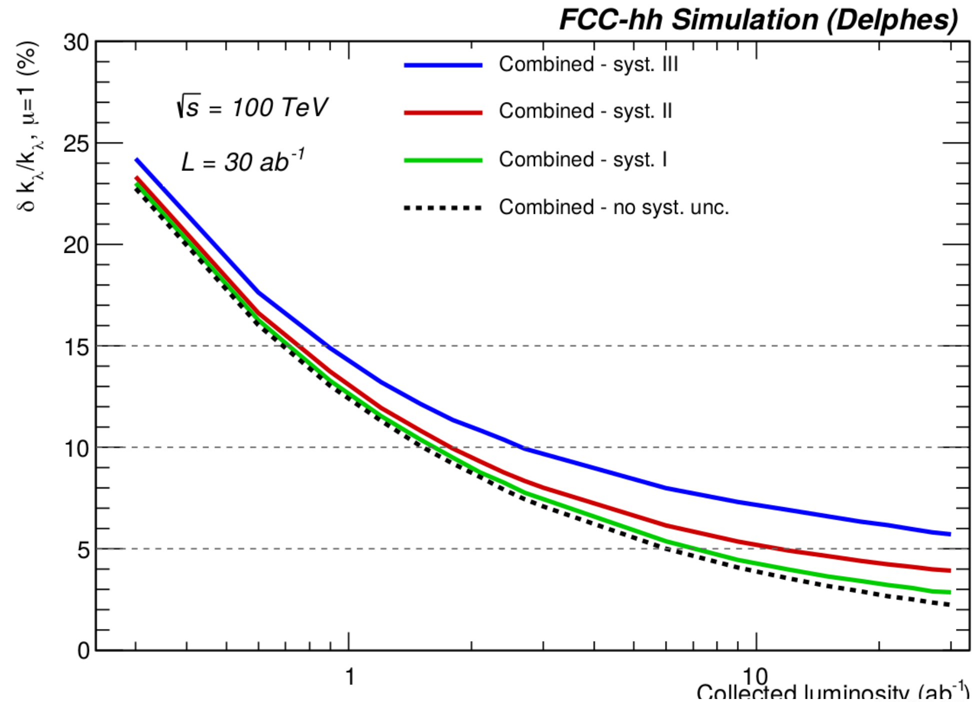


- 68% Cl uncertainty on κλ: 24-26%
  - dominated by statistical uncertaint

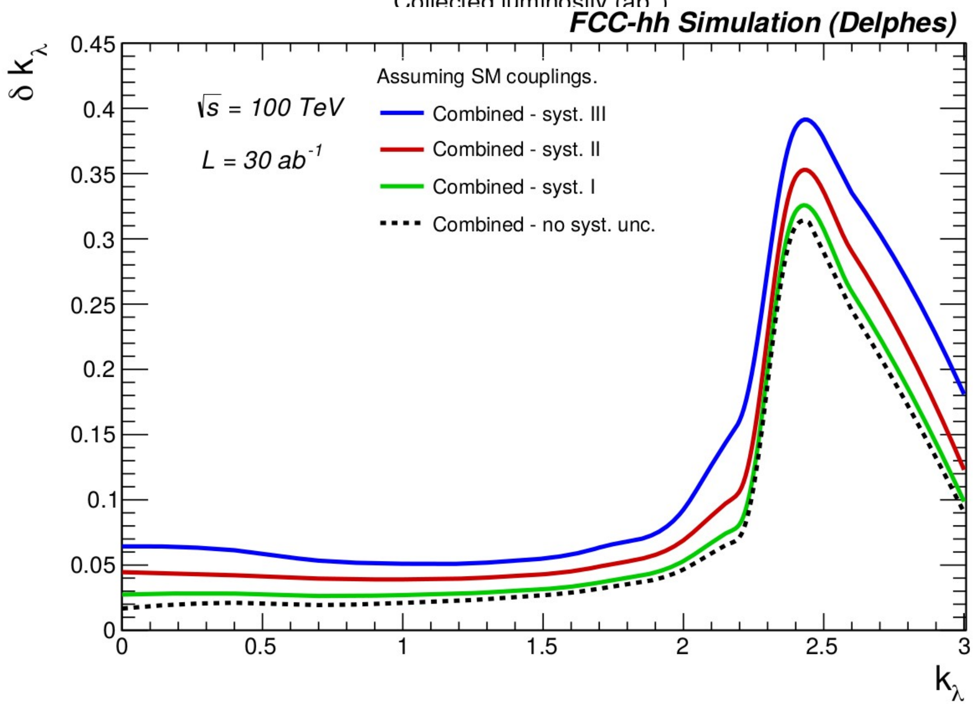


FCC-hh Combined HH results

- Evolution with time:

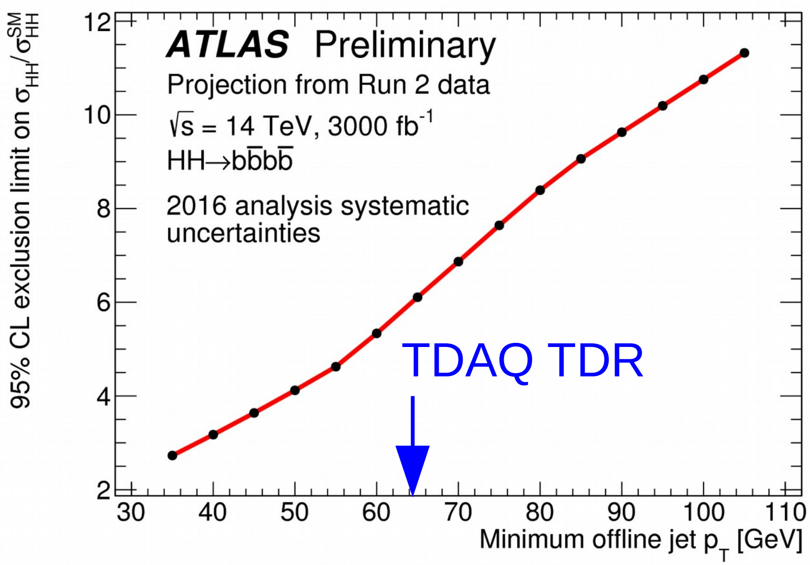


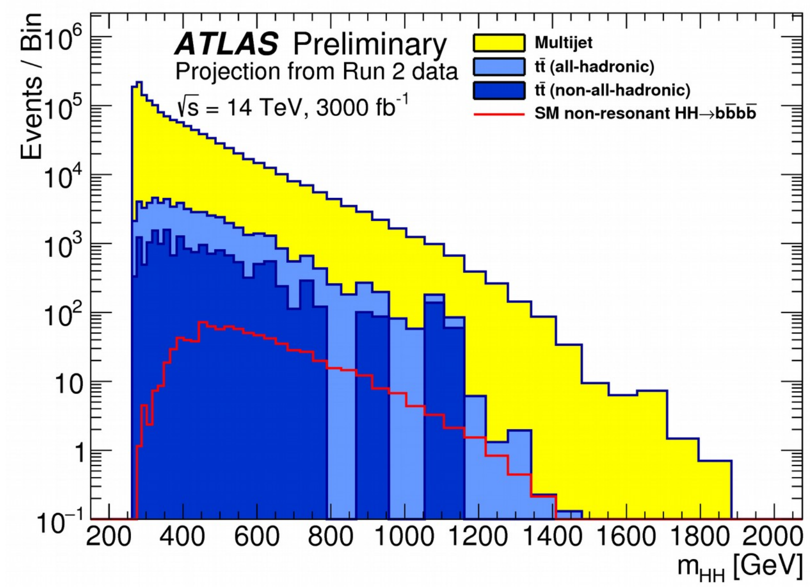
- 68% CL uncertainty on κ_λ for different values of κ_λ:
  - best precision for κ_λ=0
  - worst precision for κ_λ=2.4 (max interference)



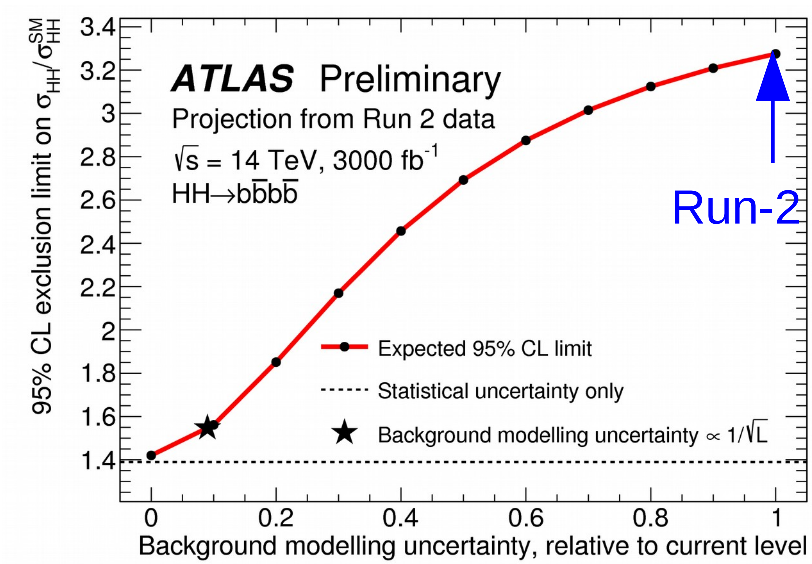
HH→$b\bar{b}b\bar{b}$ (ATLAS)

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





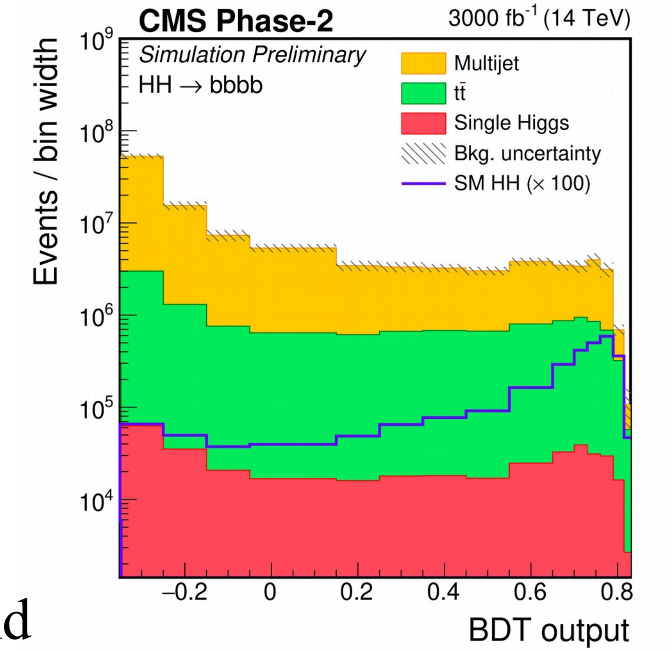
- Systematics
  - dominated by multijet data-driven model
  - conservative assumption: Run-2 systematics used



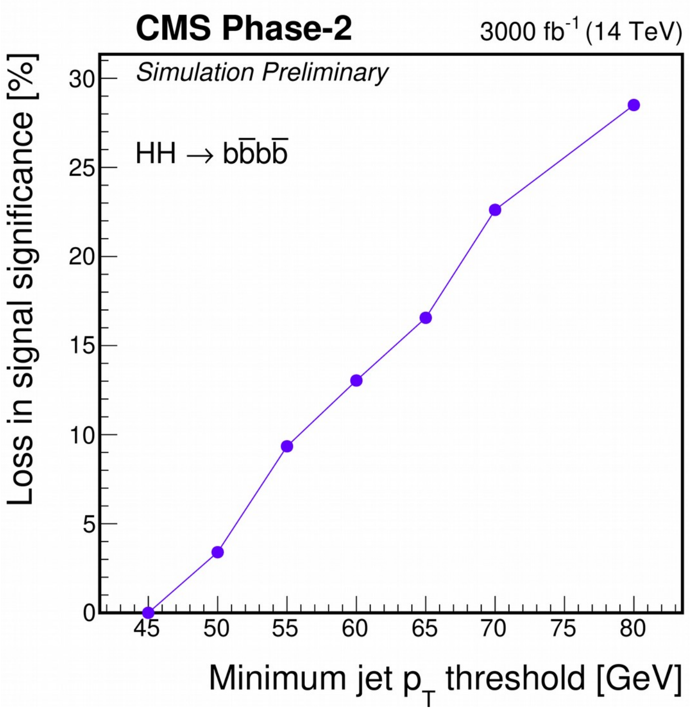
- Significance: 1.4/0.61σ without/with syst

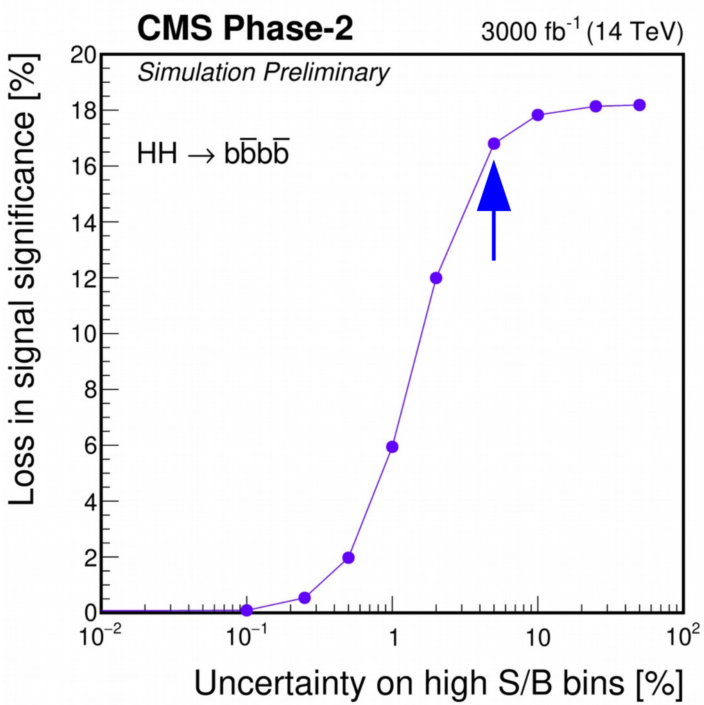
HH→b$\bar{b}$b$\bar{b}$ (CMS)

- 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



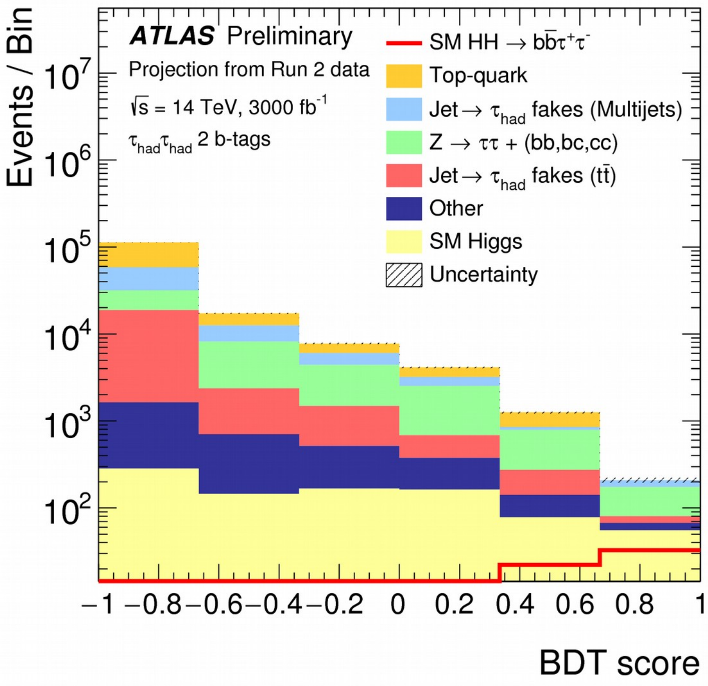
- Significance:
  1.2σ wo/syst
  0.95σ w/ syst

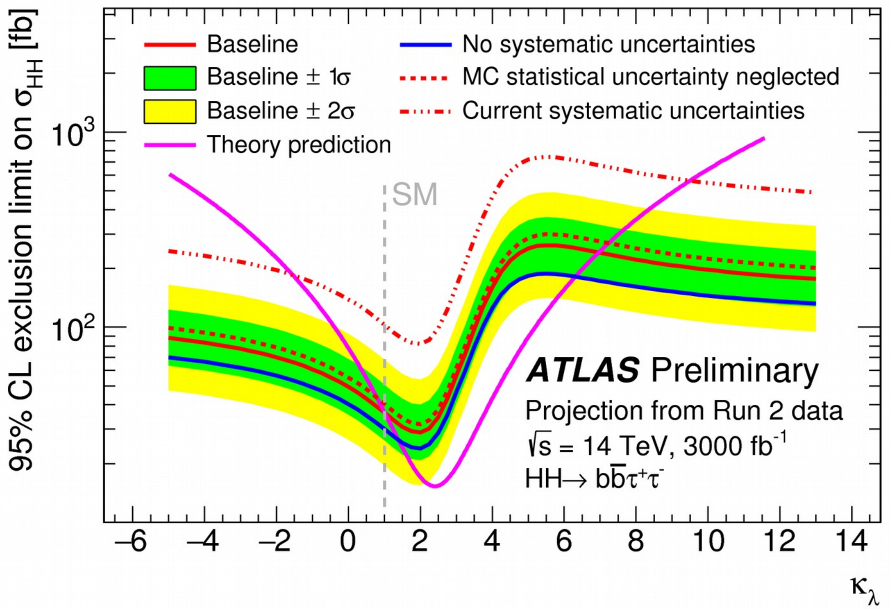




HH→$b\bar{b}\tau\tau$ (ATLAS)

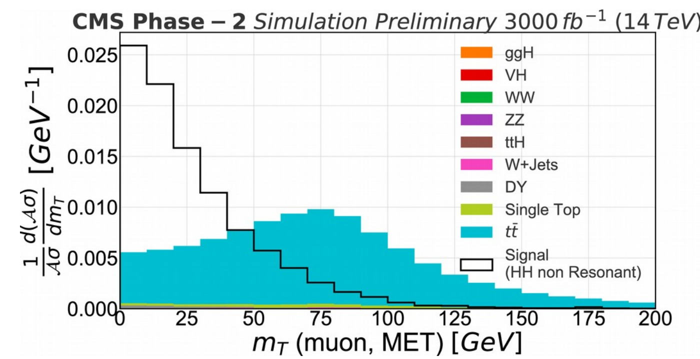
- Extrapolation from Run-2 analysis
- Three signal regions:
  - $\tau_{lep}\tau_{had}$ (Single Lepton Trigger)
  - $\tau_{lep}\tau_{had}$ (Lepton Tau Trigger)
  - $\tau_{had}\tau_{had}$ (Single Tau Trigger and Di-Tau Trigger)
- BDT output used as final discriminant
  - binning adapted to higher statistics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



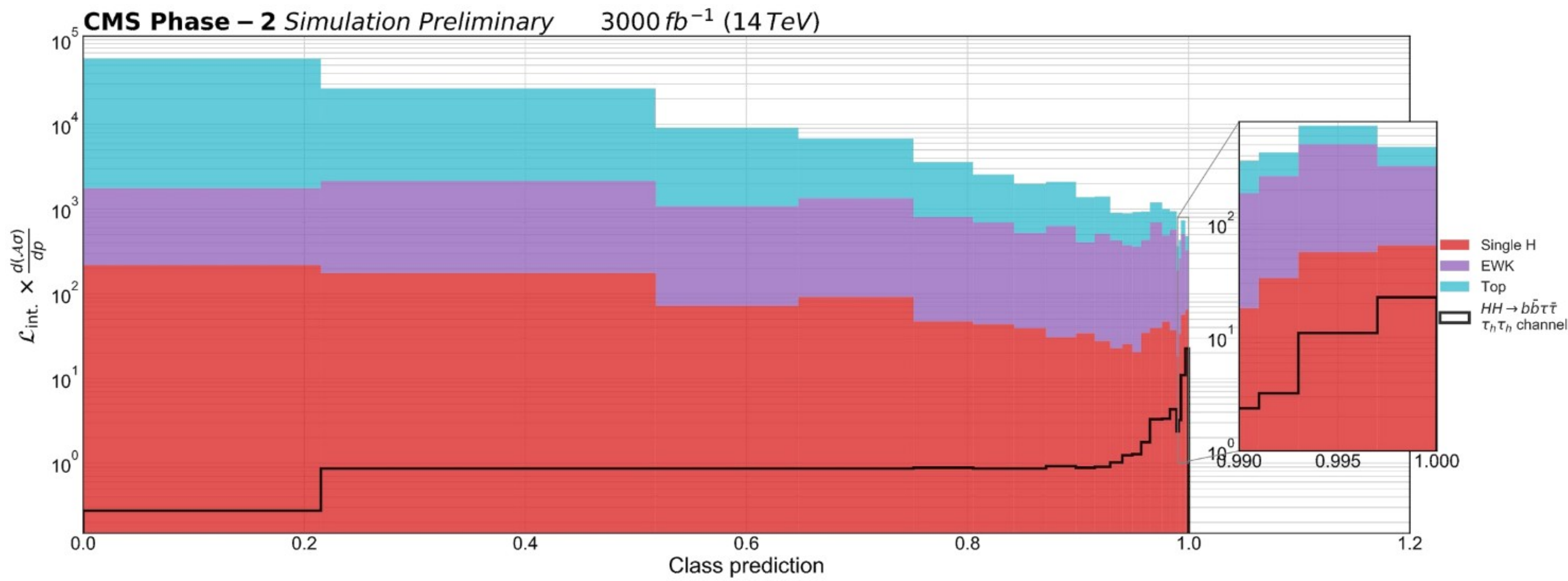


HH→$b\bar{b}\tau\tau$ (CMS)

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



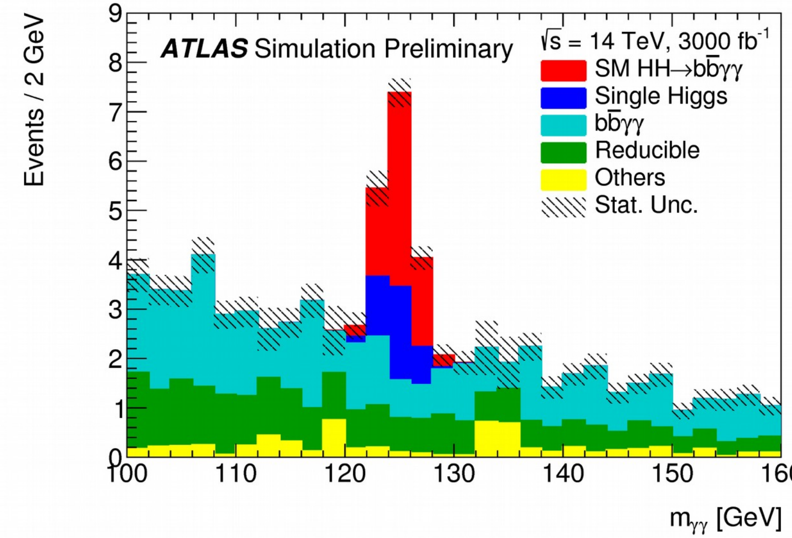
- Use of a Deep Neural Network
  - 27 basic + 21 reconstructed + 4 global features
  - deep learning techniques, with optimal data preprocessing, study of the activation functions, and data augmentation

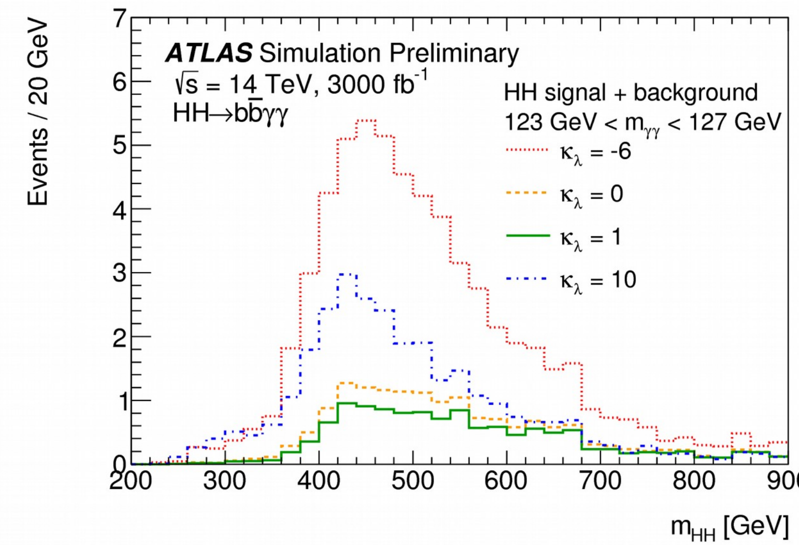


- Simultaneous fit of the NN output for the 3 decay channels
  - discriminant binned per decay channel via adaptive binning
- Significance: 1.6/1.4σ without/with syst

HH→$b\bar{b}\gamma\gamma$ (ATLAS)

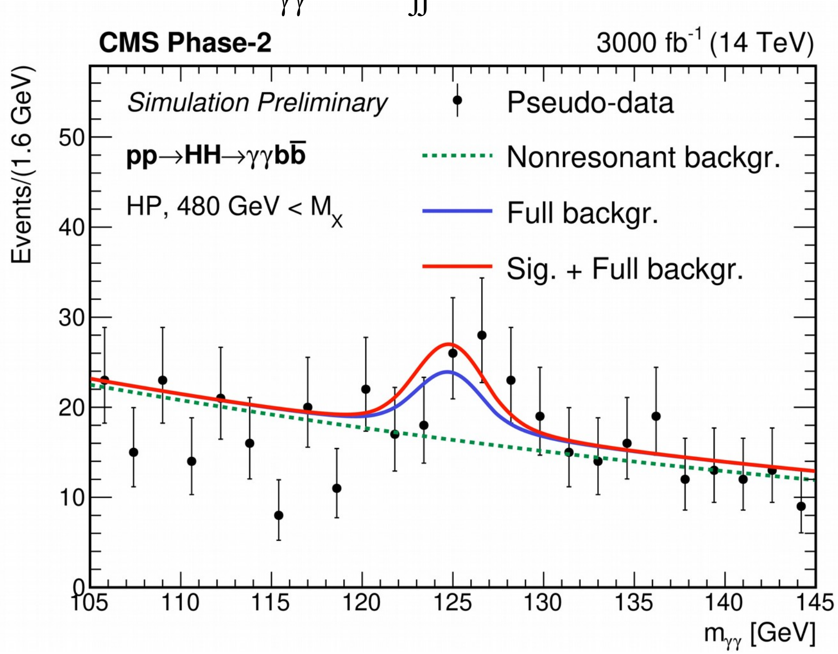
- Dedicated analysis with smearing functions: upgraded detector geometry and performance functions
  - $m_{\gamma\gamma}$ resolution ~ 1.6 GeV
- Dedicated BDT trained to remove continuum background and main single-Higgs background ($t\bar{t}H$)
- Limit on κ_λ: use of the $m_{b\bar{b}\gamma\gamma}$ distribution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

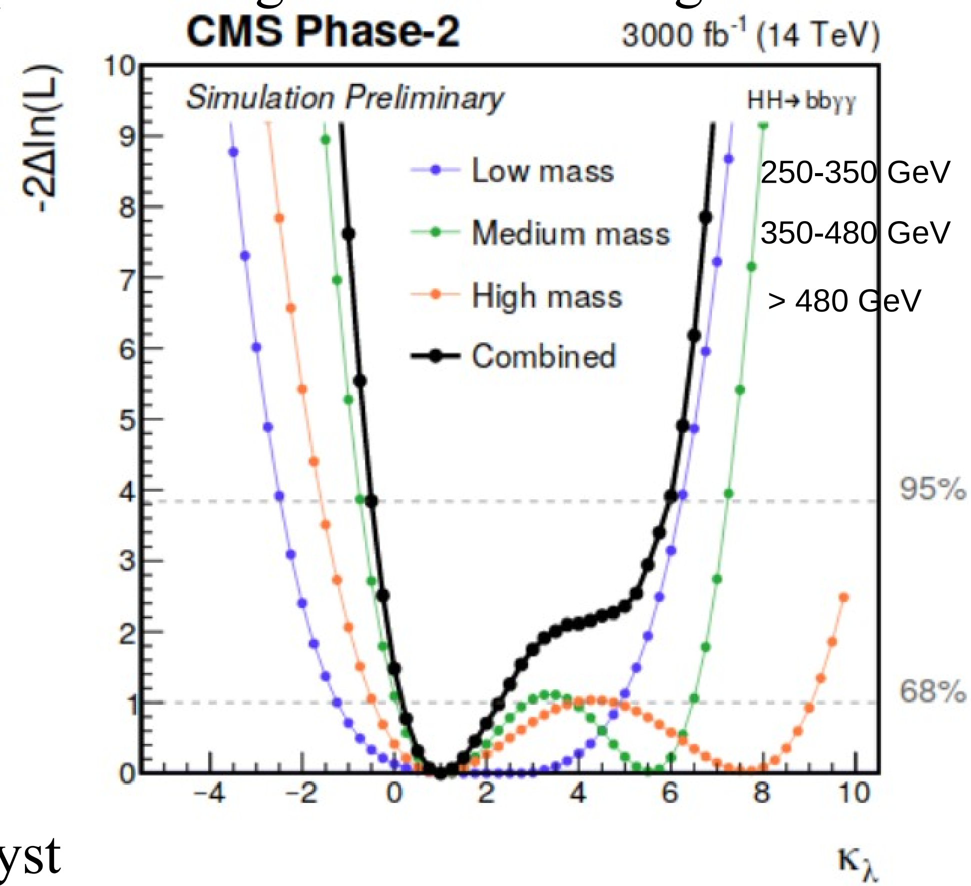




$HH\to b\bar{b}\gamma\gamma$ (CMS)

- 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

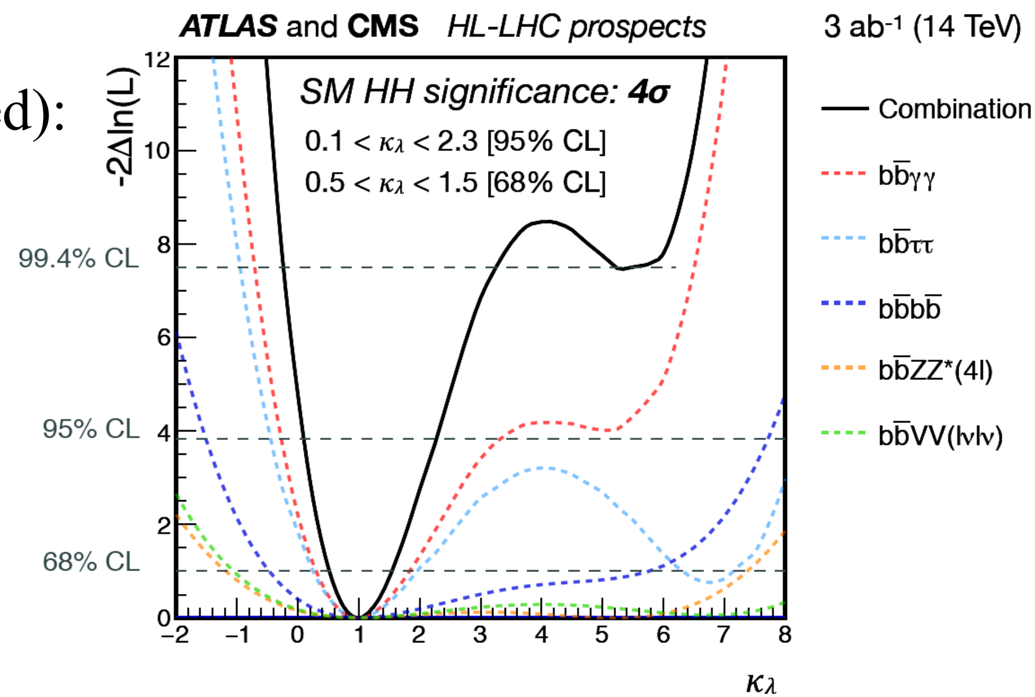
HL-LHC Combined results (1)

- 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	

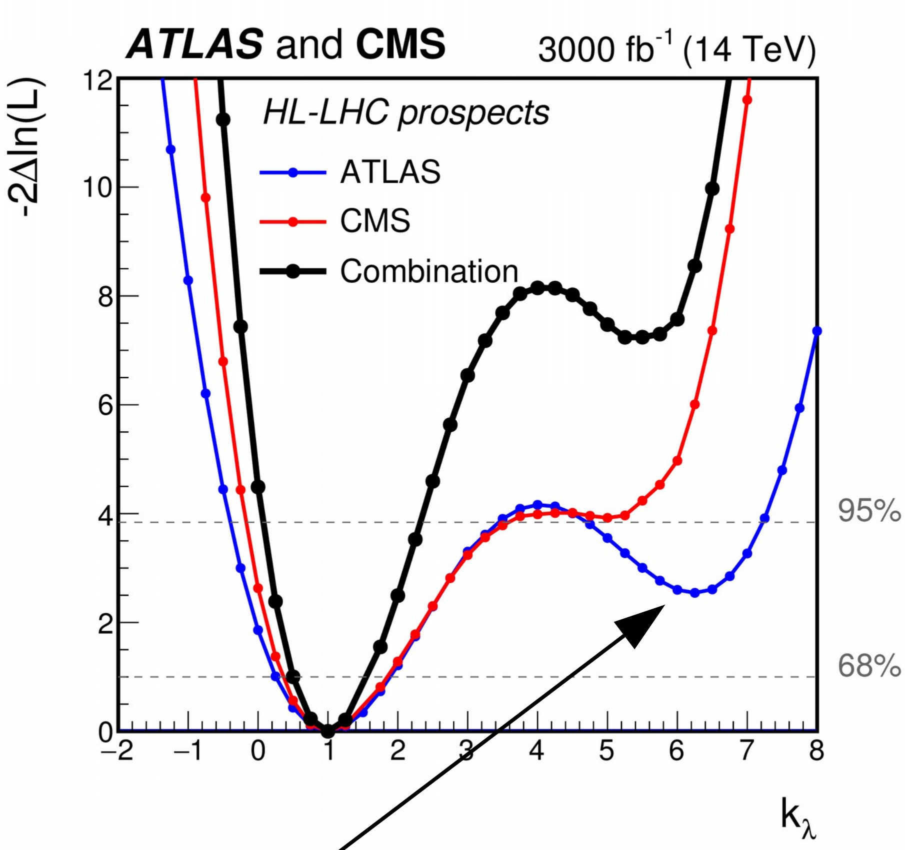
  – 4σ expected with ATLAS+CMS!

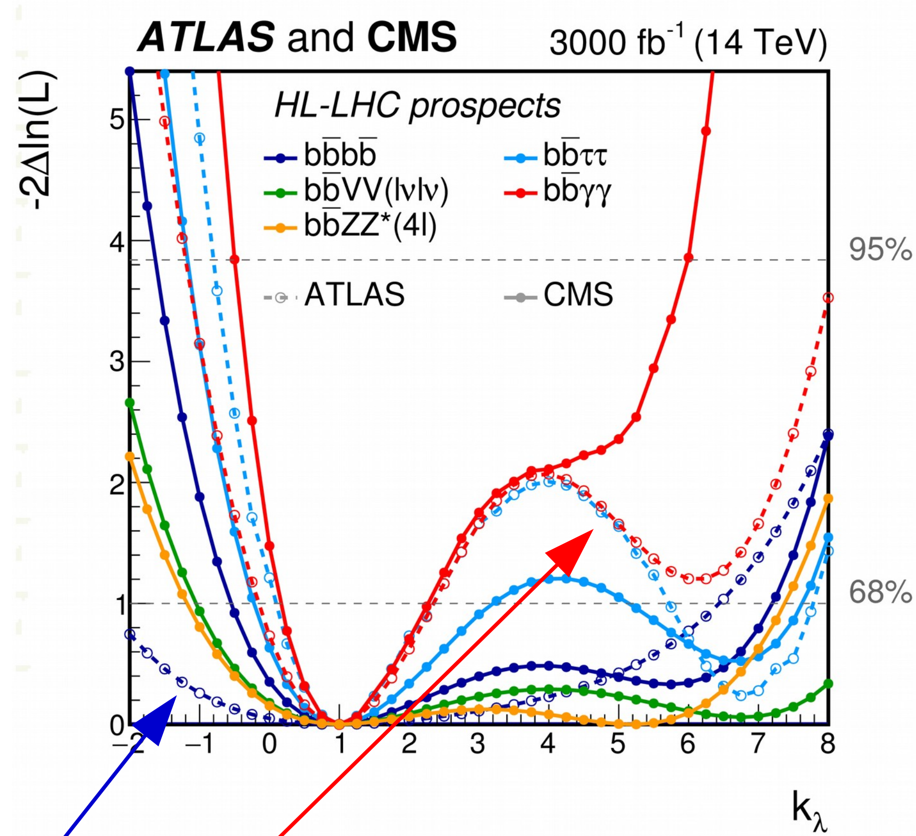
- Measurement of μ (SM signal injected):
  – δμ/μ ~25% (30%) without (with) systematics
- μ = 0 (no SM HH signal) excluded at 95% CL
- Measurement of κ_λ:
  – 68% CI: [0.5; 1.5]
  – 2[nd] minimum excluded at 99.4% CL thanks to the m_{HH} shape information



HL-LHC Combined results (2)

- Comparison of negative log-likelihood ratios:

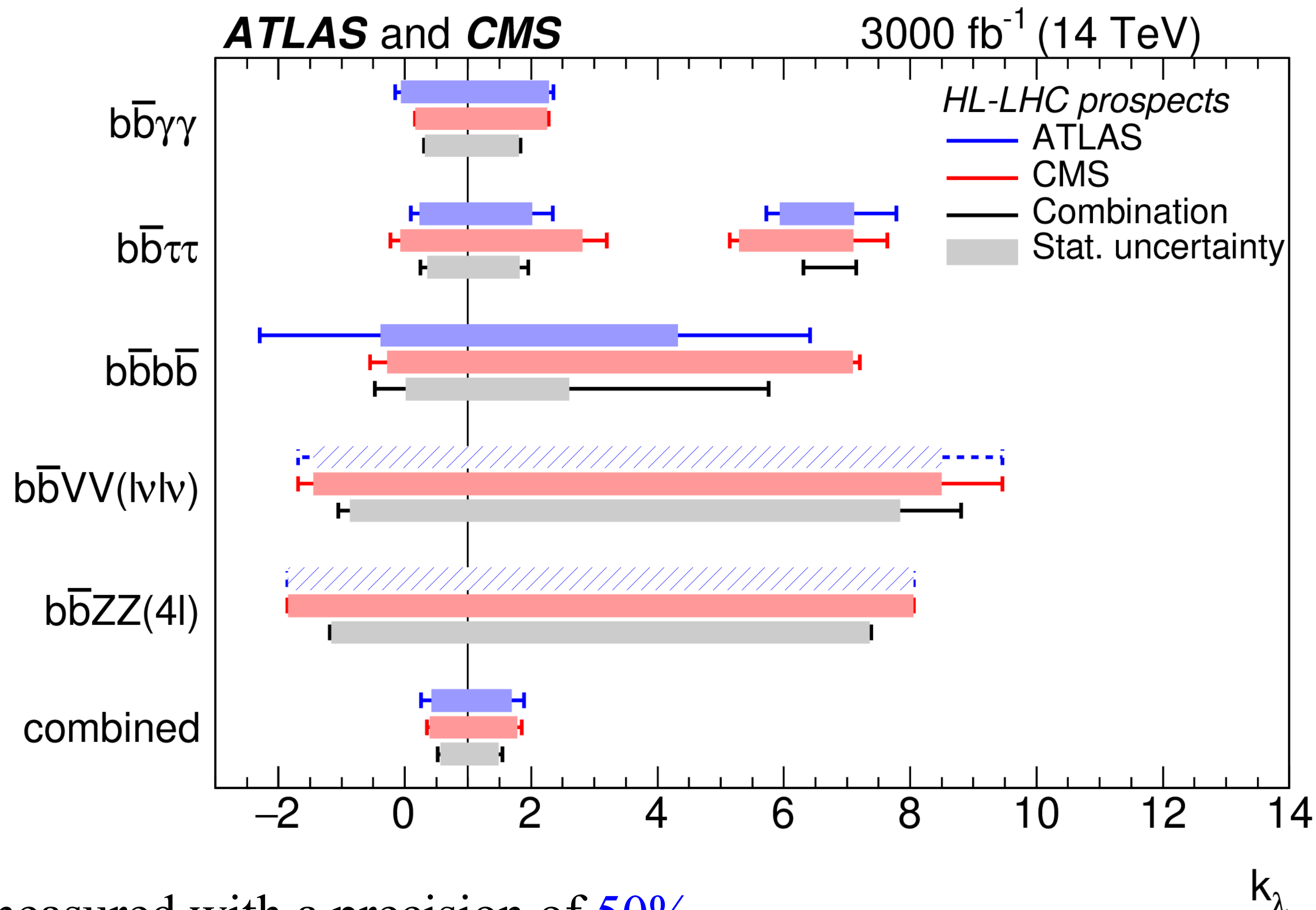




- Difference on 2nd minimum mainly from the $b\bar{b}\gamma\gamma$ channel: 3 categories of m_{HH} (especially a low-m_{HH} one) to remove the degeneracy around κ_λ=6 (while this low-m_{HH} category has no effect around 1)
- CMS slightly better below 1: $b\bar{b}b\bar{b}$ + other smaller channels

HL-LHC Combined results (3)

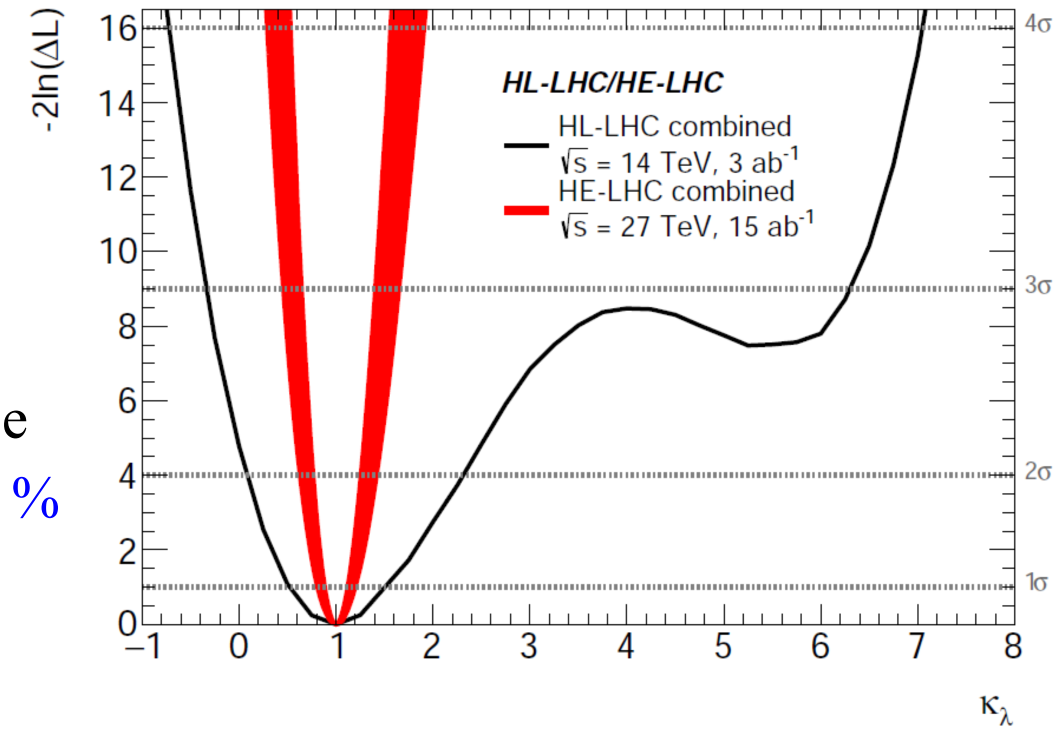
- 68% CI, channel by channel
- Dashed line = no ATLAS analysis, using value from CMS (as for Higgs couplings)



- κ_λ measured with a precision of 50%

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 %



Quartic couplings

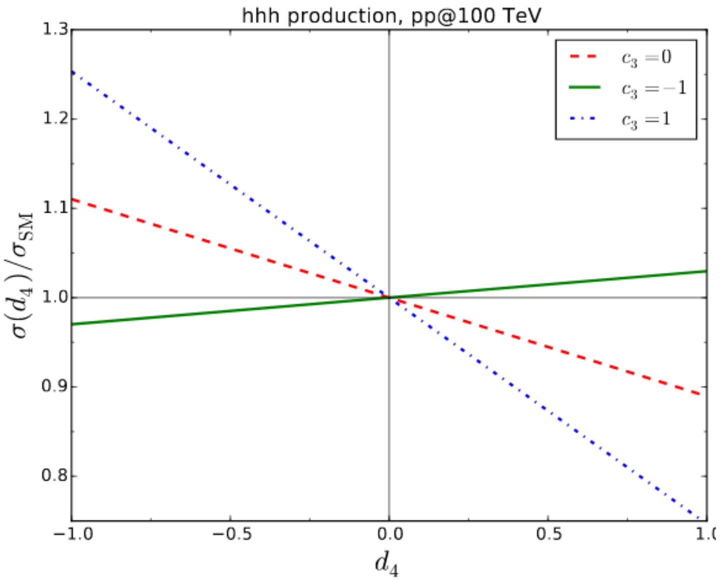
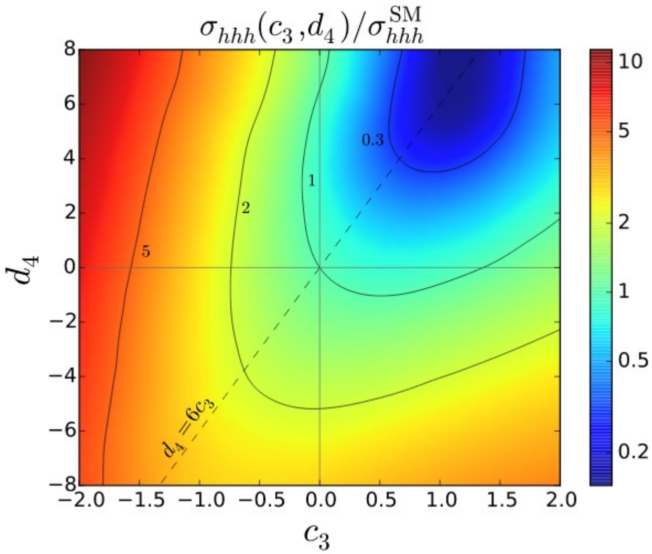
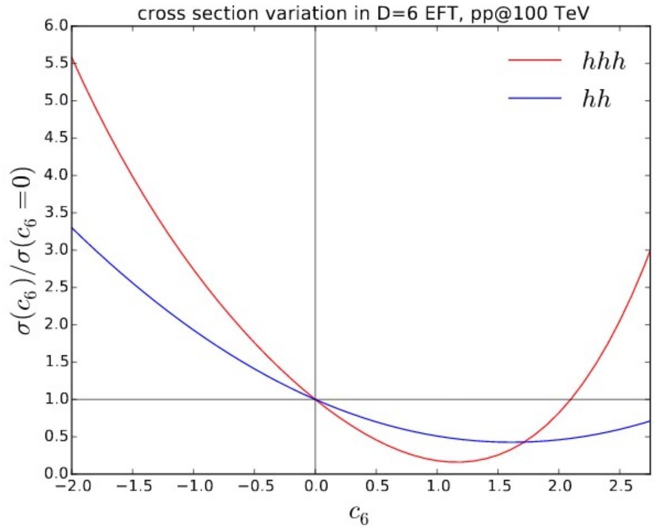


FIG. 2: Total cross section ratio normalised to the Standard Model values for gluon-fusion-initiated triple Higgs production at 100 TeV obtained by varying the c_3 and d_4 parameters independently (see Eq. 1). The Higgs boson mass was fixed to $m_h = 125$ GeV. The SM cross section at leading order is ~ 2.88 fb. The `NNPDF23_nlo_as_0119` parton density function set was used.

$$V_{\rm self} = \mu^2 |H|^2 + \lambda |H|^4 + \mathcal{O}_6, \; \mathcal{O}_6 \equiv \frac{c_6}{\Lambda^2} \lambda |H|^6,$$

$$c_3 = c_6, \; d_4 = 6 c_6$$





$$\frac{\sigma(c_3, d_4)_{hhh}}{\sigma(\mathrm{SM})_{hhh}} - 1 = 0.0309 \times c_3^4 - 0.2079 \times c_3^3$$
$$+ 0.0407 \times c_3^2 d_4 + 0.7384 \times c_3^2$$
$$+ 0.0156 \times d_4^2 - 0.1450 \times c_3 d_4$$
$$- 0.1078 \times d_4 - 0.6887 \times c_3$$

1909.09166

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:

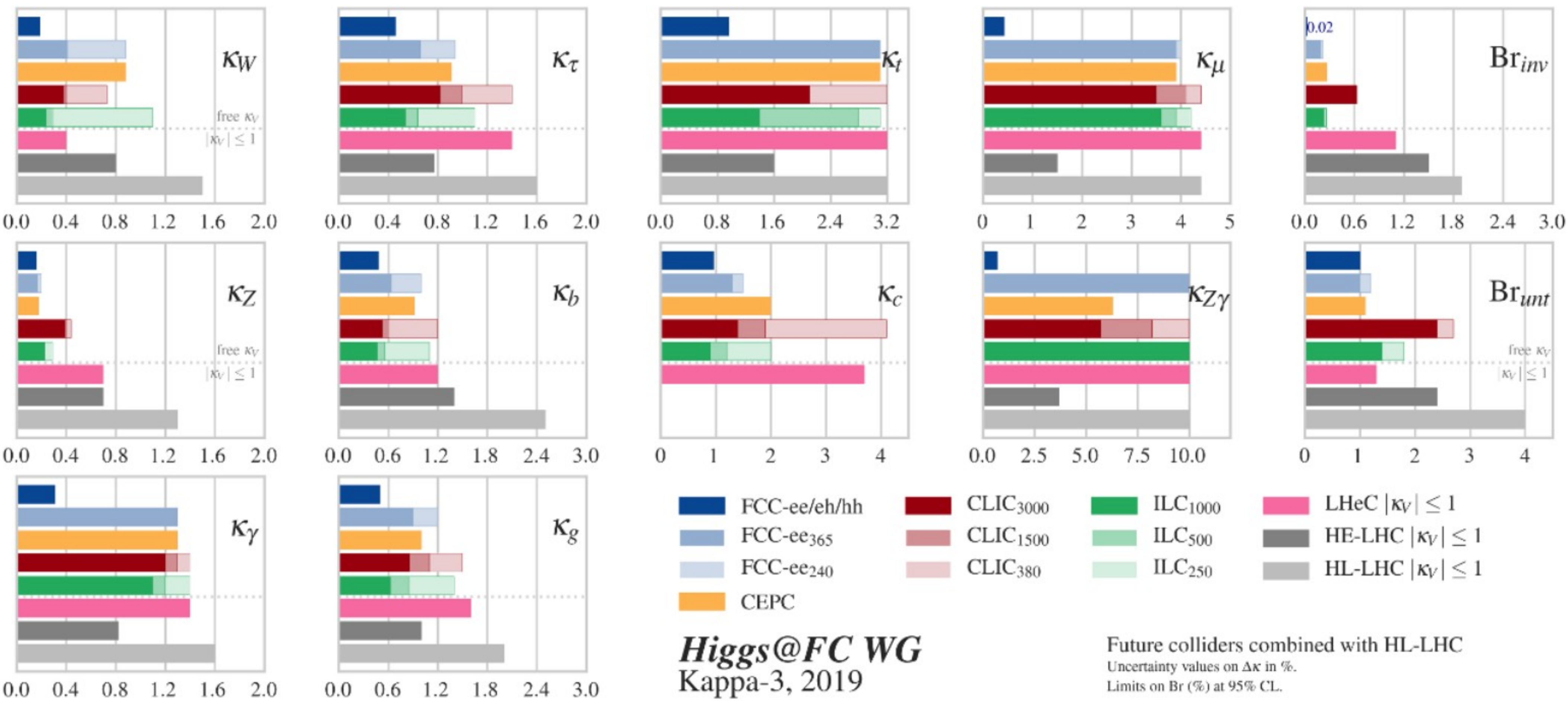
$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{\mathrm{inv}} + BR_{\mathrm{unt}})}$$

- 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 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

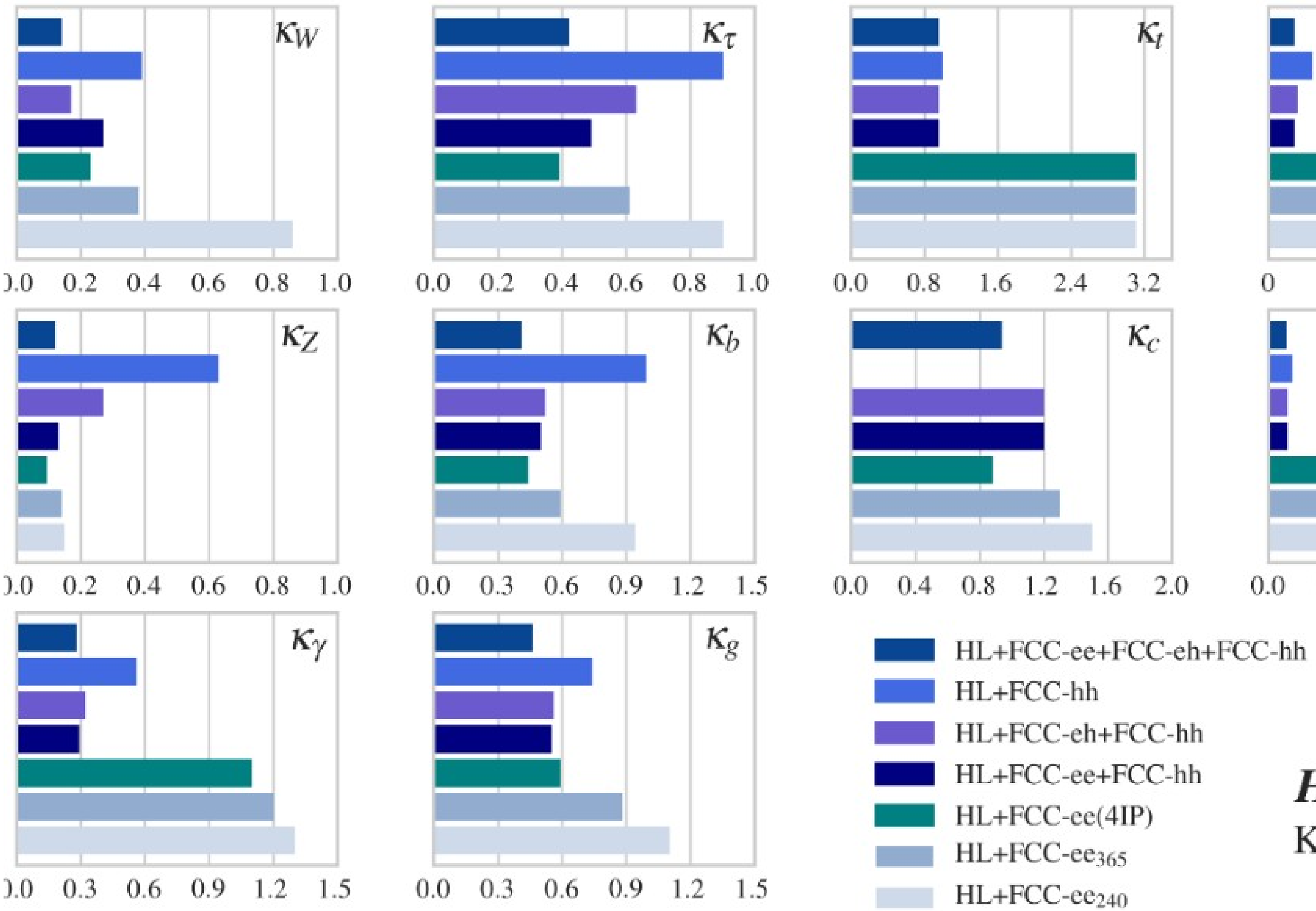
	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.6	1.4	2.8	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	≥ 10^2	≥ 10^2	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	≥ 10^2	≥ 10^2	≥ 10	≥ 10^2	≥ 10^3	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

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

Higgs couplings: additional scenarios (1)

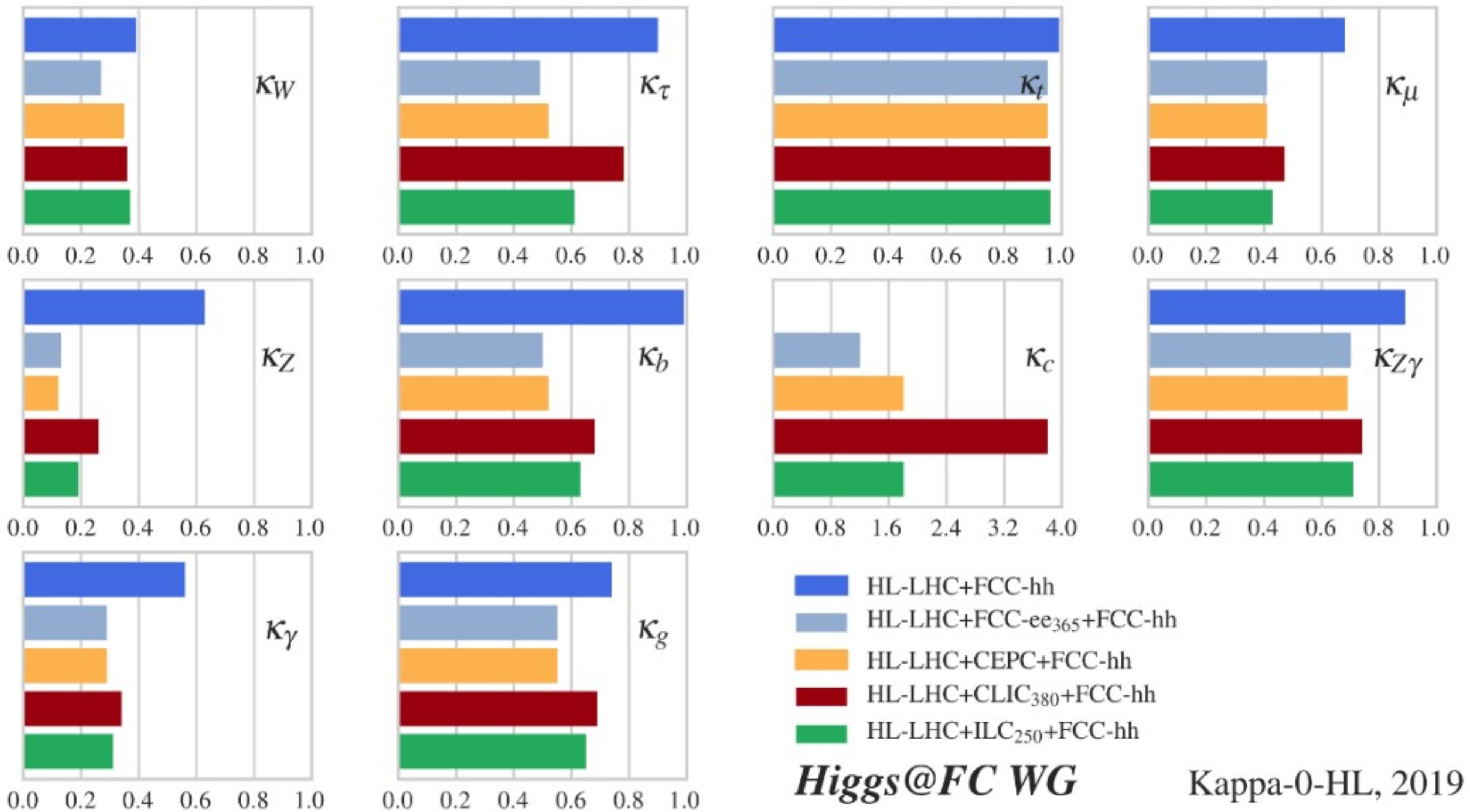
- Comparison of the different FCC scenarios in the kappa-0-HL scenario (similar to kappa-0 in that it does not allow any BSM decay, but including HL-LHC data)



Higgs@FC WG
Kappa-0-HL, 2019

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