Constraining the Higgs boson self-coupling at the ATLAS experiment

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B. Di Micco
on behalf of the ATLAS collaboration

Università degli Studi di Roma Tre

The SM after Higgs boson discovery and measurements

$$
\begin{aligned}
\mathcal{L} = \\
& -\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a} \\
& +\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{\ell}_i i\not{D}\ell_i \\
& + \left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i \ell_j H + c.c.\right) \\
& -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H
\end{aligned}
$$

not observed

not observed in: e, μ, c, u, d, s
(coupling to ordinary matter still to be proven!!)

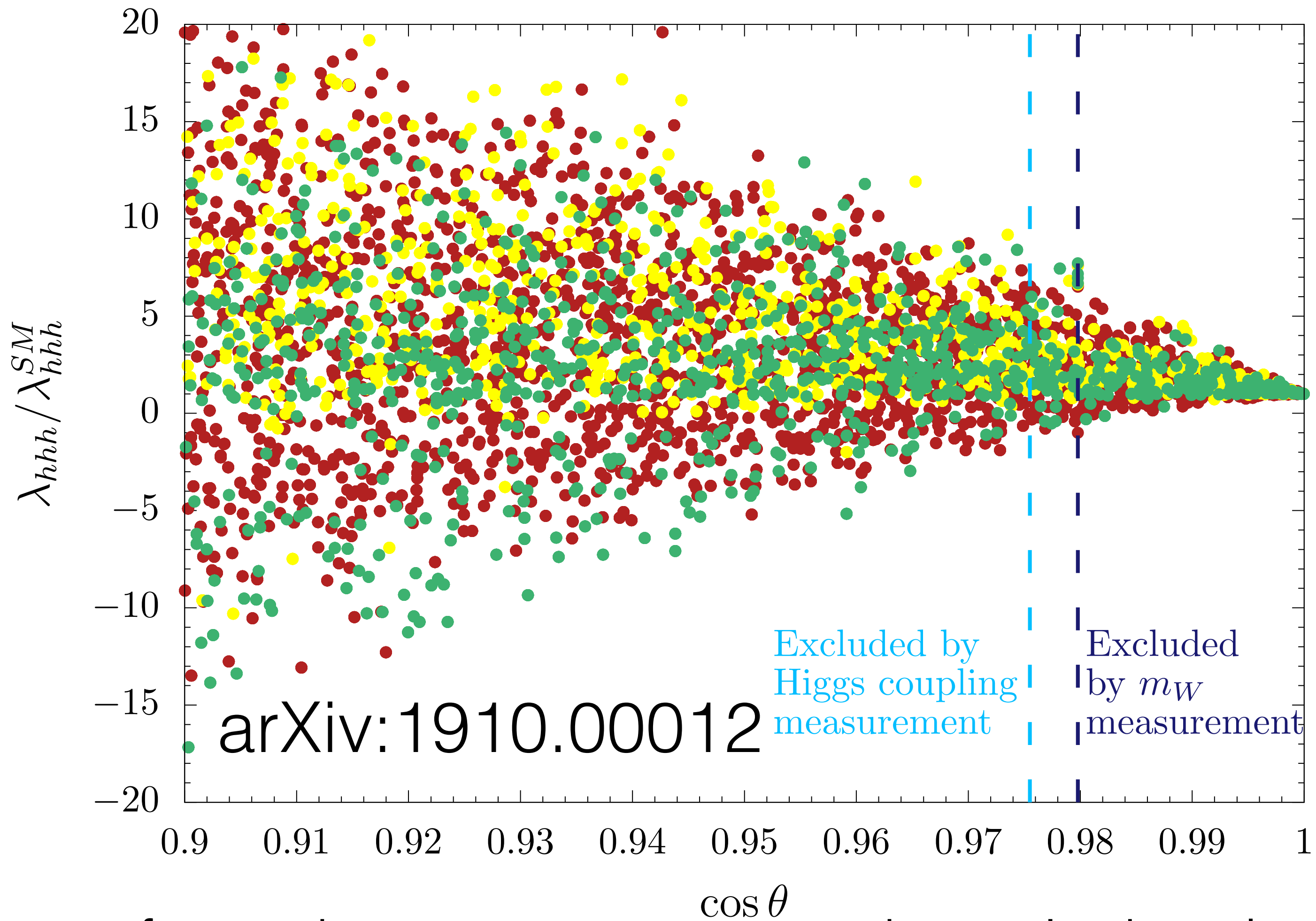
- define the Higgs boson energy potential, it is still unobserved
- the potential term is a peculiarity of the Higgs boson, no other field in the SM has a potential term

Studying the Higgs boson at the highest possible precision is now a priority of LHC physics

Room for new physics in Higgs self-coupling

Possible impact of new physics on the Higgs potential parameters:

- it can be evaluated using a singlet model: addition of a SU(2) singlet to the SU(2) doublet of the SM;
- relevant parameters: mixing of the singlet with the doublet (θ) and modification of the Higgs self coupling λ_{HHH}.



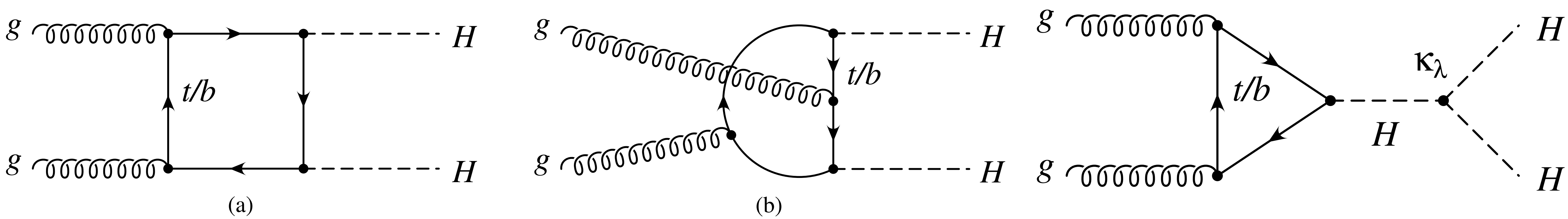
Parameter space underconstrained, scan performed on parameters not shown in the plot
The singlet affect the Higgs boson potential and can affect vacuum stability and comsmogenesis

Vacuum stability: red: unstable yellow: metastable green: stable

The present constraints leave space for modification of λ_{HHH} by large factors

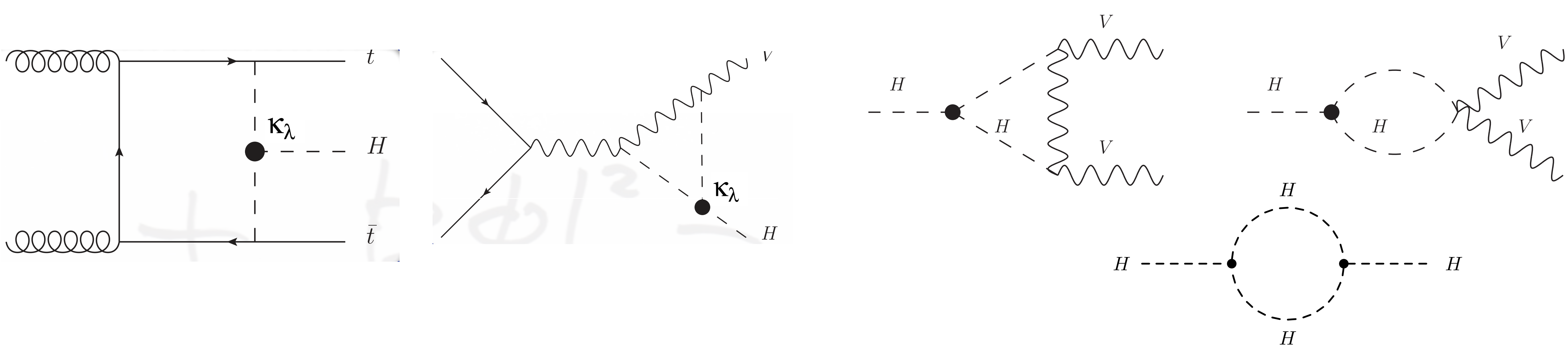
How to access the Higgs boson self-coupling

Direct production: $pp \rightarrow HH$ $\kappa_t = y_t/y_t^{SM}$ $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$



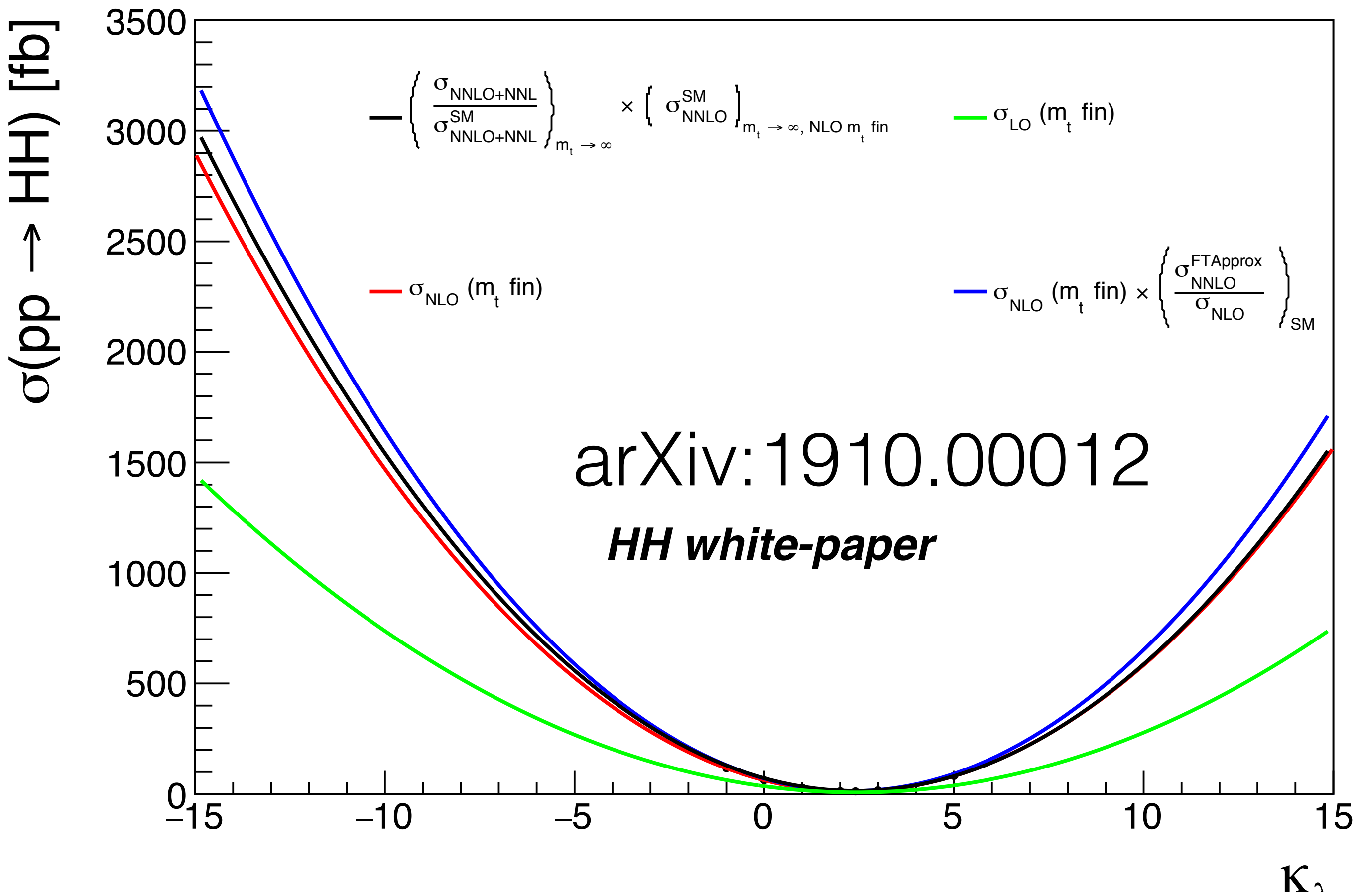
Irreducible SM background depends on k_t, self coupling enters multiplied by κ_t as well.

Indirect determination from single-Higgs production cross section and decay

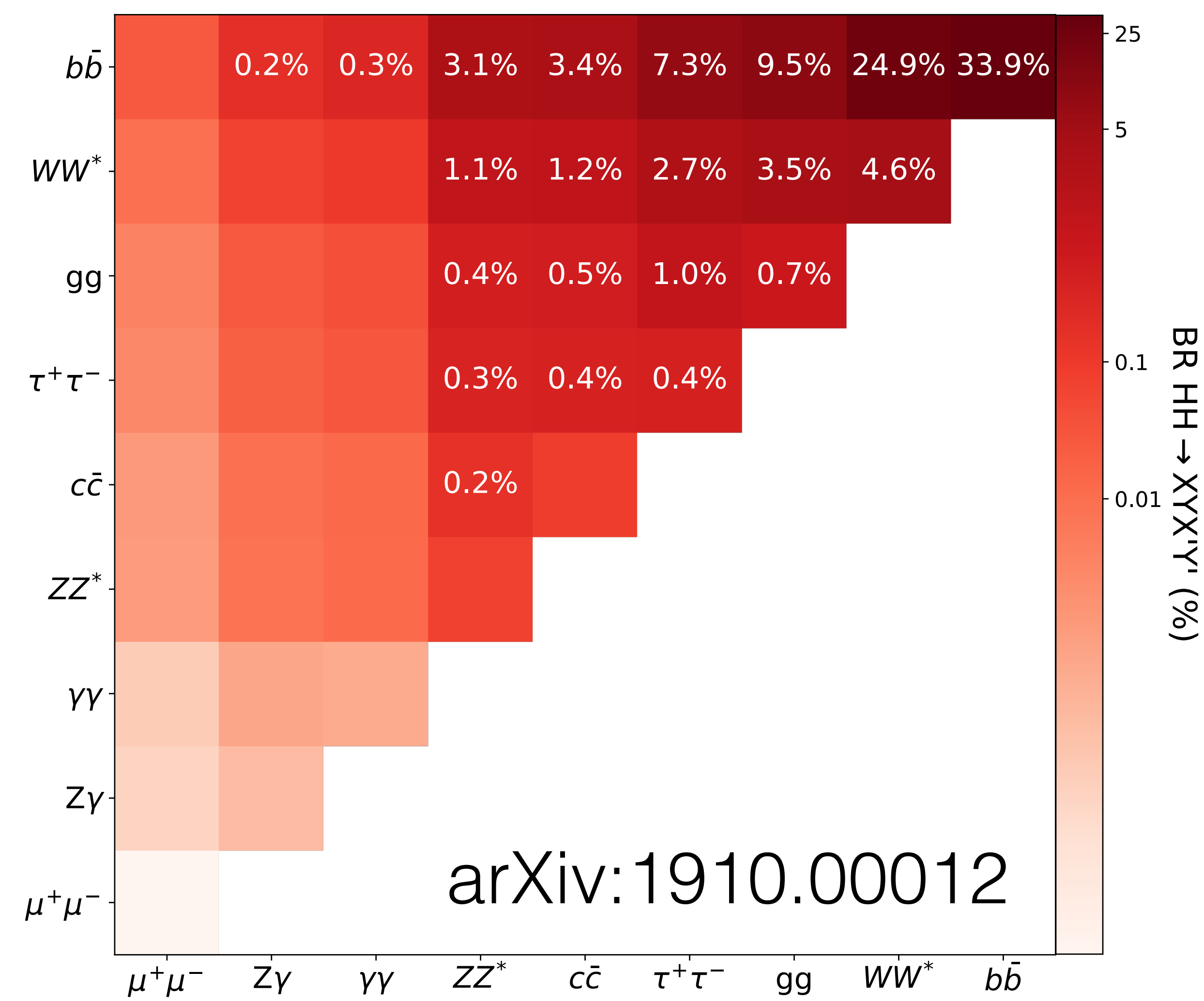


HH production and decay

- *pp* → *hh* cross section known up to NNLO+NNL with finite m_t corrections as a function of κ_λ;
- huge enhancements respect to the SM cross section (31 fb) for values departing from the SM expectation by ~10, it allows to make a discovery with the current LHC dataset if new physics shows up.



hh pair can decay in different final states, many channels can be exploited

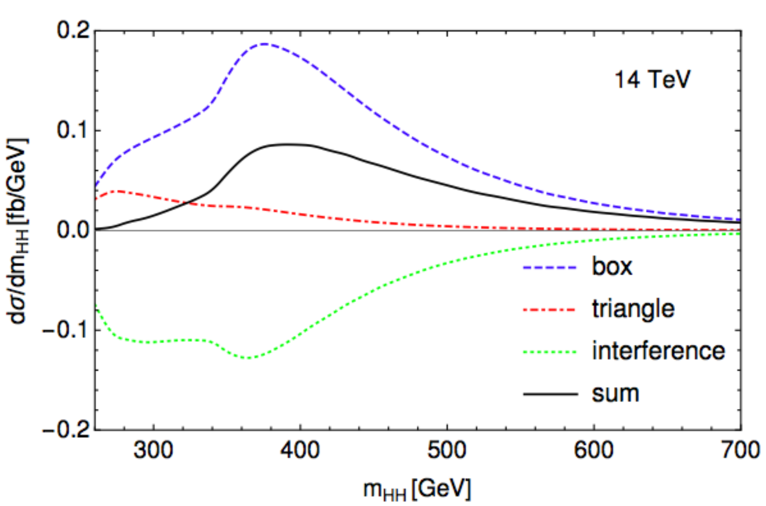


Channels studied by ATLAS and CMS

arXiv:1910.00012

Search channel		References	Luminosity	Discriminant
$b\bar{b}b\bar{b}$	ATLAS	[150]	27.5–36.1	m_{HH}
	CMS	[461]	35.9	BDT
$b\bar{b}\gamma\gamma$	ATLAS	[151]	36.1	$m_{\gamma\gamma}/m_{HH}$
	CMS	[442]	35.9	$m_{b\bar{b}}, m_{\gamma\gamma}$ (2D)
$b\bar{b}\tau^+\tau^-$	ATLAS	[152]	36.1	BDT
	CMS	[438]	35.9	BDT/m_{T2}
$b\bar{b}VV^*$	ATLAS	[462]	36.1	e.c.
	CMS	[463]	35.9	DNN
$WW^*\gamma\gamma$	ATLAS	[228]	36.1	$m_{\gamma\gamma}$
	CMS	–	–	–
WW^*WW^*	ATLAS	[464]	36.1	e.c.
	CMS	–	–	–

New! arXiv:1910.00012



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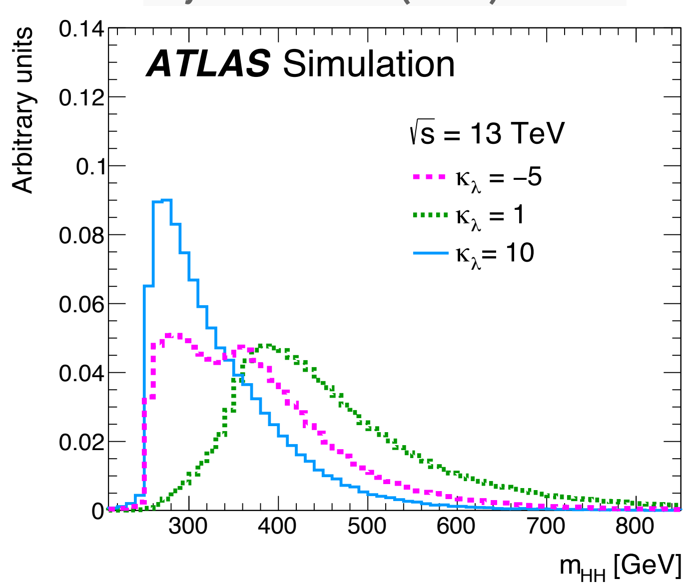
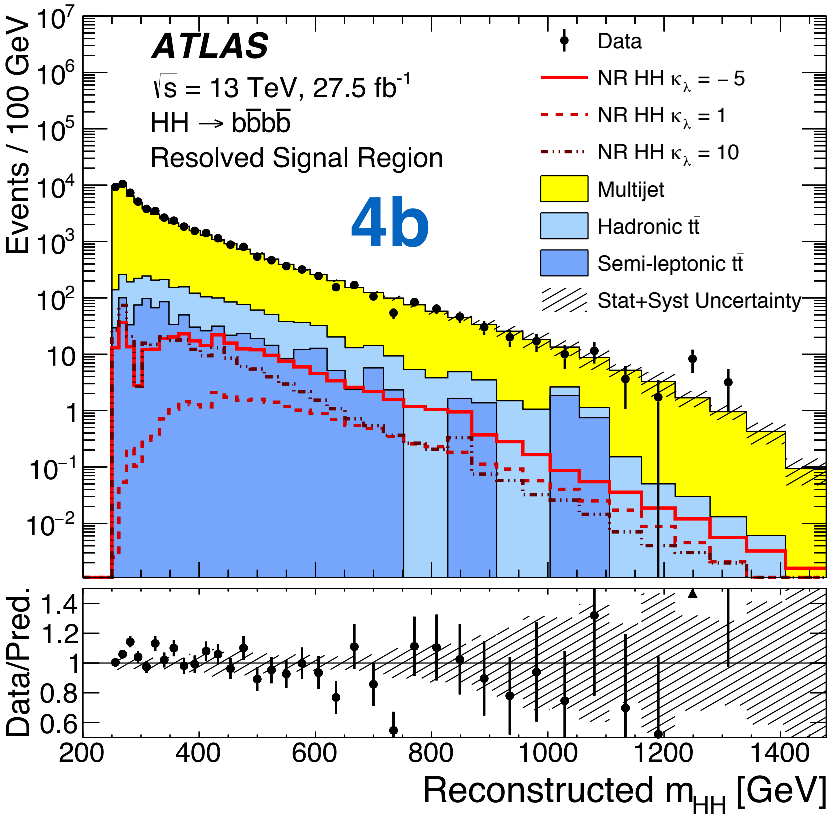
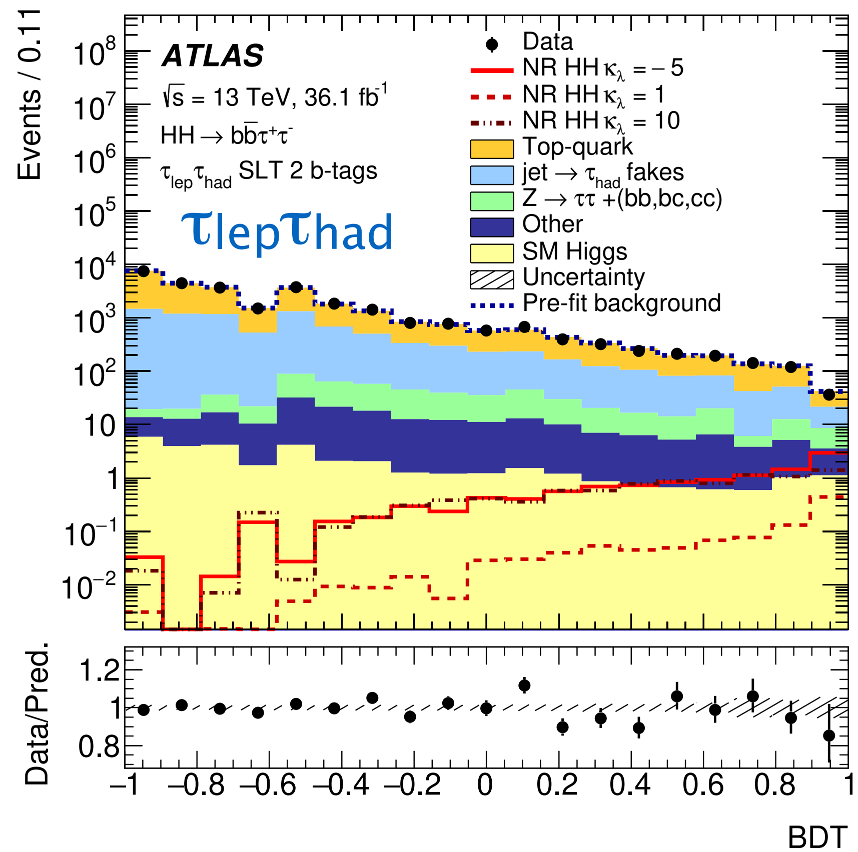


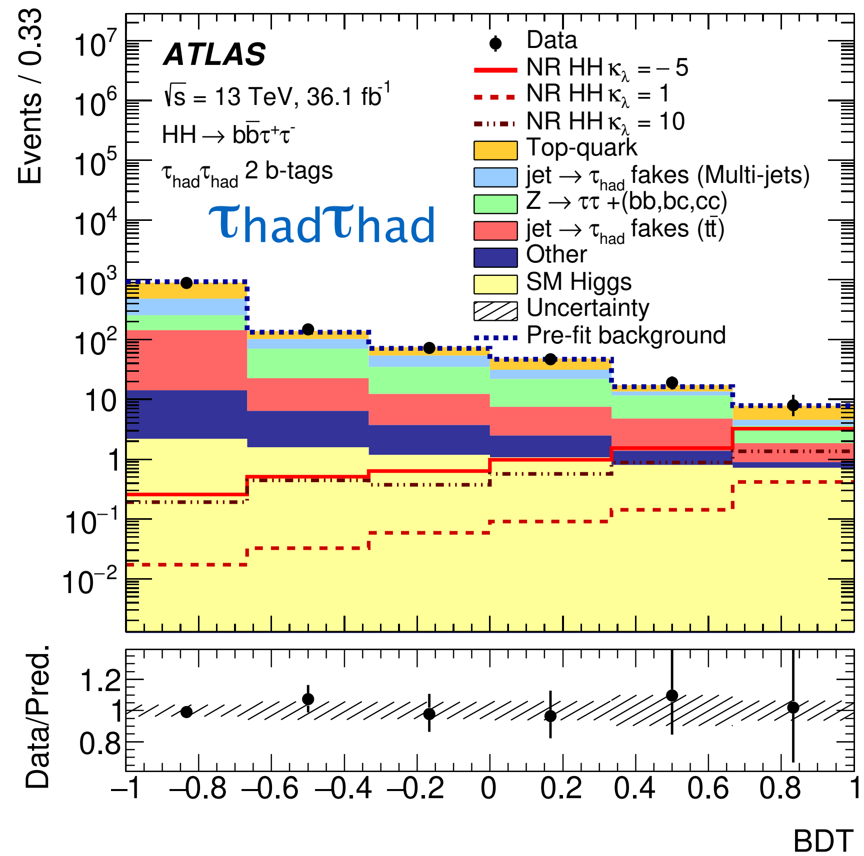
- hh production is studied also in different BSM contexts, like search for heavy resonances decaying to Higgs boson pairs;
- only most sensitive channels have been used to set constraints on κ_λ;
  - the 4b channel profits of the high H→bb branching fraction and the reconstruction of the full final state;
  - bbγγ of the clean signature of diphoton final state and of the optimum γγ invariant mass resolution;
  - bbττ is the best compromise between the two, providing the best results.

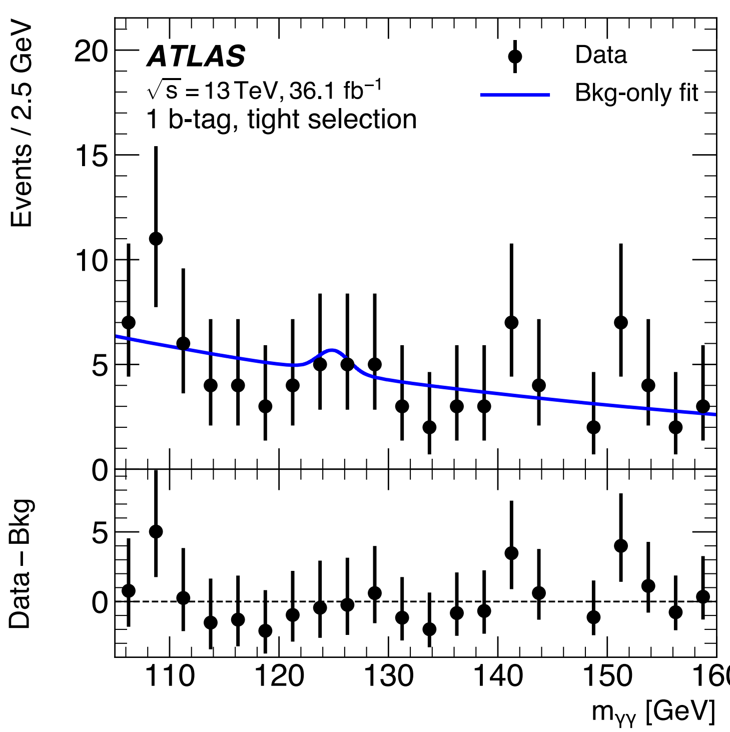
The sensitivity to κ_λ derives mainly from the cross section, 4b and bbττ have exploited also differential information through fit to m_{HH} and BDT output variable

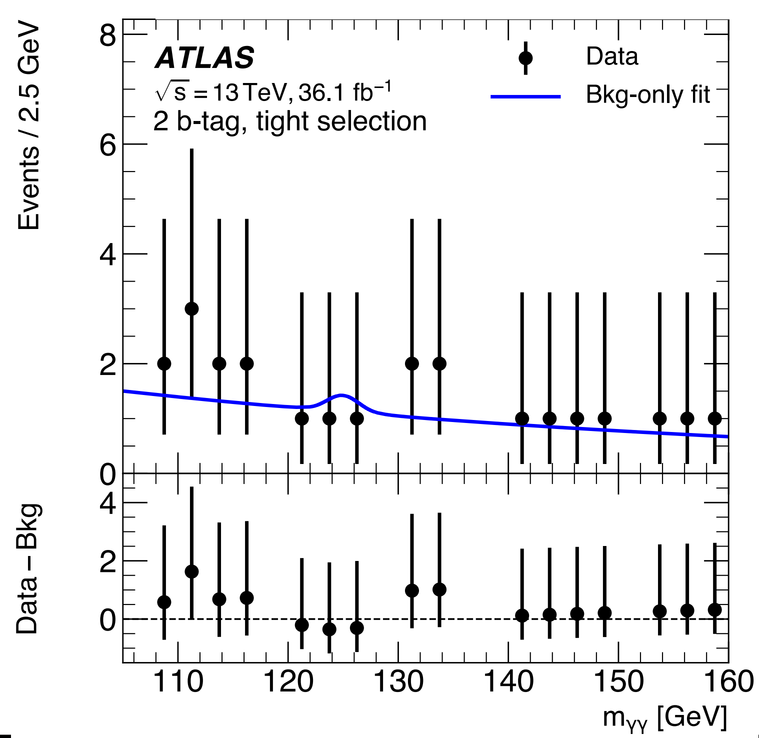
HH analyses: discriminating variables











different discriminators used

- **4b** m_{4j} invariant mass
- **bbττ** BDT using all available information from jets and taus
- **γγbb**, add 1-btag category to increase statistics

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HH analyses: results

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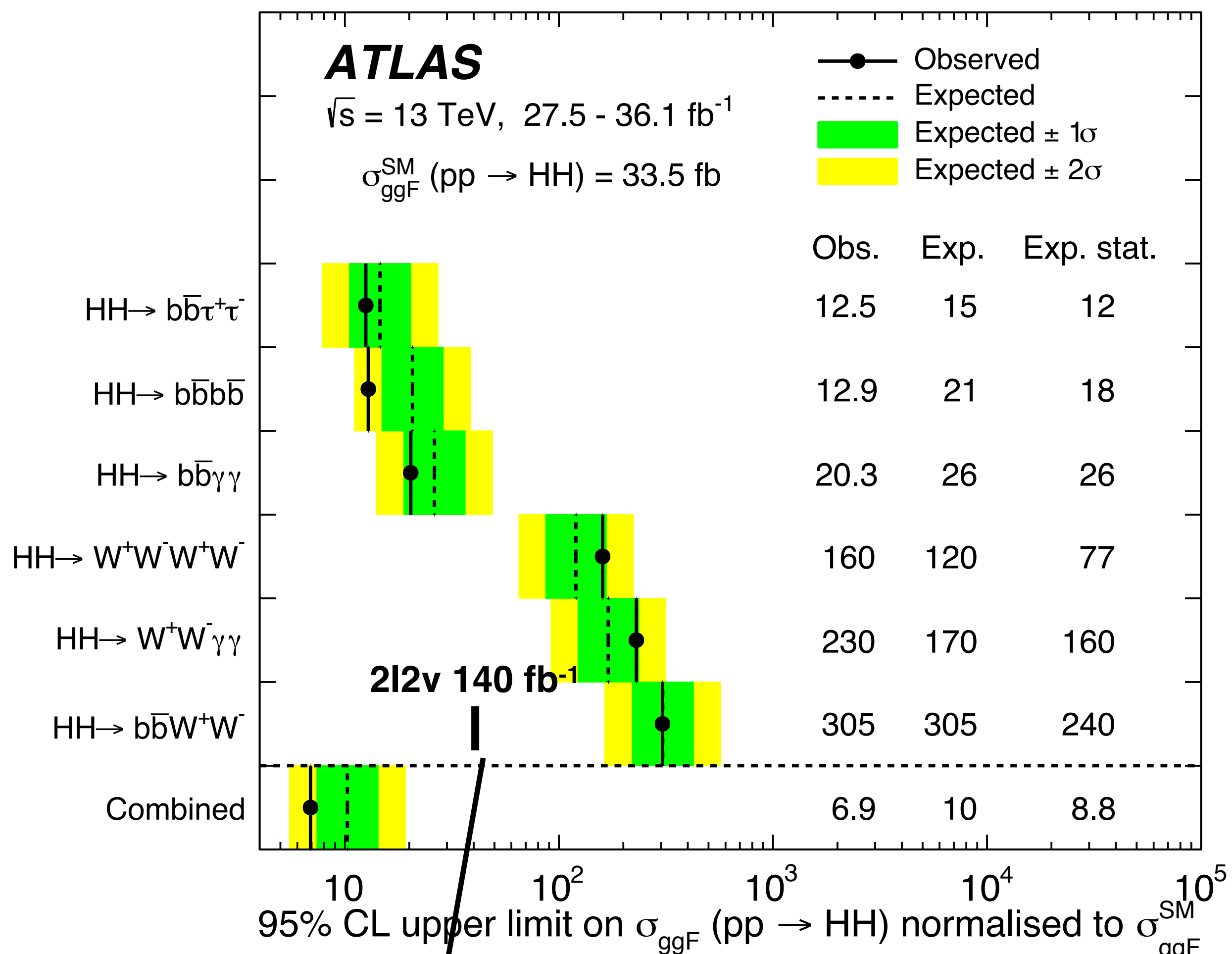

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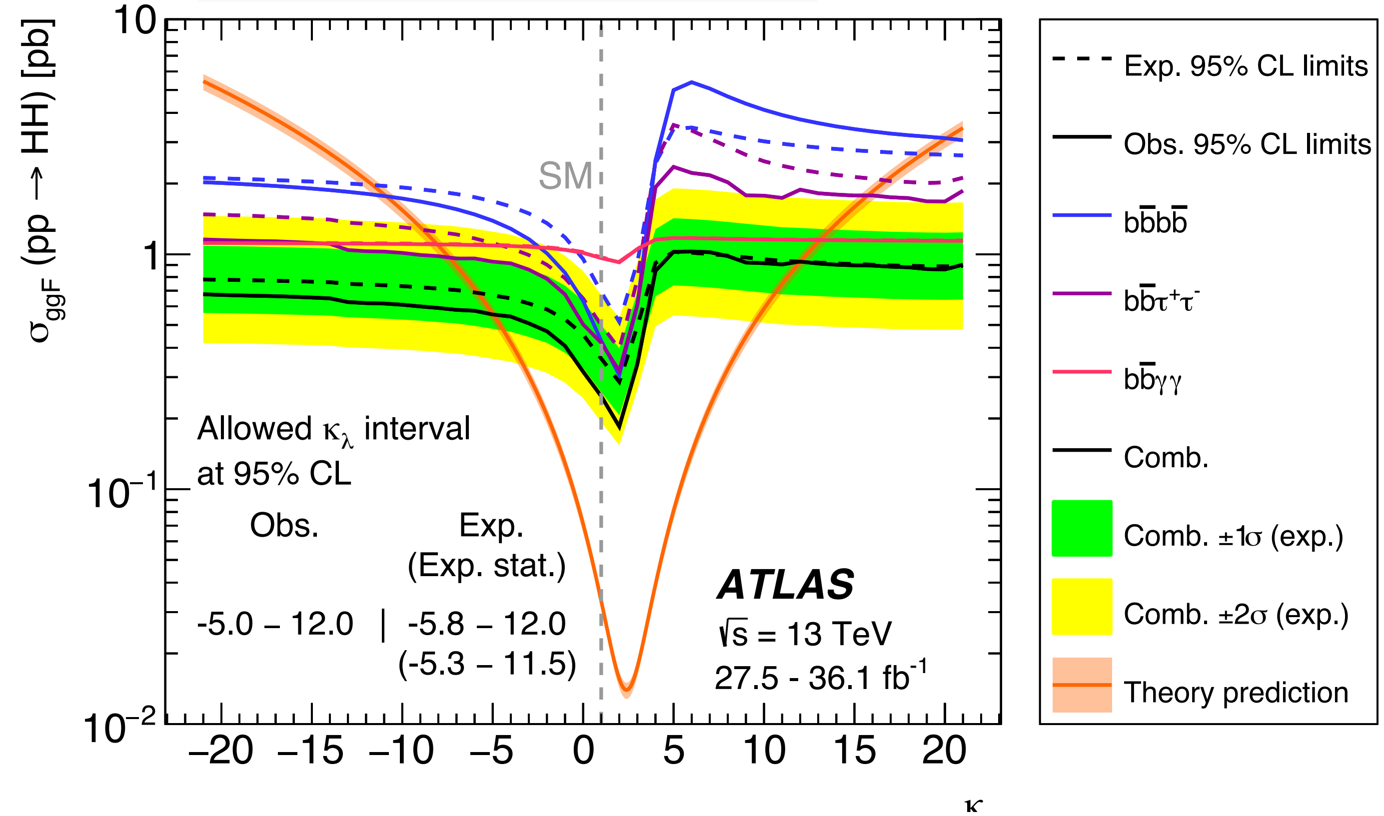


NLO effects on the Higgs BR are neglected in this table

results obtained assuming κ_t = 1

	Allowed κ_λ interval at 95% CL		
Final state	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	−10.9 — 20.1	−11.6 — 18.8	−9.8 — 16.3
$b\bar{b}\tau^+\tau^-$	−7.4 — 15.7	−8.9 — 16.8	−7.8 — 15.5
$b\bar{b}\gamma\gamma$	−8.1 — 13.1	−8.1 — 13.1	−7.9 — 12.9
Combination	−5.0 — 12.0	−5.8 — 12.0	−5.3 — 11.5

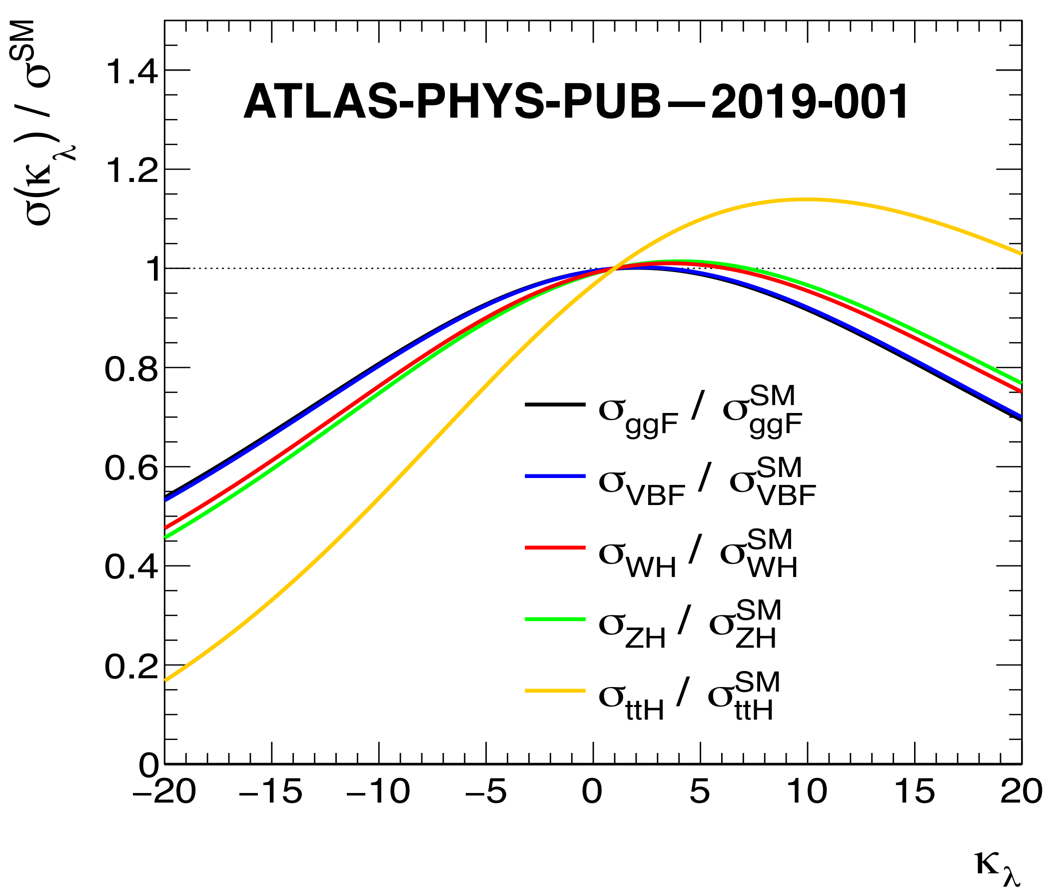
Indirect determination from single-Higgs measurements

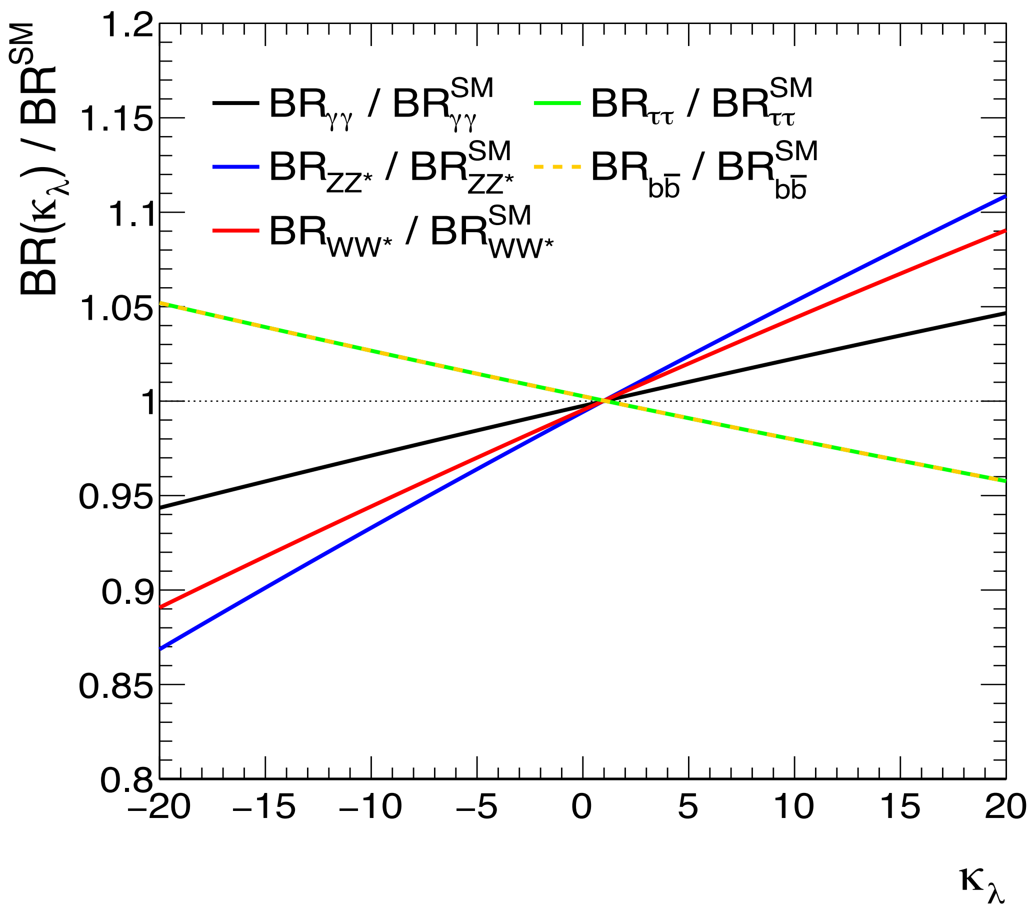
Production cross sections and decay branching fractions can be parameterised as a function of κ_λ using NLO-EWK corrections, while BSM effects on other κ's are treated at LO

$$\mu_{if}(\kappa,\kappa_\lambda,\kappa_t) = \mu_i(\kappa,\kappa_\lambda) \times \mu_f(\kappa,\kappa_\lambda) = \frac{\sigma_i(\kappa,\kappa_\lambda)}{\sigma_{SM,i}} \times \frac{BR_f(\kappa,\kappa_\lambda)}{BR_{SM,f}}$$

κ generic scale factor for BSM couplings (κ_t, κ_f, κ_b, κ_l)

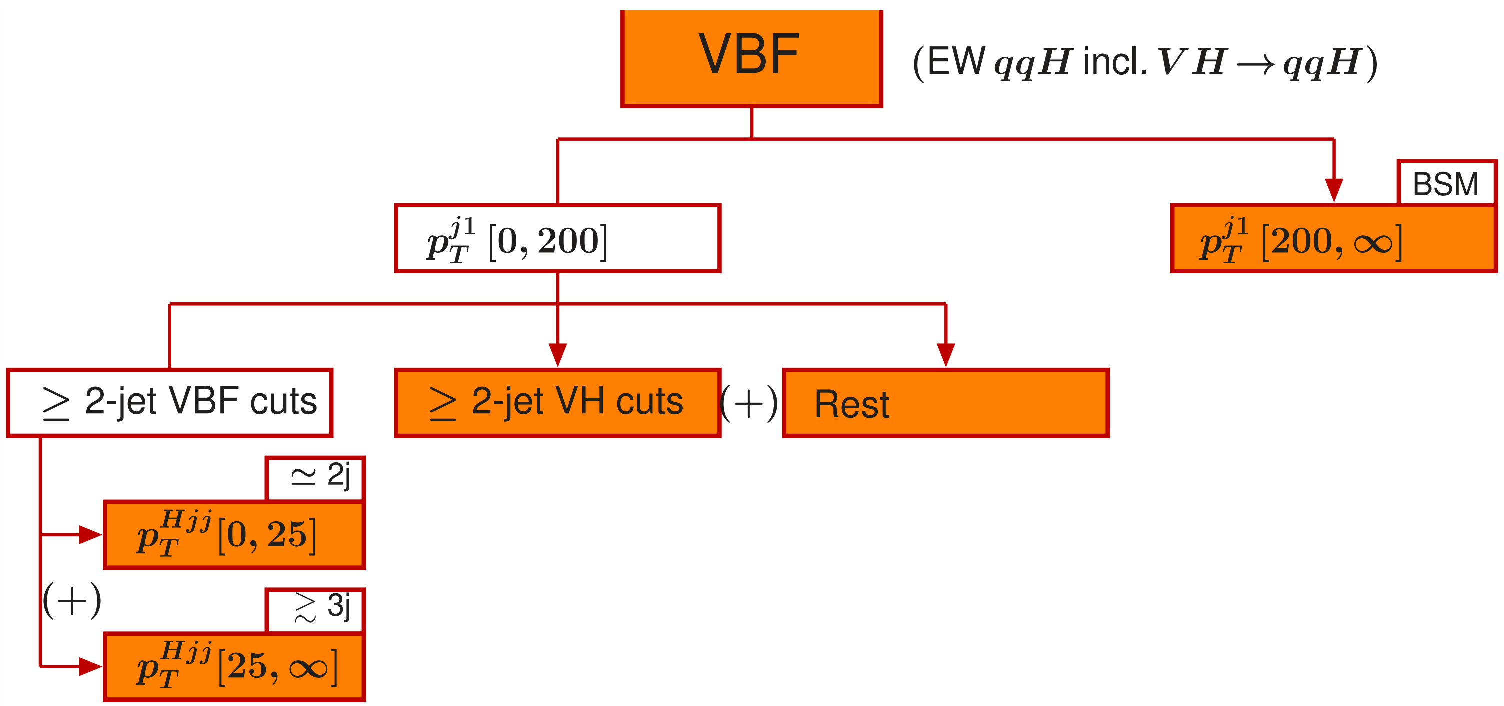
$$\mu_i(\kappa,\kappa_\lambda) = Z_H^{BSM}(\kappa_\lambda)\left[\kappa^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{EW}^i}\right] \qquad \mu_f(\kappa,\kappa_\lambda) = \frac{\kappa^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j BR_j^{SM}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

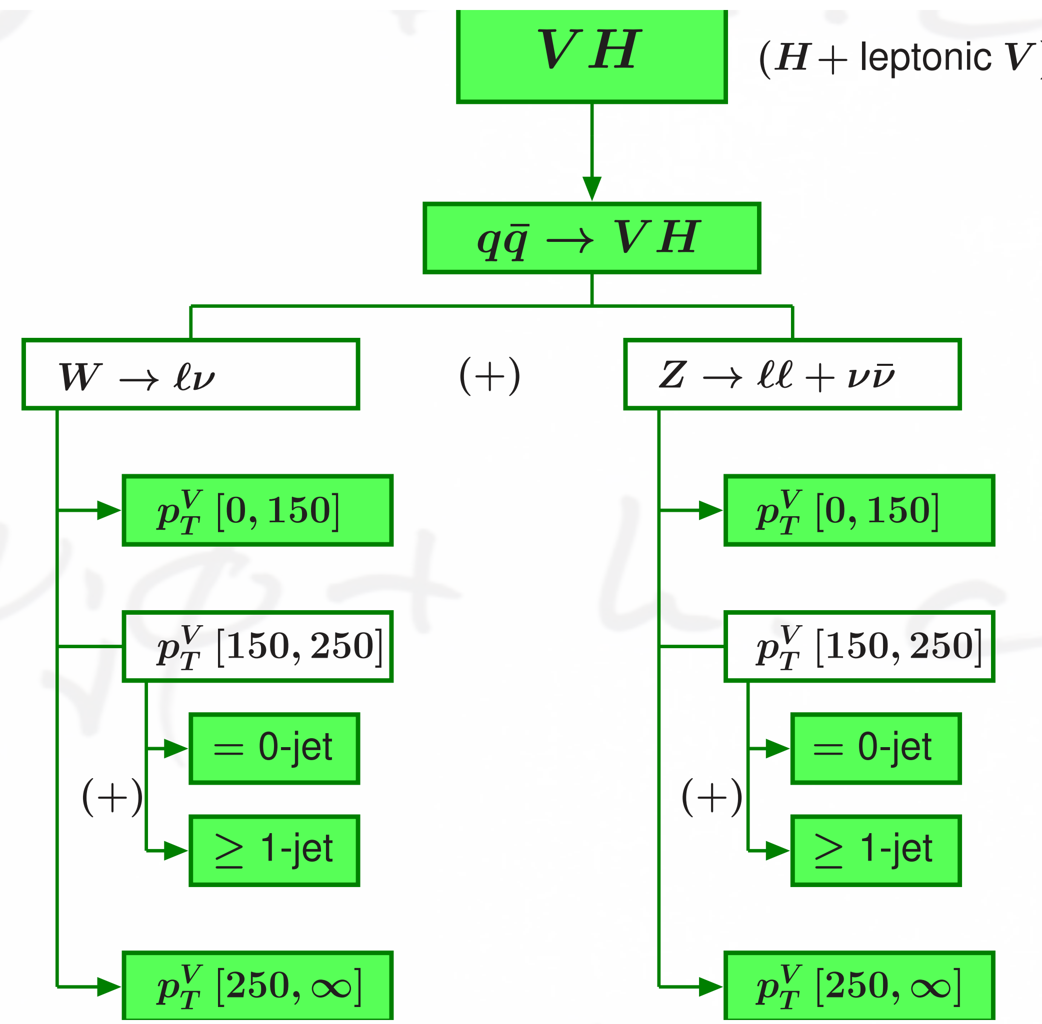




Single Higgs data inputs

The VBF and VH categories are subdivided in differential bins according to the Simplified Template Cross Section scheme. The ggF and ttH are treated as inclusive (the first misses κ_λ dependent theoretical computations), the second misses experimental informations



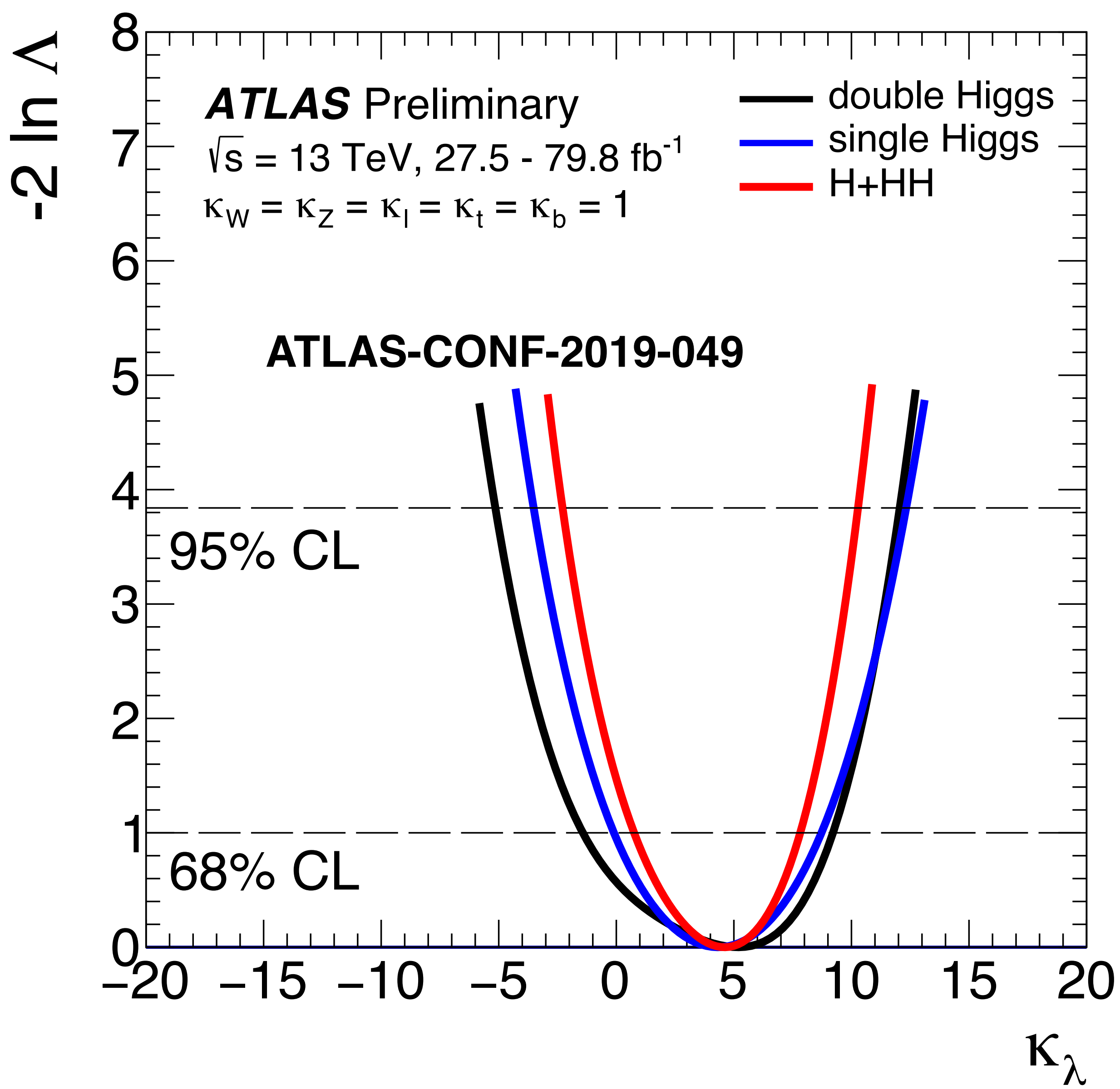


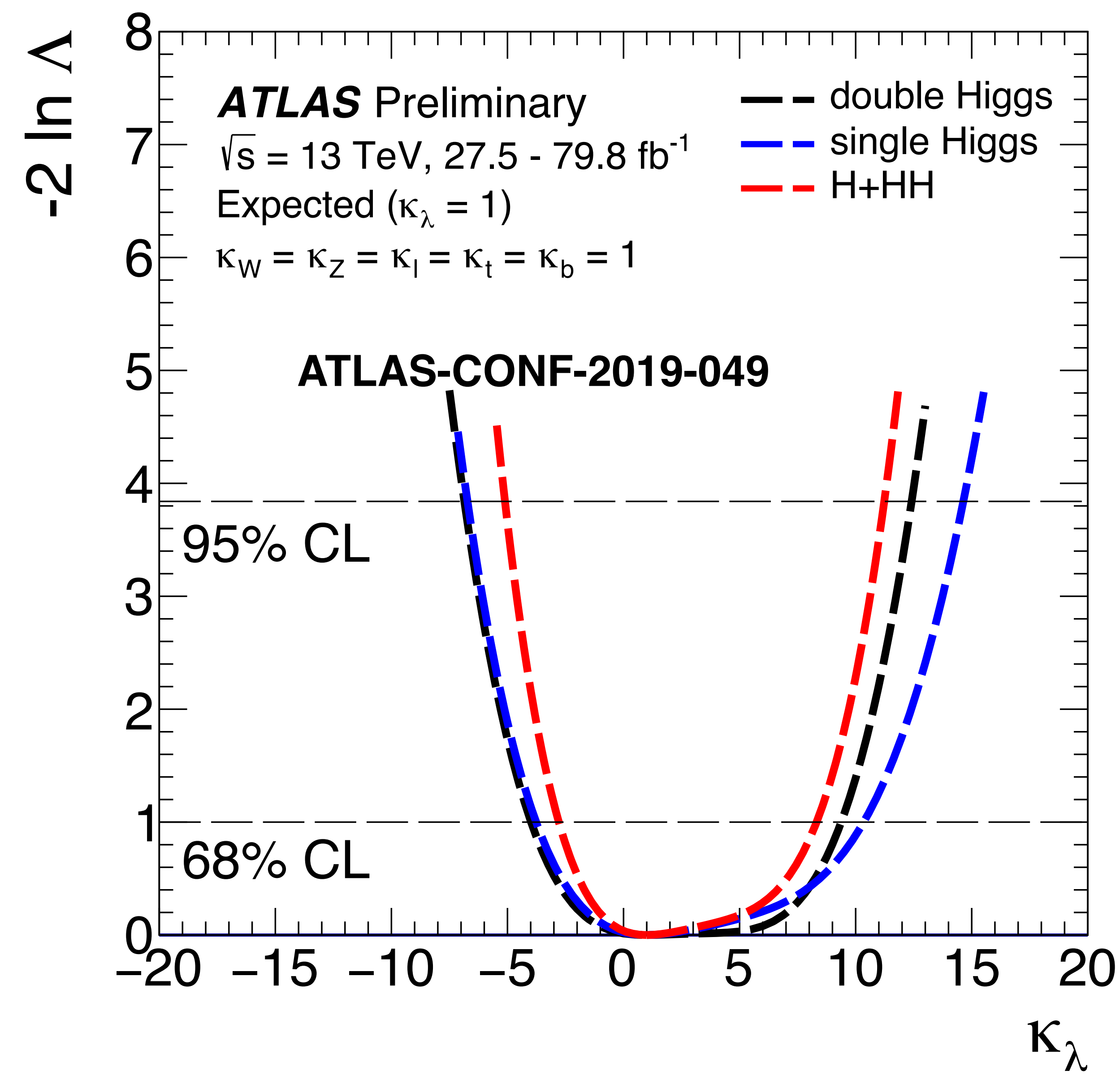
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

Constructed from Figures in arXiv: 1610.07922

Adding single Higgs data

	Double Higgs	Single Higgs	Combination
exp.	$-5.8 < \kappa_\lambda < 12.0$	$-6.2 < \kappa_\lambda < 14.4$	$-5.1 < \kappa_\lambda < 11.2$
obs.	$-5.0 < \kappa_\lambda < 12.0$	$-3.2 < \kappa_\lambda < 11.9$	$-2.3 < \kappa_\lambda < 10.3$



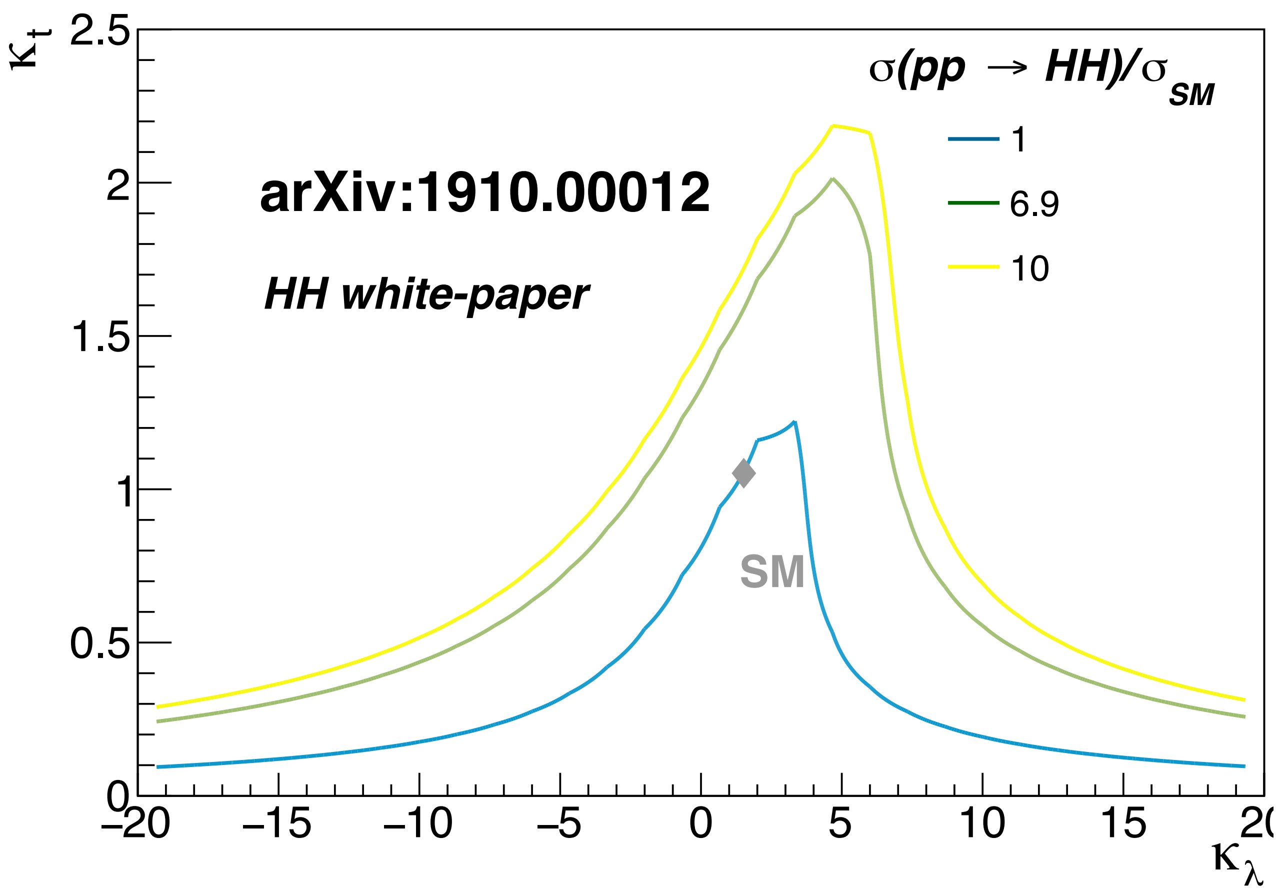


recent results also released by CMS on single Higgs: **CMS PAS HIG-19-005**

Multi-parameter fit H + HH combination

Double Higgs production alone doesn't allow to constraint κ_λ without assumptions on κ_t

Single Higgs observables have a better constraining power, and in combination with *HH* produce good constraints of both κ_t and κ_λ



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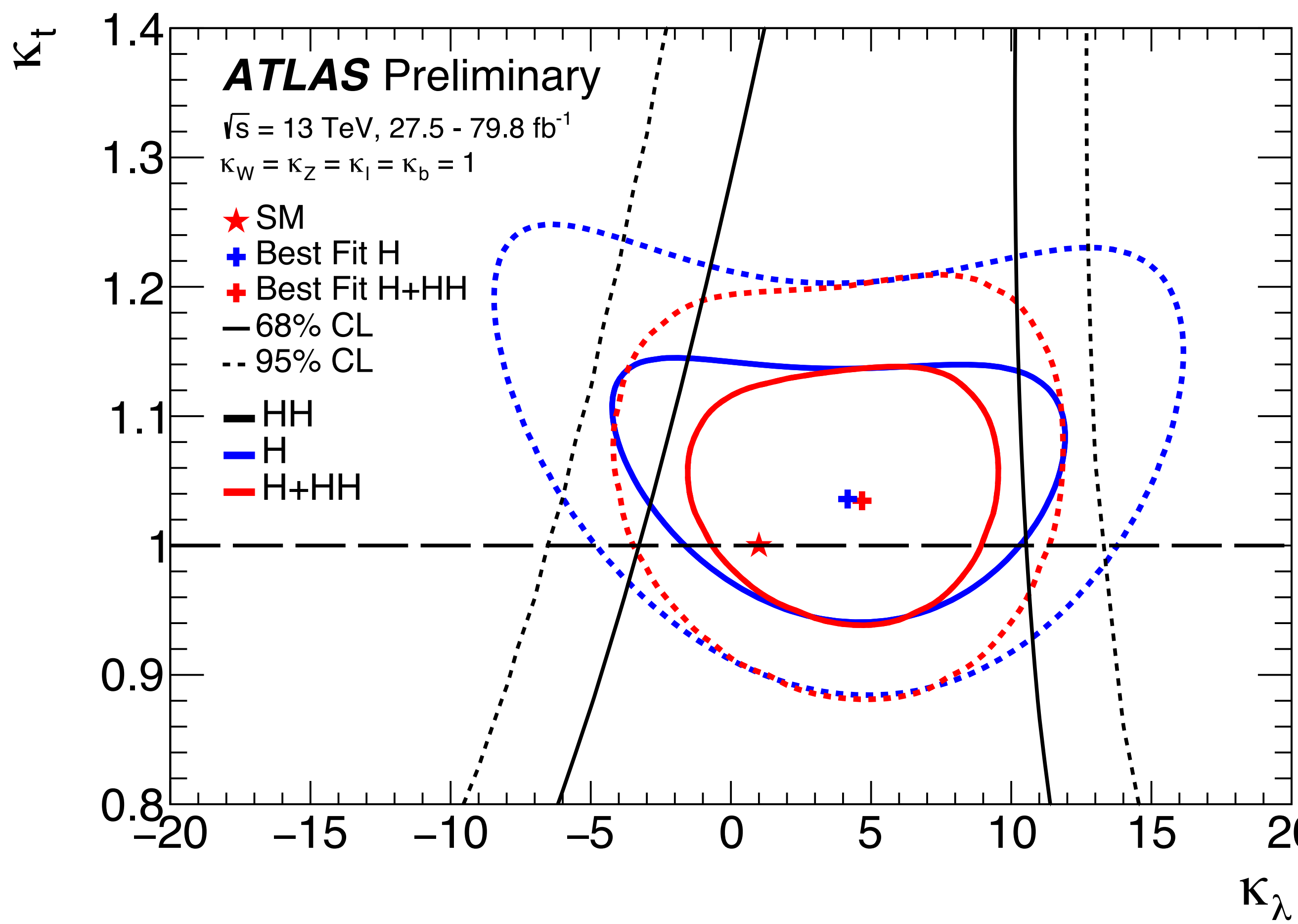
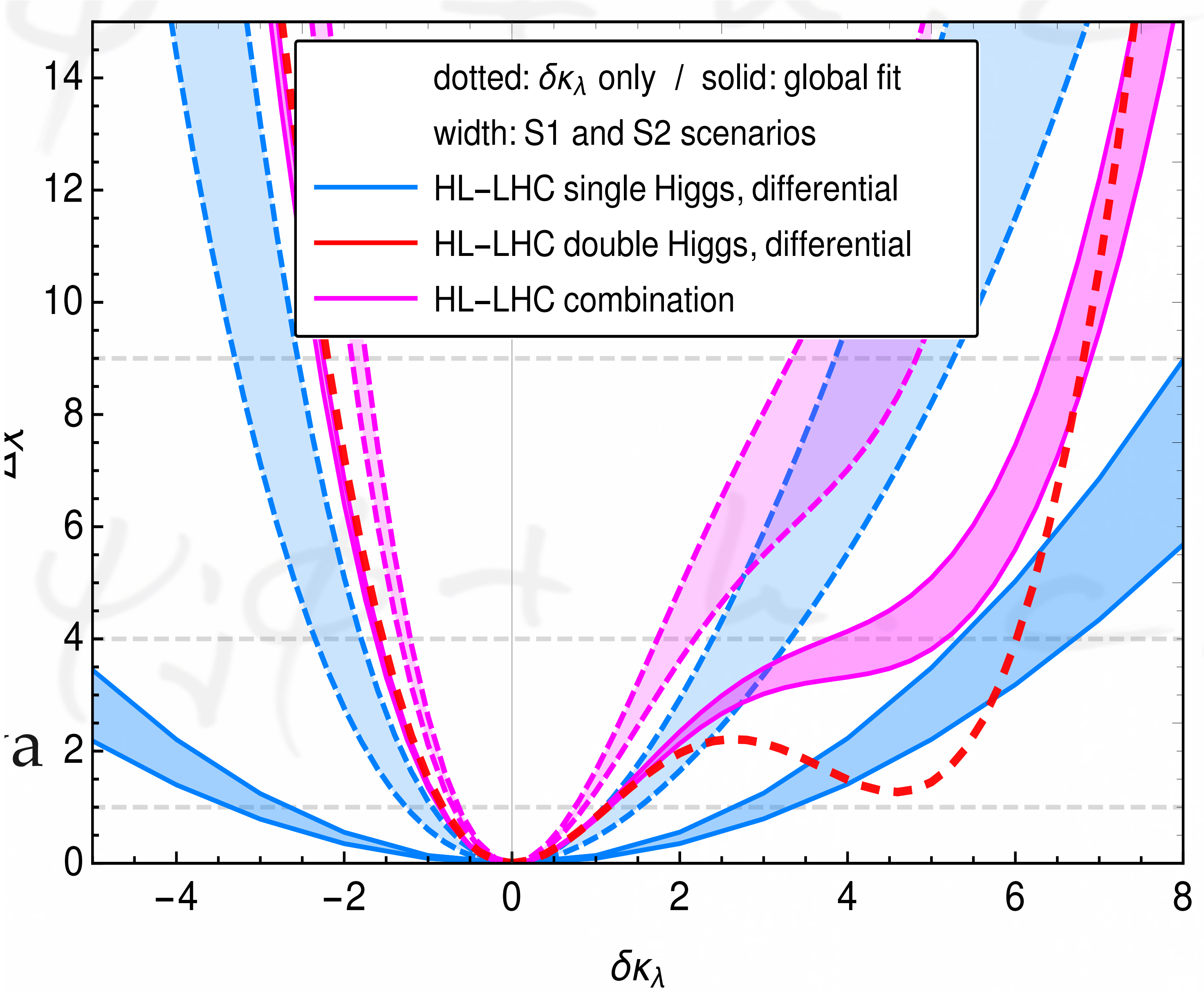


HL-LHC expectations



HL-LHC prospects, Yellow Report results

arXiv:1902.00134v2

- *The weight of single Higgs production measurements reduces at HL-LHC*
- *the high statistics makes single Higgs measurement systematic dominated*
- *at 2σ level single Higgs measurements are even more constraining than double Higgs ones, due to the double minimum structure of double Higgs production*

Conclusions

- the measurement of the triple-Higgs boson coupling is the first attempt to probe the Higgs boson potential;

- this measurement is already relevant today, due to low constraints on it deriving from other precision measurements and the possibility that new physics can induce large deviations of the self-coupling from its SM expectation;

- the Higgs boson energy potential and the self-coupling, as a consequence, have relevant cosmological implication;

- with the present statistics the ATLAS collaboration is already probing regions previously unexplored and that could be affected by new physics (more updates will come with the Run2 and Run3 statistics)

- HL-LHC will measure the self-coupling with a 30% precision, assessing its not null value, precision measurements of the self-coupling need to wait the next generation lepton and/or hadron colliders obs. $-3.5 < \kappa_\lambda < 14.5$

exp. $-5.1 < \kappa_\lambda < 13.7$

CMS-PAS-HIG-19-005