Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

Arantxa Ruiz Martínez (aranzazu.ruiz.martinez@cern.ch)

on behalf of the ATLAS Collaboration

Lake Louise Winter Institute
19-25 February 2023

ATLAS EXPERIMENT

IFIC INSTITUT DE FÍSICA CORPUSCULAR

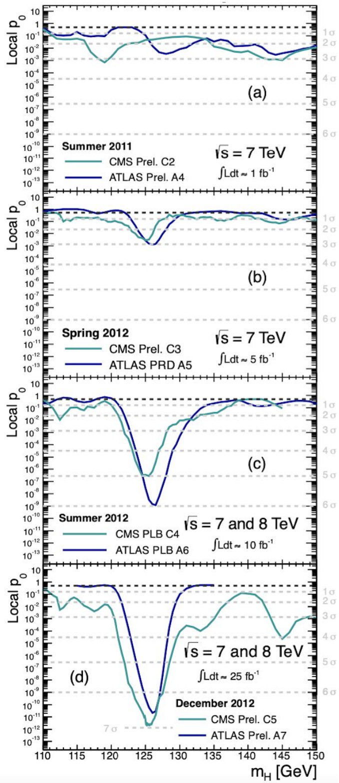
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

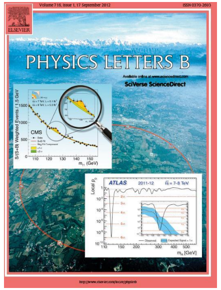
VNIVERSITAT DE VALÈNCIA

Higgs boson discovery

A new era in particle physics and cosmology

PDG 2013





F. Englert & R. Brout, PRL 13, 321–323 (1964)

P. W. Higgs, PRL 13, 508–509 (1964)

ATLAS Collaboration, PLB 716, 1–29 (2012)

CMS Collaboration, PLB 716, 30–61 (2012)

THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

KUNGL. VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

10th anniversary of the Higgs boson discovery
CERN, 4 July 2022
https://indico.cern.ch/event/1135177/

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery
ATLAS Collaboration, Nature 607 (2022) 52–59

A portrait of the Higgs boson by the CMS experiment ten years after the discovery
CMS Collaboration, Nature 607 (2022) 60-68

Higgs boson - couplings

Bosons

Electroweak Symmetry Breaking (EWSB)

BEH Mechanism confers mass to bosons W and Z:

$\mathbf{SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}}$

$$g_{HVV} = \frac{2m_V^2}{v}$$

Fermions

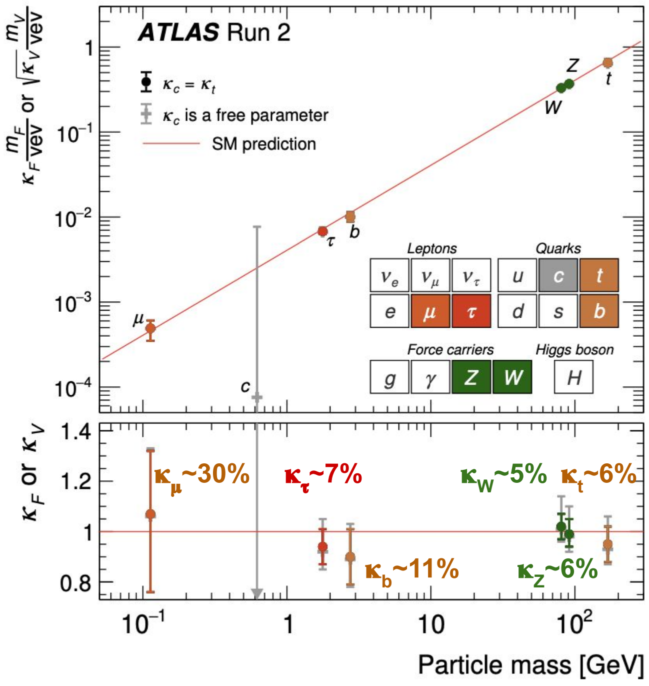
Yukawa coupling

Proportional to the fermion mass

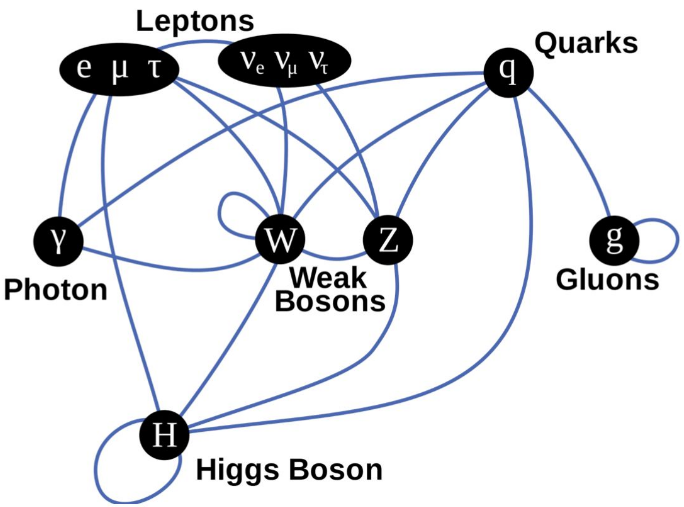
Unique interaction which distinguishes between the three generations of fermions

$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

Run 2



ATLAS, [Nature 607 (2022) 52–59]



DiHiggs production - not observed experimentally (yet)

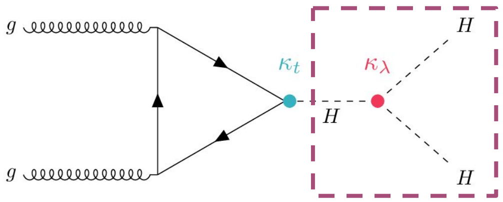
SM non-resonant production (pp → HH)

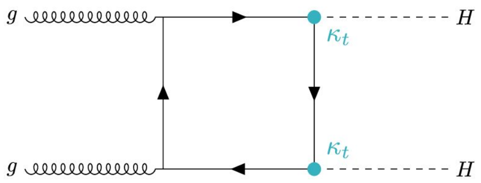
Trilinear self-coupling λ_{HHH}
Coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

Destructive interference between the triangle and box diagrams

gluon-gluon Fusion (ggF)

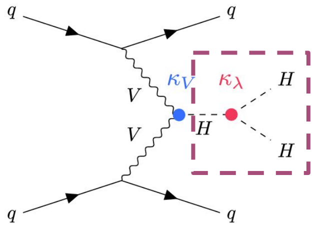
(dominant production ~90%)

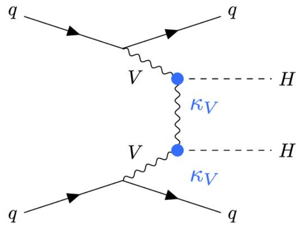


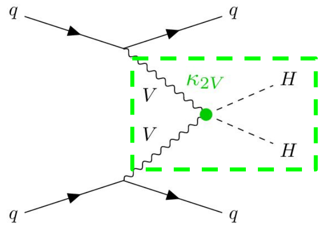


Vector Boson Fusion (VBF)

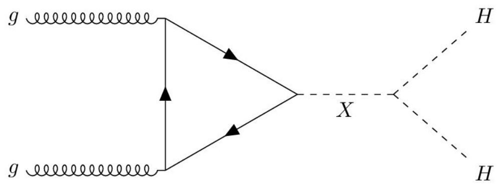
(subdominant production)





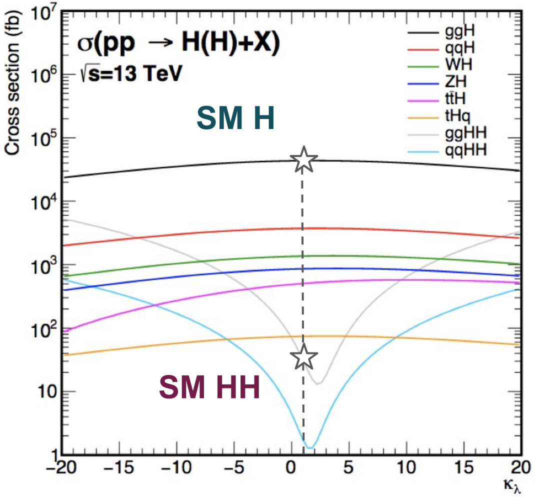


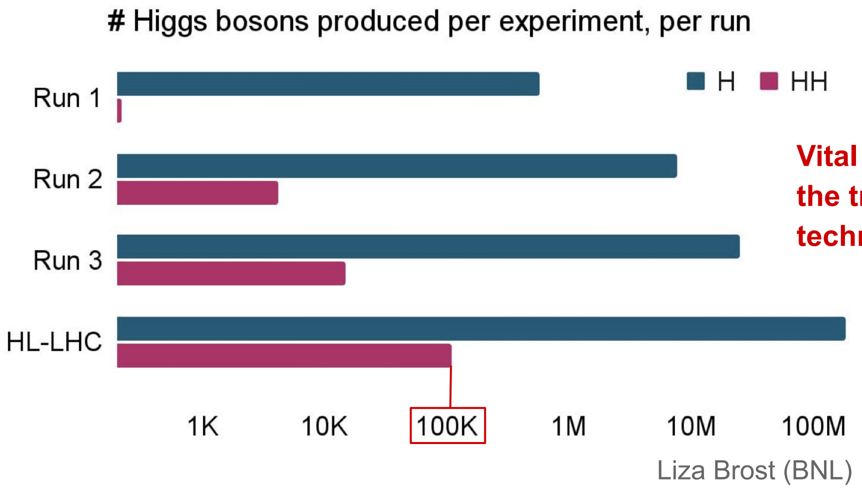
BSM resonant production (pp → X → HH)



DiHiggs production search

DiHiggs production x1000 smaller than single Higgs production in the Standard Model





Vital the optimization of the trigger and analysis techniques for HH signal

Higgs sector as a portal to new physics BSM:

- ➢ **Loop corrections** including new particles
- ➢ **Anomalous couplings** between the Higgs boson and other Standard Model particles
- ➢ **New resonances X → HH** (motivated by BSM theories: e.g. 2-Higgs Doublet Model, etc.)

Why the Higgs boson self-coupling is so important?

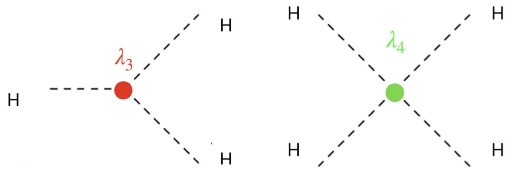
Higgs potential

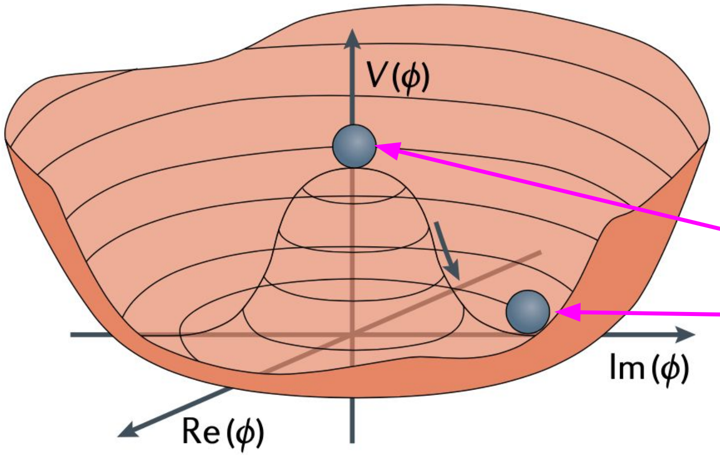
$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 = \frac{1}{2}m_h^2 h^2 + \lambda_3 h^3 + \lambda_4 h^4$$

$\lambda v^2 = \frac{1}{2}m_h^2$, $\lambda v = \lambda_3$, $\frac{1}{4}\lambda = \lambda_4$

Mass term	Higgs triple coupling	Higgs quartic coupling

Transition of the Higgs field to the minimum responsible for the **electroweak symmetry breaking mechanism**





The Higgs field has different vacuum states:

At high energy (**false vacuum)** → unstable local maximum

At low energy (**true vacuum)** → current universe

Vacuum expectation value (v.e.v.): $v = (\sqrt{2}\, G_F)^{-1/2}$ = 246 GeV

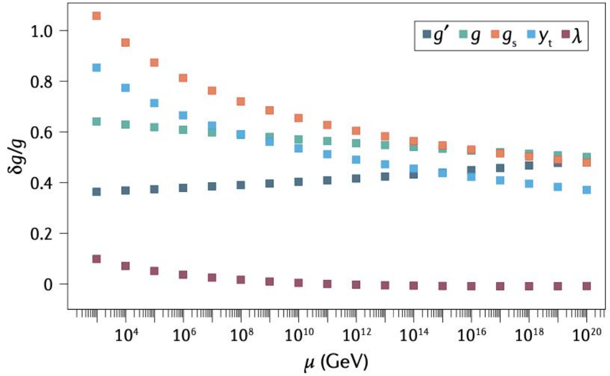
coupling: $\lambda = M_H^2/2v^2$ = 0.13

Experimental measurements

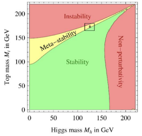
$$M_H = \sqrt{2\mu^2} \equiv \sqrt{2\lambda v^2}$$

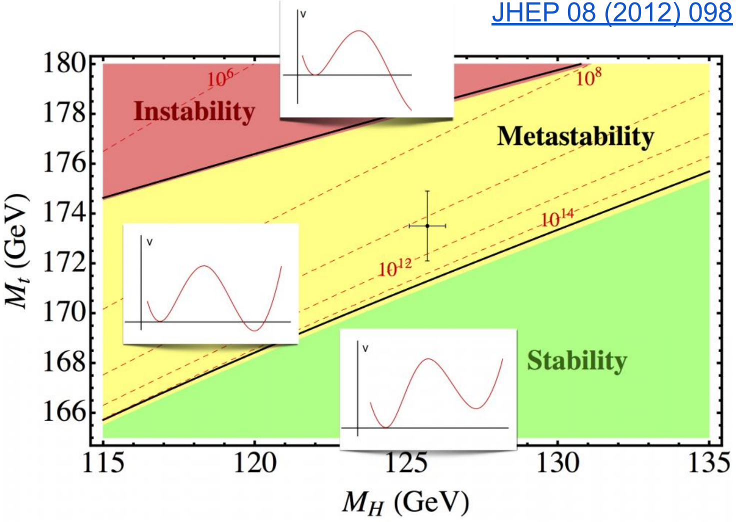
Higgs potential - vacuum stability of the universe

- Higgs boson self-coupling depends on the energy $\lambda(\mu)$
- At high energy $V_{\text{eff}}(h) = \dfrac{\lambda(\mu)}{4}h^4$
- The Standard Model could have a second “true” minimum (metastability of the universe)
- If there is a deeper minimum, transition can happen via quantum tunnelling

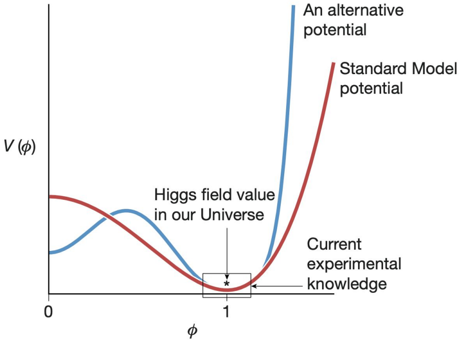


G. Degrassi et al.
[JHEP 08 (2012) 098]

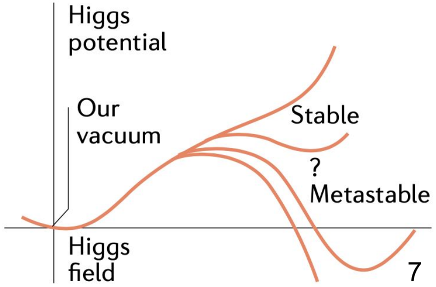




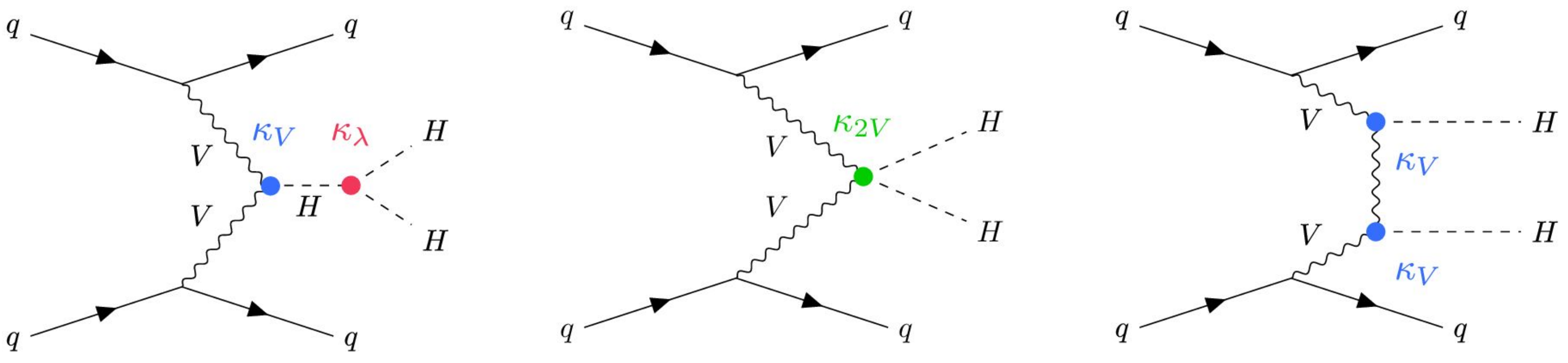
G. Salam, L-T Wang, G. Zanderighi
[Nature **607**, 41–47 (2022)]



S. Bass, A. De Roeck, M. Kado
[Nature **3**, 608–624 (2021)]



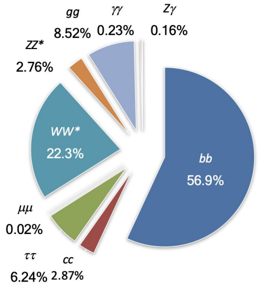
HH VBF production mechanism



(a) (b) (c)

- In the SM, the divergences in the (b) and (c) VBF diagrams exactly cancel out due to perturbative unitarity
- As κ_V and κ_{2V} depart from their SM value of 1, this canceling out no longer occurs, linear dependence of the cross-section on the effective CoM energy of the incoming vector bosons
- Non-SM κ_V / κ_{2V} scenarios are expected to be to be more energetic and more central in the detector on average

DiHiggs searches - state of the art



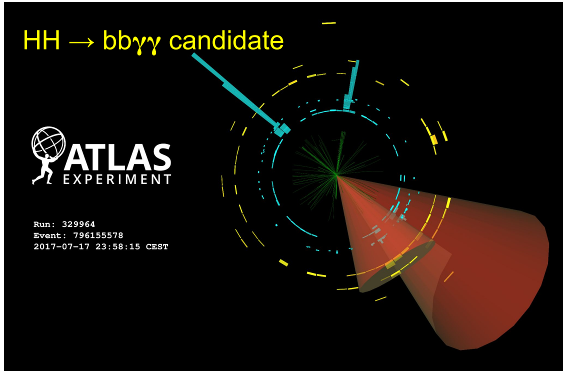
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

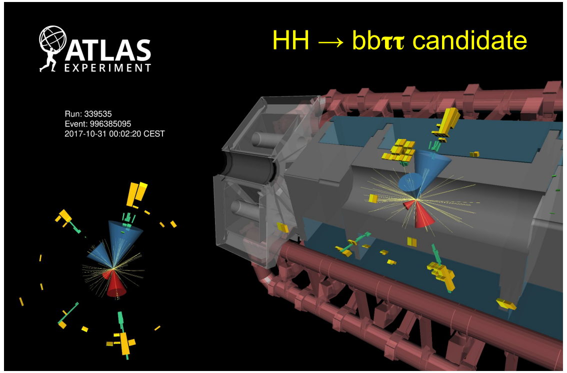
1st batch: intermediate Run 2 dataset

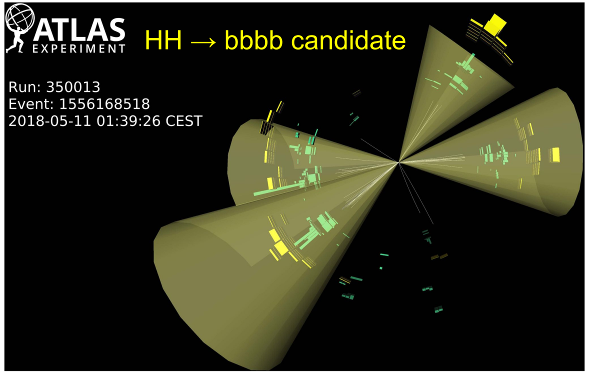
Channel	**2015-2016 (36 fb^{-1})**
$HH \to bb\gamma\gamma$	JHEP 11 (2018) 040
$HH \to bb\tau\tau$	PRL 121 (2018) 191801
$HH \to bbbb$	JHEP 01 (2019) 030
$HH \to bbWW^*$	JHEP 04 (2019) 092
$HH \to WW^*WW^*$	JHEP 05 (2019) 124
$HH \to WW^*\gamma\gamma$	EPJC 78 (2018) 1007
Combination	PLB 800 (2020) 135103

2nd batch: full Run 2 dataset

Channel	**2015-2018 (126-139 fb^{-1})**
$HH \to bb\gamma\gamma$	PRD 106 (2022) 052001
$HH \to bb\tau\tau$	arXiv:2209.10910, JHEP 11 (2020) 163
$HH \to bbbb$	arXiv:2301.03212, PRD 105 (2022) 092002, JHEP 07 (2020) 108
$VHH \to$ 0L, 1L, 2L, 4b	arXiv:2210.05415
Combination	arXiv:2211.01216, ATLAS-CONF-2021-052



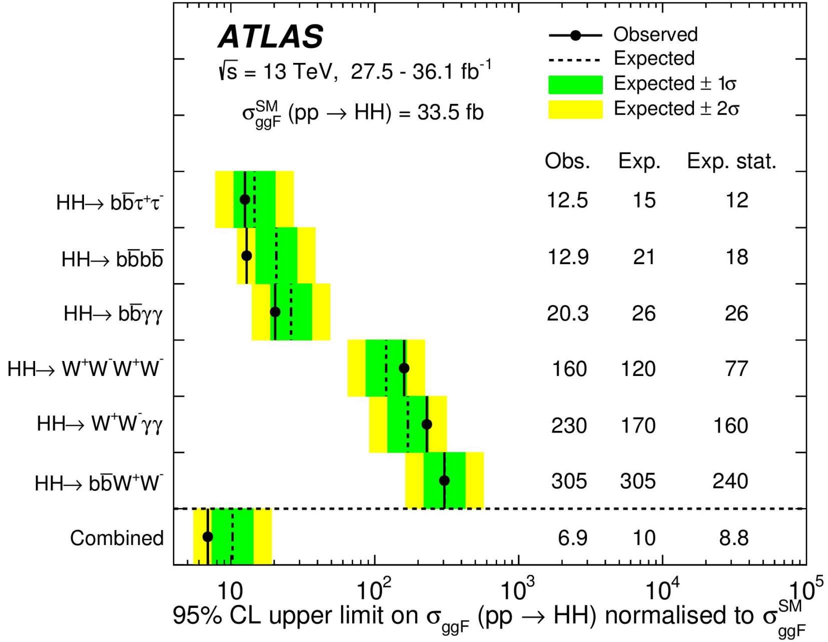




Combination diHiggs searches - non-resonant production

Combination of channels to achieve ultimate sensitivity

6 channels, 36 fb^{-1} [PLB 800 (2020) 135103]

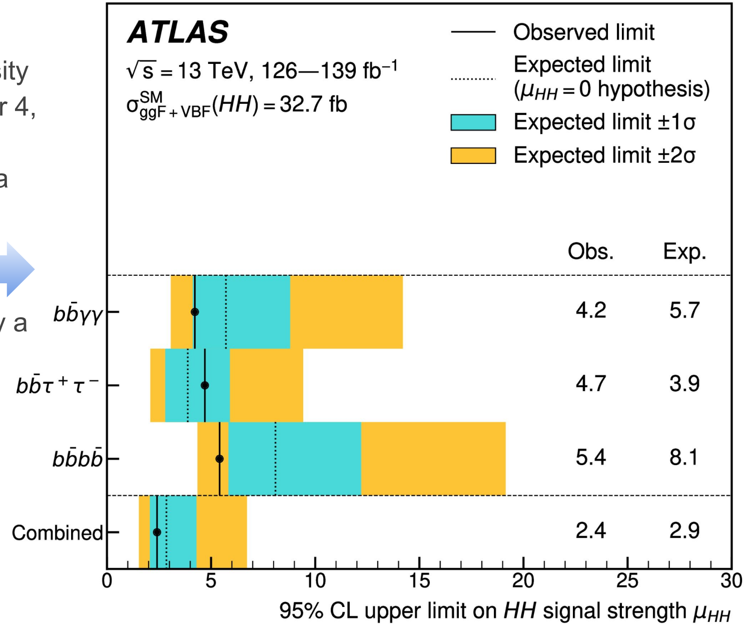


Obs. (exp.) 95% CL limit: 6.9 (10) x SM prediction

Integrated luminosity increase by a factor 4, leading to an improvement of a **factor 2**

Limits improved by a **factor 3.4**

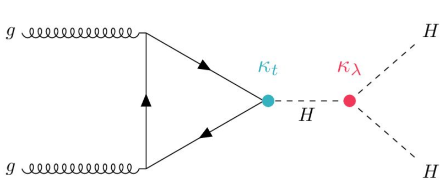
3 channels, 139 fb^{-1} [arXiv:2211.01216]

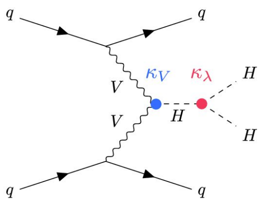


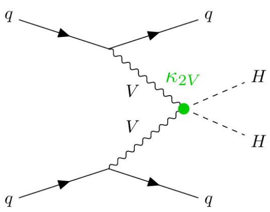
Obs. (exp.) 95% CL limit: 2.4 (2.9) x SM prediction

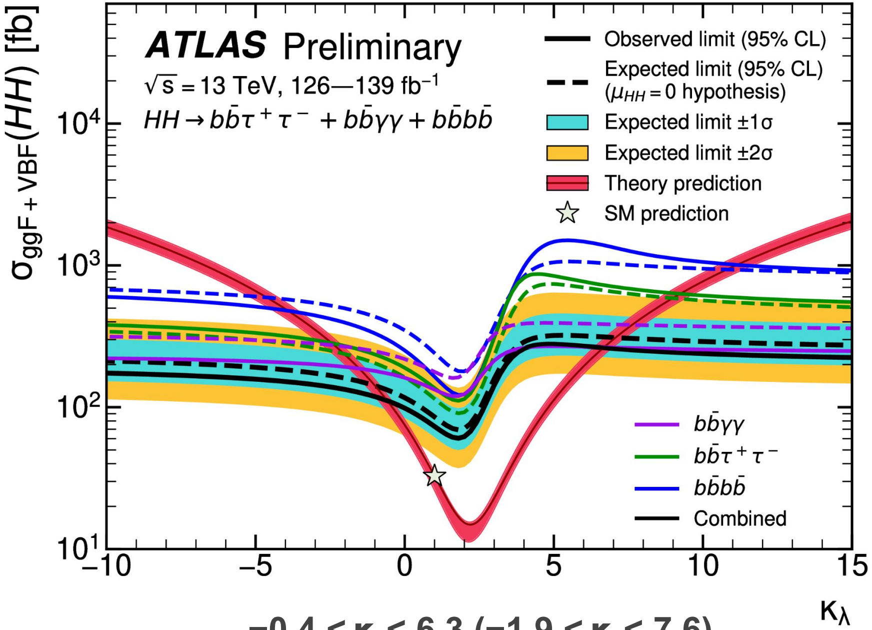
Combination diHiggs searches - non-resonant production

[arXiv:2211.01216](https://arxiv.org/abs/2211.01216)

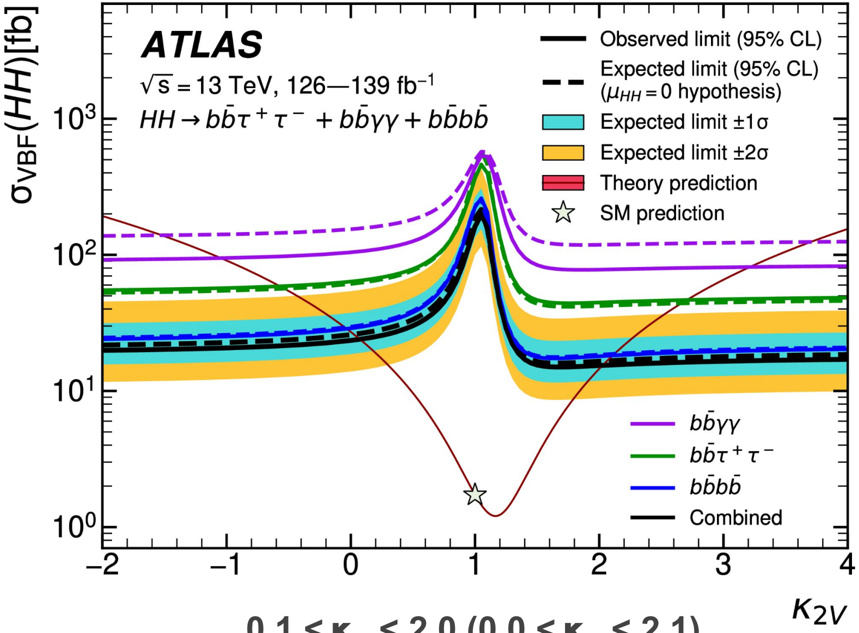








$-0.4 < \kappa_\lambda < 6.3$ ($-1.9 < \kappa_\lambda < 7.6$)

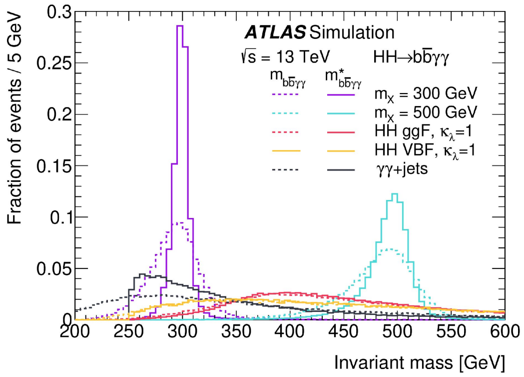


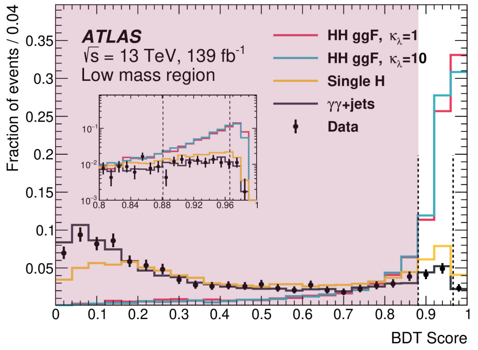
$0.1 < \kappa_{2V} < 2.0$ ($0.0 < \kappa_{2V} < 2.1$)

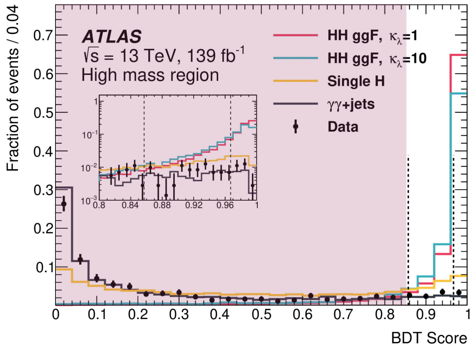
HH → bbγγ search

PRD 106 (2022) 052001, Limit: 4.2 (5.7) x SM prediction

- Largest BR (H → bb) + high resolution (H → $\gamma\gamma$)
- **Dominant backgrounds:** $\gamma\gamma$ + jets, small contribution from single Higgs
- **4 categories** defined based on the four-body mass and BDT score





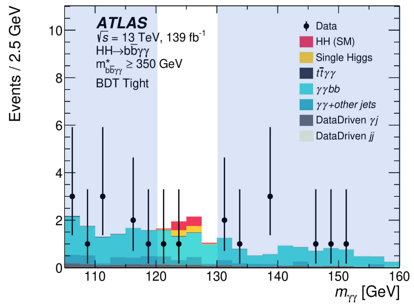


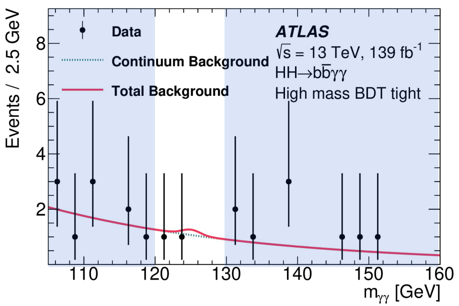
Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$

Discriminant: $m_{\gamma\gamma}$

Parametrization:

- **Crystal Ball** for HH signal
- **exp(a·$m_{\gamma\gamma}$)** for $\gamma\gamma$ + jets (normalized to sidebands)





HH → bbττ search

arXiv:2209.10910 [hep-ex], Limit: **4.7 (3.9) x SM prediction**

3 categories driven by trigger:

- $\tau_{had}\tau_{had}$: BDT
- $\tau_{lep}\tau_{had}$ SLT, LTT: NN

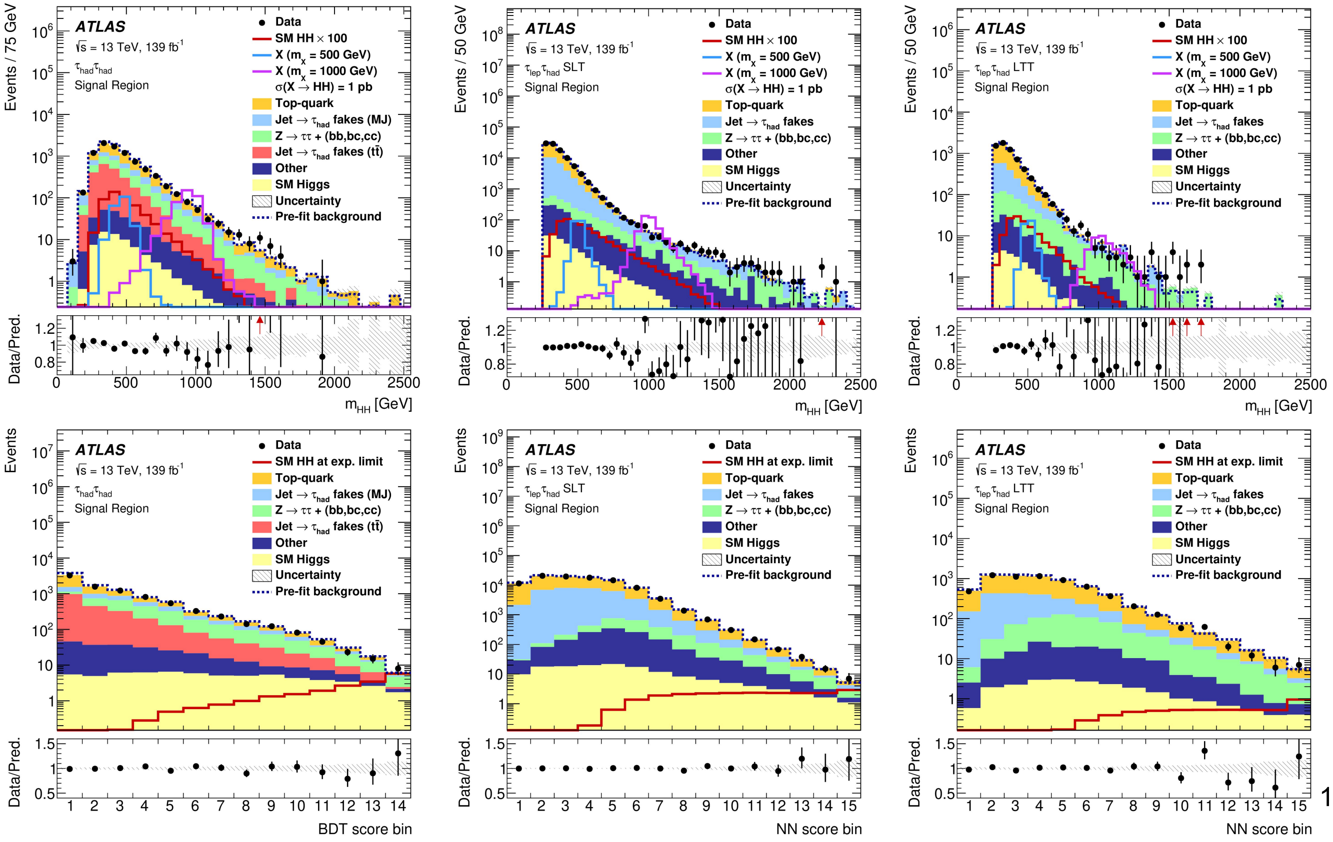
Dominant backgrounds: tt, multijet, Z+heavy flavor jets

Discriminant: MVA outputs

Sensitivity of non-resonant search improved by a factor 4 wrt previous analysis:

- half due to statistics
- half due to $\tau_{had\text{-}vis}$ and b-jet reconstruction improvements

$\tau_{had}\tau_{had}$ | $\tau_{lep}\tau_{had}$ Single Lepton Trigger (SLT) | $\tau_{lep}\tau_{had}$ Lepton+Tau Trigger (LTT)



HH → bbbb search

arXiv:2301.03212 [hep-ex], Limit: 5.4 (8.1) x SM prediction

Exploits the decay mode with the largest BR

Main backgrounds: 90% multijet, 10% ttbar

Jet pairing obtained minimizing ΔR separation for the higher-p_T jet pair (efficiency: 90%)

Top-veto discriminant:

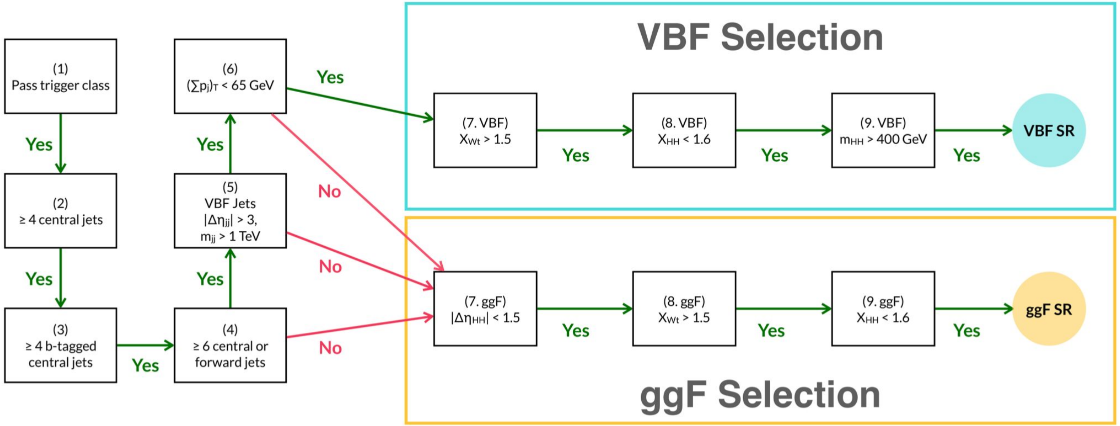
$$X_{Wt} = \min\left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}}\right)^2}\right]$$

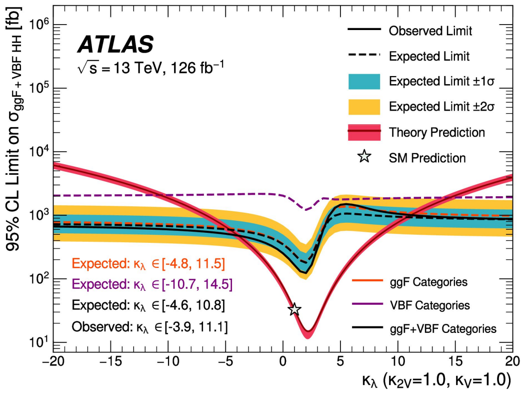
X_{HH} discriminant:

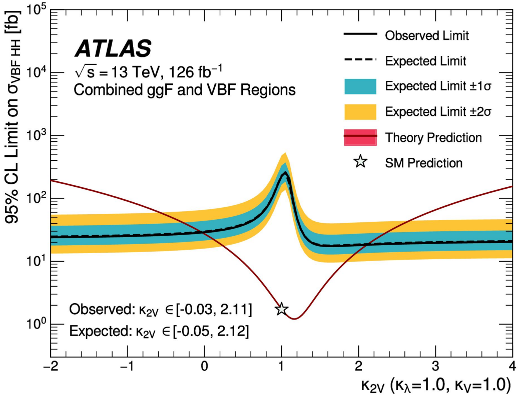
$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ \text{GeV}}{0.1\ m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ \text{GeV}}{0.1\ m_{H2}}\right)^2}$$

Results:

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{\text{ggF+VBF}}$	5.4	4.3	5.8	8.1	12.2	19.1







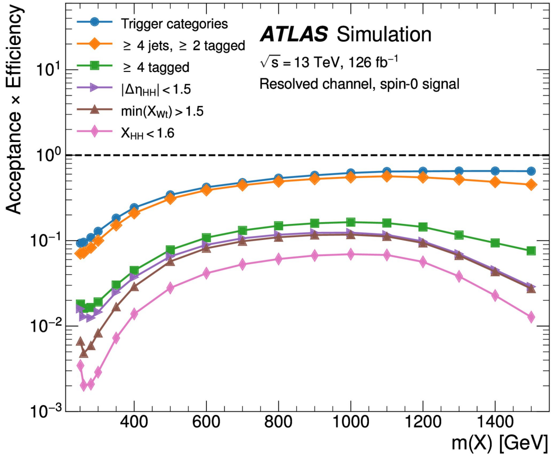
Improvements for Run 3

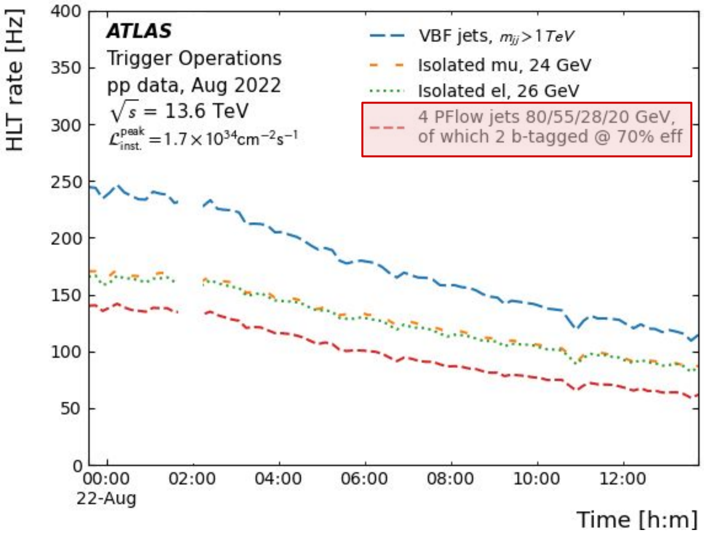
HH → bbbb search in Run 2
[Phys. Rev. D 105 (2022) 092002]

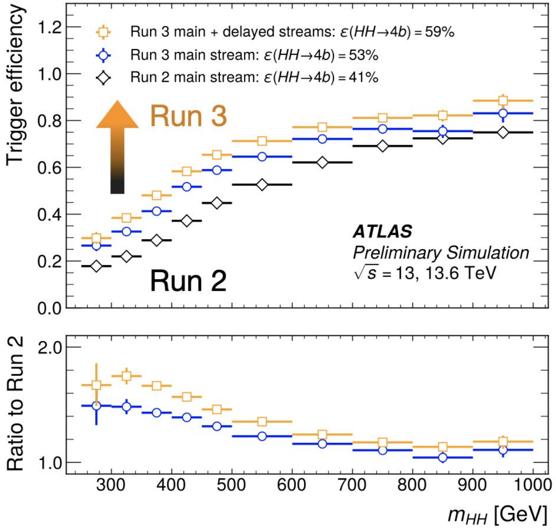
"The efficiency at low resonance masses is mainly limited by the trigger"

Run 3

- ➢ **80%** improvement in the trigger efficiency for the HH → bbbb signal (asymmetric 3-jet trigger instead of symmetric 4-jet trigger at Level-1)
- ➢ New **diHiggs delayed stream** with increased rate





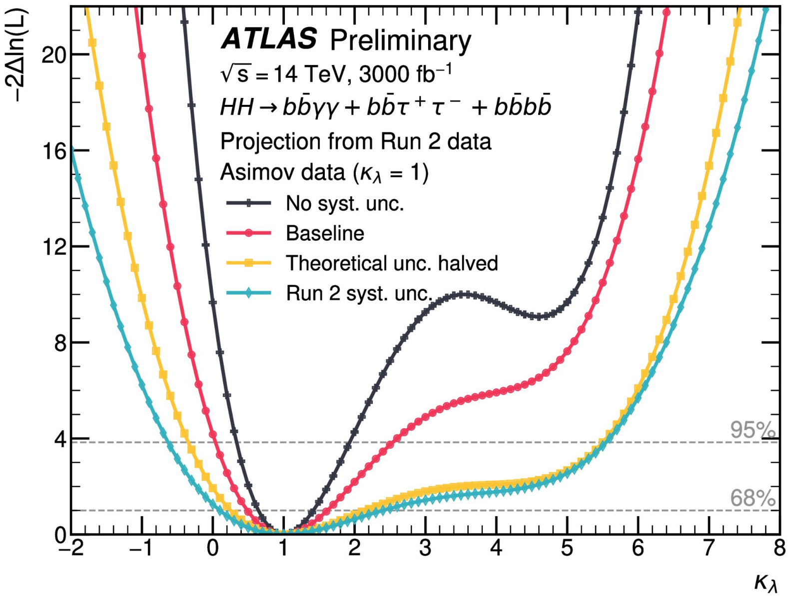


Prospects

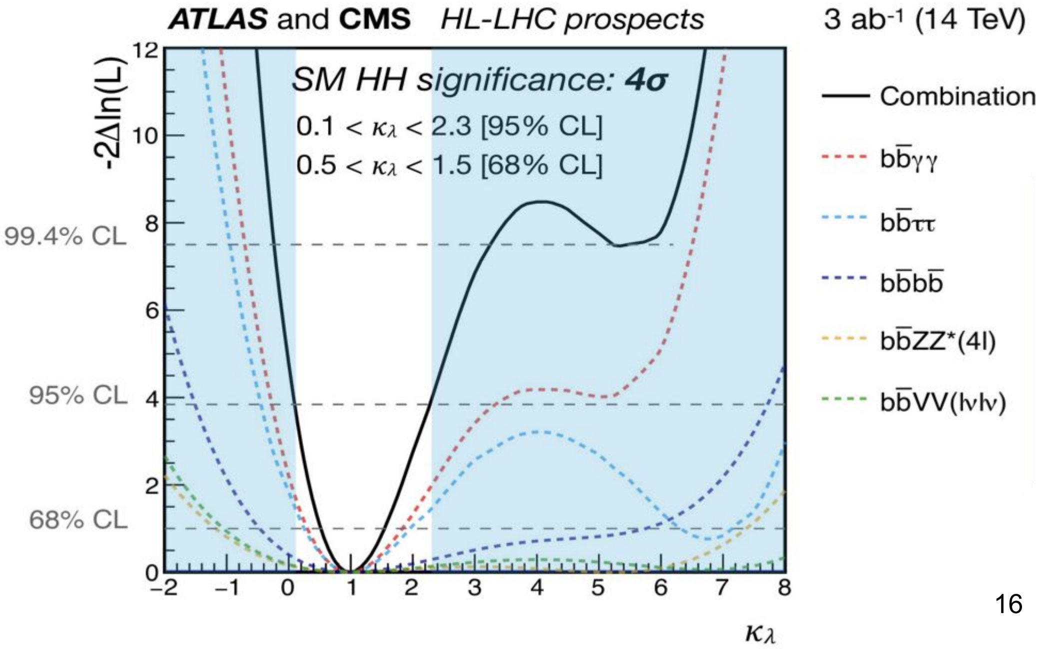
HL-LHC (3000 fb^{-1}):

- 3.4σ SM HH evidence combining bb$\gamma\gamma$, bb$\tau\tau$ and bbbb in ATLAS
- 5σ SM HH observation expected to be reached combining ATLAS and CMS

ATL-PHYS-PUB-2022-053



Yellow report [CERN-2019-007]

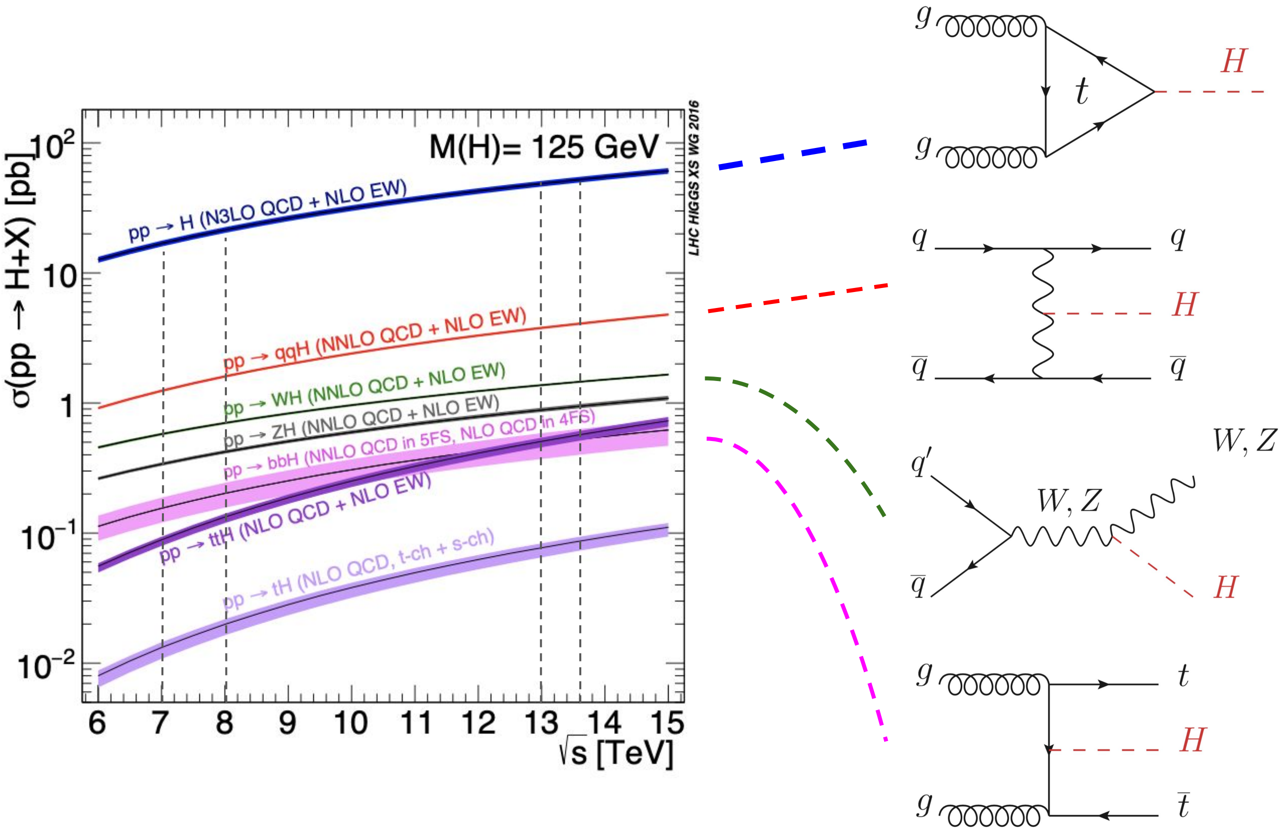


Conclusions

- After the discovery of the Higgs boson, the **observation of the Higgs boson self-coupling is one of the main priorities of the LHC physics program** (**physics driver**)
- State-of-the-art diHiggs searches in ATLAS using the full Run 2 dataset presented, good agreement with SM expectations observed so far
- A 95% CL **upper limit of 2.4 times the cross section predicted by the SM is set on HH non-resonant production** (combining the most relevant channels bb$\gamma\gamma$, bb$\tau\tau$, bbbb)
- Run 3 effort starting now, it can be a game-changer for HH
- Vital the optimization of the trigger and analysis techniques to maximize the HH signal
- According to the projections, observation of the SM HH production expected at the end of the HL-LHC (3000 fb^{-1})
- ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults

BACKUP

Higgs boson - production mechanisms



gluon gluon Fusion (ggF)

87%

Vector Boson Fusion (VBF)

7%

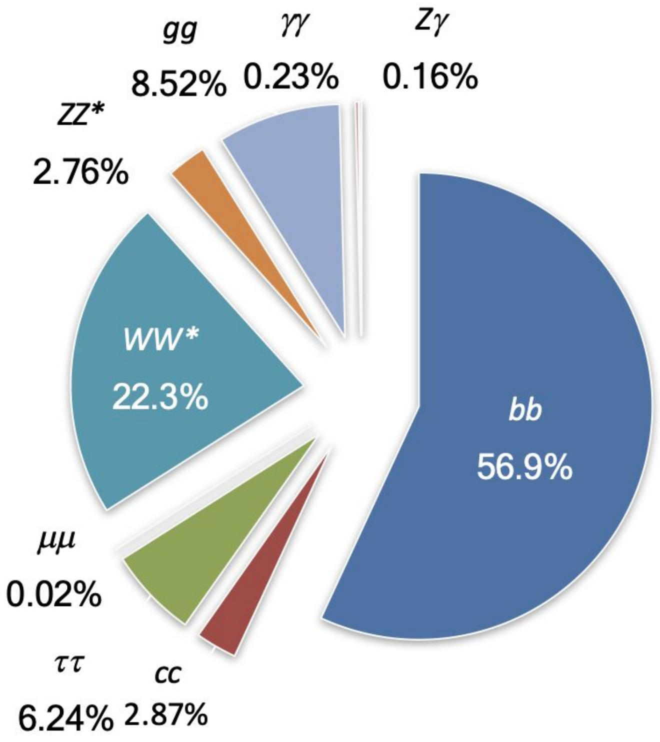
VH

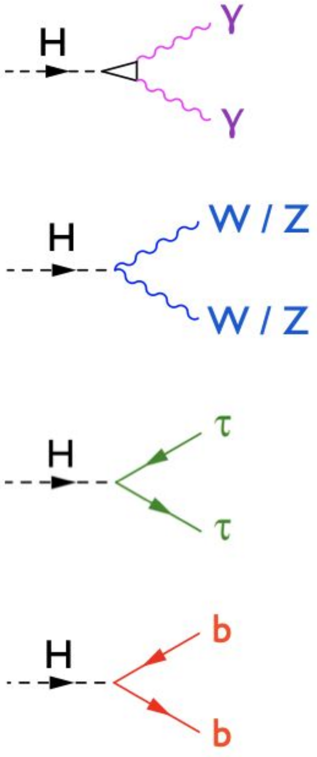
5%

ttH

0.6%

Higgs boson - decay channels





Higgs bosons per fb^{-1} (13 TeV)

	produced	selected
$H \to \gamma\gamma$	130	46
$H \to ZZ^*$	1400	1.5
$H \to WW^*$	12000	42
$H \to \tau\tau$	3500	17
$H \to b\bar{b}$	32000	66

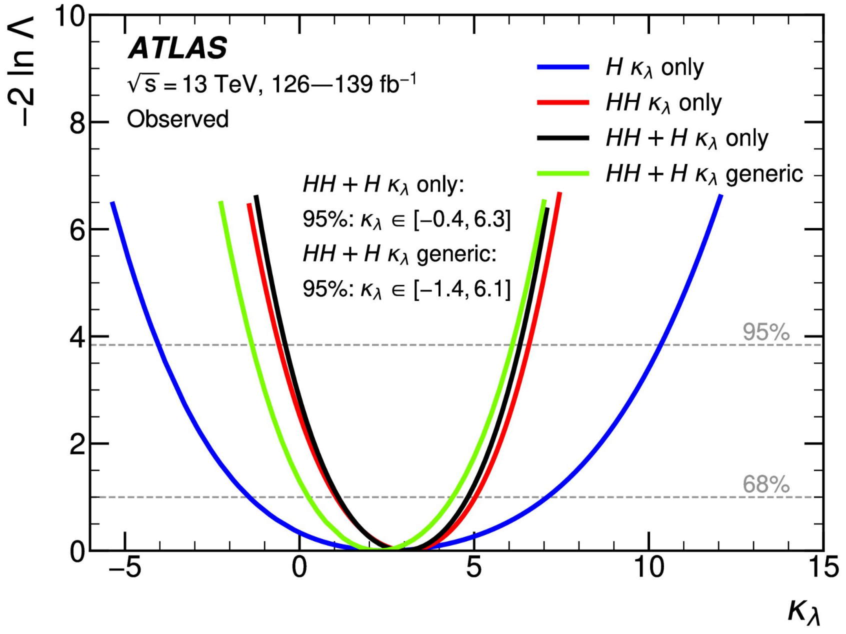
Observed in **Run 1**

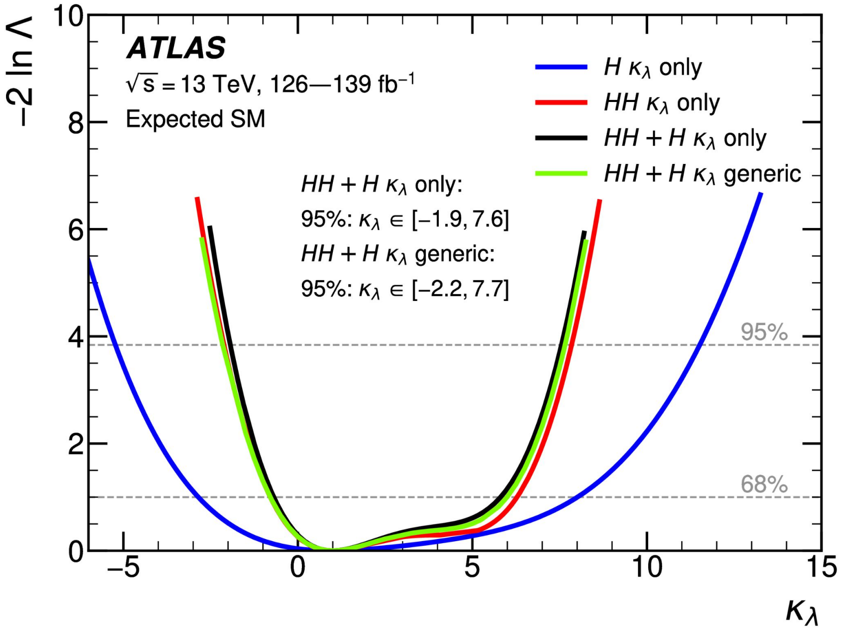
Discovery channels: H→$\gamma\gamma$, H→ZZ*, H→WW*

Observed in **Run 2** (dominant channel)

Trilinear coupling HHH

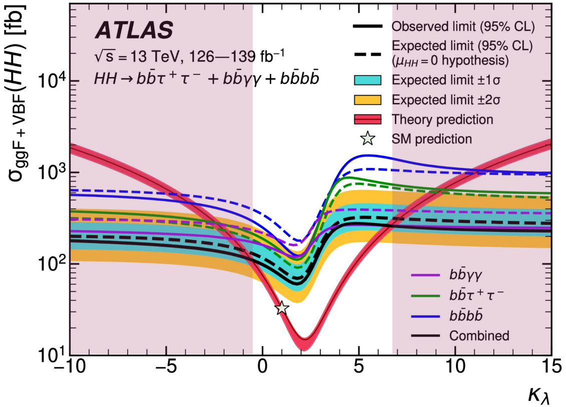
arXiv:2211.01216 [hep-ex]

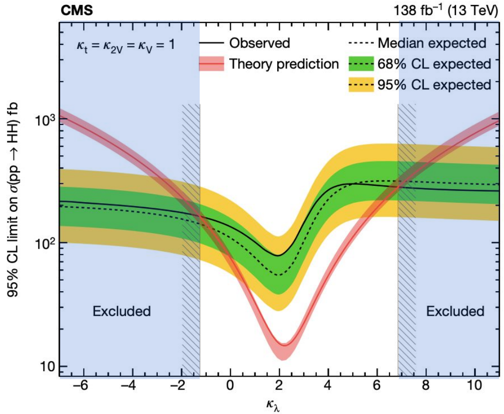




Trilinear coupling HHH - ATLAS vs CMS

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

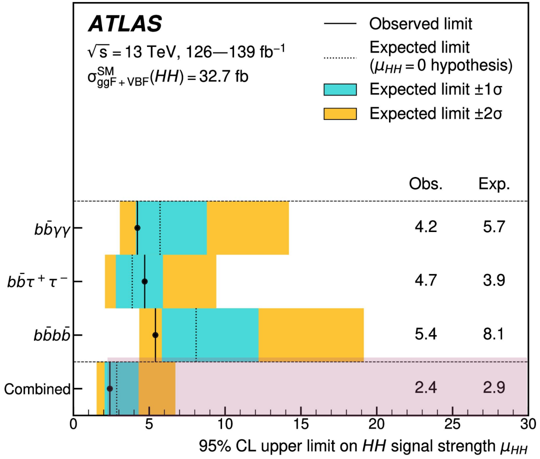




ATLAS, [arXiv:2211.01216](https://arxiv.org/abs/2211.01216) [hep-ex]

Limit: 2.4 x SM prediction

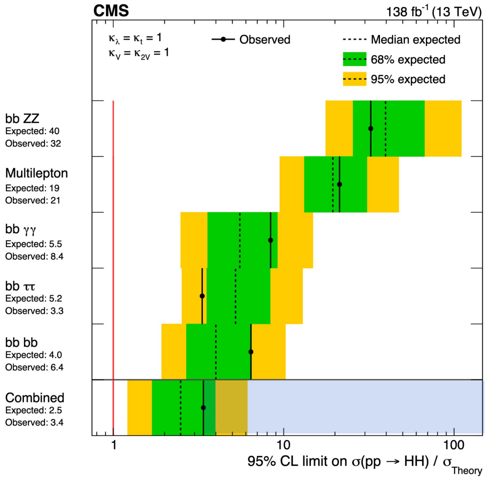
$-0.4 < \kappa_\lambda < 6.3$



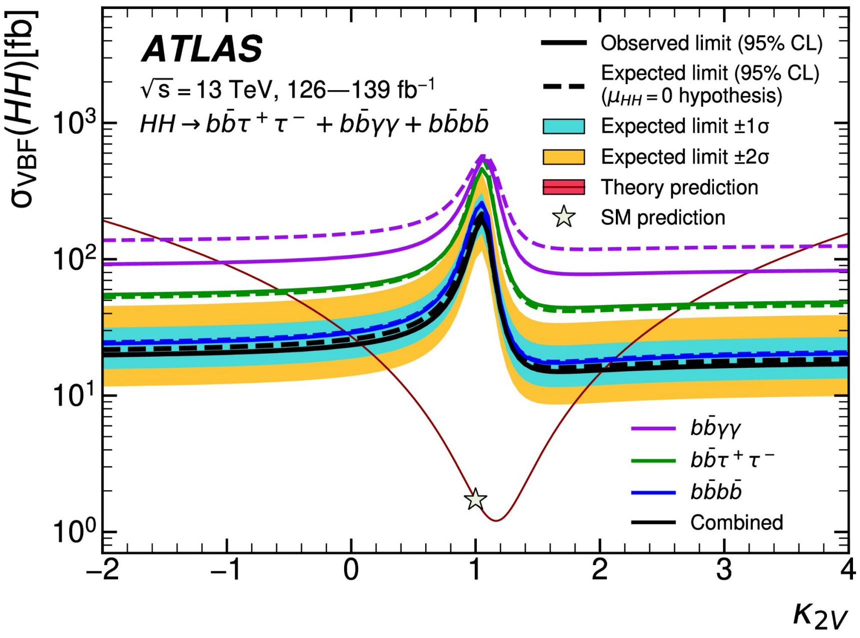
CMS, [Nature 607 (2022) 60-68]()

Limit: 3.4 x SM prediction

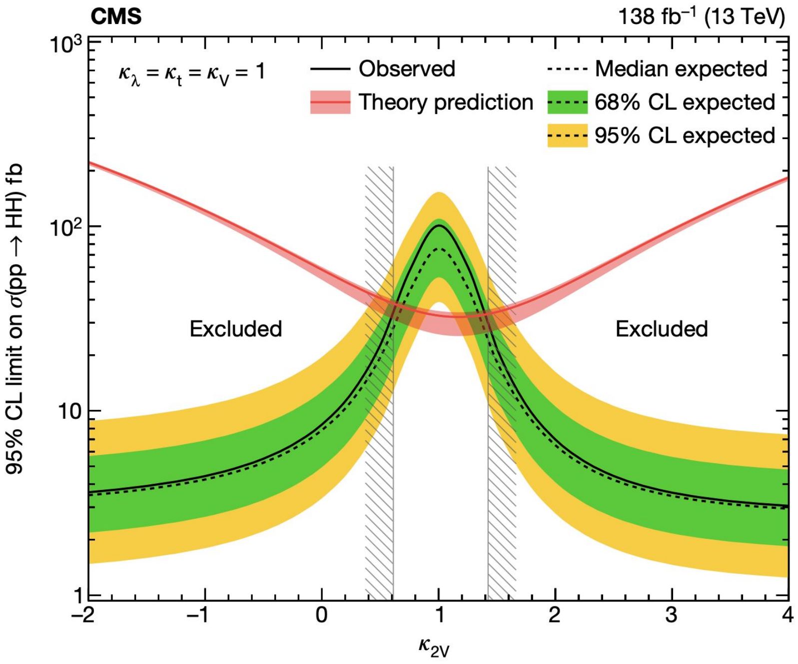
$-1.24 < \kappa_\lambda < 6.49$



Quartic coupling VVHH - ATLAS vs CMS



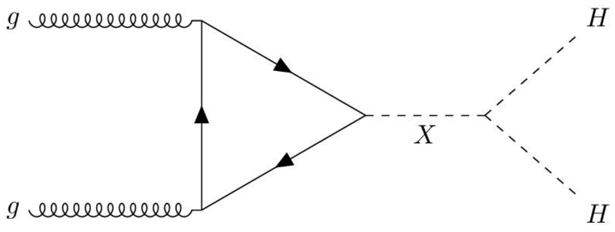
ATLAS, Nature 607 (2022) 52–59

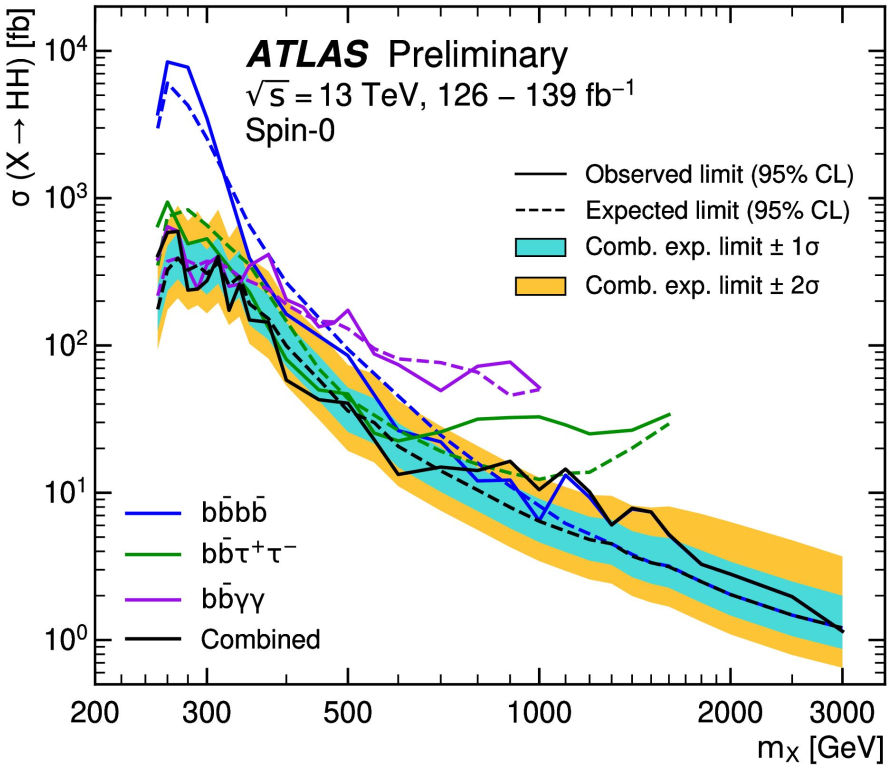


CMS, Nature 607 (2022) 60-68

Combination of diHiggs resonant searches

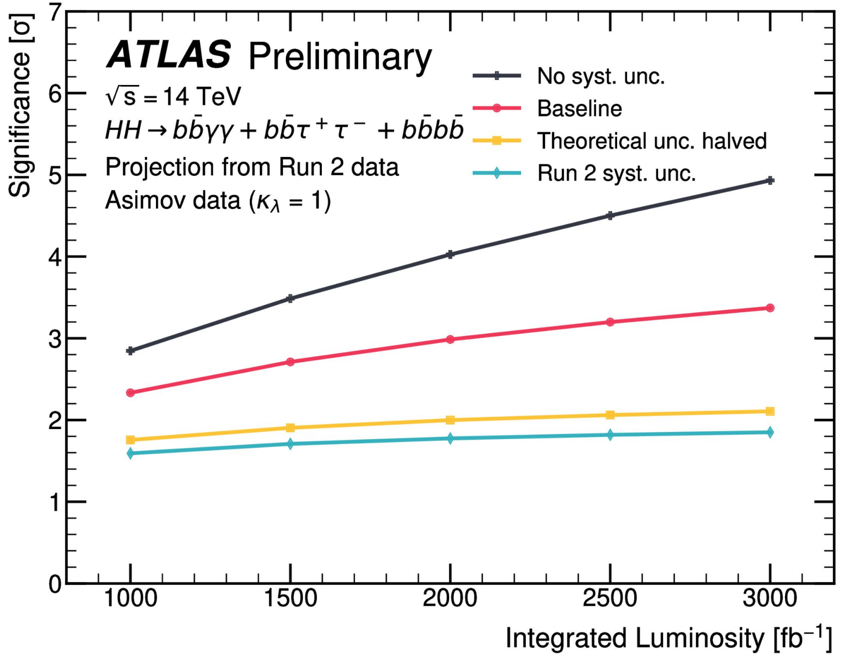
ATLAS-CONF-2021-052

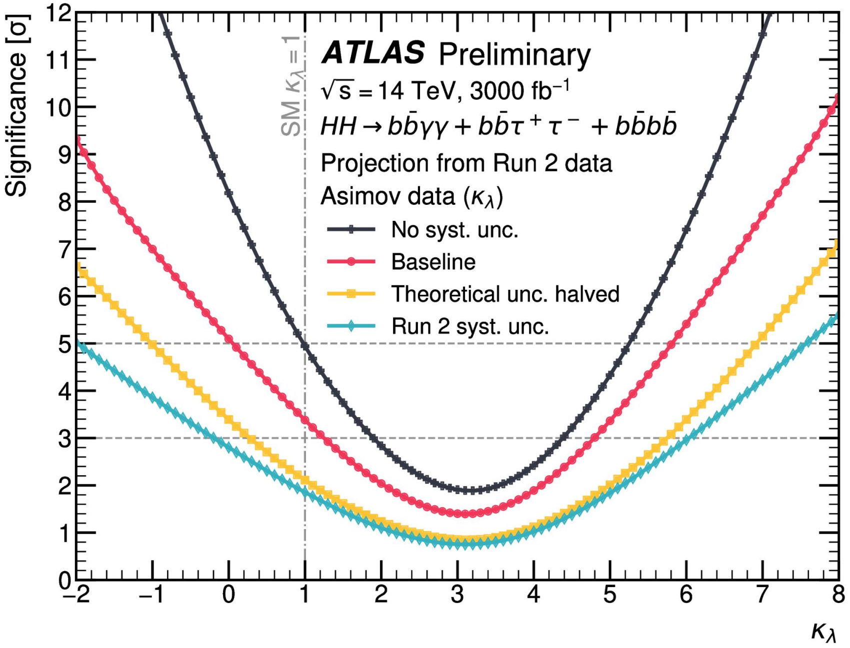




HL-LHC prospects for HH in ATLAS

ATL-PHYS-PUB-2022-053





HL-LHC prospects for HH in ATLAS

ATL-PHYS-PUB-2022-053