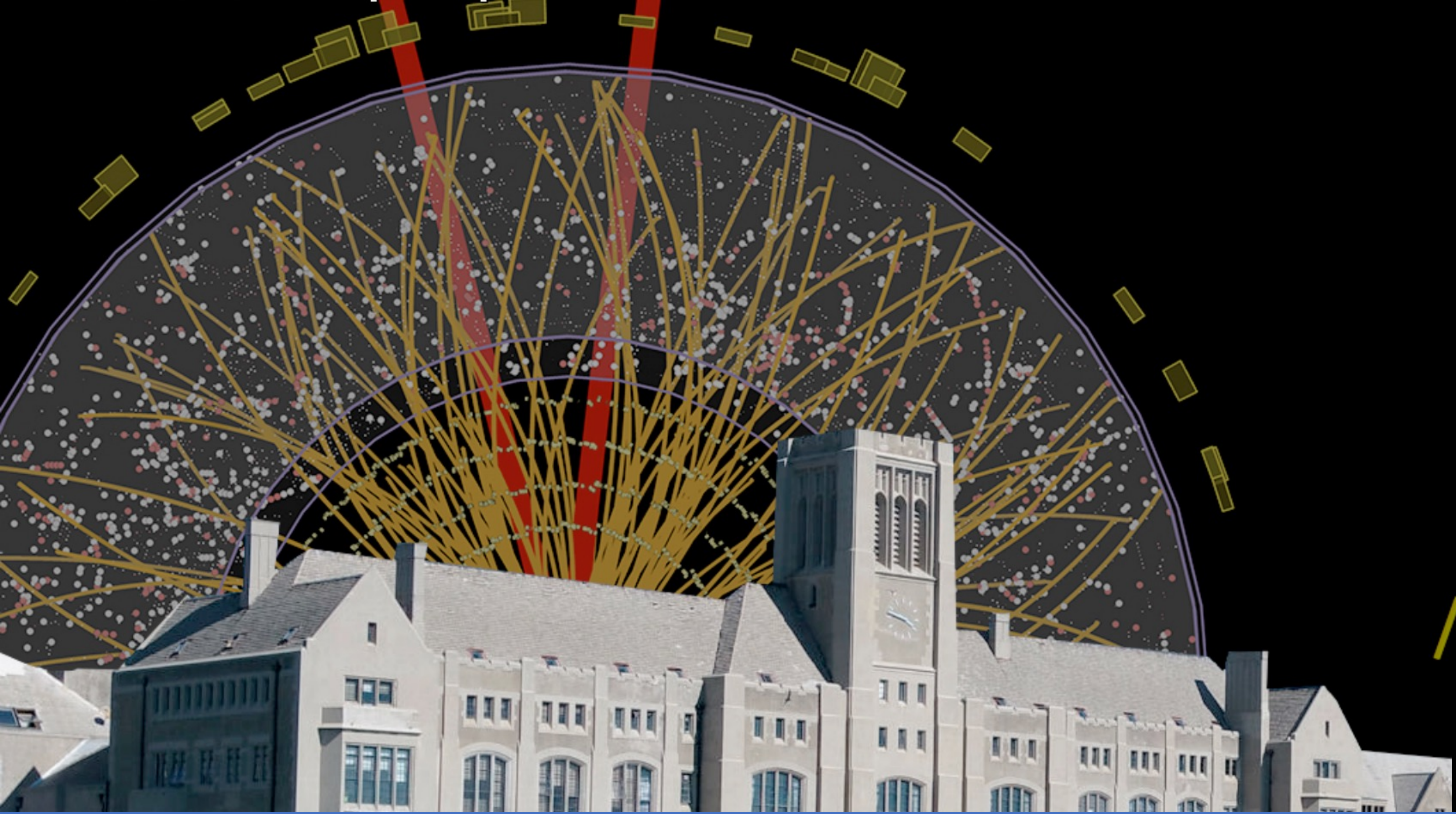


ATLAS EXPERIMENT

HEP2023, 9-13 January 2023
UTFSM, Valparaíso, Chile

Search for Higgs pair production at the LHC with the ATLAS detector

Edson Carquin
(UTFSM)
On behalf of the ATLAS Collaboration

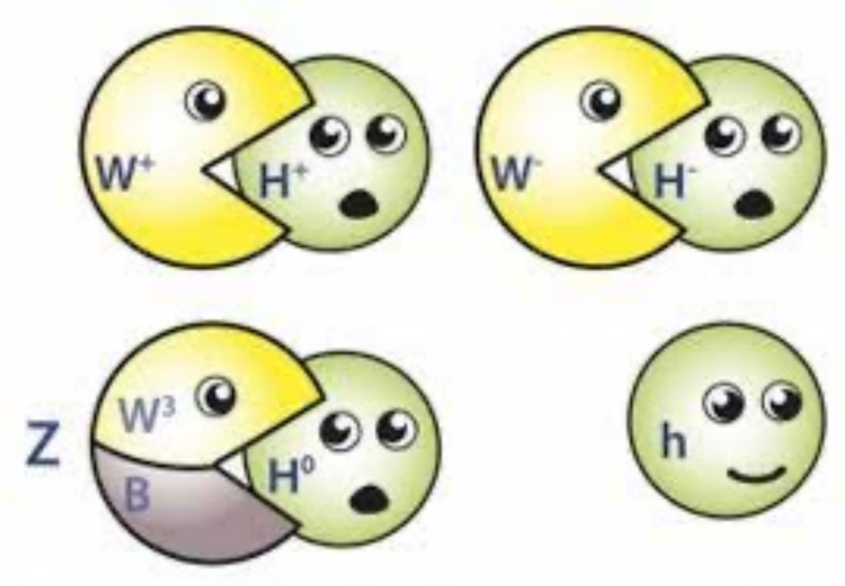
EX UMBRA IN SOLEM

CCTVal
CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO

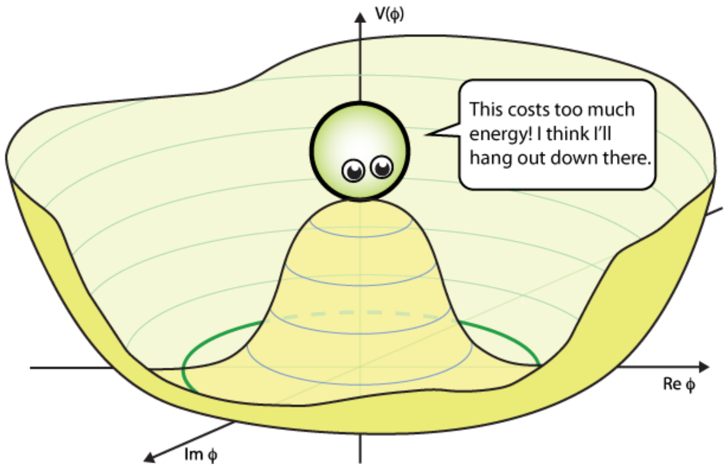
https://atlas-utfsm.web.cern.ch/

Why looking for Higgs pairs at LHC?

- In the SM, Higgs pair production is driven by the (still unmeasured) Higgs self-coupling $\lambda_{HHH} = \frac{m_H^2}{2v}$ (with $m_H = 125\ GeV$ and $v = 246\ GeV$)
- λ_{HHH} plays a crucial role in the Electroweak Symmetry breaking mechanism.
- New Physics can cause resonant Higgs pair production and/or introduce modifications on the effective Higgs self-coupling enhancing DiHiggs production rates.

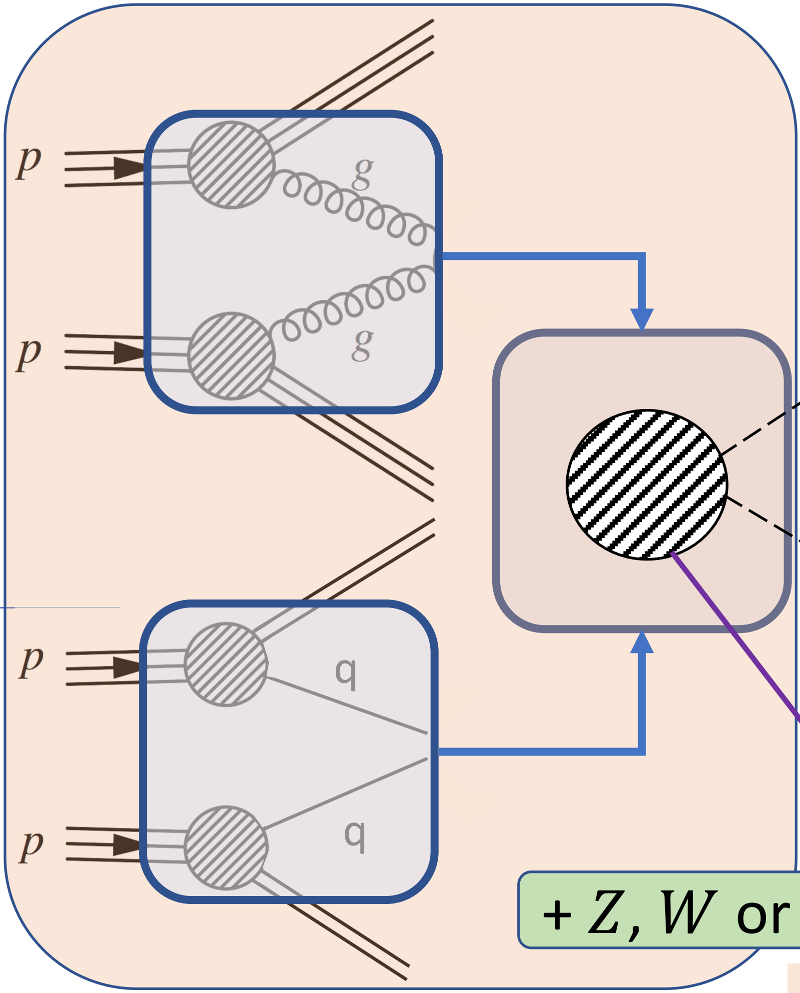


SM Higgs mass production mechanism can be tested!



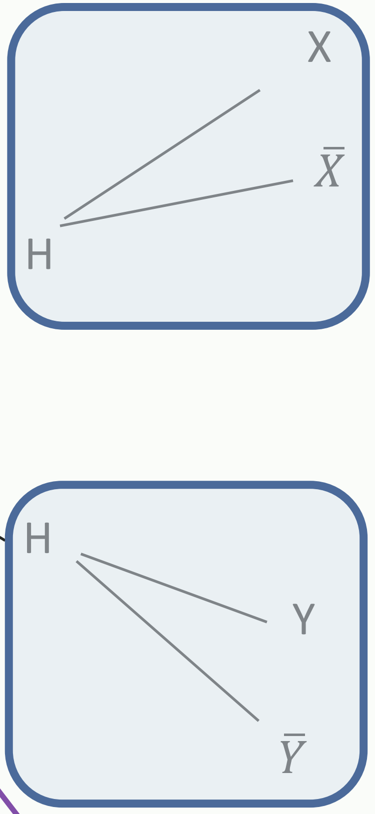
How to measure Higgs pair production at the LHC

Production



$+ Z, W$ or $t\bar{t}$

Decay



$X\bar{X}/Y\bar{Y}$	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%

Then combine all production and decay modes together

Full Run 2 ATLAS searches

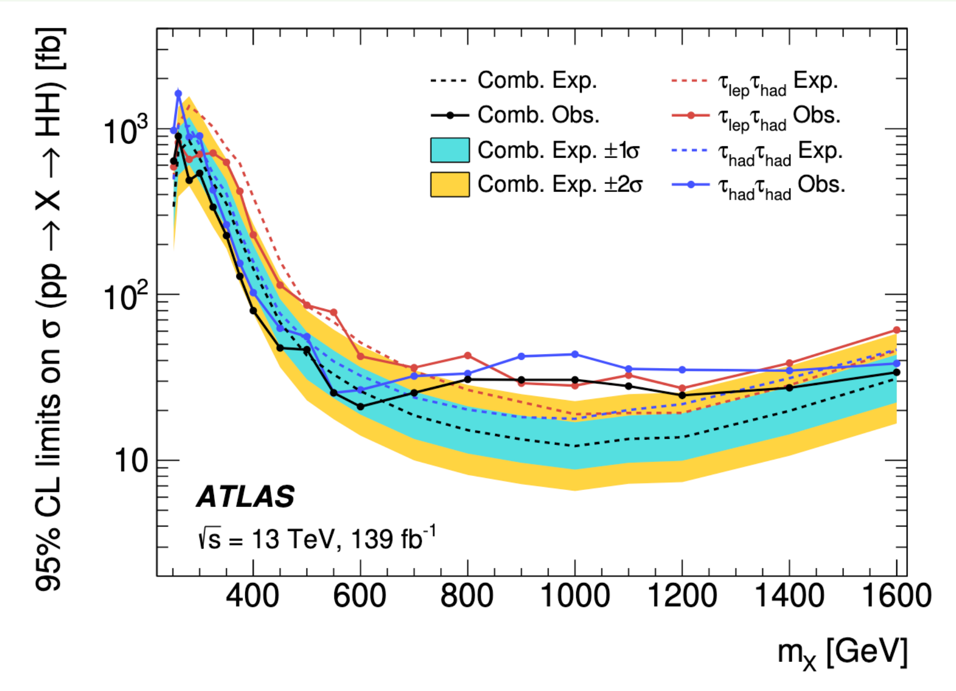
In this talk ■

Decay channel	Target production mode	Reference	Release date
bbγγ	Non-resonant (ggF*) & resonant	Phys. Rev. D 106 052001	22 Dec 2021
bbττ	Non-resonant (ggF*) & resonant	arXiv:2209.10910	22 Sep 2022
	Resonant (merged H→ττ & H→bb)	JHEP 11 (2020) 163	29 July 2020
bbbb	Resonant	Phys. Rev. D 105 092002	15 Feb 2022
	Non-resonant (ggF & VBF)	arXiv:2301.03212 NEW!	30 May 2022
	VHH (leptonic V, res. & non-res.)	arXiv:2210.05415	11 Oct 2022
bblνlν	Non-resonant (ggF)	Phys. Lett. B 801 135145	19 Aug 2019
Combination	Non-resonant & resonant (ggF*)	ATLAS-CONF-2021-052	16 Oct 2021
	Non-resonant + single Higgs	arXiv:2211.01216	3 Nov 2022
Interpretations	HEFT interpretations	ATL-PHYS-PUB-2022-019	18 Mar 2022

*** VBF accounted for, but not specifically targeted**

HH→bb$\tau\tau$ Resonant/Non-resonant search

- Three signal regions considered:
  - $\tau_h\tau_h$ (fully hadronic)
  - $\tau_l\tau_h$ (semi-leptonic), single lepton and lepton+tau triggers considered separetely
- Multiple background sources are important for this analysis, most of them are estimated from simulation.
- Background sources containing fake-τ_{had} in $t\bar{t}$ and multijet production are estimated by the fake factor method, by using template distributions obtained in fake enriched regions.
- Parametrized neural networks (PNN) are trained as a function of the resonant mass in this search.

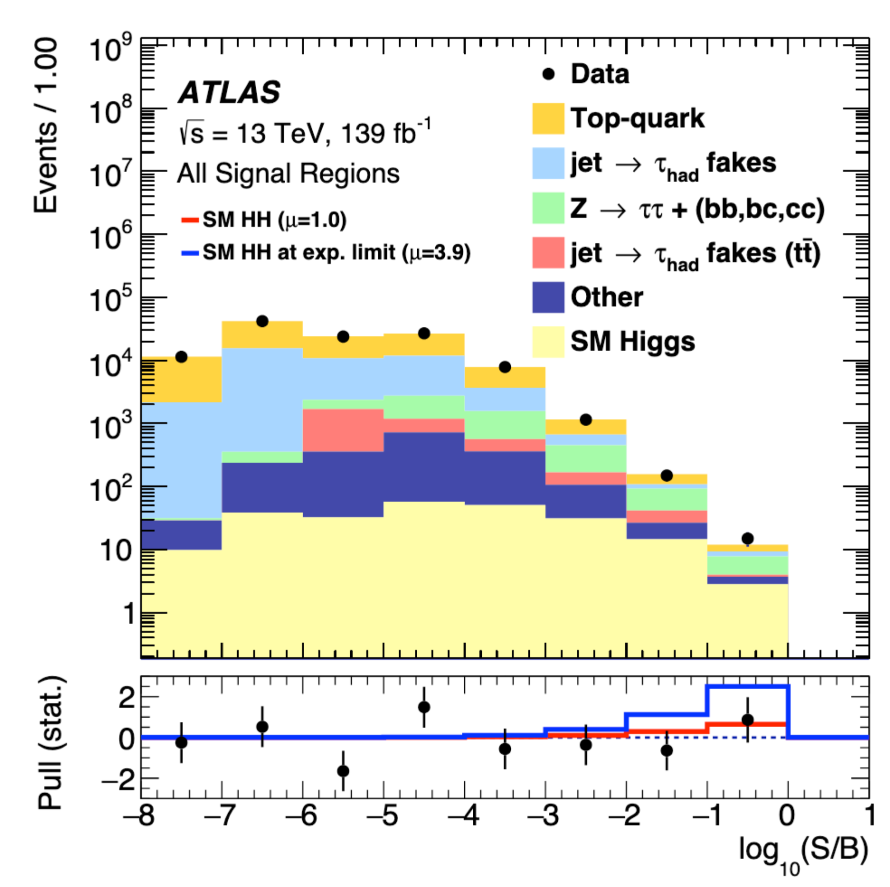


The largest deviation is found for the resonant case at a mass of 1 TeV, corresponding to a global significance of 2.0 σ

arXiv:2209.10910

HH→bb$\tau\tau$ Resonant/Non-resonant search

- For the non-resonant analyses a BDT/NN is trained for the $\tau_h\tau_h/\tau_l\tau_h$ channels Respectively.
- The data is found to be compatible with the background-only assumption.
- The non-resonant limits are the second better, only beaten by $bb\gamma\gamma$ atm!



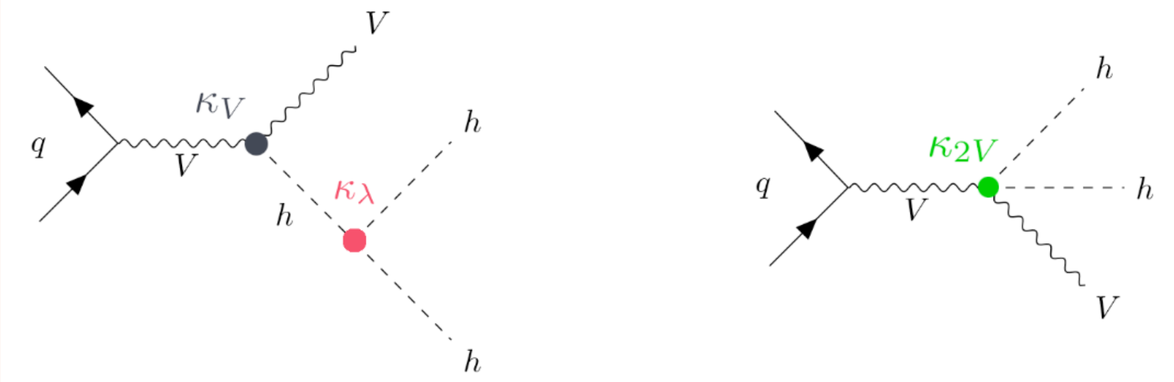
		Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
$\tau_{\rm had}\tau_{\rm had}$	$\sigma_{\rm ggF+VBF}$ [fb]	150	70	95	130	180	240
	$\sigma_{\rm ggF+VBF}/\sigma^{\rm SM}_{\rm ggF+VBF}$	5.0	2.4	3.2	4.4	6.1	8.2
$\tau_{\rm lep}\tau_{\rm had}$	$\sigma_{\rm ggF+VBF}$ [fb]	280	120	170	230	320	430
	$\sigma_{\rm ggF+VBF}/\sigma^{\rm SM}_{\rm ggF+VBF}$	9.7	4.2	5.6	7.8	11	15
Combined	$\sigma_{\rm ggF+VBF}$ [fb]	140	62	83	110	160	210
	$\sigma_{\rm ggF+VBF}/\sigma^{\rm SM}_{\rm ggF+VBF}$	4.7	2.1	2.8	3.9	5.4	7.2

arXiv:2209.10910

Vhh ($hh \to bbbb$) Resonant and non-resonant search

FIRST time at LHC

- 0, 1 and 2 lepton selections for $Z \to \nu\nu$ (MET), $W \to l\nu$ and $Z \to ll$ associated production.
- Interpreted in:
  - Two resonant benchmark models: Narrow scalar and 2HDM
  - SM-like κ framework ($\kappa_V, \kappa_{2V}, \kappa_\lambda$)
- BDT discriminant constructed for each number of leptons categories and for each signal model.
- Main backgrounds from top and V+jets, constrained in dedicated CRs.



$-34.4 < \kappa_\lambda < 33.3$ @ 95% CL

Assuming $\kappa_V = 1$

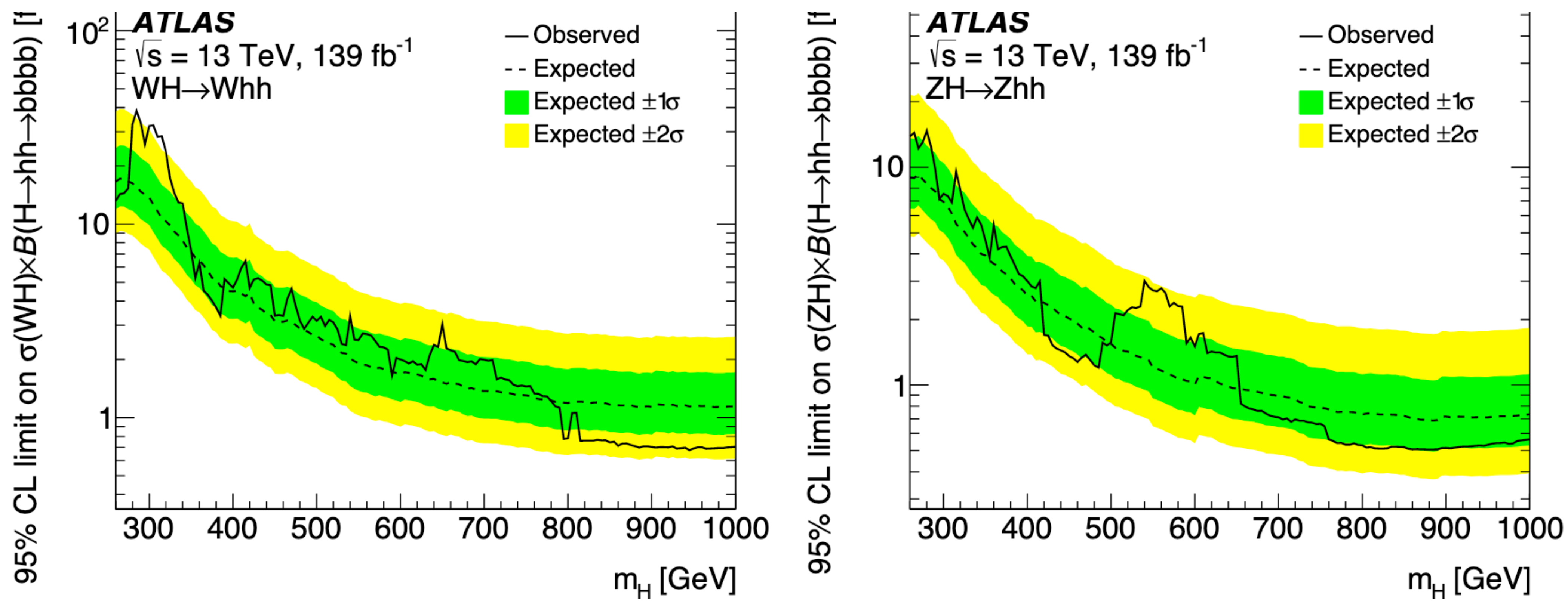
$-8.6 < \kappa_{2V} < 10.0$ @ 95% CL

$-12.3 < \kappa_{2W} < 13.5$ $-9.9 < \kappa_{2Z} < 11.3,$ @ 95% CL

Separated results for Z & W

arXiv:2210.05415

SM-like signal strength limit set at 183 (87) times σ_{SM} @ 95% CL



Vhh ($hh \rightarrow bbbb$) Resonant and non-resonant search

Cross section limits on the narrow scalar benchmark model

arXiv:2210.05415

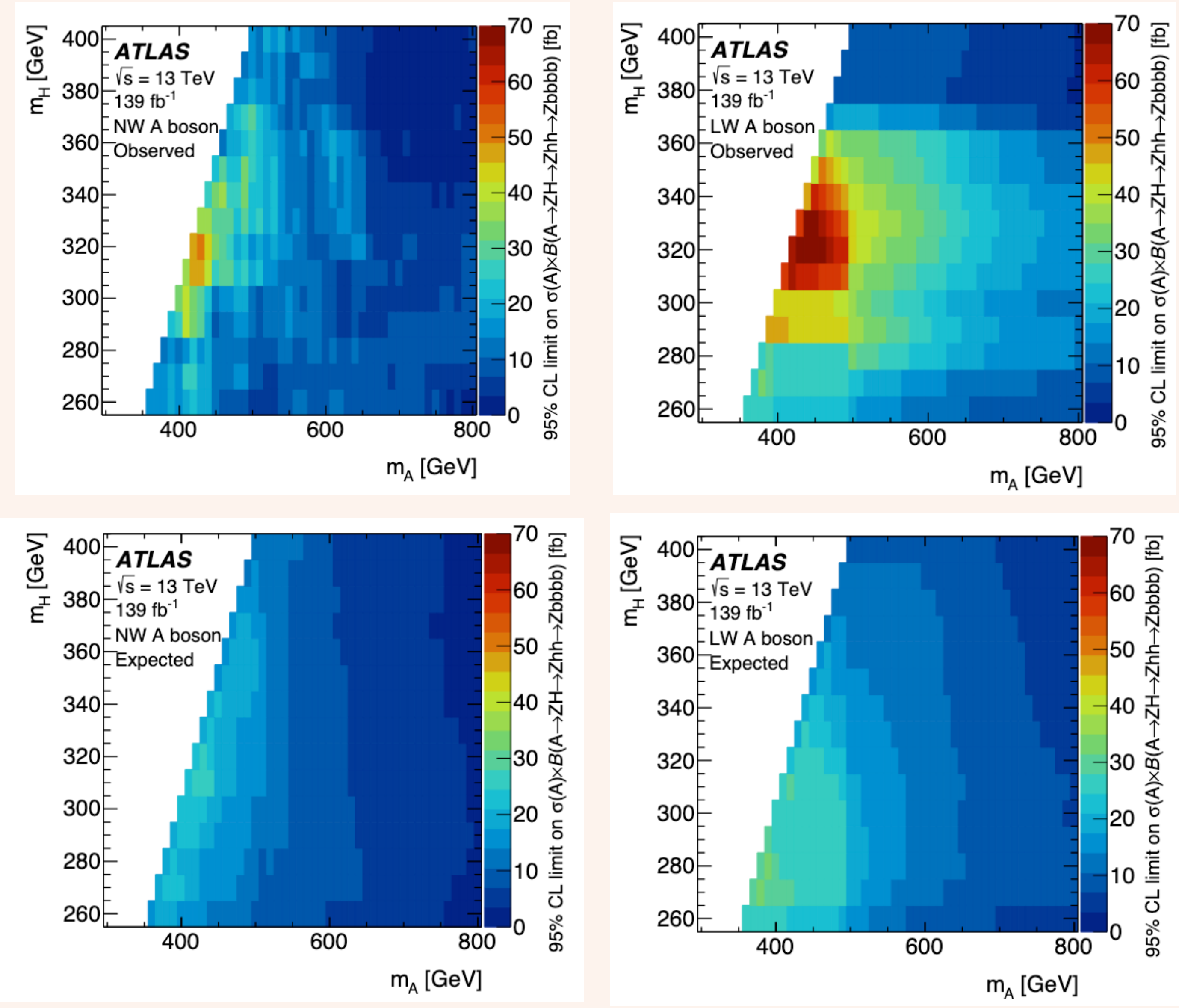
Vhh ($hh \rightarrow bbbb$) Resonant and non-resonant search

- Setting limits on 2HDM model through

$$A \rightarrow ZH \rightarrow Zhh$$

- Narrow and Large (20%) Pseudoscalar widths considered

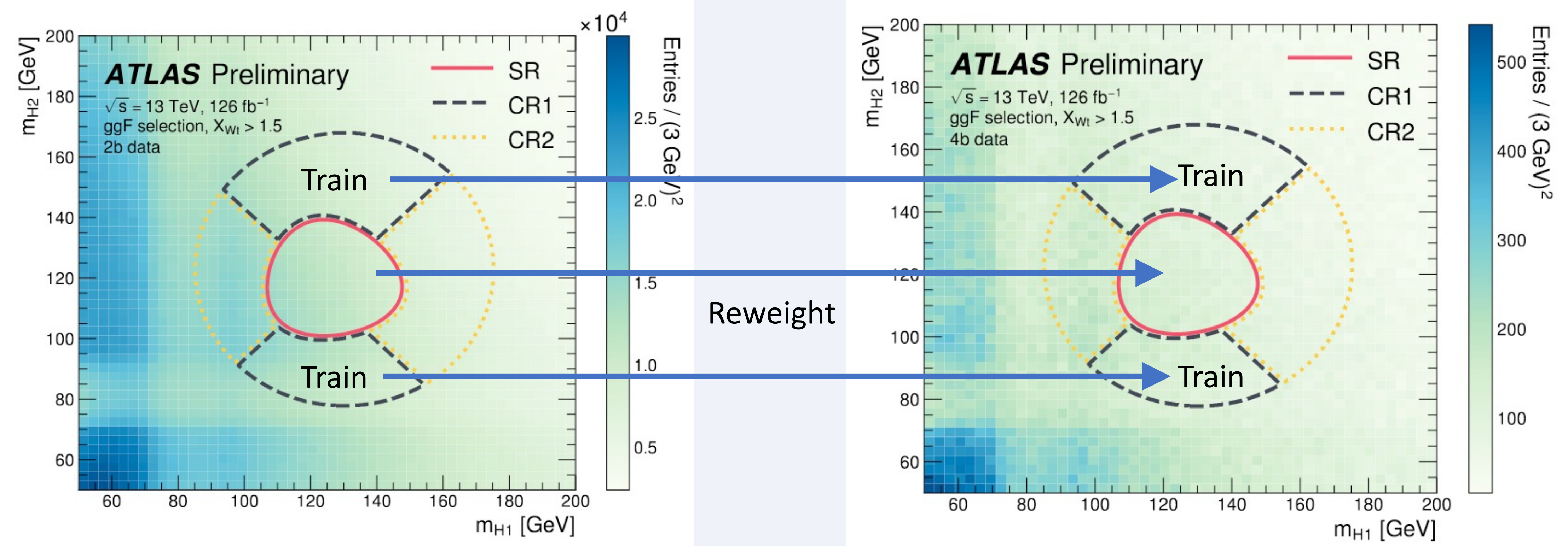
- Largest excess ($Z_{global} = 2.8\sigma$) found in large-width scenario @ $(m_A, m_H) = (420, 320)\ GeV$



arXiv:2210.05415

$hh \rightarrow bbbb$ non-resonant search

- Fully hadronic channel with the largest BR, but a difficult to estimate background from multijets (90%) and $t\bar{t}$ (10%).
  - ✓ Fully data driven method
  - ✓ NN based (trained) extrapolation from 2 b-tag to 4 b-tag data CRs.
- ggF and VBF signal regions optimized separately
  - ✓ Using m_{hh} as discriminating variable

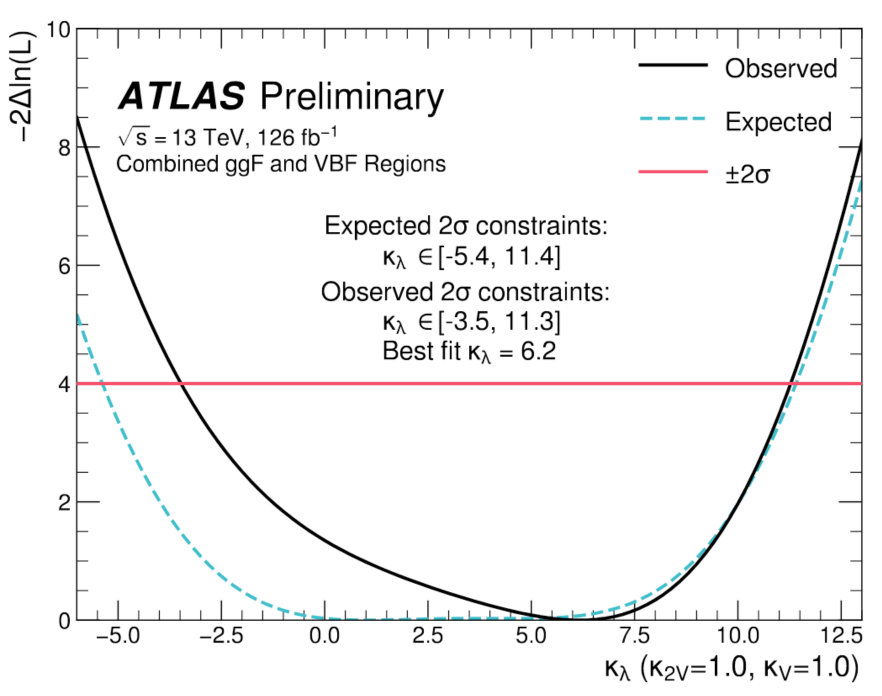


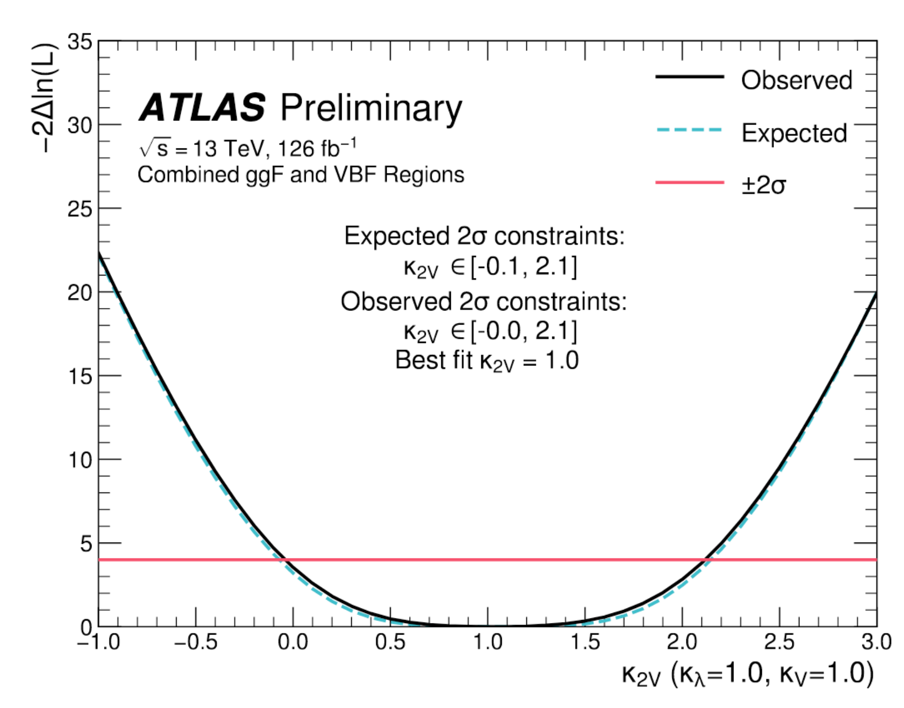
arXiv:2301.03212

$hh \rightarrow bbbb$ non-resonant search

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
$\sigma_{\mathrm{ggF}}/\sigma_{\mathrm{ggF}}^{\mathrm{SM}}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{\mathrm{ggF+VBF}}/\sigma_{\mathrm{ggF+VBF}}^{\mathrm{SM}}$	5.4	4.3	5.8	8.1	12.2	19.1

New signal strength limits for SM–like production are:
2.5 (ggF) and 4.1 (VBF) times better than the previous result



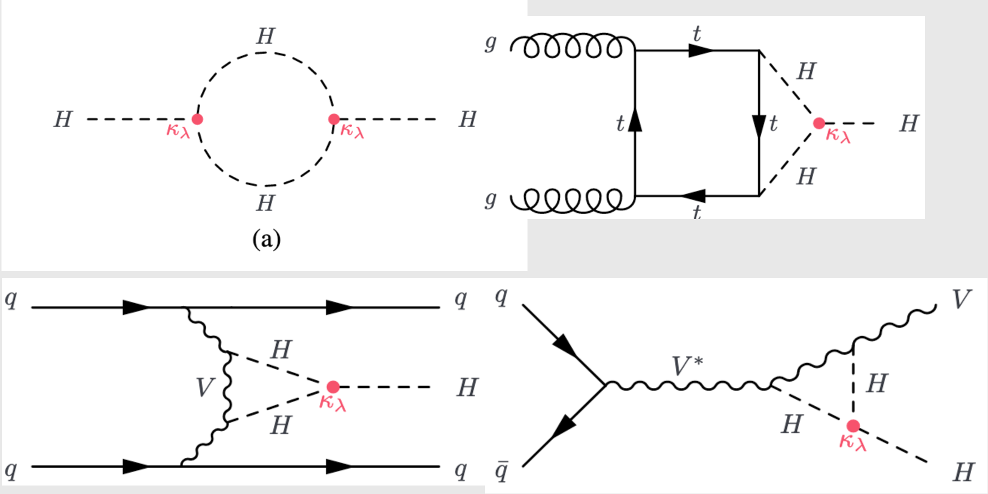


[arXiv:2301.03212](https://arxiv.org/abs/2301.03212)

Limits are also set on κ_λ (HHH coupling) and κ_{2V} (HHVV couplings)

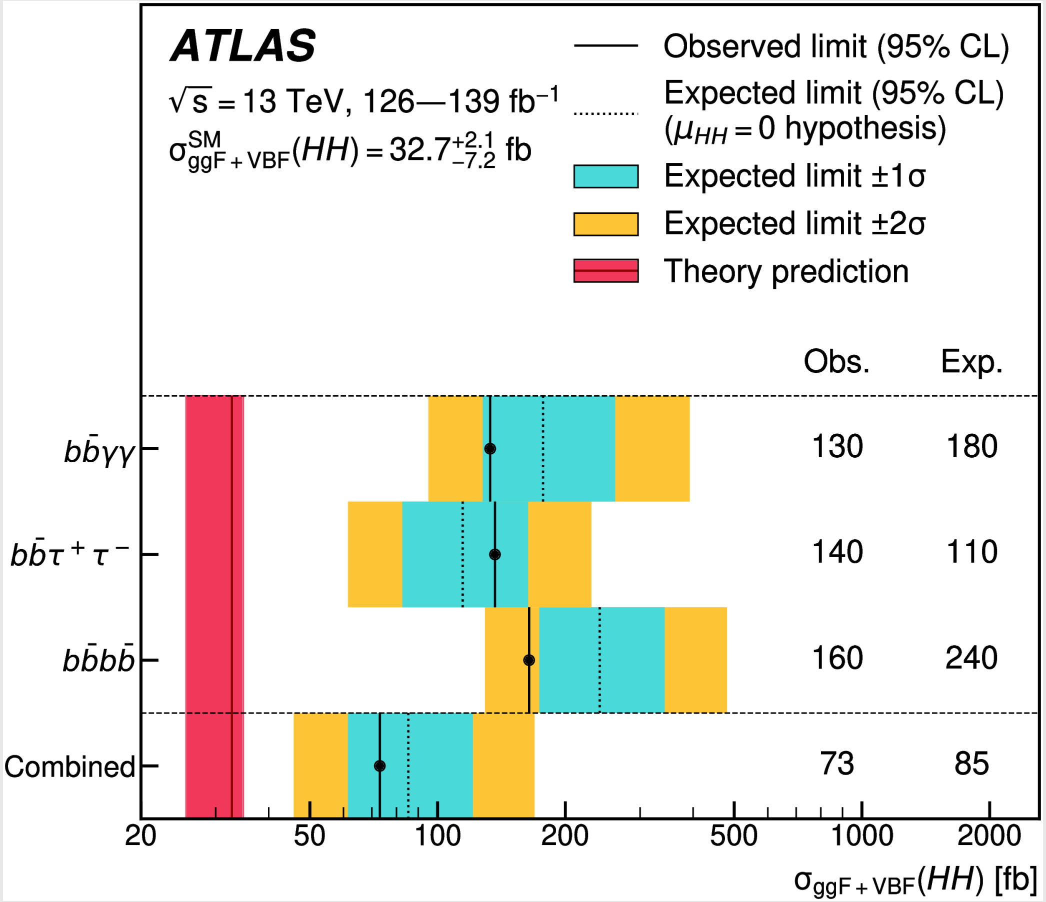
HH+H combination

Adding EW first order corrections to single Higgs production involving the HHH coupling, and combine with direct HH searches



arXiv:2211.01216

Combine the three most sensitive channels for SM-like signal strength limits.

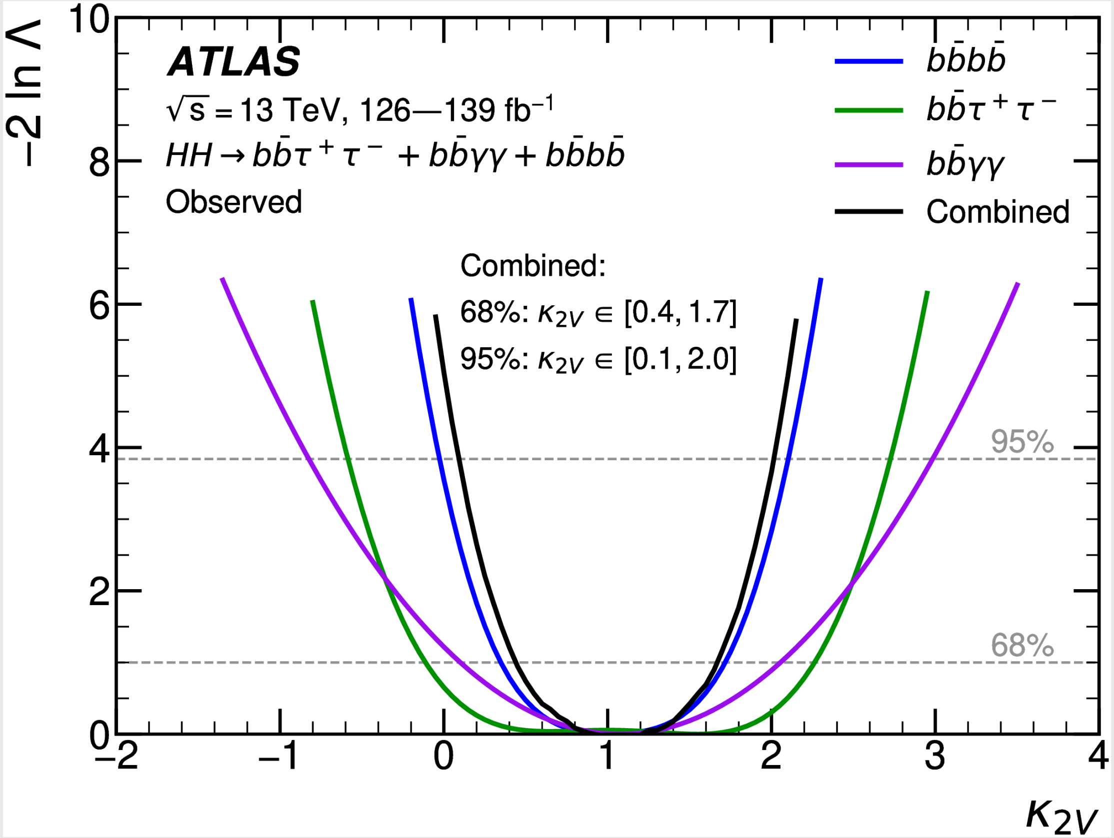


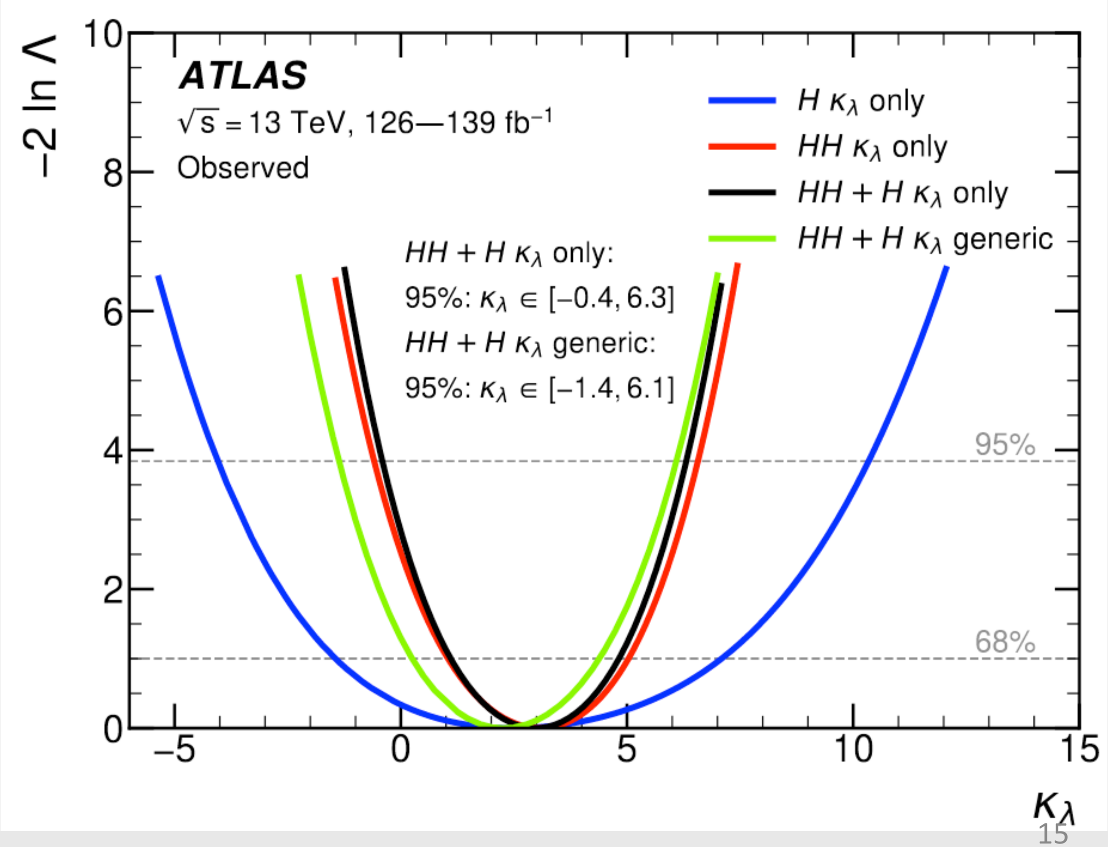
Getting closer in SM cross section!

HH+H combination

Combination provides the strongest constraints to date on κ_λ and κ_{2V}

- κ_λ limits dominated by HH channels
- κ_{2V} limits driven by HH→bbbb, as it has a dedicated VBF selection

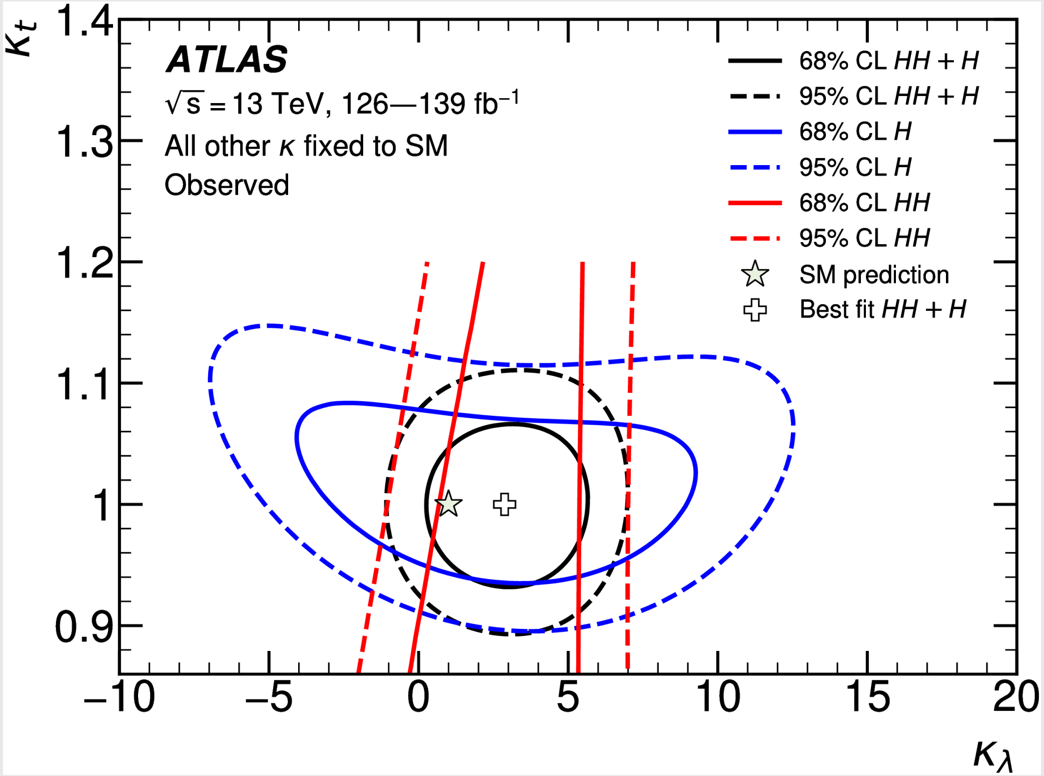




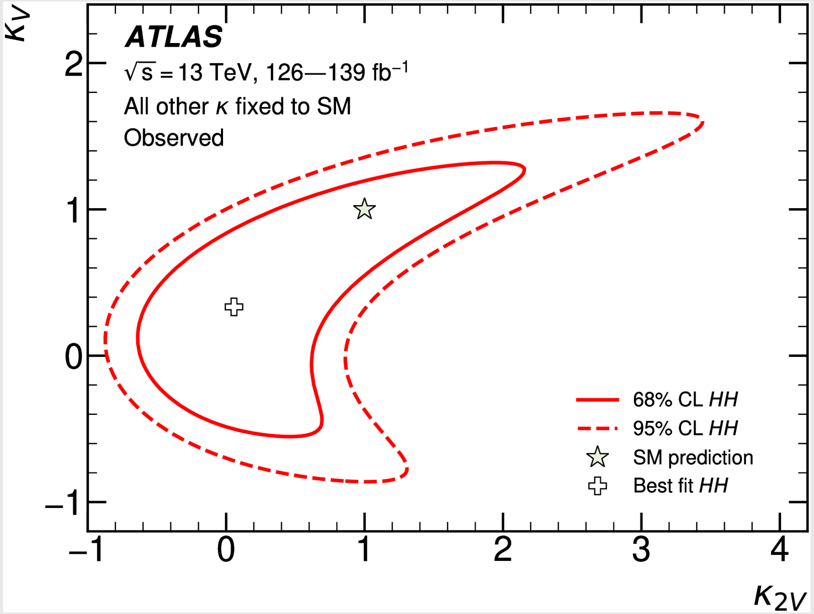
arXiv:2211.01216

HH+H combination

- Single Higgs + HH combination produce stronger constraints on κ_λ, κ_t plane compared to single-H only.
- κ_λ limits are obtained in a variety of combination assumptions

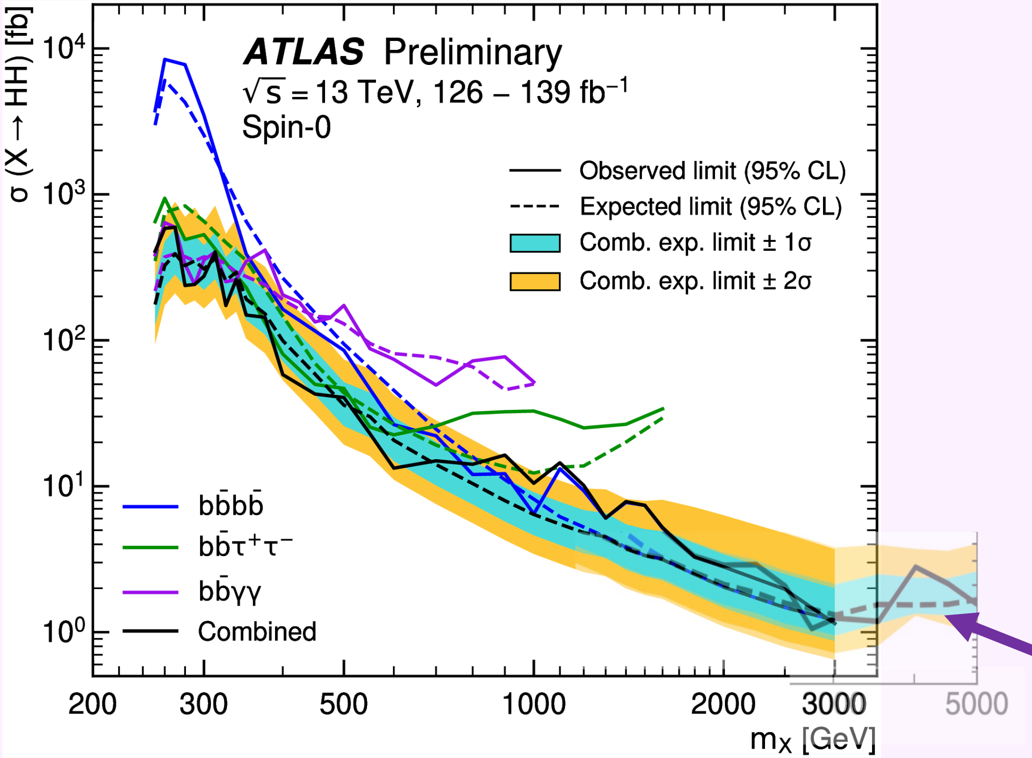


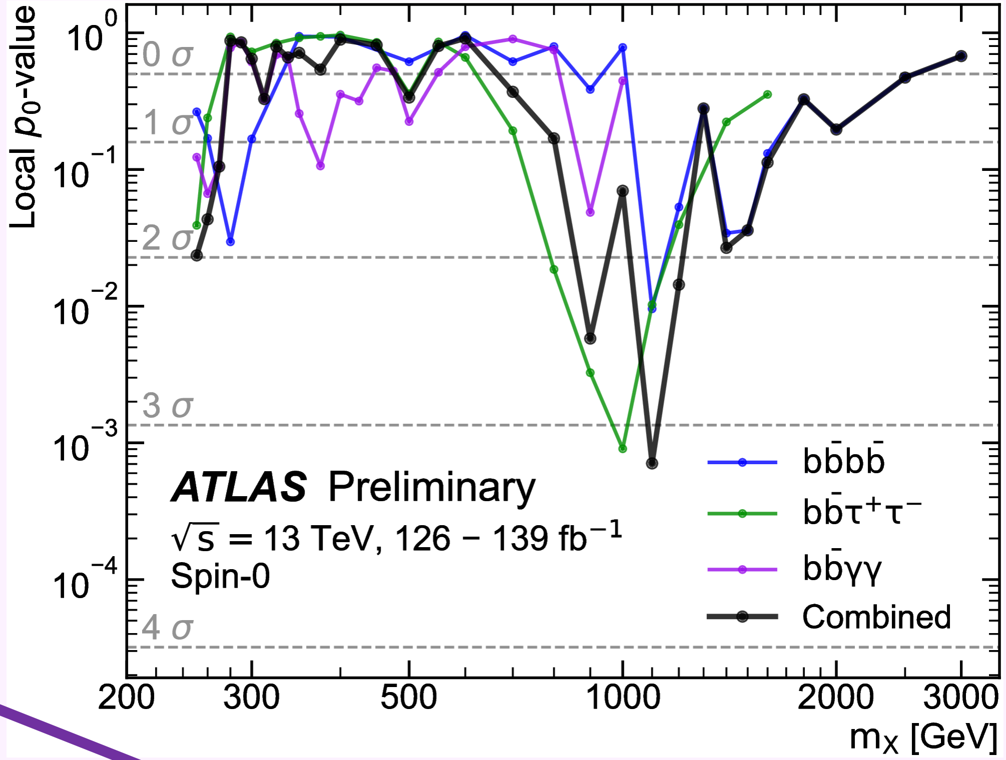
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$



arXiv:2211.01216

Resonant searches combined





ATLAS-CONF-2021-052

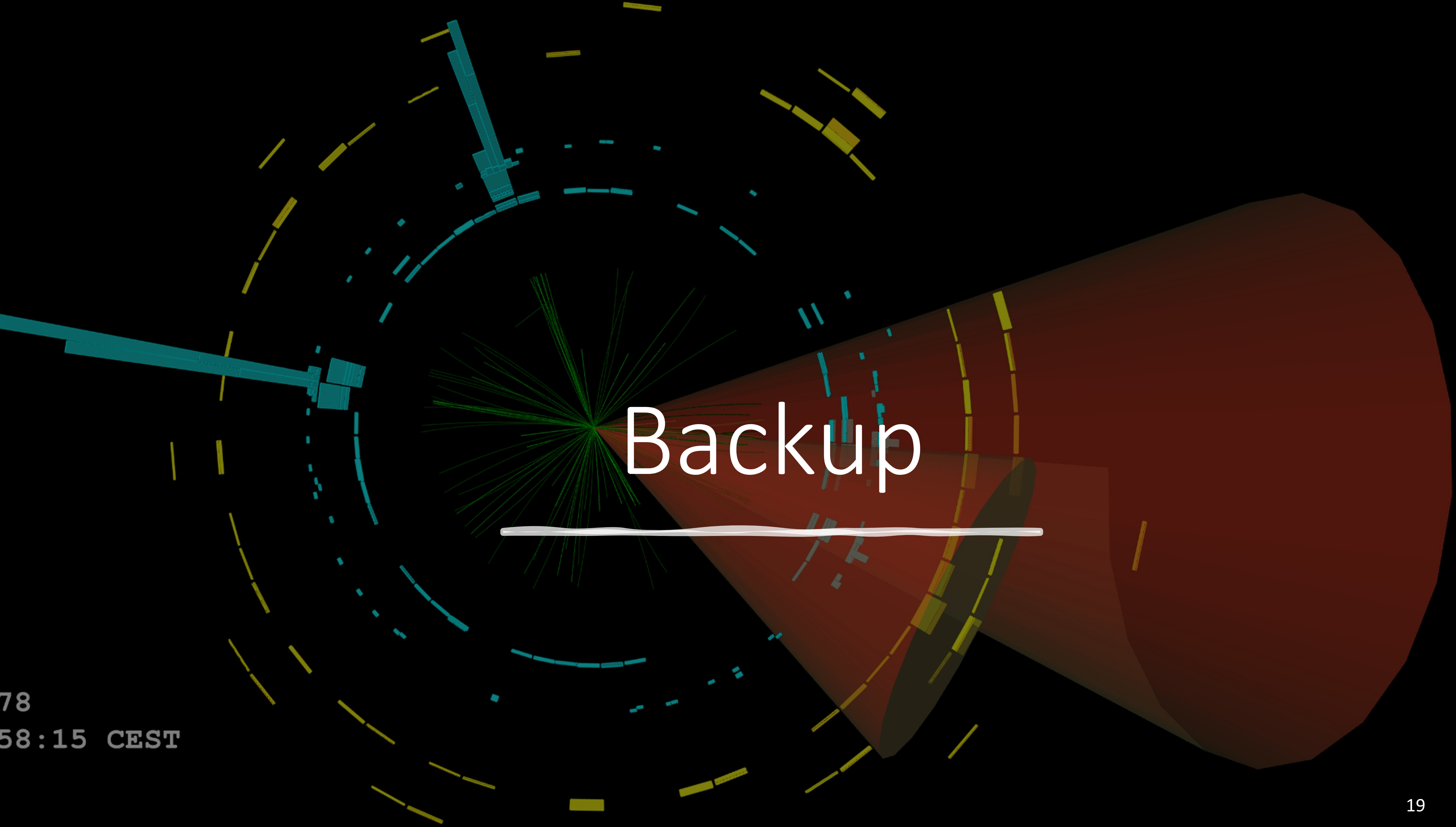
4b extended (Phys. Rev. D 105 092002)

No major updates to this picture since a while

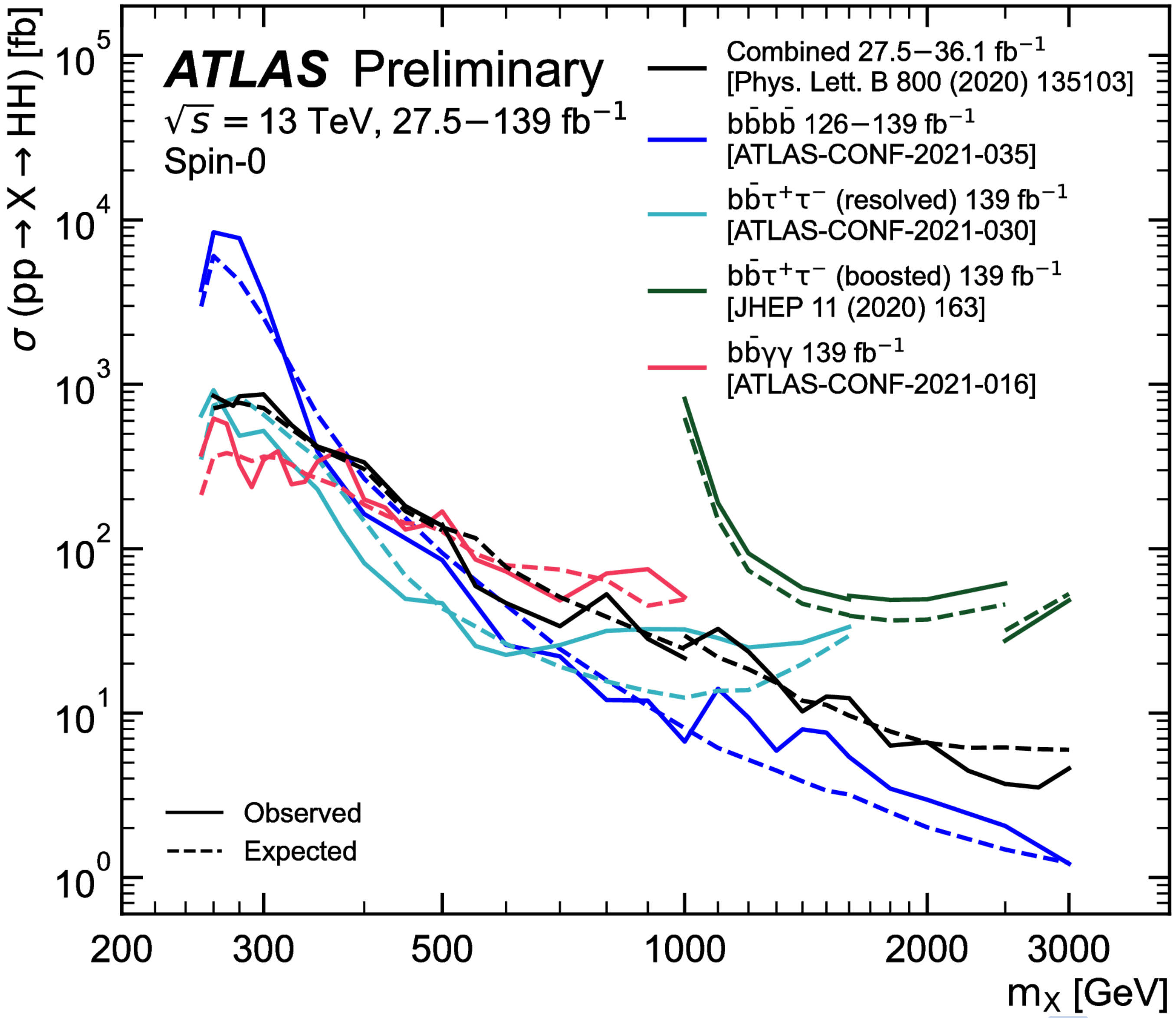
Good complementarity in sensitivity between channels

Summary & Outlook

- ATLAS has developed an extensive search program for double Higgs production using the full Run 2 dataset obtaining plently of new results.
- The double Higgs (+ single Higgs) analyses combinations provide the best limits to date in κ_λ and κ_{2V} found by ATLAS, getting closer to the SM expected values and providing strong constraints in a wealth of BSM models.
- A bunch of new results using the full Run 2 data expected to appear soon and with the advent of fresh data from Run 3 improved limits can be expected.



Backup


ATLAS Preliminary
√s = 13 TeV, 27.5−139 fb−1
Spin-0
Combined 27.5−36.1 fb−1
[Phys. Lett. B 800 (2020) 135103]
bb̄bb̄ 126−139 fb−1
[ATLAS-CONF-2021-035]
bb̄τ+τ− (resolved) 139 fb−1
[ATLAS-CONF-2021-030]
bb̄τ+τ− (boosted) 139 fb−1
[JHEP 11 (2020) 163]
bb̄γγ 139 fb−1
[ATLAS-CONF-2021-016]
Observed
Expected
σ (pp → X → HH) [fb]
m_X [GeV]
200
300
500
1000
2000
3000
10^0
10^1
10^2
10^3
10^4
10^5