Probing the nature of electroweak symmetry breaking with Higgs boson pair-production at ATLAS

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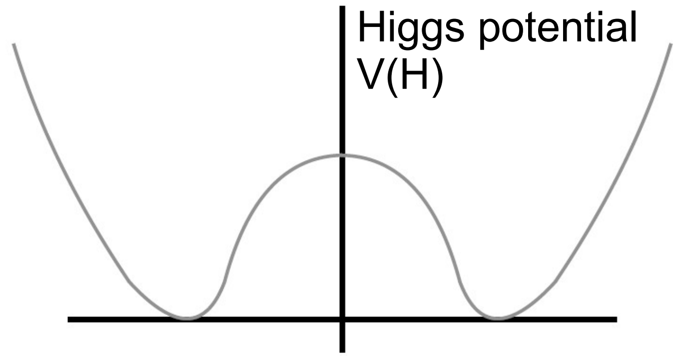
Introduction

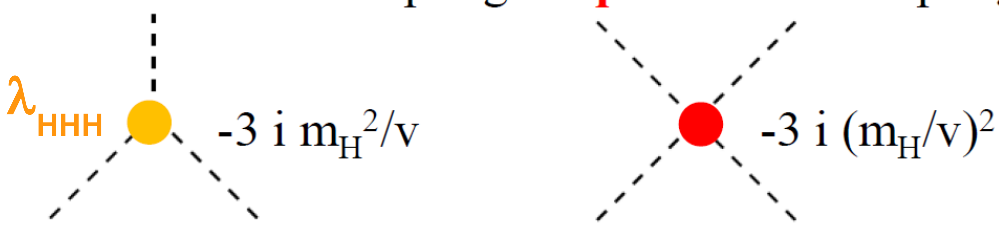
Di-Higgs production is a key process for Standard Model and Beyond-the-SM physics

Discovery of **non-resonant HH production** would establish the shape of the Higgs potential and tests an important prediction of the SM by measuring λ_{HHH}



$$V(H) = \lambda v^2 H^2 + \lambda v H^3 + (1/4)\lambda H^4$$

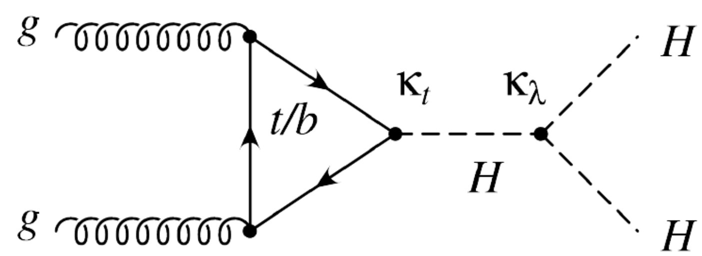
related to Higgs mass ($\lambda v^2 H^2$) — **trilinear** self-coupling ($\lambda v H^3$) — **quartic** self-coupling ($(1/4)\lambda H^4$)



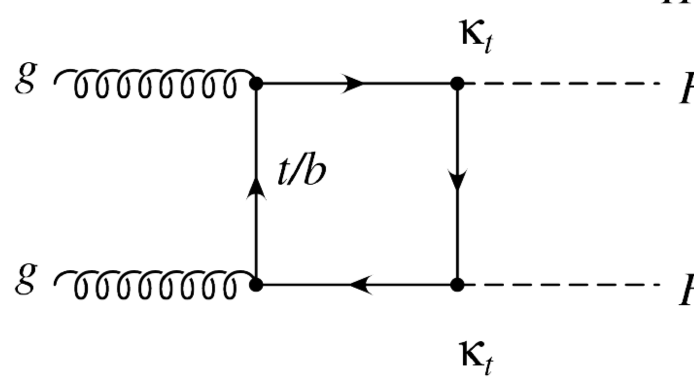
$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$ SM predicts κ_λ =1

Gluon fusion:

The Box and Triangle diagrams interfere destructively
SM HH cross section at 13 TeV is tiny: $\sigma(gg\to HH)$ = 31.05 fb
For comparison: $\sigma(gg\to H)$ = 48.68 **p**b



Triangle



Box

In case of deviations from the SM ($\kappa_\lambda \neq 1$), the HH cross section increases considerably (also m_{HH} shape changes).

→ Can already now establish constraints on that parameter κ_λ

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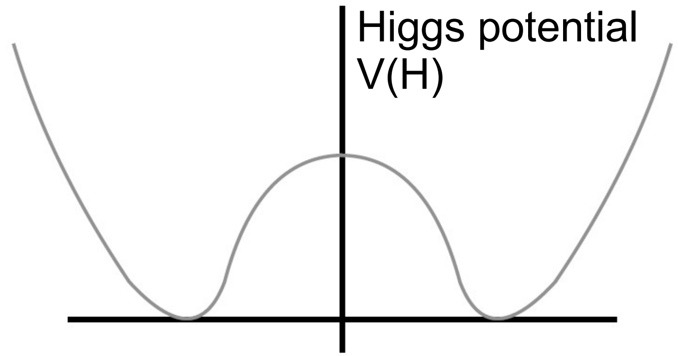
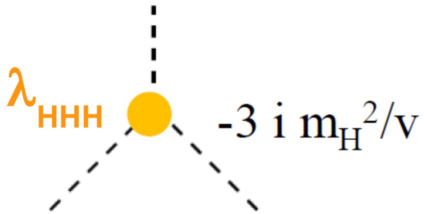
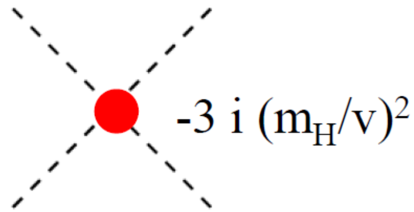


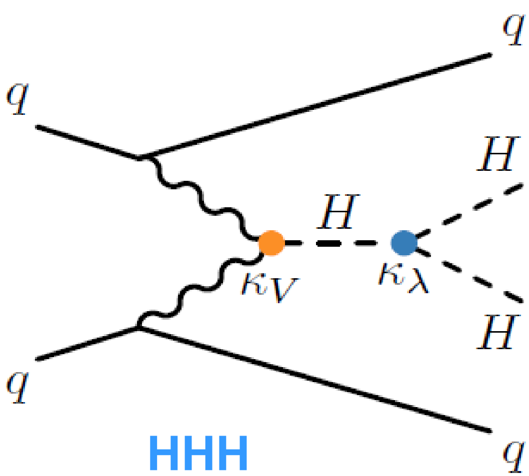
$$V(H) = \lambda v^2 H^2 + \lambda v H^3 + (1/4)\lambda H^4$$

related to Higgs mass | trilinear self-coupling | quartic self-coupling

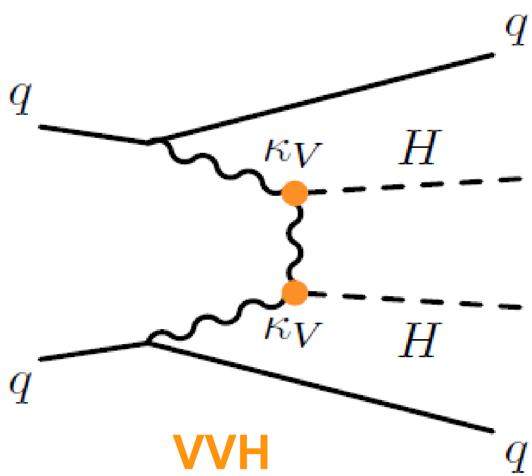




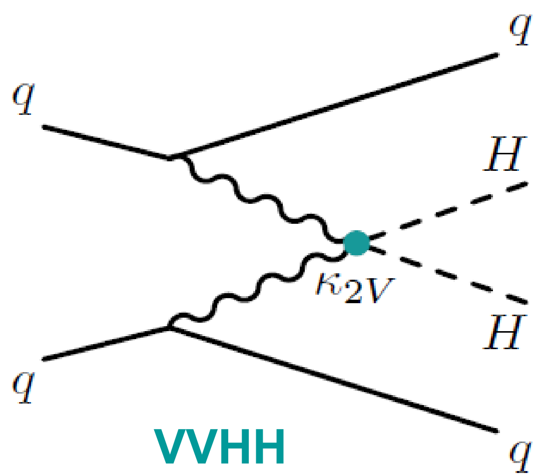
Vector boson fusion:



HHH



VVH



VVHH

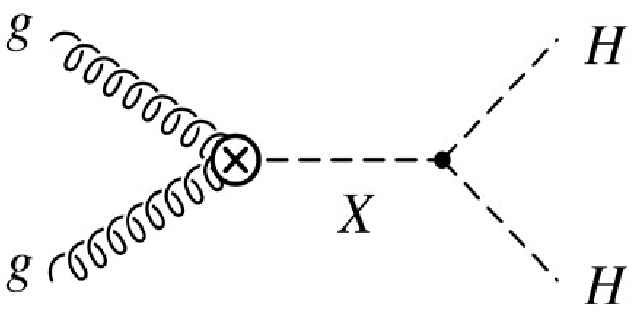
Cross section for non-resonant VBF (13 TeV): 1.726 fb

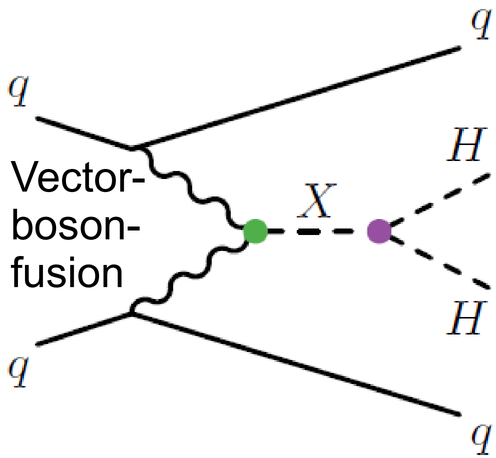
VBF production is sensitive to κ_{2V} coupling

Introduction

Searches for **resonant production** of Di-Higgs could establish the presence of new particles

Limits on the production of these resonances can be used to constrain BSM model parameters





Benchmark signal models:

Narrow scalar (S, or H) with a negligible decay width could for example be a heavy Higgs in the 2HDM

Spin-2 gravitons as predicted by the bulk Randall-Sundrum model with $k/\overline{M}_{Pl}=1$ (width ranging from 3-13% of m_X)

	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%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	0.0005%

published by ATLAS

← **Branching ratios of HH decay channels** (H is the SM Higgs boson)

The most sensitive HH channels contain at least one $b\bar{b}$ decay, taking advantage of its large BR.

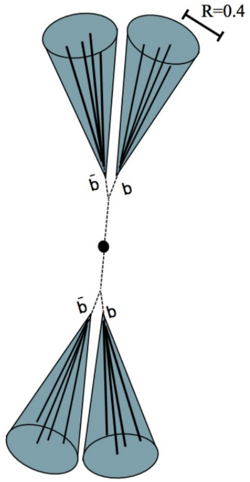
Overview of ATLAS Di-Higgs Results

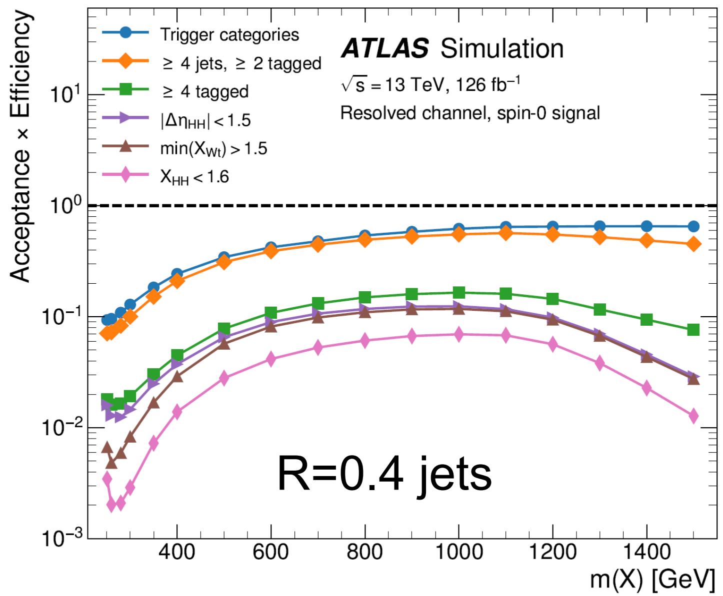
Channel	Dataset	References
(X→) HH → bbγγ	139/fb	HDBS-2018-34
X→HH → 4b (X→) HH → 4b	126-139/fb 28-36/fb	HDBS-2018-41 EXOT-2016-31
(X→) HH → bbττ	139/fb	ATLAS-CONF-2021-030
Boosted X → HH → bbττ	139/fb	HDBS-2019-22
HH → bbWW(/ZZ/ττ) → bblνlν	139/fb	HDBS-2018-33
HH → 4W	36/fb	HIGG-2016-24
(X→) HH → bbWW → bbqqlν	36/fb	HIGG-2016-27
(X→) HH → WWγγ	36/fb	HIGG-2016-20
HH Combination (2-3 channels) HH Combination (all channels)	126-139/fb 36/fb	ATLAS-CONF-2021-052 HDBS-2018-58
H+HH Combination	36-80/fb	ATLAS-CONF-2019-049
HEFT Interpretations	139/fb	ATL-PHYS-PUB-2022-019
VBF HH → 4b	139/fb	HDBS-2018-18
Updated HL-LHC Projections	3/ab	ATL-PHYS-PUB-2021-044 ATL-PHYS-PUB-2022-001 ATL-PHYS-PUB-2022-005

X → HH → 4b (gluon fusion only)

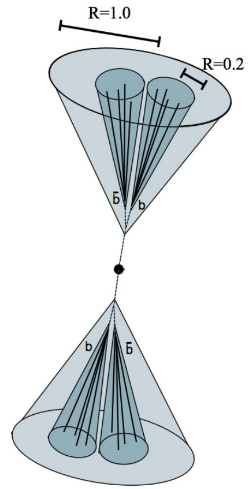
HDBS-2018-41

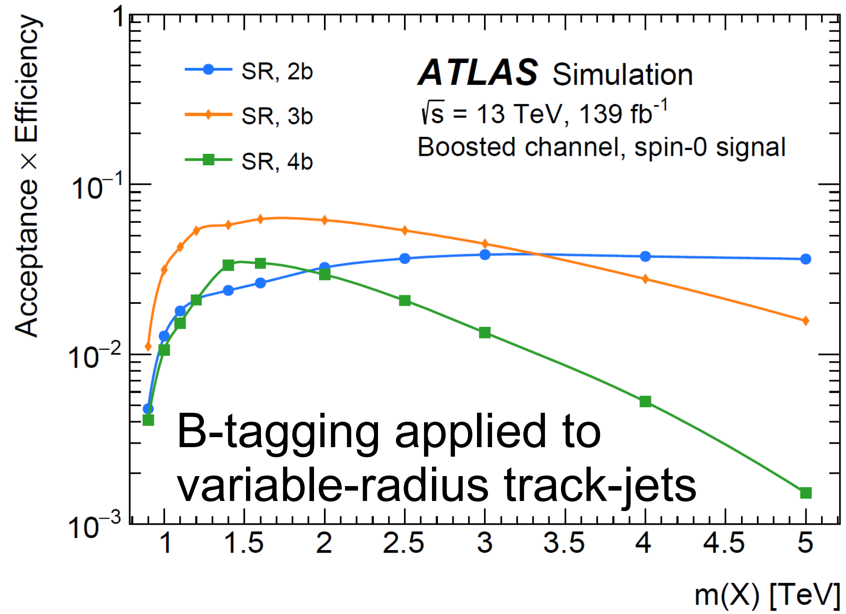
Resolved



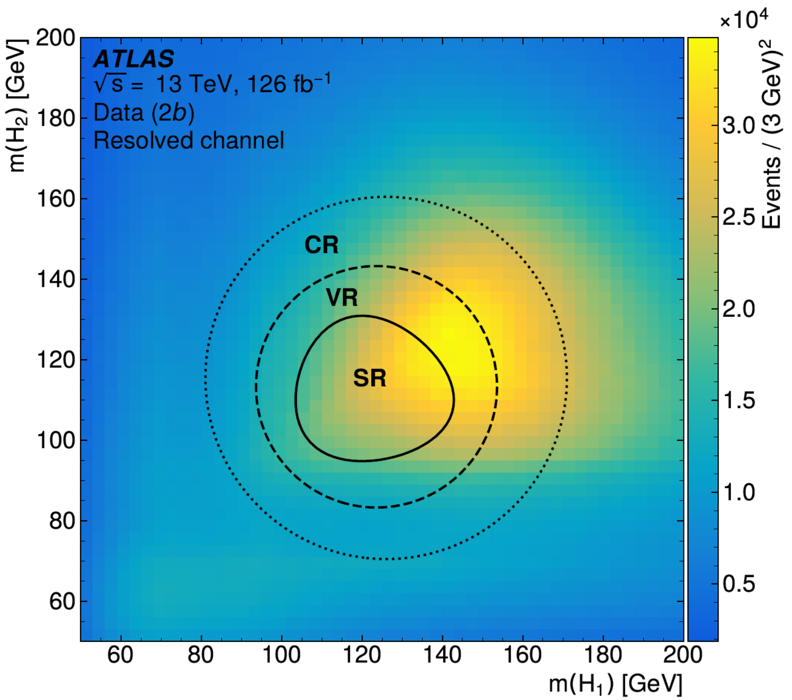


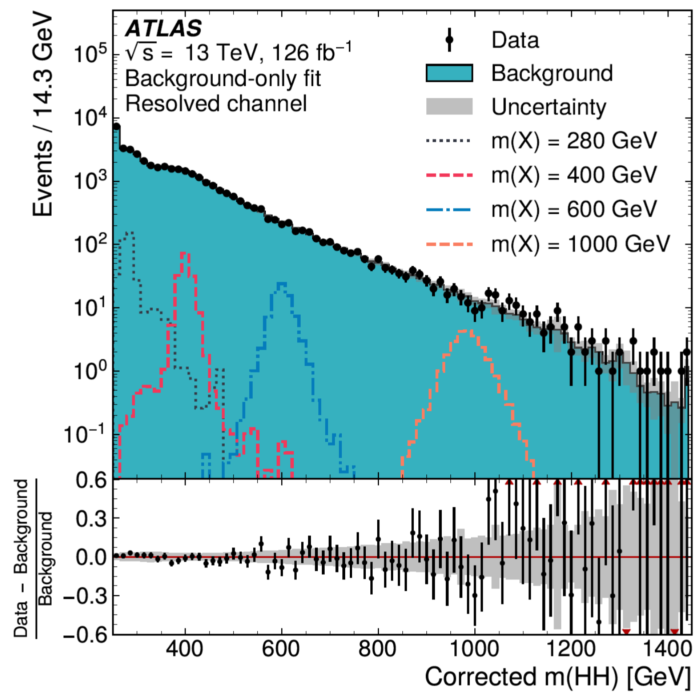
Boosted





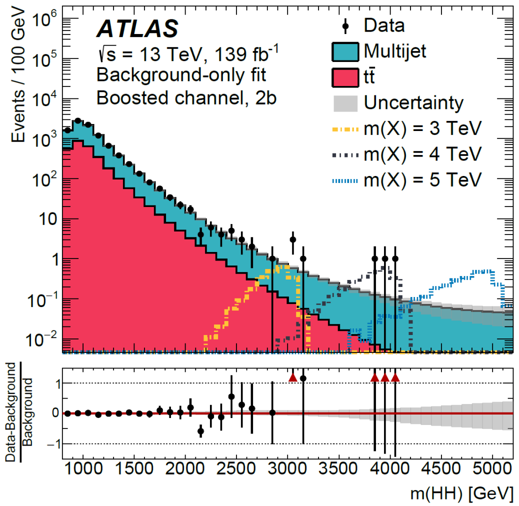
Challenge: Multi-jet background estimation:

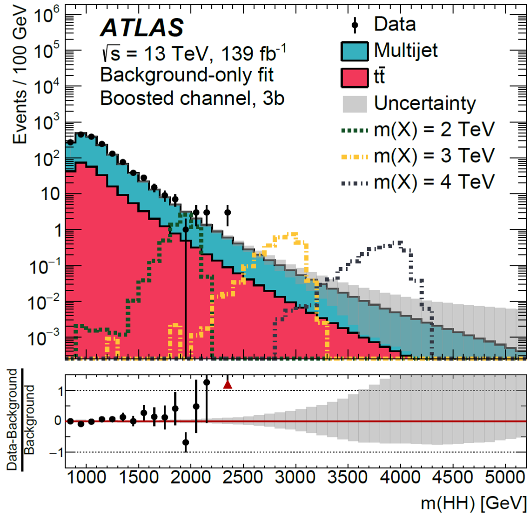


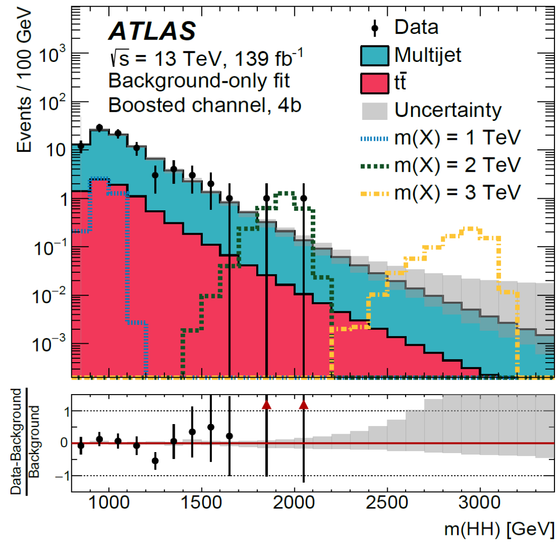


- Background estimated from control region data with less b-tags
- This data gets reweighted to match signal region kinematics using a neural network in the resolved channel, or a spline-based reweighting for the boosted channel
- Independent and extensive validation by comparing reweighted data from the CR to data from a validation region

(X→) HH → 4b (gluon fusion only)





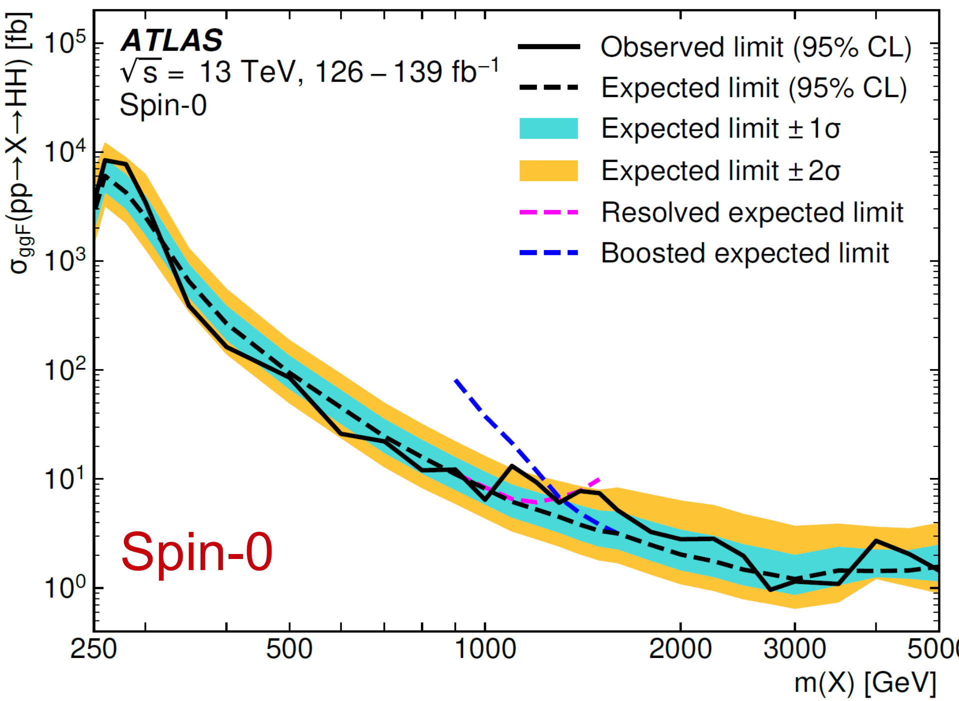


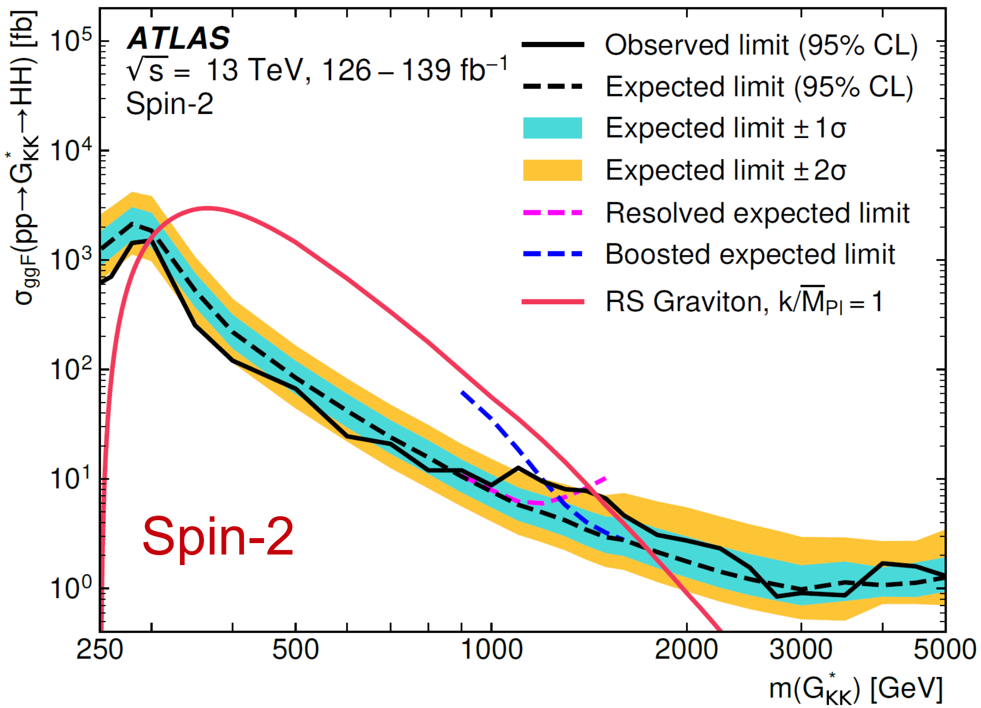
Mass range: 251 GeV - 5 TeV (extended wrt. previous paper)

Smooth background prediction obtained by fitting the mass with analytic function for m_X>1.2 TeV

Limits at high mass evaluated with pseudo-experiments

Combination of resolved and boosted analyses:





Limit on SM HH: (2015/16 dataset only):

12.9 x σ_{SM} (observed)

20.7 x σ_{SM} (expected)

(see 1804.06174)

Largest excess: 1.1 TeV (2.3-2.5σ local, 0.4-0.8σ global significance)

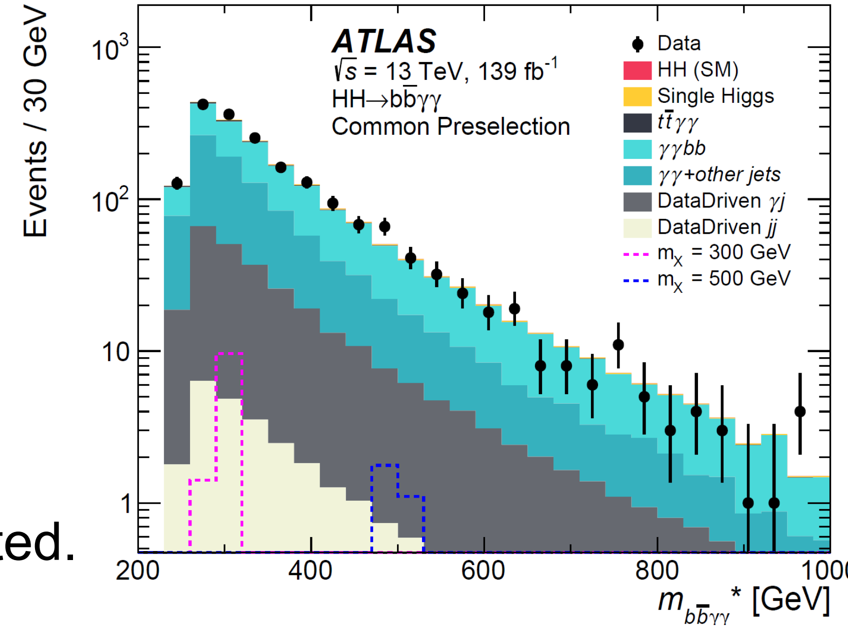
$X \rightarrow HH \rightarrow bb\gamma\gamma$ (Resonant Analysis)

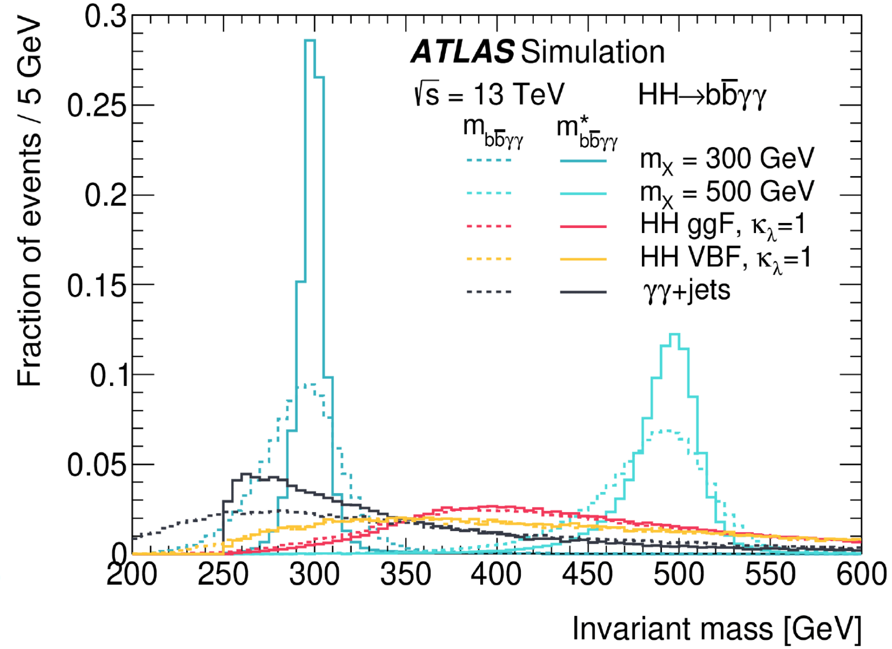
Gluon fusion production only

Two BDTs trained:
-One against continuous backgrounds ($\gamma\gamma$, $tt\gamma\gamma$)

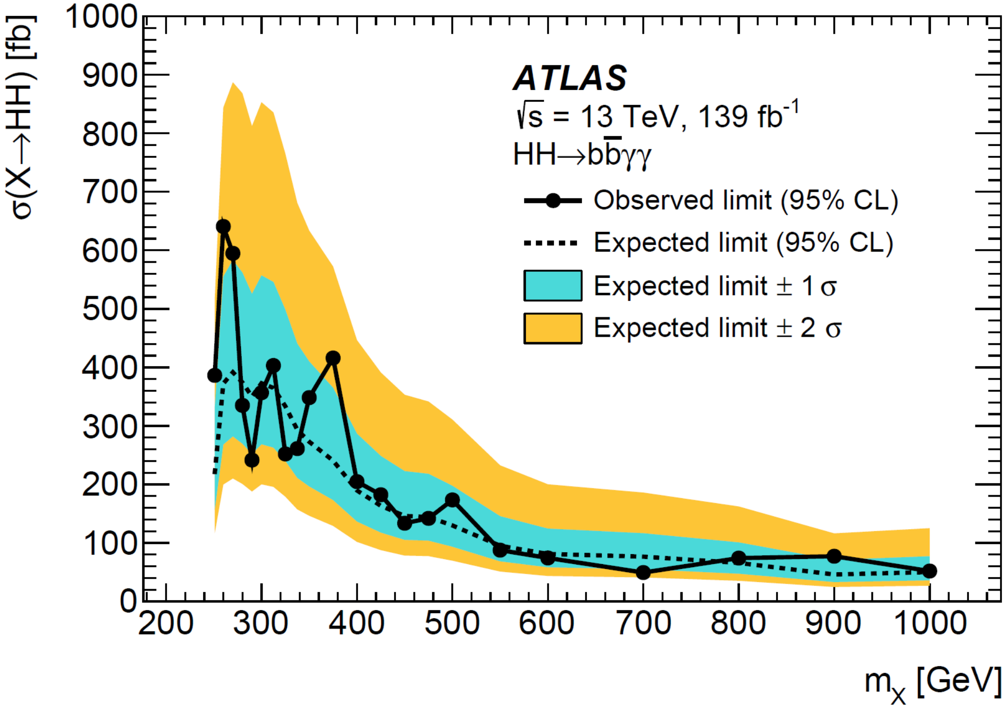
-One against the resonant backgrounds (ZH, ttH)

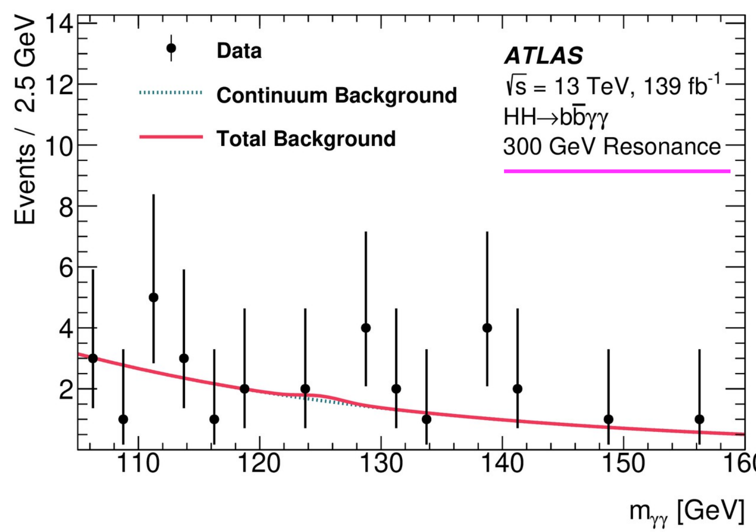
Both BDTs are then combined with both scores optimally weighted. Final cut on BDT score that is optimized for each m_X hypothesis.

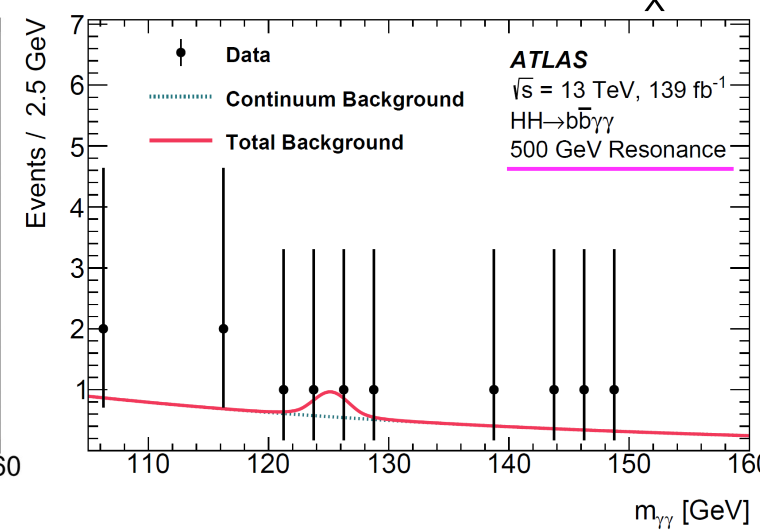




- Cut on $m^*_{bb\gamma\gamma}$ ($\pm 2\sigma$), $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV
- Final discriminant is diphoton mass, bkg modelled with exponential function.
- No significant excess found Very strong limits for low m_X!





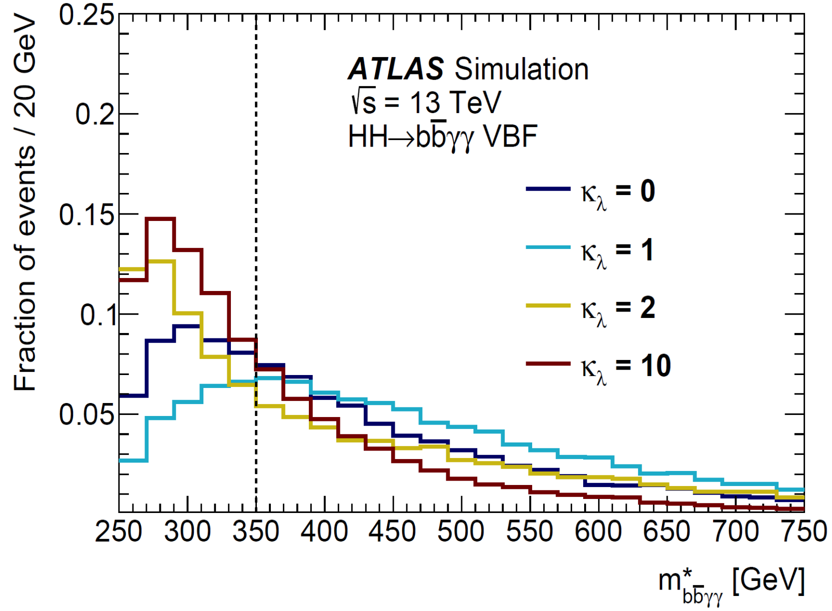


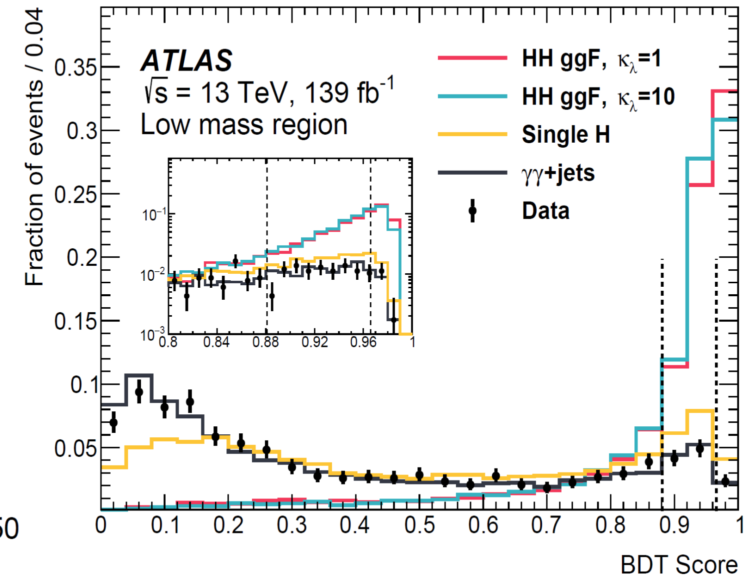
Gluon fusion production and vector boson fusion considered

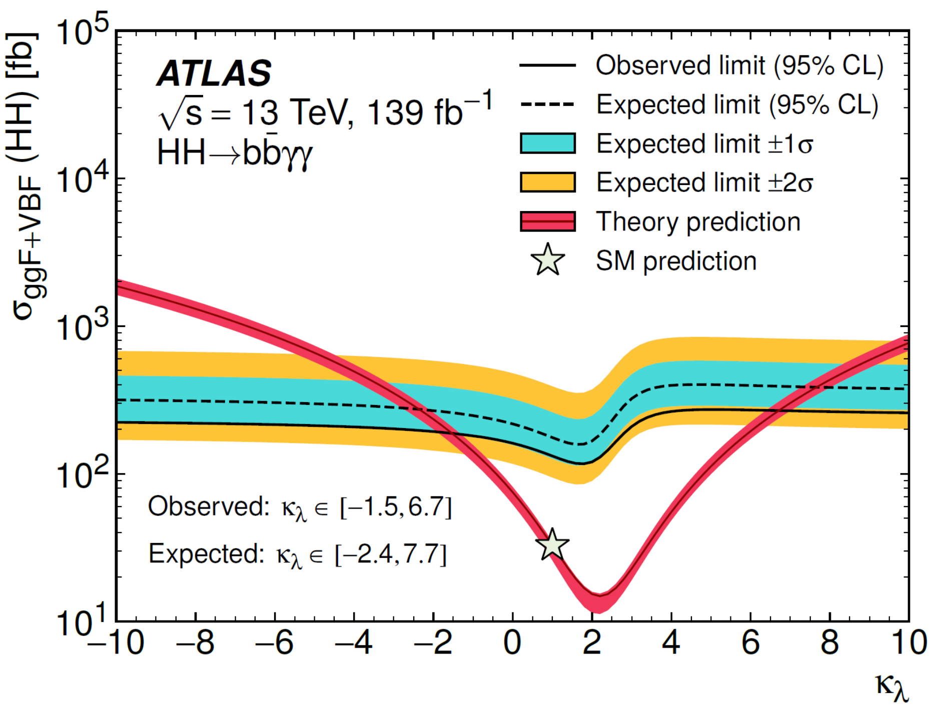
4 categories:

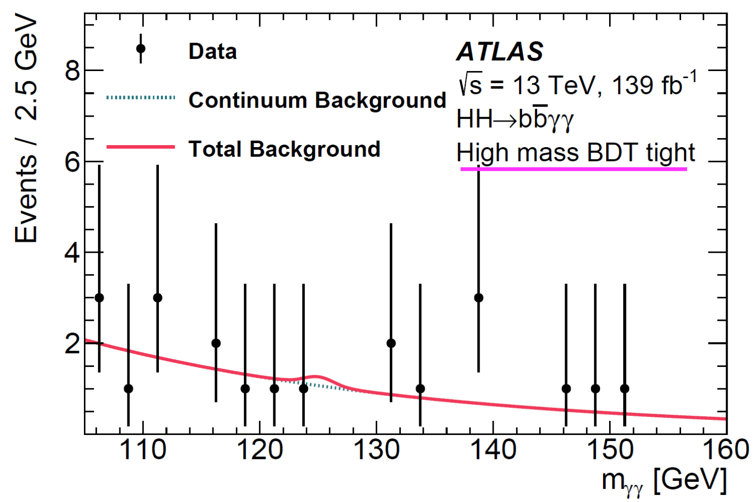
High/low mass (split at $m^*_{bb\gamma\gamma}$=350 GeV)
SM shape tends to be more high mass, while BSM is lower mass.

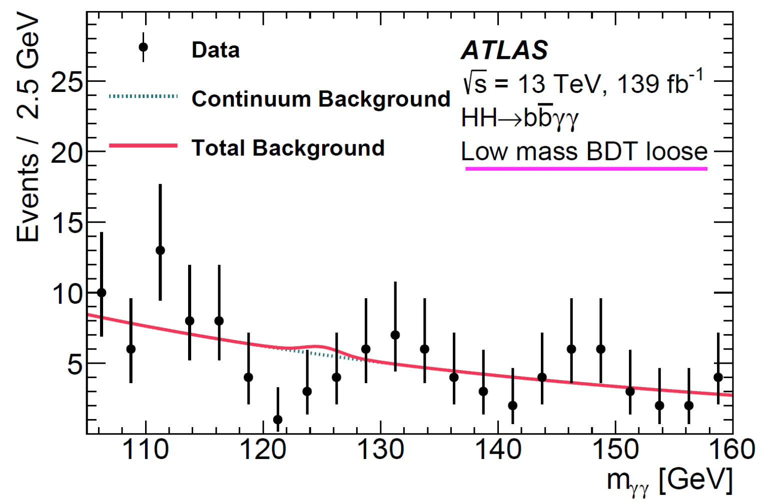
BDTs trained in each mass category, **BDT score** used to define 2 categories (BDT tight/loose).









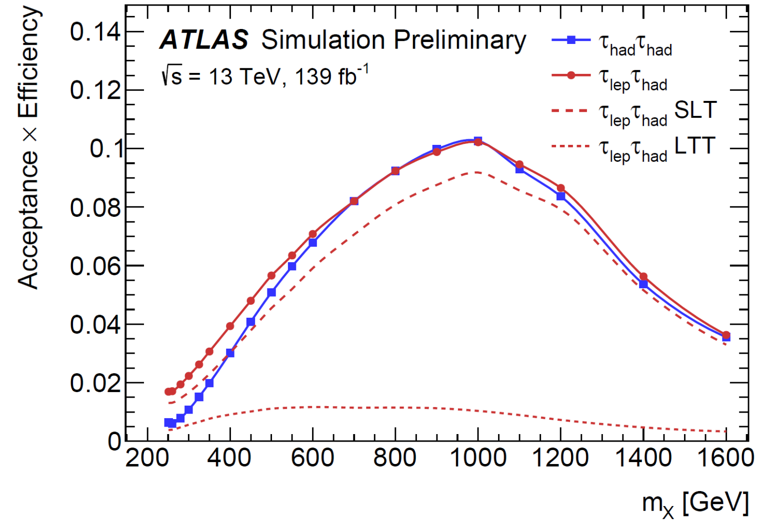


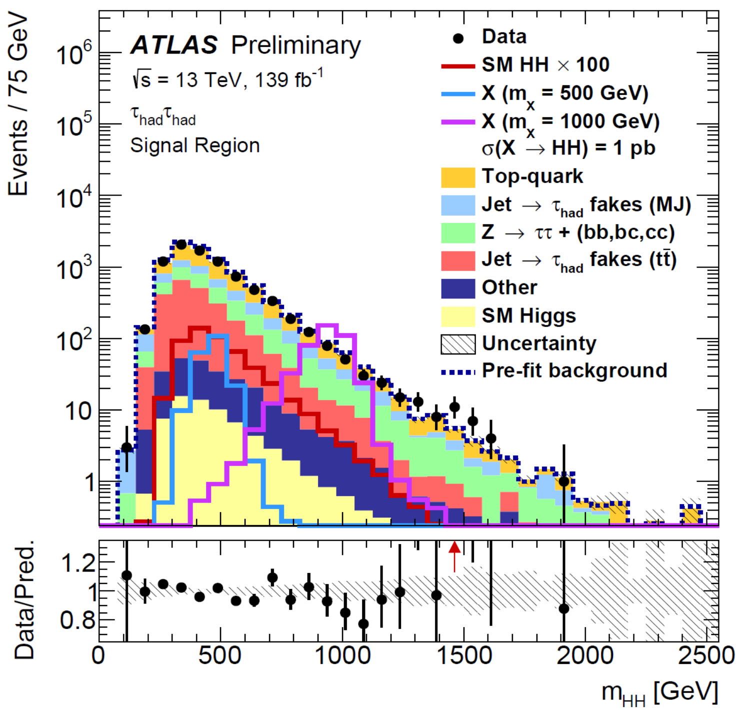
Limits on SM HH: 4.2 x σ_{SM} Observed, 5.7 x σ_{SM} Expected

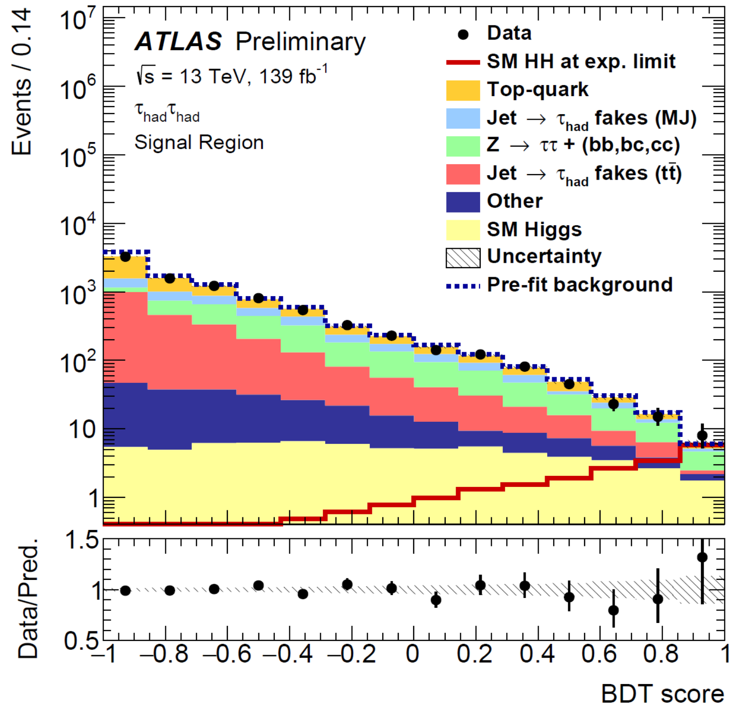
Constraints on κ_λ: [-1.5, 6.7] Observed, [-2.4, 7.7] Expected

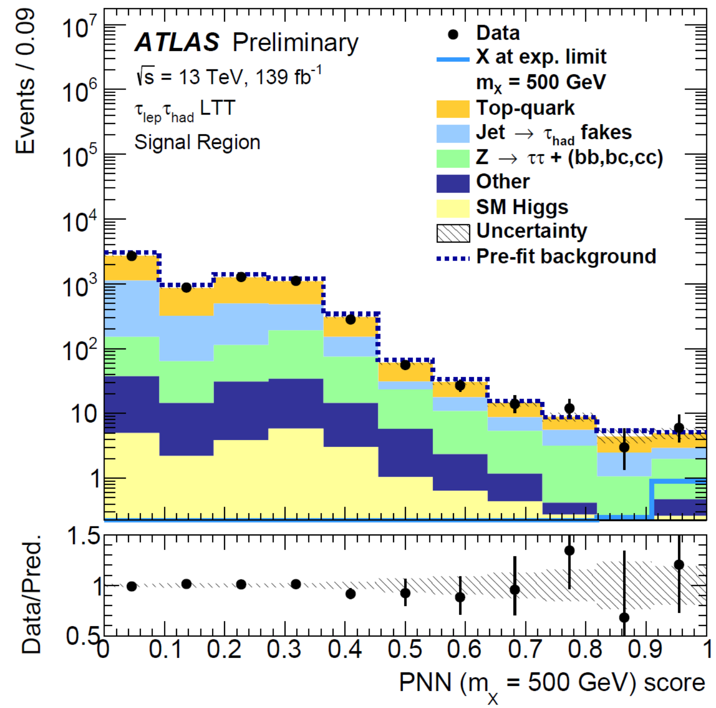
(X→) HH → bbττ ATLAS-CONF-2021-030

- This channel had the best sensitivity to non-resonant HH in the 2015+2016 analysis round
- **3 signal-enriched categories:**
  - had-had channel,
  - lep-had channel triggered by single lepton trigger („SLT“)
  - lep-had channel triggered by lepton+tau trigger („LTT“)
- Machine learning techniques for signal extraction (parametrized NN or BDT)
- Final fit done to the MVA output scores
- Backgrounds containing jets faking taus estimated from data
- Resonant search considers only gluon fusion, non-resonant search includes gluon fusion and VBF

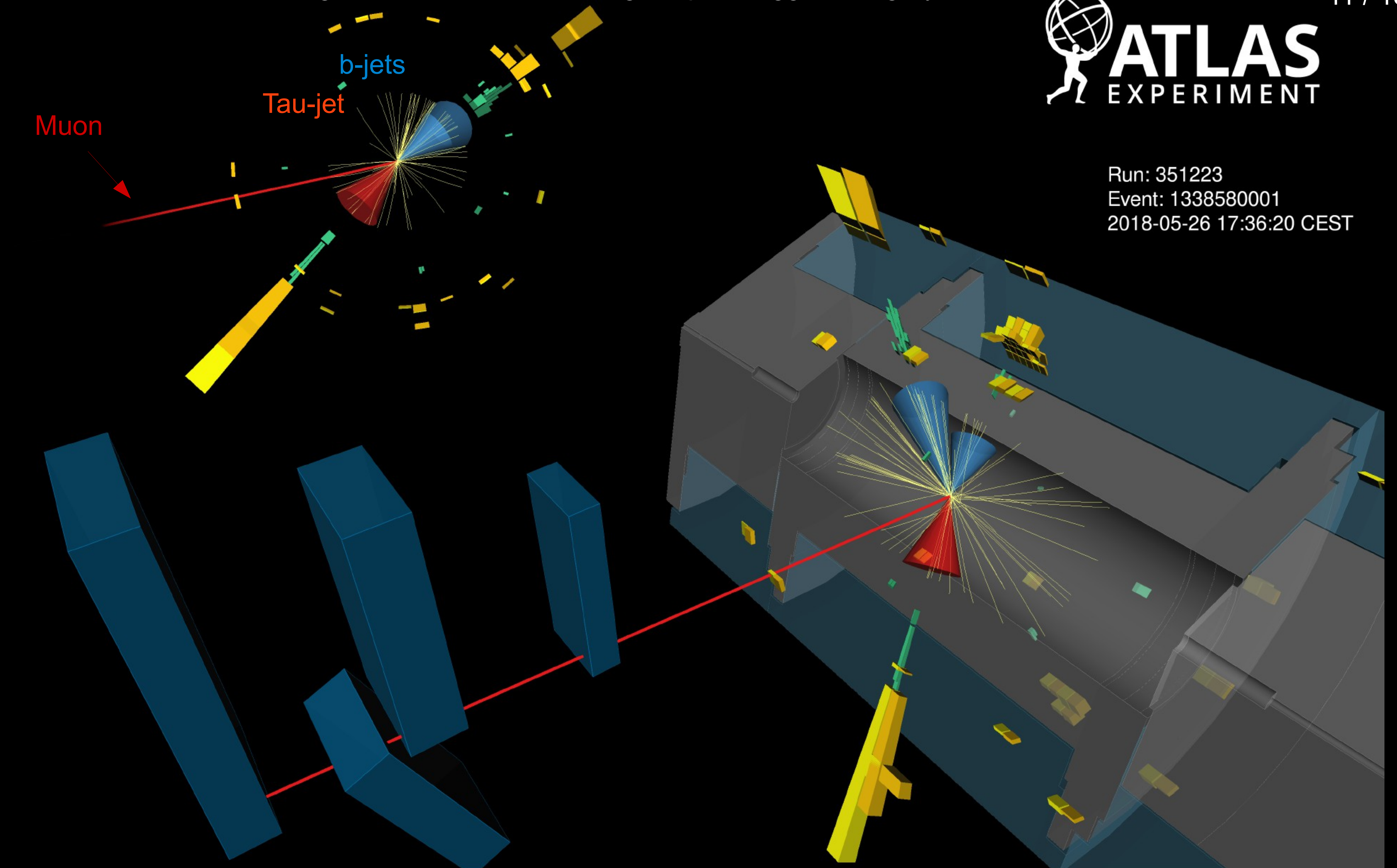








$bb\tau\tau$ event candidate with highest NN score in the single lepton trigger category



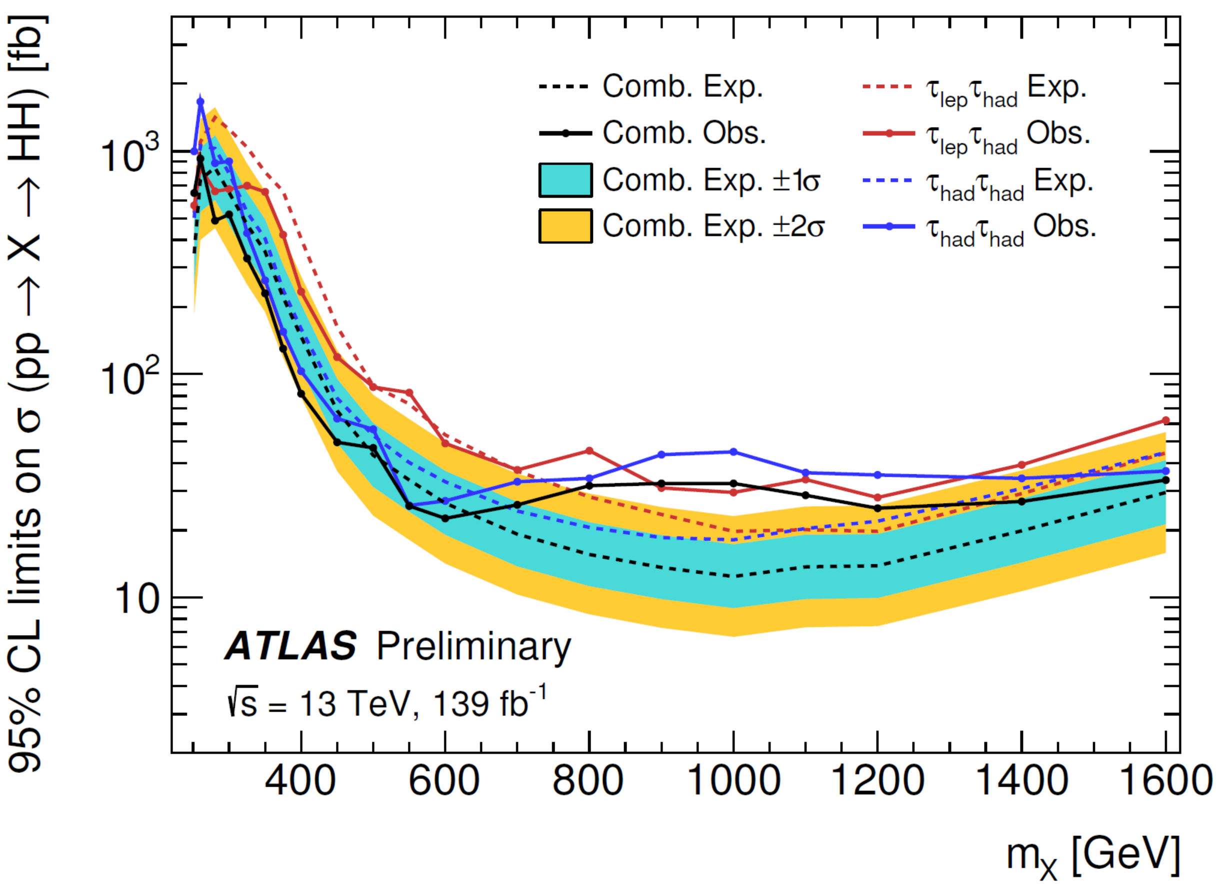
(X→) HH → bbττ ATLAS-CONF-2021-030

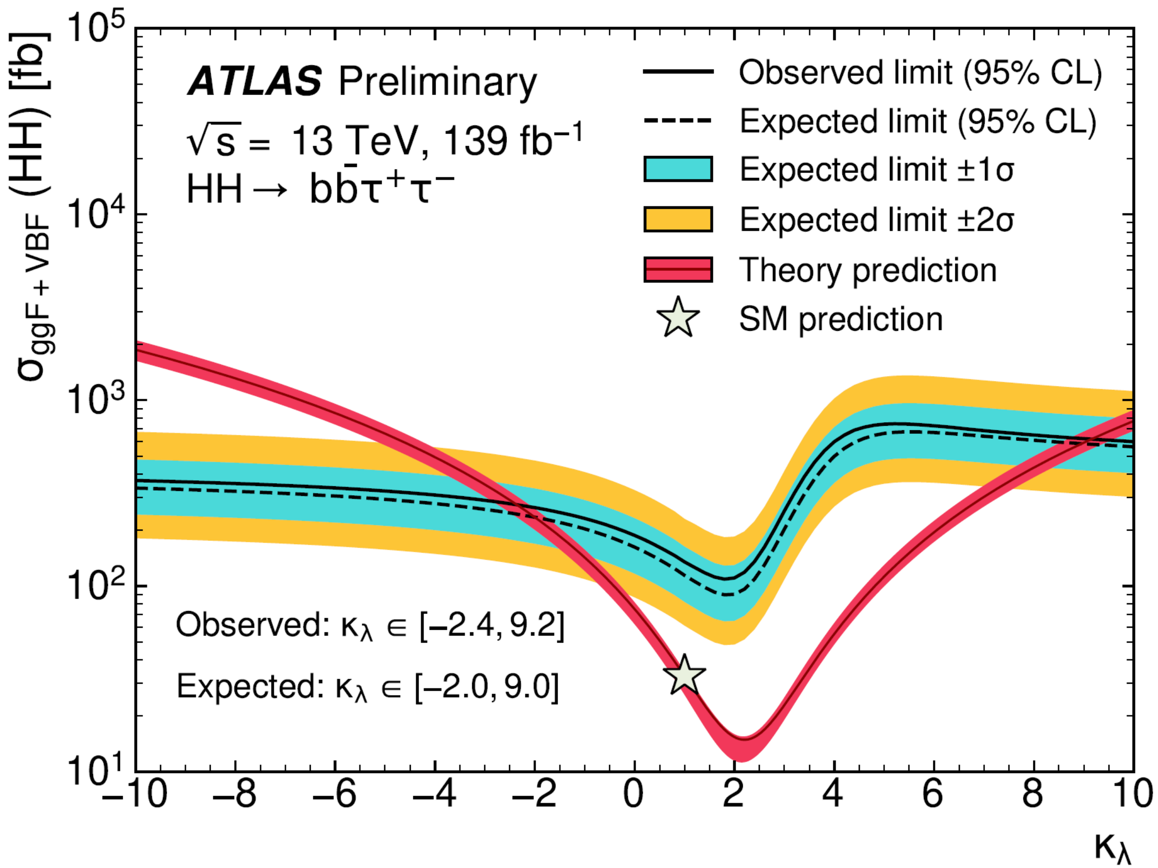
Broad excess centered at 1 TeV observed in the resonant search for m_X range of 700-1200 GeV.

Largest excess (at 1 TeV): 3σ local, 2σ global.

Limit on non-resonant SM HH:
4.7 x σ_{SM} observed, 3.9 x σ_{SM} expected

Limits on κ_λ:
[-2.4, 9.2] observed, [-2.0, 9.0] expected





Combination

ATLAS-CONF-2021-052

A full combination of all HH analyses was performed with the 36/fb dataset (2015/16), see 1906.02025.

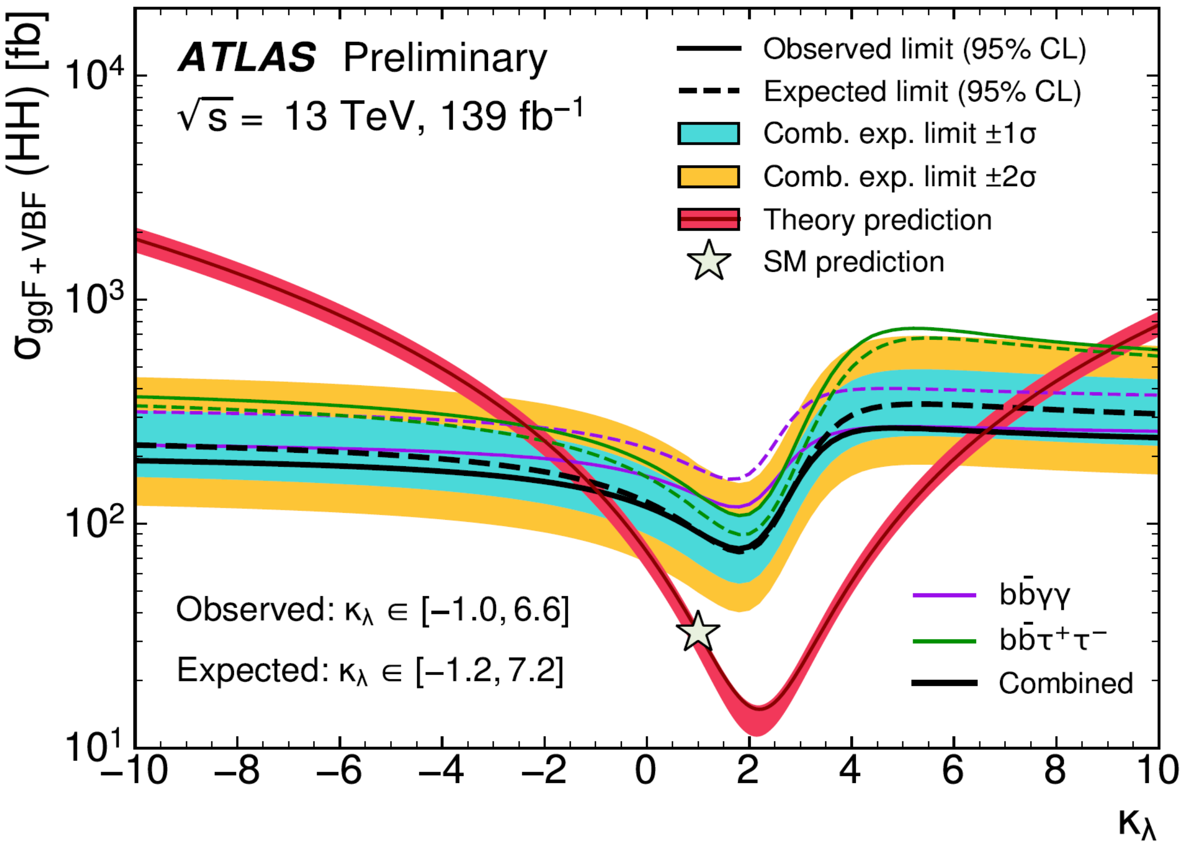
An updated combination with bbγγ, bbττ and 4b (resonant-only) is presented here.

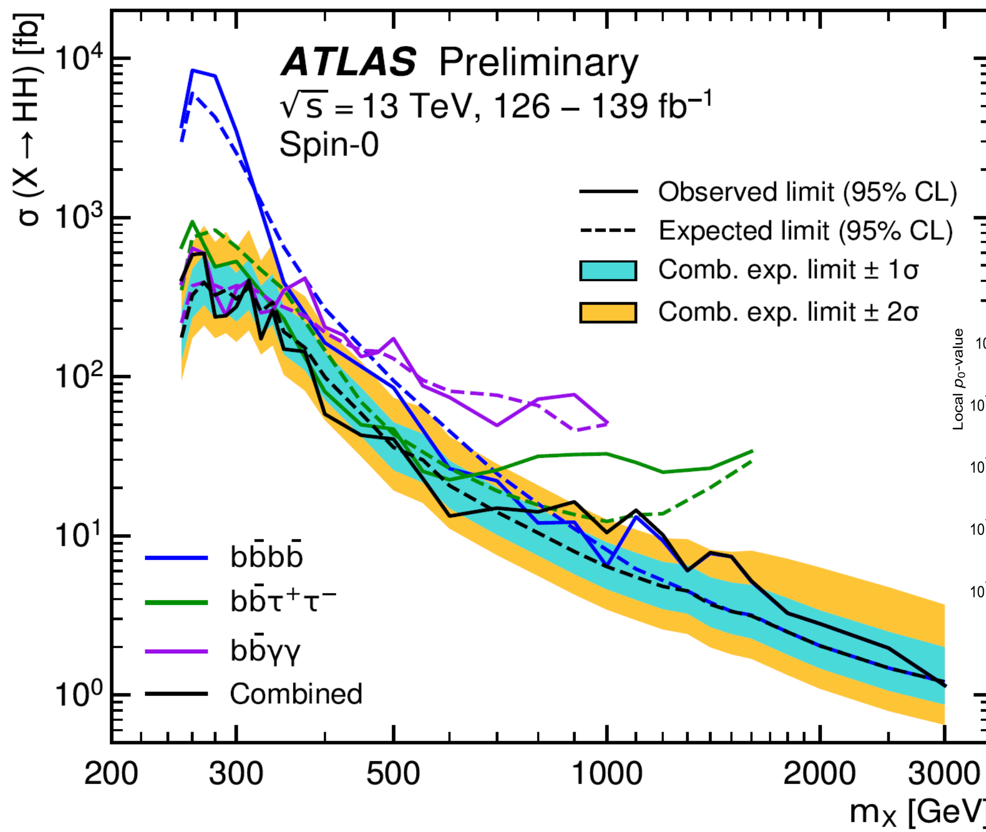
Combined limit on SM HH:
3.1 x σ_{SM} observed, 3.1x σ_{SM} expected

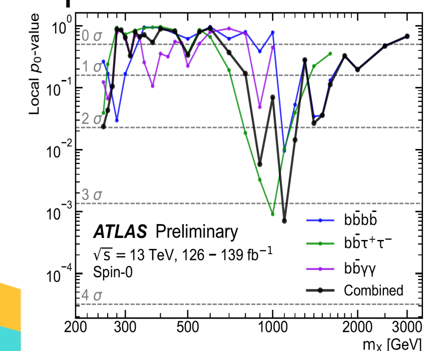
Combined limit on κ_λ:
[-1.0,6.6] observed, [-1.2,7.2] expected

Resonant combination:
Largest excess at 1.1 TeV: 3.1σ local, 2.1σ global.

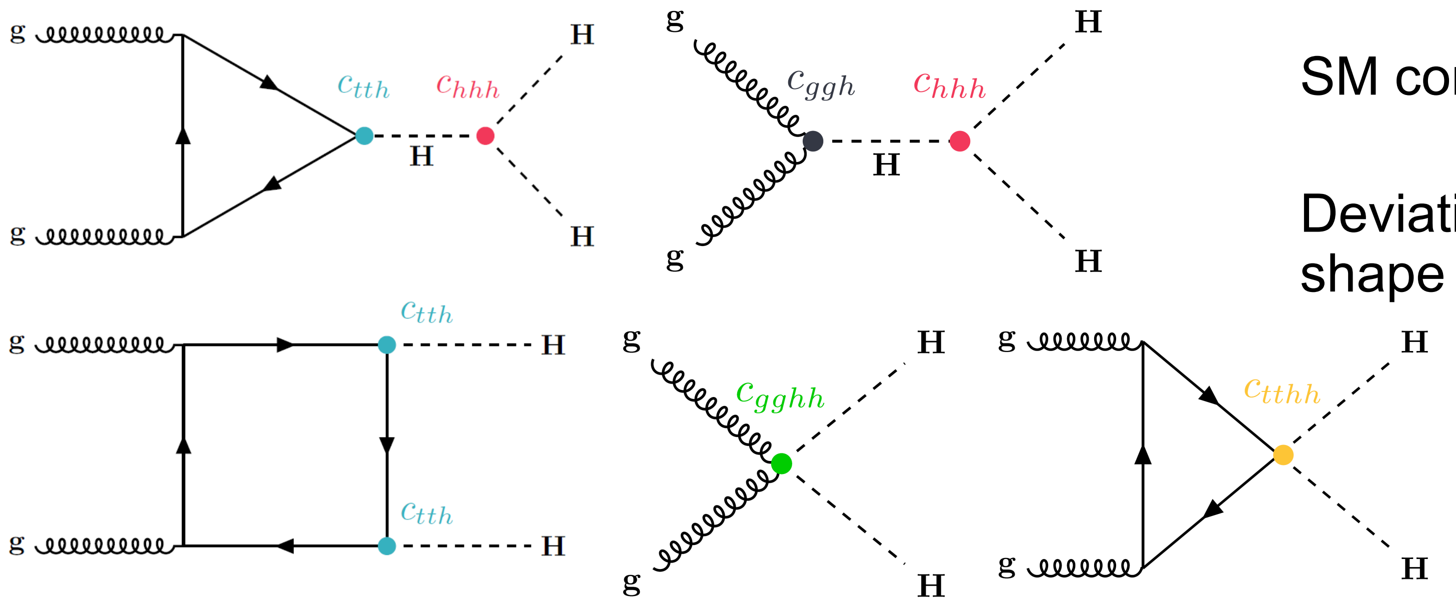
4b channel dominates at high mass (>800 GeV)
bbγγ provides strongest limit at low m_X values,
bbττ leads in the intermediate mass range







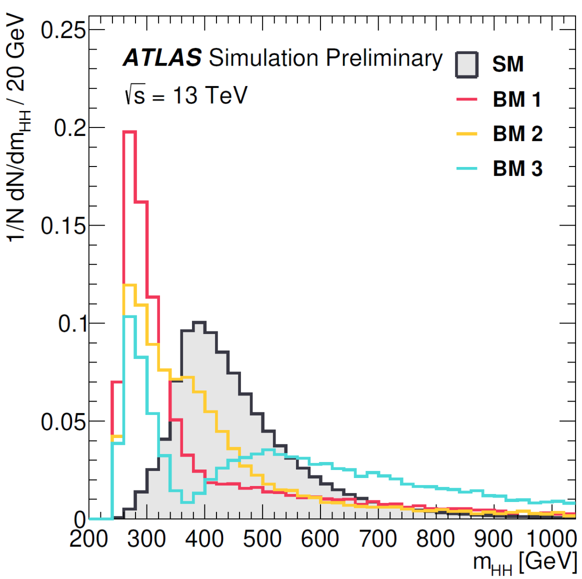
Higgs effective field theory (HEFT) provide a generic approach to parametrise the effects of BSM physics at the high energy scale in terms of effective couplings at the low energy scale.

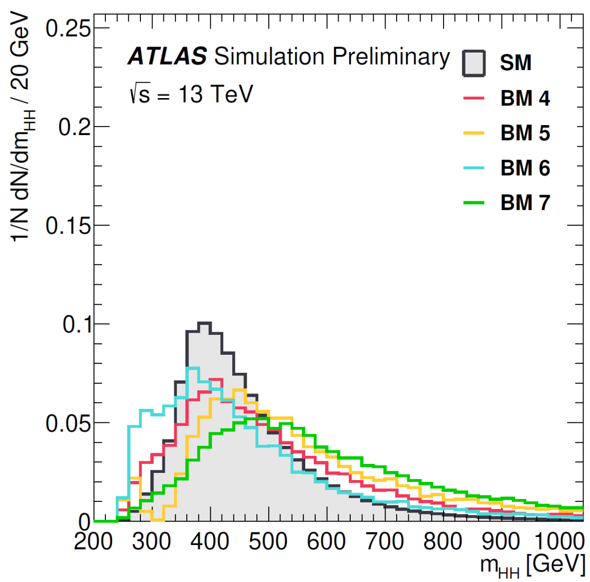


SM corresponds to $c_{hhh}=c_{tth}=1$ and $c_{tthh}=c_{ggh}=c_{gghh}=0$

Deviations from these values will impact rate and shape of the predicted signal.

7 benchmarks defined that efficiently cover the large parameter range of the Wilson coefficients:





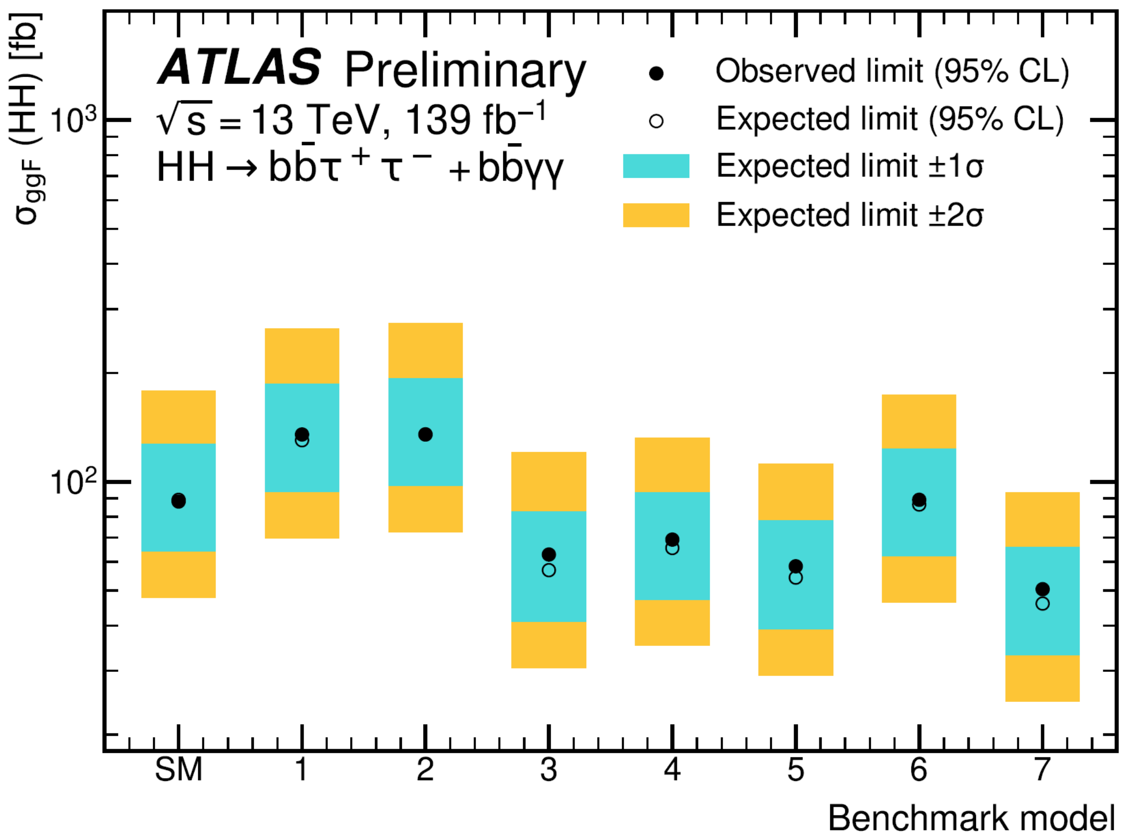
Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1

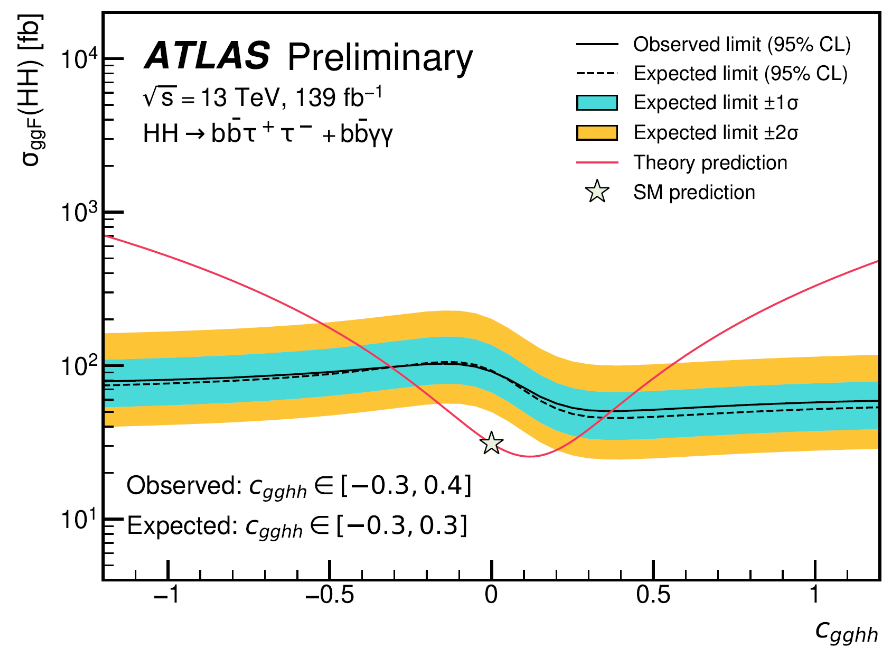
bbττ and bbγγ non-resonant analyses are used and combined in the HEFT framework

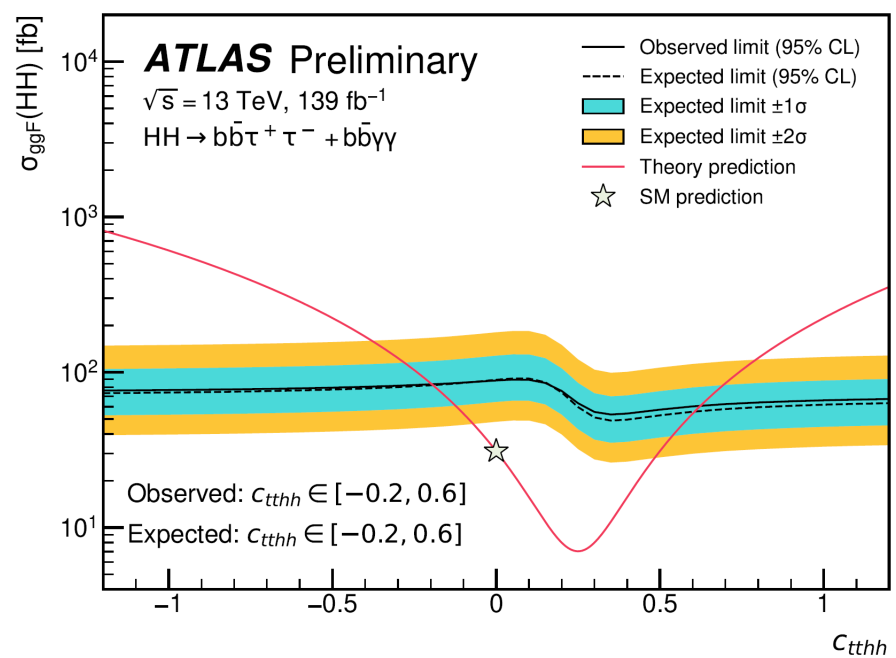
mHH predictions obtained by reweighting the SM HH simulation.
Only shape differences are considered, no acceptance impacts.

Limits on production cross section set in each benchmark model.

Values of c_{gghh} and c_{tthh} constrained strongly







HL-LHC: Projected sensitivity (combining bbττ and bbγγ) ATL-PHYS-PUB-2022-005

Benchmark: 14 TeV, 3/ab

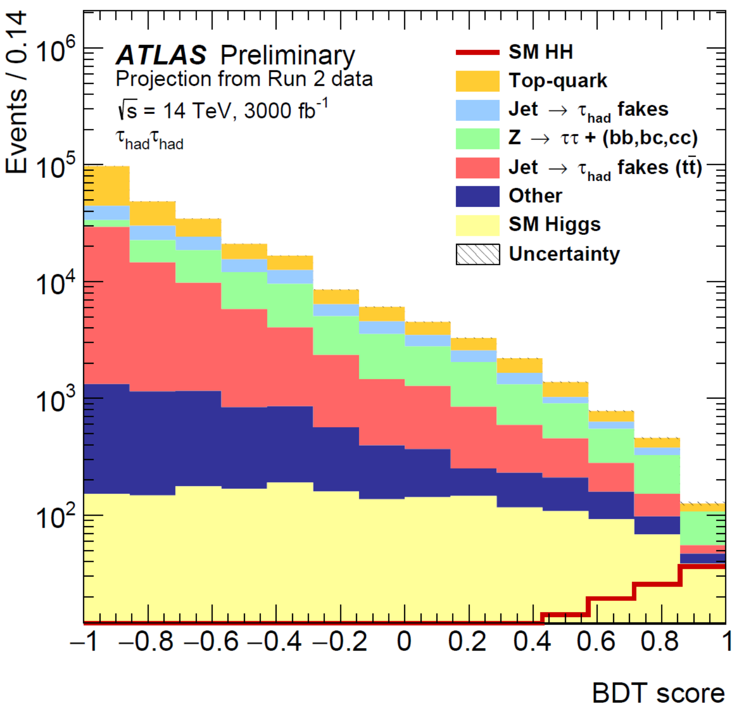
Assumptions:
- same object reconstruction and ID efficiencies as run-2
- 4 systematic uncertainties scenarios (very optimistic to very pessimistic)

Not considered, but could have impact:
Increased pile-up, different triggers, detector upgrades

Process	Scale factor
Signals	
ggF HH	1.18
VBF HH	1.19
Backgrounds	
ggF H	1.13
VBF H	1.13
WH	1.10
ZH	1.12
$t\bar{t}H$	1.21
Others	1.18

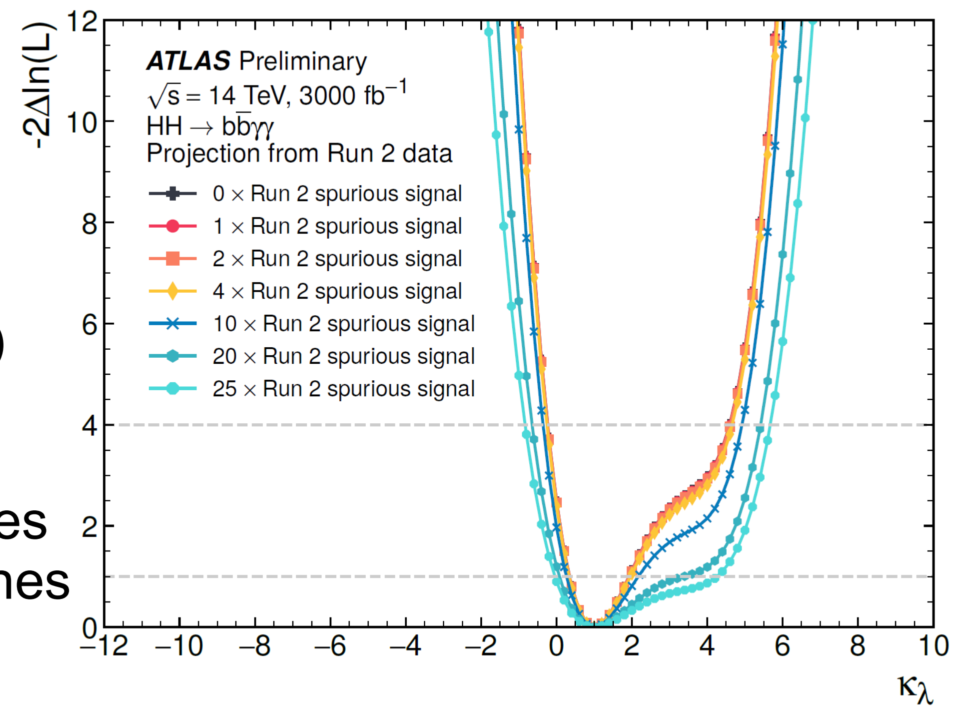
Baseline uncertainty scenario:

Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*
κ_λ reweighting	0.0	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Spurious signal	0.0	*	
Value of m_H	0.08	*	
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-τ_{had} estimation	1.0		*
MC statistical uncertainties	0.0		*
Theoretical Uncertainties	0.5	*	*



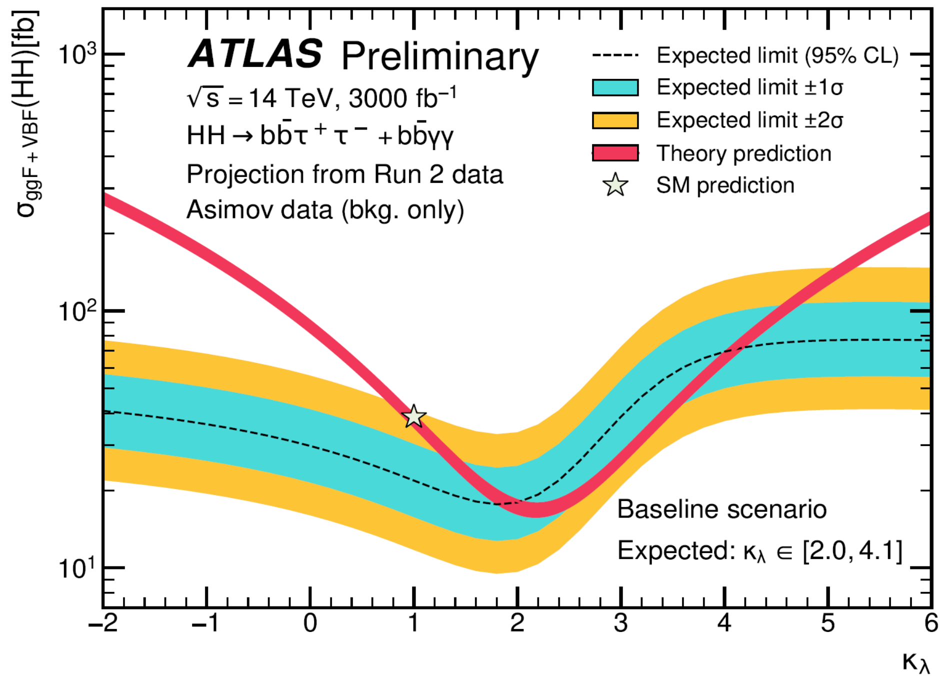
Baseline assumption for bbγγ:
Spurious signal uncertainty is removed, assuming advances in the background estimation. (Spurious signal is the amount of signal fitted in a bkg-only template)

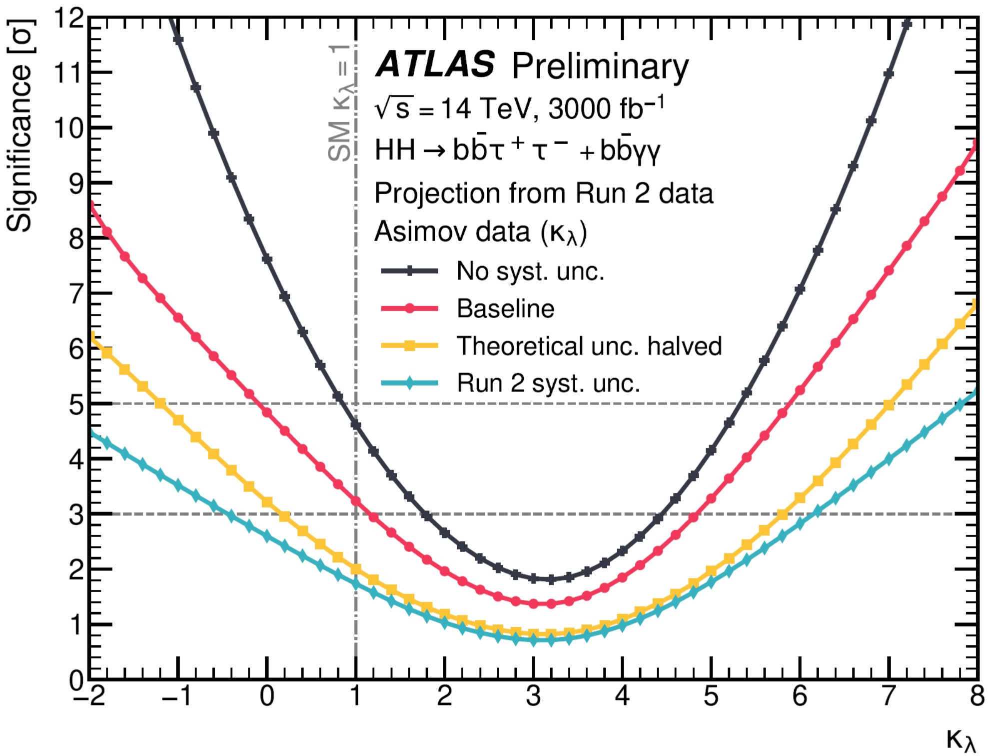
MC stat. uncertainties neglected in baseline scenario, which assumes innovative fast simulation approaches as sample sizes will be very large

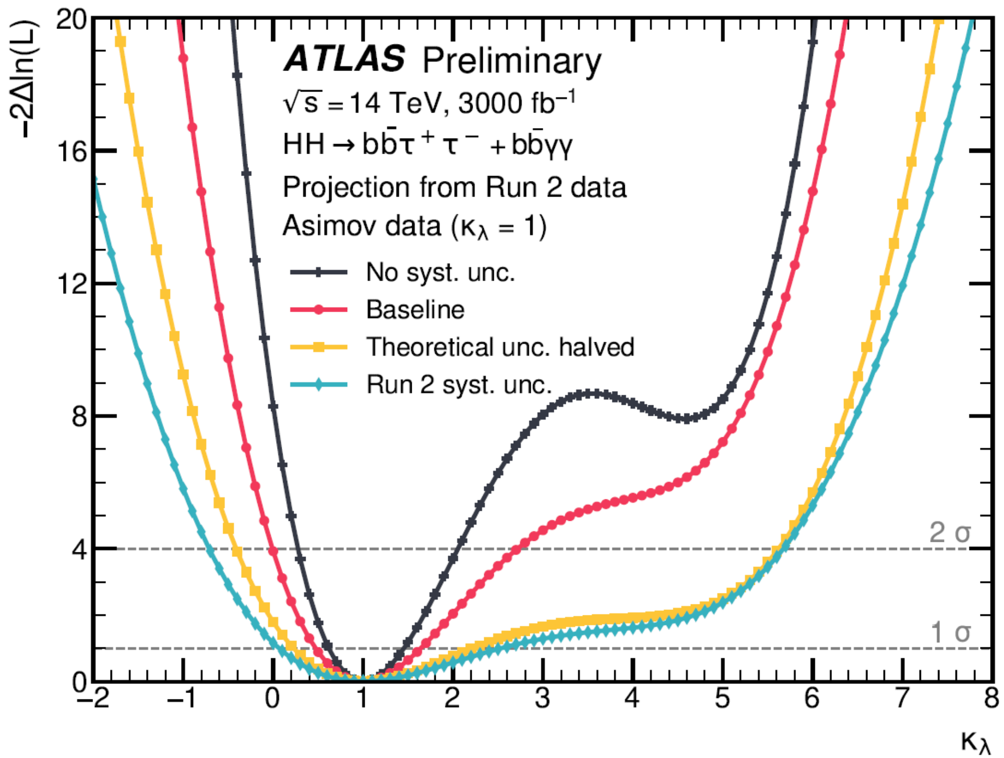


HL-LHC: Projected sensitivity (combining $bb\tau\tau$ and $bb\gamma\gamma$) ATL-PHYS-PUB-2022-005

- **Assuming baseline uncertainties:**
  Expect evidence of SM HH with 3.2σ, κ_λ constrained to [0.5,1.6]
  In case of absence of SM HH: Limit is 0.58 x SM.
- **If all uncertainties stay as they are** (most pessimistic):
  Significance reduced to 1.7σ, κ_λ constrained to [0.1, 2.5]
- **Most limiting uncertainties:** Theory uncertainties on HH, spurious signal for $bb\gamma\gamma$. If spurious signal scales with lumi, expect 10% reduction in combined sensitivity







Improvements compared to previous projection: (baseline signif.)

ATL-PHYS-PUB-2018-053

$bb\gamma\gamma$: 2.0σ→2.2σ
$bb\tau\tau$: 2.1σ→2.8σ

Summary

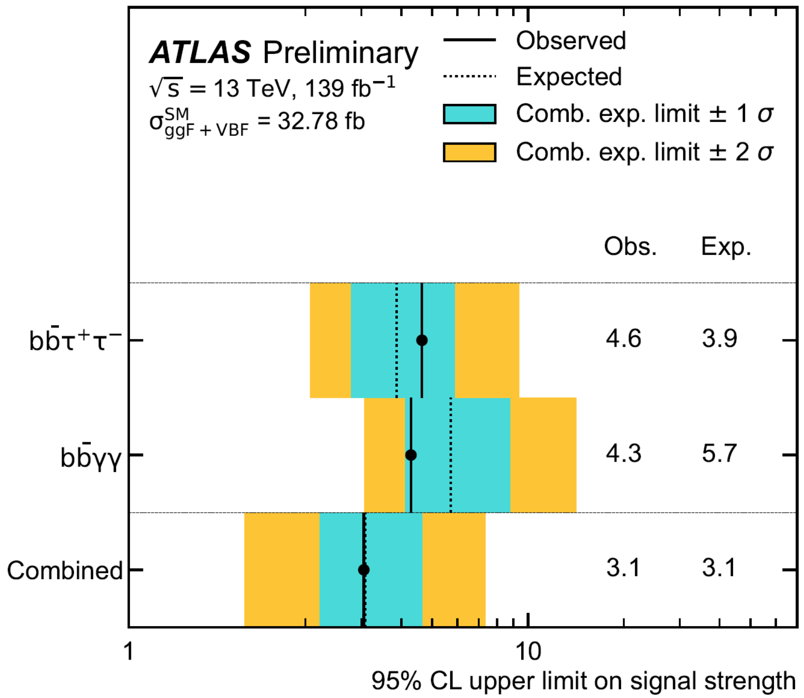
ATLAS has a strong program searching for Di-Higgs topologies!

Searches for new resonances decaying to HH performed with full dataset for $bb\tau\tau$, $bb\gamma\gamma$ and 4b. Non-resonant searches performed with full dataset for $bb\gamma\gamma$ and $bb\tau\tau$.

More updates with the full run-2 dataset will follow!

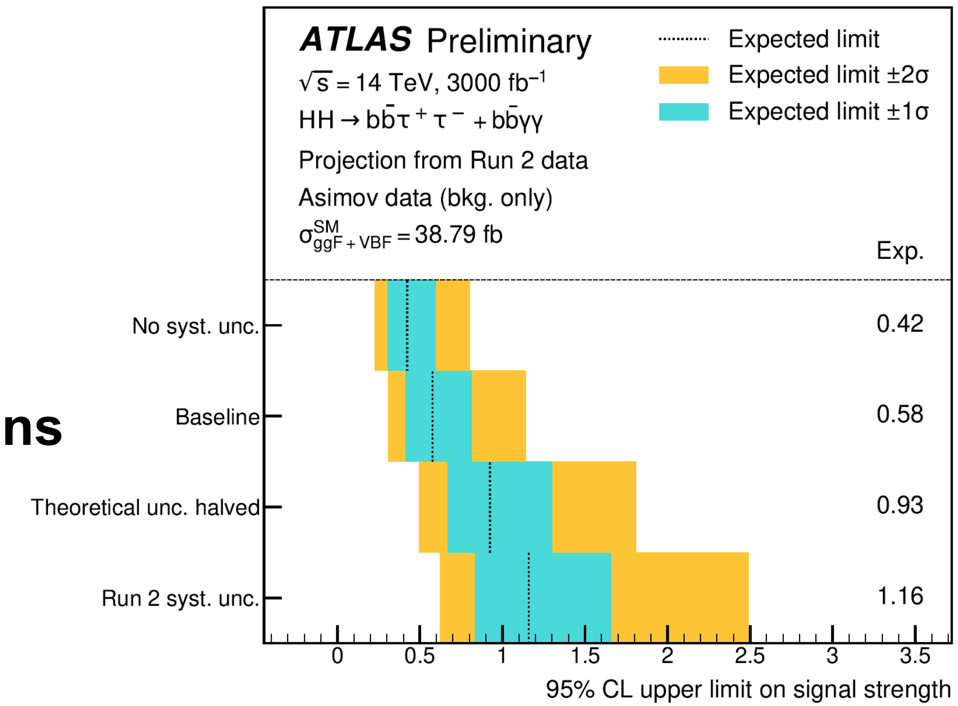
New: Interpretations of non-resonant HH searches in HEFT benchmarks!

No significant excess found in any channel, but strong constraints established.



Combined limit on SM HH:
3.1 observed, 3.1 expected
Combined limit on κ_λ:
[-1.0,6.6] obs., [-1.2,7.2] exp.

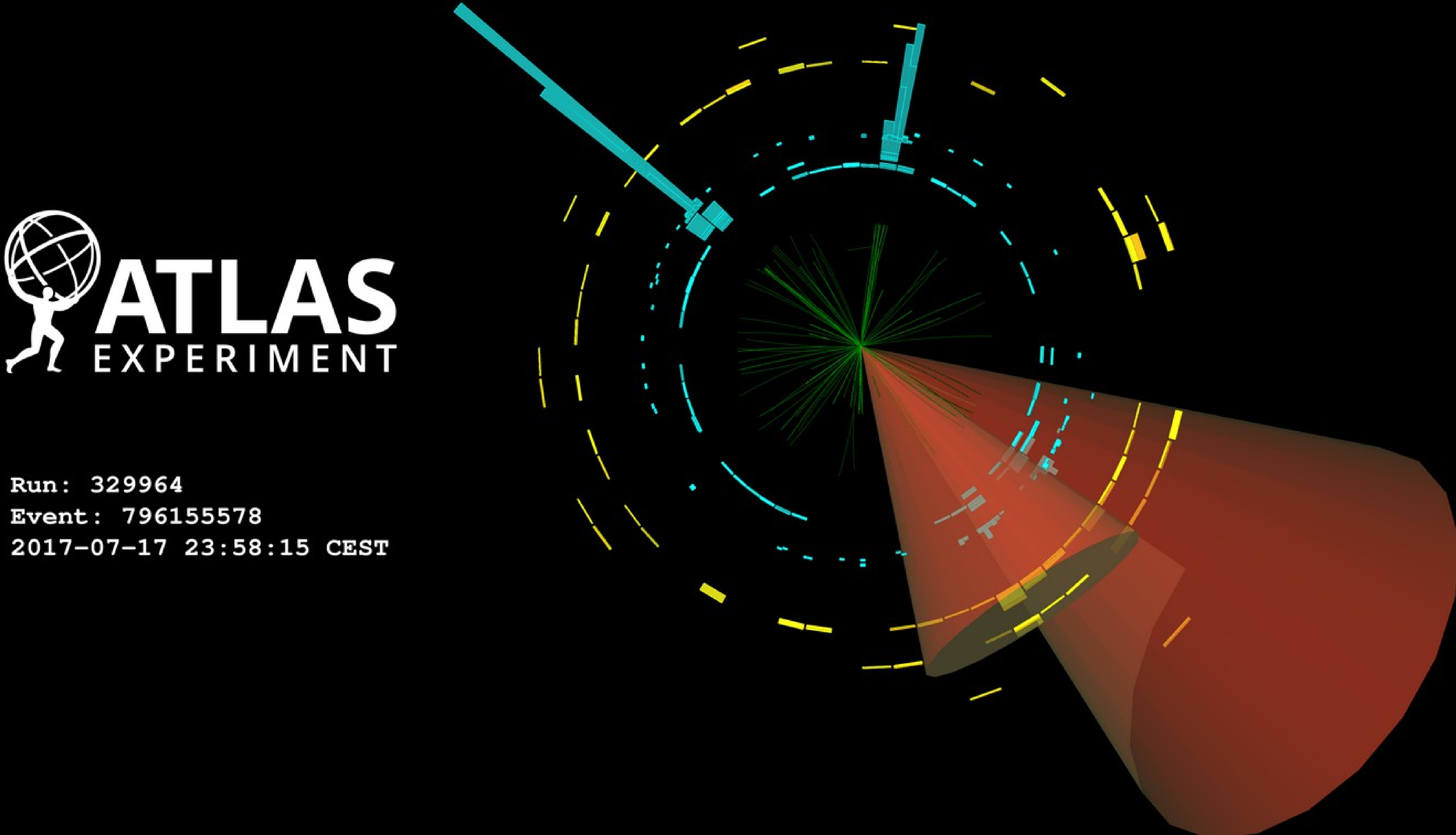
New **HL-LHC projections** (14 TeV, 3/ab) yield a significance for SM HH evidence of 3.2σ



Backup

bb$\gamma\gamma$ event candidate of the high mass BDT tight category

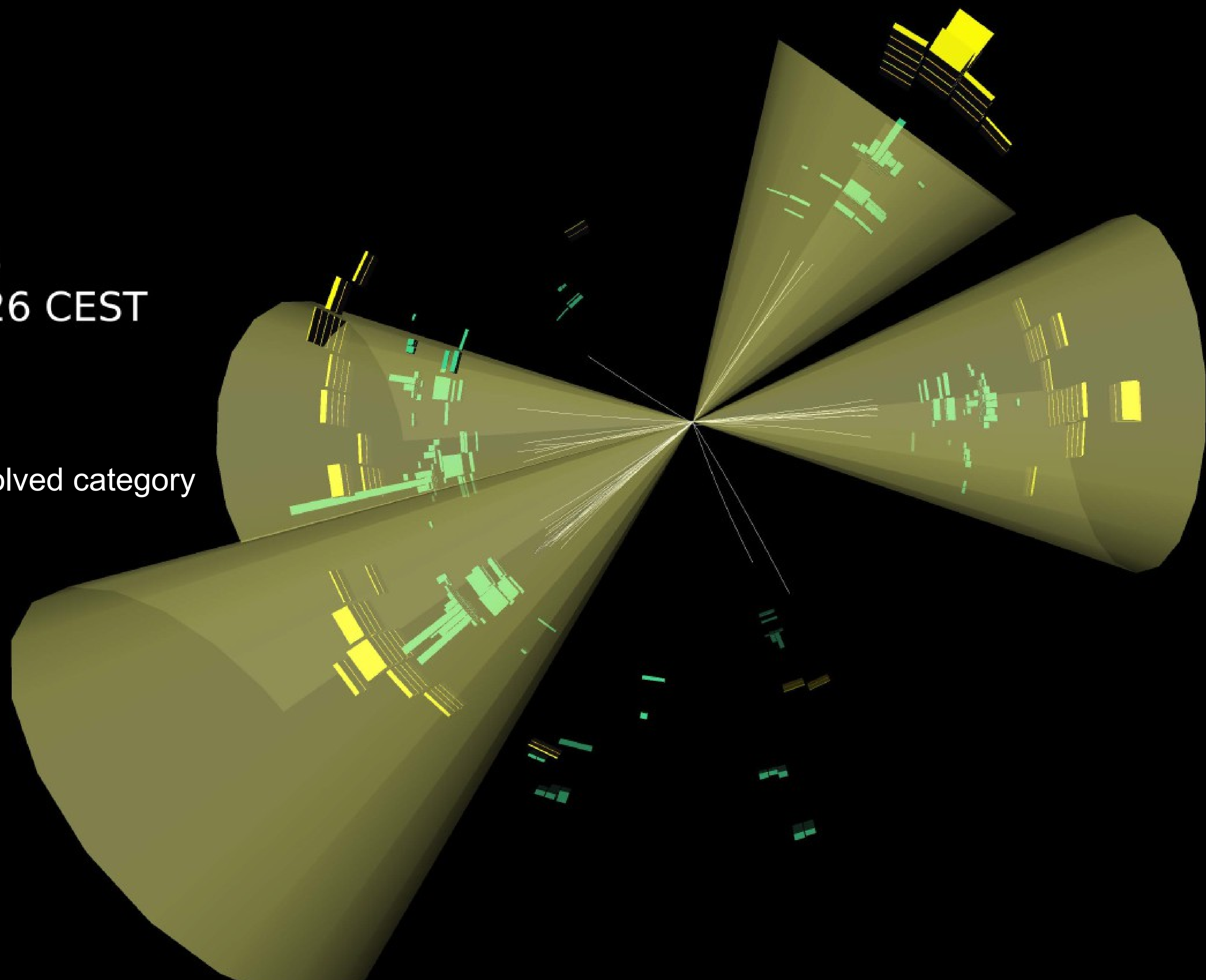
$m_{\gamma\gamma}$ = 123 GeV, m_{bb} = 113 GeV, $m^{*}_{bb\gamma\gamma}$=625 GeV



ATLAS EXPERIMENT

Run: 350013
Event: 1556168518
2018-05-11 01:39:26 CEST

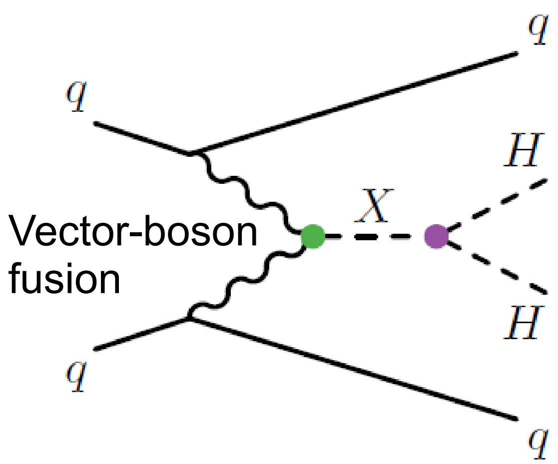
4b event candidate in the resolved category
m_{4b} is 629 GeV



VBF HH → bbbb (Full Run-2 dataset)

HDBS-2018-18

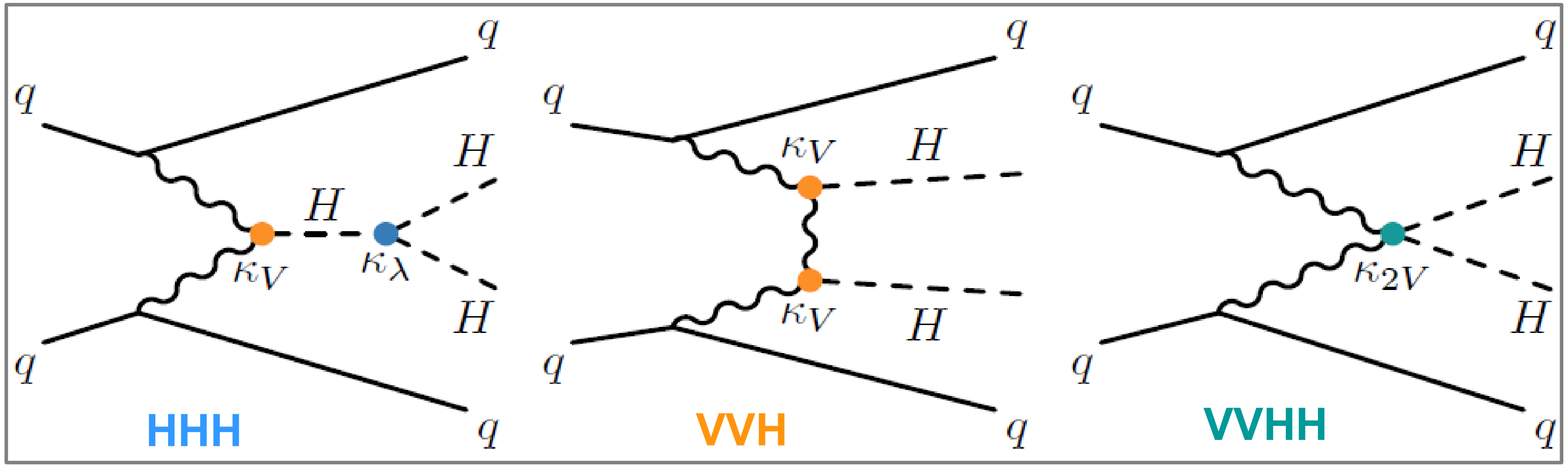
Resonant



Probing resonance mass range of 260-1000 GeV

Non-resonant

$\sigma(qq \to HH) = 1.726$ fb

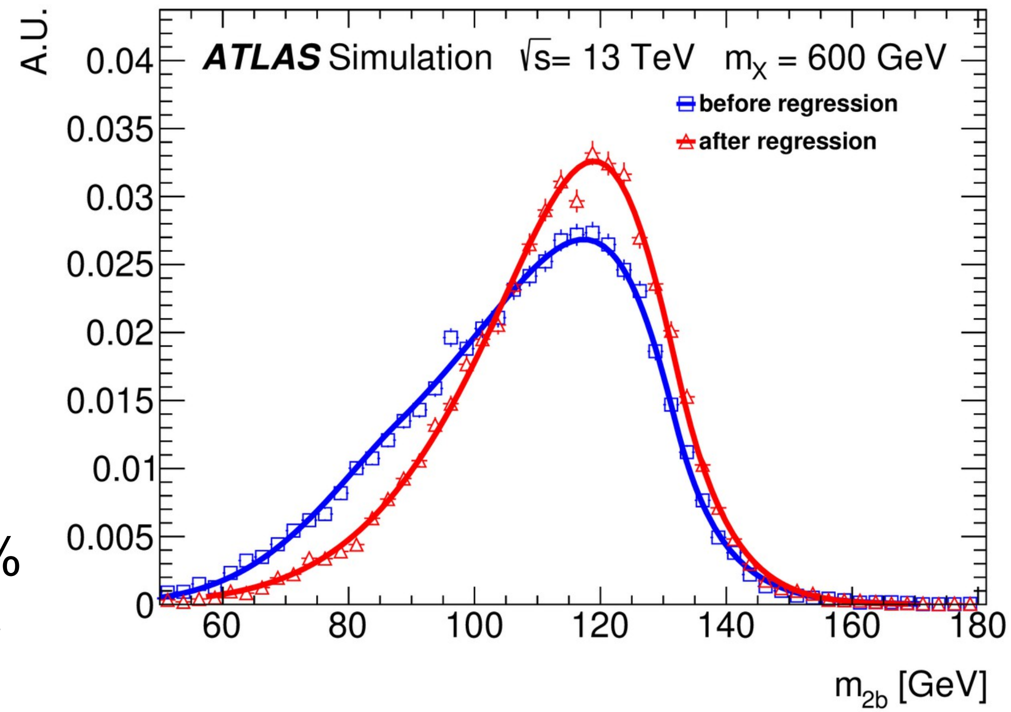


VBF production is sensitive to constraining κ_{2V} coupling

Jet and event selections:

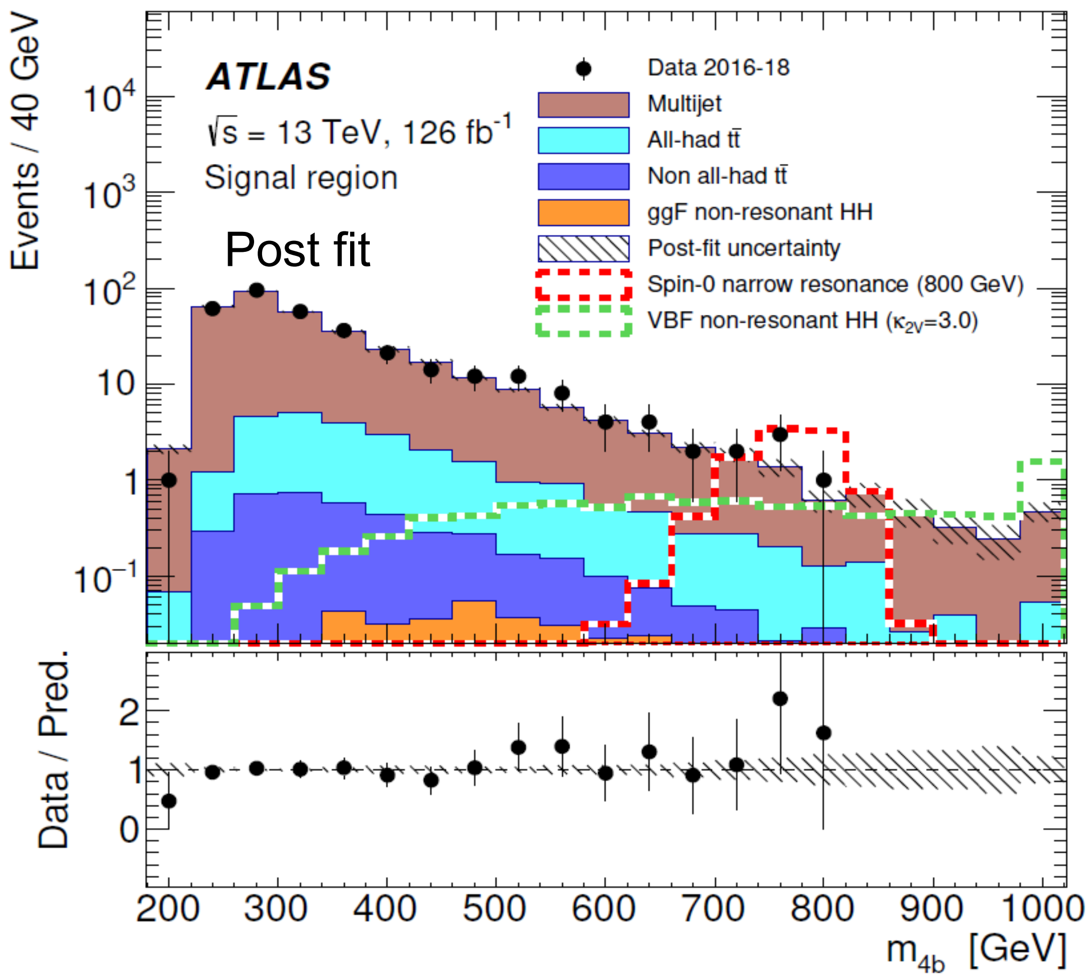
- 4 central b-jets (pT>40 GeV, $|\eta|<2.0$), used to form the 2 Higgs boson candidates
- 2 forward jets (pT>30 GeV, $|\eta|>2.0$), select events with $m_{jj}>1000$ GeV, $|\Delta\eta_{jj}|>5.0$

Jet energy regression BDT improves 2b mass resolution by 25%
(trained on b-tagging score, jet pT, jet width, energy leakage outside jet cone, energy loss from semileptonic B-decays)

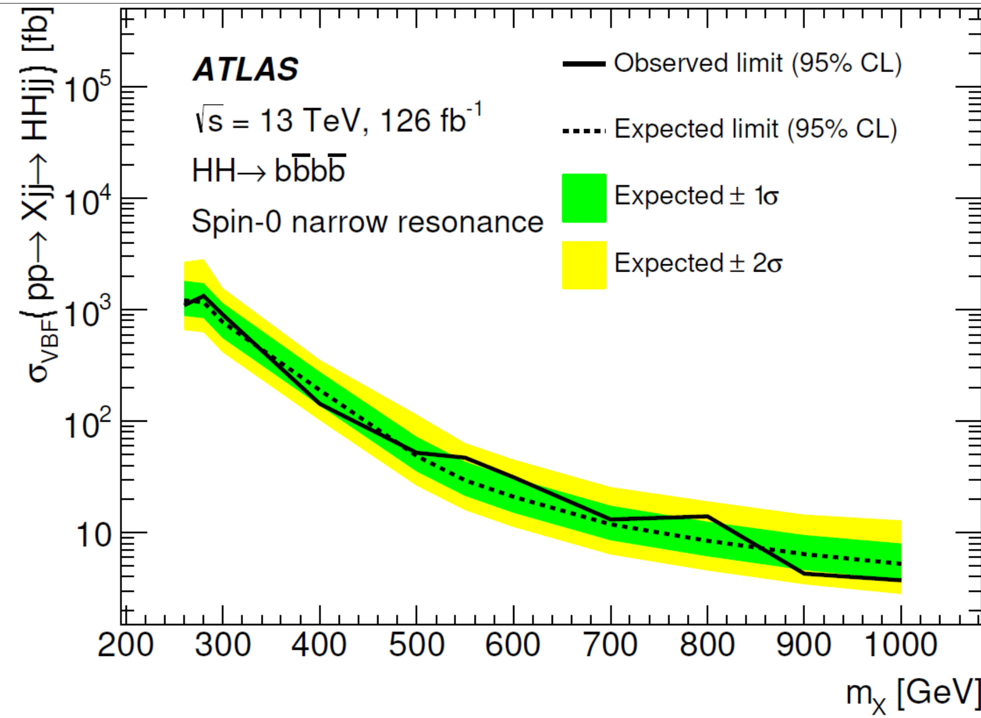


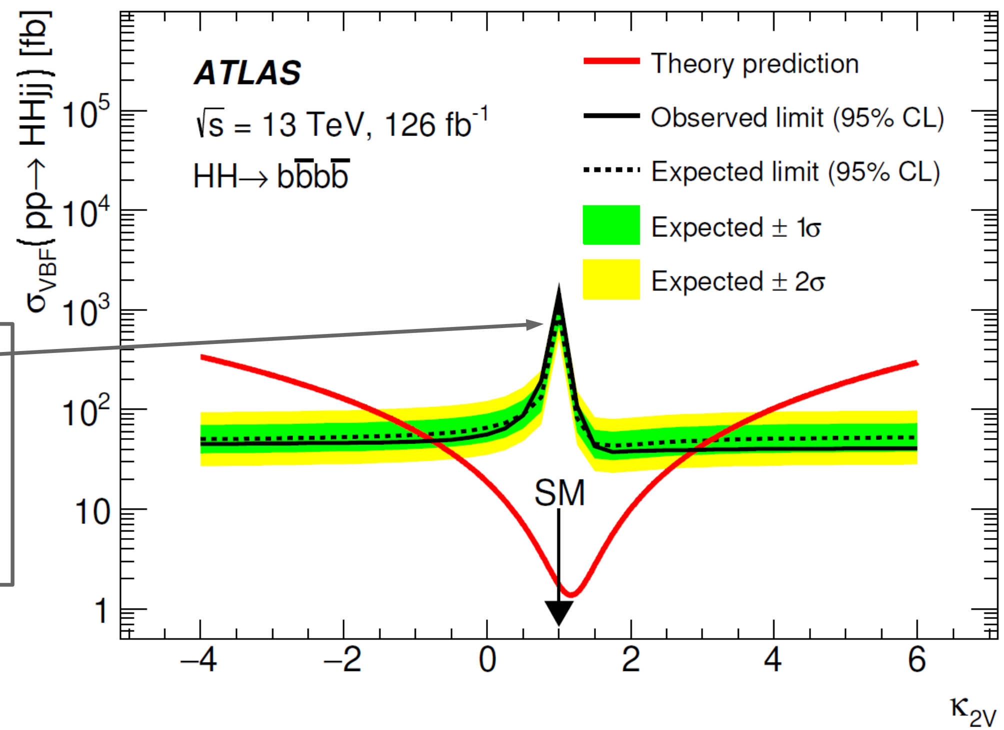
VBF HH → bbbb (Full Run-2 dataset)

HDBS-2018-18



Background estimation similar to ggF 4b analysis





Signal acceptance for κ_{2V}~1 (SM) very small because jets are very soft

Allowed κ_{2V} parameter range:

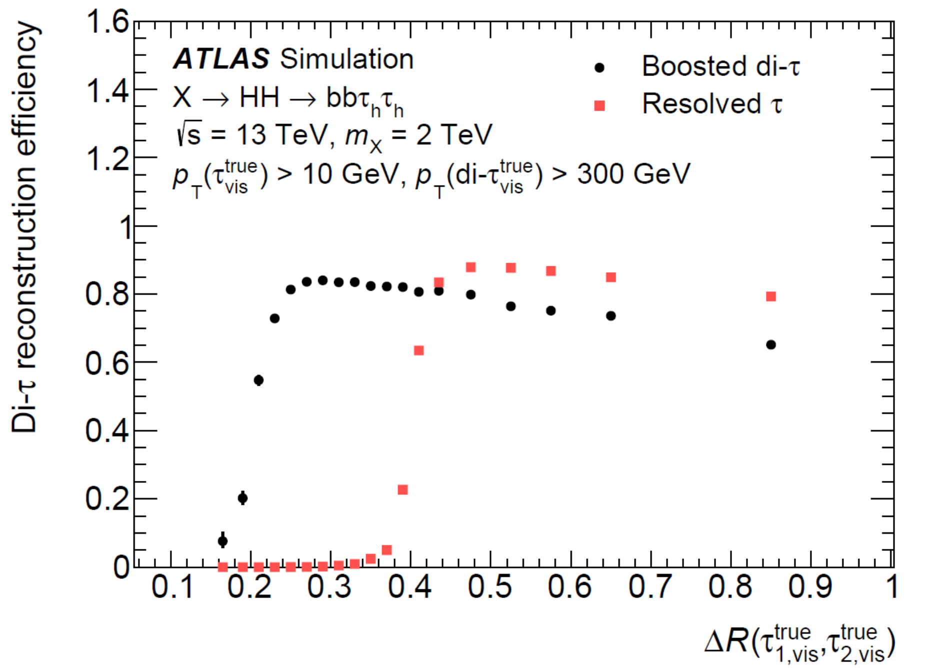
$-0.76 < \kappa_{2V} < 2.90$ (observed)

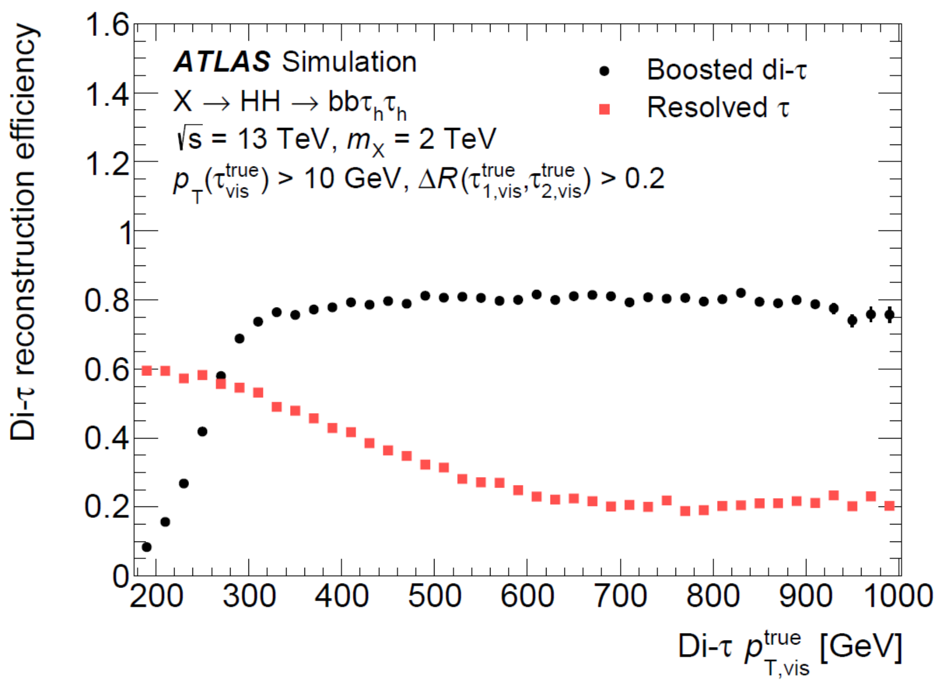
$-0.91 < \kappa_{2V} < 3.11$ (expected)

Limit on SM: 840 (observed), 550 (expected)

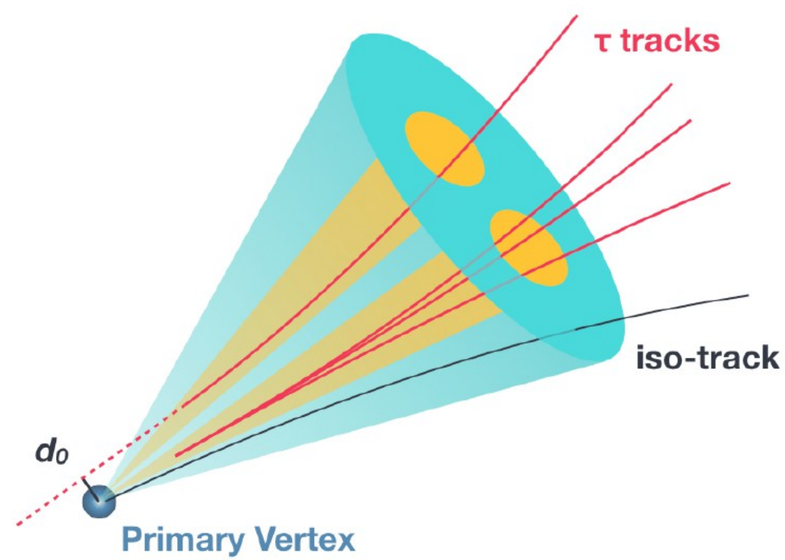
Boosted HH → bbττ (Full Run-2 dataset)

HDBS-2019-22





- Boosted bb system reconstructed as a large-R (R=1.0) jet, b-tagging applied to variable-R (0.02<R<0.4) track-jets
- In the boosted regime, also the tau jets merge and standard reconstruction (that is seeded in R=0.4 jets) becomes inefficient
- **Boosted di-tau reconstruction and ID:**
  - seeded in R=1 jets
  - Reclustering the constituents into 0.2 subjets
  - 2 leading subjets define the di-tau system
  - Identification BDT to discriminate ditau system from gluon- or quark jets (60% efficiency WP chosen)
  - 1 or 3 tracks geometrically matched to the subjets (ΔR<0.2)

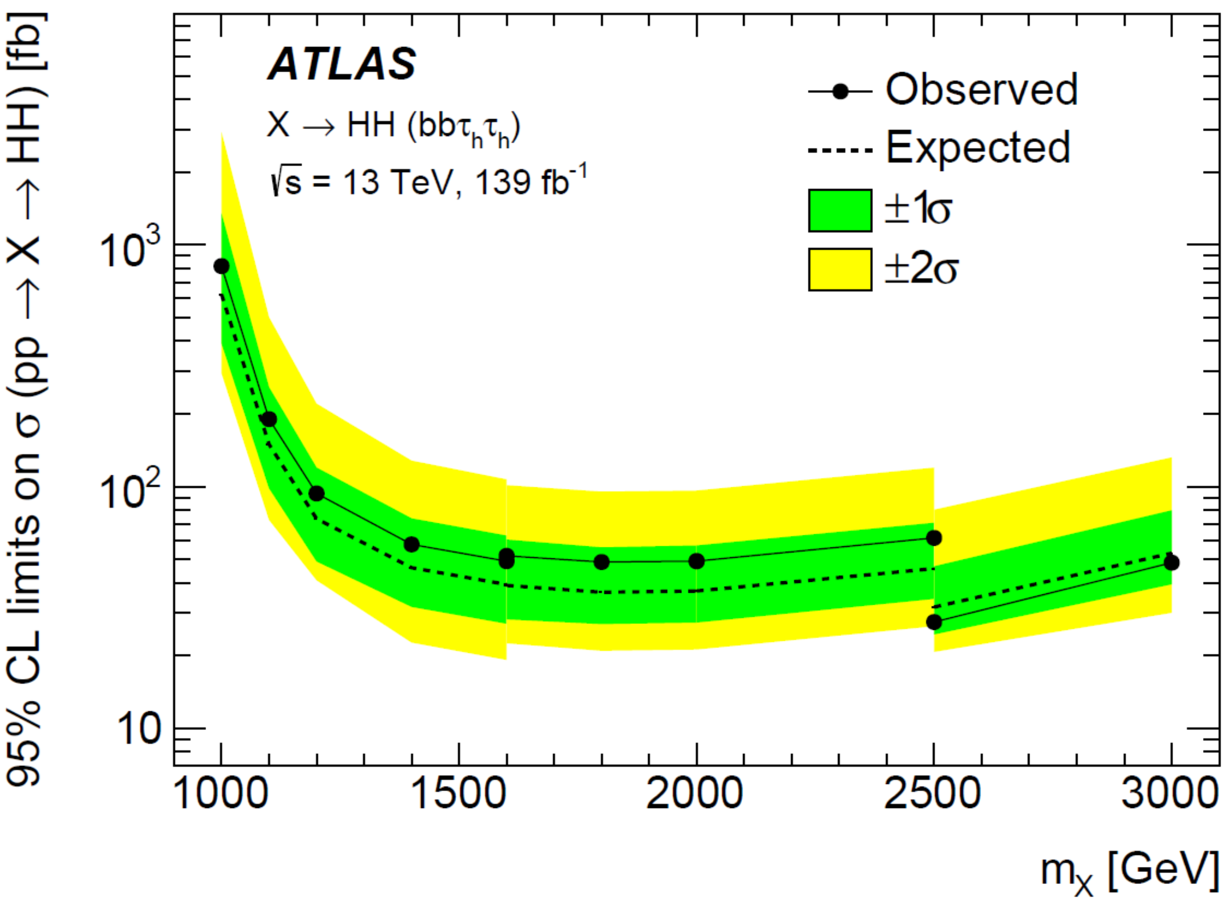


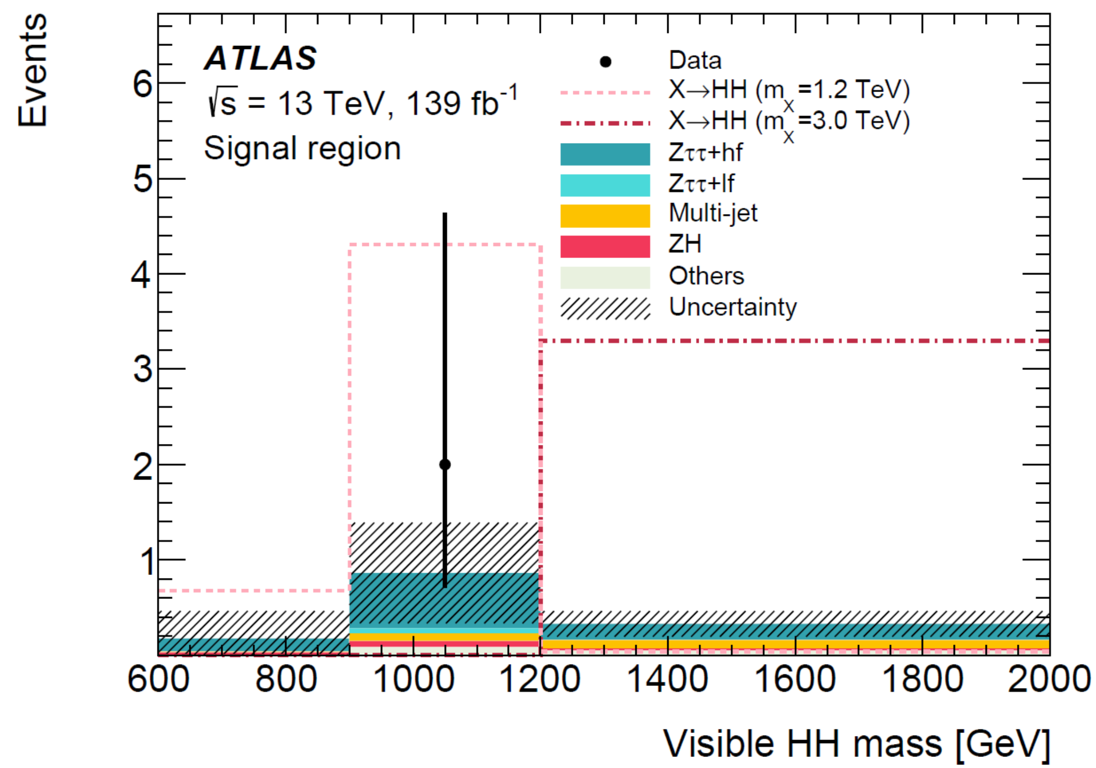
Boosted HH → bbττ (Full Run-2 dataset)

HDBS-2019-22

- 3 final mX-dependent selections on m_{HH} that define the SRs used for event counting
- Multijet background data-driven (fake factor method), Z+HF normalized in a CR
- Severely statistics limited analysis, not competitive with boosted HH → 4b

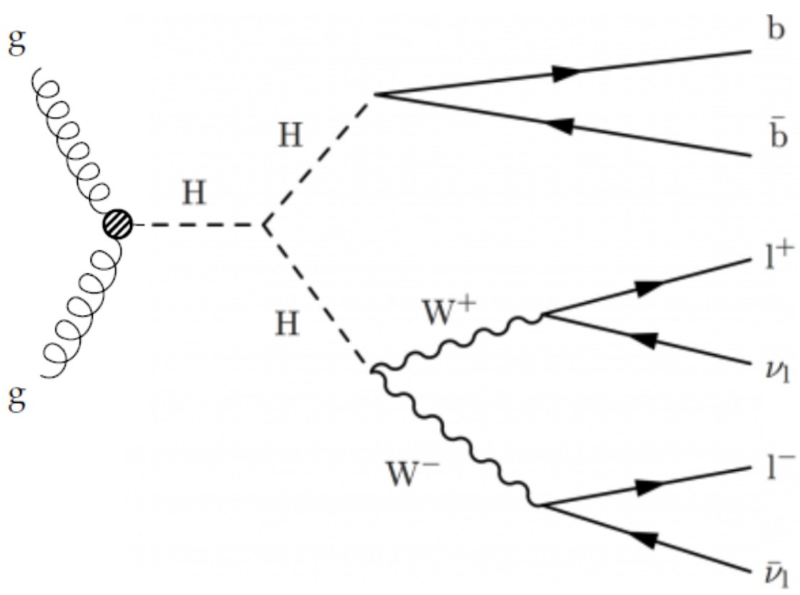
Selection on m_{HH}^{vis}	> 0 GeV	> 900 GeV	> 1200 GeV
$Z\tau\tau$+hf	$0.89 \pm 0.25^{+0.37}_{-0.35}$	$0.75 \pm 0.21^{+0.47}_{-0.37}$	$0.17 \pm 0.05 \pm 0.07$
$Z\tau\tau$+lf	$0.05 \pm 0.05 \pm 0.03$	$0.05 \pm 0.05 \pm 0.03$	-
Multi-jet	$0.18 \pm 0.03 \pm 0.14$	$0.17 \pm 0.03 \pm 0.13$	$0.09 \pm 0.02 \pm 0.07$
ZH	$0.11 \pm 0.01 \pm 0.04$	$0.09 \pm 0.01 \pm 0.03$	$0.02 \pm$ - ± 0.01
Others	$0.13 \pm 0.05^{+0.15}_{-0.07}$	$0.13 \pm 0.05^{+0.15}_{-0.07}$	$0.05 \pm 0.03^{+0.12}_{-0.03}$
Sum of backgrounds	$1.36 \pm 0.26^{+0.42}_{-0.38}$	$1.19 \pm 0.23^{+0.51}_{-0.40}$	$0.33 \pm 0.07^{+0.16}_{-0.10}$
Data	2	2	0





HH → bblνlν (Full Run-2 Dataset)

HDBS-2018-33



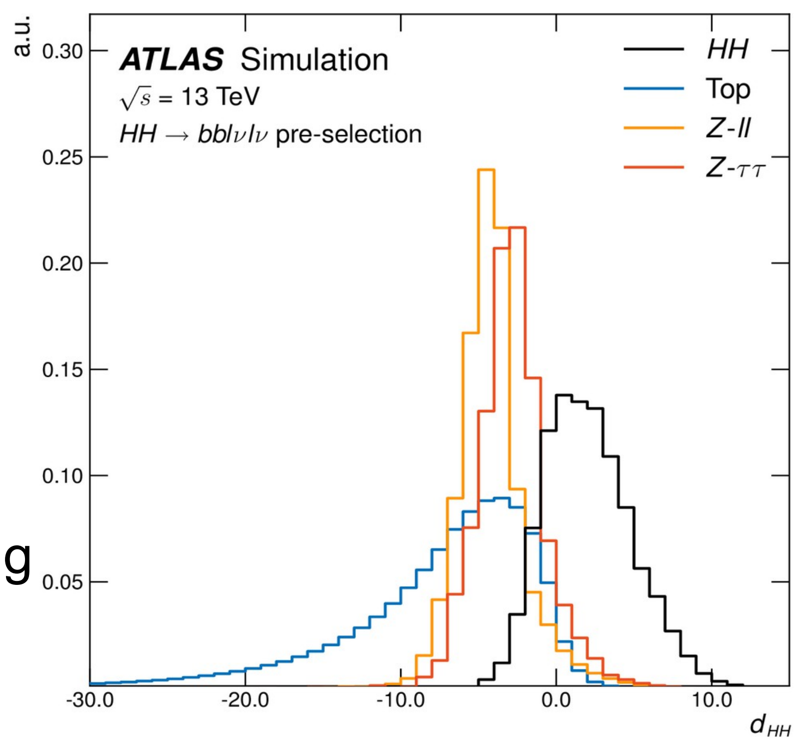
- Search for **non-resonant** HH production only
- Select events with 2 (resolved) b-jets and 2 leptons (e/μ), signal dominated by bbWW but bbZZ and bbττ also included
- Cuts on m_{ll} and m_{bb} efficiently suppress background (20 GeV < m_{ll} < 60 GeV, 110 GeV < m_{bb} < 140 GeV)
- Backgrounds estimated mainly from simulation but normalized in signal-depleted data CRs enriched in top and Z+HF events

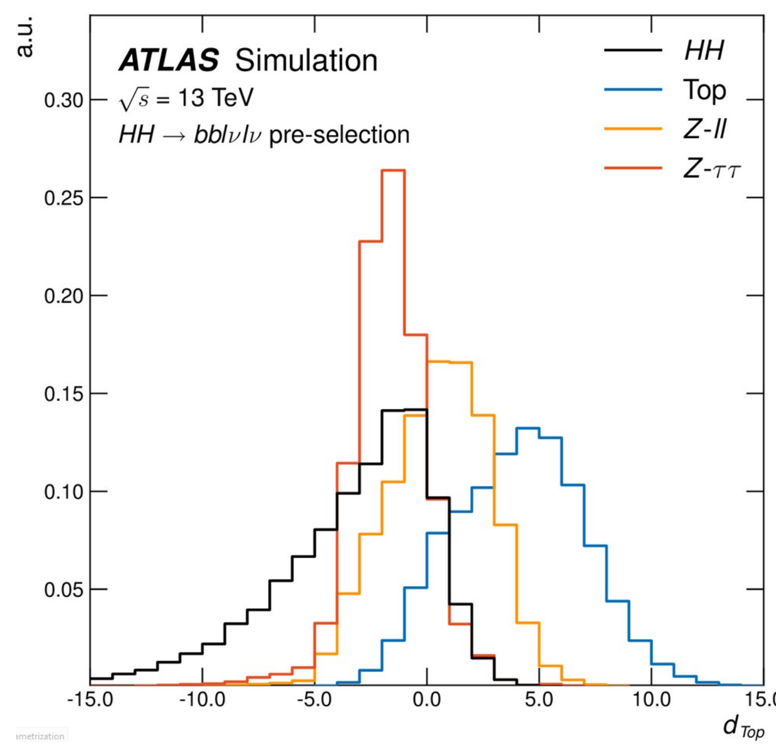
Deep neural network classifier that produces multiple outputs:

- one discriminant for each HH, top, Z(ll) and Z(ττ) components

- final cut placed on d_{HH} discriminant

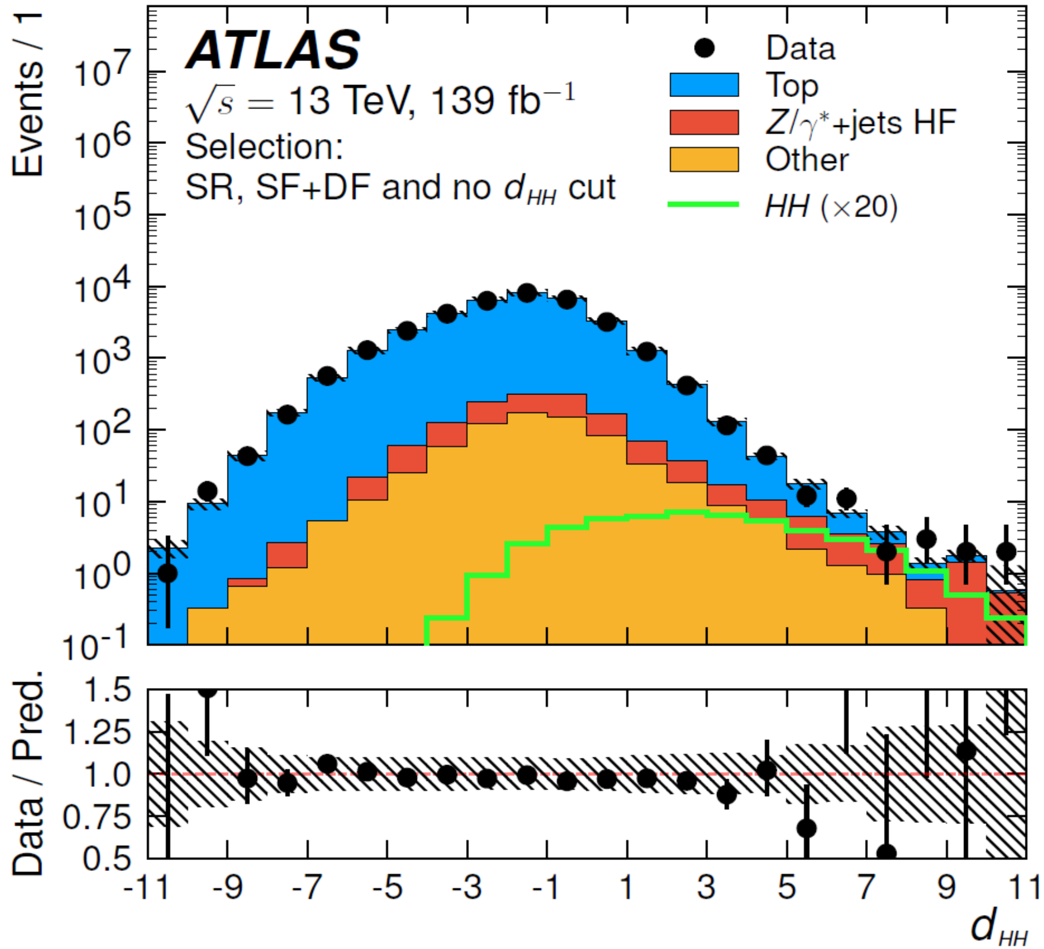
- 35 input variables enter the DNN training

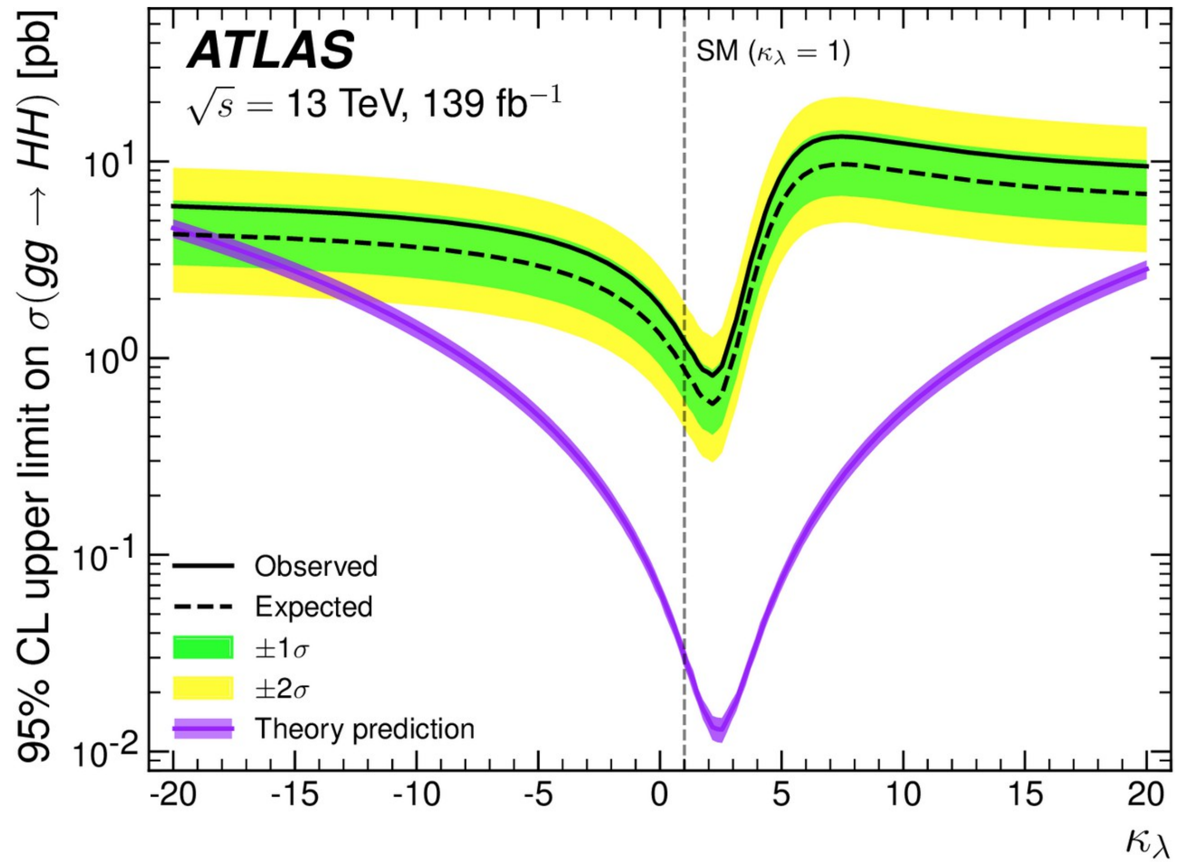




HH → bblνlν (Full Run-2 Dataset)

HDBS-2018-33





No values of κ_λ excluded, DNN trained on SM only

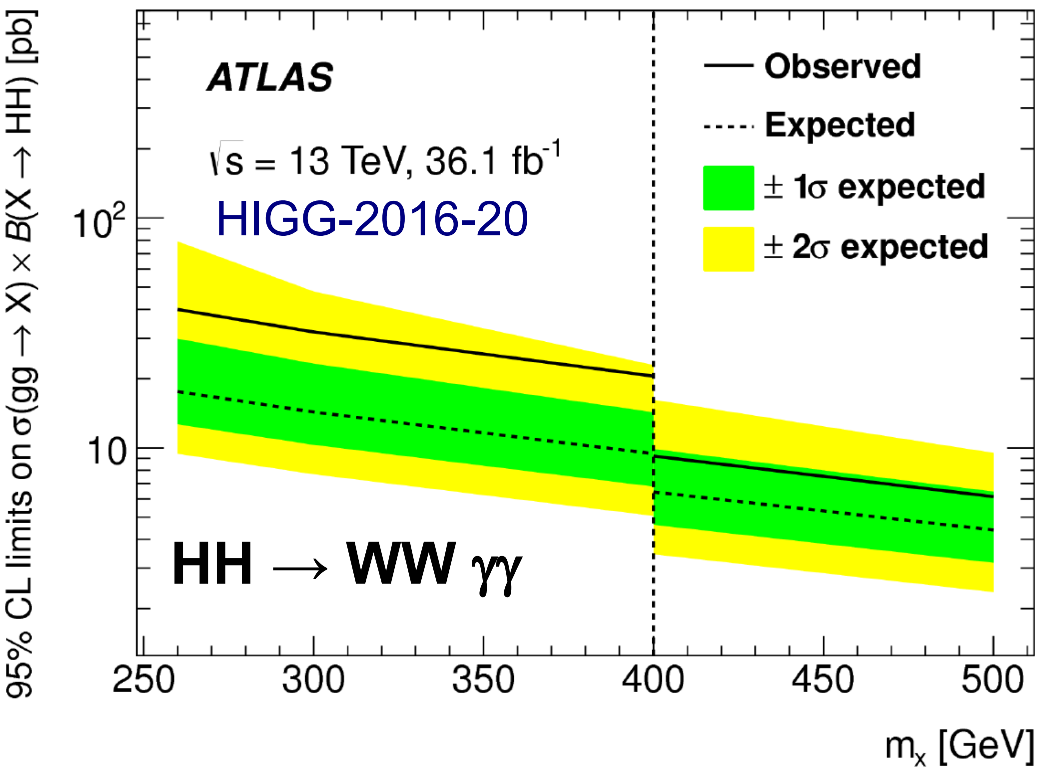
Final cut placed at d_{HH} > 5.45 (5.55) for ee/μμ (eμ)

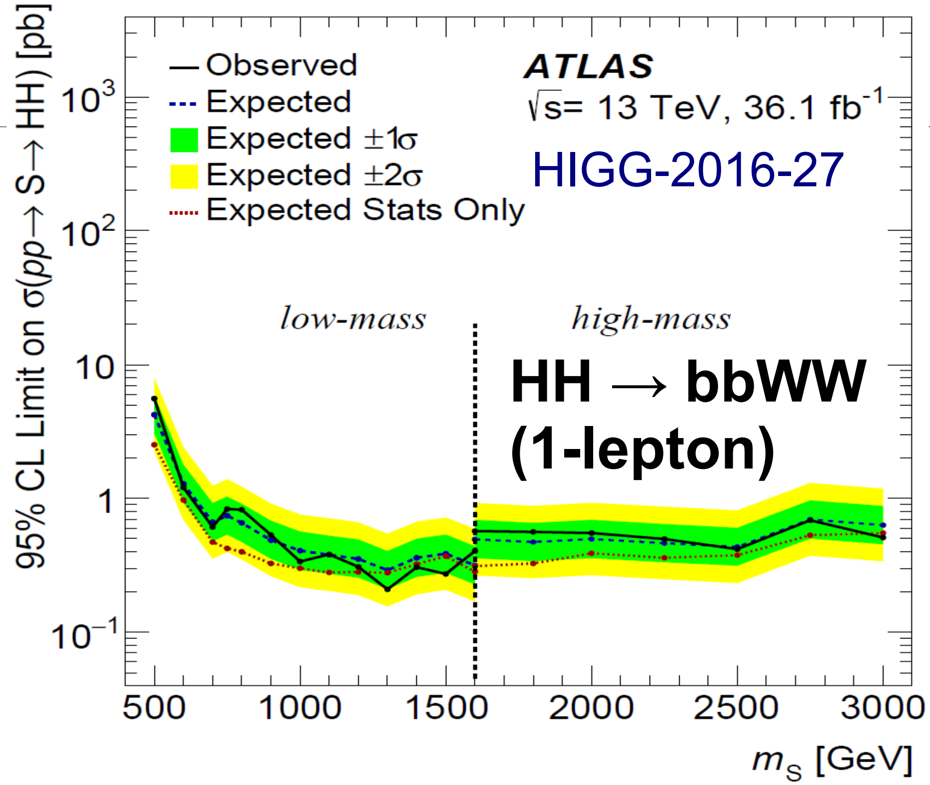
Event counts fitted simultaneously in two SR and two CR (top, Z+HF) for limit setting

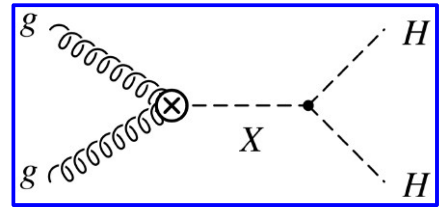
95% limits on SM non-resonant HH production:

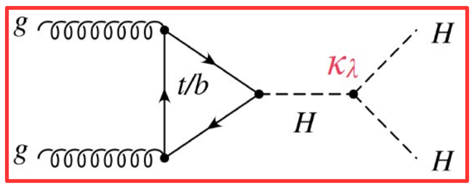
	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{SM}(gg \to HH)$	14	20	29	43	62	40

HH → 4W, bbWW, WWγγ (36/fb)



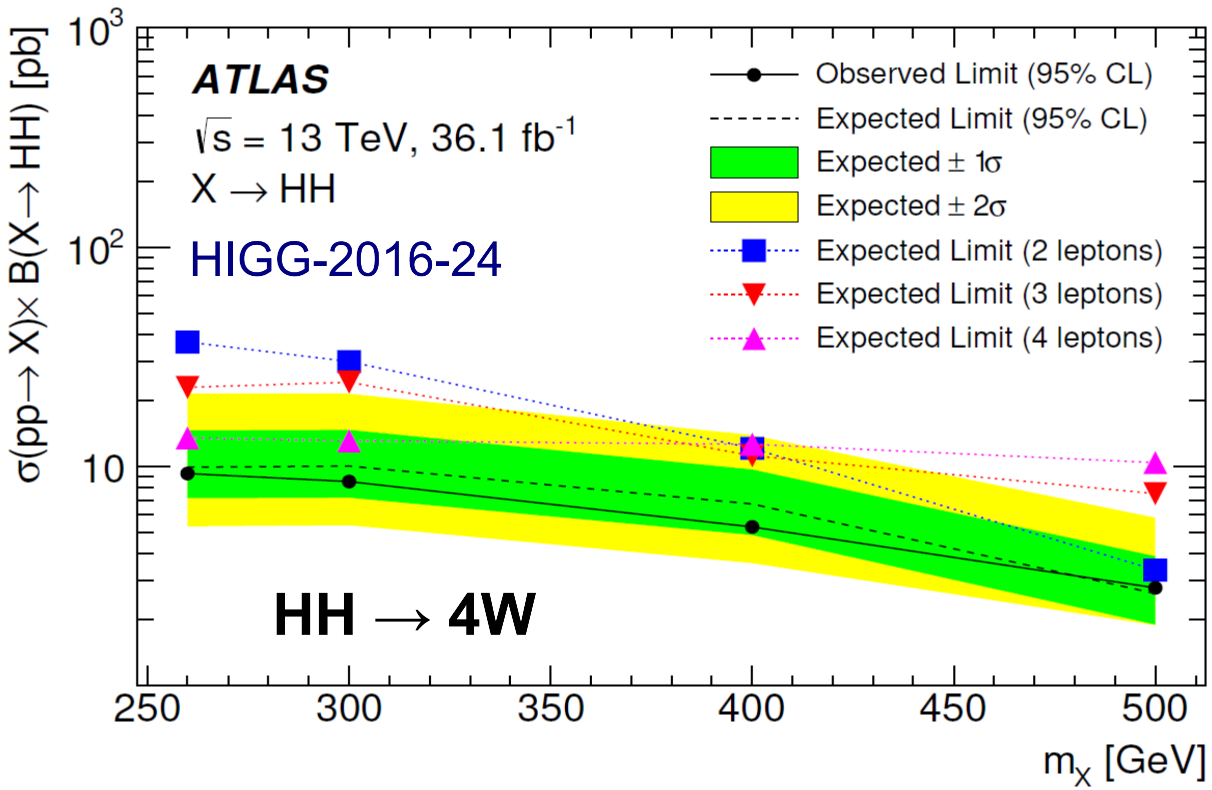






Limits on non-resonant HH production [x SM]:

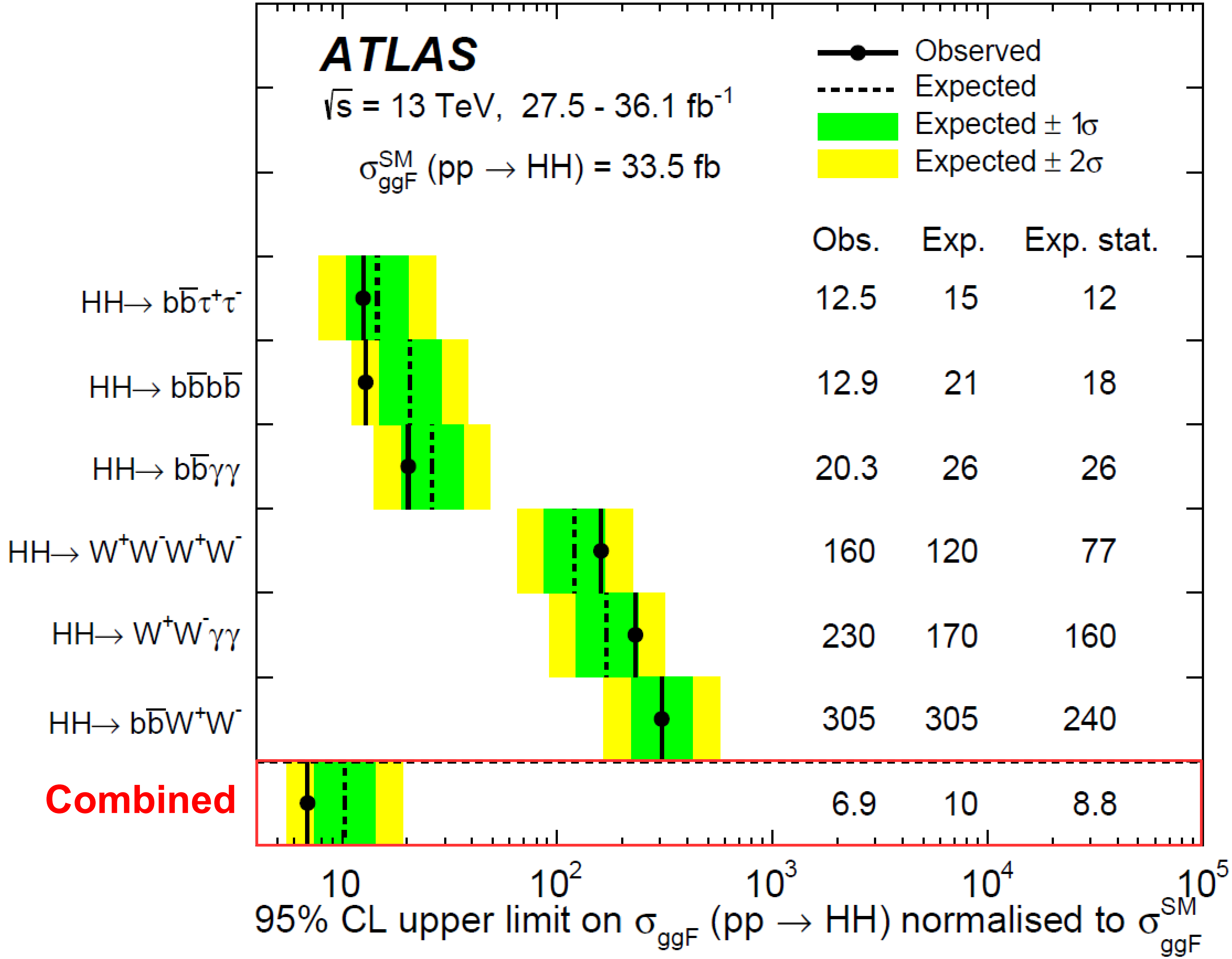
	4W	bbWW 1lep	WWγγ
observed	160	300	230
excluded	110	300	160



HH Combination (36/fb)

HDBS-2018-58

Limits on non-resonant HH production:



„Big-3“ channels dominate:

- bbττ
- bbbb
- bbγγ

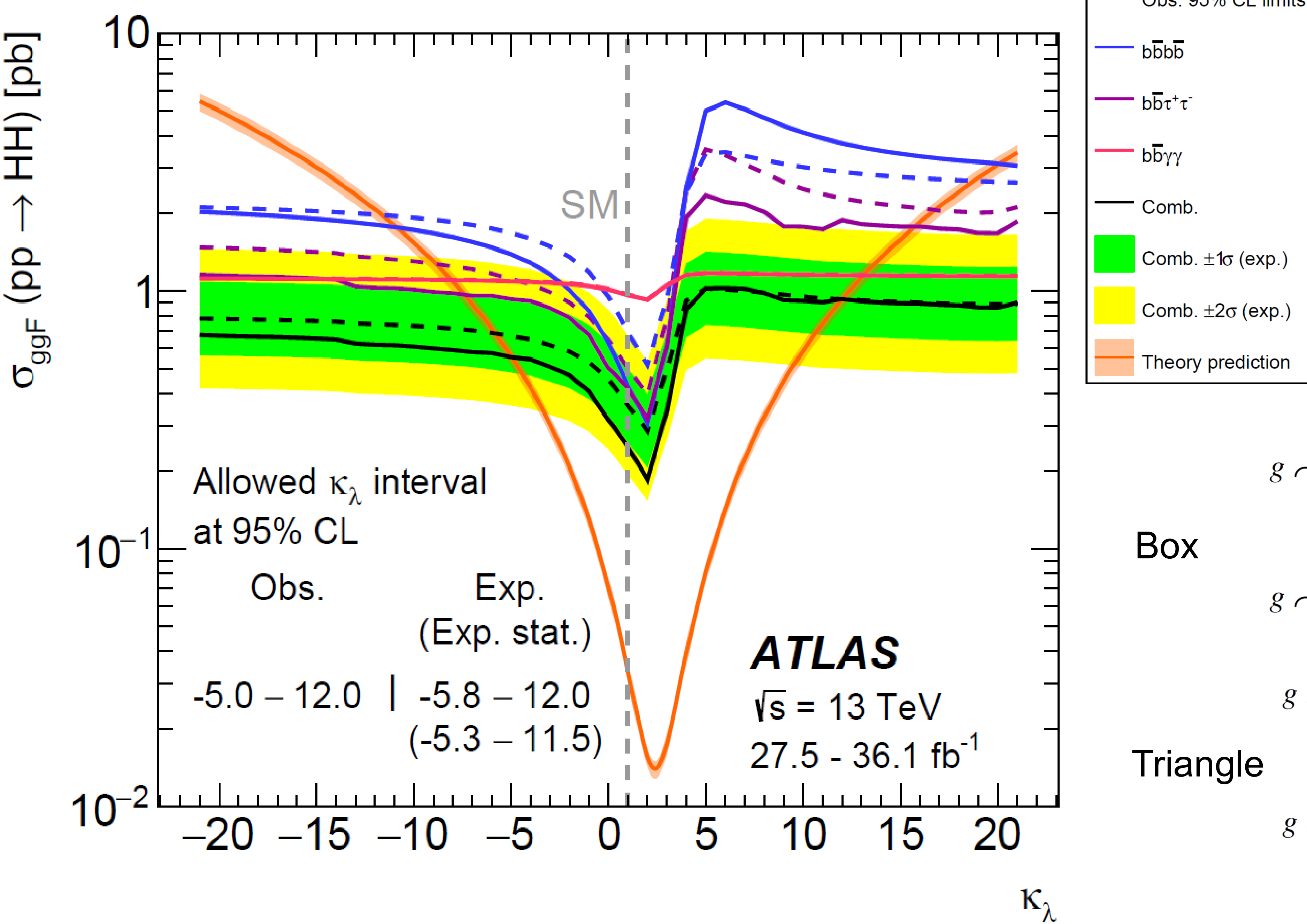
bblνlν not included

For full run-2 dataset update, expect improvements not only from larger statistics, but also more sophisticated analyses

HH Combination (36/fb)

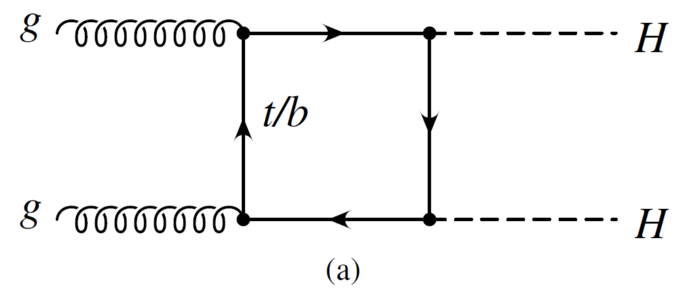
HDBS-2018-58

Limits on non-resonant HH production:

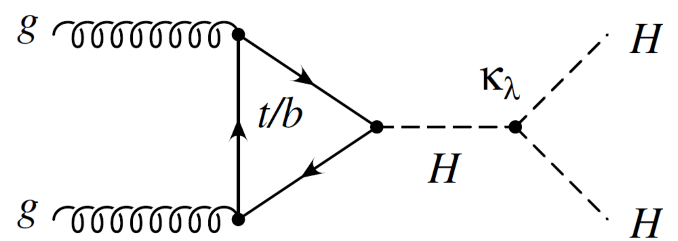


- Large abs. values of κ_λ excluded
- bbττ and bbγγ limited by data statistics

Box



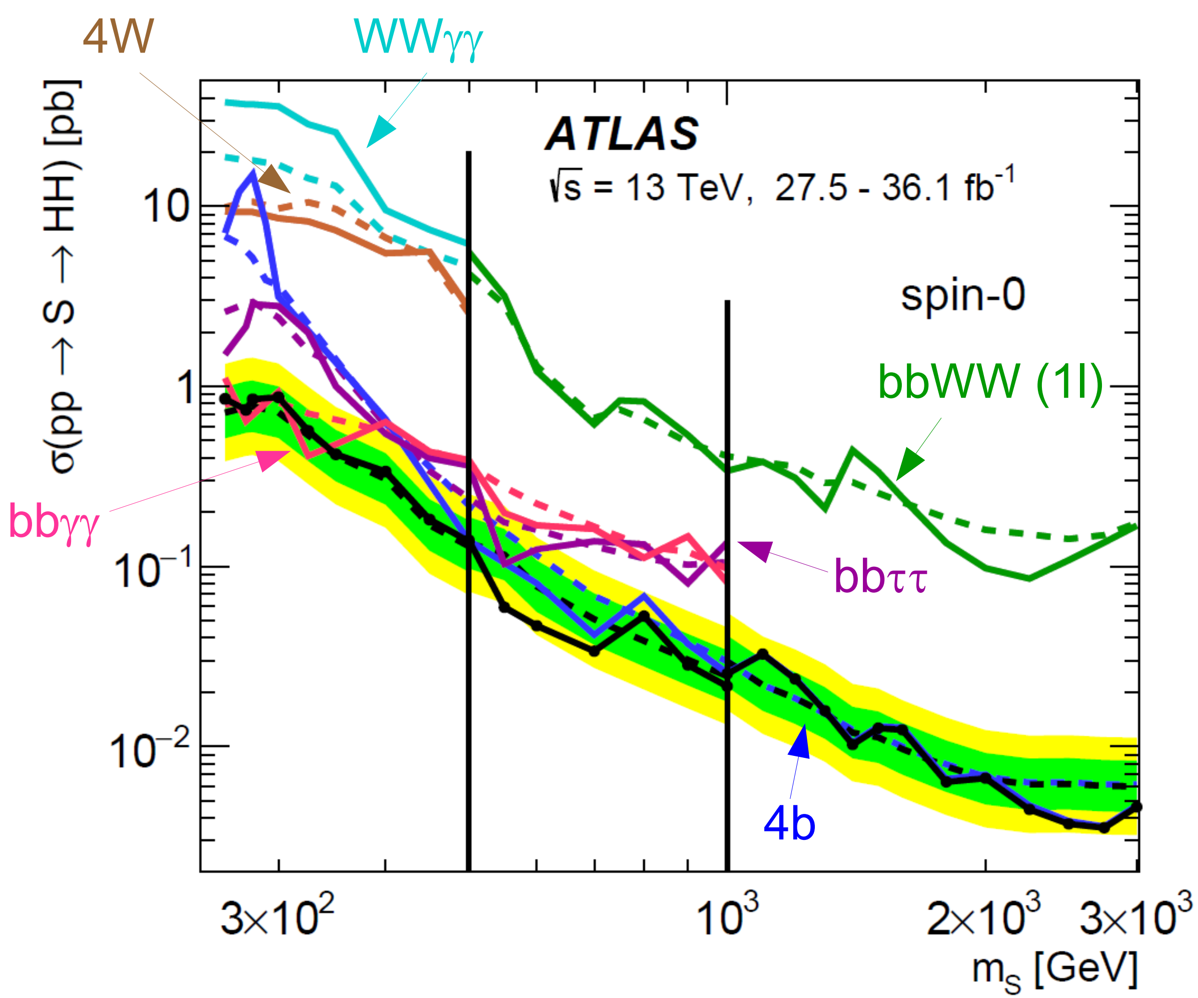
Triangle

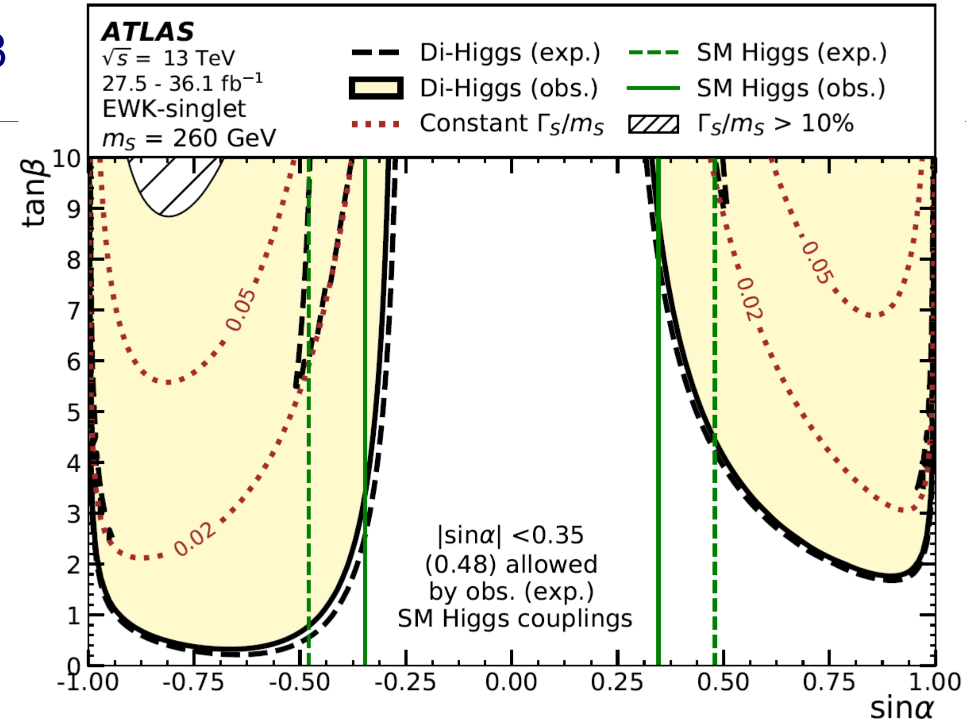


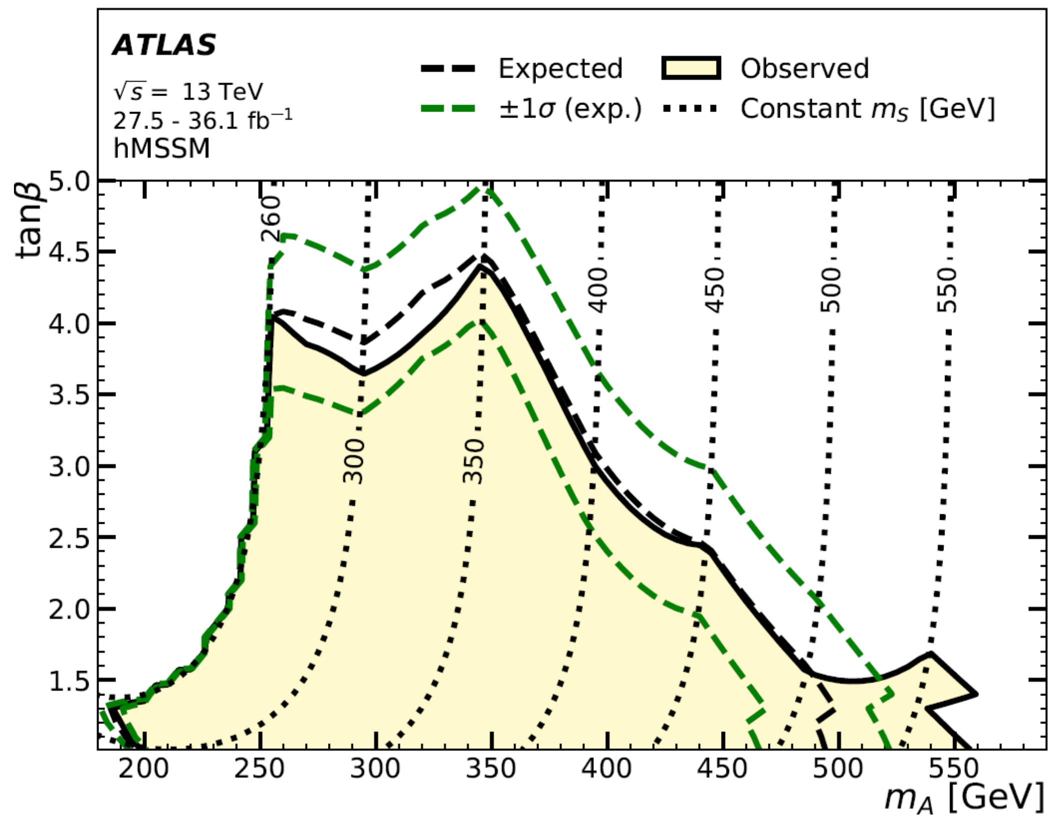
HH Combination (36/fb)

HDBS-2018-58

Limits on resonant X → HH production:







Resonant searches were interpreted in models that predict at least one heavy additional Higgs boson: **EWK-singlet** model, and **hMSSM** (type-II 2HDM)

→ range of model parameter values excluded

H+HH Combination (36-80/fb)

ATLAS-CONF-2019-049

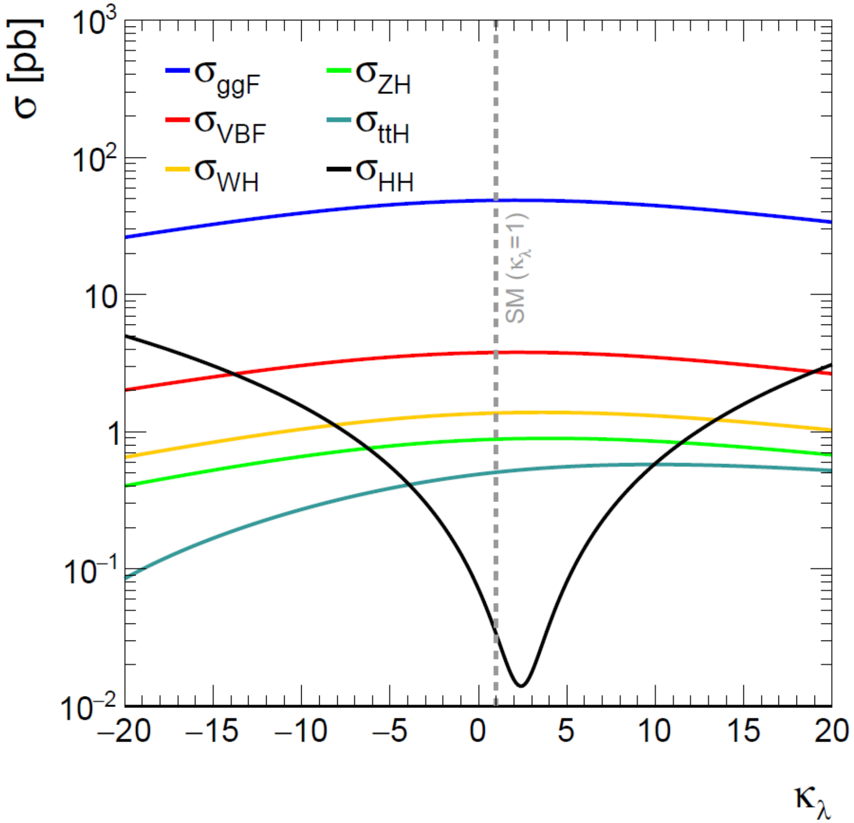
Constraints on κ_λ can be obtained from single Higgs measurements (as well as HH searches)

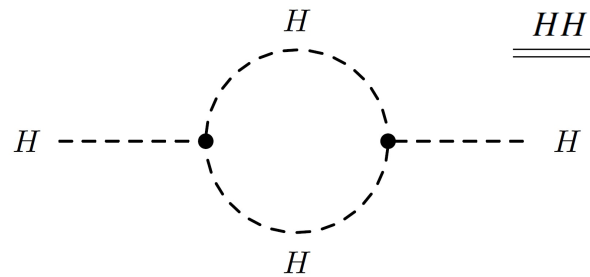
NLO EW corrections depend on λ_{HHH} and impact inclusive and differential cross sections & branching ratios

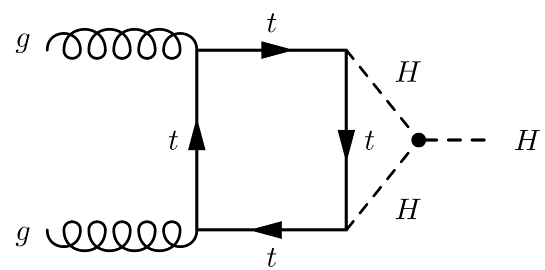
Differential information encoded via the simplified template cross sections (STXS) framework for single H

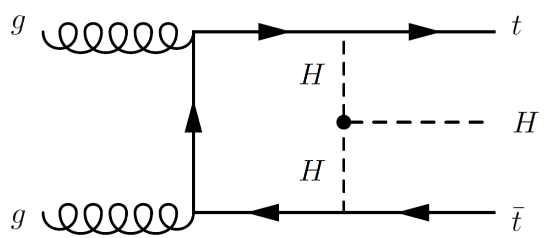
Channels included:

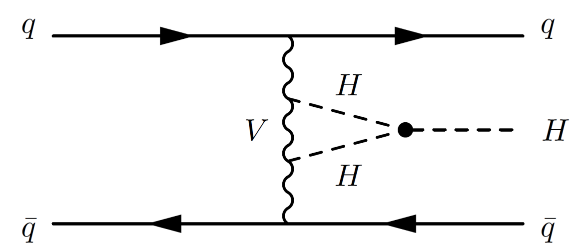
Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (excluding $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau^+\tau^-$	36.1
VH, $H \to b\bar{b}$	79.8
$t\bar{t}H$, $H \to b\bar{b}$	36.1
$t\bar{t}H$, $H \to$ multilepton	36.1
$HH \to b\bar{b}b\bar{b}$	27.5
$HH \to b\bar{b}\tau^+\tau^-$	36.1
$HH \to b\bar{b}\gamma\gamma$	36.1

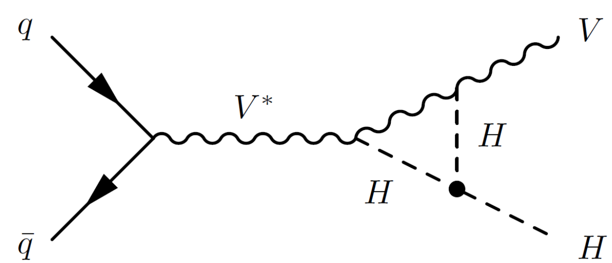






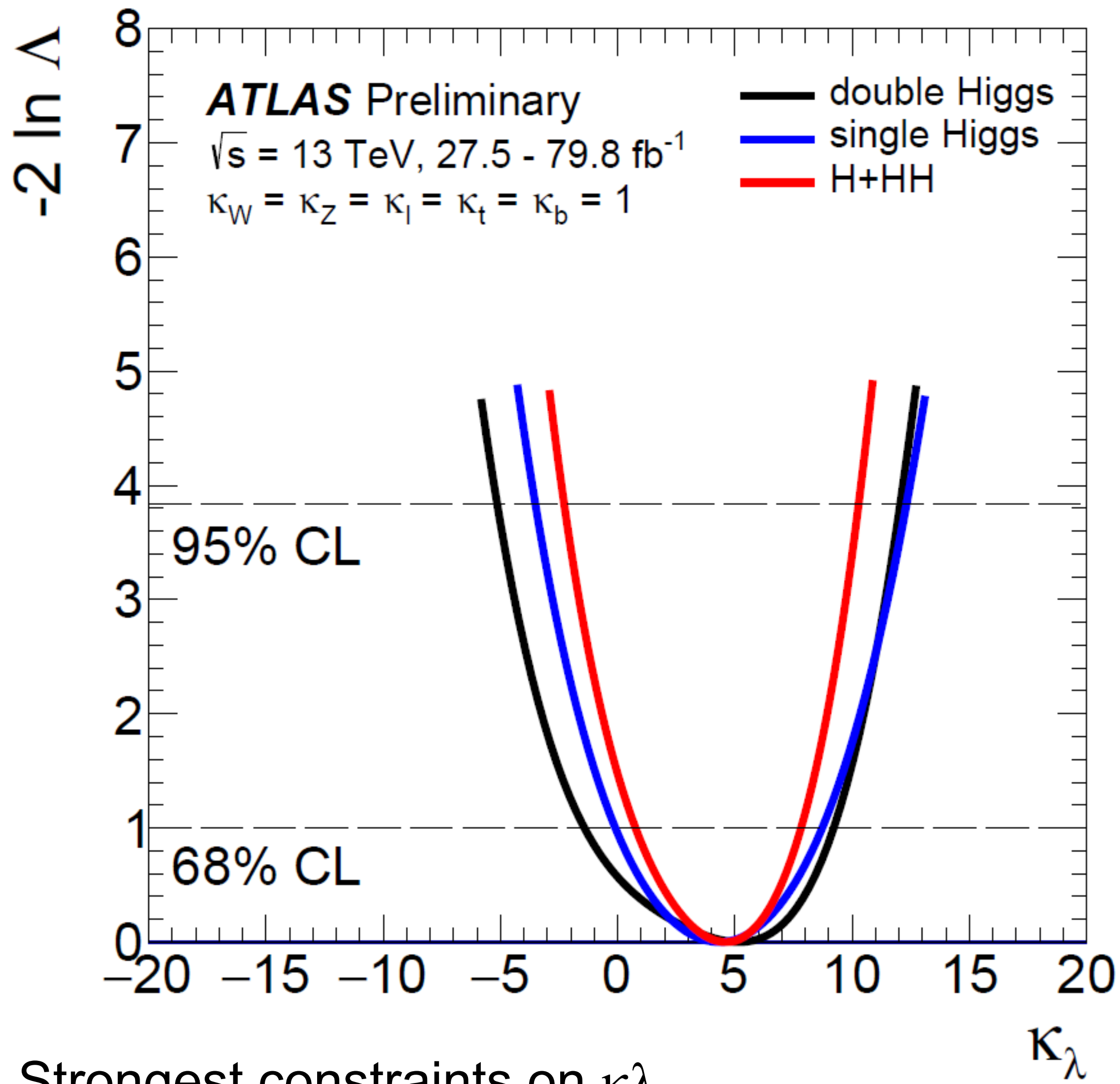






H+HH Combination (36-80/fb)

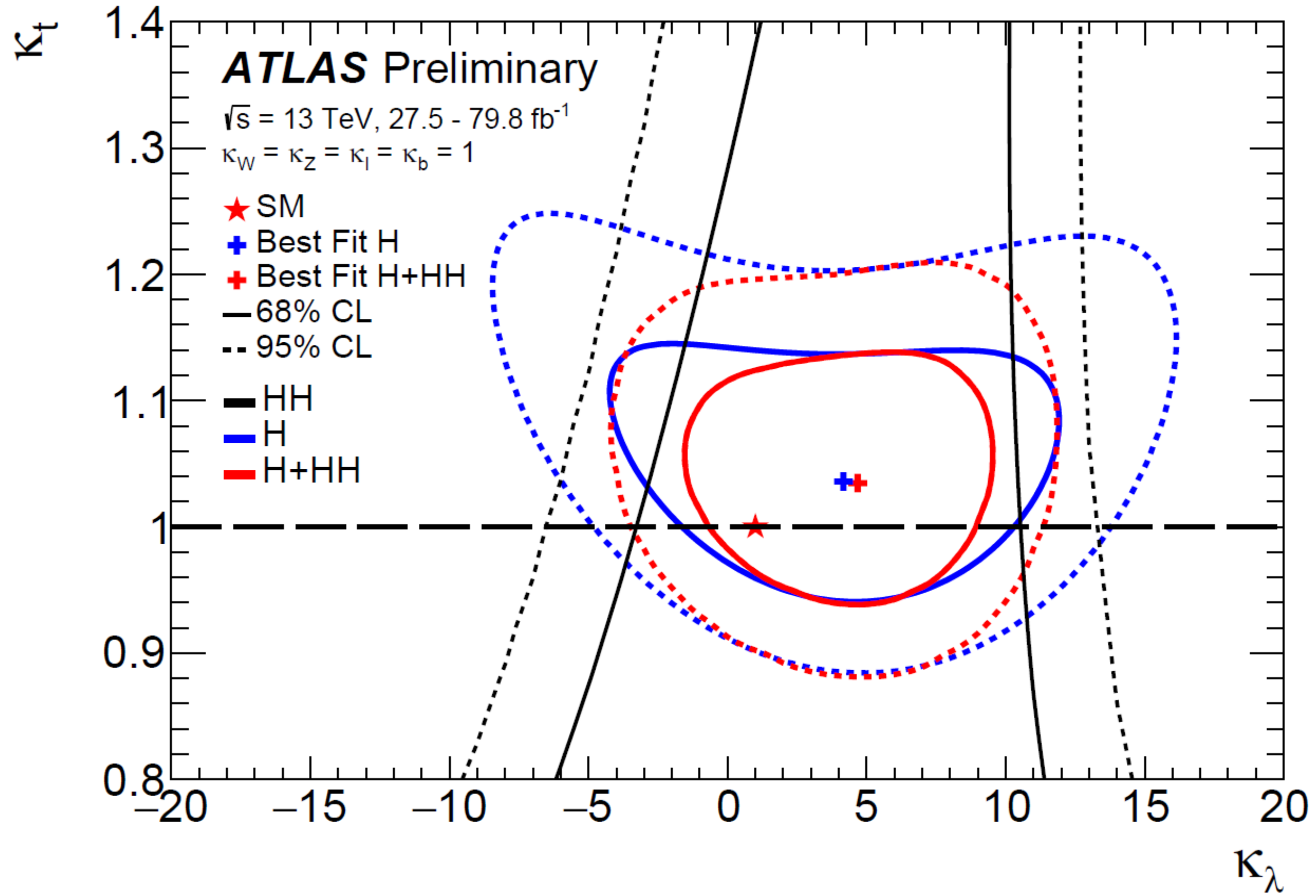
ATLAS-CONF-2019-049



Strongest constraints on κλ
assuming new physics will only impact κλ:

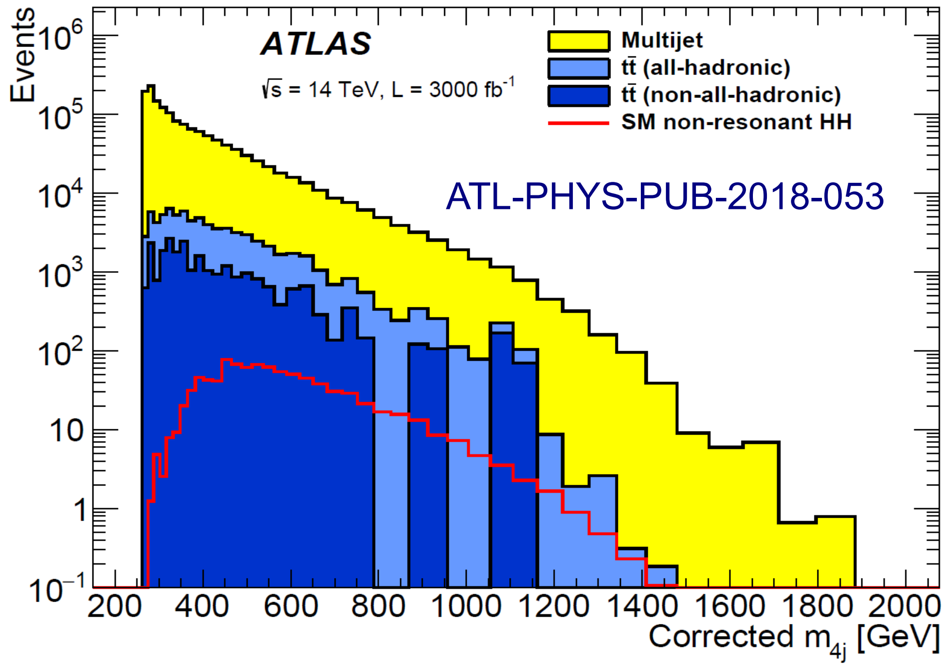
Observed:	$-2.3 < \kappa\lambda < 10.3$
Expected:	$-5.1 < \kappa\lambda < 11.2$
HH-only expected:	$-5.8 < \kappa\lambda < 12.0$

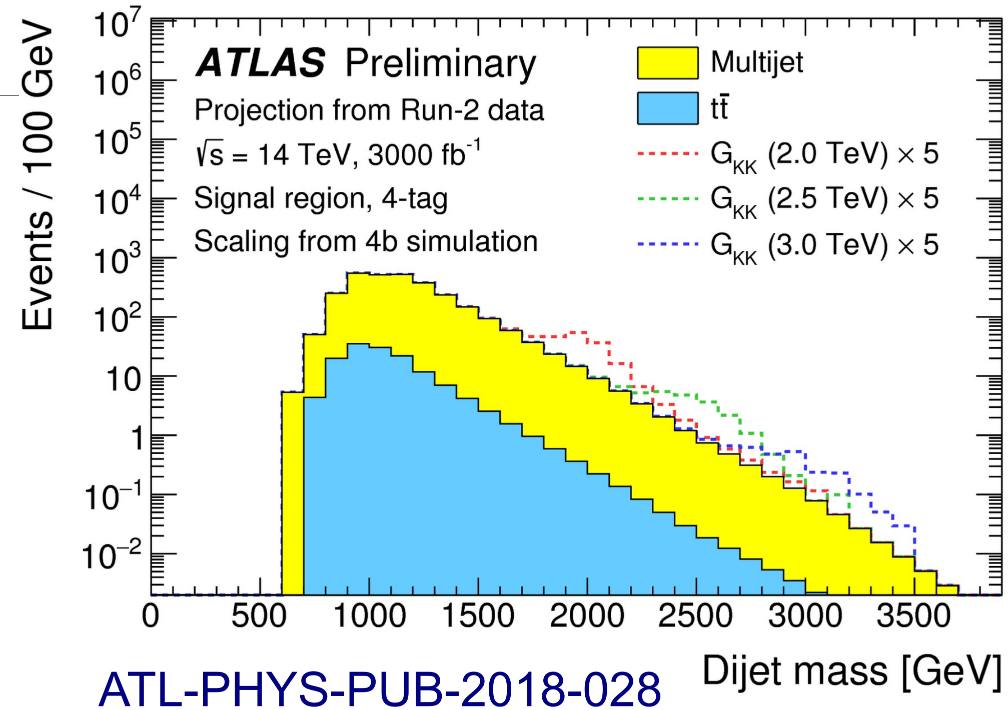
HH alone cannot simultaneously constrain κλ and κt
But H+HH combination can constrain both parameters



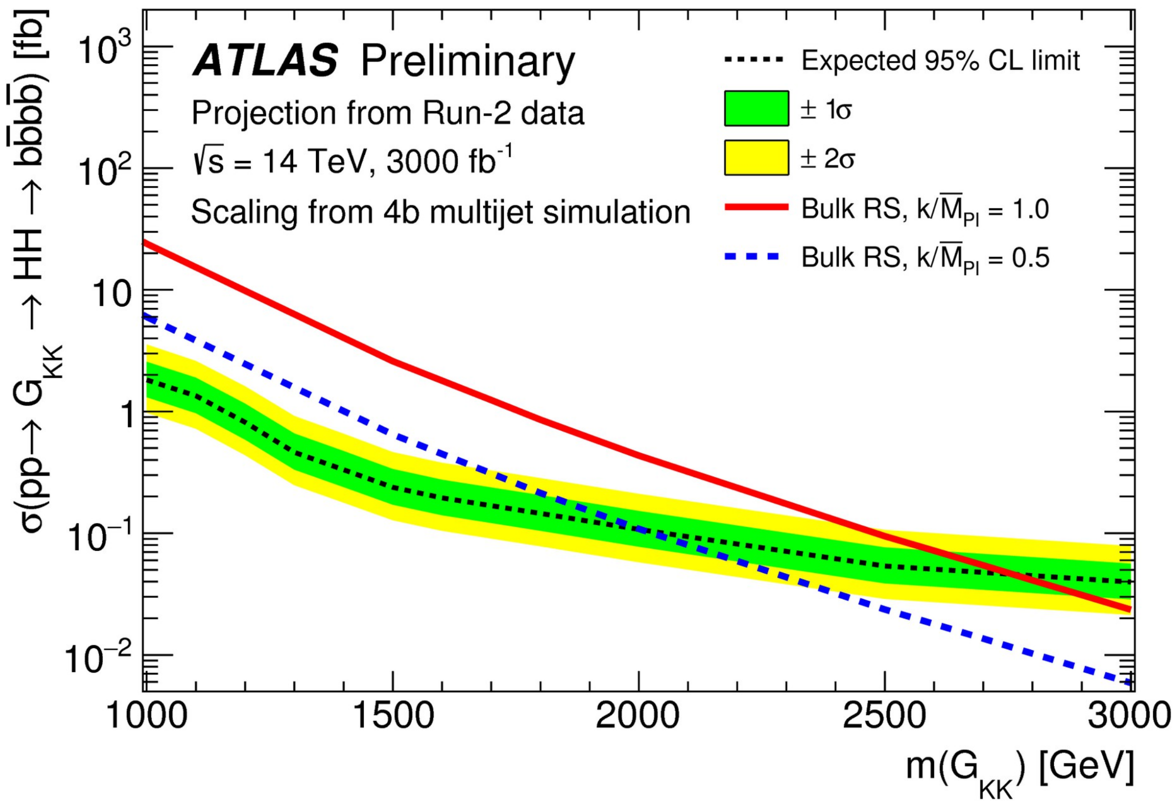
Profiling the other coupling modifiers results in less stringent constraints

HL-LHC: HH → bbbb





ATL-PHYS-PUB-2018-028



Extrapolation of the 36/fb analysis to 14 TeV, 3/ab *(top),* assuming 8% higher b-tagging efficiency.
In future runs, the minimal pT threshold of the jet triggers willl increase. A trigger pT increase from 40→75 GeV is equivalent to halving the dataset size. The trigger is a major challenge for this channel, along the difficulties of estimating the large multijet background.

Prospects for the boosted resonant search *(right):* based on extrapolations of the 36/fb analysis but with corrections to account for 13 → 14 TeV changes and HL-LHC b-tagging at <μ>=200 GeV