Results of Searching for HH Production with the ATLAS Experiment

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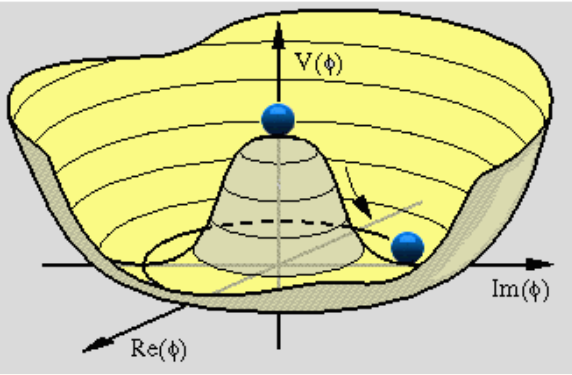
ATLAS EXPERIMENT

Probing Higgs potential



- The Higgs potential is introduced in SM. It has the following form when expanding the field around the ground state:

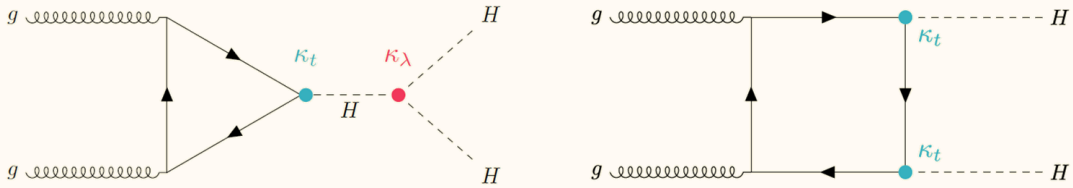
$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda v H^3 + \cdots$$

  - the 2nd term is the mass term, indicating a physical particle, the Higgs boson, which has been discovered 10 years ago
  - the 3rd term is the Higgs self-interaction terms
- HH production allows direct probing of the Higgs boson self-interaction thus probing the shape of Higgs potential
- The deviation from the SM predicted self-interaction could indicate new physics

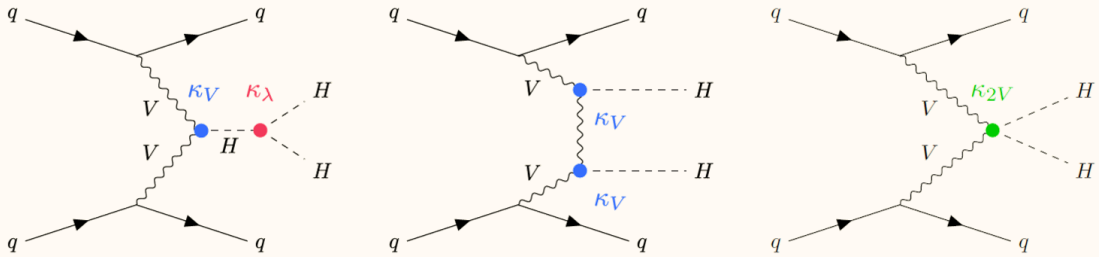
Higgs boson pair production at the LHC

- Di-Higgs production processes at the LHC are predicted by the SM

  - Gluon-gluon fusion
    - $\sigma_{ggF}^{SM} \simeq 31\ fb\ [13\ TeV]$
    - the dominant mode
    - two diagrams interferes destructively



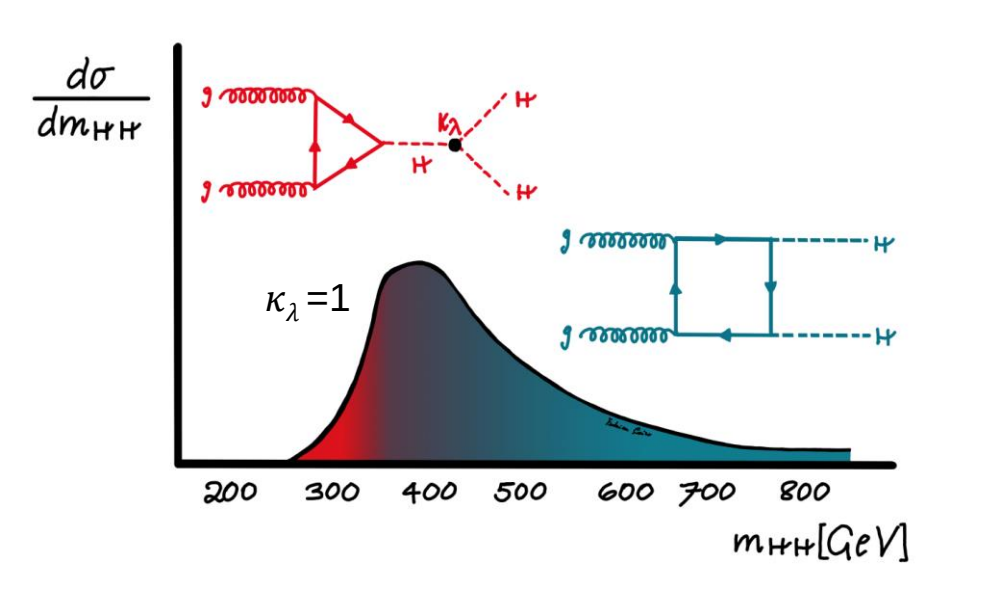
  - Vector-boson fusion
    - $\sigma_{VBF}^{SM} \simeq 1.7\ fb\ [13\ TeV]$
    - the second dominant mode



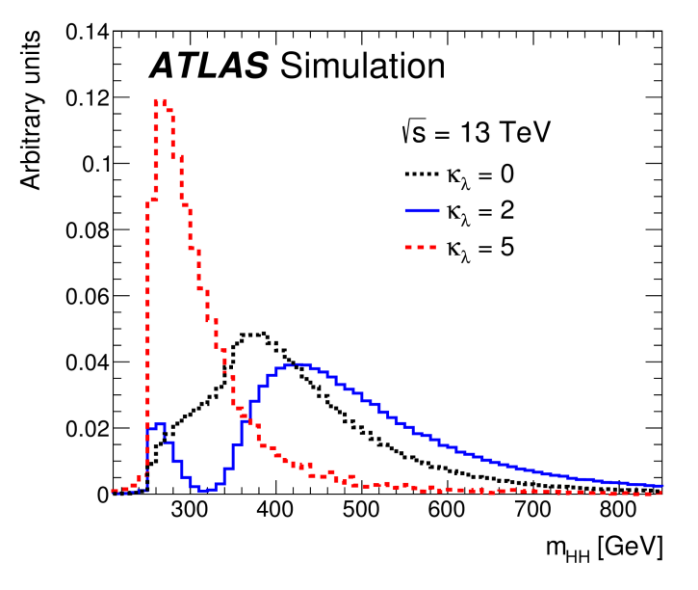
  - Associated productions, HHV, HHtt
    - with much smaller production cross-sections

SM HH mass distribution

- Particles from the HH production in the self-interaction process are soft
  - Challenging for hadronic triggers and detector object reconstruction/identification!
- $\kappa_\lambda \neq 1$ modifies the cross-section and kinematical properties of HH events



Physics Briefing: Twice the Higgs, twice the challenge



Combination of searches for Higgs boson pairs in pp collisions at s=13TeV with the ATLAS detector

Higgs boson pair decay channels

- Each Higgs boson decays to one of the bb/WW/gg/$\tau\tau$/ZZ/$\gamma\gamma$ final states
- Different channels have different detection opportunities/challenges
  - results from bbbb, bb$\tau\tau$, bb$\gamma\gamma$ are presented today, which providing the best sensitivity to HH production

	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%

by Katharine Leney

HH → *bbbb*

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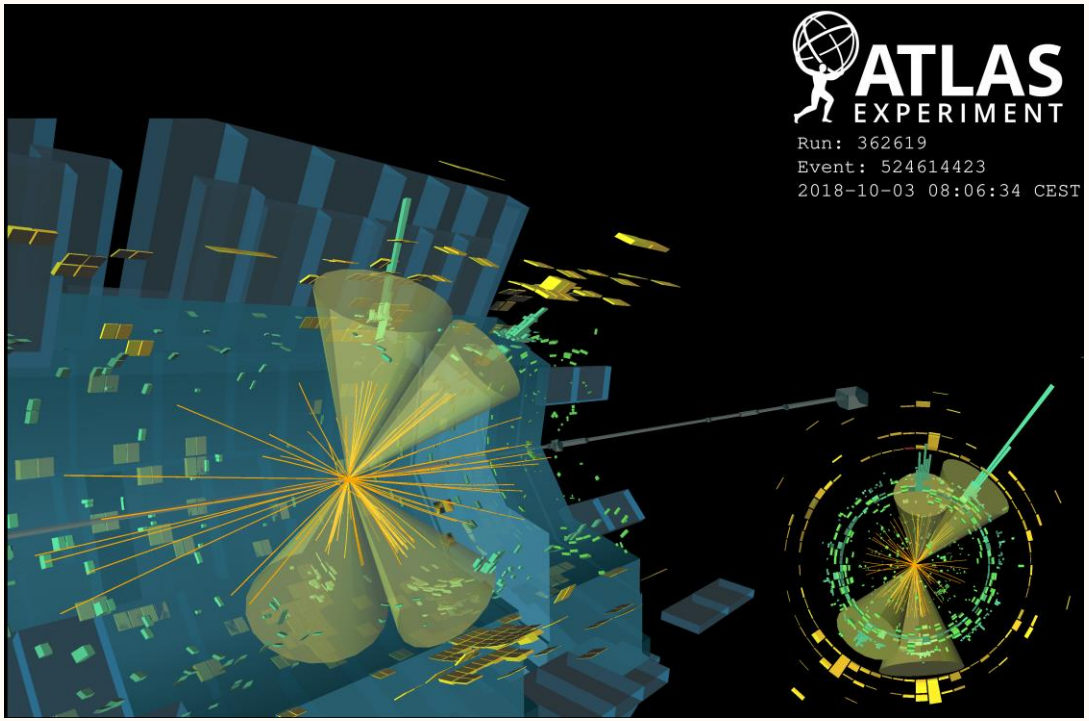
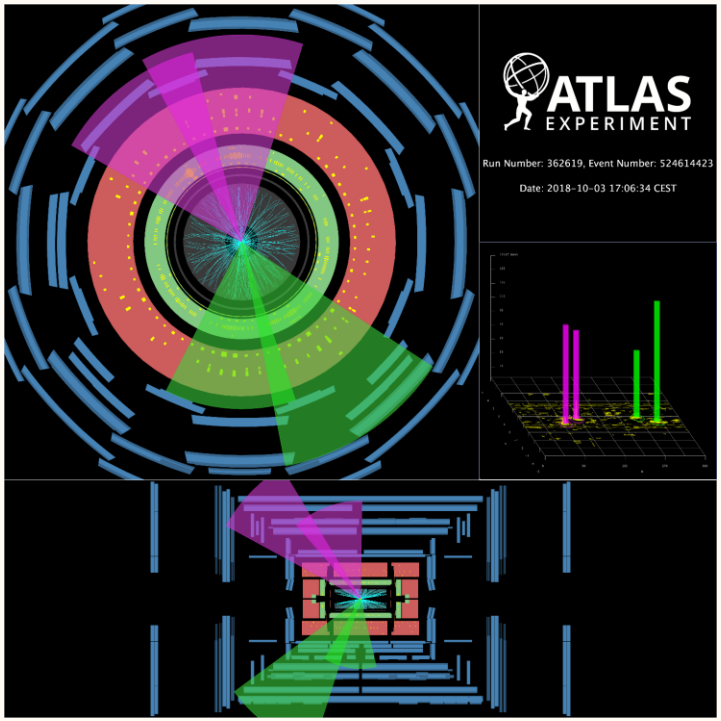
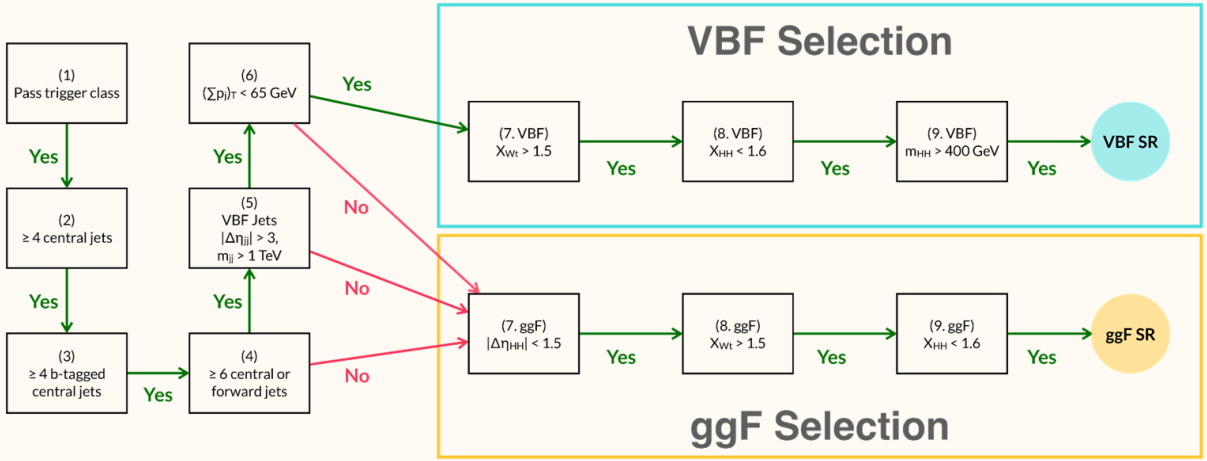


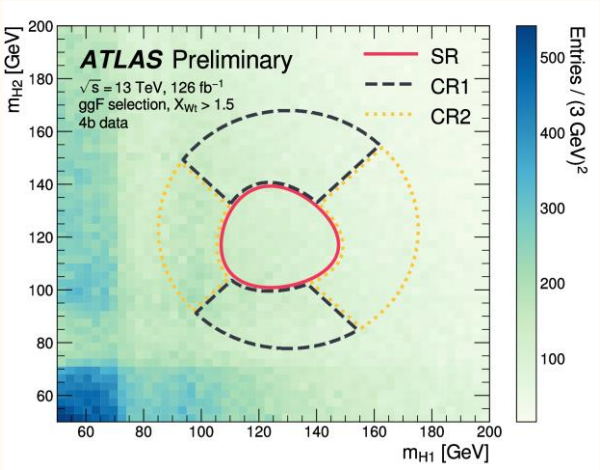


- highest branching ratio
- sensitive to HH events with large transverse momentum p_T^H
- large multi-jet background

$HH \rightarrow bbbb$

- Events considered are selected online with the “2b2j” and “2b1j” trigger signature
- Selection & reconstruction of 4b system starts from the requirement to have at least 4 jets with $p_T > 40\ GeV$, at least 2 of which are b-jets
- Signal region (SR) is set to have two b-jets pairs with good compatibility with a Higgs boson
- Data-driven background model based on 2 b-tags CR event re-weighting
  - Re-weighting function derived with machine-learning techniques in CRs around the SR

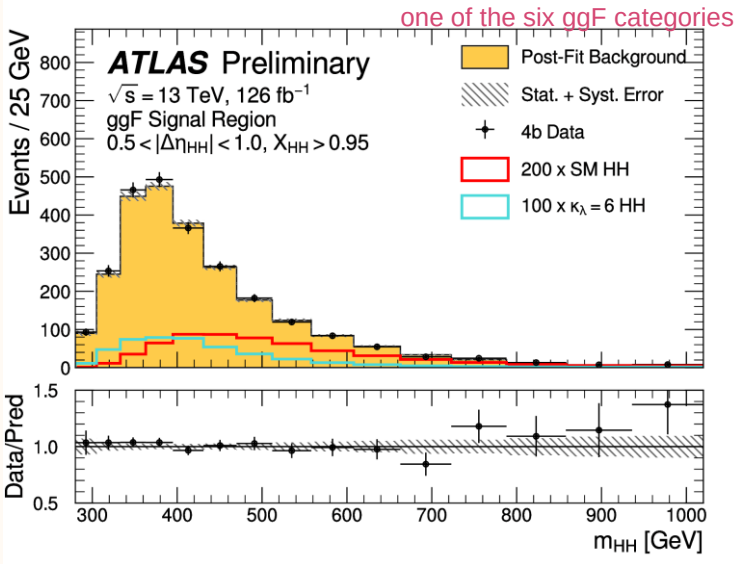




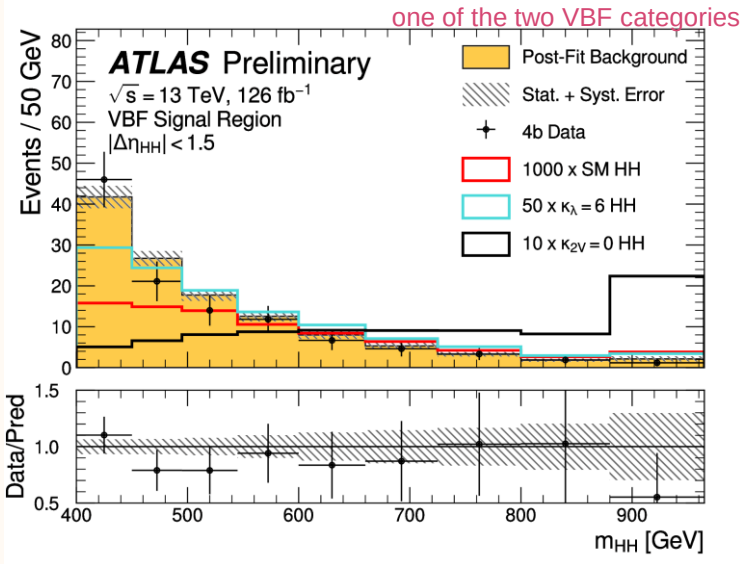
HH → $bbbb$: Results in SM HH production search

- m_{HH} used as the discriminating variable for fitting

one of the six ggF categories



one of the two VBF categories



Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
κ_λ	-4.6	10.8	-3.9	11.1
κ_{2V}	-0.05	2.12	-0.03	2.11

	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

HH → $bb\tau\tau$

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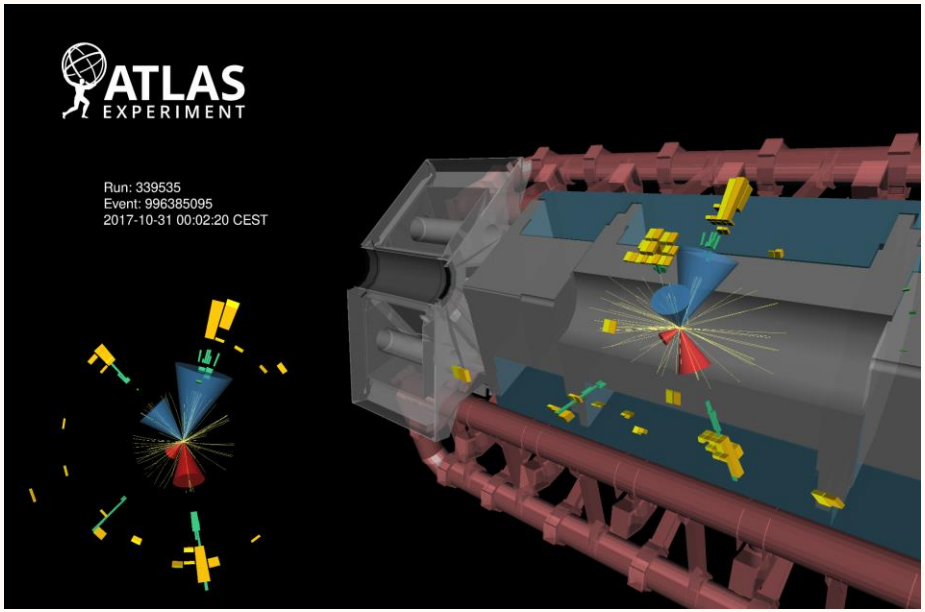
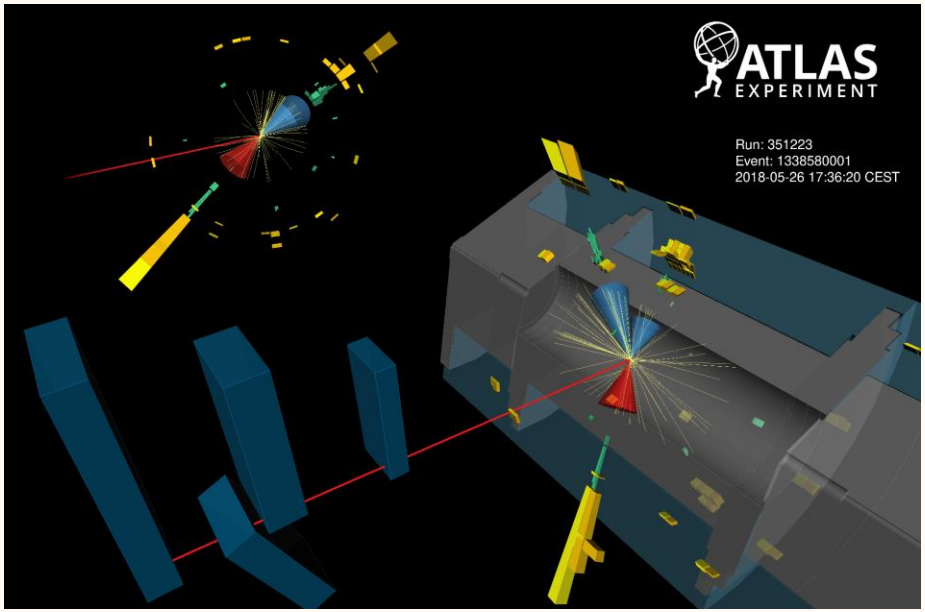




- Intermediate branching fraction
- Relatively clean final states
- Moderate backgrounds

$\mathrm{HH} \rightarrow bb\tau\tau$

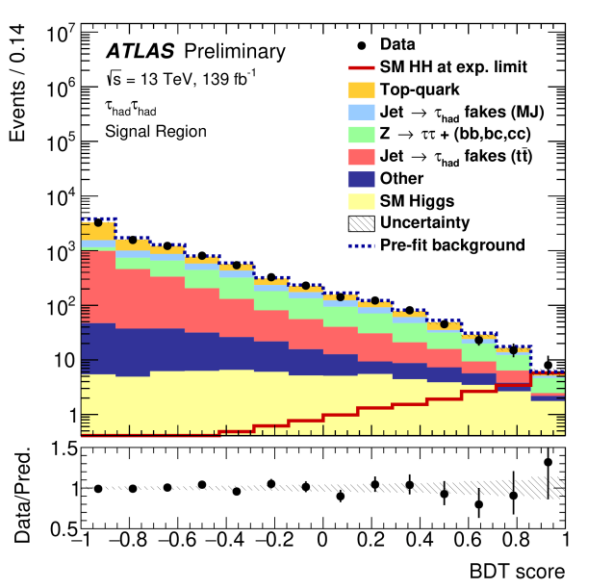
- Signal regions recorded with different trigger strategies

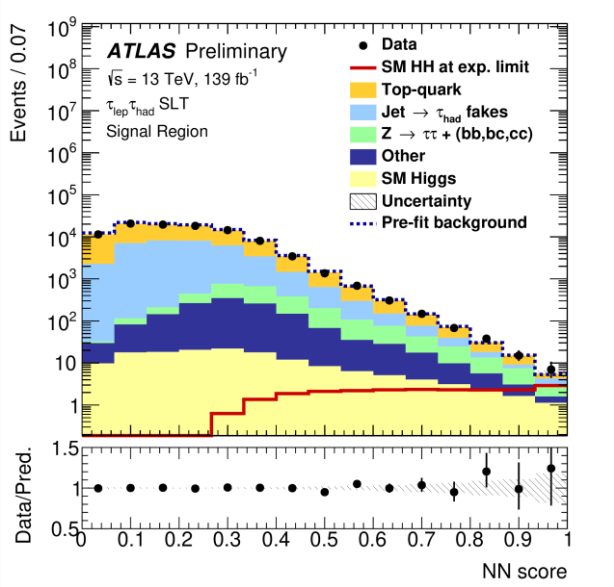
Category	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	
Trigger	single τ_{had} triggers (STTs)	di-τ_{had} triggers (DTTs)	single-lepton triggers (SLTs)	lepton-plus-τ_{had} triggers (LTTs)
Region	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ - SLT	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ - LTT

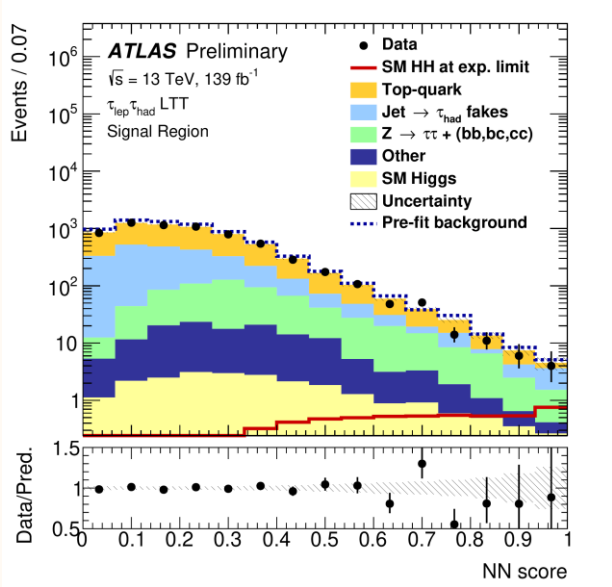
- Background modeling
  - combination of simulation-based and data-driven techniques
- The analysis is dominated by statistical uncertainties

HH → $bb\tau\tau$: Results in SM HH production search

- MVA scores used as discriminating variable for fitting







		Observed	$-2\,\sigma$	$-1\,\sigma$	Expected	$+1\,\sigma$	$+2\,\sigma$
$\tau_{\text{had}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{\text{lep}}\tau_{\text{had}}$	$\sigma_{\text{ggF+VBF}}$ [fb]	265	124	167	231	322	432
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{\text{ggF+VBF}}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{\text{ggF+VBF}}/\sigma^{\text{SM}}_{\text{ggF+VBF}}$	4.65	2.08	2.79	3.87	5.39	7.22

MVA features

Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{\text{T}}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_{T}		✓	
m_{T}^{W}		✓	
$E_{\text{T}}^{\text{miss}}$		✓	
$\mathbf{p}_{\text{T}}^{\text{miss}}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
S_{T}			✓

- No significant data excess over predicted background
- Cross-section limits are set as listed in the table

HH → $bb\gamma\gamma$

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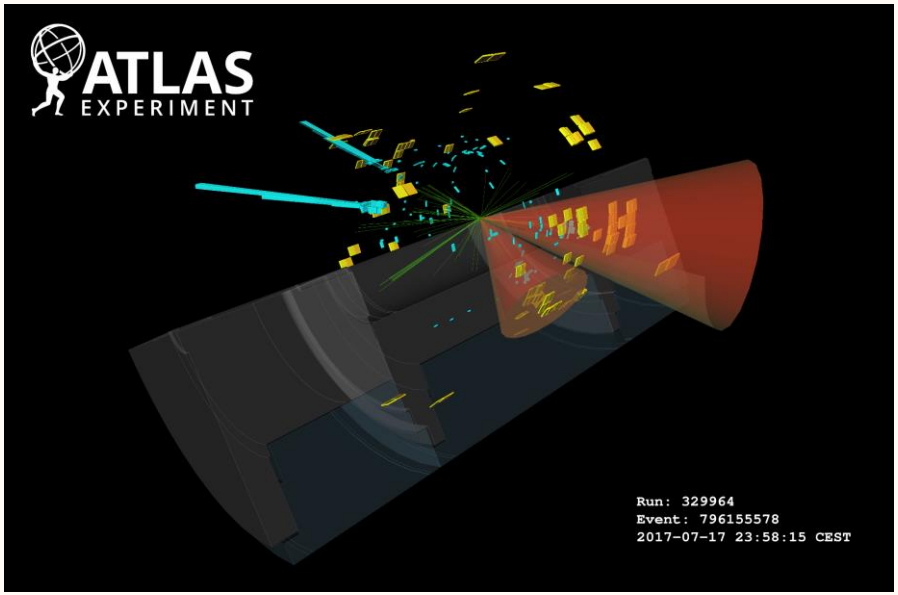
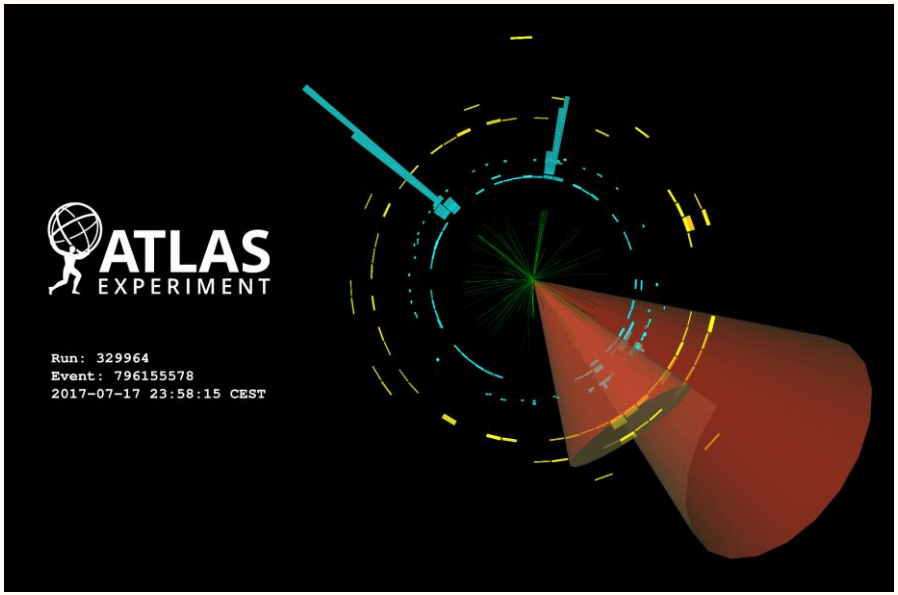
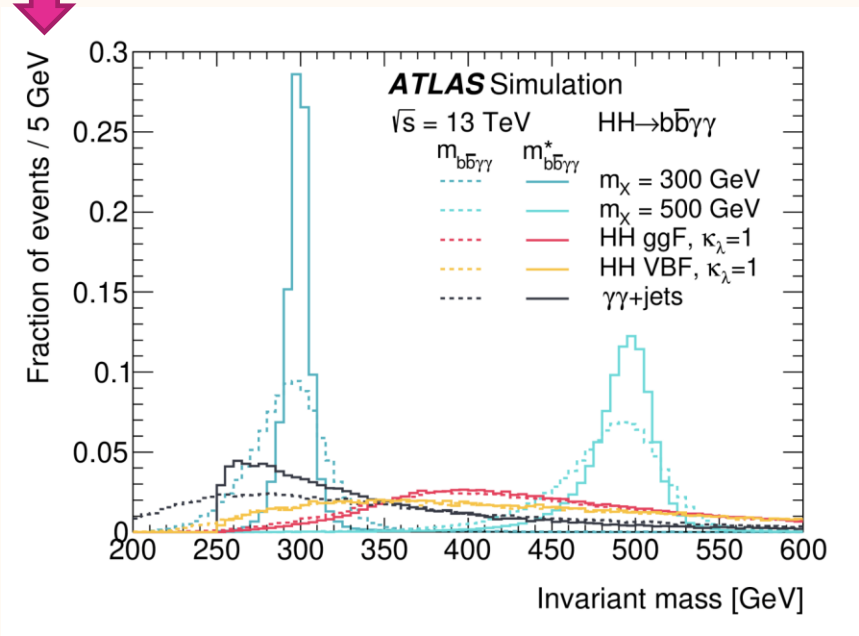




- Small branching fraction
- Very clean signature → excellent $m_{\gamma\gamma}$ resolution with small backgrounds
- Enhanced sensitivity at low m_{HH} → enhanced sensitivity to the Higgs boson self-interaction

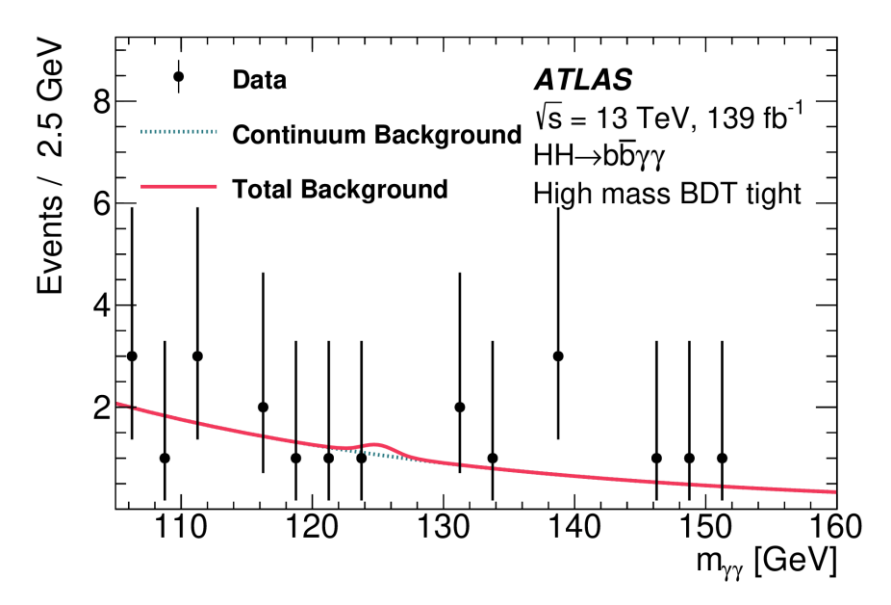
$\mathbf{HH} \rightarrow \boldsymbol{bb\gamma\gamma}$

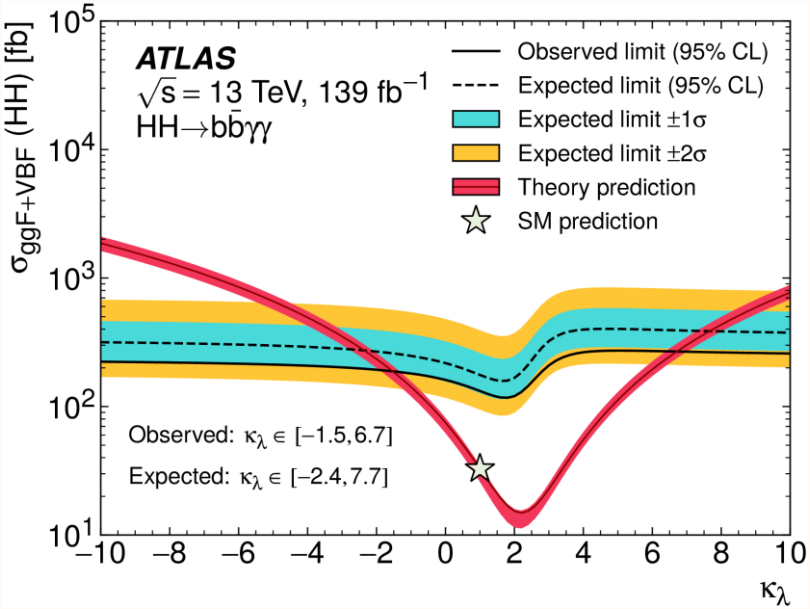
- Event selection
  - events considered use a di-photon trigger and exactly 2 b-jets
  - after common preselection, extra different selections are applied for resonant/non-resonant studies
- Events category based on $m^*_{bb\gamma\gamma}$ and MVA scores
  - $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250\ \mathrm{GeV}(\sim 2\mathrm{m_H})$
- Signal/background modeling
  - H / HH shape from simulation
  - continuum background shape from data
- The analysis is dominated by statistical uncertainties



$HH \rightarrow bb\gamma\gamma$: Results in SM HH production search

- $m_{\gamma\gamma}$ used as discriminating variable for fitting



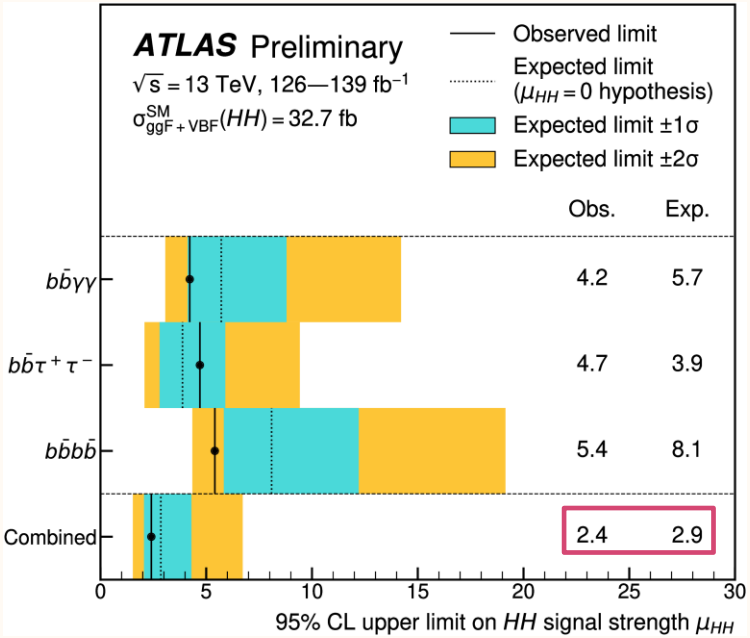


observed (expected) upper limit at 95% CL on the signal strength

➢ 4.2 (5.7) times the SM prediction

HH combination results (95% CL)

limits on $\sigma^{HH}_{ggF+VBF}$



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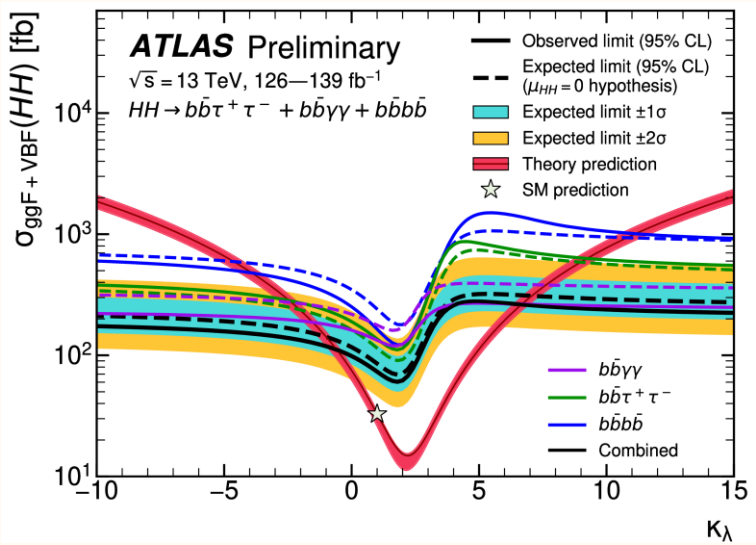
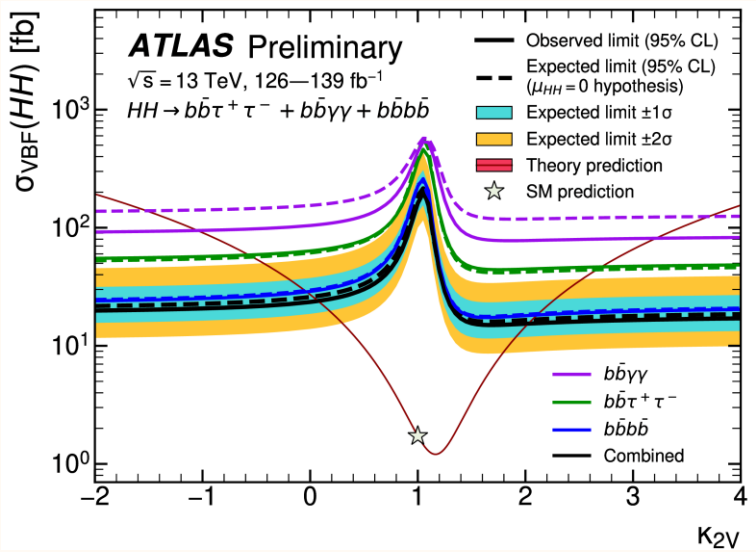
limits on κ_λ



limits on κ_{2V}



HH resonant results (95% CL)

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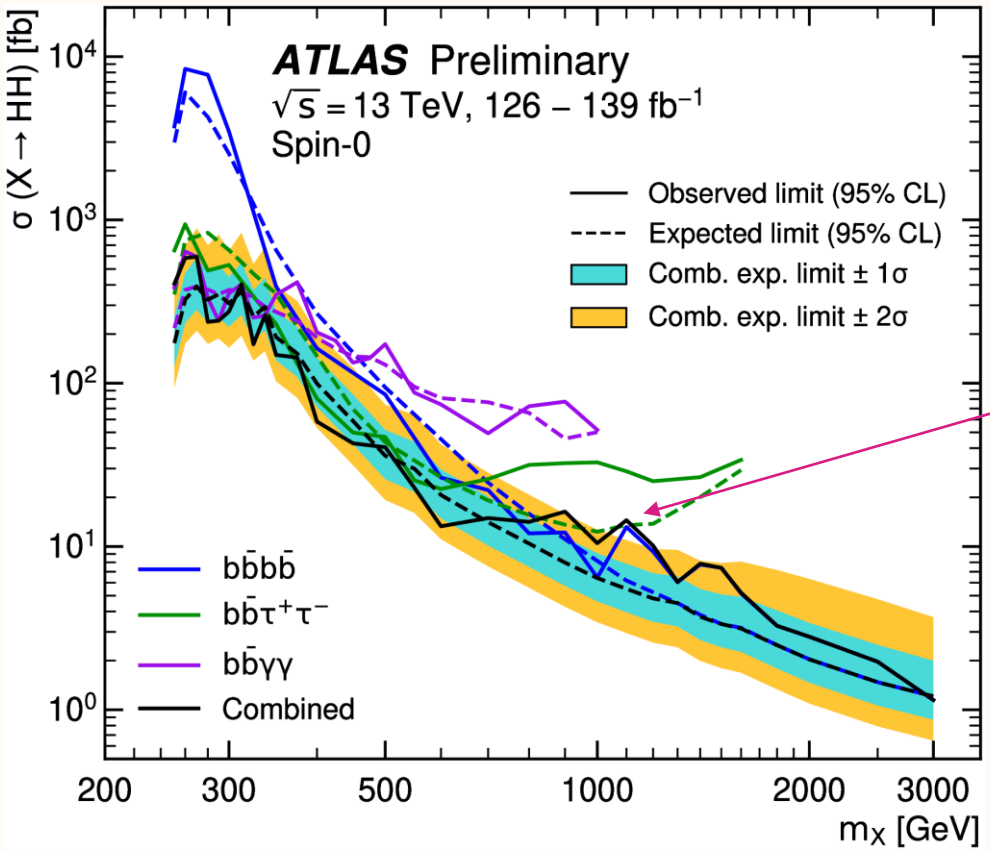
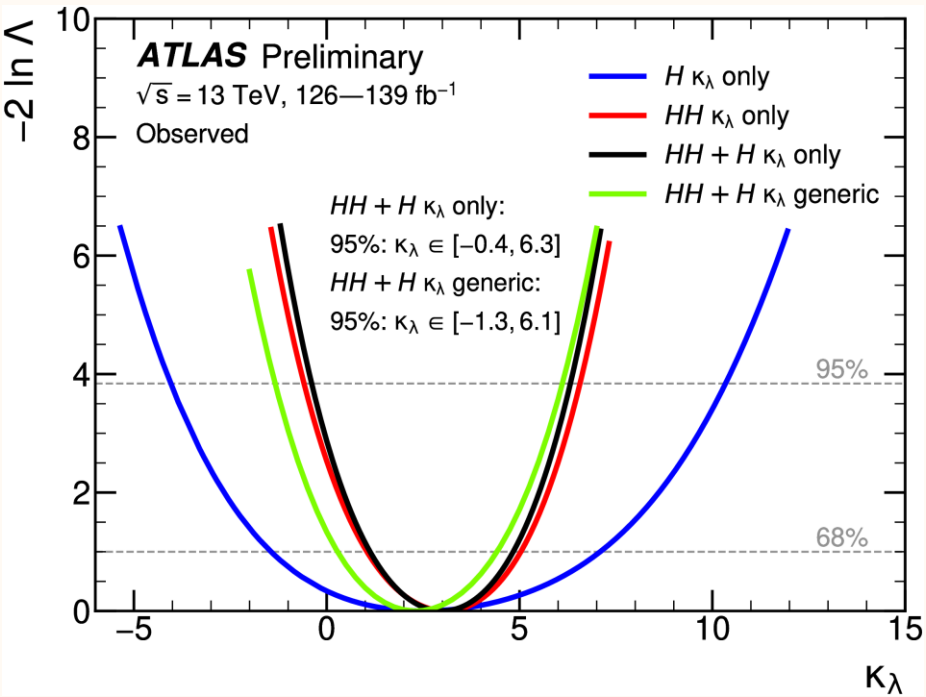
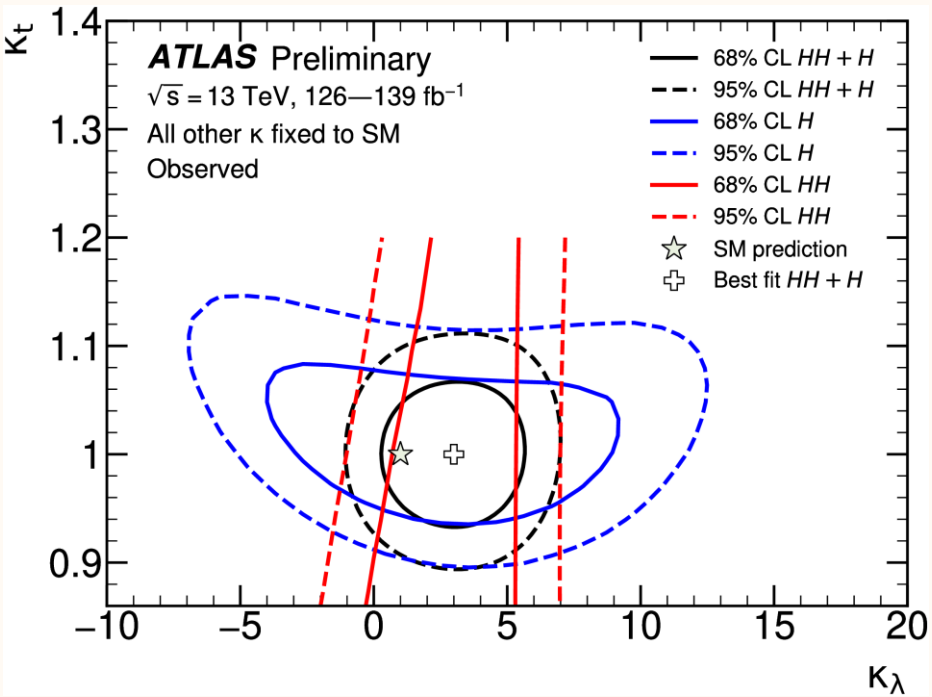


significance
- local: 3.2 σ
- global: 2.1 σ

HH+H: constraints on κ_λ

- Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:
  - HH searches only, single-H measurements only, or their combinations





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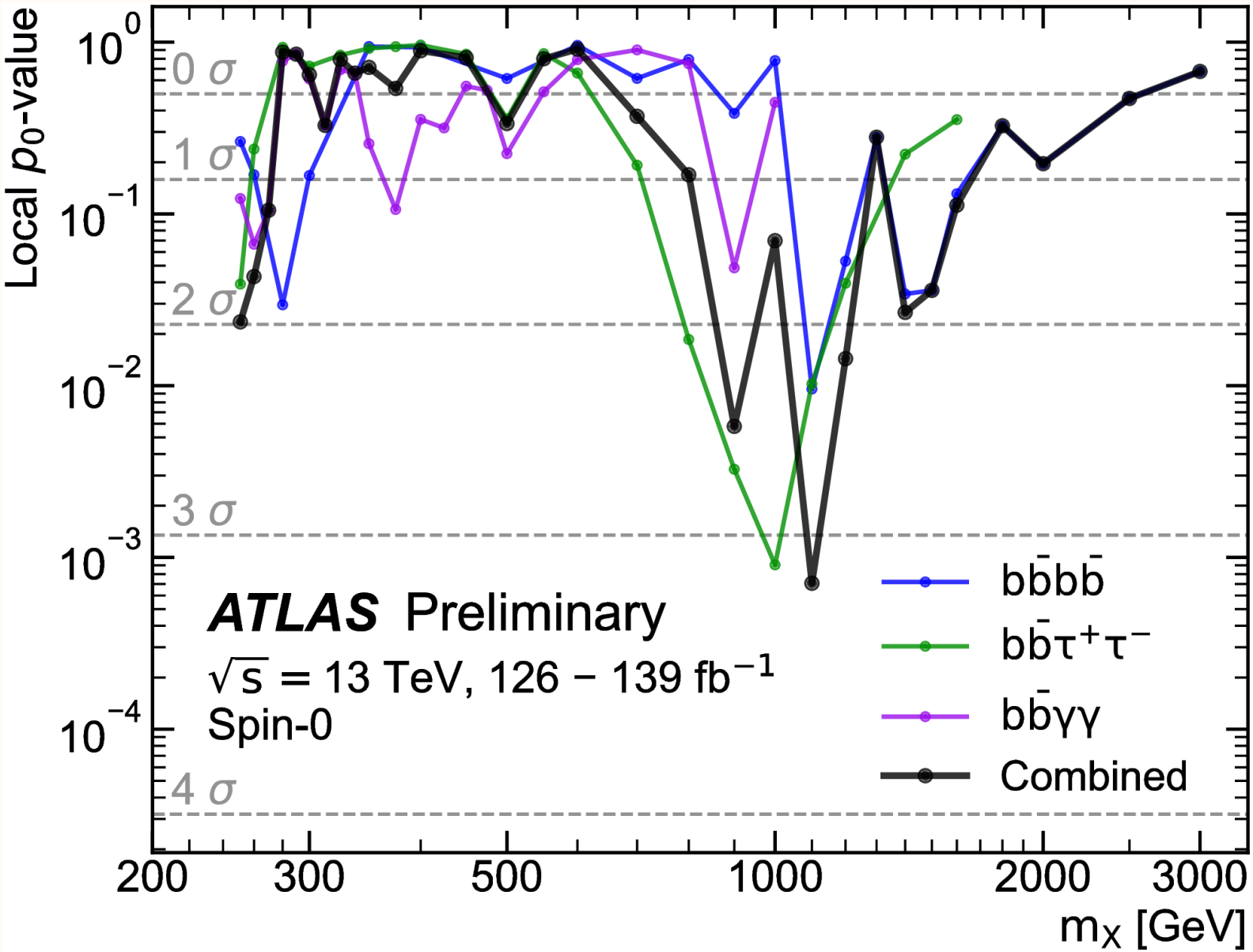
- Results
  - Profile κ_λ only: $-0.4 < \kappa_\lambda < 6.3$ (95% CL)
  - Profile $\kappa_\lambda, \kappa_t, \kappa_V, \kappa_b, \kappa_\tau$: $-1.3 < \kappa_\lambda < 6.1$ (95% CL)

Summary

- Observation and measurement of the HH production is crucial to probe the shape of the SM Higgs potential and search for new physics BSM
- The combined searching results from the $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$ channels set the observed (expected) limits of the σ_{HH} of 2.4 (2.9) times the SM prediction at 95% CL based on 139 fb^{-1} data collected by the ATLAS experiment in Run2.
  - The Higgs self-interaction allowed κ_λ range is also set at 95% CL
    - $\kappa_\lambda \in [-0.6, +6.6]$ (HH combination)
    - $\kappa_\lambda \in [-0.4, +6.3]$ (HH + H combination)
- Looking forward to Run3 and future HL-LHC programs to increase the data sets to probe the Higgs potential structure with much better sensitivity
  - Run 3: factor of ~3
  - HL-LHC: factor of ~20

Back-up

HH resonant (95% CL) : p0-value



HL-LHC studies: $bb\gamma\gamma + bb\tau\tau$

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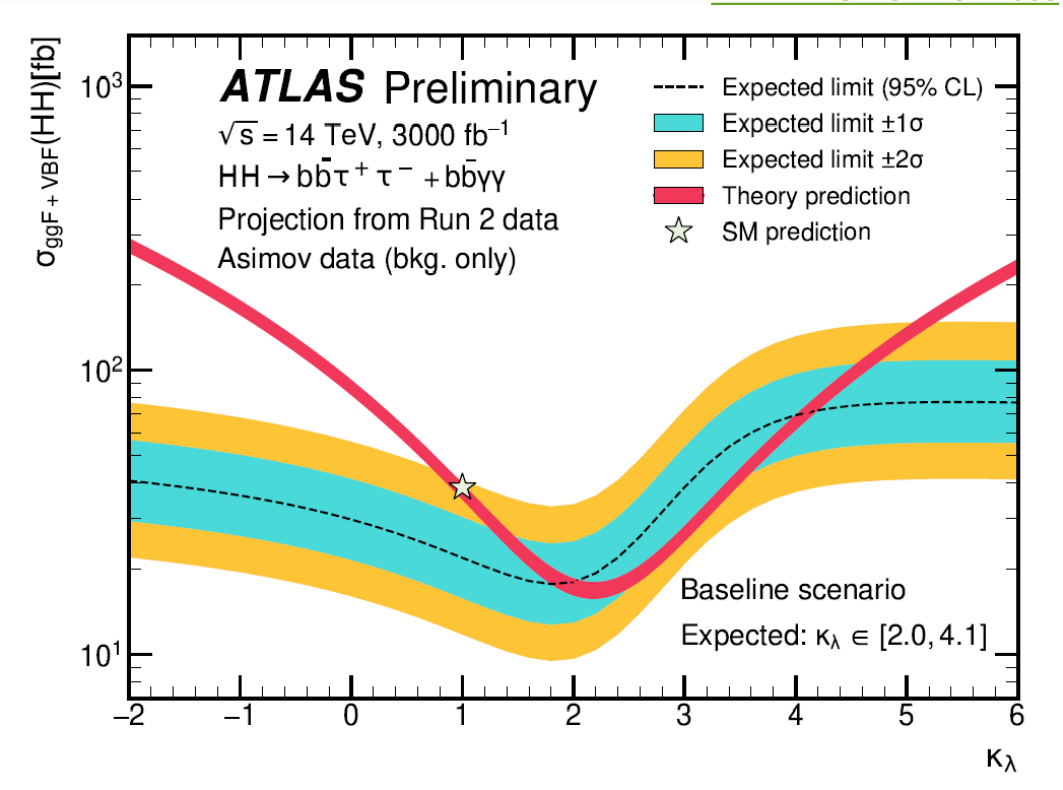

Uncertainty scenario	95% CL limits on κ_λ from cross-section scan		
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination
No syst. unc.	[1.2, 4.2]	[2.4, 4.5]	[2.6, 3.6]
Baseline	[1.1, 4.3]	[1.7, 5.4]	[2.0, 4.1]
Theoretical unc. halved	[0.1, 5.2]	[0.9, 6.2]	[1.2, 5.0]
Run 2 syst. unc.	[0.1, 5.3]	[0.6, 6.5]	[0.9, 5.1]