Searches for Higgs Boson Pair Production with the Full LHC Run 2 Dataset in ATLAS

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On behalf of the ATLAS Collaboration

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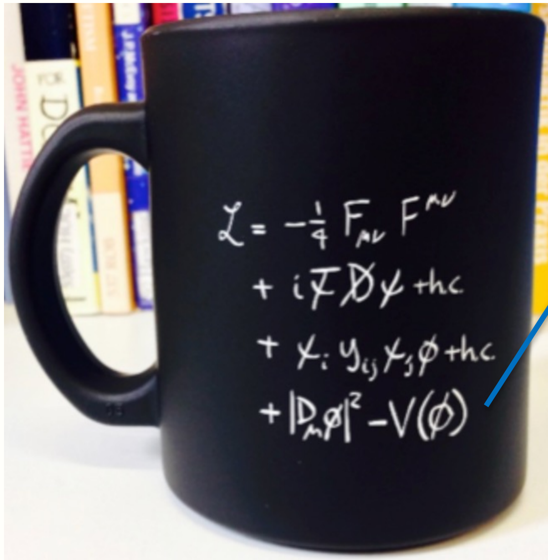
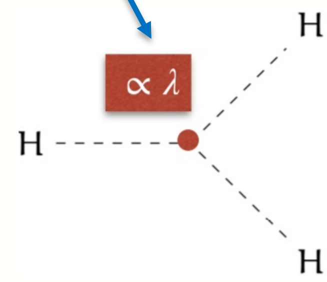
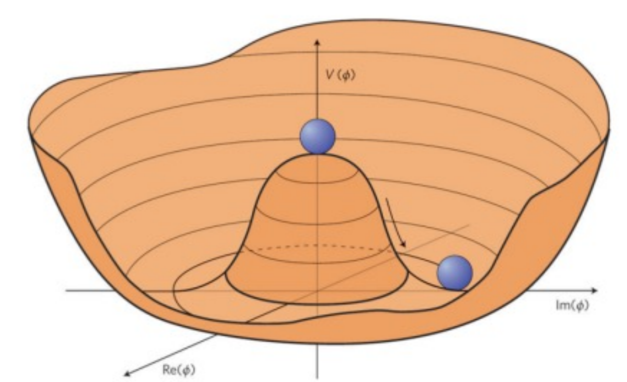
Physics Motivation



$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Direct access to λ in Higgs boson pair (HH) production
Standard Model (SM) prediction: λ = ~0.13

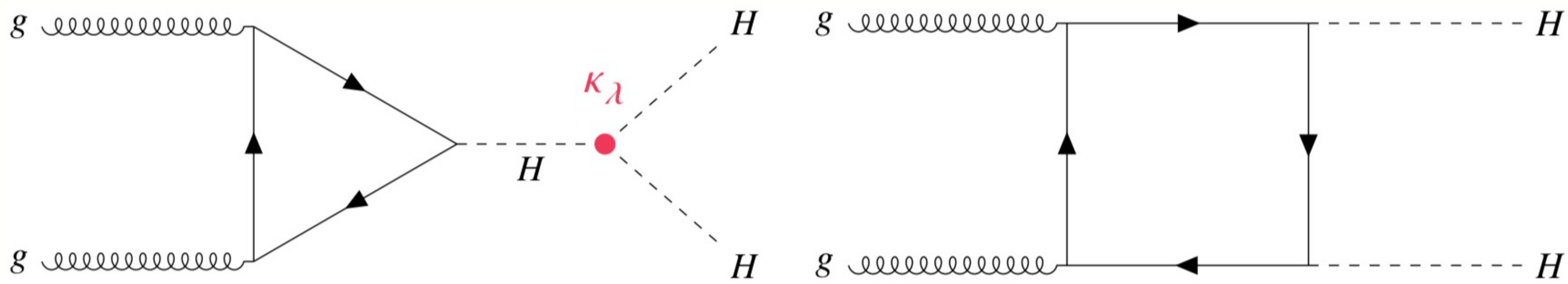




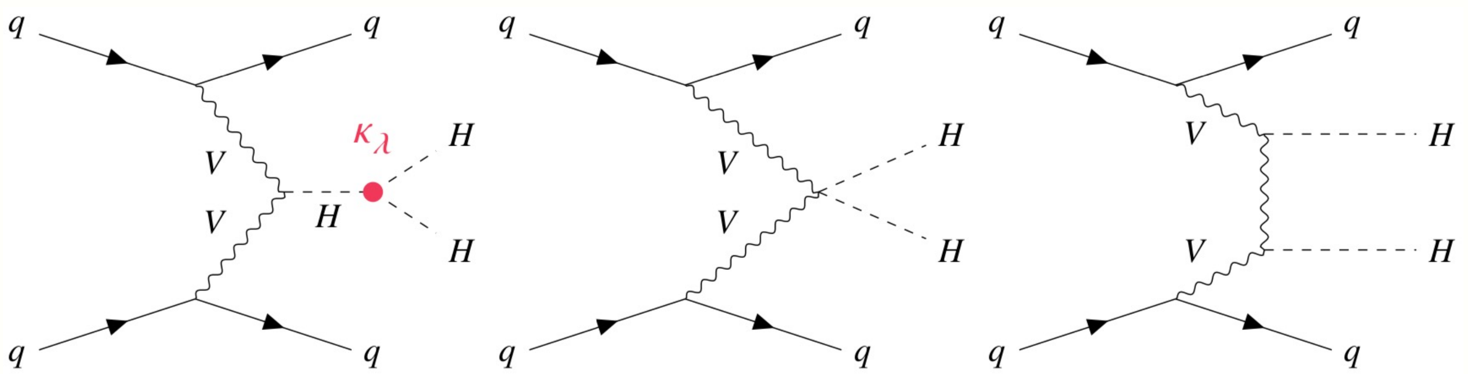
New physics can alter the Higgs boson self coupling λ, therefore measuring κ_λ ($\lambda_{HHH}/\lambda_{SM}$) via searches for HH production is important for studying the Higgs boson property and probing physics Beyond the SM (BSM)

SM Non-resonant HH Production

Gluon-gluon fusion (ggF) production mode: 31.05 fb



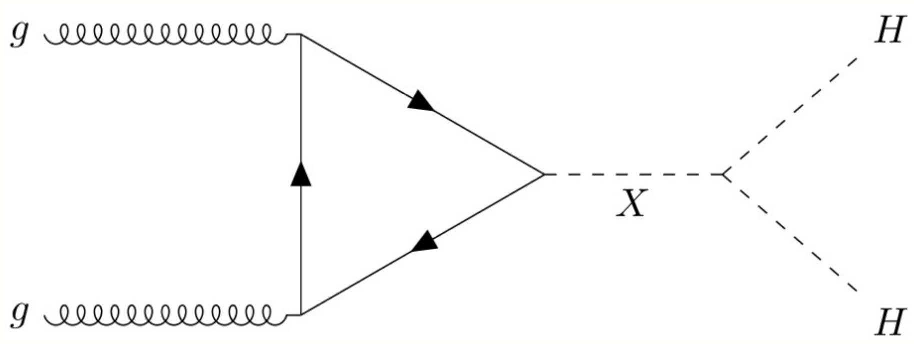
Vector boson fusion (VBF) production mode: 1.73 fb



New physics can appear as κ_λ != 1, which will have impact on σ_{HH} and kinematics

BSM Resonant HH Production

- Various BSM theories predict heavy resonances which can decay into Higgs bosons pair, such as
  - Spin-0 heavy scalars
  - Spin-2 gravitons from the Randall–Sundrum model
- Only ggF production mode is considered for the resonant searches in the talk today



HH Decay Channels

~4k HH events expected to be produced during Run 2
Complementarity and combination of various decay channels to maximize the sensitivity

Branching Ratio	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

- For the talk today, I will cover the latest results at ATLAS:
  - HH→bb$\tau\tau$ (non-resonant and resonant): ATLAS-CONF-2021-030
  - HH→bb$\gamma\gamma$ (non-resonant and resonant): ATLAS-CONF-2021-016
  - HH→bbbb (resonant): ATLAS-CONF-2021-035
  - HH combination: ATLAS-CONF-2021-052

Non-resonant HH Search

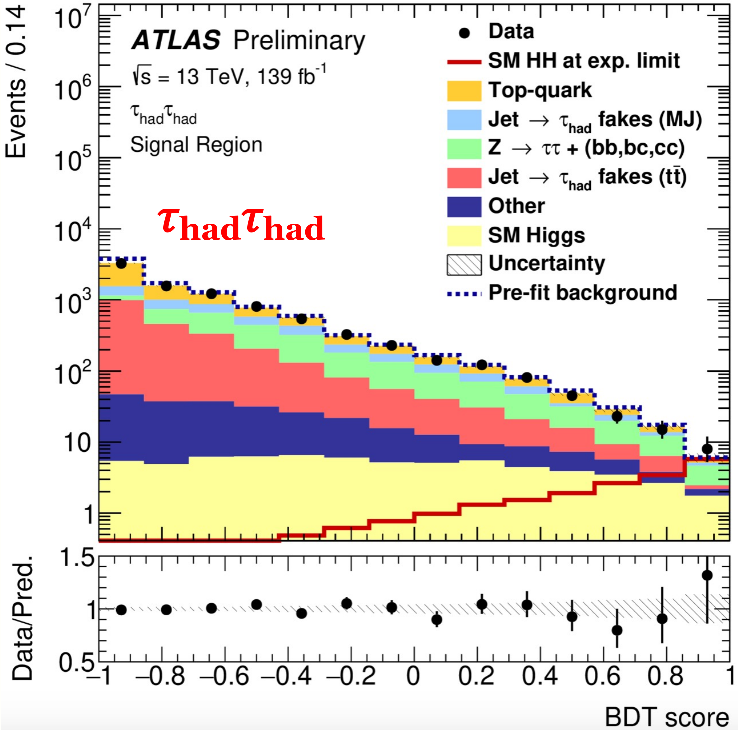
HH→bbττ Analysis

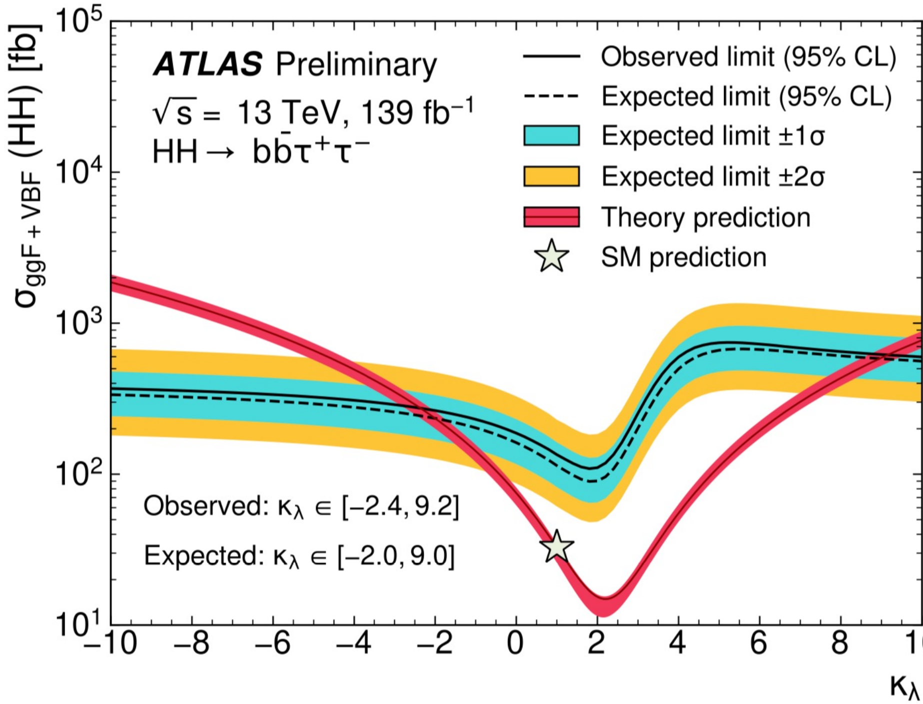
- 7.4% of the total HH branching ratio (BR): relatively clean signature and low background
- Signal signature: two b-jets (DL1r tagger, 77%) and $\tau_{had}\tau_{had}/\tau_{lep}\tau_{had}$ with opposite charge

Signal region	Tau/Lepton	Trigger
$\tau_{had}\tau_{had}$	2 hadronic τ	Single or Di-tau Trigger
$\tau_{lep}\tau_{had}$ SLT	1 hadronic τ + 1 e/μ	Single lepton trigger (SLT)
$\tau_{lep}\tau_{had}$ LTT	1 hadronic τ + 1 e/μ	Lepton+tau trigger (LTT)

- Real τ background from simulation; fake τ background estimated with data-driven methods
- Multivariate (MVA) method used for signal and background separation

Non-resonant HH→bbττ Results





Observed (expected) limit at 95% CL: 4.7 (3.9) × σ_{SM}
4x improvement over 36.1 fb^{-1} result (12.7 × σ_{SM})

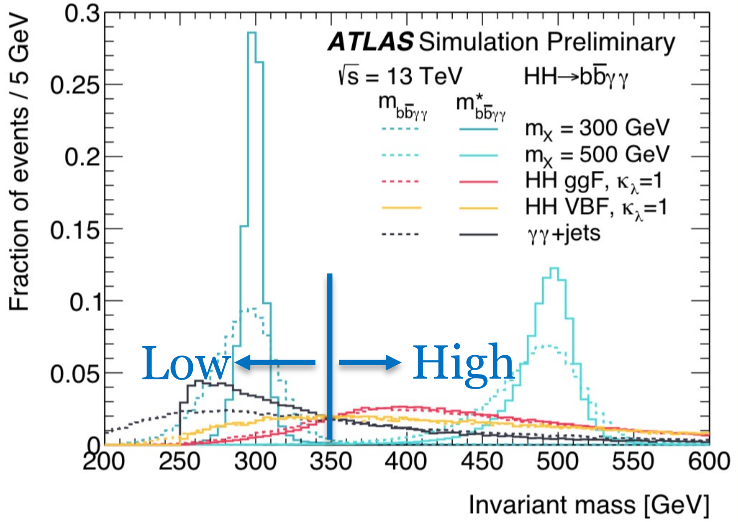
Observed (expected) constraint on κ_λ: $-2.4 \leq \kappa_\lambda \leq 9.2$ ($-2.0 \leq \kappa_\lambda \leq 9.0$)

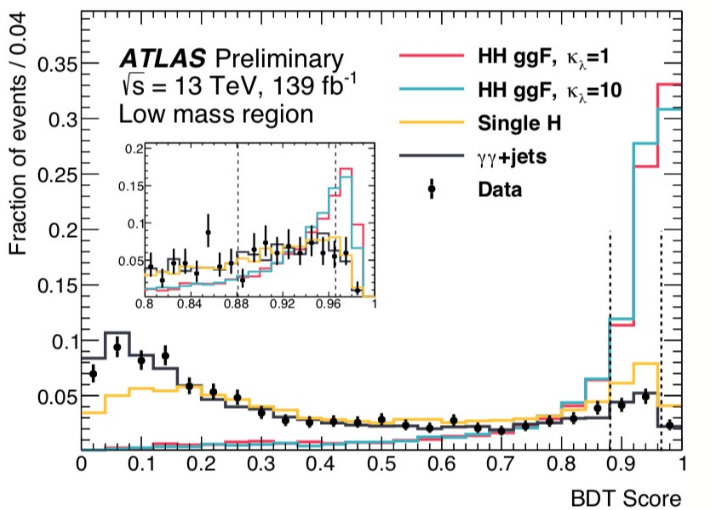
HH→bbγγ Analysis

- 0.26% of HH BR, H→$\gamma\gamma$ decay provides clean trigger, event selection and excellent m_H resolution
- 2 photons, 2 b-jets (DL1r, 77%)
- 105 GeV < $m_{\gamma\gamma}$ < 160 GeV → final discriminant for fitting
- Non-resonant: 4 categories (split by $m^*_{bb\gamma\gamma}$ at 350 GeV, and then split by BDT into tight and loose)

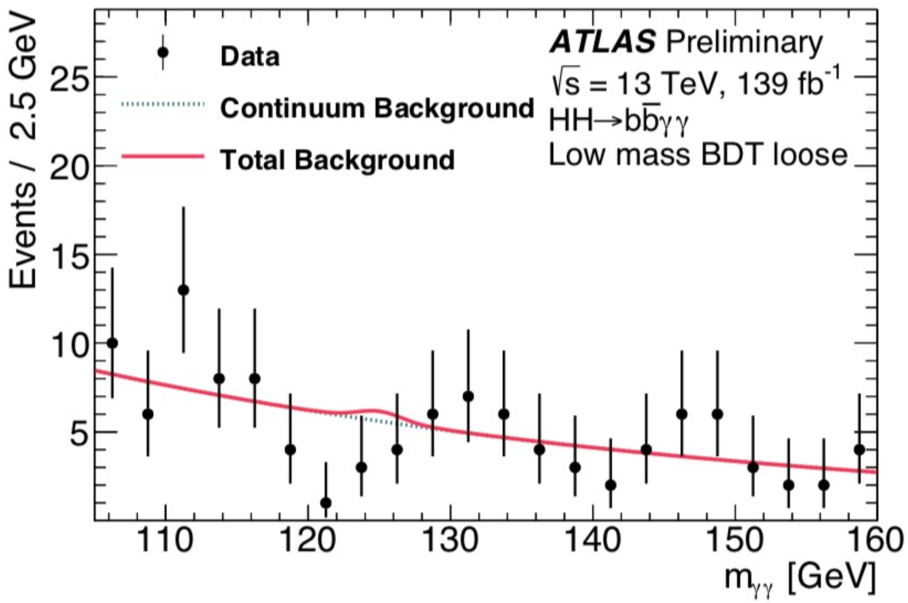
$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV}$$

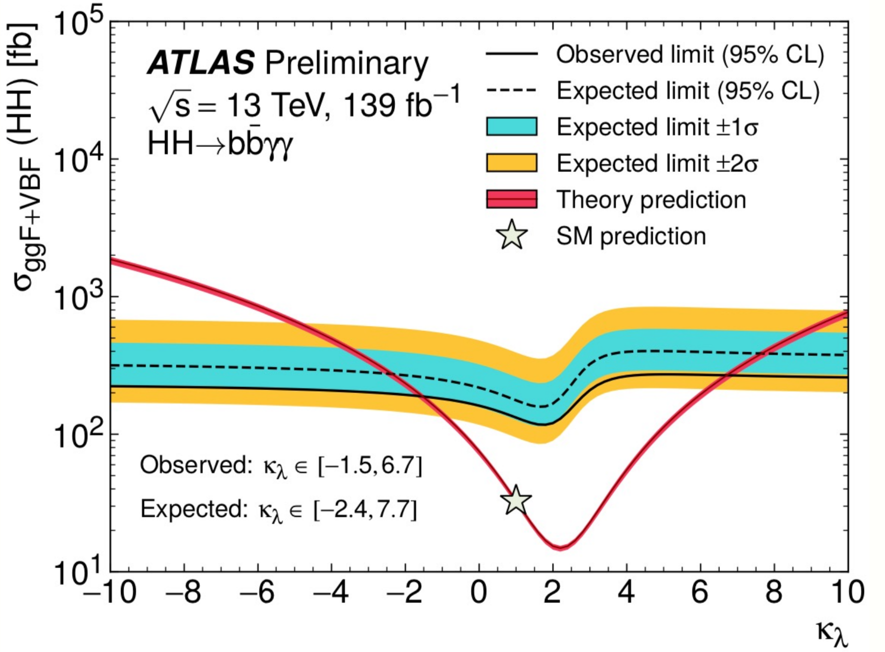
- Resonant: 1 category based on BDT output





Non-resonant HH→bbγγ Results





Obs. (exp.) limits: 4.1 (5.5) × σ_{SM}
5× improvement compared with previous result (25 × σ_{SM}), 3× due to analysis improvement

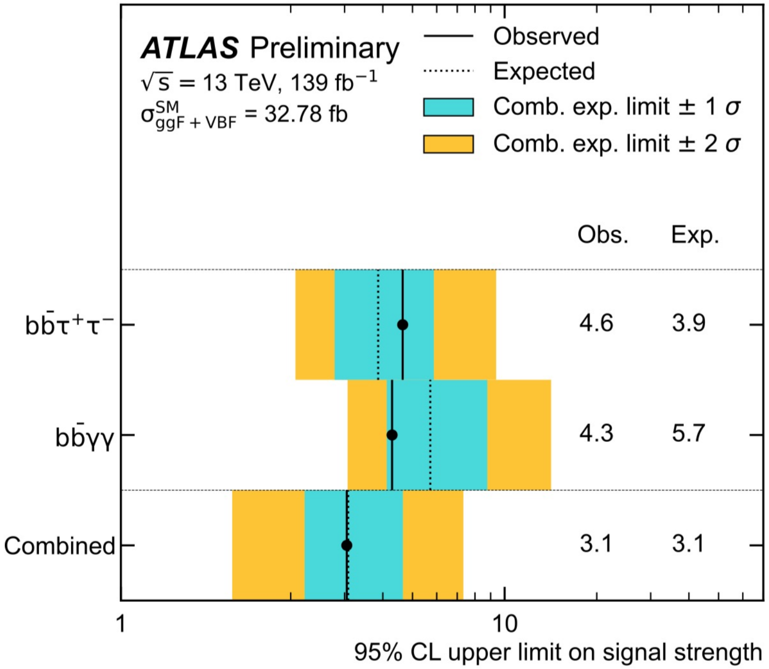
Obs. (exp.) constraint on κ_λ: $-1.5 \leq \kappa_\lambda \leq 6.7$ ($-2.4 \leq \kappa_\lambda \leq 7.7$)

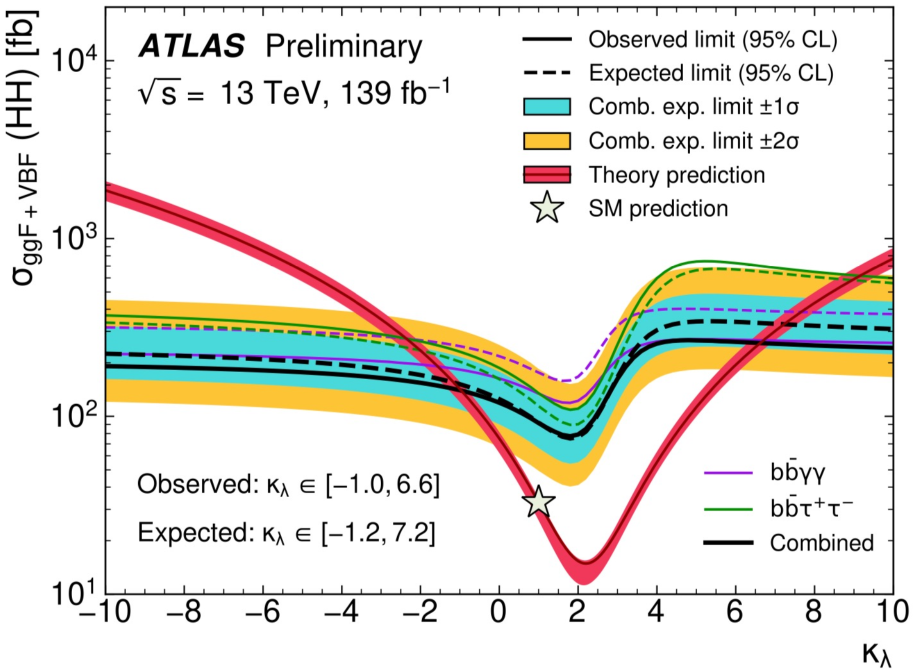
HH Combination

New!

- Performed statistical combination for different HH analyses to maximize sensitivity to HH production
- Non-resonant: including bb$\tau\tau$ and bb$\gamma\gamma$
  - bb$\tau\tau$ outperforms at around $\kappa_\lambda = 1$ due to more boosted signal and higher BR, while bb$\gamma\gamma$ outperforms at high κ_λ values due to high acceptance
- Systematics correlated where appropriate (like luminosity, flavor tagging, signal theory uncertainties, etc)

Non-resonant Combination Result





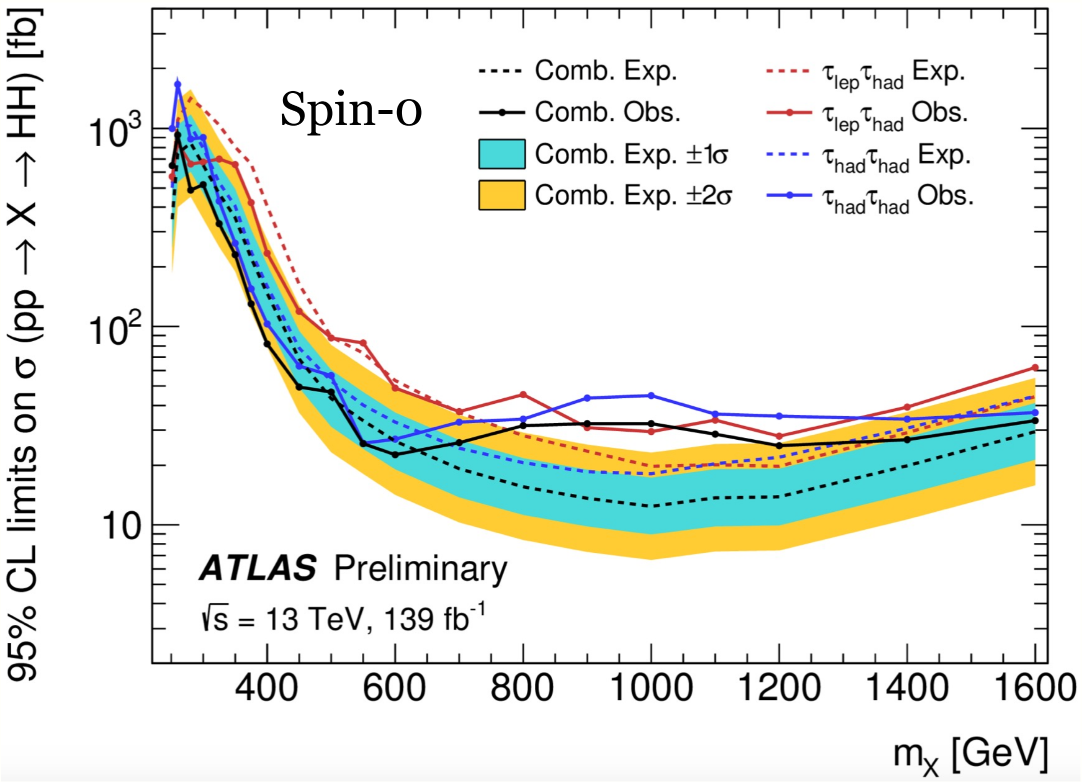
Obs. (exp.) limits: 3.1 (3.1) × σ_{SM}

Obs. (exp.) constraint on κ_λ: $-1.0 \le \kappa_\lambda \le 6.6$ ($-1.2 \le \kappa_\lambda \le 7.2$)

The best constraints on HH signal strength and κ_λ to date!

Resonant HH Search

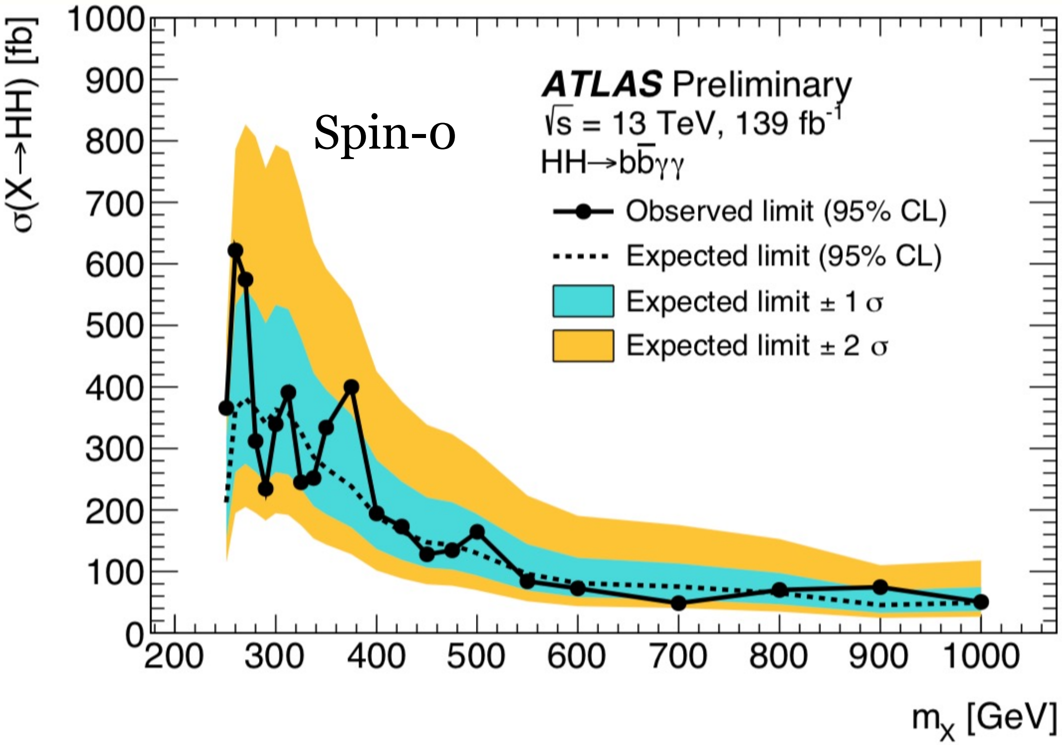
Resonant HH→bbττ Results



Observed (expected) upper limits: 920-23 fb (840-12 fb) depending on the mass region

Local (global) significance for 1 TeV is 3.0σ (2.0σ)

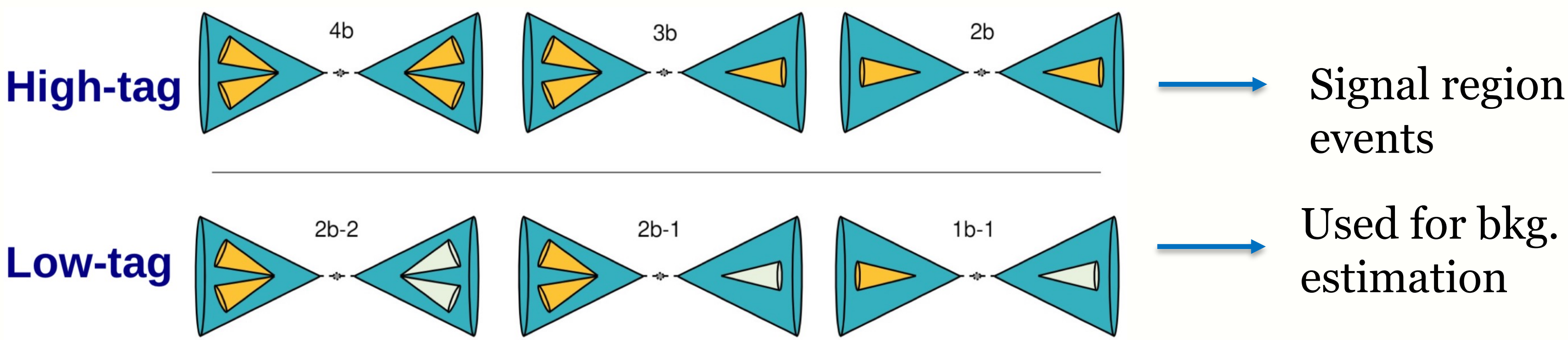
Resonant HH→bbγγ Results



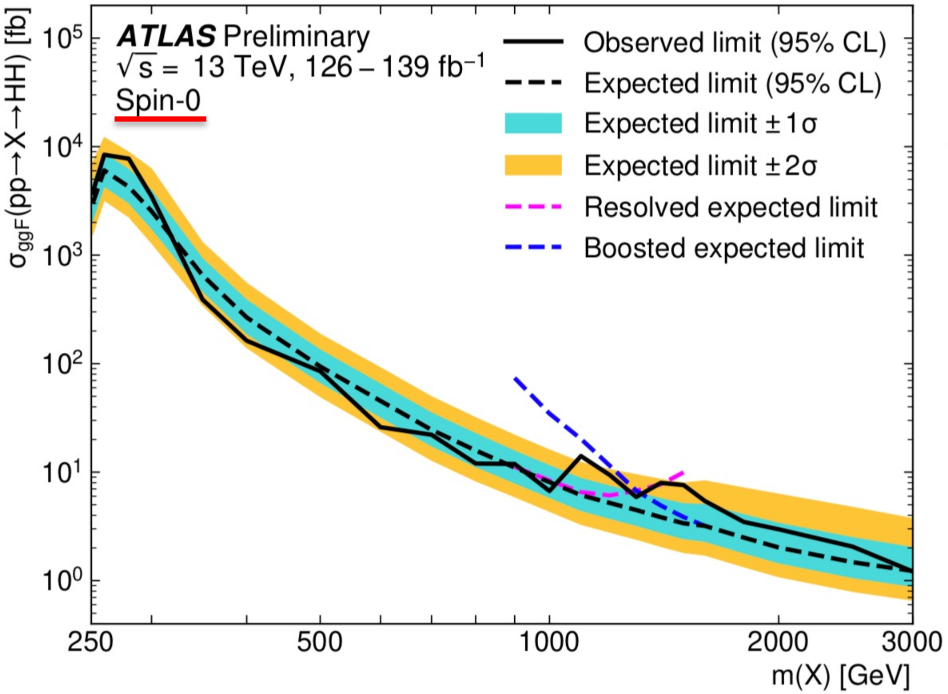
- The obs. (exp.) limits: 610–47 fb (360–43 fb) in the range 251–1000 GeV
- 2-3× improvement depending on the mass range compared with previous publication

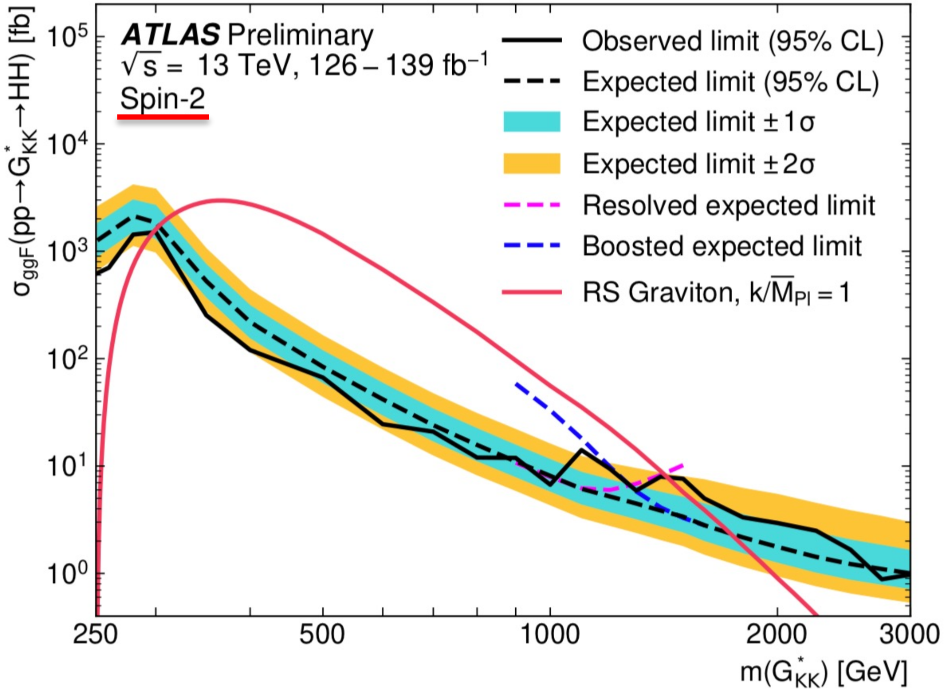
Resonant HH→bbbb Analysis

- 4b channel has largest BR (33%) but suffering from large background from multi-jet process
- Two channels: resolved and boosted
- Resolved: 4 b-tagged jets; targeting low mass region (251 GeV to 1.5 TeV)
- Boosted: 2 large-R jets as Higgs candidates; targeting high-mass region (900 GeV to 3 TeV)



Resonant HH→bbbb Results

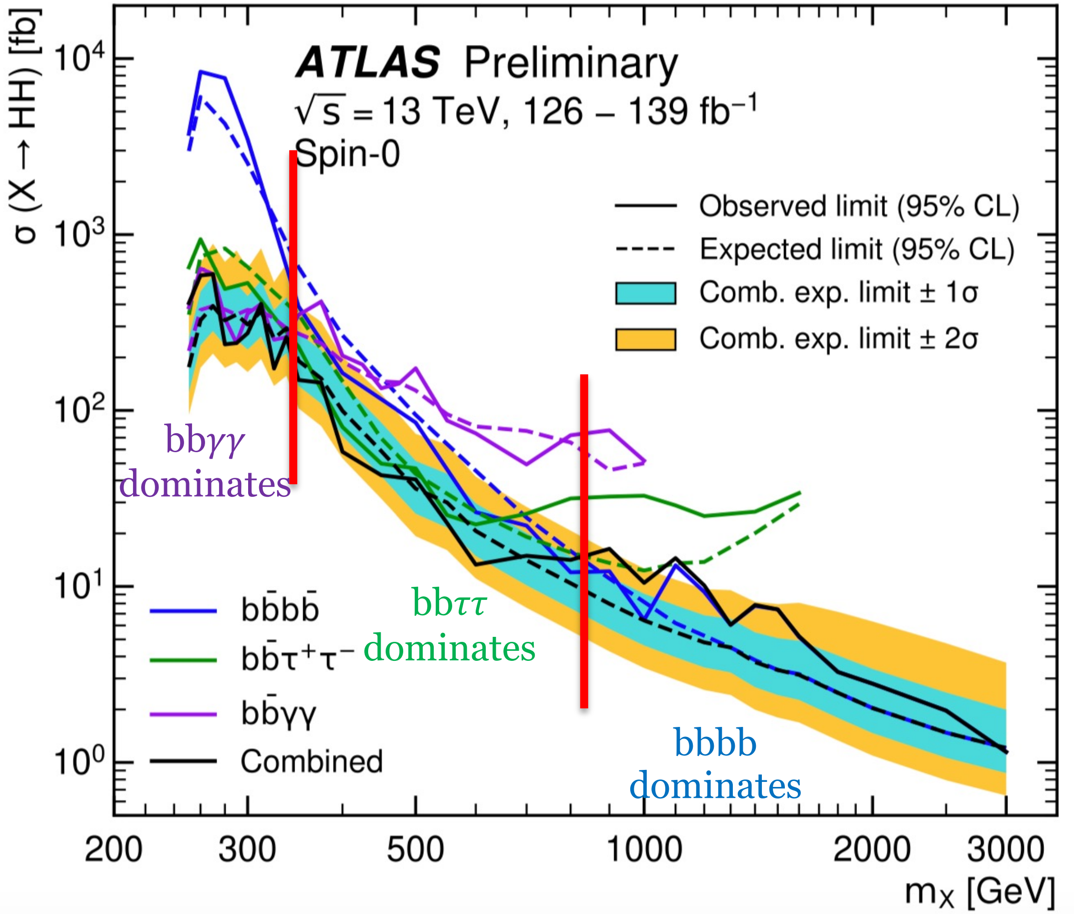




The bulk RS model excluded for graviton masses between 298 GeV and 1440 GeV

For excess at 1.1 TeV, the local (global) significance: 2.6σ (1.0σ) for spin-0 and 2.7σ (1.2σ) for spin-2

Resonant Combination Result



No statistically significant excess found, largest excess at 1.1 TeV: local (global) significance is 3.2σ (2.1σ)

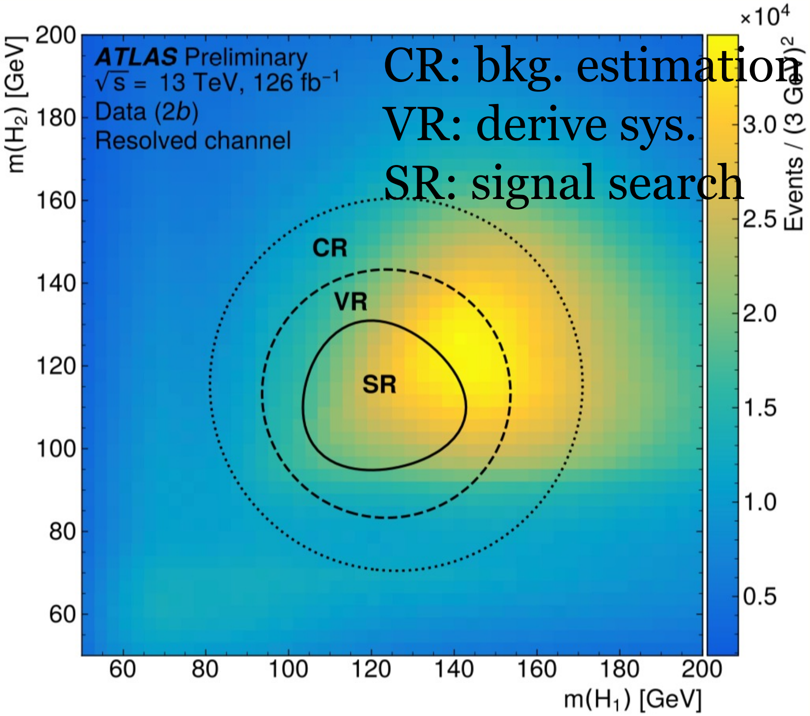
Summary

- Presented the latest HH searches with $bb\tau\tau$, $bb\gamma\gamma$ and bbbb final states, as well as the HH combination
- Significant improvement on the results comparing with the previous publications: the best constraints on HH signal strength and κ_λ is shown!
- ~300 fb^{-1} data expected during the LHC Run 3, which can provide more room for probing HH production
- More exciting results in the coming years!

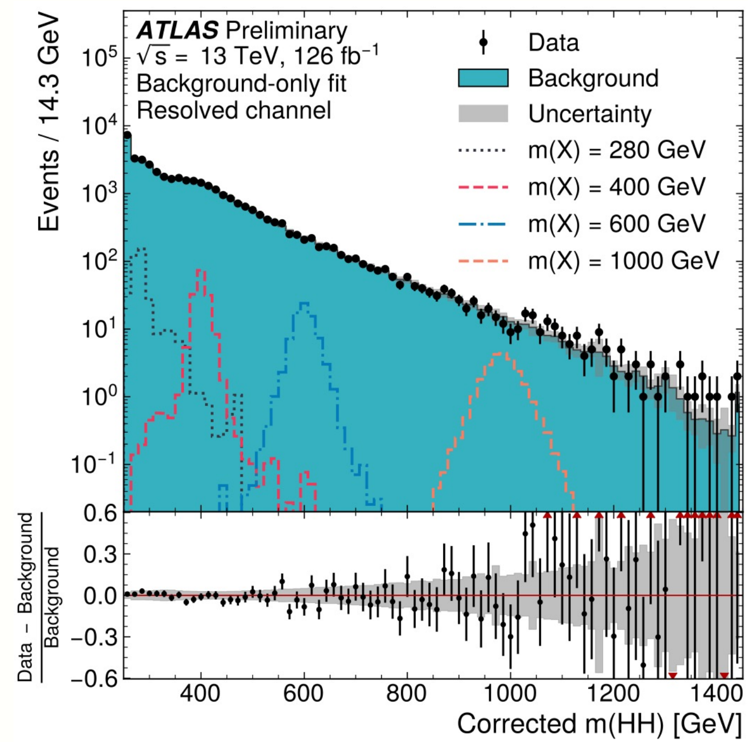
Backup

Resonant HH→bbbb

- Resolved: multi-jet (95%) and ttbar (5%); data-driven estimation
- Boosted: multi-jet from data-driven estimation; ttbar from simulation



CR: bkg. estimation
VR: derive sys.
SR: signal search



HL-LHC Projection

Channel	Measured μ (Statistical-only)	Measured μ (Statistical + Systematic)
$HH \to b\bar{b}b\bar{b}$	1.0 ± 0.6	1.0 ± 1.6
$HH \to b\bar{b}\tau^+\tau^-$	1.0 ± 0.4	1.0 ± 0.5
$HH \to b\bar{b}\gamma\gamma$	1.0 ± 0.6	1.0 ± 0.6
Combined	1.00 ± 0.31	1.0 ± 0.4

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \leq \kappa_\lambda \leq 1.7$	$-0.10 \leq \kappa_\lambda \leq 2.7 \cup 5.5 \leq \kappa_\lambda \leq 6.9$
Systematic uncertainties	$0.25 \leq \kappa_\lambda \leq 1.9$	$-0.4 \leq \kappa_\lambda \leq 7.3$

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