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

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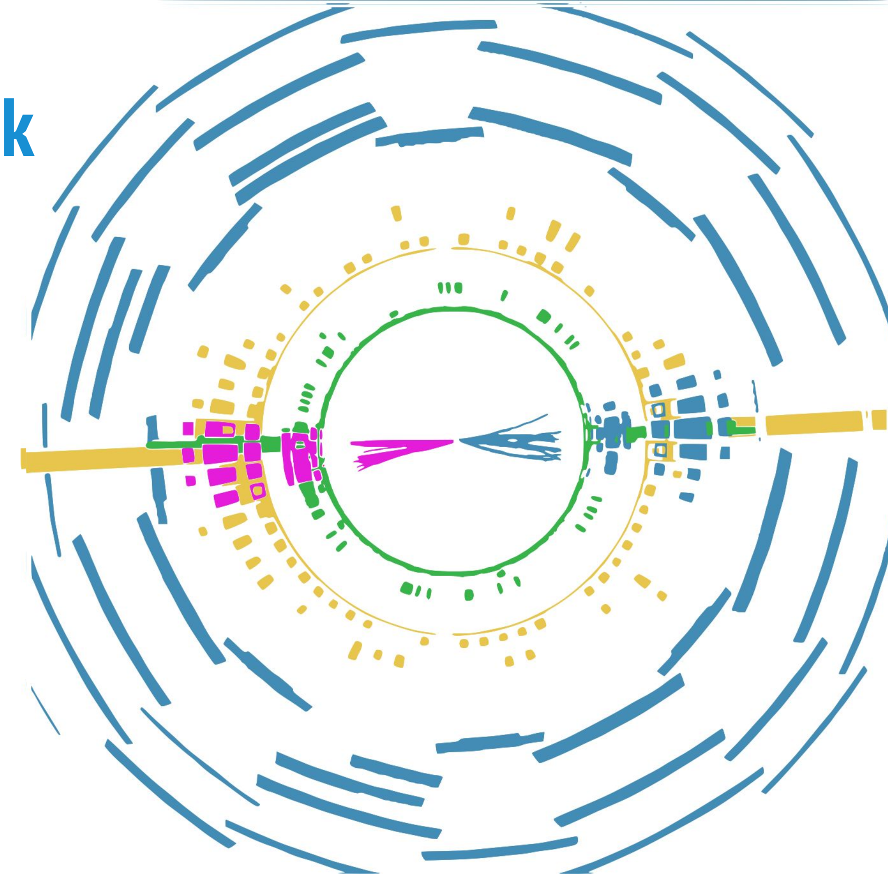
On behalf of the ATLAS Collaboration

Phenomenology symposium 2022, 9-11 May 2022



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ATLAS EXPERIMENT

Overview

Full Run-2 LHC dataset:

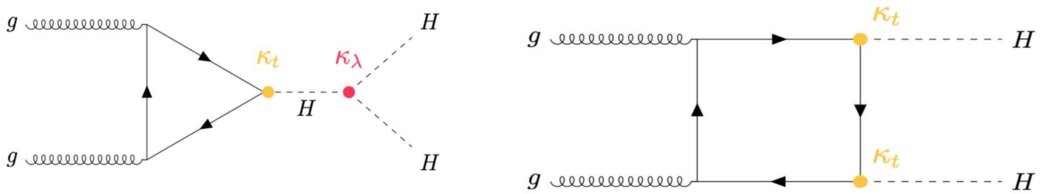
- Integrated luminosity of 126-139 fb^{-1} of data collected at $\sqrt{s}$ = 13 TeV

- **Di-Higgs results with full Run 2 dataset at the ATLAS Experiment**
  - Resonant **HH→bbbb** [CERN-EP-2021-229]
  - Resonant and non-resonant **HH→bbττ** [ATLAS-CONF-2021-030]
  - Resonant and non-resonant **HH→bbɣɣ** [CERN-EP-2021-180]
  - Resonant and non-resonant combination [ATLAS-CONF-2021-052]
  - HEFT interpretation using **HH→bbɣɣ** and **HH→bbττ** [ATL-PHYS-PUB-2022-019]

- **HL-LHC projections with the ATLAS detector**
  - **HL-LHC prospects for HH→bbττ** [ATL-PHYS-PUB-2021-044]
  - **HL-LHC prospects for HH→bbɣɣ** [ATL-PHYS-PUB-2022-001]
  - **HL-LHC Prospects for HH (bbɣɣ + bbττ combination)** [ATL-PHYS-PUB-2022-005]

Non-Resonant di-Higgs Production at the LHC

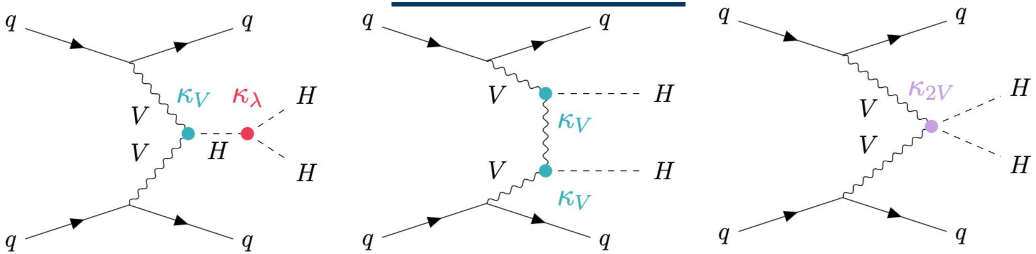
ggF channel



$$\sigma^{SM}_{ggF} = 31.05^{+6\%}_{-23\%}(scale + m_{top}) \pm 3.0\%(PDF + \alpha_S) fb$$

at NNLO for √s = 13 TeV!

VBF channel



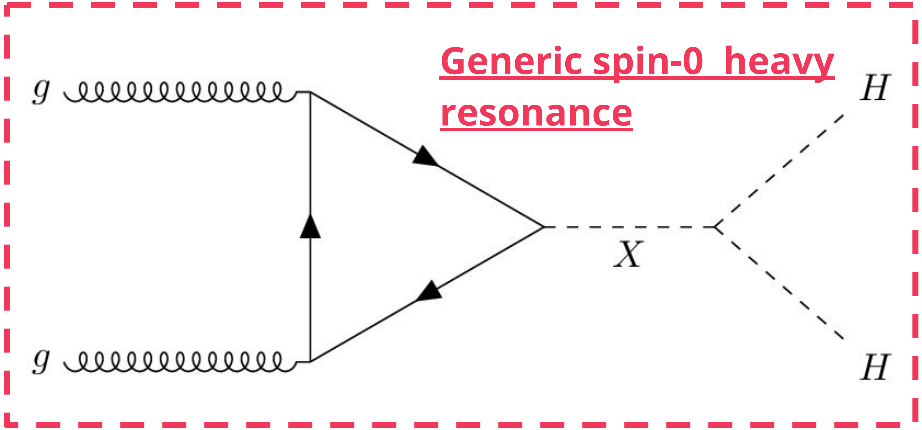
$$\sigma^{SM}_{VBF} = 1.73^{+0.03\%}_{-0.04\%}(scale + m_{top}) \pm 2.1\%(PDF + \alpha_S) fb$$

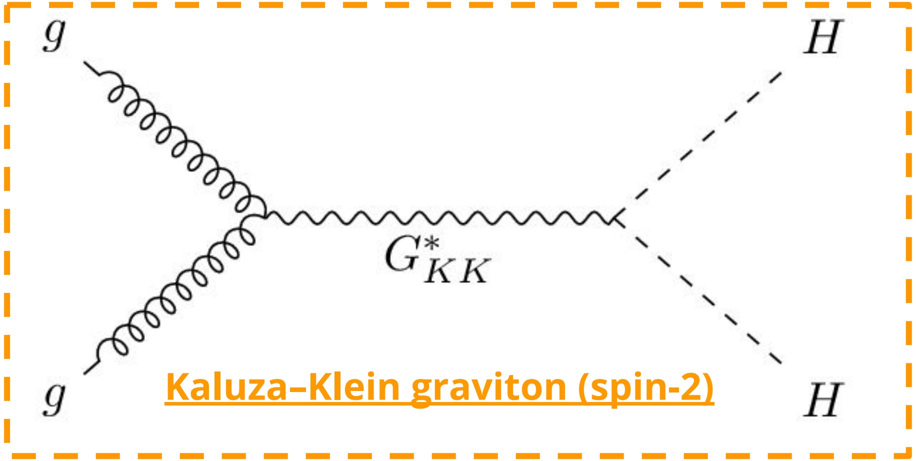
at N3LO for √s = 13 TeV!

Search for **non-resonant** pair production of Higgs bosons

- Trilinear self-coupling of the Higgs boson (H)
  - $\lambda^{SM}_{HHH} = \frac{m_H^2}{2v^2}$
- Test the theory of electroweak symmetry breaking
- Very sensitive to anomalous trilinear self-coupling
  - $\kappa_\lambda = \frac{\lambda^{measured}_{HHH}}{\lambda^{SM}_{HHH}}$

Resonant di-Higgs Production





Search for **resonant** pair production of Higgs bosons

- Representative benchmark models:
  - Generic spin-0 boson
    - Predicted by Higgs-doublet models, e.g. MSSM
  - Spin-2 Kaluza–Klein graviton
    - As in the bulk Randall–Sundrum (RS) model
- Assumptions:
  - Spin hypothesis
  - Generated resonance width
    - Spin-0 boson with a narrow width of 10 GeV
    - Kaluza–Klein graviton width based on model prediction

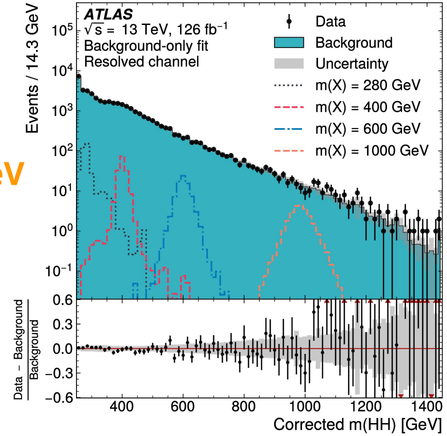
Resonant HH->bbbb

CERN-EP-2021-22

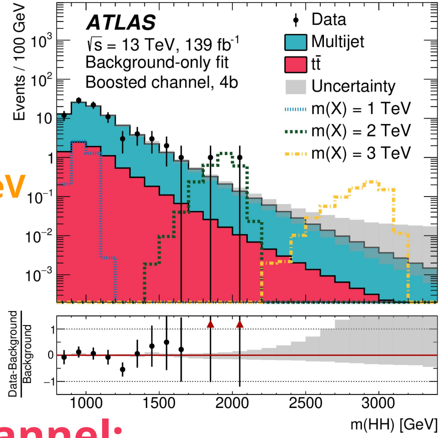
Resolved channel:

- H->bb: 2 b-tagged R=0.4 pflow jets
- Data-driven background estimation
  - Neural Net
  - Use 2b tagged events
  - Captures multijet and tt
- Corrected m_{HH} used in the fit
  - $m_{H1}=m_{H2}=125$ GeV

$m_{X/G} \in [251, 1500]$ GeV



$m_{X/G} \in [900, 5000]$ GeV



Boosted channel:

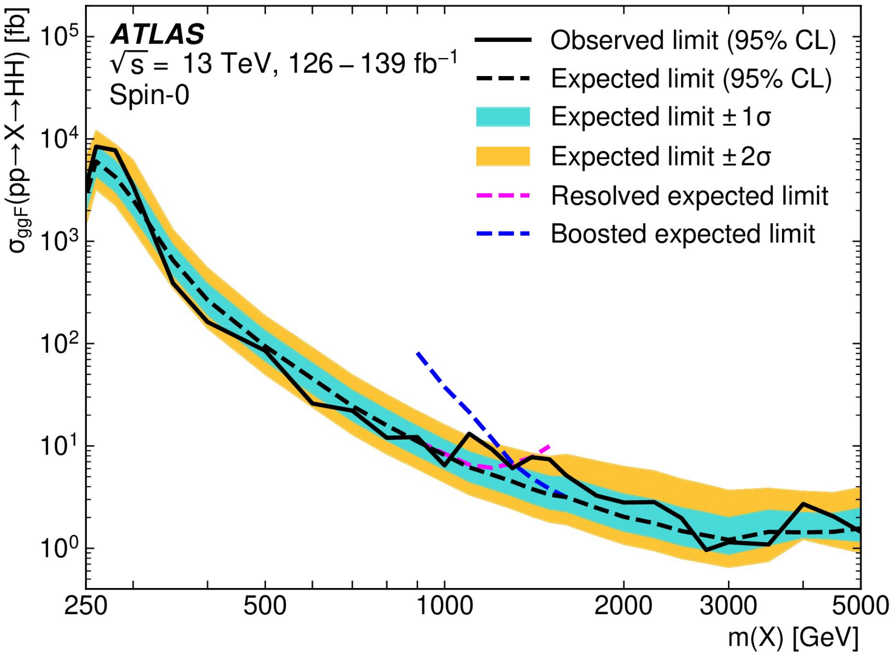
- H->bb: 1 merged R=1.0 calo jet
  - **Variable-radius track jets** for b-tagging
- Background estimation
  - **tt:** Monte Carlo samples
  - **Multijet:** data-driven method
    - Use low-tag events
- 2b, 3b, 4b categories, m_{HH} fitted

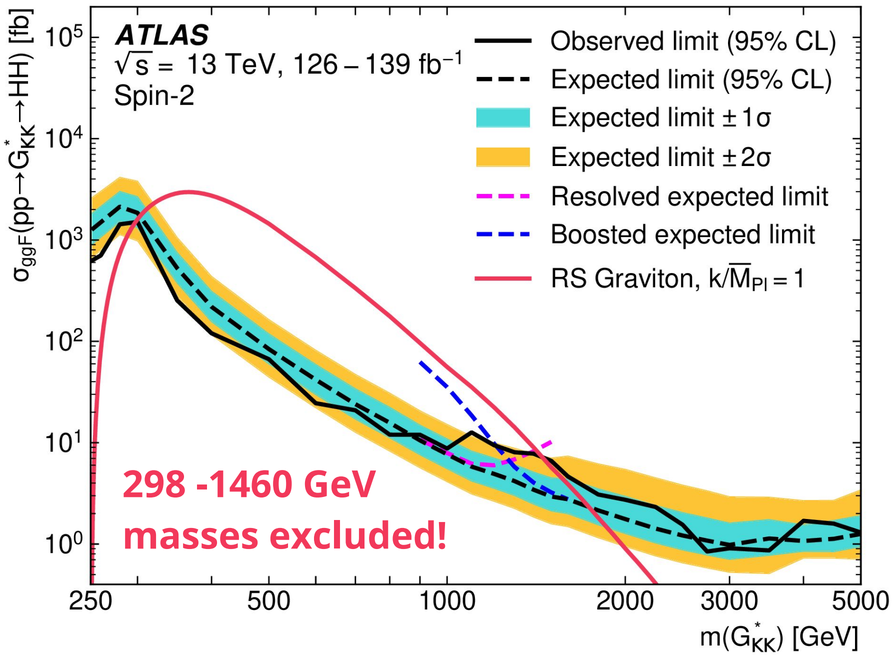
Resonant HH->bbbb

CERN-EP-2021-22

No significant evidence of a signal is observed!

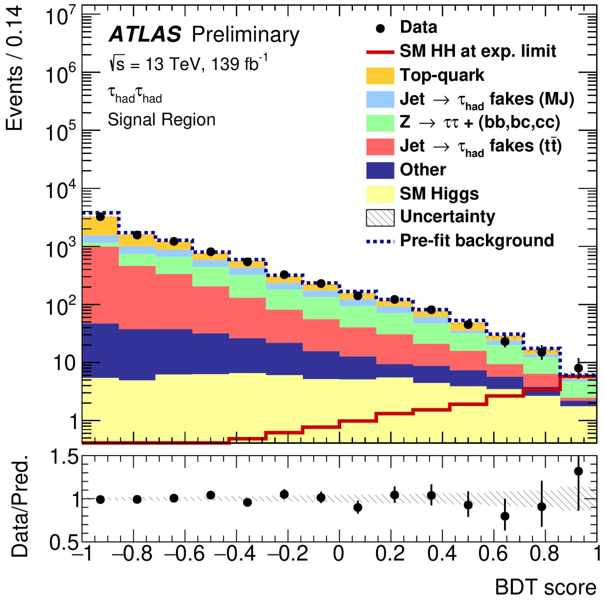
- Powerful at high resonance masses!
  - Improvements in the **boosted channel**
  - **3-5 TeV range** covered for the first time
- $m_{X/G} \in [900, 1500]$ GeV resolved and boosted fitted together





HH->bbττ

ATLAS-CONF-2021-030



- H->bb: 2 b-tagged pflow jets
- $H\to\tau_{had}\tau_{had}$ or $H\to\tau_{lep}\tau_{had}$ opposite charge!
- $H\to\tau_{lep}\tau_{had}$ categorized on based the event passing certain triggers
- Dominant tt and Z + heavy flavor
- Fit a machine learning observable

Non-resonant analysis:

- MLs trained on non-resonant HH ggF signal
  - Boosted decision tree in $H\to\tau_{had}\tau_{had}$
  - Neural network in $H\to\tau_{lep}\tau_{had}$

Resonant analysis:

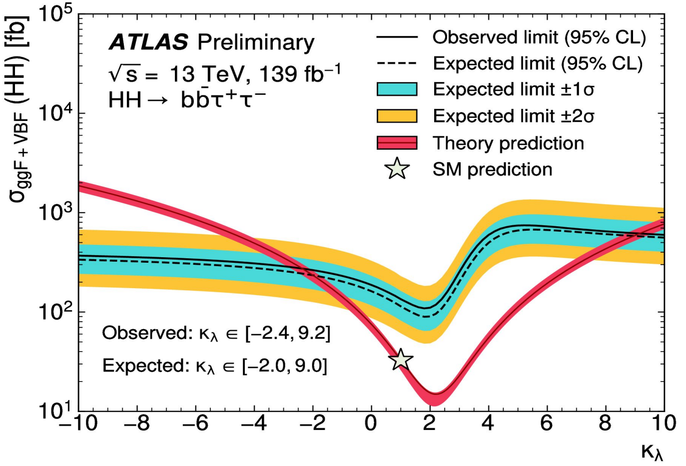
- $m_X \in$ [251, 1600] GeV
- Parameterized neural network
  - Heavy resonance mass parameterized in the training

HH->bbττ

ATLAS-CONF-2021-030

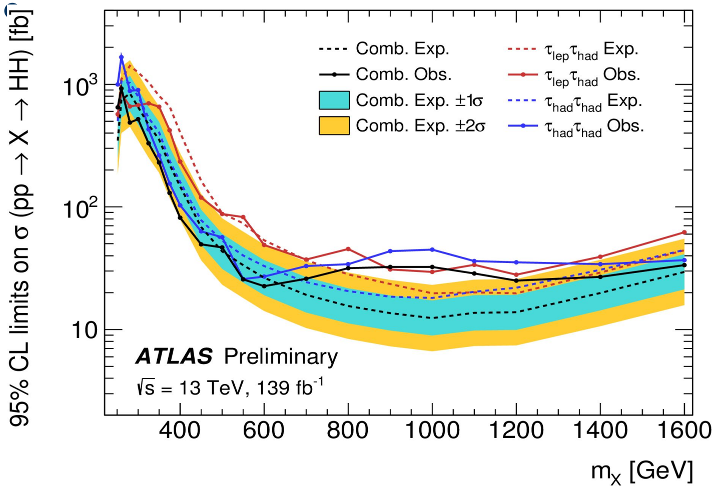
Non-Resonant results:

- Observed (expected) upper limits on the cross-section: **4.7 (3.9) times the SM expectation**
- ***κ_λ* ∈ [-2.4, 9.2] ([-2.0, 9.0])** (published in ATLAS-CONF-2021-052)



Resonant results:

- Compatible with the background-only hypothesis
- Deviation from SM at 1 TeV local (global) significance: 3.0 σ (2.0 $^{+0.4}_{-0.2}$ σ)



HH->bbɣɣ

CERN-EP-2021-180

- H->bb: 2 b-tagged pflow jets
- H->ɣɣ: 2 high p_T ɣ
- No leptons
- Categories constructed from:
  - $m^*_{bbɣɣ}$ cuts
  - ɣ and jet related kinematics
  - missing transverse momentum variables

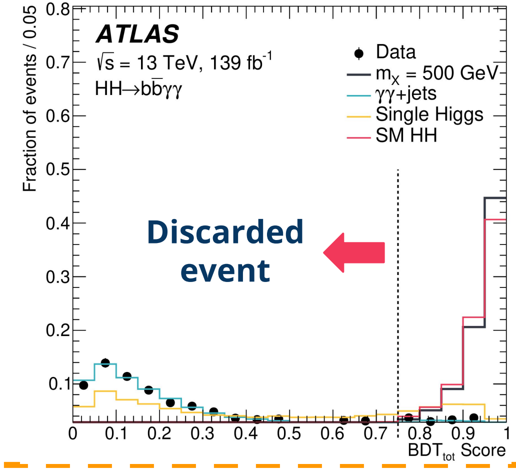
- Main backgrounds: non-resonant ɣ ɣ , single Higgs decays
- Model signal and background $m_{ɣɣ}$ shapes with analytic function
- Categorise on BDT score
- Fit $m_{ɣɣ}$

Non-resonant analysis:

Low and high mass category
- BDT trained for each

Resonant analysis:

$m_X \in$ [251, 1000] GeV
- BDT: joint training for all m_X



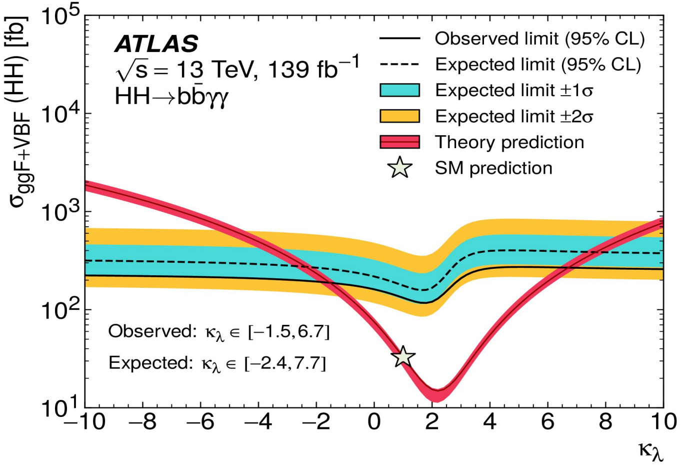
ATLAS EXPERIMENT

HH->bbγγ

CERN-EP-2021-180

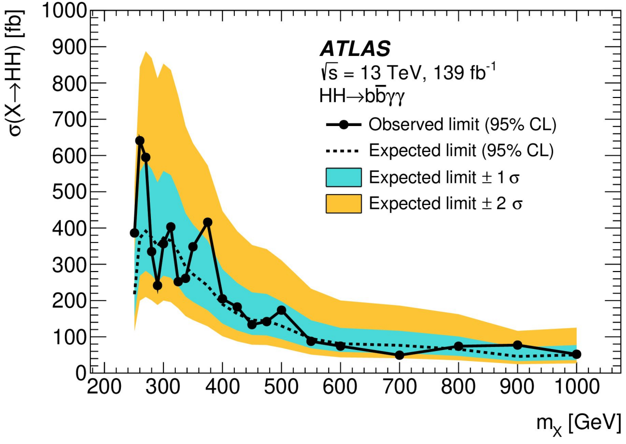
Non-Resonant results:

- Observed (expected) upper limits on the cross-section: **4.2 (5.7) times the SM expectation**
- **$\kappa_\lambda \in$ [-1.5, 6.7] ([-2.4, 7.7])**

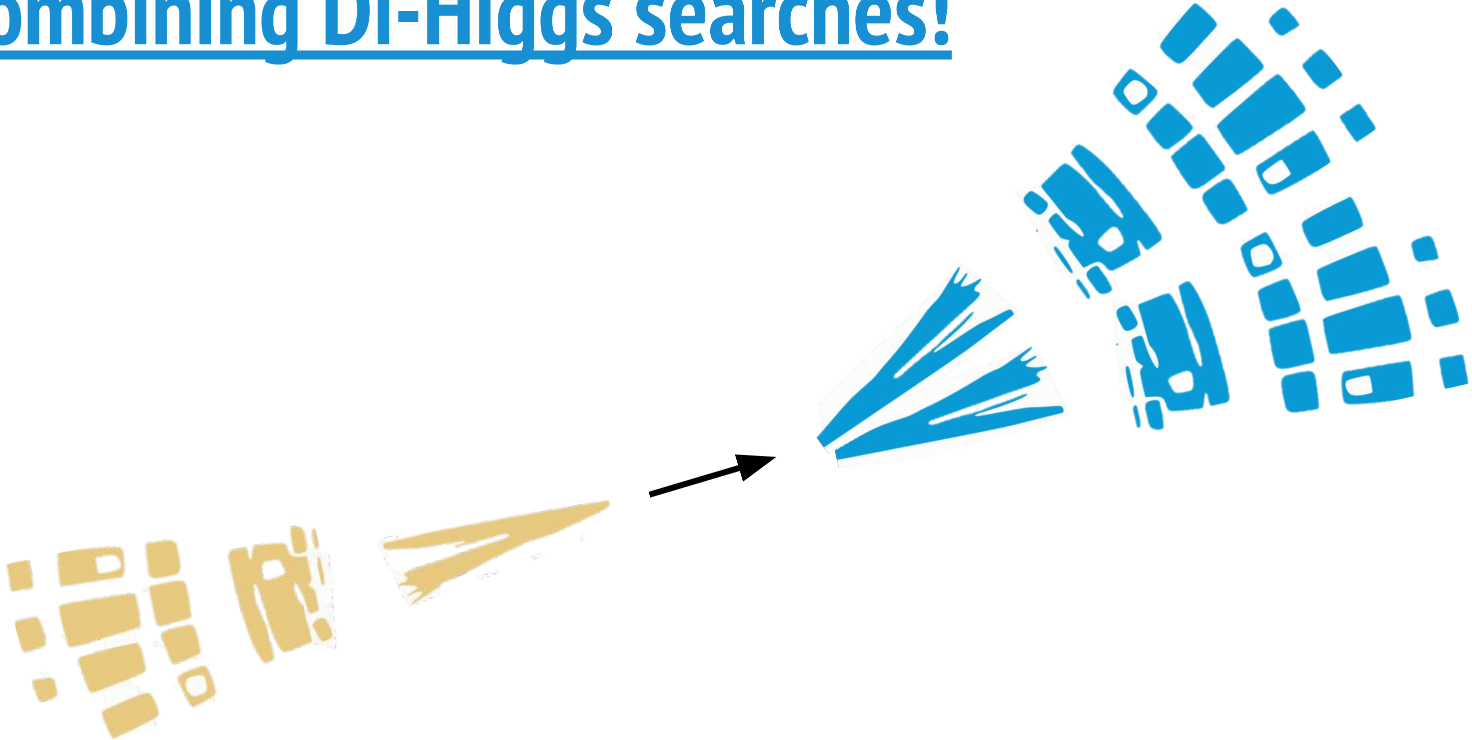


Resonant results:

- Compatible with the background-only hypothesis
- Powerful at low resonance masses



Combining Di-Higgs searches!

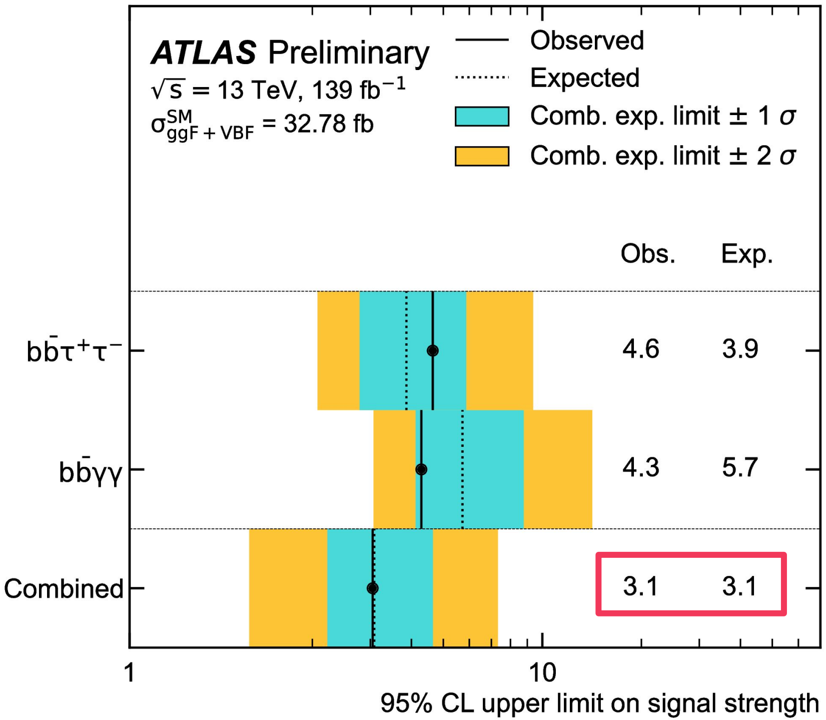


ATLAS EXPERIMENT

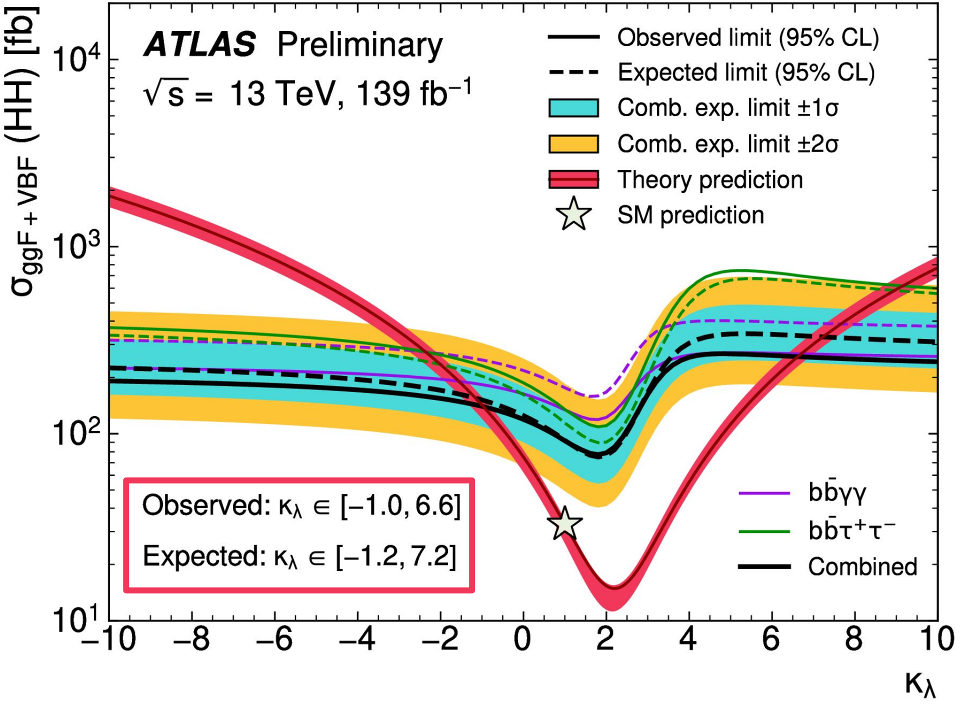
Combination Non-Resonant bbγγ and bbττ

ATLAS-CONF-2021-052

Signal strength for non-resonant SM di-Higgs production



Non-resonant di-Higgs production cross-section



Combination bbbb, bbγγ and bbττ resonant decay channels

ATLAS-CONF-2021-052

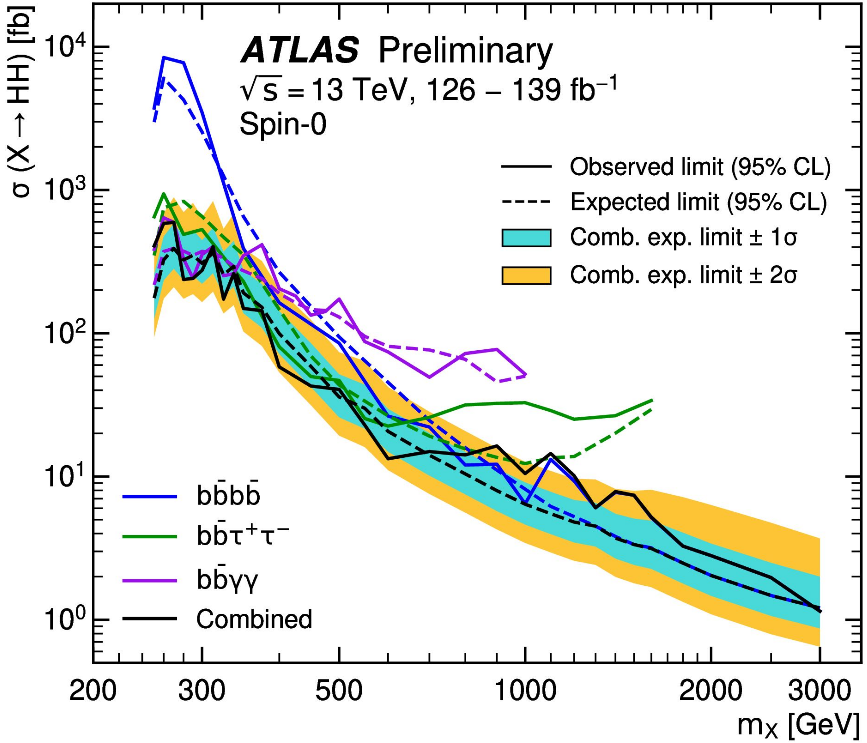
No significant evidence of a signal is observed!

Observe good complementarity between the channels

- Each most sensitive in a different mass range
  - Low mass **bbγγ** dominant
  - Mid range **bbττ** dominant
  - High mass **bbbb** dominant

Largest deviation from SM at **1.1 TeV**

- Local (global) significance **3.2 σ (2.1 σ)**



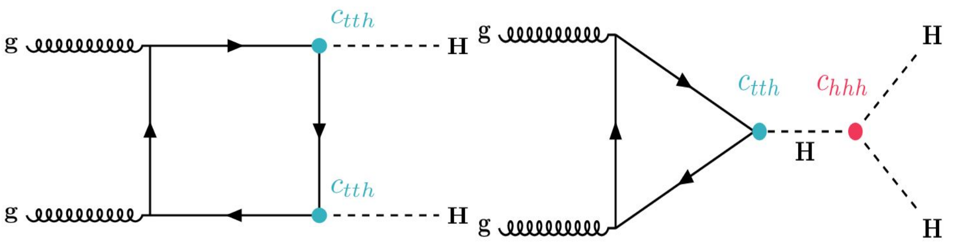
HEFT interpretation of bbγγ and bbττ

ATL-PHYS-PUB-2022-019

- Higgs Effective Field Theories (HEFT)
- Dominant source of new physics: anomalous H couplings in the electroweak sector
  - Treat Single H and HH couplings separately

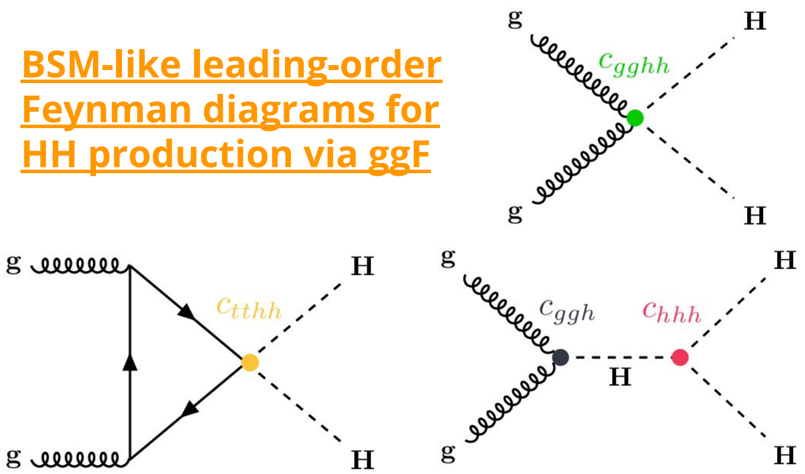
The seven HEFT benchmark models considered

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



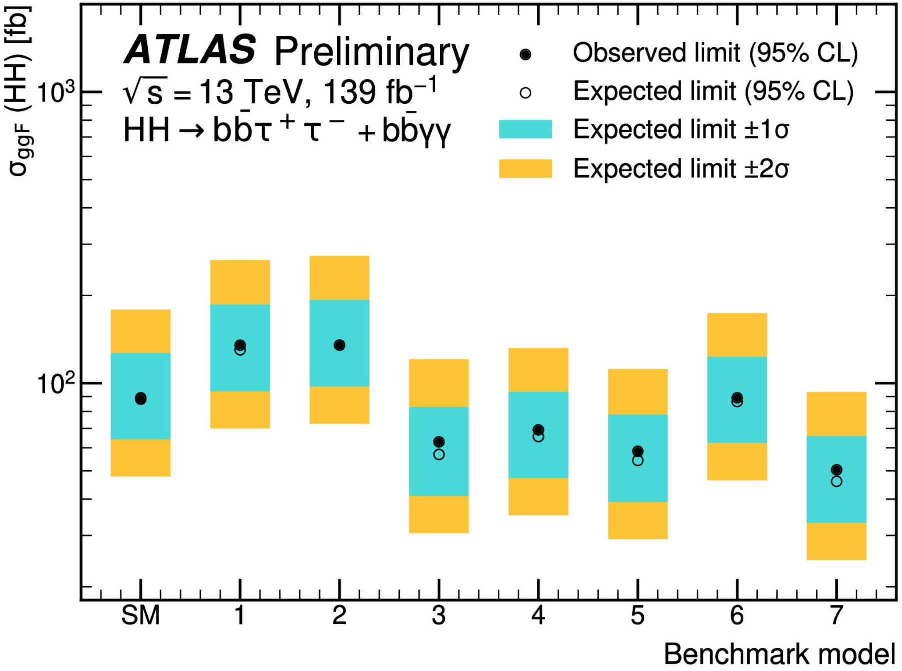
SM-like leading-order Feynman diagrams for HH production via ggF

BSM-like leading-order Feynman diagrams for HH production via ggF



HEFT interpretation of bbɣɣ and bbττ

ATL-PHYS-PUB-2022-019



- The observed (expected) limits range from **50.4 (46.0) fb** (benchmark model 7) to **135.1 (135.1) fb** (benchmark model 2)
- Allowed observed (expected) ranges on the two Wilson coefficients:
  - **c_{gghh} ∈ [-0.3, 0.4] ([-0.3, 0.3])**
  - **c_{tthh} ∈ [-0.2, 0.6] ([-0.2, 0.6])**

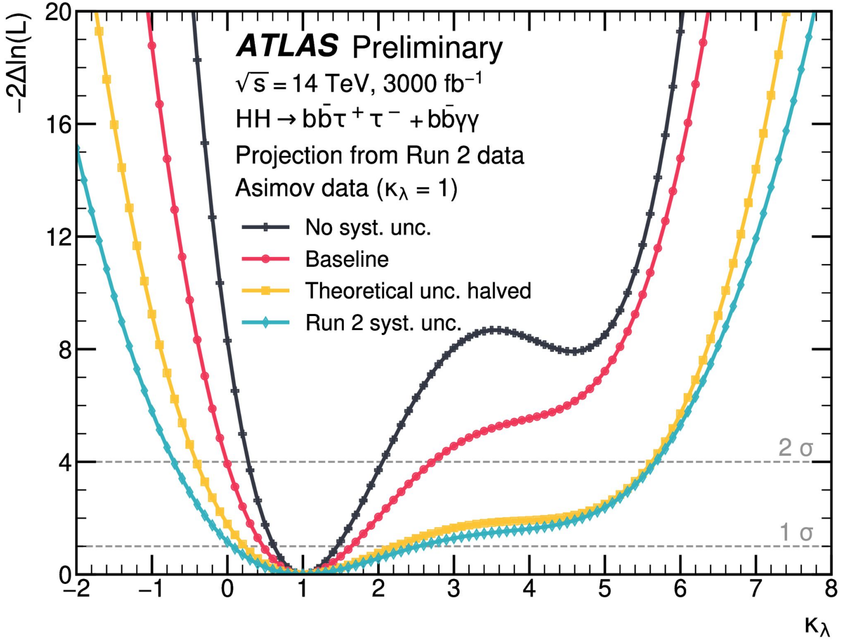
HL-LHC Prospects for di-Higgs

- **The High Luminosity LHC (HL-LHC) plans:**
  - Deliver **3000**-4000 fb^{-1} integrated luminosity @ **$\sqrt{s}$ = 14 TeV** p-p collisions
- **Basis of the projection studies**
  - Extrapolate from full Run 2 **HH→bbγγ** and **HH→bbττ** analysis
  - Use Run 2 object reconstruction and identification efficiencies

➔ **1 σ confidence interval $\kappa_\lambda \in$ [0.5,1.5] ([0.6,1.5])** for baseline (no systematics)

➔ Significance of expected observation of SM di-Higgs production is **3.2 σ (4.6 σ)** for baseline (no systematics)

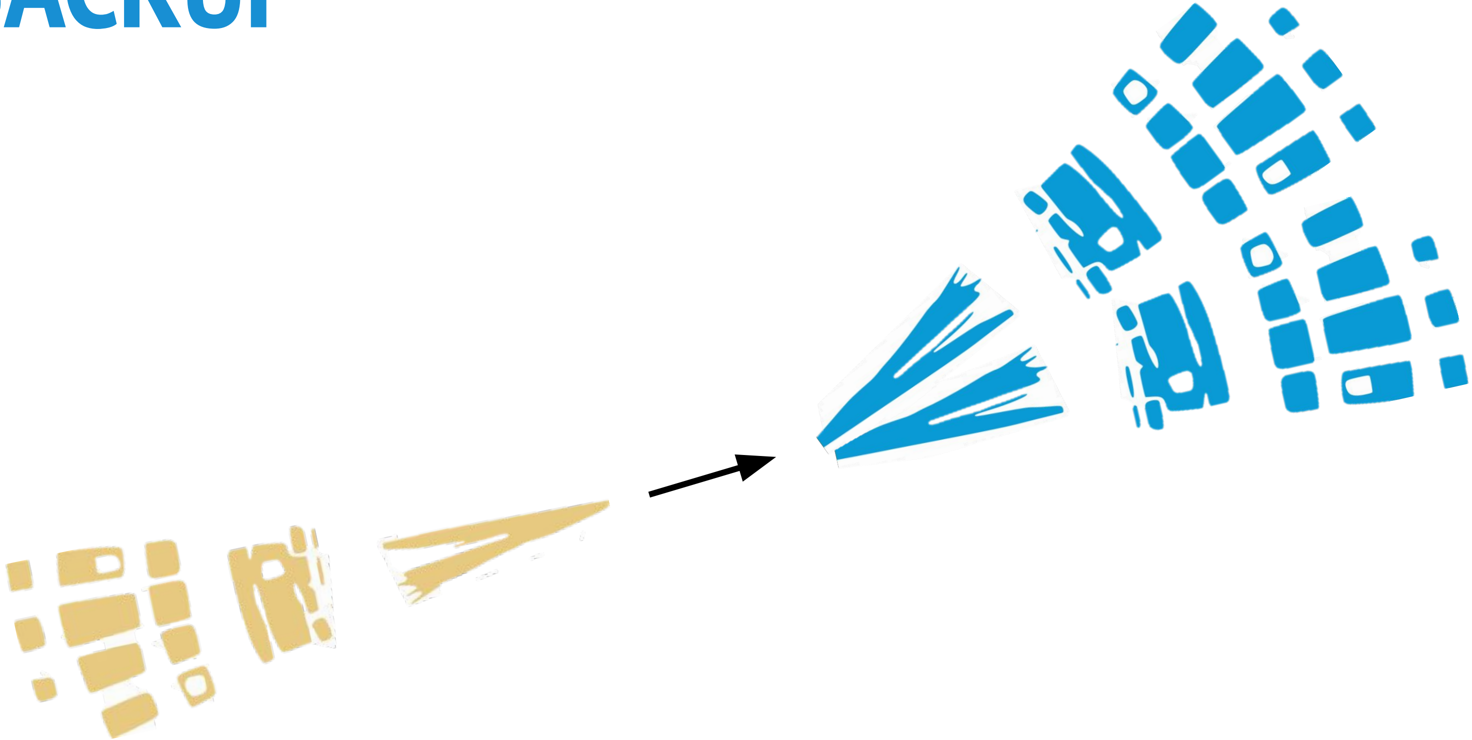
➔ **HL-LHC prospects for HH→bbττ** [PUB]
➔ **HL-LHC prospects for HH→bbγγ** [PUB]
➔ **HL-LHC Prospects for HH (bbγγ + bbττ combination)** [PUB]



Summary of the results presented

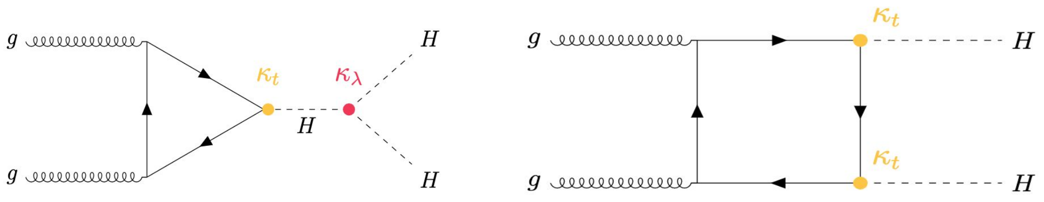
- **The LHC Run-2 data is a sensitive dataset to new physics in the Higgs sector.**
  - ATLAS has a full programme of **Di-Higgs searches** constraining this important process
- **Di-Higgs results with full Run 2 dataset at the ATLAS Experiment**
  - Combined **resonant searches** in the **bbγγ, bbττ** and **bbbb** final state set upper limits on the cross-section of a **spin-0 heavy scalar resonance** in the mass range of 251 GeV ≤ m_X ≤ 3 TeV
  - Combined **non-resonant searches** in the **bbγγ** and **bbττ** final state and set limits on the SM signal strength and allowed ranges of κ_λ
  - **HEFT interpretation** using the **bbγγ** and **bbττ** final state upper limits on the cross section for seven benchmark models and allowed ranges of c_{gghh} and c_{tthh}
- **HL-LHC projections with the ATLAS detector**
  - Assume **3000 fb^{-1}** integrated luminosity at **$\sqrt{s}$ = 14 TeV**
  - Combined non-resonant searches in the **bbγγ** and **bbττ** final states used to give expected **1σ confidence interval** on κ_λ

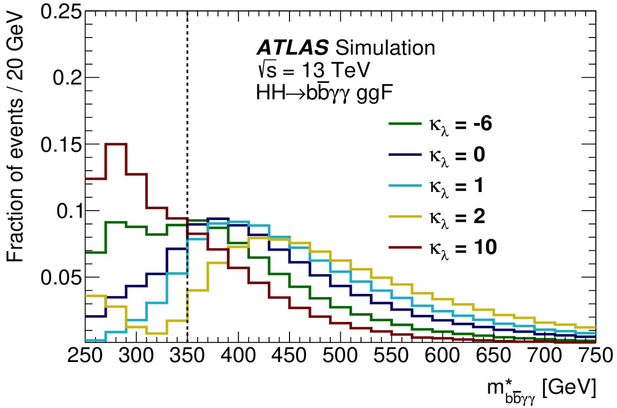
BACKUP



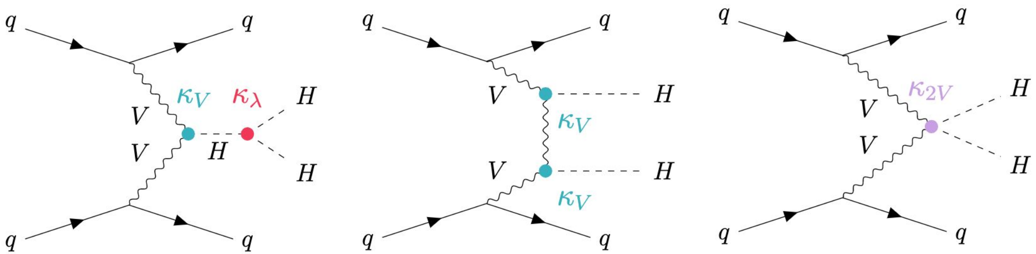
Non-Resonant di-Higgs Production

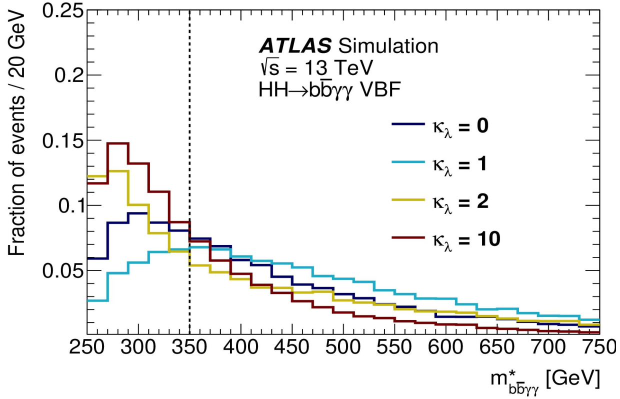
ggF channel





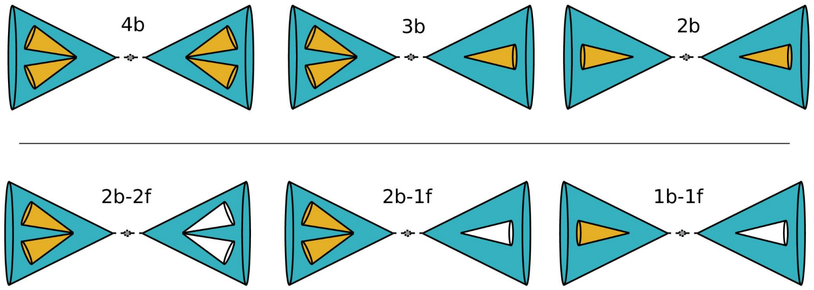
VBF channel

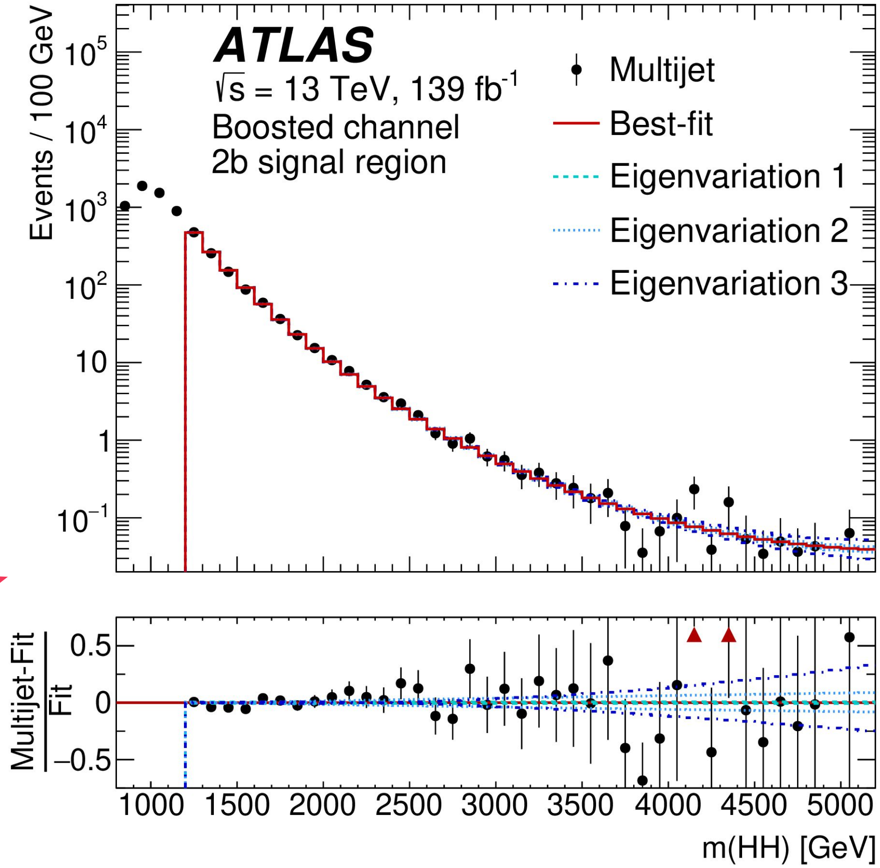




- **Boosted channel:**

The high-tag and low-tag categories used in the multijet background estimation.

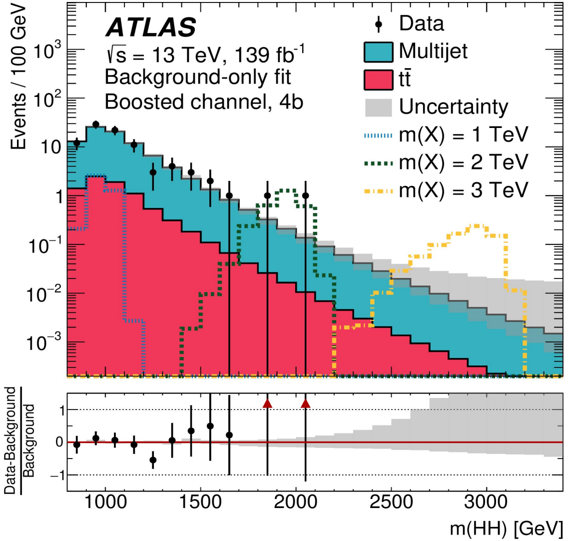


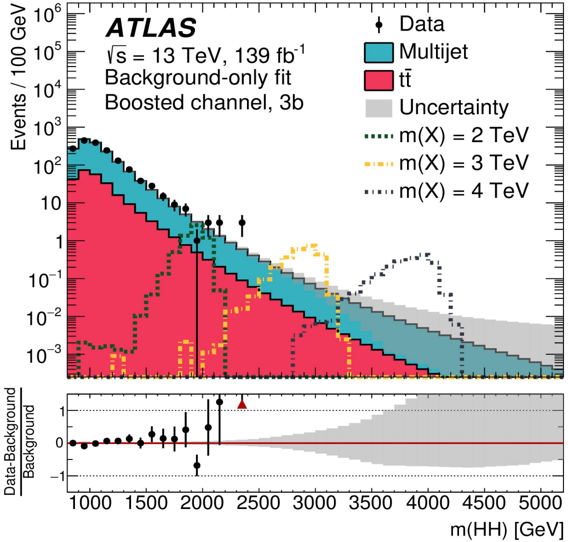


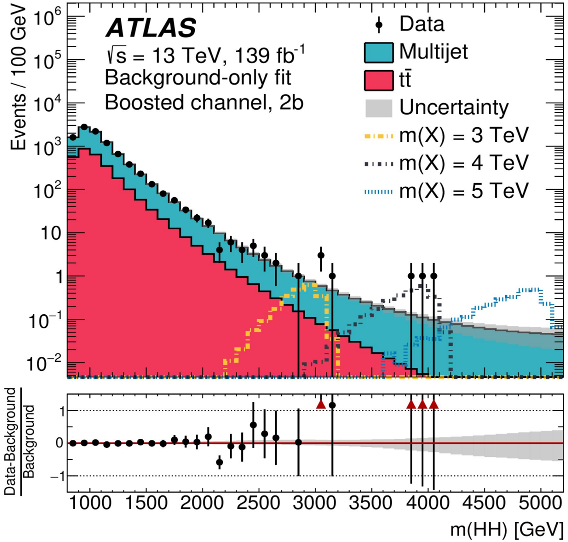
The unsmoothed and smoothed multijet background estimates.

Resonant bbbb

- **Boosted channel:**

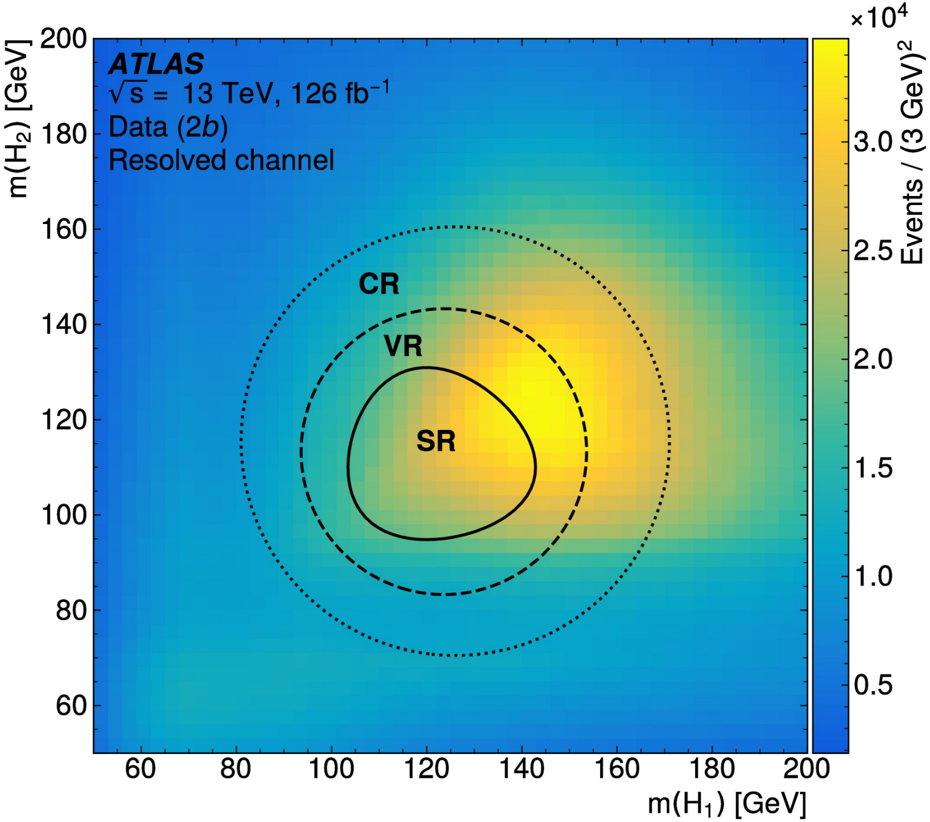






Resonant HH->bbbb

- **Kinematic region definitions in the Resolved channel**



$HH \to bb\tau\tau$

ATLAS-CONF-2021-030

- H->bb: 2 b-tagged pflow jets
- $H \to \tau_{had}\tau_{had}$ or $H \to \tau_{lep}\tau_{had}$ opposite charge!
- $H \to \tau_{lep}\tau_{had}$ categorized on based the event passing the following trigger:
  - Single-lepton trigger
  - Lepton-plus-tau trigger
- Backgrounds
  - Dominant **tt** and **Z + heavy flavor**
    - Normalization for **Z + heavy flavor** and **tt** simulated samples constrained from likelihood fits of signal and control regions
  - **Fake τ** estimations based on data-driven method and simulations, mainly from tt or multijet
  - Other backgrounds: W+heavy flavor, diboson, single Higgs boson and multi-jet production
- Fit a machine learning observable (ML)
  - Shared input variables in non-resonant and resonant analysis, differences between categories

Non-resonant analysis:

- MLs trained on non-resonant HH ggF signal
  - Boosted decision tree in $H \to \tau_{had}\tau_{had}$
  - Neural network in $H \to \tau_{lep}\tau_{had}$

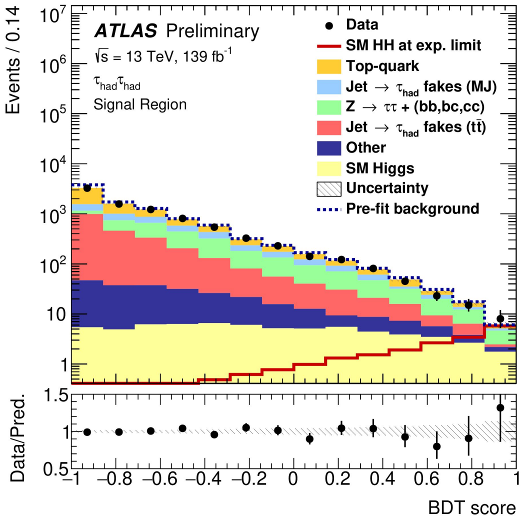
Resonant analysis:

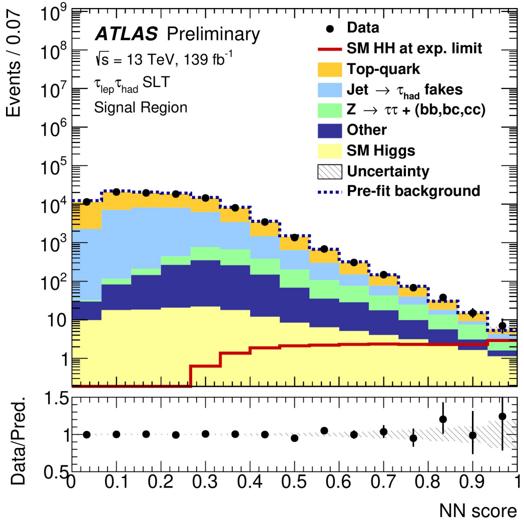
- $m_X \in [251, 1600]$ GeV
- Parameterized neural network
  - Heavy resonance mass parameterized in the training

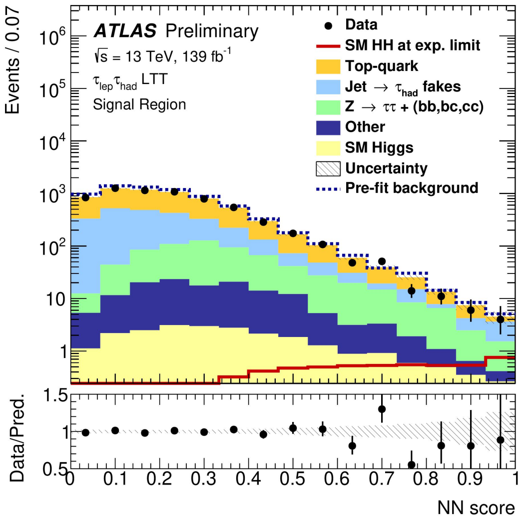
HH->bbττ: Variables used as inputs to the MLs

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

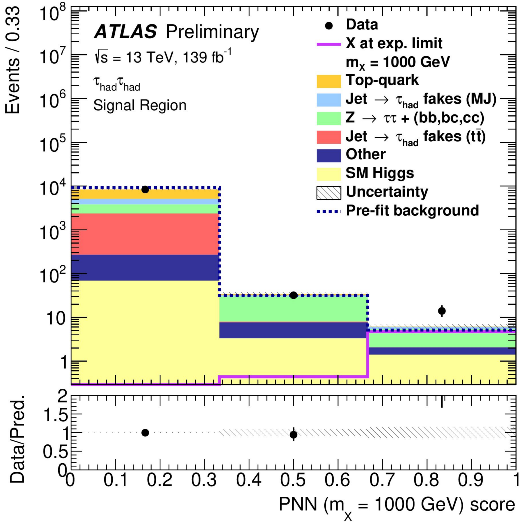
HH->bbττ: Variables used as inputs to the MLs

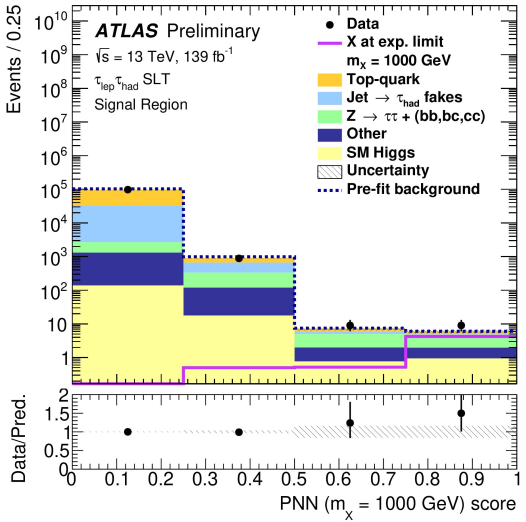


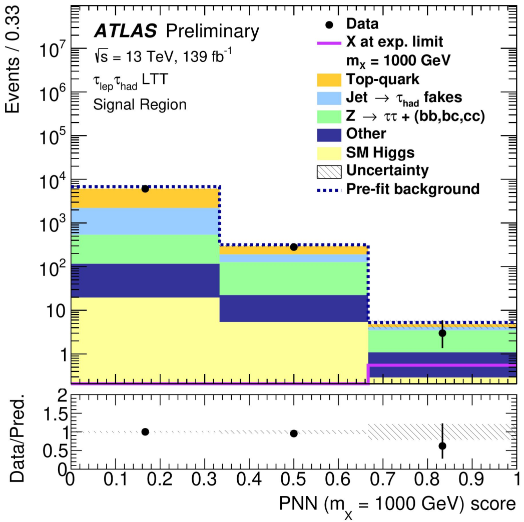




HH->bbττ: Resonant







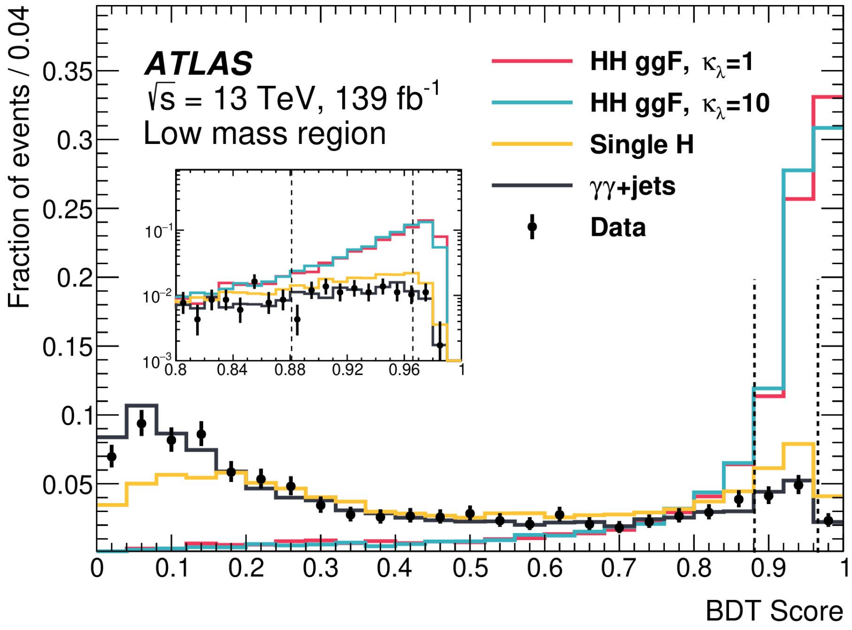
HH->bbɣɣ: Variables used in the BDT for the resonant analysis

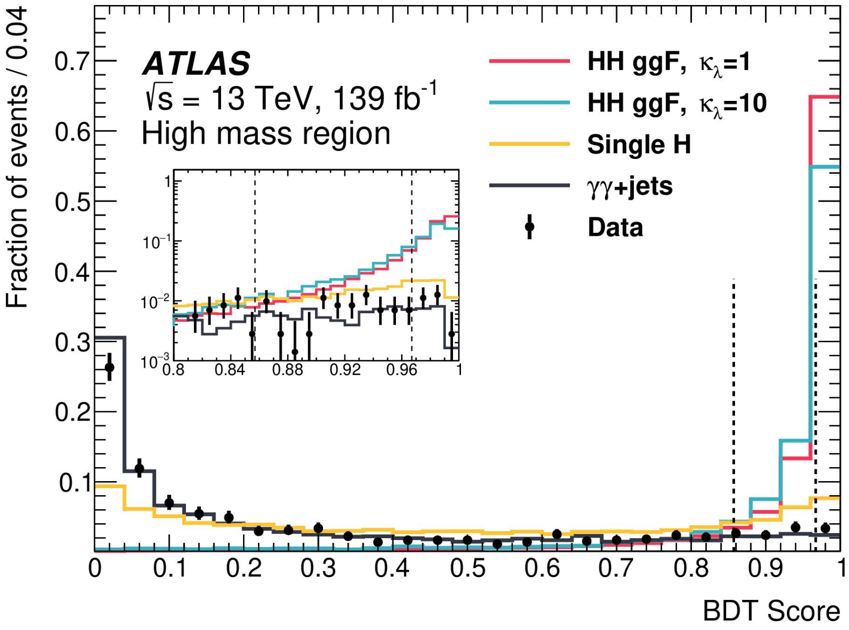
Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the diphoton system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angle and ΔR between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}$, $p_{\mathrm{T}}^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the b-tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angle and ΔR between the two b-tagged jets
N_{jets} and $N_{b\text{-jets}}$	Number of jets and number of b-tagged jets
H_{T}	Scalar sum of the p_{T} of the jets in the event
Diphoton+dijet-related kinematic variables	
$m^{*}_{b\bar{b}\gamma\gamma}$	Invariant mass of the diphoton plus b-tagged jets system
$\Delta y_{\gamma\gamma,b\bar{b}}$, $\Delta\phi_{\gamma\gamma,b\bar{b}}$ and $\Delta R_{\gamma\gamma,b\bar{b}}$	Distance in rapidity, azimuthal angle and ΔR between the diphoton and the b-tagged jets system
Missing transverse momentum variables	
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum

HH->bbɣɣ: Variables used in the BDT for the non-resonant analysis

Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}/m_{\gamma\gamma}$	Transverse momentum of each of the two photons divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of the leading and subleading photon
Jet-related kinematic variables	
b-tag status	Tightest fixed b-tag working point (60%, 70%, or 77%) that the jet passes
p_{T}, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_{\mathrm{T}}^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the b-tagged jets system
$m_{b\bar{b}}$	Invariant mass of the two jets with the highest b-tagging score
H_{T}	Scalar sum of the p_{T} of the jets in the event
Single topness	For the definition, see Eq. (**??**)
Missing transverse momentum variables	
$E_{\mathrm{T}}^{\mathrm{miss}}$ and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

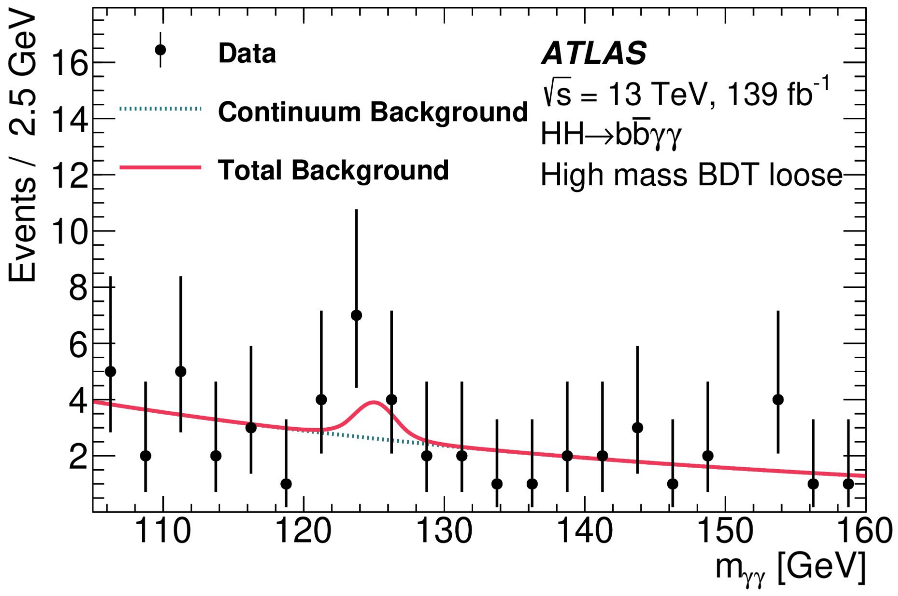
HH->bbɣɣ: BDT for the non-resonant analysis



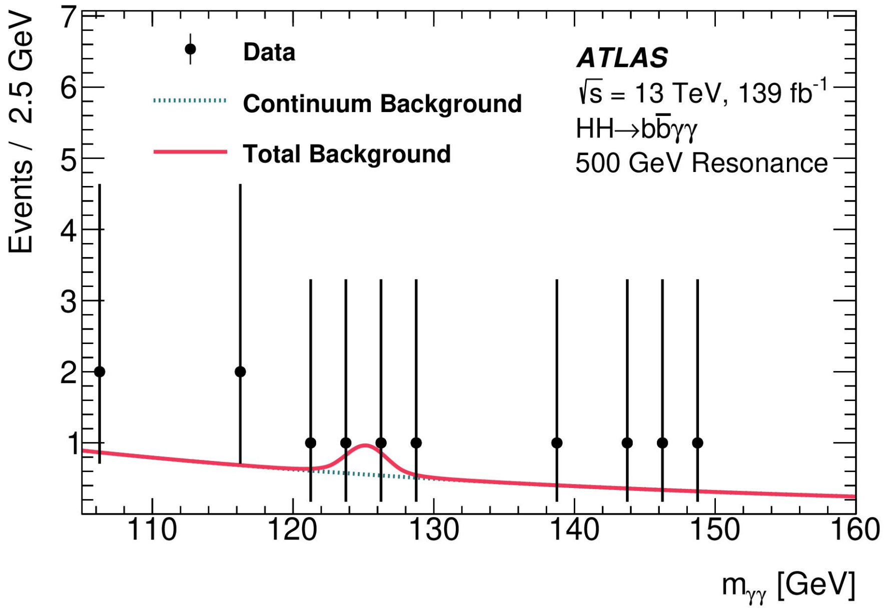


HH->bbγγ

Non-Resonant channel:



Resonant channel:



HL-LHC Prospects for di-Higgs

- **The High Luminosity LHC (HL-LHC) plans:**
  - Deliver **3000**-4000 fb^{-1} integrated luminosity at $\sqrt{s}$ = 14 TeV
  - p-p collisions

- ➔ **HL-LHC prospects for HH→bbττ** [ATL-PHYS-PUB-2021-044]
- ➔ **HL-LHC prospects for HH→bbγγ** [ATL-PHYS-PUB-2022-001]
- ➔ **HL-LHC Prospects for HH (bbγγ + bbττ combination)** [ATL-PHYS-PUB-2022-005]

- **Basis of the projection studies**
  - Extrapolate from the full Run 2 **HH→bbγγ** and **HH→bbττ** analysis
    - 139 fb^{-1} at $\sqrt{s}$ = 13 TeV
  - Assume Run 2 object reconstruction and identification efficiencies
  - Assume **3000 fb^{-1}** integrated luminosity at **$\sqrt{s}$ = 14 TeV**

Extrapolation procedure:

1. Scale signals and backgrounds by $L = \frac{L_{HL-LHC}}{L_{Run2}}$
2. Change of cross-sections to account for $\sqrt{s}$ = 14 TeV
3. Consider different systematics scenarios

Systematics Scenarios

[ATL-PHYS-PUB-2022-005]

Systematics Scenarios:

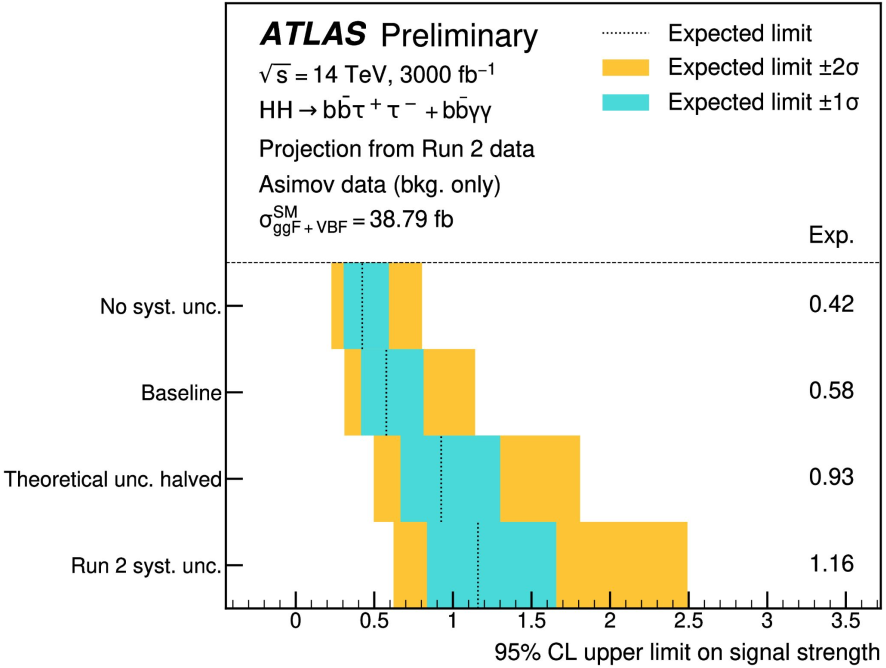
1. No systematic uncertainties
2. **Baseline Systematics**
3. Theoretical uncertainties halved
   a. Run 2 systematics uncertainties everywhere else
4. Run 2 systematics uncertainties

Baseline Systematics

- Uncertainty on integrated **luminosity** ~1% (1.7 % in Run 2)
- **Theoretical** uncertainties halved
- Statistical uncertainties on **Monte Carlo** samples neglected
- **Experimental** uncertainties
  - Statistical competent scaled by 1/√L
  - Detector components kept the same or modified according to detector and performance upgrades
- **bbɣɣ** specific uncertainties:
  - Spurious signal neglected
  - Uncertainty on Higgs boson mass 20 MeV (240 MeV in Run 2)

Combination results for bbɣɣ and bbττ

[ATL-PHYS-PUB-2022-005]



Projected 95% CL upper limits on the expected signal strength for SM HH production:

- Expected exclusion at more than 99% CL for “no systematics” and “baseline” scenarios
  - **3.2 σ (4.6 σ) significance** “baseline” (“no systematics”) scenarios
- Expected accuracy $^{+34\%}_{-31\%}$ (23%) “baseline” (“no systematics”)

Combination results

[ATL-PHYS-PUB-2022-005]

- **1σ confidence interval** **$\kappa_\lambda \in [0.5,1.5]$ ([0.6,1.5])** in baseline (no systematics) scenario
- Main limitations to the HH sensitivity
  - **HH→bbɣɣ**
    - Background modelling uncertainties
  - **HH→bbττ**
    - Theoretical uncertainties on:
      - σ_{HH}
      - Additional heavy-flavour jet radiation in some single H production modes
    - Limited size of simulated event samples