Search for Higgs boson pair production in $\gamma\gamma$bb final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Zihang Jia[1,2]

[1]IHEP, [2]Nanjing University

Outline

- **Motivation**
- **Analysis overview**
- **Categorization**
- **Signal and backgound modeling**
- **Results**
- **Summary**

ATLAS-CONF-2021-016 (this talk)

JHEP 11 (2018) 040 (ATLAS 36 fb^{-1})

JHEP 03 (2021) 257 (CMS)

ATLAS-PHYS-PUB-2021-031 (HH summary)

Motivation – HH production

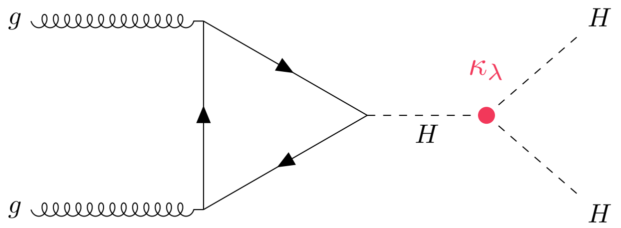
➢ Measuring **HH production** gives us access to the **trilinear Higgs self-coupling (λ_{HHH}).**

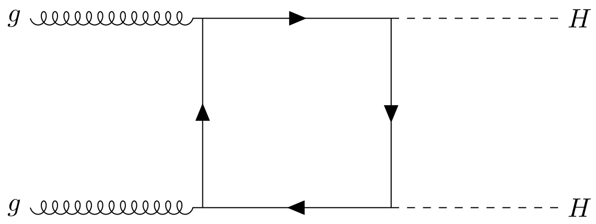
$$\boldsymbol{\kappa_\lambda} = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

SM LHCHWGHH

Gluon-gluon fusion (ggFHH)

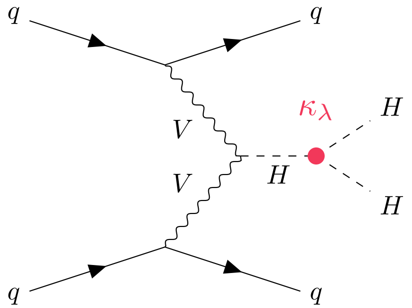
- σNNLO = **31.02** [fb] @13 TeV, mH = 125.09 GeV

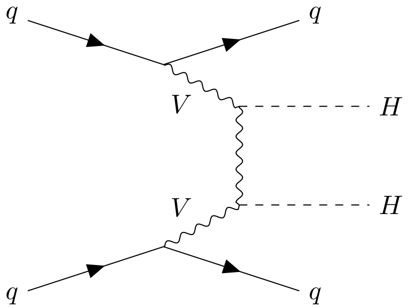


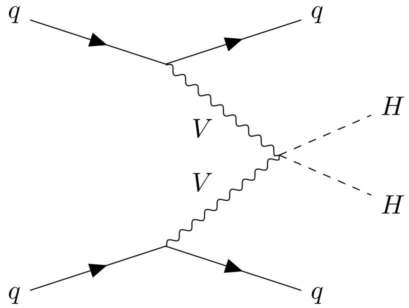


Vector boson fusion (VBFHH)

- σN3LO = **1.723** [fb] @13 TeV, mH = 125.09 GeV







BSM enhancement

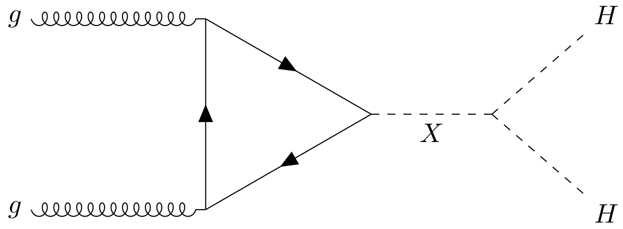
Non-resonant HH production

- Anomalous couplings ($\boldsymbol{\kappa_\lambda} \neq 1$, etc.)

Resonant HH production

- Two Higgs Doublet Model

  X: a narrow-width scalar particle



HH$\gamma\gamma bb$ Analysis overview

Search for Non-resonant and Resonant HH production in $\boldsymbol{\gamma\gamma bb}$ **channel** (full Run2 data, 139 fb^{-1}).

One of the most sensitive HH final states:

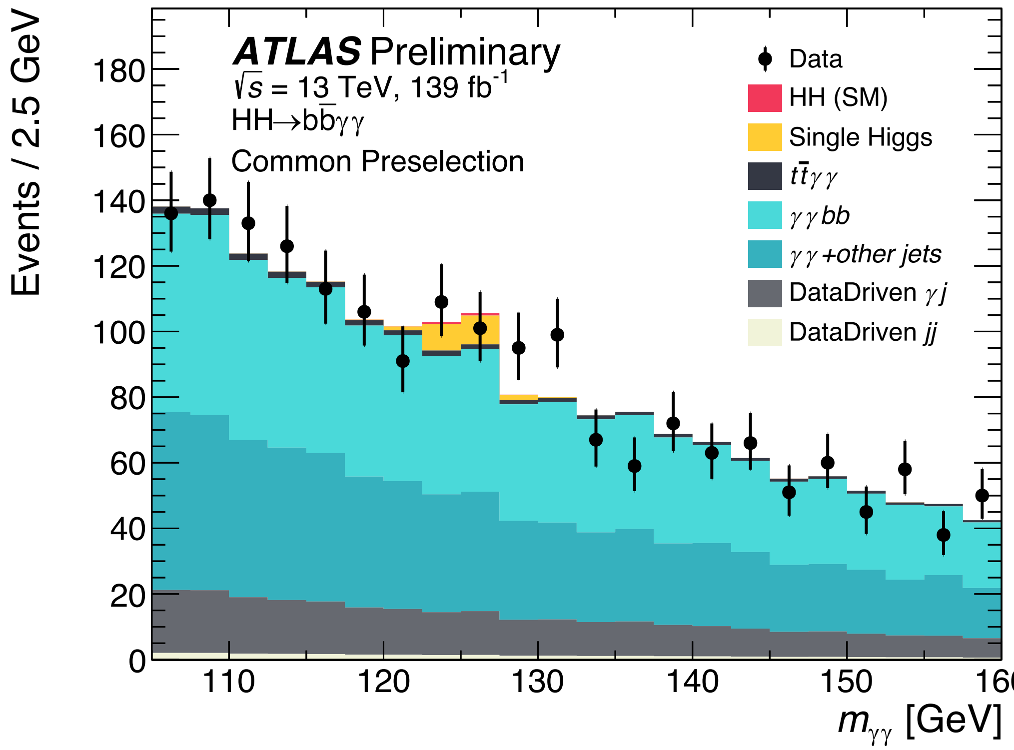
- Large branching ratio for $H \to bb$
- Excellent photon resolution and relatively small background for $H \to \gamma\gamma$

Main backgrounds

- Non-resonant $\gamma\gamma$ backgrounds
- Single Higgs production

Common Preselection

- Triggered by the presence of 2 photons
- 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- Fewer than 6 central jets (reject ttH events)
- Exactly 2 b-tagged jets (77% DL1r b-tagging efficiency)
- Veto events containing an electron or muon



Categorization

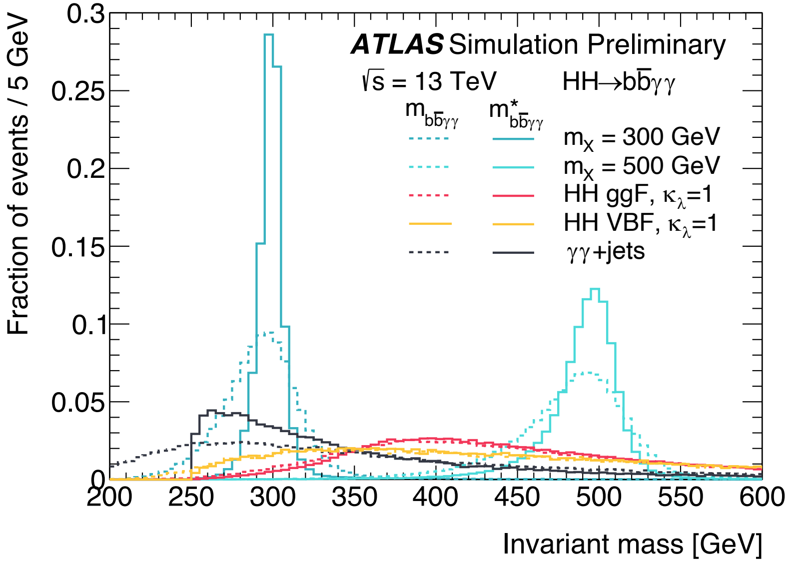
Non-resonant analysis: target SM HH → $\gamma\gamma bb$ processes, and possible modifications to κ_λ.

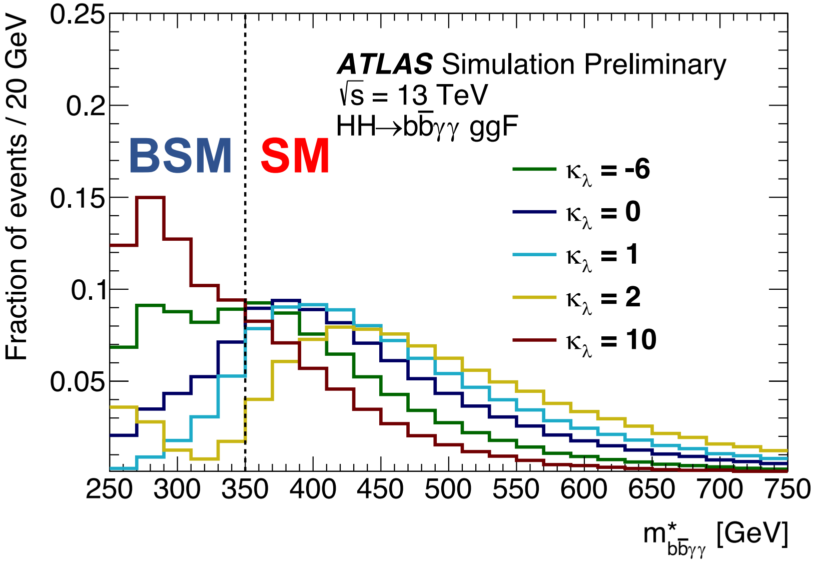
Target mainly ggF HH production, but VBF HH events also considered as signal

Signal regions defined using $m^*_{\gamma\gamma bb}$ and BDT score

- **Modified invariant mass $m^*_{\gamma\gamma bb} = m_{\gamma\gamma bb} - m_{\gamma\gamma} - m_{bb} + 250\ GeV$**

- Provides cancellation of experimental resolution effects
- Low and high mass categories provide enhanced sensitivity to κ_λ





Low mass region
Targeting BSM
$m^*_{\gamma\gamma bb} < 350\ GeV$

High mass region
Targeting SM
$m^*_{\gamma\gamma bb} > 350\ GeV$

Categorization

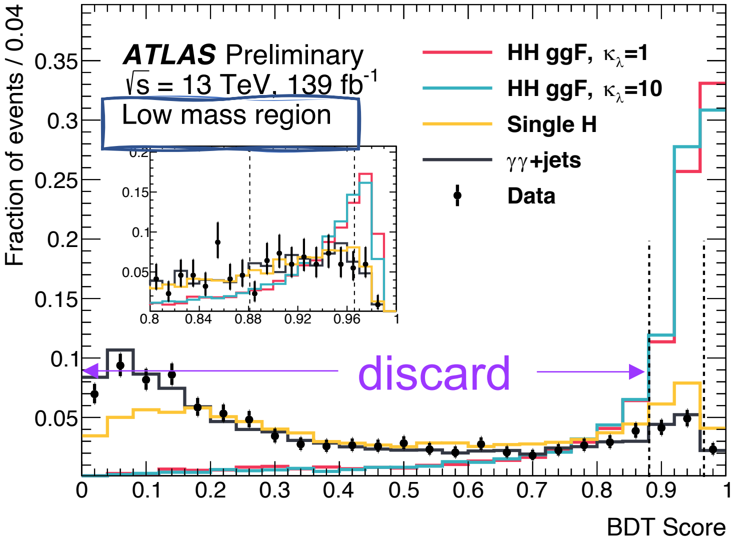
Non-resonant analysis: target SM HH → $\gamma\gamma bb$ processes, and possible modifications to κ_λ.

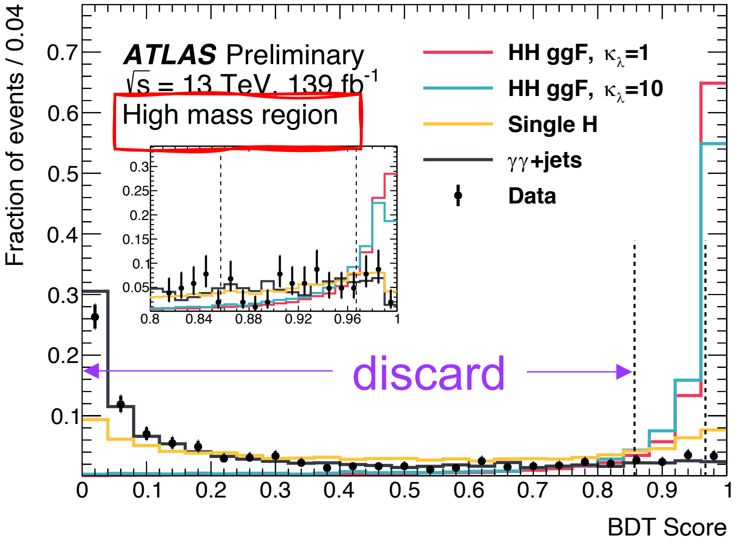
Target mainly ggF HH production, but VBF HH events also considered as signal

Signal regions defined using $m^*_{\gamma\gamma bb}$ and BDT score

➢ **Boosted Decision Tree**

- Against $\gamma\gamma$ and single Higgs backgrounds
- BDT trained on photon, jet and missing transverse energy variables





Low mass region
Signal: κ_λ =10 ggF HH
Loose
Tight

High mass region
Signal: κ_λ =1 ggF HH
Loose
Tight

Categorization

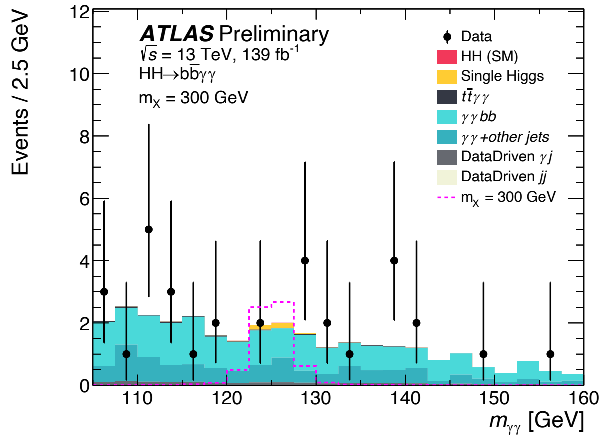
Resonant analysis: target BSM HH → $X \to \gamma\gamma bb$ processes, with $m_X \in [251, 1000]$ GeV.

Non-resonant SM HH production included as background

Signal regions defined using $m^*_{\gamma\gamma bb}$ and BDT score

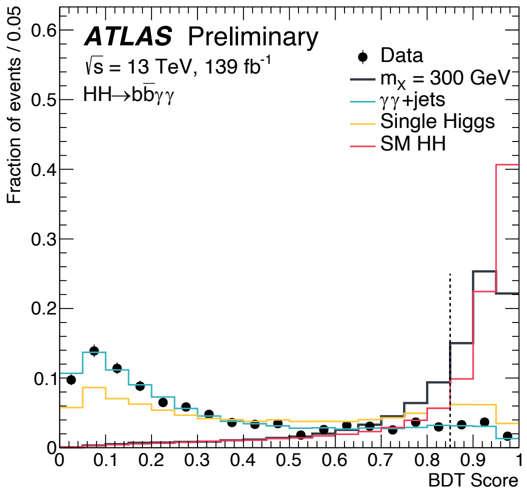
➢ **Modified invariant mass**

- 2σ window cut around each mass hypothesis of the resonance



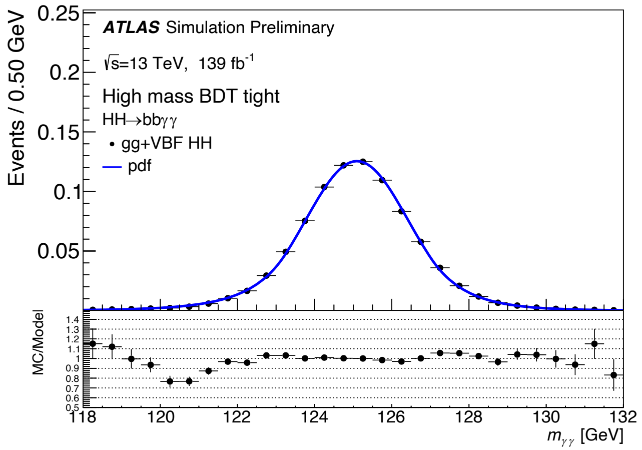
➢ **Boosted Decision Tree**

- Shared by all resonance masses to avoid lack of background at high mass
- BDTs trained on photon, jet and missing transverse energy variables
- Two BDTs against $\gamma\gamma$+$tt\gamma\gamma$ and single Higgs backgrounds respectively
- For each m_X, cut on the combined BDT score.



Signal and background modeling

Maximum likelihood fit performed on $m_{\gamma\gamma}$ simultaneously with all the categories.
(Non-resonant: 4 categories; Resonant: 1 category for each m_X)



➢ Signal parameterization

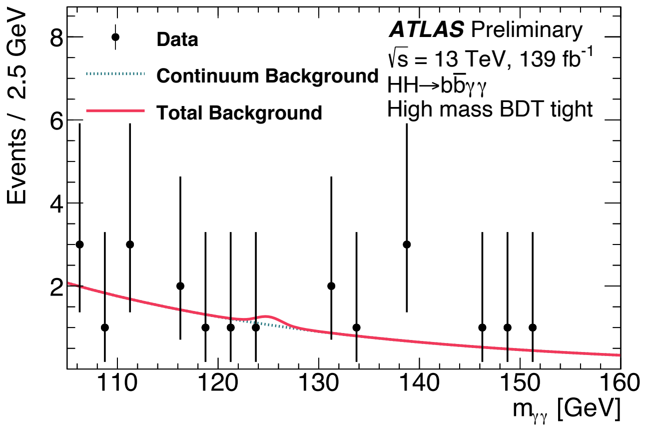
Normalization fixed to SM, shape from a **double sided crystal ball (DSCB)** fit to MC

Non-resonant

- Fit to SM HH signal, model shared with H background

Resonant

- Fit to resonance signals, model shared with SM HH and H background



➢ Background parameterization

Normalization floating, shape from a **exponential function** fit to data

- Function form determined from **spurious signal** studies

Observed (Expected) Results

Limits at 95%CL are set based on the profile likelihood ratio approach.

Non-resonant

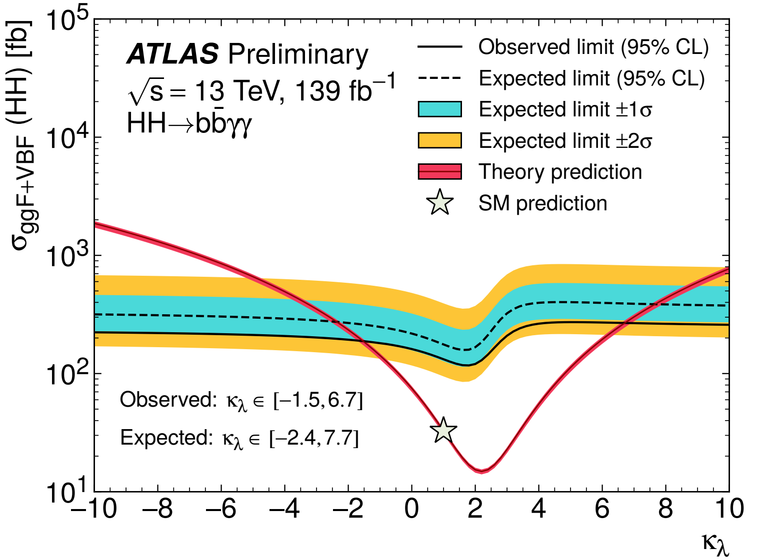
- μ_{HH} **limit**: 4.1 x SM (5.5 x SM)
- κ_λ **interval**: [−1.5, 6.7] ([−2.4, 7.7])

~ 5 improvement w.r.t 36 fb^{-1}
~2 from increase of lumi
~2.5 from analysis strategy

Shrinks by a factor of ~2

ATLAS 36 fb^{-1} [JHEP 11 (2018) 040]
μ_{HH} **limit:** 22 (28) x SM
κ_λ **interval:** [-8.2, 13.2] ([-8.3, 13.2])

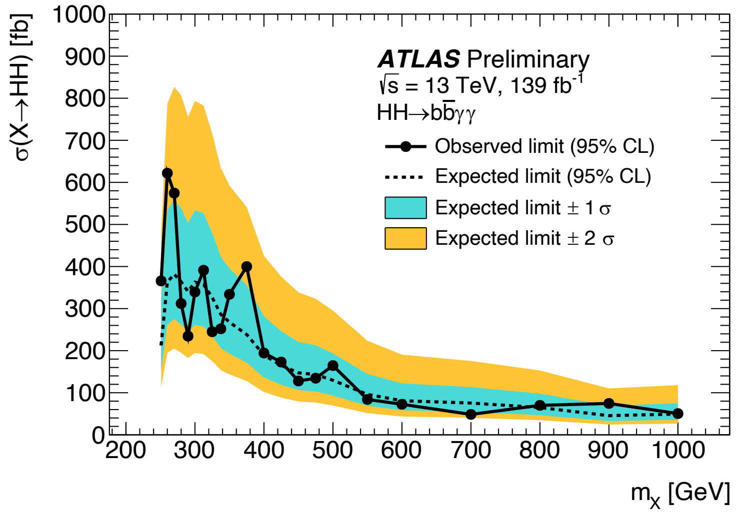
CMS [JHEP 03 (2021) 257]
μ_{HH} **limit:** 7.7 (5.2) x SM
κ_λ **interval:** [-3.3, 8.5] ([-2.5, 8.2])



Resonant

- **XS limits** vary between 610-47 fb (360-43 fb)

~2-3 improvement depending on the m_X value
~2 from increase of lumi; ~1.2 from analysis strategy
Expands the analyzed mass range of the resonance search to lower values.



Summary

Searches for non-resonant and resonant HH production are performed in the $bb\gamma\gamma$ final state (139 fb^{-1}).

No significant excess with respect to the SM background expectation is observed.

Improvement compared to the previous ATLAS result based on 36 fb^{-1} of 13 TeV pp collisions

- Extends the data set by more than a factor of 4
- Incorporates a categorization based on $m^{*}_{\gamma\gamma bb}$ and multivariate event selections
- More precise object reconstruction and calibration

Publication of the Run 2 paper soon.

Preparing the dedicated analysis for VBFHH signal.

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

NANJING UNIVERSITY 1902

ATLAS EXPERIMENT

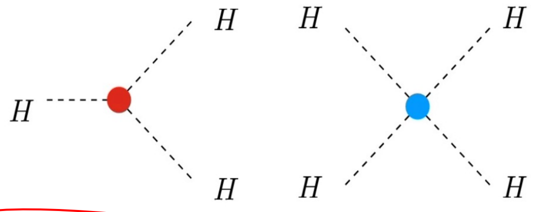
Thanks!

Motivation – Higgs self-coupling

- **The Higgs boson** completes the Standard Model of Particle Physics.
- However, the shape of **the Higgs potential** has yet to be measured.
- We can probe the Higgs potential by measuring the **Higgs self-coupling (λ)**.

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

$$V(\nu + h) = V_0 + \frac{1}{2}{m_h}^2 h^2 + \lambda v h^3 + \lambda h^4 + \ldots$$



$$\boxed{\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}}$$

Background Samples

Table 1: Summary of single Higgs boson background samples, split by production modes, and continuum background samples. The generator used in the simulation, the PDF set, and tuned parameters (tune) are also provided.

Process	Generator	PDF set	Showering	Tune
ggF	NNLOPS [65–67] [68, 69]	PDFLHC [42]	PYTHIA 8.2 [70]	AZNLO [71]
VBF	POWHEG BOX v2 [39, 66, 72–78]	PDFLHC	PYTHIA 8.2	AZNLO
WH	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$qq \to ZH$	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$gg \to ZH$	POWHEG BOX v2	PDFLHC	PYTHIA 8.2	AZNLO
$t\bar{t}H$	POWHEG BOX v2 [73–75, 78, 79]	NNPDF3.0nlo [80]	PYTHIA 8.2	A14 [81]
bbH	POWHEG BOX v2	NNPDF3.0nlo	PYTHIA 8.2	A14
$tHqj$	MADGRAPH5_aMC@NLO	NNPDF3.0nlo	PYTHIA 8.2	A14
tHW	MADGRAPH5_aMC@NLO	NNPDF3.0nlo	PYTHIA 8.2	A14
$\gamma\gamma$+jets	SHERPA v2.2.4 [56]	NNPDF3.0nnlo	SHERPA v2.2.4	–
$t\bar{t}\gamma\gamma$	MADGRAPH5_aMC@NLO	NNPDF2.3lo	PYTHIA 8.2	–

Common selections

On top of the trigger requirements, events are selected if:

- there are at least two photons passing the object selection criteria detailed in Section 4.1;
- the di-photon invariant mass, built with the two leading photons, satisfies 105 GeV < $m_{\gamma\gamma}$ < 160 GeV;
- the leading (sub-leading) photon p_T is larger than 35% (25%) of the mass of the di-photon system;
- there are exactly two b-tagged jets;
- no electrons or muons are present;
- fewer than six central ($|\eta|$ < 2.5) jets are required, to help rejecting $t\bar{t}H$ events where the top quarks decay hadronically.

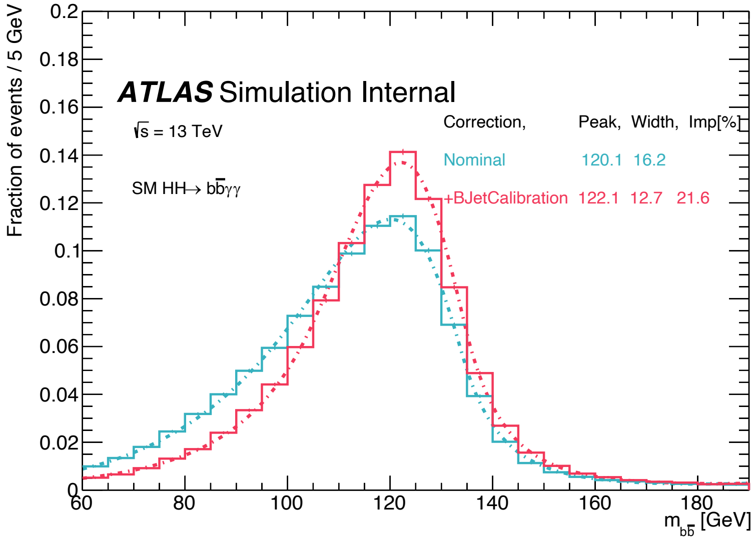
- $p_T^{\gamma 1} > 35\ GeV,\ p_T^{\gamma 2} > 25\ GeV$
- Photon Tight ID, FixedCutLoose
- $105 < m_{\gamma\gamma} < 160\ GeV$
- $p_T^{\gamma 1}/m_{\gamma\gamma} > 0.35,\ p_T^{\gamma 2}/m_{\gamma\gamma} > 0.25$
- $N_{photon} \geq 2$
- $N_{b77\ jets} = 2$
- $N_{lepton} = 0$
- $N_{central\ jets} < 6$

H(bb̄)

- PFlow jets (AntiKt4PFlowCustomVtxHggJets) with pT > 25 GeV and $|\eta|$<2.5 passing JetVertexFraction (JVT) tight and Jet cleaning
- Exactly 2 b-jets passing the 77% DL1r b-tagging WP and ranked by pT

  mbb̄ resolution improved by a muon-in-jet correction, as well as a pT-reco correctic to account for pT loss due to neutrinos and objects outside of the jet cone.

  - **Resolution improves by about 22%**



Non-resonant BDT variables

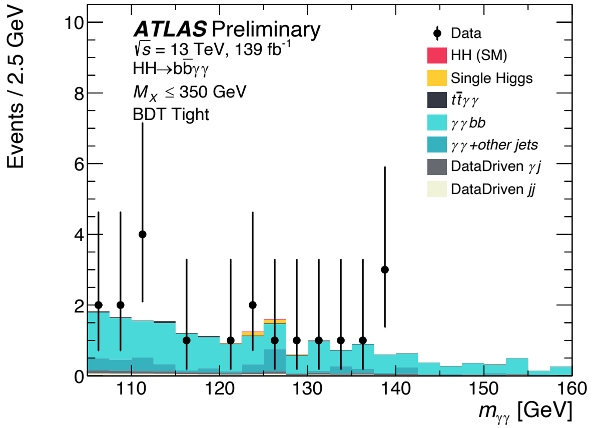
Table 2: Variables used in the BDT for the non-resonant analysis. The b-tag status identifies the highest fixed b-tag working point (60%, 70%, 77%) that the jet passes. All vectors in the event are rotated so that the leading photon ϕ is equal to zero.

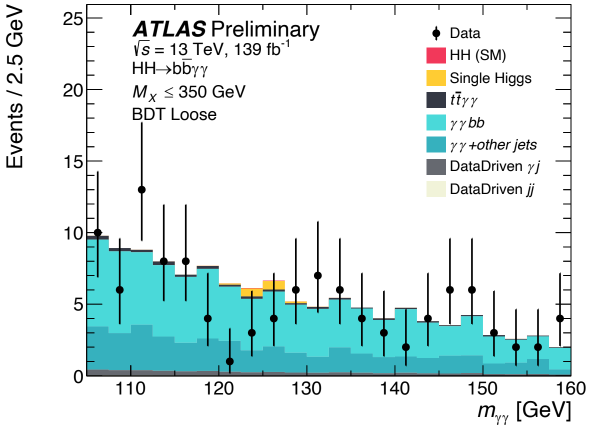
Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
b-tag status	Highest fixed b-tag working point that the jet passes
p_{T}, η and ϕ	Transverse momentum, pseudo-rapidity 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, pseudo-rapidity and azimuthal angle of b-tagged jets system
$m_{b\bar{b}}$	Invariant mass built with 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. (1)
Missing transverse momentum-related variables	
$E_{\mathrm{T}}^{\mathrm{miss}}$ and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

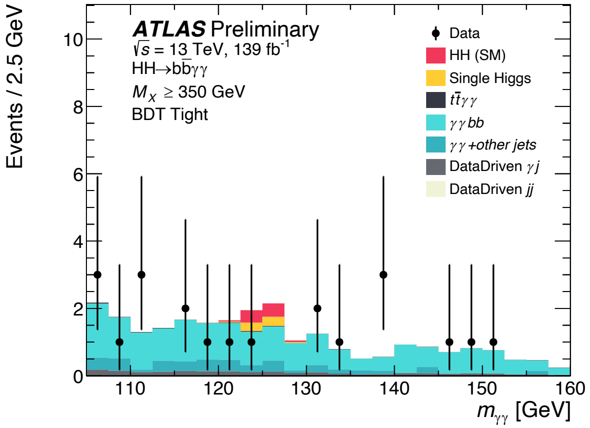
Categorization

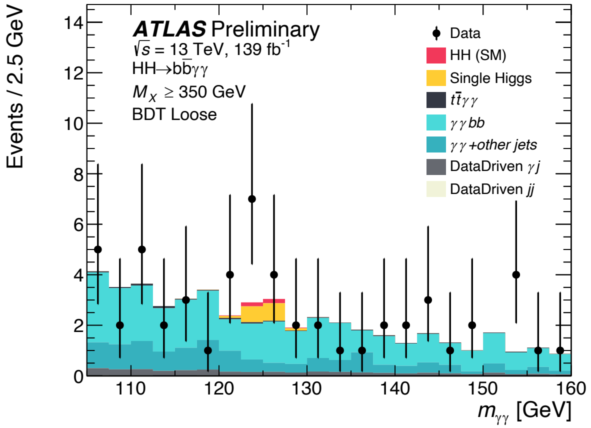
$$Z = \sqrt{2 * [(s+b) * \log(1 + s/b) - s]}$$

Low mass region | **High mass region**









Resonant BDT variables

Table 4: Variables used in the BDT for the resonant analysis. For variables depending on b-tagged jets, only jets b-tagged using the 77% working point are considered as described in Section 4.1.

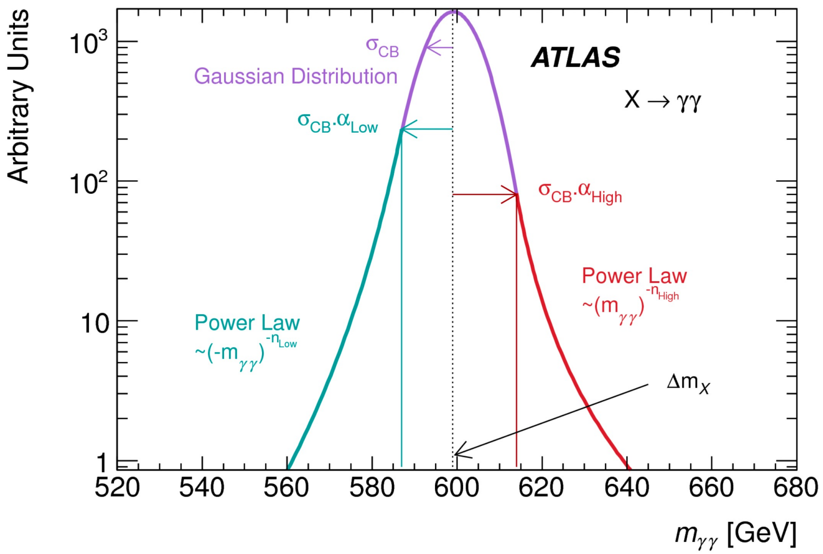
Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the di-photon system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angular distance and ΔR between the two photons
Jet-related kinematic 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 angular distance and ΔR between the two b-tagged jets
N_{jets} and $N_{b-\mathrm{jets}}$	Number of jets and number of b-tagged jets
H_{T}	Scalar sum of the p_{T} of the jets in the event
Photons and jets-related kinematic variables	
$m_{b\bar{b}\gamma\gamma}$	Invariant mass built with the di-photon and 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 di-photon and the b-tagged jets system

$$\mathrm{BDT}_{\mathrm{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}}\sqrt{C_1^2\left(\frac{\mathrm{BDT}_{\gamma\gamma}+1}{2}\right)^2 + C_2^2\left(\frac{\mathrm{BDT}_{\mathrm{Single}H}+1}{2}\right)^2}$$

Signal modeling - DSCB

A Gaussian core + asymmetric power law tails

$$f_{\mathrm{DSCB}}(m_{\gamma\gamma}) = N \times \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{low} \leq t \leq \alpha_{high} \\ \dfrac{e^{-\frac{1}{2}\alpha_{low}^2}}{\left[\frac{1}{R_{low}}\left(R_{low} - \alpha_{low} - t\right)\right]^{n_{low}}} & \text{if } t < -\alpha_{low} \\ \dfrac{e^{-\frac{1}{2}\alpha_{high}^2}}{\left[\frac{1}{R_{high}}\left(R_{high} - \alpha_{high} + t\right)\right]^{n_{high}}} & \text{if } t > \alpha_{high} \end{cases}$$



where N is a normalization factor and the six parameters are

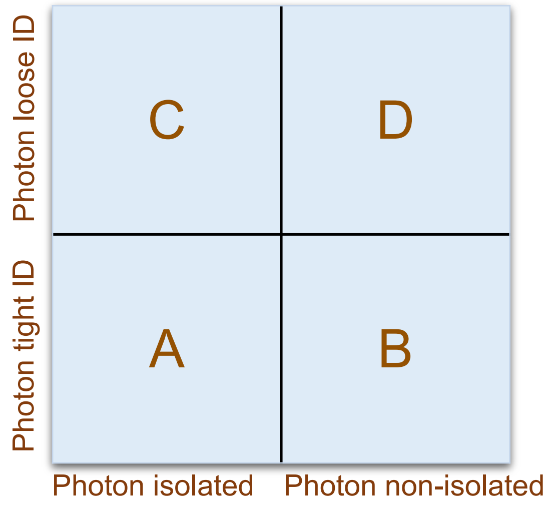
- μ_{CB} and σ_{CB} describe the mean and the width of the Gaussian core, which are combined in $t = \left(m_{\gamma\gamma} - \mu_{\mathrm{CB}}\right)/\sigma_{\mathrm{CB}}$;
- α_{low} and α_{high} are the positions of the transitions with respect to μ_{CB} from the Gaussian core to power-law tails, in unit of σ_{CB}, on the low and high mass sides respectively;
- n_{low} and n_{high} are the exponents of the low and high mass tails. With the α's, they define $R_{low} = \frac{n_{low}}{\alpha_{low}}$ and R_{high} similarly.

Diphoton background decomposition

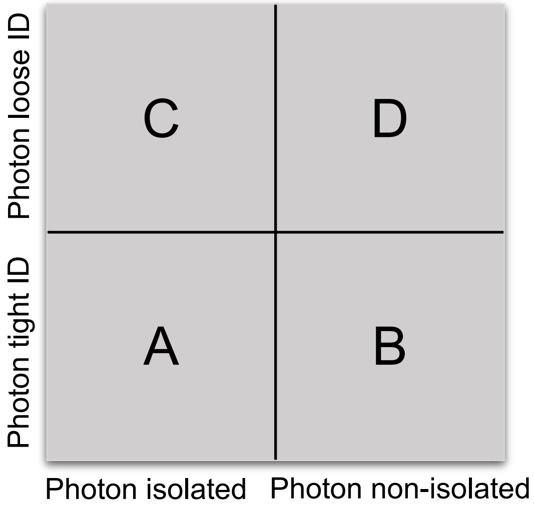
Reconstructed $\gamma\gamma$ events is mainly composed of $\gamma\gamma$, γ-jets and jet-jet events, where the jet(s) fake(s) a real photon.

The 2x2D sideband method is developed using the discriminating power of photon identification and isolation criteria.

The event yields in the signal region and the 15 sidebands can be expressed as **functions** of the photon efficiencies, jet fake rates and correlation coefficients.



Leading object



Sub-leading object

CC	CD	DC	DD
CA	CB	DA	DB
AC	AD	BC	BD
AA	AB	BA	BB

Reference

Suffers from low statistics, not used in constructing the background templates for the spurious signal procedure.

Spurious signal

Spurious signal: bias estimated from a signal + background fit to a background-only MC template.

$$N_{sp} = \max_{121<m_H<129\ GeV} |N_s(m_H)|$$

- **Selection criteria:**

- The function should satisfy at least one of the following criteria:

Nominal criteria

$$N_{sp} < 10\%\ N_{s,exp}$$

or

$$N_{sp} < 20\%\ \sigma_{bkg}$$

Relaxed criteria (for low-statistic bkg MC)

$$\boldsymbol{N_{sp}} = \zeta_s(m_{\gamma\gamma}) = \begin{cases} N_s + 2\Delta_{MC}, & N_s + 2\Delta_{MC} < 0 \\ N_s - 2\Delta_{MC}, & N_s - 2\Delta_{MC} > 0 \\ 0, & \text{otherwise} \end{cases}$$

- $N_{s,exp}$ = expected SM signal events
- σ_{bkg} = stat. uncertainty on Nsig when fitting the sig+bkg model to the asimov dataset
- Δ_{MC} = local statistical fluctuation of the MC background template

- The function must satisfy a simple χ^2 requirement in a background-only fit to the MC template:

$$p - value(\chi^2) > 1\%$$

The χ^2 is computed with a background template uniformly binned over 105 < $m\gamma\gamma$ < 160 GeV.

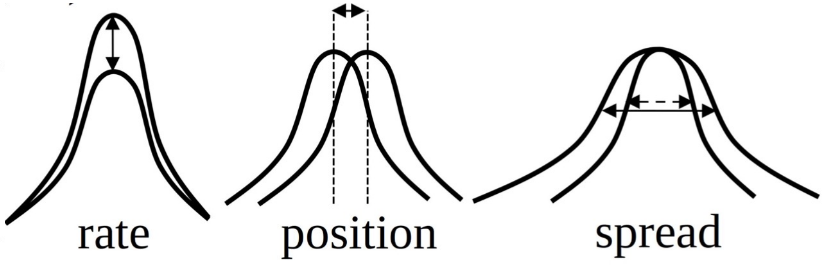
- **The least number of parameters** is preferred.
- The **smaller systematic uncertainty** (spurious signal) is preferred.

Wald tests show that the data do not prefer a higher degree functional form with respect to the exponential form.

Systematic uncertainties

In general the analysis is almost completely statistically dominated with the Run 2 dataset

		Relative impact of the systematic uncertainties in %	
Source	Type	Non-resonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy scale	Norm. + Shape	5.2	2.7
Photon energy resolution	Norm. + Shape	1.8	1.6
Flavor tagging	Normalization	0.5	< 0.5
Theoretical			
Heavy flavor content	Normalization	1.5	< 0.5
Higgs boson mass	Norm. + Shape	1.8	< 0.5
PDF+α_s	Normalization	0.7	< 0.5
Spurious signal	Normalization	5.5	5.4



Statistical model

Likelihood

$$\mathcal{L} = \prod_{c} \left(\mathrm{Pois}(n_c | \boxed{N_c(\boldsymbol{\theta})}) \cdot \prod_{i=1}^{n_c} \boxed{f_c(m_{\gamma\gamma}^{i}, \boldsymbol{\theta})} \cdot G(\boldsymbol{\theta}) \right)$$

Event parameterization

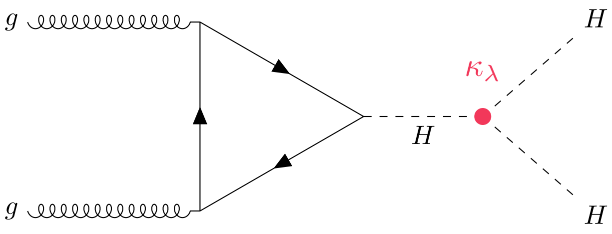
$$\boxed{N_c(\boldsymbol{\theta})} = \mu \cdot N_{HH,\mathrm{c}}(\boldsymbol{\theta}_{HH}^{\mathrm{yield}}) + N_{\mathrm{bkg,c}}^{\mathrm{res}}(\boldsymbol{\theta}_{\mathrm{res}}^{\mathrm{yield}}) + N_{\mathrm{SS,c}} \cdot \boldsymbol{\theta}^{\mathrm{SS,c}} + N_{\mathrm{bkg,c}}^{\mathrm{non-res}}$$

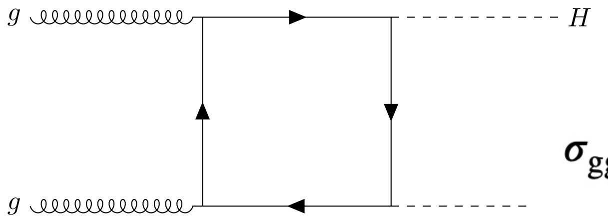
Model PDF

$$\boxed{f_c(m_{\gamma\gamma}, \boldsymbol{\theta})} = [\mu \cdot N_{HH,\mathrm{c}}(\boldsymbol{\theta}_{HH}^{\mathrm{yield}}) \cdot f_{HH,\mathrm{c}}(m_{\gamma\gamma}, \boldsymbol{\theta}_{HH}^{\mathrm{shape}}) + N_{\mathrm{bkg,c}}^{\mathrm{res}}(\boldsymbol{\theta}_{\mathrm{res}}^{\mathrm{yield}}) \cdot f_{\mathrm{bkg,c}}^{\mathrm{res}}(m_{\gamma\gamma}, \boldsymbol{\theta}_{\mathrm{res}}^{\mathrm{shape}})$$
$$+ N_{\mathrm{SS,c}} \cdot \boldsymbol{\theta}_{HH}^{\mathrm{SS,c}} \cdot f_{HH,\mathrm{c}}(m_{\gamma\gamma}, \boldsymbol{\theta}_{HH}^{\mathrm{shape}}) + N_{\mathrm{bkg,c}}^{\mathrm{non-res}} \cdot f_{\mathrm{bkg,c}}^{\mathrm{non-res}}(m_{\gamma\gamma}, \boldsymbol{\theta}_{\mathrm{non-res}}^{\mathrm{shape}})] / N_c(\boldsymbol{\theta}_{\mathrm{non-res}}^{\mathrm{yield}})$$

κ_λ reweighting for ggF HH samples

The method derives the scale factors as a function of κ_λ in **bins of m_{HH}** by performing a linear combination of samples generated at $\kappa_\lambda = 0, 1, 20$.





$$\mathcal{A}(\kappa_t, \kappa_\lambda) = \kappa_t^2 \mathcal{A}_1 + \kappa_t \kappa_\lambda \mathcal{A}_2$$

$$\sigma_{\mathrm{ggF}}(pp \to HH) \propto \int \kappa_t^4 \left[|\mathcal{A}_1|^2 + 2\left(\frac{\kappa_\lambda}{\kappa_t}\right) \mathfrak{R}(\mathcal{A}_1^* \mathcal{A}_2) + \left(\frac{\kappa_\lambda}{\kappa_t}\right)^2 |\mathcal{A}_2|^2 \right]$$

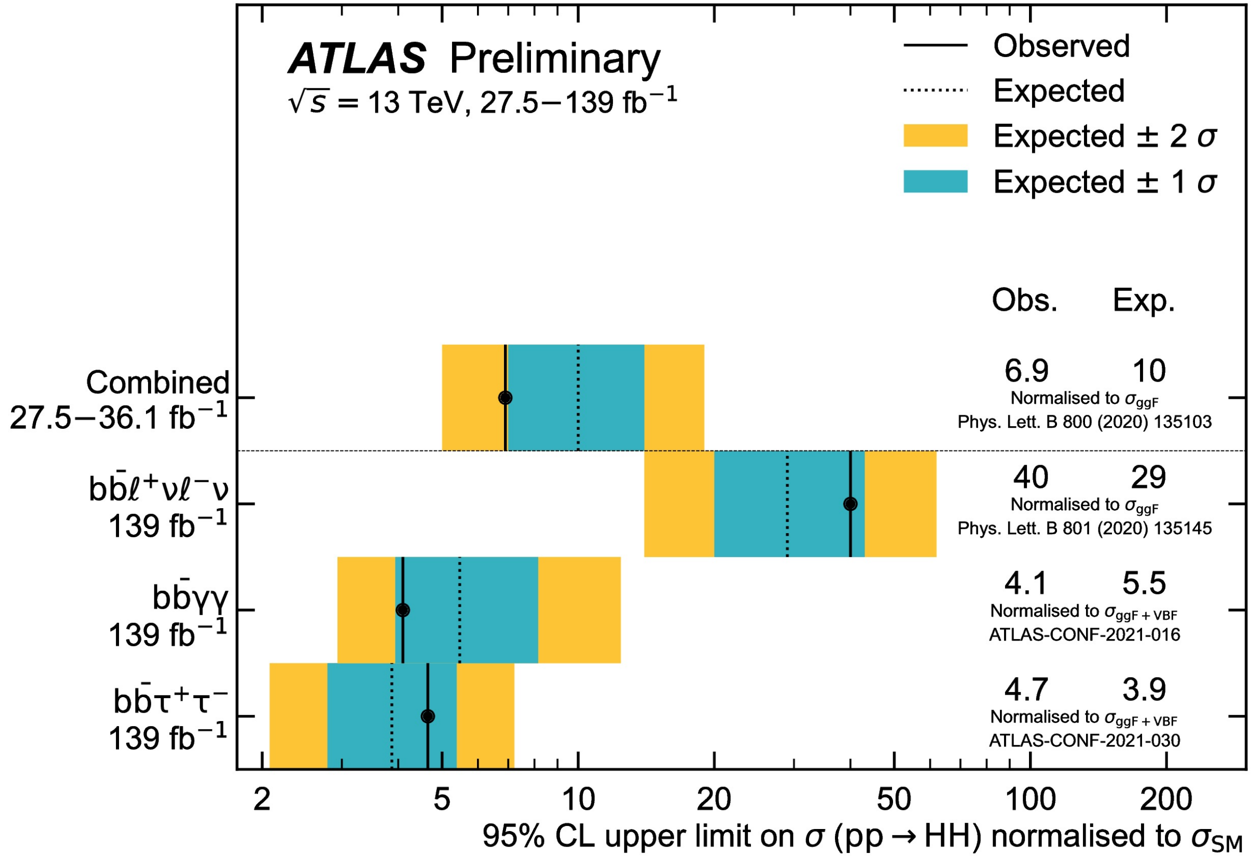
$$\sigma(\kappa_t = 1, \kappa_\lambda = 0) \sim |\mathcal{A}_1|^2$$

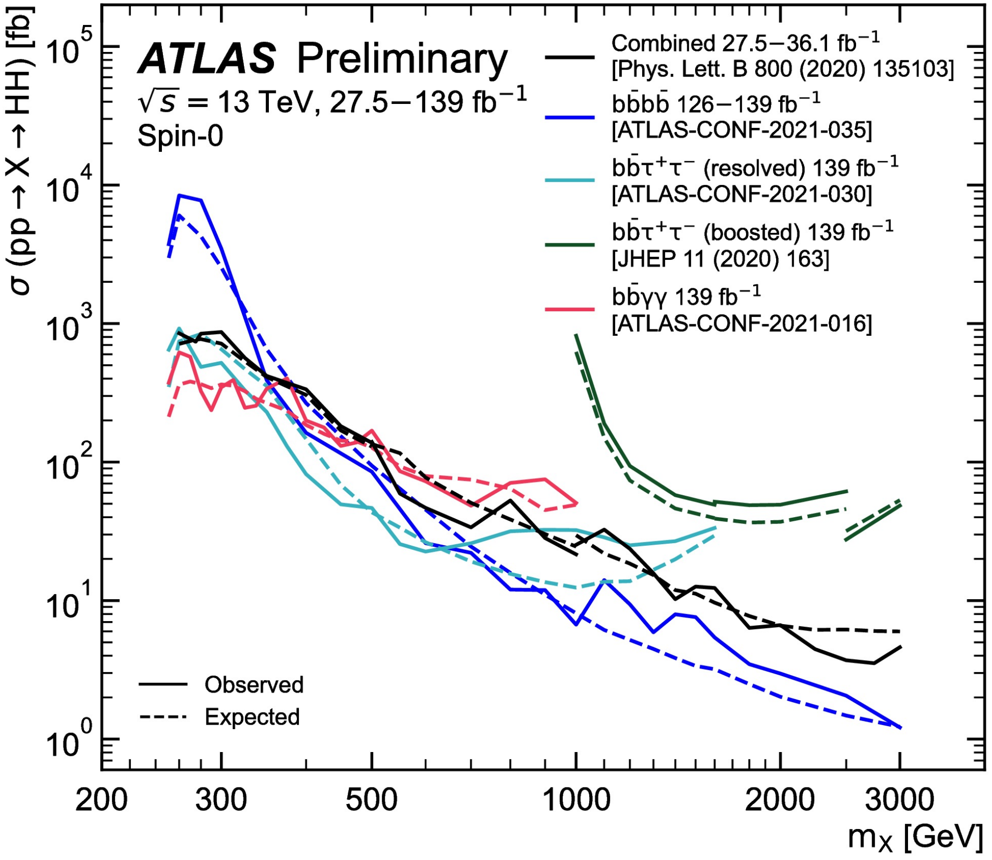
$$\sigma(\kappa_t = 1, \kappa_\lambda = 1) \sim |\mathcal{A}_1|^2 + 2\mathfrak{R}\mathcal{A}_1^* \mathcal{A}_2 + |\mathcal{A}_2|^2$$

$$\sigma(\kappa_t = 1, \kappa_\lambda = 20) \sim |\mathcal{A}_1|^2 + 2 \cdot 20\mathfrak{R}\mathcal{A}_1^* \mathcal{A}_2 + 20^2 |\mathcal{A}_2|^2$$

$$\sigma(\kappa_t, \kappa_\lambda) \sim \kappa_t^2 \Bigg[\left(\kappa_t^2 + \frac{\kappa_\lambda^2}{20} - \frac{399}{380}\kappa_\lambda \kappa_t\right) |S(1,0)|^2 + \left(\frac{40}{38}\kappa_\lambda \kappa_t - \frac{2}{38}\kappa_\lambda^2\right) |S(1,1)|^2 + \left(\frac{\kappa_\lambda^2 - \kappa_\lambda \kappa_t}{380}\right) |S(1,20)|^2 \Bigg]$$

HH summary





good sensitivity at low resonant masses